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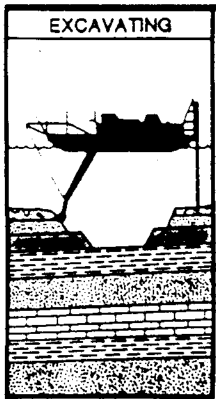
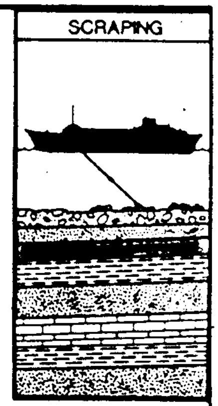
FINAL REPORT

SYNTHESIS AND ANALYSIS OF EXISTING INFORMATION REGARDING ENVIRONMENTAL EFFECTS OF MARINE MINING





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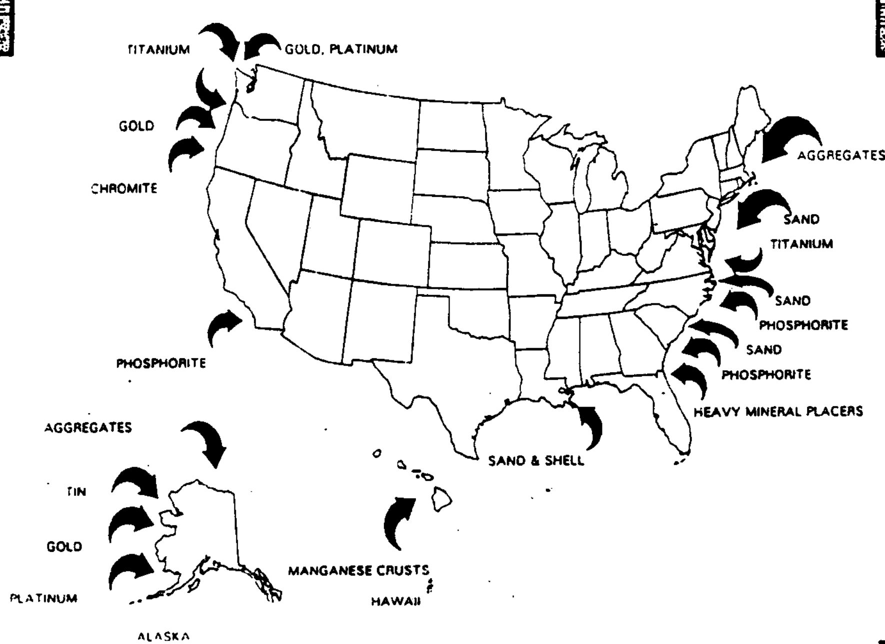

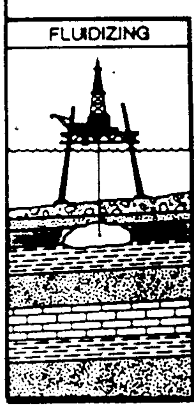

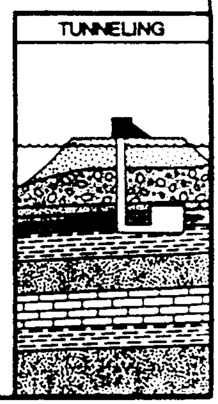

Prepared for:

MMS

U.S. Department of the Interior
Minerals Management Service
Office of International Activities
and Marine Minerals (INTERMAR)

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FINAL REPORT

Synthesis and Analysis of Existing Information Regarding Environmental Effects of Marine Mining

March 1993

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ACKNOWLEDGEMENTS

The Program Manager (Richard M. Hammer) and Scientific Editor (Brian J. Balcom) of Continental Shelf Associates, Inc. (CSA) wish to thank all of the participants in this program for helping to produce a comprehensive set of study products. We acknowledge and appreciate the team effort.

Michael J. Cruickshank and Charles L. Morgan served as Principal Authors for the program as independent consultants. They deserve special thanks for their contribution to the quality of the manuscript.

Barry S. Drucker was the Contracting Officer's Technical Representative for the Minerals Management Service (MMS), and George Valiulis was the MMS Contract Inspector. Both provided helpful technical guidance, assistance, and review throughout the course of the program.

Numerous individuals provided literature and information for the program. We especially appreciate the assistance of Kristen L. Metzger of the Harbor Branch Oceanographic Institution who conducted the computer literature searches and secured many documents for the program.

Several people at CSA other than the CSA Program Manager and Scientific Editor were instrumental to the successful completion of the program. David A. Gettleson provided direction and support throughout the program. Karen M. Daignault collected information relevant to the program through telephone calls and library visits. David B. Snyder, Luis M. Lagera, Jr., and Brock E. Stanaland wrote the annotations for the program. Alan D. Hart was responsible for the reference database. Suzanne R. Short prepared the figures and tables for the manuscript. Virginia A. Erbrick and Lynn A. Ugartemendia word processed the manuscript. Pamela S. Jones and Melody B. Powell coordinated the preparation of the deliverables, and were assisted by Deborah M. Cannon.

This study was funded by the Minerals Management Service, U.S. Department of the Interior, Washington, D.C., under Contract Number 14-35-0001-30588.

LIST OF ACRONYMS AND ABBREVIATIONS

ADCPs	acoustic Doppler current profilers
ADDAMS	Automated Dredged and Disposal Alternatives Management System
ATOS	anti-turbidity overflow system
BACT	Best Available Control Technology
BAT	Best Available Technology
BIE	Benthic Impact Experiment
BLM	Bureau of Land Management
CCOP	Committee for Coordination of Joint Prospecting for Mineral Resources in Asian Offshore Areas
CEQ	Council on Environmental Quality
CLB system	continuous line bucket system
CSA	Continental Shelf Associates, Inc.
DEIS	Draft Environmental Impact Statement
DIFCD	Disposal from a Continuous Dump
DIFHD	Disposal from a Hopper Dump
DIFID	Disposal from an Instantaneous Dump
DISCOL	Disturbance and Recolonization Experiment
DOD	U.S. Department of Defense
DOM	dissolved organic matter
DOMES	Deep Ocean Mining Environmental Study
DSHMRA	Deep Seabed Hard Mineral Resources Act
DSL	deep scattering layer
DSSRS	Deep Sea Sediment Resuspension System
EDTA	ethylenediaminetetraacetic acid
EEZ	Exclusive Economic Zone
EIS	Environmental Impact Statement
EPA	U.S. Environmental Protection Agency
ESP	Environmental Studies Program
FEIS	Final Environmental Impact Statement
FPEIS	Final Programmatic Environmental Impact Statement
GESAMP	Joint Group of Experts on the Scientific Aspects of Marine Pollution
HI, DBED	State of Hawaii, Department of Business and Economic Development
ICES	International Council for the Exploration of the Sea
INTERMAR	Office of International Activities and Marine Minerals
LMEs	Large Marine Ecosystems
MAFF	Ministry of Agriculture, Forestry, and Fisheries
MMS	Minerals Management Service
MMTC	Marine Minerals Technology Center
My	million years
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization

LIST OF ACRONYMS AND ABBREVIATIONS
(Continued)

NEPA	National Environmental Policy Act
NGDC	National Geophysical Data Center
NHPA	National Historic Preservation Act
NIMBY	not-in-my-back-yard
NMFS	U.S. National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NOMES	New England Offshore Mining Environmental Study
NRC	National Research Council
NTIS	National Technical Information Service
OBSs	optical backscatter sensors
OCD	Offshore and Coastal Dispersion
OCS	Outer Continental Shelf
OCSLA	OCS Lands Act
OTA	Office of Technology Assessment
OTEC	ocean thermal energy conversion
PCBs	polychlorinated biphenyls
PIPRA	Provisional Interim Preservational Reference Area
PMS	polymetallic sulfides
ppb	parts per billion
ppm	parts per million
RMS	root mean square
SOPAC	South Pacific Applied Geoscience Commission
SPM	suspended particulate matter
SPREP	South Pacific Regional Environment Program
TSP	total suspended particulates
USACE	U.S. Army Corps of Engineers
USBM	U.S. Bureau of Mines
USC	U.S. Congress
USDOC	U.S. Department of Commerce
USDOI	U.S. Department of the Interior
USDOS	U.S. Department of State
USGS	U.S. Geological Survey
WHOI	Woods Hole Oceanographic Institution
WPRFMC	Western Pacific Regional Fishery Management Council

TABLE OF CONTENTS

Page

LIST OF TABLES xv

LIST OF FIGURES xix

CHAPTER 1 INTRODUCTION 1
1.1 Historical and Regulatory Perspective 1
1.2 Study Objectives 4
1.3 Study Methods 6
1.3.1 Information Collection and Annotation 6
1.3.1.1 Computer Searches 8
1.3.1.2 Telephone Contacts 8
1.3.1.3 Review of Documents and Citations and Document Collection 8
1.3.1.4 Preparation of Annotated Bibliography (Reference Citations and Description Forms) 9
1.3.2 Information Analyses 9
1.3.2.1 Analysis of Extent of Environmental Information 9
1.3.2.2 Analysis of Mitigation Measures and Techniques 9
1.3.2.3 Analysis of Models 11
1.3.2.4 Identification of Data Gaps, Research Needs, and Recommendations 11
1.4 Manuscript Organization and Additional Study Products 12

CHAPTER 2 ENVIRONMENTAL CONSIDERATIONS 13
2.1 Mineral Resource Groups 13
2.1.1 Industrial Minerals 19
2.1.2 Mineral Sands 23
2.1.3 Phosphorites 23
2.1.4 Metalliferous Oxides 25
2.1.5 Hydrothermal Deposits 30
2.1.6 Dissolved Minerals 31
2.2 Operational Methods and Technology 31
2.2.1 Mining 34
2.2.1.1 Scraping 34
Conventional Shallow Water Systems 34
Tested Deep Water Systems 37
Speculative Deep Water Systems 43
2.2.1.2 Excavating 48
Conventional 48
Submersible 57
2.2.1.3 Tunneling 59

TABLE OF CONTENTS
(Continued)

Page

2.2.1.4 Fluidizing 59
Fluidizing (Slurries) 59
Fluidizing (Solutions) 63
2.2.2 Processing of Ores and Disposal of Waste 63
2.2.2.1 Beneficiation 63
On the Mining Platform 63
On the Bottom 65
Onshore 65
2.2.2.2 Extractive Metallurgy 65
Conventional Onshore 65
Speculative 74
2.2.3 Transportation 76
2.2.3.1 Bulk Ore Carriers 76
2.2.3.2 Slurry Pipelines 77
2.2.3.3 Other Transport Systems 78
2.2.4 Cycling of Materials 78
2.3 Affected Environments 81
2.3.1 Deep Ocean 93
2.3.1.1 Atmospheric Environment 96
2.3.1.2 Oceanic Environment 96
Red Sea Muds 96
Massive Sulfides 97
Manganese Crusts 97
Manganese Nodules 101
2.3.1.3 Geological Environment 103
Red Sea Muds 103
Massive Sulfides 104
Manganese Crusts 104
Manganese Nodules 105
2.3.1.4 Biological Environment 105
Birds 105
Marine Mammals 106
Plankton and Fish 107
Benthos 109
Threatened and Endangered Species 117
2.3.1.5 Social and Economic Environments 117
Commercial Fisheries 117
Small Island Groups 120
2.3.2 Continental Shelf 121
2.3.2.1 Atmospheric Environment 127

TABLE OF CONTENTS
(Continued)

		Page
2.3.2.2	Oceanic Environment	127
	Natural Effects	133
	Induced Effects	133
2.3.2.3	Geological Environment	135
	Holes in the Seabed	138
	Fine Sediment Deposition	138
	Altered Habitats	139
2.3.2.4	Biological Environment	139
	Birds	139
	Marine Flora	139
	Marine Mammals	141
	Plankton	142
	Nekton	143
	Benthos	144
	Threatened and Endangered Species	148
2.3.2.5	Social and Economic Environments	149
	Military and Special Uses	149
	Human Environment	150
	Commercial and Recreational Fisheries	150
	Regional and Local Economies	153
	Cultural Resources	153
2.3.3	Coastal	154
2.3.3.1	Atmospheric Environment	155
2.3.3.2	Oceanic Environment	155
	Natural Effects	156
	Induced Effects	156
2.3.3.3	Geological Environment	156
2.3.3.4	Biological Environment	157
	Benthos	157
	Sensitive Habitats	158
	Threatened and Endangered Species	158
2.3.3.5	Social and Economic Environments	158
	Human Environment	158
2.3.4	Onshore	159
2.3.4.1	Atmospheric Environment	160
2.3.4.2	Aquatic Environment	164
	Natural Effects	164
	Induced Effects	164
2.3.4.3	Geological Environment	164

TABLE OF CONTENTS
(Continued)

Page

2.3.4.4 Biological Environment 164
Marine and Aquatic Fauna 164
Sensitive Habitats 166
Threatened and Endangered Species 166
2.3.4.5 Social and Economic Environments 166
Human Environment 166
2.4 Characterization of the Literature Evaluated 167
2.5 Summary of Environmental Effects by Resource Affected 176
2.5.1 Air Quality 183
2.5.2 Water Quality 183
2.5.2.1 Deep Ocean and Outer Continental Shelf 185
2.5.2.2 Coastal and Onshore 185
Heavy Metals 186
Terrestrial Sites 186
2.5.2.3 Natural Effects 186
2.5.2.4 Induced Effects 186
2.5.3 Geological Resources 187
2.5.3.1 Mineral 187
2.5.3.2 Other 187
2.5.4 Biological Resources 187
2.5.4.1 Birds 191
2.5.4.2 Mammals 191
2.5.4.3 Marine and Aquatic Fauna 194
Effects of Suspended Sediment 195
Pleuston and Neuston 198
Plankton 198
Nekton 199
Benthos 199
2.5.4.4 Flora 204
2.5.4.5 Sensitive Habitats 204
2.5.4.6 Threatened and Endangered Species 204
2.5.5 Social and Economic Resources 205
2.5.5.1 Human Resources 205
Social Impacts 205
Legal Impacts 205
Political Impacts 206
2.5.5.2 Commercial and Recreational Fisheries 206
Fishery Resources 206
2.5.5.3 Regional Economies 207
2.5.5.4 Local Economies 207

TABLE OF CONTENTS
(Continued)

Page

2.5.5.5 Cultural Resources 207
Archaeological Resources 208
2.5.5.6 Technical Resources 208

CHAPTER 3 SUMMARY OF MITIGATION MEASURES AND THEIR EFFECTS .. 209
3.1 Institutionally-Derived Mitigation 215
3.1.1 Time-Based Constraints 216
3.1.2 Location-Based Constraints 217
3.1.3 Restrictions on Materials Cycles 217
3.1.4 Restrictions on Technology Use 217
3.1.5 Controlled Remediation Planning 217
3.2 Summary of Mitigation Measures by Resources Affected 218
3.2.1 Air Quality 218
3.2.1.1 Global 218
3.2.1.2 Regional 219
Oceanic and Outer Continental Shelf 219
Coastal 219
Onshore 219
3.2.2 Water Quality 219
3.2.2.1 Deep Ocean and Continental Shelf 220
3.2.2.2 Coastal and Onshore 220
3.2.3 Geological Resources 221
3.2.3.1 Seabed 221
3.2.3.2 Terrestrial 222
3.2.4 Biological Resources 222
3.2.4.1 Birds 222
3.2.4.2 Marine Mammals 222
3.2.4.3 Marine and Aquatic Fauna 222
Water Column Populations 223
Benthos 223
3.2.4.4 Sensitive Habitats 224
3.2.4.5 Threatened and Endangered Species 225
3.2.5 Social and Economic Resources 225
3.2.5.1 Human Resources 225
3.2.5.2 Commercial and Recreational Fisheries 225
3.2.5.3 Regional and Local Economies 226
3.2.5.4 Cultural Considerations 226

CHAPTER 4 PREDICTIVE MODELS 227
4.1 Scope 227
4.2 Model Types 227
4.2.1 Closed Form 227

TABLE OF CONTENTS
(Continued)

Page

4.2.2 Brief Review of Early Model Development 227
4.2.3 Finite Difference 229
4.2.4 Finite Element Models 230
4.3 Constraints 231
4.3.1 Scale-Dependent Description of Turbulent Dispersion 231
4.3.2 Quantification of Particle-Aggregation Processes 233
4.3.3 Site Description 234
4.4 Field Tools for Describing Sites and Tracking Plumes 234
4.4.1 Currents 234
4.4.2 Water Quality 236
4.4.3 Light Attenuation 237
4.5 Predictive Capabilities 238
4.5.1 Near-Field Surface Dispersion 238
4.5.2 Far-Field Dispersion 238
4.5.3 Model Selection for Applied Studies 239
4.6 Air Quality Modeling for OCS Mining 240
4.6.1 Analysis 240
4.6.2 Results 241

CHAPTER 5 DATA GAPS, RESEARCH NEEDS, AND RECOMMENDATIONS . . . 243
5.1 Environmental Considerations 243
5.1.1 Air Quality 243
5.1.2 Water Quality 244
5.1.3 Geological Resources 244
5.1.4 Biological Concerns 245
5.1.4.1 Large Marine Ecosystems 246
5.1.5 Socioeconomic Concerns 246
5.2 Mitigation Measures 250
5.3 Predictive Models 250
5.4 Recommended Priorities 251

CHAPTER 6 SUMMARY AND CONCLUSIONS 253

CHAPTER 7 LITERATURE CITED 273

APPENDIX A: ANNOTATED BIBLIOGRAPHY 301

LIST OF TABLES

Table	Description	Page
2.1	Classification of global marine mineral resources (From: Cruickshank 1992)	14
2.2	Present demand, estimated cumulative demand to A.D. 2000, apparent land resources, adequacy of land resources, and apparent marine resources for 90 mineral commodities excluding fluid hydrocarbons (Adapted from: Cruickshank 1978)	16
2.3	Areas surveyed and estimated offshore sand resources of the United States (From: U.S. Congress, Office of Technology Assessment 1987)	22
2.4	Summary of global beach and offshore mining activities (Adapted from: Hale and McLaren 1984)	24
2.5	Distribution of phosphorites in Miocene sediments along continental margins (From: Riggs et al. 1987)	26
2.6	Examples of metal grades and values for crusts and nodules (From: Riggs et al. 1987)	29
2.7	Concentration and amounts of 60 of the elements present in seawater (From: Cruickshank and Marsden 1973)	33
2.8	Options for concentration of marine placer minerals (Adapted from: Cruickshank 1987)	66
2.9	Estimated inputs and wastes for a manganese nodule processing plant handling three million metric tons of ore and associated seawater per year	73
2.10	Estimated inputs and wastes for a manganese crust processing plant handling 700,000 metric tons per year	75
2.11	Selected dredging operations offshore (Adapted from: Cruickshank 1973)	85
2.12	Data on underground mines operating offshore (Adapted from: Cruickshank and Marsden 1973)	87

LIST OF TABLES
(Continued)

Table	Description	Page
2.13	Operational plants for the extraction of minerals from seawater (From: Cruickshank 1973)	88
2.14	Environmental systems elements affecting the exploration and exploitation of marine mineral deposits, with examples in parentheses (Adapted from: Cruickshank 1978)	94
2.15	Postulated system characteristics of nodule mining compared to crust mining (Adapted from: U.S. Department of the Interior, Minerals Management Service and State of Hawaii, Department of Business and Economic Development 1990)	102
2.16	Geological and geophysical permits issued by USDOI to prospect for OCS minerals other than oil, gas, and sulfur (Adapted from: U.S. Department of the Interior, Minerals Management Service 1989a)	124
2.17	Mineral leases sold in the U.S. OCS since 1953 (Adapted from: U.S. Department of the Interior, Minerals Management Service 1989a)	125
2.18	Normal environmental disturbances in the water column and seabed from mining (From: Cruickshank et al. 1987)	126
2.19	Summary of Project NOMES (From: U.S. Congress, Office of Technology Assessment 1987)	128
2.20	Definitions and resource categories used in the assessment of environmental effects (From: U.S. Department of the Interior, Minerals Management Service 1991)	129
2.21	Orders of birds (From: Reader's Digest 1977)	140
2.22	Coastal mines and their environmental impact assessment programs (Adapted from: Ellis 1987)	161
2.23	Species found on heavy tailings (60+ cm) at Island Copper Stations 15 and 16 from 1977 to 1989 (From: Ellis and Taylor 1988)	165
2.24	Subject classification used for analyses of references	173

LIST OF TABLES
(Continued)

Table	Description	Page
2.25	Examples of marine mineral resources development vs. affected environments	175
2.26	General summary of environmental effects of EEZ development in the deep ocean, continental shelf, coastal zone, and onshore (Adapted from: Coastal States Organization 1987)	177
2.27	Avoidable impacts of marine mining and responsible authorities in the U.S. (From: U.S. Department of Commerce, National Oceanic and Atmospheric Administration 1981)	178
2.28	Unavoidable impacts of marine mining and responsible authorities in the U.S. (From: U.S. Department of Commerce, National Oceanic and Atmospheric Administration 1981)	180
2.29	Projected discharges from marine mining compared with drilling discharges in the Gulf of Mexico (Adapted from: Zippin 1988)	184
2.30	Technological systems elements involved in the exploration and exploitation of marine mineral deposits, with examples in parentheses (From: Cruickshank 1978)	189
2.31	Environmental systems elements affecting the exploration and exploitation of marine mineral deposits, with examples in parentheses (Adapted from: Cruickshank 1978)	190
2.32	Coastal water quality criteria for toxic substances other than biocides (From: Clark 1974)	192
2.33	Orders of mammals (From: Reader's Digest 1977)	193
2.34	Key factors affecting the degree of environmental impact (From: Cruickshank et al. 1987)	201
3.1	U.S. laws affecting mineral operations on the outer continental shelf (Adapted from: U.S. Department of the Interior, U.S. Geological Survey and Bureau of Land Management 1981a,b)	210
3.2	Environmental ethics (Adapted from: Miller and Kirk 1992)	212

LIST OF TABLES
(Continued)

Table	Description	Page
5.1	Key spatial and temporal scales and principal elements of a systems approach to the research and management of large marine ecosystems (From: Sherman 1991)	248
6.1	Summary of various marine mining technologies	255
6.2	Summary of environmental effects of marine mining by resources affected	261
6.3	Summary of marine mining mitigation measures by resources affected	267

LIST OF FIGURES

Figure	Description	Page
1.1	Domestic offshore mineral deposits of interest to the marine mining industry	2
1.2	State-Federal task forces	5
1.3	Major tasks and milestones	7
1.4	Reference description form for citations pertaining to environmental impacts of marine mining	10
2.1	Global distribution of seabed mineral deposits (Adapted from: Hoagland and Broadus 1987)	15
2.2	Categories of mineral resources and ore reserves used by the U.S. Bureau of Mines and U.S. Geological Survey (upper) compared with that used by the United Nations (lower) (Adapted from: U.S. Department of the Interior, Bureau of Mines and U.S. Geological Survey 1980)	20
2.3	Belt of high grade manganese nodules between the Clarion and Clipperton Fracture Zones in the Pacific (From: Teleki et al. 1985)	27
2.4	Known cobalt crust distribution in the world's oceans (Adapted from: Manheim and Lane-Bostwick 1989)	28
2.5	Distribution of known and suspected metalliferous sulfide deposits and active hydrothermal vents in the Pacific Ocean (From: Scott 1987)	32
2.6	The four basic methods of mining (From: Cruickshank et al. 1987)	35
2.7	A deep water dragline dredge (From: Cruickshank et al. 1987)	36
2.8	Trailing suction hopper dredge and various drag heads (Adapted from: Cruickshank et al. 1987)	38

LIST OF FIGURES
(Continued)

Figure	Description	Page
2.9	Trailing suction hopper dredge for 5,000 m water depths (Adapted from: Kaufman et al. 1985)	40
2.10	Deep seabed miner for manganese nodule recovery (From: Ocean Mining Company 1978)	41
2.11	Schematic of subsystems required for deep seabed suction dredge with self-propelled miner (From: United Nations 1984)	42
2.12	A continuous line bucket dredge (From: Masuda et al. 1971)	44
2.13	Operating principal of a modular mining system for the deep seabed (From: United Nations 1984)	46
2.14	A proposed deep seabed cobalt crust mining machine (Adapted from: Halkyard and Felix 1987)	47
2.15	Clamshell hopper dredge (From: Cruickshank et al. 1987)	49
2.16	Bucket ladder dredge with headline and anchors for offshore operations (From: Cruickshank and Marsden 1973)	50
2.17	The bucket ladder dredge *Bima* used for a gold operation in Alaska (Adapted from: WestGold 1990)	52
2.18	A small bucket wheel dredge for use on a standard back hoe (Adapted from: Ellicott Machine Corp.)	53
2.19	Schematic illustration of suction pump-type mining vessel. (A) Without booster pump. (B) With booster pump (Adapted from: Tsurusaki et al. 1988)	54
2.20	Dynamically anchored suction dredge on location in the Red Sea (Adapted from: Fletcher and Mustaffi 1980)	55

LIST OF FIGURES
(Continued)

Figure	Description	Page
2.21	Cutterhead suction dredge with spuds (From: Cruickshank et al. 1987)	56
2.22	Plan view and longitudinal section of the *Tramrod* as deployed in Nome in 1989 (From: Garnett 1991)	58
2.23	Mining of sub-seabed deposits with access through an artificial island (Adapted from: Cruickshank et al. 1987)	60
2.24	Fluid mining by slurrying from a fixed platform in shallow water (Adapted from: Hrabik and Godesky 1985)	61
2.25	Schematic diagram of the bulk sampling operation for offshore phosphate (Adapted from: Drucker et al. 1991)	62
2.26	Fluid mining by leaching of deep, hard-rock deposits, artificially fractured in place (From: Cruickshank et al. 1987)	64
2.27	Processing of metalliferous oxides by gas reduction and ammoniacal leach (From: Haynes and Magyar 1987)	68
2.28	Processing of metalliferous oxides by cuprion ammoniacal leach (From: Haynes and Magyar 1987)	69
2.29	Processing of metalliferous oxides by high-temperature/high-pressure sulfuric acid leach (From: Haynes and Magyar 1987)	70
2.30	Processing of metalliferous oxides by reduction and hydrochloric acid leach (From: Haynes and Magyar 1987)	71
2.31	Processing of metalliferous oxides by smelting and sulfuric acid leach (From: Haynes and Magyar 1987)	72

LIST OF FIGURES
(Continued)

Figure	Description	Page
2.32	Transport streams for slurry receiving facilities (From: U.S. Department of the Interior, Minerals Management Service and State of Hawaii, Department of Business and Economic Development 1990)	79
2.33	Cycle of materials in a marine mining operation	80
2.34	The ocean zones, including the Exclusive Economic Zone (EEZ) (Adapted from: U.S. Congress, Office of Technology Assessment 1987)	82
2.35	Exclusive Economic Zones (EEZs) of U.S. Insular and Trust Territories in the Pacific (From: U.S. Congress, Office of Technology Assessment 1987)	83
2.36	Nature of dynamics of marine media during mining operations (Adapted from: Cruickshank 1978)	89
2.37	Impacts of offshore mining on the marine environment (Adapted from: U.S. Congress, Office of Technology Assessment 1987)	90
2.38	Basic natural interfaces in the marine environment (Adapted from: Cruickshank 1987)	91
2.39	Diamond mining in rough seas of Southwest Africa (From: Webb 1965)	92
2.40	World map of large marine ecosystems (From: Sherman 1991)	95
2.41	Outer continental shelf Planning Areas in the lower 48 states (From: Dellagiarino 1986)	122
2.42	Outer continental shelf Planning Areas in Alaska (From: Dellagiarino 1986)	123

LIST OF FIGURES
(Continued)

Figure	Description	Page
2.43	Locations of three fjords and coastal onshore mine sites in British Columbia at Rupert Inlet (Island Copper Mine), Howe Sound (Anaconda Britannia Mine), and Alice Arm (AMAX Kitsault MolybdenumMine) (Adapted from: Ellis 1987)	163
2.44	Graphical analysis of references evaluated, by study location	168
2.45	Graphical analysis of references evaluated, by study environment .	169
2.46	Graphical analysis of references evaluated, by mineral group	170
2.47	Graphical analysis of references evaluated, by action reported	171
2.48	Graphical analysis of references evaluated, by affected resource . .	172
2.49	Matrix for evaluation of interactions between marine mining technology and the marine environment (From: Cruickshank 1978)	188
3.1	Environmental ethics vs. mining (Part 1)	213
3.2	Environmental ethics vs. mining (Part 2)	214
5.1	Predominant variables influencing changes in fish species biomass in large marine ecosystems. Predominant variables include predation (X), environment (O), pollution (P), and inconclusive information (+) (From: Sherman 1991)	247
5.2	Research objectives and tasks in the Ecosystem Processes Program Element of the Northeastern California Current Ecosystem study plan (From: Sherman 1991)	249

CHAPTER 1 INTRODUCTION

1.1 Historical and Regulatory Perspective

In addition to offshore oil, gas, and sulfur resources, there are approximately 90 different mineral commodities available in the marine environment. In this document, these commodities are referred to as marine minerals, whereas petroleum minerals are referred to as oil and gas. Industry interest in mining of U.S. marine minerals has focused on sand and gravel, precious and heavy metal placers, cobalt-rich manganese crusts, polymetallic sulfides (PMS), and phosphorites (**Figure 1.1**). International interest has also been oriented towards a wide array of prospects, including (1) sand and gravel in Denmark, France, Japan, the Netherlands, and the United Kingdom; (2) tin in Burma, Indonesia, and Thailand; (3) diamonds off southwest Africa; (4) phosphorite off New Zealand; and (5) metalliferous muds (containing copper, silver, and zinc) in the Red Sea.

The U.S. recognizes a strategic importance and potential economic benefit of marine mining, as well as the potential for environmental impacts associated with marine mining activities. The U.S. Department of the Interior (USDOI), Minerals Management Service (MMS) is responsible for the management of exploration and development of mineral resources on submerged Federal lands on the Outer Continental Shelf (OCS) seaward of State boundaries. On behalf of the MMS, its Office of International Activities and Marine Minerals (INTERMAR) functions as a liaison for agency involvement in international activities, and provides policy direction for management and regulation of marine mineral resource activities on the OCS for minerals other than oil, gas, and sulfur. The MMS has set four priority goals to meet the management responsibilities for marine minerals:

- To evaluate and achieve the potential of the U.S. OCS as a domestic supply source for strategic and other non-energy mineral resources;
- To provide an effective consultation process for coastal States and the Federal Government on marine minerals;
- To assure that OCS mineral activities are fully coordinated and compatible with other uses of the ocean; and
- To safeguard the ocean and coastal environments by assuring that all OCS mineral activity is environmentally sound and acceptable.

Under the Environmental Studies Program (ESP), the MMS has funded numerous studies relating to potential environmental impacts of OCS oil and gas activities (USDOI, MMS 1990a). Although considerable information from these ESP studies is transferable to an evaluation of potential impacts of marine mining, the MMS has sponsored only limited research on marine minerals, due primarily to the lack of marine mining industry activity. Until recently, the level of domestic marine mining activity may have been inhibited by marginal economics, high risk, and the lack of comprehensive regulations applicable to the recovery of marine minerals. This is in contrast to Europe, Asia, and other international locations where marine mining industries have developed within a framework of supportive government regulation. Domestic rules and regulations have recently been designed to

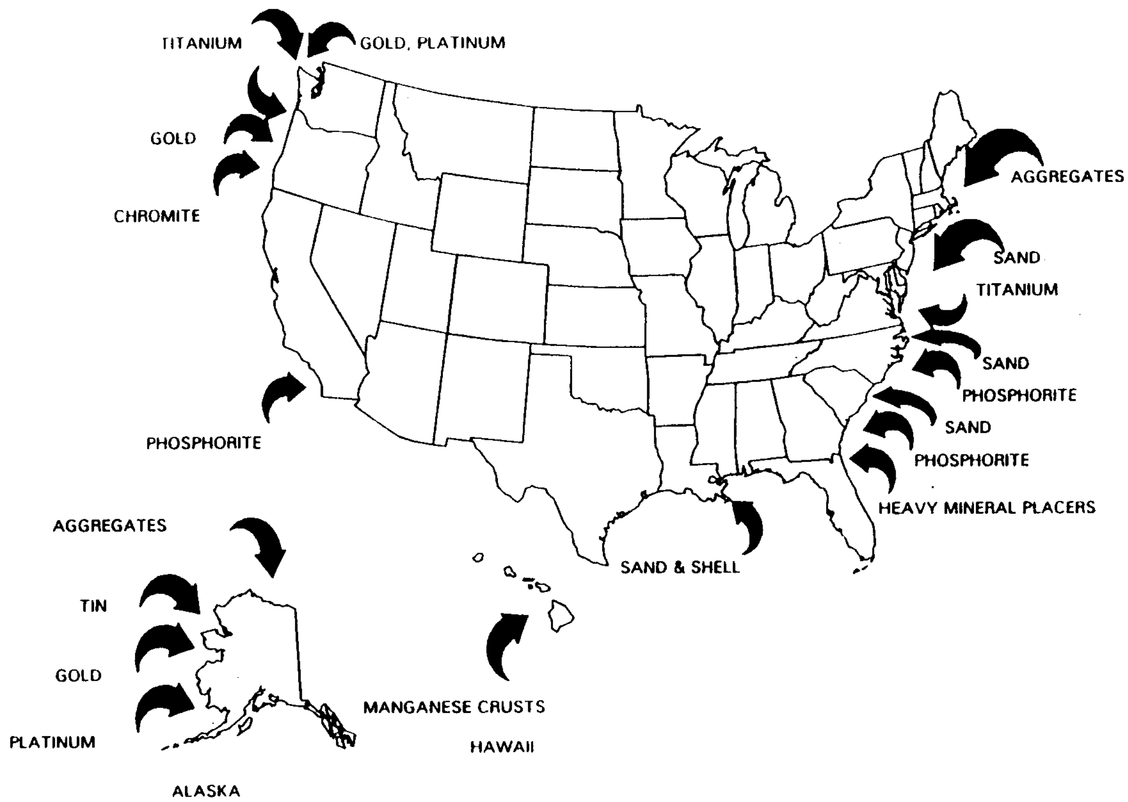

Figure 1.1. Domestic offshore mineral deposits of interest to the marine mining industry.

dispel uncertainty and demonstrate governmental commitment to environmentally compatible OCS marine minerals development and production.

The MMS has a strong mandate with respect to the potential environmental impacts of marine mining. Existing rules and regulations governing domestic marine mining provide a framework for comprehensive environmental protection during prospecting and scientific research activities and postlease operations (e.g., 30 CFR Parts 280, 281, and 282). Requirements exist for site-specific and commodity-specific evaluations and lease stipulations that include appropriate mitigation measures.

Guidelines for protecting the environment stem from a wide variety of laws, including the OCS Lands Act (OCSLA), National Environmental Policy Act (NEPA), Endangered Species Act, Marine Mammal Protection Act, National Historic Preservation Act (NHPA), Clean Water Act, and others. The provisions require activities to be conducted in a safe manner to prevent or minimize the likelihood of any occurrences that may cause damage to the environment. Such provisions also permit the cancellation or suspension of operations if there is a threat of serious, irreparable, or immediate harm to the marine, coastal, or human environments. The MMS takes a case-by-case approach in conducting environmental analyses, as required by NEPA and the Council on Environmental Quality (CEQ) regulations (40 CFR Parts 1500-1508). Protection of the environment is a high priority at each stage of the marine mining process, from prospecting through postlease operations.

In recent years, there has been increasing interest in marine mining on the OCS and in the U.S. Exclusive Economic Zone (EEZ). Examples of documents prepared by or for the MMS in connection with planned, proposed, or ongoing activities include the following:

- An Environmental Impact Statement (EIS) for a proposed minerals lease sale in Norton Sound off the coast of Alaska (USDOI, MMS 1991);
- A workshop to design baseline and monitoring studies for the OCS mining program in Norton Sound, Alaska (Hood 1990);
- An EIS for exploitation of manganese crust deposits in the EEZ adjacent to Hawaii and Johnston Island (USDOI, MMS and State of Hawaii, Department of Business and Economic Development [HI, DBED] 1990);
- A preliminary overview of environmental effects of marine mining (Cruickshank et al. 1987);
- An EIS for a proposed arctic sand and gravel lease sale (USDOI, MMS 1983a); and
- A draft EIS for a polymetallic sulfide mineral lease offering in the Gorda Ridge area offshore Oregon and northern California (USDOI, MMS 1983b).

The MMS has set a premium on effective public communication, outreach, and interaction. As of December 1992, nine State-Federal task forces, cooperative agreements, and arrangements existed to ensure substantive government and public involvement and attention to regional, State, and local issues including leasing, engineering, economic, and environmental aspects of marine mining (**Figure 1.2**).

Under the OCSLA, the MMS is required to conduct environmental studies to obtain information useful for decisions related to marine mineral activities. The MMS has developed an environmental strategy to provide this information. Several efforts are currently in progress. Existing State-Federal task forces are being directed to identify key environmental issues and develop action plans to address issues of concern. The Marine Minerals Technology Center (MMTC) and Sea Grant Program are developing environmentally-sound technology applicable to marine mining. The MMS has also initiated the design of generically-oriented environmental studies to provide information for programmatic marine mining decisions at MMS Headquarters and OCS Regional Offices.

This manuscript and attendant deliverables represent the first environmental program to be administered through the MMS Office of International Activities and Marine Minerals using ESP funds. Entitled "Synthesis and Analysis of Existing Information Regarding Environmental Effects of Marine Mining," this program was initiated by Continental Shelf Associates, Inc. (CSA) in September 1991 under MMS Contract No. 14-35-0001-30588. In addition to CSA scientific, editorial, and support staff, this study effort employed the marine mining expertise of Drs. Michael J. Cruickshank and Charles L. Morgan who served as consultants to CSA and are associated with the University of Hawaii.

1.2 Study Objectives

The primary objectives of this study were as follows:

- To survey and analyze existing literature regarding the environmental impacts of marine mining; and
- To summarize this literature in a single, monograph-style manuscript.

In addition to addressing the environmental impacts of marine mining, the secondary objectives of this study were as follows:

- To summarize the various marine mining technologies currently available and the respective target minerals and/or deposits of interest;
- To discuss viable mitigation measures;
- To evaluate models designed to predict the fate of mining-related discharges and determine the biological impacts of mining operations; and
- To identify data gaps and research needs.

Select environmental documents consulted during the study have been annotated and compiled in both printed form and in a electronic format that will allow them to be incorporated into the Minerals/Mining Reference Database administered by the MMS Office of International Activities and Marine Minerals. In meeting these objectives, this manuscript should prove invaluable in the preparation of more accurate and detailed lease

Figure 1.2. State-Federal task forces.

sale environmental impact statements and assessments, and for making other decisions concerning potential offshore non-energy minerals activities.

1.3 Study Methods

The major tasks and milestones for this study effort are outlined in **Figure 1.3**. Methods used for each of the tasks are described in greater detail in the following text. Aside from management and meetings, tasks were organized into the following categories and subcategories:

Information Collection and Annotation
- Information Collection
- Reference Citation
- Reference Description

Information Analyses
- Analysis of Extent of Environmental Information
- Analysis of Mitigation Measures and Techniques
- Analysis of Models
- Identification of Data Gaps and Research Needs

Preparation of Study Products
- Preparation of Manuscript
- Executive Summary
- Technical Summary
- Reference Database

Information collection and annotation, and information analyses are discussed in **Sections 1.3.1** and **1.3.2**, respectively. The organization of this manuscript and a summary of additional study products is presented in **Section 1.4**.

1.3.1 Information Collection and Annotation

The information collection aspects of the program had two primary goals: (1) to provide literature and data to be considered for inclusion in respective chapters of the manuscript; and (2) to produce an annotated bibliography to be included in the manuscript. The term "annotated bibliography" encompasses the reference citations and reference description forms, both of which are discussed in the following text.

Information collection and annotation was the responsibility of CSA. In conjunction with its independent consultants, CSA developed and reviewed lists of citations, searching for appropriate references for annotation. This approach also provided access to the extensive library maintained by the independent consultants applicable to marine mining, including environmental aspects.

The sequence of events comprising information identification, collection, and annotation is described below.

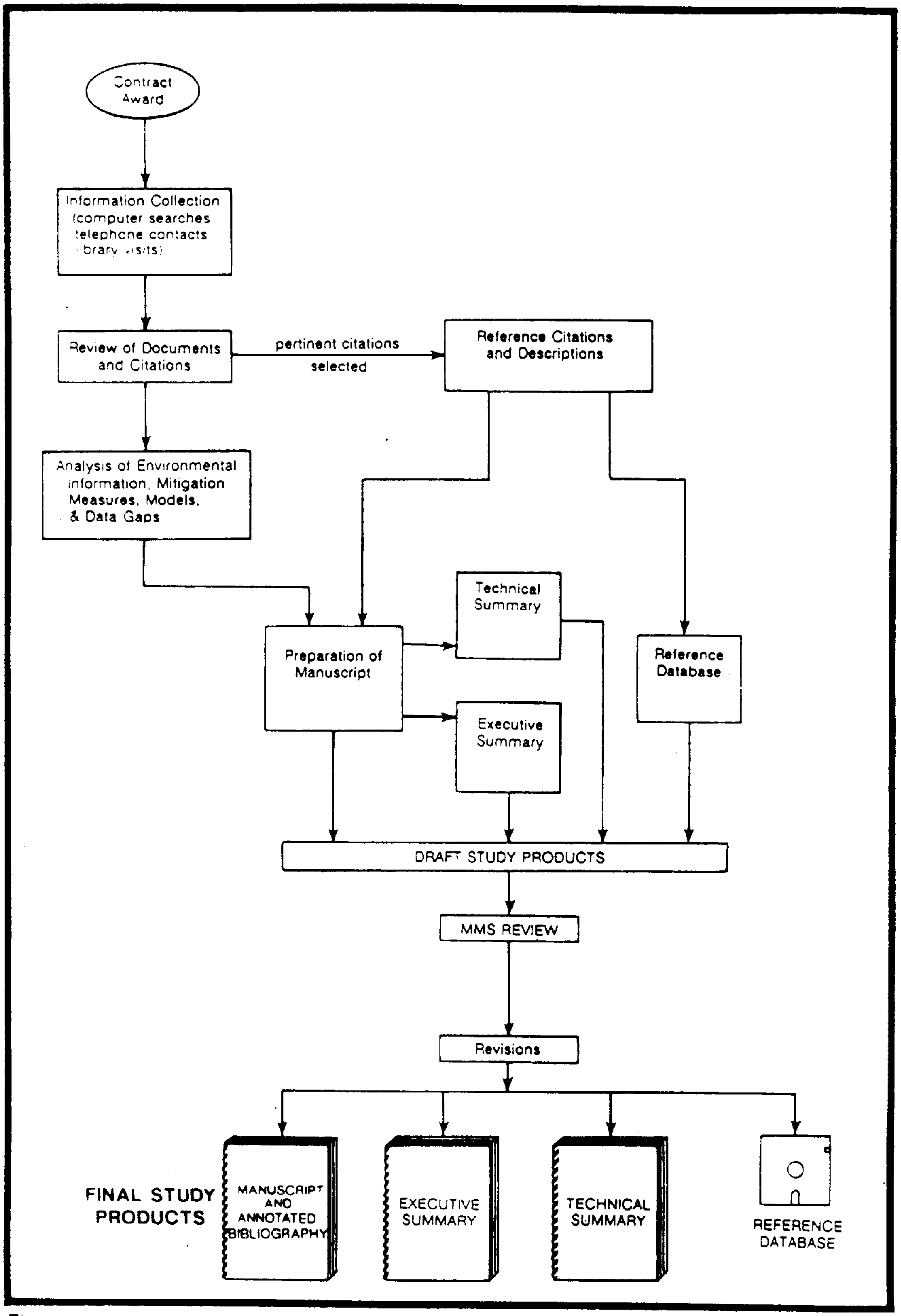

Figure 1.3. Major tasks and milestones.

1.3.1.1 Computer Searches

In an iterative process involving marine mining experts and MMS technical staff, a series of computer searches were conducted using the Lockheed DIALOG Information Retrieval Service. In an attempt to maximize search success, preliminary searches were limited (i.e., only the number of identified sources, or "hits", with a specific key word combination were listed). The final searches provided a complete entry (i.e., author, title, key words, abstract) for each data source. Key words selected and the specific databases accessed were determined based on professional experience of CSA technical staff and its consultants. Databases searched included the following:

- AQUATIC SCIENCE AND FISHERIES ABSTRACTS
- BIOSIS PREVIEWS (Biological Abstracts)
- CA SEARCH (Chemical Abstracts)
- CONFERENCE PAPERS INDEX
- DISSERTATION ABSTRACTS
- DOE ENERGY
- GEOREF
- LIFE SCIENCES COLLECTION
- METEOROLOGICAL/GEOASTROPHYSICAL ABSTRACTS
- NTIS (National Technical Information Service)
- OCEANIC ABSTRACTS
- POLLUTION ABSTRACTS
- SCISEARCH DATABASE (Science Citation Index)

Literature searches were coordinated through Harbor Branch Oceanographic Institution, Fort Pierce, FL. Other databases and bibliographies from various government agencies were also reviewed, including a preliminary database on marine minerals from the U.S. Department of Commerce (USDOC), National Oceanic and Atmospheric Administration (NOAA), National Geophysical Data Center (NGDC).

1.3.1.2 Telephone Contacts

To supplement the citation lists developed from searches of the computerized databases and in-house library files, numerous individuals and organizations involved in marine mining were contacted. Requests were made for pertinent references, bibliographies, recent publications, etc. on environmental aspects of marine mining.

1.3.1.3 Review of Documents and Citations and Document Collection

Review of potentially salient references led to development of an edited citation list. Listed documents were secured through CSA and consultants' libraries, as well as through library and interlibrary loan (i.e., from and through the Harbor Branch Oceanographic Institution).

1.3.1.4 Preparation of Annotated Bibliography (Reference Citations and Description Forms)

References to be annotated were selected based upon discussions between CSA and the MMS. References from the master list of documents cited in the manuscript (i.e., **Chapter 7**, Literature Cited) were reviewed and prioritized. Pertinent references concerning potential impacts to various components of the environment were chosen for annotation. In most cases, citations concerning technology, policy, mitigation, and models were not considered as priority items for annotation. Individual annotated citations have been assembled into the Annotated Bibliography (**Appendix A**).

Each annotation was completed on a standard reference description form (**Figure 1.4**) and included (1) a unique entry number; (2) complete citation; (3) type(s) of study; (4) geographic location(s) of study; (5) applicable OCS Planning Area(s); (6) type(s) of environment(s); (7) mineral(s) of interest; (8) type(s) of mining operation(s); (9) environmental resource(s) affected; (10) date(s) of study; (11) study technique(s); (12) conclusion(s); and (13) key words. Data from the standard reference description form were entered onto CSA's computer system using dBASE III PLUS to develop the Reference Database.

1.3.2 Information Analyses

1.3.2.1 Analysis of Extent of Environmental Information

The purpose of this task was to evaluate the state of knowledge regarding environmental impacts of marine mining. Six basic mineral resource groups were subject to examination, including industrial minerals, mineral sands, phosphorites, metalliferous oxides, hydrothermal deposits, and dissolved minerals.

Discussions of operational methods and technology were separated into four categories, including mining techniques, processing of ores and disposal of waste, transportation, and cycling of materials. Mining techniques included scraping, excavation, tunneling, and fluidizing. Land- and sea-based processing by traditional and non-traditional methods were evaluated. Transportation and cycling of materials within both onshore and offshore environments were considered.

In terms of the affected environment, four separate classifications were used in this analysis, including deep ocean, continental shelf (i.e., beyond the three-mile boundary or beyond the seaward extent of territorial waters), coastal (i.e., estuarine and coastal waters within three miles), and onshore. Each marine-related classification was further sub-divided into atmospheric environment, oceanic or aquatic environment, geological environment, biological environment, and social and economic environments.

1.3.2.2 Analysis of Mitigation Measures and Techniques

The purpose of this task was to review information on the techniques available to lessen, minimize, or avoid environmental impacts attributed to marine mining operations.

REFERENCE DESCRIPTION FORM

Entry Number: ______________________________

Citation: ______________________________

____

____

Type(s) of Study: ______________________________

____

Geographic Location(s): ______________________________

OCS Planning Area(s): ______________________________

____

____

Type(s) of Environment(s): ______________________________

____

Mineral(s): ______________________________

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Type(s) of Mining Operation(s): ______________________________

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Environmental Resource(s): ______________________________

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Date(s) of Study: ______________________________

Study Technique(s): ______________________________

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Conclusion(s): ______________________________

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Key Words: ______________________________

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Figure 1.4 Reference description form for citations pertaining to environmental impacts of marine mining.

The summary was grouped according to the resource to which the mitigation measure applies (e.g., air quality, water quality, geological resources, biological resources, social and economic resources). Strengths and weaknesses of each mitigation measure were discussed.

The criteria used to determine the suitability of the various mitigation methods included evaluations of technical and socioeconomic factors. Technical ranking was based on successful actions reported, experience, and theoretical estimates of the success of the method being ranked. This analysis was complex because of the variety of environments and activities examined. The socioeconomic factors considered related to management techniques and involved the ranking of alternative approaches (e.g., autocratic management imposed by inspection and negative deterrents; application of economic incentives based on market characteristics). In both cases, cost factors were a significant factor in the ranking of alternative methods, however the paucity of verifiable data from actual operations imposed severe restraints on these evaluations. The need for flexibility in mitigation management was determined.

1.3.2.3 Analysis of Models

The purpose of this task was to review information about (1) models that have been used to predict the environmental impacts and fate of discharged particulate matter into the water column as a consequence of mining operations; and (2) models useful in evaluating impacts associated with seabed disturbance resulting from marine mining. The strengths and weaknesses of each model were discussed.

The synthesis effort on models focused primarily on what can be done with existing technologies, rather than on extensively documenting what has been done with old technologies. The discussion was organized in four parts. The first part summarized the types of models available and appropriate for the major discharge types expected from marine mining. The second part described the constraints of predictive models. The third part discussed field tools for describing sites and tracking plumes. The fourth part reviewed the status of predictive success obtained to date for actual mining discharges and other discharges similar to those expected from mining operations. This organization permitted a straightforward assessment of the areas where more data acquisition and technique development are necessary.

1.3.2.4 Identification of Data Gaps, Research Needs, and Recommendations

In the process of reviewing the environmental information as described above, perceived shortcomings in existing databases were noted. Efforts were made to identify and assess data gaps and information needed to determine potential environmental impacts. Criteria used to describe gaps included such factors as type of technical activity, geographic coverage, environmental characteristics, and resources affected. The findings were summarized, and research projects to fill the data gaps were recommended.

1.4 Manuscript Organization and Additional Study Products

The manuscript was organized in seven major chapters as follows:

- Chapter 1 Introduction
- Chapter 2 Environmental Considerations
- Chapter 3 Summary of Mitigation Measures and Their Effects
- Chapter 4 Predictive Models
- Chapter 5 Data Gaps, Research Needs, and Recommendations
- Chapter 6 Summary and Conclusions
- Chapter 7 Literature Cited

Chapters 2 through **5** and **Chapter 7** were prepared by Drs. Cruickshank and Morgan, with technical editorial input provided by CSA. **Chapter 1** was prepared by CSA, while **Chapter 6** represents a cooperative effort between CSA and its consultants.

In addition to the main manuscript, several other study products were prepared by CSA under this study effort (**Figure 1.3**), including (1) an Annotated Bibliography; (2) an Executive Summary; (3) a Technical Summary; and (4) a Reference Database. The Annotated Bibliography was described in **Section 1.3.1.4** and incorporated into this manuscript as **Appendix A**, creating a complete report deliverable.

The Executive Summary was prepared as a separate document. The Executive Summary briefly describes the study methods and technical findings, as presented within this manuscript, with text oriented towards a technically-literate reader.

A Technical Summary, another separate deliverable, was prepared according to MMS criteria. The summary consisted of a three-page description which outlines (1) contractual specifications for the study; (2) report and deliverable specifications; and (3) the study's significant findings (i.e., background, objectives, description, significant conclusions, study results, and study products).

The Reference Database is the electronic version of the Annotated Bibliography. The Reference Database was prepared in dBASE III PLUS format and submitted separately to the MMS.

CHAPTER 2 ENVIRONMENTAL CONSIDERATIONS

Pollution of the marine environment means the introduction by man, directly or indirectly, of substances or energy into the marine environment, including estuaries, which results or is likely to result in such deleterious effects as harm to living resources and marine life, hazards to human health, hindrance to marine activities, including fishing and other legitimate uses of the sea, impairment of quality for use of seawater and reduction of amenities.

United Nations Convention on the Law of the Sea, Article 1:1(4).

In this chapter, the state of knowledge regarding the environmental effects of marine mining is discussed and evaluated. In logical sequence, the discussions address the potential mineral resource groups or targets (**Section 2.1**), the operational methods and technology applicable to marine mining (**Section 2.2**), the environments potentially affected by selected marine mining operations (**Section 2.3**), and a characterization of the literature evaluated (**Section 2.4**). The summary discussion in **Section 2.5** addresses the information on environmental effects in terms of the environmental resources affected, under the categories of air quality, water quality, and geological, biological, and socioeconomic resources.

2.1 Mineral Resource Groups

For the purpose of this study, mineral resources are defined as *any mineral deposit found in the marine environment, other than oil and gas but including salt, sulfur, geothermal resources, and precious corals.* The mineral resources are classified in six groups: industrial minerals, mineral sands, phosphorites, metalliferous oxides, hydrothermal deposits, and dissolved minerals. These groups are differentiated largely on the basis of the character of the deposits and the technical requirements for their mining or recovery. The classification is universal and each class is discussed separately in the text that follows, with emphasis on the nature and distribution of the mineral deposits.

The nature and distribution of the apparent global marine mineral resource is highly significant though quantitative determinations at this time are for the most part speculative. Several publications have addressed the issue in some detail (Cruickshank 1974a; McKelvey 1986; Earney 1990; **Table 2.1**; **Figure 2.1**). Current geological research and exploration continue to support many of the optimistic forecasts that the oceans may contain mineral deposits of even greater potential than those presently found onshore (Cruickshank and Kincaid 1990). Comparative values were developed in **Table 2.2** for "apparent marine mineral resources" for 90 mineral commodities tracked by the U.S. Bureau of Mines (USBM). In every case where data were available and where deficiencies had been predicted, alternative marine resources were indicated which exceed existing land resources, with the exception of asbestos, graphite, platinum, and quartz crystal (Cruickshank 1978).

Unconsolidated		Consolidated		Fluid	
Seabed	*Subseabed*	*Seabed*	*Subseabed*	*Seabed*	*Subseabed*
Conshelf *Industrial Materials* sand & gravel shell sands aragonite coral sands *Mineral Sands* magnetite ilmenite rutile chromite monazite	**Conshelf** *Mineral Sands* gold platinum cassiterite gem stones *Bedded Deposits* phosphorites	**Conshelf** *Outcrops* exposures of veins, etc.	**Conshelf** *Vein, Stratified, Disseminated or Massive Deposits* coal phosphates carbonates potash ironstone limestone metal sulfides metal salts	**Conshelf** *Seawater* magnesium sodium uranium bromide and salts of 26 other elements	**Conshelf** *Freshwater Springs*
Ocean Basins *Muds or Oozes* metalliferous carbonaceous siliceous calcareous baritic *Nodules* manganese cobalt nickel copper		**Ocean Basins** *Crusts* phosphorite cobalt manganese *Mounds and Stacks* metal sulfides	**Ocean Basins** *Vein, Stockwork, Stratbound or Massive Deposits* metal sulfides	**Ocean Basins** *Seawater* magnesium sodium uranium bromine and salts of 26 other elements	**Ocean Basins** *Hydrothermal Fluids*

Table 2.1. Classification of global marine mineral resources (From: Cruickshank 1992).

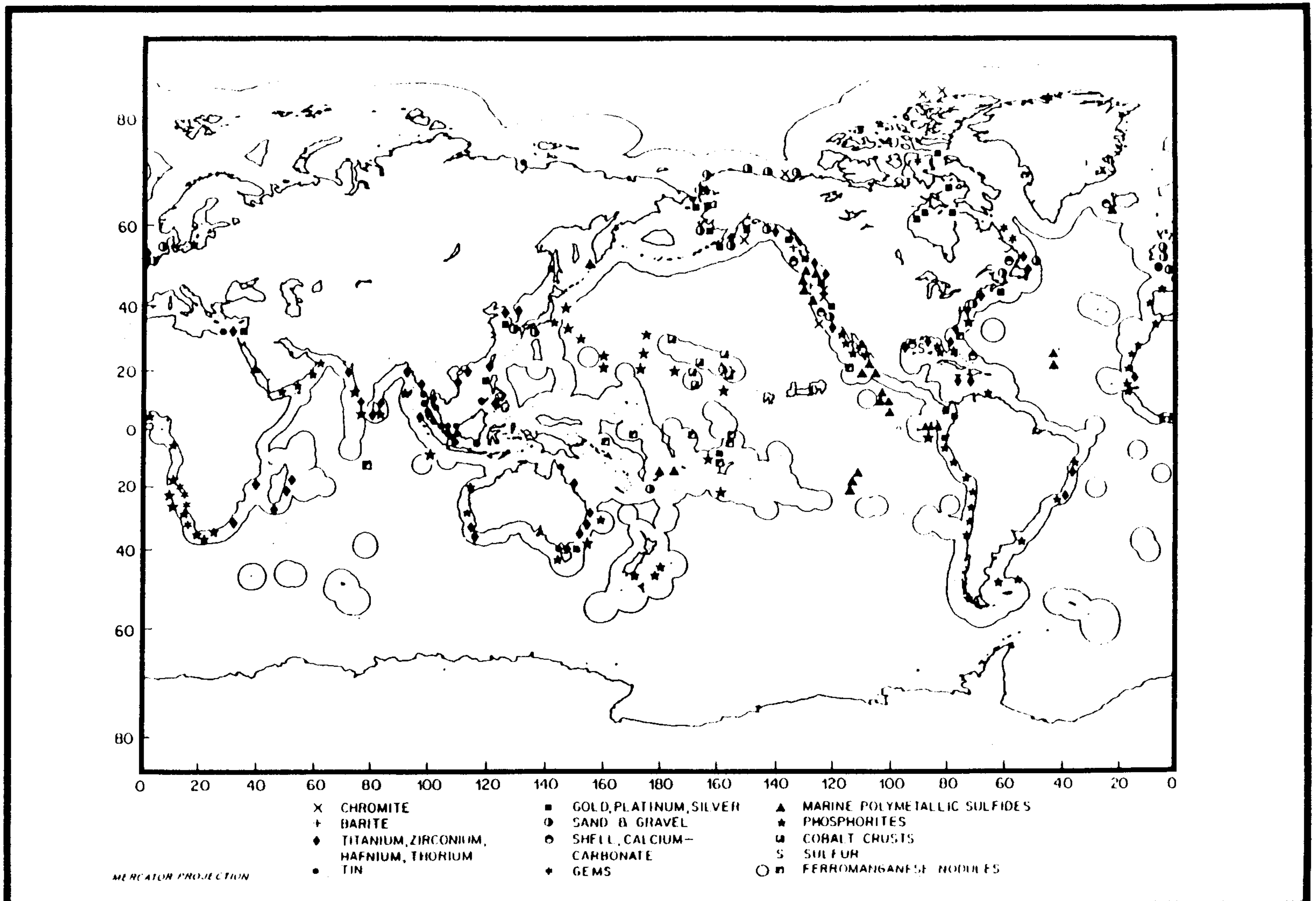


Figure 2.1 Global distribution of seabed mineral deposits (Adapted from: Hoagland and Broadus 1987).

Energy resources	*Sym-bol*	*Present demand*		*Cumulative demand to A.D. 2000*		*Apparent resources (land)*		*Adequacy (land)*		*Apparent resources (marine)*		
		U.S.	*World*	*U.S.*	*World*	*U.S.*	*World*	*U.S.*	*World*	*Diss.*	*Unc.*	*Con.*
Anthracite	C	8·862	10·173	10·208	11·549	11·580	13·297	+	+	NA		13·11
Bituminous coal and lignite	C	10·233	11·103	12·195	12·556	13·182	14·234	+	+	NA		13·87
Geothermal	—	ND	ND	ND	ND	14·196	14·305	+	+	ND		14·11
Carbon	C	9·550	10·378	11·286	12·161	—	—	+	+	13·363		NA
Helium	He	8·253	8·268	10·267	10·311	11·281	11·281	+	+	ND		ND
Hydrogen	H	9·515	10·186	12·148	12·319	—	—	+	+	ND		ND
Natural gas	—	10·311	10·486	12·380	12·850	11·471	12·188	—	—	NA		ND
Peat	C	8·106	10·258	9·584	12·114	12·161	13·336	+	+	NA		NA
Petroleum	HC	11·137	11·316	12·878	13·243	13·102	13·173	+	—	NA	15·36	NA
Shale oil	HC	—	8·900	11·600	11·822	13·909	15·951	+	+	NA		15·36
Thorium	Th	7·150	7·27	9·256	9·859	10·818	11·239	+	+	11·209	11·18	11·11
Uranium	U	8·509	8·924	11·450	11·833	11·309	11·384	—	—	12·578	14·28	11·16
Deuterium	—									(20·246)		ND
		11·204	11·563	13·174	13·466	14·123	15·983			13·423‡	11·16	15·38

Ferrous minerals	*Sym-bol*	*Present demand*		*Cumulative demand to A.D. 2000*		*Apparent resources (land)*		*Adequacy (land)*		*Apparent resources (marine)*		
		U.S.	*World*	*U.S.*	*World*	*U.S.*	*World*	*U.S.*	*World*	*Diss.*	*Unc.*	*Con.*
Chromium	Cr	8·241	9·105	10·147	10·639	9·106	11·412	—	+	10·429	14·14	10·44
Cobalt	Co	8·262	8·817	10·124	10·369	9·603	10·890	—	+	11·227	14·22	11·35
Columbium	—	7·590	8·119	9·483	10·110	9·435	11·276	—	+	ND	12·26	11·90
Iron	Fe	11·129	10·659	11·669	12·342	12·277	13·174	+	+	10·236	NVA	12·32
Manganese	Mn	8·637	9·457	10·288	11·250	10·376	13·104	+	+	10·169	14·20	11·23
Molybdenum	Mo	8·904	9·224	10·596	11·159	11·102	11·175	+	+	12·497	14·86	10·13
Nickel	Ni	9·300	9·878	11·210	11·618	10·978	12·138	—	+	11·576	14·71	11·62
Rhenium	Re	6·400	7·100	8·367	8·840	9·232	12·609	+	+	ND		9·48
Silicon	Si	9·148	9·488	10·839	11·322	12·144	13·144	+	+	18·132	NVA	14·33
Tantalum	Ta	8·114	8·197	8·935	10·175	8·704	10·678	—	+	ND		11·18
Tungsten	W	8·427	9·197	10·450	11·141	10·165	10·879	—	—	ND	12·71	10·22
Vanadium	V	8·196	8·578	10·229	10·537	11·123	11·425	+	+	11·156	15·87	12·15
		10·203	10·911	12·116	12·510	12·460	13·511			14·138	16·16	14·34

Table 2.2. Present demand[1], estimated cumulative demand to A.D. 2000[1], apparent land resources[1], adequacy of land resources, and apparent marine resources[2], for 90 mineral commodities excluding fluid hydrocarbons (Adapted from: Cruickshank 1978).

Non-metallic minerals	*Symbol*	*Present demand*		*Cumulative demand to A.D. 2000*		*Apparent resources (land)*		*Adequacy (land)*		*Apparent resources (marine)*		
		U.S.	*World*	*U.S.*	*World*	*U.S.*	*World*	*U.S.*	*World*	*Diss.*	*Unc.*	*Con.*
Argon	Ar	8·269	8·681	10·206	10·495	<00	<00	+	+	ND		NA
Asbestos	—	8·704	9·302	10·374	11·200	9·172	9·862	—	—	0		9·32
Barium	Ba	8·204	8·574	10·102	10·398	9·887	10·222	—	—	11·121	11·10	10·43
Boron	B	8·411	9·113	10·292	10·866	11·170	11·340	+	+	14·333	12·26	9·58
Bromine	Br	8·845	9·113	10·476	10·713	<00	<00	+	+	15·576		9·70
Calcium	Ca	9·364	10·111	11·238	11·749	<00	<00	+	+	15·235	15·42	11·58
Chlorine	Cl	9·607	10·136	11·483	12·116	12·360	<00	+	+	17·209		10·59
Clays	—	9·240	10·151	11·195	12·103	11·848	12·410	+	+	ND		—
Corundum and emery	—	6·400	7·9	8·294	9·150	8·720	10·100	+	+	0		—
Diamond	—	8·444	9·398	10·442	11·373	0	10·428	—	—	0		ND
Diatomite	—	8·275	9·103	10·207	11·102	11·348	12·116	+	+	ND	13·64	—
Feldspar	—	7·820	8·263	9·627	10·202	10·620	11·124	+	+	ND		10·46
Fluorine	—	8·646	9·180	10·527	11·166	9·540	10·388	—	—	13·199		11·33
Garnet	—	7·200	7·250	9·183	9·235	9·735	10·368	+	+	0	10·76	—
Gemstones	—	9·510	10·114	ND	11·342	ND	ND	+	+	0		—
Graphite (natural)	—	7·300	8·265	9·173	10·196	8·500	10·520	—	+	0		10·19
Gypsum	—	8·574	9·204	10·330	11·118	11·734	12·367	+	+	0		12·14
Iodine	I	7·530	8·149	9·402	10·113	11·189	11·945	+	+	11·181		9·30
Kyanite and related minerals	—	7·940	8·260	9·858	10·239	10·250	10·886	+	+	0	12·12	10·33
Lithium	Li	7·490	7·820	9·391	9·637	10·767	11·111	+	+	13·282		11·23
Mica	—	7·760	8·193	9·338	10·485	LOW	NK	—	NK	0		—
Nitrogen	N	9·702	10·245	11·398	12·180	12·345	12·368	+	+	12·176		10·11
Oxygen	O	9·139	9·454	10·751	11·290	<00	<00	+	+	ND		NA
Perlite	—	7·410	7·890	9·280	9·685	10·790	11·296	+	+	0		—
Phosphorus	P	9·156	9·516	11·120	11·504	12·306	12·981	+	+	11·482	11·53	11·22
Potassium	K	9·119	9·478	11·104	11·471	11·127	13·366	+	+	15·140	11·20	12·36
Pumice	—	7·61	8·237	9·471	10·200	10·158	11·158	+	+	—		—
Quartz crystal	—	6·200	6·400	7·640	8·778	0	NK	—	NK	0		—
Sand and gravel	—	10·102	10·745	11·767	12·555	11·666	12·333	—	—	0	14·31	—
Sodium	Na	9·308	10·101	11·223	11·799	12·240	<00	+	+	16·301	NVA	12·21
Stone	—	10·122	10·845	11·915	12·648	<00	<00	+	+	0		—
Strontium	Sr	6·300	6·600	8·252	8·488	8·554	9·245	+	+	13·977		10·91
Sulphur	S	9·382	10·144	11·253	12·104	11·128	12·104	—		15·504	NVA	10·81
Talc, soapstone and pyrophyllite	—	7·620	8·318	9·407	10·274	9·623	10·350	+	+	0		—
Vermiculite	—	7·550	7·820	9·374	9·805	10·588	11·588	+	+	0		—
		10·585	11·302	12·416	13·229	12·936	13·360	+	+	15·348	15·46	12·88

Table 2.2. (Continued).

Non-ferrous minerals	Symbol	Present demand		Cumulative demand to A.D. 2000		Apparent resources (land)		Adequacy (land)		Apparent resources (marine)		
		U.S.	World	U.S.	World	U.S.	World	U.S.	World	Diss.	Unc.	Con.
Aluminium	Al	10·198	10·525	12·295	12·832	10·678	11·678	—	—	13·390		11·77
Antimony	Sb	8·193	8·632	10·122	10·339	9·266	10·393	—	+	11·280		8·76
Arsenic	As	7·380	7·840	9·182	9·412	9·304	9·672	+	+	11·490		9·13
Beryllium	Be	8·407	8·593	10·307	10·492	11·134	12·190	+	+	ND	NVA	12·10
Bismuth	Bi	7·920	8·304	9·495	10·158	9·154	9·870	—	—	11·245	12·45	9·66
Cadmium	Cd	8·353	8·830	10·316	10·832	9·554	10·381	—	—	10·806	NVA	9·40
Cesium	Cs	—	—	6·400	6·700	0	9·132	—	+	10·919		11·23
Copper	Cu	10·130	10·774	12·168	12·697	11·684	12·287	—	—	11·129	13·62	11·16
Gallium	Ga	6·400	7·110	8·236	8·705	10·324	11·300	+	+	13·834	NVA	13·67
Germanium	Ge	7·200	7·920	9·131	9·630	8·123	9·240	—	—	ND	NVA	12·13
Gold	Au	9·259	10·116	11·214	11·773	11·117	11·470	—	—	12·246	13·91	10·20
Hafnium	Hf	7·310	7·740	9·204	9·493	11·213	11·527	+	+	ND		12·35
Indium	In	7·150	7·530	8·739	9·273	8·318	9·196	—	—	ND		10·32
Lead	Pb	9·243	9·931	11·133	11·445	10·837	11·278	—	—	11·413	12·47	10·17
Magnesium	Mg	9·144	9·511	11·346	11·589	11·106	13·182	—	+	<17·141	NVA	13·61
Mercury	Hg	8·332	9·138	10·362	11·153	9·500	10·803	—	—	10·634		10·29
Platinum-group metals	—	9·202	9·643	11·141	11·496	9·583	11·824	—	+	ND	10·17	10·96
Radium	Ra	—	—	—	—	10·117	11·117	+	+	ND		11·13
Rare-earth elements	—	8·204	8·354	10·150	10·308	11·171	11·306	+	+	11·138	13·19	12·25
Rubidium	Rb	—	—	6·100	6·200	6·900	8·288	+	+	13·166		6·37
Scandium	Sc	—	—	7·230	7·260	9·351	10·351	+	+	ND	NVA	13·81
Selenium	Se	7·550	8·134	9·245	9·659	9·255	9·964	+	+	12·628		9·38
Silver	Ag	9·193	9·728	11·132	11·496	11·105	11·231	—	+	12·287	9·24	10·26
Tellurium	Te	7·130	7·238	8·594	9·119	9·205	9·739	+	+	ND	13·34	7·89
Thallium	Tl	—	6·100	7·190	7·84	7·199	8·110	+	+	ND		11·62
Tin	Sn	9·196	9·819	11·322	11·653	9·153	11·303	—	—	11·136	12·69	9·96
Titanium	Ti	9·414	10·127	11·385	12·115	11·667	12·388	+	+	10·404	12·74	13·26
Yttrium	Y	7·340	7·450	9·291	9·407	10·146	11·120	+	+	12·514	12·20	13·19
Zinc	Zn	9·380	10·146	10·241	12·109	10·810	11·335	+	—	11·413	14·91	10·72
Zirconium	Zr	8·342	8·179	9·447	10·604	11·375	12·104	+	+	ND	11·19	—
		10·553	11·210	12·680	13·214	12·290	13·326			14·159	14·21	14·18

INC, included in total; NVA, present, but no value assigned; NA, not applicable; ND, no data; NK, not known.

†Gemstones 10·114; world, multiply by 0·30. ‡High numbers (>10^{14}) which would mask general trends have been excluded from these totals.

1 Converted from data in U.S. Bureau of Mines (1970). All data are expressed in order of magnitude dollars ($OM) where the exponent to the base 10 is to the left of the decimal point and its decimal fraction to the right (i.e., $86.2 million or $0.862 x 10^8 is expressed as $OM 8.862).

2 Apparent resources less cumulative consumption.

Table 2.2. (Continued).

It is useful to define the terms *ore, mineral resources, and ore reserves* which appear commonly in the literature and are often misunderstood. A more definitive discussion of the principles of the resource/reserve classification for minerals and forecasting methods used in the U.S. is given in USDOI, USBM and U.S. Geological Survey (USGS) (1980) and Teleki et al. (1985). A comparison of U.S. and accepted United Nations resource categories is given in **Figure 2.2**.

Ore is *a natural aggregate of mineral materials which can be mined at a profit* (American Geological Institute 1972). Prices of metals and other mineral derived commodities fluctuate widely over time due to a variety of technical, economic, political, and social factors such as engineering capabilities, supply and demand, wars and embargoes, or needs and fashions. What is ore in the ground today may be a scientific curiosity tomorrow, and vice versa. A prime example of this occurred with the repeal of the $35/oz gold standard in 1968 which led to a rise in price to $400 in 1980. Similar elasticity of price can be seen for cobalt, copper, silver, and others metals.

Mineral Resources include *all potentially recoverable minerals in a specified area, including measured ore reserves and undiscovered speculative deposits.* Most marine mineral deposits, because they are still speculative, are presently classed as mineral resources.

Ore Reserves are *currently economic mineral resources that have been measured, indicated, or inferred from acquired geological data*; only those reserves which are measured or indicated will normally be used in the evaluation of a mineral property. There are few ore reserves in the marine environment other than those of operating mines because, by definition, the deposit must be currently mineable. Most marine mining technology is still in the development stage.

Classified mineral resource groups are discussed in greater detail in the following pages.

2.1.1 Industrial Minerals

Industrial minerals are those bulk materials which are recovered for use directly as an industrial commodity rather than for their metal content. They include sand and gravel derived from glacial and alluvial sources; biogenic materials such as shell, coral, and carbonate sands; aragonite, a denser and harder form of calcium carbonate commonly of marine origin; salt; sulfur; and precious corals. Phosphorites are treated as a special case because of the maturity and complexity of the U.S. phosphate industry. A key distinguishing feature of the industrial mineral class is that a major percentage (60% to 100%) of the deposits is composed of saleable material and only simple beneficiation may be required to prepare the commodity for market. Within the U.S., the most important commodity appears to be unconsolidated deposits of sand and gravel for use in coastal protection, beach replenishment, and industrial construction.

Sand and Gravel are terms used for different size classifications of unconsolidated sedimentary material composed of numerous rock types. The major

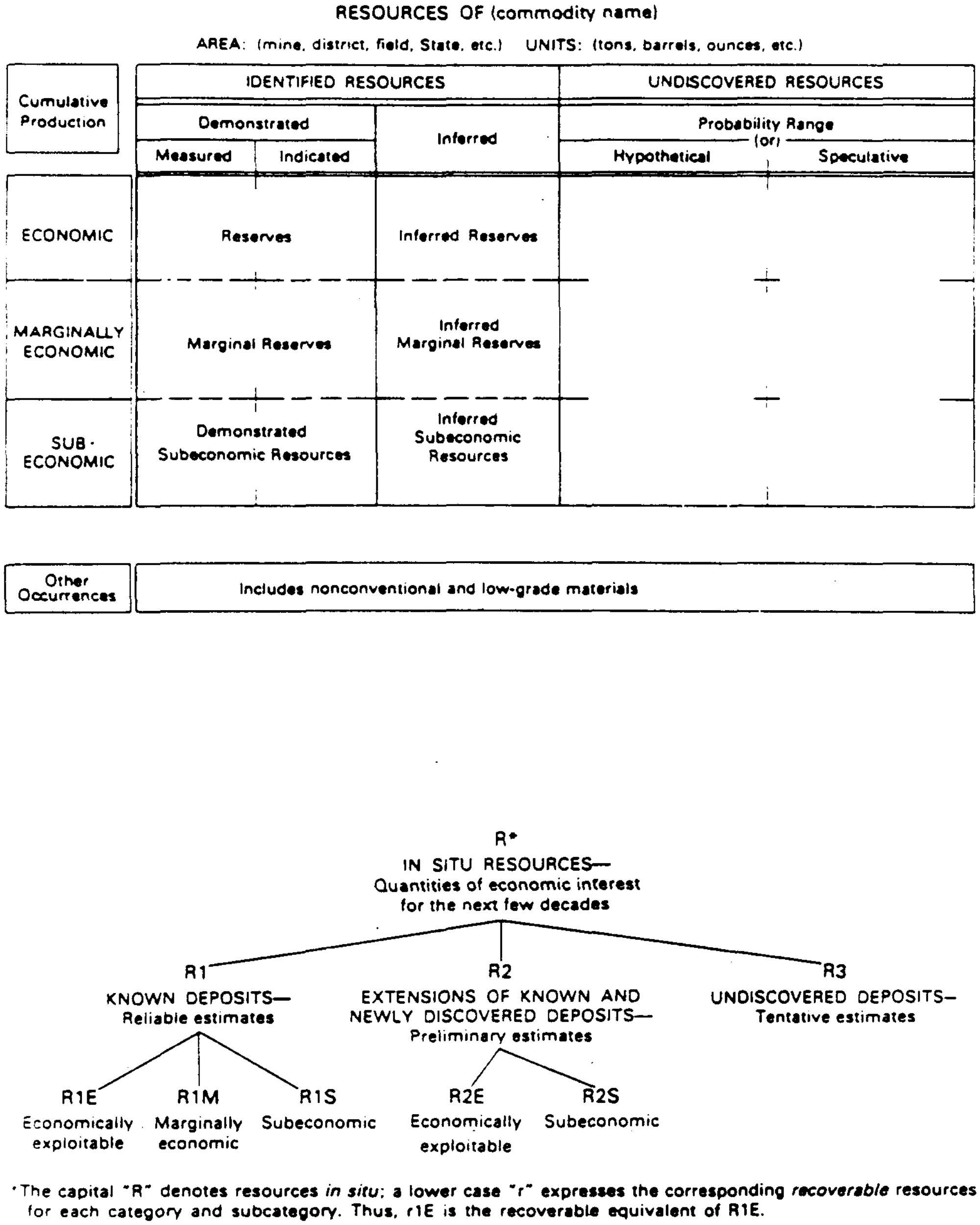


Figure 2.2. Categories of mineral resources and ore reserves used by the U.S. Bureau of Mines and U.S. Geological Survey (upper) compared with that used by the United Nations (lower) (Adapted from: U.S. Department of the Interior, Bureau of Mines and U.S. Geological Survey 1980).

constituent of sand is normally quartz, although other minerals such as rock fragments or carbonates may be present, and may even be dominant, as is the case with tropical reef-derived sands. Gravel, because of its larger size, usually consists of multi-grained rock fragments. Sand is generally defined as material that passes through a #4 mesh (0.475 cm) U.S. Standard sieve and is retained on a #200 mesh (0.0074 cm) U.S. Standard sieve. Gravel diameter ranges from 0.475 to 7.62 cm. **Table 2.3** provides an indication of the areal extent and estimated offshore sand resources for the U.S. Resources of sand and gravel in the U.S. EEZ appear to be not only adequate, but almost ubiquitous; McKelvey (1986) cites resources of more than two trillion metric tons (mt). However, on the OCS (U.S. seabeds seaward of the territorial limits of the States), it is doubtful if there are any known deposits that could be classified at this time (1993) as commercial reserves. The reason for this is that resource information is quite sparse. To evaluate a deposit for commercial use, it is necessary to know the specifications of the material needed for sale in that particular market. Similarly, it is necessary to ascertain that sufficient tonnage of saleable material exists within the deposit to sustain a profitable operation. This means that not only the areal extent, but the volume of the deposit, the grain size, the nature and quality of the grains, and the percentage and location of unsaleable material within the deposit must be ascertained. It is likely that, of the vast quantities indicated as resources, a considerably lesser amount will in fact be mineable. There is little doubt that very substantial, mineable resources of sand and gravel aggregates exist off the U.S. coasts (Cruickshank 1988). Deposits of pure silica sand which are valuable for optical and other special purposes are found in certain environments. Methods for the exploration of sand and gravel deposits are both conventional and satisfactory, and many references to such exploration technology are available (Parkinson 1970; Cruickshank and Marsden 1973; Macdonald 1983). Some 20% of total sand and gravel production in Japan (Okamura 1992) and 15% in the United Kingdom (Earney 1990) is currently obtained from offshore.

Biogenic materials are formed by living creatures and include shells, reef corals, foraminifera, and associated carbonate sands. Deposits of oyster, clam, and mollusc shells are commonly found in temperate waters in embayments or near the coast (Bouma 1976). Reef corals form coastal deposits in tropical or subtropical waters (Dollar 1979). Foraminifera, which are the skeletal remains of calcareous plankton, are found extensively in deep equatorial waters above the calcium carbonate compensation depth of 4,000 to 5,000 m.

Aragonite ($CaCO_3$) is a common deposit in shallow tropical waters as a constituent of muds or in the upper part of coral reefs. Extensive deposits are mined for industrial purposes in the Bahamas for export to the U.S. (Earney 1990).

Precious corals are important deep seabed resources with worldwide distribution. Although the richest beds are found on seamounts in the western North Pacific Ocean and the western Mediterranean Sea, the industry extends worldwide. The USBM lists corals in its mineral statistics reports, although most countries (including the U.S.) regulate the industry as fisheries. Precious coral fisheries have existed in the Mediterranean Sea since ancient times. Beds of commercial density were not developed elsewhere until the early 19th century off Japan. In 1966, about 95% of the world's coral was dredged off Japan, Okinawa, and Taiwan. Overfishing led to stock depletion while intensive exploration

Geographic area	Seismic miles	Cores	Area surveyed (mile^2)	Sand volume ($\times 10^6$ cubic yards)
New England:				
Maine			10	123
Massachusetts (Boston)			175	57
Rhode Island			25	141
Connecticut (Long Island Sound)			50	130
Area totals	1,900	280	260	531
Southshore Long Island:				
Gardiners-Napeague Bays			100	162
Montauk to Moriches Inlet			160	1,912
Moriches to Fire Island Inlet			350	2,404
Fire Island to East Rockaway Inlet			125	1,359
Rockaway			50	1,031
Area totals	955	122	785	6,868
New Jersey:				
Sandy Hook	255	10	50	1,000
Manasquan	86	11	25	60
Barnegat	200	32	75	448
Little Egg	389	38	120	180
Cape May	760	107	340	1,880
Area totals	1,660	198	610	3,568
Virginia:				
Norfolk	260	57	180	20
Delmarva	435	78	310	225
North Carolina	734	112	950	218
Florida:				
Northern:				
Fernandina—Cape Canaveral	1,328	197	1,650	295
Southern:				
Cape Canaveral	356	91	350	2,000
Cape Canaveral—Palm Beach	611	72	450	92
Palm Beach—Miami	176	31	141	581
Area totals	2,471	391	2,591	2,673
California:				
Newport—Pt. Dume	360	69	140	491
Pt. Dume—Santa Barbara	145	34	90	90
Area totals	505	103	230	599
Hawaii	Unknown	Unknown	Unknown	Unknown
Great Lakes:				
Erie	Unknown	Unknown	Unknown	Unknown
Grand totals	8,920	1,341	7,266	15,011

SOURCES: Published and unpublished reports of U.S. Army Corps of Engineers Coastal Engineering Research Center; David B. Duane, "Sedimentation and Ocean Engineering: Placer Mineral Resources," *Marine Sediment Transport and Environmental Management*, D.J. Stanley and D.J.P. Swift (eds.) (New York, NY: John Wiley & Sons, 1976), p. 550

Table 2.3. Areas surveyed and estimated offshore sand resources of the United States (From: U.S. Congress, Office of Technology Assessment 1987)

led to discoveries off Hawaii (i.e., at the junction of the Emperor Seamounts and the Hawaii Ridge system, about 805 km west of Midway). In 1980, these corals represented about 90% of the world's precious coral production. Although the production of pink coral from Midway was about 140,000 kg in 1983, only about 10% of the beds lie within the U.S. EEZ and the fishery is virtually unregulated. Through history, precious coral production has followed the pattern of exploration, discovery, exploitation, and depletion. Precious corals are particularly long lived and beds are characterized by low rates of recruitment and high natural mortality rates. These factors make the "mining" of corals a non-sustainable activity (Western Pacific Regional Fishery Management Council [WPRFMC] 1990). U.S. participation in coral production began in 1966 when commercial corals were discovered off Makapu'u Point in Hawaii. In 1988, regulations (50 CFR 680) were issued by the U.S. National Marine Fisheries Service (NMFS) to control these activities in the EEZs of Hawaii and the U.S. Pacific island possessions. At present, there is no production of precious corals from within U.S. waters.

2.1.2 Mineral Sands

Mineral sands is the current generic industry term for sands containing gold, precious gemstones, or minerals of tin (cassiterite), titanium (rutile, leucoxene, ilmenite), and other metals derived from the breakdown of rocks by weathering. Other terms commonly used in the literature are placer, alluvial, and heavy mineral deposits. The major distinction between industrial minerals and mineral sands is that the commercially valuable portion of the mineral sands is rarely more than a few percent of the amount dredged. As a consequence, the waste product from these operations is generally over 95% of the total material mined and processed. For the special cases of gold and platinum, the amount of saleable metal is measured in parts per million (ppm); for diamonds, measurements in parts per billion (ppb) are common. For all mineral sands or placers, the beneficiation processes are usually based on the physical differences between the ore mineral and the waste materials and rarely employ chemical additives. Mineral sands are widely distributed throughout the world (**Table 2.4**; **Figure 2.1**), generally in coastal areas. However, the occurrence of many mineral sands deposits has also been indicated for the U.S. OCS (Grosz and Escowitz 1983). The occurrence of gold placers in submarine sand channels at depths greater than 2,500 m has been postulated by Dobson (1990), based on new side-scan imagery of the U.S. EEZ off southeastern Alaska, an interesting potential for future deep seabed activities.

2.1.3 Phosphorites

Phosphorites are industrial minerals which have been classed separately because of their special significance (i.e., in terms of an already established and complex industry) and the variety of technologies proposed for their mining offshore. The deposits are most commonly bedded marine rocks of carbonate fluorapatite in the form of laminae, nodules, oolites, pellets, and skeletal or shell fragments. The commercial term "phosphate rock" includes phosphatized limestones, sandstones, shales, and igneous rocks containing apatite. Marine phosphorites vary in character depending on their genesis and are found as crusts, nodules, and sands in shallow basins, submerged plateaux, on the slopes of islands, and in tropical lagoons. Extensive bedded deposits are indicated offshore of the

Commodity	Country	Current Status
Placer Minerals		
cassiterite (tin)	Indonesia; Thailand; U.S.S.R.;	offshore mining
	United Kingdom;	offshore pilot-scale mining
	New Zealand;	offshore exploration
	Australia	previous beach and offshore explorat
chromite (chromium)	U.S.A.;	previous beach mining and offshore exploration
	Mozambique	previous offshore exploration
diamonds	Namibia	beach and offshore mining
gold	Canada; New Zealand;	previous beach mining/offshore exploration
	Philippines;	previous offshore mining; present status unknown
	U.S.A.;	previous beach mining, offshore exploration and mining
	U.S.S.R.;	offshore exploration/mining
	Fiji;	estuarine mining operation
	India	offshore exploration
iron sands	Brazil;	previous offshore mining; present status unknown
	Fiji; South Africa,	beach mining
	Japan;	previous beach and offshore minin
	Australia; New Zealand; Florida, U.S.A.;	previous beach mining
	Philippines;	previous beach mining, present status unknown
	Mozambique; S.W. India;	previous or ongoing offshore explora
	Sri Lanka	beach mining, offshore exploration
monazite (rare earths and thorium)	Australia;	previous beach mining
	S.W. India;	offshore exploration
	Brazil; Sri Lanka;	beach mining
phosphorite (phosphorous)	Australia; Mexico; New Zealand; U.S.A.	past or ongoing offshore exploration
platinum	U.S.A.	previous beach mining, and ongoing exploration
rutile	Australia; Brazil; S.W. India; Sri Lanka;	beach mining, offshore exploration
	Canada	previous offshore exploration
zircon	Sri Lanka;	beach mining, offshore exploration
	Canada;	previous exploration
	Australia;	previous offshore exploration
	Mozambique	

Table 2.4. Summary of global beach and offshore mining activities (Adapted from: Hale and McLaren 1984).

eastern U.S. Marine phosphorites commonly contain minor quantities of uranium/thorium, platinum, cadmium, and rare earths (Manheim et al. 1980; Riggs et al. 1987). The widespread distribution of phosphorites in continental margins is indicated in **Table 2.5** and in **Figure 2.1**.

2.1.4 Metalliferous Oxides

Metalliferous oxides are primarily oxides of manganese and iron. These ubiquitous seabed deposits contain potentially commercial quantities of manganese (20 to 30%), cobalt, copper, and nickel (less than 3% combined). They occur in all oceans primarily as discrete potato-sized nodules overlying soft sediments in water depths between 4,000 and 6,000 m (**Figure 2.3**) or as encrustations up to 40 cm, but more commonly 3 to 5 cm thick, on the exposed rocks of island slopes, seamounts, or submerged plateaux in water depths between 800 and 2,400 m (**Figure 2.4**). The nodules are commonly referred to as manganese nodules, or polymetallic nodules and are primarily valued for their nickel content (**Table 2.6**). The crusts are commonly referred to as manganese crust, cobalt crust, or high-cobalt manganese crust and are primarily evaluated on the basis of their cobalt content; the crusts are commonly associated with platinum and phosphorites. The deposits apparently form directly on the seabed through chemical precipitation from seawater and sediment pore-water fluids. Iron and manganese are the two most common transition metals in the earth's crust. The precipitation process is apparently occurring virtually everywhere on the seabed where the bottom water is oxygenated and represents an end result of the transport of these metals from terrigenous rocks. Such deposits seem to form commonly where natural sedimentation rates are not high enough to overwhelm chemical accretion processes.

Extensive research has been conducted to elucidate and quantify deposit formation processes. Interest has been prompted by the prevalence of these deposits in the oceans of the world and apparent links with the global processes of weathering, primary production, and transport of metals through the world's marine ecosystems.

Large deposits of manganese nodules with relatively large concentrations of cobalt, copper, and nickel are found on the seabed surface in the major oceanic basins. Deposits in several areas have been investigated for commercial recovery potential, including the following:

- Clarion-Clipperton region of the northeastern tropical Pacific Ocean (approximately lat. 5° to 20° N, long. 110° to 155° W);
- Central Indian Ocean south of India (approximately lat. 5° to 10° S, long. 75° to 88° E);
- EEZ of the Cook Islands in the South Pacific (approximately lat. 15° to 25° S, long. 155° to 165° W); and
- Blake Plateau off the Atlantic coast of the U.S. (approximately lat. 30° to 35° N, long. 65° to 80° W).

Excellent summaries describing what is known of formation processes and the geological setting of these deposits have been assembled (Wogman et al. 1973; Bischoff

CONTINENTAL MARGIN	REGION
East Atlantic:	Portugal, Northwest Africa through South Africa, and Agulhas Bank
West Atlantic:	North Carolina through Florida, Cuba, Venezuela, and Argentina
East Pacific:	California through Baja California, Mexico, and Peru through Chile
West Pacific:	Sakalin Island, Sea of Japan, Indonesia, Chatham Rise east of New Zealand, and East Australian shelf

Table 2.5. Distribution of phosphorites in Miocene sediments along continental margins (From: Riggs et al. 1987).

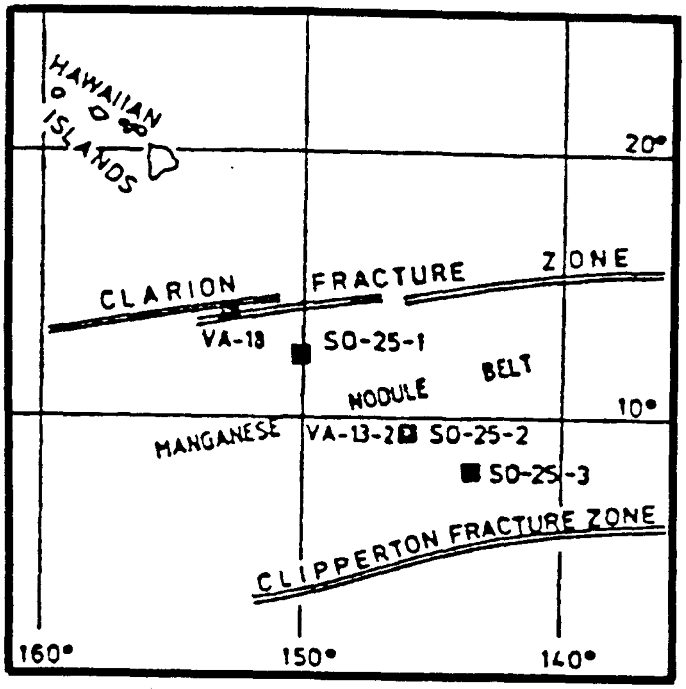


Figure 2.3. Belt of high grade manganese nodules between the Clarion and Clipperton Fracture Zones in the Pacific (From: Teleki et al. 1985).

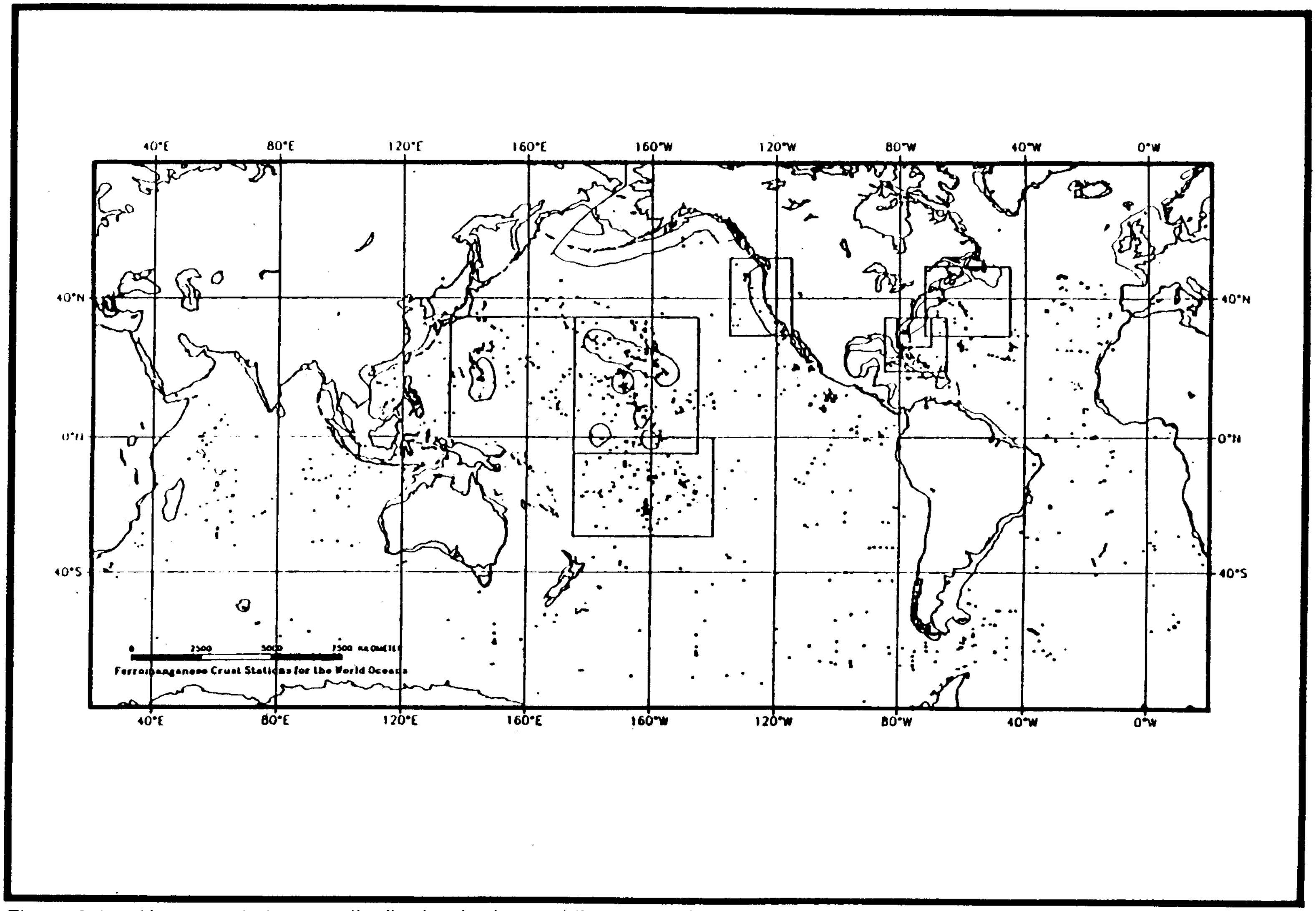


Figure 2.4 Known cobalt crust distribution in the world's oceans (Adapted from: Manheim and Lane-Bostwick 1989).

Compo- nent	Price ($/kg)	MPM crusts				Line Is. crusts				MIDPAC				Nodule (NB)			
		% dry	% wet	$/t wet	$/m²	% dry	% wet	$/t wet	$/m²	% dry	% wet	$/t wet	$/m²	% dry	% wet	$/t wet	$/m²
Co	27.56	0.83	0.54	148.82	2.98	1.00	0.65	179.14	3.58	0.79	0.51	140.56	2.81	0.24	0.16	44.10	0.44
Ni	4.98	0.49	0.32	15.94	0.32	0.55	0.36	17.93	0.36	0.49	0.32	15.94	0.32	1.21	0.79	39.34	0.39
Cu	1.77	0.07	0.05	0.89	0.02	0.07	0.05	0.89	0.02	0.07	0.04	0.71	0.01	1.00	0.65	11.51	0.12
Mo	10.58	0.06	0.04	4.23	0.08	0.06	0.04	4.23	0.08	0.06	0.04	4.23	0.08	0.04	0.03	3.17	0.03
**	1.52	25.0	16.25	247.00	4.94	25.0	16.25	247.00	4.94	24.6	15.99	243.05	4.86	25.2	16.38	248.98	2.49
***	0.58	25.0	16.25	94.25	1.89	25.0	16.25	94.25	1.89	24.6	15.99	92.74	1.85	25.2	16.38	95.00	0.95
Total																	
**				416.88	8.34			449.19	8.98			404.49	8.08			347.10	3.47
***				264.13	5.29			296.44	5.93			254.18	5.07			193.12	1.93

Table 2.6. Examples of metal grades and values for crusts and nodules (From: Riggs et al. 1987).

and Piper 1979; Cronan 1980; Halbach et al. 1988). Recent listings of nodule compositions for these and other areas have been compiled in reports (Botbol and Evenden 1989; Japan International Cooperation Agency 1991) and, for many sites, are available as computer databases maintained by the USDOC, NOAA, NGDC.

Although research into the genesis, composition, and distribution of ferromanganese crust deposits has lagged behind that for manganese nodules, there have been significant advances during the past 10 years. Recently, a comprehensive tabulation of crust compositions for worldwide occurrences has been assembled by Manheim and Lane-Bostwick (1989).

It is currently believed that both crusts and nodules grow as precipitates on the seabed surface. Two general sources for the metals seem to dominate: (1) pore-water solutions and colloidal suspensions within the host sediments; and (2) seawater itself. Copper, manganese, and nickel seem to be relatively more important components in the pore-water source, while cobalt and iron are relatively more important in the seawater source. Deep seabed manganese nodules are derived from mixtures from these two sources, usually with the pore waters providing the majority of the material. Manganese crust deposits seem to be composed almost entirely of material derived directly from seawater.

Growth rates for the deposits have been determined using several techniques (Heye 1975; Mangini and Sonntag 1977; Segl et al. 1984; Mangini et al. 1986). These vary between less than 1 mm of growth per million years (mm/My) to more than 20 mm/My. Crusts grow at the lower bound of this range, several times more slowly than the nodules. Though some aspects of these dating techniques are subject to doubt, the correlation of results among different techniques suggests that the range of values described here are fairly accurate.

Because crust deposits are derived almost completely from direct precipitation from seawater, they offer a potentially important record of the ocean's chemical environment during the past 80 to 100 My. In contrast, nodule deposits are primarily the products of multiple episodes of precipitation and partial dissolution. Previous work (Halbach and Puteanus 1984; DeCarlo 1991; Hein et al. 1992) on Pacific deposits indicates that the layers of deep ocean seamount deposits show significant differences that are related to regional, and perhaps global, changes in the marine chemical environment. Future research on the crusts can be expected to produce at least a partial history of seabed chemistry reaching back for at least 80 My. As the links between the deposit formation and seawater chemistry are more fully understood, it is quite possible that the crust-deposit stratigraphic record will enable the establishment of basic constraints to the variability of basic parameters of current interest (e.g., the long-term oceanic rates of absorption of CO_2, heavy metals, and other pollutants). The association of crusts with the rare earth metals has also been described by DeCarlo (1991).

2.1.5 Hydrothermal Deposits

Hydrothermal mineral deposits are formed by the action of circulating waters which dissolve, transport, and redeposit the elements and compounds in the earth's crust.

Most of the familiar hard rock mineral lodes of barite, copper, gold, lead, silver, and tin on land or in the submerged continental shelves are hydrothermally derived. Recently discovered and potentially significant, deep seabed hydrothermal sulfide deposits (McMurray 1990) are commonly referred to as metalliferous or polymetallic sulfides (PMS). These deposits may carry sulfides of almost any of the metallic elements, including copper, gold, lead, silver, and zinc. They are formed in the vicinity of active diverging plate boundaries throughout the world's oceans. **Figure 2.5** indicates their known distribution in the Pacific. Current knowledge of the grades, sizes, occurrences, and settings of the marine deposits is rudimentary, but consistent with the notion that this type of deposit will ultimately be as important as, or more important than, any other type of marine deposit (Koski et al. 1985; Malahoff 1985; Rona 1985). Deposits which are presently forming are frequently characterized by venting streams of hot (300°C) mineralized fluid (i.e., smokers) which result in the local formation of metalliferous mud, mounds, or rock chimneys rich in sulfides. In the upper fractured zone or deep in the rock mass beneath the vents, vein or massive sulfide deposits may be formed by the circulating fluids and preserved as the crustal plates move across the oceans. These off-axis deposits are potentially the most significant resources of hydrothermal deposits, even though none have yet been located.

2.1.6 Dissolved Minerals

The most significant source of minerals for sustainable recovery may be ocean waters, which include nearly all the known elements in some degree of solution (**Table 2.7**). Current production of dissolved minerals from seawater is limited to fresh water, magnesium, magnesium compounds, salt, bromine, and heavy water (i.e., deuterium oxide). Various techniques designed for the recovery of copper, gold, and uranium by solution or via bacterial methods have been carried out in several countries. Although these techniques have been developed for application onshore, it is likely that these methods will be fully transferable to the marine environment (Earney 1990). The potential for extraction of dissolved materials from naturally enriched sources (e.g., hydrothermal vents) may be high.

2.2 Operational Methods and Technology

This section briefly outlines the technical aspects of marine mining in continental shelf and deep ocean environments, both of which are found in the U.S. EEZ under management of the MMS. Two additional environments, the coastal zone and the onshore, have also been included in this analysis. If the technical aspects of a given operation are specific to only one environment, this fact has been noted.

The mining industry generally encompasses companies with activities directed towards mineral exploration, development, mining, and processing of ores and marketing of mined materials. The marine mining industry is influenced by a heterogeneous mix of international entrepreneurs, advanced engineering companies, politicians, environmentalists, legal experts, long-time dredge operators, and a few old-line mining companies. Despite historical setbacks, many aspects of the work done to date by the marine mining industry have been serious and well founded.

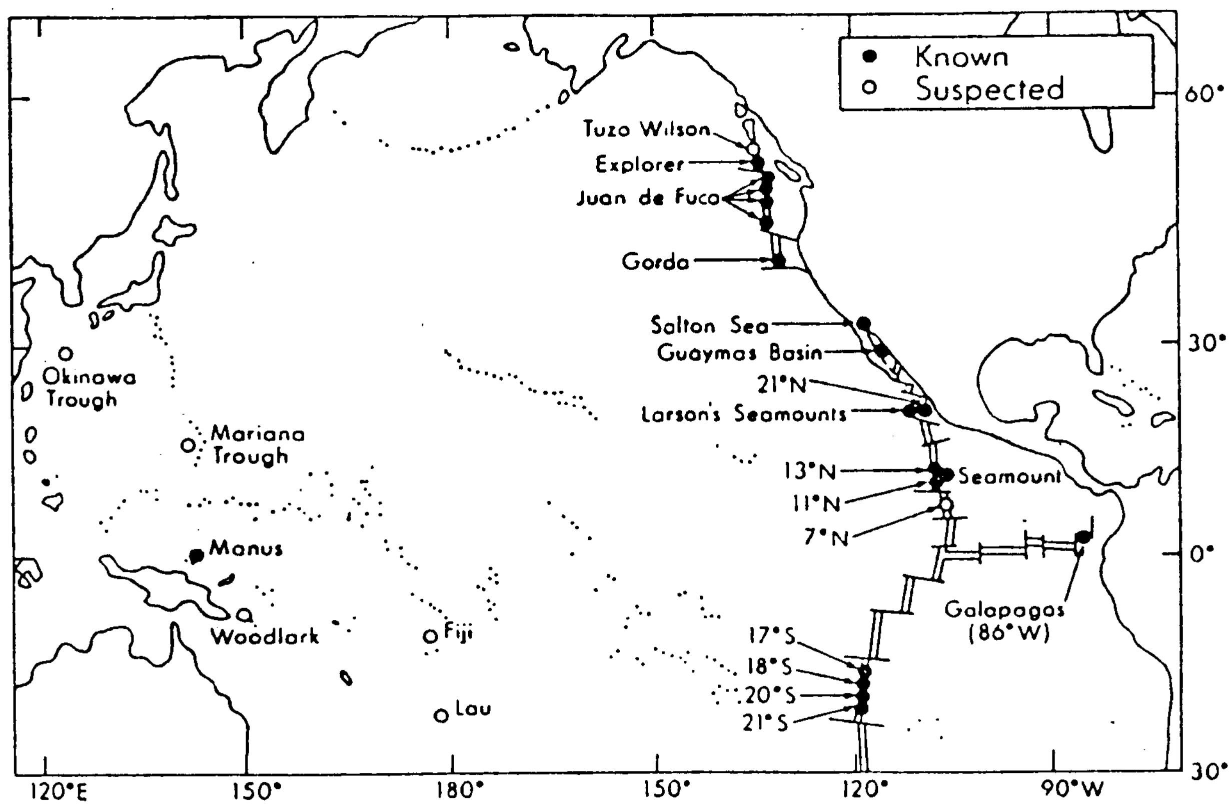


Figure 2.5 Distribution of known and suspected metalliferous sulfide deposits and active hydrothermal vents in the Pacific Ocean (From: Scott 1987).

Element	Concentration, Mg per L*	Amount of Element in Seawater, Tons per Cu Mi	Total Amount in the Oceans, Tons
Chlorine	19,000.	89.5×10^6	29.3×10^{15}
Sodium	10,500.	49.5×10^6	16.3×10^{15}
Magnesium	1,350.	6.4×10^6	2.1×10^{15}
Sulfur	885.	4.2×10^6	1.4×10^{15}
Calcium	400.	1.9×10^6	0.6×10^{15}
Potassium	380.	1.8×10^6	0.6×10^{15}
Bromine	65.	306,000	0.1×10^{15}
Carbon	28.	132,000	0.04×10^{15}
Strontium	8.	38,000	$12,000 \times 10^9$
Boron	4.6	23,000	$7,100 \times 10^9$
Silicon	3.	14,000	$4,700 \times 10^9$
Fluorine	1.3	6,100	$2,000 \times 10^9$
Argon	0.6	2,800	930×10^9
Nitrogen	0.5	2,400	780×10^9
Lithium	0.17	800	260×10^9
Rubidium	0.12	570	190×10^9
Phosphorus	0.07	330	110×10^9
Iodine	0.06	280	93×10^9
Barium	0.03	140	47×10^9
Indium	0.02	94	31×10^9
Zinc	0.01	47	16×10^9
Iron	0.01	47	16×10^9
Aluminum	0.01	47	16×10^9
Molybdenum	0.01	47	16×10^9
Selenium	0.004	19	6×10^9
Tin	0.003	14	5×10^9
Copper	0.003	14	5×10^9
Arsenic	0.003	14	5×10^9
Uranium	0.003	14	5×10^9
Nickel	0.002	9	3×10^9
Vanadium	0.002	9	3×10^9
Manganese	0.002	9	3×10^9
Titanium	0.001	5	1.5×10^9
Antimony	0.0005	2	0.8×10^9
Cobalt	0.0005	2	0.8×10^9
Cesium	0.0005	2	0.8×10^9
Cerium	0.0004	2	0.6×10^9
Yttrium	0.0003	1	5×10^8
Silver	0.0003	1	5×10^8
Lanthanum	0.0003	1	5×10^8
Krypton	0.0003	1	5×10^8
Neon	0.0001	0.5	150×10^6
Cadmium	0.0001	0.5	150×10^6
Tungsten	0.0001	0.5	150×10^6
Xenon	0.0001	0.5	150×10^6
Germanium	0.00007	0.3	110×10^6
Chromium	0.00005	0.2	78×10^6
Thorium	0.00005	0.2	78×10^6
Scandium	0.00004	0.2	62×10^6
Lead	0.00003	0.1	46×10^6
Mercury	0.00003	0.1	46×10^6
Gallium	0.00003	0.1	46×10^6
Bismuth	0.00002	0.1	31×10^6
Niobium	0.00001	0.05	15×10^6
Thallium	0.00001	0.05	15×10^6
Helium	0.000005	0.03	8×10^6
Gold	0.000004	0.02	6×10^6
Protactinium	2×10^{-9}	1×10^{-5}	3,000
Radium	1×10^{-10}	5×10^{-7}	150
Radon	0.6×10^{-15}	3×10^{-12}	1×10^{-3}

* After Goldberg, 1963 (see reference in Mero, 1965).

Table 2.7. Concentration and amounts of 60 of the elements present in seawater (From: Cruickshank and Marsden 1973).

Generalizations pertinent to marine mining technology and the environment would be premature. At present, examination of each activity on a "case-by-case" basis is the most reasonable approach to a summarization of operational methods and technology. Some degree of order has been established, however, as (1) mineral deposit types have been classified; (2) mining systems have been categorized; (3) legal regimes have been established in various countries; and (4) the environmental aspects of marine mining have been the object of consideration and measurement. Despite the interest engendered in the last three decades, there are few operating mines offshore; the likelihood of new offshore operations will be dependent on the economics of the market and national and international politics.

2.2.1 Mining

Despite the fact that every mine is different, there are only four basic methods of mineral extraction on land or at sea, including (1) scraping the surface; (2) excavating a pit or quarry; (3) tunneling underground; and (4) extracting the mineral through a bore hole or other conduit as a fluid (**Figure 2.6**). All mining methods are based on variations of these technologies.

2.2.1.1 Scraping

Scraping methods involve the removal of surficial material from the seabed by means of a device which traverses the deposit. Examples of scraping methods used in conventional shallow water systems, tested deep water systems, and speculative deep water systems are described in greater detail below.

- **Conventional Shallow Water Systems**

Conventional shallow water systems include (1) mechanical dragline dredges, commonly used for placer recovery; and (2) trailing suction hopper dredges, used for recovery of sand and gravel.

Dragline Dredge: Dredges of this type are used in offshore mining and deep seabed sampling, as well as in construction. Their use has been advocated for the recovery of deep seabed nodules and slabs of phosphorites (Mero 1965). Material would be recovered by large dredge buckets that scrape it from the surface of the deposit and feed it into barges for transportation to shore (**Figure 2.7**).

Annual production of phosphorite from an OCS mine could be on the order of 360,000 mt, or roughly 138,000 m^3 of ore. This rate of production could involve 38 m^3 buckets scraping an average of 18 mt of phosphorite from the seabed every 20 min in a water depth of about 180 m. At an average abundance of 9 kg/m^2, over 5 km^2 (2 mi^2) of seabed would be mined annually. At a mine life of 20 years, a total of 104 km^2 (40 mi^2) would be affected if the deposits were confined to the seabed surface.

The continuous line bucket (CLB) system, described later as a tested deep water system, consists of a series of dragline buckets operating in a continuous loop. The

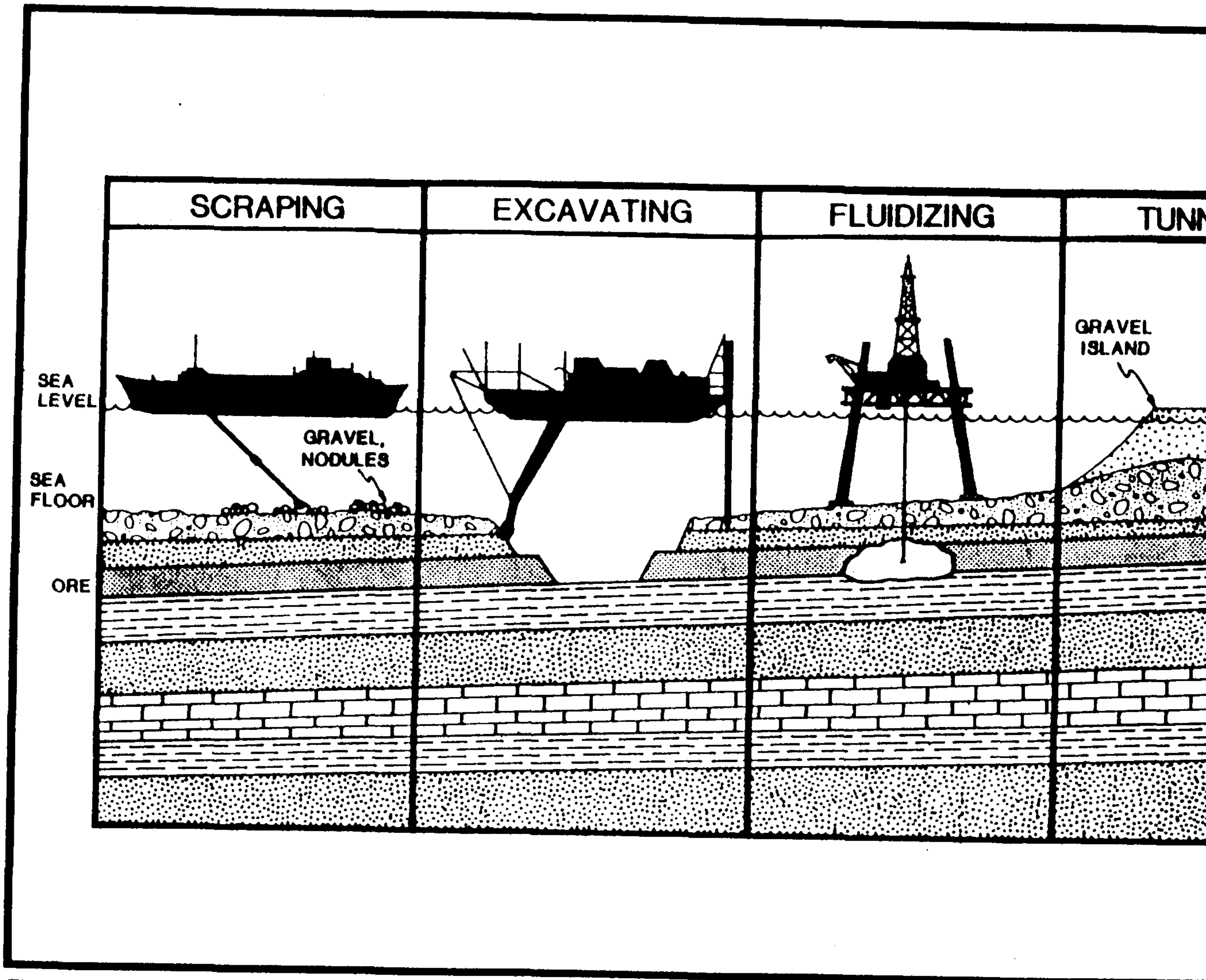


Figure 2.6. The four basic methods of mining (From: Cruickshank et al. 1987).

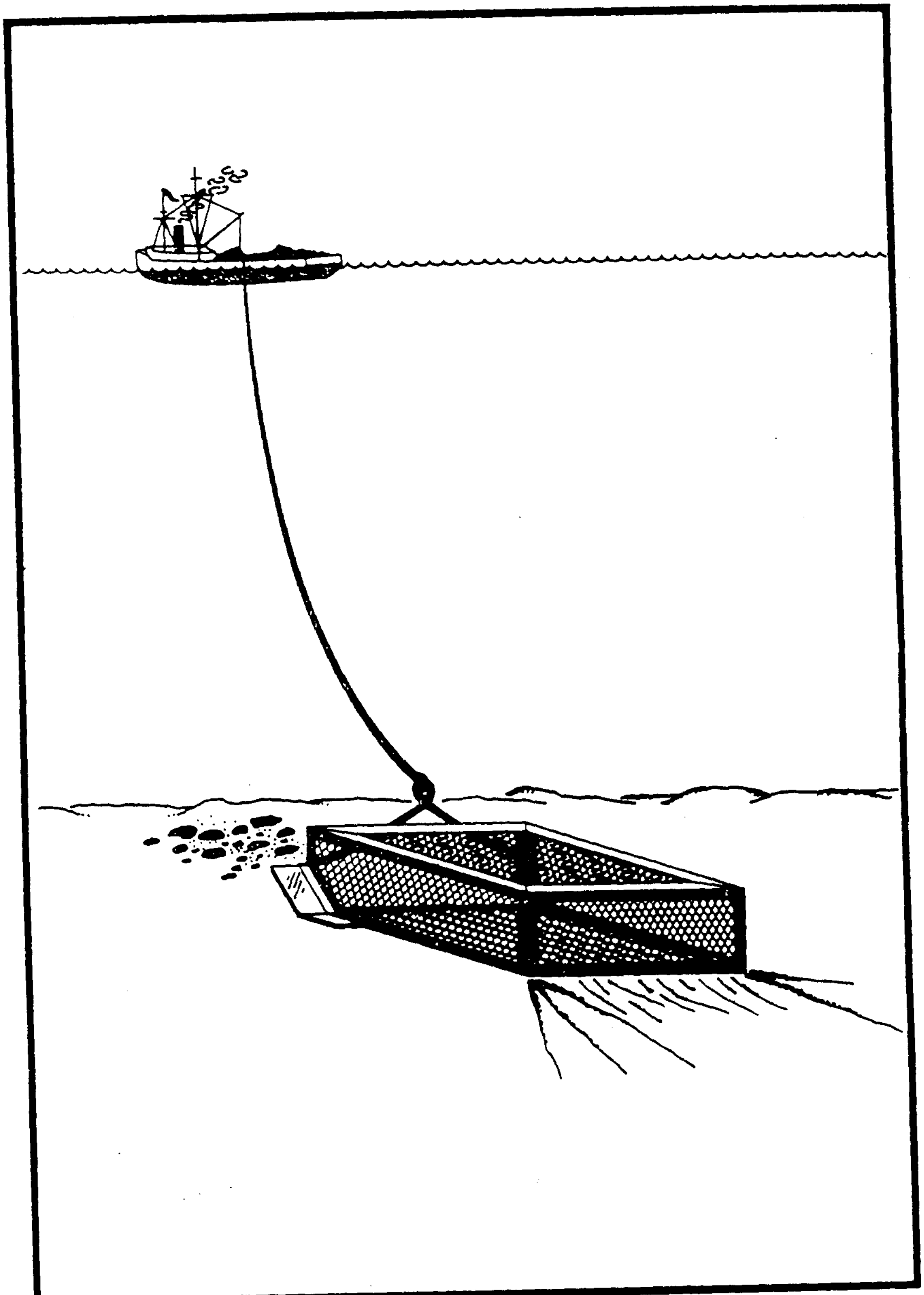


Figure 2.7. A deep water dragline dredge (From: Cruickshank et al. 1987).

use of the CLB system for mining shallow deposits in coastal areas or sheltered waters has been proposed and may be encountered in the future (Masuda et al. 1991).

Trailing Suction Hopper Dredge: A suction hopper dredge uses a pump to draw a slurry of bottom water and sediment into a riser or pipe leading to the mining vessel. As the sediment accumulates in the hopper, the water decants overboard. This system is used primarily for maintaining harbor channels. It is also used extensively for mining sand and gravel in water depths up to 36 m in the North and Baltic Seas (Padan 1983; Uren 1988). New vessels (e.g., *ARCO Avon*, launched in 1986) are designed to extend mining capability to depths of 45 m (Drinnan and Bliss 1986).

As its name implies, the trailing suction hopper dredge mines while in motion, creating numerous shallow trenches in the seabed commonly about 1 m wide and 0.3 m deep (**Figure 2.8**). This dredge uses one of several drag heads, each of which is equipped with a coarse-grid steel framework positioned across the opening of the suction head to prevent large rocks from entering the suction pipe. Coarse particle sizes are screened out and rejected after passing through the pump. Fine materials are washed overboard with the slurry overflow. In some cases, vibrating screens allow part of the sand fraction to be dumped back into the ocean because the ratio of sand to gravel mined may differ from the desired marketable mix. The use of sand and gravel as construction material requires that stringent measures be taken to avoid mining any clay layers, as the entire shipload could become contaminated and unmarketable. Additional detail on the equipment used and extensive photographic documentation are given by Hess (1971).

The volume of material that may be mined includes the sum of the marketable material, the fraction to be rejected, and the overburden initially stripped away. For example, in moving 0.9 million mt of product to shore annually, an equal amount of sand might be rejected to reduce the sand/gravel ratio from 70:30 to a more marketable 40:60 (National Academy of Sciences [NAS] 1975). The 1.8 million mt of annual excavation would result in a gradual lowering of the ocean floor by about 0.6 m over an area of 2.59 km^2 or about 1.6 million m^3.

- **Tested Deep Water Systems**

Deep water systems tested for the recovery of manganese nodules include (1) towed or self-powered mining devices which feed via a hydraulic lift to a surface platform; and (2) CLB systems, with drag line buckets suspended from a line looped around a surface platform.

Development of systems to recover deep seabed manganese nodules has accelerated during the past 20 years, particularly within the private sector and among government-subsidized international consortia. Mining manganese nodules is unique for mineral extraction, not only because it involves transport of the ore through 4,500 to 5,000 m of seawater, but also because the deposits are essentially two-dimensional with no overburden. Mining manganese nodules is much more analogous to harvesting potatoes than it is to strip-mining operations for stratiform deposits such as coal and other conventional ores.

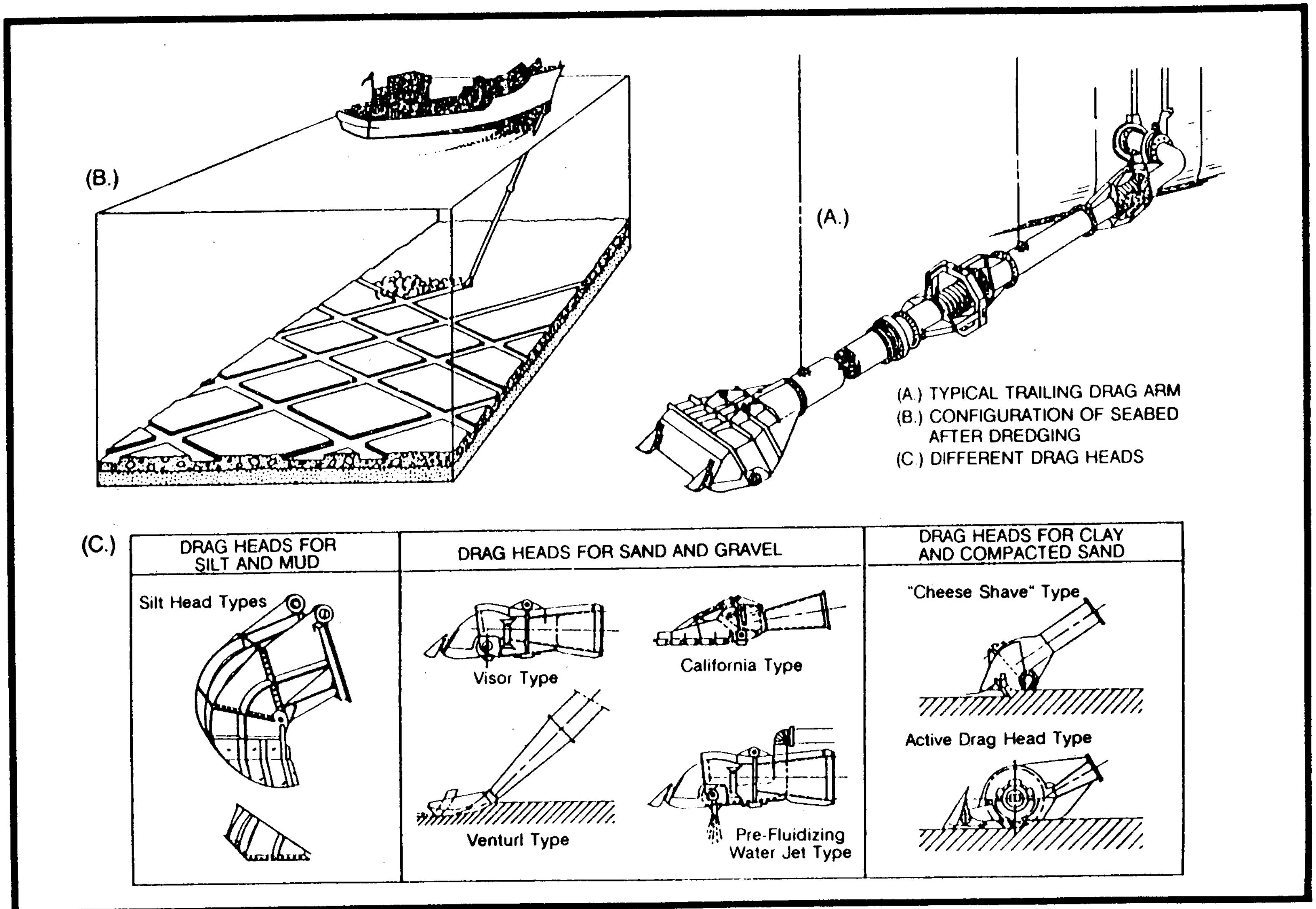


Figure 2.8 Trailing suction hopper dredge and various drag heads (Adapted from: Cruickshank et al. 1987).

Mining operations consist of removing nodules from the seabed surface of fine-grained pelagic sediments (pickup), followed by conveyance to the ocean surface (lift). Many strategies have been tested to accomplish these two tasks, ranging in complexity from simple, towed dredges to self-propelled, highly maneuverable systems. The environmental impacts of these different systems are likely to be equally diverse. Impact assessment will depend very much upon the specific design proposed. Systems which have been tested in actual scale-model tests in the deep seabed include (1) several tests of different hydraulic systems, which pick up the nodules with a towed or self-propelled harvester and then lift the ore to the surface with simple hydraulic or air-assisted lift systems; and (2) a CLB system. Brief descriptions of both types of systems are provided below.

Hydraulic Systems: Operating characteristics for hydraulic systems are well documented (USDOC, NOAA 1981; United Nations 1984), as outlined in **Figure 2.9**. Hydraulic miners use airlift or hydraulic lift with towed or self-propelled collectors. Towed mining devices (or passive systems) are similar to a scraper or harrow being dragged over a plowed field. Nodules are picked up by tines at the front of the miner and fed into the suction pipe by conveyor belt or by the forward movement of the device. Separation of fine sediment is accomplished automatically by the screening effect of the tines and use of a screen on the lifting part of the miner. Active or self-propelled miners are more complex and may be fitted with separate propulsion, navigation, nodule pickup, and crushing systems (**Figure 2.10**). The complexities of the design for these systems are illustrated in **Figure 2.11** for a hydraulic lift with self-propelled collector as used by Ocean Mining Company during successful tests in the Pacific Ocean (Welling 1981).

The first hydraulic system for recovery of deep seabed manganese nodules was tested by Deepsea Ventures, Inc. on the Blake Plateau during the summer of 1970 (Geminder and Lecourt 1972). Subsequent tests were completed by this group and several other international consortia between 1970 and 1980. Several tests were monitored by U.S. and other researchers to estimate potential environmental impacts. Monitoring results from efforts on the Blake Plateau are discussed in greater depth in **Section 2.3.1**. For the purposes of impact assessment, the following distinctions among these tested systems are useful to consider:

<u>Precision of Mining Track</u>: Several systems tested were towed from the surface while others had passive controls on the seabed collector to provide limited steering capability. Several systems were entirely self-propelled, with interactive, real-time steering. From the perspective of the miner, a trade-off exists between the degree of control attained and the cost and complexity of the design. From the perspective of an impact assessment, two factors are important. High precision allows efficient recovery of the mineral resources and also permits accurate avoidance of areas deemed to be worthy of protection and preservation.

Technological advances which have occurred since these tests were carried out, particularly with regard to telemetry and control systems, strongly suggest that future hydraulic systems will be steerable with high (i.e., sub-meter) precision. At least one

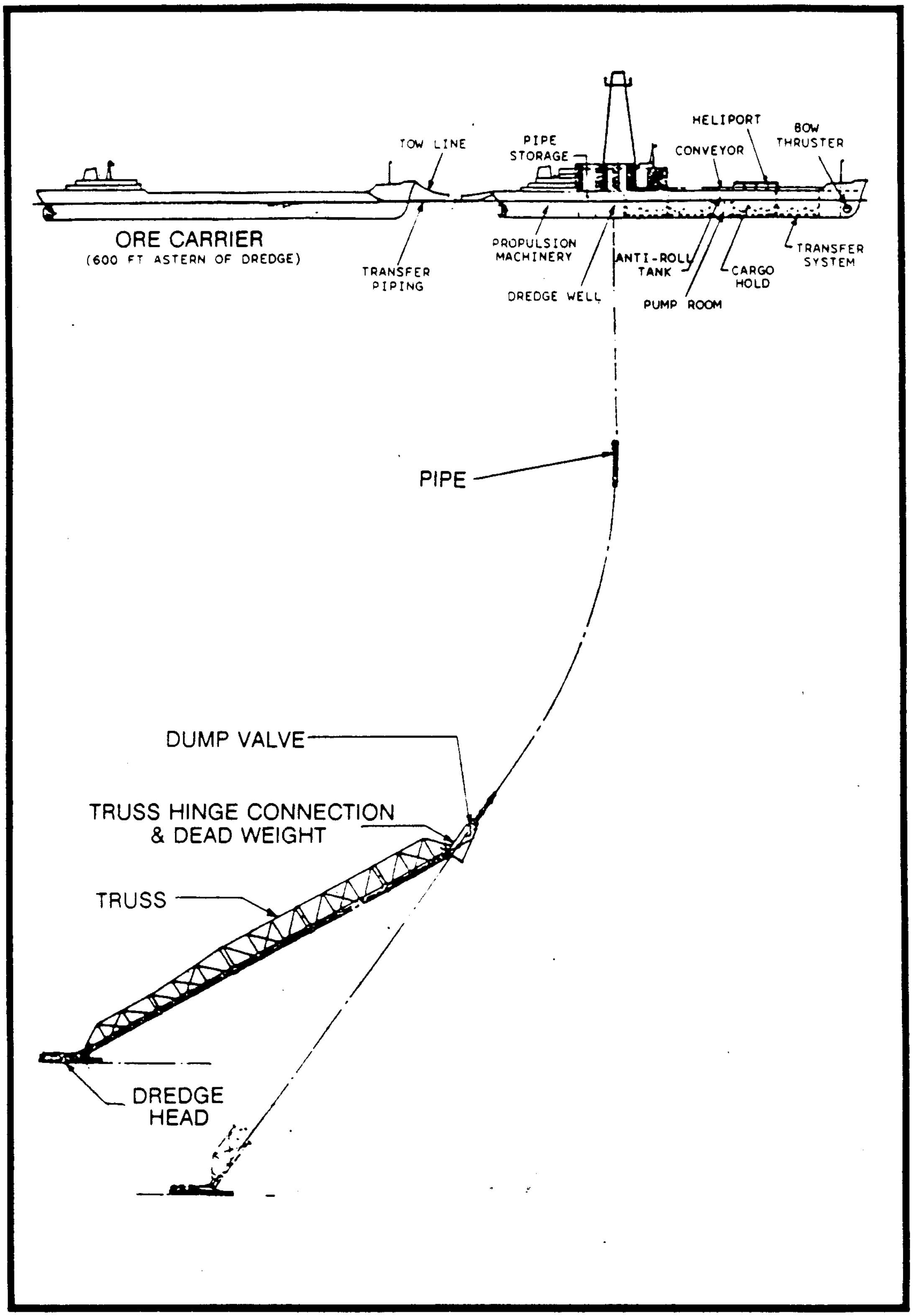


Figure 2.9 Trailing suction hopper dredge for 5,000 m water depths (Adapted from: Kaufman et al. 1985).

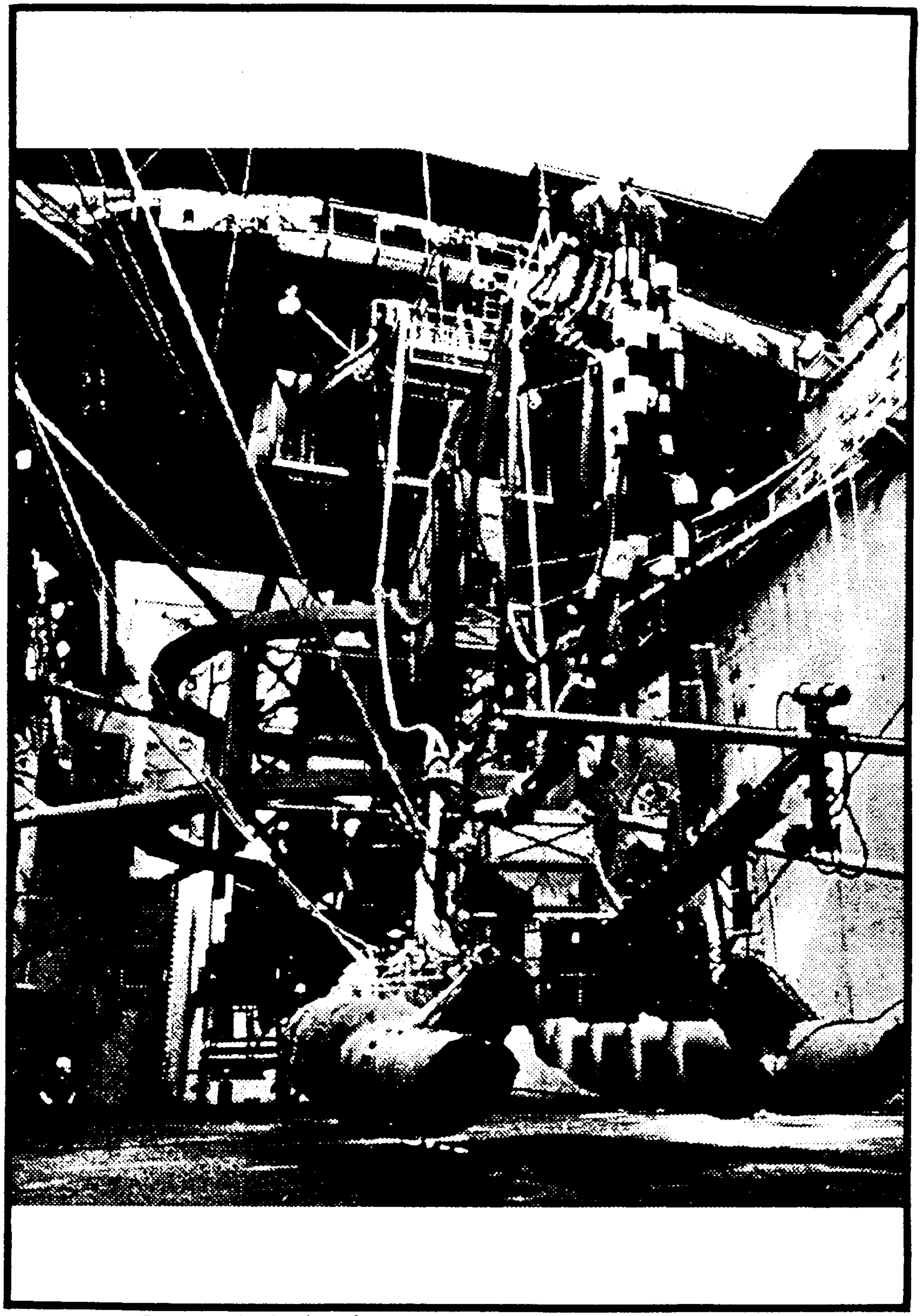


Figure 2.10 Deep seabed miner for manganese nodule recovery (From: Ocean Mining Company 1978).

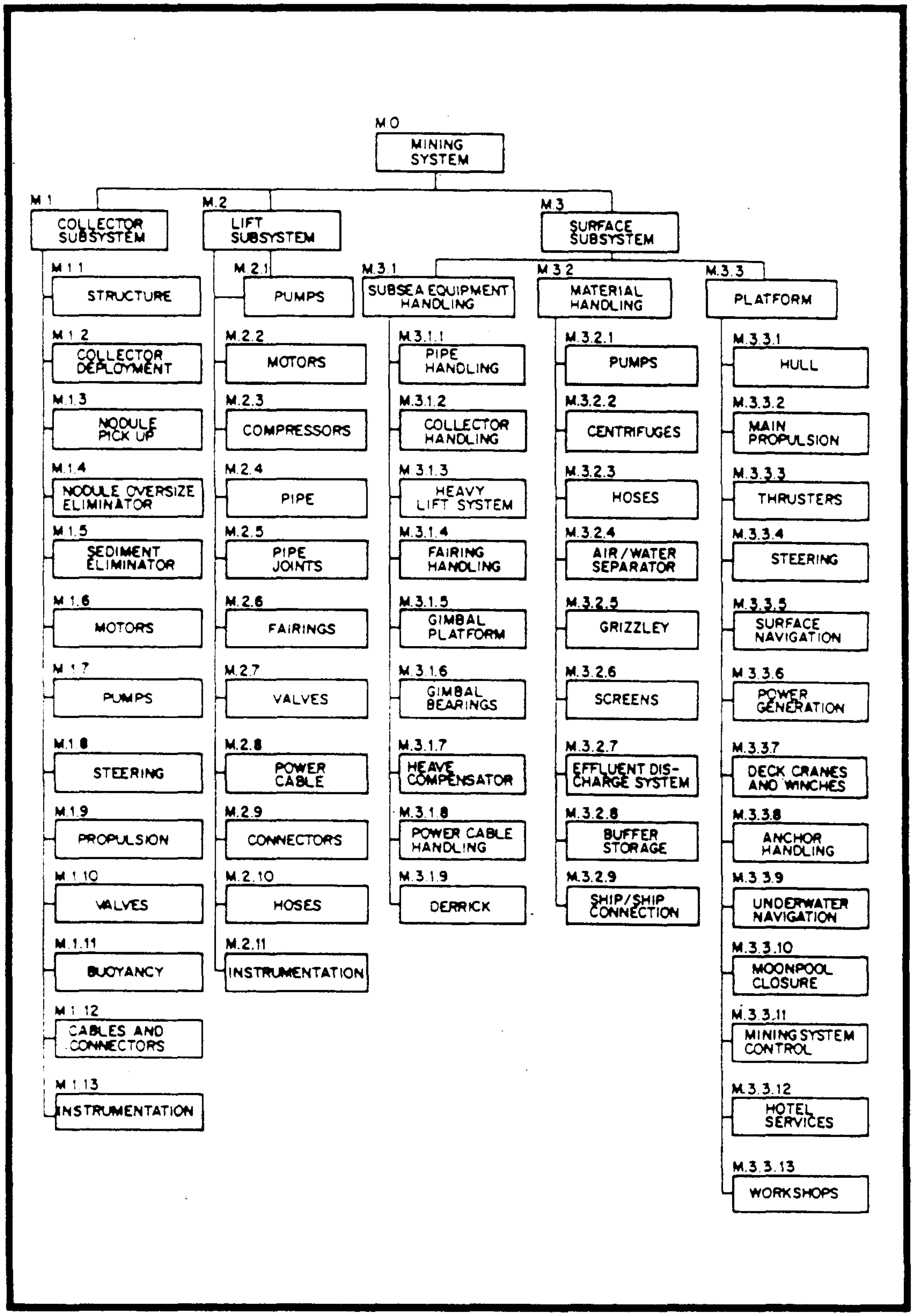


Figure 2.11. Schematic of subsystems required for deep seabed suction dredge with self-propelled miner (From: United Nations 1984).

system, currently under development by French interests, is designed to have such high resolution controls.

Separation of Nodules from Sediments: All systems are designed to minimize the amount of sediment which is lifted along with the nodules. Nodules have been raked up and/or washed before being collected. For the miner, the trade-offs lie with energy costs, maintenance costs, and reliability. From an environmental assessment perspective, the main concerns rest with the efficiency of the collection and separation and with the dispersion of sediments in bottom waters. The optimal design must provide an acceptable balance among these potentially conflicting concerns.

Discharge of Suspended Solids: After collection, the nodules will be lifted to the surface, probably after being crushed to cobble-sized dimensions. The dynamics of slurried solids require fairly uniform dilutions in seawater and subsequent discharge of the lifted seawater along with some fraction of suspended solids. For simple economic reasons, all recovery systems will seek to minimize the amount of sediments and fine-grained nodule fragments in this discharge stream. Some suspended sediment discharge is likely to accompany any design. However, the miner is likely to have complete control over the depth at which this discharge is set (USDOI, MMS and HI, DBED 1990). Thus, a primary concern for impact mitigation (**Section 3.1**) will be the selection of the receiving waters for these discharges.

CLB System: The CLB system (**Figure 2.12**) has been tested for possible future use in recovering manganese nodules (Masuda et al. 1971) and is described in NOAA's EIS for deep seabed mining (USDOC, NOAA 1981). The CLB system has also been proposed for mining phosphorite nodules and slabs and for cobalt crust mining. The original CLB system used one ship, with empty buckets going down from the stern, and partially filled buckets coming in at the bow. The distance between the downward moving and the upward moving parts of the loop of rope is dependent on the length of the ship and, thus, cannot be altered. Entanglement can be avoided by achieving an optimum combination of ship speed and length of line or by use of hydrodynamic deflectors. The optimum combination may be influenced by various other factors, including the nature of the seabed, underwater currents, variations in the ship's course because of weather heading, or bad weather conditions.

To minimize these disadvantages and to add to the flexibility of operation, a two-ship system has been designed where the empty buckets go down to the seabed from one ship and are brought to the ocean's surface at a nearby sister ship. The distance between the descending and ascending parts of the loop and the curve of the loop can be influenced by the relative positioning of the two ships (United Nations 1984).

- **Speculative Deep Water Systems**

Concepts for deep water autonomous submersible miners for manganese nodules have been developed. Deep submersible modular systems would mine and transport ore from the seabed to an attendant platform on the surface. Seabed mining

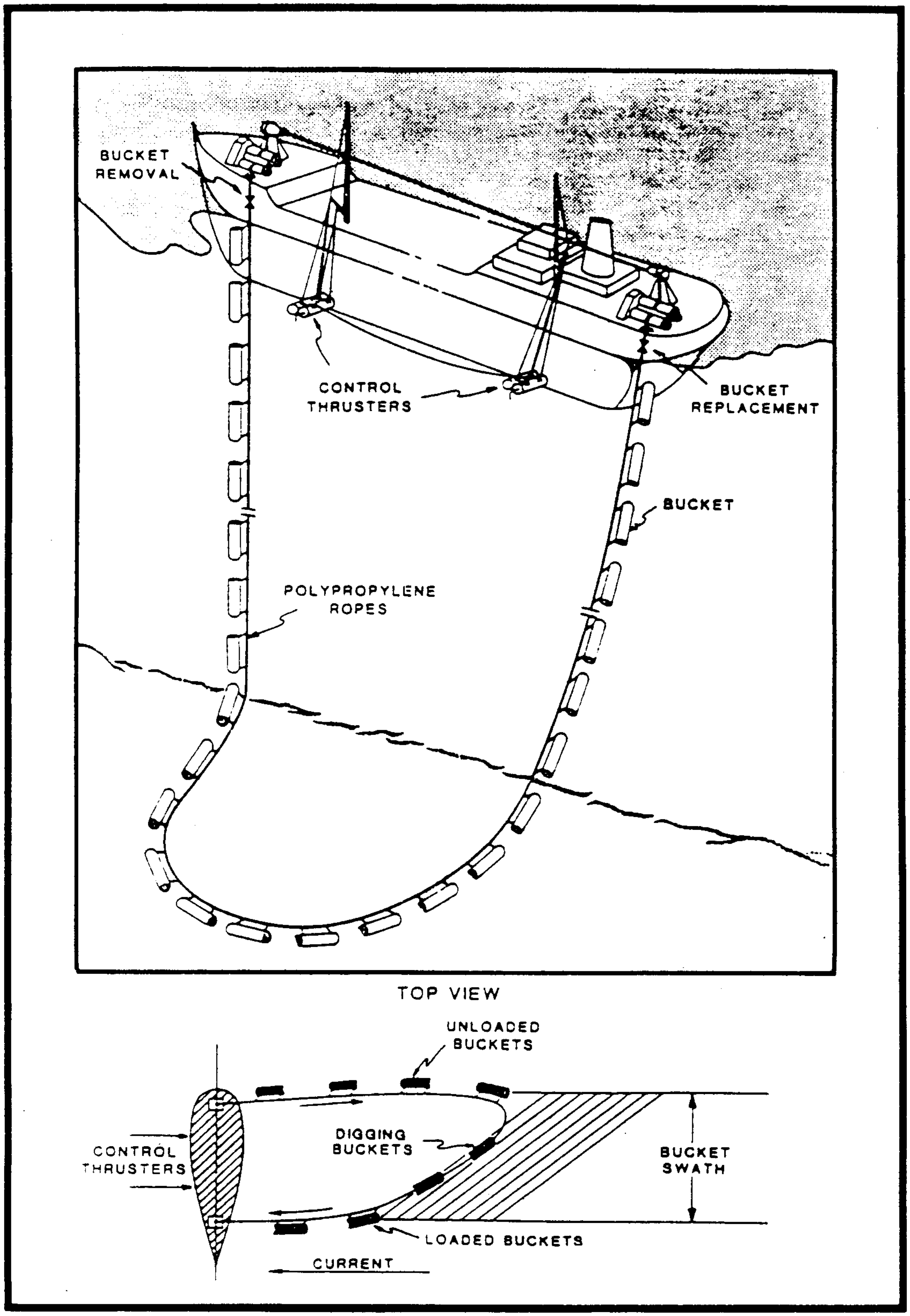


Figure 2.12. A continuous line bucket dredge (From: Masuda et al. 1971).

machines, or crust miners, have been proposed to fragment and deliver cobalt crust to a vertical hydraulic lift system.

Modular Mining System: In the modular mining system, an autonomous collector vehicle would be launched with ballast material such that the weight of the ballast in water is equal to the weight in water of the nodules to be collected. The collector is designed to have sufficient buoyancy so that the vehicle is weightless in water. Thus, in descent, thrusters propel the unit down steadily against hydrodynamic resistance alone. On the bottom, the collector is propelled over the bottom, and as collection proceeds, ballast material is simultaneously ejected on an equal weight-in-water basis. In this manner, a small net weight in water of the collector is maintained. Mining is terminated shortly before ballast material ejection. Ballast material ejection is continued until the weight of the vehicle is zero or slightly negative. Finally, the vehicle is propelled by thrusters to the surface, docked with the surface ship, unloaded, serviced, and re-ballasted for a new mining cycle. In theory, very little onboard power is required to collect the nodules because the major source of energy is the potential energy of the ballast material. The operating principle of this system is illustrated in **Figure 2.13**. Processed tailings have been suggested for use as ballast. Advantage might also be taken of ambient currents to propel the vehicle, in a fashion similar to a sailplane or glider.

Crust Miner: Recent interest in manganese oxide crusts containing relatively high values of cobalt and, in some cases, platinum has led to proposals to develop the deposits. Manganese crusts are physically similar to hard coal (Cruickshank and Paul 1986), and vary in thickness from mere stains to layers as much as 40 cm thick. The crusts, which occur extensively in the Pacific on seamounts and submarine ridges at depths between 800 and 2,400 m, cover a variety of substrate rocks ranging from hard basalt to weak hyaloclastite. Mining systems proposed for manganese crusts include a vessel equipped with hydraulic lift systems and active bottom miners (Halkyard and Felix 1987; USDOI, MMS and HI, DBED 1990). The proposed systems would be capable of breaking and removing the thin crust from the underlying rock and feeding it to a hydraulic lift system through hydrocyclones to separate entrapped substrate (**Figure 2.14**). The roughly cleaned ore would be pumped to the surface vessel for further cleaning and transport to shore. The mining machine would provide its own propulsion and travel at a speed of approximately 20 cm/s. The miner would have articulating cutting devices which would allow the crust to be fragmented while minimizing the amount of substrate collected. Behind the cutter heads of the miner, a series of parallel pickup devices would be installed consisting of either articulated, hydraulic suction heads or a mechanical scraper/rake device. Approximately 95% of the fragmented material would be picked up and processed through a gravity separator prior to lifting.

Under normal operations, the mining ship and the miner would follow a coordinated track following seafloor contour lines. System speed and/or pipe length would have to be altered to accommodate changes in depth ≥100 m. Steering of the miner would be used to maneuver around obstacles, over areas of particularly high abundance, or around a previously mined swath.

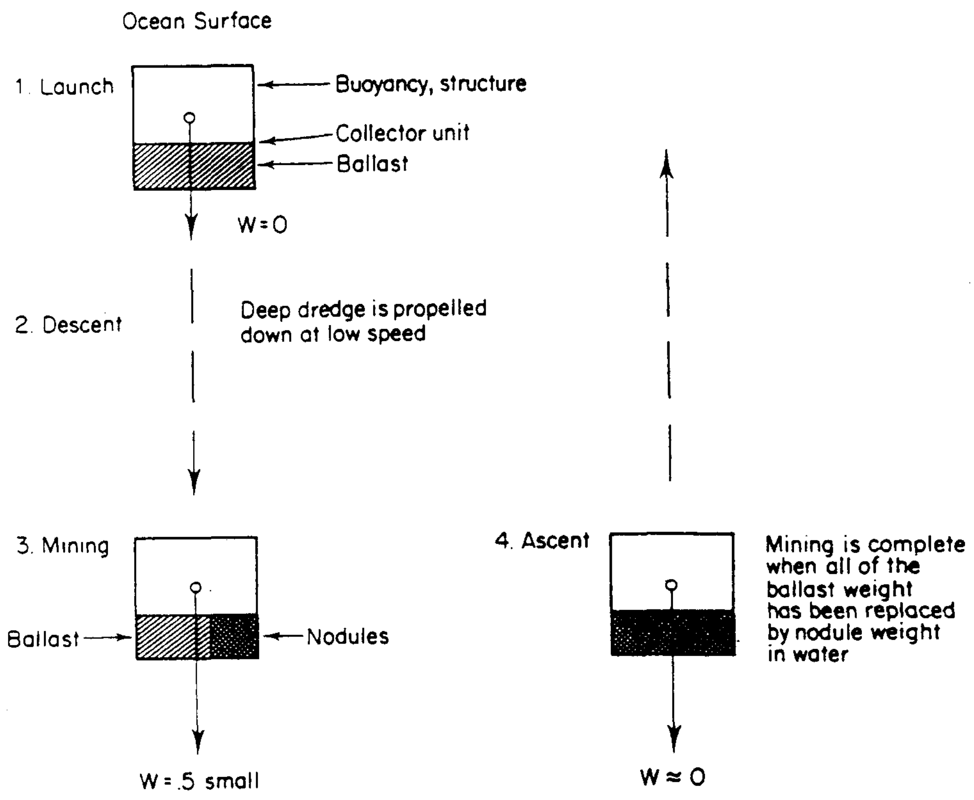


Figure 2.13. Operating principal of a modular mining system for the deep seabed (From: United Nations 1984).

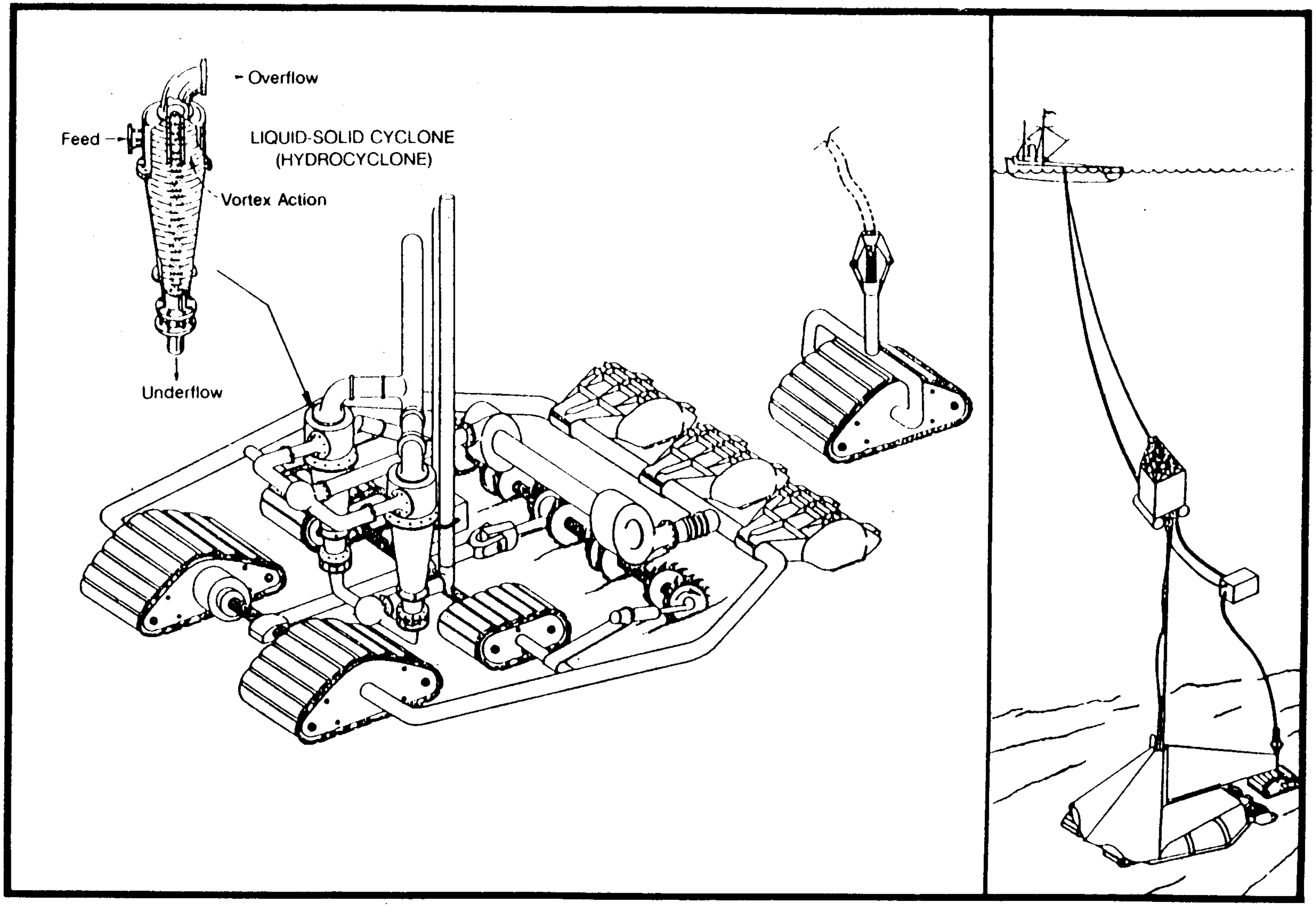


Figure 2.14 A proposed deep seabed cobalt crust mining machine (Adapted from: Halkyard and Felix 1987)

2.2.1.2 Excavating

Mineral deposits that are located predominantly within or under the seabed may be removed by excavation. These deposits include thick deposits of sands; metalliferous muds; layered or disseminated deposits of unconsolidated placer minerals or overlying bedrock; and deposits of consolidated minerals in vein, tabular, or massive form which may extend for considerable distances into the bedrock. The mining system used will depend largely on (1) the ease with which the material may be excavated and removed from the surrounding environment; (2) the water depth; and (3) the ocean climate in the area of operations (Cruickshank et al. 1969, 1987). Examples of seabed mining operations discussed in the following pages range from the excavation of free-flowing materials to the excavation of hard rock using conventional surface located systems, as well as systems designed to operate totally submerged.

- **Conventional**

Examples of conventional dredges operating from floating platforms include the clamshell bucket, bucket ladder dredge, bucket wheel suction dredge, stationary suction dredge, and cutterhead suction dredge; each of these conventional dredges operates in a stationary or anchored mode. A scale-model system for recovery of metal-rich metalliferous muds was tested in the Atlantis Deep (2,200 m water depth) of the Red Sea during 1981 (Guney and Marhoun 1984). This system is also an example of a hydraulic-lift system, however, the collector was much simpler than that required for nodules because the muds could be directly entrained into the lift stream. Of particular environmental concern for this mining system is the final discharge stream, which must include significant quantities of dissolved and fine-grained metal species. In cases where the mineral deposit is hard rock rather than sediment, it may be necessary to drill and blast or otherwise fracture the seabed material prior to lifting the broken material to the surface by conventional means.

Clamshell Bucket: Clamshell buckets (or clamshell hopper dredges) have been used offshore to mine sand and gravel in Japan and tin in Thailand, and to sample phosphorite off New Zealand. The buckets are mechanically actuated to bite into the seabed and remove material (**Figure 2.15**). The need for multiple cables to actuate the grabs can cause complications, particularly in heavy seas where wave compensating devices may also be needed. Moreover, the clamshell is inefficient in clearing bedrock of fine materials. It is best suited for excavation of large-size granular material where accuracy of positioning and cleanup is not important. The size of buckets may range from a few cubic meters to as much as 7.6 m^3.

Bucket Ladder Dredge: The bucket ladder consists of a chain of closely connected digging buckets mounted over a heavy supporting arm or ladder (**Figure 2.16**). This system is most efficient for the excavation of deposits containing boulders, clay, and/or tree stumps and weathered bedrock. Dredges of this type have been used successfully all over the world for mining gold, platinum, and tin placers and diamond deposits, although their use offshore has been limited to gold and tin. Bucket ladder dredges are frequently used for clearing harbors because of their capability for digging into broken rock and coral. The system delivers a virtually water-free product to the mineral dressing plant

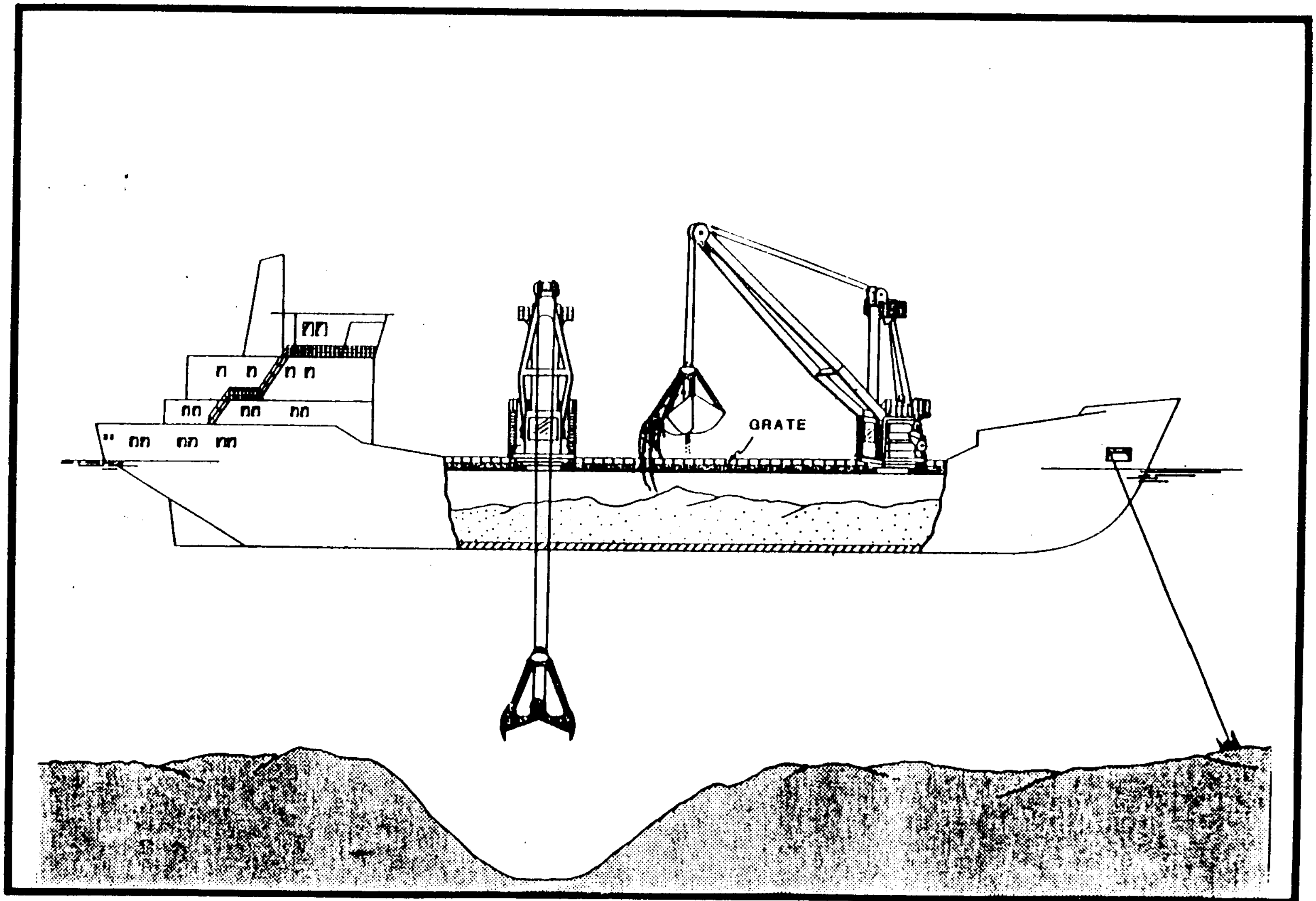


Figure 2.15. Clamshell hopper dredge (From: Cruickshank et al. 1987).

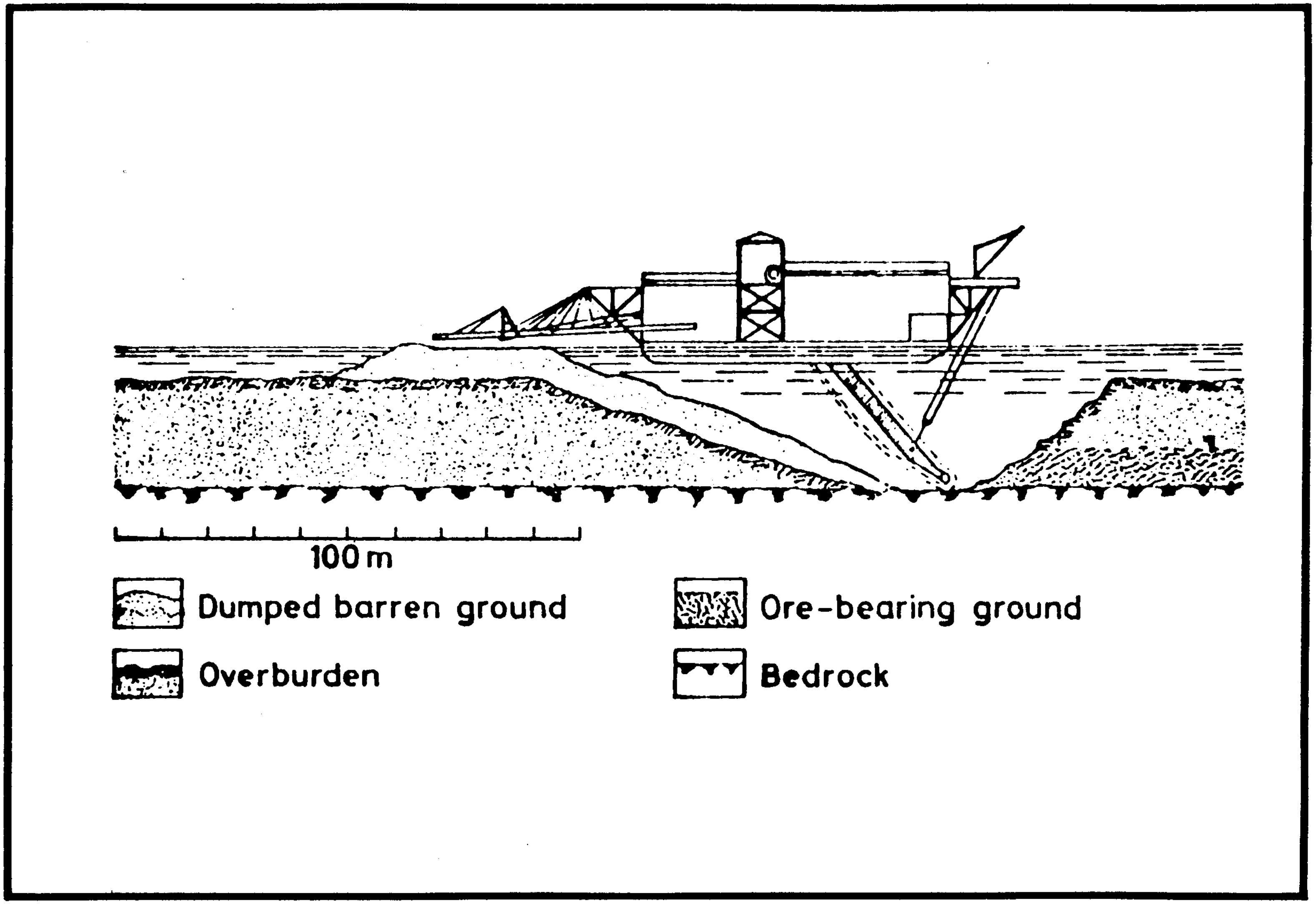


Figure 2.16. Bucket ladder dredge with headline and anchors for offshore operations (From: Cruickshank and Marsden 1973).

on board the dredge. Discharge of water from the shipboard operations is limited to that needed to concentrate the valuable constituents; techniques are based on the use of flowing water to remove the less dense materials. In the case of gold, the bulk of concentrate recovered is only a few parts per million (i.e., virtually all the material removed from the deposit is returned to the seabed). The ocean-going bucket ladder dredge *BIMA*, used for mining gold offshore of Nome, AK was of this type (**Figure 2.17**).

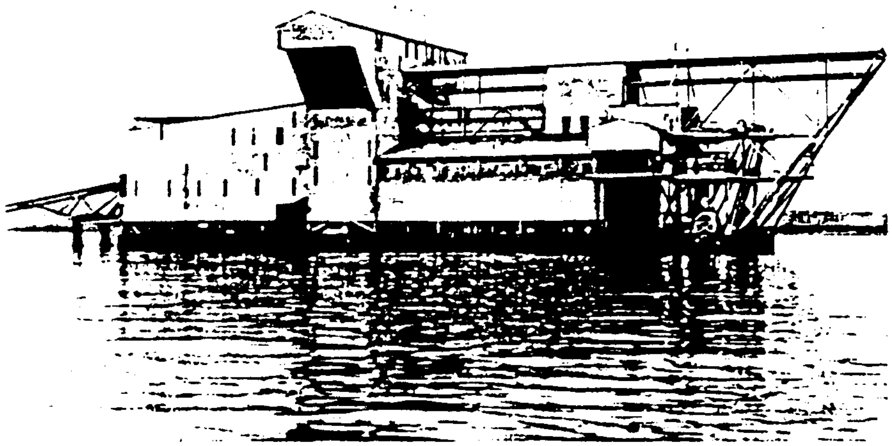
Considerable turbulence accompanies these operations which may involve the movement of up to 4.9 million m^3 of material per year. Operation of bucket ladder dredges is limited to digging depths of about 45 m below sea level and they are rarely used in water depths exceeding 20 m. Few of these dredges have been built for offshore mining in the last 20 years, and it is likely that they will be superseded by the bucket wheel suction dredge.

Bucket Wheel Suction Dredge: Bucket wheel suction dredges use a small-diameter bucket wheel mounted on the suction ladder to excavate material. This combines the best aspects of the bucket ladder and the suction dredge (**Figure 2.18**). Very high torque or digging power can be applied to the wheel, which can deliver the excavated material directly into the mouth of a suction pipe for transport to the sea surface. Digging capability is equal to that of the bucket ladder with respect to ease of digging and bucket capacity, while the depth capability using submerged pumps is almost unlimited. The combination of simultaneous digging and suction at the seabed provides the option to either treat the ore on the vessel or pipe it to shore.

Stationary Suction Dredge: Stationary, or anchored, suction dredges (**Figure 2.19**) are widely used in Japan for mining sand and gravel in depths less than 30 m and are being designed for digging to depths as great as 200 m (Tsurusaki et al. 1988). These dredges have been used in Britain as well, although the vessels built since 1980 are almost all trailing suction dredges (Drinnan and Bliss 1986). In contrast to the trenches left by trailing suction dredges, anchored suction dredges leave deep pits in the seabed which can create problems.

An anchored suction dredge was also tested for mining metalliferous muds at a depth of 2,000 m in the Red Sea (**Figure 2.20**). A deep-drilling oil exploration vessel, the *SEDCO 445*, was converted to carry a specially designed mud pump and delivery pipe that was lowered to the seabed in a manner similar to the lowering of a drill pipe. The pump was vibrated into the mud with a waterjet to fluidize the material, and the ore pumped to the ship for treatment.

Cutterhead Suction Dredge: Typically, cutterhead suction dredges are used to excavate fairly compacted, granular materials in water less than 30 m deep. The rotating cutterhead is usually an open basket with hardened teeth or cutting edges, somewhat like an over-sized dentist's drill (**Figure 2.21**). The end of the suction pipe is normally located within the basket. In standard practice, the dredge is swung back and forth in an arc pivoted from a large post or spud attached to the stern. The cutterhead cuts downward a short distance with each swing. Because the cutterhead rotates in one direction only, the bite is much stronger on one swing than the other. In mining for heavy mineral sands, the



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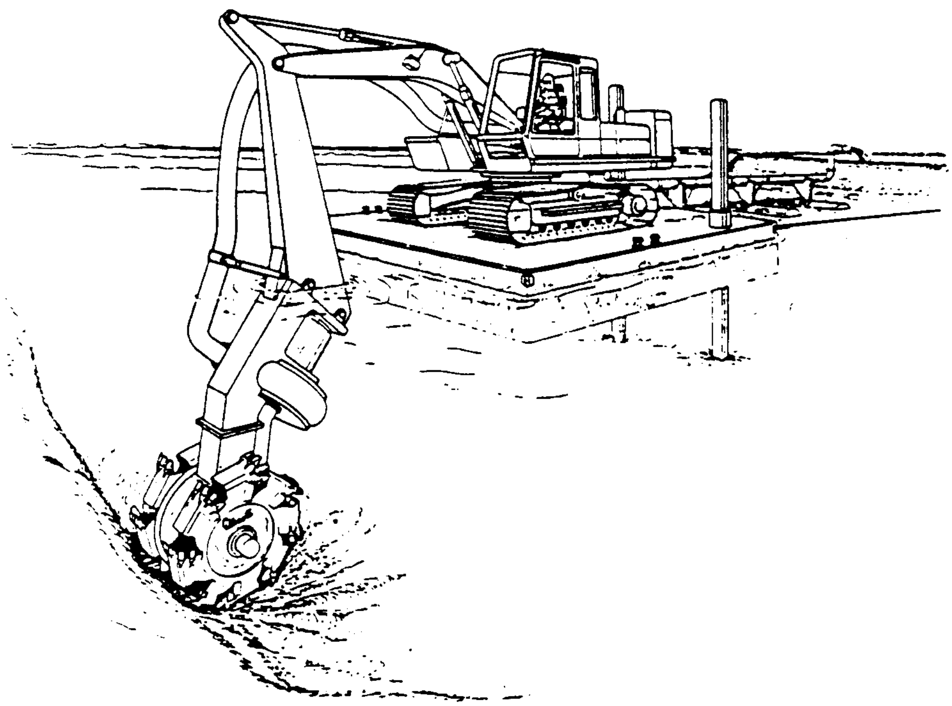
UNITED STATES OF AMERICA

Figure 2.17 The bucket ladder dredge *Bima* used for a gold operation in Alaska (Adapted from: WestGold 1990).

HOE-MOUNTED DREDGING EXCAVATOR



GENERAL DESCRIPTION

The Ellicott hoe-mounted dredging excavator makes possible the continuous excavation and pumping of underwater material while utilizing a standard model track-mounted backhoe. The combination of a standard backhoe and the dredging excavator maximizes the capability of the backhoe and provides continuous excavation and material transport from point of acquisition to point of disposition without the interruption for swinging, booming and bucket-curling typical of normal backhoe operation. This combination brings to both the construction industry and the mining industry, an entirely new tool which will allow continuous accurate underwater excavation of both loose and hard-to-excavate materials.

The machine makes it possible to undertake small dredging projects or hard-to-reach alluvial deposits by taking advantage of the mobility of the track-mounted backhoe and its ability to walk to a project. Further, the backhoe may be walked onto a barge and operated as a swinging ladder type dredge while discharging to a shore point, into a barge or to an attendant mineral processing system.

In short the Ellicott hoe-mounted dredging excavator brings to industry an entirely new and versatile excavation system which may be mounted on virtually any manufacturer's backhoe which has sufficient size and power to support it.

ELLICOTT MACHINE CORPORATION

Figure 2.18. A small bucket wheel dredge for use on a standard back hoe (Adapted from: Ellicott Machine Corp.).

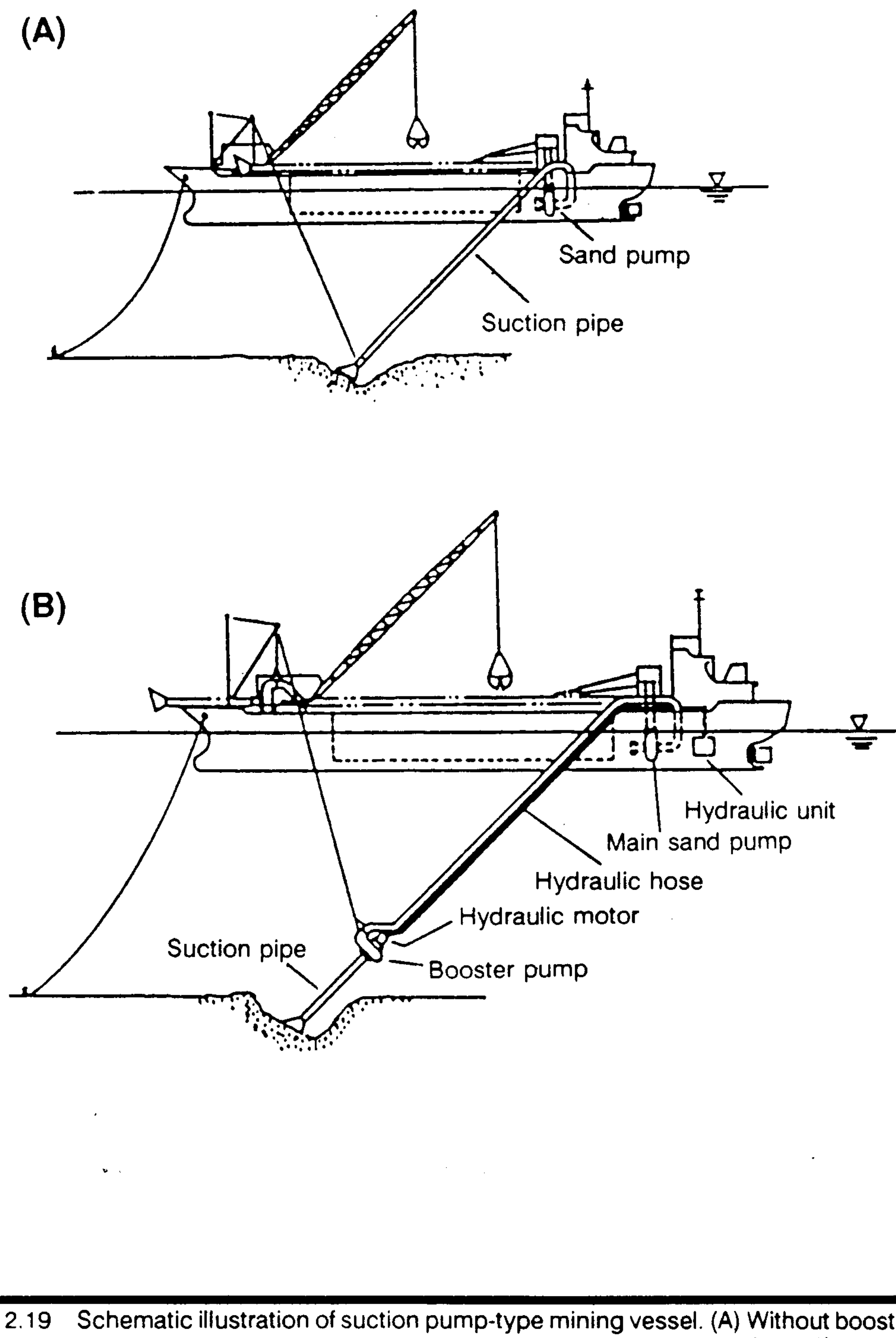


Figure 2.19 Schematic illustration of suction pump-type mining vessel. (A) Without booster pump. (B) With booster pump (Adapted from: Tsurusaki et al. 1988).

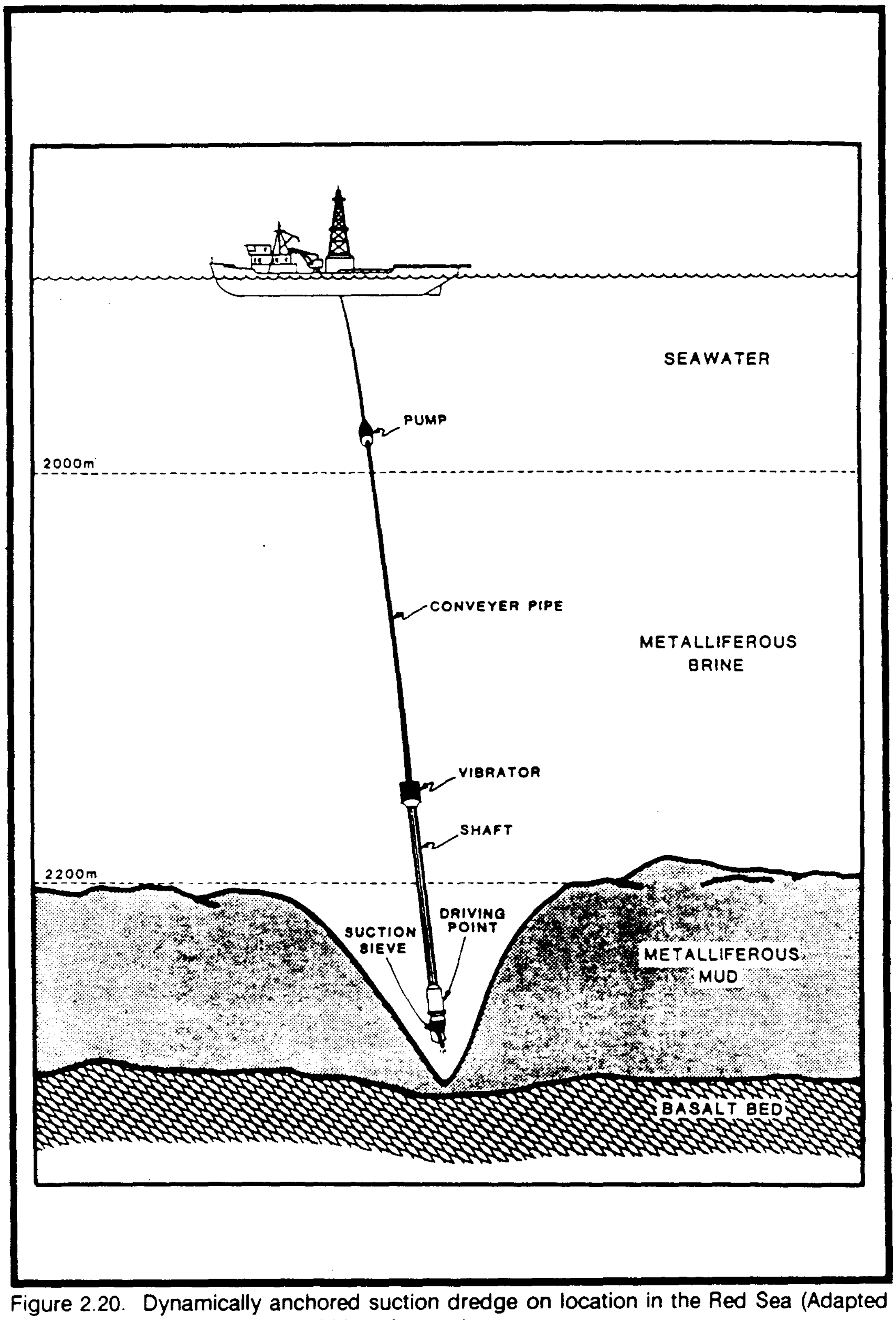


Figure 2.20. Dynamically anchored suction dredge on location in the Red Sea (Adapted from: Fletcher and Mustafa 1980).

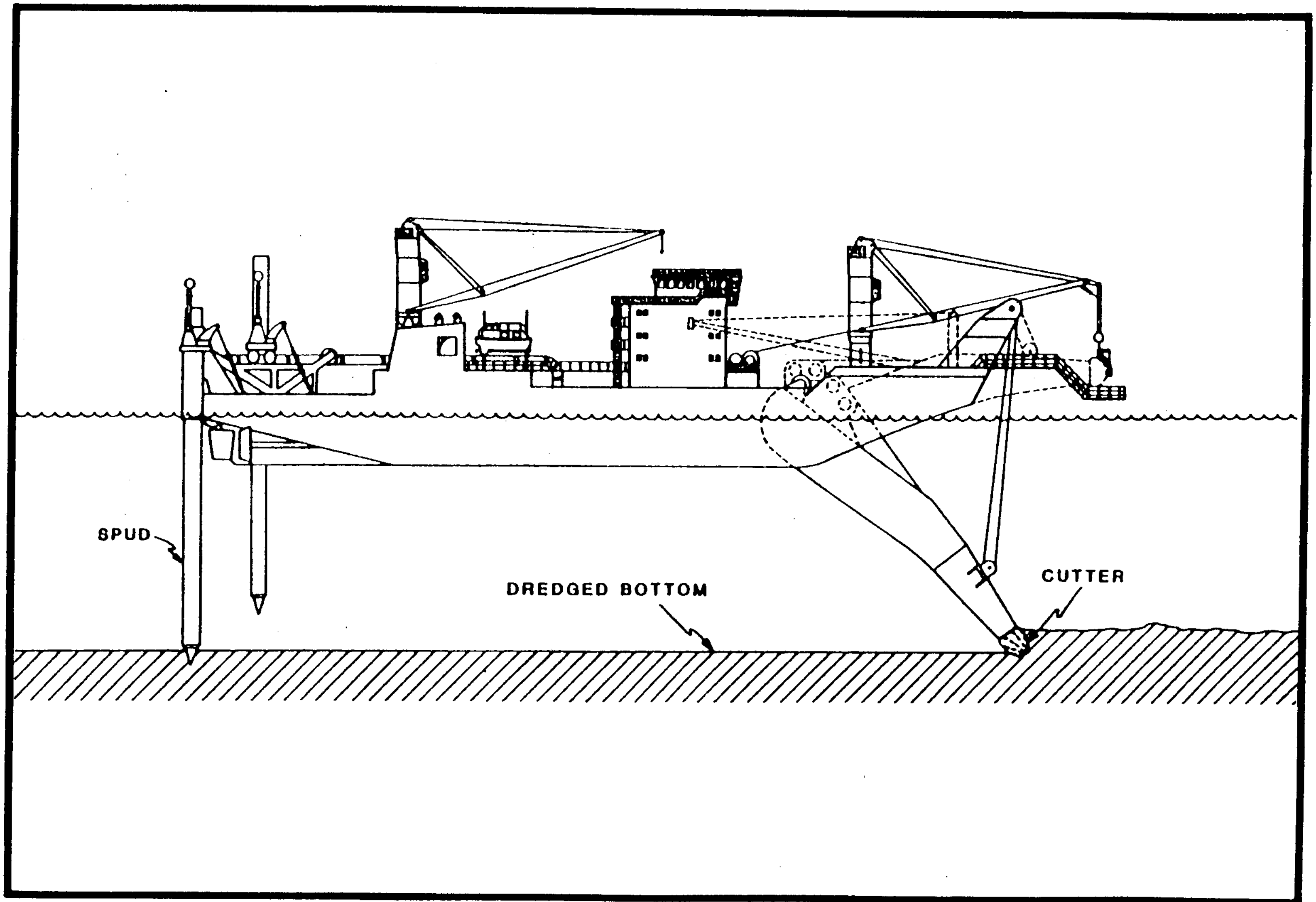


Figure 2.21. Cutterhead suction dredge with spuds (From: Cruickshank et al. 1987)

action of the cutterhead tends to disintegrate the material, allowing heavy minerals to separate, fall below the cut, and remain on the seabed. Cutterhead suction dredges have never been used successfully for mining gold, although they have been widely used for mining cassiterite (i.e., tin placers) in west Thailand; the deposits are rich enough in this region to economically sustain the inefficient cleanup (Chansang 1988).

Suction dredges circulate large quantities of slurry that must be decanted on board the dredge or pumped ashore by pipeline. In either case, there is a significant discharge of water containing fine particulate materials. Treatment of the decanted solids may be unnecessary for construction sand and gravel but may be required for heavy minerals. The valuable constituent or concentrate from these ores will rarely amount to more than a few percent of the materials mined. Therefore, more than 95% of the material dredged from such deposits must normally be disposed of either at the mine site or at an onshore treatment site. Cutterhead suction dredges may also be equipped with a multiblade ripper to cut into moderately consolidated rock. The present use of these systems is limited to excavating soft rock, such as coal and shale. However, advances in rapid tunneling technology suggest that rock cutterheads could be designed for medium strength rocks, such as limestone and sandstone (Hignett and Banks 1984).

Drilling and Blasting: Deposits that are too hard to excavate by dredging must be broken by other means. The normal system for excavating hard-rock deposits is to drill into the deposit for the placement of explosives. Fracturing using highly pressurized fluids is also possible but would represent a very special case and has not been considered in this analysis. Blasting of the material is only an intermediate step and would be followed by gathering and lifting the ore by one of the methods previously described. Blasting operations are designed to expend as much force as possible on fragmenting the ore so that the water column effects are much lower than those for equivalent, unconfined explosions from which most available data have been derived. With respect to the possibility of mining deep seabed deposits that require fragmentation, many more aspects need to be examined. Technically acceptable means of drilling and fragmenting hard rock in deep water have not yet been developed. However, methods of gathering and lifting the fragmented material may be assumed to be similar to the methods developed for deep seabed nodule mining.

- **Submersible**

Submersible systems include tracked suction dredges operating on the seafloor. Several such machines have been developed over the years for the excavation of nearshore sands for beach replenishment, for preparation of aquaculture beds, and for general oilfield excavation work. A good example is the *Tramrod*, built by Alluvial Mining Ltd. in the United Kingdom for excavation around petroleum structures in the North Sea. The machine was tested on a gold deposit in Norton Sound, AK in 1989 (**Figure 2.22**) with some success, and has since been fitted with a bucket wheel excavator. It has yet to be used in a production mode, but it is very likely that this type of dredge will find many applications in the marine mining industry. No such vehicles have been designed for deep water at this time, although such use is considered feasible and very likely.

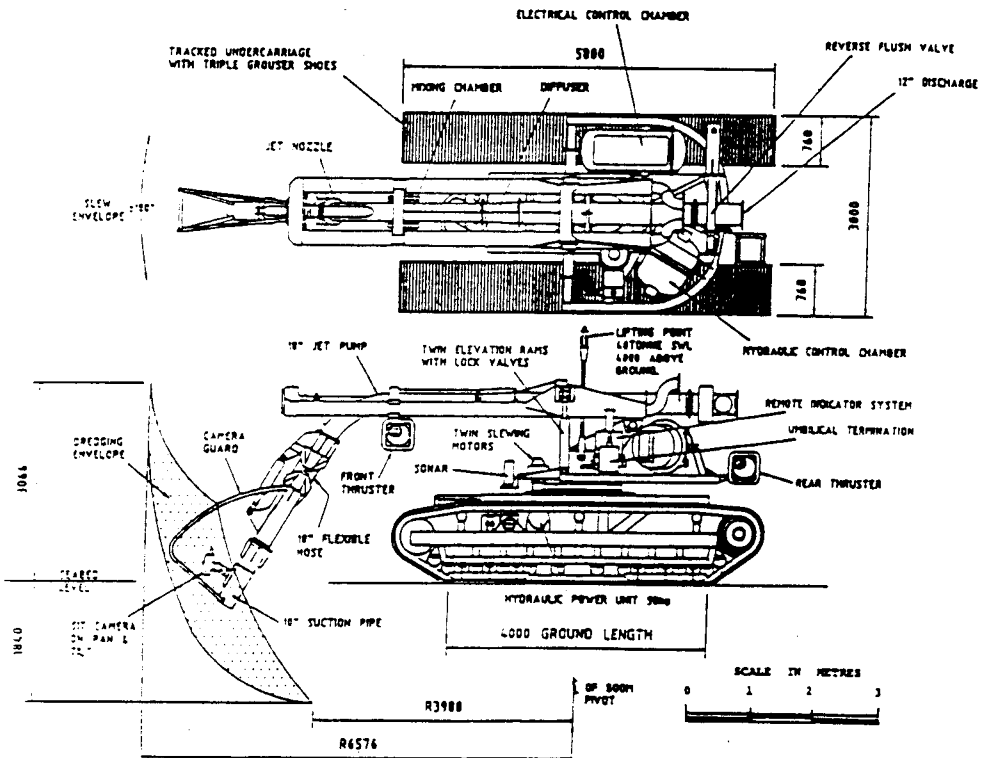


Figure 2.22. Plan view and longitudinal section of the *Tramrod* as deployed in Nome in 1989 (From: Garnett 1991).

2.2.1.3 Tunneling

Conventional underground mining methods involve tunneling from a surface entrance or a shaft and working the mine in an unpressurized environment. In certain cases, sub-seabed deposits of bedded coal, ironstone, and potash, as well as veins of copper, lead, and tin have been mined by conventional underground methods. Entry to these mines is either from the shore or from natural or artificial islands in shallow waters (**Figure 2.23**). The location of the mines in the seabed only slightly adds to conventional problems of access, safe overhead cover, and ventilation. The effect on the environment is similar to that for any shoreside mine. The possibility of developing underground access through seabed airlocks has been considered for special cases (Austin 1967).

2.2.1.4 Fluidizing

Development and removal of mineral deposits other than oil and gas in fluid form may be accomplished in four ways: (1) by capture of already fluid deposits such as seawater, hydrothermal vent fluids, or geothermal heat; (2) by slurrying granular deposits; (3) by melting the deposit, as with the Frasch sulfur process; or (4) by dissolving the contained minerals (e.g., similar to solution mining of copper sulfides on land). In most cases, the fluids are removed through boreholes, however, methods have been proposed to cap hydrothermal vents and to leach surficial crust deposits underneath an impermeable membrane. Common terms for fluidizing methods are bore hole mining, solution mining, and *in situ* mining.

- **Fluidizing (Slurries)**

Under proper conditions, certain types of unconsolidated or marginally consolidated mineral deposits may be mined as a fluid slurry through drillholes penetrating the sea-bed. Sub-seabed sand was mined in this way in shallow waters offshore Japan in 1974 (Padan 1983). Recent onshore experiments in Florida proved the capability of this approach in recovering phosphate from beneath thick overburden (Savanick 1985). In this instance, a borehole was drilled from the land surface to the base of the ore body, then a waterjet cutting system was inserted through the borehole and used to fragment the loosely consolidated phosphate (**Figure 2.24**). At the same time, a down-hole slurry pumping system recovered the phosphate through the borehole, thereby creating a waterfilled cavity with a 5.5-m radius. After mining was completed, the cavities were backfilled with sand to prevent ground subsidence. A USBM study found this system to be cheaper than conventional land mining systems if the overburden is at least 45 m thick (Hrabik and Godesky 1985). A similar experiment conducted off Georgia from an anchored barge (**Figure 2.25**) confirmed the potential for borehole mining for phosphorite as an economically and environmentally attractive alternative to dredging (Drucker et al. 1991). In the recovery of sulfur, super-heated water is pumped into the deposit to melt the sulfur so that it may be removed as a fluid (Cummins and Given 1973).

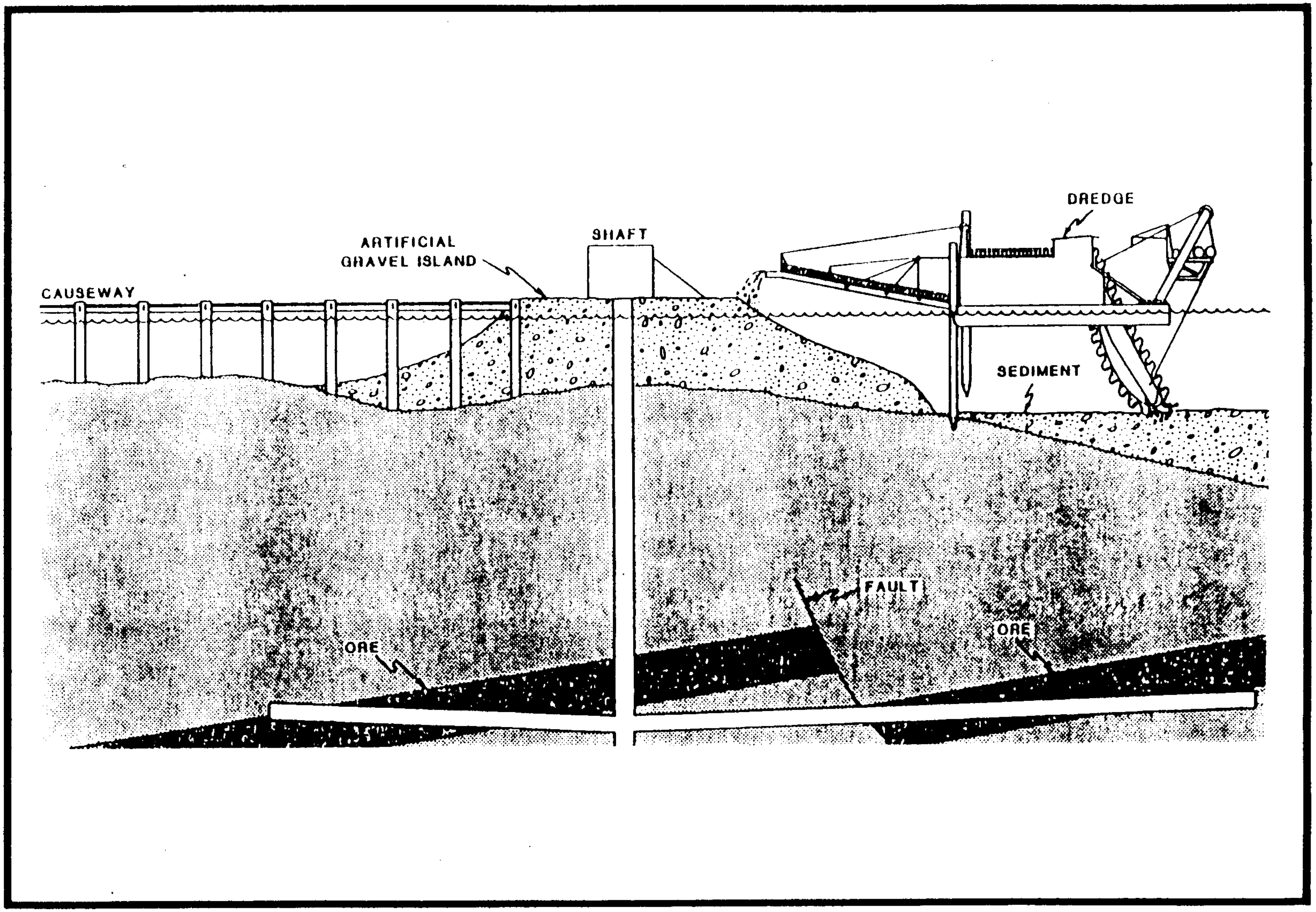


Figure 2.23. Mining of sub-seabed deposits with access through an artificial island (Adapted from: Cruickshank et al. 1987).

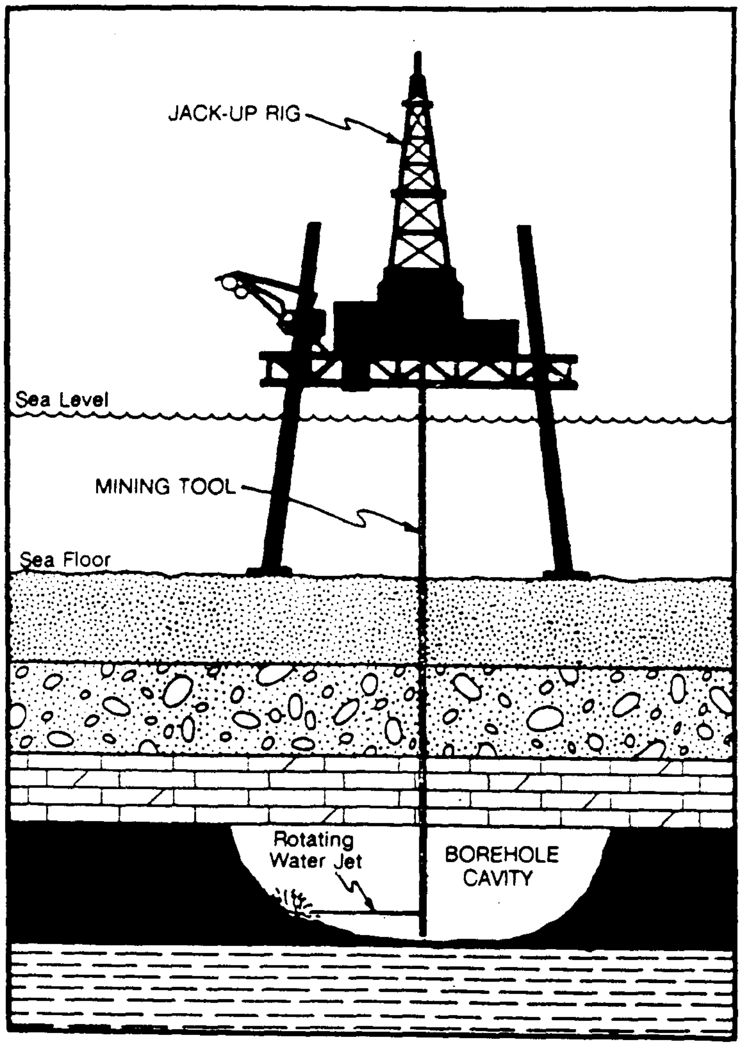


Figure 2.24 Fluid mining by slurrying from a fixed platform in shallow water (Adapted from: Hrabik and Godesky 1985).

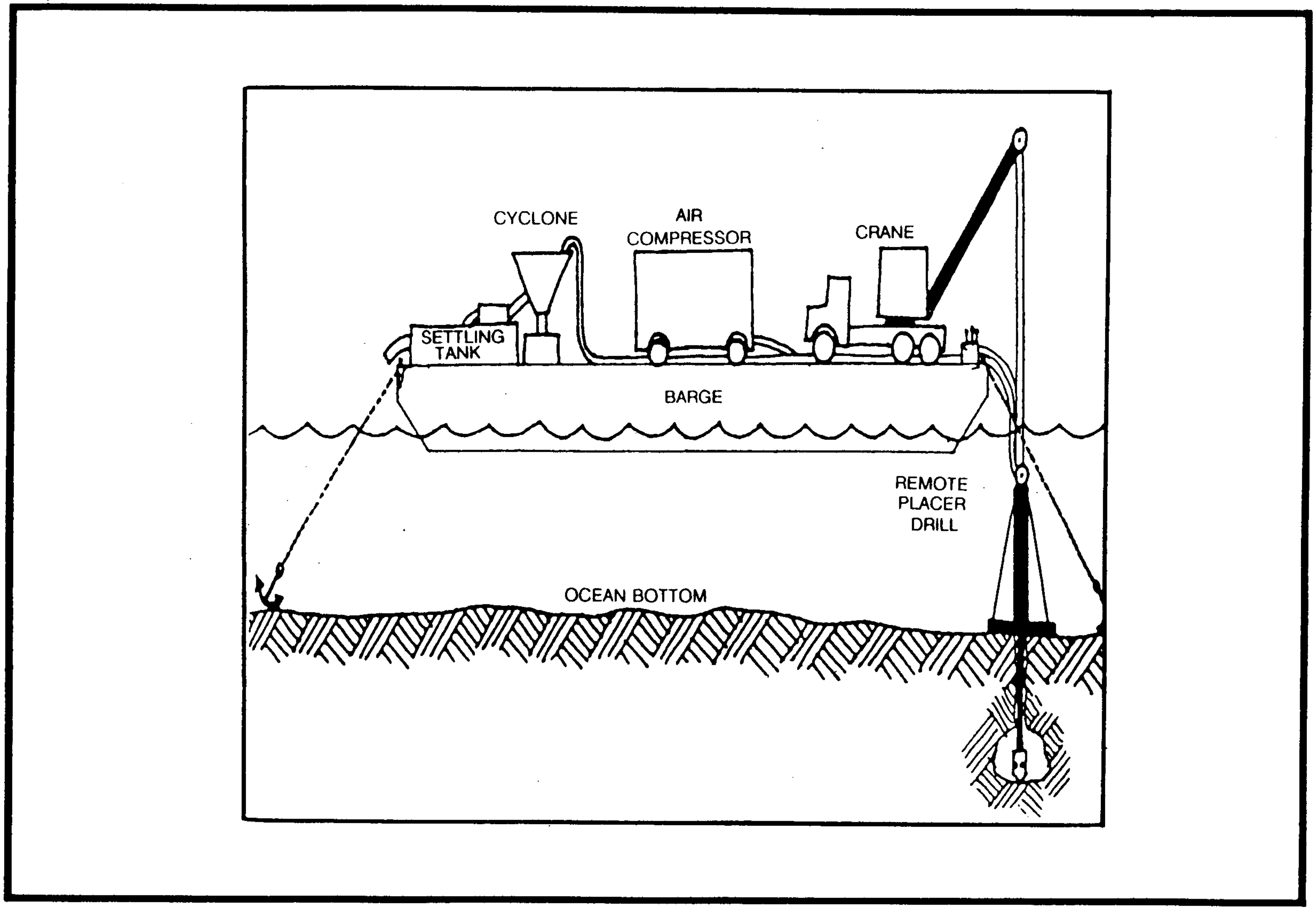


Figure 2.25 Schematic diagram of the bulk sampling operation for offshore phosphate (Adapted from: Drucker et al. 1991).

- **Fluidizing (Solutions)**

Hard-rock deposits that are amenable to hydrometallurgical treatment of their ores are potentially extractable by dissolving the valuable constituent in place and removing the pregnant solution through a borehole (**Figure 2.26**). There are major unsolved problems in dealing with toxic or corrosive solvents used in (1) enlarging fractures to provide a flow path for the solvent through the deposit; and (2) selectively extracting the desired metals in complex ores. However, these problems are being overcome on land. The methods developed onshore should be applicable, in a more sophisticated form, to seabed deposits. Effects of accidental spills of solvents would depend on the nature of the solvents and the sites affected. If the solvent is water soluble, the effects should be localized because of the rapid dilution in the ocean and the buffering capacity of seawater.

2.2.2 Processing of Ores and Disposal of Waste

There are two areas in the processing of marine ores which call for special treatment when compared to the processing of terrestrial ores. One is the effect of platform motion on separation processes carried out at sea. The other is in the extraction of metals from specific marine ores such as manganese nodules and crusts. Some industrial materials (e.g., specialty sands) may require washing to remove salt water. For the most part, however, marine ores do not otherwise differ from those on land and conventional methods of treatment may be employed.

Materials handling in the marine environment is complicated by the motions of the platform and the need, in most cases, for closed-cycle systems and stringent controls to avoid spillage or contamination. These issues are normally addressed in the environmental analyses that are a part of the planning process. In the case of deep seabed mining, the problems would be addressed on a case-by-case basis.

2.2.2.1 Beneficiation

The beneficiation process is that which is first used to beneficiate or upgrade an ore by simple physical means following mining. Beneficiation normally results in (1) an ore concentrate; and (2) a tailings or waste fraction of excess rock or substrate resulting from the mining process. Processing technology applied to placer materials has been fairly well established over the years. However, due to the conservative nature of the minerals industry, there is a great need for improvement using newer technology, particularly as operators need to recover lower-grade materials and work very-fine-grained deposits in the marine environment.

- **On the Mining Platform**

The use of placer processing technology on board floating platforms subject to the rigors of oceanic motion has been quite limited to date. Thus, in the selection of processing equipment for proposed operations at sea, considerable testing will be required to confirm the suitability of the processing plant in terms of the nature of the material and the environment in which the processing takes place. Initial selection of treatment methods

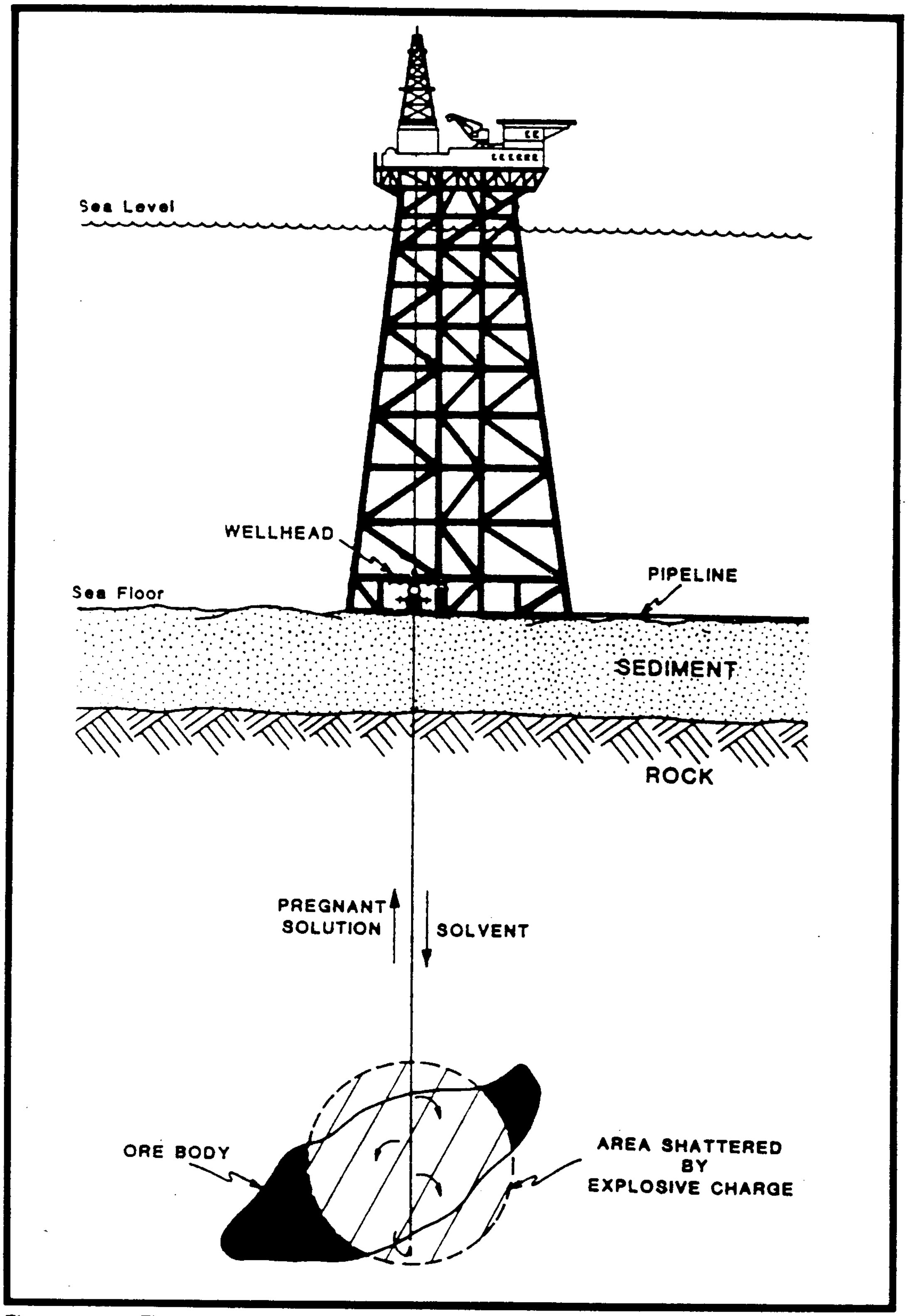


Figure 2.26. Fluid mining by leaching of deep, hard-rock deposits, artificially fractured in place (From: Cruickshank et al. 1987).

can be indicated from laboratory tests using a few pounds of sample. In complex ores, which includes most placers, pilot plants are normally required in order to run tests on tens or hundreds of tons of sample. Various options for separation applicable to marine placers are provided in **Table 2.8**.

- **On the Bottom**

Very little work has been done in the development of *in situ* processing technology (i.e., on the bottom). Any new operations will almost certainly require preliminary development work to be completed on a case-by-case basis.

- **Onshore**

Normal processing will include one or more stages of ore treatment by gravity concentration, or magnetic, electrostatic, or high tension separation. These standard beneficiation methods are well described in most textbooks or handbooks (e.g., Weiss 1985) and have not been evaluated further in this analysis.

2.2.2.2 Extractive Metallurgy

After beneficiation (i.e., to remove the bulk of waste material not intimately associated with the ore mineral), it is necessary to separate the economic fraction from the ore or concentrate in a saleable form. These fractions are usually metals and are normally isolated by the application of heat (e.g., in a furnace) or by the dissolution of the components in an appropriate solvent for subsequent precipitation. These two methods of extraction are termed pyrometallurgical and hydrometallurgical, respectively. The selection of one method over the other is dependant on numerous factors, consideration of which is beyond the scope of this analysis. In environmental terms, the choice of method may be significant.

- **Conventional Onshore**

Among the mineral commodities considered in this analysis, only the metalliferous oxide nodules and crusts are substantially different from conventional land ores in terms of special metallurgical treatment requirements. The metalliferous oxides differ from most land ores of base metals in that they are oxides, not sulfides. This characteristic imposes basic differences in the treatments required to extract the metals from the ore and also results in very different waste products. The land ores which are most similar to the nodules and crusts are laterites, which occur as surficial sedimentary deposits, primarily in tropical rain forests. The processing methods which have been proposed and tested for nodules and crusts are mostly modifications of techniques originally developed for laterites.

Sulfide ores occur in a variety of forms. Because of their chemical instability, these ores are rarely found as surface or alluvial deposits. Tailings dumps from sulfide ore bodies have the potential of producing sulfuric acid through the oxidation of sulfide minerals which remain after the ore has been processed.

OPTIONS	Au	pgm	di	Sn	Fe	Th	Ti	Zr	Cr
PRETREATMENT									
Slurrying	(*)	*	(*)	(*)	*	*	*	*	*
Sizing	(*)	*	(*)	(*)	(*)	*	*	*	*
Classification	*	*	(*)	*	(*)	*	*	*	*
Densification	*	*	*	*	*	*	*	*	*
Distribution	(*)	*	(*)	(*)	(*)	*	*	*	*
GRAVITY CONCENTRATION									
Riffles	*	*		*					
Pinched sluices								*	
Spirals				(*)1	*	*	*	*	*
Jigs	(*)	*		(*)	*				
Tables	*		(*)						*
Cones				*					
Heavy medium	*		(*)						
MAGNETIC SEPARATION									
Wet process					(*)	*	*		
Dry process					*	*	*	*	*
ELECTROSTATIC SEPARATION									
Normal						*	*		*
High tension								*	

* = suitable for normal use.
(*) = documented use at sea.
1 = but not in successful production
pgm = platinum group metals.
di = diamonds.

Table 2.8. Options for concentration of marine placer minerals (Adapted from: Cruickshank 1987)

Extractive Processes for Manganese Nodules: Of the various types of processing schemes available for manganese nodule processing, five are considered most probable for first-generation commercial applications (Haynes and Magyar 1987) as follows:

(1) Gas reduction and ammoniacal leach (modified Caron);
(2) Cuprion ammoniacal leach;
(3) High-temperature/high-pressure sulfuric acid leach;
(4) Reduction and hydrochloric acid leach; and
(5) Smelting and sulfuric acid leach.

The two ammoniacal and high-temperature and high-pressure sulfuric acid processes are designed to recover three metals (i.e., cobalt, copper, and nickel); remaining processes are designed to recover four metals (i.e., cobalt, copper, nickel, and manganese). In the three-metal processes, manganese could also be recovered from the tailings if favorable economic conditions exist. This recovery would alter both the chemical and physical characteristics of the tailings. A brief flowsheet of each process is presented in **Figures 2.27** through **2.31**. More thorough discussions of these processes are provided elsewhere (U.S. Congress, Office of Technology Assessment [USC, OTA] 1987).

The nature and characteristics of the wastes generated by these processes will depend, to a large extent, on the actual process scheme used. Haynes and Law (1982) examined the five process types cited above and produced estimates of the various major, minor, and trace components which would result in respective waste streams. In comparison to wastes produced from sulfide ores, it is important to recognize that nodule- or crust-related wastes would generally be more stable and less liable to release toxic metals into the environment. The potential for sulfuric acid production does not exist for these oxides.

It is suggested that the most common of the processes proposed to date is the sulfuric acid leach. **Table 2.9** presents estimates of the major inputs and outputs of metals that would be expected from this process, assuming a throughput of 3 million mt of ore (dry weight) and the same process stream as that used in the processing scenario developed for manganese crusts (USDOI, MMS and HI, DBED 1990). Nodule composition data for **Table 2.9** was derived from Haynes and Law (1982). The waste streams include the filtered wash water (elutriate), consisting of sea salts diluted in freshwater, and the dissolved and solid tailings which must be discharged (i.e., leach liquor and leach residue).

Extractive Processes for Manganese Crusts: Potential extractive processes applicable to manganese crusts differ in two basic ways from those used with manganese nodules. First, a crust processing plant is expected to handle less than a third of the ore processed through a nodule plant. This is assumed because the market for cobalt, the principal value metal in crusts, is much smaller than the nickel and copper markets (i.e., the cobalt market would drive the sizing of a nodule plant). Second, crust ore is likely to require pre-treatment to remove the underlying substrate rocks, which are expected to be unavoidably recovered with the crusts.

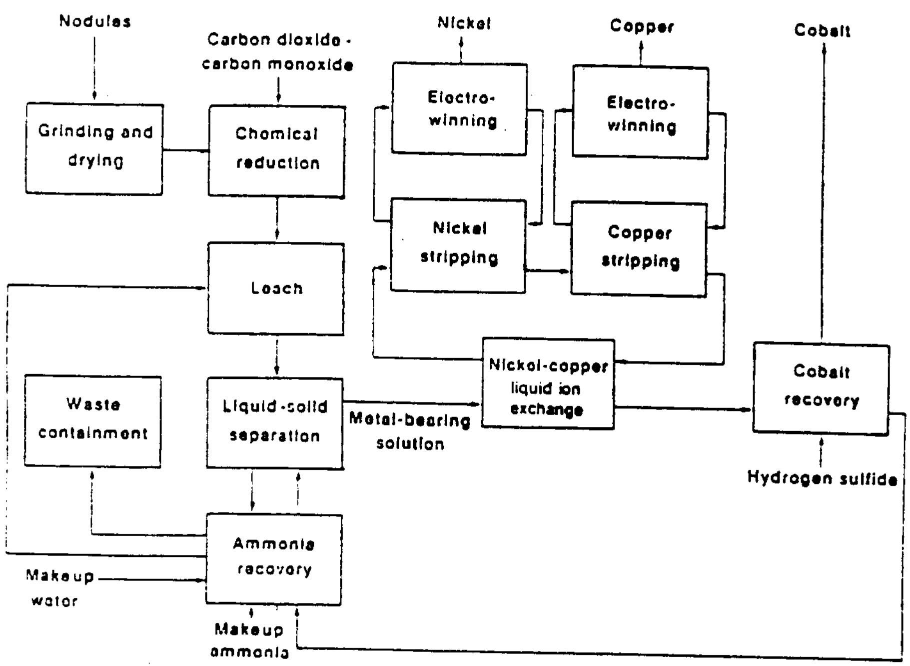


Figure 2.27. Processing of metalliferous oxides by gas reduction and ammoniacal leach (From: Haynes and Magyar 1987).

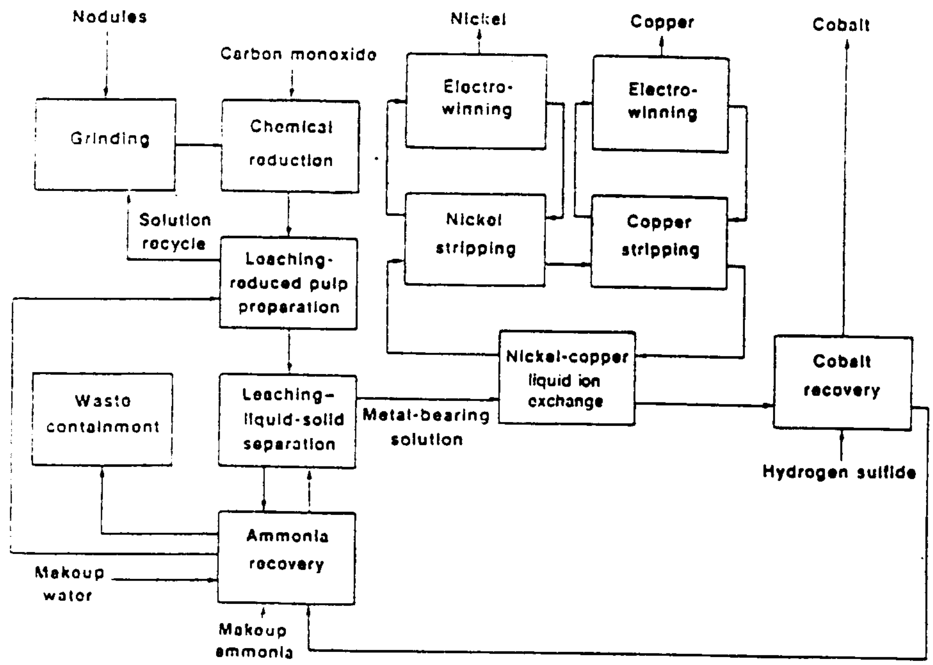


Figure 2.28. Processing of metalliferous oxides by cuprion ammoniacal leach (From: Haynes and Magyar 1987).

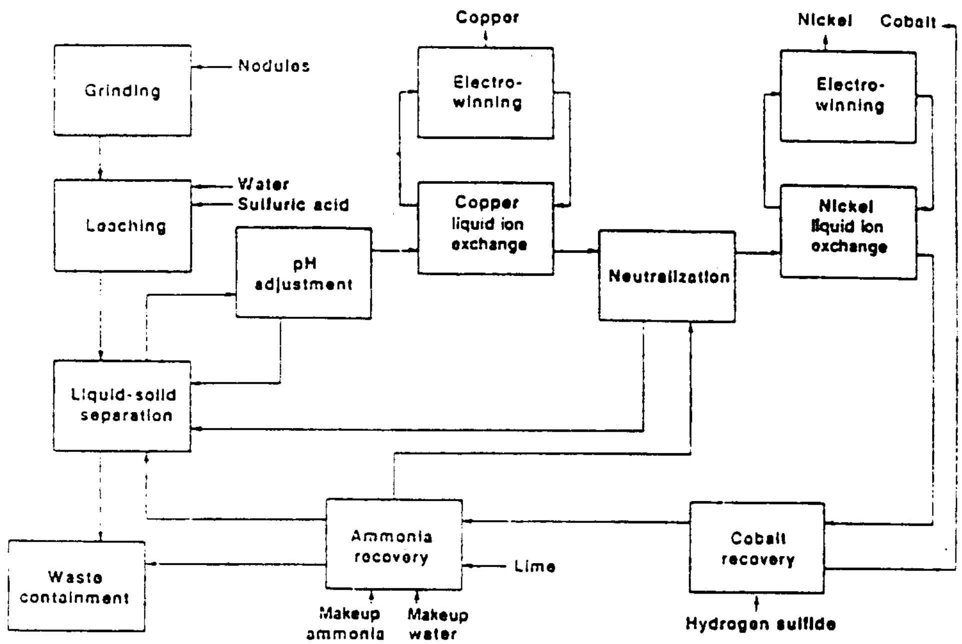


Figure 2.29. Processing of metalliferous oxides by high-temperature/high-pressure sulfuric acid leach (From: Haynes and Magyar 1987).

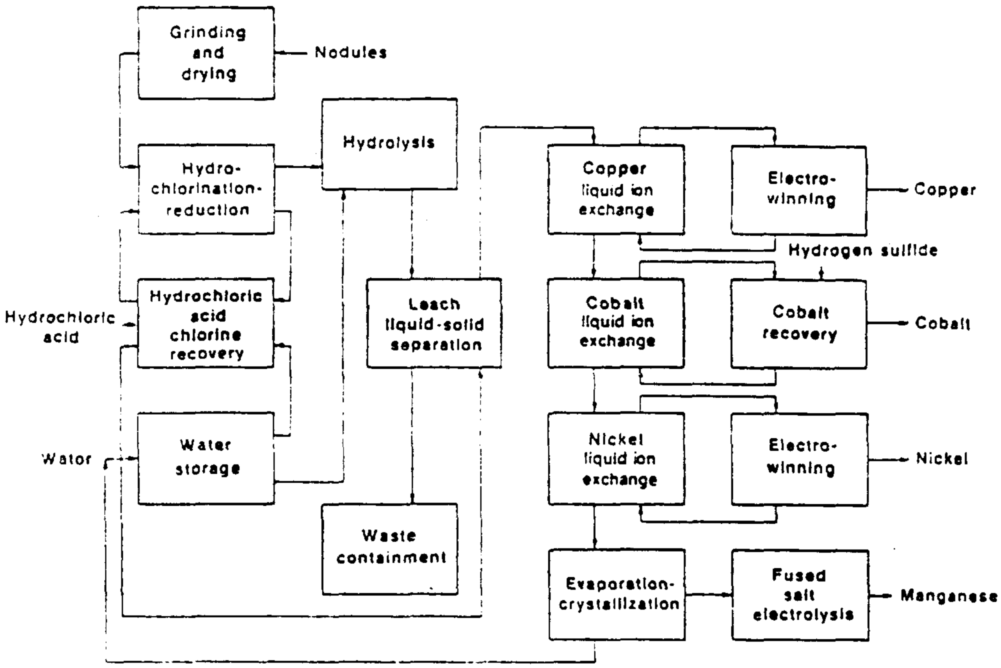


Figure 2.30 Processing of metalliferous oxides by reduction and hydrochloric acid leach (From: Haynes and Magyar 1987).

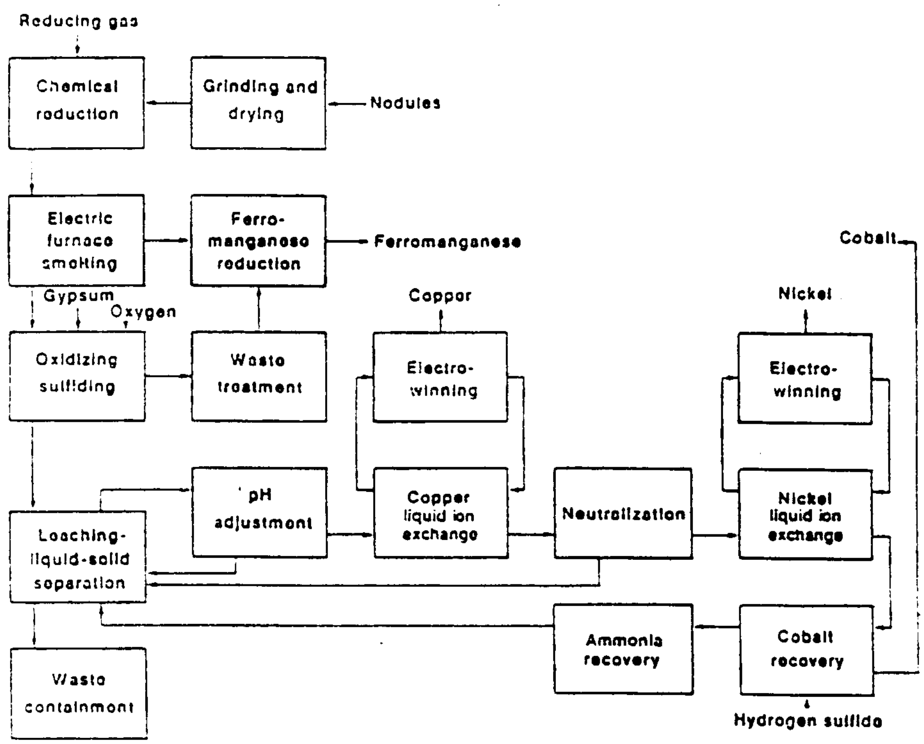


Figure 2.31. Processing of metalliferous oxides by smelting and sulfuric acid leach (From: Haynes and Magyar 1987).

Component	Wt%	ppm	t/yr	Eleutriate	Liquor	Residue
From ore						
Aluminium	2.9		87.000		8.700	78.300
Antimony		37	111			112
Arsenic		159	477			471
Barium	0.3		8.310			8.310
Cadmium		12.3	37			39
Calcium	1.7		51.000			51.000
Carbon	0.2		5.700		5.700	
Cerium		532	1.596			1.596
Chlorine	0.5		15.900		15.900	
Chromium		27	81			73
Cobalt	0.2		7.200			1.009
Copper	1.0		30.600			6.393
Iron	6.9		207.000		4.140	202.860
Lead		450	1.350			1.350
Magnesium	1.7		49.500		42.075	7.425
Manganese	25.4		762.000		38.100	723.900
Mercury		0.2	0.46			0.46
Molybdenum		520	1.560			1.638
Nickel	1.3		38.400			4.178
Phosphorus	0.2		6.900			6.900
Platinum		0.1	0.29			
Potassium	0.7		21.000		4.200	16.800
Silicon	7.6		228.000		6.840	221.160
Silver		0.1	0.30			0.3
Sodium	2.8		83.700		66.960	16.740
Strontium		450	1.350			1.221
Sulfur	1.8		55.200			55.200
Thallium		5.4	16			16
Titanium	0.5		15.900			15.900
Vanadium		470	1.410			1.504
Yttrium		20.5	62			57
Zinc	0.1		4.200		3.831	429
From Associated seawater						
Barium		70	210	189	21	
Calcium		400	1.200	1.080	120	
Chlorine	2.0		60.000	54.000	6.000	
Fluorine	0.3		9.000			9.000
Magnesium	0.1		3.900	3.510	390	
Potassium		400	1.200	1.080	120	
Sodium	1.1		33.000	29.700	3.300	
Sulfur		900	2.700	2.430	270	

Table 2.9. Estimated inputs and wastes for a manganese nodule processing plant handling three million metric tons of ore and associated seawater per year.

The amount of substrate fragmented depends on substrate hardness, cohesion to crust, thickness of crust, morphology of the crust/substrate interface, and roughness of the crust surface. Mathematical simulations of crust mining suggest that 50% or more of the material originally lifted from the seabed will be substrate rock (Morgan et al. 1988). Simulation parameters assume realistic limits for discrimination between crust and substrate on the irregular seamount surfaces where they are found. Assuming that the substrate is hyaloclastic deposits (common in Hawaiian EEZ samples recovered to date) and that the fragmentation model described in USDOI, MMS and HI, DBED (1990) is accurate, dilution based on present fragmentation methods will be between 25 to 70% (i.e., fragmented substrate will amount to 25 to 70% of the total material fragmented).

Further data should be obtained on crust roughness, thickness variation, and substrate properties to confirm these values. Harder substrates, such as basalt, would result in lower dilution of the crusts recovered. Because higher dilutions are likely to be uneconomic to mine, a dilution value of 25% has been assumed as a base case for fragmentation performance. Achieving this lower value for dilution will require (1) selection of a mine site with lower root mean square (RMS) roughness values than assumed for the base case; (2) development of new fragmentation methods; or (3) preferential mining on harder substrates.

Separation of recovered substrate from crust may be performed using screens, gravity settling, hydrocyclones, or possibly froth flotation. Preliminary work at the USBM, Salt Lake City Research Center indicates that over 90% removal of several substrate types can be accomplished with froth-flotation (Hirt et al. 1990). This processing step could be performed on the mining ship and possibly on the seabed. It is unlikely that the return of substrate rock to land can be economically viable without at least some elimination of this unwanted material.

As noted previously, processing schemes applicable to crusts are likely to be similar to those utilized on nodules after the substrate materials have been removed. Fine tuning of the process stream would, however, emphasize efficient extraction of cobalt at the expense of nickel. In any case, the waste streams would be similar, but scaled down to reflect the smaller size of the operation. **Table 2.10** presents the estimated inputs and wastes for a crust plant using the same assumptions as those used for manganese nodules, but with the expected smaller production level.

- **Speculative**

Methods for mining and beneficiating several offshore ore types remain within the realm of speculation. Ideas that appear feasible at this time follow.

On the Mining Platform: It is likely that future generations of deep seabed mining operators will utilize at-sea processing incorporating self-contained energy systems and closed-circuit processes. Future technologies will utilize all of the materials from the ore to make saleable products with little or no waste discharge. Some of these concepts were discussed at a recent conference on Very Large Ocean Structures convened in 1991 in Kona, HI (Cruickshank 1991).

Component	Wt%	ppm	t/yr	Fleut.	Diss.	Solids
From ore						
Aluminum	1.5		10,430		1,043	9,387
Antimony		65	46			46
Arsenic	0.2		1,050			1,036
Barium	0.2		1,400			1,400
Cadmium		5.4	4			4
Calcium	2.5		17,570			17,570
Carbon	0.2		1,050		1,050	
Cerium	0.2		1,120			1,120
Chlorine	0.6		4,270		4,270	
Chromium		200	140			126
Cobalt	0.9		6,230			873
Copper		800	560			117
Iron	17.2		120,400		2,408	117,992
Lead	0.2		1,260			1,260
Magnesium	1.3		8,960		7,616	1,344
Manganese	21.3		149,100		7,455	141,645
Mercury		0.3	0.2			0.2
Molybdenum		400	280			294
Nickel	0.5		3,290			358
Phosphorus	0.5		3,150			3,150
Platinum		0.4	0.3			
Potassium	0.7		4,900		980	3,920
Silicon	3.6		25,200		756	24,444
Silver		1.4	1			1
Sodium	1.9		13,020		10,416	2,604
Strontium		300	210			190
Sulfur	0.2		1,470			1,470
Thallium		100	70			70
Titanium	1.2		8,400			8,400
Vanadium		600	420			448
Yttrium		200	140			130
Zinc		700	490		447	50
From Associated seawater						
Barium		70	49	44	5	
Calcium		400	280	252	28	
Chlorine	2.0		14,000	12,600	1,400	
Fluorine	0.3		2,100			2,100
Magnesium	0.1		910	819	91	
Potassium		400	280	252	28	
Sodium	1.1		7,700	6,930	770	
Sulfur		900	630	567	63	

Table 2.10. Estimated inputs and wastes for a manganese crust processing plant handling 700,000 metric tons per year.

In situ: Future processing plants positioned on the seabed may be developed to take advantage of some of the ambient properties of the high pressure environment.

2.2.3 Transportation

Transportation represents a key component of mining, from exploration activity to process-waste disposal. Tasks which must be addressed range from the transport of survey crews and sensitive equipment to potential deposit sites, to moving millions of tons of ore from the mine to the processing plant. Economic viability for any marine mining venture depends upon efficient transportation. For low-value ores (e.g., industrial minerals), transportation can comprise the largest cost component for the entire operation. Environmental impact analyses for any marine mining operation must seriously consider the methods which are proposed, both for direct effects of the expected transportation operation and for potential adverse effects of transportation accidents.

Transportation operations which move large volumes of ore are of primary concern in this section, as they are of greatest concern to impact analyses. For transport of more than a few miles over water, bulk ore carriers must be used. For shorter distances, such as from the seabed to the mining ship and from the dock to the processing plant, conveyor belts and slurry pipelines can be used. The general characteristics of each of these methods have been described in the joint MMS/State of Hawaii EIS (USDOI, MMS and HI, DBED 1990) for manganese crusts. They have been generalized, as appropriate, for other commodities in the following sections.

2.2.3.1 Bulk Ore Carriers

Vessels for the transport of materials such as metalliferous oxides, massive sulfides, or phosphorites can be only generally described until (1) the specific features of the mining system are delineated; (2) the destination ports are determined; and (3) other uses of the transport are defined. Ores may be transported (1) in ore-carrier hulls which restrict the centerline cargo hold to a small part of the available hull space; or (2) in standard bulk carriers where load-dense ores are carried in only a few cargo holds (i.e., leaving others empty). In either configuration, extra steel is needed to provide compartmentalization and adequate hull strength for concentrated loads of dense ore. Combination ships may be able to carry any ore, bulk, cargo, or oil. Such ships are flexible for carriage and pumping of other liquid cargoes.

Normally ore carriers have no cargo handling gear, although many ships are equipped with cranes, and a few have self-unloading conveyors. All dry bulk ships are generally described as gearless, house-aft, diesel-propelled, single-screw designs. The occurrence of multiple cargo holds and power-operated, rolling hatch covers increases with larger ship size. Bow thrusters are now common for ease of docking operations.

For proper stability, an ore-carrying type ship should be designed with a reduced hold width and higher hold center of gravity. This configuration is essential whether the ore is in slurry or dry form. In addition, the transport of fuels, supplies, and waste by the ore carrier would probably be necessary. The slurry-pumping ship is basically a bulk carrier with water jets and discharge pumps installed in the lower compartment, under the cargo holds. Additional piping is present for slurry loading, seawater handling, and dewatering and decanting of the holds.

Given that the water depth inside major U.S. harbors is about 12 to 14 m (salt water, at low tide), and allowing for tidal rise and deeper dredging at berths, it is expected that laden vessels with no greater than a 12- to 14-m draft could transit most large U.S. harbors. These draft limitations are equivalent to vessels of about 65,000 deadweight (dwt); recent proposed shallow draft designs increase the potential vessel deadweight to over 100,000 dwt. Deadweights are typically less for older ships capable of higher speeds and possessing relatively deep drafts.

2.2.3.2 Slurry Pipelines

Many ores would be raised in a slurry from the ocean floor (i.e., within an upward flow of seawater) by a hydraulic system for transfer between vessels. Improved pumping efficiency will be achieved when small particles are produced by grinding the ore either at the seabed, on the mining ship, or both. Because of the ease of handling and reduced chance of spillage of either coarse or fine particles, ship-based slurry handling is considered most likely.

Ores raised from the seabed may be transferred at sea from the lift ship to the transport ship. Conventional dry-bulk handling methods (e.g., using belt or screw conveyors and buckets) may be satisfactory to handle the material as raised. For transport, water should be drained after loading to reduce transport weight and to assure a stable cargo. Unfortunately, metalliferous oxides, phosphorites, and, to a lesser extent, massive sulfides tend to disintegrate into small particles during handling (e.g., when stacked in large piles and in ship holds). Thus, a persistent problem to be expected at every point of transfer between slurry and other systems is the suspension of fine-grained ore particles in discharge waters.

Ore and other bulk materials may be removed from the transport ship by pumping a slurry of spent process water. Fresh water can be used in place of process water to slurry and to remove salt. Pumps may be located on the transport, or, to permit better maintenance, on the pier. Experience indicates that the high cost of shipboard slurry pump and maintenance results in shoreside pump installation as being more reliable and less expensive (B.V. Andrews, 1986, personal communication, private consultant).

Slurry terminals in deep water harbors are generally comparable to tanker terminals. Essential elements of this type of crust terminal would include the dock, wharf, or pier; mooring dolphins; pipeline connections; an access trestle; a shore-based receiving pond; and a pumping station.

Portable units are necessary when a conventional ship is used for slurry transport. The units can be lifted by a small crane and placed in each transport hold for shore discharge. Provision for handling ore as a slurry may be included in any new single-purpose terminal, because crust slurry pipeline systems may cost less than conventional dry bulk conveyor systems to deliver ore to a processing plant.

The slurry pond at the receiving terminal should have capacity equivalent to several shiploads or 10 days' receipts (minimum). Often, capacity many times this amount would be provided for buffer stock storage. If the processing plant is located nearby, a plant stockpile of two or three month's production may be located at the terminal, if space is available. Each 35,000 dwt ship load should fill a pond measuring (after dewatering) 85 m per side to a 10-m depth, or 0.65 hectares per ship load. A process or fresh water recycling tank of large capacity is also needed. Approximately 10,000 t of fresh water would be necessary for startup and 1 h of operation. A pumping station for onland slurry movement and a pipeline to the processing plant would require 0.4 hectares. Utilities and parking would require an additional 0.4 hectares. At a minimum, a total of 3 hectares of land would be required for a slurry terminal.

Projected major transport streams for slurry receiving facilities are illustrated in **Figure 2.32**. Because of the intense demands currently placed on coastal property at sites where processing activities could take place, this schematic assumes that there would be some distance (e.g., several miles) between the coast and the processing plant. The ore would be suspended with seawater in a slurry, then pumped from the cargo vessel directly to dockside holding tanks. The ore would subsequently be delivered, at some significantly lower rate (Flow Path A, **Figure 2.32**) to the plant. Slurry water would be largely recycled, and the decant-water holding tanks could be placed dockside or at the plant site. Discharge X (**Figure 2.32**) represents the discharge of decanted slurry water, if required; this discharge may also encompass accidental spills of slurries. Generally, Discharge X should be controllable, restricted as a function of the expected toxicity of the ore in coastal waters and the sensitivity of the ecosystems in potential receiving waters. Flow Path B, representing return stream from the processing plant, could include decanted seawater from A, low-salinity wash water, treated process water, or some combination of these. Flow Path C would be composed of process waste water and suspended tailings. Discharge Y represents the tailings-pond overflow and other onshore inputs to freshwater systems. Both the economics and environmental impacts of the venture would depend, to a large extent, upon the design of these transport systems.

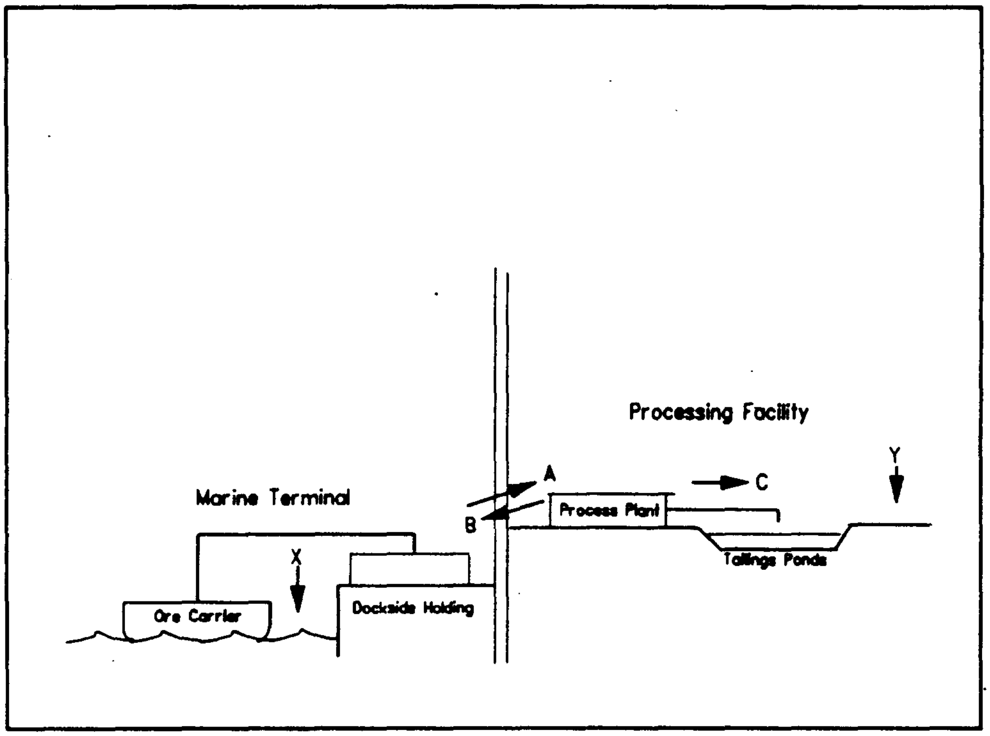
2.2.3.3 Other Transport Systems

Other transport modes are possible and potentially important for marine mining operations. Dry-bulk conveyor belts could be used instead of slurry transport for ore when the process requires dried material. Trucks and railroads could provide transportation for relatively high-value materials or for local delivery of small quantities of materials. Marine container and air-freight transport can be used for long-distance delivery of materials and equipment which require special treatment. For impact analysis, these operations are generally much less important than large volume transport of ore.

2.2.4 Cycling of Materials

All industrial operations have an input of raw materials, manufactured materials or supplies, and energy. Similarly, they have an output comprised of product (in this case ore, concentrate, or refined material) plus waste materials in liquid, gaseous, or solid form (**Figure 2.33**). Although most waste materials from mining operations are in solid form and

Key Flows of Materials for a Coastal Slurry System



A: Slurry feed to processing plant
B: Return flow of slurry water
C: Flow to settling ponds
X: Discharges to coastal sea water
Y: Discharges to freshwater systems

Figure 2.32. Transport streams for slurry receiving facilities (From: U.S. Department of the Interior, Minerals Management Service and State of Hawaii, Department of Business and Economic Development 1990).

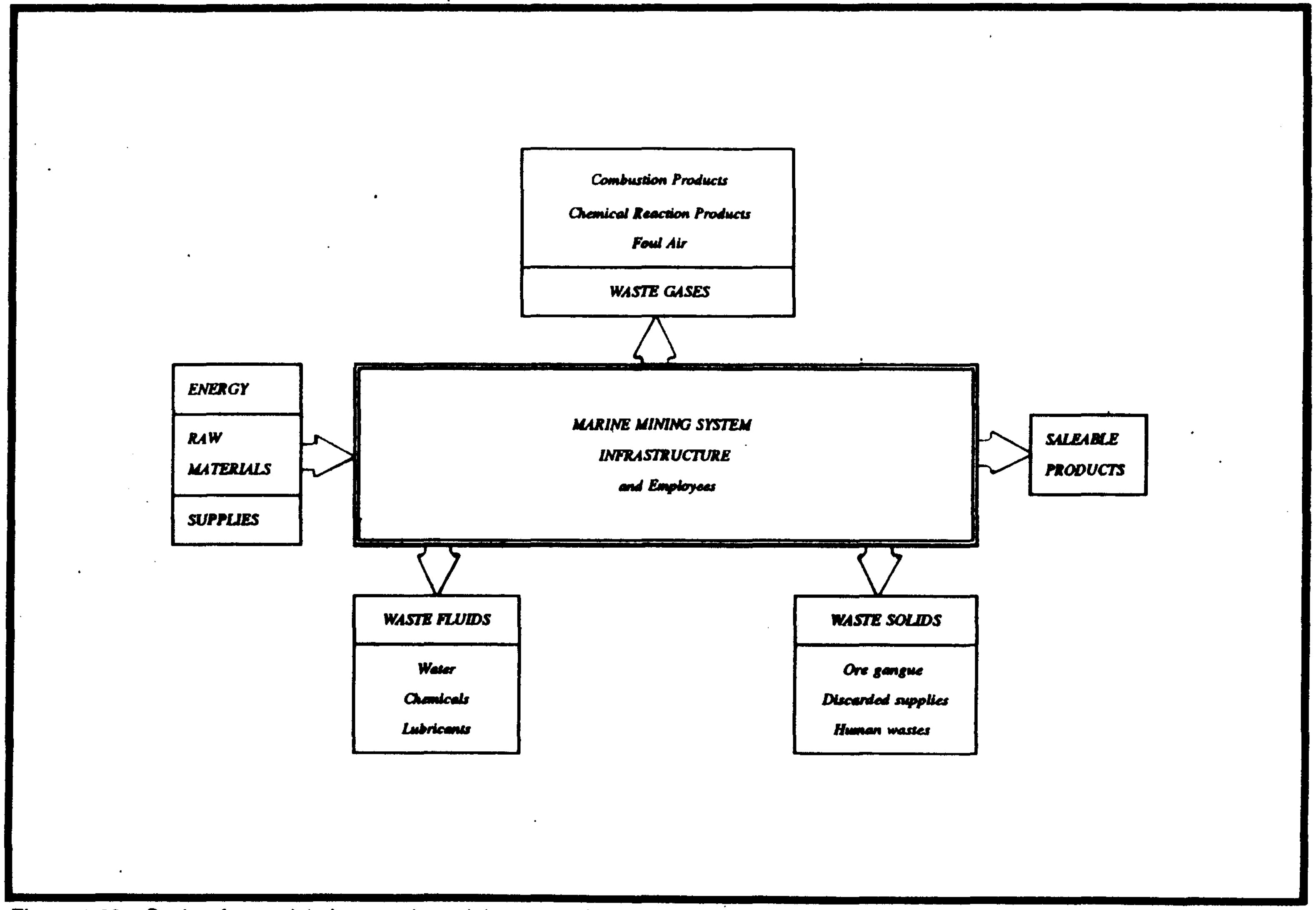


Figure 2.33. Cycle of materials in a marine mining operation.

consist of natural materials from the ore body or from its development, disposal of these materials may present some unique problems for marine mining operations. Problems must be addressed in a case-specific manner in pre-mining environmental documents.

2.3 Affected Environments

This section describes the nature of the various environments in which marine mining may take place and the anticipated effects that mining operations may have on those environments. Where possible, examples of actual operations are cited, rather than presentation of a speculative scenario. The geographic extent of the environments involved is global, even where reference is made to the U.S. EEZ. Descriptive material, therefore, is directed to areas selected by the authors as being representative of possible future mine sites. Examples from areas outside of the U.S. are used where appropriate.

Natural environments likely to be affected by marine mining may be logically classified on a global basis. These environments are depicted in **Figure 2.34** and defined in the following text in one of the following categories:

(1) Deep Ocean;
(2) Continental Shelf;
(3) Coastal Zone; and
(4) Onshore.

Deep Ocean: Deep ocean is comprised of seabed areas lying beyond the normal depths (200 m) of the continental shelf. In Pacific oceanic island areas, these depths may be within a few kilometers of shore; off Alaska, they may be hundreds of kilometers from shore. U.S. National Seabeds in the deep ocean are most extensive in the Pacific (**Figure 2.35**) although, pending new legislation, the responsibility for minerals development authorized by the OCSLA and administered by MMS is limited to the EEZ offshore of State waters. Development of seabed minerals by U.S. nationals in the area beyond national jurisdiction is authorized by the Deep Seabed Hard Mineral Resources Act (DSHMRA), administered by NOAA. Manganese nodules, cobalt crusts, and metalliferous sulfides are the prime mineral resource targets found in the deep ocean. Of these, crusts are prolific within the EEZ of U.S. Pacific Islands, whereas sulfides have been found in the U.S. EEZ only off California and Oregon in the area of the Gorda Ridge. The Blake Plateau (depth 200 to 600 m), because of its continental nature, is included in the continental shelf.

Continental Shelf: The geologic continental shelf is defined as that part of the continental margin between the shoreline and the continental slope, generally marked by a sharp steepening of the gentle incline of the shelf. This break generally occurs at a depth of about 200 m. For this study, the term "continental shelf" includes those areas of seabed which, in U.S. waters, are known as the OCS, but limited to that part of the continental margin from the seaward boundary of the territorial waters of the coastal States to the outer edge of the geologic shelf. Development of the minerals of the OCS is authorized by the OCSLA (PL 83-212, 67 Stat. 462 (1953), amended 1978) under the jurisdiction of the USDOI. The USDOI claims jurisdiction under the OCSLA over all seabeds between the territorial waters of the States and the outer boundary of the continental shelf or the 200 nm EEZ,

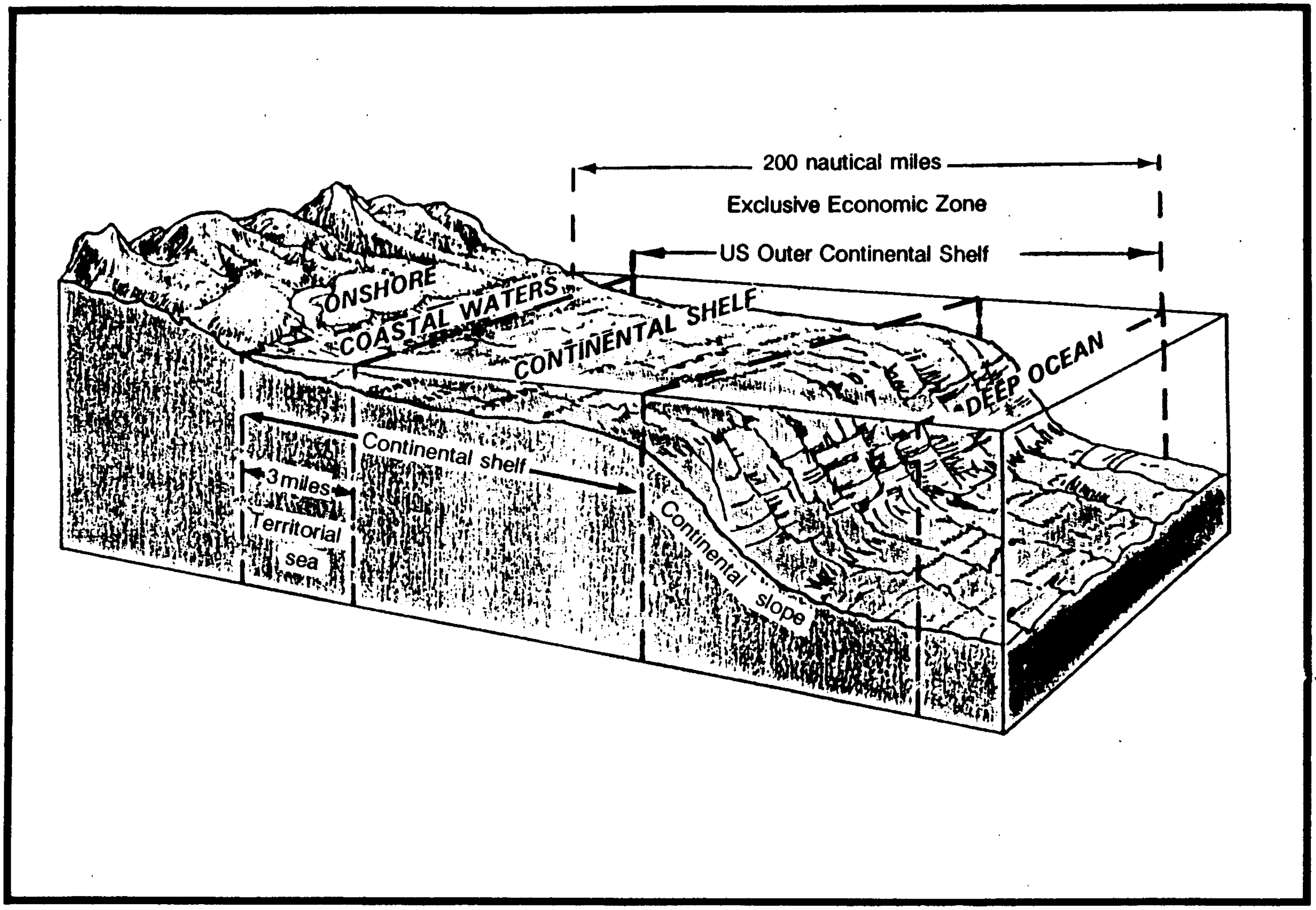
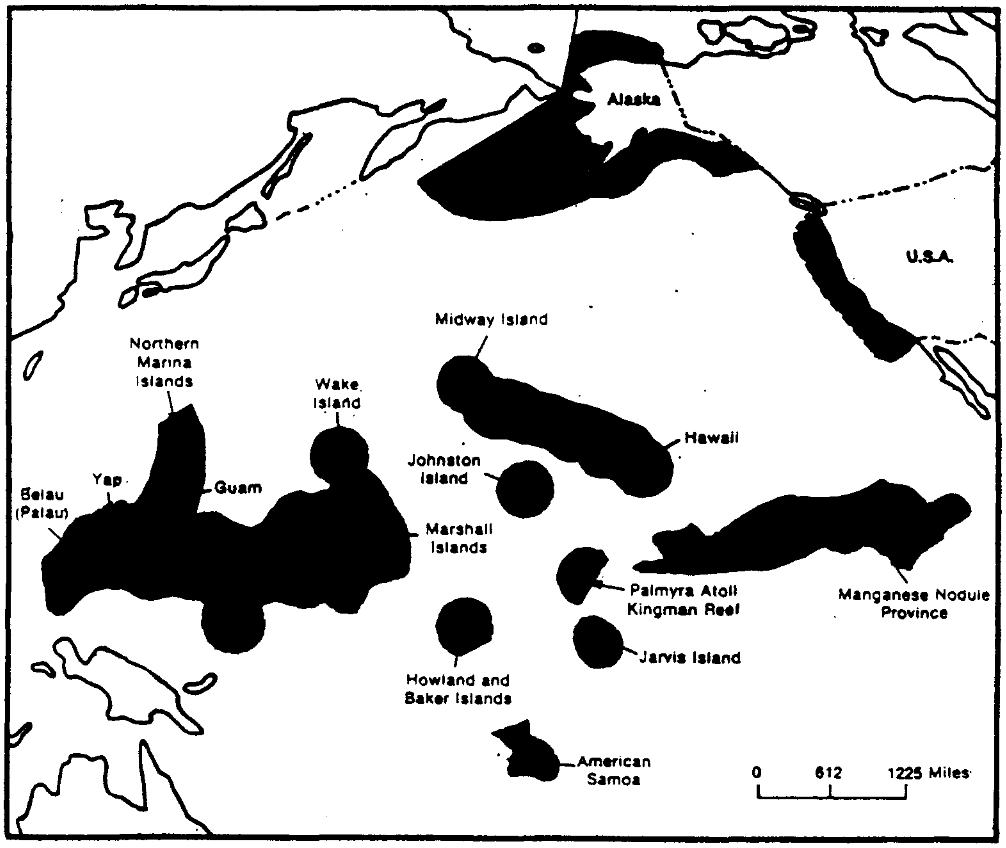


Figure 2.34 The ocean zones, including the Exclusive Economic Zone (EEZ) (Adapted from: U.S. Congress, Office of Technology Assessment 1987).



In addition to the waters off the fifty states, the Exclusive Economic Zone includes the waters contiguous to the insular territories and possessions of the United States. The United States has the authority to manage these economic zones to the extent consistent with the legal relationships between the United States and these islands.

SOURCES: Office of Technology Assessment, 1987; J.R. Hein, L.A. Morgenson, D.A. Clague, and R.A. Koski, "Cobalt-Rich Ferromanganese Crusts From the Exclusive Economic Zone of the United States and Nodules From the Oceanic Pacific," in D. Scholl, A. Grantz, and J. Vedder, eds., "Geology and Resource Potential of the Continental Margin of Western North America and Adjacent Ocean Basins," American Association of Petroleum Geologists Memoir 43; in press.

Figure 2.35 Exclusive Economic Zones (EEZs) of the U.S. Insular and Trust Territories in the Pacific (From: U.S. Congress, Office of Technology Assessment 1987).

whichever is the greater. The continental shelf may be host to any type of mineral deposit found on land, but the primary examples of OCS minerals (other than oil and gas) are sand, gravel, carbonates (including shells and shell sands), heavy mineral placers (including gold-, tin-, and titanium-bearing sands), phosphate, sulfur, salt, potash, coal, and cobalt-manganese deposits on the Blake Plateau.

Coastal Waters: Coastal waters include territorial seas, embayments, fjords, estuaries, lagoons, and some coastal wetlands. Jurisdiction over the minerals of coastal waters lies with the adjacent State. Coastal waters are a common source of construction materials, mineral sands, coal, and bedded ironstones. In many cases, where the coast is heavily populated, conflicts with other users (e.g., fisheries) may be severe.

Onshore: The onshore environment, which includes rivers, lakes, and freshwater embayments, is discussed only with reference to those areas which (1) are dedicated to a marine mining activity; or (2) are affected by mining or processing operations which discharge mined waste into the marine environment.

Details of selected marine mining operations that have been active during the past 20 years are given, in tabular form, for unconsolidated deposits (**Table 2.11**) consolidated deposits (**Table 2.12**), and dissolved deposits (**Table 2.13**). The data of Cruickshank (1973) remain a significant source of descriptive text and are indicative of the current spread of mining activities. Recent publications indicate the nature and extent of region- or mineral-specific activity, including (1) 450 sand and gravel dredges working offshore in Japan (Tsurusaki et al. 1988); (2) 14 companies with 53 dredgers and >1,000 seamen miners employed in the sand and gravel industry offshore of the U.K. (Uren 1988); (3) >5,000 small, illegal tin dredges working offshore of western Thailand in the early 1980s; and (4) >150 large freshwater conversion plants established worldwide (**Table 2.13**).

Marine environmental systems are comprised of three materials: solids, fluids, and organisms which occur in nature under conditions of dynamic equilibrium (i.e., the environment is undergoing constant natural change with respect to time). Marine mining may affect the environment in four ways, as depicted in **Figures 2.36** and **2.37**, including the following:

(1) Material may be removed;
(2) New material may be introduced;
(3) Material may be mixed in place; and
(4) Material may be replaced after removal.

All interactions occur at an interface where physical, chemical, or biological energy is transferred. In the ocean, the major natural interfaces are the air/sea interface and the sea/seabed interface. Most energy transfers take place at these two junctions on a widespread and generally nonviolent scale (**Figure 2.38**). In the coastal zone where both major interfaces come together, physical energy exchange can become significant and violent (**Figure 2.39**; Webb 1965). Other lesser important interfaces are those between organisms and ocean water. When the effects on the environment are examined, however,

DREDGE DATA								OPERATING DATA (selected)						
Name of dredge	Dredge type	Hull type	Tonnage	Depth range	Mooring	Rated capacity	Capital cost $	Period	Operating depth	Deposit type	Monthly throughput cu. yds.	Cost/yd	Deposit value $/yd	Remarks
DIAMONDS Tidal Diamonds (S.W.A.)														
Pomona	5x18" suction	Barge 205x60	4800 T	<150'	anchor	15,000 T/day	7,000,000	7/64-6/65 1/68-6/68	100 ft. 70 ft.	Diamond gravel	10,450 8,940	$41.6 $36.2	39.6 33	All dredges crew 114 closed 1971
Terra Marine Oniginner I	14" hymatic jet lift & jet cutter	Tanker 200x39x15		<150'	4 anchor	15,000 T/day	1,400,000	9/66	70 ft.	Diamond gravel	n.k.	n.k.	n.k.	
GOLD														
Aurora Mining Co. Bluff, Alaska	Suction	Barge	500	110'	N.K.	N.K.	N.K.	Aug. 68	110'	Gold placer	N.K.	N.K.	N.K.	Beached in storm
Metachewan Canadian Gold, Ltd., Nova Scotia	Suction	N.K.	N.K.	60	N.K.	150 yd³/hr	N.K.	1969	60'	Gold placer	N.K.	N.K.	.30	Blocking out reserves summer 1969
TIN														
Aokam Tin Mining Ltd. (Thailand) No. 2 Dredge	14 cf. bucket line	Barge	n.k.	110'	6 anchor		2,560,000	1968	85'	Tin alluvial	226,000	n.k.	1.75	
Aokam Tin Berhad Phuket No. 3 Dredge	15-cubic-foot bucket	Barge	N.K.	117'	6 anchor	650 yd³/hr	N.K.	1969		Tin alluvial	N.K.	N.K.	2±	Completed Oct. 68
Southern Kinta Consolidated Ltd. Takuapa, Thailand	Side trailing suction	Barge 200x50	n.k.	<50'	n.k.	n.k.	1,650,000	69-70	<80	Tin alluvial	90,000	N.K.	1.0716 sans throughout 1969	
Tongkah Harbour Tin Dredging Ltd. (Thailand) "Sea Dredge"	15 cu ft bucket line	Barge 230x72x12	2,500 T	100	6 anchor	18,000 T/day		1966	<100'	Tin alluvials	171,000 yd	22¢	1.10	
Thailand Exploration & Mining Company	Suction	N.K.	N.K.	N.K.	N.K.	N.K.	6 million	1971 expected	<100'	Alluvial tin	5 million yd³/yr			
Indonesian State Tin Mining Enterprises Bangka, & Sinkep	1x7 cu ft	bucket dredge line	n.k.		6 anchor			1959-61	100-130'	Tin alluvial	150,000	31.0¢		
	8x14 cu ft	bucket barge line	n.k.		6 anchor			1959-61	100-130'	Tin alluvial	300,000	31.0¢		
"Bangka I"	18 cu ft bucket line	Barge 300x80x16		131	6 anchor	26,000 T/day	10,000,000	1966	82'	Tin alluvials				
Coastal Prospecting Ltd. Cornwall, U.K.	3-inch suction	Ship	25	65'	4 anchor	250 gpm	N.K.	1967	15-40'	Alluvial tin	N.A.	N.A.	N.K.	Pilot operation
HEAVY MINERAL SANDS														
Titanium & Zirconium Industries Pty. Ltd.	Suction dredges (2)	Ocean going	n.k.	n.k.						H.M. sands beach dep.				Details n.k.
Waipipi Iron Sands Ltd	Cutter head suction dredge	N.S	N.S.	N.S.	N.S.	2,000 yd³/hr	7,000,000	1971	<100'	Fe Sand 20%	—	20¢	$2.00	estimated
Taho Maru	8" bell mouth suction	Ship (6)	90	45-90'	4 anchor	120 T/hr	N.K	1969	16'	Fe Sand 3-5%	8,000	N.S.	20-35¢	—
CALCAREOUS SANDS AND SHELLS														
Iceland Govt. Cement Works (Iceland)	24" hydraulic suction	Ship 150'	1,100 T	140'	Free	9,600 T/day	n.k.	1964	130'	Shell sand	10,000 MT	n.k.	n.k.	
Southern Industries Corp. (La. USA) "Mallard"	18" hydraulic cutter	Barge 200x50'	1,239 T	55'	Spuds & 2 anchor	36,000 T/day	n.k.	1964	50'/55'	Oyster shell	600 y.p.l.		n.k.	
Ideal Cement Work (S. F. U.S.A.) Texas	16" hydraulic cutter	Barge		30'	Spuds & 2 anchor			1966	27'	Oyster shell	625,000	n.k.	n.k.	closed 1970

Table 2.11. Selected dredging operations offshore (Adapted from: Cruickshank 1973).

Ocean Industries Inc. Bahamas	Suction	N.K.	N.K.	N.K.	N.K.	8,000 T/day	N.K.	Under development		Aragonite				Reserves 575 million tons
SAND AND GRAVEL														
U.S. Corp of Eng. (Coastal U. S.)	Hydraulic dredges 8"-20" (20)	Ship	—	<55'	Free	20,000 T/day	±630,000		0-50'	Sands & clays		10.9¢	n.k.	
United Sand & Gravel Co. (S. F. Bay) "Sandpiper"	16" hydraulic	LSM Conversion	n.k.	80'	Free	6,000 T/day	n.k.		n.k.	Gravel fill			n.k.	
U.S. Corps of Engineers, Texas "McFarland"	Twin suction	Ship	N.K.	60	Free	1,500,000 yd^3/month	17 million	1967-1969	45'	Sand & clay	1,000,000	22.4¢	N.A.	
Sand & Gravel Association Great Britain (63 Locations)	Suction (55 dredges)	Hopper dredge	Various	<150'	Free	100-2500 tons	N.K.	Present	<155'	Sand & gravel	1 million	N.K.	N.K.	
Hall & Company Lumber Kingdom AA Raymond	20" hydraulic suction	270x46x23 Hopper dredge	5,400 T	50'	Free	15,000 T/day	n.k.	1967	n.k.	Gravel	60,000		n.k. n.k. n.k.	
Monterey Sand Co. Monterey, Calif.	Fixed dragline	N.A.	3-3500	12'	Buoy	45 T/hr	N.K.	June 68	Surf zone 150' offshore	Coarse silica sand	1,000,000 yd/yr		4.50	
Ocean Dredging Inc. Fla "Crawlcutter"	12" hydraulic cutter	Submerged D8 Cat	—	100'	Umbilical	750HP. 4160V	N.S.	1970	50'	Sand	—	—	connect	working prototype
MANGANESE NODULES														
Deepsea Ventures Inc., U.S.A.	24-inch suction	332' ship	N.K.	3000'	Dynamic	N.K.	N.K.	1970	3000'	Mn nodules (Blake Plateau)	N.K.	N.A.		Scheduled pilot operation
Chiyoda Maru No. 2	Continuous bucket line	Ship 300	—	6000'	Free	—	260,000	1970	12,000'	Mn Nodules	—	—	—	project cost, temporary conversion for systems test
Hughes Tool Co.	—	> 800'	35,000	> 10,000'	—	—	—	—	—	Manganese nodules	—	—	—	Crew 100, Delivery due 1972
(new entries for 1972)														
Anglo Dutch Dredging Co. "IJsselmeer"	Trailing Suction	Ship	N.K.	230	Free	N.K.	N.K.	1971	230 ft.	Sand	500,000	N.K.	N.K.	Submerged Pumps
K. Maru No. 2	C.L.B.	Ship	N.K.	12,000 15,000 ft.	Free	100 T/day	(1.5 million	1972	12,000 15,000 ft.	Manganese nodules	-	-	-	6 Weeks Test
Hughes Glomar Explorer	N.S.	Ship 618x115x60 Barge 324 ft.	36,000	12,000 18,000 ft.	N.S.	N.S.	>$36 million	1972	—	Manganese nodules	N.S.	-	-	Launched 1972

Table 2.11. (Continued).

Name of Mine	Location	Company	Minerals	Depth below Sea Level Ft	Max. Dist. From Shore	Access	Method of Working	References
Collieries (5)........	Nova Scotia	Dominion Coal Co. Ltd.	Coals 5-ft 7-in. seam @ 4–24°	300–1,000	5 mi (reserves)	Adit on shore	Room & pillar, 300–1,000 ft Longwall below 1,000 ft	MMTC
Chien Chi coal.......	Taiwan	Chien Chi Coal Mine Co.	Coal, 0.3–3.3 m @ 9–47°	0–1500	9,000 ft	Adit on shore	Longwall	MMTC
Kozlu coal..........	Turkey	Eregli Coal Mines Ltd.	Coal, 19 seams @ 45° 3–60′	1,500	1,000 m	Vert. shaft on shore	Stepped long-wall	MMTC
Collieries (11)	Japan	Mitsui Mining Co. Ltd.	Coal	600–2,400	5 mi	Inclined & vert. shafts on shore & artificial islands	10 operating mines	MMTC RRI 1970
Collieries (31).......	U.K.	National Coal Board	Coal	300–8,800	5 mi	20 shafts on shore, 1 natural island, 1 artificial island	Longwall	Armstrong, 1965
Lotaschwager........	Chile	Lotaschwager Coal Co.	Coal	3,000	4 mi	Shaft on shore	NK	MMTC
Jusarro Gruva.......	Finland	Oy Vuoksenniska Ab	Magnetite quartz banded iron ore	30 m, steep dipping	1,000	Shaft on shore	Shrinkage stoping	MMTC
Levant..............	Cornwall	Geevor Tin Mines	Tin, vert. lodes lodes	Holed through	1 mi	Shaft on shore	Underhand stoping	Batchelor, 1969
Grand Isle..........	U.S.A., La.	Freeport Sulphur Co.	Sulfur, 220–425;ft dome	2,000	5 mi	Drill holes	In-situ Frasch process	Lee, 1960
Camenada*.........	U.S.A., La.	Freeport Sulphur Co.	Sulfur	—	—	Drill holes, offshore platform	In-situ Frasch process	MJ, 5/66; EMJ, 8/67; WSJ 2/69
Castle Island........	Alaska	Alaska Barite Co.	Barite	50	1 mi	Sea surface	Blast and dredge	Thompson, 1970
Yorkshire Potash†...	England	Rio Tinto Zinc Corp.	Potash	3,500	5 mi	Shaft on shore	Room & pillar	MJ, 5/69
Goderich............	Canada, Ont.	Sifto Salt (1960) Ltd.	Rock salt, 75 ft, 0.2°	1,170	2,500 ft	Vert. shaft on fill	Room & pillar	Mamen, 1969
Cape Rosier.........	Maine	Callahan Mining Corp.	Cu/Zn sulfides	Tidal	—	Land surface	Open-pit	Beck, 1970

* Closed temporarily, 1969.
† Under development. Production scheduled 1970.

Table 2.12. Data on underground mines operating offshore (Adapted from: Cruickshank and Marsden 1973).

Mineral	Location	Company	Process	Raw Materials	Annual Production	Value	% Domestic Production
Magnesium metal	U.S.A.	Dow Chemical Co. Freeport	Precipitation	Sea water & dolomite, electric power	106,000 tons	$708/ton	41% world production
	U.S.A.	National Lead Co.	Solar evaporation & electrolytic reduction	Great Salt Lake Bitterns	45,000 tpy	708/Ton	30
	Norway	Norsk Hydro Electric, Heroga	Precipitation	N.K.	70,000 tons		
Magnesium compounds	World-wide	Over 25 plants	Precipitation	Sea water, carbonate rock	N.K.		
	Canada	Sea Mining Corp. Ltd.,[1] Aguathuna, NF	Precipitation	Sea water, limestone	36,500 tons		
	Eire	Quigley Co. Inc.,[1] Dungarven	Precipitation	Sea water, dolomite	75,000 tons		
	U.S.A.	Dow Chemical Co. Freeport, Texas	Precipitation	Sea water & oyster shells			
	U.S.A.	F.M.C. Corp. Newark, Calif.	Precipitation	Bitterns			
	U.S.A.	A. P. Green Refractories Freeport	Precipitation	Sea water & oyster shells			
	U.S.A.	Kaiser Refractories Moss Landing, Calif.	Precipitation	Sea water & dolomite	690,000 tons	$665/ST	74%
	U.S.A.	E. J. Lavino Co. Freeport					
	U.S.A.	Merck & Co. San Francisco	Precipitation	Sea water & carbonate rock			
	U.S.A.	Michigan Chemical Corp., Port St. Joe	Precipitation	Sea water & carbonate rock			
	U.S.A.	H. K. Porter Co. Pascagoula					
	Israel	Dead Sea	Evaporation	Dead Sea Brines	N.K.	—	—
Sodium chloride	U.S.A.	Leslie Salt Co. San Francisco	Solar evaporation	Sea water	1.25 million tons	$23/Ton	29%
	Japan			Sea water	0.9 million tons		100%
	Colombia	Institute de Fomento Industrial	Solar evaporation	Sea water,	300,000 tons		
	Malaysia	NS. Ipoh	N.S.	Sea Water	N.K.	—	100%
	Nicaragua	Salinas Nicaraguenses S.A. Tamarinda River	Solar evaporation	Sea Water	20,000 T	$20/Ton	N.K.
	Uganda	Uganda Devpt. Corp.	N.S.	Lake Katwe Brine	N.S.	—	—
Bromine	U.S.A.	Ethyl Dow Chemical Co., Freeport, Texas	Chlorine displacement	Sea water			
	U.S.A.	Westraco Chem. Div. of F.M.C. Corp. Newark, Calif.		Sea water bitterns	102,000 tons	$3/lb.	70%
Fresh water	World-wide	Over 150 plants	Various	Sea water	150 million gal.	36¢/ton[3]	
	Holland	Dutch Government	Expansion evaporation	Sea water	30,000 m^3/day		
	Mexico	Aqua Chem Inc. Rosarito, Mexico		Sea water	800 l/su		
Heavy water	Canada	Glace Bay, Nova Scotia	N.K.	Gulf Stream water	73,000 tons	N.K.	100%

[1]New plants
[2]Closed down 1969
[3]McIlhenny (1969) values rounded

Table 2.13. Operational plants for the extraction of minerals from seawater (From: Cruickshank 1973).

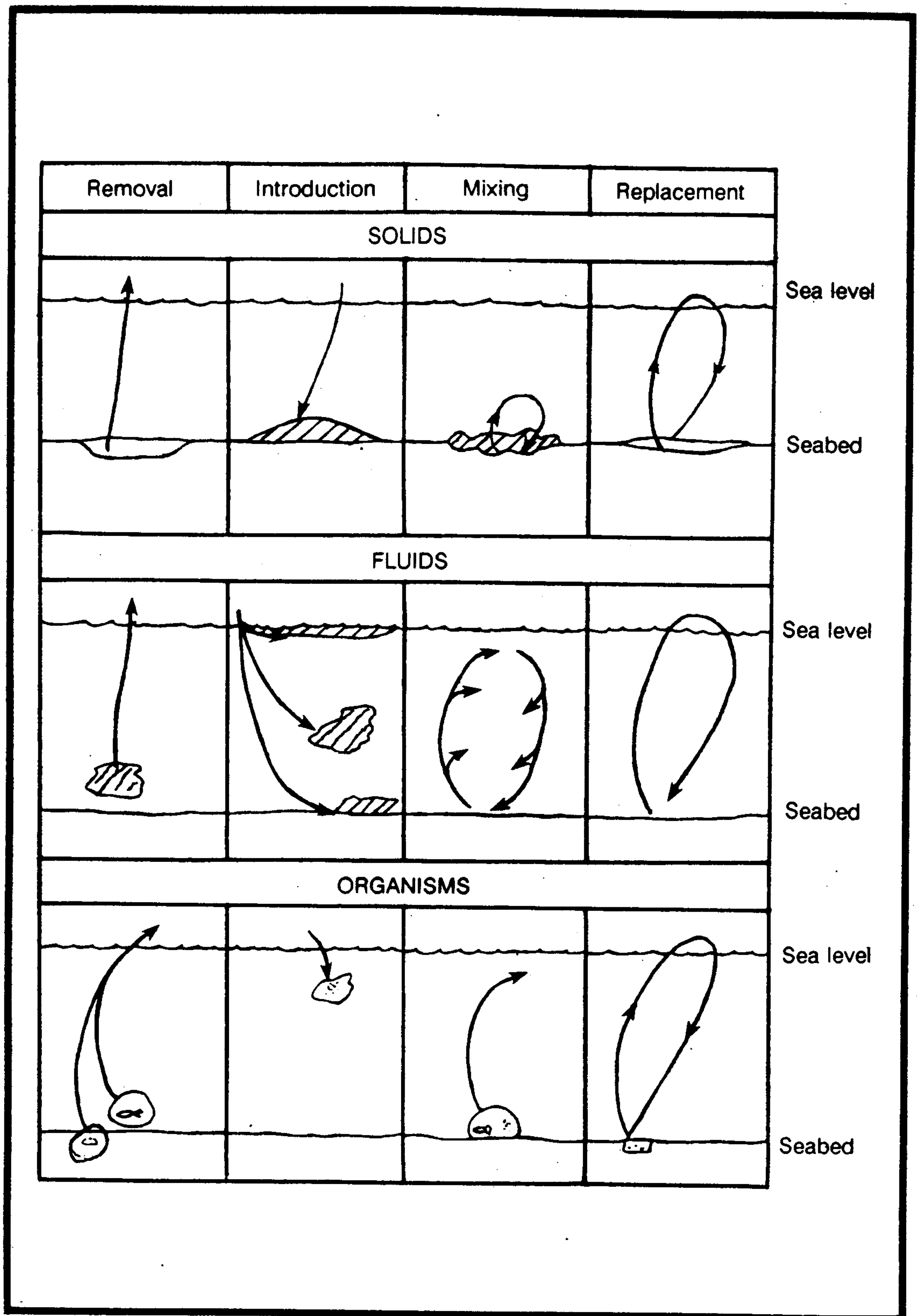


Figure 2.36 Nature of dynamics of marine media during mining operations (Adapted from: Cruickshank 1978).

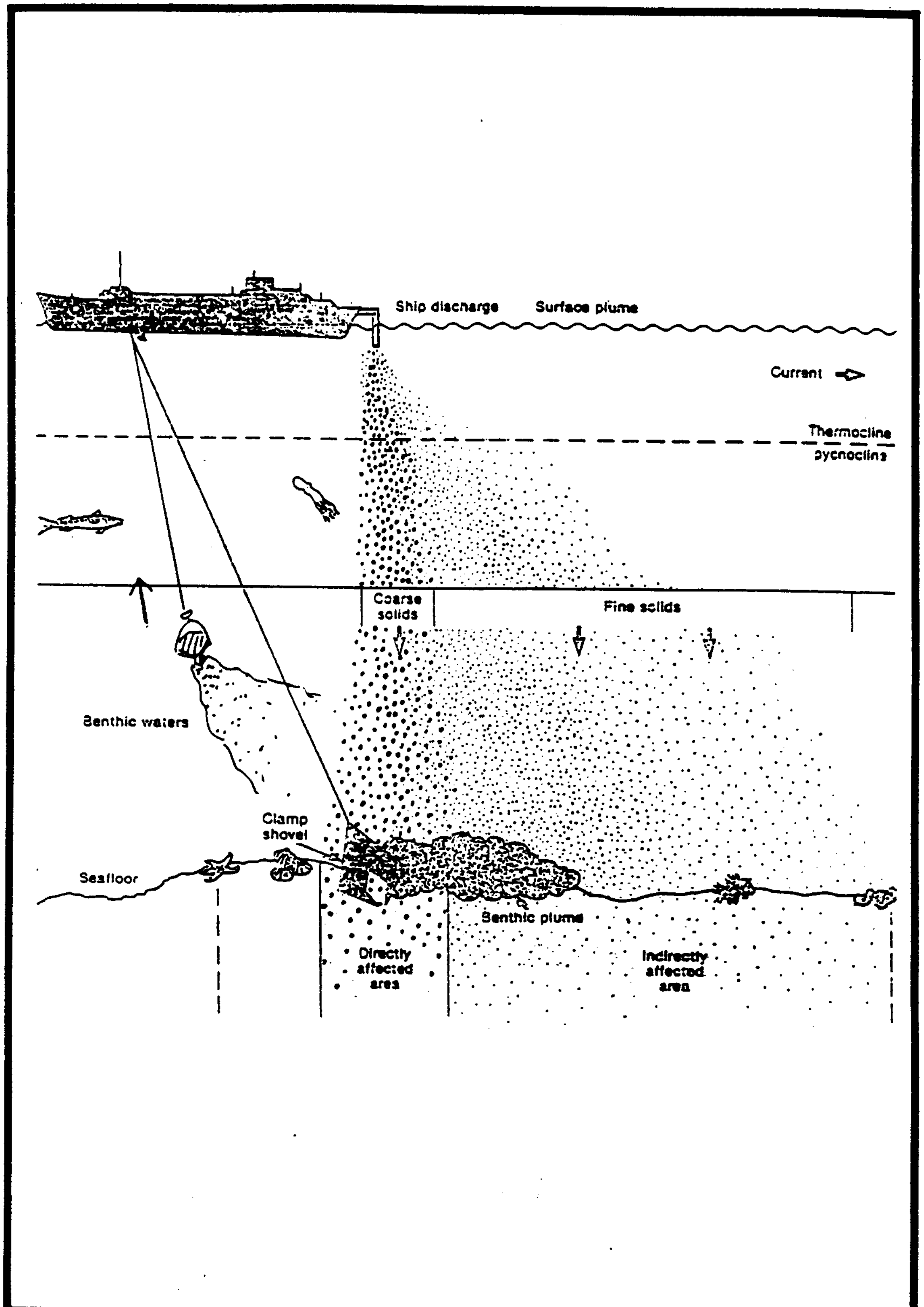


Figure 2.37. Impacts of offshore mining on the marine environment (Adapted from: U.S. Congress, Office of Technology Assessment 1987).

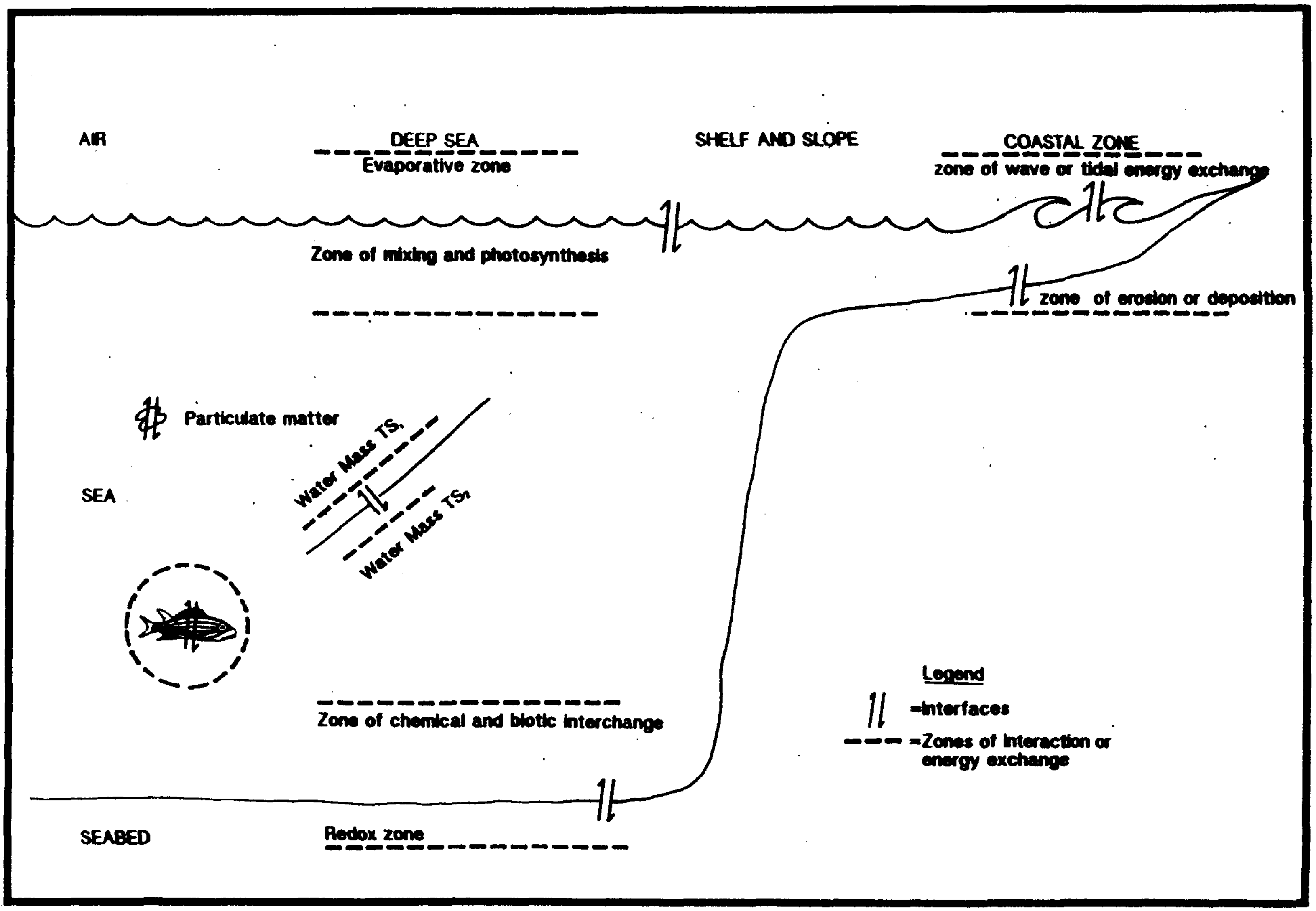


Figure 2.38. Basic natural interfaces in the marine environment (Adapted from: Cruickshank 1987).

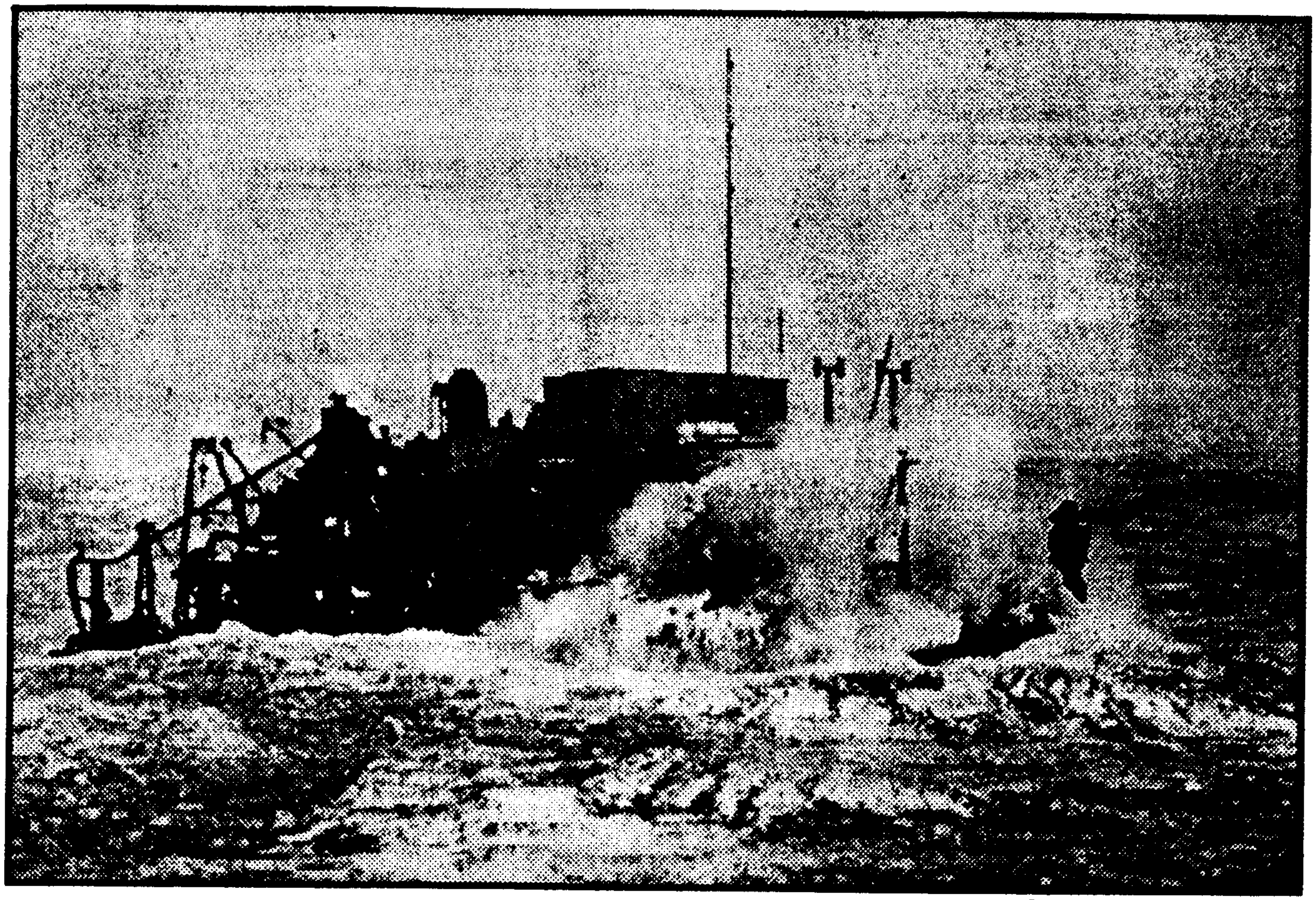


Photo credit: M.J Cruickshank

Figure 2.39 Diamond mining in rough seas of Southwest Africa (From: Webb 1965).

the classification tends to emphasize the effect of the quality of the non-living environment on the living.

For the purposes of this analysis, environmental effects are classified according to the environment they affect, including atmospheric environment (i.e., air quality), oceanic environment (i.e., water quality), geologic environment (i.e., seabeds), and the effect of these on the biological environment which comprises all living things except humans. Many of the human environmental interfaces are man-made and are as dynamic as those of nature. The social and economic environments are also considered. Examples of these environments are given in **Table 2.14**.

Measurement and understanding of environmental dynamics, particularly in the oceans, is still a relatively new field. With recent advances in marine scientific instrumentation, more accurate environmental measurements are constantly being made. With each improvement or change in scale, other interfaces become apparent which may be particularly significant in terms of trace element geochemistry, microbiology, or bacteriology. In the prediction of environmental impacts, the effect of the new interfaces and interactions which take place are considered in terms of the total effect of the operations on the environment. Conversely, where the environment becomes important with respect to the safety and cost of the operation, then these potential effects, risks, or hazards need to be given the same consideration as the potential environmental impacts, and become a part of the equation in the benefit cost analysis. These aspects have been discussed in a number of publications (e.g., Cruickshank et al. 1969; Cruickshank 1974a).

The concept of Large Marine Ecosystems (LMEs), as presented by Sherman (1991), is a very useful approach for analyzing the environment from a global and regional perspective (**Figure 2.40**). LMEs are relatively large areas (i.e., 200,000 km^2 or more) and are typically located in waters adjacent to land masses which encompass the areas under greatest stress from over-exploitation, pollution, and habitat alteration.

2.3.1 Deep Ocean

Deep ocean environments comprise by far the largest fraction of the world's oceans. Being generally remote from most human activities, they have also traditionally been the most poorly understood. International efforts during the past 20 years to develop deep seabed mineral deposits have led to a significant increase in studies of deep sea ecosystems, particularly benthic ecosystems. During the last 5 to 10 years, several long-term research programs have commenced to acquire basic information about deep ocean environments, particularly in surface waters. These studies have been prompted by the growing general awareness of the importance of deep ocean environments to worldwide issues such as long-term climate modification or the removal of combustion gases by marine processes. This section summarizes the important results obtained to date in these efforts relevant to the development of deep seabed minerals.

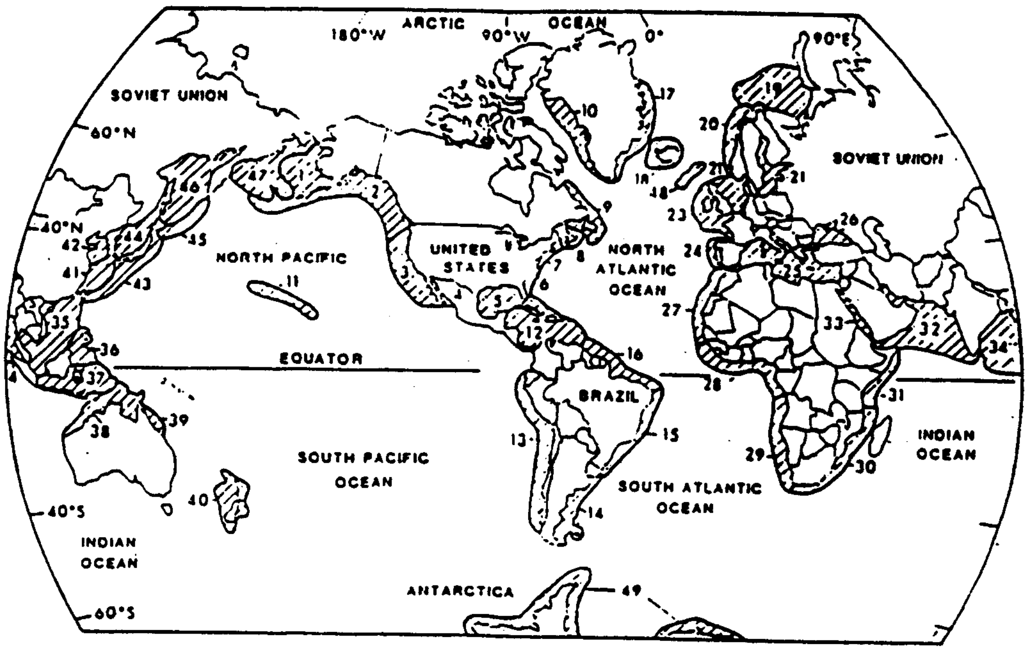
Natural Systems

- Meteorologic
  - Climate
    - Temperature
    - Winds
    - Precipitation
  - Air Quality
    - Gases
    - Water Vapor
    - Particulates
    - Radiation (Acoustic, seismic, electric, magnetic, nuclear
  - Natural Hazards
    - (Storms, ice)
- Hydrologic
  - Coastal
    - Surface water
      - Drainage (Rivers, channels)
    - Groundwater
      - Drainage
        - Flow rates (Aquifers, springs)
    - Retention
      - Capacities
      - Leakage
      - Overflow (Underground lakes)
    - Recharge
    - Water quality
    - Physical Properties
    - Chemical Properties
  - Natural Hazards (Tsunamis, storms, floods)
- Marine
  - Upper boundary layer
    - Sea state (Climate)
      - Waves
      - Swell
      - Current
      - Tides
      - Temperature
    - Boundary gradients (Water quality)
      - Physical properties (Temperature, density (STD))
      - Transmissivity (Optical, acoustic, electric)
      - Chemical properties
        - Dissolved (Salinity, chlorinity, trace elements)
        - Particulates
  - Intermediate Layer
    - Climate
      - Temperature
      - Circulation pattern
      - Mixing pattern
    - Water quality
      - Physical
      - Chemical
- Marine (cont.)
  - Bottom Layer
    - Climate
    - Temperature
    - Circulation
  - Boundary Gradients (Water quality)
    - Physical
    - Chemical
- Natural Hazards
  - (Storms, turbidity currents, geothermal plumes, submarine waves)
- Geologic
  - Regional geology
    - Morphology
    - Tectonics
    - Petrology
    - Mineralogy
  - Mineral deposits
    - Ore minerals
    - Distribution
    - Origin
    - Ore reserves
  - Geotechnique and geomechanics
    - Index properties (Specific gravity, density, grain size, water content, Atterberg limits)
    - Engineering properties (Compression, shear, permeability, consolidation)
  - Natural Hazards (Earthquakes, slides, plate motion)
- Biologic
  - Diversity and abundance
    - Floral
      - Terrestrial (Trees, shrubs, grasses, crops)
      - Marine (Algae, seaweed, phytoplankton)
    - Faunal
      - Airborne (Birds, flying insects)
      - Terrestrial (Animals, reptiles, insects)
      - Marine
        - Pelagic (Zooplankton, fish, mammals, reptiles)
        - Benthic (Epifauna, infauna)
  - Ecosystems
    - Zonation
    - Influences (Physical, chemical, trophic)
  - Natural Hazards (Plankton blooms, fish attacks)
- Physiologic
  - Operational Personnel
    - Numbers
    - Ethnics
      - Aptitude

Artificial Systems

- Social
  - Regional Population
    - Distribution
    - Quality of life (Health, education, welfare, income, livelihood)
- Social (cont.)
    - Social amenities (Housing, schools, fire protection, police, services)
  - Transient Population
    - Number of transients
    - Purpose (Vacation, seasonal workers, fishing)
- Economic
  - Resource Value (Minerals, fisheries, real estate)
  - Resource Markets
  - Conflicting uses
    - Airspace
      - Aesthetics
      - Commercial (Transport, communications, research)
    - Water
      - Residential
      - Commercial (Fisheries, transport, farming, ports)
      - Industrial (Cooling, dumping)
      - Recreational
      - Educational
      - Defense
    - Land (Sea-bed)
      - Residential
      - Agricultural
      - Industrial
      - Recreational
      - Educational
      - Defense
- Legal
  - Ownership (Territorial waters, outer continental shelf, deep sea)
  - Jurisdictional agencies
  - Restraints (Rights of way, precedential rights)
- Political
  - Existing regime
    - Policies
    - Representation
    - Relevant functions
- Historical and Archaeological
  - Distribution of sites and objects (Ruins, artifacts, shipwrecks)
  - Importance
  - Description
- Technical
  - Materials R&D
  - Design
- Restoration
  - Sealing
  - Removal
  - Restoration
- Accident (Fire, explosion, spillage, inundation, collapse)

Table 2.14. Environmental systems elements affecting the exploration and exploitation of marine mineral deposits, with examples in parentheses (Adapted from: Cruickshank 1978)



WORLD MAP OF LARGE MARINE ECOSYSTEMS

1. Eastern Bering Sea
2. Gulf of Alaska
3. California Current
4. Gulf of California
5. Gulf of Mexico
6. Southeast U.S. Continental Shelf
7. Northeast U.S. Continental Shelf
8. Scotian Shelf
9. Newfoundland Shelf
10. West Greenland Shelf
11. Insular Pacific–Hawaiian
12. Caribbean Sea
13. Humboldt Current
14. Patagonian Shelf
15. Brazil Current
16. Northeast Brazil Shelf
17. East Greenland Shelf
18. Iceland Shelf
19. Barents Sea
20. Norwegian Shelf
21. North Sea
22. Baltic Sea
23. Celtic-Biscay Shelf
24. Iberian Coastal
25. Mediterranean Sea
26. Black Sea
27. Canary Current
28. Guinea Current
29. Benguela Current
30. Agulhas Current
31. Somali Coastal Current
32. Arabian Sea
33. Red Sea
34. Bay of Bengal
35. South China Sea
36. Sulu-Celebes Seas
37. Indonesian Seas
38. Northern Australian Shelf
39. Great Barrier Reef
40. New Zealand Shelf
41. East China Sea
42. Yellow Sea
43. Kuroshio Current
44. Sea of Japan
45. Oyashio Current
46. Sea of Okhotsk
47. West Bering Sea
48. Faroe Plateau
49. Australia

Boundaries of 49 LMEs.

Figure 2.40. World map of large marine ecosystems (From: Sherman 1991).

2.3.1.1 Atmospheric Environment

The remoteness of most deep ocean areas from large land masses results in some of the clearest, cleanest air on the planet's surface. The lack of obstructions to air circulation leads to generally rapid dispersal of air pollutants. Marine minerals developments in deep ocean environments, based upon existing concepts for development of metalliferous oxides (USDOC, NOAA 1981; USDOI, MMS and HI, DBED 1990), sulfides (USDOI, MMS 1983b), and Red Sea muds (Mustaffi and Amann 1978; Gideiri 1984), are not expected to produce significant air pollution.

Air emissions expected in these operations are limited chiefly to the exhausts from various marine engines (mostly diesels) which power the mining ships and ore-handling equipment. These discharges would be insignificant compared to emissions from normal marine shipping or commercial jet aircraft. Because deep ocean air basins are generally open systems with major and persistent winds, chronic local and adverse air quality effects are not expected. Unless some future marine mining concept requires large-scale, on-site metallurgical processing of ore using a system with massive air emissions, it is unlikely that deep seabed mining will cause significant effects on air quality.

2.3.1.2 Oceanic Environment

The same remoteness and open circulation which maintain generally high air quality in deep ocean air masses also result in generally high water quality. Suspended sediment and trace metal concentrations of these waters generally meet or exceed the most stringent drinking-water standards (USDOC 1981). Most of the existing deep seabed mining concepts depend upon seawater as a vehicle to lift and transfer ore through hydraulic lifting and slurry pumping (see **Section 2.2.3.2**). These systems usually require some form of overflow discharge. Also, the necessary interactions between ore collectors and the seabed have the potential, particularly where the ambient surface deposits are unconsolidated and fine-grained, to produce substantial clouds of suspended sediments in benthic waters. In the clearer oceanic waters beyond the continental shelf, reductions of light levels from mining discharge plumes sufficient to measurably reduce rates of photosynthesis may be present for 30 to 50 km downcurrent (Chan and Anderson 1981).

For these reasons, it is likely that the most significant effects caused by such operations to deep ocean water quality will be caused by these disturbances, and a fair amount of attention has been given to their prediction. The following paragraphs describe the key results of this work for each deposit type.

- **Red Sea Muds**

Among all the deep seabed deposit types, mining of Red Sea mud deposits probably has the greatest potential for water quality effects. The deposits are very fine-grained, chemically-reduced (i.e., oxygen-deficient) sulfides of zinc, copper, and silver (Gideiri 1984). Waste streams would contain significant amounts of these materials, as well as reduced lead (60 ppm), cadmium (40 ppm), and elevated levels of chloride, sulfate, and other soluble salts. The reduced nature of the deposit provides a potential, when the minerals are well-oxygenated in acidic solutions, for the generation of relatively soluble, biologically active, and possibly toxic metals. Seawater is well buffered and able to eliminate acids quite effectively, which would naturally offset the production of soluble metals. Laboratory tests using sulfide-ore tailings in seawater suspensions initially exhibited significant elevations in dissolved concentrations of lead, copper, and other metals which gradually decreased after time (USDOI, MMS 1983b). Thus, the potential for bioaccumulation and biomagnification of lead and possibly mercury cannot be discounted. The fine-grained character of the muds could lead to persistent turbidity in a significant area near the discharge point. Given these factors, strong recommendations from studies done to date have included consideration of a benthic discharge for mining waste streams (Mustaffi and Amann 1978; Gideiri 1984). The deposit sites are in heavy brine layers on the seabed which are effectively isolated from the ambient waters and already saturated with components present in the discharge.

- **Massive Sulfides**

Sulfide deposits are similar in composition to the Red Sea muds, but differ in terms of physical character. They are poorly to well consolidated and coarse-grained (i.e., sand-size and larger). Sulfides have the potential to mobilize cadmium, lead, and possibly other toxic metals. However, because of their coarse-grained and consolidated nature, they would generally settle out faster and would expose far less surface area to biological interactions and dissolution. Necessary handling operations, such as excavating, grinding, and lifting, would generate a certain fraction of fine-grained material; however, the ore would probably still be easier to handle and less likely to generate clouds of suspended tailings than Red Sea muds.

Preliminary examination was made by the MMS of water quality effects of mining massive sulfide deposits in the Gorda Ridge, off the coastline of Oregon and northern California (USDOI, MMS 1983b). Researchers concluded that the persistent release of large quantities of dissolved metals and nutrients was unlikely, either from mining or transportation operations.

- **Manganese Crusts**

Because manganese crusts are oxide and not sulfide deposits, the potential for production of soluble and biologically-active metals is much less than the previous two deposit types. Because crusts are completely consolidated and are hosted by similarly consolidated substrates, the potential for generating suspended solids in the water column is considered similar to the massive sulfides. A detailed examination of the water quality effects of crust mining was formulated by the MMS (USDOI, MMS and HI, DBED 1990). This examination touched upon aspects relevant to other deposit types being considered in this analysis, as discussed below.

Trace elements may enter surface waters from bottom waters, interstitial waters, or from equilibria reactions with sediment, substrate, and crust fragments. Trace element introduction into surface waters may occur during recovery, separation, and waste-stream discharge (e.g., in the surface plume). Consistent depth-concentration relationships are generally absent for trace metals in seawater, and bottom waters are similar to surface waters in metals content. Ozretich (1981) reported concentrations of copper and nickel elevated by 20 and 40 times, respectively, in interstitial waters of the Clarion-Clipperton region of the northeastern tropical Pacific which was the site of the Deep Ocean Mining Environmental Study (DOMES). The abyssal plain of the DOMES study area, however, is characterized by very fine silt and clay sediments and a reducing interstitial environment which is not representative of the relatively sediment-free crustal environment atop seamounts. Assuming, however, a maximum potential 40-fold elevation of trace metal concentrations in interstitial waters (i.e., over bottom or surface concentrations), the maximum concentration at discharge, neglecting any chemical reactions, would be as follows: (1) if the lifted volume is 7% solids and the solids contain 80% interstitial water, then 5.6% of the lifted volume would be interstitial water; and (2) assuming that bottom and surface metal concentrations are equal, then the proportionate increase in the discharged water would be approximately a factor of three. The plume model produced for this program shows that these concentrations will be diluted to ambient concentrations within a few meters of the vessel. Effects would be very low.

Bioaccumulation and Biomagnification: Heavy metals are a recognized subject of concern because they are known to be present in manganese crusts. Several heavy metals (e.g., copper, manganese, selenium, and zinc) are biologically essential trace elements; others (e.g., arsenic, chromium, lead, mercury, and thallium) have no known metabolic function. All heavy metals may be toxic if present in excess quantities.

Food web transfer, or biomagnification, of toxic substances, especially organic substances which are selectively concentrated in fatty tissues (i.e., lipophilic substances), was first documented in the 1960s in terrestrial organisms. It was erroneously assumed that the same phenomenon took place in aquatic ecosystems. Subsequent research has shown that metals do not biomagnify in aquatic systems, with the possible exception of organic mercury and a few organic compounds. Because mercury is found only in trace amounts in manganese crusts, biomagnification is not considered a problem.

Unfortunately, the initial error in assuming that processes in aquatic systems are the same as those in terrestrial systems has led to confusion in the public mind as well as in the technical literature. To avoid confusion, the terms "bioaccumulation," "bioconcentration," and "biomagnification," as used in this document, are defined as follows:

Bioconcentration: The process by which toxic substances enter an aquatic organism, by gill or epithelial tissue, from the water.

Bioaccumulation: The uptake of toxic substances by aquatic organisms either by bioconcentration or by direct consumption.

Biomagnification: The process by which tissue concentrations of bioaccumulated toxic substances increase as the material passes up through two or more trophic levels.

As noted above, there are significant differences between aquatic and terrestrial ecosystems which operate such that biomagnification does not occur normally. These differences relate to the fact that aquatic organisms are permeable to the external environment and, because of the relatively low oxygen concentration in water compared to air, must pass large quantities of water across respiratory surfaces. This facilitates the uptake of substances in the water (Isaacs 1975). It should be noted, however, that biomagnification does not necessarily result from such uptake.

Diet is thought to be of minor importance as a source of most contaminants in the aquatic food web (Scura and Theilacker 1977; Macek et al. 1979; Narbonne 1979). The majority of studies on the accumulation of trace contaminants by aquatic organisms deals only with uptake from the external medium. Only a limited number of studies have attempted to determine the uptake via food alone or via food and water combined. Even this latter type of study does not usually attempt to separate and evaluate critically the details of the process.

A comprehensive literature survey conducted by Kay (1984) concluded that biomagnification of heavy metals in marine ecosystems could not be documented with the possible exception of organic mercury. Organisms do bioaccumulate essential trace elements and may also bioaccumulate those with no known biological function. Unless acute toxicity occurs, or Food and Drug Administration criteria for edible fish and shellfish are exceeded, the significance of this bioaccumulation is largely unknown; there are currently no widely accepted methods or evaluation procedures to determine potential chronic effects.

Metal Adsorption: A second concern is the release of metals to the water during mining from fragments of crust. A considerable volume of research has shown that trace metal ions can strongly adsorb to the surfaces of metal oxide particles in reversible equilibria reactions. Exchange of metal ions between discharged crust fragments and surface waters may occur in either direction.

Benjamin and Feely (1981) completed a comprehensive set of experiments using manganese nodule fragments and artificial seawater to determine the release of metals under various conditions of pH, temperature, fragment concentration, and metal-complexing ligand concentration. In the pH and temperature ranges of concern, no metal ion release from nodule fragments could be detected except for very concentrated suspensions of nodule fragments. In those exceptional cases, cadmium and copper concentrations could be elevated by a factor of 10. Although pH is the most important factor in determining the direction of the equilibria reactions, organic ligands may increase or decrease trace metal adsorption. High concentrations of the strong chelating agent ethylenediaminetetraacetic acid (EDTA) increased metal release on about a one-to-one molecular basis. Copper was the preferred metal for EDTA attachment, and other metals were affected only after copper was exhausted. In an independent examination of this problem, Hanson et al. (1982) concluded that some bioaccumulation of metals at the lower trophic levels is possible, however, the risk of biomagnification is very small.

These observations exaggerate potential natural reactions because of the strength of the EDTA as a complexing agent and the concentration of the ligand. It is not known if natural ligands present will show the same affinity for copper as EDTA; if so, there would probably be no release of any other metals because of saturation of available ligands. The possibility exists that the dominant reaction direction would be toward adsorption, and that the crust fragments discharged into the surface plume will scavenge dissolved metal ions. This would almost certainly be the case for cobalt which shows an extremely high affinity for adsorption onto manganese oxides.

As a result of these findings, there could be a localized region near the discharge where cobalt concentrations are depressed from ambient levels. In previous experiments, cobalt was not released into solution at any pH or fragment concentration studied. Researchers noted that, for nodules (inferring that crusts are similar), internal surfaces are near equilibrium with ambient seawater metals concentrations. In the absence of strong chelators, metal ion exchange in either direction will be minimal. The maximum soluble metals concentrations in the surface discharge plume would be within an order of magnitude of ambient concentrations. Subsequent effects would be very low.

Suspended Particulate Matter and Light Attenuation: Suspended particles may result from a series of activities, including (1) resuspension of bottom sediments, or suspension of fragments of crust and substrate caused by passage of the tracked miner along the bottom; (2) actions of fragmentors, crushers, or screens prior to collection; (3) bottom settler overflow; (4) lift system dumping; and (5) abrasion in the lift and surface systems. A major difference between the manganese crust and manganese nodule mining scenarios is that crust deposits are nearly void of sedimentary overburden. In either scenario, only the surface discharge has the potential to increase light attenuation. Other discharges are below the photic zone. The discharge model employed by Noda & Associates and Koh (1985) predicted that concentrations at the end of the jet phase (i.e., 6.4 min, 155.9 m downstream) would be 0.14, 0.74, and 0.025 ppm by volume for the largest to smallest particle classes. With a 2 cm overburden, concentrations would be 0.23, 10.5, and 9.8 ppm by volume.

Lavelle and Ozturgut (1981) developed a theoretical model for the behavior of particles in the surface plume resulting from nodule test mining and extrapolated their results to commercial scale mining. Their results indicated that sea surface concentrations of particles will rapidly diminish over the first several hours following discharge. For particles with relatively large settling velocities (e.g., 1 cm/s), concentrations will be reduced one order of magnitude within 5 h and four orders of magnitude within the first 50 h following release. At the lowest settling velocity modeled (i.e., 0.001 cm/s), reduction in concentration occurs more slowly. For example, concentrations after 100 h vary from 3 to 7% of the initial value, depending on the effectiveness of the pycnocline in retarding vertical diffusivity. For commercial scale mining, the model predicts that surface concentrations would be about 1 μg/L at 70 km downstream. This would be superimposed on ambient suspended particulate matter (SPM) values of 30 to 50 μg/L.

In a worst case scenario where crust mining results in a surface discharge, the collapse portion of the plume ends at a distance of 2,428 m after an elapsed time of about

2 h. The fine particles would, in theory, remain in the water column from 2.5 to 49 years. This, however, neglects the actions of flocculation, coagulation, and biological activity (e.g., ingestion, pelletization, etc.) which would be significant in reducing the concentration of fine particles in the water column. The examination of how these poorly understood processes concentrate fine particles will be an important part of monitoring experiments with test mining operations. During the monitoring of test manganese nodule mining operations in the northeastern tropical Pacific, academic and government observers measured the fluxes of fine particles from mining ships. Using high resolution field mapping of the resulting sediment plume, researchers noted that the fine particles disappeared much faster than their modeling of the dispersion process predicted (USDOC, NOAA 1981).

Light attenuation through the water column is dependent on the concentration of suspended particles and other water column components. The conclusions of Lavelle and Ozturgut (1981) were that phytoplankton in the nodule mining surface plume are exposed to reduced light at distances of 80 to 100 km downstream of the vessel. The 50% light level returns to ambient levels at about 40 km from the vessel. Assuming an advection velocity of 25 cm/s, restoration of half light for an individual plankter was calculated to require no more than 40 h, and restoration of full light would occur within 80 to 100 h.

Light attenuation is also important to the aesthetic effect of the mining plume. Because the normal discharge is predicted to have less than 10% of the solids discharge rate of the manganese nodule mining operation, there would be no means of detecting (instrumentally) a plume, at its center, more than a few kilometers from the mining vessel. The plume would be visible at some fraction of this distance. The visible effect could be removed by a relatively shallow subsurface discharge (a few tens of meters). However, this may not be the environmentally preferred method, because the processes of particle flocculation, coagulation, and biological pelletization are generally far more efficient in surface waters than in deeper waters (e.g,. Hunt 1980; Morgan and Lovorn 1985). Thus, only a few tens of km^2 could, at worst, be made visibly turbid and the expected effect to water clarity in the general area would be very low.

- **Manganese Nodules**

In terms of their potential effects on water quality, the most important differences between mining of crusts and nodules include the difference in substrate (rock vs. mud), postulated magnitudes of the operations, and general habitat (seamount flanks vs. deep ocean basins). Potential environmental effects attributable to the last of these factors (i.e., general habitat) are discussed in **Section 2.3.1.4**. The other two differences are discussed below.

Anticipated differences in magnitude between a crust mining operation and a nodule mining operation are summarized in **Table 2.15**. The assumed production rates are 3 million mt/year for nodules and 1 million mt for crusts, based upon the relative current worldwide consumption rates for nickel and cobalt. As demonstrated in this table, the spatial density of crusts is expected to be considerably higher than nodules, while the needed production would be much lower. Thus, given the assumptions of these scenarios, a commercial nodule mining operation would have to mine more than 40 times the area per

Parameter	Units	Resource	
		Nodules	Crust
Resource Density	wet kg/m^2	10	72
Recovery Rate	dry t/day	10,000	3,398
Operating Days	#/year	300	206
Area Mined	km^2/year	1,260	28.4
Suspended Benthic Sediments	dry t/day	106,000	2,400
Surface Plume Water	m^3/day	50,000	15,569
Surface Plume Sediment	dry t/day	2,000	34
Surface Plume Ore	dry t/day	500	85

Table 2.15. Postulated system characteristics of nodule mining compared to crust mining (Adapted from: U.S. Department of the Interior, Minerals Management Service and State of Hawaii, Department of Business and Economic Development 1990).

year than a crust mining operation to maintain production. Similar differences between the predicted benthic and surface water discharges exist. In considering these predicted effects, NOAA researchers who completed the impact analysis concluded that these activities would only affect an insignificant portion of the region and were not likely to result in significant effects on water quality (USDOC, NOAA 1981). They did maintain, however, that a number of aspects of the problem were not sufficiently well defined to permit confident prediction. These included (1) the potential for accumulation of surface discharged particles at the major interface zone between waters of different densities (i.e., pycnocline); and (2) possible interactions between discharged solids and surface planktonic and benthic populations, as discussed in **Section 2.3.1.4**.

2.3.1.3 Geological Environment

The geological environment includes the seabeds of abyssal seas, deep ocean trenches, back arc basins, active spreading ridges, seamounts, and volcanic island slopes. Effects on the seabed attributed to marine mining include alteration of bathymetry, change of habitat, and removal or deposition of material.

The four types of deep seabed mining considered in this analysis would operate in markedly different geological settings and must be considered separately. With the possible exception of the mining of Red Sea muds, postulated activities would be expected to affect only very small percentages of the particular habitats in question. Nevertheless, the poor state of knowledge which currently exists with regard to these deep seabed settings does not support confident predictions for any of these potential mining activities. The general features of the geological settings are described below for each resource type, along with preliminary estimates of how commercial recovery operations could conceivably affect them.

- **Red Sea Muds**

The Red Sea constitutes a unique environment, with a highly diversified, rich, and varying fauna and flora at the reef-covered coasts, and delicately organized pelagic life and benthos in deep graben waters (Mustaffi and Amann 1978). The metalliferous muds of the region were discovered in 1963 by the research vessel *R/V Atlantis II*, operated by Woods Hole Oceanographic Institution (WHOI). These muds exist in isolated deep seabed holes, occasionally beneath a layer of hot brine; their origin is believed to be related to volcanic activity and consequent hydrothermal circulation which accompanies the active seafloor spreading taking place along this juncture between the African and Arabian continental shields. Approximately 18 such isolated benthic holes have been found along the axis of this spreading center. Only one, appropriately named the Atlantis II Deep, has been considered for exploitation. The ore exists in layers approximately 10 to 30 m thick in water depths between 2,100 and 2,200 m.

Removal of these deposits would result in some changes in the bottom topography of the Atlantis II Deep. Because this basin seems to be effectively isolated from other water masses, however, it is unlikely that this change could have any subsequent effects on surrounding habitats. As discussed below, because of the high temperatures and salinities characteristic of these grabens, no life is expected to be found at the deposit site itself.

- **Massive Sulfides**

The Gorda Ridge deposits examined to date are all surficial mounds of sulfide minerals occurring either on hard substrates or in sedimentary deposits. The geometry and settings of other deposits can be expected to be highly variable, based upon the variety of land-based deposits found to date (e.g., Anderson and Nash 1972; Constantinou and Govett 1973; Hutchinson 1973; Sillitoe 1980). Because of the still rudimentary knowledge concerning these marine deposits, it is not possible to generally characterize the geological settings which are most likely to contain commercial deposits. It does appear, however, that significant occurrences will be found along the flanks of the spreading centers and within back-arc and fore-arc basins.

- **Manganese Crusts**

Manganese crust deposits are currently believed to have been formed primarily (though not exclusively) through precipitation of metal oxides directly from seawater; thus they are termed "hydrogenetic" deposits (Bonatti et al. 1972). This formation mechanism is very slow but fairly continuous, resulting in just a few millimeters of crust per million years (Halbach et al. 1983). Certain metals in these deposits (e.g., cobalt, copper, manganese) are also believed to precipitate preferentially from seawater, which has relatively low concentrations of dissolved oxygen (Halbach et al. 1983; Aplin and Cronan 1985; Chave et al. 1986). In general, the oxygen concentrations of open ocean waters are depressed at mid-depths. The concept of "permissive depth," used for resource assessment purposes for the MMS/State of Hawaii assessment work (USDOI, MMS and HI, DBED 1990), was based upon the observation that thick, cobalt-rich deposits have been discovered most frequently between the 800 to 2,400 m depth range (Clark et al. 1984). Data collected by Wiltshire and Morgan (1986) confirm this observation and are also consistent with the proposed relationship to oxygen concentration.

However, as pointed out by Manheim (1986), deposits in French Polynesia, the Marshall Islands, and the western Hawaiian Archipelago have shown the same general relationship with depth. The oxygen minimum zone in these areas, however, is poorly developed compared to the minimum zone in the equatorial productivity belt.

Crust deposits occur on virtually any seafloor surface but are most common on hard substrates such as rocks and consolidated sediments. At a number of sites, crusts are interlayered with marine phosphate deposits which may themselves comprise a potentially exploitable resource (Burnett 1986; Burnett et al. 1987).

In summary, the thickness of crust deposits appears to be directly proportional to the age of the deposit. The cobalt concentration and deposit thickness appear to be inversely proportional to the water depth of the deposit and may be related to the oxygen minimum zone. However, more work must be done to test the validity of the proposed relationship with the oxygen minimum zone.

Removal of crusts in commercial operations is not expected to significantly modify the topographic features of the mine site. Removal of 10 to 20 cm of surface deposits would not, in general, be noticeable in areas of very high relief. However, such mining could change the habitat significantly and might have some effects on recolonization processes of benthic fauna (see **Section 2.3.1.4**).

- **Manganese Nodules**

As described previously in **Section 2.1.4**, both crusts and nodules are currently believed to grow as precipitates from pore-water solutions and colloidal suspensions within host sediments and from seawater itself. Deep seabed manganese nodules are derived from both of these sources, usually with the pore-waters providing the majority of the material. In contrast, manganese crust deposits appear to be composed almost entirely of material derived directly from seawater.

Growth rates for the deposits vary between less than 1 mm/My to more than 20 mm/My. Crusts appear to grow at the lower bound of this range, several times more slowly than the nodules. This implies that thicker crusts contain some record of the deep sea chemical environment for perhaps 80 to 100 My, almost as old as most of the existing seamounts. Manganese nodules can be expected to provide information about deep seabed basin environments for the last 8 to 10 My. It has been stated that on a global basis, the metals in the nodules are being concentrated at a rate greater than their current consumption, and are therefore a renewable resource. This is an erroneous assumption when applied to individual deposits. Whether considering manganese crusts or nodules, removal of the minerals should be considered permanent. An assessment of biological effects caused by this removal is provided in **Section 2.3.1.4**. Possible effects caused by topographic modification would be insignificant.

2.3.1.4 Biological Environment

- **Birds**

With the exception of the Red Sea deposits, all deep seabed mineral resources considered in this analysis occur in the open ocean, generally several hundreds to thousands of miles from land. No site-specific information concerning potential effects of marine mining on birds or marine mammals which frequent the central Red Sea is available. Given the serious concerns about surface discharges at Red Sea sites (see **Section 2.3.1.2**), it is unlikely that significant surface plumes will be allowed. Possible interactions with birds would be limited to the presence and operation of mining and transport vessels.

Of primary concern in open ocean regions are the wide-ranging seabird species, including the albatrosses and terns, among others. Seabirds feed at various distances from land, ranging from inshore (e.g., for several terns and noddies) to far offshore (e.g., for albatrosses and sooty terns). The Laysan albatross, for example, has been reported to fly over 483 km/d (Fefer et al. 1984). Most seabirds feed from within the upper 0.5 m of the water column on prey of appropriate size. Prey size for terns and shearwaters ranges from 2 to 8 cm, while boobies prefer prey in the 10 to 20 cm range

(Harrison and Hida 1984). Common prey animals include flying fish, squids, opelu, goatfish, several mesopelagic fish species, and crustaceans. A limited number of species utilize minute prey in the surface neuston layer.

Direct effects of marine mining may result from the presence of a surface discharge. In the surface plume, near-vessel turbidity will be increased and prey detection by seabirds consequently inhibited. Because of vertical discharge momentum, rapid dilution, and particle settling, significantly decreased transparency of the upper 0.5 m of the water is expected to be restricted to a very small area near the mining vessel.

Indirect effects on bird species are of greater concern. Adverse effects may be realized through several mechanisms, including introduction of exotic predators, insects, or vegetation, and human disturbance of breeding colonies. In addition, for seabirds, there exists the possibility of bioaccumulation or biomagnification of heavy metals, particularly for sulfide-mining discharges. However, potential toxic effects on seabirds may be mitigated by natural physiological mechanisms of metals detoxification (Stoneburner and Harrison 1981).

Hydrocarbons may enter the environment by spillage, shipwreck, or bilge discharge. Oil slicks may attract fish which in turn attract birds. Oil on seabird feathers can adversely affect insulation and buoyancy properties, with possibly fatal consequences. Ingestion of petroleum products may cause physiological or behavioral changes, including reproductive failure and mortality. Quantities of oil likely to enter surface waters from operations of a mining vessel, however, are small.

- **Marine Mammals**

The following discussion is limited to open ocean deposits due to the inadequacy of data for the Red Sea and the incomplete definition of a mining operation for these deposits. Direct effects of open ocean marine mining on marine mammals will result from increased vessel traffic (Norris and Reeves 1978), and from any surface discharges generated by the operation. The expected increase in vessel traffic encompasses a miner vessel and a few transport vessels.

Noise will be generated by mining and surface activities. Underwater noise may temporarily affect marine animals (Wenz 1962; Malme et al. 1986a,b). Acoustic transmissions and/or reception can adversely affect hearing ability and reproductive potential or, in extreme cases, the survival of an affected population or species. Ambient noise in the ocean exhibits considerable spatial and temporal variation, being generally higher in coastal waters. Wind conditions, sea state, and, very importantly, rainfall affect ambient underwater noise levels. When sea states are relatively low, traffic or industrial types of noise such as would be generated in the mining operation could be a major localized component of the ambient noise. These noises are generally in the 10 to 1,000 Hz frequency range. Above 1,000 Hz, rain noise is the most important source (Myrberg 1978).

In general, marine mammals' range of peak noise sensitivity correlates well with their own signal frequency characteristics; on occasion, this peak noise sensitivity correlates with that of their prey. For example, the echolocation clicks of some marine mammals are brief, high-frequency, high-energy pulses. These mammals are also highly sensitive to a wide range of high frequency sounds. Phocids (e.g., the Hawaiian monk seal) must have good hearing on land as well as in water. Development of the high frequency recognition capability is not as developed as in non-amphibious species. Phocids may, however, also use "pseudo-hearing" to receive ultrasonic frequencies by bone conduction. The most important sound frequencies for pinnipeds are in the range of 500 Hz to 30 to 45 kHz; frequencies ranging from 3 kHz to 120 to 145 kHz are prevalent for odontocetes (Myrberg 1978). It is likely that most species which rely on acoustic reception perform some amount of signal processing to receive biologically important signals even at low amplitude. These perceptions are aided by the spectral composition of the signal, its relative stability, and redundancy.

Experiments on the harbor seal indicated that signal detection is dependent on background noise, but is probably limited to about 1,000 m (Myrberg 1978). Industrial noises, being of low frequency, have little affect on this seal, particularly compared to its loss in sensitivity during periods of rain. Results of experiments with the bottlenose dolphin showed that these animals vary the intensity of their signal according to ambient interfering noise. Because of this adaptability, the high frequency bias, and the effects of distance, masking of dolphin acoustic reception by miner or transport vessels would not be a significant adverse effect.

- **Plankton and Fish**

Red Sea Deposits: Direct effects of marine mining operations have been analyzed by Gideiri (1984), including an expected effect from the discharge of tailings. In the immediate vicinity of the discharge plume, neuston and small phytoplankton species could become the centers of flocculating solids, and thus destroyed. Larger zooplankton would not commonly be affected in this way, but would have to utilize extra energy through ingestion of particles with no nutritive value. Primary productivity would also be suppressed due to the localized turbidity. These potential effects could be greatly alleviated by a discharge below the photic zone (e.g., greater than a few hundred meters water depth). However, they could not be completely eliminated, due to common daily migrations of many plankton species to and from greater depths.

It should be noted that Red Sea populations, including fish, are well adapted to large, unpredictable fluctuations in water column particulates. Because of the surrounding deserts, sand storms commonly provide large inputs of sediments. Man-induced inputs would be relatively very small. However, because discharges would consist of fine-grained sulfides instead of relatively inert silicate sands, potential effects should be determined.

Open Water Deposits: Open water neuston and plankton species would be affected in the same way as Red Sea species. It is suggested that open water species would not be as quickly adaptable because these populations are not normally subject to significant turbidity. In the various EISs prepared for manganese nodule mining (USDOC, NOAA 1981), the mining of marine sulfides from the Gorda Ridge (USDOI, MMS 1983b), and the mining of manganese crusts (USDOI, MMS and HI, DBED 1990), the effects to these populations have been predicted to be very low.

Oceanic species, including bigeye tuna and striped marlin, are less tolerant of increased turbidity than many nearshore fishes. Feeding is visual in tunas (Magnuson 1963) and they are usually caught in clear waters, rarely in turbid waters, presumably because of better perception of food in clear waters (Bane 1961).

The only study of tuna behavior in turbid waters was conducted by Barry (1978), who observed the reaction of captive yellowfin tuna and kawakawa to a turbidity cloud of suspended deep sea mud. No ill effects were observed as a result of short-term exposure to turbidities ranging from about 9 to 59 mg/L. Although the tunas were sometimes observed to avoid the turbid cloud, they readily passed through it as the cloud circled the tank. Maximum turbidities (at the point where tunas passed through the cloud) ranged from 2.7 to 4.7 mg/L for yellowfin tuna and 2.28 to 6.8 mg/L for kawakawa. Feeding occurred in turbidities to 11.2 mg/L, although the test tunas sometimes stopped feeding in turbid water. Barry (1978) indicated that it would be difficult to extend these findings to tunas in the wild because (1) captive tunas may have developed a higher tolerance to pre-experimental turbidity in the tank; and (2) the ability of tunas to detect turbidity clouds in the wild might differ from that of captive tunas. Based on similarities in feeding habits, open ocean habitat, and migratory behavior, billfishes should be similarly affected by turbidity.

Although tunas and billfishes have the capability to swim through and out of plume waters and to feed in plume waters above seamount mining sites, they may have greater difficulty locating prey in turbid waters. Similarly, a tuna or billfish searching for food in a very turbid layer might not find the bait on a longline (Ozturgut et al. 1978). Bigeye tuna, striped marlin, and other relatively mobile, adult epipelagic species would move away from the subsurface turbidity layers, either upward or horizontally with little or no mortality (Ozturgut et al. 1978).

Pelagic fish larvae are concentrated in the surface layers of the ocean and are most likely to be affected by shipboard de-watering operations, the latter of which release cold, bottom waters and suspended solids at the surface. Of the various changes which may occur to the near-surface environment as a result of shipboard operations, increased turbidity in surface water and the discharge of cold bottom water at the surface are considered most likely to affect eggs and larvae.

Matsumoto (1984) examined the potential effects of deep sea bed mining discharges on the larvae of tunas and billfishes. Using small-scale test mining results, projections to full-scale mining effects were attempted using available information. Beyond the efforts of Matsumoto (1984), there have been very few studies of the effects of suspended solids and turbidity on larvae of tunas and billfishes. There is some evidence that the normal development of embryos, larvae, and postlarvae of pelagic fishes inhabiting the surface layers of ocean could be affected by mining-related sedimentation, loss of illumination due to turbidity, and changes in the properties of water, such as temperature (Matsumoto 1984). Reduced illumination caused by turbidity has been reported to affect feeding by reducing reactive distance and feeding efficiency of fish larvae. These effects have been overcome by some species which increase their swimming speed and area of search for prey. Because of the exceptionally large eyes and mouth and the rapid development of the fins in larvae of tunas and billfishes, it is expected that these larvae could compensate for reduced illumination better than most fish larvae. Fish larvae in the wild may be able to avoid turbid waters. Miller (1974) surveyed larval fish densities in waters off sugar mills, sewage outfalls, oil refineries, thermal outfalls, urban discharges, and in harbors in Hawaii. Data indicated that species density and abundance were reduced by 75% and 55%, respectively, for fish larvae in turbid waters. Turbidity, whether natural or man-made, was negatively correlated with larval fish abundance.

Direct effects of suspended solids on the early developmental stages of fishes (e.g., via blocked food intake, clogged gills) generally occurs at much higher turbidities and after much longer exposures than anticipated for the mining-related turbidity plume. The combined effects of low concentration and rapid dissipation of particulates in test mining and the extremely rapid development of the eggs and larvae of tunas (i.e., hatching within ~24 h following fertilization) are expected to reduce the risk of prolonged exposure. Limited exposure consequently should prevent ill effects during the critical early life stages. Matsumoto (1984) concluded that increased turbidity resulting from shipboard discharge would not affect the survival of these larvae.

Supersaturation of atmospheric gases in receiving waters could be a problem if fish are exposed for any length of time. In discharges from an airlift mining operation, supersaturation lasted only minutes due to rapid dilution; exposure of fish to supersaturated gases is not expected to be a concern (Ozretich 1981).

Bottom water is much colder than surface water. There is reason to believe that eggs and larvae coming into direct contact with the cold discharge water could be affected adversely. Because of rapid dissipation of the cold water soon after initial mixing, such effects would be limited to the area within 5 m of the outfall. Contact of surface-drifting larvae with cold water could (1) cause the cessation of embryonic development; (2) cause the development of deformed larvae; (3) result in thermal shock to the larvae, causing them to lose equilibrium or become easy targets to predators; or (4) result in death (Matsumoto 1984).

- **Benthos**

Animals and organisms living on the seabed (*epifauna*) or in the seabed (*infauna*) are termed benthos. They are frequently referred to in the literature as mine site species. The types of benthic life occupying potential mine sites are very different for different deposit types. Similarly, predicted effects would be very different between deposit types, as discussed in the following pages.

Red Sea Muds: No accurate assessment or characterization of the benthic life associated with Red Sea muds is available. Because of the high salinities, low oxygen and nutrient levels, and high temperatures (e.g., as high as 60° C), benthic life forms are limited but unusual (Fletcher and Mustaffi 1980). Assuming a benthic discharge of all mine tailings, about 2 to 4% of all benthic life in the Atlantis II Deep would probably be destroyed by resuspended sediments (Gideiri 1984). Significant research would have to be completed before reasonable predictions could be made.

Massive Sulfides: Since the discovery of sulfide-based ecosystems at active hydrothermal vents (Corliss et al. 1979), extensive research has been carried out to explore the occurrence, ecology, and biochemistry of these populations at many deep seabed vent sites (e.g., Rona et al. 1986; Laubier 1987; Prince et al. 1988; Kim et al. 1989; Danaher and Stein 1990; Javor et al. 1990; Kim and Sakai 1991). These hydrothermal communities consist of abundant and previously unknown species of clams, mussels, vestimentiferan worms, and other smaller organisms. The primary chemical energy which supports these communities comes from the oxidation of the suspended sulfides emitted by the vent systems, making these communities the only ones known which do not depend ultimately on solar energy for their maintenance and survival.

Current research in this area has potentially exciting implications, particularly in regards to questions about the evolution of life and our understanding of basic biochemical pathways. Research to date indicates that these ecosystems are by no means unique, but rather seem to prosper with amazing variety in deep seabed hydrothermal systems worldwide. Preliminary assessments of potential environmental effects on vent communities pointed out their uniqueness (USDOI, MMS 1983b; Caughill 1987) and the need for research, which is currently underway. The concern for research is still valid, but must be put in perspective because vent communities have been found in active hydrothermal systems in virtually every ocean.

Predictions of the effects attributable to sulfide mining are greatly limited by a lack of definition of specific deposit settings and methods of recovery. In the preliminary assessment which discussed the effects of mining within Gorda Ridge deposits (USDOI, MMS 1983b), six types of potential effects were examined resulting from (1) preliminary sampling of the deposits; (2) release of toxic metals; (3) increased turbidity; (4) increased sedimentation; (5) direct effects of the ore collector system; and (6) potential use of explosives to fracture consolidated deposits. The analysis concluded that a major fraction of the vent communities would be destroyed by mining operations nearby, but that there would not likely be any significant effects on pelagic or other benthic populations. The study recommended that mining operations be confined to areas which are not too near active vents and the associated vent communities.

Manganese crusts: A preliminary analysis of the potential effects of seabed mining on seamount benthic communities was recently completed by the USDOI, MMS and HI, DBED (1990). Results from this analysis of benthic community composition and predicted effects are summarized in the following text.

<u>Benthic Microfauna</u>: Most of the organisms encrusting manganese crusts are relatively small (i.e., less than 5 mm in maximum dimension) and cannot be identified in bottom photographs. Electron micrographs of dredged crust samples reveal mostly foraminifers and a few small metazoans. The organisms are mostly sessile. Feeding strategies include (1) obligate suspension feeding; (2) active deposit and/or suspension feeding; and (3) passive deposit or dissolved organic matter (DOM) feeding. Fourteen of

20 reported protozoan taxa (70%) have been collected elsewhere on manganese concretions in the North Pacific, while three protozoan taxa have also been reported from the North Atlantic. Of the 12 metazoan taxa, however, only three (25%) have been reported from other manganese substrates (Mullineaux 1985).

Benthic Macrofauna: From July through September 1984, the Hawaii Institute of Geophysics (University of Hawaii) conducted cruises in support of the resource investigation of selected seamounts in Hawaii's EEZ. Baseline qualitative biological data were collected from sites which ranged in depth from 400 to 2,700 m (AECOS, Inc. 1986). Data were collected from direct observations of seabirds and marine mammals, bottom dredge-hauls, and bottom photographs. Results of dredge-haul sampling indicated that community diversity and abundance was dominated by arborescent coelenterates, primarily octocorals. The next most significant group, in terms of number of taxa, number of specimens, and biomass, was the echinoderms. Other groups collected were much less commonly encountered and less diverse than gorgonians and echinoderms.

Photographic survey results were dominated, in order of decreasing abundance, by Echinodermata, Coelenterata, Porifera, Chordata, Arthropoda, and Mollusca. Among the echinoderms were representatives of all five living classes, with the ophiuroids (i.e., brittle stars) being most numerous in this predominantly soft bottom environment. Regular echinoids (i.e., sea urchins) were next most abundant. Less common classes included crinoids (i.e., sea feathers), holothurians (i.e., sea cucumbers), and asteroids (i.e., sea stars). Scattered large rocks harbored the crinoids, coelenterates (e.g., sea pens, sea anemones), and sponges. Chordata and Mollusca were represented by bathypelagic fishes and octopods, respectively.

As part of the USDOI, MMS and HI, DBED (1990) program, Cross Seamount was selected as a representative area for biological and geological reconnaissance. Located about 161 km south of Oahu, HI (lat. 18°40'N, long. 158°17'W), the seamount was characterized by biotic depth zones.

The density of organisms in the upper depth interval (i.e., 300 to 400 m) was examined photographically. Mean epifaunal density was about 0.79 organism/m^2, approximately three times higher than that encountered in the second interval (i.e., 400 to 500 m). The most significant components of the fauna in the 300- to 400-m depth range were gorgonian corals and solitary anemones, followed (in relative abundance) by bamboo corals and zoanthids. All of these organisms are suspension feeders which consist of a sessile polyp with a tentacle-ringed mouth.

The density of organisms observed in the 400- to 500-m depth interval was about 0.25/m^2, or about one organism per 4 m^2 of ocean bottom. In these depths, solitary anemones were clearly the most abundant organisms, while gorgonians and bamboo corals exhibited reduced abundances as compared to the upper depth interval. Primnoid gorgonians, specifically, accounted for about 4.4% of the organisms within this depth range.

From 500 to 600 m, total organism density declined markedly to about 0.13 organism/m^2, or one organism per 8 m^2. Primnoids were clearly dominant, and other gorgonians were the second most abundant organisms encountered.

In the 600- to 700-m depth range, the density of organisms declined further to $0.035/m^2$, or about one organism per 28.6 m^2. In this range, grenadier fish were most abundant, followed by eels and unidentified fish. The most common sessile organisms were solitary anemones, feather stars, and sponges.

Below 700 m, there seemed to be an increase in faunal density, peaking at about 850 m with a possible secondary peak near 1,250 m.

In 700 to 800 m water depths, feather stars and ophiuroids were most abundant, while in the 800 to 900 m depth range, ophiuroids were most abundant, followed by gorgonians, primnoids, and feather stars. These same organisms shared numerical dominance in 900- to 1,000-m water depths. Organisms were rarely observed below 1,000 m. The small peak evident between 1,200 and 1,300 m was attributed primarily to gorgonians, and secondarily to shrimp.

Observed fauna were overwhelmingly composed of various types of sessile, epibiotic suspension feeders. In terms of study limitations, estimates of infaunal organisms cannot be determined using the photographic technique. Further, highly mobile organisms may be underestimated in the data due to their avoidance of the camera.

In terms of the physiological requirements of deep sea fauna, studies at WHOI (Anon. 1973) on biological oxygen demand showed that deep seabed animals require two orders of magnitude less oxygen than those living in shallow water.

Predicted Effects from Crust Mining: Effects of crust mining activities on bottom communities may result from (1) passage of the miner over the bottom; (2) the generation of a bottom plume and associated resedimentation; (3) the generation of a plume from an emergency dump and associated resedimentation; and (4) resedimentation and indirect effects from the surface plume. The expected results of these activities are described as follows.

Organisms living on or near the deep ocean floor are adapted to an environment of low SPM concentration. Mining-related bottom disturbances will create a plume of SPM which will settle back to the bottom under the influence of several factors. Factors which affect the duration of suspension and the area affected by the disturbance (or distance from the disturbance) include (1) initial plume distribution; (2) settling velocities of the suspended particles; (3) vertical eddy diffusivity; and (4) near bottom current vectors.

Based on results of laboratory experiments, observations of pilot-scale ocean mining of manganese nodules, and theoretical modeling conducted in the DOMES Program, Lavelle and Ozturgut (1981) concluded that after 10 h of suspension, all material with settling velocities of 1 cm/s or greater should be redeposited. Further, they noted that most particles within these size classes will be deposited within 20 m of the miner track. For the smaller particle fractions, only about 1% of particles with settling velocities of 0.001 cm/s or less will be redeposited after 100 h. From the test mining data, the authors calculated that about 90% of the resuspended material would be redeposited within 70 m of the miner track; maximum redeposition thickness would be 15.5 mm near the center line of the track.

The crust mining scenario envisions recovery of about two-thirds of the ore volume, as compared to the nodule mining scenario, but the former assumes a much thinner range of overburden. Maximum redeposition thicknesses for the worst case discharge were found to range from 12 to 72.4 mm from the surface discharge, depending on water depth. Peak base case redeposition thickness for a crust miner was 0.032 mm; the estimate from the base case emergency discharge was 0.027 mm. A highly significant difference exists between the two mining scenarios. The largest depositional scenario for crust mining, mining at the most shallow depth, and superimposition of surface and bottom plume footprints, would result in less than 1/150 of the maximum deposition in the nodule mining scenario.

From the DOMES baseline macrofaunal data (i.e., $\bar{x}=168$ individuals/m^2) and a hypothetical nodule mining scenario, Jumars (1981) calculated that passage of the miner would directly destroy 1.06×10^{11} individuals weighing 1×10^{8} g/year. In comparison, data from Cross Seamount indicated that passage of the crust miner over 28.4 km^2/year would directly destroy 1.2×10^{5} and 1.4×10^{4} macrofaunal organisms at 800 and 2,400 m water depths, respectively. The DOMES and Cross Seamount databases differ (i.e., infaunal organisms were not sampled in the Cross Seamount reconnaissance). Nevertheless, from consideration of the relative sizes of the areas to be mined in the two scenarios and the relative lack of infaunal habitat (sedimentary overburden) in crust areas, it can be concluded that the number of macrofaunal organisms to be destroyed annually by miner passage is orders of magnitude less in the crust mining scenario than the nodule mining scenario.

The severity of effects on populations within areas adjacent to the miner track would be determined by the intensity of the disturbance, the proximity of sensitive individuals or communities to the track, and the type of feeding behavior characteristic of the population. Highly motile scavengers such as fish, amphipods, and shrimp would be most able to avoid localized areas of high redeposition and turbidity. Once conditions become minimally tolerable, these organisms would be attracted into the mined area to feed on dead and damaged organisms. After this temporary food supplement was exhausted, however, these organisms would tend to disperse.

According to Jumars (1981), subsurface deposit feeders are potentially the least affected feeding guild. These organisms would be isolated from the direct effects of resedimentation and might also receive a food subsidy in the form of dead and buried organisms. The baseline data from Cross Seamount underestimated densities of subsurface deposit feeders because of the photographic sampling technique used. Nevertheless, prime crust areas are characterized by little sediment overburden, and subsurface deposit feeders would find little available habitat (USDOI, MMS and HI, DBED 1990). Further, the sediment deposition thicknesses modeled for the crust mining scenario are so thin that redeposited, macerated bottom fauna would be available to surface scavengers, with probably little reserved for subsurface feeders. DOMES researchers concluded that the increased amount of organic matter available for bacterial decomposition (and its associated biological oxygen demand) would not significantly alter the dissolved oxygen concentrations at or near the bottom. Consequently, mass mortalities of subsurface populations due to anoxia would not be anticipated. Oxygen depletion would be even less of a concern in the crust mining scenario because of the smaller quantities of organics generated. Because of the small area of the seafloor which will be subjected to increased levels of suspended sediments, effects on bioluminescing organisms are judged to be insignificant.

Surface deposit feeders and suspension feeders are the most likely feeding guilds to be negatively affected by crust mining activity. Both feeding types would be directly affected by the presence of the plume and particle deposition. In both cases, the quality of available food resources would be diluted by the addition of significant quantities of inorganic particles on and above the bottom. Because of the sensitivity of their feeding apparatus to clogging, sessile suspension feeders would be the most severely affected by resuspension and redeposition. These types of organisms, including ophiuroids, gorgonians, primnoids, and feather stars, are overwhelmingly the most abundant in the Cross Seamount baseline data. Burrowing species probably have limited ability to change their subsurface depth because, in this environment, natural sedimentation occurs at the very slow rate (e.g., 1 mm per thousand years). Considering that most of these organisms are less than 0.5 mm in length, burial by even a millimeter or less could be fatal. Burrowing species, not yet identified as a significant component of the Cross Seamount fauna, should not be adversely affected because crust mining resedimentation thicknesses are much less than a millimeter.

The plume fallout model used by Noda & Associates and Koh (1985) predicted maximum redeposition thicknesses on the order of 0.1 mm. The significance of this potential effect depends on several unquantified variables. The plume footprint is extremely dependent on prevailing currents. Plume footprints of very different shape (e.g., long and narrow to essentially circular) were generated by changing the current record input to the model. A second major unknown is the rate at which these organisms can cleanse themselves of settled particles. A third unknown is the significance of physical damage to these organisms by fallout of the larger-sized particles. This may be a function of the shape of individual organisms. A plan view of the base case miner discharge showed a maximum lateral plume extent of about 12 m on either side of the plume center line. At 60 m downstream, the point at which nearly all larger-sized particles have fallen out, the plume width had been reduced to about 10 m on each side of the center line.

Recolonization rates for benthic organisms disturbed by mining activities are not presently known, however, this subject is one being pursued at the University of Hawaii and other institutions (e.g., WHOI). At this time, it is assumed that recolonization rates in deep sea benthos are very slow, possibly decades. Ultimately, recolonization of disturbed areas will occur. Whether a crust substratum would reform is unknown. If not, the long-term nature of the community could be altered to one more representative of hard substrate communities without crusts.

Recent research performed on Cross Seamount (Grigg et al. 1987) indicates that many sessile organisms apparently avoid crust substrates. If subsequent work shows that this is true avoidance and not simply coincidental low abundances due to other factors, then recolonization could be expected to produce higher abundances than were present under pre-mining conditions. If the existing populations are low for some other reason (e.g., low nutrient levels), then recolonization to a state similar to pre-mining conditions would be expected.

Manganese Nodules: The first program to seriously consider the effects of mining manganese nodules in the Clarion-Clipperton region of the northeastern tropical Pacific was the DOMES program. DOMES was a comprehensive, five-year (1975-1980) research program funded by NOAA. The intent of the program was to develop an environmental database to satisfy NEPA requirements to assess the potential environmental effects of manganese nodule recovery operations (USDOC, NOAA 1981). The objectives of the first phase of the program were (1) to establish environmental baselines at three sites chosen as representative of the range of selected environmental parameters likely to be encountered during nodule mining; (2) to develop an initial capability to predict potential environmental effects of nodule mining; and (3) to contribute to the information base available to industry and government for development of appropriate environmental guidelines. The second phase of DOMES consisted of monitoring actual pilot-scale mining simulation tests. Its objectives were (1) to observe actual environmental effects relevant to forecasting effects; and (2) to refine the database for guideline development.

The environmental baseline data collected and the conclusions drawn regarding potential effects of nodule mining in the DOMES area are somewhat applicable and have been applied in varying degrees to the previous analysis of crust mining. However, significant differences exist and must be noted in this type of comparison. For example, baseline benthic biological data collected in the DOMES area are less applicable in the present analysis than are the pelagic data. Further, the depth range of concern for crust mining is 800 to 2,400 m, while bottom stations sampled in the DOMES area varied in depth from 4,350 to 5,150 m. In the deep ocean, depth is more important than horizontal distance in determining faunal abundance, and samples from relatively shallow stations (e.g., near the summit of Cross Seamount) can be expected to have greater faunal abundance than those collected from the abyssal floor. A final important difference, as discussed previously in **Section 2.3.1.2**, is that the benthic substrata in the DOMES area is composed of very fine-grained pelagic clays and radiolarian oozes, while much of the seamount summits covered by crustal deposits is solid or covered by a thin sediment veneer. In the latter areas, the importance of the infaunal community will be reduced as compared to that of the epifaunal community. Epifaunal communities are also somewhat different. Seamount communities are dominated by sessile suspension feeders, reflecting both the increased availability of hard substrata for attachment and possibly more vigorous bottom currents. In the DOMES area, the larger types of benthic fauna (as observed in photographs) were dominated by motile echinoderms and deposit-feeding forms such as holothurians (Morgan et al. in press).

In addition to the biological differences between the two areas, there are significant differences between the two mining scenarios. **Table 2.15** highlights the differences relevant to the impact analyses. In summary, a major difference exists between the predicted benthic sediment discharge plumes. The nodule mining scenario assumes a high quantity of resuspended sediments, more than 20 times the amount of crust and substrate estimated under the crust mining scenario. Solids in the crust benthic plume are diluted by a factor of 200 compared with the nodule scenario.

Another key difference between the DOMES area and seamount areas is the potential for upwelling and eddy currents which exists in waters overlying EEZ crust deposits. Such potential for upwelling and eddy currents does not exist in the DOMES area. This difference may lead to a relative enrichment of biota, including commercial fish, in the waters overlying seamounts as compared to nearby areas.

The DOMES program, as summarized within the Final Programmatic Environmental Impact Statement (FPEIS) (USDOC, NOAA 1981), concluded that effects on benthic biota were not predictable given the very limited knowledge available about benthic life and the poorly defined character of present and future seabed ore collection systems. A strong recommendation was made to pursue basic biological studies of the benthos in the areas which might be mined. Where possible, it was recommended that mining simulations be conducted to monitor the effects of activities which might be analogous to actual mining. These studies, including the NOAA/USSR Benthic Impact Experiment (BIE) using a Deep Sea Sediment Resuspension System (DSSRS) (USDOC, NOAA 1991) and the German Disturbance and Recolonization Experiment (DISCOL) (Thiel et al. 1991), are currently in progress and are rapidly improving the predictive capability in this important area. The following discussion summarizes the most recent results from these ongoing research efforts.

Because the mining system will cover or destroy most of the sessile and slow-moving life in its path, the key to predicting net environmental effects depends upon the rates of recolonization following cessation of mining activity. Recent experiments conducted in the deep northeastern Pacific to address this issue have been conducted by placing artificial mounds of sediment on the seabed, then monitoring and sampling the buried area sequentially from a deep diving submersible (Kukert and Smith in press). The results of this study, based upon data collected over a period of almost two years, support the hypothesis that the benthic biota maintain their high species diversity. Small-scale perturbations (*e.g.*, *carcass falls, pulses of sedimentation*, predation by larger organisms) are common enough to hold populations of competitively dominant species below the carrying capacity of the habitat, allowing many inferior competitors to coexist in any given patch and resulting in high species diversity. It can be inferred from these results that benthic communities will recover from marine mining activities via recolonization unless massive areas of benthos are affected. Subsequent experiments in the DOMES area are presently in progress, and have promise of clarifying the situation further.

Another experimental effort involving simulations of mining disturbance is presently being conducted in a potential mining area of the southeastern tropical Pacific, approximately 927 km west of Peru (Foell et al. 1992a,b). In this experiment, an area of 10.8 km^2 has been disturbed with a simulated collector after the collection of baseline measurements (i.e., pre-disturbance benthic faunal occurrences). The plan is to make repeated assessments of the communities in this area for several years to determine the rates and composition of recolonization. Preliminary DISCOL results indicate that the complexity of the task of impact assessment in the abyssal ocean make broad and sweeping generalizations inappropriate in discussions of the environmental effects of ocean mining on the benthos. Key questions concerning the type and degree of impact and the potential for recovery can only be addressed, in the opinion of the authors, by the monitoring of industrial tests or pilot mining operations conducted at sufficiently large temporal or spatial scales to provide the quantitative information needed for carrying out the required evaluations.

A preliminary environmental assessment of mining impacts to benthic life has also been made for operations in the central Indian Ocean Basin (Sharma and Rao 1991). Results indicate that very similar types of benthic organisms to those in the Clarion-Clipperton region have been found, and very similar estimates of effects are predicted.

With the possible exception of the hydrothermal vent communities, discussed previously, no particularly sensitive habitats have been identified for those deep sea areas with marine mining potential. During the continuing development of regulations pertinent to the international licensing of deep seabed mining in the Clarion-Clipperton region, specific areas known as Provisional Interim Preservational Reference Areas (PIPRAs) have been set aside and precluded from development. These efforts are primarily intended as conservative, preventative measures against currently unknown effects which might be discovered later. The preservation of several large areas will guarantee the survival of existing benthic habitats. It is not truly accurate, however, to classify these preserved areas as particularly sensitive.

- **Threatened and Endangered Species**

No assessment of the potential effects of marine mining on threatened and endangered species is available for waters overlying Red Sea sulfide deposits. For the three open ocean environments, the species of concern include birds, marine mammals, and sea turtles. EISs for these deposit types (USDOC, NOAA 1981; USDOI, MMS 1983b; USDOI, MMS and HI, DBED 1990) all predict that there will be no significant effects.

2.3.1.5 Social and Economic Environments

Two areas of concern in this category have been identified for the deep seabed, including (1) possible effects on commercial fisheries; and (2) indirect effects on the economies and cultures of relatively remote island-based societies. Each topic is considered in the following text.

- **Commercial Fisheries**

No assessment is available for commercial fisheries impacts associated with the mining of Red Sea deposits. For the Gorda Ridge massive sulfide deposits, several fish species (i.e., albacore, salmon, and steelhead) are found in the area and caught by commercial fishermen. For areas containing deep seabed manganese nodules, only various tuna species are commercially fished. The impact analyses for these potential mining ventures predict no significant effects (USDOI, MMS and HI, DBED 1990).

For areas containing manganese crusts, several species of bottom and pelagic fish are commercially fished, and some are known to congregate around seamounts (USDOI, MMS and HI, DBED 1990). Crust mining operations could affect existing and potential commercial fisheries in one or more of the following ways:

(1) Direct destruction of precious coral and deep sea shrimp populations, squid eggs, or their respective habitats by the passage of the miner over the bottom;

(2) Disruption of shrimp, precious coral populations, squid eggs, or their respective habitats near the miner track as a result of (a) resedimentation of solids originating from the separation/rejection of material by the miner, (b) from a failure of the mining system, causing a backflow and discharge of the contents of the lift system, or (c) from deposition of the heavier particles in the surface turbidity plume;

(3) Effects on groundfish or pelagic fish adults or larvae from turbidity plumes generated above the bottom by mining or at the surface from shipboard dewatering operations;

(4) Effects on pelagic fish larvae at the surface from discharge of cold, bottom water during shipboard dewatering operations; and

(5) Possible aggregation of pelagic fishes by the surface mining ship.

The predicted effects of each of these are summarized below with reference to specific species.

Precious Corals: Most species of precious corals found in the EEZ off Hawaii occur at depths of 100 to 400 m (Grigg 1986), depths which are too shallow to be directly disturbed by mining. Two species, however, occur deeper and could be directly affected. The depth range of *Corallium* spp. *nov.*, or Midway deep sea coral, is 900 to 1,500 m, but this species has never been recorded south of 28° N latitude. *Corallium regale*, or garnet coral, is distributed throughout the Hawaiian Archipelago at depths of 500 to 700 m (Grigg 1986); corals within these depths ranges could be affected by mining even though these depths are shallower than the optimal depth range for mining (i.e., 800 to 2,400 m). Populations of *C. regale* directly in the miner track would be destroyed.

Precious corals are known to be sensitive to sedimentation (Grigg 1984). Sediment-free surfaces are required for coral planulae to attach and grow. Operation of the mining device along the bottom will cause resedimentation of material dislodged during mining and discharged by the miner. A second, less likely source of resedimentation could also occur in an emergency. For example, during a power failure, the mined slurry being pumped to the surface through the lift system would be released above the seabed. A third source of resedimentation is the shipboard surface discharge, though this material would be very widely dispersed.

Most of the particles discharged by the miner during normal operations or during an emergency are relatively large and have high settling velocities. Dispersion modeling of the suspended solids suggests that the larger particles would settle out within 60 to 200 m from the miner track. The peak thickness would be 0.03 mm. Smaller particles would be more widely dispersed (Noda & Associates and Koh 1985). Precious coral populations (most probably *C. regale*) and habitats within a 200-m radius of the mining site could be affected by resedimentation. There are no precise estimates of the total amount of seafloor in the Hawaii EEZ which might be suitable for precious coral habitat, but the percentage of available habitat which could be affected by mining is so small as to be almost insignificant. *C. regale*, a species whose commercial value is significantly less than that of other species of pink coral, is likely to be the only precious coral whose habitat is directly affected. Effects on precious corals are expected to be very low.

Deep Sea Shrimp: The most important species of deep sea shrimp (*Heterocarpus laevigatus*) occurs throughout the Hawaiian Island chain at depths (i.e., 450 to 800 m) which could be directly disturbed by seabed mining, although this depth range is outside the optimal range for mining (800 to 2,400 m). It is not known whether shrimp occur at similar depths on the off-axis seamounts considered for leasing, but there is no reason to suspect that they are not present. Any shrimp populations directly in the path of the mining device would be dislocated. Being mobile scavengers, shrimp have a better chance than less motile animals to escape immediate destruction.

Bottom materials suspended or discharged by the miner will be redeposited as a sediment layer which becomes thinner at greater distances from the miner site. Modeling results indicate that the maximum thickness of deposition could be as much as 0.07 mm, unlikely to affect fauna as mobile as deep sea shrimp. Approximately 5,000 km^2 of deep sea shrimp habitat has been charted in the Hawaiian Archipelago (WPRFMC 1984). Mining operations would directly disturb a small fraction of this, certainly no more than 0.5% of the total area during the entire 20-year lease period. Mobile scavengers, like shrimp, that survived the immediate effects of mining and burial could find a new temporary food source in the form of injured and displaced animals near the miner track. Thus, net effects are expected to be very low.

Squid: Although there are conflicting theories of the early life history of oceanic squids in the central North Pacific, one hypothesis is that their eggs are laid on the summits or slopes of seamounts, perhaps as deep as 1,000 m (Uchida 1982). If this hypothesis is correct, any egg masses in the miner track or near enough to be covered by resedimentation would be directly affected. Over a 20-year lease term, about 1% of the ocean bottom within the 800 to 2,400 m depth range in the Hawaii EEZ would be directly affected by mining. If this depth range serves as an important nursery grounds for oceanic squid (this hypothesis remains to be proven) and if no single EEZ seamount or seamount group is more important than the others in providing habitat for squid eggs, the loss of nursery grounds and the expected effect due to mining would be very low when compared to the total seamount habitat. However, if only certain seamounts provide suitable nursery grounds and if these are more greatly affected by mining than others, the damage could be more significant. Without more information about the early life history of oceanic squids, assessment of the level of effect on this resource is speculative.

Seamount Groundfish: The groundfish assemblage associated with central North Pacific seamounts includes a large number of species, only a few of which have commercial value. The most important commercial species are the pelagic armorhead, *Pseudopentaceros wheeleri*, and the alfonsin, *Beryx splendens*. Neither species is known to occur in commercial concentrations at off-axis seamounts. The present fishing grounds are limited to (1) a few on-axis seamounts in the Hawaii EEZ, northwest of Kure Atoll; and (2) seamounts outside the EEZ, in the Emperor Range.

The groundfish species which are present on the summits and slopes of the off-axis seamounts are able to avoid areas being actively mined. Plankton are an important food item for certain species of seamount groundfish (Humphreys et al. 1984). Both the armorhead and the alfonsin are known to make diurnal migrations through the water column related to feeding behavior. This seems to reflect the importance of organisms associated with the deep scattering layer (DSL) in their diets. The DSL changes depth in response to light penetrating through the surface layers of the ocean. Lavelle and Ozturgut (1981) predicted that some light reduction is likely to occur within a radius of 100 km from the mining ship, but that exposure to substantially reduced light levels would be unlikely to last more than 80 to 100 h. Short-term shading is not expected to affect the DSL appreciably, as it would take several days for plankton to adapt to a new light regime (Chan and Anderson 1981).

Vertically migrating, adult mesopelagic species probably could not live permanently above or below the layers and would tend to move away from the areas in which the layers occurred. Their relocation might involve some mortality (Ozturgut et al. 1978). Some kinds of fish larvae occur below the mixed layer and might be affected by the turbid layers (Ozturgut et al. 1978). Based upon this reasoning, it is suggested that the effects of the crust mining on seamount groundfish would be very low.

Pelagic Fishes: Effects of marine mining on pelagic fishes, including all the tunas and several other species, were discussed previously in **Section 2.3.1.4.**

- **Small Island Groups**

The establishment of a marine mining industry in the deep seabed has the potential of affecting island cultures if the islands are used as major staging centers or for metallurgical processing. Social and cultural effects related to the onshore processing activities are discussed in greater detail in **Section 2.3.4.5.** General cultural effects which might accompany the intrusion of modern equipment and foreign personnel into an island community were examined in detail for the Hawaiian Islands (USDOI, MMS and HI, DBED 1990) and are briefly summarized in the following text.

Four particular activities are viewed as having the potential for generating social effects:

(1) Induced population growth -- Available evidence suggests that "boomtown" growth levels would be a theoretical concern only for one small region in Hawaii. Among other Pacific islands, however, induced population growth must be considered a major concern. Until recently, social scientists believed that substantial social disruption generally accompanies such rapid growth, but recent evidence is conflicting.

Proper planning designed to avoid an overload of existing island infrastructure and services could also help to alleviate social disruption;

(2) Coastal location -- In addition to symbolic and value concerns, the location of a proposed processing facility, for example, could interfere with subsistence food gathering. Specific effects cannot be analyzed until a definite site is known;

(3) Industrial activity in rural area -- While the actual effect on lifestyles and values is difficult to assess, the general concept of marine mining is likely to generate considerable controversy. Conflicts may arise between residents concerned with economic survival and those who view a "smokestack" industry as incompatible with their reasons for living in a rural area. Controversy may be particularly keen among the native Hawaiian population in Waianae or Puna; and

(4) Unfamiliar technologies involving hazardous waste -- Research on risk perception suggests there will be substantial apprehension no matter what technical experts may conclude about actual statistical risk.

While some potential mitigations involve matters such as job training or planning residential growth location, other significant effects will occur in the planning stage and must subsequently be handled through public involvement and negotiation.

2.3.2 Continental Shelf

For administrative purposes, the USDOI divides the OCS into four regions (i.e., Atlantic, Gulf of Mexico, Pacific, and Alaska). Each region is further subdivided into a series of individual Planning Areas, as indicated in **Figures 2.41** and **2.42**. Industrial interest to date in the U.S. OCS has been formally expressed by the issuance of 45 geological and geophysical prospecting permits during the period 1966 to 1988. Of this total, 33 were issued for the Alaska region, 7 were issued for the Atlantic, 4 were issued for the Pacific, and a single permit was issued for the Gulf of Mexico (USDOI, MMS 1989a; **Table 2.16**). Minerals of interest included industrial minerals (36 permits), mineral sands (4 permits), phosphorites (3 permits), and metalliferous oxides (2 permits). During the same period, 7 lease offerings were held, of which 6 were for industrial minerals (i.e., salt and sulfur) in the Gulf of Mexico and one was for phosphorites off southern California (**Table 2.17**).

A variety of environmental effects can result from offshore mining operations (**Table 2.18**). In simplistic terms, the presence of a mining facility may result in the release and dispersion of atmospheric plumes carrying fine, chemically-active vapors, particles, and odors. Mining creates bottom disturbances by removal and perturbation of seabed materials. Secondary disturbances are realized through the dispersion of plumes of perturbated, spilt, or discharged material either at the seabed, in the water column, or on the sea surface. Plume material consists of particulate matter which will settle to the bottom and dissolved matter which will be more widely dispersed. Effects from these plumes, which may include changes in water quality, bottom shoaling, and benthic smothering, lead

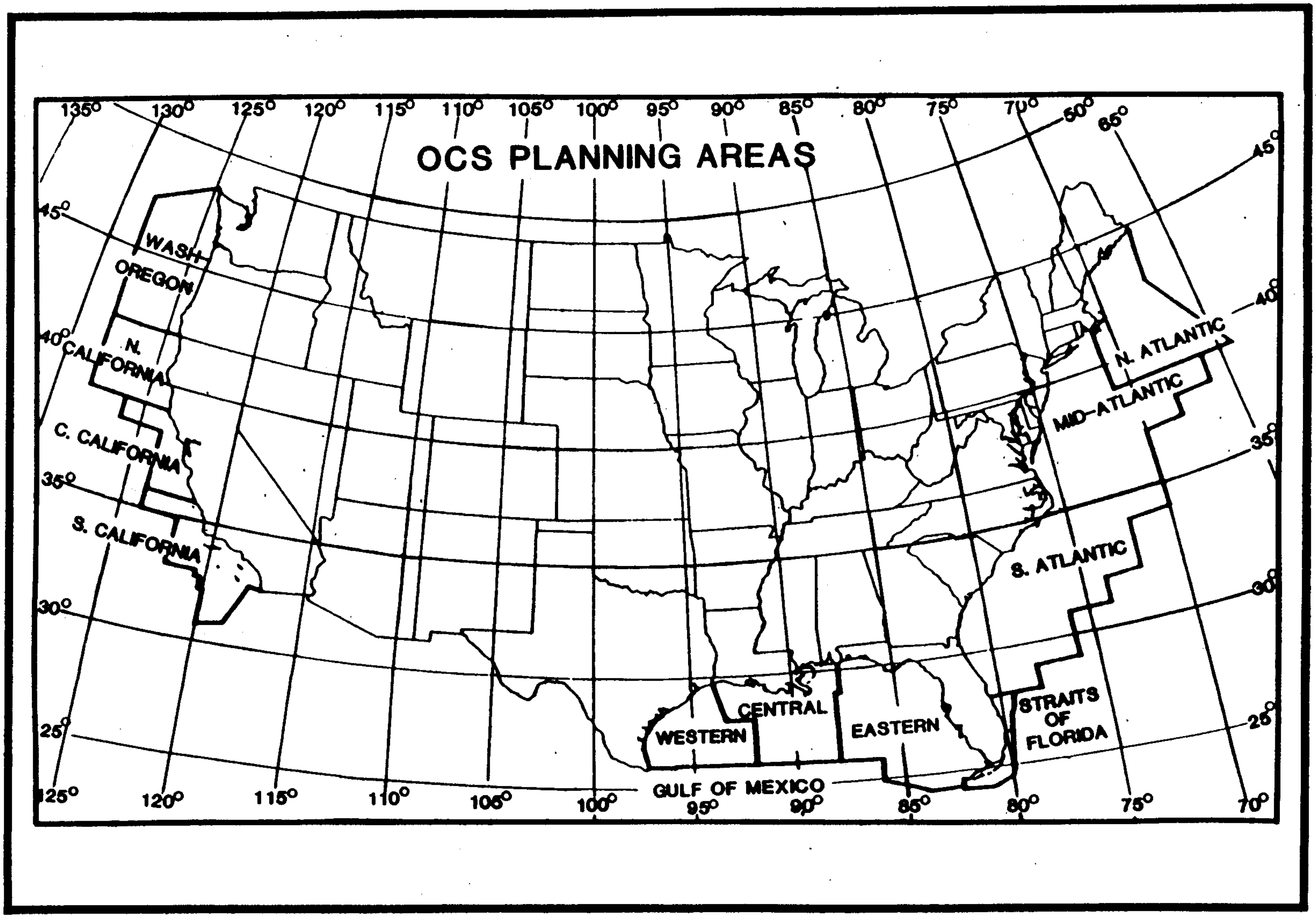


Figure 2.41. Outer continental shelf Planning Areas in the lower 48 states (From: Dellagiarino 1986).

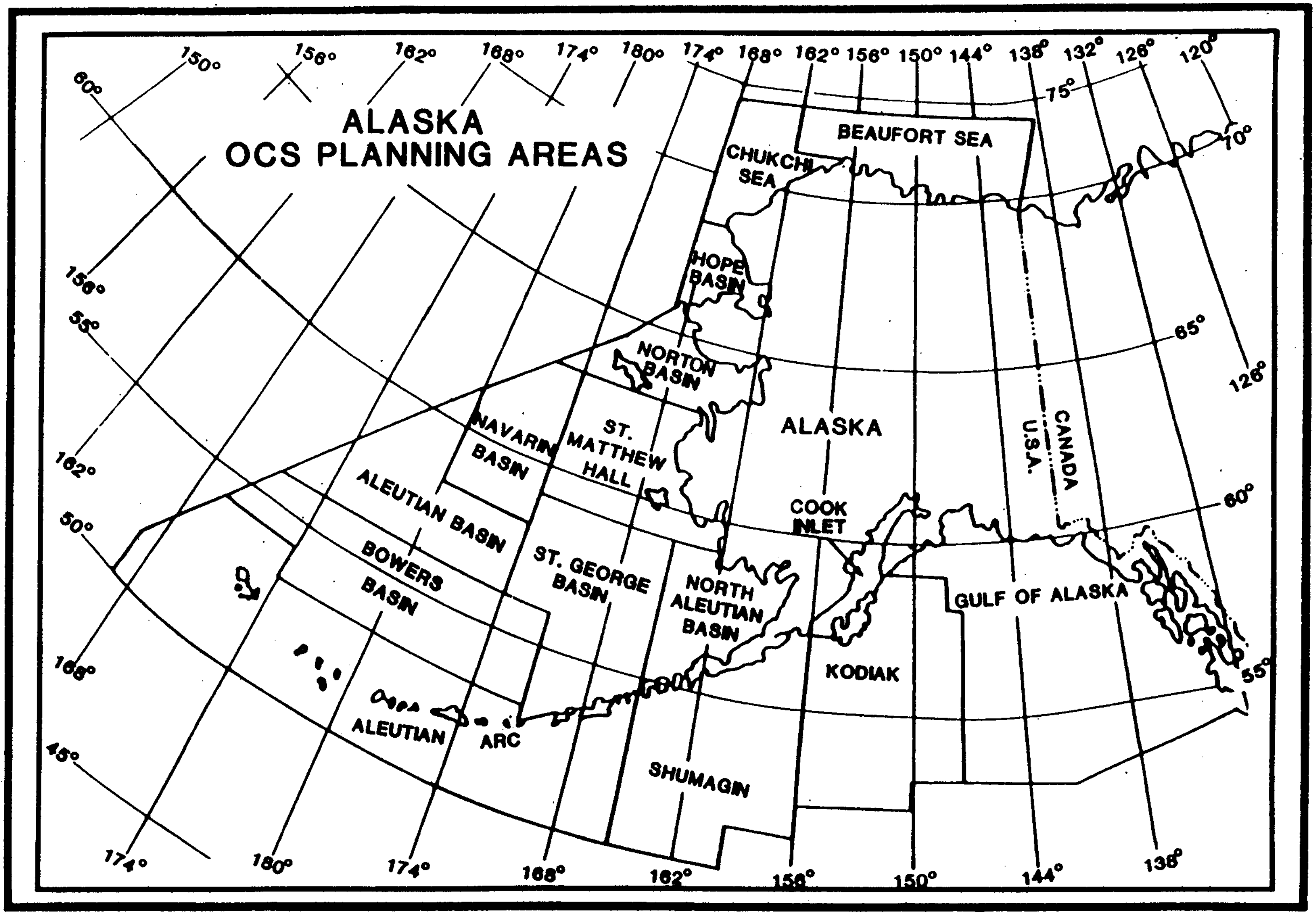


Figure 2.42. Outer continental shelf Planning Areas in Alaska (From: Dellagiarino 1986).

OCS Region	Permittee	Minerals of Interest	Year
Atlantic	Newport News Shipbuilding	Phosphate	1966
Pacific	Ocean Resources, Inc.	Phosphorite	1967
Pacific	Bear Creek Mining Co.	Phosphorite	1967
Atlantic	Global Marine, Inc.	Sand and gravel	1969
Atlantic	Ocean International, Inc.	Heavy minerals	1969
Pacific	Global Marine, Inc.	Sand and gravel	1969
Atlantic	Deepsea Ventures, Inc.	Manganese nodules	1970
Gulf of Mexico	Radcliff Materials, Inc.	Sand and gravel	1975
Alaska	Harding Lawson	Sand and gravel	1982
Alaska	Sohio	Sand and gravel	1982
Alaska	Tenneco	Sand and gravel	1982
Alaska	Geocubic	Sand and gravel	1983
Alaska	Geocubic	Sand and gravel	1983
Alaska[1]	Woodward	Sand and gravel	1983
Alaska[1]	Woodward	Sand and gravel	1983
Alaska	Sohio	Sand and gravel	1983
Alaska	Dames & Moore	Sand and gravel	1983
Alaska	Dames & Moore	Sand and gravel	1983
Alaska	Harding Lawson	Sand and gravel	1983
Alaska	Harding Lawson	Sand and gravel	1983
Alaska	Harding Lawson	Sand and gravel	1983
Alaska	McClelland	Sand and gravel	1983
Alaska[1]	McClelland	Sand and gravel	1983
Alaska[1]	Harding Lawson	Sand and gravel	1984
Alaska[1]	Harding Lawson	Sand and gravel	1984
Alaska	Ertec	Sand and gravel	1984
Alaska	Harding Lawson	Sand and gravel	1984
Alaska	Harding Lawson	Sand and gravel	1984
Alaska	Harding Lawson	Sand and gravel	1984
Alaska	MTS	Sand and gravel	1984
Alaska	Comap	Sand and gravel	1984
Alaska[1]	Comap	Sand and gravel	1984
Alaska	Sohio	Sand and gravel	1984
Alaska[1]	Sohio	Sand and gravel	1984
Alaska	Harding Lawson	Sand and gravel	1984
Alaska	Union	Sand and gravel	1984
Alaska	McClelland	Sand and gravel	1984
Alaska	McClelland	Sand and gravel	1984
Alaksa	Harding Lawson	Sand and gravel	1985
Alaska	Harding Lawson	Sand and gravel	1986
Atlantic[2]	E. I. Du Pont de Nemours & Company, Inc.	Heavy minerals	1986
Atlantic[2]	Associated Minerals Co.	Heavy minerals	1986
Pacific	East-West Center	Cobalt-rich crusts	1986
Alaska[2]	Inspiration Gold, Inc.	Heavy minerals	1986
Atlantic	Geomarex	Carbonate sands	1987

[1] No geological or geophysical data acquisition activities were initiated under these permits.
[2] Two separate permits were issued, one for geological work and one for geophysical work.

Table 2.16. Geological and geophysical permits issued by USDOI to prospect for OCS minerals other than oil, gas, and sulfur (Adapted from: U.S. Department of the Interior, Minerals Management Service 1989a).

Lease Offering	Date of Offering	Location	No. of Tracts Offered	Acres Offered	No. of Tracts Bid On	Total Bonus High Bid	No. of Tracts Leased	No. of Bids Rejected	No. of Bids Received
Gulf of Mexico Salt & Sulfur Lease Offerings:[1]									
1	10/23/54	Sul-LA	108	523,630	5	$ 1,233,500	5	0	5
8	05/19/60	Sa-LA	10	22,085	1	75,250	1	0	1
13	12/14/65	Sul-TX	658	957,520	50	33,740,309	50	0	113
17	09/05/67	Sa-LA	8	16,995	1	30,584	1	0	1
20	05/13/69	Sul-LA	120	165,605	38	3,678,045	4	34	43
S/S	02/24/88	Sul-CGOM	51	593,971	14	15,149,327	14	0	20
Total			955	2,279,806	109	53,906,995	75	34	183
Pacific Phosphate Lease Offering:[2]									
PH	12/15/61	So-CA	16	80,640	6	122,000	6	0	6

[1] Total amount of all bids received for all lease offerings - $82,527,068. Total amount of all rentals for all lease offerings - $297,860.
[2] Total amount of all bids received - $122,000. (Total bonuses [and rentals] were refunded due to discovery of unexploded Naval projectiles on ocean floor.)

Table 2.17. Mineral leases sold in the U.S. OCS since 1953 (Adapted from: U.S. Department of the Interior, Minerals Management Service 1989a).

Mining Methods		Seabed					Water Column	
Mining Approaches	Mining Systems	Fragmentation/ Collection	Excavation	Subsidence	Turbidity Plume	Resedimentation	Suspended Particulates	Dissolved Substance
Scraping	Dragline dredge	X			X	X	X	X
	Trailing suction dredge	X			X	X	X	X
	Crust-miner	X			X	X	X	X
	Continuous line bucket	X			X	X	X	X
Excavating	Clam shell bucket		X		X	X	X	X
	Bucket ladder dredge		X		X	X	X	X
	Bucket wheel dredge		X		X	X	X	X
	Anchored suction dredge		X		X	X	X	X
	Cutterhead suction dredge		X		X	X	X	X
	Drilling and blasting		X					
Fluidizing (Sub-Seafloor)	Slurrying			X				
	Leaching							
Tunneling Beneath Seafloor	Shore entry			X				
	Artificial island entry			X				

X= Disturbance expected. Magnitudes of the disturbances are also dependent on the nature of the mineral deposit and the amounts of fine particles present on the seabed. Closed circulation systems are assumed for slurrying and leaching. Open circuluaion would result in plumes and resedimentation.

Table 2.18. Normal environmental disturbances in the water column and seabed from mining (From: Cruickshank et al. 1987).

to ecosystem stress, alteration, or mortality. Bottom disturbances may cause changes in coastal wave energy dispersion and in the benthic ecology. Other potentially significant effects on the artificial environment may be as site-specific as the effects on the natural environment.

The earliest U.S. studies assessing the environmental effects of marine mining were carried out in 1972 through the MMTC (Tiburon, CA), in cooperation with the State of Massachusetts and NOAA. Termed the New England Offshore Mining Environmental Study (Project NOMES), the scope of the research effort has been described in **Table 2.19**. Unfortunately, the study was not completed, however, the planning effort established many precedents for future environmental work. The most thorough and realistic of the EISs completed to date has been prepared for the proposed Norton Sound Gold Lease Sale (USDOI, MMS 1991) because it was based on an ongoing operation in the same vicinity (i.e., in State rather than Federal waters). An assessment of anticipated effects on each of the area's affected resources was completed using assigned definitions, as shown in **Table 2.20**, along with severity ratings as indicated (i.e., from negligible to major).

2.3.2.1 Atmospheric Environment

The climate and air quality in the OCS varies considerably between regions, so only broad generalities can be made for this analysis. The climate of the areas under consideration in this analysis vary from tropical to Mediterranean, from coastal rain forest to arctic. Temperatures rarely fall below 65°F in tropical climes and rarely rise above 65°F in arctic environments. Annual precipitation may exceed 635 cm in some areas or may rarely exceed 51 cm in others. Winds range from sustained velocities of hurricane strength to light and variable. The nature of severe weather episodes experienced in these OCS regions vary from ice fog and blizzards in arctic areas, to typhoons in the Pacific Ocean, and hurricanes in the Gulf of Mexico and along the Atlantic coast.

Existing air quality adjacent to the OCS regions under consideration ranges from well within allowable National and State Ambient Air Quality Standards (e.g., areas in the Pacific Ocean) to severe non-attainment status with regard to these standards (e.g., California coastal areas). Generally, the air quality in and around coastal urban areas is worse than that of the rural and undeveloped coastal areas (USDOI, MMS 1991). Under the 1990 Clean Air Act Amendments, the U.S. Environmental Protection Agency (EPA) is responsible for regulating offshore activities within 40 km of seaward State boundaries and is required to limit emissions as though the activity were onshore. Potential problems in Alaska from offshore operations have been summarized in **Table 2.20** and include effects of sulfur-containing exhaust emissions on Alaskan tundra and effects associated with the accidental combustion of spilled fuel. Most effects in Alaska were expected to be negligible.

2.3.2.2 Oceanic Environment

The character of the oceans overlying the U.S. continental shelf is extremely varied, ranging from the arctic areas of the Alaskan Beaufort Sea, through the Bering Strait and Gulf of Alaska to the eastern Pacific (i.e., Washington, Oregon, California coasts), through the Gulf of Mexico, and along the western Atlantic (i.e., from Florida to the U.S.

Project NOMES

The New England Offshore Mining Environmental Study (Project NOMES) was begun in 1972 in an attempt to clarify the environmental impacts associated with marine mining. Uncertainties about the extent, severity, and permanence of negative effects of offshore activities highlighted by the Santa Barbara, CA oil spill had led to a moratorium on offshore mining. NOMES was a joint study sponsored by the Commonwealth of Massachusetts and the National Oceanic and Atmospheric Administration. A 1-year study of baseline conditions at a sand and gravel deposit centered in Massachusetts Bay at 40° 21′41″ N, 70° 47′10″ W, was to be followed by a period of well-monitored commercial-scale mining. Two years of post-experiment monitoring were planned to document mining-induced changes in the seafloor and water column as well as alterations resulting from natural processes.

The project was terminated in 1973 because a suitable disposal area had not been identified by the Commonwealth for the 1 million cubic yards of sand and gravel to be mined during the planned 1974 test. The principal investigators were funded through a project wrap-up phase; two were funded an additional year to study baseline conditions in plankton and benthic organisms.

The principal research in Stage 2 would have involved:

- Modeling the distribution of suspended sediment.
- Studying chemical interactions between sediments and water: e.g., release of nutrients and toxic substances to the water, and the effect of suspended particles on the scattering and absorption of light.
- Studying energetic relationships in organisms stressed by the presence of sediments: physical and/or chemical effects on respiration, photosynthesis, assimilation, feeding rates, and reproductive potential in adults, juveniles, and larvae of key species (including benthic invertebrates, benthic algae, zooplankton, phytoplankton, and fish).

Recommendations

1. Laboratory studies of the effects of turbidity on marine organisms should be continued. This work should be broadened to include nonphysiological responses, such as organisms' avoidance of a turbidity plume. Results may be extremely relevant to local commercial fishermen.

2. Once a site has been agreed upon, a 2-year period should be devoted to pre-mining studies—at least the first time. The first year should be devoted to the development of sound sampling and test procedures for coordinated use the second year. The main focus of the baseline studies should be the long-term effects of a change in substrate characteristics caused by the blanket of fine materials.

3. The mining test should be at a commercial scale and should continue for at least 1 year. A brief period of mining should not be extrapolated to long-term mining.

4. Although the period of mining must be well-monitored, the post-mining environment can be examined less frequently but should continue for at least 2 years.

SOURCE: J.W. Padan (ed.), New England Offshore Mining Environmental Study (Project NOMES), U.S. Department of Commerce, National Oceanic and Atmospheric Administration (Seattle, WA: April 1977).

Table 2.19. Summary of Project NOMES (From: U.S. Congress, Office of Technology Assessment 1987).

NEGLIGIBLE	MINOR	MODERATE	MAJOR
Rescource Category			
Air Quality			
Emissions cause measurable increases in concentrations of criteria pollutants (e.g. SO_2, CO, NO_2, O_3, and PM_{10}) over one localized portion of a Federal attainment area, resulting in the consumption of less than 5 percent of the available Prevention of Significant Deterioration (PSD) increment for NO_2, SO_2, or TSP or 5 percent of the available National Ambient Air Quality Standards[1/] (NAAQS) concentration for NO_2, PM_{10}, CO, or O_3; no observed adverse effects on human health or vegetation; and/or no significant decrease in onshore visibility.[2/]	Emissions cause measurable increases in concentrations of criteria pollutants over more than a localized portion of a Federal attainment area; resulting in the consumption of at least 5 percent but less than 20 percent of the available PSD increment for NO_2, SO_2, or TSP or 5 percent of the available NAAQS concentration for SO_2, PM_{10}, CO, or O_3; no observed adverse effects on human health or vegetation; and/or significant decrease in onshore visibility.	Emissions cause measurable increases in concentrations of criteria pollutants over more than half of a Federal attainment area (regional effect), resulting in the consumption of at least 20 percent but less than 50 percent of the available PSD increment for NO_2, SO_2, or TSP or 5 percent of the available NAAQS concentration for SO_2, PM_{10}, CO, or O_3; small but measurable short-term adverse effects on human health or vegetation; and/or significant decrease in onshore visibility.	Emissions cause measurable increases in concentrations of criteria pollutants over more than half of a Federal attainment area (regional effect), resulting in the consumption of at least 50 percent of the available PSD or NAAQS concentration increments; readily identifiable adverse long-term effects on human health or vegetation; and/or significant decrease in onshore visibility.
Water Quality[3/]	LOCAL--changes in water quality from one or more sources, extending beyond the edge of a mixing zone (100-m perimeter about the dredge footprint), but affecting less than 180 km² (30% of the sale area) about each discharge.		
	REGIONAL--changes in water quality over an area of at least 180 km² or larger about a discharge source.		
No regulated contaminant (such as mercury or other trace metal) is discharged into the water column, or some amount is discharged, but the resulting concen-tration of contaminant does not exceed the chronic State standard or EPA criterion.	A regulated contaminant (such as mercury or other trace metal) is discharged into the water column and the resulting concentration of contaminant occasionally exceeds but does not increase the average beyond the chronic State standard or EPA criterion.	A regular contaminant (such as mercury or other trace metal) is discharged into the water column and the resulting concentration of contaminant averages (sampling period set by permit) more than the chronic State standard and EPA criterion, but does not exceed acute (toxic) State Standards and EPA criteria and does not exceed 7,500 ppm suspended-sediment concentration.	A regulated contaminant (such as mercury or other trace metal is discharged into the water column and the resulting concentration of contaminant is above the acute (toxic) State standard or EPA criterion. Turbidity exceeds 7,500 ppm suspended sediment concentration.

Table 2.20. Definitions and resource categories used in the assessment of environmental effects (From: U.S. Department of the Interior, Minerals Management Service 1991).

NEGLIGIBLE	MINOR	MODERATE	MAJOR
Rescource Category			
Commercial Fishing			
Conflicts are rare. One-year losses to important commercial fisheries do not exceed 1 percent.	Minor conflicts develop. Losses of 1 to 3 percent, for periods of 1 or more years, occur in important commercial fisheries.	Minor conflicts are frequent or significant conflicts occur occasionally. Losses of 3 to 10 percent, for periods of 1 or more years, occur in important commercial fisheries.	Major disruptions to fishing occur. Conflicts are frequent and significantly affected fishing. Losses exceed 10 percent, for periods of 1 or more years, in important commercial fisheries.
Subsistence-Harvest Patterns			
Subsistence resources could be affected but with no apparent effects on subsistence harvests.	Subsistence resources would be affected for a period of less than 1 year, but no resource would become unavailable.	One or more subsistence resources would become locally unavailable for a period of time not exceeding 1 year.	One or more important subsistence resources would become locally unavailable for a period of time exceeding 1 year.
Sociocultural Systems			
Periodic disruption of local sociocultural systems occurs without apparent effects.	Short-term disruption of local sociocultural systems without a tendency toward the displacement of existing institutions.	Long-term (5 years or more), chronic disruption of local sociocultural systems occurs without a tendency toward the displacement of existing institutions.	Long-term (5 years or more), chronic disruption of local sociocultural systems occurs with a tendency toward the displacement of existing institutions.
Archaeological Resources			
No detectable archaeological resources (including landforms and sites) are expected to be present and disturbed.	Few archaeological resources (including landforms and sites) are expected to be present and disturbed.	Some archaeological resources (including landforms and sites) are expected to be present and disturbed.	Many archaeological resources (including landforms and sites) are expected to be present and disturbed.
Recreation and Tourism Resources			
Barely detectable reduction in recreation and tourism aesthetic qualities and economic expenditures.	Slight reduction in recreation and tourism aesthetic qualities and economic expenditures over one-fourth of the area lasting approximately 1 year.	Some reduced recreation and tourism aesthetic qualities and economic expenditures over one-half of the area lasting for approximately 2 years.	Much reduced recreation and tourism aesthetic qualities and economic expenditures over the whole area for approximately 3 to 4 years or longer.

Table 2.20. (Continued).

Biological Resources (Lower-Trophic-Level Organisms, Fishes, Marine and Coastal Birds, Nonendangered Marine Mammals)			
No measurable short-term or long-term change in numbers or distribution of individuals occurs in a population.	A specific group of individuals of a population in a localized area and/or over a short time period (one generation or less) is affected; the regional population is not affected.	A portion of a population in the region changes in abundance and/or distribution over more than one generation, but the change is unlikely to affect the regional population.	A population or species in the region declines in abundance and/or distribution beyond which recruitment would not return it to its former level within several generations.
Endangered and Threatened Species			
No measurable change occurs.	A specific group of individuals of a population in a localized area is affected over a short time period (less than one breeding cycle).	A portion of a regional population declines in abundance and/or distribution, and recovery requires more than one breeding cycle[a/] but less than one generation.	A regional population or species declines substantially in abundance and/or distribution, and recovery requires at least one generation.[a/]
Economy of Nome			
Economic effects occur which have no measurable effects on governmental policies, planning, or budgeting, or no measurable effect on the economic well-being of residents of the area.	Economic effects occur which may require slight marginal changes in governmental policies, planning, or budgeting, or may marginally affect the economic well-being of residents of the area.	Economic effects occur which will require some but not major modification of governmental policies, planning, or budgeting, or may create problems such as an increased rate of price inflation or housing shortages, or may substantially affect the economic well-being of residents of the area.	Economic effects occur which will require major changes in governmental policies, planning, or budgeting, or which have the potential to create major problems or to cause important and sweeping changes in the economic well-being of residents of the area.

Table 2.20. (Continued).

Land Use Plans and Coastal Management Programs[6/]			
Proposed activities generally conform with existing land use and have negligible effects on protected coastal resources and uses.	Proposed activities infringe on an existing land use, or create minor effects on protected coastal resources or uses.	Proposed activities alter a preferred land use, or create moderate effects on one or more protected coastal resources or uses.	Proposed activities are incompatible with or displace a preferred land use, or create major effects on one or more protected coastal resources or uses.
Human Health			
No change to the hair-mercury levels of any of the Nome population.	Hair-mercury levels of some of the general population residing in Nome would approach but not exceed recommended levels set for the general adult population. Any changes in hair-mercury levels of pregnant women do not reach 6 ppm.[7/]	Hair-mercury levels of one or more women of child-bearing age (because of potential effects to the developing fetus) residing in Nome would be elevated but would not exceed recommended levels set for pregnant women.[8/]	Hair-mercury levels of one or more women of child-bearing age (because of potential effects to the developing fetus) residing in Nome would exceed recommended levels set for pregnant women.[9/]

Source: MMS, Alaska OCS Region.

1/ NAAQS are based on the protection of human health. Numerical standards for each pollutant are given in Table III-2. PSD increments are supplements to the NAAQS protecting existing high air-quality areas. Regional refers to effects on areas that are as large as, or larger than, about one-half the area of the North Slope of Alaska. Local refers to effects limited to tens of miles near the shoreline. Short term refers to hours, days, or weeks; long term refers to seasons or years.

2/ Visibility criteria are applied only to PSD Class I areas; significance is determined by EPA visibility-analysis guidelines. Long term refers to seasons or years. Short term refers to hours, days, or weeks.

3/ a. The State standard and EPA chronic criterion for mercury are both 0.025 ppb.
b. The acute State standard and EPA criterion for mercury are both 2.1 ppb.
c. State standards and EPA criteria allow exceedence of trace-metal limits once per 3-years on the average.
d. For water turbidity, the State standard is 25 NTU and EPA criterion is a 10-percent decrease from seasonally averaged compensation depth.

4/ A breeding cycle is the average time period between the births of successive offspring.

5/ A generation is the average time period between the birth of the parents and birth of their offspring.

6/ Definitions reflect inconsistences between the proposal and land and water regulatory regimes, not effects of the proposal on the regulations.

7/ The WHO environmental health criteria in 1976 established 200 ppb mercury in blood or 60 ppm in hair as the level where effects from methylmercury exposure begin to be seen in adults.

8/ "Elevated" is defined as 6-10 ppm in hair.

9/ The new World Health Organization (WHO) environmental health criteria document (to be published in 1990) will state that the occasional psychomotor retardation effects from prenatal exposure to methylmercury can be seen in infants and children whose mothers had mercury hair levels between 10 and 20 ppm (Clarkson, 1989, oral comm.)

Table 2.20. (Continued).

Canada border). Isolated insular shelves are found off the Virgin Islands, Puerto Rico, western Samoa, and Guam. Hawaii and other Pacific Island associations have no continental shelf but have some seabed of continental shelf depths within their EEZs. The major physical characteristics of the ocean are its depth, temperature, and density. The last two characteristics exhibit extreme spatial and temporal variability due to the effect of currents, waves, and tides. Ocean currents are three dimensional in their direction of motion and in their extent, and their movement is the result of winds and thermohaline circulation. Both surface and subsurface currents are of concern to the ocean miner with respect to the transport and dispersion of plumes of turbid and dissolved materials along the surface, at midwater depths, and on the bottom. Waves are caused by winds and are a major consideration in the safety of operations at sea and the likelihood of spillage or accident. In general, tidal effects distal to coastal areas are not prominent, however, there are exceptions where tides may have a significant influence on local currents. The capability of the oceans to chemically buffer otherwise undesirable inputs from discharged wastes is well known. There is a considerable amount of misconception evident concerning the effects of minerals and other mined materials, both of which are frequently considered by lay persons to be the equivalent of toxic wastes (see **Section 2.3.1**).

- **Natural Effects**

Effects of natural ocean phenomena, such as freshwater springs, petroleum seeps, tidal currents, upwelling, and red tides, may be the cause of significant local or regional environmental change on a seasonal or random basis. These changes may be mistakenly perceived to be the result of mineral development operations and it may be prudent to carefully conduct monitoring in areas of mineral operations.

- **Induced Effects**

The impacts of marine mining on water quality will vary greatly with the type of mining operation (see **Section 2.2**) and its geographic location. Levels of impacts can be predicted only when the plan for a specific operation is submitted. Effects on water quality will result from introduction of materials at the seabed or discharged from the mining platform, either of which can occur deliberately or accidentally. The materials will generally be in the form of particulate solids or dissolved substances, however, the introduction of bulk materials (e.g., minerals cargo, industrial trash) is also possible. Major changes in water quality anticipated, or reported, include increases in turbidity, nutrient enrichment, trace metal enrichment, and floating materials. Each topic is discussed in greater detail in the following text.

Increase in Turbidity: According to Cruickshank et al. (1987) seabed mining will create turbidity plumes at the seafloor as fine materials are resuspended or created during mining. The properties of the plume, particularly the settling times of the particles, will depend on their size distributions, specific gravities, and relative concentrations. These are also the properties of greatest biological significance. Particle size and specific gravity determine residence time in the water column and potential for resuspension. The largest of these plumes may be created by mining systems designed to reject fine material at the seabed during ore retrieval. In general, the chemical characteristics of the smaller, slower settling particles in these plumes will be similar to existing suspended sediment. Under certain circumstances, however, dissimilar chemical characteristics may exist between ambient resuspended sediment and mining-related particles. For example, during the mining of anoxic layers, the solubility of adsorbed metals can differ greatly between reducing and oxidizing environments. The effects of such differences are likely to be local and brief due to rapid dilution by oxygenated waters. Rock fragments created by mining are likely to consist of relatively inert material and are less likely to be a source of dissolved metals than are resuspended sediments. Additional turbidity may be created as the mined material is raised to the surface (see **Figure 2.37**).

Surface turbidity plumes, created when wastes are discharged from shipboard operations, will vary in proportion to the amount of fine material discharged and the disposal technique. The fine sediment fractions will tend to remain in suspension on board the mining vessel, to be discharged with the slurry water. In a continuous mining operation, a continually renewed plume is present. Sediment concentrations in any one parcel of water decrease as the water mass moves away from the point of discharge. As each parcel is replaced by another, high concentrations are always found near the discharge point even though the concentrations in each parcel are continually decreasing (Cruickshank et al. 1987). Field studies and modeling results indicate that both surface and benthic plumes can be detected over distances on the order of kilometers and, in certain cases, tens of kilometers. Plumes from coastal dredging typically are visible for only 1 to 5 km but may be visible up to 20 km (USDOI 1974). Lavelle et al. (1981) measured plumes up to 120 km from the point of discharge, however, the detection of plumes at these distances requires the measurement of substances that are prominent in the mining discharge but rare in natural waters (e.g., manganese in the discharges from manganese crust or nodule mining).

A typical bucket ladder dredge operation (e.g., similar to the *Bima* as described in **Section 2.2.1.2**) produces a plume of particulates extending 300 m at the surface and 500 m near the bottom. In the immediate vicinity of the operation, the surface concentration of particles is about 500 g/L, which decreases rapidly with distance. In the water column, particle concentrations are about 100 mg/L. However, when mining stops, the turbidity plume settles rapidly (USC, OTA 1987).

Reporting on an operation in Baie de Seine, France, the International Council for the Exploration of the Sea (ICES) (1975) indicated that approximately 1.2 x 10^6 m^3 of material was dredged in three-day periods between January 1974 and July 1975. Particles larger than 40 μm settled within 1.5 km of the test site, and 10% of the fines were still in suspension 6 to 12 km from the point of origin. With strong winds and wave heights of 3 m, the settling velocity of the plume was measured at approximately 1.5 mm/s with longitudinal and transverse velocities of 0.01 to 0.4 m/s, respectively; about 5 to 25 g/L of solids had particle diameters less than 0.3 mm. Within 15 to 30 min after cessation of discharge, homogeneity of particle distribution was evident over the entire vertical section. The mean settling velocity of the particles measured in the natural environment was about 1.5 mm/s, or about 10 times greater than the median velocity measured in the laboratory. The reason for the difference is not known, though it may be due to flocculation or agglomeration.

Nutrient Enrichment: Depending on the type of material disturbed on the seafloor and in the seabed, the water column may become enriched with certain nutrients. Data obtained during pilot mining of manganese nodules in the Pacific revealed higher than normal concentrations of nitrate and silicate. Increases in these nutrients leads to increased productivity in certain types of plankton. Tests in the Blake Plateau showed similar anomalies (Amos et al. 1972). Conversely, the oxygen concentration in the water column can be reduced by suspended sediments that provide an increase in surface area available to bacteria (Padan 1977), resulting in the release of unoxidized biogenic material. While this is not likely in the case of mining, it could occur if fine-grained, organic-rich overburden is removed during a placer operation. Reduced oxygen levels have been of short-term duration and have caused little concern (Wakeman 1976; Public Works Canada 1982).

Trace Metal Enrichment: The resuspension or discharge of particulates into the water column may result in dissolution of certain trace metals, resulting in an increase in their concentration above normal levels. The type and concentration of metals would depend on the characteristics of the particulate matter and the temperature, salinity, pH, and oxygen content of the water. Adsorption by organic and inorganic particulate matter quickly removes excess trace metals from the water column. Due to such factors as dilution, precipitation, and adsorption, the release of significant amounts of dissolved metals from mining operations is unlikely.

Floating Materials: Oil pollution associated with mining operations may include (1) oil spilled during fuel transfer operations; (2) deck drainage from ships or platforms; (3) discharges of bilge water; and (4) possible fuel tank rupture. The fate of the released oil is dependent on the type of oil; temperature of the water; wind, wave, and current action; light intensity; and the concentration of nutrients and particulate matter. Most of the spilled oil will be removed by evaporation, dissolution into the water column, and microbial degradation. There may be a small remainder which could form tar balls and be dispersed widely from the point of origin. The NAS states that there is no evidence of irrevocable damage to marine resources either by chronic inputs of oil or by major oil spills (USDOI, MMS 1988a). Due to the removal processes described above, the likelihood that concentrations of oil in the water column from mining operations could reach levels which would cause significant environmental effects is extremely low.

2.3.2.3 Geological Environment

The geological nature of the seabeds off the U.S. coast is described briefly in the following text for each OCS region (U.S. Department of State [USDOS] 1975).

The continental shelf is the zone lying adjacent to a continent which extends from the low-water line to the depth at which there is a marked increase in slope to greater depths. The forward (or seaward) edge of the shelf lies approximately at 183 m, but this is far from uniform. On a global basis, the edge of the continental shelf ranges in depth from 20 to 550 m with an average of 130 m (Emery 1969). U.S. continental shelf depths vary greatly from the 183 m mark; in fact, some believe that a 132-m depth is a more accurate figure for the forward edge of the shelf with the single greatest mark set at 457 m (Thornbury 1969). When the zone below the low-water line is highly irregular and includes depths in excess of those typical of the continental shelves, the term continental borderland is applied.

The shelf ranges in width from zero to 1,500 km with an average of 78 km; the continental shelves underlie only 7.5% of the total area of the oceans, but they are equal to 18% of the earth's total land area (Emery 1969). These figures are representative of all the continental shelves of the world's continents, inclusive of those of the U.S.

The geomorphology of the continental shelf has a great deal to do with the nature and effect of mining operations. Off the eastern U.S. coast, the continental margin can be divided into three different sections (1) from the Bay of Fundy southward to Cape Cod; (2) from Cape Cod southward to Cape Hatteras; and (3) from Cape Hatteras to the tip of Florida.

Irregular topography, with rows of banks and shallow water on the outer margin and deeper water inshore, is characteristic of the shelf from the Bay of Fundy southward to Cape Cod. The topography is very complex due to the presence of knolls, ridges, swells, and basins. These geomorphic features are, for the most part, the product of Pleistocene glaciation. The sedimentary strata overlays Paleozoic basement rock; the age range is from Triassic to Tertiary. The surficial sediments are mainly sand, sandy gravel, and gravelly sand. Some clay and silt are present locally. A significant amount of the sediment in this area is glacial in origin.

The continental shelf from Cape Cod to Cape Hatteras is distinctly different from that described above. A uniform and smooth surface that slopes gently seaward and almost disappears near Cape Hatteras is characteristic of this shelf. The continental shelf along this section has not been subaerially eroded or subjected to glaciation. Another important characteristic of the shelf includes the presence of numerous submarine canyons (e.g., Oceanographer, Hydrographer, Wilmington, Baltimore, Washington, Norfolk, and Hudson).

The third and southernmost section of the eastern U.S. OCS extends from Cape Hatteras to South Florida. South of Cape Hatteras, the shelf widens to nearly 121 km off the coast of Georgia. South of Georgia, the shelf starts to narrow again until it almost disappears off Miami, FL. The Blake Plateau is located in the Cape Hatteras-Florida section of the continental shelf; the plateau is intermediate in height between the shelf and seafloor. Much of the plateau surface is flat; with a maximum width of 274 km, this feature lies 300 to 732 m below the level of the inner shelf. The Blake Escarpment, the plateau's eastern edge, drops 3,658 m to the floor of the ocean basin.

Further south, between Miami and Key West, is the Straits of Florida. The main axis of the northern straits, lying west of Little Bahama and Grand Bahama Banks, has been formed aseismically by non-deposition and limited erosion. In contrast, the southern straits located north of Cuba has been formed by a half-graben structure with the down-dropped portion tilted towards the south (Malloy and Hurley 1970).

West of Florida, the continental shelf of the eastern Gulf of Mexico widens to about 241 km only to narrow again off the coast of Alabama and Mississippi. The shelf widens again west of the Mississippi delta, extending to a distance of 185 km off the coast of Louisiana and Texas. Three major escarpments bound the Gulf of Mexico, including the West Florida Escarpment on the south. The most notable submarine troughs in the Gulf are the De Soto Canyon and the Mississippi Trough. These two features, however, are not as large as comparable troughs on the U.S. Atlantic and Pacific shelves. Another significant feature in the Gulf is the Mississippi River delta. The delta has been built up by sediment carried to the Gulf by the Mississippi River and deposited over a 700 mi^2 area; the deltaic sediments extend to the edge of the continental shelf with turbidity currents transporting some sediment to the abyssal plain.

Salt domes occur in the western portion of the shelf and have resulted in structures which form petroleum traps frequently capped by large deposits of sulfur. Many salt domes are known to occur on the coastal plain of Louisiana, Mississippi, and Alabama, indicating that their occurrence is not limited to shelf areas.

In terms of areal extent, the continental margin off the western U.S. is not nearly as large as the margin off the eastern U.S. coast. In general, the maximum width of the shelf ranges from 16 to 42 km. Topography of the shelf varies significantly from that off the eastern U.S. coast; this difference is due to many irregularities resulting from regional and local tectonic activity, and to a lesser extent by depositional and erosional processes. This is particularly true of the shelf off southern California which is cut by numerous faults, grabens, and horsts. From San Francisco north to the California-Oregon border, the shelf width narrows to about 16 km, then widens to about 32 km off the Oregon and Washington coast. Some of the bottom topography that exists off southern California is also reflected in this area. However, there are a few glacial features on the shelf off Oregon and Washington that are absent off the southern California shelf.

There are numerous submarine canyons off the U.S. west coast, with the Monterey Canyon the largest and best known. Prominent submarine escarpments exist in association with the shelf that includes the Punta Gorda, Mendocino, and Patton Escarpments, which mark the shelf's western edge. The strata overlying the Jurassic and Cretaceous crystalline rocks range in age from Cretaceous to Tertiary.

With regard to the continental shelf off Alaska, it is found to be only a few kilometers wide at the southern end of the Alexander Archipelago, widening to about 80 km at the northwest side of Cross Sound. This section has numerous submarine valleys and fjords. Westward, around the Gulf of Alaska, the shelf widens to 193 km near Kodiak Island. This section has numerous islands and troughs that have been extensively modified by glaciation.

The continental shelf south of the Aleutian Islands is relatively smooth, with gradual decreases in water depth to about 183 m. At this point, a sudden, sharp drop occurs into the Aleutian Trench to a maximum depth exceeding 7,500 m. The upper part of the shelf in this area is cut by trough-like valleys which are believed to have a significant amount of fault control. The axial area of the trench is flat because of the large volume of accumulated turbidities (Piper et al. 1973).

West of Alaska, in the Bering Sea, the shelf is very smooth with only a few submarine valleys (e.g., Ogotorul Sea Valley, Chukchi Sea). Further north in the Beaufort Sea, the shelf is relatively smooth, although some submarine canyons do occur (e.g., Barrow Sea Valley, Mackenzie Sea Valley).

Effects of mining on the seabed include alteration of bathymetry or alteration of habitats caused by removal, perturbation, or deposition of materials. These activities have not been well studied under controlled conditions. Certain qualitative data, however, are available from sand and gravel operations which leave holes in the seabed, deposit fine sediment from discharge plumes, and alter habitats.

- **Holes in the Seabed**

Where operational water depths exceed 10 m, holes or pits created by dredging operations, particularly stationary dredges, may be from 1 to 70 m deep. Such holes or pits very rarely fill in either via sediment transport or backfilling (due to slumping of the sides of the pit) as noted by de Groot (1986). A second potential problem lies with the accumulation of fine sediment within the pits where water movement has been reduced. Typically weak, unstable mud fills pits in areas that were once sandy bottoms (de Groot 1979a). The reduction of water movement may also lead to anoxic environments; however, this has not been, nor is it expected to be a significant problem. The furrows left by trailer suction dredges do not seem to have any long-term environmental implications, because they infill quite rapidly (ICES 1979). Coastal erosion may occur when large-scale, nearshore dredging modifies the seabed such that there are changes in wave patterns and sediment movement. For example, dredging off Hallsands, Devon, England during the early 1900s resulted in severe wave damage to the coast and large-scale erosion that extended well into the village (Drinnan and Bliss 1986). Motyka and Willis (1974) found that erosion increased when dredging occurred in water depths less than one half the normal wave length, or less than one fifth the extreme of the waves.

- **Fine Sediment Deposition**

According to Cruickshank et al. (1987), the fine particulate material suspended in plumes eventually falls to the seafloor, forming a thin layer over a large area. The measurable effects of sedimentation will be much more localized than those of plumes. Lavelle et al. (1981), for example, found that 90% of the sediments suspended by manganese nodule mining were redeposited within 70 m, even though the mine site was covered with clays that would be expected to form a plume of small-sized, slow-settling particles. Thicknesses of the sediment layers resulting from mining were less than 1 to 5 mm at 200 m from the disturbed area, about 2 to 4 mm at 50 m, and 8 mm at 25 m. Thicknesses of resedimentation may be considerably higher in some mining operations, but the pattern of rapid decline in sedimentation at increasing distances can still be expected. In examination of the dispersion of spilled barite fines from the Castle Mine in southeastern Alaska, traces were found on the seabed several kilometers from the mine in both directions, but no effects on the benthos were measured (Noakes and Harding 1982).

- **Altered Habitats**

Dredging may change the original sediment substrate by exposing underlying bedrock or a different sediment type. Sediment size composition can be altered when selective sizing of dredged material is undertaken. For example, the presorting of sediment at the dredgehead (i.e., via an intake grill) leaves boulders on the surface. Resettling of material rejected after onboard physical processing can also alter the sediment size composition of a mined area (ICES 1975; Padan 1977; de Groot 1979a; Drinnan and Bliss 1986).

2.3.2.4 Biological Environment

The flora and fauna of the continental shelf is extremely variable (USDOI 1974). The following text provides brief discussions of the avifauna and marine flora and fauna of the continental shelf. Special reference is made to specific environmental issues which include marine mammals, sensitive habitats, and threatened and endangered species.

- **Birds**

There are over 8,000 species of birds (**Table 2.21**). Noise from dredging operations may affect birds during nesting season because they are more susceptible to external stimuli at that time. While this would not generally be a problem for operations far from the coast, it should be considered, particularly in those areas where offshore islands (i.e., prominent breeding and nesting sites for marine birds) are located. In quantitative terms, however, those terrestrial and coastal species that might be affected most by activities at or near potential support and processing bases would include brown pelicans, least terns, piping plovers, bald eagles, and peregrine falcons. They may nest on or near shorelines and feed directly or indirectly in coastal waters. Such nesting or feeding could be temporarily interrupted or modified by increased noise from support vessel and aircraft traffic and associated activities (Packer 1987). Besides these effects, increased heavy metal concentrations in birds or other terrestrial biota are unlikely, and collisions between vessels and feeding birds would be possible but unlikely. Of greater concern are nesting birds, small mammals, reptiles, insects, and plants that might be adversely affected by habitat reduction associated with expansion of onshore support or processing facilities during mining. While these effects could be locally significant, they would be negligible during preliminary activities that would involve use of existing facilities (USDOI, MMS 1983a).

- **Marine Flora**

Very little information is available relating marine flora, including kelp and other macroflora, to mining on the continental shelf. Turbidity from mining plumes may reduce the penetration of sunlight into the upper water column and consequently reduce primary production by phytoplankton in near-surface waters. No significant quantitative field studies were identified pertaining to mining-related turbidity and its effects on phytoplankton productivity.

Orders of Birds

There are more than 8,000 species of birds—a figure both intimidating and unwieldy. Thus the class Aves (birds) is usually broken down into 27 living orders. Like other taxonomic groups, the orders contain vastly different numbers of species. For example, the order Struthioniformes has only one kind of bird (the ostrich), while the order Passeriformes has some 5,000—more than half of all living species. Below is a list of the orders, with representatives given for each. Note that the technical names all end in *-iformes*.

Apterygiformes: kiwis
Struthioniformes: ostrich
Rheiformes: rheas
Casuariiformes: cassowaries, emu
Tinamiformes: tinamous
Podicipediformes: grebes
Gaviiformes: loons
Sphenisciformes: penguins
Procellariiformes: albatrosses, shearwaters, petrels
Pelecaniformes: pelicans, cormorants, darters, gannets, frigatebirds
Ciconiiformes: herons, storks, ibises, spoonbills, flamingoes
Anseriformes: screamers, ducks, swans, geese
Falconiformes: eagles, hawks, vultures, falcons, osprey, secretary bird, condors
Galliformes: megapodes, curassows, grouse, guinea fowl, turkeys, hoatzin
Gruiformes: cranes, trumpeters, bustards, sun bittern, rails, finfoots, limpkin
Charadriiformes: gulls, auks, sandpipers, plovers, oystercatchers, avocets, phalaropes
Columbiformes: pigeons, sandgrouse
Psittaciformes: parrots, parakeets, cockatoos, macaws, lories
Cuculiformes: cuckoos, touracos
Strigiformes: owls
Caprimulgiformes: nightjars, frogmouths, oilbird, potoos
Apodiformes: swifts, hummingbirds
Trogoniformes: trogons, quetzal
Coliiformes: mousebirds
Coraciiformes: kingfishers, hornbills, rollers, hoopoe, todies, motmots
Piciformes: woodpeckers, barbets, toucans, puffbirds, jacamars, honeyguides
Passeriformes: finches, sparrows, wrens, thrushes, starlings, tits, larks, swallows

Table 2.21. Orders of birds (From: Reader's Digest 1977).

- **Marine Mammals**

Marine mammals are of particular concern to the organizations responsible for management of ocean and coastal resources. According to USDOI, MMS (1991), the degree to which mammals might be affected by mining operations for hard minerals depends on 10 variables, including (1) the commodity being mined, particularly the composition and concentration of its toxic components; (2) the mining method and technology employed, both of which determine the characteristics and extent of sediment plumes at or near the surface, within the water column, or near or on the seafloor; (3) the phase of activity, whether exploration, delineation, testing, or mining and the level of operations; (4) the location of activities, particularly their proximity to marine mammal habitats; (5) the incidence of accidentally discharged toxic materials other than the commodity being mined, such as fuel or on-site processing agents; (6) the physical presence and numbers of animals, either year round, as seasonal residents or migrants, or as occasional visitors; (7) the customary or preferred habitat(s) of animals; (8) their activities and behavioral attributes in a habitat; (9) their feeding habits and food preferences; and (10) their susceptibility and sensitivity to impact-producing agents, particularly relative to the level of the operations involved.

Depending on these variables, the potential adverse effects on marine mammals may include (1) decreased feeding success and prey availability in areas of increased activity-related turbidity; (2) increased heavy metal concentrations caused by prolonged ingestion of zooplankton or free-swimming prey which feed directly or indirectly on phytoplankton that accumulate abnormally high amounts of metals (see also **Section 2.3.1.2** on bioaccumulation); (3) death or injury due to collisions with support and possibly other lease activity-related vessels; (4) behavioral and stress-related reactions to increased noise from aircraft, support vessels, and mining, and from support base or onshore processing operations; (5) death, injury, or behavioral modifications due to shock waves produced by explosives and/or geophysical surveying activities; and (6) physiological stress or physical injury due to contact with accidental discharges of potentially toxic materials incidental to mining.

Without site- and operations-specific knowledge, however, it is not possible to quantitatively project the effects of minerals operations. Qualitative generalizations are discussed in the following text in terms of turbidity, heavy metals, collisions, noise, shock waves, and spilled fuels or lubricants.

Turbidity: Surface and subsurface sediment plumes might reduce the ability of visually-feeding marine mammals to locate their prey, thereby diminishing their feeding success. Presumably, few animals would remain near offshore mining sites. As the plume areas would be comparatively small and prey abundance probably lower in the plumes, potentially involved mammals should be able to feed successfully outside the plumes.

Heavy Metals: *Because marine mammals and some of their finfish prey are* long lived, the potential exists for bioaccumulation of ore-derived heavy metals and other environmental contaminants. This potential exists despite the fact that both the prey species and the zooplankton on which they feed apparently do not bioaccumulate significant heavy metal loads from phytoplankton on which they both feed.

Collisions: When present in areas transitted by support or seismic survey vessels, some beaked, pilot, and pygmy sperm whales might be subject to collisions because of their proclivity to sleep, rest, or loll motionless at or near the surface. Seals, sea lions, and northern sea otters might be subject to collision when feeding, migrating, drifting, or rafting offshore. Harbor porpoises and minke whales (small baleen whales), because of their comparatively slow swimming speeds, may have difficulty in avoiding fast moving vessels.

Noise: It is recognized that noise will affect marine mammals, however, the significance of this effect is not known because there is very little information about the intensity, frequency, and duration of the noises produced by marine mining operations. Stationary suction dredges operating in the Canadian Beaufort Sea for construction of artificial islands did not appear to disturb beluga and bowhead whales, although their swimming patterns did change within 2 to 4 km of dredging operations (Cruickshank et al. 1987). Noises from aircraft, boats, and other lease-related operations are known to affect marine mammals such as seals and sea lions, but the degree of impact has not been measured.

Shock Waves: The effects of shock waves produced by explosives, seismic surveys, or undersea blasting are not well known. The available literature, derived mainly from experiments and observations of endangered whales, indicates that the effects of air guns on marine mammals are generally negligible at distances of 5 km or more from seismic operations (Young 1977).

Accidental Discharges: The possibility of discharges of small amounts of fuel or other deleterious fluids is always present during operations at sea. Apart from massive oil spills, the effect on marine mammals has not been recorded.

- **Plankton**

Plankton growth may be affected by the decrease in light levels caused by the presence of a fine sediment plume, at least down current in the vicinity of the mining vessel. This may be due to absorption by suspended particles or changes in the spectral composition, because particles scatter blue light (short wave) more than red light (de Groot 1979a). Zooplankton and meroplankton might also be affected by ingestion of the fine particles themselves, particularly if they are toxic. Most nutrients are contained in the bottom sediments. When released by dredging, they are made available to plankton resulting in a temporary change in the local species diversity and production (de Groot 1979a). Total effects would depend on the type, duration, and size of the plume, the characteristic of the site, and the species involved (USDOI, MMS 1991). Stationary placer mining operations will continuously generate a turbidity plume on site. In contrast, sand and gravel operations using hopper dredges tend to be discontinuous and associated plumes would be dispersed over a larger area. Because the concentration of the suspended particles in the plume diminishes rapidly with time and distance from the source, the effects on fauna are reduced (de Groot 1979a; Cressard 1981; Evans et al. 1982; Cruickshank et al. 1987). In general, the effects of turbidity on phytoplankton (due to light reduction) or on pelagic fish and invertebrates (due to gill irritation, and reduction of light levels on visual feeders) are considered small (de Groot 1979a; Cressard 1981). One of the major factors upon which this conclusion is based is that the plume is generally small in scale (relative to the total marine coastal environment) and duration (Drinnan and Bliss 1986). Other research has indicated that the impact of fine-grained discharges from such activities is small; frequently, the material is quickly dispersed (Gillie and Kirk 1980; Cressard and Augris 1982). Within the water column, the effects of particulates on the drifting biotic communities are considered negligible because of the limited area affected and the characteristically short exposure time (National Research Council [NRC] 1985).

- **Nekton**

For mobile, free-swimming organisms, such as most pelagic fish, the potential effects of fine sediment plumes are reduced due to the ability of the organisms to avoid the resuspension area (NRC 1985). A considerable amount of work has been done in this field, particularly with anadromous species. In one experiment in Canada, coho salmon were found to be the most tolerant of the fish tested, closely followed by winter flounder and silverside (Boehmer et al. 1975). Although initially more tolerant of higher concentrations of suspended sediment than menhaden, yellow flounder, and hake, silverside was less tolerant at longer durations. This led to the conclusion that with some species the toxicity of suspended fine sediment is more dependent on the duration of the exposure, whereas with other species the toxicity is more dependent upon the concentration. Boehmer et al. (1975) noted that the tolerance to suspended sediment varies from species to species, and varies with particle size and composition. Furthermore, they believed that the toxicity of suspended sediment is physical in nature. This is supported by the fact that during tests the coho salmon that died were found to have their gills clogged with sediment. Campbell (1954) conducted an experiment in the Powder River of Australia while dredging occurred for gold. With a turbidity of 1,000 to 2,500 ppm, eyed rainbow trout eggs died within a six-day period. Adult rainbow trout did not tolerate the silted waters either; within a 20-day period, 57% of the adults died. Similarly, de Groot (1979b) characterized herring trying to avoid suspended sediments from dredging activities in the North Sea. For fine sediment (i.e., median particle diameter = 4.5 μm), the threshold concentration for avoidance was 19.5 mg/L. For coarser material containing 30% sand, the threshold concentration increased to 30.5 mg/L. Owen (1977) noted that several investigators have reported that suspended sediments can clog or interfere with the gills of fish; further, levels of suspended materials greater than 270 ppm have been related to the disease fin-rot. In general, water clarity (transparency) increases with increasing distance from shore (de Groot 1979a). The effects of resuspended matter will be greater in clearer offshore waters than in the coastal zone where the water is already turbid. Visual feeders, such as mackerel and turbot, will avoid turbid waters and will return once fine sediments settle (de Groot 1979a). Species which use olfactory senses for feeding will tend to be less disturbed by turbid waters. The impact of a turbidity plume from a sand and gravel operation is far less than for placer mining for several reasons. Most sand and gravel operations avoid areas with more than 5% fines to avoid contamination of the cargo. Secondly, dredging runs are not of long duration; a vessel may spend only 3 to 4 h in a 24-h period actually on location, with the remaining time spent in travelling and offloading (Drinnan and Bliss 1986).

The principal environmental concern with offshore sand and gravel mining has not been the removal of aggregates (which involves rather small geographic areas), but rather with the plume of fine sediments (Boehmer et al. 1975). However, Evans et al. (1982) pointed out that it is extremely unrealistic to anticipate sediment load anywhere near the maxima used in the Boehmer et al. study, especially for suction hopper dredging. This is because the dredge is only on-site for 3 to 4 h during a 24-h period. This discontinuous method of mining enables the suspended sediments which enter the water to dilute, dissipate, and settle.

- **Benthos**

The effects on the benthos from continental shelf dredge mining operations is probably the most evident and widely documented. The primary effects including entrainment, turbidity, and sedimentation, are influenced by water depth, current velocity, and benthic species. Increased turbidity may smother non-mobile benthic dwellers in the immediate vicinity of the mining operation. It is assumed that nearly total destruction of the benthic community occurs directly at the mining site by entrainment and for a short distance down current by smothering of benthic organisms from resedimentation.

Turbidity: Particulate matter may have deleterious effects on filter feeders and gilled organisms. Most demersal fish, like their pelagic cousins, are able to avoid turbidity which, in general, will dissipate quickly as it moves from the source. Turbidity is a transient condition which arises in all dredging operations and is usually of little long-term consequence (Joint Group of Experts on the Scientific Aspects of Marine Pollution [GESAMP] 1977). In offshore dredging, transport by currents and ambient mixing conditions can normally be expected to be effective in reducing the concentration of waste material from a discontinuous source to insignificant levels over a time period of 5 to 10 h. A conclusion of the Dredged Material Research Program was that the biological conditions of most shallow water areas with high wave action appear to be influenced to a much greater extent by natural variation in the physical and chemical environment than by dredging. The NOMES project (**Table 2.19**) and Sea Grant studies corroborate the U.S. Army Corps of Engineers' (USACE) finding that, in shallow water, there is much natural variation in both the distribution and abundance of species on the unaltered seafloor. According to the USC, OTA (1987), turbidity plumes are primarily a matter of aesthetic impact rather than biological impact. Boehmer et al. (1975) noted that the highest tolerance to turbidity was exhibited by the adult stage of the quahog, soft shell clam, and oyster. However, their tolerance could be attributed to the fact that they are filter feeders. Though these shellfish species were found to be the most tolerant, another adult shellfish, the bay scallop, was found to be the most susceptible of the species tested. Bay scallop larvae were found to be more tolerant than adults, thereby supporting the belief that the susceptibility of an organism may vary by life stage. Lobster, tested longer than any other species, was found to be relatively tolerant to suspended sediments. They are, however, vulnerable to suspended fine sediment while molting. Cressard (1981) stated that an important fact about the turbidity front outlined by the Commissariat de l'Energie Atomique is that it does not appear to affect, to any significant degree, benthic or pelagic biological populations. Herbich and Schiller (1973), reporting on a study concerning the effects of dredging, indicated that dredging did not increase the mortality of oysters. Damage to shellfish only occurred in the immediate neighborhood of the dredge when they were covered by large particles of mud; no damage was observed beyond 69 to 366 m from the dredge. In turbidity as high as 2,000 mg of silt or 4,000 mg of kaolin per liter, oyster larvae have been shown to live at least 14 d covering the time period between egg and setting size (U.S. Army Engineer District 1974). In another case, oyster larvae showed no effect under experimental conditions to 48 h of exposure to suspended sediment concentrations of 10 g/L (10,000 ppm). Further, no effects among quahog clams, soft shelled clams, and oysters were noted during short-term (i.e., 48- and 96-h acute static bioassays) exposures to silt- and clay-sized particles of 80 g/L (80,000 ppm). In other studies, it has been found that the physical effects of dredging operations are minor when compared to turbidity and the increase in suspended solids due to natural events (e.g., high runoff from land, wind and wave action). However, if dredging is continuous, then the area affected may be substantially increased (California Department of Fish and Game 1977).

Entrainment: Capture or entrainment of benthic organisms, both epifaunal and infaunal, generally occurs when they are unable to avoid the vicinity of the dredgehead. Motile organisms such as fish may swim too close and get drawn in with the intake of water. Burton (1979) evaluated a proposed sand mining operation at Madeleine Islands, Quebec and reported that the number of mortalities was small and would not result in either short- or long-term environmental effects. A Beaufort Sea study conducted at McKinley Bay and Tuktoyaktuk to monitor fish entrainment from dredging operations encountered such difficulties in the monitoring procedure itself that it was impossible to provide quantitative kill estimates or to determine the effectiveness of the monitoring devices (Pelletier and Wilson 1981). Aurand and Mamontov (1982) reported that dredging would result in the destruction of the local resident benthic community. Recovery does appear to be rapid, however, and is usually complete within one or two years. After destruction of the resident population, recolonization begins from adjacent areas by larval recruitment and lateral migration of adults if the sediment type is compatible. Cressard (1981) suggested that dredging of sandy shoals and banks of the mobile dune type was not expected to significantly affect bottom biota, whose numbers are generally small because of the mobile nature of the sand substrate. Investigations in Gulf of Mexico waters off Alabama indicated that bottom dwelling organisms recovered six months after dredging for sand and mudshell (Packer 1987). The first signs of recovery were evident after a few months; six months after dredging, the number of organisms was about the same or even higher than pre-dredging conditions. There was also an increase in diversity and distribution of species. During the Southwould-Thorpeness Project in the UK, biological monitoring (following the use of a trailing suction dredge) indicated that although destruction of the benthos occurs in the path of the dredge, no effects on the animal community were noticed in the area as a whole (ICES 1975). It was confirmed by de Groot (1979b) that bottom dwelling organisms in the path of the dredgehead will be destroyed. However, as long as a layer of the original substrate remains, the same type of bottom dwelling organisms may be able to return through recolonization. Reported rates of recolonization, varying from one to five months in temperate waters to up to 12 years in arctic waters (Wright 1977), are generally on the order of one to two years (Aurand and Mamontov 1982). The rate of repopulation will depend upon factors such as (1) the extent and type of biological activity of the area (i.e., mobile adults allow faster recolonization of large disturbed areas, especially if the larval stage is nonmobile); (2) the environmental setting of the region; and (3) the season in which dredging occurs (Cruickshank et al. 1987). The precise extent and significance of specific impacts can not be determined until an actual mining site is known and the nature of the benthic community is determined.

Sedimentation: It is expected that the area physically affected by sedimentation from the mining operation would be limited to within 1 to 2 km of the dredge and would be negligible with respect to the total OCS area. As the distance from the mining site increases, increasing numbers of species and individuals would be able to survive the decreasing level of resedimentation. However, additional effects may occur in hard bottom or live bottom areas proximal to mining operations where continued siltation may produce long-term effects (i.e., potentially long recuperative times). Sedimentation may hinder the recruitment of planktonic larvae to the community. Secondary problems may occur if toxicants, such as heavy metals, are released into the water column. Although the potential effects of toxicants are site-specific, it is expected that they would affect a greater area than the direct physical effects. In two sets of experiments in which invertebrates and fish were exposed to varying concentrations of kaolin clay (i.e., 10 to 100 g/L) and bentonite clay (i.e., 6 to 60 g/L; 10-d exposure), Peddicord (1976) found that most test species had extremely high tolerance for suspension of inert solids; the mortality rate was 10% after 10 d exposure to concentrations of 100 g/L. Small mussels were among the more sensitive species. Those that were sensitive were more easily killed at warmer temperatures.

An unspecified mineral dredging operation, probably for tin off western Thailand, was described at a United Nations working group as using bucket ladder dredges, rotary cutter suction dredges, and diver operated suction dredges. Operations produced a heavy turbidity plume from the ocean floor to the surface. Contrary to previous assumptions, it was reported that the offshore mining did not have adverse effects on the marine ecology. Although the turbid waters did affect the filter-feeding benthos, there were many animals tolerant to silt. The proliferation of filter feeders in turbid water may also occur because predatory fish are temporarily kept away from the area due to the turbidity. One year after the initial study, in very shallow waters of 10 m or less, there was a reduced number of species evident; in open waters of 20 to 30 m depth, there was no obvious effect evident (United Nations 1981).

Modification of Habitat: Modification of habitat may be the most persistent and wide ranging effect of offshore mining operations. In areas of high energy, where sand, gravel, and recent placer deposits might typically be mined, the physical effects would likely be evident for at least one full season (i.e., covering a year or less). Storm events and the natural high energy regime of these areas should mitigate the physical effects of the mining operations fairly rapidly. Recolonization of the area by the mobile fishery resources should also occur rapidly, but demersal or benthic fish species may not approach pre-mining levels (or be as stable as in the natural system) because of reduced benthic prey.

The major concern resulting from habitat modification would involve those species which spawn demersal eggs and have specific spawning grounds. Perturbation of the spawning areas for the Georges Bank Atlantic herring stock may cause modification of a relatively small area (in relation to the overall distribution of the population) but could have appreciable effects on abundance. Although direct mortality of the egg life stage would only occur during the spawning season, modification of the sediment structure by direct mining activities or resedimentation from nearby operations could have effects that span more than one year class. As Padan (1977) stated, it is important to understand the natural variability within the ecosystem.

In Project NOMES, over 650 species of benthic invertebrates were sampled. From month to month, up to 100% variability was reported. In fact, a species numerically dominant one month was absent the next. It was also found that species tended to change with sediment type. If the original sediment substrate is changed, the result may be no recolonization or recolonization by a different flora and fauna (ICES 1975; Padan 1977; de Groot 1979a; Drinnan and Bliss 1986). In contrast, the natural variability within the marine ecosystem, as observed in Project NOMES (Padan 1977), means that a change in a small area may have very little observable effect on the region. No studies have been done to directly address the consequences of pre-sorting, but it is generally accepted that the nature of the bottom flora and fauna is closely related to the substrate and, in particular, particle size (Dickson 1975). Changes in the residual sediment type will therefore result in changes in the nature of the bottom flora and fauna. Regeneration of bottom fauna measured by biomass sampling in and outside of old marine sand extraction pits offshore Europe took two to three years. Only in areas where tidal currents were minimal was full recovery not reached within four years (ICES 1979). It was found that the effects of dredging reduced the biomass values by about one-half.

It has been determined that bottom ecosystems will be less affected by dredging activities during the winter period and early spring, because bottom dwelling organisms have the best chance of recovering during summer. In one case, after 8,000 m^3 of material was removed, the bottom fauna recovered after 28 d. However, it is debatable whether recolonization actually occurred or whether migration from unaffected areas was coincidental (Wright 1977). Within the Canadian Arctic Circle, the full recovery of benthic communities reportedly takes more than 12 years (Aurand and Mamontov 1982). While there is obviously a relationship between dredging and the loss of epibenthic and benthic communities, the time for recovery has not been established. It is recognized that the time for recolonization of some dredged areas seems slow (Millner et al. 1977), and it appears that the reestablishment of benthos is dependent on the nature and stability of the sediment.

Sensitive Habitats: Sensitive habitats include such areas as coral reefs, spawning grounds, parks, and preserves. Chansang (1988) described the serious effects that sedimentation from tin dredging operations had on coral reefs in the Phuket area of Thailand. She stated that the immediate physical effects of dredging included gross disturbance of the area and creation of large quantities of suspended solids which affected biological resources in different ways. The most damaging effects occurred in sessile benthic organisms in shallow subtidal waters and intertidal areas. The sedimentation destroyed the reefs in the vicinity of the dredging operations, especially on the lower slopes. Partial recovery took place when dredging stopped during the monsoons and sediments were dispersed. However, repeated dredging resulted in what appeared to be permanent damage. The reef was subsequently host to the Crown of Thorns starfish and it was difficult to distinguish the causes of the further deterioration. In the United Kingdom, sensitive species and communities affected by marine aggregate mining have been listed to include sand eels, herring, coregonids, edible crabs, and infaunal communities (ICES 1992).

- **Threatened and Endangered Species**

This subsection addresses marine species (e.g., several species of whales, southern sea otters, manatees, and marine turtles) which are listed as endangered or threatened under the Endangered Species Act (USDOI, MMS 1991). These species would be subject to effects of the same nature and extent as the marine mammals discussed previously (e.g., turbidity, heavy metals, thermal shock, collision, shock waves, and noise). With the exception of whales, the species listed would be more likely found in coastal waters.

Increased Turbidity and Heavy Metals: Apart from certain whales, most of the endangered animals have their habitats in coastal areas and would not be affected by OCS operations three miles or more from shore. Leatherback turtles, which prey primarily on jellyfish, probably could not feed in a plume and would soon leave it. Thus, effects of mining on marine species would be dependant on the presence of the animals and their capability for plume avoidance.

Thermal Shock: During Project DOMES, it was shown that the introduction of cold water from the seabed (i.e., 3,000 to 4,000 m depth; temperatures of 3 to 4°C) into surface water had a detrimental effect on some organisms. In dredging operations on the relatively shallow continental shelf, the temperature difference between seafloor and sea surface water is small and would have less of an impact than that observed in the deep ocean.

Collision Impacts: Collisions of support vessels with slow swimming or feeding whales (e.g., fin, humpback, and right whales) is possible, especially as these species migrate through or become temporary residents of comparatively shallow coastal waters. Collisions with green, loggerhead, and Ridley marine turtles could also occur in coastal waters. Manatees that commonly occupy waters near onshore support bases could also be affected. Leatherback turtles (offshore) and sperm whales (sleeping or resting at or near the surface, usually farther offshore) could also be involved in collisions with support vessels. Overall, however, the effects due to these activities would probably be negligible, especially if voluntary or mandatory boat speed restrictions and sighting programs were conducted in areas of known or suspected concentrations of these animals.

Noise: Noise from aircraft could temporarily disturb seals and sea lions on their rookeries and haul out areas, although there are few data on this problem. In Alaska, a few southern sea otters are likely to inhabit waters near potential support bases, but no appreciable effects on a significant part of the population were anticipated due to collisions or increased noise (USDOI, MMS 1991).

Impacts of Shock Waves: Explosives and geophysical activities would probably not affect marine species in coastal waters, but they could have slight to moderate effects on the preferentially pelagic whale (i.e., blue, sei, and sperm whales) and turtle (i.e., leatherback) species farther offshore. Effects of explosives on marine mammals would be negligible as noted previously. A relatively small number of sperm whales might encounter geophysical shock waves in an offshore or deep water lease area. If present, these whales could experience some disturbance and indirect feeding effects when foraging at depths of up to 1,000 m or more, especially if sound waves produced by air guns were directed downward from their source. At present, there are no quantitative data on the effects of shock waves.

Accidental Discharges: Similar observations noted previously regarding marine mammals and the negligible impact of accidental discharges of oil, also apply to all endangered and threatened marine species. Effects on exclusively or dominantly terrestrial endangered and threatened species would depend primarily on which support bases were used and if ore were processed onshore. Before mining begins, existing facilities at the potential support base locations would probably require little or no expansion. Hence, associated adverse impacts on terrestrial species (e.g., plants, insects, reptiles, most birds, and mammals) in and near coastal areas or estuaries would be minimal or non-existent. After mining begins, new or expanded onshore support bases and processing facilities might be required. However, the precise locations of or necessary changes to existing port and processing facilities needed during mining will be unknown until exploration and testing are partially completed. Impacts on the environment, and especially on endangered and threatened species, that might result from development at these locations will be reviewed and evaluated when industry submits specific mining proposals with the level of detail needed for such evaluation.

2.3.2.5 Social and Economic Environments

OCS mineral operations could result in changes of land use, demographic conditions, and employment, particularly when coastal onshore support bases or processing facilities are located in areas of traditional commercial fisheries. The degree of change will depend on the size and nature of the operations and the existing characteristics of the affected coastal region. If the region is already heavily developed and populated, the potential effects are likely to be insignificant and easily absorbed. On the other hand, in sparsely populated coastal regions or areas with a simple economic base, the potential effects could be significant (USDOI, MMS 1991).

- **Military and Special Uses**

Portions of the air and water spaces of the OCS, except in the Alaska Region, are designated for military operations essential for national security and defense (USDOI, MMS 1991). These areas are under the control of the U.S. Department of Defense (DOD). In the Atlantic OCS, designated areas are set aside for use by the National Aeronautics and Space Administration (NASA). In such areas, potential government/industry conflicts or hazards may occur through interference of electromagnetic signals, weapon systems testing, missile launches, and collisions among ships. Other special uses involve designations as parks and sanctuaries.

National Marine Sanctuaries: Certain areas of the OCS, except in the Alaska Region, are included within the boundaries of national marine sanctuaries designated, or to be designated, under the Marine Protection, Research and Sanctuaries Act of 1972. This law was enacted to protect significant marine resources through special management plans and regulatory measures. The program is administered by the USDOC, NOAA. Management plans for most of the sanctuaries include measures restricting or prohibiting OCS oil and gas activities and minerals dredging.

- **Human Environment**

The human environment, as used here, refers to the effects of operations on human health and safety, including affected subsistence activities.

Health and Safety: The potential for affecting human health as a result of OCS dredging operations has been a point of contention only in the Norton Sound Lease Sale EIS (USDOI, MMS 1988b, 1990b, 1991). In this case, it was feared that free mercury (Hg) from previous gold amalgamation activities during beach mining might affect the local population through a build up of mercury in fish and shellfish in the area. Extensive studies were initiated in November 1988 with a workshop on *Mercury in the Marine Environment* (USDOI, MMS 1989b) as a result of the scoping process for the Draft EIS. Experts in the areas of water and sediment sampling, effects of trace metals on marine organisms, habitat alteration, and mercury effects on human health provided their knowledge to assist in development of the EIS. Sampling in that year showed that the levels of mercury in the water column did not exceed established EPA criteria. A second Draft EIS was prepared in June 1990 (USDOI, MMS 1990b) in which it was indicated that the conversion of mercury to the more toxic and bioaccumulative methyl mercury was unlikely to reach significant levels. Even on a cumulative scale, dangerous levels in the Nome area were not expected. There are no other records of danger beyond the standard hazards to health of living and working in the ocean environment, mainly due to heavy weather.

Subsistence: Subsistence is a system of production and consumption activities based on the harvest of naturally-occurring resources. Many Alaskan Natives and American Indians depend on subsistence for their livelihood and for linkages to their cultural heritage. In Alaska, some Eskimo tribes are dependent on the availability of certain whales, seals, fishes, and birds which occupy or transit the same offshore areas as potential mineral resources. Their subsistence lifestyle could be severely affected by mining operations. These concerns could apply also to areas offshore Washington and Oregon where certain American Indian Nations, through treaties with the U.S. Government, possess special fishing rights on certain species.

- **Commercial and Recreational Fisheries**

Potential effects of OCS mining on nearby fishery resources will include direct coincident mortality, habitat modification, and sublethal effects (USDOI, MMS 1991), as well as a number of real or perceived conflicts that may be site-specific. The nature or severity of these effects will depend on a combination of operational and site-specific variables such as the mining system used, the site environmental characteristics, and the species involved.

Direct Coincident Mortality: The level of risk to a particular species will vary indirectly with the mobility of the species and directly with the species abundance at the site. Less mobile species, such as molluscs, crabs, and some demersal fish, will be at risk to a greater degree than more mobile forms. If a species demonstrates a higher degree of habitat or location fidelity, it may be at greater risk. The most susceptible species are the bivalve molluscs; many of the commercially valuable species in this group can be found in the well-sorted, large-grain-size, offshore environments which are potential sand and gravel mining sites. In general, the potential to significantly affect the population level of these typically wide-ranging species by mining is not great. However, for some species, such as calico scallops off the south Atlantic coast that have limited distribution, mining operations in the major distribution areas could affect the population level for a few years. Some of the less mobile crustacean and fish species may be affected to a degree; however, the direct lethal effects of OCS mining operations may be limited to a relatively small number of individuals and should have no significant effect on the total population or its distribution. The distribution of dispersed fines is reportedly of concern to fisheries personnel; however, Millner et al. (1977) addressed the smothering of eggs and fish larvae by fines and concluded that the outwash material from a dredging vessel would not have a significant effect, especially in areas with a high natural turbidity due to tides or storm waves.

Habitat Modification: The flow of water over the seabed generates noise spectrum characteristics that could represent a means for herring to recognize and return to their spawning grounds. Furthermore, species will tend to spawn on particular substrate types, such as herring which spawn on gravel bottoms devoid of sand (de Groot 1979b). Thus, if dredging changes the nature of the seabed in known spawning sites, it could affect fisheries (GESAMP 1977). Extraction of material may expose boulders or other natural objects, increasing the potential for damaging fishing gear; however, this is not a widely-voiced concern. Furthermore, the furrows created by trailer suction dredging are usually quite shallow (i.e., less than 0.5 m) and the potential for increasing the exposure of boulders is quite small. Removal of sand from a rocky subsurface (e.g., Seine Bay, France) resulted in new animal communities which had hardly any value to bottom fish. In the immediate future, the local fishing industry could suffer (de Groot 1979a). In contrast, Drinnan and Bliss (1986) reported that research has been carried out by scientists of the Ministry of Agriculture, Forestry, and Fisheries (MAFF) in the U.K. Although not conclusive, results from more than two years of study indicated that no permanent damage was evident and overall recruitment appeared to be normal in the dredged area.

Sublethal Effects: Sublethal effects may occur as a result of resuspension of bottom sediments in the immediate area of the operations, causing decreased growth of filter- or suspension-feeding organisms (e.g., molluscs) due to decreases in normal respiration, metabolism, growth, reproductive capacity, response to external stimuli, and predator response. Elevated levels of toxicants in the water column resulting from resuspension of previously sediment-bound sources would exacerbate these sublethal effects but may only be evident within a kilometer or two downcurrent of the mining site. The overall effects on commercial fisheries resources may be insignificant on a regional scale but can be serious from the point of view of individual fishermen and must be addressed initially in the mining plan. The potential or perceived effects will include spatial exclusion, gear damage, reduction of harvest, and reduction in quality of fish stocks.

Spatial Exclusion: Complaints of space-use conflicts with miners can be anticipated in three areas of commercial fishing activities, including (1) dock and repair facilities; (2) onshore service facilities; and (3) offshore areas (USDOI, MMS 1991). In many areas of the U.S., dock space is at a premium and it is becoming increasingly difficult for commercial fishing operators to find adequate and affordable dockage. Thus, some space-use conflicts may occur in these areas between commercial fishing vessels and the service boats or tugs of the OCS mining industry. It is also possible that mining operations could compete for commercial fishing industry onshore facilities such as processing plants and warehouses, particularly where these facilities are limited. Competition for these facilities would increase the daily operations costs for fishermen. Probably most important, at least in perception, would be lost or preempted fishing areas excluded from the immediate vicinity of the operations. These areas would not necessarily be large, however, as most dredging activities on the continental shelf do not cover more than a few square kilometers. The combined dredging and ongoing development activities on the WestGold leases off Nome, AK covered about 10 km^2 at any one time, which is typical of placer deposits.

Gear Damage: Loss of gear can be a serious area of conflict between miners and fishermen (Tsurusaki et al. 1988). Losses might be generally limited to fixed gear such as pots, gillnets, and longline, and may be caused by the increased traffic on the fishing grounds as a result of servicing the mining operation or by natural causes.

Reduction in Harvest: Some reduction in harvest might occur as a result of mining operations if spawning areas are destroyed. More likely, the harvest will not be affected, or may be improved because of increases in nutrients from the seabed made available by the benthic perturbations. The attraction of fish to the tin dredge areas in southeast Asia has been reported to one of the authors (M. J. Cruickshank). The dredges, like oil and gas platforms in the Gulf of Mexico, are reputedly superior locations for fishing. The effect of sand and gravel operations using hopper dredges will be transient; large placer mining dredges are generally operating in the same location for decades, prompting long-lived, mining-related effects.

Reduction in Quality: It is not anticipated that any mining operations would have an effect on the quality of any regional commercial harvest. Most OCS areas are beyond the normal range of heavy metal and other pollutants normally found in harbor and other coastal areas contaminated by dumping. Nevertheless, the possibility of contamination from disturbed sediments is a sensitive issue and would need to be addressed.

- **Regional and Local Economies**

For many States, the coastal zone shoreward of the OCS is the most important natural resource and economic asset in the long term. The potential effects of OCS development on the environment is a serious and sensitive issue because of its impact on regional economics and the quality of life. Analysis of the benefits and costs of OCS mining may require extensive and objective research to determine local and regional characteristics. The effect of operations on local or regional economies must be determined on the basis of site-specific, commodity-specific. and time-specific analyses.

Recreation and Tourism: There are many types of mineral deposits, mining methods, and environments in which OCS mining may occur. However, the operations will not be within three nautical miles or greater than 200 nautical miles from shore. In that context, the effect of the operations on recreation and tourism must be considered. The effect may be entirely subjective to some people (e.g., an operation of this nature could be an attraction). An effect on recreation and tourism that is currently topical is the need for beach restoration in many areas of the U.S. and elsewhere. It was ill-advised and is no longer permissible to sacrifice unused beaches to replenish recreational beaches in populated areas. Sources of sand for replenishment are being sought in the OCS and in territorial waters. Whereas the technology is not well advanced for characterization of offshore sands, particularly in tropical reef areas, the need to produce offshore sands is critical in many locations. There may be some effects due to the need for shoreside facilities, but they would be considered in the same light as any other commercial waterfront project. Impacts of such sand recovery operations in the coastal zone are discussed in the coastal section (**Section 2.3.3**).

- **Cultural Resources**

The involvement of the Federal Government in the protection and management of archaeological resources on the OCS is mandated by environmental laws which are designed to govern postlease discovery, delineation, and mining of minerals other than oil, gas, and sulfur. Important statutes include (1) NEPA [P.L. 91-190], which declares as a national policy the preservation of important archaeological resources on the OCS; (2) OCSLA [P.L. 95-372], which mandates that activities must not disturb any significant archaeological resources located on the OCS; and (3) NHPA [P.L. 89-665], as amended, which states that any Federal agency, prior to approving Federally-funded undertakings, must take into consideration the effects of that undertaking on any property listed on or eligible for, the National Register of Historic Places. Implied in this legislation and Executive Order 11593 is that an effort must be made to locate such sites prior to development of an area. Section 11(9)(3) of the OCSLA, as amended, states that "such exploration will not...disturb any site, structure, or object of historical significance." Activities which might affect offshore historic sites include anchoring and mining. The potential for such an effect occurring as a result of OCS operations is very low because of the distance offshore, however, the potential presence of shipwrecks and other artifacts must be evaluated. Sites of prehistoric habitation by early man (e.g., during periods of lower sea level) may also be found.

2.3.3 Coastal

Coastal areas include territorial waters as well as associated estuaries, fjords, bays, and wetlands. Estuaries and wetlands are generally defined as bodies of water which have a limited exchange capability with the sea. The degree to which this exchange with the sea occurs determines many physical and biological characteristics of the estuary. Estuaries are found at the mouths of rivers, in bays, or behind barrier islands and spits. In all cases, the variation in salinity within the estuary and nearshore (adjacent) coastal waters is a singular property. The sources of this variation are freshwater inflow and runoff, precipitation, and evaporation, with the latter two factors playing a minor role where inflow is high.

The following habitat types are generally characteristic of the wetland and estuarine environments: (1) estuarine open water and bottom; (2) seagrass beds; (3) barrier islands; (4) mangroves; (5) tidal marshes; (6) forested wetlands; and (7) terrestrial habitats. These habitats usually occur in this sequence lying in bands parallel to the coast. The habitats are sharply delineated, highly productive, and consist of zones of diverse species. Many fish and wildlife species are dependent upon the estuarine environment for part of their life cycle, or rely on its abundant food sources. Estuarine habitats are especially important to migratory waterfowl and many endangered or threatened species of birds, reptiles, and mammals.

Benthic communities in coastal environments are distributed largely on the basis of sediment type and water depth. Additional factors which control the occurrence of benthic organisms are salinity, temperature, currents, and food availability. Benthic infaunal and epifaunal representatives offshore include almost all animal phyla.

Coastal habitats are highly productive for a great number and a wide variety of invertebrates, fish, reptiles, amphibians, birds, and mammals. The central origin of biologic productivity on the Gulf of Mexico coast are the vegetated estuarine habitats; on the U.S. west coast, wetlands and estuaries are extremely important as spawning or nursery area, also serving as a nutrient source for several fisheries.

Impacts to wetlands from coastal mining operations might be adverse if operations were actually located within wetlands. These activities could result in local disturbances or destruction of the wetland or estuarine environments from drilling, extensive dredging, or other such activity.

The primary marine mining operations in coastal environments include recovery of industrial minerals and mineral sands. These operations can also take place further offshore in the OCS, and there is significant overlap between the two regions with respect to the affected environments and the potential effects. To avoid unnecessary redundancy, these areas of overlap have been covered previously in **Section 2.3.2**. This section focuses on issues which are strictly coastal, with reference to the previous section where appropriate to complete the examination.

Large-scale dredging operations in coastal waters are taking place worldwide to maintain waterways and recover aggregates for construction and beach replenishment. It is estimated that nearly 90% of this activity pertains to maintenance dredging. For example, between 1979 and 1985 in the North Atlantic, North Sea, and Baltic Sea, more than 400 million m^3/year were moved to maintain waterways, while about 50 million m^3/year of sand and other aggregates were recovered for construction, beach replenishment, and recovery of valuable minerals (de Groot 1986). This is the equivalent of more than 150 full-scale manganese-nodule mining operations.

Extensive environmental studies have accompanied these operations for the past 20 years, and the state of knowledge is quite advanced in many areas. Recent summaries are available which discuss the major conclusions from this work (e.g., Wilson and van Dam 1989). Some of the key aspects from this work are described in the following text.

2.3.3.1 Atmospheric Environment

The most important differences between the surface atmosphere on the coast and in the OCS is the proximity to people and the potential for accumulation and trapping (e.g., inversion layers) of pollutants. Existing air quality in coastal areas worldwide varies tremendously, from almost pristine in some regions to extremely polluted in others. Marine mining can affect air quality primarily through emissions from power equipment. Such emissions constitute only a very small percentage of the emissions for most areas where marine mining has been considered, and air quality effects have been predicted and observed to be insignificant (e.g., USDOC, NOAA, 1981; USDOI, MMS, 1983b; USDOI, MMS and HI, DBED 1990).

2.3.3.2 Oceanic Environment

Probably the most significant type of effect potentially caused by coastal marine mining operations is the incidental introduction of materials into the water column. As discussed in **Section 2.4**, among all the published data sources examined for this study, those dealing with water quality effects on coastal environments were the most common. Recovery of industrial minerals and mineral sands requires the removal of large quantities of seabed materials, a step which inevitably leads to varying amounts of turbidity and disruption in the water column and modifications to the seabed. Water quality effects, in general, are the same as those discussed in detail in **Section 2.3.2**. In coastal environments, water quality concerns are usually more complex and more intense than further offshore. Prediction of water quality effects is completely site-specific and often not successful. Much progress has been made in the conceptual tools and field techniques which can be employed (see **Chapter 4**), and it is currently possible, with combined modeling and field verification, to predict with fair accuracy the mean characteristics of a dredging discharge plume (e.g., Garvin et al. 1991).

- **Natural Effects**

In coastal environments, the dominating influences on human and natural resources are generally effects of natural processes (e.g., tides, storms, volcanic emissions, and river discharges). Industrial minerals and mineral sands are both created and often occur in high-energy environments, where current speeds reach levels which can transport dense, relatively large mineral grains to the deposit sites. Fine-grained, less dense materials are also carried away from the site. Assessment of the effects of marine mining on these resources must be based upon the often widely variable conditions which are found at operation sites.

In these high-energy environments, both the mining operators and their potential regulators face significant uncertainties regarding performance predictions for recovery and transportation of deposit materials. Operators cannot expect the government to provide clear, unambiguous guidance to avoid significant environmental impacts. Further, the government must be able to provide site-specific evaluations for mitigation of potential environmental effects for each operation and provide sound performance restrictions where required.

- **Induced Effects**

Effects of mining operations on water quality of coastal waters are generally the same as those discussed previously for the continental shelf (see **Section 2.3.2.2**). The aspects of water quality most likely to be affected are (1) the turbidity generated by the primary recovery of the ore; and (2) the discharge of mined tailings. In shallow coastal waters, resuspension of tailings piles can also be significant (Rusanowski et al. 1987). Gold mining operations in the coastal waters off Nome, AK produced significantly elevated turbidity levels to distances of 0.5 to 1 km downstream from the operation (USDOI, MMS 1991). Sand and gravel recovery operations produced similar but larger turbidity plumes (USDOI, MMS 1983a). Increased levels of trace metals are not generally caused by coastal offshore mining of placer deposits, which are accumulations of physically and chemically stable minerals.

If there is a relatively large fraction of fine-grained materials in the recovered ore, the oxygen level and trace metal content in coastal waters may potentially be affected. However, depressed or elevated oxygen levels can be expected only in close proximity to the actual operation. Extensive monitoring of the WestGold mining operation off Nome and nearby coastal waters clearly showed that there were no significant increases of mercury, lead, arsenic, or other dissolved trace elements attributed to mining (Crecelius et al. 1990).

2.3.3.3 Geological Environment

As discussed previously in **Section 2.3.2.3**, coastal marine mining can affect the geological environment primarily by (1) modification of the seabed through removal of materials; or (2) by deposition of suspended particles. Activities which move large amounts of material, including most coastal mining operations, can alter water circulation patterns and modify littoral sediment transport. Such changes can result in major changes to coastlines and significant alteration of benthic habitats (Otvos and Sikora 1991). Extensive research has been done in recent years to effectively address such problems associated with large dredging operations (e.g., Isobe 1987; Bakker et al. 1988; Hurme and Pullen 1988). Several efforts are also underway to address the unique characteristics of tropical island operations; these operations are relatively small, but require more exacting standards for prediction (Levin 1971; Gerritsen et al. 1992). These efforts include extensive computer and physical modeling combined with field verification. Optimally, these will become standard planning tools for development of coastal deposits.

2.3.3.4 Biological Environment

Effects on biological communities from coastal mining are caused primarily by the turbidity plumes and seabed habitat modification described previously. Although these effects are similar to those discussed for the continental shelf (**Section 2.3.2.4**), they tend to be more acute. Effects on birds, plankton, fish, special habitats, threatened and endangered species, and other organisms are completely site-specific and technology-specific and not amenable to a generic examination. Effects on benthic life do have some common denominators which are discussed in the following text.

As noted previously, maintenance dredging is more important quantitatively than dredging for marine mining. Much of the research in this area is quite properly focused on maintenance dredging. Because of the magnitude of maintenance dredging, its environmental effects can be expected to be significantly larger. In addition, the types of materials which are handled in maintenance dredging are generally of much greater concern than those which are dredged for construction aggregates, beach replenishment, or recovery of placer minerals. Deposits utilized to provide these latter three commodities must be of fairly coarse texture (i.e., medium sand or larger) and generally do not contain the toxic metals and organic compounds which accumulate in waterways. It is critical to keep these basic differences in mind when assessing the potential effects of both activities.

After many years of intensive monitoring of beach replenishment operations in mainland U.S. waters, it is apparent that very few significant effects on benthic life occur if (1) the replacement sand has similar properties to the original; and (2) the long-term topographic profiles of the beach and the borrow site are not drastically modified (Hurme and Pullen 1988).

- **Benthos**

Additional potentially lethal or sublethal effects may also be expected from mining operations in benthic environments of coastal waters (e.g., fouling of feeding structures, increased predation, decreased prey). Studies of change in the macrobenthos in a dredged shallow area at Goose Creek, NY indicated that recolonization of crabs and small bivalves occurred within one to five months; however, after 11 months, the biomass was still lower than the original values (Kaplan et al. 1975).

Biological Effects of Bottom Perturbation: In 1974 and 1975, a study was performed offshore La Havre, France where the River Seine enters the North Sea. The design of the study was to determine the environmental effects of channel dredging. Dredging plans called for removal of 1.2 x 10^6 m^3 of sand, creating a channel measuring 1,700 m long, 70 to 150 m wide, and 4 to 6 m deep (ICES 1975). Two months after dredging was completed, the pebbles in the trench were thickly covered by two species of hydroid and a single species of bryozoan. After four months, many other species had recolonized the area including both attached sessile animals and members of the mobile epibenthos. In conclusion, it was found that the removal of the overlying sand resulted in the development of completely different species on the gravel substrate. The larvae from the plankton, rather than movement of adults, appeared to be the most important source of recolonization.

- **Sensitive Habitats**

Sensitive habitats include such areas as marine sanctuaries, coral reefs, seagrass beds, and spawning grounds. Turbidity appears to be of concern only in special cases involving ecosystems with unusually high sensitivity. Two possible examples are coral reefs and seagrass beds (Drinnan and Bliss 1986).

- **Threatened and Endangered Species**

The possible presence of threatened and endangered species in a mining area would be determined very early in the environmental analysis and would be a prime consideration for any operation. Examples of threatened and endangered species in U.S. coastal waters include monk seals, sea otters, and certain migratory whale species.

2.3.3.5 Social and Economic Environments

The general concerns pertaining to these environments have been discussed previously in **Section 2.3.2.5** for the continental shelf. Where specific problems may exist that are unique to coastal waters, additional discussion is provided.

- **Human Environment**

The effects of mining operations on human health and safety are of paramount importance and include secondary effects such as those due to mercury dispersion (Minimata, Japan) or overcrowding (Takua Pa, Thailand). As with the biological effects, social and economic effects of coastal operations are similar to, but often more intense than, the effects caused by mining on the continental shelf. Potential effects on commercial fisheries include direct use conflicts and damage to breeding grounds. Effects on local tourist economies may be significant if turbid sediment clouds or noisy and unsightly equipment are visible from the shore. Strong opposition was indicated at public hearings in Waikiki, HI with regard to the proposed dredging of beach fill material from offshore in 1991. The sight of a dredging vessel offshore Ocean City, MD in the summer of 1992 did not seem to affect the tourism industry in that area (B. S. Drucker, 1992, personal communication, USDOI, MMS). Personnel supporting the mining operation can affect the social structure of very small communities in potentially undesirable ways.

In general, it is essential that the potential coastal miner be very sensitive to these and other potential effects early in the planning of any coastal operation. Maximum use of local talent, minimization of noise and surface plumes, and recognition of known fishing grounds are wise policy guidelines.

2.3.4 Onshore

Offshore mining activities carried out to date and discussed in **Sections 2.3.2** and **2.3.3** for the continental shelf and coastal environments have been limited to the production of construction materials, and placer operations for diamonds, gold, and cassiterite (an inert oxide of tin). In these circumstances, the onshore environments affected have been limited to relatively small areas used for staging and storage (see also **Section 2.4, Tables 2.25** and **2.26**). Beneficiation is carried out on the placer dredges and the concentrates brought ashore for further treatment are usually only a minor fraction of the dredge throughput. The environmental literature on these aspects of the operations is very limited and has been cited in appropriate sections of this document.

Onland activities involving offshore phosphates have been considered in Georgia and North Carolina (Drucker 1992). Major problems arising would be similar to those in existing phosphate mining areas on land. In these areas, the effects on water quality related to the disposal of processed fines are of major concern, resulting partially from low lying, flat terrain and near-surface water tables.

In the case of deep seabed mining for nodules, crusts, or sulfides, onshore impacts due to the processing of the submarine ores have been considered in some detail. This onshore emphasis is attributable to the fact that the early operations will require land-based rather than sea-based processing. These actions have been considered in the EISs prepared for proposed licensing or leasing of the minerals by the U.S. Government. For nodules, four major activities associated with onshore processing were identified as having potential significant effects: (1) use of port facilities; (2) transportation of nodules from port to processing plant; (3) processing of the nodules; and (4) waste disposal. Each of these activities would result in construction and operational effects. Waste disposal presents the greatest concern because of the high volume of material and the chemical and physical nature of the wastes, depending on the process used. Land use, contamination of surface and ground waters from runoff and seepage, and dust are the principal environmental concerns expressed. Onshore disposal of the large quantities involved, up to 3 million tons/year, in either land fills or tailings ponds will require relatively large areas of land.

The ability to use a landfill depends on the water content of the waste material, which can be reduced if an energy intensive drying step is included. In general, only slags from a smelting process appear to be suitable for landfill. For tailings ponds, land reclamation would largely depend on the physical characteristics of the tailings and the degree to which the tailings stabilize when free water evaporates or is removed. Depending on the processing techniques and the net evaporation rate typical of the region in which the disposal facilities are located, it is possible that the tailings could remain unstable for years and, as a further consequence, that the land could remain unsuitable for other uses for an extended period of time. The contamination of local ground water, surface waters, or aquifers as a result of seepage of liquid wastes from slurry tailings ponds and leachates from landfills may be one of the more significant potential problems associated with the onshore disposal methods. Negative environmental effects could be mitigated by (1) locating the disposal facilities in arid or semi-arid regions; (2) locating the facility in an area where the subsurface geology consists of relatively impermeable soil or rock; or (3) providing a compacted, relatively impervious base of clay type soils or a man-made liner for the landfill or tailings pond (USDOC, NOAA 1981). More recent studies have indicated that it might be possible to process the tailings from these plants into saleable products such as building materials or fill (Wiltshire 1993).

The situation with regard to high-cobalt crusts, examined in general terms for Hawaii, is very similar to that for nodules. Nearshore biota and terrestrial biota in the immediate vicinity of the processing plant would be affected by the construction and operation of the processing plant. Land use once changed from conservation or agricultural zoning to residential, industrial, or commercial use zoning probably would not be rezoned to its current zoning. Considerable resources would be diverted from other uses to service the operation (USDOI, MMS and HI, DBED 1990).

In the case of metalliferous sulfides, onshore activities associated with support bases and ore processing operations were identified as key issues (USDOI, MMS 1983b). Processing of sulfide ores is distinctly different from that of oxide ores but the requirements for mitigation, in general, would be similar. Land ore mining mitigation options have been well examined over the years.

No production operations for any of these minerals has yet taken place, however, the processing scenarios postulated in these documents are considered to be still valid, within the limits of the assumptions made at the time. The conclusions on onshore effects of processing of manganese nodules are summarized in **Section 2.5** (see **Tables 2.27** and **2.28**) and are indicative of the types of effects for other commodities.

Because it is based on actual measurements, the work done in evaluating the effects of mineral tailings on marine biota (as analyzed and reported by Ellis [1987, 1988, 1989] and Ellis and Hoover [1990]) is probably of more significance at this time. Their efforts were based on the monitoring of tailings disposal into the marine environment from coastal mines onshore. Examples of 29 such operations are given in **Table 2.22**. Of particular significance are the data from three operations in fjords in British Columbia at Rupert Inlet (Island Copper Mine), Howe Sound (Anaconda Britannia Copper Mine), and Alice Arm (AMAX Kitsault Molybdenum Mine), as shown in **Figure 2.43**. In each case, tailings were discharged into the sea; changes in the biota were recorded during the operations (i.e., while tailings were being discharged) and following closure of the mining facility. The only exception is the Island Copper Mine which remains operational.

2.3.4.1 Atmospheric Environment

As was noted for coastal areas, the variety of climate among onshore locations is very great, ranging from tropical rainforest and hot desert to arctic tundra. Onshore air

Mine	Main Product	Tailings Disposal	Environmental Monitoring (see key below)
		Canada	
Island Copper	Cu/Mo	Fjord 50 m depth (Waste rock-shoreline)	All listed components
Kitsault	Mo	Fjord 50 m depth	"
Polaris	Pb/Zn	Lake (Relict marine inlet)	g, h
Nanisivik	Pb/Zn	Lake (Marine disposal assessed)	a, b, f, h
Wesfrob	Fe/Cu	Fjord 12 m depth	a, b, f, h, j, m, n
Yreka (closed)	Cu	River and shoreline, fjord	None
Texada (closed)	Fe	Surface Open Coast	Post-closure h
Jordan River (closed)	Cu	10 m Depth Open Coast	a, b, d, f, h, j, m, n
Brynnor (closed)	Fe	Beach	Post-closure k
Britannia (closed)	Cu	River and shoreline, fjord	n
		U.S.A.	
Quartz Hill (under development)	Mo	Probably deep to fjord	All listed components
		Greenland	
Black Angel	Pb/Zn	42 m depth, fjord	a, d, f, g, h, j, n
		Norway	
Fosdalens Bergverk	Fe	60 m depth, fjord Some barging	a
Orkdalfjorden	Cu	Not known	j
Repparfjord	Fe/Cu	50 m depth, fjord	a
Stjernøy	Fe	Fjord	No information
		U.K.	
Cleveland Potash	Potash	Submarine	a, f, j, l
Hayle estuary (closed)	Sn/Cu	Estuary	f, n post-closure
St. Austell (closed)	China clay	River and Sea	j, k, l post-closure

Table 2.22. Coastal mines and their environmental impact assessment programs (Adapted from: Ellis 1987).

Mine	Main Product	Tailings Disposal	Environmental Monitoring (see key below)
		Mediterranean	
Pennaroya	Pb/Zn/Fe		No information
		South America	
El Salvador (Chile)	Cu, Mo	Shoreline	a, f, j, k, l, m, n
Potrerillos (closed)	Cu	Shoreline	No information
Toquepala Cuajone (Peru)	Cu	Shoreline	No information
		East Asia/Oceania	
Ma On Shan (Hong Kong) (closed)	Fe	Shallow Inlet	f, j, n
Marcopper (Phillippines)	Cu	Surface Open Coast	Most listed components
Atlas (Philippines)	Cu	Surface, Open Coast	"
Bougainville (P.N.G.)	Cu	River and Shoreline	"
Ok Tedi (P.N.G.)	Cu/Au	River	"
		Australia	
Tamar River (Tasmania) (closed)	Au	River	"

Key to environmental monitoring components

a. Tailing discharge rates and chemical analyses
b. Acute bioassays (LD_{50}s, etc.)
c. Other bioassays (long-term *in situ*, etc.)
d. Turbidity (suspended solids, etc.)—ambient levels
e. Density current (tailings plume)
f. Tailing deposition (coring, bathymetry, chemical, mechanical, etc.)
g. Physical oceanography (current measures, stratification, etc.)
h. Chemical oceanography (trace metals, dissolved oxygen, nutrients, etc.)
i. Biological oceanography (primary production, phytoplankton, chlorophyll, zooplankton, ichthyoplankton)
j. Benthos (stocks and dynamics)
k. Shellfish (stocks and dynamics)
l. Fish and wildlife (stocks and dynamics)
m. Shoreline (stocks and dynamics)
n. Trace metal bioaccumulation and biomagnification

Table 2.22. **(Continued).**

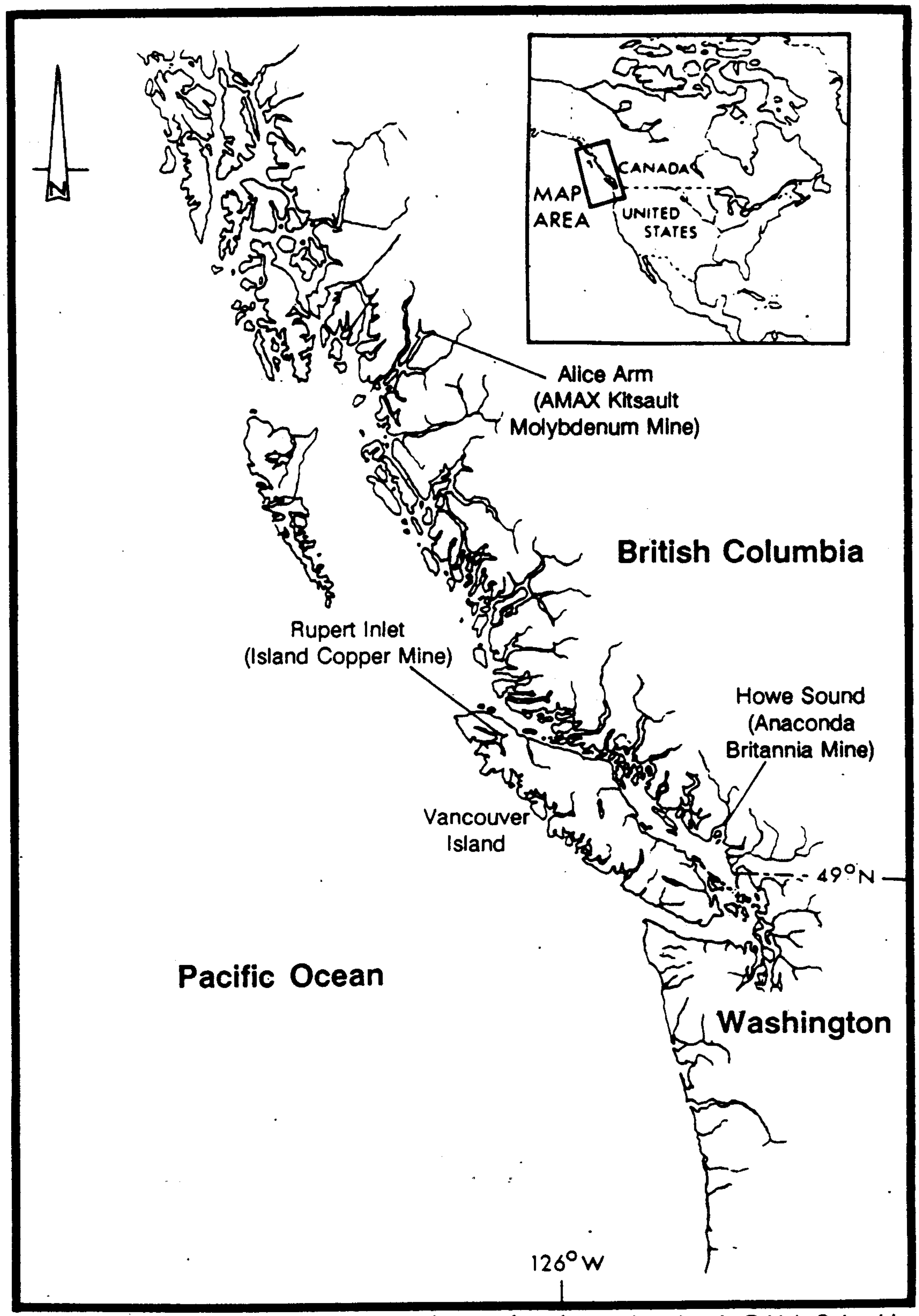


Figure 2.43. Locations of three fjords and coastal onshore mine sites in British Columbia at Rupert Inlet (Island Copper Mine), Howe Sound (Anaconda Britannia Mine), and Alice Arm (AMAX Kitsault Molybdenum Mine) (Adapted from: Ellis 1987).

quality will likely be more sensitive to incremental increases in pollutants than offshore locations. These matters should be addressed in site-specific studies.

2.3.4.2 Aquatic Environment

Aquatic environments of concern onshore include (1) proximal supplies of freshwater, for dedicated mineral processing facilities, and the possibility of contamination from the plant (USDOI, MMS and HI, DBED 1990); and (2) the adjacent waters into which processing or mine wastes may be discharged for disposal.

- **Natural Effects**

Effects of natural systems (e.g., floods, ice, tidal bores, tsunamis) would tend to increase the need for contingency planning in development of onshore facilities. Small island areas are probably the most at risk in the U.S.

- **Induced Effects**

Induced effects occur as a result of mining infrastructure or processing operations. For example, excessive use of a critical aquifer or the addition of chemicals to the ground water system represent induced effects attributable to the mining operation. These concerns would necessarily be addressed in the early stages of planning.

2.3.4.3 Geological Environment

Effects on the coastal zones, including erosion or siltation of coastlines, tidal waters, coastal waterways or streams, are normal concerns of onshore coastal zone planning. The effect of placement of large quantities of material on adjacent coastal seabeds might be significant and should be subject to stringent analyses.

2.3.4.4 Biological Environment

The effects of mining activities on the onshore biological environment (e.g., birds and mammals) would not be unique to the association with a marine mining operation. The delineation of impacts would require a standard analytical approach. The same would apply to marine and aquatic flora and would be site-specific.

- **Marine and Aquatic Fauna**

Ellis and Hoover (1990) documented the pattern and rate of tailings recolonization by benthic species at three British Columbia mines. The nature of reported changes is illustrated in **Table 2.23** which summarizes the data for two stations monitored at Island Copper between 1977 and 1989. These stations, all located near the outfall, were the most affected. A total of 43 different taxa were recorded over the study period with a pronounced change evident in the particular species present, most of which were polychaete worms. Recoveries from an occasional total absence of some species indicated that smothering or removal by turbidity currents was the reason for their demise, rather than

	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	Means	Total
No. organisms/m^2															
Stn. 15	133	180	380	1033	6	0	33	26	1373	940	53	73	660	376.2	
Stn. 16	646	0	26	793	100	440	1420	886	633	26	240	620	3473	715.6	
Number of taxa															
Stn.15	4	5	4	9	1	0	2	2	11	8	3	6	7	4.8	27
Stn. 16	4	0	3	8	3	5	2	4	4	2	9	10	10	4.9	29
Glycera capitata (PE)	15	15		15,16		16			15		16	16	16		
Heteromastus filobranchus (PS)	15	15	15	15				16	15		15,16		16		
Tharyx multifilis (PS)	15												15		
Corophium sp. (CA)	15												15		
Calliophius sp. (CA)	16														
Gammaridae immat. (CA)	16														
Tiron sp. (CA)	16			16											
Flabelligeridae immat. (PS)	16														
Lumbrineris sp. (PE)		15		15											
Psephidia lordi (BM)		15													
Chaetozone setosa (PS)		15	15	15					15	15					
Lumbrineris bicirrata (PE)			15						15						
Lumbrineris luti (PE)			15,16	16	15,16	16	15		15	15	16	15,16	15,16		
Cumella vulgaris (CC)			16												
Eualis sp. (CD)			16						16						
Crangon alaskensis (CD)				15											
Phyllodoce groenlandica (PE)				15											
Cossura sp. (PS)				15,16	16										
Pista cristata (PS)				15									16		
Prionospio steenstrupi (PS)				15,16					15	15					
Axinopsida serricata (BM)				16	16							15			
Nephtys sp. (PE)				16						15					
Polynoidae sp. (PE)				16							15				
Nephtys cornuta (PE)						16	15,16	15,16	15,16	15	15,16	15,16	16		
Cossura pygodactylata (PS)						16	16	15,16	15,15	15,16		16	15,16		
Nephtys ferruginea (PE)						16			15			16			
Gattyana cirrosa (PE)								16			16	16	16		
Cerebratulus sp. (N)									15						
Polydora sp. (PS)									15			15			
Corophium insidiosum (CA)									16						
Tharyx sp. (PS)										15			16		
Caridea immat. (BM)											15,16				
Aoroides columbiae (CA)											16				
Cumacea indet. (CC)											16				
Harmothoe extenuata (PE)											16				
Capitella capitata (PS)												15			
Spiophanes sp. (PS)												15			
Halcampa decemtentaculata (A)												16	16		
Syrrhoe longifrons (CA)												16			
Hippolytidae (CD)												16			
Tubularia sp. (H)												16			
Euchone incolor (PS)													15		
Nephtys punctata (PE)													16		

Total Taxa		43	Total Occurrences		123
PS	Polychaeta sedentaria	13	PS	Polychaeta sedentaria	44
PE	Polychaeta errantia	12	PE	Polychaeta errantia	54
CA	Crustacea amphipoda	7	CA	Crustacea amphipoda	9
BM	Bivalve mollusca	3	BM	Bivalve mollusca	6
CD	Crustacea decapoda	3	CD	Crustacea decapoda	4
CC	Crustacea cumacea	2	CC	Crustacea cumacea	2
A	Anthozoa	1	A	Anthozoa	2
B	Hydrozoa	1	H	Hydrozoa	1
N	Nemertea	1	N	Nemertea	1

Table 2.23. Species found on heavy tailings (60+ cm) at Island Copper Stations 15 and 16 from 1977 to 1989 (From: Ellis and Taylor 1988).

tailings toxicity. Substantial differences were noted in the benthic fauna of the three mine tailings sites, which varied in depths from 13 to 149 m, 25 to 100 m, and 264 to 351 m, suggesting that the depth of the seabed was a determinant in the type of species present.

- **Sensitive Habitats**

Sensitive habitats include such areas as parks, wilderness regions, mangrove beds, tidal flats, and breeding grounds for endangered species. Such sensitive habitats require consideration in any environmental analysis of mining operations which include an onshore component. These habitats are well addressed in the EIS for crust development in Hawaii, which deals in some detail with the siting of an onshore processing plant (USDOI, MMS and HI, DBED 1990). In this document, the environmental consequences of constructing and operating a land-based metallurgical plant to process high cobalt manganese crusts was considered for three separate locations at Puna and Kohala on the Big Island and at Ewa on Oahu. Impacts were examined on fish in coastal waters near the plant sites, island seabirds and their habitats, threatened and endangered species and their habitats, nearshore marine life, potable water supplies, historical and archeological resources, native Hawaiian and other rural lifestyles, freshwater quality in the vicinity of the sites, and on other issues of a sensitive nature involving human and animal habitation. Each of these issues was discussed at length in public hearings and during the scoping process.

- **Threatened and Endangered Species**

There are numerous threatened and endangered species with critical habitats onshore in the coastal zone. In the absence of site-specific information regarding onshore processing siting, it is not possible to identify applicable environment assessments. The consideration of threatened and endangered species and their critical habitat is generally carried out early in the scoping process for any project.

2.3.4.5 Social and Economic Environments

Two major examples of social and economic environmental impact are present in the literature. In the Lake Superior taconite district, considerable problems arose following the disposal of asbestos-bearing taconite tailings into the lake which was used by surrounding communities as a source of potable water (Pycha 1968). In contrast, most of the Canadian mines with marine disposal were very isolated and did not strongly influence or create social problems (Ellis 1987). The disposal of waste materials and tailings from land-based processing plants is a problem common to all metallurgical plants of this nature, and further detailed discussion of potential impacts is not considered within the scope of this report.

- **Human Environment**

The effects of mining operations on human health and safety are of paramount importance. Secondary effects, such as those due to mercury dispersion or to overcrowding, are also of concern. Other aspects which are not considered in this section include effects on commercial and recreational activities, regional economies, local economies, and cultural resources.

2.4 Characterization of the Literature Evaluated

The purpose of this section is to discuss the nature of the literature acquired and to analyze, in a qualitative manner, the general nature of its content. There are a number of major documents that exist which together address the current level of knowledge at the time of compilation. Major documents, cited by preparer(s), include the following:

- USDOI, Bureau of Land Management (BLM) (1974): Draft Environmental Impact Statement (DEIS) for OCS mining regulations;
- USDOS (1974): DEIS for deep seabed mining;
- EPA (1975): Estuarine pollution control;
- USDOI, USGS (1976): Final Environmental Impact Statement (FEIS) for OCS geological and geophysical regulations;
- Hirsch et al. (1978): Impact of dredged disposal;
- USDOI (1979): Program feasibility document;
- USDOC, NOAA (1981): FPEIS for deep seabed mining;
- USDOI, MMS (1983b): FEIS Alaska OCS sand and gravel;
- USC, OTA (1987): Exploring our new frontier;
- Earney (1990): Marine mineral resources;
- USDOI, MMS and HI, DEBD (1990): FEIS Hawaii and Johnston Island;
- Thiel et al. (1991): Potential environmental effects of deep seabed mining; and
- USDOI, MMS (1991): OCS mining, Norton Sound.

These volumes alone contain over 5,000 references selected for their relevance to the subject matter addressed; many of the citations pertain to the environmental effects of mining. Results of literature search and review under the present study indicate that even more citations of interest exist. More than 3,570 references were scanned, 1,100 selected titles were categorized, and approximately 350 were used as references in this document. Analyses of the categories are presented in graphical form in **Figures 2.44** through **2.48**, and discussed in the following text.

For purposes of classification, a total of 1,136 report titles were organized into the five categories which follow in the text and in **Table 2.24**. The number of titles in each category was counted and ranked according to their sub-classifications as shown in the figures.

Location: N. America: 345; Europe and Africa: 85; Oceania: 50; Asia: 30; S. America: 10; Unspecified: 616.

Environment: Coastal: 415; Onshore: 70; Deep ocean: 45; Continental shelf: 30; Unspecified: 576.

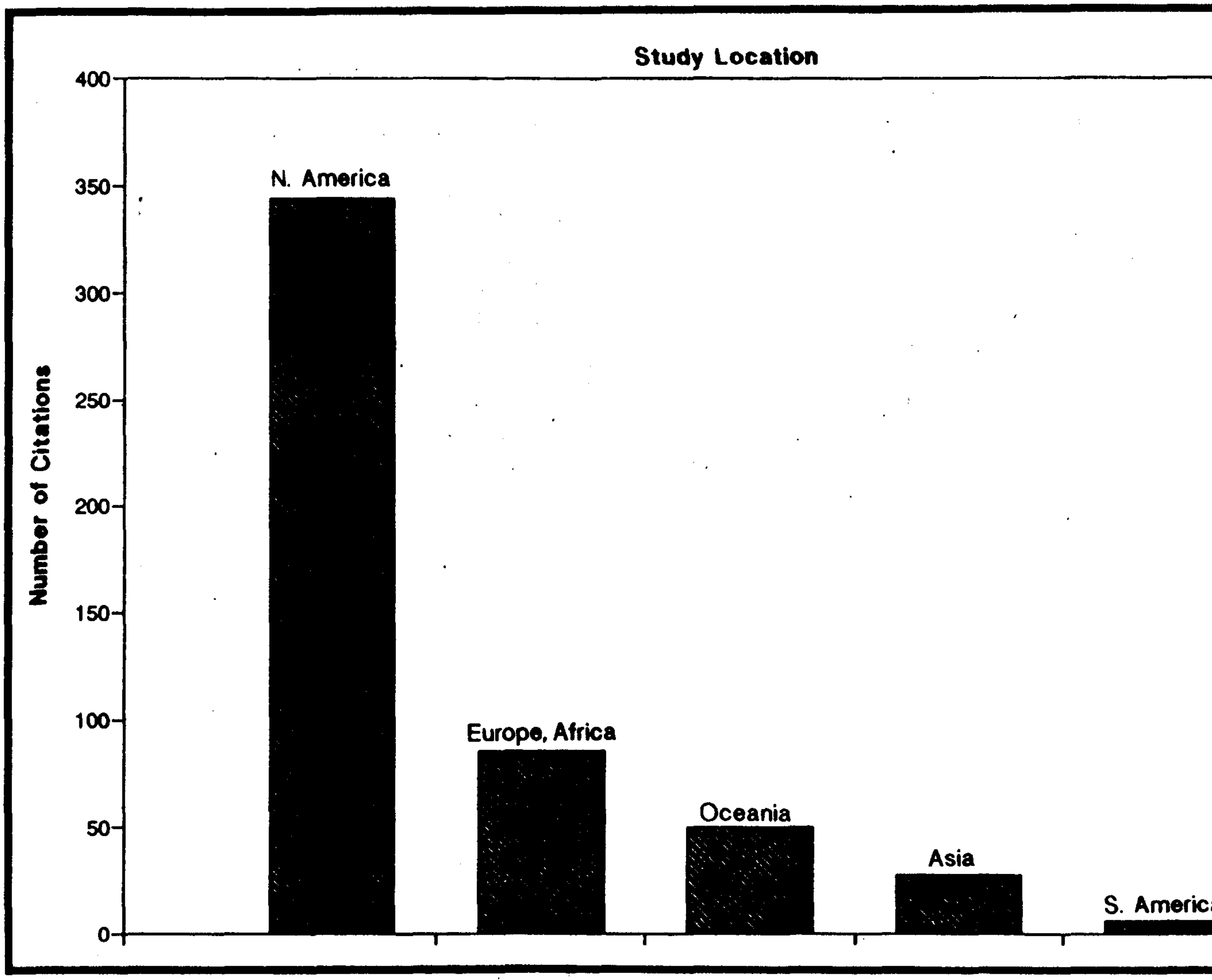


Figure 2.44 Graphical analysis of references evaluated, by study location.

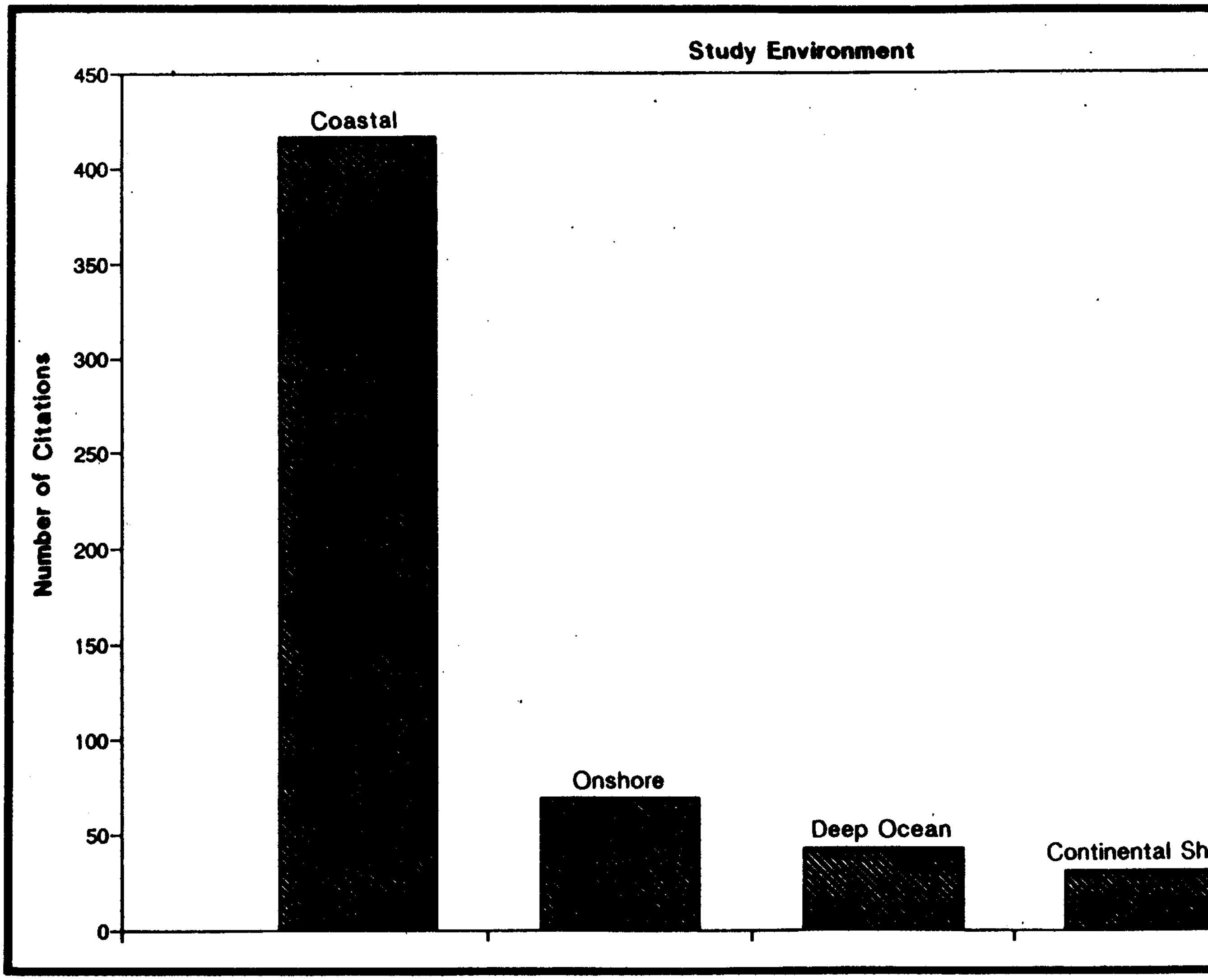


Figure 2.45. Graphical analysis of references evaluated, by study environment.

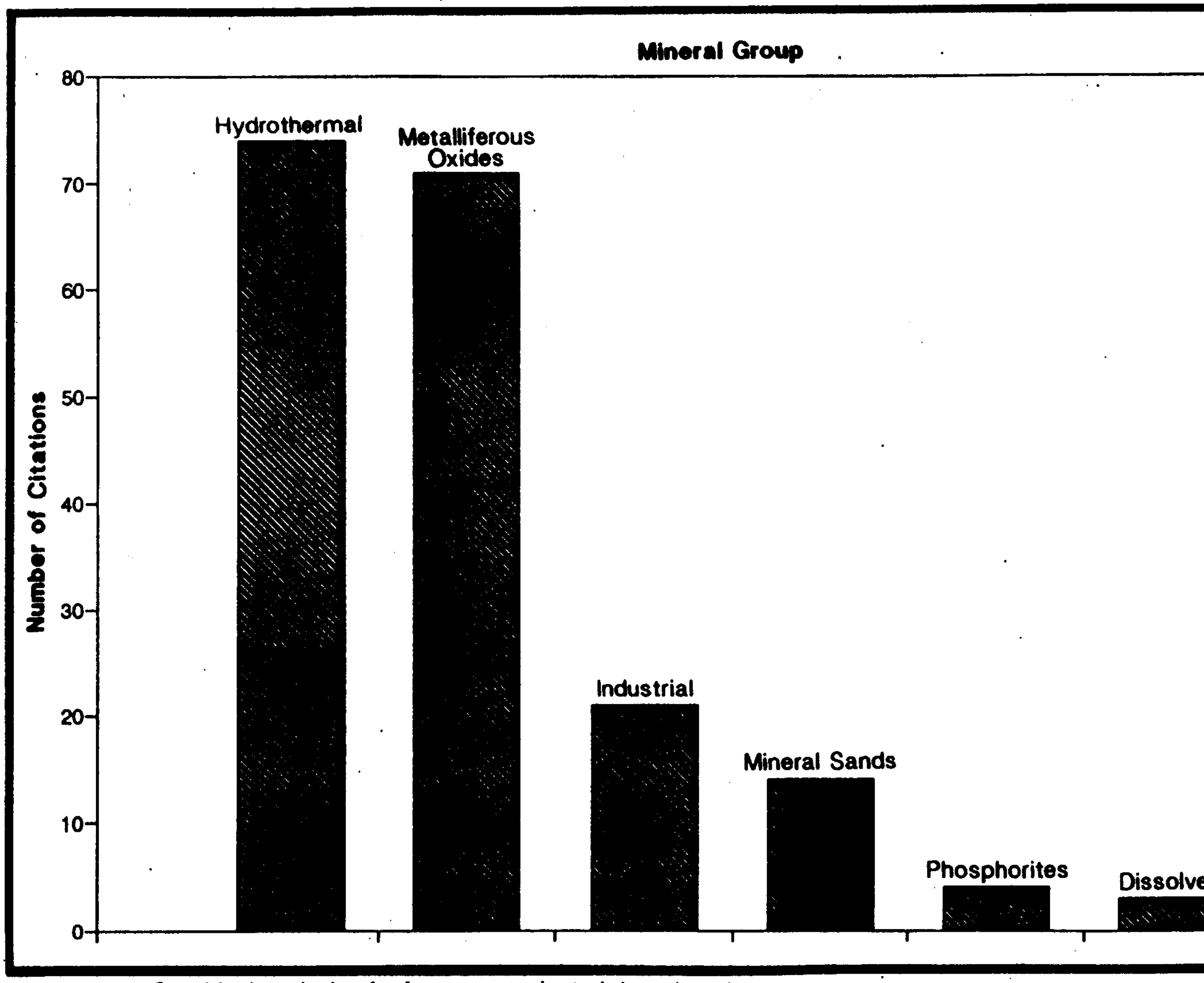


Figure 2.46 Graphical analysis of references evaluated, by mineral group.

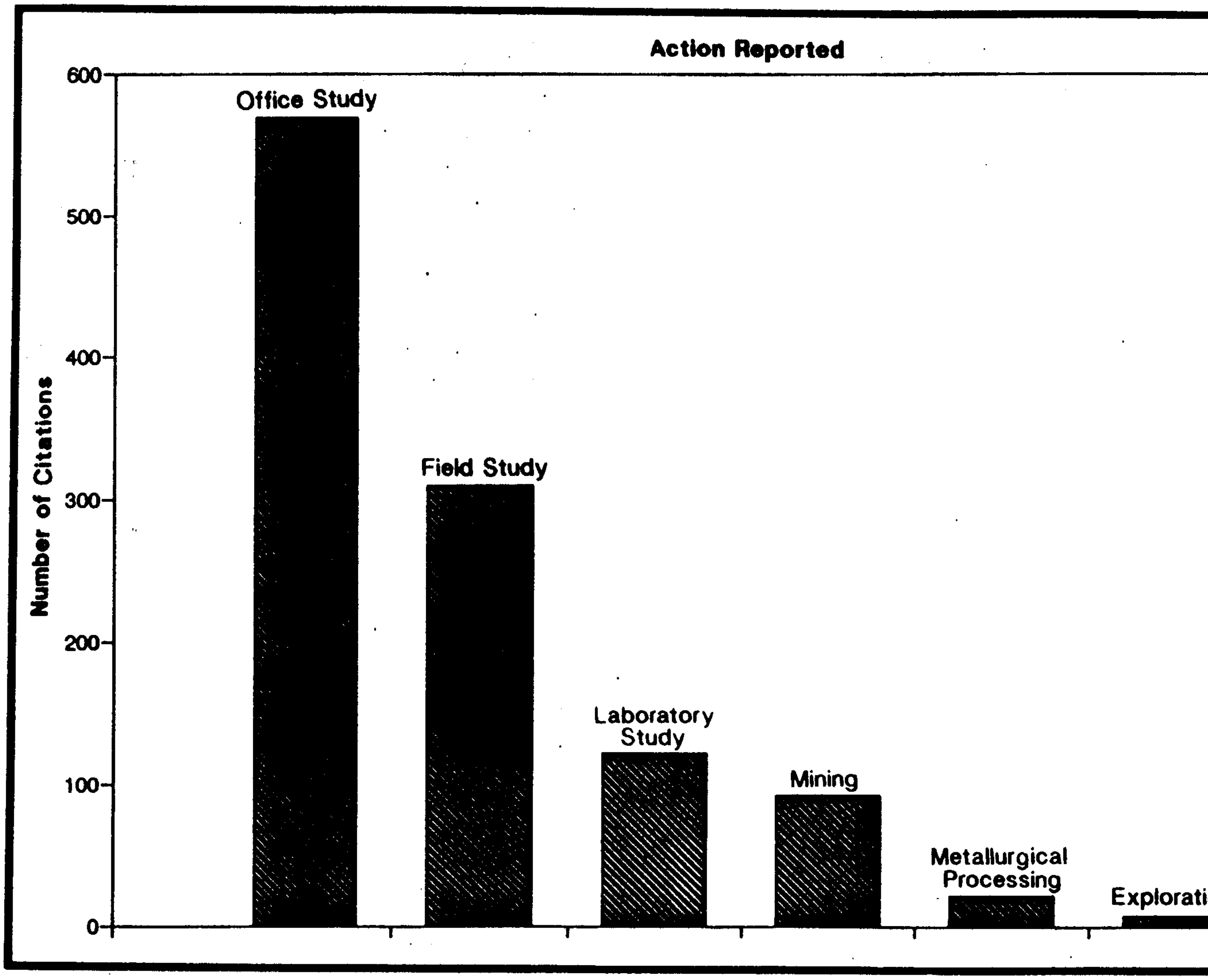


Figure 2.47 Graphical analysis of references evaluated, by action reported.

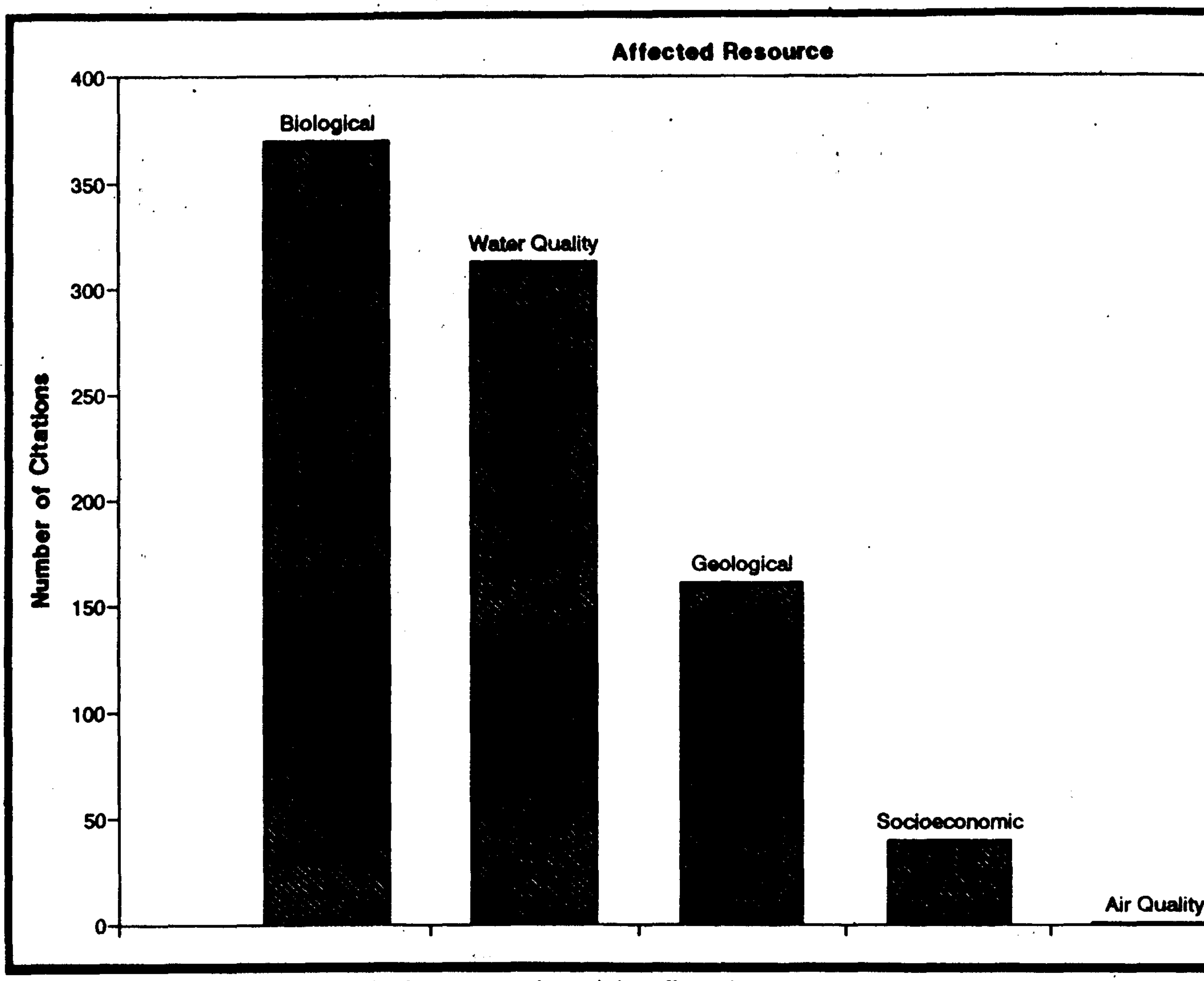


Figure 2.48 Graphical analysis of references evaluated, by affected resource.

1.	LOCATION	
	N	North America
	S	South America, including Mexico, Caribbean
	E	Europe, including Africa, Greenland
	A	Asia, including Indian Ocean
	O	Oceania, including Pacific Basin, Australia, New Zealand
	U	Unspecified, unknown, uncertain, unable to ascertain
2.	ENVIRONMENT	
	D	Deep Ocean, beyond the Continental Shelf
	S	Continental Shelf, including polar seabeds, OCS, and EEZ off continental states
	C	Coastal, including fjords, bays, estuaries, tropical islands
	O	Onshore, including rivers, freshwater embayments, wetlands, lakes, Black Sea, Baltic Sea
	U	Unspecified, unknown, uncertain, unable to ascertain
3.	MINERALS	
	I	Industrial minerals
	M	Mineral sands
	P	Phosphorites
	O	Metal oxides
	S	Hydrothermal deposits
	D	Dissolved minerals
	U	Unspecified, unknown, uncertain, unable to ascertain
4.	ACTION REPORTED	
	E	Exploration operations
	M	Mining operations
	P	Processing operations
	F	Field studies, site-specific
	L	Laboratory studies, species-specific
	O	Office studies, computer modeling, reporting
	U	Unspecified, unknown, uncertain, unable to ascertain
5.	AFFECTED RESOURCE	
	A	Atmospheric, including air quality
	M	Aquatic, including marine and freshwater quality
	G	Geologic, including seabeds, geologic structures, subbottom
	B	Biologic, including air, sea, land creatures
	S	Socioeconomic
	U	Unspecified, unknown, uncertain, unable to ascertain

Table 2.24. Subject classification used for analyses of references.

Mineral Group: Hydrothermal: 73; Metalliferous oxides: 72; Industrial: 22; Mineral sands: 15; Phosphorite: 4; Dissolved: 3; Unspecified: 947.

Action Reported: Office study: 570; Field study: 310; Laboratory study: 115; Mining: 93; Metallurgical processing: 20; Exploration: 10; Unspecified: 18.

Affected Resource: Biological: 365; Water quality: 310; Geological: 163; Socioeconomic: 42; Air quality: 3; Unspecified: 253.

The results of this classification are very general. A summary of the results are as follows:

Location: (**Figure 2.44**). For example, 54% of the citations reviewed were not country-specific; however for those that were, 66% pertained to North America.

Environment: (**Figure 2.45**). More than half of the papers did not specify the environment to which they related; of those that did, nearly 75% were coastal, with the remainder almost equally split between onshore, continental shelf, and deep ocean. Perhaps more significantly, only 3% of the total documents referred specifically to the OCS.

Mineral Group: (**Figure 2.46**). Only 17% of the citations pertained specifically to mineral deposits; of those, 40% each applied to deep ocean oxides and hydrothermal deposits, which is probably an indication of the scientific interest in these deposits by the academic and oceanographic research community.

Action Reported: (**Figure 2.47**). Nearly 50% of the papers were office studies, while close to 30% were based directly on field work and 10% on laboratory research.

Affected Resource: (**Figure 2.48**). More than 20% of the documents did not specify which resource was affected; of those that did, biology, water quality, geology, socioeconomics, and air quality comprised 41%, 35%, 18%, 5%, and 1% of the citations identified, respectively. The air quality findings were surprising considering the emphasis given to air quality in recent EISs.

In summary, the bulk of the work currently in print seems to have centered on North American coastal biology, which probably indicates a bias based on accessibility and generalized coastal concerns. This is quite understandable in general terms but is of concern in terms of the cost of the ESP directed at mineral recovery in the OCS.

Some prime examples of operations in each of the affected environments (e.g., deep ocean, continental shelf, coastal, and onshore) are given in **Table 2.25** for each class

MINERAL RESOURCE	DEEP OCEAN	CONTINENTAL SHELF	COASTAL	ONSHORE
Industrial Minerals	No precedents	US: Sand and gravel operations off Alaska (USDOI, MMS 1983a). Sulphur operations in Gulf of Mexico (USDOI, MMS 1985). Bahamas: Aragonite deposits worked offshore Japan: sand deposits mined at depths to 30 m	U.S.: Sand and gravel, oyster shells and aragonite are mined Australia: Proposed leasing of gravel deposits in New South Wales (Consolidated Gold Fields Australia Ltd. and Arc Marine 1988)	U.S.: Dedicated shoreside facilities for sand and gravel plants
Mineral Sands	No precedents	U.S.: Proposed lease sale for gold in Alaska (USDOI, MMS 1991) S.E. Asia: Tin operations off Indonesia and Thailand	U.S.: Alaska operation for gold. Environmental report (Rusanowski 1991)	
Phosphorites	None at this time but the possibility exists in certain Pacific areas in connection with metalliferous crusts	U.S.: Blake Plateau deposits have potential; area leased in 1963 at 40 mile bank off S. Calif.		
Metalliferous Oxides	U.S.: Manganese nodules in the Pacific (USDOC, NOAA 1981); Proposed leasing for cobalt crust in EEZ of Hawaii and Johnston Island (USDOI, MMS and HI, DBED 1990)	U.S.: Blake Plateau crusts and nodules	No precedents	U.S.: Dedicated shore facilities for manganese nodule processing
Hydrothermal Deposits	U.S.: Proposed leasing for metal sulfide deposits in the Gorda Ridge off OR/CA (USDOI, MMS 1983b)		U.S.: Castle Island barite mine in S.E. Alaska	
Dissolved Minerals	Shipboard desalination plants only; no precedents for mineral extraction	No precedents	R & D only (Earney 1990)	U.S.: See Table 2.13 (Dissolved Minerals)

Table 2.25. Examples of marine mineral resources development vs. affected environments.

of mineral resource, where applicable. This table provides major references and compares, in matrix form, the general status of marine mineral resources development with respect to the *four affected environments categorized in this report.*

2.5 Summary of Environmental Effects by Resource Affected

A generalized approach has been taken in this summarization of the environmental effects of marine mining in the deep ocean, continental shelf, coastal, and where appropriate, onshore environments (**Table 2.26**). Based on limited information available from actual operations, some effects subject to mitigation are avoidable (i.e., mitigable) as outlined in **Table 2.27**; others are unavoidable, as summarized in **Table 2.28**.

Marine mining operations affect both natural resources (including atmosphere, land, sea surface, water column, seabed, and all living things therein) and artificial resources which have been developed to suit human social needs (including governance, commercial activities, technology, economics, and aesthetics). As indicated in **Section 2.3**, the direct or primary effects of marine mining on the environment may include (1) removal of the mined material; (2) introduction of new materials as processing wastes, tailings, and discharges, or of energy as heat, light, or seismic and acoustic waves; (3) perturbation or mixing at the seafloor due to the mining operation; and (4) subsequent replacement of mined material as waste, tailings, or discharges. These primary effects result in physical, chemical, and biological changes such as alteration of the shape or character of the seabed, leaving holes, mounds, or boulders, exposing new surfaces, or leaving garbage or lost hardware strewn about; changes in the quality of the air and water in the vicinity of the operation; and impacts on biological and other resources. It is stressed that a reliable analysis of effects, or environmental impacts, of any mining operation must be based on commodity-specific, site-specific, and technology-specific information.

The USDOI, in response to Section 20(e) of the OCSLA, reported to Congress for the first time the cumulative effects on the environment since implementation of the USDOI's oil and gas program in 1954 (USDOI, MMS 1988c). Several of the findings are significant in light of the USDOI's current program for the development of other minerals. Marine mining has already attracted considerable attention on environmental issues. Therefore, it is essential that decision makers have available the most complete picture on the potential and likely environmental effects of marine mining operations. With the perspective of over 30 years of experience, an excellent summary by Zippin (1988) noted that short-term, near-field perturbations of apparent significance are separated from long-term, far-field environmental impacts which are shown to be largely insignificant. Many public perceptions are influenced by EISs. Apart from the loss of wetlands in the Mississippi River delta and contrary to most assessments projected from EISs, the cumulative environmental effect of the marine oil and gas program in the U.S. over the last 33 years has not been significant.

The environments for marine minerals on the continental shelf are very similar to those for oil and gas. When needed information is lacking for an EIS, a "worst case scenario" is invoked, resulting sometimes in the forecasting of exaggerated effects from the proposed activity. This is normally the case for marine mining where little field information

POSSIBLE EFFECTS OF OFFSHORE (EEZ) DEVELOPMENT

National Benefits
—improved domestic supply of strategic and critical resources
—reduced trade deficit
—improved food supply
—increased national security
—enhanced economic growth
—increased federal revenues

Regional/Local Benefits
(some public, some private)
—increased jobs
—increased investment earnings
—increased tax revenue

Offshore Environmental Impacts
—deterioration of marine water quality
—deterioration of air quality
—addition of toxins to the environment, and possibly the food chain
—visual disturbance
—potential accidents

Onshore Environmental Impacts
—increased risk of accidents
—degradation of coastal esthetics
—reduction in quality of coastal recreation experience
—reduction in tourism

Offshore Displacement Impacts
—prevention or disruption of usual fishing patterns
—interference with commercial and recreational navigation

Onshore Displacement Impacts
—competition for limited commercial and recreational port and harbor space
—competition for sites for processing, storage and transportation facilities
—competition for limited recreational beach space

Onshore Socio-economic Impacts
—increased population
—public facilities and infrastructure
—public services
—housing, water supplies
—additional requirements on local government planning processes

Table 2.26. General summary of environmental effects of EEZ development in the deep ocean, continental shelf, coastal zone, and onshore (Adapted from: Coastal States Organization 1987).

POTENTIAL ENVIRONMENTAL IMPACTS	AVOIDANCE/MITIGATION STRATEGIES	RELEVANT FEDERAL LEGISLATION/AUTHORITY			AGENCY
		STATUTE	REGULATIONS	REQUIREMENT	
1. Deposition of dredged or fill material in waters of the United States and contiguous wetlands	Utilize upland disposal areas, contain spoil	Clean Water Act* (33 U.S.C. 1344)	33 C.F.R. 323	Minimize deposition in wetlands and waters	COE/ EPA/ States
2. Interference with federally designated Marine Sanctuaries	Avoid existing or potential Marine Sanctuaries	Marine Protection- Research and Sanctuaries Act of 1972 (16 U.S.C. 1432-1433)	15 C.F.R. 922	Preserve and protect Marine Sanctuaries	DOC
3. Interference with state designated Estuarine Sanctuaries	Avoid existing or potential Estuarine Sanctuaries	Coastal Zone Management Act of 1972 (16 U.S.C. 1461)	15 C.F.R. 921	Preserve and protect Estuarine Sanctuaries	DOC/ States
4. Interference with historical and/or archaeological sites, structures, or objects	Perform adequate historic and archeologic surveys, avoid designated sites and structures	National Historic Preservation Act (16 U.S.C. 470f) Preservation of Historical & Archaeological Data Act (16 U.S.C. 469-469b). Exec. Order No 11593	36 C.F.R. 800 36 C.F.R. 800	Review by state and Federal officials to preserve and protect historic and archaeologic sites	State/ACHP all fed. agencies
5. Jeopardizing existence of endangered or threatened species or adversely modifying their habitats	Perform adequate biological surveys, avoid endangered species habitats	Endangered Species Act (16 U.S.C. 1531-1541)	50 C.F.R. 17 50 C.F.R. 222, 226, 227 50 C.F.R. 402	Review to protect endangered and threatened species	FWS/ NMFS/ States
6. Harassment or "incidental taking" of marine mammals	Perform adequate biological surveys, avoid critical areas	Marine Mammal Protection Act (16 U.S.C. 1361-1382)	50 C.F.R. 18 50 C.F.R. 215-225	Protect marine mammals	FWS/ NMFS/ States?
7. Increased risk of loss from or damage by flooding	Locate structures outside flood hazard areas	Exec. Ord. No 11514 Exec. Ord. No 11988	-- --	No practicable alternative to encroaching on flood plain	all fed. agencies

Table 2.27. Avoidable impacts of marine mining and responsible authorities in the U.S. (From: U.S. Department of Commerce, National Oceanic and Atmospheric Administration 1981).

POTENTIAL ENVIRONMENTAL IMPACTS	AVOIDANCE/MITIGATION STRATEGIES	RELEVANT FEDERAL LEGISLATION/AUTHORITY			AGENCY
		STATUTE	REGULATIONS	REQUIREMENT	
8. Destruction or modification of wetlands	Locate all development outside wetlands	Exec. Ord. No. 11990	--	Minimize effect on wetlands	all fed. agencies
9. Conflict with designated Wilderness Areas	Locate away from designated Wilderness Areas	Wilderness Act (16 U.S.C. 1131-1135)	43 C.F.R. 19 36 C.F.R. 293 50 C.F.R. 35	Protect and preserve Wilderness Areas	DOI
10. Conflict with designated Wild or Scenic Rivers	Locate away from designated Wild or Scenic Rivers	Wild and Scenic River Act (16 U.S.C. 1271-1286)		Protect and preserve Wild and Scenic Rivers	DOI
11. Conflict with Prime and Unique Farmland	Avoid areas of designated Prime or Unique Farmland	16 U.S.C. 590 a-f	7 C.F.R. 657	Protect Prime and Unique Farmland	USDA
12. Release of toxic or hazardous materials as a result of flood tsunami, hurricane, or seismic activity	Avoid natural hazard areas	Clean Water Act* 33 U.S.C. 1321 (c)(2) Resource Conservation and Recovery Act (42 U.S.C. 6901)	40 C.F.R. 1510 40 C.F.R. 260-267	Oil and hazardous substances spill contingency planning	EPA/CG

* The reader should note that the following are subject to the EPA consolidated permit program 40 C.F.R. 122-125, 45 F.R. 33287-33558 (May 19, 1980)

- Resource Conservation and Recovery Act (Hazardous Waste Management Program)
- Safe Drinking Water Act (Underground Injection Control Program)
- Clean Water Act (National Pollutant Discharge Elimination System and Dredge and Fill Programs)
- Clean Air Act (Prevention of Significant Deterioration Program)

Table 2.27. (Continued).

ACTIVITY/ FACILITY	POTENTIAL ENVIRONMENTAL IMPACTS	POSSIBLE MITIGATION STRATEGIES	MAJOR RELEVANT FEDERAL LEGISLATION			AGENCY
			STATUTE	REGULATIONS *	REQUIREMENT	
1. Transhipment from port to plant						
1.1 Channel and dockage	Marine traffic congestion, accidents	Improved navigation and traffic control	Ports and Waterways Safety Act (33, U.S.C. 1221-1227)	33 C.F.R. 160-165	Conformance with safety regulations	USCG
	Dredging, bottom disruption	Optimum location and timing	Rivers and Harbors Act of 1899 (33 U.S.C. 40[illegible]	33 C.F.R 322	Permit	COE
	Modification of waters		Fish and Wildlife Coordination Act (16 U.S.C. 661-665)	50 C.F.R. Part 470 Regulations reproposed 45 F.R. 83412, 12/18/80	Coordination	COE/ FWS/NMFS States
	Land use conflicts	Conformance with local land use plans	Coastal Zone Management Act of 1972 (16 U.S.C. 1456)	15 C.F.R. 930	Consistency with state Program	DOC/ States
1.2 Marine terminal and transportation system	Construction noise	Equipment design and shielding	Noise Control Act (42 U.S.C. 4901-4917)	40 C.F.R. 204 (const. equipment)	Conformance to equipment standards	EPA
	Operating noise	Buffer zones, quiet operations			Local controls	
	Dust	Containment and treatment	Clean Air Act* (42 U.S.C. 7410)	40 C.F.R. 50-81	Conformance to standards, permits, monitoring, modeling.	EPA/ States
	Liquid effluents	Containment and treatment	Clean Water Act* (33 U.S.C. 1311-1321, 1341-1345)	40 C.F.R. 104-142	Conformance to standards, permits	EPA/ States
	Land use conflicts	Conformance with local land use plans and coastal management programs	Coastal Zone Management Act of 1972 (16 U.S.C. 1456)	15 C.F.R. 930	Consistency with state Programs	DOC/ States
2. Nodule Processing						
	Noise	Equipment design and shielding	Noise Control Act (42 U.S.C. 4901-4917)	40 C.F.R.204 (constr. equipment)	Conformance to equipment standards	EPA

Table 2.28. Unavoidable impacts of marine mining and responsible authorities in the U.S. (From: U.S. Department of Commerce, National Oceanic and Atmospheric Administration 1981).

ACTIVITY/ FACILITY	POTENTIAL ENVIRONMENTAL IMPACTS	POSSIBLE MITIGATION STRATEGIES	MAJOR RELEVANT FEDERAL LEGISLATION: STATUTE	REGULATIONS	REQUIREMENT	AGENCY
	Dust, gaseous emissions	Process design, containment, and treatment; avoidance of "non-attainment" areas and Class I (pristine) areas	Clean Air Act* (42 U.S.C. 7401-7643)	40 C.F.R. 50-81	Conformance to standards, permits, monitoring, modeling	EPA/ States
	Liquid effluents	Process design, containment, and treatment	Clean Water Act* (33. U.S.C. 1311-1321, 1341-1345)	40 C.F.R. 104-142	Conformance to standards, permits	EPA/ States
	Energy consumption	Conservation, use of coal and/or other alternative fuels	Power Plant and Industrial Fuel Use Act of 1978 (92 Stat. 3291-3314)	18 C.F.R. 285	Use of coal and/or other alternative fuels in new large power plants	DOE
	Land use conflicts	Conformance with local land use plans and coastal management program	Coastal Zone Management Act of 1972 (16 U.S.C. 1456)	15 C.F.R. 930	Consistency with state programs	DOC/ States
	Exposure to toxic or hazardous materials	Process design, containment, and treatment	Hazardous Materials Transportation Act (49 U.S.C. 1804-1806) Toxic Substances Control Act of 1976 (15 U.S.C. 2604-2627)	41 C.F.R. 171-179 40 C.F.R. 715 et seq. 40 C.F.R. 1257	Minimize exposure to toxic and hazardous materials	EPA/ DOT
			Resource Conservation and Recovery Act* 42 U.S.C. 6901	40 C.F.R. 260-267		
	Erosion and sedimentation, particularly during construction	Design and construction standards		40 C.F.R. 260-2667	Local controls	EPA
3. Waste Disposal						
3.1 Onshore	Aquifer contamination	Optimum disposal area location, design and operation	Safe Drinking Water Act* (42 U.S.C. 300h-3001)	40 C.F.R. 146	Conformance to standards for underground injections	EPA/States
			Resource Conservation and Recovery Act (42 U.S.C. 6901)	40 C.F.R. 260-267		

Table 2.28. (Continued).

ACTIVITY/ FACILITY	POTENTIAL ENVIRONMENTAL IMPACTS	POSSIBLE MITIGATION STRATEGIES	MAJOR RELEVANT FEDERAL LEGISLATION			AGENCY
			STATUTE	REGULATIONS	REQUIREMENT	
	Dust	Surface treatment of landfill, containment and treatment	Clean Air Act[a] (42 U.S.C. 7410)	40 C.F.R. 50-82	Conformance to standards, permits, monitoring, modelling	EPA/States
	Contamination by toxic solid wastes	Optimum disposal area location, design, and operation	Resource Conservation and Recovery Act[a] (42 U.S.C. 6901-6979)	40 C.F.R. 260-267 seq 30 C.F.R. 60?	Conformance to standards, permits	EPA/States
	Liquid effluents	Optimum disposal area location, design and operation; containment and treatment	Clean Water Act[a] (33 U.S.C. 1311-1321 1341-1345)	40 C.F.R. 104-142	Conformance to standards, permits	EPA/States
			Resource Conservation and Recovery Act (42 U.S.C. 6901)	40 C.F.R. 260-267		
	Fossil Fuel consumption	Energy conservation	Energy Supply and Environmental Coordination Act 15 U.S.C. 792		Regulate the use of oil and gas by power plants and other major fuel burning installations	DOE
	Land use conflicts	Conformance with local land use plans and coastal management prog.	Coastal Zone Management Act of 1972 (16 U.S.C. 1456)	15 C.F.R. 930	Consistency with State programs	DOC/States
3.2 Offshore	Marine traffic congestion, accidents	Improved navigation and traffic control	Ports and Waterways Safety Act (33 U.S.C. 1221-1227)	33 C.F.R. 160-165	Conformance with safety regulations	USCG
	Water pollution, bottom deposition, benthic smothering	Deposit well offshore in deep water, over infertile bottoms	Marine Protection Research & Sanctuaries Act of 1972 (33 U.S.C. 1411-1418)	40 C.F.R. 220-229	Permits	EPA/COE?

[a] The reader should note that the following are subject to the EPA consolidated permit program 40 C.F.R. 122-125, 45 F.R. 33287-33558 (May 19, 1980)
- Resource Conservation and Recovery Act (Hazardous Waste Management Program)
- Safe Drinking Water Act (Underground Injection Control Program)
- Clean Water Act (National Pollutant Discharge Elimination System and Dredge and Fill Programs)
- Clean Air Act (Prevention of Significant Deterioration Program)

Table 2.28. (Continued).

exists. For example, as of late 1992, no more than two holes penetrated below the exposed surface of any metalliferous sulfide deposits on the deep seabed; the character of these potentially large sub-seabed deposits must be based on tenuous assumptions, which in the worst case scenario may exaggerate the problems of mining them (USDOI, MMS 1983b). The EIS prepared for proposed cobalt crust leasing (USDOI, MMS and HI, DBED 1990) used a mining scenario that may highly exaggerate the effect of ripping the crust from the bottom, while subsequent information suggests that economic production might be initially obtained by dredging up much lesser quantities of already detached crust material from tallus slopes on the sides of seamounts (Zippin 1988).

In any event, the key environmental concerns expressed in the literature have focused on air quality, water quality, seabed perturbation, biological resources (including marine mammals), and socioeconomic resources (including commercial and recreational fisheries). It is these aspects that form the basis of the summary discussion.

2.5.1 Air Quality

Emissions of gaseous or particulate matter to the atmosphere or the generation of noise or light common to most large industrial activities might be of concern from mining platforms or support vessels. Principle emissions are normally nitrous oxides and residual (reactive) organic compounds. During exploration and test mining, these emissions may have little effect onshore as they are dependent on the location of the activity and prevailing meteorological and onshore air quality conditions. Emissions from platforms have not been demonstrated to adversely affect onshore air quality. Emissions from marine mining sources are expected to be qualitatively and quantitatively similar to oil and gas related sources, which were regulated by the MMS to onshore U.S. ambient air quality standards and are now regulated under the Clean Air Act of 1990 by the EPA. In the deep ocean, some gases might be released from seawater brought to the surface from the seabed via hydraulic dredging at great depths, but information on this effect is sparse and confined to the ocean thermal energy conversion (OTEC) literature. Airborne noise from non-explosive seismic exploration activity is generally dismissed as insignificant (USDOI, MMS 1988d). In terms of global or regional effects, there is little discussion in any of the literature on this subject for marine mining. Effects are generally examined on the site-specific level and do not appear to offer significant problems or priority areas for research at this time.

2.5.2 Water Quality

A zone of influence for an offshore mining operation may be defined in general terms which provides a useful perspective on the potential magnitude of the effects of the operation. Zippin (1988) indicated that dredging operations for minerals may result in discharges of solid materials to the water column of 1 to 8 x 10^6 mt/year, compared with a cumulative annual discharge from oil and gas drilling in the Gulf of Mexico of 1.3 x 10^6 mt/year (**Table 2.29**). The extent of plume dispersion from sediment and other effluents discharged into the water column is generally measured in thousands of meters and rarely in tens of kilometers. The extent of bottom disturbance from the operation will be much less, within hundreds of feet per day for a stationary dredge, and a few linear kilometers for a trailing suction dredge, the most mobile of the mining systems. The

Offshore Activity	Annual discharge metric tons x 10^6	Working days/year
Proposed OCS gold mining, AK	3.2	150
Proposed EEZ cobalt crust mining, HI	1.5	206
Proposed EEZ metalliferous sulfide mining, Gorda Ridge	1.0	300
Proposed deep seabed manganese nodule mining	8.4	300
Oil and Gas drilling, Gulf of Mexico[1]	1.3	365

[1] Approximate conversions based on annual discharge of 5.8 million barrels of mud and cuttings

Table 2.29. Projected discharges from marine mining compared with drilling discharges in the Gulf of Mexico (Adapted from: Zippin 1988).

application of these zones in preliminary planning will permit appropriate selection and limitation of pre-mining or baseline environmental studies and can be applied to each marine environment regardless of water depth.

2.5.2.1 Deep Ocean and Outer Continental Shelf

Far from shore, the impacts of marine mining operations on water quality are difficult to assess. The capacity for assimilation of plumes increases, but layering of the water below the thermocline and low velocity benthic currents might prolong the effects of plumes more than in the shallow coastal zone. These effects need to be examined on a site-specific basis.

Water quality is affected by discharges of production waste and spillage of garbage, lubricating oils, processing chemicals, or fuel. Mining excavation and dredging disturb the seabed, causing benthic sediment plumes. Depending upon how the mined material is lifted to the surface or tailings are discharged, suspended sediment may be released anywhere in the water column.

Dilution of the discharge to low concentrations is rapid, with solid concentrations reduced to 1,000 ppm within 2 min of discharge and 10 ppm within 1 h (Neff 1985, 1981). Typically, the affected zone down current of a discharge extends 1,000 to 2,000 m (ECOMAR 1983). Even where muds, produced formation waters, and other waste discharges from oil and gas activities containing trace quantities of arsenic and metals were monitored in the Gulf of Mexico, measurements indicated that pollutants were rapidly reduced to background levels (Middleditch 1981). No long-term, chronic environmental effects of these discharges have been observed. Because of the high potential for adverse impacts on marine ecosystems. this remains a subject for further study.

Annual discharges of muds and cuttings into the Gulf of Mexico are estimated to be 1.3×10^6 mt. This is comparable to the discharges projected in hypothetical EIS mining scenarios. Although the mining discharges would be more concentrated, they are subject to the same settling and dilution factors that minimize the effect of oil and gas related discharges. Turbidity from resuspended sediments may be detected down current over many kilometers but direct effects and indirect effects (e.g., nutrient or trace metal enrichment, increased biological or chemical oxygen demand, and reduced penetration of sunlight) are limited to the immediate area of operations (Hirsch et al. 1978).

Accidental releases of oil into the marine environment have been well studied (USDOI, MMS 1988d). Oil in the water undergoes weathering and organic decomposition over time. The Santa Barbara Channel spill of 1969 had few observable effects noted after less than two years (Straughan 1971). Petroleum spills from marine mining activities would be limited to fuels, mostly during transfer, and possibly from tanker loss (Zippin 1988).

2.5.2.2 Coastal and Onshore

Marine mining would affect water circulation and water quality proportionally to the extent that operations, transportation, storage, or terminal facilities were located in coastal waters. It is conceivable and has been proposed that large stockpiles of marine minerals or mining wastes could be usefully maintained or disposed of at convenient sites near to shore. The impact of such activities could only be assessed by analysis of the site-specific conditions. Coastal and estuarine water quality is affected by seasonal variations in waves and tides and by freshwater runoff. The shallow and confined nature of many coastal waters makes them susceptible to perturbation or pollutants. Turbidity is generally not considered a problem in the recovery of sand and gravel with trailing suction dredges because mining operations are "discontinuous" and the deposits rarely contain large amounts of silt-sized or contaminated material. With good management practices, there should be no serious environmental effects. In Thailand, however, the impact of large tin dredges in intertidal and shallow water areas has been significant with turbidity and resedimentation shown to be the main cause of biodegradation (Chansang 1988).

- **Heavy Metals**

The possible release of toxic trace metals due to dredging and the discharge of overflow material was of great concern in the early literature. This concern was related to experience with channel and harbor dredging, where a buildup of industrial waste contaminants such as polychlorinated biphenyls (PCBs) and trace metals (e.g., cadmium, copper, lead, mercury, zinc) in the sediments is common. Such chemicals are rarely found in significant concentrations in the offshore environment and the likelihood of release of such elements is considered minor (de Groot 1979a; Gillie and Kirk 1980; Aurand and Mamontov 1982; Evans et al. 1982; Drinnan and Bliss 1986; Cruickshank et al. 1987; USC, OTA 1987). Similarly, there is no documentation on any toxic substances occurring as a result of offshore tin mining in Thailand (Chansang 1988).

- **Terrestrial Sites**

Impacts on water quality at shoreside facilities may be due to emissions in the form of gaseous, liquid, and solid wastes, and would be similar to other industrial activities. Potentially serious marine problems that have been identified are attributed to the dumping of mined tailings and processing wastes into adjacent waterways; these activities have to be constantly monitored. The nature of the effect will be heavily influenced by the type of material being dumped, and the nature of the waterway and its ecosystem.

2.5.2.3 Natural Effects

In general, the natural effects of environmental change are easily recognized. However, there may be occasions where they are not so obvious and care may be exercised to allocate the causes to the correct source. For example, phenomena such as red tides, megaplumes resulting from seabed hydrothermal activity, and storm- or earthquake-induced slides may result in significant but temporary changes in water quality.

2.5.2.4 Induced Effects

Normal effects on water quality induced by mining operations may include turbidity and nutrient or trace metal enrichment, resulting in secondary effects throughout the trophic web due to reduction in light levels and changes in water chemistry.

2.5.3 Geological Resources

The primary effect on the geological resources is the removal of the ore. Additional secondary effects may include alteration of the value of remaining mineral resources because of grade depletion, and alteration of the seabed in a number of ways (e.g., changing its value or its effect on other uses).

2.5.3.1 Mineral

Mineral deposits will be removed by mining resulting in an irretrievable transfer of the mineral from a resource base to a consumptive use.

2.5.3.2 Other

Major geologic impacts of marine mining result from activities in the coastal zone where wave energy is a prime factor. The effects of large excavations or shoaling resulting, for example, from the mining of mineral sands will depend on their location with respect to the local environment. Changes in wave or current patterns induced by altered conditions can cause changes in shoreline equilibrium, resulting in erosion or deposition. Possible effects from sub-seabed fracturing using conventional or other type explosives are not well discussed in the literature and should be the basis for additional study and observation, particularly in offshore areas susceptible to slumping and in deep water where the physical conditions are very different than on land. Some problems in shallow water have been related to the pits formed by removal of sand or gravel using stationary suction dredges. Coral reef growth may be severely affected by siltation from mining (Chansang 1988) and this may affect the supply of coral sands to adjacent beaches, particularly in tropical, fringing reef environments.

2.5.4 Biological Resources

Most biological impacts are secondary, attributed to some alteration in the existing physical, chemical, or trophic equilibrium. Impacts in the coastal zone have a greater tendency to be significant because of the higher energy levels generally recorded there. The extent of the impacts are usefully analyzed using a matrix of the type illustrated in **Figure 2.49** and described in detail by Cruickshank (1978). Check lists of technological systems and environmental systems are presented in **Tables 2.30** and **2.31**, respectively. Physical changes which may induce biological effects include changes in temperature, current patterns, amount of particulates present, nature of the substrate, and introduction of new habitats. Significant chemical changes may include changes in the presence of nutrients, trace elements, or toxics. Trophic changes may include removal or influence on existing species by involving them in the operating cycle. Criteria on which to judge pollution or significant biological change are, in many cases, arbitrary. Where they are given, they may err on the side of safety based mostly on the assumption that no change is the preferred state. This assumption may be open to argument, however, and more data will be required before generalizations, if possible, can be made.

Technological systems impacting on the environment

	Transient				Transient to short term							Transient					Short term									Long term				Transient to long term									Total *
	Infrastructure				Operational prerequisites							Exploration					Exploitation									Restoration				Accident									
																	Operational cycles					Material cycles									Natural				Induced					
Environmental systems impacted	Plant	Transportation	Utilities	Services	Shoreside facilities	Environmental prediction	Platforms	Power systems	Navigation and survey	Control systems	Data processing	Water sampling	Sea floor sampling	Drilling	Geophysical sensing	Geochemical sensing	Mining	Lifting	Material handling	Transporting	Beneficiation	Gases	Solubles	Insolubles	Radioactives	Sealing	Removal	Disposal	Restoration	Storm	Tsunami	Earthquake	Slide	Fire	Explosion	Spillage	Inundation	Collapse	
Natural systems																																							
Meteorological																																							
Climate																																							
Air quality																																							
Hydrologic																																							
Coastal: Surface water																																							
Ground water																																							
Water quality																																							
Marine: Upper boundary layer																																							
Sea state																																							
Boundary gradients																																							
Intermediate layers																																							
Climate																																							
Water quality																																							
Bottom layer																																							
Climate																																							
Boundary gradients																																							
Geologic																																							
Regional geology																																							
Mineral deposits																																							
Geotechnique																																							
Biologic																																							
Diversity and abundance																																							
Floral																																							
Faunal																																							
Airborne																																							
Terrestual																																							
Marine																																							
Nekton																																							
Benthos																																							
Ecosystems																																							
Physiologic																																							
Operational personnel																																							
Artificial systems																																							
Social																																							
Regional population																																							
Transient population																																							
Economic																																							
Property value																																							
Product markets																																							
Conflicting resource use																																							
Air																																							
Water																																							
Land																																							
Legal																																							
Ownership																																							
Jurisdictional agencies																																							
Jurisdictional restraints																																							
Political																																							
Existing regime																																							
Historical and archaeological																																							
Distribution of sites and objects																																							
Technical																																							
Materials supply																																							

* The following time related factors may be usefully applied to numerical ratings before totalling:

Transient	divide by 10
Short term	multiply by 1
Long term	multiply by 10
Irreversible	multiply by 100

Figure 2.49 Matrix for evaluation of interactions between marine mining technology and the marine environment (From: Cruickshank 1978).

<u>Infrastructure</u>

- Plant
  - (Docks, platforms, materials handling equipment, mill plant, dump sites, storage facilities)
- Transportation
  - (Pipelines, carriers, roads, rail, ditches)
- Utilities
  - (Power plants, transmission lines)
- Services
  - (Living quarters, sanitary facilities, recreation facilities

<u>Operational Prerequisites</u>

- Shoreside facilities
- Environmental prediction (weather and seas)
  - Observation
  - Forecasting
- Platforms
  - (Airborne, floating, submersible, sea-bed, divers)
- Power systems and power transmission
  - (Conventional, nuclear, solar)
- Navigation and survey systems
  - (Airborne, marine, submarine, seabed)
- Platform control and communications
  - (Static anchoring, dynamic anchoring, auto functioning)
- Data transmission and processing
  - (Shipboard, remote)

<u>Exploration and Characterization Systems</u>

Sampling
- Superjacent waters
- Sea-floor
- Sub-bottom

Geotechnical measurement
- Physical properties
- Mechanical properties

Geophysical sensing
- Optical
  - Transmissivity
  - Reflectivity
- Mass
  - Density
  - Gravitation
- Magnetism
  - Terrestrial
  - Atmospheric
  - Electromagnetic
- Electrical
  - Conductivity/Resistivity
  - Self-potential
  - Induced polarization
- Thermal
  - Heat flow
  - Thermal gradients
  - Media thermal conductivity
  - Thermal anomalies
- Elastic
  - Seismic velocity
  - Reflection
  - Refraction
- Radioactive
  - Natural
  - Neutron induced
  - Gamma backscattering
  - Gamma spectroscopy

Geochemical Analyses
- Wet chemical
- Neutron activation
- X-ray diffraction
- Mass spectroscopy
- Atomic absorption
- Fluorescence spectroscopy
- Other

<u>Mining Systems</u>

Extraction
- Scraping
- Excavating
- Fluidizing
- Tunnelling

Lifting
- Mechanical
  - Repetitive suspended (dragline, clamshell, hoist)
  - Buoyant (bulk submersible)
  - Continuous (bucket-line, conveyor)
- Hydraulic
  - Single-phase (suction, H. P. water injection)
  - Multi-phase (gas injection, light medium liquid injection, light medium solid injection, heavy medium closed-circuit flow)

Transport and handling
- Bulk carrier
  - Surface
  - Submerged (Air cargo analog)
  - Sea-floor (Ground effects vehicle analogs)
- Pipelines
  - Surface
  - Submerged
  - Sea-Floor
- Transfer of materials

<u>Mineral Extraction Systems</u>

Ore Treatment
- Separation processes, based on
  - Mass
  - Optical properties
  - Surface properties
  - Magnetic properties
  - Electrical properties
  - Elastic properties
  - Radioactive properties
- Extractive processes
  - Chemical activity
    - Hydrometallurgical
    - Pyrometallurgical
  - Atomic structure
  - Biochemical activity

Cycle of Materials
- Gases
- Solubles
  - Processing
  - Storing
  - Dumping
  - Dispersing
  - Recycling
- Insolubles
  - Processing, etc.
- Radioactives
  - Processing, etc.

Table 2.30. Technological systems elements involved in the exploration and exploitation of marine mineral deposits, with examples in parentheses (From: Cruickshank 1978).

Natural Systems

- Meteorologic
  - Climate
    - Temperature
    - Winds
    - Precipitation
  - Air Quality
    - Gases
    - Water Vapor
    - Particulates
    - Radiation (Acoustic, seismic, electric, magnetic, nuclear
  - Natural Hazards
    - (Storms, ice)
- Hydrologic
  - Coastal
    - Surface water
      - Drainage (Rivers, channels)
    - Groundwater
      - Drainage
        - Flow rates (Aquifers, springs)
    - Retention
      - Capacities
      - Leakage
      - Overflow (Underground lakes)
    - Recharge
    - Water quality
    - Physical Properties
    - Chemical Properties
  - Natural Hazards (Tsunamis, storms, floods)
- Marine
  - Upper boundary layer
    - Sea state (Climate)
      - Waves
      - Swell
      - Current
      - Tides
      - Temperature
    - Boundary gradients (Water quality)
      - Physical properties (Temperature, density (STD))
      - Transmissivity (Optical, acoustic, electric)
      - Chemical properties
        - Dissolved (Salinity, chlorinity, trace elements)
        - Particulates
  - Intermediate Layer
    - Climate
      - Temperature
      - Circulation pattern
      - Mixing pattern
    - Water quality
      - Physical
      - Chemical
- Marine (cont.)
  - Bottom Layer
    - Climate
    - Temperature
    - Circulation
  - Boundary Gradients (Water quality)
    - Physical
    - Chemical
- Natural Hazards
  - (Storms, turbidity currents, geothermal plumes, submarine waves)
- Geologic
  - Regional geology
    - Morphology
    - Tectonics
    - Petrology
    - Mineralogy
  - Mineral deposits
    - Ore minerals
    - Distribution
    - Origin
    - Ore reserves
  - Geotechnique and geomechanics
    - Index properties (Specific gravity, density, grain size, water content, Atterberg limits)
    - Engineering properties (Compression, sheer, permeability, consolidation)
  - Natural Hazards (Earthquakes, slides, plate motion)
- Biologic
  - Diversity and abundance
    - Floral
      - Terrestrial (Trees, shrubs, grasses, crops)
      - Marine (Algae, seaweed, phytoplankton)
    - Faunal
      - Airborne (Birds, flying insects)
      - Terrestrial (Animals, reptiles, insects)
      - Marine
        - Pelagic (Zooplankton, fish, mammals, reptiles)
        - Benthic (Epifauna, infauna)
  - Ecosystems
    - Zonation
    - Influences (Physical, chemical, trophic)
  - Natural Hazards (Plankton blooms, fish attacks)
- Physiologic
  - Operational Personnel
    - Numbers
    - Ethnics
      - Aptitude

Artificial Systems

- Social
  - Regional Population
    - Distribution
    - Quality of life (Health, education, welfare, income, livelihood)
- Social (cont.)
    - Social amenities (Housing, schools, fire protection, police, services)
  - Transient Population
    - Number of transients
    - Purpose (Vacation, seasonal workers, fishing)
- Economic
  - Resource Value (Minerals, fisheries, real estate)
  - Resource Markets
  - Conflicting uses
    - Airspace
      - Aesthetics
      - Commercial (Transport, communications, research)
    - Water
      - Residential
      - Commercial (Fisheries, transport, farming, ports)
      - Industrial (Cooling, dumping)
      - Recreational
      - Educational
      - Defense
    - Land (Sea-bed)
      - Residential
      - Agricultural
      - Industrial
      - Recreational
      - Educational
      - Defense
- Legal
  - Ownership (Territorial waters, outer continental shelf, deep sea)
  - Jurisdictional agencies
  - Restraints (Rights of way, precedential rights)
- Political
  - Existing regime
    - Policies
    - Representation
    - Relevant functions
- Historical and Archaeological
  - Distribution of sites and objects (Ruins, artifacts, shipwrecks)
  - Importance
  - Description
- Technical
  - Materials R&D
  - Design
- Restoration
  - Sealing
  - Removal
  - Restoration
- Accident (Fire, explosion, spillage, inundation, collapse)

Table 2.31. Environmental systems elements affecting the exploration and exploitation of marine mineral deposits, with examples in parentheses (Adapted from: Cruickshank 1978).

Clark (1974) presented standards established by the EPA for toxic substances in coastal waters (**Table 2.32**); he also reported quantitative criteria for temperature, oxygen, pathogens, and toxic substances and qualitative criteria for circulation, turbidity, sedimentation, habitat, salinity, nutrients, fauna, and productivity. The assessment of these items for any mining area and/or operation will require considerable field study, however, unless the specific site of operations is known, these criteria would probably not be useful.

Biological impacts are, without doubt, the major enigma of assessing impacts on the natural environment. Generalizations rarely allow meaningful predictions of the effects of specific minerals operations; additional biological studies should be directed on a case-by-case basis to respond to specific needs. The effects of turbidity, sedimentation, explosives, light, and noise on marine biota were reviewed by Cruickshank et al. (1987) for the OCS. Many of the data available come from studies of deep seabed mining, OCS oil and gas activity, or academic research. In those cases cited, the information is assumed to be transferable to a general mining situation. Information on the effects of offshore placer mining is very limited, and in many cases, has been inferred from river and harbor dredging. The main environmental concerns associated with placer mining relate to the turbidity plume and possible smothering of organisms due to the high volume of waste discharged (USDOI, MMS 1991). As much as 99% of the dredged material is waste, with most placer dredges working continuous operations on site 24 h per day throughout the year, except where curtailed by weather.

2.5.4.1 Birds

Large petroleum spills which have the potential to kill numerous sea birds and shore birds are not anticipated from marine mining operations. Effects of small spills tend to be localized and short lived. There is a low probability of such an accident occurring during mining. Nevertheless, this particular subject is given a great deal of weight in current environmental analyses for OCS mining (USDOI, MMS 1983a, 1991).

2.5.4.2 Mammals

Marine mammals represent a highly diverse group (**Table 2.33**), many of which are endangered or threatened species. The effect of mining operations may include loss of feeding areas, uptake of heavy metals, and noise impacts. Oil spills are not considered significant because of the low risk. Many marine mammals are migratory and wide ranging. Although only limited research has been conducted on this topic, some researchers have suggested that marine mammals can easily avoid turbidity plumes which are unlikely to harbor food prey. Suggestions of enhanced biological activity around dredging operations in southeast Asia might usefully be investigated. Whales and other long-lived marine mammals may accumulate trace metals from plumes or discharges, although this is considered unlikely. There was no documentation of trace metal contamination in marine mammals (USDOI, MMS 1988d), however, this may not be representative of likely effects from hard minerals mining. The potential release of ore-derived heavy metals from mining activity has been a controversial issue in prior hard mineral EISs (USDOI, MMS 1983b). Recent strandings of bottlenose dolphin along the Atlantic coast and the harbor seal mortality in northern Europe point to high levels of environmental stress from all sources

SUBSTANCE	Maximum Acceptable Concentrations (96 hr LC_{50})[1,2]	Maximum Acceptable Concentrations (Milligrams or Micrograms/liter)[2]	Minimum Risk Threshold (Milligrams or Micrograms/liter)[3]
Aluminum	1/100	1.5 mg/l.	0.2 mg/l.
Antimony	1/50	0.2 mg/l.	N.A.[4]
Arsenic	1/100	0.05 mg/l.	0.01 mg/l.
Barium	1/20	1.0 mg/l.	0.5 mg/l.
Beryllium	1/100	1.5 mg/l.	0.1 mg/l.
Bismuth	N.A.	N.A.	N.A.
Boron	1/10	N.A.	5.0 mg/l.
Bromine[5]	N.A.		N.A.
Cadmium[6]	1/100	0.01 mg/l.	0.2 ug/l.
Chromium[7]	1/100	0.1 mg/l.	0.05 mg/l.
Copper	1/100	0.05 mg/l.	0.01 mg/l.
Fluorides	1/10	1.5 mg/l.	0.5 mg/l.
Iron	N.A.	0.3 mg/l.	0.05 mg/l.
Lead[7]	1/50	0.05 mg/l.	0.01 mg/l.
Manganese	1/50	0.1 mg/l.	0.02 mg/l.
Mercury[8]	1/100	1.0 ug/l.	N.A.
Molybdenum	1/20	N.A.	N.A.
Nickel	1/50	0.1 mg/l.	0.002 mg/l.
Phosphorus	1/100	0.1 ug/l.	N.A.
Selenium	1/100	0.01 mg/l	0.005 mg/l
Silver	1/20	0.5 ug/l.	N.A.
Thallium[9]		0.1 mg/l.	0.05 mg/l.
Uranium	1/100	0.5 mg/l.	0.1 mg/l.
Vanadium	1/20	N.A.	N.A.
Zinc	1/100	0.1 mg/l.	0.02 mg/l.
Cyanides[10]	1/10	0.01 mg/l.	0.005 mg/l.
Detergents	1/20	0.2 mg/l.	N.A.
Phenolics	1/20	0.1 mg/l.	N.A.
Phthalate Esters	N.A.	0.3 ug/l.	N.A.
PCBs[11]	N.A.	0.002 ug/l.[12]	N:A.
Sulfides[13]	1/10[12]	0.01 mg/l.[12]	0.005 mg/l.[12]

1 The maximum acceptable concentration figures in this column are expressed as fractions of the 96 hr LC_{50} for the most sensitive species in a given area. The 96 hr LC_{50} is that concentration of a substance which kills 50 % of the test species within 96 hr under standard bioassay conditions.

2 Data are Environmental Protection Agency official criteria where available; National Academy of Sciences data are used where EPA data were not available.

3 National Academy of Sciences data, for concentrations "below which there is a minimal risk of deleterious effects."

4 N.A. ~ adequate data not available.

5 The maximum acceptable concentration for free (molecular) bromine is 0.1 mg/l, for ionic bromate, 100 mg/l.

6 In the presence of copper or zinc in concentrations of 1 mg/l or more, the minimum risk threshold should be lower by a factor of 10.

7 In oyster growing areas, the minimum risk threshold should be lower.

8 According to the National Academy of Sciences, "Fish-eating birds should be protected if mercury levels in fish do not exceed 0.5 mg/g. Since the recommendation of 0.5 mg/g in fish provides little or no safety margin for fish-eating wildlife (birds), it is recommended that the safety of the 0.5 mg/g level be reevaluated as soon as possible."

9 1/20 of the 20-d LC_{50}

10 Marine and estuarine aquatic and wildlife criteria not available; freshwater criteria are used (by EPA).

11 According to the Environmental Protection Agency: "The maximum acceptable concentrations of PCB in any sample consisting of a homogenate of 25 or more whole fish of any species that is consumed by fish-eating birds and mammals, within the size range consumed is 0.5 mg/kg on a net weight basis."

12 Data supplied by National Academy of Sciences.

13 These concentrations are valid only if salt water pH is between 6.5-8.5.

Table 2.32. Coastal water quality criteria for toxic substances other than biocides (From: Clark 1974).

Mammals—A Highly Diversified Group

From platypus to peccary, from bat to bison, what makes a mammal different from other animals is that mammals nourish their young with milk. This characteristic plays more than a nutritional role in a mammal's world, for it often creates a strong relationship between mother and offspring. In certain species, this relationship is short-lived; some mice are weaned 2 weeks after birth and breed at 5 weeks. At the other extreme is the walrus, which is believed to nurse for 2 years.

Mammals, like birds, are "warm-blooded." What this term means is that their body temperatures are relatively independent of the surroundings. Because of this, mammals are able to live in the coldest of climates and move about in practically any temperature. (Cold-blooded species require a certain amount of heat to become active.) Of course, this does not mean that all mammals are active at all times. Hibernators conserve energy by resting throughout the winter (see page 65); certain species, such as desert jerboas, become torpid in summer (see illustration on page 206). Aestivation is the name for this summer torpor.

Most mammals have two sets of limbs. (Whales, manatees, and dugongs are the exceptions.) But the method of locomotion varies tremendously from species to species. Cheetahs run, rabbits jump, monkeys climb, beavers swim, gibbons swing, bats fly, and "flying" lemurs glide. Other mammals simply walk on all fours.

The Successful Rodents

Present-day mammals are classified into about 20 orders, depending on the system of classification used. A similar number of orders contain only extinct species. For example, the order Pantodonta is composed of the pantodonts—large hoofed creatures that died out about 35 million years ago.

As you can see from the list here, the different orders vary greatly in importance. Among mammals, rodents dominate the earth, in both number of species and total population. (There are some 2,000 kinds of rodents—about half of all mammalian species. And there may be more rodents on earth than all the other mammals put together.) In contrast, the aardvark, or earth-pig—an African termite-eater—has an order all to itself. The name of its order, Tubulidentata, refers to the microscopic tubules in aardvark teeth.

Teeth are highly significant in the classification of mammals. For one thing, they indicate an animal's eating habits. For example, aardvarks, like other mammals that eat termites or ants, have only a few teeth. The tropical animals known as anteaters have *no* teeth. (They are in the order Edentata, which means "lacking teeth.")

Fortunately for taxonomists, teeth are durable structures that are frequently preserved as fossils. And fossils are perhaps *the* most important clue to relationships between groups of animals. Fossil evidence was a major reason for the taxonomic relocation of rabbits and their relatives. Once part of the order Rodentia, they are now in a separate order called Lagomorpha.

Mammalian Orders

Monotremata: platypus, spiny anteater
Marsupialia: opossums, pouched "mice" and "rats," koala, wombats, kangaroos, wallabies, Tasmanian devil
Insectivora: hedgehogs, shrews, desmans, moles
Dermoptera: cobegos (flying lemurs)
Chiroptera: bats
Primates: lemurs, lorises, galagos, monkeys, gibbons, gorillas, chimpanzees
Edentata: sloths, anteaters, armadillos
Pholidota: pangolins
Lagomorpha: pikas, rabbits, hares
Rodentia: squirrels, chipmunks, cavies, chinchillas, mice, rats, beavers, muskrat, voles, kangaroo rats, hamsters, gerbils, porcupines, pacas, hutias
Cetacea: whales, dolphins, porpoises, narwhales
Carnivora: dogs, foxes, wolves, bears, raccoons, kinkajous, pandas, weasels, ferrets, minks, martens, fisher, wolverine, badgers, skunks, otters, genets, civets, mongooses, fossa, aardwolves, hyenas, lynxes, cats, caracal
Pinnipedia: sea lions, seals, walruses
Tubulidentata: aardvark
Proboscidea: elephants
Hyracoidea: rock hyraxes, dassies
Sirenia: manatees, dugong
Perissodactyla: horse, tapirs, rhinoceroses, zebras, burros, mules
Artiodactyla: pigs, peccaries, hippopotamuses, camels, chevrotains; antelopes, deer, giraffes, sheep, goats, cattle, musk ox, takin

Table 2.33. Orders of mammals (From: Reader's Digest 1977).

and indicate a need for careful monitoring of widespread pollutant loading in the marine environment.

Noise is a ubiquitous effect from any offshore operation, potentially affecting endangered whales and marine mammals by altering normal behavioral patterns. For oil and gas operations in offshore waters of Alaska, the issue has focused on how operational noise may affect whale migrations, feeding behavior, breeding, and calving. Location and timing are critical aspects for noise effects. Some exploratory operations in the Beaufort Sea that are in the path of migrating endangered bowhead whales have historically been seasonally restricted so that the whales do not alter their migratory path as a noise avoidance response. Despite the sensitivity of some animals to noise, no long-term adverse effects from noise have been documented on either populations or species behavior (USDOI, MMS 1988c). Most behavioral responses are elicited at such close range that noise effects can be avoided. Mining activities located away from known migratory pathways and calving or feeding grounds are unlikely to adversely affect marine mammal populations, although individual transient animals near mining sites may be startled or show avoidance behavior. However, because all oil and gas or mining activities are site-specific, it may be difficult to eliminate all noise effects if activities are proposed in sensitive habitats.

Very little is known about the intensity, frequency, and duration of mining-related noise. The type of collector most likely to be used for mining manganese nodules may attract scavengers (e.g., rat-tail fish) that communicate by sound (USDOC, NOAA 1981). Noise also affects marine mammals, but the significance is not well known (USDOI, MMS 1983a,b). Most research has been conducted on the effects of OCS oil and gas activities on endangered and/or threatened marine mammals. Some researchers (e.g., Geraci and St. Aubin 1980) suggested that most animals become habituated to low-level background noise, such as ship traffic and offshore petroleum activities; however, some animals show abrupt responses to sudden disturbances. Responses to continuing abrupt noise disturbance by California sea lions, Stellar sea lions, and harbor seals are fairly well documented (USDOI, MMS 1983b). Gales (1982) found that, although there were no significant physiological effects, other possible effects from a sonic boom, a pulse somewhat similar to explosive seismic pulses, include startle, flight, auditory discomfort, and hearing loss. Stationary dredging operations in the arctic did not seem to greatly disturb beluga and bowhead whales, but their swimming patterns did change within 2.4 km of dredging operations (USDOI, MMS 1983a). MMS-sponsored studies of the effects of noise on gray whales off the California coast also found that ship and air gun noises affect behavior, but much less so than biologically meaningful sounds, such as the sounds of killer whales. This response seems likely to be true of other animals as well. It is probable that the effects of mining noise will resemble the effects of noises from harbors, mechanized fishing gear, military maneuvers, and shipping (Cruickshank et al. 1987).

2.5.4.3 Marine and Aquatic Fauna

In general, the effects of mining operations on living marine resources can be assessed as beneficial, insignificant, or adverse. To date, several beneficial effects have been recorded or discussed, including (1) the attraction of fish to offshore structures; (2) the enhancement of substrate habitats by alteration of the texture; (3) the enhancement of substrate habitats by the presentation of new surface nutrients by mixing and replacement of the benthos; (4) thermal stimulation of growth; and (5) introduction of nutrients by mixing of water masses and enhancement of phytoplankton growth (Cruickshank 1974b).

A longer list of potentially adverse effects includes the following:

(1) Direct toxic effects of pollutants on individual organisms, causing abnormal growth, reduced adult fecundity, behavioral changes, accumulation effects in the trophic web, poisoning, restriction of motor functions, erosion of gill filaments, suffocation, pressure shock, embolism, and thermal shock; and

(2) Disruption of community and ecosystem structure, including changes in diversity and abundance caused by disruption of food webs, changes in predator-prey relationships, reduction in community stability in response to environmental fluctuations, changes in age structure of populations by selective mortality, changes in dynamic behavioral patterns, concentration of toxic fractions through food web transfers, loss of bottom habitat, provision of new habitat, migration of population, and introduction of dormant species from bottom to surface waters.

Analyses of potential impacts require a knowledge of the pre-mining populations and their natural cycles so that a differentiation can be made between natural fluctuations and impact response. At the present time, there is little agreement within the scientific communities as to what constitutes adequate knowledge of pre-mining conditions, or baselines. Difficulties arise in the selection of indicator species which will adequately represent the biotic community and its reaction to a disturbance. When measuring baseline conditions, the effect of long-term regional cycles on local communities may be overlooked or unsuspected. Conversely, the effect of local impacts on regional or global communities may be underestimated or overestimated.

- **Effects of Suspended Sediment**

In addition to sediment concentrations, there are three other potential sources of concern. First, the presence of toxins in sediments can greatly increase the adverse impacts of turbidity. However, the data showing such effects are based on studies of sediments from harbors and estuaries in which toxins (e.g., pesticides, heavy metals) are introduced to the marine environment and subsequently adsorbed to the surfaces of sediment particles. Such contaminants are rarely found in more than trace amounts in the OCS environment. Moreover, in natural mineral deposits exposed to seawater, the biologically active metals are in nearly insoluble forms and, generally, are biologically inert.

Second, fluid muds (fluff) may form near the water-sediment boundary and persist for weeks if there is insufficient circulation to disperse them. However, lack of circulation is rare in OCS waters, although fluff may form in coastal waters. Shell dredging operations in Galveston Bay, for example, resulted in a nearbottom mud flow with particle concentrations from 20 to 150 g/L that lasted throughout the dredging operations (Masch and Espey 1967, as cited in Peddicord 1976). Such a condition could be a problem for fauna that are not equipped to move through this layer to reach the less turbid environment (Hirsch et al. 1978). However, the significance of this layer is partially a function of its thickness, a parameter which can be affected by the mining method. The potential for fluid mud formation when fine, noncohesive materials are resuspended or discharged, along with the resulting hazards, will strongly depend on the site and the operating conditions.

Third, in all cases where mining involves the mechanical fracturing of the rocks, the particles produced are more likely to have sharper, more angular edges than resuspended bottom sediments. These sharp fragments may damage organisms more than natural sediments.

Turbidity: Both laboratory and field observations have been made of various organisms under conditions of increased suspended sediments for various durations. The results, when compared with increased concentrations expected in the water column, suggest that these effects may not be a concern if the dilution factor is high and there are no exceptionally sensitive bottom communities in the area. For instance, a study of animals from San Francisco Bay found that at least 90% of the animals in most of the 18 species tested were alive after 10 days exposure to concentrations of 100 g/L kaolin clay suspensions (Peddicord 1976). Even the more sensitive species were only adversely affected by tens of grams per liter of processed bentonite clays over several days time. However, these experiments did show that the sensitivity of some species to bentonite increased with higher temperatures (e.g., 18°C) or lower oxygen concentrations (Wakeman et al. 1975). This suggests that in San Francisco Bay, seasonal changes in these two parameters may be important in determining the severity of impact from dredging and disposal. However, Peddicord (1976) noted that the laboratory experiments did not evaluate physiologically sublethal effects, which may be more important ecologically than direct mortality. Lunz et al. (1984), in a recent summary of data for eggs, larvae, and adults of fish and shellfish harvested in the coastal zone, found that several of the molluscs and crustaceans tested were sensitive to 100 mg/L or more of suspended sediments during multiday exposures. In contrast, other species were tolerant of higher levels of suspended sediment (i.e., 100 g/L or more) for 1- to 3-day exposures, a thousand-fold difference in concentration.

The results of laboratory studies of marine fish vary. Moore and Moore (1976) found that turbidities of 126 to 135 mg/L increased the time for the European flounder to identify its prey. Although this finding is likely to be of minor importance if the plume is short-lived, this nonlethal effect would reduce the feeding rate and, hence, the vigor of the affected animals. Effects of manganese nodule mining plumes on captive yellowfin tuna and kawakawa have been studied by exposing the fish to deep sea clays and nodule fragments. No detectable effect was found in adults at concentrations ranging from 9 to 59 mg/L. Feeding continued to occur in concentrations of 11 mg/L, and no change in behavior was noted in the presence of a turbidity cloud (Barry 1978). However, preliminary results by Barry suggested that turbidities greater than 4 mg/L sometimes caused feeding inhibition and coughing-like reaction in tuna in laboratory tests (Matsumoto 1984).

Other field observations have been made on the behavior of marine fish in areas of high turbidity (Shelton and Rolfe 1971; Shelton 1973; Wilson and Conner 1976).

The results suggest that adults are less sensitive than juveniles and that there are differences among species. Whitebait (immature herring) and sprats have been found to avoid areas where china clay wastes were discharged. Mackerel, however, do not seem to avoid these areas and exhibited no problems in feeding despite being visual feeders. Fish are observed to be abundant off the mouth of the Columbia River where sediment concentrations may reach 10 to 100 mg/L (Pruter and Alverson 1972). Ritchie (1970) noted no adverse effects from overboard dredge spoil disposal on 44 species of fish from Chesapeake Bay. Observations off Hawaii showed that densities of fish larvae were negatively correlated with higher turbidities, whether natural or man-related, which Miller (1974) suggested may be caused by avoidance of turbid areas. Lunz et al. (1984) summarized laboratory reports of significant mortality of white perch, yellow perch, and striped bass larvae at suspended sediment concentrations of 500 to 5,400 mg/L after 1 to 4 d of exposure. Larvae in the open ocean would not be exposed to such concentrations for such long periods, as they would drift with the diluting turbidity current; the potential significance of exposures in the field may be overstated by these laboratory data. In general, fish species that are sensitive to suspended sediment (e.g., herring and turbot) will avoid the affected area (de Groot 1979a). In tests reported by Owen (1977), there was an indication that high levels of suspended material can clog or interfere with the gill tissue of fish and may have attributed to the disease fin-rot. However, there are some species which can tolerate high silt concentrations and might proliferate in turbid water because predatory fish may be temporarily kept away from the area (Peddicord 1976; United Nations 1981).

Turbidity will affect fish to a lesser extent than bottom fauna because fish have the ability to avoid an area (de Groot 1979a). Suspended material is reported to have adverse effects on mussels close to the dredge which grew less than those further away, and on settlement of encrusting organisms near the dredge site (ICES 1979). Turbidity from dredging operations did not seem to have an adverse effect on oyster larval development, quahog clams, soft shelled clams, and oysters (U.S. Army Engineer District 1974, California Department of Fish and Game 1977). Similar findings were noted for lobsters, which are relatively tolerant to suspended sediment except while molting (Boehmer et al. 1975).

The impact of the turbidity cloud from aggregate dredging operations on sensitive benthic organisms will be far less than placer mining, because aggregate operations avoid areas with a significant amount of fines and are not of continuous duration. Although turbidity plumes from dredging cause the widest ranging impacts, it is still generally small relative to the overall marine coastal environment. Also, the material is quickly dispersed and exposure is of short duration (GESAMP 1977; Gillie and Kirk 1980; Cressard and Augris 1982; Drinnan and Bliss 1986; U.S. Congress, Office of Technology Assessment 1987). The effects of a turbidity plume on pelagic fish, invertebrates, and bottom dwelling organisms were noted as minor by Herbich (1975) and Cressard (1981).

Smothering Effects: In the literature related to the smothering effects of ocean mining operations, it was reported that smothering of bottom dwelling organisms due to the settlement of suspended sediments can be a problem, as well as the associated depletion of oxygen in surrounding waters. There is a far greater potential for adverse effects from smothering where the ecosystem has an usually high sensitivity, such as coral reefs and seagrass beds (Aurand and Mamontov 1982). Damage to shellfish from smothering associated with ocean mineral dredging was reported to be limited to within 366 m of the dredge (Herbich and Schiller 1973). As aggregate mining takes place for clean, well-sorted coarse materials (e.g., gravels, sands), the likelihood of smothering from suspended sediments would be small. With placer mining, however, there could be a greater proportion of fine sediment associated with the deposit and with the overflow material returned to the seafloor. Smothering represents a greater concern in placer mining operations.

In summary, while most of the studies of dredge spoil and mine tailings disposal have been close to shore and may have limited relevance to the OCS (Bigham et al. 1982), adverse effects to the biota from increased turbidity are likely to be insignificant as long as there is a high dilution of the material (Kaplan et al. 1974). Most OCS organisms are adapted to natural variations in turbidity and can tolerate the short-term higher turbidities that may result from mining unconsolidated sediments. As noted above, swimming organisms can avoid a plume, while nonswimming organisms will drift with the plume as it rapidly dilutes. Mining consolidated rock should be less of a problem as a turbidity source because the particles released into the water column are expected to be larger and will settle more rapidly.

Pollutants: Pollutants in the oceans may affect living organisms in different ways, particularly growth and reproductive rates (Davis 1972). Most studies to date have listed the possible pollutants as thermal pollution, salinity changes, insecticides, oil and detergents, inorganic pollutants, radioactive wastes, and eutrophication; of these, only inorganics might apply to marine mining operations. The effects of pollutants on the physiology of marine animals is little understood and should be studied. However, such studies do not appear to be a pressing need. Portmann (1979), however, listed the possible inorganic pollutants from mining and included antimony, arsenic, beryllium, bismuth, cadmium, chromium, cobalt, copper, lead, mercury, nickel, selenium, tin, uranium, and zinc. In no case has sufficient work been done to draw conclusions on the dangers of these elements to human or animal life from a marine mining operation, but caution is suggested. The author indicated that the risk is low for dredging manganese and phosphorite nodules because they are unlikely to become finely divided. Portmann (1979) did not take into account the need to reduce the particle size for processing.

- **Pleuston and Neuston**

The exposure of free-floating organisms to high turbidity concentrations will be limited because they drift with the plume as it disperses, and are characteristically exposed for only short periods of time. Consequently, any potentially detrimental effects will be small (Cruickshank 1974b; NRC 1985).

- **Plankton**

Effects on marine phytoplankton have been observed in response to decreased illumination in the laboratory, but these shading effects are not expected to be a problem in open waters. The high dilution that would immediately occur prevents significant effects. Measurements of primary productivity and light intensity in a mining plume from deep seabed test mining showed a possible 50% reduction of productivity in an area of 36 km^2 over several hours (USDOC, NOAA 1981). In a commercial mining operation, a 50% reduction in primary production may occur over an area measuring approximately 400 km^2 (Chan and Anderson 1981). Plankton in the mixed layer might be expected to encounter reduced light over an 80- to 100-h period. This effect is similar to the effect of a cloudy day (USDOC, NOAA 1981).

An excellent review of potential adverse effects on zooplankton from a deep seabed manganese nodule mining plume was conducted by Hanson et al. (1982). Many of these species are filter feeders which ingest particles on the basis of size. Research has shown that zooplankton would most likely ingest nonnutritive particles from a mining plume (Hirota 1981; Hu 1981), effectively reducing their food intake. Not surprisingly, large increases in the ratio of nonnutritive to nutritive particles are harmful. For example, concentrations of 0.6 to 6 mg/L of clay wastes from aluminum extraction resulted in lower body weights of copepods (Paffenhofer 1972). However, the effects of nonnutritive ingestion caused by the presence of mining may not be readily distinguished from natural variability. Hanson et al. (1982) concluded from their review of manganese nodule mining wastes that the oceanic zooplankton community would probably not be significantly harmed. Even though these wastes included trace metals released from the nodule fragments and pelagic clays as well as suspended load, they noted the plumes would be rapidly diluted, exposures would be brief, and the animals could tolerate slight increases in trace metal concentrations.

Some studies of larval fish have shown feeding behavioral modifications because of decreased illumination, a possible consequence of increased turbidity (Riley 1966; Saksena and Houde 1972; Wyatt 1972; Houde 1975; Houde 1977; Blaxter 1980; Kawamura and Hara 1980). However, Matsumoto (1984) concluded from a review of existing literature that the dilution of the plume from manganese nodule mineship discharges would be rapid enough to prevent any significant adverse impact on tuna and billfish eggs, larvae, and adults.

- **Nekton**

It is apparent from research reported in the literature that the free-swimming pelagic, anadromous, and demersal fish will not be adversely affected by mining operations, as adults and juveniles are capable of avoiding stress inducing situations by swimming away. The only potentially significant area of concern is the effect on spawning grounds of herring and similar species, a site-specific problem.

- **Benthos**

Effects at the seafloor, particularly those resulting from resedimentation of the benthic turbidity plume, actual destruction of biota, and changes in seafloor topography, will generally be more important than effects of changes in the water column. This conclusion is founded upon both observations of dredging operations and laboratory studies of the effects of suspended materials. Given the relatively rapid dilution of suspended sediments and dissolved substances, their concentrations should fall within acceptable ranges near the point of discharge. Factors, both biological and nonbiological, that may affect the validity of this conclusion are listed in **Table 2.34**. Each of these factors should be considered in the determination of potential environmental effects (Cruickshank et al. 1987).

The sensitivity and natural resiliency of the epifaunal and infaunal benthic community is important in determining the recovery of the affected biota as a whole (ICES 1975). Some species of organisms will likely be more affected than others because of their feeding mode (e.g., filter feeders), life habit (e.g., surface dwellers), degree of mobility (e.g., tube dwellers), or sensitivity of life stage (e.g., larvae). Those organisms living in an environment with episodes of high turbidity and sedimentation can likely withstand some disturbance. For example, oysters, which are filter feeders, are able to endure some increases in sedimentation (Mackin 1961; Loosanoff 1962; Dunnington 1968), and benthic deposit feeders can burrow out from an increase in deposition (Hirsch et al. 1978; Maurer et al. 1978; Nichols et al. 1978). However, for both deposit and filter feeders, there are redeposition thicknesses and rates beyond which the animals cannot survive.

Several general, and numerous specific, factors have been found to be critical in determining the rate at which a disturbed area is recolonized by species that were previous residents. A mobile adult stage allows faster recolonization of large disturbed areas, especially if the larval stage is not mobile (Dauer and Simon 1976; Levin 1984).

The season, duration, and areal extent of the disturbance can be critical, if the disturbance occurs during a period when stability of the seafloor is important to the survival of certain life stages of a species. For example, some fish lay eggs on the seafloor and would be very sensitive to mining before the eggs hatch. Hence, changes in the shape of the seafloor could affect the survival of members of even those species that spend most of their life in the water column.

These examples illustrate the multiplicity of factors that may influence the degree of impact from OCS mining. Early identification of those factors is important in determining the degree of impact and recovery rates, and allows mining proposals to be developed that consider potential impacts and possible mitigating measures. However, until the areas of mining are known, it is of limited value to try to predict further the severity of impact from a particular mining activity (Cruickshank et al. 1987).

According to Zippin (1988), sources of impact to the benthos include physical disturbance, removal of the seabed, and effects of turbidity and contaminated discharges, all of which result from both oil and gas or mining operations. Although oil and gas activities disturb the seabed and bury adjacent benthic habitat, the areal extent of this effect is small, generally less than 1,000 m^2 (USDOI, MMS 1988c). Moreover, muds and cuttings may be recolonized and, although the new benthic community may be different from the natural one, opportunistic fauna may demonstrate great success (Clark 1988). Despite long-standing and wide-ranging oil and gas related discharge activities in the Gulf of Mexico, no cumulative adverse effects on benthos have been detected. Elimination of the benthic substrate is a singular property of most mining methods. Compared with individual oil and gas activities, the area affected by removal and by smothering from deposition of suspended sediments during mining is greater by several orders of magnitude. However, Plume Effects (swimming or floating species)

Nonbiological

1 - areal extent
2 - season
3 - duration
4 - concentration
5 - currents
6 - water depth

Biological

1 - stage of development when impacted
2 - physiological sensitivity of species
3 - dispersal ability of species
4 - feeding mode
5 - dependency on light
6 - geographic range

Resedimentation Effects (benthic species)

Nonbiological

1 - degree of alteration of substrate type
2 - depth of redeposition
3 - duration
4 - season
5 - areal extent
6 - currents
7 - water depth

Biological (primary effects)

1 - stage of development
2 - physiological sensitivity of species
3 - dispersal ability
4 - feeding mode
5 - life habit (e.g., burrowers)
6 - geographic range

Table 2.34. Key factors affecting the degree of environmental impact (From: Cruickshank et al. 1987).

while the local impact to the benthos would be severe, the overall effect on the marine environment and productivity may be insignificant (Zippin 1988).

Feeding mode, life habit, degree of mobility, or sensitivity of life stage all affect the vulnerability of organisms to sedimentation. Some organisms are able to burrow out from tens of centimeters of sediment, although there seems to be a maximum depth below which no escape response is initiated (Hirsch et al. 1978; Maurer et al. 1978; Nichols et al. 1978). Other species can tolerate a slight increase in sediment deposition above natural loads. Oysters have been found to be fairly tolerant of some increase in sedimentation, although a large amount of deposited material causes suffocation (Mackin 1961; Dunnington 1968). Adults react to slight increases through increased pumping, or in some cases, through closing their valves. However, Loosanoff (1962) found some animals died when stress was prolonged for more than 48 h. Larvae and eggs were most sensitive, with normal development being affected at 188 mg/L and stopping at 2 g/L. In general, clam larvae and eggs exhibited less sensitivity to increased concentrations of silt (Davis and Hidu 1969).

The resiliency of benthic animals may be much less if their typical natural environment has low turbidity, such as is found in much of the tropics. Hermatypic corals are known to depend on light for growth (Goreau 1961), with growth being inversely related to the amount of resuspended sediment (Dodge et al. 1974). Consequently, a substantial increase in suspended sediment in areas of coral growth could be of concern, even though many corals can withstand some sedimentation through active removal. Bak (1978) studied the growth rates of fringing corals before and after dredging in the Caribbean. Although light levels were reduced to approximately 1% of the surface illumination for only a few days, growth of *Madracis mirabilis* and *Agaricia agaricites*, both efficient sediment rejectors, was reduced by one-third for more than 1 month. Colonies of *Porites astreoides*, however, became covered with sediment which they were unable to remove, lost their symbiotic algae (zooanthellae), and died.

Other areas that may not be able to withstand slight increases in sediment deposition are those used by bottom spawning fish. For example, in the North Sea where gravel dredging resulted in large pits 3 to 5 m deep, water flow over these areas was slowed, resulting in finer sediments being deposited (Dickson and Lee 1973a,b). Resedimentation rates measured in many of these pits suggest that it may take decades before they fill with silt and they may never return to pre-mining conditions. Similarly, monitoring of dredge channels along the U.S. Atlantic coast has likewise shown that silt-clay particles fill in the channels, in contrast to the surrounding sand environment, resulting in an altered substrate (Taylor and Saloman 1968). In Europe, recommendations have been made to avoid those areas where herring attach their eggs to the seafloor as well as those areas and times of sand eel spawning (ICES 1975; de Groot 1979b). Similar bottom spawning species exist off both coasts of the U.S. (e.g., herring, winter flounder, sand eels, rock sole) and deserve attention, as the spawning areas of these species may be affected by increased sedimentation, especially if a fluid mud layer is created (Hirsch et al. 1978). Also, there are special environments, such as the Arctic (USDOI, MMS 1983a), where recolonization may be extremely slow, but on which little information is available. Wright (1977) observed that full benthic recovery may take more than 12 years as a consequence of dredging for gravel islands in the Canadian Beaufort Sea.

In cases where most of the benthic community is adversely affected, recolonization will have to occur from populations outside the disturbed area. The rapidity of this process seems to be highly influenced by the similarity of the new substrate to the pre-mining condition (de Groot 1979a). Recovery of the benthic fauna was estimated by de Groot (1979b) to take two to three years following sand and gravel mining. Recovery is aided if some of the sand and gravel deposit is left so that the substrate remains similar. Pfitzenmeyer (1970) found that the upper Chesapeake Bay recovered to its original condition 18 months after dredge spoil disposal when there was no major topographic or stratigraphic change and the sediment was similar. Kaplan et al. (1974) found that the number of species in an enclosed bay in Long Island differed as a function of sediment type before and after dredging, with sediment changes being related to the circulation changes that resulted from the dredging.

Similar effects would be expected from metal mining activities. Disturbance of large areas of the seabed by mining would alter habitats, which could affect feeding and spawning. An important impact that cannot be assessed in advance is the uptake of heavy metals which might be released by mining or tailings discharge. Trophic effects, from uptake by plankton through human consumption, would be a major concern. Concern that the dumping of taconite tailings into Lake Superior was destroying the lake trout industry were dispelled when studies indicated that the decline was universal in the Great Lakes and due to other causes (Pycha 1968). Nevertheless, the dumping of taconite did produce a serious environmental problem because of the content of finely divided asbestos.

Benthic organisms may serve as indicators of pollutants, and the structure of the benthic community may be indicative of a stressed or disturbed environment (Glasby 1985). The need to study benthos in regard to the potential environmental impact of any mining of the Chatham Rise phosphorites is obvious (Dawson 1984).

Other studies of dredged, inshore areas have found rapid recovery (Harrison 1967; Cronin et al. 1971; Conner and Simon 1979). However, in many cases, while the biomass may reach pre-dredging conditions, the diversity and distribution of species do not always replicate the pre-mining environment (May 1973; de Groot 1979a). Such a shift in community structure has been reported in experiments with recolonization boxes at depths greater than 1 km (Desbruyers et al. 1980; Levin and Smith 1984; Grassle 1985). Opportunistic species able to move rapidly into an unoccupied area were the first organisms to settle in the boxes and exhibited greatest abundances. The number of those species, however, was low in comparison to adjacent areas. After 26 months, the species composition of the boxes in the deep waters still differed greatly from adjacent areas.

Light and noise generated by mining equipment may disturb nearby benthic organisms and possibly modify behavior. However, many, if not most, mobile, nonterritorial organisms should be able to move away from the disturbance. Even though there is little natural light below 1 km, deep sea organisms have functional eyes and the light introduced during mining will attract some organisms and cause others to move away. Moreover, observations from submersibles indicate that fish exposed to bright, artificial light may be at least temporarily mesmerized, possibly blinded. The exact impact has not been determined (USDOC, NOAA 1981; Cruickshank et al. 1987).

With respect to the dumping of mine tailings from coastal mines in inshore waters, recovery does occur. What is not clear at this time is the manner and rate of recovery of damaged ecosystems. The concept of parallel level bottom communities (i.e., where the same or closely related species in different geographic regions inhabit similar sediments) allows for extrapolation of measured data to other areas (Ellis and Hoover 1990).

Benthic species recolonizing tailings in one place are likely to be the same ones to recolonize in similar tailings elsewhere. Therefore, for proposed mining activity in new areas, a search of the regional taxonomic literature could indicate the species likely to recolonize new tailings beds. Environmental specialists could then develop the taxonomic skills necessary to monitor the rate and pattern of benthic impact and recovery, as indicated by Ellis and Hoover (1990). This approach might also apply to the deep water environments on the continental shelf and the deep seabed. Knowledge of which species naturally colonize tailings beds, as well as their ecological niches, might allow for targeting such species to use in artificial reclamation; according to Ellis and Taylor (1988), such information is used in established procedures for designing artificial reefs.

2.5.4.4 Flora

In general, the effects of marine mining on flora are not regarded in the literature as a major focus. There are, however, other non-mining changes that would appear to influence the growth of plant life, including algae on the surface (pleuston and neuston), as well as phytoplankton in the photic zone and elsewhere in the water column.

2.5.4.5 Sensitive Habitats

In some sensitive areas, such as shallow Arctic waters, or in deep seabeds, slow re-growth might present problems if the biome represents a critical niche in the ecosystem. Dunton et al. (1982) stripped the organisms from a small area in a cobble-kelp community in the Arctic and found most of the areas still bare after three years. Such slow recovery of a community suggests that the arctic environment may deserve special attention. Deep sea environments probably would be equally slow to recover, because they are also very cold and food is limited (USDOC, NOAA 1981). Areas of hydrothermal vents along mid-ocean ridge crests where discharge temperatures are as much as 300° C support unusual benthic colonies of crabs, clams, and tube worms. Regulations would make allowance for avoidance of such environments in the event of mining (USDOI, MMS 1983b).

2.5.4.6 Threatened and Endangered Species

The site-specific nature of the threatened and endangered species listed by the appropriate government agencies makes it inappropriate to generalize beyond the fact that in all cases where mineral developments are planned, these species are given prior and serious consideration in the U.S.

2.5.5 Social and Economic Resources

This concept is similar to endangered species because it is site-specific and of very broad variety. Most actions resulting in environmental query are triggered on the basis of some social or economic need. These aspects are built into the scoping process for the environmental documents. The literature is voluminous and scattered.

2.5.5.1 Human Resources

The effects of marine mining on human resources include health, employment, and infrastructural needs (e.g., water, sewage, etc.). In a purely marine scenario, all of these needs must be taken care of at sea. A significant impact might be that of prolonged operations at sea on individuals. Where processing plants as well as mining operations are developed from platforms, or where seabed mining operations are carried out in the hard rock, there could be considerable effects on operating personnel arising from extended periods of relative isolation (i.e., not coming ashore for months at a time). Mitigation might require shift changes (e.g., two weeks on, then two weeks off, as sometimes done in the oil and gas industry) or a restructuring of the social aspects of isolated work (e.g., by involving family participation as an accepted part of the field operations).

- **Social Impacts**

The social environment, being a personal environment for each individual, is extremely variable and widely described. No studies specific to marine mining were identified. Disturbances may not be welcome unless they bring benefits. Thus, a basic consideration of the social environment is conflict of interest. Like most human affairs, the ranking of multiple uses may be highly subjective and may ultimately depend on assessment of the greatest benefit for the greatest number. A considerable amount of material has been written on these areas of human ecology and man's concern with the environment. Marine minerals may have an important place in this scenario, as has been indicated by the extensive work done by the Preparatory Commission on Seabed Mining under the Law of the Sea Convention. The United Nations produces periodic reports of the Preparatory Commission for the International Seabed Authority and the International Tribunal for the Law of the Sea which is now in its 10th session.

- **Legal Impacts**

Laws are sometimes a restraining force on mining operations. On occasion, as was the case in early U.S. history, mining operations are so influential that they call for the formulation of new laws. The mining of the sea is no exception. For many marine minerals, national laws are not adequate and international laws regarding the mining of the seafloor are still not well defined. In many areas where social need has developed rapidly (particularly for deep sea minerals), national and international laws have lagged. Thus, there is a need for creative revision of the laws to encourage development and social benefits. It is now widely recognized that mineral resources are not inexhaustible; exploitation cannot be properly effective without a regard for resource conservation. Conflicting requirements for use of the mineralized areas by others must be duly considered. Each of these aspects will have a significant effect on the planning and conduct of operations (USDOI, MMS 1988c,d). Thiel et al. (1991) offer a detailed analysis of the legal environment currently in existence for international marine mining activities.

- **Political Impacts**

Ideally, the political environment is one in which morals or human rights are paramount and in which laws are formulated as an effect of disturbance of the *status quo*. The path through the political environment is delicate and difficult; the quantification of the interactions for analyses tend to be subjective because of individual likes and dislikes, as well as rights and responsibilities. Political inputs to operations can be very significant, and some of them are discussed in more detail in **Chapter 3**.

2.5.5.2 Commercial and Recreational Fisheries

The literature from Europe pertaining to commercial and recreational fisheries is more extensive than in the U.S. Experience in the U.K. has shown that modern prospecting operations cause little disturbance to the marine environment or minimal interference with other activities at sea. As a result, there is no formal government consultation procedure for a prospecting license. The MAFF cannot, and does not, object to granting licenses (Pasho 1986); for mining, however, the permitting process is substantive (Nunny and Chillingworth 1986).

- **Fishery Resources**

Fishery resources must be viewed from two perspectives, including (1) the fish as a resource; and (2) fishing as an economic activity. Standing stocks of the resource are affected by turbidity, pollutant loading, and physical disturbance, particularly to the extent recruitment may be reduced. Marine mineral activities may interfere with fishing activities and compete for space at sea and in port (Zippin 1988).

Direct effects of oil contamination or turbidity can be avoided by most fish owing to their motility. Indirect effects include damage to eggs, larvae, and juveniles; sublethal uptake of hydrocarbons and pollutants; loss of prey; loss of habitat; or reduced reproductive success. It is virtually impossible to isolate the effects of offshore oil and gas activities on mobile populations like fish, however, offshore platforms do support reef-like communities of fish with little evidence of tainting or adverse effect. Oil and turbidity can reduce recruitment but no such effects have been identified.

Of recent interest has been the potential for marine geophysical surveys to reduce catchability of fish and damage fish eggs and larvae. Limited studies have shown that spatially-concentrated use of seismic energy sources over extended periods can disturb the spatial distribution of fish in the water column and reduce catchability (Straughan 1971). Ongoing studies of seismic energy source pulse waves on eggs and larvae indicate that effects are highly localized, with lethal effects contained within several meters of the energy source. Despite the issuance of more than 8,000 permits for offshore oil and gas exploration activities and the compilation of millions of line-miles of seismic surveys, no cumulative adverse effects on fishery resources have been detected.

Relative to commercial fishing, space-use conflicts between fishermen and vessel operators have occurred with entanglement or severing of net and trap lines. Coordination efforts between the two industries have helped avoid most conflicts. Offshore drilling rigs and platforms also can preclude access to fishing grounds, while debris from offshore activities can damage fishing gear. Except for fixed platforms, the displacement effect is temporary and has no effect on populations of commercial fish species. It is expected that there has been some loss of individual income through lost catch opportunity, gear loss, and increased cost of port space.

According to Nunny and Chillingworth (1986) in a definitive report on offshore sand and gravel mining in the U.K., increased scientific understanding is needed for a determination of (1) the residual effects upon habitats within exhausted dredging grounds; (2) the potential role of localized unfishable areas as fish reserves; (3) the spawning behavior of the local fish stock; (4) the behavior of ovigerous crabs; and (5) the long-term economic value of inshore fishing grounds. Increased data generation during prospecting was suggested by Nunny and Chillingworth (1986) as a means of acquiring (1) relatively superficial site-specific data on the natural environment, including tides, turbidity, substrates, benthic communities, and fishing potential, along with detailed prospecting data to enable better assessment of acceptability of dredging proposals; and (2) environmental data acquired during investigations on a scale closely related to the expected level of anticipated problems and the level of financial return. These recommendations are worth serious consideration in the U.S.

2.5.5.3 Regional Economies

Our present social system and technological advancement is based on money that people can measure and understand. The impact of resource disturbance will thus be measurable on the economy. How large the economic impact will be resulting from any given action is affected by many factors. Recent studies have examined the impact of marine mining on the market. As Sorensen and Mead (1969) noted in referring to an offshore phosphorite venture, and considering the risk involved from the point of view of both costs and eventual markets, it is not unreasonable to predict that expected net rates of 30 to 40% return on investment in marine mining will be required to secure the necessary capital for a pioneering venture. In cases where the externalities of a marine mining venture are very substantial, several different economic approaches must be made. With the strong national and global emphasis on sustainable development, however, it is apparent that value or cost is no longer strictly a monetary function.

2.5.5.4 Local Economies

Local economies are driven by several factors. Because they are, for the most part, very site-specific, it is not appropriate to generalize these effects.

2.5.5.5 Cultural Resources

Effects on cultural resources are particularly difficult to quantify because the intangible cultural systems are subject to the historical and contemporary changes induced by all human activities. It appears, however, that in the comparison of alternatives which relate to the same time frame, semi-quantitative methods of factor analysis might be valid (Cruickshank 1974a). These concepts are discussed also by Cruickshank (1978).

- **Archaeological Resources**

Archaeological sites may be significant and, in cases where important sites are located during mineral exploration, it is likely that the regulated action taken for their discovery would add to our knowledge of human history and would, therefore, be beneficial. Although search for such sites is mandated by U.S. law, there were no good examples of such discoveries in the literature.

2.5.5.6 Technical Resources

The technical environment which interfaces with technical operations can be regarded as largely one-sided. Its major impact on technology is in the form of disturbances to the system due to materials failure (i.e., primarily effected by motion, pressure, corrosion, and biological fouling). The impact on the environment is relatively small. The operation will not affect the motion of the sea, the pressure at depth, the means of corrosion, or the fouling capabilities of the biota to any great extent. There may be limited and minor local effects which must be considered due to the size of large operations, however, these local effects have not been evaluated within the present study effort.

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CHAPTER 3 SUMMARY OF MITIGATION MEASURES AND THEIR EFFECTS

Exploration, testing, development, production, and processing activities proposed to be conducted under a lease will only be approved by the Director upon the determination that the adverse impacts of the proposed activities can be avoided, minimized, or otherwise mitigated.

(30 CFR 282 1989)

Mitigation is defined here as actions taken to make the effects of marine mining as harmless to the environment as possible. In this sense, the proper management approach to mitigation is ideally focused on system design optimization, rather than retrofits or prescriptive constraints. Under less than ideal circumstances, social mores or political expediency may impose constraints on marine mining activities that are less than optimal and frequently contradictory. CEQ Regulations (40 CFR 1508.20) define mitigation to include (1) avoiding the impact altogether by not taking a certain action or parts of an action; (2) minimizing impacts by limiting the degree or magnitude of the action and its implementation; (3) rectifying the impact by repairing, rehabilitating, or restoring the affected environment; (4) reducing or eliminating the impact over time by preservation and maintenance operations during the lifetime of the action; and (5) compensating for the impact by replacing or providing substitute resources or environments (U.S. Council on Environmental Quality 1978).

For U.S. waters, the mineral resources of the marine environment are managed (1) in territorial waters by the adjacent States (Giordano 1989); (2) in OCS waters by the USDOI, MMS (PL 83-212 as amended); and (3) in seabeds, beyond national jurisdiction, by NOAA (PL 96-283). In the OCS, the USDOI operates under the sometimes conflicting authority of 35 Federal laws (**Table 3.1**), of which 24 are applicable to operations for minerals other than oil and gas (USDOI, USGS and BLM 1981a,b). Environmental issues have been an important and contentious element in OCS leasing policy since the time of the Santa Barbara oil spill in 1969. Even for minerals other than oil and gas, this air of controversy has affected the stance of policy makers for marine minerals development at the State, national, and international level. In attempting to institutionalize the management needs for marine minerals, however, the assignment of specific weights to environmental risks is extremely difficult, particularly for an industry in early stages of development.

To deal with these factors in a productive way, the USDOI has assigned regulatory controls to be applied on a case-by-case basis. The type of risk that might be applicable to mining development includes effects on air and water quality, interference with natural shoreline processes, alteration of habitats and species distributions, and conflicts with fishing, recreation, or other commercial activities. The mitigation of these risks or effects by the application of optimal engineering design, generally referred to as internal costs, can be reasonably calculated. However, if the effect is imposed on others (e.g., fishermen, recreational boaters, or other categorical opponents) with or without compensation of some kind, the cost becomes an external cost. If all of the external costs

Administrative Procedure, 5 USC 551-559, Including Provisions of the Freedom of Information Act, Privacy Act, and the Government in the Sunshine Act
Clean Air Act
Crude Oil Windfall Profits Tax Act of 1980
Deepwater Port Act of 1974
Department of Energy Organization Act
Emergency Natural Gas Act of 1977
Emergency Petroleum Allocation Act of 1973
Endangered Species Act of 1973
Energy Policy and Conservation Act
Energy Reorganization Act of 1974
Energy Supply and Environmental Coordination Act of 1974
Environmental Quality Improvement Act of 1970
Federal Energy Administration Act of 1974
Federal Water Pollution Control Act
Fish and Wildlife Act of 1956
Fish and Wildlife Coordination Act
Land and Water Conservation Fund Act of 1965
Marine Mammal Protection Act of 1972
Marine Protection, Research and Sanctuaries Act of 1972
Marine Resources and Engineering Development Act of 1966, Including the Coastal Zone Management Act of 1972
Mining and Minerals Policy Act of 1970
National Advisory Committee on Oceans and Atmosphere Act of 1977
National Environmental Policy Act of 1969
National Historic Preservation Act
National Ocean Pollution Research and Development and Monitoring Planning Act of 1978
Natural Gas Act
Natural Gas Pipeline Safety Act of 1968
Natural Gas Policy Act of 1978
Occupational Safety and Health Act of 1970
Outer Continental Shelf Lands Act
Outer Continental Shelf Lands Act Amendments of 1978
Pipeline Safety Act of 1979
Ports and Waterways Safety Act
Submerged Lands Act
Withdrawal of Lands for Defense Purposes Act

Table 3.1. U.S. laws affecting mineral operations on the outer continental shelf (Adapted from: U.S. Department of the Interior, U.S. Geological Survey and Bureau of Land Management 1981a,b).

of development could be quantified with precision, a benefit-cost approach would provide relatively clear-cut economic guidance for development control. Unfortunately, such precision is not possible and decision making is frequently based on qualitative and subjective information (Cruickshank 1974a; Farrow et al. 1990) which may be interpreted by decision makers according to ethical, political, or professional constraints.

Miller and Kirk (1992) discussed and classified four ethics (**Table 3.2**), adopted by different people which can be used to explain some of the sociocultural effects of contemporary marine development, including mining. The holothetics perceive the world to be inviolate, and vulnerable to the triggering of catastrophic events by otherwise minor acts; the tribals know "you can't fool mother nature" and that interference beyond that needed for survival will bring retribution; the compassionates believe we can and should protect our weaker brothers in the animal-vegetable kingdom; and the developmentalists believe we can do all things in balance with nature.

These beliefs are largely based on the social environment in which the individual believers were raised, and frequently reinforced by the individual's experience in life. There is no question, however, that if consensus is required to initiate development, then these aspects of belief cannot be ignored (**Figures 3.1 and 3.2**). They are the subjective end of the benefit-cost equation. People will fight for what they believe and, in a modern democratic society which puts individual rights high on the list of legally supported institutions, early identification of the presence of such socioeconomic conflicts will go far in providing mitigating solutions.

Conceptual and practical measures are addressed with respect to the needs for mitigation from the institutional point of view and from the resource point of view. The former are to be found scattered throughout the literature on policy, benefit-cost analyses, and laws and regulations, whereas the latter are referred to additionally in scientific and engineering studies which may be specific to particular sites or activities. Most mitigation efforts are resource directed and are an attempt to improve some potentially threatening or undesirable situation identified by management. Depending on the point of view, however, these efforts might be inconsistent or conflicting and may be biased towards fisheries or mining, or toward public benefits such as revenues, environmental protection, or public safety. Historically, public lands in the U.S. are governed under the common law public trust doctrine which protects the public's rights and interests in the use of resources and space. This doctrine has not yet been applied to the marine environment and there remains within the Federal government a confusion of single sector management responsibilities with overlapping and sometimes contradictory authorities. Conflicts relating to living resources and other uses such as mining are difficult to resolve. There are obviously different perceptions of priorities. Archer and Jarman (1992), for example, in recommending new rules based on the public trust doctrine, state the following:

> *"Marine mining operations, which by nature encompass large ocean areas, are tantamount to an exclusive use, precluding uses of the area for fishing and navigation. In addition, the operations could result in a "take" of protected species if, for example, they are located along a migratory route of a whale species. In applying the presumption of non-exclusive over exclusive uses,*

A TYPOLOGY OF ENVIRONMENTAL ETHICS		
HUMAN POTENCY	ENVIRONMENTAL POTENCY	
	Powerful	Vulnerable
Powerful	DEVELOPMENT ETHIC Sustainable development Positive benefit-cost	COMPASSIONATE ETHIC Endangered species Marine mammal protection
Vulnerable	TRIBAL ETHIC The Gods are angry Veneration of nature	HOLOTHETIC ETHIC Endangered world Everything is connected

Table 3.2. Environmental ethics (Adapted from: Miller and Kirk 1992).

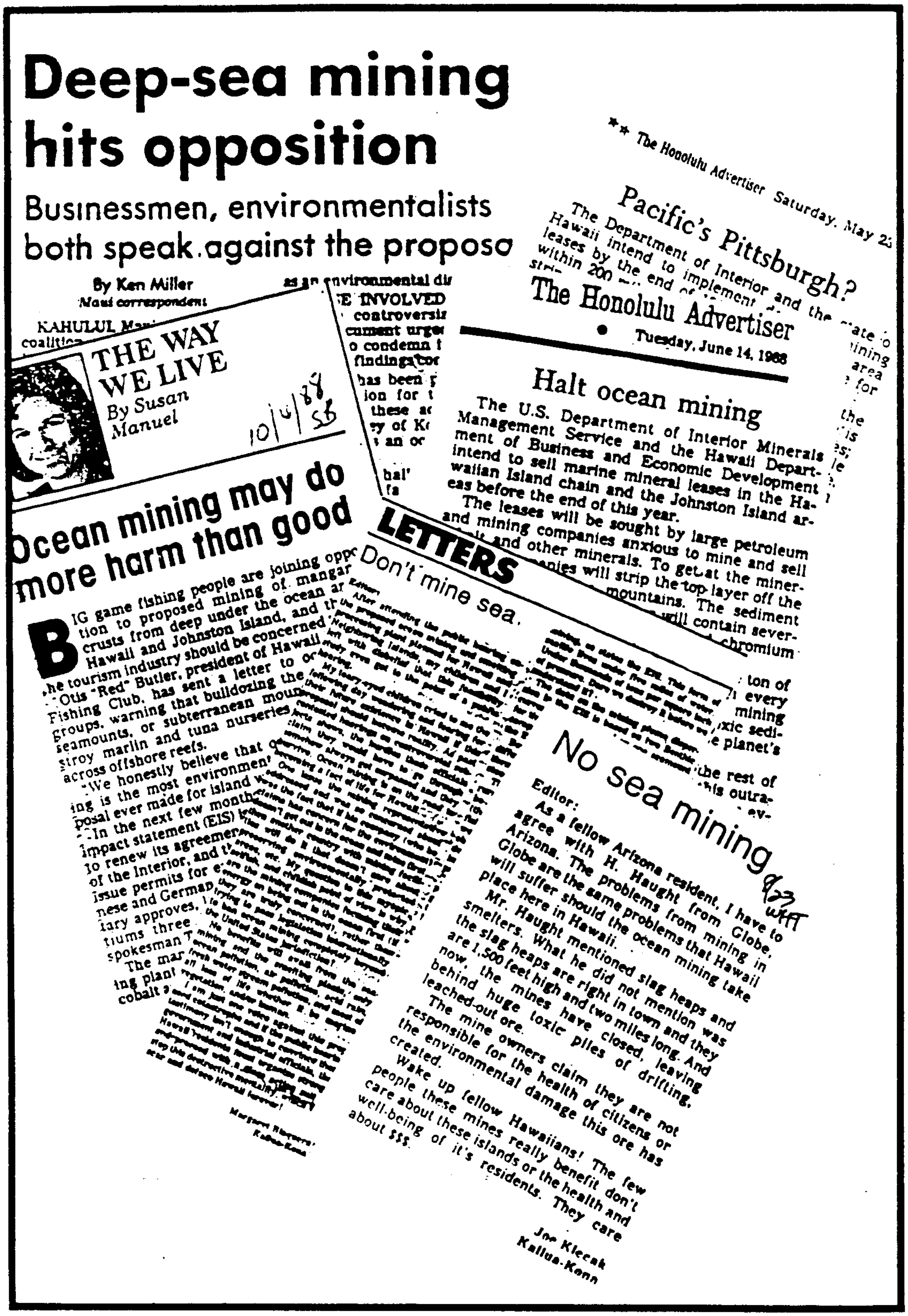


Figure 3.1. Environmental ethics vs. mining (Part 1).

Mining Journal, London, May 18, 1990

N.Z. Steel In Land Dispute

Discovery of Maori remains during the course of mining at its Waikato North Head site last month has deprived New Zealand Steel Ltd of supplies of ironsand for the past fortnight and rekindled a 130-year-old dispute. According to *Reuters*, operations at the nearby Glenbrook mill south of Auckland are at risk as the ore stockpile is depleting rapidly. The local Ngati Te Ata tribe say that four ancient burial sites occur on 250 ha of disputed land and have placed a curse on the area to protect the sanctity of the sites. N.Z. Steel has mining rights over a total of 1,250 ha and pays the government a royalty. The land was originally confiscated in 1860 after wars between the local Maoris and the former colonial British Government.

Vietnam
Prospecting in Nghe Tinh

Mining Digest 8/91

Hundreds of thousands of gem prospectors have flocked in recent months to Vietnam's Nghe Tinh province south of Hanoi following the discovery of rubies. The ruby fever has led to dozens of deaths caused by landslides and fights among the prospectors. The sudden influx of prospectors has created severe supply problems for the region, press reports said, adding that "a single small township in the district now has more than 50,000 new inhabitants."

"There is a human flood searching for rubies and the discovery of a small piece of stone can mean instant death. The law of hoodlums is being openly applied." The daily newspaper claimed the leaders of the prospectors are armed and ready to kill anyone who enters their territory.

IN THE PACIFIC - Australia
No Mining at Coronation Hill

The Australian government will not allow mining at Coronation Hill in the Northern Territory. Prime Minister Bob Hawke said the fact that the site is considered sacred to the Jawoyn aborigines outweighed the economic benefits of mining. The Australian Mining Council said the move will hurt investors confidence in Australia, but Hawke said that this was a special circumstance and would not have implications elsewhere.

The property is believed to contain at least 1.2 million oz gold, as well as significant deposits of platinum and palladium. Newcrest Mining Ltd. (Newmont Mining Corp. 14% and BHP Co. 23%) and Plutonic Resources Ltd. each have a 45% interest in the deposit. Poseidon Gold Ltd. has a 11.5% share.

The Jawoyn believe that the spirit Bula lives in the hill and would bring sickness and destruction if it were disturbed. The minister for aboriginal affairs 'aid that the Jawoyn are not opposed to 'ning. He said they have signed an 'ement with Normandy Poseidon to 'e for gold, diamonds, and base 'near Coronation Hill, but not on 'd site. *Mining Digest 8/91*

Figure 3.2. Environmental ethics vs. mining (Part 2).

mineral mining should be precluded in productive fishing areas and in traditional navigation or migratory routes. In the alternative, mining operators must show that the disruption is temporary and that other viable alternatives exist for navigation and fisheries during the period of the disruption. To the extent that mining activities involve the irreversible commitment of resources, courts should evaluate both the long-term and short-term implications of such a commitment and balance them against the urgency of present need for the minerals to be mined from the ocean. The biodiversity presumption would require mining operators either to locate their sites outside the path of migratory marine mammals or to restrict their operations during the periods of migration. Mining should not be permitted unless the operator can demonstrate that the mining will be carried out in an environmentally sound manner using the best technology achievable."

This analysis focuses on one of the most important mitigating measures possible, which is the acquisition and promulgation of facts concerning the marine minerals environment and the effects of mining. Whereas mitigation itself is specific to select operations in select environments, the form of the mitigation is strongly influenced by institutional procedures and perceptions. These "institutional" aspects of mitigation are discussed in the following section. Subsequently, **Section 3.2** outlines some of the important aspects of actual mitigation measures which have been proposed or implemented.

3.1 Institutionally-Derived Mitigation

In many instances, mitigation may be accomplished by the direct application of regulatory incentives. An examination of existing international instruments for marine environmental protection reveals a piecemeal and uncoordinated system of control strategies. In developing global strategies for marine environmental protection, GESAMP (1991) concluded that the parallel aims of further human development and environmental protection can only be satisfied through the adoption of an integrated and comprehensive management strategy based on common principles, agreed goals, and scientific methods. Appropriate principles derived from the 1972 Stockholm Convention, the Law of the Sea Convention, and the World Commission on Environment and Development include sustainable development, prevention of harm, holistic management, and international cooperation. The first three principles listed are applicable to the total system rather than its individual parts, thus avoiding transfer of risk from one part to another, as exemplified by the not-in-my-back-yard (NIMBY) policies of many regional or sub-regional groups.

An appropriate goal would be to protect the marine environment against the adverse effects of human activities so as to conserve marine ecosystems and to safeguard human health, while providing for rational use of living and non-living resources. Scientific methods would be the basis for environmental planning and assessment and, as part of their contribution to economic and social development, science and technology must be applied to the identification, avoidance, and control of environmental risks and to the solution of environmental problems for the common good.

Four principles are emerging as doctrine in environmental affairs which may strongly influence the nature of national and international regulation (Broadus 1991). First is the traditional approach of regulation and enforcement by a central authority, exemplified by the OCSLA and its accompanying rules and regulations. OCSLA can be quite explicit about the use of technological practice and procedures to protect the environment. This approach places great emphasis on monitoring, detection, and enforcement measures, all of which can be very costly. Other less centralized approaches which may be more efficient are based on market incentives, tax subsidies, and tradable permits.

The second principle is the specification of uniform standards for such aspects as emissions, water quality, or technology in terms of inputs, ambient quality, or performance. Too rigid application of such standards which may ignore differences in technical capability, alternative opportunities, or compliance costs may lead to inequitable results offering less protection than more flexible methods.

The polluter pays, which is the third principle, requires that the cost of environmental pollution be charged to the polluter. Although it sounds reasonable, this approach may deter the creation of public compensation pools to cover unidentified or accidental polluters, particularly from developing countries.

The fourth doctrine is the precautionary principle which seeks to avoid environmental risk in the face of scientific uncertainty. Proof of harm is not required to prohibit possibly harmful activities in the marine environment. If rigidly enacted, the requirement to show "no harm" without giving weight to the relative degree of risk, or the benefits acquired as trade offs, or the costs of alternative activities, could result in inequitable solutions.

In a free market economy, there are two major factors that influence the choice of solutions for mitigation: (1) adverse effects are largely external to the producer; and (2) mitigation results in benefits to all. The overriding question remains: Who pays? There are three general alternatives, including voluntary action, regulation, or monetary incentives. The first results in no direct return for the effort expended; the second is largely punitive and expensive to enforce; the third, however, which uses such techniques as the distribution of tradeable environmental loading allowances, is an innovative and potentially cost-effective method (Schenk 1971). For example, tradeable units for air or water quality can be allocated to individual operators within a region, with a total allocation supporting a number of operations.

Careful consideration of proposed marine mining activities on a case-by-case basis and a flexible system of environmental management, able to adjust to changes in both institutional and natural constraints, is essential. The nature of the more common regulatory constraints is discussed below, with examples.

3.1.1 Time-Based Constraints

Time is used most commonly to set protective windows around life cycle events for selected species that might be otherwise damaged by the proposed operations. Examples include the nursing period for whales in the Beaufort Sea (Malme et al. 1986b), nesting periods for migratory shorebirds in marshlands (Bouma 1976), or spawning periods for herring in areas of gravel beds (ICES 1977). In sensitive areas, dredging or other activities may be limited to certain seasons or times of the day. The incentive to avoid these time periods is the avoidance of monetary fines.

3.1.2 Location-Based Constraints

Avoidance of certain locations may be required to prevent interference with pipelines (USDOI, USGS and BLM 1981a,b), fishing or spawning grounds (Pasho 1986), or other commercial applications such as oil and gas, or recreational activities (USDOI, MMS and HI, DBED 1990). The acceptance of boundary constraints on property is standard practice and not addressed in regulations. Infringements are generally challenged in the courts.

3.1.3 Restrictions on Materials Cycles

Most restrictions apply to discharges containing materials which are perceived to be harmful to the environment. Uniform standards are commonly used to designate the limits for discharges, generally specified in terms of the quantities and size of the solid materials present in the discharge and less commonly for mining operations, the chemical nature of the solids present. No records were identified which pertained to regulation of the materials cycle for plants to produce minerals from seawater in the open ocean. All seawater minerals plants developed to date have been coastal, presumably regulated under a coastal zone management plan.

3.1.4 Restrictions on Technology Use

Regulations to date have been quite sensitive about imposing restrictions or specifying the use of particular technologies because of the rapid changes taking place in industrial technology. In the U.S., the use of Best Available Technology (BAT) is required for commercial recovery of manganese nodules in the deep oceans (15 CFR 971.423), but the term is not defined and the requirement is exempted where the incremental benefits are clearly insufficient to justify the incremental costs of using such technologies. No restrictions on technology usage are specified in the OCS regulations, provided it is part of an approved plan (30 CFR 282.27).

3.1.5 Controlled Remediation Planning

Controlled remediation planning is a framework for managing the rational use of the marine environment in which the management processes are continuous, institutional functions rather than functions that are triggered by individual development proposals. This is supposedly standard procedure in the U.S. However, because of the diversity of authorities determined by congressional legislation, there is a definite need for specific and coordinated policies for minerals and the oceans. These policies would serve as a foundation upon which a workable framework can be based. In the case of developing countries, such a framework encourages the development of indigenous management capabilities and can be adapted to the needs of social and economic progress (GESAMP

1991). Mitigating measures for control of environmental effects can be applied through leasing stipulations, research and monitoring, and technology transfer (USDOS 1975).

3.2 Summary of Mitigation Measures by Resources Affected

The resources to which mitigation is directed include most of those analyzed or discussed in the previous chapter, with particular emphases on water quality, benthic marine life in mined areas, commercial fish, and recreational and commercial fishing. These resources are the ones which have been stressed in the literature as major concerns. The following section reviews the particular measures which have been considered in these critical areas for marine mining. Additionally, a general discussion is presented which pertains to other potentially affected resources and how mitigation might be used to minimize any negative effects.

3.2.1 Air Quality

As discussed in **Chapter 2**, air quality issues have been given relatively little attention in this study, partially because they are very site-specific and partially because the available environmental assessments of marine mining conclude that air quality effects are not expected to be significant. The major exceptions to this conclusion are related to power generation and to pyrometallurgical processing. This section considers briefly the types of mitigation which might be relevant to these activities.

3.2.1.1 Global

Mitigation at this level is indistinguishable from a direct comparison of alternatives. Given the currently high level of effort applied to the problems of the global carbon dioxide budget and acid rain, it is appropriate to consider the trade-offs between marine mining and terrestrial mining with respect to these issues. With respect to power generation, the recovery and processing of marine ores can generally be expected to be very similar to terrestrial ores. Using conventional combustion-driven power sources, primary recovery in a marine setting might require more combustion energy than recovery of terrestrial ores. However, subsequent marine transportation can be expected to be significantly more efficient and less polluting than over-land transportation.

With respect to metallurgical processing, the type of ore being recovered is much more important than whether or not the ore is recovered from a marine or terrestrial deposit. Oxide ores can be expected to require more energy to process than sulfide ores, basically because oxygen-metal chemical bonds generally require more energy to break than sulfide-metal bonds. Unfortunately, processing of sulfides also may have the undesirable characteristic of producing acid rain, whereas oxides will not. The best combination, relative only to air quality effects, would therefore be oxide ores processed using power which is derived from a non-combustible source, such as hydroelectric power, geothermal power, solar power, wave energy, or OTEC.

3.2.1.2 Regional

The regional environment is much more site-specific, however, it is not always possible to make generalizations except for similar regions. The Large Marine Ecosystems concept discussed previously (**Section 2.3**) is a natural regionalization, whereas many of the regional boundaries that have to be considered in operations planning are artificial and cut across natural regions. In any case, there would be little correlation between LMEs and air quality data.

- **Oceanic and Outer Continental Shelf**

As discussed previously (**Sections 2.3.1** and **2.3.2**), air quality effects for marine mining activities in the deep oceans and continental shelf are not expected to be significant or to require any special mitigation.

- **Coastal**

The site-specific nature of coastal activities precludes the reasonable evaluation of mitigation options, particularly for air quality effects. The available environmental assessments of marine mining proposals (USDOC, NOAA 1981; USDOI, MMS 1983a,b; USDOI, MMS and HI, DBED 1990; USDOI, MMS 1991) universally conclude that offshore activities in coastal areas are not expected to cause significant effects on air quality and would not require mitigation beyond existing regulatory controls.

- **Onshore**

Because the bulk of the power consumption and air emissions for marine mining will be caused by metallurgical processing, and because all currently proposed marine mining ventures would require onshore processing, air quality effects can be expected to be most acute in this region. As discussed previously (**Section 2.3.1**), natural processes which minimize the effects of air emissions (i.e., dispersion and chemical neutralization) can be expected to be much more efficient in the open ocean than on land. Therefore, a general consideration to mitigate such effects might be to seek the development of processes which can be efficiently implemented at sea. Processing at the mine site would also lower the required overall energy consumption of the venture, as only ore concentrates would have to be moved from the mine site to the immediate consumer. Unfortunately, at this time, the technical problems associated with at-sea processing (e.g., energy costs, platform stability, infrastructure requirements, etc.), as well as the highly political aspects of marine environments, have precluded serious efforts for its development.

3.2.2 Water Quality

The water quality issues discussed previously include issues related specifically to marine water quality and fall naturally into two groups: (1) deep sea and continental shelf; and (2) coastal. The following discussion examines mitigation possibilities for each.

3.2.2.1 Deep Ocean and Continental Shelf

In environmental assessments of deep seabed mining (USDOC, NOAA 1981; USDOI, MMS and HI, DBED 1990), the potential for mitigation of effects from mine ship discharges have been considered in detail. A requirement for subsurface discharge of mine tailings was suggested by many environmental groups to eliminate potential effects on the habitats in the surface photic zone (i.e., roughly the top 50 to 100 m). Such a requirement is not expected to be difficult or expensive to achieve. Further, subsurface discharge would eliminate any potential interactions with the most densely populated region of the deep seas and put discharged solids completely out of sight.

However, surface waters are much more turbulent and oxygen-rich than deeper zones, and contain much more abundant populations of planktonic filter feeders. The turbulence and high oxygen levels would ensure rapid dispersal and stabilization of discharges, while the plankton provide a very effective means for encapsulation and rapid sedimentation of fine-grained materials as fecal material. Extensive knowledge about the fates and effects of discharged materials in deep ocean waters will be necessary before intelligent choices about discharge depth can be made.

3.2.2.2 Coastal and Onshore

Significant efforts have been made, particularly in Europe and Japan, to develop coastal mining systems with minimum generation of turbidity and generally minimum impacts on water quality. In the French studies off Le Havre, radioactive labeling of sediments was used to trace the dispersion of material discharged from a dredge. Increased turbidity was detected throughout an area of 50 to 70 km^2 around the dredge, although particles larger than 40 μm were found to settle within 1.5 km of the test site (ICES 1977).

Reporting on a hopper dredge plume experiment, Poopetch (1982) described a hopper dredge turbidity plume caused by dragheads and screws. Further, within 15 min of dredging, a hopper overflow plume was also characterized. A homogenous mixture of these plumes occurred 100 to 200 m from the stern. The initial sediment concentration at the overflow ports was 3.5 g/L which decreased to 0.5 g/L within 50 m. Ambient levels of plume could be detected 800 m down stream and 150 m laterally.

Tests in Japan on a hopper dredge turbidity plume caused by dragheads and screws showed that within 15 min of dredging there was also a hopper overflow plume. The area affected by plume sedimentation can be reduced by subsurface discharge or other techniques that force the particulate material to settle close to its source, but this creates a heavier accumulation in that smaller area. The appropriate sedimentation pattern, and thus the appropriate disposal methods, will depend upon the characteristics of the site, including the biota. The Japanese also indicated problems with seawater pollution associated with the discharge of dredged material at the sea surface during deep dredging of sand in areas affecting commercial fisheries. To mitigate the problem, the turbid water overflow from the dredge hopper was returned to the dredge intake. This is partially recycled with the dredged material which presumably improves the efficiency by increasing the density of the sand slurry. No turbid water dispersion was observed and the improvement was reportedly reviewed favorably by the fishermen (Okamura 1992). Ofuji and Ishimatsu (1976) showed that the concentration of suspended particles was reduced and water transparency was increased during hopper overflow before and after an anti-turbidity system was installed.

The turbidity plume can be reduced by using silt curtains to contain the plume within a specified area. This technique limits the maneuverability of the dredge and is limited in use to areas where currents are less than 1 kn. Overflow waste may be returned to the seafloor by a return pipe. This technique may be extremely useful for placer mining where the mining platform is anchored and moves slowly. The main concerns are associated with the discharge of large amounts of waste material. Closing the upper side of the bucket ladder on a bucket ladder dredge reduces the mid-water and surface turbidity plume. Alternatively, enclosing individual dredge buckets does the same thing but appears to have more potential than enclosing the bucket ladder.

Application of the anti-turbidity overflow system (ATOS) removes air bubbles from the overflow of a hopper dredge; air bubbles in the overflow make the particles buoyant and prolong settling, and their removal allows particles to settle at a faster rate. This system has been successfully applied to trailing suction hopper dredges off the coast of Japan (Ofuji and Ishimatsu 1976).

Other suggestions given for mitigation of the effects of dredging include selection of the most appropriate dredging system for the site. An example might be the use of trailing suction hopper dredges, instead of using the stationary suction hopper dredges, in areas of high bottom trawling activity. Daily or annual limits can be placed on the quantity of dredged material to minimize potential effects on benthic communities and decrease the potential for coastal erosion. The number of vessels or operations in given areas can be limited. The overboard disposal of equipment and other debris should be prohibited, possibly by implementing a system of equipment manifest/labelling, inspection, and fines.

3.2.3 Geological Resources

The geologic resources affected include the mined material which is removed for sale or use, and the seabed which is altered in some way by the mining activity. In the case of high value materials such as gold or platinum, the volume of material removed is insignificant; the swell factor, however, applied to the ore material mined and subsequently returned after treatment as waste, is generally about 1.5 which means the volume of material increases by that amount. This can be very significant in water of only moderate depths.

3.2.3.1 Seabed

Clearly, the local hydrodynamic conditions and the type of deposit being mined must be taken into account when establishing a minimum water depth for dredging in order to avoid the possibility of coastal erosion. As a general guideline, the British Crown Estates Commission has adopted a water depth of 18 m as the minimum for dredging (Nunny and Chillingworth 1986). The actual depth limit identified for potential damage was 13 m but 5 m were added as a precautionary measure.

Large excavations can also lead to coastal erosion if the wave patterns and sediment movements are sufficiently changed nearshore. These effects are being studied in the U.S. by the USACE, but an interim guide to safe practices can be obtained from British experience. In British coastal zones, dredging reportedly causes no problems in water depths greater than half the normal wave length or more than one-fifth the length of extreme waves. Dredging in waters over 20 m deep is usually approved by the regulatory authorities with only a desk review. Proposals for dredging in 10 to 20 m get more detailed review and may require site-specific information. Proposals for dredging in waters shallower than 10 m may require substantial study (Drinnan and Bliss 1986).

3.2.3.2 Terrestrial

The use of marine mining for sand and gravel production eliminates the scarring of onshore environments due to quarrying. Further, unsightly and unsafe operations with major dust, noise, and traffic problems are alleviated (Fischer 1988).

3.2.4 Biological Resources

The resources affected by mining operations will include birds, mammals, marine and aquatic fauna, sensitive habitats, and endangered species.

3.2.4.1 Birds

Significant effects of marine mining activities on birds have not been identified in the available literature, and thus mitigation techniques have not been seriously considered.

3.2.4.2 Marine Mammals

Collisions with marine mammals and alteration of migratory patterns through generation of noise in the water column have been identified in several studies as potential effects. Collisions could be eliminated or significantly minimized by requiring or encouraging reduced boat speeds in areas of known or suspected concentrations of these animals or when animals are sighted ahead of a vessel. It is assumed that operators could exercise appropriate measures to avoid such encounters when whales are detected either visually or by sonar from operating seismic vessels, thereby reducing or eliminating feeding-related adverse effects due to geophysical activities (USDOI, MMS and HI, DBED 1990; USDOI, MMS 1991). Reduction of noise of the primary recovery and ore-lift operations could be considered to mitigate the second type of effect if quantitative information about the actual sensitivities of the marine mammals involved could be determined.

3.2.4.3 Marine and Aquatic Fauna

Marine and aquatic fauna are found on the water surface, within the water column, and on the bottom.

- **Water Column Populations**

In the literature available for this study, effects on neuston, phytoplankton, zooplankton, fish, and other organisms which live in the water column are directly dependent upon water quality. Therefore, consideration of mitigation options for effects on these populations is reduced to the mitigation of water quality effects.

- **Benthos**

In the development of deep seabed sulfide deposits and manganese nodule and crust deposits, many mitigation options are possible to minimize the effects of mining on benthic habitats. Dispersal of suspended particles in benthic waters can be minimized during mining to limit the smothering of both epifauna and infauna. Small patches within mine sites can be left unmined to provide nearby populations (of relatively unaffected organisms) to repopulate the mined areas. Large areas can be left pristine to preserve potentially unique populations, such as the hydrothermal vent communities which can be associated with potentially valuable sulfide deposits. Unfortunately, none of these is currently justified because of the very poor state of knowledge which exists about the populations which occupy these habitats. Basic research to determine the relevant parameters of sediment dispersion, species succession, and habitat composition is ongoing in the manganese nodule deposit areas of the northeastern tropical Pacific, but no such work is currently being supported for the natural hard substrate populations which inhabit crust deposit sites.

With respect to coastal mines, it appears that many opportunistic species can colonize tailings disposed of in the sea, with some becoming very abundant and dominating the fauna. The colonization is variable from year to year and appears to show trends through a range of different species, at least for the first 10 years or so. The fauna appear to be largely deposit feeders consisting initially of sedentary polychaete worms but gradually including molluscs, crustaceans, and echinoderms. The genera include those found on mining waste in the Mediterranean (Nicolaidou et al. 1989) and offshore Nome, AK (Jewett et al. 1990), adding support to the concept of parallel bottom communities.

Problems with ongoing bottom fisheries can be avoided through management practices that do not allow the use of stationary dredges in areas where bottom trawling, bottom scallop dragging, or clam raking is normally practiced (de Groot 1979a). Though not widely voiced, a potential fisheries problem is the exposure of boulders due to dredging that could increase the potential for damaging trawling gear. However, the likelihood of this happening is quite small when using the trailing suction hopper dredge (Drinnan and Bliss 1986; Cruickshank et al. 1987).

Both the scraping and excavating approaches to mining can also change the character of the substrate by exposing materials with different properties. For example, if exposure of silts and clays is a concern, it may be necessary to require that the bottom portion of the layer being mined be left in place to minimize such change. However, for sand and gravel mining and for some other minerals, the economics of mining may provide strong incentives not to expose silts or clays. If so, such regulations may be unnecessary (Cruickshank et al. 1987).

The impact of pits on bottom trawling operations is illustrated by experience off the coast of Hastings in the U.K., where stationary suction dredges mining sand and gravel have created a "lunar-like landscape," thereby preventing the use of bottom trawling gear in a previously good trawling ground. Because of this, the English dredging fleet no longer uses stationary suction dredges (de Groot 1979a). The removal of sand from a rocky subsurface in Seine Bay, France resulted in repopulation by species which had very little value to bottom fish, with the possibility that the local fishing industry could suffer in the future (de Groot 1979a).

The furrows left by drag suction dredgers are only about 20 to 30 cm deep, so there would be minimal danger of damaging bottom fishing gear (ICES 1979). A layer of the original substrate should be left on the seafloor, however, as this increases the chances that the original benthic communities will recolonize.

The predominant trophic niche of deposit feeders, represented by fauna on mine tailings with low organic content, suggested to Ellis and Hoover (1990) that some form of seabed fertilization by organic sludges, such as from sewage treatment plants, could facilitate reclamation of undersea tailings beds. This is an interesting concept if these opportunistic fauna are important to the functioning of that ecosystem. Could this concept also be applied to deeper seabed ecosystems? There may be a need for more systematic research on these aspects.

3.2.4.4 Sensitive Habitats

For water column habitats in general, the rapid and effective dispersive processes virtually eliminate the possibility of special, sensitive habitats. Possible exceptions include neuston layers, where significant populations of sensitive larvae can congregate, and confined straits and other waterways which form migratory pathways. Mitigation of possible effects on these habitats will generally consist of avoidance (through restriction of the activities) or through modification of the activities, such as subsurface discharges.

Probably the most serious limitation on the evaluation and mitigation of effects on sensitive habitats in deep seabed environments is a general lack of knowledge regarding the deep sea benthos. For virtually all deep seabed habitats, key relevant factors (i.e., growth and recolonization rates and vectors, species succession, and substrate selectivity) are generally unknown, which makes it very difficult to establish whether or not these habitats are particularly sensitive to mining activities. This makes it impossible to consider rationally any mitigation which would be appropriate, except to avoid them until they are properly characterized.

Of particular concern for nearshore activities which suspend materials in the water column for transport are the downstream coastal communities which may be affected by discharge plumes or other activities. Coral reefs, mating and spawning shoals and beaches, and sensitive estuarine habitats must be very seriously considered during the process which authorizes mining activities. The role of dispersion modeling (see **Chapter 4**) in these efforts is critical to providing basic guidance for rational mitigation.

3.2.4.5 Threatened and Endangered Species

Within the available EISs reviewed in this study (USDOC, NOAA 1981; USDOI, MMS 1983a,b; USDOI, MMS and HI, DBED 1990; USDOI, MMS 1991), significant examinations of potential effects to threatened and endangered species have been carried out. Specific areas have been removed from consideration where significant effects could possibly result. Other forms of mitigation which specifically address threatened and endangered species have not been identified to date.

3.2.5 Social and Economic Resources

These may take the form of voluntary, mandated, or economic measures. For example, subsurface mines and slurry mining cavities may cause local seafloor collapse or subsidence, possibly leading to coastal erosion or changes in sediment patterns. This problem can be avoided by proper mine design. In the case of borehole mining, cavities are likely to be water-filled during the mining, and waste can be injected into the cavity before the site is abandoned. Both practices reduce the potential for collapse of the rock overlying the cavity and waste injection reduces the volume of waste discharged at the surface (Cruickshank et al. 1987).

3.2.5.1 Human Resources

Effects in this category are confined to issues which deal with human health and safety. Most of these issues are too site-specific for a rational discussion of general mitigation options. As in any other large industrial activity, safety is an important issue in every aspect of the operation, while health issues are focused on perceived or actual threats to public health through effects on air or water quality or through the generation of excessive noise. Mitigation of air and water quality effects has been discussed previously. In bucket ladder dredging operations, it has been suggested that noise can be reduced by hanging rubber mats over the ladder wellway.

3.2.5.2 Commercial and Recreational Fisheries

Most of the potential problems related to social and economic environments would be very site-specific and concerned with onshore processing facilities. The key area of possible conflict is related to commercial and recreational fisheries. Most current development strategies are biased toward the development of sustainable and renewable resources rather than non-renewable resources such as mineral deposits. Therefore, marine miners in general must be prepared to avoid any potential conflicts with fishing interests in operational areas or prove that such operations will not jeopardize ongoing or anticipated fishing activities.

One mitigation measure proposed in the environmental assessment of manganese crust mining in the Hawaiian EEZ (USDOI, MMS and HI, DBED 1990) would facilitate early identification and resolution of potential problems in this area by requiring active solicitation of inputs from the pertinent fishing industry representatives early in the planning process for marine mineral development. This measure may be useful for consideration in all new marine mineral development efforts.

Effects such as the creation of trenches, pits, or mounds on the seafloor may affect the biota and fishery operations for years. Boulders may be uncovered, forming permanent obstructions that snag fishing trawls. To counter this, the French have experimented with abutting dredging tracks to obtain an unobstructed seabed. In other cases, rejected oversize materials can be guided back into the collector tracks immediately behind the mining device. Similarly, the use of trailing suction dredges, which interfere much less with bottom fisheries than do anchored suction dredges, reduces conflicts with commercial fisheries (Drinnan and Bliss 1986).

3.2.5.3 Regional and Local Economies

As discussed previously, marine mining ventures can be relatively large enterprises and have the potential to affect regional and local economies, both positively and negatively. General strategies to mitigate the negative effects include (1) job discrimination in favor of local residents and associated training populations to implement such discrimination; (2) process plant location in areas with maximum development to avoid large influxes of new residents in predominantly rural areas (as well as to take advantage of existing infrastructure); and (3) local requirements for the establishment of infrastructure when necessary (USDOI, MMS and HI, DBED 1990; USDOI, MMS 1991). Such measures have been implemented with varying degrees of success for many other industries. Eventual success depends on thorough planning and detailed interfacing with existing authorities and public interest groups.

3.2.5.4 Cultural Considerations

Land-based operations devoted to the development of marine minerals must be implemented with particular consideration given to the unique mores and traditions of the local population. For operations in presently underdeveloped or undeveloped areas, careful accommodation must be made to permit the introduction of what may be perceived as a radical change in lifestyle. The study of a hypothetical development of a mineral processing plant on the island of Hawaii led to significant opposition by native Hawaiian groups. This opposition was based primarily on a very conservative reverence of the ocean in general and a very specific opposition to activities which were believed to disrupt a primarily rural, almost subsistence, agricultural lifestyle (USDOI, MMS and HI, DBED 1990). In contrast, the mining activities which took place in the coastal waters offshore Nome, AK resulted in negligible and minor effects on local cultural lifestyles (USDOI, MMS 1991). These and other examples show clearly that the local cultures and attitudes are of primary importance in the consideration of land-based operations sites. Further, extensive public education and outreach efforts, though necessary, may not be sufficient to overcome potentially fatal opposition to development.

CHAPTER 4 PREDICTIVE MODELS

Mathematical models to portray natural dynamic functions are widely used to forecast and predict events and effects. The advent of powerful desktop computers makes these previously expensive tools available to a wide range of users.

4.1 Scope

The scope of the following discussion is limited to physical dispersion through the water column and sedimentation on the seabed. Air emissions, chemical transformations, and demographic processes are considered too site-specific to warrant useful consideration in the present analysis.

4.2 Model Types

There are a number of model types used by researchers in this field. The predominant models are described in detail in the following text.

4.2.1 Closed Form

Natural processes are ideally modeled using differential equations for which analytical solutions may be found in closed form. Though most natural processes are too complex or known with insufficient completeness to be modeled solely in analytical closed form, such models are often used as first approximations. Typically, analytical models incorporate the development of constant coefficients which represent poorly understood or unknown variables. These coefficients are then found from empirical data or are estimated based on historical experience. The value of the dependent variable anywhere in the model space can be found directly from the solution of the differential equation.

Equations containing transcendental functions (e.g., trigonometric functions) are often solved analytically in terms of other, simpler transcendental functions. Such equations may still be considered solved in closed (but not exact) form. Final numerical solutions are usually obtained by series expansions of the relevant terms or by other methods of approximation.

Although hydrodynamic problems such as sediment transport and plume modeling are usually not adequately described by such simple equations, most of the evolution of descriptive models has occurred through the use of these forms.

4.2.2 Brief Review of Early Model Development

Analytical expressions for the vertical distribution of suspended sediments in a turbulent stream were first developed by Schmidt (1925) where they were applied to dust particles in the atmosphere. Subsequent modifications were made in the 1930s by Ippen and Rouse who introduced velocity distribution functions originated by von Karman. The basic differential equation describes the equilibrium between the turbulent upward transport of sediment, balanced by the downward settling due to gravity. A typical solution is given as

$$\frac{c}{c_a} = \left(\frac{h-z}{h-a}\ \frac{a}{z}\right)^{z}$$

where $z=\frac{w_s}{k\beta u_*}$; c_a is a reference concentration at depth a; h = total depth; w_s represents settling velocity of the particles; k = the von Karman constant; $\beta = \epsilon_z/\epsilon_m$, the ratio of the sediment mass exchange coefficient to the momentum transfer coefficient; $u_*=\sqrt{\frac{\tau_o}{\rho}}$, the shear velocity; τ_0 is the bottom shear stress; and ρ = the fluid density.

Dobbins (1944) examined vertical sediment distribution in the transient state. He found solutions as a series expansion.

Ippen (1971) and Jobson and Sayre (1970) examined the exponent Z in detail, finding that the variation of velocity distribution due to the presence of sediments is important only in cases of high concentration. Studying suspended solids in the silt range, they found fall velocity to be the primary factor for controlling the rate of descent of sediments, with turbulence being relatively negligible.

Finding the settling velocities of suspended particles is considered to be one of the toughest problems in this type of modeling. Partheniades (1964, 1971), Krone (1972), and Einstein and Krone (1962) all studied the deposition of fine clays. They found that fine sands are suitably modeled by application of Stokes' law, while the settling of clays is affected by aggregation and flocculation processes.

Harleman (1971) used Taylor expansions to modify earlier models to account for tidal oscillation velocities. Holley et al. (1970) also studied tidal oscillation effects, finding that an order-of-magnitude accuracy in the values of dispersion coefficients is sufficient for modeling continuous injection of suspended sediments under tidal conditions.

Dispersion in periodic flow was also studied in detail by Okubo (1967, 1971). He found dispersion coefficients using the method of moments to find the variance of σ_x^2 of a longitudinal distribution. He also provides a comprehensive review of previous work on horizontal diffusion coefficients in the ocean.

Three-dimensional models were tried by Wnek and Fochtman (1972). They considered neutrally buoyant particles only, and ignored the problems associated with modeling tidal currents. They assumed constant dispersion coefficients, and found analytical solutions in terms of error functions.

Project NOMES, undertaken by NOAA beginning in 1972, was intended to study the environmental effects of offshore mining for sand and gravel in Massachusetts Bay. It was terminated before completion, but some significant work was done extending model studies. Significant work was done by Hess (1973), who developed a preliminary model intended for use in predicting the dispersion of suspended sediments. Tides and vertical diffusion were not considered. Horizontal diffusion coefficients were obtained from dye experiments.

Model development was continued by several workers after the termination of NOMES and led to a modern, three-dimensional analytical model developed by Christodoulou et al. (1974) on whose work the foregoing historical review is, in part, based. In Christodoulou's model, sediments are considered to be continuously introduced along a line source oriented vertically. A velocity field is assumed to consist of the superposition of a net drift and a sinusoidal tidal velocity at any angle to the net drift. A one-layer shear flow with a logarithmic velocity profile is assumed. Three-dimensional dispersion equations are used, to which a separation of variables technique is applied, allowing horizontal and vertical dispersion to be treated separately. Settling velocities are treated using Stokes' law for sediments other than clays. Settling velocities for clays were measured in the laboratory. Horizontal and vertical dispersion coefficients were separately developed to account for turbulent diffusion and non-uniformities in the velocity distribution. This model also takes into account some of the particle aggregation processes described in greater detail below, especially Brownian motion, local shear or velocity gradients, and differential settling of particles.

4.2.3 Finite Difference

Differential equations for which solutions in closed form are not available must be solved for their dependent variables using numerical methods. Hydrodynamic models of various types have been typically solved using some gridding of the model space, with a calculation scheme developed to successively approximate the value of the dependent variable at each point. To initiate the calculation process, boundary values and/or initial values for appropriate parameters must be known. With the advent of computers, such schemes have evolved rapidly. The simplest such schemes are called finite-difference methods. They rely on gridding the model space with identical grid elements applied over the entire model space, usually squares (for 2-D models) or cubes (for 3-D models). The value of the independent variable at each grid point is found at each successive iteration as a function of the values of its immediate neighbors. Higher-order, finite-difference schemes allow each grid point to be influenced by non-immediate neighbors as well, with a corresponding increase in computational power required. Such models are typically time-stepped as well, to show process behavior. Most sediment-transport and plume dispersion models currently available are of this type. Examples of relatively modern models of this type, which are available off-the-shelf for relatively easy application, evolved from seminal work by Koh and Chang (1973).

Brandsma and Divoky (1976) revised and extended the Koh-Chang model. They considered the dispersion of sediments dumped from a ship either as an instantaneously dumped cloud or clump, or as a continuous dumping process. In either case, they modeled the process in several phases, corresponding to the convective descent of material after initial release, equilibration of the material once it encounters neutral buoyancy, dynamic collapse of the cloud with continued fall of heavy material, and, eventually, the passive diffusion of remaining material from an equilibrium layer. The dumped material is modeled as an ellipsoidal cloud with a Gaussian distribution of concentration and position in the water column. In addition to advection of the cloud, it grows as a result of turbulent diffusion, with horizontal dispersion based upon the commonly assumed four-thirds law $K=AL^{4/3}$ and vertical dispersion based upon a Fickian model. Settling velocities are handled by considering a size distribution of particles, with a constant settling velocity assigned to each size fraction based upon empirical experience.

Johnson and Holliday (1977) and Johnson (1978) began testing and revising these models for the USACE. The models have been designated as DIFID (Disposal from an Instantaneous Dump), DIFCD (Disposal from a Continuous Dump), and recently hybridized as DIFHD (Disposal from a Hopper Dump). They have been tested in Hawaii (Johnson and Holliday 1977), at Alcatraz (Trawle and Johnson 1986), and in Puget Sound (Trawle and Johnson 1986). Recent work includes application of these models to Puget Sound (B. Johnson, 1992, personal communication, USACE Waterways Experiment Station, Vicksburg, MS.). A comprehensive and "friendly" computer user interface has been developed for these models (Walski and Hayes 1986; EPA 1991), designated as ADDAMS (Automated Dredged and Disposal Alternatives Management System), and is available from Dr. B. H. Johnson at the USACE Waterways Experiment Station in Vicksburg, MS.

4.2.4 Finite Element Models

Finite difference models, discussed previously, are a special restricted case of a more general class called finite element models. Finite element models allow gridding with grid elements of arbitrary shape and size at each point. As the computational requirements escalate very rapidly with this generalization, it is still applied with limitations. Typically, shape restrictions are relaxed to allow "somewhat-square" or "somewhat-cubical" grid regions, such as with curved sides restricted to parabolic curves. Other schemes use triangular gridding with straight-sided triangles. The sizing of grid regions is relaxed, allowing arbitrary sizes in various parts of the model space. This provides the ability to describe areas with steep gradients or irregular boundary geometry with greater precision than can be achieved using finite difference schemes. Again, computations require boundary values and/or initial values of relevant parameters. Calculation of the values of independent variables at each grid point or within each grid region may be determined by successive approximation, considering nearest neighbors, or including more remote neighbors, or the influence of all grid points in the model space. Such models are typically time-stepped to elucidate process behavior.

The extreme computational requirements of these models have allowed their development only recently. Guymon et al. (1970) developed numerical solutions of diffusion-convection equations by the finite element method in 1970. Zienkiewicz (1971) described the application of the finite element method to engineering problems in general. Smith et al. (1973) applied Rayleigh-Ritz and Galerkin finite-element methods to the diffusion-convection problem. Ariathurai (1974) considered the application of the finite-element method to sediment-transport models in his Ph.D. research. In this approach, he developed a general model of suspended-phase transport in a time-varying, two-dimensional flow field. It included expressions for erosion, deposition, and aggregation, and can be applied to the transport of any conservative quantity. It can even be applied to the transport of non-conservation quantities (e.g., radioactive decay) provided the decay rates are known. Ariathurai continued to work with Krone (1963) on applying such methods to cohesive sediment problems. This work was further extended by Ariathurai et al. (1977) with the development of Sediment II, a sediment-transport model tested using data from the Savannah River. This is the only model currently available which applies finite-element methods to sediment-transport or plume dispersion problems. Apparently, no finite element model has been developed which specifically tracks plume clouds in a similar fashion to the USACE DIFID, DIFCD, and DIFHD models.

4.3 Constraints

4.3.1 Scale-Dependent Description of Turbulent Dispersion

The description of turbulent dispersion used in plume modeling varies somewhat depending on exactly which aspect of the process is being modeled. Turbulent dispersion is often considered from the standpoint of the effects of energy dissipation, advection, and diffusion on concentration. Diffusion and advection have differing roles in mixing processes, and models have been developed incorporating both in various ways. The literature on turbulence has many hypotheses for the ways in which diffusion and advection interact, ranging from statistical mechanics theory to empirically-based theories derived from elementary hypotheses together with laboratory or field data. Existing models may further be characterized as one-equation or two-equation models. This distinction is of more fundamental significance than whether a model is analytical or numerical in nature.

The dependence of eddy diffusivity on some length scale of the turbulent eddies present turns out to be a key consideration. Under one-equation models, this length scale is unknown, and the modeler is forced to select a length scale somewhat arbitrarily, based on experience with the nature of the problem at hand. Typical eddy diffusivity is expressed as some power law of the chosen length scale, usually measured by the standard deviation of the concentration distribution. The power law must also be chosen somewhat arbitrarily. The 4/3-law is an example of such an approach. One-equation models are thus considered consequences of the length-scale-dependent eddy diffusivity hypothesis.

Models which are based on single equations were first developed in the 1920s and all share the necessity for complete definition of the current structure in receiving waters. It is important to note that these formulations are Eulerian, consequently the flow field must be known. Analytical versions have been under study ever since and, recently, numerical versions have been under extensive development, especially by Lam et al. (1984). The key finding has been that eddy diffusivity is proportional to the cross-sectional length scale of the plume. Theoretical investigations of the proportionality constants and power indices were undertaken by several workers (Csanady 1973; Okubo 1976). They showed connections of these parameters to many geophysical and environmental parameters, such as energy dissipation rates, current velocities, and the Coriolis' parameter. Model coefficients for one-equation models have been empirically determined with certainty only recently, mostly by means of dye-diffusion experiments (Okubo 1971; Csanady 1973; Murthy and Miners 1980).

In dealing with the dissipation of energy by the turbulent action of eddies, statistical methods are traditionally used. As successive refinements are sought, statistical moments of successively higher order must be used. This leads to the closure problem. Each equation leads to a higher-order moment, and eventually a closure hypothesis must be made. Such a hypothesis makes assumptions about the remaining higher-order moments describing the process. These assumptions lead to eddy diffusion coefficients of some order.

In one common Eulerian approach, advection and diffusion are considered together. In this formulation, advection and diffusion carry precise definitions which differ slightly from their definitions in other model approaches. Advection in the current context is the bulk transport of a parcel of a plume or patch by the mean component of the current. Diffusion is the spreading of the parcel as a consequence of the turbulence associated with the currents. A further key assumption is that mean and random components are considered separately. Diffusivity is defined in the current context through the use of a rank-two tensor. Empirical studies have shown that under the one-equation turbulence closure hypothesis, length-scale dependence differs in along-flow and cross-flow directions, making the diffusivity tensor anisotropic. The effects of the flow field on this anisotropy must be studied empirically.

Concentration is typically treated in a turbulent flow by means of ensemble averaging (Fisher 1979). The distribution of flow fields is considered to be a set of probable flow fields varying from each other by random fluctuations about some ensemble mean. The details of the statistical definition of concentration vary among various workers.

One formulation of the advection-diffusion equation for a turbulent flow field may be given as

$$\frac{\partial c}{\partial t}+\vec{u}\cdot\nabla c=\nabla\overline{\vec{u}'c'}+D\nabla^2 c$$

where c is the mean absolute concentration, $\nabla\overline{\vec{u}'c'}$ represents turbulent flux, $D\nabla^2 c$ represents molecular diffusion, D = molecular diffusivity, and u' and c' represent the fluctuating components of the velocity field and the concentration, respectively. Application of the turbulent eddy diffusivity concept (Fischer 1979) expands this equation into a nine-component tensor as

$$\frac{\partial c}{\partial t}+\vec{u}\cdot\nabla c = \begin{array}{l} \frac{\partial}{\partial x}K_{xx}\frac{\partial c}{\partial x}+\frac{\partial}{\partial x}K_{xy}\frac{\partial c}{\partial y}+\frac{\partial}{\partial x}K_{xz}\frac{\partial c}{\partial z} \\ +\frac{\partial}{\partial y}K_{yx}\frac{\partial c}{\partial x}+\frac{\partial}{\partial y}K_{yy}\frac{\partial c}{\partial y}+\frac{\partial}{\partial y}K_{yz}\frac{\partial c}{\partial z} \\ +\frac{\partial}{\partial z}K_{zx}\frac{\partial c}{\partial x}+\frac{\partial}{\partial z}K_{zy}\frac{\partial c}{\partial y}+\frac{\partial}{\partial z}K_{zz}\frac{\partial c}{\partial z} \end{array} +D\overline{\nabla^2}$$

Further assumptions may be applied to simplify this equation, and allow its use in the study of horizontal turbulent diffusion processes alone, or full three-dimensional diffusion processes.

The careful study of such processes by many workers has led to several well-known diffusion models. The Fickian diffusion model uses a constant diffusivity K. The linear length-scale model uses K proportional to some length scale L. The inertial sub-range diffusion model uses K proportional to the powers of the product of the energy dissipation rate ϵ and a length scale L. The power laws may be determined through dimensional analysis of the inertial sub-range of the turbulent energy spectrum. The applicable power law turns out to be $K \propto \epsilon^{1/3} L^{4/3}$.

Higher-order turbulence closure hypotheses have been used to develop more sophisticated two-equation mixing and dispersion models.

4.3.2 Quantification of Particle-Aggregation Processes

Particle-aggregation processes play an important, but poorly understood part in the dispersion of suspended sediments. Six different mechanisms are involved. For a continuous size distribution of particles, Fuchs (1964) described the time-evolution of the number concentration (number/cm^3) of particles N(r,t) as

$$\frac{\partial N(r,\ t)}{\partial t} = -N(r,t)\int_0^\infty K(r,r_i)\,N(r_{it})\,dr_i + \frac{1}{2}\int_0^\infty\int_0^\infty K(r_i,r_j)\,N(r_i,t)\,N(r_j,t)\,dr_i$$

The first term on the right describes the reduction in number of particles with radius r by coagulation processes, and the second term on the right describes the production of new particles of radius r by coagulation of particles with radius r_i and r_j such that

$$r_i^3 + r_j^3 = r^3$$

Four mechanisms influence the coagulation constant K (Morgan and Lovorn 1985). **Brownian motion** depends upon fluid properties at rest, such as temperature and viscosity. Collisions may occur **inertially**, or as a result of **fluid shear**, or because of **differential sedimentation**. These depend upon relative particle motion induced by turbulent fluid flow, as well as fluid properties at rest. The net coagulation constant is

$$K_{TOT} = K_b + (K_{sh}^2 + K_I^2 + K_{ds}^2)^{1/2}$$

Chemical aggregation may also be considered to play a role at particularly dense concentrations in suspended sediments in the clay range, though this role is believed to be of minor importance. The individual mechanisms are highly specific to the chemistry of the constituents. and are not being considered in detail in this analysis.

Biological scavenging also plays a role in reducing concentrations of suspended sediments. Organisms over a wide range of sizes, from microplanktonic forms to large fish, are all involved in removing material from the water column. Removal, resuspension as organic detritus, further recycling by uptake by subsequent organisms, transport by fish and other forms, all complicate the overall biological scavenging process. The quantification of interior and boundary scavenging by biological processes has been considered in detail in models developed by GESAMP (1986).

4.3.3 Site Description

The geometry and flow conditions at a marine mining or dredging site significantly influence the dispersion of suspended sediments. While open water dumping of dredged material presents the simplest case of an essentially unbounded model, most real world cases must include consideration of shorelines, bathymetry, and water layers of varying densities containing currents varying in strength and direction.

Shorelines present special problems for dispersion models because nearshore processes are often very complex. Shoreline processes include wave action, tides and tidally-induced currents, other chronic or periodic currents, the presence of river discharges, coastline geometries (which may include bays and other enclosures), as well as other factors. Nearshore models intended to provide predictive capabilities in real world cases must allow for the inclusion of the more important of these factors, determined on a case-by-case basis. The inclusion of such factors must often be based on empirical data, especially in the case of flow fields, tidal oscillations and their associated currents, and so on. As discussed previously, the successful inclusion of such factors in analytical and numerical models has progressed significantly in the last 50 years.

Bathymetry must be taken into consideration not only in nearshore cases, but also in any model where strong flows are found in the model space. Bathymetric features may cause near-bottom mixing, which will significantly influence dispersion and settling times. Lee waves and other bathymetrically influenced flow features may influence far-field dispersion by redistributing suspended materials in the water column.

Gridding methods used in dispersion models may introduce additional constraints on the predictive usefulness of such models. Finite difference models, as noted previously, typically use relatively simple gridding, which in some cases poorly describes a real world site. Finite-element modeling schemes are much better in their ability to use variable gridding to describe important features bounding a model space or contained within it. With increases in computing power, the detrimental effects of inadequate gridding will be further reduced in significance.

4.4 Field Tools for Describing Sites and Tracking Plumes

4.4.1 Currents

As currents and turbulence at varying scales are among the most important influences on plume movement, a wide range of current measurement methods have been tried successfully. These fall into two broad categories including (1) Lagrangian methods, in which a particular parcel of water is tagged or identified and its progress noted; and (2) Eulerian methods, in which a fixed coordinate system is used.

For the Lagrangian approach, the simplest of the mechanical methods uses drifters and floats. A typical drifter (or drogue) consists of a sail-like structure with a flat area of 3 m^3 or so deployed at some desired depth, and marked at the surface with a buoy. The progress of the drogue over time may be charted, giving an estimate of horizontal current direction and magnitude at the chosen depth. Drogues are influenced somewhat by wind and drag forces, and provide only a rough estimate of current.

Another Lagrangian method often used is the marking of a parcel of water with dye. A wide variety of brightly-colored, fairly long-lived dyes have been used, including fluoresceins, Rhodamine-B, and others. Typically, a small amount of dye is used to tag a water parcel, most commonly at the surface, and the current magnitude and direction are found by observing the spread of the dye patch. Tracking may be conducted from aircraft in the case of large-scale studies. The dispersion of the tagged water parcel can also be estimated, something unavailable with the use of drifters. Application of dyes has occurred to a limited extent to tag water parcels beneath the surface, however subsurface tracking is much more difficult than tracking at the surface.

Eulerian methods are ones which are referenced to a fixed coordinate system, against which water movement is measured. A wide variety of Eulerian current meters have been developed for oceanographic use, and all can be used in plume tracking studies. Typically, a current meter or string of current meters is moored in a chosen location, and water velocity may be measured directly. Depending on the technology used, varying degrees of accuracy may be available. Current meters may be direct-reading; that is, the meter may be monitored in real-time by observing its output on board ship, or with some remote-reading output device. More commonly, a current meter records its measurements locally, or transmits its record in real-time or batch-mode to a central data logger, for later decoding.

The simplest current meters are so-called sum-logs, consisting of a ducted propeller and a counter. These crude devices were dragged behind ships to measure their speed, the counts converted to distance.

Propeller-driven and rotor-driven current meters evolved from sum-logs, and a very wide variety exist, providing a wide range of accuracies. Ducted propeller types, and related Savonius-rotor meters provide essentially one-dimensional current measurement, providing magnitude but not direction. When coupled to a suitable vane and support electronics, horizontal direction can also be derived. In some instruments, an array of several rotors is used to extract two- or three-directional components of current magnitude, providing much more usefully complete data at any one location.

Inductive electromagnetic water current meters detect the mass flow of water through an induction coil, providing an output proportional to the flow rate. These meters are accurate and can be made quite small. They are usually grouped to provide three-axis water current information and often are packaged with recording equipment. They remain relatively high in cost but are in widespread use.

Acoustic Doppler current profilers (ADCPs) are the most modern method in use for determining currents in the water column. They are capable of providing simultaneous three-dimensional current data with high resolution using a single transceiver or a typical cluster of four transceivers deployed at a single location. The ADCP is based on the Doppler principle, where the apparent frequency of a back-scattered acoustic signal will differ from the transmitted frequency by an amount proportional to the relative velocity of the transceiver and the backscattering object. To quantify the principle, a water mass "cell" is ensonified by a narrow-beam acoustic signal. The backscattered signal is compared to the transmitted signal. The Doppler frequency shift of the water mass cell is

$$f_D = \frac{2f_t(V\cos\theta)}{C}$$

where f_D = Doppler frequency shift; V = scattering velocity; θ = angle between velocity vector and acoustic beam; f_t = transmitted frequency; and C = velocity of sound at the transmitter interface. The quantity V may be accordingly computed. In a single beam system, $V\cos\theta$ measures the component of flow velocity in the direction of the acoustic beam. A single transceiver system can only produce a one-dimensional velocity profile measurement. Two non-parallel, vertically-inclined beams produce vertical profiles of two-dimensional horizontal velocities, but ignore vertical currents. A three beam system allows measuring profiles of three orthogonal components of currents. Typical systems utilize a fourth beam for redundancy. A high spatial resolution is achieved by periodically transmitting short bursts, then making multiple measurements of the Doppler-shifted frequency of the water mass echoes in discrete time intervals. A quantified picture of flow velocity versus range along each beam is developed. With the precise beam geometry known, the total mean flow velocity vector may be computed by properly combining the velocity component measurements from each beam. This current profile may be recorded as north, east, and vertical components.

4.4.2 Water Quality

Definitions of water quality have widely differing meanings in various contexts and are often the subject of specific legislative language. In the context of marine mining, water quality is often considered from the standpoint of its effects on the marine environment.

Using criteria adopted for the Norton Sound EIS (USDOI, MMS 1991), changes in **local** water quality effects are considered to be those which extend slightly beyond the edge of a mixing zone, such as beyond a 100-m perimeter surrounding a mining or dredging footprint, but affecting less than 180 km^2 around each discharge. **Regional** changes in water quality are considered to be those affecting an area of at least 180 km^2 around a discharge source.

Within the context of these spatial definitions, the **impact** of the change in water quality is typically used to assess the water quality itself, as defined by USDOI, MMS (1991).

A **negligible** water quality impact is considered to be one in which no regulated contaminant (e.g., mercury or a trace metal) is discharged into the water column, or one in which some amount is discharged but the resulting concentration of the contaminant is so small as not to exceed the chronic State standard or EPA criterion. A **minor** water quality impact is one in which a regulated contaminant is discharged into the water column and the resulting concentration of contaminant occasionally exceeds but does not increase the average beyond the chronic State standard or EPA criterion. A **moderate** water quality impact is considered to be one in which a regulated contaminant is discharged into the water column and the resulting concentration of contaminant averages (i.e., sampling period set by permit) more than the chronic State standard and EPA criterion, but does not exceed acute or toxic State standards and EPA criteria and does not exceed 7,500 ppm suspended sediment concentration. A **major** water quality impact is considered to be one in which a regulated contaminant is discharged into the water column and the resulting concentration of contaminant is above the acute (toxic) State standard or EPA criterion, or where turbidity exceeds 7,500 ppm suspended sediment concentration.

Accordingly, the measurement of water quality varies widely, depending upon the parameters considered important in the relevant definition. Often the concentration of some contaminant is the defining parameter; in some cases, biological contaminants are considered (e.g., coliform counts used in the context of sewage disposal), while in the case of dredging or other types of marine mining, the concentrations of certain dredged materials or trace contaminants are considered. The relevant measurement is, in each case, typically a specialized technique suitable for that specific contaminant. Turbidity measurement, discussed in **Section 4.4.3**, is a relatively crude method of suspended sediment concentration which does not single out particular contaminants, but often provides adequate information which can be widely used.

4.4.3 Light Attenuation

Turbidity may be determined by measuring transmitted or reflected (i.e., scattered) light. Transmissometers measure the attenuation of light caused by absorption, scattering, and blockage by suspended particles and dissolved matter in the water. In artificial light transmissometers, a light source shines through a relatively short water path. A detector measures the transmitted light. In natural light or ambient light transmissometers, a detector (irradiometer) is lowered into the water column, and the attenuated natural light is measured. Typically, a second sensor is used to measure light at or near the surface as a reference value.

Optical backscatter sensors (OBSs) and nephelometers detect radiation scattered by particles. Particularly useful are infrared OBSs which utilize a part of the spectrum where absorption by water itself is high, providing a relatively low-noise (essentially dark) environment for measurement. A typical instrument consists of an infrared energy source together with an adjacent detector. This type of sensor responds primarily to high-angle backscattered radiation, providing an excellent measure of turbidity caused by particulate and dissolved matter in water.

Performance of all irradiometric instruments is degraded by very high turbidity concentrations because of multiple reflections by scattering particles. At high concentration levels, however, other techniques may also be used to track plumes, so this does not present a significant problem. At moderate and low concentrations, these instruments perform very well, providing excellent tracking capabilities for researchers seeking to characterize spreading, dilute plumes. Problems typically remain, however, in collecting data at a sufficient number of data points to characterize the three-dimensional dispersion of a spreading plume.

4.5 Predictive Capabilities

4.5.1 Near-Field Surface Dispersion

Although numerous sediment transport and dispersion models have been devised in recent years, most testing has been via computer simulation. Useful field testing of dispersion models has been limited to less than a dozen efforts. Kent and Pritchard (1959) tested mixing length theories in the context of nearshore estuarine modeling. More recently, testing of the DIFID and DIFCD models have been conducted at several sites (Johnson and Holliday 1977; Johnson 1978; Bowers and Goldenblatt 1978; Trawle and Johnson 1986). Testing of these models has resulted in the successive tuning of these models. Coefficient values have been confirmed within successively narrower ranges. These models have also been expanded in their flexibility in input formatting, allowing a wide range of reasonable coefficient values to be tried during model testing.

Despite these efforts, the predictive capabilities of the present generation of dispersion models is still limited, due to insufficient testing/tuning and the inability to include enough important parameters in sufficient detail to afford accurate predictive results. Typically, the effects of unusual bathymetry cannot be accounted for; only relatively simple flow fields can be accommodated; and the influences of complex shorelines can only be crudely considered. The effects of turbulence on various length scales further complicates the picture. The use of eddy diffusivity coefficients, which crudely describe complex flows, does not provide good near-field predictive capability. Finite element models, with their variable gridding capabilities, will help in future efforts.

Near-field predictive capability is relatively good very near to a discharge or sediment dump location (i.e., before the full effects of the turbulent flow field occur). Within even a few hundred meters of a discharge, the ability to predict concentrations within an order of magnitude at any particular location becomes limited. However, if average concentrations are considered within bounded regions increasing in size with increasing distance from the discharge, predictive capability is improved.

4.5.2 Far-Field Dispersion

Testing of far-field predictive capabilities of dispersion models has been hampered by numerous difficulties, including the need for large numbers of measurements over large spatial and temporal scales. Plumes of suspended material originating from human activity have not been generated on large scales for the purposes of testing dispersion models. The effects of large-scale natural phenomena such as continental rivers, oceanic rivers (e.g., Gulf Stream), and other mixing processes have been extensively studied, and provide better source material for empirical far-field studies. In these cases, natural tracers are followed. Examples are given in GESAMP (1986), where oceanic-scale models are considered.

Far-field predictive capabilities of sediment transport models are thus rather poor, with the predictive capability simply degrading with distance. What is considered far-field depends upon the context. For typical regional water quality concerns, distances exceeding about 15 km are clearly considered far-field. At such distances, with present-day models, prediction of concentrations within one to two orders of magnitude is difficult at any chosen location. The development and refinement of water quality criteria and standards for distances greater than 15 km from a discharge source will have to be undertaken with considerable caution if reasonable expectations for measurement and compliance are to be met.

4.5.3 Model Selection for Applied Studies

The current pressing need for easy-to-use models which may be applied to real-world problems of plume dispersion and transport incident to marine mining is adequately met only by the USACE models, now collectively called "the ADDAMS family". As discussed previously, these models have been recently upgraded with a user-friendly interface, and are available on floppy disk for use on PC-class computers. These models are appropriate for the kinds of plumes generated by the dumping of dredged material from a mining operation. Their underlying code deals with near-field effects especially well, including initial dumping effects, dynamic collapse, gravitational effects, and so on. Far-field effects, which are generally much harder to account for, are also addressed in the context of such plumes, but are less accurate. These far-field effects continue to undergo mathematical refinement in the ADDAMS models. It is noteworthy that these models are finite-difference models, and are intrinsically less powerful than finite-element models have the potential to be.

The finite-element models stemming from the work of Ariathurai are more powerful in principle, but are harder to apply, requiring more detailed knowledge of the site, but may provide greater descriptive accuracy under real-world conditions. The model called Sediment II is particularly applicable to sediment-transport problems such as those which arise in river flow situations. To our knowledge, these finite element models have not been packaged with any convenient user-friendly interface, and are not available for general distribution as are the ADDAMS models.

Far-field models discussed in the appendix sections of GESAMP (1986) may be particularly useful for solving large-scale, far-field problems. These models are presented there in skeletal form, and would require computer coding to be applicable; that is, they are not ready off-the-shelf for easy application. Nonetheless, they may be useful when considering oceanic-scale problems. They include parameters for the decay of concentration of suspended materials, which more accurately model some real processes than the other models mentioned above.

The continued development and testing of mathematical models, especially those for suspended sediment and dispersion problems, developed with the use of finite-difference and finite-element modeling methods will improve predictive capabilities. Eventually, perhaps, reasonable predictions can be made for certain classes of materials at scales of regional concern.

4.6 Air Quality Modeling for OCS Mining

4.6.1 Analysis

Because of the wide variety of OCS areas under consideration, an analysis was conducted by the MMS (USDOI, MMS 1991) to assess the onshore impacts from a typical vessel that could be used to carry out mining activities regulated by these rules. A meteorological database was used that included predominately onshore wind flow and frequently stable atmospheric conditions. These factors would lead to predicted impacts that would define the upper limit of expected impacts from future activities regulated by these rules. The location of the hypothetical mining operation analyzed was 32 km from the reference coastline, an assumption which was considered conservative and would lead to higher than expected predicted impacts.

A typical vessel used for the mining of minerals on the OCS may be equipped with diesel engines. These engines produce all the criteria air pollutants: nitrogen oxides (NO_x), sulfur dioxide (SO_2), total suspended particulates (TSP) or dust particles, carbon monoxide (CO), and hydrocarbons (HC). The pollutant emitted in the largest quantity is NO_x.

There are two classes of air pollutants that were assessed. The first class is the inert or non-reactive pollutants: NO_x, SO_2, CO, and TSP. The analysis for these pollutants was conducted using the Offshore and Coastal Dispersion (OCD) air quality model approved for use in these analyses by both the MMS and EPA.

The second class of pollutants is the reactive pollutant HC, which in the atmosphere participates in the formation of ozone. Though NO_x also participates in the formation of ozone, it is not regulated as a reactive pollutant because it serves as both a precursor and a scavenger of ozone in the atmosphere. Because no air quality model exists which is capable of assessing the impact from a single operation on onshore ozone concentrations, the analysis of the impacts consists of a comparison of the expected HC emissions to an allowable emission level calculated by using the expected distance of the operation in the following equation: $E = 33.3D$; where E is the allowable HC emissions, in tons per year, for the operation and D is the distance, in miles, of the operation from shore.

The typical vessel modeled under this scenario was equipped with eight diesel engines with a total power capacity of 20,000 HP. The emission rate for each engine, by pollutant, was as follows: NO_x, 13.8 g/Hp-h; SO_2, 0.7 g/Hp-h; CO, 1.4 g/Hp-h; TSP, 1.1 g/Hp-h; and HC, 0.3 g/Hp-h. Because the emissions of NO_x were the highest, its emission rate was used in the analysis and the results were presented for this pollutant. The results are applicable to the other pollutants and can be linearly scaled downward according to the reduced emission level for a particular pollutant.

4.6.2 Results

The results of the modeling exercise for the inert pollutants predicted that the maximum annual and short-term impacts from a typical vessel located 32 km from shore were less than 5% of any of the National Ambient Air Quality Standards. In most cases, the impacts would be less than 1%. The typical HC emissions were less than 10% of the allowable emissions level for this typical operation. These predicted impacts would be in excess of the USDOI significance levels applicable to oil and gas activities but would be reduced by the installation of Best Available Control Technology (BACT) required of similar oil and gas sources which exceed the significance levels. The resulting impacts after the installation of BACT would still be slightly above the USDOI significance levels for the hypothetical activity analyzed.

Site-specific analyses will be needed as specific projects are considered. The MMS analysis (USDOI, MMS 1991) indicates that few marine mining projects, if any, will significantly increase onshore pollutant concentrations in areas adjacent to the OCS.

CHAPTER 5 DATA GAPS, RESEARCH NEEDS, AND RECOMMENDATIONS

Based on the results of environmental studies that have been described in previous chapters, this chapter focuses on the gaps still apparent in the data and information available from the published literature. Research needs and recommendations for further work designed to fill those data gaps, including field studies, are presented.

5.1 Environmental Considerations

There are significant data gaps in the U.S. knowledge base, as indicated by the literature, in the following areas:

(1) Water quality modeling of the generation and dispersion of particulate and dissolved materials in the water column, based on, or at least confirmed by empirical data acquired from marine mining operations;

(2) The effects of significant alterations of the seabed on adjacent coastlines;

(3) Understanding of the characteristics, behavior, and recolonization response of organisms in various mine site areas (e.g., deep seabed, seamounts, guyots, OCS, and coastal) under the stress of production operations;

(4) The effects of processing discharges from onshore mines on coastal biota; and

(5) Understanding the realities of mining in perspective with other natural processes and man-induced activities.

Other less significant areas of concern that may not yet have been adequately addressed by research activities are discussed under the respective headings of air quality, water quality, biological resources, geological resources, and socioeconomic concerns.

5.1.1 Air Quality

Based upon all the available information used for this study, it is clear that the effects of marine mining on air quality will be minimal. Assessments made for the existing environmental impact studies are quite adequate and, in many cases, overstated. Air quality effects from metallurgical processing can be very significant, but these are also so site-specific and technology-specific as to be nearly impossible to assess in a generic sense.

Recommendation: Additional research on the effects of marine mining on air quality should not be seriously pursued.

5.1.2 Water Quality

The effects of mining operations on water quality are generally the most important for marine mining and have received significant research support. A significant gap still remains, however, between the mathematical modeling of these effects and their actual field measurement. Of particular concern in this area is the treatment of the fine-grained materials in discharge plume modeling. In general, researchers who develop models have not found straightforward mathematical means for dealing with the complicated phenomena such as coagulation, flocculation, adsorption, and interactions with filter-feeding biota. Field studies also reveal perpetual problems in relating measurements of turbidity to actual concentrations of fine materials. Fine-grained materials are the primary contributors to turbidity and do not settle out in reasonable times by gravity alone.

The major consequence of these shortcomings is unrealistic predictions of discharge plume size and persistence in the water column. Because most models lack representation of the real mechanisms which efficiently remove fine-grained materials from the oceans, they predict continual build-up of these materials and much larger sediment plumes than are observed in field verification studies. This shortcoming is often realized by the developer of the model, but it is usually justified as being a conservative assumption.

Recommendation: Marine mining operations could benefit greatly from research which uses combined modeling and field work to deal directly with this problem, substituting empirical calibrations when necessary to produce reproducible and believable model predictions.

5.1.3 Geological Resources

There are many knowledge gaps with regard to morphological changes due to the excavation of sulfides from the deep seabed. In light of the many other unknowns, it is not a major concern at this time. Substrate alteration is considered a biological problem. The creation of holes and mounds in the shelf and coastal regions as a result of mining operations can cause significant environmental effects. This information is transferable from different geographic areas more assuredly than biological data. The number of offshore operations is so limited that it is conceivable to consider a global database, including existing marine mining operations anywhere in the world, from which environmental data from actual operations can be acquired. There are regional organizations such as the South Pacific Applied Geoscience Commission (SOPAC), the Committee for Coordination of Joint Prospecting for Mineral Resources in Asian Offshore Areas (CCOP) in Asia, the South Pacific Regional Environment Program (SPREP), the North Atlantic Treaty Organization (NATO), and the United Nations Global Seas Program which would be ideal vehicles for cooperation in these activities. Because of the tailings problems from the Reserve Mining operation on Lake Superior, discharges from onshore mines into coastal waters are not acceptable in the U.S. Such discharges are still prevalent elsewhere, however, and may be significant on a global basis. The data will in most cases be transferable to other sites in the U.S. Information on monitoring techniques and the effects of these activities would be invaluable.

Characterization of carbonate aggregates in tropical island environments is an area of increasing importance with many unknowns. Although deposits of reef-derived carbonate sands may be small compared to continentally-derived deposits, usually of silicates, they are becoming increasingly important to island communities where land use conflicts, environmental regulations, and scarcity of land deposits restrict the supplies of these resources. Characterization and assessment of these deposits, and the environmental effects of their development, are needed in many areas throughout the Pacific and Caribbean island communities to provide new sources of materials for beach replenishment and industrial aggregates.

Recommendation: Efforts should be made to develop a global database on the effects of marine mining on the environment, utilizing field data from current operations throughout the world. The field work would ideally be carried out in cooperation with appropriate regional environmental bodies and would involve U.S. participation as working partners rather than as observers or mentors. Continued research efforts should be directed at the technology for fast, accurate, and simple characterization and assessment of reef-derived carbonate sands in U.S. associated tropical island areas.

5.1.4 Biological Concerns

The deep sea benthos is a major part of the marine ecosystem. For most categories of marine life, environmental assessments of potential effects of mining are properly carried out as the mining operation develops and after its major characteristics are well defined. The clear exception to this sequence of events is the benthic life of deep seabed areas with potentially commercial minerals such as cobalt crusts, manganese nodules, and massive sulfides. Preliminary studies suggest that recolonization rates for some deep seabed benthic habitats can be hundreds to thousands of years, and the general paucity of information about these ecosystems makes even the most rudimentary assessment efforts dubious.

Long-term, relatively inexpensive research is needed to address basic questions of species succession, recolonization rates, and relationships to other ecosystems. Some internationally sponsored efforts in this area are currently active for manganese nodule deposits, but no work is being done to address these issues for manganese crusts or massive sulfides. If this work is delayed until commercial development is ongoing, there may not be time to acquire sufficient information for confident prediction of effects. If added to mineral characterization or general geological studies of these deposit types, such research could be conducted very efficiently.

Recommendation: Research efforts should be directed towards characterization of deep seabed ecosystems in mineralized areas within the EEZs of the U.S. and associated entities. Long-term research efforts should be established to address specific biological questions of species succession, recolonization rates, and relationships between adjacent ecosystems in areas of crusts and sulfides within the U.S. EEZ.

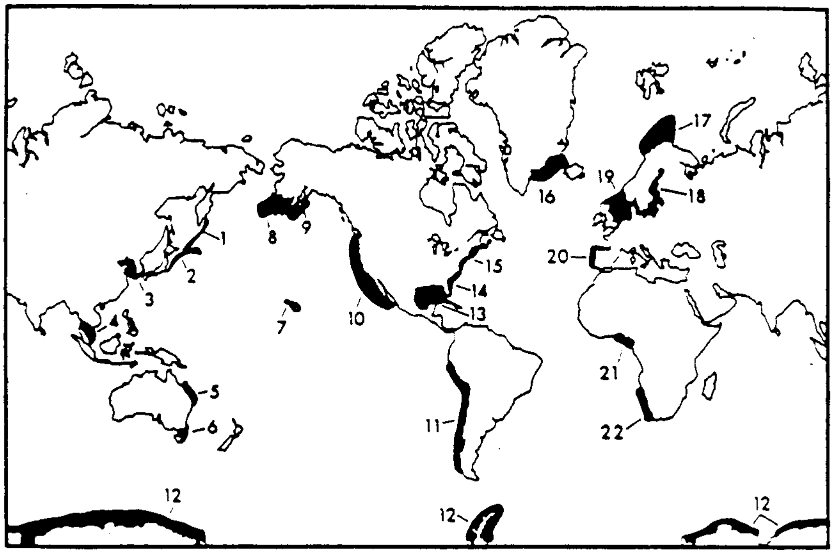
5.1.4.1 Large Marine Ecosystems

Most marine mining operations are overseas, but it appears that, through an ecosystems approach, it may be possible to transfer useful information from one part of the world to another. LMEs are relatively large areas of 200,000 km^2 or more and are typically located in waters adjacent to land masses which encompass the areas under greatest stress from over-exploitation, pollution, and habitat alteration. Taking the ecosystems approach to understand ocean problems highlights the interrelationships within the systems and encourages cooperative dialogues across traditional disciplinary boundaries (Knauss 1991). The approach recognizes the interrelationships of systems within natural boundaries, rather than institutional or legal boundaries and may be relevant in transferring information on a global basis between widely separated, but similar, ecosystems. Major biological risks have been recognized on a broad scale such as predation, habitat alteration, and pollution, with others as yet unrecognized (**Figure 5.1**). Key elements of the system are described in **Table 5.1** and **Figure 5.2**.

Recommendation: Research efforts should continue or accelerate in a cooperative approach to environmental studies through the concept of LMEs and should inject into that program the knowledge of minerals development in those areas where the MMS has access to a unique base of expertise.

5.1.5 Socioeconomic Concerns

There are serious gaps in terms of public understanding of minerals development activities in the oceans, as well as on land. A co-founder of Greenpeace is quoted as saying "It doesn't matter what is true, it only matters what people believe is true. You are what the media defines you to be..." (Haywood 1991). There are many examples in the literature of what appear to be public misconceptions, including perceptions that (1) mining activities are equivalent to maintenance dredging activities in terms of volumes of material dredged, effects of dumping at sea, and the content of toxic materials; (2) oxides from cobalt crusts and sulfides from hydrothermal deposits are chemically the same in terms of potential pollutant emissions; and (3) discharges from mining operations are equivalent to, or potentially more harmful than, benthic discharges from hydrothermal vents, volcanoes, or perturbations from storms.



1 OYASHIO CURRENT ECOSYSTEM (O)
2 KUROSHIO CURRENT ECOSYSTEM (O)
3 YELLOW SEA ECOSYSTEM (X)
4 GULF OF THAILAND ECOSYSTEM (X)
5 GREAT BARRIER REEF ECOSYSTEM (X)
6 TASMAN SEA ECOSYSTEM (+)
7 INSULAR PACIFIC ECOSYSTEM (+)
8 EAST BERING SEA ECOSYSTEM (+)
9 GULF OF ALASKA ECOSYSTEM (+)
10 CALIFORNIA CURRENT ECOSYSTEM (O)
11 HUMBOLDT CURRENT ECOSYSTEM (O)
12 ANTARCTIC ECOSYSTEM (+)
13 GULF OF MEXICO ECOSYSTEM (+)
14 SOUTHEAST CONTINENTAL SHELF ECOSYSTEM (+)
15 NORTHEAST CONTINENTAL SHELF ECOSYSTEM (X)
16 EAST GREENLAND SEA ECOSYSTEM (+)
17 BARENTS SEA ECOSYSTEM (O)
18 BALTIC SEA ECOSYSTEM (P)
19 NORTH SEA ECOSYSTEM (+)
20 IBERIAN COASTAL ECOSYSTEM (O)
21 GULF OF GUINEA ECOSYSTEM (+)
22 BENGUELA CURRENT ECOSYSTEM (O)

Figure 5.1 Predominant variables influencing changes in fish species biomass in large marine ecosystems. Predominant variables include predation (X), environment (O), pollution (P), and inconclusive information (+) (From: Sherman 1991).

Spatial	Temporal	Unit
1. Spatial-temporal scales		
1.1 Global (world ocean)	Millennia–decadal	Pelagic biogeographic
1.2 Regional (exclusive economic zones)	Decadal–seasonal	Large marine ecosystems
1.3 Local	Seasonal–daily	Subsystems
2. Research elements		
2.1 Spawning strategies		
2.2 Feeding strategies		
2.3 Productivity, trophodynamics		
2.4 Stock fluctuations, recruitment, mortality		
2.5 Natural variability (hydrography, currents, water masses, weather)		
2.6 Human perturbations (fishing, waste disposal, petrogenic hydrocarbon impacts, aerosol contaminants, eutrophication effects)		
3. Management elements—options and advice—international, national, local		
3.1 Bioenvironmental and socioeconomic models		
3.2 Management to optimize fisheries yields		
4. Feedback loop		
4.1 Evaluation of ecosystem status		
4.2 Evaluation of fisheries status		
4.3 Evaluation of management practices		

Table 5.1. Key spatial and temporal scales and principal elements of a systems approach to the research and management of large marine ecosystems (From: Sherman 1991).

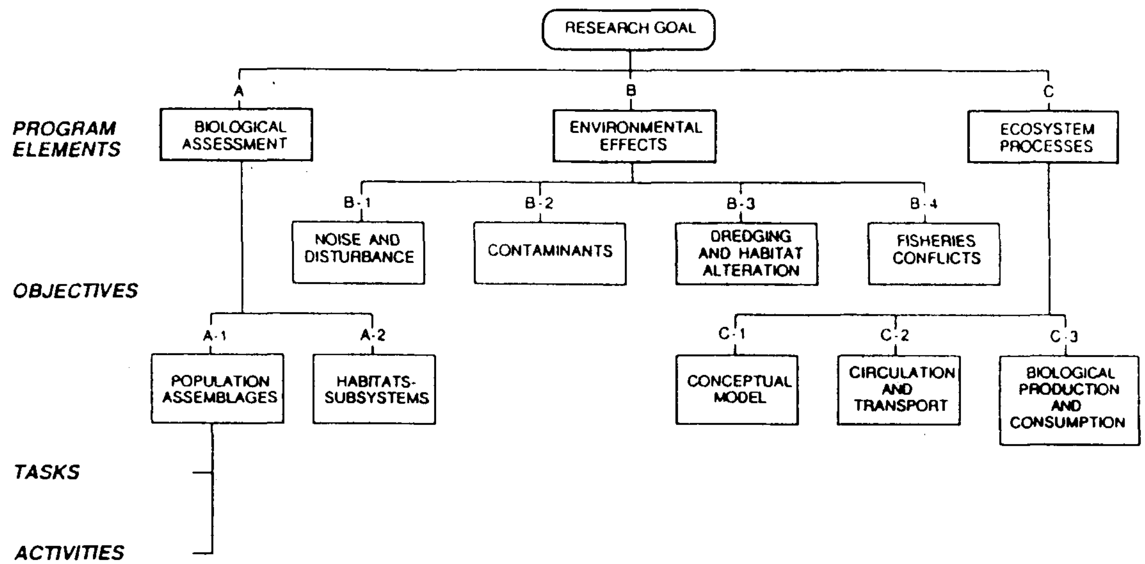


Figure 5.2 Research objectives and tasks in the Ecosystem Processes Program Element of the Northeastern California Current Ecosystem study plan (From: Sherman 1991).

Recommendation: Research efforts should continue to be based on a philosophy that emphasizes the sustainable development concept of mineral resources, placing environmental issues up front. Specific research efforts could be directed to controversial issues which can be resolved by the presentation of facts drawn from field examination. This research would interface closely with the use and development of a global database. In terms of dealing with industrial or commercial interests which may be conflicting (e.g., fishing and recreation), the commendable task force approach employed by the MMS would provide appropriate guidance for the research.

5.2 Mitigation Measures

Substantive principles for resolving marine use conflicts have not been developed by the courts under the public trust doctrine. Related judicial approaches legally separating exploration rights from development rights aids the resolution of marine use management conflicts significantly, according to Hildreth (1989). These legal approaches to mitigation are of concern to the MMS and should be considered appropriately.

In most cases, it is not some perceived damage to the environment that must be mitigated, but the public's perception of damage based on misconceptions of the possible outcomes. The Precautionary Principle, which requires that proof of no negative effect is needed before any action is taken, is almost instinctively applied at the local level. The gathering of facts and the formulation of clear explanatory texts are an essential part of the mitigation process.

Also needed are good inter-industry relations between fishermen and miners to allow fishing of dredging grounds and to develop controlled dredging seasons, if necessary. Improved forward planning of resource information by miners will allow realistic time scales for environmental assessment.

Financial incentives are a powerful tool to effect mitigation by persons involved in supporting and opposing operations which might occur in their area of personal interest. Some examples include use of a unit tax deductible award for attendance at planning or scoping meetings, or for development of appropriate suggestions for mitigation. Other examples include free workshops as a forum for discussions between protagonists in conflict of interest scenarios, and serious analytical studies of the many available options. Very early involvement at the local level is an essential part of such activities and may obviate the later cost of lawsuits and other legal and costly aggravations.

5.3 Predictive Models

As outlined in **Chapter 4**, extensive mathematical and computer programming efforts have been made to predict the dispersive behavior of discharged materials in marine environments. Adequate mathematical and computer-based tools are available. Unfortunately at this time, sufficient field efforts have not been completed to confirm these tools and to adequately discriminate among them.

5.4 Recommended Priorities

Priorities for individual research needs at the project level are very subjective. Looking in the long term, the authors believe that two major gaps should be approached together as a first priority, including (1) verification of the very extensive models that have been developed for plume dispersion; and (2) utilization of ongoing operations in areas outside of the U.S. to verify the models and to develop a database on other real environmental needs determined from actual mining operations in the field.

There appears to be a major gap in field environmental research directed to actual mining operations. Some opportunities to acquire unique data have been lost as offshore operations shut down or other countries (e.g., Thailand) tighten their environmental quality regulations. There is still a substantial opportunity, however, to direct environmental research efforts in a manner which focuses on real problems of the minerals industry working in the oceans. Such work has been initiated by the MMS in ongoing benthic repopulation field studies to evaluate the impacts of offshore dredging activities (B. S. Drucker, 1992, personal communication, USDOI, MMS). It is recommended that this and similar studies, together with dispersion model verification, be given the highest priority.

Understanding of marine biological systems and their responses to stresses induced by marine mining operations is still very close to the bottom of the learning curve. The work already done in other countries should be carefully analyzed, and cooperative field programs should be initiated to monitor active marine mining operations. Prime examples include tin operations in Thailand and Indonesia; sand and gravel operations in Japan and the U.K.; diamond operations offshore Namibia; and beach or nearshore placer operations in India and Australia. Such an approach will benefit U.S. relationships with other governments which are also under pressure to implement the new world order of sustainable development. With adequate analyses, it should be possible to prepare strong justification for funding this type of work even in a competitive arena. Funding justifications include (1) it is critical research; (2) it is low cost compared to the information to be acquired; and (3) the nature of the information makes it admirably exchangeable for goodwill and more valuable than many overseas assistance programs because it involves cooperative work in the field. Some initial activities might be carried out using in-country monetary credits.

The involvement of local interests in proposed marine minerals activities through regional task forces should continue to be given the highest priority.

The encouragement for minerals development mandated under the Mining and Minerals Policy Act of 1976 gives strong justification for the support of research which might directly influence government policy allowing for financial incentives to the general public for involvement in marine minerals planning and operations. This effort is deemed to be less pressing at this time, but would form part of a long-term research plan.

It is considered an important part of any research plan to guard against pressures to expend limited resources in research areas not directly related to marine mining operations. For example, detailed studies of the migratory patterns of birds that might pass through or near a mining area should be left to some other organization with objectives more in line with such studies. There are many such examples.

The authors concur with the conclusions of the Office of Technology Assessment that a compendium of available studies and the data produced on both shallow and deep water environments is needed. A great deal of research on environmental effects of activities in offshore areas performed by government agencies and other institutions has never appeared in peer-reviewed literature. These studies, for which the combined research budgets represent hundreds of millions of dollars, must be useful in describing both the altered and unaltered offshore environment and may be directly applicable to proposed mining scenarios. Such data collection could not be duplicated by the private and academic sectors in this century and new research efforts would benefit from easy access to this wealth of information. The needs and the information available go beyond this present compilation and would be of a high priority in the establishment of an appropriate global database.

CHAPTER 6 SUMMARY AND CONCLUSIONS

The primary objective of the study, to survey and analyze the existing literature regarding the environmental impacts of marine mining, has resulted in the disclosure of considerably more written material on this subject than initially expected. At least 10,000 documents are in the public domain, many in the areas of grey literature, and it is anticipated that many more would be disclosed, given simpler access to foreign sources. The second objective of the study, to summarize the literature in a single, monograph-style manuscript, has been met with the development of this document. The document addresses the literature from several points of view, including environmental considerations, viable mitigation measures, predictive models, and data gaps, research needs, and recommendations.

In **Chapter 2**, Environmental Considerations, the state of knowledge regarding the environmental effects of marine mining is discussed and evaluated. Discussions address: (1) the potential mineral resource groups or targets (**Section 2.1**); (2) the operational methods and technology applicable to marine mining (**Section 2.2**); (3) the environments potentially affected by selected marine mining operations (**Section 2.3**); (4) a characterization of the literature evaluated (**Section 2.4**); and (5) a summary of environmental effects by resource affected (**Section 2.5**). The summary discussion addresses the information on environmental effects under the categories of air quality, water quality, and geological, biological, and socioeconomic resources.

Mineral resources have been defined as any mineral deposit found in the marine environment, other than oil and gas but including salt, sulfur, geothermal resources, and precious corals. These resources have been classified into six groups, including industrial minerals, mineral sands, phosphorites, metalliferous oxides, hydrothermal deposits, and dissolved minerals. Mineral resources are differentiated largely on the basis of the characteristics of the deposits and the technology required for their mining or recovery. The classification is universal and each class is discussed separately with emphasis on the nature and distribution of the deposits.

The technical aspects of marine mining in the environments of the deep ocean, continental shelf, coastal zone, and onshore are discussed in detail in **Section 2.2**. The environments of the continental shelf and the deep ocean are both found in the U.S. EEZ and managed by the MMS.

The "mining industry" referred to in the study generally encompasses companies whose activities are directed to mineral exploration, development, mining, processing of ores, and marketing of mined materials. The marine mining industry is influenced by a heterogeneous mix of international entrepreneurs, advanced engineering companies, politicians, environmentalists, legal experts, long-time dredge operators, and a few old-line mining companies. Despite setbacks, many aspects of the work done to date have been serious and well founded.

It is still early to generalize about marine mining technology and the environment. Examination of each activity on a "case-by-case" basis appears to be the most reasonable approach at this time. Despite the fact that every mine is different, there are only four basic methods of mineral extraction on land or at sea, including (1) scraping; (2) excavating; (3) tunneling; and (4) fluidizing (i.e., extracting the mineral through a bore hole or other conduit as a fluid). All mining methods are based on variations of these technologies. The specifics of each marine mining method are summarized in **Table 6.1**.

There are three areas in which the processing of marine ores call for special treatment compared to the processing of terrestrial ores. One is the effect of platform motion on separation processes carried out at sea. The second is the effect of complete submergence on beneficiation processes. The third is in the extraction of metals from specifically marine ores such as manganese nodules and crusts. Some industrial materials such as specialty sands may require washing to remove salt water, but for the most part, marine ores do not otherwise differ from those on land and use conventional methods of treatment.

Materials handling in the marine environment is complicated by the motions of the platform and the need in most cases for closed-cycle systems and stringent controls to avoid spillage or contamination. These issues are normally addressed in the environmental analyses that are a part of the planning process. In the case of marine mining, the problems would be addressed on a case-by-case basis.

The nature of the various environments (e.g., deep ocean, continental shelf, coastal zone, onshore) in which marine mining may take place and the anticipated effects of mining operations on those environments are discussed in **Section 2.3**. Where possible, real examples of operations have been cited and discussed, rather than speculative methods. The geographic extent of the environments under consideration in this analysis is global, even if the U.S. EEZ is the only region for which a particular mining operation or environmental effect is documented. The descriptive material has been directed to areas selected by the authors as being representative of possible future mine sites. Examples from areas outside of the U.S. are commonly used, including southeast Asia, Europe, and the Pacific Basin.

The nature of the available and salient literature acquired during this study is discussed in **Section 2.4**. The general nature of its content has been analyzed in a qualitative manner. Thirteen major documents exist that together address the state of knowledge at the time of compilation. These volumes alone contain more than 5,000 references selected for their relevance to the subject matter addressed, many of which pertain to environmental effects of mining. During the present analysis, more than 3,570 references were scanned, over 1,100 selected titles were categorized, and approximately 350 sources were used as references. Analysis of the documents categorized indicated that 54% were not country specific; of those that were, 66% pertained to North America. More than half of the literature sources did not specify to which environment they pertained; of those that did, 75% were coastal and only 3% of the total referred to the OCS. Only 17% of the documents reviewed pertained specifically to mineral deposits; of those, 80% applied to deep ocean oxides and hydrothermal deposits. Nearly 50% of the sources reviewed

Operational Method and Systems	Description	Comments
SCRAPING		
Conventional Shallow Water Systems:		
Dragline Dredge	Material recovered by large dredge buckets that scrape it from the surface of the deposit and feed it into barges for transport to shore.	Used in offshore mining, deep seabed sampling, and construction. Use has been advocated for the recovery of deep seabed nodules and slabs of phosphorites. Annual production of phosphorite from an OCS mine could be on the order of 360,000 metric tons, or roughly 138,000 m^3 of ore.
Trailing Suction Hopper Dredge	Dredge employs a pump to draw a slurry of bottom water and sediment into a riser or pipe leading to a surface mining vessel.	Used primarily for maintaining harbor channels, as well as extensive use in the mining of sand and gravel in water depths of up to 36 m in the North and Baltic Seas. New vessels are designed to extend mining capability to depths of 45 m. Volume of material that may be mined includes the sum of the marketable material, the fraction to be rejected, and the overburden initially stripped away. Use of sand and gravel as construction material requires stringent measures be taken to avoid mining any clay layers due to potential contamination.
Tested Deep Water Systems:		
Hydraulic Systems	Hydraulic miners use airlift or hydraulic lift with towed or self-propelled collectors.	Towed mining devices (or passive systems) pick up nodules via tines at the front of the miner; nodules are fed into the suction pipe by conveyor belt or by the forward movement of the device. Separation of the fine sediment is accomplished automatically by the screening effect of the tines and use of a screen on the lifting part of the miner. Active or self-propelled miners are more complex and may be fitted with separate propulsion, navigation, nodule pickup, and crushing systems. Important factors include precision of mining track, separation of nodules from sediments, and discharge of suspended solids.
Continuous Line Bucket (CLB) System	Original CLB systems used one ship, with empty buckets going down from the stern, and partially filled buckets coming in at the bow. A two-ship system has been designed where the empty buckets go down to the seabed from one ship and are brought to the ocean's surface at a nearby sister ship.	CLB system has been tested for possible future use in recovering manganese nodules and proposed for mining phosphorite nodules and slabs and cobalt crusts. In a one-ship system, the distance between the downward-moving and the upward-moving parts of the loop of the rope is dependent on the length of the ship. Entanglement can be avoided by achieving an optimum combination of ship speed and the length of the line or by the use of hydrodynamic deflectors. The optimum combination may be disturbed by various other factors, including the nature of the seabed, underwater currents, variations in the ship's course because of weather heading, or bad weather conditions. For two-ship systems, the distance between the descending and ascending parts of the loop and the curve of the loop can be influenced by the relative positioning of the two ships

Table 6.1. Summary of various marine mining technologies.

Operational Method and Systems	Description	Comments
Speculative Deep Water Systems:		
Modular Mining System	An autonomous collector vehicle would be launched with ballast material such that the weight in water of the ballast is equal to the weight in water of the nodules to be collected.	The collector is designed to have sufficient buoyancy so that the vehicle is weightless in water. Thus, in descent, thrusters propel the unit down steadily against hydrodynamic resistance alone. On the bottom, the collector is propelled over the bottom, and as collection proceeds, ballast material is simultaneously ejected on an equal weight-in-water basis. In this manner, a small net weight in water of the collector is maintained. Mining is terminated shortly before ballast material ejection. Ballast material ejection is continued until the weight of the vehicle is zero or slightly negative. Finally, the vehicle is propelled by thrusters to the surface, docked with the surface ship, unloaded, serviced, and re-ballasted for a new mining cycle. In theory, very little onboard power is required to collect the nodules because the major source of energy is the potential energy of the ballast material. The operating principle of this system is illustrated in United Nations (1984). Processed tailings have been suggested for use as ballast. Advantage might be taken of ambient currents to propel the vehicle similarly to a sailplane or glider.
Crust Miner	Proposed systems would be capable of breaking and removing the thin manganese oxide crusts from the underlying rock and feeding it to a hydraulic lift system through hydrocyclones to separate entrapped substrate.	Recent interest in manganese oxide crusts containing relatively high values of cobalt and platinum has led to proposals to develop the deposits. The manganese crusts vary in thickness from mere stains to layers as much as 40 cm thick, and cover a variety of substrate rocks ranging from hard basalt to weak hyaloclastite. The physical properties of the crusts are similar to a hard coal, and they occur extensively in the Pacific on seamounts and submarine ridges at depths between 800 and 2,400 m. Mining systems proposed for this work include a vessel equipped with hydraulic lift systems and active bottom miners (Halkyard and Felix 1987; USDOI, MMS and HI, DBED 1990). The roughly cleaned ore would be pumped to the surface vessel for further cleaning and transport to shore. The mining machine would provide its own propulsion and travel at a speed of approximately 20 cm/s. The miner would have articulating cutting devices which would allow the crust to be fragmented while minimizing the amount of substrate collected. Behind the cutter heads, a series of parallel pickup devices would be positioned, consisting of either articulated hydraulic suction heads or a mechanical scraper/rake device. Approximately 95% of the fragmented material would be picked up and processed through a gravity separator prior to lifting. Under normal operations, the mining ship and the miner would follow a coordinated track following bottom contour lines. System speed and/or pipe length would have to be altered to accommodate changes in depth over approximately 100 m. Steering of the miner would be used to maneuver around obstacles, over areas of particularly high abundance, or around a previously mined swath.

Table 6.1. (Continued).

Operational Method and Systems	Description	Comments
EXCAVATING		
Conventional:		
Clamshell Bucket	Clamshell buckets are mechanically actuated to bite into the seabed and remove material.	Clamshell buckets have been used offshore to mine sand and gravel in Japan and tin in Thailand, and to sample phosphorite off New Zealand. The need for multiple cables to actuate the grabs can cause complications, particularly in heavy seas where wave compensating devices may also be needed. The clamshell is best suited for excavation of large-size granular material where accuracy of positioning and cleanup is not important; this system is inefficient in clearing bedrock of fine materials. The size of buckets may range from a few cubic meters to as much as 7.6 m^3.
Bucket Ladder Dredge	The bucket ladder consists of a chain of closely connected digging buckets mounted over a heavy supporting arm or ladder.	The bucket ladder dredge is most efficient for excavation of deposits containing boulders, clay, and/or tree stumps and weathered bedrock. Dredges of this type have been used successfully all over the world for mining gold, tin, and platinum placers and diamond deposits; offshore use has been limited to gold and tin. They are frequently used for clearing harbors because of their capability for digging into broken rock and coral. This system delivers a virtually water-free product to the mineral dressing plant onboard the dredge. Discharge of water from shipboard operations is limited to that needed to concentrate valuable constituents (i.e., use of flowing water to remove the less dense materials). In the case of gold, the bulk of concentrate recovered is only a few parts per million; virtually all the material removed from the deposit is returned to the seabed. Turbulence accompanies these operations, which may involve the annual movement of up to 4.9 million m^3. Bucket ladder dredges are limited to 45 m water depths, rarely operating at depths over 20 m.
Bucket Wheel Suction Dredge	Bucket wheel dredges use a small-diameter bucket wheel mounted on the suction ladder to excavate material, combining the best aspects of the bucket ladder and suction dredges.	Advantages of this system include very high torque or digging power available for application to the wheel, delivering the excavated material directly into the mouth of a suction pipe for transport to the surface. Digging capability is equal to that of the bucket ladder dredge with respect to ease of digging and bucket capacity; the depth capability using submerged pumps is nearly unlimited. A combination of concurrent digging and suction at the seabed allows for vessel treatment or transport to shore.

Table 6.1. (Continued).

Operational Method and Systems	Description	Comments
Stationary Suction Dredge	Operates under similar principles as other suction dredges.	Anchored suction dredges are widely used in Japan (i.e., mining sand and gravel) at depths less than 30 m. Current designs will extend depth limits to 200 m (Tsurusaki et al. 1988). An anchored suction dredge has also been tested for mining metalliferous muds at a depth of 2,000 m in the Red Sea (Fletcher and Mustaffi 1980). Stationary, or anchored, suction dredges are used extensively in Britain, although most vessels built since 1980 are trailing suction dredges. Anchored suction dredges leave deep pits in the seabed.
Cutterhead Suction Dredge	This method uses a rotating cutterhead which is usually comprised of an open basket with hardened teeth or cutting edges. The end of the suction pipe is normally located within the basket.	Typically, cutterhead suction dredges are used to excavate fairly compacted, granular materials in water less than 30 m deep. In standard practice, the dredge is swung back and forth in an arc pivoted from a large post or spud attached to the stern. The dredge cutterhead cuts downward a short distance with each swing. Because the cutter rotates in one direction only, the bite is much stronger on one swing than the other. In mining for heavy mineral sands, the action of the cutter tends to disintegrate the material, allowing heavy minerals to separate, fall below the cut, and be left on the seabed. Cutter suction dredges have been used successfully for mining cassiterite (tin placers). Suction dredges circulate large quantities of slurry, creating a significant discharge of water containing fine particulate materials. Treatment of the decanted solids may be unnecessary for construction sands and gravel but may be required for heavy minerals. The valuable constituent or concentrate from these ores will rarely amount to more than a few percent of the materials mined. The cutterhead suction dredge may also be equipped with a multi-blade ripper to cut into moderately consolidated rock. Present use is limited to the excavation of soft rock, such as coal and shale. However, advances in rapid tunneling technology suggest that rock cutterheads could be designed for medium strength rocks, such as sandstone and limestone (Hignett and Banks 1984).
Drilling and Blasting	Involves the use of explosives to fracture a formation; subsequent retrieval of the mineral resource requires one of the methods noted above.	Blasting operations are designed to expend as much force as possible on fragmenting the ore so water column effects are much lower than those for equivalent, unconfined explosions from which most available data have been derived. With respect to the possibility of mining deep seabed deposits that require fragmentation, many more aspects need to be examined. Technically acceptable means of drilling and fragmenting hard rock in deep water have not yet been developed. However, methods of gathering and lifting the fragmented material may be assumed to be similar to the methods developed for deep seabed nodule mining.

Table 6.1. (Continued).

Operational Method and Systems	Description	Comments
TUNNELING	Conventional underground mining methods involve tunneling from a surface entrance or a shaft and working the mine in an unpressurized environment.	Sub-seabed deposits of bedded coal, ironstone, potash, and veins of copper, lead, and tin have been mined by conventional underground methods. Entry to these mines is either from the shore or from natural or artificial islands in shallow waters. The location of the mines in the seabed only slightly adds to conventional problems of access, safe overhead cover, and ventilation. The effect on the environment is similar to that for any shoreside mine. The possibility of developing underground access through seabed airlocks has been considered for special cases (Austin 1967).
FLUIDIZING		
Fluidizing (Slurries)	This mining methods entails drilling of a borehole to the base of the ore, then applying a means through the borehole to granulate or fluidize the resource. The slurry is recovered through the borehole, creating a waterfilled cavity which may be backfilled with waste material.	Under proper conditions, certain types of unconsolidated or marginally consolidated mineral deposits may be mined as a fluid slurry through drillholes penetrating the seabed (e.g., sand, phosphorite). Sub-seabed sand was mined in this way in shallow waters offshore Japan in 1974 (Padan 1983), and recent onshore experiments in Florida proved the capability of this approach in recovering phosphate from beneath thick overburden (Savanick 1985). This system was determined to be cheaper than conventional land mining systems if the overburden is at least 45 m thick (Hrabik and Godesky 1985). Similar experiments conducted off Georgia (Drucker et al. 1991) from an anchored barge confirmed the potential for borehole mining for phosphorite as an economically and environmentally attractive alternative to dredging. In the recovery of sulfur, super-heated water is pumped into the deposit to melt the sulfur so that it may be removed as a fluid (Cummins and Given 1973).
Fluidizing (Solutions)	Using this method, hard rock deposits (and associated ores) amenable to hydrometallurgical treatment are extracted by dissolving the valuable constituent in place and removing the pregnant solution through a borehole.	Major unsolved problems are noted in dealing with toxic or corrosive solvents used in enlarging fractures to provide a flow path for the solvent through the deposit and selectively extracting the desired metals in complex ores. Effects of accidental solvent spills would depend on the nature of the solvents and the sites affected. If the solvent is water soluble, effects should be localized because of rapid dilution and the buffering capacity of seawater.

Table 6.1. (Continued).

were office studies, while nearly 30% were based directly on field work, and 10% were based on laboratory studies. More than 20% of the sources evaluated did not specify which resource was affected; of those that did, three resource categories were prevalent, including biology (41%), water quality (35%), and geology (18%). Socioeconomics and air quality were identified in only 5% and <1% of the resource-specific citations, respectively. The bulk of the work appears to have centered on North American coastal biology.

Based on limited information available from actual operations, a general approach was used in **Section 2.5** in summarizing the environmental effects of marine mining in the deep ocean, the continental shelf, the coastal region, and where appropriate, onshore. Marine mining operations affect both natural resources (e.g., atmosphere, land, sea surface, water column, seabed, and all living things therein) and artificial resources which have been developed to suit human social needs (e.g., governance, commercial activities, technology, economics, and aesthetics). The direct or primary effects of marine mining on the environment may include (1) removal of the mined material; (2) introduction of new materials as processing wastes, tailings, and discharges, or of energy as heat, light, or seismic and acoustic waves; (3) perturbation or mixing at the seafloor due to the mining operation; and (4) subsequent replacement of mined material as waste, tailings, or discharges. These primary effects result in physical, chemical, and biological changes such as alteration of the shape or character of the seabed (e.g., leaving holes, mounds, or boulders; exposing new surfaces; or leaving garbage or lost hardware strewn about); changes in the quality of the air and water in the vicinity of the operation; and impacts on biological and other resources.

The key environmental concerns expressed in the literature have focused on air quality, water quality, seabed perturbations, biological resources, and socioeconomic resources (including commercial and recreational fisheries). These aspects form the basis of the summary discussion, but it is stressed that a reliable analysis of effects, or environmental impacts, of any mining operation must be based on commodity-specific, site-specific, and technology-specific information. A synopsis of findings for each resource affected is presented in **Table 6.2**.

Chapter 3 summarizes viable mitigation measures and their effects. Mitigation with respect to marine mining is potentially a subjective concept. For purposes of this analysis, mitigation is intended to make the effects of marine mining as harmless to the environment as possible. CEQ Regulations (40 CFR 1508.20) define mitigation to include (1) avoiding the impact all together by not taking a certain action or parts of an action; (2) minimizing impacts by limiting the degree or magnitude of the action and its implementation; (3) rectifying the impact by repairing, rehabilitating, or restoring the affected environment; (4) reducing or eliminating the impact over time by preservation and maintenance operations during the lifetime of the action; and/or (5) compensating for the impact by replacing or providing substitute resources or environments (U.S. Council on Environmental Quality 1978).

For the U.S., the mineral resources of the marine environment are managed in territorial waters by the adjacent States. In OCS waters, mineral resources are managed by the USDOI, MMS. In the seabeds beyond national jurisdiction, the USDOC, NOAA

Resource and Environment	Significant Findings	Salient References*
AIR QUALITY	Emissions of gaseous or particulate matter to the atmosphere are of greatest potential concern. Principle emissions are nitrous oxides and residual (reactive) organic compounds. During exploration and test mining, emissions are expected to have little effect on onshore air quality except offshore California where high background pollution already exists. Emissions from marine mining sources are expected to be qualitatively and quantitatively similar to oil and gas related sources. In the deep ocean, some gases might be released from seawater brought to the surface from the seabed via hydraulic dredging; information on this effect is sparse. Noise from non-explosive seismic exploration activity is generally dismissed as insignificant. In terms of global or regional effects of marine mining, there is only limited literature on this subject. Effects are generally examined on a site-specific level. No significant problems or priority areas for research are noted.	USDOI, MMS (1988b) OTEC publications
WATER QUALITY		
Natural Effects	In general, the natural effects of environmental change are easily recognized. Phenomena such as red tides, mega-plumes resulting from seabed hydrothermal activity, and storm- or earthquake-induced slides may result in significant but temporary changes in water quality.	
Induced Effects	Induced effects (e.g., turbidity, nutrient or trace metal enrichment) may result in secondary effects throughout the trophic web.	
Deep Ocean and OCS	Impacts are difficult to assess. The capacity for assimilation of plumes increases in deep water, however other factors (e.g., presence of a thermocline, low velocity benthic currents) may prolong the effects of plumes compared to shallow coastal waters. Effects should be examined on a site-specific basis. Dilution of a discharge to low concentrations is rapid (i.e., reduced to 1,000 ppm within 2 min of discharge; to 10 ppm within 1 h). The affected zone typically extends 1,000 to 2,000 m down current. Field studies of drilling muds and other discharges indicate that pollutants are rapidly reduced to background levels. Long-term, chronic effects of these discharges have not been observed. Mining discharges are subject to the same settling and dilution factors as oil and gas related discharges. Turbidity from resuspended sediments may be detected down current over many km; direct effects and indirect effects (e.g., nutrient or trace metal enrichment, increased biological or chemical oxygen demand) are limited to the immediate area of operations. Petroleum spills from marine mining activities would be limited to fuels (during transfer) and tanker loss.	Aurand and Mamontov (1982) Cruickshank et al. (1987) de Groot (1979b) Drinnan and Bliss (1986) ECOMAR (1983) Evans et al. (1982) Gillie and Kirk (1980) Hirsch et al. (1978) Middleditch (1981) Neff (1981, 1985) U.S. Congress, Office of Technol. Assess. (1987) Zippin (1988)
Coastal and Onshore	Marine mining would affect water circulation and water quality proportionally to the level of activity. Large stockpiles of marine minerals or mining wastes could be usefully maintained or disposed of at convenient sites near to shore; impacts from these activities can only be assessed by analysis of site-specific conditions. The shallow and confined nature of many coastal waters makes them susceptible to perturbation or pollutants. Turbidity is generally not considered a problem (e.g., sand and gravel mining operations are discontinuous; deposits rarely contain large amounts of silt-sized material). Good management practices are critical to eliminate potential impacts. A very low potential exists for release of chemicals normally associated with harbor and channel dredging (e.g., PCBs, trace metals).	U.S. Congress, Office of Technol. Assess. (1987)

Table 6.2. Summary of environmental effects of marine mining by resources affected.

Resource and Environment	Significant Findings	Salient References*
Terrestrial Sites	Impacts on water quality at shoreside facilities are attributed to gaseous, liquid, or solid waste emissions. Potentially serious problems include the dumping of mined tailings and processing wastes into adjacent waterways. The nature of the effect will be influenced by the characteristics of the dumped material, the nature of the waterway, and its ecosystem.	Ellis (1987, 1988, 1989) Ellis and Hoover (1990)
GEOLOGICAL RESOURCES	The primary effect is the removal of the ore; additional secondary effects may include alteration of the value of remaining mineral resources (grade depletion) and alteration of the seabed.	
Mineral	Mineral deposits removed by mining result in an irretrievable transfer of the mineral from a resource base to a consumptive use.	
Other	Major geologic impacts of marine mining result from activities in the coastal zone where wave energy is a prime factor. The effects of large excavations or shoaling resulting, for example, from the mining of mineral sands will depend on location. Changes in wave or current patterns induced by altered conditions can cause changes in shoreline equilibrium, causing erosion or deposition. Possible effects from sub-seabed fracturing using conventional or other type explosives are not well discussed in the literature; additional study and observation (i.e., in offshore areas susceptible to slumping, in deep water) was suggested. Coral reef growth may be severely affected by siltation, altering the supply of coral sands to adjacent beaches.	Chansang (1988)
BIOLOGICAL RESOURCES	Most biological impacts are secondary, attributed to some alteration in existing physical, chemical, or trophic equilibria. Impacts in the coastal zone have a greater tendency to be significant because of higher energy levels. Physical changes which may induce biological effects include changes in temperature, current patterns, amount of particulates present, nature of the substrate, and introduction of new habitats. Significant chemical changes include changes in the presence of nutrients, trace elements, or toxics. Trophic changes include removal or alteration of indigenous species. Biological impacts are the major enigma of impact assessment. Criteria upon which significant biological changes are based are typically arbitrary. Generalizations rarely allow meaningful prediction of the effects of specific mining operations. Biological studies should be directed on a case-by-case basis to respond to specific needs. Effects of turbidity, sedimentation, explosives, light, and noise on marine biota have been reviewed. Other data sources were noted from deep seabed mining, OCS oil and gas, and academic research.	Cruickshank et al. (1987)
Birds	Large oil spills which have the potential to kill numerous sea birds and shore birds are not anticipated from marine mining operations. Effects of small spills tend to be localized and short-lived.	USDOI, MMS (1983b, 1991)
Mammals	Effects of operations may include loss of feeding areas, uptake of heavy metals, and noise. Oil spills are not considered significant because of the low risk. Mining activities located away from known migratory pathways and calving or feeding grounds are unlikely to adversely affect marine mammal populations although individual transient animals near mining sites may be startled or show avoidance behavior. Limited research suggests habituation to low-level noise.	Gales (1982) Geraci and St. Aubin (1980) USDOC, NOAA (1981) USDOI, MMS (1983a,b)

Table 6.2. (Continued).

Resource and Environment	Significant Findings	Salient References*
Marine and Aquatic Fauna	Both adverse and beneficial impacts have been noted. Beneficial impacts include the attraction of fish to offshore structures; enhancement of substrate habitats by alteration of the texture; enhancement of substrate habitats by the presentation of new surface nutrients by mixing and replacement of the benthos; thermal stimulation by growth; introduction of nutrients by mixing of water masses; and enhancement of phytoplankton growth by increasing turbidity in ultra clear waters. Adverse effects include direct lethal toxic effects (e.g., abnormal growth, reduced adult fecundity, behavioral changes, etc.) and disruption of community and ecosystem structure (e.g., changes in diversity and abundance via food web disruption, changes in predator-prey relationships, etc.). Analyses of potential impacts requires a knowledge of the pre-operating populations and their natural cycles, allowing a differentiation between natural fluctuations and impact response. Adequate knowledge of pre-operating conditions (baseline) is debatable. Difficulties arise in the selection of indicator species. Effects of marine mining operations occur from turbidity, smothering, and pollutants (from mined formations). Turbidity effects may not be a concern if dilution rates are high and sensitive communities are not proximal to the mining site. Numerous studies have been conducted regarding the effects of turbidity on indigenous fauna, especially fishes. The exposure of free-floating organisms (e.g., plankton) to high turbidity concentrations will be limited. Turbidity impacts from aggregate dredging operations on sensitive benthic organisms will be far less than placer mining. Smothering of bottom dwelling organisms is due to the settlement of suspended sediments and associated depletion of oxygen in surrounding waters. Coral reefs and seagrass beds are particularly sensitive. Smothering is perceived as being of greatest concern in placer mining operations. Pollutants may affect growth and reproductive rates. The effects of pollutants on the physiology of marine fauna has received only limited study. Effects on marine phytoplankton are observed in response to decreased illumination in the laboratory, but these shading effects are not expected to be a problem in open waters. In the benthos, some species will likely be more affected than others because of feeding mode (filter feeders), life habit (surface dwellers), degree of mobility (tube dwellers), or sensitivity of life stage (larvae). Areas that may not be able to withstand slight increases in sediment deposition include coral reefs and areas used by bottom spawning fish. In cases where a majority of the benthic community has been adversely affected, recolonization will occur from populations outside the disturbed area. Benthic organisms may serve as indicators of pollutants and the structure of the benthic community may be indicative of a stressed or disturbed environment.	Aurand and Mamontov (1982) Bigham et al. (1982) Blaxter (1980) Chan and Anderson (1981) Clark (1988) Cressard (1981) Cressard and Augris (1982) Cruickshank (1974a,b; 1987) Dawson (1984) de Groot (1979a,b) Drinnan and Bliss (1986) Ellis and Hoover (1990) Gillie and Kirk (1980) Glasby (1985) Hanson et al. (1982) Hirota (1981) Hu (1981) ICES (1979) Kawamura and Hara (1980) Levin (1984) Lunz et al. (1984) Matsumoto (1984) NRC (1985) Pfitzenmeyer (1970) U.S. Army Engineer District (1974; California Department of Fish and Game 1977) U.S. Congress, Office of Technol. Assess. (1987) United Nations (1981) USDOC, NOAA (1981) USDOI, MMS (1988b)
Flora	Effects on flora are not regarded as a major concern.	
Sensitive Habitats	In sensitive areas (e.g., Arctic waters), particularly in shallow water, or in the deep seabeds, slow regrowth of affected communities is expected. Areas of hydrothermal venting along mid-ocean ridge crests support unusual benthic colonies. Draft regulations have provided for avoidance of such environments.	Dunton et al. (1982) USDOC, NOAA (1981) USDOI, MMS (1983a)

Table 6.2. (Continued).

Resource and Environment	Significant Findings	Salient References*
Threatened and Endangered Species	Impacts were discussed under respective biotic resource categories. Impacts are associated with noise (marine mammals, birds), accidental oil or fuel spills, and increased turbidity.	
SOCIAL AND ECONOMIC RESOURCES	Most actions resulting in environmental query are triggered on the basis of some social or economic need. Such aspects are built into the scoping process for respective environmental documents. The literature is voluminous and scattered.	
Human Resources	Effects on human resources include health, employment, and infrastructural needs. For processing plants and mining operations conducted from platforms or seabed mining operations carried out in the hard rock, extended periods of relative isolation create impacts on mining personnel. The social environment is extremely variable and widely described, but not specifically for marine mining. Disturbances must be weighed against benefits. The ranking of multiple uses is potentially highly subjective. From a legal perspective, national laws are not adequate for many minerals and international laws regarding the mining of the seafloor are still not well-defined. In many instances, national and international laws have lagged behind rapid social change. Several aspects have a significant effect on planning and conduct of operations, including the exhaustible nature of mineral resources, resource conservation, and multiple uses of mineralized areas.	USDOI, MMS (1988a,b)
Commercial and Recreational Fisheries	Literature from Europe is more extensive on this subject than in the U.S. Modern European prospecting operations cause little disturbance to the marine environment and do not interfere with other activities at sea; no formal government consultations procedure exists for a prospecting license, however, the permitting process is substantive. As a resource, standing fishery stocks are affected by various factors (e.g., turbidity, pollutant loading, physical disturbance). Direct effects of oil or turbidity are limited due to the mobility of fish. Indirect effects include damage to eggs, larvae, and juveniles; sublethal uptake of hydrocarbons and pollutants; loss of prey; loss of habitat; and reduced reproductive success. Marine mineral activities may interfere with fishing activities and compete for space at sea and in port. Space use conflicts between fishermen and vessel operators have occurred with entanglement or severing of net and trap lines. Coordination efforts between the two industries have helped avoid most vessel conflicts. Recent research interest has included assessment of the potential for marine geophysical surveys to reduce catchability of fish and damage to fish eggs and larvae. Long duration, spatially concentrated use of seismic energy sources can disturb the spatial distribution of fish in the water column and reduce catchability. It is expected that there has been some loss of individual income through lost catch opportunity or gear loss and increased cost of port space.	Nunny and Chillingworth (1986) Pasho (1986) Zippin (1988)
Regional Economies	Impacts from resource disturbance will be measurable on the economy. The extent of the economic impact resulting from a given action is affected by various factors. A determination of a prospect's feasibility must consider the net rate of return on the investment.	Sorensen and Mead (1969)
Local Economies	Local economies are site-specific, driven by many factors.	

Table 6.2. (Continued).

Resource and Environment	Significant Findings	Salient References*
Cultural Resources	Effects are particularly difficult to quantify because intangible cultural systems are subject to the historical and contemporary changes induced by all human activities. A comparison of alternatives using semi-quantitative methods of factor analysis might be valid. Archeological resources may be significant and should be protected.	Cruickshank (1974a)
Technical Resources	Major impacts on technology appear in the form of disturbances to the system due to *materials failure* primarily effected by motion, pressure, corrosion, and biological fouling. Impacts on the environment are relatively small.	

* - Salient references indicate key sources; several reference listings (e.g., **Marine and Aquatic Fauna**) have been pared, given tabular space constraints.

Table 6.2. (Continued).

retains primary management responsibility within the U.S. Federal Government. In OCS waters, the USDOI operates under the sometimes conflicting authority of 35 Federal laws, 24 of which are applicable to operations for minerals other than oil and gas. Environmental issues have been an important and contentious element in OCS leasing policy since the time of the Santa Barbara oil spill in 1969. Even for minerals other than oil and gas, this air of controversy has affected the stance of policy makers for marine minerals development at the State, national, and international levels. In attempting to institutionalize the management needs for marine minerals, however, the assignment of specific weights to environmental risks is extremely difficult, particularly for an industry in the early stages of development.

To deal with these factors in a productive way, the USDOI has assigned regulatory controls to be applied on a case-by-case basis. The type of risk that might be applicable to mining development includes effects on air and water quality, interference with natural shoreline processes, alteration of habitats and species distributions, and conflicts with fishing, recreation, or other commercial activities. The mitigation of these risks or effects by the application of optimal engineering design, generally referred to as internal costs, can be reasonably calculated. However, if the effect is imposed on others such as fishermen, recreational boaters, or other categorical opponents, with or without compensation of some kind, the cost becomes an external cost and is difficult to assess.

This analysis has focused on one of the most important mitigation measures possible, the acquisition and promulgation of facts concerning the marine minerals environment and the effects of mining. Whereas mitigation itself is specific to specific operations in specific environments, the form of the mitigation is strongly influenced by institutional procedures and perceptions. These "institutional" aspects of mitigation are discussed at some length in **Section 3.1**, while **Section 3.2** outlines some of the important aspects of actual mitigation measures which have been proposed or implemented. A summary of potential mitigation measures is presented in **Table 6.3** on the basis of resources affected.

Chapter 4 addresses the state-of-the-art and use of mathematical models to predict impacts resulting from marine mining activities. Models for the portrayal of natural dynamic functions have been widely used in forecasting and predicting events and effects. The advent of powerful desktop computers has made these previously expensive tools available to a wide range of users. For the purposes of this analysis, the use of models in marine mining environmental analyses has been limited to the study of physical dispersion through the water column and sedimentation on the seabed. Air emission, chemical transformation, and demographic processes were considered too site-specific to warrant useful consideration in this analysis. Although numerous sediment transport and dispersion models have been devised in recent years, most testing has been via computer simulation. Useful field testing of dispersion models has been limited to less than a dozen separate efforts. Despite these efforts, the predictive capabilities of the present generation of dispersion models is still limited, due to insufficient testing/tuning and the inability to include enough important parameters in sufficient detail to afford accurate predictive results. Typically, the effects of unusual bathymetry cannot be accounted for; only relatively simple flow fields can be accommodated; and the influences of complex shorelines can only

Resource and Environment	Significant Findings
AIR QUALITY	Air quality issues tend to be site-specific. Available environmental assessments of marine mining conclude that air quality effects are not expected to be significant except offshore California. Major exceptions to this conclusion are related to power generation and pyrometallurgical processing. With respect to power generation, the recovery and processing of both marine and terrestrial ores is considered very similar. Primary recovery in a marine setting might require more combustion energy than recovery of terrestrial ores, however, subsequent marine transportation can be expected to be significantly more efficient and less polluting than over-land transportation. In metallurgical processing, the type of ore being recovered is much more important than whether or not the ore is recovered from a marine or terrestrial deposit. Oxide ores can be expected to require more energy to process than sulfide ores; processing of sulfides may also produce acid rain, whereas oxides will not. Air quality effects for marine mining activities in the deep oceans and OCS are not expected to be significant or to require any special mitigation. The site-specific nature of coastal activities precludes the reasonable evaluation of mitigation options, particularly for air quality effects. The available environmental assessments of marine mining proposals (USDOC, NOAA 1981; USDOI, MMS 1983a,b; USDOI, MMS and HI, DBED 1990; USDOI, MMS 1991) universally conclude that offshore activities in coastal areas are not expected to cause significant effects on air quality and would not require mitigation beyond existing regulatory controls. Because the bulk of the power consumption and air emissions for marine mining will be caused by metallurgical processing, and because all currently proposed marine mining ventures would require onshore processing, air quality effects can be expected to be most acute in this region.
WATER QUALITY	In environmental assessments of deep seabed mining (USDOC, NOAA 1981; USDOI, MMS and HI, DBED 1990), the potential for mitigation of effects from mine ship discharges have been considered in detail. Subsurface discharge of deep sea or OCS mine tailings is a cost-effective means of eliminating potential effects on the habitats in the surface photic zone. Turbulence and high oxygen levels in surface waters would ensure rapid dispersal and stabilization of discharges; plankton play a role in encapsulation and sedimentation of fine-grained materials. Significant efforts have been made, particularly in Europe and Japan, to develop coastal mining systems with minimum generation of turbidity and generally minimum impacts on water quality. The area affected by plume sedimentation can be reduced by subsurface discharge or other techniques that force the particulate material to settle close to its source; this approach also creates a heavier accumulation of discharge material in a smaller area. Appropriate sedimentation pattern and appropriate disposal methods will depend upon the characteristics of the site, including the biota. Other mitigation methods include (1) a system to return turbid water overflow from the dredge hopper to the dredge intake; (2) use of silt curtains to contain the plume within a specified area; (3) return of overflow waste to the seafloor (i.e., shunting); (4) closing the upper side of the bucket ladder on a bucket ladder dredge, reducing the mid-water and surface turbidity plume; (5) enclosing individual dredge buckets; (6) application of an anti-turbidity overflow system (ATOS), removing air bubbles from the overflow of a hopper dredge; (7) selection of the most appropriate dredging system for the site; (8) imposition of daily or annual limits on the quantity of dredged material; (9) limiting the number of vessels or operations in given areas; and (10) prohibitions on overboard disposal of equipment.
GEOLOGICAL RESOURCES	Geological resources affected include the mined material and the seabed from which the mined material is removed. In the case of high value materials (i.e., gold or platinum), the volume of material removed is insignificant. Local hydrodynamic conditions and the type of deposit being mined must be taken into account when establishing a minimum water depth for dredging in order to avoid the possibility of coastal erosion. Large excavations can also lead to coastal erosion if the wave patterns and sediment movements are sufficiently changed nearshore. U.S. regulations are being developed. In Britain, coastal dredging reportedly causes no problems in water depths greater than half the normal wave length or more than one-fifth the length of extreme waves. The use of marine mining for sand and gravel production eliminates the scarring of onshore environments due to quarrying. Further, unsightly and unsafe operations with major dust, noise, and traffic problems are alleviated (Fischer 1988).

Table 6.3. Summary of marine mining mitigation measures by resources affected.

Resource and Environment	Significant Findings
BIOLOGICAL RESOURCES	
Birds	Significant effects of marine mining activities on birds have not been identified in the available literature. No mitigation measures were identified.
Marine Mammals	Collisions with marine mammals and alteration of migratory patterns (via noise in the water column) have been identified as potential effects. Collision could be eliminated or significantly minimized by requiring or encouraging reduced boat speeds in areas of known or suspected concentrations of marine mammals or sightings. Reduction of noise of the primary recovery and ore-lift operations could be considered to mitigate the second type of effect if quantitative information about the actual sensitivities of the marine mammals involved could be determined.
Marine and Aquatic Fauna	Effects on neuston, phytoplankton, zooplankton, fish, and other water column organisms are directly dependent upon water quality. Consideration of mitigation options for effects on these populations is reduced to the mitigation of water quality effects. In the development of deep seabed sulfide deposits and manganese nodule and crust deposits, several mitigation options are possible to minimize the effects of mining on benthic habitats. Mitigation methods include (1) maximizing the dispersal of suspended particles to minimize benthic smothering; (2) mining in a discontinuous fashion, leaving small patches within mine sites unmined; and (3) exclusion of large areas which contain potentially unique populations (e.g., hydrothermal vent communities). For coastal mines, many opportunistic species can colonize tailings; colonization is variable from year to year and encompasses a range of different species, most of which are deposit feeders. Problems with ongoing bottom fisheries can be avoided through management practices that do not allow the use of stationary dredges in areas where bottom trawling, bottom scallop dragging, or clam raking is normally practiced. In situations where exposure of silts and clays is a concern, it may be necessary to require that the bottom portion of the layer being mined be left in place to minimize such change. Some form of seabed fertilization by organic sludge could facilitate reclamation of undersea tailings beds.
Sensitive Habitats	For water column habitats in general, the rapid and effective dispersive processes virtually eliminate the possibility of special, sensitive habitats. Possible exceptions include neuston layers, where significant populations of sensitive larvae can congregate, and confined straits and other waterways which form migratory pathways. Mitigation of possible effects on these habitats will generally consist of avoidance (through restriction of the activities) or through modification of the activities, such as subsurface discharges. Probably the most serious limitation on the evaluation and mitigation of effects on sensitive habitats in deep seabed environments is a general lack of knowledge regarding the deep sea benthos. In nearshore environments, materials in the water column can be transported downstream, affecting coastal benthic communities. Coral reefs, mating and spawning shoals and beaches, and sensitive estuarine habitats are particularly sensitive; mitigation measures, if feasible, must be developed on a site-specific basis.
Threatened and Endangered Species	Within available environmental impact statements for proposed mining (USDOC, NOAA 1981; USDOI, MMS 1983a,b; USDOI, MMS and HI, DBED 1990; USDOI, MMS 1991), regulatory agencies have undertaken extensive examination of effects to threatened and endangered species. Specific areas have been removed from consideration where possibly significant effects could result. No other forms of mitigation which specifically address threatened and endangered species have been identified.

Table 6.3. (Continued).

Resource and Environment	Significant Findings
SOCIAL AND ECONOMIC RESOURCES	
Human Resources	Effects in this category are confined to issues which deal with human health and safety. Most issues are too site-specific for a rational discussion of general mitigation options. Safety is an important issue in every aspect of the operation, while health issues are focused on perceived or actual threats to public health through effects on air or water quality or through the generation of excessive noise. Mitigation of air and water quality effects has been discussed previously. In bucket ladder dredging operations, it has been suggested that noise can be reduced by hanging rubber mats over the ladder wellway.
Commercial and Recreational Fisheries	Most of the potential problems related to social and economic environments would be site-specific and concerned with onshore processing facilities. A key area of possible conflict is related to commercial and recreational fisheries. Most current development strategies are biased toward the development of sustainable and renewable resources rather than non-renewable resources, and marine mining interests must be prepared to avoid any potential conflicts with fishing interests in operational areas or prove that such operations will not jeopardize ongoing or anticipated fishing activities. Mitigation measures include (1) active solicitation of inputs from the pertinent fishing industry representatives early in the planning process for marine mineral development; (2) possible use of abutting dredging tracks to obtain an unobstructed seabed and minimize creation of mounds, trenches, and pits; and (3) use of trailing, rather than anchored, suction dredges in bottom fishery areas.
Regional and Local Economies	Marine mining ventures have the potential to affect regional and local economies, both positively and negatively. General strategies to mitigate the negative effects include (1) job discrimination in favor of local residents and associated training populations to implement such discrimination; (2) process plant location in areas with maximum development to avoid large influxes of new residents in predominantly rural areas (as well as to take advantage of existing infrastructure); and (3) local requirements for the establishment of infrastructure when necessary. Such measures have been implemented with varying degrees of success. Eventual success depends on thorough planning and detailed interfacing with existing authorities and public interest groups.
Cultural Considerations	Land-based operations devoted to the development of marine minerals must be implemented with particular consideration given to the unique mores and traditions of the local population. For operations in presently underdeveloped or undeveloped areas, careful accommodation must be made to permit the introduction of what may be perceived as a radical changes in lifestyle. Local cultures and attitudes are of primary importance in the consideration of land-based operations sites. Further, extensive public education and outreach efforts, though necessary, may not be sufficient to overcome potentially fatal opposition to development.

Table 6.3. (Continued).

crudely be considered. The effects of turbulence on various length scales further complicates the modeling process. The use of eddy diffusivity coefficients which crudely describe complex flows does not provide good near-field predictive capability. Finite element models, with their variable gridding capabilities, are expected to play a greater modeling role in future efforts.

Near-field predictive capability is relatively good in close proximity to a discharge or sediment dump location, (i.e., before the full effects of the turbulent flow field occur). Within even a few hundred meters of a discharge, the ability to predict concentrations within an order of magnitude at any particular location becomes limited. If, however, average concentrations are considered within bounded regions increasing in size with increasing distance from the discharge, predictive capability is improved.

Testing of far-field predictive capabilities of dispersion models has been hampered by numerous difficulties, including the need for large numbers of measurements over large spatial and temporal scales. Plumes of suspended material originating from human activity have not been effectively generated on large scales for the purposes of testing dispersion models. The effects of large-scale natural phenomena (e.g., continental rivers, oceanic rivers such as the Gulf Stream, and other mixing processes) have been extensively studied, and provide better source material for empirical far-field studies. Far-field predictive capabilities of sediment transport models are rather poor, with predictive capability degrading with increasing distance from the source. What is considered far-field depends on the context. For typical regional water quality concerns, distances exceeding 15 km are clearly considered far-field. At such distances, with present day models, prediction of concentrations within one to two orders of magnitude is difficult at any chosen location. The development and refinement of water quality criteria and standards for distances greater than 15 km from a discharge will have to be undertaken with considerable caution if reasonable expectations for measurement and compliance are to be met.

The continued development and testing of mathematical models, especially those predicting suspended sediment and dispersion characteristics through the use of finite-element modeling methods, will improve predictive capabilities. Based on the present analysis, it is feasible that reasonable predictions can be made in the near future for certain classes of materials at distances of regional concern.

Chapter 5 addresses data gaps, research needs, and recommendations in those areas where environmental studies have been described in the literature or where the authors have personal knowledge. Discussion focuses on the gaps still apparent in the data and information available from the published literature, and presents recommendations for further work including field studies. There are significant data gaps in the U.S. knowledge base, as indicated by the literature in areas concerning (1) water quality modeling (i.e., the generation and dispersion of particulate and dissolved materials in the water column based on, or at least confirmed by, empirical data acquired from marine mining operations); (2) effects of significant alterations of the seabed on adjacent coastlines; (3) understanding of the characteristics, behavior, and recolonization response of mine site benthos in the deep seabed and in other specific sites (e.g., seamounts and guyots); (4) understanding of the characteristics and behavior of OCS and coastal mine site fauna under the stress of production operations, and subsequent recolonization responses; (5) impacts of processing discharges from onshore mines on coastal biota; and (6) understanding the realities of mining in perspective with other natural processes and man-induced activities. Other less significant areas of concern that may not yet have been adequately addressed by research activities have been presented under the respective headings of air quality, water quality, geological resources, biological resources, and socioeconomic concerns.

Substantive principles for resolving marine use conflicts have not been developed by the courts under the public trust doctrine. Related judicial approaches legally separating exploration rights from development rights aids the resolution of marine use management conflicts significantly. These legal approaches to mitigation are of concern to the MMS and should be considered appropriately.

Extensive mathematical and computer programming efforts have been made to predict the dispersive behavior of discharged materials in marine environments. Adequate mathematical and computer-based tools are available. Unfortunately at this time, sufficient field efforts have not been completed to confirm these tools and to adequately discriminate among them.

Priorities for individual research needs at the project level are very subjective. In the long term, however, the authors believe that two major data gaps should be addressed concurrently as a first priority: (1) the verification of very extensive models that have been developed for plume dispersion; and (2) the opportunity to utilize ongoing operations in areas outside of the U.S. to verify existing models and to develop a database on other environmental needs determined from actual mining operations.

A considerable amount of useful data are available with regard to the environmental effects of marine mining. An adequate collation of these data, particularly in the foreign grey literature has not been possible within the constraints of the present study. At present, there is no global database directed to address these matters. New data are needed to address many specific aspects of concern. In many cases, such data could be acquired at low cost in cooperation with foreign governments and operators. Economic decisions on marine minerals development may be based on the perceived cost of overcoming implied environmental effects which are defined on the basis of supposition rather than measurement. The acquisition of data and information to verify such conceptual models is of the highest importance.

CHAPTER 7 LITERATURE CITED

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APPENDIX A

ANNOTATED BIBLIOGRAPHY

Appendix A serves as the Annotated Bibliography for the Final Report titled "Synthesis and Analysis of Existing Information Regarding Environmental Effects of Marine Mining." The Annotated Bibliography was prepared by Continental Shelf Associates, Inc. (CSA) for the Minerals Management Service (MMS) under Contract No. 14-35-0001-30588.

As described in **Section 1.3.1** of the Final Report, the information collection and annotation phase of the program had two primary goals: (1) to provide literature and data to be considered for inclusion in respective chapters of the manuscript; and (2) to produce an annotated bibliography to be included in the manuscript. The term "Annotated Bibliography" encompasses the reference citations and reference description forms, both of which are discussed in the following text.

Reference citations to be annotated were selected based upon discussions between CSA and the MMS. Citations from the master list of documents referred to in the manuscript (i.e., **Chapter 7**, Literature Cited) were reviewed and prioritized. Pertinent citations concerning potential impacts to various components of the environment were chosen for annotation. In most cases, citations concerning technology, policy, mitigation, and models were not considered as priority items for annotation.

Each annotation was completed on a standard reference description form (see **Figure 1.4** of the Final Report). Each standard reference description form included information entry headers as given at the bottom of this page. Annotation data from the standard reference description form were entered onto CSA's computer system. A printout of this information is provided on the following pages as **Appendix A**.

The Reference Database is the electronic version of the Annotated Bibliography. The Reference Database was prepared in dBASE III PLUS format and submitted separately to the MMS. The Reference Database differs from the Annotated Bibliography in **Appendix A** only in that the information entry headers were abbreviated and capitalized for compatability with the dBASE III PLUS format. The 13 information entry headers for the Annotated Bibliography and the Reference Database are as follows:

Annotated Bibliography	**Reference Database**
Entry Number	ENTRY_NO
Citation	CITATION
Type(s) of Study	STUDY_TYPE
Geographic Location(s)	LOCATIONS
OCS Planning Area(s)	OCS_P_AREA
Type(s) of Environment(s)	ENVIRON
Mineral(s)	MINERALS
Type(s) of Mining Operation(s)	MINING_OPS
Environmental Resource(s)	RESOURCES
Date(s) of Study	STUDY_DATE
Study Technique(s)	TECHNIQUES
Conclusion(s)	CONCLUSION
Key Words	KEY_WORDS

Entry Number: 0001.

Citation: AECOS, Inc. 1986. *Supplemental biological studies made during ferromanganese crust resource assessment cruises in the Hawaiian Islands EEZ and their application to an environmental assessment of ocean mining operations.* Report prepared for the U.S. Department of the Interior, Minerals Management Service, and the State of Hawaii.

Type(s) of Study: Field.

Geographic Location(s): Hawaii, United States.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Deep seabed.

Mineral(s): Metalliferous oxides

Type(s) of Mining Operation(s): Scraping.

Environmental Resource(s): Benthos; Birds; Marine mammals.

Date(s) of Study: 12 July to 9 September 1984.

Study Technique(s): Biological data were acquired during geological survey cruises by the R/V KANA KEOKI. Over a one-hour period each day, counts of seabirds by species were conducted within a quadrant having a radius of approximately 100 m from the ship. Counts were done over a 5-min period every 15 min. Benthic specimens from deep sea sites were also collected whenever geological samples were taken. Samples were preserved in formalin and sorted, identified, and counted in the laboratory. Color stereo photographs were taken of the seafloor and examined for organisms. Densities and percent cover estimates were derived from the photographs.

Conclusion(s): Terns, shearwaters, albatrosses, tropic birds, noddys, and boobys were observed. Sightings ranged from 0 to 2 birds per day during three cruises. Benthic samples included coelenterates, echinoderms, mollusks, sponges, annelids, and bryozoans. Samples were dominated by octocorals in terms of numbers of species and biomass. A negative correlation was reported between numbers of species and the depth from which the sample was collected. Due to the quality of the photography, it was difficult relating dredge data to the presence or abundance of benthic species. The same phyla reported from the dredge samples were identified in the photographs, however, taxonomic confirmation was uncertain. The potential impact of ocean mining for ferromanganese minerals on biological resources was discussed.

Key Words: Metalliferous oxides; Scraping; Benthos; Birds; Marine mammals.

Entry Number: 0002.

Citation: Amos, A. F., C. Garside, K. C. Haines, and O. A. Roels. 1972. Effects of surface-discharged deep sea mining effluent. *Mar. Technol. Soc. J.* 6:40-46.

Type(s) of Study: Field; Laboratory.

Geographic Location(s): Blake Plateau, North Atlantic Ocean.

OCS Planning Area(s): South Atlantic.

Type(s) of Environment(s): Deep seabed.

Mineral(s): Metalliferous oxides.

Type(s) of Mining Operation(s): Scraping.

Environmental Resource(s): Geology; Water quality; Plankton.

Date(s) of Study: Summer 1970.

Study Technique(s): The effect of deep sea mining effluent discharge on the surface waters of the North Atlantic Ocean was studied in the field. Dye studies were conducted to determine the rate of dispersion of the discharged water. Samples of the discharged water were incubated in the laboratory to study oxygen and nutrient dynamics. Incubations of filtered and unfiltered samples from the deep sea effluent were used to determine its effects on phytoplankton production. The stimulatory effects of discharge water on natural and cultured phytoplankters were also studied.

Conclusion(s): Discharged deep sea effluent water did not show significant impacts on surface water quality under the conditions of the study. Results of dye tracking indicated that the discharged water remained within the euphotic zone. After four hours, the dye patch remained within the upper 10 m of surface waters. Laboratory incubation experiments indicated that phytoplankton growth utilized 95% of the nutrients contained within discharged water. Experiments also showed that the organic material contained in the discharge water was readily oxidized. Deep sea effluent stimulated phytoplankton production due to its nutrient content. Production in the cultured phytoplankton was greater than in natural phytoplankton incubations. The sediment contained in the discharge increased primary production by an order of magnitude, however the precise mechanism prompting this increase remains unclear. Laboratory experiments indicated that at least 10% of the surface water must be composed of deep sea effluent for phytoplankton production to be increased.

Key Words: Metalliferous oxides; Scraping; Geology; Water quality; Plankton.

Entry Number: 0003.

Citation: Bak, R. P. M. 1978. Lethal and sublethal effects of dredging on reef corals. *Mar. Pollut. Bull.* 9(1):14-16.

Type(s) of Study: Field.

Geographic Location(s): Piscadera Bay, Curacao, Netherlands Antilles.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Coastal.

Mineral(s): Industrial minerals.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Water quality; Benthos; Sensitive habitats.

Date(s) of Study: Summer 1972.

Study Technique(s): The effects of dredging activities on a coral reef were studied. The study site was located 700 m from the dredging area at a depth of 12 to 13 m. Underwater light measurements were made at the coral reef prior to the dredging to determine initial light levels at depth. Observations were made on the survival and growth of the hermatypic (reef-building) corals.

Conclusion(s): Prior to dredging, the light value at depth (i.e., 12 to 13 m) was equivalent to 30% of the surface value. After the dredging occurred, light levels were reduced to 1% of surface values. A layer of sediment more than 1 cm thick covered most of the reef except for the corals which had an ability to reject the sediment. The sediment caused lethal and sublethal effects on the coral reef. Colonies of *Porites asteroides* died due to their inability to reject sediment. Some species, such as *Agaricia agaricites* and *Colpophyla natans*, exhibited areas where sediment collected. Two species of hermatypic coral which were the subject of growth studies (*Madracis mirabilis*, *Agaricia agaricites*) showed an acute decrease in growth as measured by calcification rates. Sediment-induced stress due to dredging caused a 33% reduction in growth. Reduction in growth was thought to be due to metabolic shock from the expulsion of the symbiotic algae (zooxanthellae) found in the tissues of hermatypic corals. The study also reported that the reduction in growth continued after the sediment deposition on the corals had ceased.

Key Words: Industrial minerals; Scraping; Excavating; Water quality; Benthos; Sensitive habitats.

Entry Number: 0004.

Citation: Barry, M. 1978. Behavioral response of yellowfin tuna, *Thunnus albacares* and Kawakawa, *Euthynnus affinis,* to turbidity. Deep ocean mining environmental study (DOMES). Unpublished manuscript number 31. Seattle, WA: U.S. Department of Commerce, National Oceanic and Atmospheric Administration. NTIS No. PB-297 106.

Type(s) of Study: Laboratory.

Geographic Location(s): Not applicable.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Deep seabed; Continental shelf; Coastal.

Mineral(s): Industrial minerals; Mineral sands; Phosphorites; Metalliferous oxides; Hydrothermal deposits; Dissolved minerals.

Type(s) of Mining Operation(s): Scraping; Excavating; Tunneling; Fluidizing.

Environmental Resource(s): Water quality; Nekton; Commercial and recreational fisheries; Local economies.

Date(s) of Study: Unavailable.

Study Technique(s): Two species of tunas (*Thunnus albacares, Euthynnus affinis*) were held in large outdoor tanks to determine behavioral response to turbidity. The tanks had a continuous flow of low turbidity seawater. Under a variety of conditions (day, night, hungry, feeding, satiated, and with and without barriers), the tunas were subjected to a regulated series of turbidity clouds made from deep sea mud or pure bentonite clay. Behavioral changes and reactions of the tunas to the sediment clouds were carefully noted.

Conclusion(s): The tunas were able to detect turbidity clouds in the test tanks and made efforts to avoid them. The tunas were better at avoiding turbidity clouds during the day than at night. Turbidity clouds significantly altered the behavior of the tunas. Vision appeared to play the major role in avoiding turbidity, though smell may have been important at low levels. The tunas responded more to the visual qualities of the sediment clouds than to the concentrations of suspended material. Responses of both species were very similar.

Key Words: Industrial minerals; Mineral sands; Phosphorites; Metalliferous oxides; Hydrothermal deposits; Dissolved minerals; Scraping; Excavating; Tunneling; Fluidizing; Water quality; Nekton; Commercial and recreational fisheries; Local economies.

Entry Number: 0005.

Citation: Bigham, G., T. Ginn, A. M. Soldate, and L. McCrone. 1982. *Evaluation of ocean disposal of manganese nodule processing waste and environmental considerations*. Final report prepared for the U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Office of Ocean Minerals and Energy, and U.S. Environmental Protection Agency, Ocean Programs Branch, Criteria and Standards Division, 423. Seattle, WA: Tetra Tech, Inc.

Type(s) of Study: Review.

Geographic Location(s): Hawaii, United States; Pacific Northwest, United States; Southern California Bight, United States; Western Gulf of Mexico.

OCS Planning Area(s): Western Gulf of Mexico; Southern California; Washington-Oregon.

Type(s) of Environment(s): Deep seabed; Continental shelf; Coastal.

Mineral(s): Metalliferous oxides.

Type(s) of Mining Operation(s): Scraping.

Environmental Resource(s): Water quality; Neuston; Plankton; Nekton; Benthos; Marine mammals; Threatened and endangered species; Sensitive habitats; Commercial and recreational fisheries.

Date(s) of Study: Not applicable.

Study Technique(s): This document reviews the characteristics of ocean waste disposal associated with the processing of manganese nodules, their potential environmental effects, and the regulatory framework surrounding the process. Technologies concerning manganese nodule processing and waste streams were described. Characteristics of representative disposal areas were examined.

Conclusion(s): The primary waste from nodule processing will be 1) leached residue or rejects from the hydrometallurgical processing; and 2) granulated slag from smelting. Nearshore waste disposal was projected to be primarily by barge dumping or pipeline discharge. Simplified models were used to predict the behavior of the reject stream from a barge dump. The use of pumps to discharge the reject slurry to depths below the euphotic zone was recommended for maximum containment. Compaction of the waste material into blocks to be dumped nearshore (e.g., forming artificial reefs) was also examined. Depending on the specific disposal method, volume of the waste stream, and site characteristics, the potential environmental effects include 1) effects on primary production; 2) direct toxic effects; 3) effects on behavior and feeding of marine organisms; 4) bioaccumulation; and 5) intertrophic effects. Open ocean disposal was reported as the option with the lowest environmental significance.

Key Words: Metalliferous oxides; Scraping; Water quality; Neuston; Plankton; Nekton; Benthos; Marine mammals; Threatened and endangered species; Sensitive habitats; Commercial and recreational fisheries.

Entry Number: 0006

Citation: Blaxter, J. H. S. 1980. Vision and the feeding of fishes. In *Fish Behavior and Its Use in the Capture and Culture of Fishes*, eds. J. E. Bardach, J. J. Magnuson, R. C. May, and J. M. Reinhart, 32-56. *Proceedings, International Center for Living Aquatic Resources Management*. Manila, Phillipines.

Type(s) of Study: Review.

Geographic Location(s): Worldwide.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Deep seabed; Continental shelf; Coastal; Estuarine; Freshwater.

Mineral(s): Industrial minerals; Mineral sands; Phosphorites; Metalliferous oxides; Hydrothermal deposits; Dissolved minerals.

Type(s) of Mining Operation(s): Scraping; Excavating; Tunneling; Fluidizing.

Environmental Resource(s): Water quality; Nekton; Commercial and recreational fisheries; Local economies.

Date(s) of Study: Not applicable.

Study Technique(s): Scientific literature concerning the role and characteristics of vision in sight-feeding fish was reviewed and findings compared, contrasted, and discussed. Special attention was given to vision thresholds, visual fields, visual axis, acuity and contrast perception, prey conspicuousness, and water volumes searched for food.

Conclusion(s): As light levels, water clarity, and size of fish decreased, negative impacts on vision and feeding in fish increased. In turbid water, larger fish had advantages over smaller fish.

Key Words: Industrial minerals; Mineral sands; Phosphorites; Metalliferous oxides; Hydrothermal deposits; Dissolved minerals; Scraping; Excavating; Tunneling; Fluidizing; Water quality; Nekton; Commercial and recreational fisheries; Local economies.

Entry Number: 0007.

Citation: Boehmer, R., A. Westneat, H. Sleight, and D. Cook. 1975. Effects of suspended marine sediments on selected commercially-valuable fish and shellfish of Massachusetts. In *Proceedings, Seventh Annual Offshore Technology Conference*, 133-141.

Type(s) of Study: Laboratory.

Geographic Location(s): Not applicable.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Continental shelf; Coastal.

Mineral(s): Industrial minerals.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Water quality; Plankton; Nekton; Benthos; Commercial and recreational fisheries.

Date(s) of Study: Unavailable.

Study Technique(s): This study evaluated the effects of resuspended marine sediments on commercially valuable fish and shellfish that may be affected by offshore sand and gravel mining. A bioassay approach was used to determine tolerance of test organisms to resuspended sediments. Tests were conducted using adult shellfish and finfish and larval stages of selected species. Species tested included silversides, white flounder, yellowtail flounder, hake, menhaden, coho salmon, bay scallop, sea scallop, quahog, soft shell clam, oyster, lobster, and the larvae of bay scallop, quahog, and oyster.

Conclusion(s): Finfish were most affected by the sediment. Toxicity increased with the concentration of sediment and length of exposure, particularly with the coho salmon and silversides. Lobster were relatively tolerant although a molting lobster died during the test. Adult quahog, soft shell clam, and oyster were found to be very tolerant of the sediment for a period of several days. Clear differences were not observed between susceptibility of adult and larvae of the quahog and oyster. Adult bay scallop were very susceptible although their larvae were more tolerant. Study results suggested that most of the tested species exhibit some tolerance to short-term exposure to sediment. However, the specific impact of offshore sand and gravel mining still requires further evaluation.

Key Words: Industrial minerals; Scraping; Excavating; Water quality; Plankton; Nekton; Benthos; Commercial and recreational fisheries.

Entry Number: *0008.*

Citation: Bouma, A. H., ed. 1976. *Shell dredging and its influence on Gulf coast environments*. Houston, TX: Gulf Publishing Company.

Type(s) of Study: Review.

Geographic Location(s): Alabama, United States; Florida, United States; Louisiana, United States; Mississippi, United States; San Antonio Bay, Texas, United States.

OCS Planning Area(s): Eastern Gulf of Mexico; Central Gulf of Mexico; Western Gulf of Mexico.

Type(s) of Environment(s): Continental shelf; Coastal; Estuarine.

Mineral(s): Industrial minerals.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Geology; Water quality; Benthos; Commercial and recreational fisheries.

Date(s) of Study: Not applicable.

Study Technique(s): This book provides information on the environmental impacts of shell dredging in the Gulf of Mexico. A literature review, an economic discussion, and a general description of the shell dredging industry in the Gulf of Mexico were presented. The results of a one-year study of biological, chemical, geological, and physical conditions in San Antonio Bay, Texas were detailed. Other information on shell dredging in Florida, Alabama, Mississippi, Louisiana, and Texas was also discussed.

Conclusion(s): If properly regulated and managed, oyster shell dredging in the Gulf of Mexico could proceed with minimal impacts to the surrounding environment. Potential impacts from oyster shell dredging included alteration of water circulation patterns, resuspension of sediment contaminants, increased turbidity, and smothering of benthic organisms. States should accurately inventory shell resources using precision seismic detection systems. Each state should evaluate live versus dead shell deposits in terms of nursery function and sport and commercial fishing. The order and direction of dredging should be determined prior to dredging. All states should coordinate the search for alternative sources of oyster shell. Dredging of live or fossil oyster reefs and construction of shell pads should be done in accordance with findings of integrated scientific studies.

Key Words: Industrial minerals; Scraping; Excavating; Geology; Water quality; Benthos; Commercial and recreational fisheries.

Entry Number: 0009.

Citation: Campbell, H '954. The effect of siltation from gold dredging on the survival of rainbow trout and ey e.gs in Powder River, Oregon. In *Oregon Game Commission*, 3.

Type(s) of Study: Fielc L.boratory.

Geographic Location(s): Powder River, Oregon, United States.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Freshwater.

Mineral(s): Mineral sar ls.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Water quality; Nekton; Commercial and recreational fisheries.

Date(s) of Study: Una/ailable.

Study Technique(s): The effect of silt on the survival of rainbow trout was studied by exposing fingerlings and eggs produced in a hatchery to water contaminated with silt from gold dredging operat ons along the Powder River. The test site was located 1.5 miles downstream from an operating gold dredge. Control samples were exposed to water from a clear, unpolluted tr ou'ary of the Powder River. Eggs were held in artificial gravel beds; live trout were held ir b es and exposed to river water. Turbidity and water temperature were measured durirg the experiment. After 20 days, the number of surviving eggs and fingerlings were courted.

Conclusion(s): Turbidity at the Powder River site ranged from 1,000 to 2,500 ppm, while turbidity at the control site was zero. Exposure to polluted Powder River water caused 100% mortality in the e.gs and 57% mortality in the fingerlings. Mortality among fingerlings occurred after 6 days of exposure. Mortality at the control site was 9.5% and 6% for fingerlings and eggs, espectively.

Key Words: Miner il sands; Scraping; Excavating; Water quality; Nekton; Commercial and recreational fisheries.

Entry Number: 0010.

Citation: Chan, A. T., and G. C. Anderson. 1981. Environmental investigation of the effects of deep-sea mining on marine phytoplankton and primary productivity in the tropical eastern north Pacific Ocean. *Mar. Min.* 3(1/2):121-149.

Type(s) of Study: Field; Laboratory.

Geographic Location(s): Pacific Ocean.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Deep seabed.

Mineral(s): Metalliferous oxides.

Type(s) of Mining Operation(s): Scraping.

Environmental Resource(s): Water quality; Plankton.

Date(s) of Study: November 1978.

Study Technique(s): This project studied the potential effects on water column primary production of mining waste discharged in association with manganese nodule mining. Shipboard and *in situ* experiments were conducted to determine phytoplankton biomass, photosynthetic rates at depth, and photosynthesis vs. irradiance (P/I curves). The effect of discharge water on photosynthetic rates was also studied. Phytoplankton biomass was determined by filtration and fluorometer measurements of chlorophyll acetone extracts. Photosynthetic rates were determined from *in situ* incubations at 10 depth intervals between the surface and 100 m, as measured by the ^{14}C-uptake method. P/I curves were generated by shipboard incubations using several different irradiance levels.

Conclusion(s): Using a physical model (to predict particulate dispersal in the discharge plume over time) and hypothesized relationships between light levels and photosynthetic rates, a short-term effect of the discharge plume on primary production was predicted. Short-term diminution of primary production can be expected from plume-related increases in turbidity and concurrent decreases in irradiance at depth. The study did not show significant effects of the discharge waste on primary production through either the stimulatory effects of increased nutrient availability or the inhibitory effects of heavy metal toxicity. Extending the results of this study, the authors speculated that there would be no long-term and large-scale changes in primary production or phytoplankton species composition attributable to mining-related discharges.

Key Words: Metalliferous oxides; Scraping; Water quality; Plankton.

Entry Number: 0011.

Citation: Chansang, H. 1988. Coastal tin mining and marine pollution in Thailand. *Ambio* 17(3):223-228.

Type(s) of Study: Review.

Geographic Location(s): Thailand.

OCS Planning Area(s): Not applicable

Type(s) of Environment(s): Coastal.

Mineral(s): Mineral sands.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Geology; Water quality; Plankton; Benthos; Sensitive habitats; Commercial and recreational fisheries; Local economies; Human resources.

Date(s) of Study: Not applicable.

Study Technique(s): This review paper discusses impacts of tin mining on the coastal resources of peninsular Thailand. Studies on the environmental effects of gravel pumping and various types of dredging on mangrove swamps, coral reefs, and other coastal habitats were synthesized. Conflicts with other coastal enterprises such as tourism, fishing, and aquaculture were also discussed.

Conclusion(s): Tin mining in coastal waters of Thailand involves gravel pumping, bucket dredging, and suction dredging. Primary impacts of mining activities included increases in suspended solids and turbidity. Turbidity and siltation caused by suspended mine tailings smothered attached and infaunal invertebrates in nearshore areas. Coral reefs in the vicinity of mining activities were severely damaged by smothering and increased turbidity. Alteration of sediment structure and composition near mining sites was common and recovery was slow. In addition, sediment nutrient levels decreased from 4 to 96% in some areas, prohibiting the recolonization of mangroves and other plants. Dredging impacts were localized and recovery of benthic fauna and some corals were documented. No impacts to demersal fisheries were reported, however, shellfish farmers complained that water quality alterations affected their operations. Mining impacts also included effects on the aesthetic value of the coastal environment; this was particularly true for Phuket Island, where tourism is important to the local economy. A decline in the international demand for tin in 1985 considerably reduced mining operations and caused socioeconomic problems.

Key Words: Mineral sands; Scraping; Excavating; Geology; Water quality; Plankton; Benthos; Sensitive habitats; Commercial and recreational fisheries; Local economies; Human resources.

Entry Number: 0012.

Citation: Conner, W.G., and J. L. Simon. 1979. The effects of oyster shell dredging on an estuarine benthic community. *Estuar. Coast. Mar. Sci.* 9:749-758.

Type(s) of Study: Field.

Geographic Location(s): Tampa Bay, Florida, United States.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Coastal; Estuarine.

Mineral(s): Industrial minerals.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Geology; Water quality; Benthos.

Date(s) of Study: February 1975 to April 1976.

Study Technique(s): The effects of oyster shell mining (dredging) on the infaunal invertebrate community in Tampa Bay, Florida was investigated by quantitative sampling of infaunal organisms. Two dredged areas and one undisturbed control area were sampled before dredging and for one year after dredging. Sixteen replicate cores (0.0045 m^2) were collected biweekly for the first three months, then monthly at each site. Infaunal organisms were sorted to lowest taxonomic level, counted, and weighed. Differences in species number, density, and biomass between control and dredged sites were tested using the nonparametric Mann-Whitney U test. Community overlap between dredged and control sites was measured using the Czeckanowski coefficient. Sediment samples were taken using 1.75-cm diameter corers. Sedimentary parameters (median phi, mean phi, sorting coefficient) were determined using standard procedures.

Conclusion(s): Oyster shell dredging in Tampa Bay had an immediate effect on infaunal species number, density, and biomass. Species number was reduced by 40%, infaunal densities were reduced by 65%, and total invertebrate biomass was reduced by 90%. Six to twelve months after dredging had ceased, no statistically significant difference in species number, density, or biomass could be detected between dredged and control sites. Community overlap between dredged and control sites was reduced directly after dredging, but after six months, the pre-dredging level of similarity was regained. These results generally agreed with previous, though less rigorous studies conducted on dredging impacts in Tampa Bay and elsewhere. In this study, defaunation from dredging was not total. The observed effects of dredging on the benthos were temporary and a near total recovery occurred within 12 months.

Key Words: Industrial minerals; Scraping; Excavating; Geology; Water quality; Benthos.

Entry Number: 0013.

Citation: Crecelius, E. A., C. W. Apts, and B. K. Lasorsa. 1990. *Concentrations of metals in Norton Sound seawater samples and human hair samples, 1989: Alaska OCS Region.* OCS Study MMS 90-0010. Anchorage, AK: U.S. Department of the Interior, Minerals Management Service.

Type(s) of Study: Field.

Geographic Location(s): Norton Sound, Nome, Alaska, United States.

OCS Planning Area(s): Norton Basin.

Type(s) of Environment(s): Coastal; Estuarine; Freshwater.

Mineral(s): Mineral sands.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Water quality; Human resources.

Date(s) of Study: June and September-October 1989.

Study Technique(s): An investigation of sediment and water column concentrations of seven metals was made in the vicinity of a gold dredging operation in Norton Sound, Alaska. Water samples were collected from Norton Sound, near an operating gold dredge, and in the Snake River using Teflon-coated samplers. The upper 10 cm of sediment was collected with a corer from two sites in Norton Sound. Hair samples (10 to 20 strands) were taken from 200 Nome (Alaska) women of child-bearing age. Seawater samples were analyzed for mercury (Hg) by cold-vapor atomic florescence (CVAF) with a gold-amalgamation preconcentration step. Arsenic (As) in seawater was determined by hydride generation with a cryogenic preconcentration step. Cadmium (Cd), copper (Cu), lead (Pb), nickel (Ni), and zinc (Zn) were analyzed using graphite furnace atomic absorption (GFAA). Sediment metal concentrations were analyzed for total metals by energy dispersive x-ray florescence for As, Cr, Cu, Ni, Pb, and Zn and by CVAF for Cd and Hg, after complete dissolution of the sample in acid. Hair samples were digested in acid then analyzed for Hg by CVAF and As by GFAA.

Conclusion(s): In seawater, the concentrations of all seven metals were typical of non-polluted coastal waters, however concentrations of Cu and Ni were slightly higher than expected. There were no detectable differences among stations. Concentrations of metals in Snake River water samples were similar to concentrations in Norton Sound seawater, indicating that the river did not have a significant influence on the concentration of metals in offshore water or in seawater at the gold-dredging site. Sediment elutriate tests indicated that As and Ni may be released during sediment resuspension. The concentration of Hg and As in hair samples from Nome women were below levels of concern for human health.

Key Words: Mineral sands; Scraping; Excavating; Water quality; Human resources.

Entry Number: 0014.

Citation: Cruickshank, M. J. 1978. Technological and environmental considerations in the exploration and exploitation of marine minerals. Ph.D. thesis, Univ. of Wisconsin, Madison.

Type(s) of Study: Review.

Geographic Location(s): Worldwide.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Deep seabed; Continental shelf; Coastal; Estuarine; Freshwater.

Mineral(s): Industrial minerals; Mineral sands; Phosphorites; Metalliferous oxides; Hydrothermal deposits; Dissolved minerals.

Type(s) of Mining Operation(s): Scraping; Excavating; Tunneling; Fluidizing.

Environmental Resource(s): Geology; Physical oceanography; Water quality; Local economies; Regional economies; Human resources.

Date(s) of Study: Not applicable.

Study Technique(s): Marine-based minerals were identified and their relative value estimated relative to terrestrial deposits. Available mining technology and gaps in technology were identified and discussed. In addition, the various methods available to handle potential environmental impacts associated with various mining methodologies were examined. A benefit-cost model for marine mining was developed using alluvial gold and deep sea manganese nodules.

Conclusion(s): By the year 2000, potential scarcities exist for 31 minerals in the United States and 19 minerals worldwide. Marine minerals can be classified as freshwater and dissolved minerals in seawater; unconsolidated deposits of non-metallics, heavy minerals, and native elements in littoral regions to depths of 200 m; surficial and substratal unconsolidated deposits in bathyl regions (200 to 2,500 m); and surficial and substratal unconsolidated deposits in abyssal regions (2,500 to 6,000 m). Of 73 target minerals in the marine environment, the values of 53 exceeded those of the same commodities on land. Technological aspects discussed in this analysis included infrastructure, operational prerequisites, exploration and characterization, exploitation, restoration, and accidents. Environmental considerations evaluated included meteorological, hydrological, geological, biological, and physiological phenomena. Environmental aspects of non-natural phenomena included social, economic, legal, political, historical, and technical affairs.

Key Words: Industrial minerals; Mineral sands; Phosphorites; Metalliferous oxides; Hydrothermal deposits; Dissolved minerals; Scraping; Excavating; Tunneling; Fluidizing; Geology; Physical oceanography; Water quality; Local economies; Regional economies; Human resources.

Entry Number: 0015

Citation: Cruickshank, M. J., E. L. Corp, O. Terichow, and D. E. Stephenson. 1969. Environment and technology in marine mining. *J. Environ. Sci.* 12(2):14-22.

Type(s) of Study: Review.

Geographic Location(s): Worldwide.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Deep seabed; Continental shelf; Coastal; Estuarine; Freshwater.

Mineral(s): Industrial minerals; Mineral sands; Phosphorites; Metalliferous oxides; Hydrothermal deposits; Dissolved minerals.

Type(s) of Mining Operation(s): Scraping; Excavating; Tunneling; Fluidizing.

Environmental Resource(s): Air quality; Geology; Physical oceanography; Water quality; Neuston; Plankton; Nekton; Benthos; Birds; Marine mammals; Threatened and endangered species; Sensitive habitats; Commercial and recreational fisheries; Local economies; Regional economies; Cultural resources; Human resources.

Date(s) of Study: Not applicable.

Study Technique(s): Literature was reviewed to provide brief technological descriptions of various marine mining operations around the world. In particular, mining techniques were compared, contrasted, and explained as to their suitability under specific environmental conditions and constraints.

Conclusion(s): Successful development of marine mining technology required knowledge of potential problems presented by the marine environment and also of the advantages inherent in it. The Bureau of Mines' Marine Minerals Technology Center researches all phases of marine mining systems development.

Key Words: Industrial minerals; Mineral sands; Phosphorites; Metalliferous oxides; Hydrothermal deposits; Dissolved minerals; Scraping; Excavating; Tunneling; Fluidizing; Air quality; Geology; Physical oceanography; Water quality; Neuston; Plankton; Nekton; Benthos; Birds; Marine mammals; Threatened and endangered species; Sensitive habitats; Commercial and recreational fisheries; Local economies; Regional economies; Cultural resources; Human resources.

Entry Number: 0016.

Citation: Cruickshank, M. J., J. P. Flanagan, B. Holt, and J. W. Padan. 1987. *Marine mining on the outer continental shelf: Environmental effects overview*. OCS Report 87-0035. Washington, DC: U.S. Department of the Interior, Minerals Management Service.

Type(s) of Study: Review.

Geographic Location(s): United States.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Deep seabed; Continental shelf; Coastal.

Mineral(s): Industrial minerals; Mineral sands; Phosphorites; Metalliferous oxides; Hydrothermal deposits; Dissolved minerals.

Type(s) of Mining Operation(s): Scraping; Excavating; Tunneling; Fluidizing.

Environmental Resource(s): Geology; Physical oceanography; Water quality; Plankton; Nekton; Benthos; Sensitive habitats; Commercial and recreational fisheries.

Date(s) of Study: Not applicable.

Study Technique(s): This document provides an overview of the literature and information on the environmental effects of mining on the Outer Continental Shelf (OCS). Information is synthesized on characteristics of the OCS environment, mineral deposits, mining methods, normal operating environmental disturbances, environmental impacts, and Minerals Management Service policy for environmental protection.

Conclusion(s): Site-specific monitoring studies of environmental effects will be needed during at least pilot tests of new equipment and operations. Knowledge of the mining method, ore type, and mine site characteristics will be needed to predict potential effects. Organisms associated with the seafloor near mining operations are the most likely to be affected because of resedimentation of the benthic plume, actual destruction of the biota, and changes in the character of the seabed. Far-field resedimentation effects on benthos are least known, with resedimentation being the main concern.

Key Words: Industrial minerals; Mineral sands; Phosphorites; Metalliferous oxides; Hydrothermal deposits; Dissolved minerals; Scraping; Excavating; Tunneling; Fluidizing; Geology; Physical oceanography; Water quality; Plankton; Nekton; Benthos; Sensitive habitats; Commercial and recreational fisheries.

Entry Number: 0017.

Citation: Dauer, D. M., and J. L. Simon. 1976. Repopulation of the polychaete fauna of an intertidal habitat following natural defaunation: Species equilibrium. *Oecologia* 22:99-117.

Type(s) of Study: Field.

Geographic Location(s): Old Tampa Bay, Tampa, Florida, United States.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Coastal; Estuarine.

Mineral(s): Not applicable.

Type(s) of Mining Operation(s): Not applicable.

Environmental Resource(s): Plankton; Benthos.

Date(s) of Study: August 1971 to July 1973.

Study Technique(s): Following defaunation by red tide, benthic infauna was studied monthly for 24 months at four stations located along a transect perpendicular to shore. Stations ranged from just below mean high water to below mean low water. Five cores at each station were collected, screened to 0.5 mm, and pooled for a total sample area of 0.2 m^2. Temperature and salinity were recorded at each sampling. Quarterly sediment samples were collected and analyzed for particle size (Wentworth scale) and organic content (ash-free weight method). Other quarterly samples were analyzed for biomass on a species basis (ash-free weight). Immigration and extinction rates were calculated by comparing species lists from consecutive months. Recruitment was analyzed by length-frequency analysis of juveniles and adults.

Conclusion(s): Rates of immigration and extinction resulted in a colonization curve supporting the equilibrium model of MacArthur and Wilson. Immigration was rapid and species composition fairly constant. Contrasting to Thorson's ideas, adult dispersal proved significant in establishment of the benthic population; larval settlement provided for population maintenance. An equilibrium number of species was established in 11 months. Adult dispersal and larval settlement dampened species dominance and could explain large numbers of species of the same trophic group occupying the same habitat.

Key Words: Plankton; Benthos.

Entry Number: 0018.

Citation: Davis, H. C., and H. Hidu. 1969. Effects of turbidity-producing substances in sea water on eggs and larvae of three genera of bivalve mollusks. *Veliger* 11(4):316-323.

Type(s) of Study: Laboratory.

Geographic Location(s): Not applicable.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Continental shelf; Coastal; Estuarine.

Mineral(s): Industrial minerals; Mineral sands; Phosphorites; Metalliferous oxides; Hydrothermal deposits.

Type(s) of Mining Operation(s): Scraping; Excavating; Tunneling; Fluidizing.

Environmental Resource(s): Benthos; Commercial and recreational fisheries; Local economies.

Date(s) of Study: Unavailable.

Study Technique(s): Embryonic development, survival, and growth of the American oyster, European oyster, and hard clam were evaluated in varying concentrations of silt, clay, and Fuller's earth. Embryos and larvae of hard clams and American oysters were also tested in suspensions of pure silicon dioxide to determine particle-size effects as opposed to possible chemical effects of other suspensions.

Conclusion(s): Normal development of oyster eggs was significantly impaired in suspensions of 0.188 g/l silt, 3 g/l kaolin, and 4 g/l silicon dioxide, regardless of particle size. Clam eggs were affected by the smallest silicon dioxide particles at 4 g/l suspension. European oysters were less affected by test suspensions than the other organisms. The smallest silicone dioxide particles had the greatest effect on clam and oyster larvae. Increasing silicon dioxide particle size decreased growth of the American oyster. European oyster larvae were more sensitive to silt than larvae of other test species. Bivalve larvae grew faster in low turbidity than in clear sea water, possibly because particles chelated toxins in the water.

Key Words: Industrial minerals; Mineral sands; Phosphorites; Metalliferous oxides; Hydrothermal deposits; Scraping; Excavating; Tunneling; Fluidizing; Benthos; Commercial and recreational fisheries; Local economies.

Entry Number: 0019.

Citation: Dawson, E. W. 1984. The benthic fauna of the Chatham Rise: An assessment relative to possible effects of phosphorite mining. *Geologisches Jarbuch* D65:209-231.

Type(s) of Study: Review.

Geographic Location(s): Chatham Rise, South Island, New Zealand.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Deep seabed.

Mineral(s): Phosphorites.

Type(s) of Mining Operation(s): Scraping.

Environmental Resource(s): Geology; Physical oceanography; Water quality; Plankton; Nekton; Benthos; Commercial and recreational fisheries; Local economies; Regional economies.

Date(s) of Study: Not applicable.

Study Technique(s): Results of a literature review were used to describe the marine environment, faunal assemblages, and importance to fisheries of the Chatham Rise. Study of biological data led to the proposal and explanation that community trophic analysis, using critical path methodology, could be used to predict the environmental consequences of mining the Chatham Rise.

Conclusion(s): Considering the trophic levels of Chatham Rise biota and the importance of phosphorites to the establishment of these biota, it was concluded that some level of mining activity should be able to coexist with commercial fishing activities. Sketchy knowledge of complete faunal composition and life histories, however, would require close monitoring of the resilience and stability of marine populations.

Key Words: Phosphorites; Scraping; Geology; Physical oceanography; Water quality; Plankton; Nekton; Benthos; Commercial and recreational fisheries; Local economies; Regional economies.

Entry Number: 0020.

Citation: de Groot, S. J. 1979a. An assessment of the potential environmental impact of large-scale sand-dredging for the building of artificial islands in the North Sea. *Ocean Manage.* 5:211-232.

Type(s) of Study: Review.

Geographic Location(s): Netherlands

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Continental shelf; Coastal.

Mineral(s): Industrial minerals.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Geology; Water quality; Plankton; Nekton; Benthos; Commercial and recreational fisheries.

Date(s) of Study: Not applicable.

Study Technique(s): This review paper discusses potential impacts of sand mining and spoil island construction in the North Sea on water quality, plankton, benthos, fish, and larvae. Predicted impacts to fisheries are also discussed.

Conclusion(s): In general, damages to the environment by mining operations were expected to be temporary. Recovery of benthic communities may take three years to return to pre-mining conditions. Spoil islands will take eight years to build; after twelve years, the environment around the area should return to its pre-existing state. The stone and concrete bulkheads will attract and support a fouling community unlike any presently inhabiting the area.

Key Words: Industrial minerals; Scraping; Excavating; Geology; Water quality; Plankton; Nekton; Benthos; Commercial and recreational fisheries.

Entry Number: 0021.

Citation: de Groot, S. J. 1979b. The potential environmental impact of marine gravel extraction in the North Sea. *Ocean Manage.* 5:233-249.

Type(s) of Study: Review.

Geographic Location(s): Netherlands; United Kingdom.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Continental shelf; Coastal.

Mineral(s): Industrial minerals.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Geology; Nekton; Commercial and recreational fisheries.

Date(s) of Study: Not applicable.

Study Technique(s): This review paper discusses various gravel extraction methods and characterizes the United Kingdom sand and gravel industry. Potential impacts of gravel mining in the North Sea on spawning populations of herring and sand eels are discussed. Data from both fisheries and mining literature are synthesized to evaluate potential impacts.

Conclusion(s): Extraction of gravel in the North Sea has occurred most frequently by suction dredge with a trailing hopper. In this operation, only the surficial sediments are removed leaving a trail 20 cm deep. Some operations have employed programmed systems to maximize the efficiency and minimize environmental damage. Side-scan sonar records made before and after dredging revealed changes in seafloor topography, including increased depth and alteration of sediment texture. Mapped gravel deposits in the North Sea correspond with known spawning grounds for herring. Herring utilize gravel as spawning substrate for demersal eggs and often return to the same gravel beds year after year. Alterations of the seafloor by dredging may change important acoustic properties used by herring to relocate spawning areas. Gravel size is also an important factor in egg deposition. Gravel extraction must be conducted carefully to minimize impacts on the herring populations already depleted by the fishing industry. Sand eels are also known to lay their eggs in sand, but the eggs are vulnerable to smothering by fine sediments. Dredging of proximal gravel deposits should not be allowed during the sand eel spawning period in areas where there is an established fishery for the species. Sand eels are also important as food for larger species such as cod and turbot. Because it is estimated that marine gravel deposits will be depleted within 50 years whereas fishing will occur for many hundreds of years, careful evaluation is needed of the relative short-term benefits for the marine gravel industry and the long-term interests of the fisheries.

Key Words: Industrial minerals; Scraping; Excavating; Geology; Nekton; Commercial and recreational fisheries.

Entry Number: 0022.

Citation: de Groot, S. J. 1986. Marine sand and gravel extraction in the North Atlantic and its potential environmental impact, with emphasis on the North Sea. *Ocean Manage.* 10:21-36.

Type(s) of Study: Review.

Geographic Location(s): Belgium; Canada; Denmark; Finland; France; West Germany; Iceland; Netherlands; Poland; Sweden; United Kingdom; United States.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Continental shelf; Coastal; Estuarine.

Mineral(s): Industrial minerals.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Geology; Water quality; Plankton; Nekton; Benthos; Sensitive habitats; Commercial and recreational fisheries.

Date(s) of Study: 1979 to 1985.

Study Technique(s): Status of sand and gravel dredging in the North Sea, North Atlantic Ocean, and Baltic Sea were reviewed through correspondence and interviews with representatives from countries bordering these water bodies.

Conclusion(s): Average amounts of aggregated materials extracted per year were 40,000,000 m^3 of sand for construction purposes, 400,000,000 m^3 of sand for maintenance purposes, 9,000,000 m^3 of gravel, and 1,000,000 m^3 of calcareous material. Sand for construction purposes was mostly extracted from the southern North Sea, gravel was extracted along the English east coast and English Channel, and shell material was taken from the Wadden Sea area of the Netherlands, West Germany, and Denmark. Extensive maintenance dredging will take place in the estuaries of the southern North Sea. Short-term environmental impacts of these operations were considered minimal. However, discharge of polluted sediments dredged from the ports of Rotterdam and New York are causing problems. Initial impacts from marine aggregate dredging vary from minimal to severe and disruptions range from short to long term, depending on the sensitivity of the particular area. Dredging in sensitive areas should be avoided. Conflicts may arise with the North Sea fisheries, particularly in areas where the bottom fauna has been altered by dredging.

Key Words: Industrial minerals; Scraping; Excavating; Geology; Water quality; Plankton, Nekton; Benthos; Sensitive habitats; Commercial and recreational fisheries.

Entry Number: 0023.

Citation: Dickson, R. R. 1975. A review of current European research into the effects of offshore mining on the fisheries. In *Proceedings, (Vol. 1) Seventh Annual Offshore Technology Conference*, OTC 2159, 103-117. Houston, TX.

Type(s) of Study: Review.

Geographic Location(s): Belgium; Denmark; Finland; France; Germany; Ireland; Netherlands; Norway; Sweden; United Kingdom.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Continental shelf; Coastal; Estuarine.

Mineral(s): Industrial minerals.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Geology; Physical oceanography; Water quality; Plankton; Nekton; Benthos; Sensitive habitats; Commercial and recreational fisheries.

Date(s) of Study: 1974.

Study Technique(s): The International Council for the Exploration of the Sea established a working group to identify direct and indirect effects and international implications of different marine sand and gravel extraction methods on fisheries, to review techniques for studying the effects, and to compare codes of practice for controlling dredging activities. The working group of delegates from 11 member nations met at the Fisheries Laboratory, Lowestoft, England on 2 to 4 April 1974. The findings of the working group were the subject of this paper.

Conclusion(s): This paper described the status and expected growth of offshore sand and gravel dredging on the European Shelf, the effects on fisheries, and a review of the adequacy of related research. To minimize fishery/mining conflicts, the paper advocated cooperative fisheries research and recommended establishment of a common European code of practice for regulating dredging.

Key Words: Industrial minerals; Scraping; Excavating; Geology; Physical oceanography; Water quality; Plankton; Nekton; Benthos; Sensitive habitats; Commercial and recreational fisheries.

Entry Number: 0024.

Citation: Dickson, R. R., and A. Lee. 1973a. Gravel extraction: Effects on seabed topography (Part 1). *Offshore Serv.* 6(6):32-39.

Type(s) of Study: Field.

Geographic Location(s): United Kingdom.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Continental shelf; Coastal.

Mineral(s): Industrial minerals.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Geology; Physical oceanography; Nekton; Benthos; Commercial and recreational fisheries; Regional economies.

Date(s) of Study: 1970 to 1973.

Study Technique(s): This was the first of two papers summarizing the use of remote sensing techniques to assess the impacts of gravel dredging on seafloor topography in the North Sea. A 300 kHz scanning sonar system, capable of scanning a 30° sector electronically at a rate of 10,000 sweeps per second, was used in test trials near the Southern Bight of the North Sea. The actual monitoring study was conducted in the Hastings area of the North Sea where an experimental pit was excavated, then surveyed before, during, and after dredging operations. Hydrodynamic properties of the area, as well as sand and gravel, were evaluated using standard engineering methods. Sediment traps were used to collect samples of allocthonous sediment. A shear-velocity current meter was used to measure near bottom currents.

Conclusion(s): Sonar records indicated that infill rate of dredged pits and furrows was very slow. Based on current measurements from the test area, maximum shear (2.95 N/m^2) was capable of moving sediment up to 3.1 mm in diameter. Pebbles found within the area ranged from 3.6 to 11.4 cm, confirming that the tidal streams were totally incapable of moving the coarser bed material. In addition, these larger grains sheltered the finer sediment from extensive movements by tidal currents. The movement of large quantities of sediment by storm events was considered possible but not investigated.

Key Words: Industrial minerals; Scraping; Excavating; Geology; Physical oceanography; Nekton; Benthos; Commercial and recreational fisheries; Regional economies.

Entry Number: 0025.

Citation: Dickson, R. R., and A. Lee. 1973b. Gravel extraction: Effects on seabed topography (Part 2). *Offshore Serv.* 6(6):56-61.

Type(s) of Study: Field.

Geographic Location(s): United Kingdom.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Continental shelf; Coastal.

Mineral(s): Industrial minerals.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Geology; Physical oceanography; Nekton; Benthos; Commercial and recreational fisheries; Regional economies.

Date(s) of Study: 1970 to 1973.

Study Technique(s): This was the second of two papers summarizing the use of remote sensing techniques to assess the impacts of gravel dredging on seafloor topography in the North Sea. An experimental pit was constructed in the English Channel near Hastings in water depths of 22 m to evaluate the recovery of seafloor areas impacted by gravel mining in the North Sea. The pit was surveyed at six months and one year post-construction to evaluate recovery towards pre-dredging conditions. Dimensions of the pit were monitored remotely using a scanning sonar system and directly by divers. Tracer experiments also provided evidence on sediment movement in the area.

Conclusion(s): After a six-month period, no infill was recorded for the experimental pit. Measurements indicated that the pit was deeper than initially recorded. After one year, there was no change in the depth of the experimental pit, presumably due to the settling of a slurry of fine mud and silt interpreted by the scanner as the actual bottom of the pit during the first survey. Tracer experiments revealed that sediment movement was negligible at the 22 m depth of the test site. These results indicated that many years, perhaps decades, will be required before the area returns to pre-dredging condition.

Key Words: Industrial minerals; Scraping; Excavating; Geology; Physical oceanography; Nekton; Benthos; Commercial and recreational fisheries; Regional economies.

Entry Number: 0026.

Citation: Dodge, R. E., R. C. Aller, and J. Thomson. 1974. Coral growth related to re-suspension of bottom sediments. *Nature* 247:574-577.

Type(s) of Study: Field; Laboratory.

Geographic Location(s): Discovery Bay, Jamaica.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Coastal.

Mineral(s): Industrial minerals.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Water quality; Benthos; Sensitive habitats.

Date(s) of Study: 16 to 25 March 1973.

Study Technique(s): The effects of resuspension of bottom sediments on the growth rate of the coral *Montastrea annularis* in different parts of Discovery Bay, Jamaica were determined by a ^{228}Ra technique and X radiography. Three stations were established on the soft carbonate sediment bottom near the rear zone of the reef. Resuspension was measured in duplicate at each station by placing sediment traps 50 cm above the bottom and weighing the collected sediment. Coral heads were collected at depths of 2 to 4 m within 50 m of the station locations.

Conclusion(s): Analysis showed an inverse trend between sediment resuspension values and coral growth. Additionally, high resuspension decreased growth variability and suggested that turbidity reduced the ability of the coral to respond to more favorable environmental variables. A factor limiting coral growth is closely associated with the intensity of resuspension of bottom sediments. Other factors, such as temperature, light availability, salinity, and nutrient supply, are also important.

Key Words: Industrial minerals; Scraping; Excavating; Water quality; Benthos; Sensitive habitats.

Entry Number: 0027.

Citation: Drinnan, R. W., and D. G. Bliss. 1986. The U.K. experience on the effects of offshore sand and gravel extraction on coastal erosion and the fishing industry. In *Nova Scotia Department of Mines and Energy*, Open-File Report 86-054, 77.

Type(s) of Study: Review.

Geographic Location(s): Canada; United Kingdom.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Continental shelf; Coastal.

Mineral(s): Industrial minerals.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Geology; Commercial and recreational fisheries; Human Resources.

Date(s) of Study: Not applicable.

Study Technique(s): A review of the issues related to coastal erosion and conflicts with the fishing industry resulting from marine sand and gravel extraction was conducted in the United Kingdom. This study was divided into two phases. The first phase encompassed an extensive literature search of published information on the issues, environmental effects, and management procedures related to marine dredging and mining. The second phase consisted of interviews conducted in the United Kingdom with people who were involved with, or were affected by offshore aggregate mining or the review process by which the industry is managed or regulated.

Conclusion(s): Several concerns expressed in the United Kingdom could potentially develop in Canada should marine mining increase from present levels. Issues of concern included coastal erosion; impacts on fishing operations, fisheries resources, habitats and other environmental concerns; and administration and management. A primary cause of many issues in the United Kingdom was a lack of communication between the fishing industry and the sand and gravel mining industry. Recommendations to improve information exchange between the groups were presented. Another issue in the United Kingdom was a need for information on geological and biological resources prior to mining. Many of the issues could be prevented through the mining license application process. Recommendations for license applications included regulatory standards for mining operations, fishing industry review, scientific review, monitoring of geological and biological parameters of the mining site, and establishment of an objective compensation board.

Key Words: Industrial minerals; Scraping; Excavating; Geology; Commercial and recreational fisheries; Human Resources.

Entry Number: 0028.

Citation: Drucker, B. S., B. J. Laubach, and D. B. O'Niell. 1991. An offshore borehole mining experiment: Its operational and environmental implications. In *Proceedings, Seventh Symposium on Coastal and Ocean Management.* Long Beach, CA.

Type(s) of Study: Field.

Geographic Location(s): Georgia, United States.

OCS Planning Area(s): South Atlantic.

Type(s) of Environment(s): Continental shelf.

Mineral(s): Phosphorites.

Type(s) of Mining Operation(s): Fluidizing.

Environmental Resource(s): Geology; Water quality; Benthos.

Date(s) of Study: June 1990.

Study Technique(s): The borehole methodology, as a means of extracting phosphate from beneath layers of overburden, was field-tested on Georgia's continental shelf. Results of this field effort provided scientists with an opportunity to evaluate the environmental impacts associated with the borehole operation. The test site was located offshore of Tybee Island, Georgia, near the Savannah Light Tower. The seafloor in this area consisted primarily of sand and shell hash. Direct observations and videotapes were recorded by divers during and following the test operation. Water samples for analysis of turbidity, pH, and dissolved oxygen were taken before, during, and after the operation using Van Dorn bottles.

Conclusion(s): The borehole method of phosphate extraction may be a more environmentally-preferred method than conventional dredging. The Georgia field test showed little sediment disturbance and, therefore, reduced water column turbidity. Surface or mid-depth discharges were greatly reduced because all wastes were shunted back into the mined cavity. Dissolved oxygen and turbidity levels did not change appreciably as a result of the bulk sampling process.

Key Words: Phosphorites; Fluidizing; Geology; Water quality; Benthos.

Entry Number: 0029.

Citation: Dunnington, E. A., Jr. 1968. Survival times of oysters after burial at various temperatures. *Proceedings, National Shellfisheries Association*, 58:101-103.

Type(s) of Study: Laboratory.

Geographic Location(s): Not applicable.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Coastal; Estuarine.

Mineral(s): Industrial minerals.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Benthos; Commercial and recreational fisheries; Local economies.

Date(s) of Study: Unavailable.

Study Technique(s): Multiple series of eight oysters were buried 3 in. deep in mixed sand and mud in each of four polyethylene trays. Control oysters were placed on the sediment surface. Trays were placed in a running seawater aquarium. Sediment was tested to determine the depth of the aerobic/anaerobic interface. Five temperature ranges were tested. Periodic exhumations were made to determine survival times.

Conclusion(s): Marked differences occurred in survival times at different temperatures. Death was quicker in warmer water. Earlier death at higher temperatures may have been due to elevated metabolism and more rapid consumption of reserves. The intrusion of toxic matter and bacteria from the mud when buried oysters gaped may have significantly affected survival times and decomposition.

Key Words: Industrial minerals; Scraping; Excavating; Benthos; Commercial and recreational fisheries; Local economies.

Entry Number: 0030.

Citation: Ellis, D. V. 1987. A decade of environmental impact assessment at marine and coastal mines. *Mar. Min.* 6(4):385-417.

Type(s) of Study: Review.

Geographic Location(s): Worldwide.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Deep seabed; Continental shelf; Coastal; Estuarine.

Mineral(s): Industrial minerals; Mineral sands; Phosphorites; Metalliferous oxides; Hydrothermal deposits; Dissolved minerals.

Type(s) of Mining Operation(s): Scraping; Excavating; Tunneling; Fluidizing.

Environmental Resource(s): Geology; Physical oceanography; Water quality; Neuston; Plankton; Nekton; Benthos; Sensitive habitats; Commercial and recreational fisheries; Local economies; Regional economies; Human resources.

Date(s) of Study: Not applicable.

Study Technique(s): Published documents and gray literature of wide and limited distribution were reviewed in this paper. Case histories of marine mining projects were provided to show historical progress, as well as current and expected norms for environmental impact assessment (EIA) preparation and impact monitoring for these operations. Numerous references and sources were given covering marine mining operations of many types throughout the world.

Conclusion(s): Marine mine operators have been producing better and more relevant and comprehensive EIAs and environmental monitoring programs. Monitoring studies have evolved into detailed comparisons of impact and non-impact (control) areas in which data were collected before, during, and after the life of the mining operation. Comparisons of pre- and post-mining site conditions were considered important for actual impact assessment.

Key Words: Industrial minerals; Mineral sands; Phosphorites; Metalliferous oxides; Hydrothermal deposits; Dissolved minerals; Scraping; Excavating; Tunneling; Fluidizing; Geology; Physical oceanography; Water quality; Neuston; Plankton; Nekton; Benthos; Sensitive habitats; Commercial and recreational fisheries; Local economies; Regional economies; Human resources.

Entry Number: 0031.

Citation: Ellis, D. V. 1988. Case histories of coastal and marine mines. In *Chemistry and Biology of Solid Waste; Dredged Material and Mine Tailings*, eds. W. Solomons and U. Forstner, 73-100. Berlin: Springer-Verlag.

Type(s) of Study: Review.

Geographic Location(s): Worldwide.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Deep seabed; Continental shelf; Coastal; Estuarine; Freshwater.

Mineral(s): Industrial minerals; Mineral sands; Metalliferous oxides.

Type(s) of Mining Operation(s): Scraping; Excavating; Tunneling; Fluidizing.

Environmental Resource(s): Geology; Physical oceanography; Water quality; Neuston; Plankton; Nekton; Benthos; Sensitive habitats; Commercial and recreational fisheries; Local economies; Regional economies; Human resources.

Date(s) of Study: Not applicable.

Study Technique(s): This study was a literature review of numerous case histories of coastal mining operations which utilize ocean disposal. Types and patterns of environmental impact were noted. Comments were made about how to minimize potential impacts during conceptual design and planning of processes and discharges. Quality control and environmental monitoring were also discussed.

Conclusion(s): To some extent, all discharges of mine tailings to the marine environment have caused turbidity, seabed smothering, and bioaccumulation of trace metals. These primary impacts can lead to toxification and/or elimination of marine life, including important fishery resources. Mines that made efforts to predict, assess, reduce, and mitigate impacts most often met with some significant degree of success. Lack of adequate planning, in some cases, caused major problems.

Key Words: Industrial minerals; Mineral sands; Metalliferous oxides; Scraping; Excavating; Tunneling; Fluidizing; Geology; Physical oceanography; Water quality; Neuston; Plankton; Nekton; Benthos; Sensitive habitats; Commercial and recreational fisheries; Local economies; Regional economies; Human resources.

Entry Number: 0032.

Citation: Foell, E. J., H. Thiel, and G. Schriever. 1992a. DISCOL: A long-term large-scale, disturbance-recolonization experiment in the abyssal eastern tropical south Pacific Ocean. *Min. Eng.*, 90-94.

Type(s) of Study: Field.

Geographic Location(s): Peru Basin, South Pacific Ocean.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Deep seabed.

Mineral(s): Metalliferous oxides.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Geology; Physical oceanography; Water quality; Nekton; Benthos; Sensitive habitats.

Date(s) of Study: 2 February to 3 April 1989; 2 September to 2 October 1989.

Study Technique(s): An undisturbed 4.2 mi^2 circular area in water depths of 4,140 to 4,170 m was selected for study. Adjacent areas served as control sites. Benthos was collected at 10 sites in the study area immediately before and after disturbance with at least three box cores of 0.25 m^2 each. Meiofauna, bacteria, and sediment (for chemical analysis) were sampled by an eight tube multicorer. Megafauna was collected by 2.3-m wide epibenthic trawl. Baited traps were deployed at six depths for additional samples. Baited and unbaited cameras recorded time series visitations. Videotapes and still photos were taken of megafauna and seafloor structure. Currents, pressure, conductivity, temperature, turbidity, sound velocity, dissolved oxygen, and sediment shear strength were determined. A specially designed plow-harrow device was towed to disturb the bottom. Sampling occurred immediately before and after the disturbance and at six months following the disturbance.

Conclusion(s): Little change (recovery) was noted between immediate post-disturbance and six-month post-disturbance conditions. The data suggested that deep seabed disturbances such as those associated with mining operations might take years or decades to return to normal.

Key Words: Metalliferous oxides; Scraping; Excavating; Geology; Physical oceanography; Water quality; Nekton; Benthos; Sensitive habitats.

Entry Number: 0033.

Citation: GESAMP (IMO/FAO/UNESCO/WMO/WHO/IAEA/UN/UNEP) Joint Group of Experts on the Scientific Aspects of Marine Pollution. 1977. Scientific aspects of pollution arising from the exploration and exploitation of the sea-bed. In *Reports and Studies, No. 7,* 37. New York, NY: United Nations.

Type(s) of Study: Review.

Geographic Location(s): Worldwide.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Deep seabed; Continental shelf; Coastal; Estuarine; Freshwater

Mineral(s): Industrial minerals; Mineral sands; Phosphorites; Metalliferous oxides; Hydrothermal deposits; Dissolved minerals.

Type(s) of Mining Operation(s): Scraping; Excavating; Tunneling; Fluidizing.

Environmental Resource(s): Air quality; Geology; Physical oceanography; Water quality; Neuston; Plankton; Nekton; Benthos; Birds; Marine mammals; Threatened and endangered species; Sensitive habitats; Commercial and recreational fisheries; Local economies; Regional economies; Cultural resources; Human resources.

Date(s) of Study: Not applicable.

Study Technique(s): A working group was established to review all available data on the scientific aspects of pollution arising from exploration and exploitation of the seabed. Information was gathered and presented on all types of mining, all marine habitats in which mining occurs, and pollution problems to be expected from the extraction of each mineral.

Conclusion(s): It was concluded that pollution problems exist with all marine mining ventures. Understanding the characteristic problems of specific mining methods and their associated marine habitat can aid in coping with or alleviating these troubles. Advance planning of technology and pre- and post-impact environmental monitoring can be used to significantly reduce pollution impacts. Each mining venture is more or less unique, necessitating individual study.

Key Words: Industrial minerals; Mineral sands; Phosphorites; Metalliferous oxides; Hydrothermal deposits; Dissolved minerals; Scraping; Excavating; Tunneling; Fluidizing; Air quality; Geology; Physical oceanography; Water quality; Neuston; Plankton; Nekton; Benthos; Birds; Marine mammals; Threatened and endangered species; Sensitive habitats; Commercial and recreational fisheries; Local economies; Regional economies; Cultural resources; Human resources.

Entry Number: 0034.

Citation: Gideiri, Y. B. A. 1984. Impacts of mining on central Red Sea environment. *Deep-Sea Res.*, Part A 31(6-8A):823-828.

Type(s) of Study: Review.

Geographic Location(s): Atlantis II Deep, Red Sea.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Deep seabed.

Mineral(s): Metalliferous oxides.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Physical oceanography; Water quality; Neuston; Plankton; Nekton; Benthos.

Date(s) of Study: 1979 to 1984.

Study Technique(s): This paper summarized major findings and conclusions from a pre-pilot mining test (conducted in 1979) and numerous reports resulting from six years of programs (i.e., the Metalliferous Sediments Development of Atlantis II [MEDESA] campaigns) organized by the Saudi-Sudanese Red Sea Commission.

Conclusion(s): Chemical effects of tailings depended on the proportions of toxins in the discharge, the hydrodynamics of the discharge, and the mobilization of substances from the particulates. Dissolved phosphate, nitrate, and silicate levels were lower than expected in uncontaminated Red Sea water, presumably due to scavenging by the natural rain of sediment. The potential for biomagnification of metals should be assessed relative to long-term influence on biota. Discharge slurries with elevated salinity could modify water circulation in the Red Sea, resulting in productivity changes. It was determined that the dissolved oxygen demand of tailings should be low. A deep water discharge, below 1,100 m, would be environmentally beneficial for numerous reasons.

Key Words: Metalliferous oxides; Scraping; Excavating; Physical oceanography; Water quality; Neuston; Plankton; Nekton; Benthos.

Entry Number: 0035.

Citation: Grigg, R. W., A. Malahoff, E. H. Chave, and J. Landahl. 1987. Seamount benthic ecology and potential environmental impact from manganese crust mining in Hawaii. In *Seamounts, Islands, and Atolls*, eds. B. H. Keating, P. Fryer, R. Batiza, and G. W. Boehlert, 379-390. Geophysical Monograph 43. Washington, DC: American Geophysical Union.

Type(s) of Study: Field.

Geographic Location(s): Cross Seamount, Hawaii, United States.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Deep seabed.

Mineral(s): Metalliferous oxides.

Type(s) of Mining Operation(s): Scraping.

Environmental Resource(s): Geology; Physical oceanography; Plankton; Nekton; Benthos; Commercial and recreational fisheries.

Date(s) of Study: 9 to 18 September 1985.

Study Technique(s): This study investigated the composition and density of benthic communities, particularly benthic megafauna, on a North Pacific seamount containing manganese crust deposits. Data were used to determine the potential environmental impact of manganese crust mining. Coral and rock dredges and bottom photography were used to collect samples and data.

Conclusion(s): The environmental impacts of manganese mining activities were reported to be minimal. The study found that the benthic communities on the Cross Seamount were characterized by low diversity and abundance. These patterns were thought to be due to geographic isolation, the small habitat area, and unfavorable environmental conditions, particularly the low current velocities which allow accumulation of sediments. The highest population densities were found on large rocky outcrops and the rim of the seamount summit. At locations which exhibited thick ferromanganese crust deposits, abundance was markedly low. The authors speculated that this was due to larval avoidance of such areas. Owing to the low species diversity and abundance, as well as the lack of organisms which are unique to the area or are commercially important, the authors suggested that the environmental impact of manganese crust mining would be minimal.

Key Words: Metalliferous oxides; Scraping; Geology; Physical oceanography; Plankton; Nekton; Benthos; Commercial and recreational fisheries.

Entry Number: 0036

Citation: Hanson, P. J., A. J. Chester, and F. A. Cross. 1982. Potential assimilation by and effects on oceanic zooplankton of trace metals from manganese nodule fragments discharged from planned ocean mining operations. Prepared for National Oceanic and Atmospheric Administration, Office of Ocean Minerals and Energy. Beaufort, NC: National Marine Fisheries Service.

Type(s) of Study: Review.

Geographic Location(s): Pacific Ocean.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Deep seabed.

Mineral(s): Metalliferous oxides.

Type(s) of Mining Operation(s): Scraping.

Environmental Resource(s): Water quality; Plankton.

Date(s) of Study: Not applicable.

Study Technique(s): The document summarizes available information pertaining to the effects of trace metals from manganese nodules on oceanic zooplankton and recommends areas of research to resolve remaining questions. The report characterized the mining operation and surface discharge and the nature of the oceanic zooplankton community. The document also reviewed the likelihood of ingestion of mining particulates by zooplankton and the chemical form and bioavailability of trace metals to marine plankton. Biomagnification and food web transfer of trace metals were considered.

Conclusion(s): Potential impacts of discharged mining wastes on the oceanic community may be realized through exposure to particulate and/or dissolved components of the discharge. Removal of much of the discharged material from the water column was thought to be enhanced by the ingestion of the particles by zooplankton and deposition as fecal pellets. Elimination processes, such as excretion, fecal production, molting and egg production, rapidly reduce tissue concentrations of trace metals. Based on available information, ingestion of mining particles by zooplankton was thought to be an insignificant pathway for contamination of higher trophic levels by toxic trace metals. The physical and chemical characteristics of the discharged particles, nature of the potential biological interactions, and nature of the chemical interactions with seawater were not expected to result in significant biomagnification. Due to the paucity of data and the complexity of physical, chemical, and biological processes, conclusions about the potential impact from the dissolved pathway could not be made. This area requires additional research.

Key Words: Metalliferous oxides; Scraping; Water quality; Plankton.

Entry Number: 0037.

Citation: Harrison, W. 1967. Environmental effects of dredging and spoil deposition. In *Proceedings, 1st World Dredging Conference*, Tokyo, 535-559.

Type(s) of Study: Field.

Geographic Location(s): Chesapeake Bay, Virginia, United States.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Estuarine.

Mineral(s): Industrial minerals.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Water quality; Benthos.

Date(s) of Study: 1961; December 1965 to March 1966.

Study Technique(s): The paper describes the results from three different studies, including 1) recolonization of spoil areas in mid-Chesapeake Bay; 2) effects of sedimentation on oyster grounds adjacent to a spoil outflow in the York River; and 3) effects of sedimentation on oyster grounds adjacent to a bucket dredging operation in Hampton Roads. The first study used diver-collected cores to determine the physical characteristics and faunal density of the benthos. The second study used reference rods to determine changes in sediment depth on the oyster grounds. In addition, adult oysters were planted in marked sites in the area for later collection to determine survival rates. Similar techniques were used in the third study concerning bucket dredging.

Conclusion(s): Minimal effects on benthic communities from dredging operations were reported from the three studies. In the first study, the initial problem of delineation of the spoil site was solved by using anomalous profiles of sediment strength and void ratios. Spoil dumping was reported to have temporary effects on epifaunal and infaunal populations. The spoil sites were rapidly resettled by active migration of adults and recruitment from planktonic juveniles or larval stages. There was substantial natural variability in rates of erosion and deposition within the study area and this precluded observation of sedimentation resulting from the spoil outflow. The second and third studies also showed no detrimental effects of sedimentation from a spoil outflow or dredging on adjacent oyster grounds. Mortality in the oysters held near the spoil outflow could not be differentiated from natural mortality.

Key Words: Industrial minerals; Scraping; Excavating; Water quality; Benthos.

Entry Number: 0038.

Citation: Haynes, B. W., and S. L. Law. 1982. *Predicted characteristics of waste materials from the processing of manganese nodules.* U.S. Department of the Interior, Bureau of Mines Information Circular 8904. Washington, DC: U.S. Government Printing Office.

Type(s) of Study: Laboratory.

Geographic Location(s): Pacific Ocean.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Deep seabed.

Mineral(s): Metalliferous oxides.

Type(s) of Mining Operation(s): Scraping.

Environmental Resource(s): Air quality; Geology; Water quality; Regional economies.

Date(s) of Study: Unavailable.

Study Technique(s): Estimates of physical and chemical composition of waste materials generated from manganese nodule processing were made using flow charts of five potential processes. Probable chemical waste projections were tabulated for each process for various elements. A toxicity test was run on the wastes from a Cuprion pilot plant. Physical characteristics were estimated based on limited information from laterite processing.

Conclusion(s): Wastes from the gas reduction and Cuprion ammoniacal leach process should have moderate settling densities (50 to 60% solids), of proper size (i.e., minus 200 mesh), and have good long-term stability. The high-temperature and high-pressure sulfuric acid process should have wastes similar to that of the ammoniacal process. Wastes from the hydrochloric acid process would have somewhat lower settling densities (30 to 50% solids) at minus 270 mesh, and have only fair long-term stability. Wastes from the smelting and sulfuric acid process would be primarily glassy inert slags at >10 mesh with excellent long-term stability. Gas reduction and Cuprion ammoniacal leach tailings consisted of 80% iron hydroxide and manganese carbonate. The toxicity test results from pilot plant-generated reject waste material (from the Cuprion process) were well below maximum limits for designation as hazardous. The high-temperature and high-pressure sulfuric leach process produces iron hydroxide and manganese dioxide or oxide. Wastes from reduction and the hydrochloric acid leach process include acid-insoluble fractions of the nodules, clays, feldspars, and silica. The smelting and sulfuric acid leach process will generate mostly silicate glass, iron, and trace amounts of metal sulfides. The reject waste material generated by the five processes may have only minor environmental implications.

Key Words: Metalliferous oxides; Scraping; Air quality; Geology; Water quality; Regional economies.

Entry Number: 0039.

Citation: Herbich, J. B., and R. E. Schiller, Jr. 1973. Environmental effects of dredging. In *Proceedings of WODCON V*, 699-719. Hamburg, West Germany: United Nations.

Type(s) of Study: Review.

Geographic Location(s): Worldwide.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Continental shelf; Coastal; Estuarine; Freshwater.

Mineral(s): Industrial minerals; Mineral sands

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Geology; Water quality; Plankton; Nekton; Benthos; Commercial and recreational fisheries.

Date(s) of Study: Not applicable.

Study Technique(s): This is a review paper on the environmental effects of dredging. The authors reviewed 35 papers which dealt with 1) environmental effects of different dredging methods; 2) water quality effects; and 3) effects on marine life.

Conclusion(s): Conflicts occurred between conclusions reached in the various papers reviewed. Some conclusions indicated that dredging caused little or no damage to marine life, whereas others indicated long-term detrimental effects. The authors suggested that the possible advantageous effects of dredging include 1) removal of polluted sediments for storage or treatment; 2) advantageous change in flow patterns; 3) reoxygenation of sediments and the water column; and 4) resuspension of nutrients. The possible deleterious effects include 1) removal or burial of habitats; 2) change in flow patterns; 3) resuspension of polluted sediments; and 4) resuspended sediments acting as a barrier to the movement of marine life.

Key Words: Industrial minerals; Mineral sands; Scraping; Excavating; Geology; Water quality; Plankton; Nekton; Benthos; Commercial and recreational fisheries.

Entry Number: 0040.

Citation: Hildreth, R. G. 1989. Marine use conflicts arising from development of seabed hydrocarbons and minerals: Some approaches from the United States West Coast. *Ocean & Shoreline Manage.* 12:271-284.

Type(s) of Study: Review.

Geographic Location(s): California, United States; Oregon, United States; Washington, United States.

OCS Planning Area(s): Southern California; Central California; Northern California; Washington-Oregon.

Type(s) of Environment(s): Deep seabed; Continental shelf; Coastal.

Mineral(s): Industrial minerals; Mineral sands; Phosphorites; Metalliferous oxides; Hydrothermal deposits; Dissolved minerals.

Type(s) of Mining Operation(s): Scraping; Excavating; Tunneling; Fluidizing.

Environmental Resource(s): Commercial and recreational fisheries; Local economies; Regional economies; Cultural resources; Human resources.

Date(s) of Study: Not applicable.

Study Technique(s): Current legislation was reviewed regarding marine resource use conflicts arising from development of the seabed for mineral and oil and gas reserves.

Conclusion(s): Exploration and development of seabed mineral and hydrocarbon deposits can pose serious use conflicts, especially where potential conflicts are not dealt with prior to the creation of private rights in the deposits. General ways to avoid or reduce conflicts include multiple-use ocean planning to identify potential conflicts; separating exploration and development rights to aid in the resolution of conflicts; using activity rights to remove legal impediments to avoid conflicts; using activity schedules, corridors, and buffer zones to avoid conflicts; coordinating Federal and State planning and permit processes to reduce conflicts; and providing compensation for unavoidable conflicts.

Key Words: Industrial minerals; Mineral sands; Phosphorites; Metalliferous oxides; Hydrothermal deposits; Dissolved minerals; Scraping; Excavating; Tunneling; Fluidizing; Commercial and recreational fisheries; Local economies; Regional economies; Cultural resources; Human resources.

Entry Number: 0041.

Citation: Hirota, J. 1981. Potential effects of deep-sea minerals mining on macrozooplankton in the north Equatorial Pacific. *Mar. Min.* 3(1/2):19-57.

Type(s) of Study: Field; Laboratory.

Geographic Location(s): Pacific Ocean.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Deep seabed.

Mineral(s): Metalliferous oxides.

Type(s) of Mining Operation(s): Scraping.

Environmental Resource(s): Water quality; Neuston; Plankton.

Date(s) of Study: 1977 to 1980.

Study Technique(s): The study investigated the potential effects of discharges from deep sea mining on macrozooplankton in the North Equatorial Pacific Ocean. Particle size distribution, concentration of trace metals, and the total load of particulates in mining discharges were measured during a test mining program. Laboratory experiments were conducted to determine the effects of particulate material on zooplankton. Test organisms were exposed to mixtures of ambient seawater and mining discharge particulates for periods ranging from 24 to 48 h. Mortality was determined and fecal pellets were collected for elemental composition during the experiment. Energy Dispersive Analysis by X-Rays (EDAX) was used to analyze fecal pellets.

Conclusion(s): The effect of mining discharge particulates on zooplankton were found to be minimal. The mortality rates in experimental populations were not significantly different from the controls over a range of particulate levels. The EDAX method was reported to be useful in discriminating between fecal pellets produced from natural particulates and those produced from mining discharge material. The report also provided data on fecal pellet production rates, pellet sizes, and sinking speeds. Using these data, the authors estimated the downward flux from the activities of filter feeding copepods. The authors, further speculating on the environmental impacts of large-scale commercial mining operations, determined that surface discharge of deep sea mining wastes would have some deleterious effect on the pelagic community. A recommendation for further intensive study of the subject was made.

Key Words: Metalliferous oxides; Scraping; Water quality; Neuston; Plankton.

Entry Number: 0042.

Citation: Hirsch, N. D., L. H. DiSalvo, and R. Peddicord. 1978. *Effects of dredging and disposal on aquatic organisms.* Technical Report DS-78-5. Vicksburg, MS: U.S. Army Corps of Engineers, Waterways Experiment Station.

Type(s) of Study: Review; Field; Laboratory.

Geographic Location(s): Worldwide.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Continental shelf; Coastal; Estuarine; Freshwater.

Mineral(s): Industrial minerals.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Geology; Water quality; Plankton; Nekton; Benthos; Sensitive habitats; Commercial and recreational fisheries.

Date(s) of Study: Not applicable.

Study Technique(s): This document reviewed the literature and incorporated the results of two field and four laboratory research projects on the effects of dredging and disposal on aquatic organisms. Field projects concerned 1) recolonization by infauna of a dredged area in Monterey Bay, California; and 2) effects of fluid mud from dredging on benthic organisms in the James River, Virginia. Laboratory tests assessed the 1) ability of benthic organisms to move through an overburden of dredged material; 2) effects of suspended sediment on organisms; 3) availability and uptake of trace metals by suspension feeding organisms; and 4) uptake of oil and grease by benthic organisms.

Conclusion(s): Direct effects of dredging and disposal were restricted to the immediate areas of operation and included removal of organisms at the dredging site and burial at the disposal site. Recovery of impacted sites occurred over periods of weeks, months, or years depending on the type of environment. Disturbed sites may be recolonized by opportunistic species (not normally the ecological dominants) from adjacent undisturbed sites. With the exception of natural systems requiring clear water (such as coral reefs and some aquatic plant communities), dredging-induced turbidity should not be of major ecological concern. Sediment-associated heavy metals and hydrocarbons appeared tightly bound to sediment particles and there appeared to be minimal uptake into tissues. The experimental results suggested that indirect (long-term and sublethal) effects of dredging and disposal will be minimal. A whole-sediment bioassay using sensitive test organisms should be used to identify site-specific toxicity problems prior to dredging.

Key Words: Industrial minerals; Scraping; Excavating; Geology; Water quality; Plankton; Nekton; Benthos; Sensitive habitats; Commercial and recreational fisheries.

Entry Number: 0043.

Citation: Hu, V. J. H. 1981. Ingestion of deep-sea mining discharge by five species of tropical copepods. *Water, Air, Soil Pollut.* 15:433-440.

Type(s) of Study: Laboratory.

Geographic Location(s): Kanoehe Bay, Hawaii, United States.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Deep seabed.

Mineral(s): Metalliferous oxides.

Type(s) of Mining Operation(s): Scraping.

Environmental Resource(s): Water quality; Plankton.

Date(s) of Study: Unavailable.

Study Technique(s): The study investigated the potential effects of deep sea mining discharge on zooplankton. The elemental contents of fecal pellets from five tropical copepods exposed to mining discharge were compared to controls. Test organisms were collected from offshore of Kanoehe Bay, Hawaii and brought to the laboratory where they were exposed to mixtures of ambient seawater and mining discharge for 48 h in one liter containers. Fecal pellets from the test and control aquaria were collected, preserved, embedded in resin, and sanded for Energy Dispersive Analysis of X-Rays (EDAX) analysis. The elemental contents of fecal pellets were then compared.

Conclusion(s): Results from the study revealed differences in uptake of mining discharge among the test copepods. Three species showed evidence of uptake, one species showed possible uptake, and a third species showed no uptake. The ingestion of mining discharge by zooplankton is thought to speed up the removal of particulates from the water column. The applicability of the EDAX method to the study of fecal pellets was also discussed.

Key Words: Metalliferous oxides; Scraping; Water quality; Plankton.

Entry Number: 0044.

Citation: Hurme, A. K., and E. J. Pullen. 1988. Biological effects of marine sand mining and fill placement for beach replenishment: Lessons for other uses. *Mar. Min.* 7(2):123-136.

Type(s) of Study: Review.

Geographic Location(s): Worldwide.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Coastal; Estuarine.

Mineral(s): Industrial minerals.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Geology; Physical oceanography; Water quality; Plankton; Nekton; Benthos; Threatened and endangered species; Sensitive habitats; Commercial and recreational fisheries.

Date(s) of Study: Not applicable.

Study Technique(s): Literature pertaining to impacts of nearshore sand mining and deposition on organisms and physical characteristics were reviewed. Topics discussed included beach and nearshore environments and organisms, beach replenishment, biological effects of offshore borrowing, current concerns about impacts of offshore sand and gravel mining on marine benthos, and guidelines for planning ecologically sound offshore mining projects.

Conclusion(s): Based on what is known about ecological impacts of beach nourishment and nearshore borrow areas, nearshore and offshore mining operations should not create long-term adverse impacts on indigenous organisms or their physical environment; inherent in this determination are several factors, including appropriate site selection, proper timing, specific operational techniques, and adequate monitoring. Dredging projects should be scheduled to avoid important benthic resources (i.e, corals and seagrasses) and peak spawning seasons. Sediment should be taken from broad, shallow pits in areas with actively shifting bottom, leaving a sufficient surficial layer of similar material for recolonization by benthic species.

Key Words: Industrial minerals; Scraping; Excavating; Geology; Physical oceanography; Water quality; Plankton; Nekton; Benthos; Threatened and endangered species; Sensitive habitats; Commercial and recreational fisheries.

Entry Number: 0045.

Citation: International Council for the Exploration of the Sea (ICES). 1975. Report of the working group on effects on fisheries of marine sand and gravel extraction. In *International Council for the Exploration of the Sea, Marine Environmental Quality Committee*, Cooperative Research Report No. 46.

Type(s) of Study: Review.

Geographic Location(s): Belgium; Denmark; Finland; France; Ireland; Netherlands; Norway; Sweden; United Kingdom.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Continental shelf; Coastal.

Mineral(s): Industrial minerals.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Geology; Water quality; Plankton; Nekton; Benthos; Commercial and recreational fisheries.

Date(s) of Study: April 1974.

Study Technique(s): The International Council for the Exploration of the Sea (ICES) working group on the effects on fisheries of marine sand and gravel extraction convened at the Fisheries Laboratory, Lowestoft, England on 2 to 4 April 1974. This report details the proceedings of that meeting. The working group synthesized available information to identify the many possible effects dredging will have on fisheries, then suggested how future research may be conducted to fill gaps in knowledge.

Conclusion(s): Every effort should be made by the working group to delineate herring spawning grounds in the areas slated for mining efforts. All mining proposals should be reviewed by council members, especially when fisheries questions or issues arise. Member countries should strive to pool their scientific resources when evaluating the impacts of aggregate mining on fisheries. It was also suggested that research on the effects of the *Lithothamnion* mining industry on fisheries should begin in France, Ireland, and the United Kingdom.

Key Words: Industrial minerals; Scraping; Excavating; Geology; Water quality; Plankton; Nekton; Benthos; Commercial and recreational fisheries.

Entry Number: 0046.

Citation: International Council for the Exploration of the Sea (ICES). 1977. Second report of the ICES working group on effects on fisheries of marine sand and gravel extraction. In *International Council for the Exploration of the Sea, Marine Environmental Quality Committee*, Cooperative Research Report No. 64.

Type(s) of Study: Review.

Geographic Location(s): Belgium; Denmark; Finland; France; Ireland; Netherlands; Norway; Sweden; United Kingdom.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Continental shelf; Coastal.

Mineral(s): Industrial minerals.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Geology; Water quality; Plankton; Nekton; Benthos; Commercial and recreational fisheries.

Date(s) of Study: December 1975.

Study Technique(s): The ICES working group on effects on fisheries of marine sand and gravel extraction met at the Netherlands Institute for Fisheries on 9 to 10 December 1975. This report details the proceedings of that meeting. Working group members identified the most important areas of concern, reviewed current research in these areas, and suggested how future research may be conducted to fill gaps in knowledge.

Conclusion(s): Effects of dredging on fisheries included direct damage to fishing gear (lines, nets, and other gear), indirect damage affecting the efficiency of fishing gear (scarring of the seafloor), direct effects on fish stocks (destruction of spawning grounds, egg deposition sites, and benthic food items), and indirect effects on fish stocks (influence of turbidity on fish gills, visual feeding, and photosynthesis). Future research efforts should be organized under the same headings. It was recommended that ICES member countries delineate herring spawning grounds; seek review of the council on all proposals to extract sand and gravel in their sectors of the continental shelf; pool information and results of research programs; determine the effects of dredging for *Lithothamnion* on fisheries; and move toward the adoption of rigorous codes for dredging operations.

Key Words: Industrial minerals; Scraping; Excavating; Geology; Water quality; Plankton; Nekton; Benthos; Commercial and recreational fisheries.

Entry Number: 0047.

Citation: International Council for the Exploration of the Sea (ICES). 1979. Third report of the working group on effects on fisheries of marine sand and gravel extraction. In *International Council for the Exploration of the Sea, Marine Environmental Quality Committee*, C.M. 1979/E:3.

Type(s) of Study: Review.

Geographic Location(s): Belgium; Denmark; Finland; France; Ireland; Netherlands; Norway; Sweden; United Kingdom.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Continental shelf; Coastal.

Mineral(s): Industrial minerals.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Geology; Water quality; Plankton; Nekton; Benthos; Commercial and recreational fisheries.

Date(s) of Study: March 1979.

Study Technique(s): This report summarizes results from the third meeting of the ICES working group on effects on fisheries of marine sand and gravel extraction. The report provides an update from the member countries on their marine sand and gravel extraction activities, regulatory mechanisms, research programs, and methods for minimizing impacts of extraction activities on fisheries. The group also reviewed the progress on developing seabed charts and the reaction of the sand and gravel industry to the first working group report. The group also developed recommendations to be adopted by the member countries. Appendices contained tables on marine sand and gravel production in the ICES member countries and figures illustrated areas where current extraction activities are being pursued.

Conclusion(s): Collation and synthesis of information on marine sand and gravel resources and dredging activities is still required by the working group to further its activities. Specific required products include 1) a master chart showing the areas of seabed covered by all existing charts of surface sediment within the ICES area; and 2) a bibliography of dredging activities from each member country.

Key Words: Industrial minerals; Scraping; Excavating; Geology; Water quality; Plankton; Nekton; Benthos; Commercial and recreational fisheries.

Entry Number: 0048.

Citation: Jumars, P. A. 1981. Limits in predicting and detecting benthic community responses to manganese nodule mining. *Mar. Min.* 3(1/2):213-229.

Type(s) of Study: Review.

Geographic Location(s): Pacific Ocean.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Deep seabed.

Mineral(s): Metalliferous oxides.

Type(s) of Mining Operation(s): Scraping.

Environmental Resource(s): Benthos.

Date(s) of Study: Not applicable.

Study Technique(s): Available data on deep sea biota (macrofauna and megafauna) were reviewed and used to identify problems with detecting impacts of manganese nodule mining on benthic communities.

Conclusion(s): Accurate prediction or detection of the responses of benthic communities to manganese nodule mining is limited by the available data. Due to a basic lack of life history information for deep sea organisms, data on diet, population dynamics, modes and rates of dispersal, food web relationships, and successional rates are limited. Animals in the path of a nodule collector will suffer high mortalities. Populations which depend on manganese nodules as attachment substrata will be very slow to recover (> 1,000 year), as will food-web members dependent on this epifauna. Mobile scavengers (i.e., fishes, amphipods, and shrimps) will exploit a new temporary food source in the form of injured and displaced animals, but will shift to carnivory when mining efforts cease. Suspension and surface deposit feeders will be most affected by mining-induced resuspension and redeposition. The extent of this effect will depend on the food value of the resuspended material.

Key Words: Metalliferous oxides; Scraping; Benthos.

Entry Number: 0049.

Citation: Kaplan, E. H., J. R. Welker, and M. G. Kraus. 1974. Some effects of dredging on populations of macrobenthic organisms. *Fish. Bull.* 72(2):445-480.

Type(s) of Study: Field.

Geographic Location(s): Long Island, New York, United States.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Estuarine.

Mineral(s): Industrial minerals.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Geology; Physical oceanography; Water quality; Plankton; Benthos; Commercial and recreational fisheries.

Date(s) of Study: 1966 to 1967.

Study Technique(s): The effects of dredging were determined for epifaunal and infaunal populations in Goose Bay, a shallow bay on Long Island, New York. Sampling was conducted both before and after dredging occurred. A series of sampling stations was established within the subtidal portions of the bay which was divided into zones of high, medium, and low current velocities. Transects were established within each current zone and within intertidal areas. Sampling by suction-corer was completed along transects. Epifaunal and infaunal samples were preserved in formalin, sorted, and counted. Standing crop was estimated by weighing wet and oven-dried samples. The effects of dredging on the surrounding marsh due to dumping of spoils were also noted.

Conclusion(s): Dredging significantly reduced the number of species, densities, and standing crop of epifauna and infauna. Of particular note were reduced densities and standing crop for the clam *Mercenaria mercenaria* in the dredged channel and within the bay. Analysis of variance showed that there were no significant effects of season or sediment type (and their interactions) on biomass. Though there was recovery of *M. mercenaria* through time, macrobenthic biomass had not returned to pre-dredged levels after 11 months. Productivity was reduced from 89.87 $g/m^2/yr$ to 31.18 $g/m^2/yr$ due to the dredging. The reduction in number of species and population density both within the whole bay and within the channel due to dredging was confirmed by chi-square analysis.

Key Words: Industrial minerals; Scraping; Excavating; Geology; Physical oceanography; Water quality; Plankton; Benthos; Commercial and recreational fisheries.

Entry Number: 0050.

Citation: Kaplan, E. H., J. R. Welker, M. G. Kraus, and S. McCourt. 1975. Some factors affecting the colonization of a dredged channel. *Mar. Biol.* 32:193-204.

Type(s) of Study: Field.

Geographic Location(s): Goose Bay, Long Island, New York, United States.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Estuarine.

Mineral(s): Industrial minerals.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Geology; Physical oceanography; Water quality; Benthos.

Date(s) of Study: 1966 to 1968.

Study Technique(s): The paper describes an evaluation of colonization patterns within a shallow coastal bay following channel dredging. Several sampling stations were established adjacent to the channel and monitored before and after dredging activities. Epifauna and infauna were collected by suction sampler, preserved in formaldehyde, sorted, identified, counted, and measured for biomass. Sediment samples were also taken for particle size analysis. Population data were used to estimate diversity indices; two-way analysis of variance was used to determine sources of variation.

Conclusion(s): The study revealed a number of effects attributed to dredging. The density and standing crop of macrobenthos remained significantly lower than pre-dredging levels after 11 months. Colonization of the dredged area started with larger, mobile benthic organisms such as polychaetes and crabs. Recovery was slower in silt and mud sediments, as compared to sediments with a prevailing sand component. Numerically dominant populations found within the pre-dredging environment recovered more slowly than the less common organisms. Due to modification of the tidal velocities in the channel, sediment distributions within the bay were altered. While the species diversity in silt and mud regions did not return to pre-dredge levels after 11 months, species diversity in sandy regions was higher than pre-dredge levels.

Key Words: Industrial minerals; Scraping; Excavating; Geology; Physical oceanography; Water quality; Benthos.

Entry Number: 0051.

Citation: Kay, S. H. 1984. Potential for biomagnification of contaminants within marine and freshwater food webs. *Technical Report D-84-7*. Vicksburg, MS: U.S. Army Corps of Engineers, Waterways Experiment Station.

Type(s) of Study: Review.

Geographic Location(s): Worldwide.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Coastal; Estuarine; Freshwater.

Mineral(s): Industrial minerals.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Water quality; Neuston; Plankton; Nekton; Benthos; Commercial and recreational fisheries.

Date(s) of Study: Not applicable.

Study Technique(s): This literature review concerned biomagnification of toxic heavy metals and organic contaminants in gill-breathing species within marine and freshwater food webs. The review was based on the need to evaluate potential ecological effects of dredging activities, particularly open-water disposal, which would resuspend sediments. The toxicity and biomagnification potential of arsenic, cadmium, chromium, copper, lead, mercury, nickel, selenium, silver, tin, and zinc were evaluated. Polychlorinated biphenyls, DDT and its derivatives, dieldrin, endrin, kepone, mirex, atrazine, endosulfan, lindane, chlorinated phenols, chlorinated benzenes, and polynuclear aromatic hydrocarbons were also evaluated. Suggestions for future research were identified.

Conclusion(s): Biomagnification was found to be a limited phenomenon in marine and freshwater systems. Most heavy metals and organic compounds do not biomagnify through several trophic levels in these ecosystems. Biomagnification was least evident in trace metals, with the exception of methyl-mercury. Of the toxic contaminants evaluated, PCBs, benzo[a]pyrene, naphthalene, and possibly, kepone and mirex have the greatest biomagnification potential. Open-water disposal would not create significant ecological effects attributed to the biomagnification of trace metals and toxics released from resuspended sediments. Most available data indicate a weak potential for biomagnification. The poor experimental design upon which these studies were based made comparisons and extrapolation untenable. Laboratory data which identify the biomagnification potential of specific compounds need to be confirmed by field data. Very specific recommendations for improving the quality of laboratory and field data were provided. A substantial tabular data summary was provided.

Key Words: Industrial minerals; Scraping; Excavating; Water quality; Neuston; Plankton; Nekton; Benthos; Commercial and recreational fisheries.

Entry Number: 0052.

Citation: Lavelle, J. W., and E. Ozturgut. 1981. Dispersion of deep-sea mining particulates and their effect on light in ocean surface layers. *Mar. Min.* 3(1/2):185-212.

Type(s) of Study: Model.

Geographic Location(s): Pacific Ocean.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Deep seabed.

Mineral(s): Metalliferous oxides.

Type(s) of Mining Operation(s): Scraping.

Environmental Resource(s): Water quality; Plankton; Benthos.

Date(s) of Study: March and April 1978.

Study Technique(s): Theoretical models were developed to predict the dispersion of particulates from deep sea mining wastes and their effects on light in surface layers of the ocean. The role of the pycnocline in hindering the settlement of particulates was also evaluated. In the absence of sufficient data, only the order of the length scales of dispersion was attempted. Dispersion models were based on conservation of mass principles using assumptions of homogeneity in diffusivity. The prediction of effects of the discharge plume on light in the surface layer was based on the exponential attenuation of light intensity as a function of particulate concentration. Based on the dispersion model, the patterns in reductions of light intensity as they affect phytoplankton production were estimated.

Conclusion(s): The study suggested that there would be no accumulation of particulates at the pycnocline. When extrapolated to commercial mining conditions, study findings suggested that the plume would extend approximately 100 km from the site; lateral dimensions of the plume (width) were estimated at 30 to 40 km. Assuming an advection speed of 25 cm/s, it was estimated that five days would be required for the mean settling size to pass through the upper 100 m layer. Some degree of light reduction in the surface layer would be expected to extend a similar distance from the mining site. Due to the mobility of the mining platform, the light reductions are not expected to last for more than 80 to 100 h. Due to the insufficient nature of the data used in the study, the authors cautioned that this assessment must be regarded as tentative.

Key Words: Metalliferous oxides; Scraping; Water quality; Plankton; Benthos.

Entry Number: 0053

Citation: Lavelle, J. W., E. Ozturgut, S. A. Swift, and B. H. Erickson. 1981. Dispersal and resedimentation of the benthic plume from deep-sea mining operations: A model with calibration. *Mar. Min.* 3(1/2):59-93.

Type(s) of Study: Field; Model

Geographic Location(s): Pacific Ocean.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Deep seabed.

Mineral(s): Metalliferous oxides.

Type(s) of Mining Operation(s): Scraping.

Environmental Resource(s): Geology; Water quality; Plankton; Benthos

Date(s) of Study: March and April 1978.

Study Technique(s): The study developed techniques for determining the dispersal and resedimentation of waste material from deep sea mining of manganese nodules in the North Pacific. Pilot scale mining tests were conducted by Ocean Management, Inc. in March and April 1978 in the North Pacific near 9°N and 151°W. An analytical model using conservation of mass principles was used to describe dispersion of particulate material during mining activities. Bottom photographs of areas adjacent to the mining site and along presumed dispersion and resedimentation areas were used to estimate the distance and thickness of resedimented material. Water samples and moored nephelometers were also used to estimate concentrations and timing of movement of the discharge plume. Data derived from the field measurements were fitted to a dispersion model developed for the study.

Conclusion(s): Water samples and nephelometer profiles showed that particulate loads were elevated above ambient levels (6 μg/l) up to 50 m above the bottom due to mining. After 5.5 to 8.5 days, particulate loads of 10 μg/l were observed 2 m above the bottom. The study produced an estimate of the range in settling velocities for particulates. When used to extrapolate the effects of commercial mining activities, the model can be used to estimate the horizontal scales of the benthic plume and rates of resedimentation. The model prediction indicated that while resedimentation greater than 1 mm is not expected at distances more than 400 m from the mining track, the benthic plume, characterized by particulate concentrations elevated above ambient levels, may be expected to be detectable up to 160 km downstream from the mining track after 45 days.

Key Words: Metalliferous oxides; Scraping; Geology; Water quality; Plankton; Benthos.

Entry Number: 0054.

Citation: Levin, J. 1971. *A literature review of the effects of sand removal on a coral reef community*. University of Hawaii Sea Grant Report TR-71-01.

Type(s) of Study: Review.

Geographic Location(s): Hawaii, United States.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Coastal.

Mineral(s): Industrial minerals.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Water quality; Plankton; Nekton; Benthos; Sensitive habitats.

Date(s) of Study: Not applicable.

Study Technique(s): The document summarizes the results of a literature review to assess the environmental effects of sand mining on coral reef communities. Recommendations to minimize the impact of sand dredging on coral communities were developed. In addition to the summary, abstracts of selected references and a partially annotated bibliography were produced.

Conclusion(s): Dredging activities within Hawaii's coastal waters can cause significant degradation of coral communities. Detrimental effects are caused by the resuspension and deposition of sediments, modification of the sea bottom, and possible releases of chemicals, nutrients, and toxic materials from disturbed sediments. Coral growth is primarily affected by the resuspension and deposition of sediments which reduces light intensity required by symbiotic zooxanthellae. In addition, sediments smother and abrade corals and prevent settlement of planula larvae. The reduction in light intensity may also reduce productivity of coral community plants such as seagrasses and macroalgae. Fish and shellfish may be injured by suspended sediments similarly. The release of nutrients and toxics from the sediments can also be a cause for change in coral communities. The ultimate effects of dredging will depend upon the type and duration of environmental changes that are created, the characteristics of the site, the type of community proximal to the dredging activity, and the prevailing meteorologic and oceanic conditions.

Key Words: Industrial minerals; Scraping; Excavating; Water quality; Plankton; Nekton; Benthos; Sensitive habitats.

Entry Number: 0055.

Citation: Levin, L. 1984. *Life history and dispersal patterns in a dense infaunal polychaete assemblage: Community structure and response to disturbance. Ecology* 65(4):1185-1200.

Type(s) of Study: Field; Laboratory.

Geographic Location(s): Mission Bay, San Diego, California, United States.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Estuarine.

Mineral(s): Not applicable.

Type(s) of Mining Operation(s): Not applicable.

Environmental Resource(s): Plankton; Benthos.

Date(s) of Study: 1978 to 1981.

Study Technique(s): The role of life history and the dispersal patterns of the polychaete infauna of shallow, muddy intertidal areas in Mission Bay, California was studied to determine how such communities respond to disturbance. Field and laboratory studies, including plankton sampling, sediment coring, and settlement experiments, were conducted at three sites with differing tidal regimes. The life history of five polychaete species was investigated. Recruitment characteristics and dispersal ability (i.e., in terms of adult size, brooding, and length of planktonic stages) were determined. Small-scale disturbance was simulated by artificially defaunating small patches of the sediment. A severe storm and an accompanying spill of raw sewage into the study site provided an opportunity for studying large-scale disturbance.

Conclusion(s): Study results indicated that the rates and mechanisms of recolonization were governed by larval development, settlement, and mobility patterns. The ability of the polychaete species to persist in the face of disturbance was explained by the annual life cycles and the ability of the organisms to move in response to small-scale disturbance. All except one species was found regularly in the plankton. There were differences in the numerically dominant species in each of the three sites. The numerically dominant species in the sediments were also reflected in the plankton and in the settlement and dispersal patterns that were observed. These polychaetes reproduce throughout the year with small brood sizes. Brood protection, variable planktonic periods, and post-larval dispersal ability (i.e., an ability to disperse after passing through various larval stages) allow them to respond to small-scale disturbance. The polychaete species which are able to respond to large-scale disturbance are characterized by long-distance dispersal ability, the latter of which is related to longer-lived and more seasonal larval stages. The authors concluded that small-scale colonization ability remains distinct from long-distance dispersal.

Key Words: Plankton; Benthos.

Entry Number: 0056

Citation: Levin, L. A., and C. R. Smith. 1984. Response of background fauna to disturbance and enrichment in the deep sea: A sediment tray experiment. *Deep-Sea Res.* 31(11):1277-1285.

Type(s) of Study: Field.

Geographic Location(s): Santa Catalina Basin, California, United States

OCS Planning Area(s): Southern California.

Type(s) of Environment(s): Deep seabed.

Mineral(s): Not applicable.

Type(s) of Mining Operation(s): Not applicable.

Environmental Resource(s): Benthos.

Date(s) of Study: January to June 1982.

Study Technique(s): The response of the benthic community in a deep sea basin to disturbance and organic enrichment of the sediment was studied. Sediment from the Santa Catalina Basin was collected by box core, placed in trays, and then frozen to defaunate the sediment. One set of trays was left untreated, one set was enriched with kelp material and oxidized, and the last set was enriched with kelp material and left anoxic. Sediment trays were equipped with lids which could be opened and closed remotely. Trays were installed on a frame which was deployed over the study site. The frame settled to the bottom and the lids opened automatically. After a 140-day incubation, weights were released which closed the lids and allowed the frame to rise to the surface for recovery. Subcores were taken from each tray. Dredge samples were also taken to determine densities of natural benthic macrofaunal populations.

Conclusion(s): Results indicated slower recolonization rates in sediment trays when compared to similar shallow water experiments, an observation noted in other studies. After incubation, the macrofaunal density in the unenriched tray was 10% of that of the surrounding seafloor. Both juveniles and mature individuals of the numerically dominant species of the seafloor community (i.e., the polychaetes *Tauberia oculata*, *Tharyx* sp., and *Tharyx monolaris*, and an amphipod) were present. The oxidized, enriched tray only contained one organism, an unidentified mite. The anoxic, enriched tray contained two dorvilleid polychaetes. The authors suggested that their study supports the hypothesis that disturbance is important to the ecology of the numerically dominant species in the Santa Catalina Basin.

Key Words: Benthos.

Entry Number: 0057.

Citation: Loosanoff, V. L. 1962. Effects of turbidity on some larval and adult bivalves. *Proc. 14th Annual Session Gulf Carib. Fish Inst.*. 80-95.

Type(s) of Study: Laboratory.

Geographic Location(s): Long Island Sound, United States.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Coastal; Estuarine.

Mineral(s): Industrial minerals; Mineral sands; Phosphorites; Metalliferous oxides; Hydrothermal deposits; Dissolved minerals.

Type(s) of Mining Operation(s): Scraping; Excavating; Tunneling; Fluidizing.

Environmental Resource(s): Benthos; Commercial and recreational fisheries.

Date(s) of Study: Unavailable.

Study Technique(s): Experiments were performed to determine the effects of turbidity on adults and larvae of the eastern oyster (*Crassostrea virginica*) and the clam *Venus mercenaria*. Test animals were placed in chambers with flow-through seawater of constant salinity (27 ppt) and varying temperature (from 17 to 23°C). Test animals were placed in chambers at least 12 h before the start of experiments. Experimental turbidity levels were achieved using fine silt, kaolin, calcium carbonate, and Fullers earth. Shell movement and rate of water pumping by adult bivalves under normal conditions and after turbidity manipulations were recorded on kymographs. Exposures of adult molluscs were variable, lasting from three hours to several weeks.

Conclusion(s): Oysters were sensitive to all turbidity-causing substances to some degree. Stress or disturbance was recognized by the increased rate of water pumping by the bivalves. When silt laden water was substituted for clear seawater, normal activity resumed quickly. In some instances, small increases in turbidity resulted in favorable reactions by the larvae of clams and oysters which were reared under different turbidity regimes for as long as two weeks.

Key Words: Industrial minerals; Mineral sands; Phosphorites; Metalliferous oxides; Hydrothermal deposits; Dissolved minerals; Scraping; Excavating; Tunneling; Fluidizing; Benthos; Commercial and recreational fisheries.

Entry Number: 0058.

Citation: Lunz, J. D., D. G. Clarke, and T. J. Fredette. 1984. Seasonal restrictions on bucket dredging operations. In *Dredging and Dredged Material Disposal, Vol. 1*, eds. R. L. Montgomery and J. W. Leach, 371-383. New York, NY: American Society of Civil Engineers.

Type(s) of Study: Review.

Geographic Location(s): United States.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Continental shelf; Coastal; Estuarine.

Mineral(s): Industrial minerals; Mineral sands.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Water quality; Plankton; Nekton; Benthos; Sensitive habitats; Commercial and recreational fisheries.

Date(s) of Study: Not applicable.

Study Technique(s): Available published and unpublished literature concerning effects of suspended sediments on aquatic organisms was reviewed. Alternative strategies were proposed to provide managers with more realistic criteria from which to regulate dredging operations.

Conclusion(s): Results indicated that available studies were not standardized and often inconsistent or contradictory. Sufficient information exists, however, to suggest that most life history stages of target organisms are very tolerant of elevated suspended sediment concentrations. Therefore, instead of using mandatory seasonal dredging windows as a means of regulating dredging operations, a list of questions to solicit specific information about the project and location should initially be addressed. The questions require information about contaminant and physical properties of the sediment at the dredging location, the size and shape of the water body to be dredged, prevalent local hydrodynamic conditions, the occurrence of nearby important benthic and planktonic communities, proximity to a natural or dredged channel, and the natural turbidity characteristics of the water body.

Key Words: Industrial minerals; Mineral sands; Scraping; Excavating; Water quality; Plankton; Nekton; Benthos; Sensitive habitats; Commercial and recreational fisheries.

Entry Number: 0059.

Citation: Macek, K. J., S. R. Petrocelli, and B. H. Sleight, III. 1979. Considerations in assessing the potential for, and significance of, biomagnification of chemical residues in aquatic food chains. In *Aquatic Toxicology*, eds. L. L. Marking and R. A. Kimerle, 251-268. Philadelphia, PA: American Society for Testing Materials.

Type(s) of Study: Review; Laboratory.

Geographic Location(s): Not applicable.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Freshwater.

Mineral(s): Not applicable.

Type(s) of Mining Operation(s): Not applicable.

Environmental Resource(s): Water quality; Plankton; Nekton.

Date(s) of Study: Unavailable.

Study Technique(s): Bluegill sunfish were exposed to three organic toxic compounds for a period of 35 days to assess the relative importance of dietary and aquatic exposure to accumulation of these compounds in tissues. The accumulation, or bioconcentration, of the organic toxics in bluegills was measured using compounds labelled with radionuclides. One set of bluegills was maintained in water containing radiolabelled toxic compounds and fed with normal food items. Another set was exposed similarly but fed with loaded food items containing the toxic compounds. The concentration of radiolabelled compounds in each set of bluegills were then compared. The paper also reviewed the results of other studies on the subject.

Conclusion(s): Results indicated that the concentration of toxic organic compounds in tissues cannot be explained solely by aquatic exposure or dietary exposure. The concentrations of toxic organic compounds in bluegill tissues were not statistically different between bluegills exposed to the toxic compounds in waters alone and those which were also fed with food containing the toxic compounds. Review of the literature indicated that only DDT showed a potential for causing increases in tissue concentrations in aquatic organisms through diet. For most toxic chemicals, the contribution of residues from dietary sources to the total body burden is statistically indistinguishable from the contribution from aquatic exposure or bioconcentration.

Key Words: Water quality; Plankton; Nekton.

Entry Number: 0060.

Citation: Mackin, J. G. 1961. Canal dredging and silting in Louisiana bays. In *Publications of the Institute of Marine Science, Vol.* 7:262-319. Port Aransas, TX: The University of Texas, Institute of Marine Science.

Type(s) of Study: Review; Field; Laboratory.

Geographic Location(s): Louisiana, United States.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Coastal; Estuarine.

Mineral(s): Industrial minerals.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Geology; Physical oceanography; Water quality; Benthos; Sensitive habitats; Commercial and recreational fisheries.

Date(s) of Study: 8 to 16 June 1954; 8 to 11 January 1956; 22 to 23 March 1956.

Study Technique(s): Three dredging operations (i.e., two hydraulic dredges, one clam-shell dredge) were studied to determine resulting silt suspension and transport and turbidity changes. A coring method was developed to determine the rate, age, and origins of silt deposition. Extensive literature review was used for a full physio-chemical description of the study area. Legal claims arising from damages incurred from siltation from dredging operations were scrutinized.

Conclusion(s): Silt from dredge and fill operations was carried a maximum of 1,300 ft from the dredges. Silt dispersed rapidly by dilution and sedimentation. Turbidities within a few hundred feet of the discharge were within natural ranges (20 to 200 ppm). Oysters tested in turbidities between 5 and 700 ppm showed no harmful effects. Oxygen depletion associated with dredging operations was insufficient to produce oyster mortality in adjacent areas. Except when completely buried, oysters exhibited no detrimental effects from short-term dredge and fill activities. The oxygen requirements for the degradation of dead oysters was determined to be slightly greater than that required to support live oysters.

Key Words: Industrial minerals; Scraping; Excavating; Geology; Physical oceanography; Water quality; Benthos; Sensitive habitats; Commercial and recreational fisheries.

Entry Number: 0061.

Citation: Malme, C. I., B. Wursig, J. E. Bird, and P. Tyack. 1986b. *Behavioral responses of gray whales to industrial noise: Feeding observations and predictive modeling, environmental assessment of Alaskan continental shelf.* Report No. 6265. Prepared for the U.S. Department of Commerce, National Oceanic and Atmospheric Administration and U.S. Department of the Interior, Minerals Management Service. Cambridge, MA: BBN Laboratories, Inc.

Type(s) of Study: Field; Model.

Geographic Location(s): St. Lawrence Island, Alaska, United States.

OCS Planning Area(s): Norton Basin.

Type(s) of Environment(s): Deep seabed; Continental shelf; Coastal.

Mineral(s): Industrial minerals; Mineral sands; Phosphorites; Metalliferous oxides; Hydrothermal deposits; Dissolved minerals.

Type(s) of Mining Operation(s): Scraping; Excavating; Tunneling; Fluidizing.

Environmental Resource(s): Nekton; Marine mammals; Threatened and endangered species.

Date(s) of Study: 17 to 27 August 1985.

Study Technique(s): A two-phase program (field study and acoustic model study) was performed to assess the behavior of feeding gray whales to sounds generated by petroleum industry activities. Reactions of whales to playbacks of drillship and actual seismic (air gun) sound sources were assessed near St. Lawrence Island in the Bering Sea. Whale behavior data were obtained by observing focal whale groups, and recording surfacing-dive and blow information. Tracking of focal groups was conducted using a two-vessel triangulation method or a land-based theodolite when weather permitted. Data were collected before, during, and after sound stimuli were applied.

Conclusion(s): Field data showed that for the drillship stimulus, noise at 110 dB was the lowest level which may cause disturbance of feeding activity in gray whales. A level of 120 dB was considered the level which will probably cause avoidance of a feeding area by more than 50% of the local gray whale population. For air gun stimuli, a level of 163 dB was considered the level at which disturbance of feeding activity was possible. A level of 173 dB was established as the level at which avoidance of a feeding area by more than 50% of the local population could be expected.

Key Words: Industrial minerals; Mineral sands; Phosphorites; Metalliferous oxides; Hydrothermal deposits; Dissolved minerals; Scraping; Excavating; Tunneling; Fluidizing; Nekton; Marine mammals; Threatened and endangered species.

Entry Number: 0062.

Citation: Masch, F. D., and W. H. Espey, Jr. 1967. *Shell dredging: A factor in sedimentation in Galveston Bay.* Technical Report HYD 06-6702 CRWR-7. Univ. of Texas at Austin, Center for Research in Water Resources.

Type(s) of Study: Review; Field; Laboratory.

Geographic Location(s): Galveston Bay, Texas, United States.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Estuarine.

Mineral(s): Industrial minerals.

Type(s) of Mining Operation(s): Scraping; Excavating

Environmental Resource(s): Geology; Physical oceanography; Water quality; Benthos; Commercial and recreational fisheries.

Date(s) of Study: 1964 to 1965.

Study Technique(s): Impacts of shell dredging operations on sedimentation patterns within the Galveston Bay estuary were assessed by literature review, field, and laboratory studies. Water and sediment samples were collected using water samplers, traps, and corers at varying distances from dredging operations and under different tidal and weather conditions. Field studies were made to examine the effect of ship traffic on the movement of sediments and the movement of resuspended sediments as density currents. Laboratory studies were also conducted to determine the effects of current velocity and obstructions to flow on the movement of resuspended sediments.

Conclusion(s): Shell dredging operations increased suspended sediment concentrations by an order of magnitude over those caused by currents, wind and wave action, ship traffic, and ship swells. Dredging operations produced severe sediment conditions due to the sediment density layers which formed and moved through the estuary by gravity and currents. Below a concentration of 175 g/l, the density layers were subject to movement by gravity or tidal action. Laboratory and field results showed that obstructions to flow, such as trenches or dikes, can minimize sediment movement. Oyster reefs tended to deflect or resuspend sediment density layers. Deposition of suspended sediment in trenches was an effective way of minimizing sediment movement. Turbidity and sedimentation near important oyster reefs were also minimized by deepening old passes and opening new passes in blocked areas to increase current velocities. These techniques and the use of adequate distance criteria were expected to minimize the effects of shell dredging on commercially important reefs.

Key Words: Industrial minerals; Scraping; Excavating; Geology; Physical oceanography; Water quality; Benthos; Commercial and recreational fisheries.

Entry Number: 0063.

Citation: Matsumoto, W. M. 1984. *Potential impact of deep seabed mining on the larvae of tunas and billfishes*. NOAA-TM-NMFS-SWFC-44. Report prepared for National Oceanic and Atmospheric Administration, Division of Ocean Minerals and Energy, Southwest Fisheries Center Honolulu Laboratory, National Marine Fisheries Service.

Type(s) of Study: Review.

Geographic Location(s): Pacific Ocean.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Deep seabed.

Mineral(s): Metalliferous oxides.

Type(s) of Mining Operation(s): Scraping.

Environmental Resource(s): Physical oceanography; Water quality; Plankton; Nekton; Commercial and recreational fisheries.

Date(s) of Study: Not applicable.

Study Technique(s): To further examine the potential environmental impacts of deep sea mining activities, an assessment was made of the probable effects of discharged water on tuna and billfish eggs and larvae. Due to the lack of data, the assessment was based on available scientific literature concerning the effects of sedimentation and temperature on eggs and larvae. Using certain assumptions about the pattern of discharge and the density and distribution of eggs and larvae, an estimate was made of the number of tuna and billfish eggs and larvae that would be destroyed by surface discharge.

Conclusion(s): The discharge of mining waste to surface waters was not expected to produce significant effects. Minimal impacts to eggs and larvae were noted and attributed to increased sediment concentrations, reduced light availability, and changes in trace metals, dissolved oxygen, and salinity in the surface waters. Annual losses to the fisheries due to death of larvae from thermal shock from discharge water were estimated to represent 0.16% and 0.04% of the annual fishery for skipjack and yellowfin tuna, respectively.

Key Words: Metalliferous oxides; Scraping; Physical oceanography; Water quality; Plankton; Nekton; Commercial and recreational fisheries.

Entry Number: 0064.

Citation: Maurer, D. L., R. T. Keck, J. C. Tinsman, W. A. Leathem, C. A. Wether, M. Huntzinger, C. Lord, and T. M. Church. 1978. *Vertical migration of benthos in simulated dredged material overburdens, Vol. 1: Marine benthos.* Technical Report D-78-35. Final report prepared for Office, Chief of Engineers, U.S. Army, Washington, DC.

Type(s) of Study: Laboratory.

Geographic Location(s): United States.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Continental shelf; Coastal; Estuarine.

Mineral(s): Industrial minerals.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Benthos.

Date(s) of Study: Unavailable.

Study Technique(s): During a two-year study, the vertical migratory ability and survival of seven mobile benthic invertebrates of various taxonomic groups were tested by simulated dredge spoil burial. Sediment types were regulated, and pore and surface water temperatures and chemistry were monitored throughout several different experimental series. Experimental habitats included core tubes and 55-gal aquaria.

Conclusion(s): Mortality of test organisms generally increased with sediment depth (overburden), burial time, and degree of difference between the habitat sediment and overburden sediment. Migration of organisms within the sediment was more influenced by temperature than was mortality. Synergistic effects of experimental variables influenced migration and mortality. Many test species could vertically migrate through relatively thick sediment overburdens, particularly when similar to habitat sediment, but migratory ability was limited.

Key Words: Industrial minerals; Scraping; Excavating; Benthos.

Entry Number: 0065.

Citation: May, E. B. 1973. Environmental effects of hydraulic dredging in estuaries. *Alabama Mar. Resour. Bull.* 9(1):1-85.

Type(s) of Study: Review; Field.

Geographic Location(s): Mobile Bay, Alabama, United States.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Coastal; Estuarine.

Mineral(s): Industrial minerals.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Geology; Physical oceanography; Water quality; Nekton; Benthos; Sensitive habitats; Commercial and recreational fisheries.

Date(s) of Study: June 1969 to January 1973

Study Technique(s): Literature was reviewed to compare, contrast, and highlight findings from numerous dredging studies. During field work, data were gathered before, during, and after dredge work in Mobile Bay by a variety of methods. Turbidity, dissolved oxygen, pH, Eh, salinity, temperature, wind, currents, sedimentation, and sediment and water chemistry were evaluated. Biological collections were made. Sampling of sites was frequent during the study period.

Conclusion(s): Dredge spoil settled rapidly in open water, with no sediment transport exceeding normal levels more than 1,600 ft from a discharge. Limited, temporary reductions in the benthos were observed. Turbidity was within normal ranges a few hundred feet from the discharge. Quantity and quality of spoil and bottom configuration determined sediment transport paths and distances. Above-water discharges promoted rapid settling and consolidation of spoil. Materials in normal estuarine sediments had little effect on water quality. Biological uptake of deleterious components was not expected. Physical modifications to water flow patterns caused by spoil disposal could affect water quality. The application of limiting criteria in open estuary dredge work to protect water quality did not appear necessary.

Key Words: Industrial minerals; Scraping; Excavating; Geology; Physical oceanography; Water quality; Nekton; Benthos; Sensitive habitats; Commercial and recreational fisheries.

Entry Number: 0066.

Citation: Miller, J. M. 1974. Nearshore distribution of Hawaiian marine fish larvae: Effects of water quality, turbidity, and currents. In *The Early Life History of Fish*, ed. J. H. S. Blaxter, 217-231. New York, NY: Springer-Verlag.

Type(s) of Study: Field.

Geographic Location(s): Hawaii, United States.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Coastal.

Mineral(s): Industrial minerals; Mineral sands; Phosphorites; Dissolved minerals.

Type(s) of Mining Operation(s): Scraping; Excavating; Tunneling; Fluidizing.

Environmental Resource(s): Water quality; Plankton; Nekton; Commercial and recreational fisheries.

Date(s) of Study: 1972.

Study Technique(s): Nearshore and offshore larval fish surveys were conducted around Maui, Kauai, and Oahu, Hawaii. Nineteen nearshore (<10 m) locations either situated adjacent to major land developments or receiving major effluents were sampled. An additional 13 nearshore reference sites were also sampled. Samples were collected using a flow-metered net equipped with 505-μm mesh towed near the surface at each station during winter and summer months. Similar samples were taken in offshore waters 20 to 40 m deep. A second study was made around the offshore island of Molokini to investigate the effects of water flow on the number and variety of larvae found.

Conclusion(s): Inshore marine fish larvae were unevenly distributed around Maui, Kauai, and Oahu, Hawaii. Density, species number, and diversity were higher at shallow (<10 m) stations than deeper (>20 m) ones. Species composition of inshore larvae differed greatly from that of inshore adults. Many larval taxa collected in inshore waters were of mesopelagic or offshore origin. The abundance of inshore larvae from demersal eggs (i.e., Blenniidae) was inversely correlated with abundance of mesopelagic larvae. Although significant, the effects of shoreline developments were obscured by those of turbidity and water currents. Investigations from Molokini demonstrated the magnitude and location of the effect of island contact on the abundance of larvae. A 26-fold average increase in density of surface larvae occurred at the upstream edge of Molokini, while smaller increases appeared downstream.

Key Words: Industrial minerals; Mineral sands; Phosphorites; Dissolved minerals; Scraping; Excavating; Tunneling; Fluidizing; Water quality; Plankton; Nekton; Commercial and recreational fisheries.

Entry Number: 0067.

Citation: Millner, R. S., R. R. Dickson, and M. S. Rolfe. 1977. Physical and biological studies of a dredging ground off the East Coast of England. In *International Council for the Exploration of the Sea*, CM 1977/E:48. Fisheries Improvement Committee.

Type(s) of Study: Field.

Geographic Location(s): Southwold, England.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Continental shelf; Coastal.

Mineral(s): Industrial minerals.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Geology; Physical oceanography; Water quality; Nekton; Benthos; Commercial and recreational fisheries.

Date(s) of Study: Unavailable.

Study Technique(s): Physical and biological effects of trailer dredging were assessed using various study techniques. Sector scanning sonar was used to map and quantify dredge scars. Bottom currents were determined during periods of peak spring tides using s-rotors on frames placed approximately 28 to 152 cm above the bottom. A turbidity meter was used to examine natural turbidity (i.e., water sediment loads) in the study area. Abundance and diversity of the benthos was determined at study sites with at least triplicate 0.1 m^2/day grab samples. Samples were sieved to 1 mm. Subsamples were taken for sediment particle size analysis. Mobile epibenthic species and fish were collected in beam trawls. Long-lines were used to collect additional fish samples. Fish gut contents were compared to benthos collected.

Conclusion(s): Dredging was not uniform within the collection area. Dredge scars were 0.3 to 0.5 m in depth and were persistent due to limited bottom currents. Ambient currents were too slow to move particles greater than 6 mm diameter along the gravel bottom. Natural turbidity was high enough so that increases due to outwash fines had no significant effects. Benthos was generally reduced in dredged as opposed to undredged areas. It could not be determined that this difference was a direct effect of dredging, however, future analysis of pre-dredge samples should help with this determination. Gut contents of fish collected were compared to benthic organisms collected. The most common epibenthos collected were important components of fish diets.

Key Words: Industrial minerals; Scraping; Excavating; Geology; Physical oceanography; Water quality; Nekton; Benthos; Commercial and recreational fisheries.

Entry Number: 0068.

Citation: Motyka, J. M., and D. H. Willis. 1974. The effect of wave refraction over dredged holes. In *Proceedings, 14th Coastal Engineering Conference*, 615-625. Copenhagen, Denmark: American Society of Chemical Engineers.

Type(s) of Study: Model.

Geographic Location(s): United Kingdom.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Continental shelf; Coastal.

Mineral(s): Industrial minerals.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Geology; Physical oceanography; Water quality.

Date(s) of Study: Unavailable.

Study Technique(s): A numerical model was used to estimate the effect of wave refraction over dredged pits on the transport of sediment in the nearshore zone. The model was developed to 1) calculate breaking wave conditions from deep water wave conditions using refraction over the inshore seabed; 2) calculate the rate of alongshore sediment transport on the beach attributed to breaking wave conditions; 3) calculate changes in the beach plan shape; 4) account for the accretion and erosion which occurs over the inshore seabed; and 5) recalculate refraction and returns attributed to breaking waves.

Conclusion(s): The authors thought that the model overestimated the degree of erosion which would actually occur in nature. Beach erosion increased with increasing hole depth and decreasing original water depth. Beach erosion was negligible due to holes in water depths greater than half the length of normal waves, or a fifth of the length of extreme waves. The results suggested that, for the North Sea and English Channel coasts of Britain, the effects of wave refraction are minimal in depths >18 m.

Key Words: Industrial minerals; Scraping; Excavating; Geology; Physical oceanography; Water quality.

Entry Number: 0069.

Citation: Mustaffi, Z., and H. Amann. 1978. Ocean mining and projection of the marine environment in the Red Sea. In *Proceedings, 10th Annual Offshore Technology Conference*, 1199-1214.

Type(s) of Study: Review; Field.

Geographic Location(s): Red Sea; Saudi Arabia; Sudan.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Deep seabed.

Mineral(s): Metalliferous oxides.

Type(s) of Mining Operation(s): Fluidizing.

Environmental Resource(s): Geology; Physical oceanography; Water quality; Plankton; Benthos; Sensitive habitats; Regional economies.

Date(s) of Study: Not applicable.

Study Technique(s): The discovery of rich deposits of metalliferous muds in the deep portions of the seafloor of the Red Sea prompted concern from environmental and operational fronts. Extraction of these metals will require precautions to guard against environmental damage to the fragile systems found in the Red Sea. To evaluate potential methodologies for extraction of the metals and associated environmental impacts, a joint commission of Saudi and Sudanese scientists initiated a test mining program. The proposed mining methodology was fluidization, where fluidized muds are transported to the surface via pipeline. A series of current meters was installed to characterize the surface and near bottom currents in proposed mining areas. Baseline biological surveys were carried out in shallow coastal areas as well as the deeper portions of the Red Sea. Tests evaluating the surface disposal of mine tailings were also conducted.

Conclusion(s): The results of most aspects of the test mining project were not available at the time of publication. Preliminary current meter data showed unexpected north-flowing currents in the near bottom waters. The general pattern of surface flow in the Red Sea is southerly. Pristine coral reef areas were found to be nutrient-poor. Future studies will guide the development of technologies that will allow environmentally-sound extraction of the rich metal resources known from the depths of the Red Sea.

Key Words: Metalliferous oxides; Fluidizing; Geology; Physical oceanography; Water quality; Plankton; Benthos; Sensitive habitats; Regional economies.

Entry Number: 0070.

Citation: Myrberg, A. A., Jr. 1978. Ocean noise and the behavior of marine animals: Relationships and implications. In *Effects of Noise on Wildlife*, eds. J. L. Fletcher and R. G. Busnel, 169-208. New York, NY: Academic Press.

Type(s) of Study: Review.

Geographic Location(s): Worldwide.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Deep seabed; Continental shelf; Coastal; Estuarine.

Mineral(s): Industrial minerals; Mineral sands; Phosphorites; Metalliferous oxides; Hydrothermal deposits; Dissolved minerals.

Type(s) of Mining Operation(s): Scraping; Excavating; Tunneling; Fluidizing.

Environmental Resource(s): Nekton; Marine mammals; Threatened and endangered species; Commercial and recreational fisheries.

Date(s) of Study: Not applicable.

Study Technique(s): A review of the literature was used to illustrate, explain, and highlight various aspects of sound reception and production as related to marine fish and selected marine mammals, specifically the odontocete cetaceans and pinnipeds. Emphasis was placed on proven and theorized effects of natural and industrial acoustical noise on animals in the marine environment.

Conclusion(s): The acoustical sense of marine animals provides information on a variety of functions relative to food, competitors, potential mates, and predators. From the evidence presented, it was determined that background noise in the marine environment, particularly low frequency and more or less continuous sounds (as are produced by industrial activities), could interfere with the reception and production of bio-acoustical sound (communication) in soniferous marine life.

Key Words: Industrial minerals; Mineral sands; Phosphorites; Metalliferous oxides; Hydrothermal deposits; Dissolved minerals; Scraping; Excavating; Tunneling; Fluidizing; Nekton; Marine mammals; Threatened and endangered species; Commercial and recreational fisheries.

Entry Number: 0071.

Citation: Nichols, J. A., G. T. Rowe, C. H. Clifford, and R. A. Young. 1978. *In situ* experiments on the burial of marine invertebrates. *J. Sediment. Petrol.* 48(2):419-425.

Type(s) of Study: Field.

Geographic Location(s): Buzzards Bay, Massachusetts, United States.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Coastal; Estuarine.

Mineral(s): Industrial minerals; Mineral sands; Phosphorites; Metalliferous oxides; Hydrothermal deposits.

Type(s) of Mining Operation(s): Scraping; Excavating; Tunneling; Fluidizing.

Environmental Resource(s): Benthos.

Date(s) of Study: Unavailable.

Study Technique(s): Experiments concerning the effects of burial on natural infaunal assemblages were conducted in Buzzards Bay, Massachusetts. Bottom sediment was isolated in plexiglass boxes or tubes (coffee cans) and buried under controlled amounts of mud. Experiments lasted for 4-, 20-, or 24-h periods. Upon retrieval, cans or plexiglass boxes were subdivided into 5-cm vertical sections. All fractions were sieved through 0.42- and 0.297-mm mesh screens, then organisms were sorted, counted, and identified.

Conclusion(s): Most animals common to a soft-bottom community could escape a burial of 5 to 10 cm. At depths of 30 cm, no organisms attempted to crawl up through the column of burying sediment. Overburden stress was considered a measure which related bulk density of sediment and burial depth; once a critically high value is reached, buried animals cannot initiate an escape response.

Key Words: Industrial minerals; Mineral sands; Phosphorites; Metalliferous oxides; Hydrothermal deposits; Scraping; Excavating; Tunneling; Fluidizing; Benthos.

Entry Number: 0072.

Citation: Noda, E. K. & Associates, and R. C. Y. Koh. 1985. *Fates and transport modeling of discharges from ocean manganese crust mining*. Final report prepared for the Research Corporation of the University of Hawaii, Manganese Crust Environmental Impact Statement Project, Honolulu, HI.

Type(s) of Study: Model.

Geographic Location(s): Hawaii, United States.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Deep seabed.

Mineral(s): Metalliferous oxides.

Type(s) of Mining Operation(s): Scraping.

Environmental Resource(s): Physical oceanography; Water quality; Benthos.

Date(s) of Study: Unavailable.

Study Technique(s): The fate and transport of materials discharged during deep ocean mining of manganese crusts were estimated using numerical models. Primary discharge sites included the surface (i.e., from the surface ship) and the seafloor (i.e., from the miner). Inputs to the models included current velocities and settling velocities of the discharged particles. Current meters provided field data, used to calibrate input values to the numerical models.

Conclusion(s): The models described surface and benthic discharges for the test location. For the surface discharge, the descending jet stops its downward motion within a short distance vertically. For the base case, the descending jet stopped 50 m below the surface. At that point, collapse begins and continues for a downstream distance of about 2,000 m. At the end of the collapse, the dilution of the discharge is about 2,000:1, with a thickness of about 6 m and a width of approximately 260 m. The benthic model predicted that the plume, in the base case, collapsed vertically and spread out horizontally for a distance of about 100 m. The plume also grew to a width of about 20 m, at which the thickness was about 3 m. Current data were found to be a mandatory component in modelling, necessary to accurately predict discharge behavior at site-specific locations.

Key Words: Metalliferous oxides; Scraping; Physical oceanography; Water quality; Benthos.

Entry Number: 0073.

Citation: Nunny, R. S., and P. C. H. Chillingworth. 1986. *Marine dredging for sand and gravel.* U.K. Department of the Environment, Minerals Division. Minerals Planning Research Project No. PECD 7/1/163-99/84. London: HM Stationery Office.

Type(s) of Study: Review.

Geographic Location(s): England; Scotland; Wales.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Continental shelf; Coastal.

Mineral(s): Industrial minerals.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Geology; Physical oceanography; Water quality; Plankton; Nekton; Benthos; Sensitive habitats; Commercial and recreational fisheries; Local economies; Regional economies.

Date(s) of Study: Not applicable.

Study Technique(s): This study reviewed existing data on the resources and licensed reserves of sand and gravel in the United Kingdom sector of the continental shelf. The extent to which marine mining resources are constrained by other interests and factors controlling operations and growth of the marine aggregate industry were identified and analyzed.

Conclusion(s): It was recommended that an agency be developed to compile and update data, advise on resource availability, and ensure efficient utilization of reserves. Authorities should ensure aggregate mining the greatest consideration in coordinating applications for exclusive use of the seabed. It was suggested that previously refused mining applications be re-evaluated when criteria change or new data become available. Basic research should be initiated to establish new data and technology. Environmental data should be considered when mining applications are evaluated. The dredge industry should improve its public image and introduce monitoring programs. Land and marine planning should be similar. Handling and transportation practices should be standardized throughout the industry. Prospecting and environmental analysis should be part of all mining projects.

Key Words: Industrial minerals; Scraping; Excavating; Geology; Physical oceanography; Water quality; Plankton; Nekton; Benthos; Sensitive habitats; Commercial and recreational fisheries; Local economies; Regional economies.

Entry Number: 0074.

Citation: Ofuji, I., and N. Ishimatsu. 1976. Anti-turbidity overflow system for hopper dredge. In *Dredging: Environmental Effects & Technology, Proceedings of WODCON VII, 207-233.*

Type(s) of Study: Field; Laboratory.

Geographic Location(s): Japan.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Coastal; Estuarine; Freshwater.

Mineral(s): Industrial minerals.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Water quality; Sensitive habitats; Commercial and recreational fisheries.

Date(s) of Study: Unavailable.

Study Technique(s): The authors developed an anti-turbidity overflow system for hopper dredges. Field observations and models were used to determine the mechanisms by which turbidity was produced by hopper dredge operations. From this information, methods and equipment were developed which produced a model for testing in the laboratory. A full scale device was then constructed for field testing.

Conclusion(s): The authors developed a system for minimizing turbidity that has been field tested on three operating dredges. The mechanism was reported to be highly effective in minimizing turbidity by removing air bubbles from the dredge water before it is discharged. The removal of air bubbles and the placement of the discharge pipe at the bottom of the dredge allows the suspended sediments to settle rapidly to the bottom.

Key Words: Industrial minerals; Scraping; Excavating; Water quality; Sensitive habitats; Commercial and recreational fisheries.

Entry Number: 0075.

Citation: Otvos, E. G., and W. B. Sikora. 1991. Nearshore seashell and sand mining: Environmental impact, Gulf of Mexico examples. In *Proceedings, 23rd Annual Offshore Technology Conference*, OTC 6551. Houston, TX.

Type(s) of Study: Review.

Geographic Location(s): Alabama, United States; Florida, United States; Louisiana, United States; Mississippi, United States; Texas, United States.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Coastal; Estuarine; Freshwater.

Mineral(s): Industrial minerals.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Geology; Physical oceanography; Water quality; Plankton; Nekton; Benthos; Sensitive habitats; Commercial and recreational fisheries; Local economies; Regional economies.

Date(s) of Study: Not applicable.

Study Technique(s): A review of information on environmental impacts of mudshell and sand dredging in the fragile coastal waters of the Gulf of Mexico was conducted.

Conclusion(s): Oyster and clam shell dredging in estuarine and coastal waters of the northern Gulf of Mexico have mechanical impact on biota, alter bottom topography, resuspend sediments and cause turbidity, cause potential toxic or microbiological effects from resuspended muddy sediments, increase bottom siltation, and cause substrate change through density layer/fluid mud effects. Due to increasing erosion, offshore dredging for beach replenishment is an expanding process in the Gulf of Mexico. The impact on nearshore biota inhabiting higher energy sandy seafloor areas appears to be much less pronounced than the influence of mudshell dredging in inshore environments.

Key Words: Industrial minerals; Scraping; Excavating; Geology; Physical oceanography; Water quality; Plankton; Nekton; Benthos; Sensitive habitats; Commercial and recreational fisheries; Local economies; Regional economies.

Entry Number: 0076.

Citation: Owen, R. M. 1977. An assessment of the environmental impact of mining on the continental shelf. *Mar. Min.* 1(1/2):85-102.

Type(s) of Study: Review.

Geographic Location(s): Worldwide.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Continental shelf.

Mineral(s): Industrial minerals; Mineral sands; Phosphorites; Dissolved minerals.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Geology; Physical oceanography; Water quality; Plankton; Nekton; Benthos; Sensitive habitats; Commercial and recreational fisheries.

Date(s) of Study: Not applicable.

Study Technique(s): The author reviewed the available literature on the environmental impact of mining on the continental shelf. The paper considered the political and economic pressures associated with the potential for mining of resources on the continental shelf and the environmental impact of ocean mining. The latter discussion was organized into physical-geological impacts and the impacts on biological-chemical processes. A brief discussion of the preventive measures to minimize impacts was also provided.

Conclusion(s): The author commented that while marine mining will more likely be pursued on the continental shelf, the only major research on environmental impacts of marine mining has been focused in deep ocean areas. Such information will likely be applicable. The disruptive effect of mining activities on sediment transport processes on the continental shelf was indicated. The detrimental result of this effect may be coastal erosion and formation of navigational hazards. Mining activities can also disrupt biogeochemical processes, particularly primary production and sinks of potentially toxic materials. The author suggested that the collection of pre-mining baseline data and continuous monitoring of critical parameters should be conducted to minimize impacts, particularly in sensitive coastal areas such as reefs, fishing grounds, and semi-enclosed embayments.

Key Words: Industrial minerals; Mineral sands; Phosphorites; Dissolved minerals; Scraping; Excavating; Geology; Physical oceanography; Water quality; Plankton; Nekton; Benthos; Sensitive habitats; Commercial and recreational fisheries.

Entry Number: 0077.

Citation: Ozturgut, E., G. C. Anderson, R. E. Burns, J. W. Lavelle, and S. A. Swift. 1978. *Deep ocean mining of manganese nodules in the north Pacific: Pre-mining environmental conditions and anticipated mining effects.* NOAA Technical Memorandum ERL MESA-33.

Type(s) of Study: Field.

Geographic Location(s): Pacific Ocean.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Deep seabed.

Mineral(s): Metalliferous oxides.

Type(s) of Mining Operation(s): Scraping.

Environmental Resource(s): Geology; Physical oceanography; Water quality; Plankton; Nekton; Benthos.

Date(s) of Study: 1975 to 1976.

Study Technique(s): Prior to commercial scale manganese nodule mining operations in the tropical North Pacific, an ecological characterization of the deep sea environment was undertaken. Field studies measured currents, light (photosynthetically active radiation), suspended particulate matter, pigments, primary productivity, biochemical properties, micronekton, and zooplankton in the upper layer of the water column. Dissolved oxygen, salinity, temperature, and nutrients were measured throughout the water column. In the lower water column, currents, suspended particulate matter, and macrozooplankton were measured. On the seafloor, benthic fauna, sediments, and pore water were determined. Additional information on the area was obtained from existing literature sources.

Conclusion(s): No detectable changes in temperature, salinity, dissolved gases, and dissolved metal content of the upper water layer (due to the production of mining effluent) were expected, even in the area immediately surrounding the ship. Shipboard disposal of mine tailings was expected to cause a reduction of ambient light and, therefore, primary productivity due to an increase in suspended particulate matter. The plume was projected to reach ambient conditions about 50 km from the mining ship. Suspended particulate matter was expected to also affect zooplankton behavior and possibly planktonic food webs within the discharge area. Any discernable large-scale effects of the proposed mining operation were expected to occur within 100 km of the mining vessel. Benthic fauna contacted by the collector will be destroyed, however the areal extent of this damage will be minimal relative to the entire mining area.

Key Words: Metalliferous oxides; Scraping; Geology; Physical oceanography; Water quality; Plankton; Nekton; Benthos.

Entry Number: 0078.

Citation: Packer, T. 1987. Survey of environmental effects of marine mining. In *Special Project for the Ocean Mining Division, Energy Mines and Resources Canada*. Canada.

Type(s) of Study: Review.

Geographic Location(s): Worldwide.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Continental shelf; Coastal.

Mineral(s): Industrial minerals; Mineral sands.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Geology; Physical oceanography; Water quality; Neuston; Plankton; Nekton; Benthos; Sensitive habitats; Commercial and recreational fisheries.

Date(s) of Study: Not applicable.

Study Technique(s): The document presents a review of the environmental effects of marine mining, primarily on the continental shelf. Various marine mining systems and general characteristics of mining areas were examined. The potential physical and chemical effects from marine mining activities, as well as project planning and mitigation measures, were reviewed. A annotated bibliography was also presented.

Conclusion(s): There were two main methods identified for offshore dredging of mineral deposits: 1) mechanical, including bucket ladder and clamshell dredges; and 2) hydraulic, including the cutter suction, stationary suction, diver-operated suction, and trailing suction hopper. Each of these methods present advantages and disadvantages depending on the nature of the site and the mineral deposit. Entrainment and destruction of bottom dwelling organisms are the unavoidable physical effects of the dredging. In addition, depending on the nature of the site and mineral deposits, thermal shock, turbidity, and light reduction are potential physical effects. Dredging activities may also dislocate breeding grounds and leave persistent holes and furrows that may have detrimental effects to bottom trawl activities. When large-scale mining occurs in nearshore waters, coastal erosion may result if the seabed has been extensively modified. Mining operations have potential chemical effects. Resuspended sediments can also result in nutrient release, reduction of dissolved oxygen concentrations, and release of heavy metals.

Key Words: Industrial minerals; Mineral sands; Scraping; Excavating; Geology; Physical oceanography; Water quality; Neuston; Plankton; Nekton; Benthos; Sensitive habitats; Commercial and recreational fisheries.

Entry Number: 0079.

Citation: Padan, J. W. 1977. *New England offshore mining environmental study (Project NOMES): Final report.* NOAA Special Report. Seattle, WA: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Research Laboratories.

Type(s) of Study: Field; Laboratory.

Geographic Location(s): Massachusetts Bay, Massachusetts, United States.

OCS Planning Area(s): North Atlantic.

Type(s) of Environment(s): Continental shelf; Coastal; Estuarine.

Mineral(s): Industrial minerals.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Geology; Physical oceanography; Water quality; Plankton; Nekton; Benthos.

Date(s) of Study: 1972 to July 1973.

Study Technique(s): The New England Mining Environmental Study (NOMES) was conducted in order to resolve marine environmental impact issues that had prompted moratoria on marine mining. Initial surveys were conducted to characterize the nature of the mine site and projected impact area. These observations constituted a baseline of biological (benthos, phytoplankton, turbidity), geological (bathymetry, stratigraphy, core samples), chemical (nutrients, suspended solids), and physical oceanographic (temperature, salinity, currents and dispersion, and light penetration) data for the area. To augment these studies, one series of laboratory experiments was completed in which several test organisms were exposed to varying concentrations of suspended sediment.

Conclusion(s): The study ended prematurely and only limited data were collected. Monthly sampling of benthos revealed considerable natural spatial and temporal variability in species composition and abundance. It was noted that a method must be developed that will distinguish changes due to mining from those due to natural variability inherent in the coastal marine environment. Such a distinction is necessary before inferences about impacts can be made. Laboratory studies on the effects of turbidity on marine organisms showed low mortality in adult fish, bivalves, and shrimp. Juvenile organisms showed a higher mortality than adults. The mining site was found by subbottom profiling and delineated by core sampling.

Key Words: Industrial minerals; Scraping; Excavating; Geology; Physical oceanography; Water quality; Plankton; Nekton; Benthos.

Entry Number: 0080.

Citation: Paffenhofer, G. A. 1972. The effects of suspended red mud on mortality, body weight, and growth of the marine planktonic copepod *Calanus helgolandicus*. *Water, Air, Soil Pollut.* 1:314-321.

Type(s) of Study: Laboratory.

Geographic Location(s): Not applicable.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Continental shelf; Coastal.

Mineral(s): Mineral sands.

Type(s) of Mining Operation(s): Excavating

Environmental Resource(s): Plankton.

Date(s) of Study: Unavailable.

Study Technique(s): The effect of 'red mud', the tailings from extraction of aluminum from bauxite, on a marine planktonic copepod was investigated. Various larval stages were exposed to varying (i.e., from 1:100,000 to 1:1,000,000) mixtures of red mud and seawater in the laboratory with appropriate controls. Experiments were conducted using cultured diatoms as food. After the experiment, the animals were collected, dried, and weighed. Differences in body weight and growth rates between the experimental and control groups were then determined.

Conclusion(s): Red mud had deleterious effects on the survival, body weight, and growth of the planktonic copepod. Mortality in the experimental group was five to eight times greater than the control group. Growth in the experimental group was also delayed. Formation of ovaries was also hindered in female copepods due to ingestion of red mud. These results suggested that ocean disposal (dumping) of red mud would have significant effects on planktonic copepods.

Key Words: Mineral sands; Excavating; Plankton.

Entry Number: 0081.

Citation: Peddicord, R. K. 1976. Biological impact of suspensions of dredged material. In *Dredging: Environmental Effects & Technology, Proceedings of WODCON VII*, 605-615.

Type(s) of Study: Laboratory.

Geographic Location(s): Not applicable.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Continental shelf; Coastal; Estuarine.

Mineral(s): Industrial minerals.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Water quality; Nekton; Benthos.

Date(s) of Study: Unavailable.

Study Technique(s): Laboratory experiments were conducted to determine the effects of suspended sediments on marine and estuarine invertebrates and fish. Blue mussel, sand shrimp, shiner perch, and striped bass fingerling were exposed to varying concentrations of kaolin and bentonite clays and natural sediments. Experiments were also conducted to determine the effect of temperature and oxygen concentrations on the toxicity of suspended sediments.

Conclusion(s): Most of the organisms tested exhibited a high tolerance to suspensions of kaolin and bentonite clays (i.e., up to 100 g/l concentrations for 10 days). Test organisms which were generally found in areas with high turbidity had the highest tolerance. Temperature and dissolved oxygen conditions affected the tolerance of most organisms (i.e., increased temperatures and decreased oxygen lowered the tolerance of most organisms). Most species were also found to have a high tolerance for uncontaminated sediments. Sediments from a heavily industrialized shipyard area caused significant mortality. Decreasing the concentration of suspended sediments from the contaminated area resulted in reduced mortality.

Key Words: Industrial minerals; Scraping; Excavating; Water quality; Nekton; Benthos.

Entry Number: 0082.

Citation: Pfitzenmeyer, H. T. 1970. *Gross physical and biological effects of overboard spoil disposal in upper Chesapeake Bay: Project C, benthos*. Univ. Maryland, Nat. Res. Inst., NRI Special Report No. 3:26-38.

Type(s) of Study: Field.

Geographic Location(s): Chesapeake Bay, Maryland, United States.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Estuarine.

Mineral(s): Industrial minerals.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Geology; Physical oceanography; Benthos.

Date(s) of Study: January 1966 to December 1968.

Study Technique(s): Benthos was collected at numerous sites established along transects in and near a dredging operation. Collections were taken with a 0.1 m^2 Van Veen grab before, during, and after dredging according to an established and periodic sampling program. Sediments were analyzed for particle size and organic content. Salinity and temperature were determined for surface and bottom water. The numbers of individuals collected per site, species diversity, and dry weight biomass were used to analyze the effects of dredging and spoil disposal.

Conclusion(s): Five months after dredging, benthic biomass increased at all sites. One year after dredging and spoil disposal, benthic recovery had occurred in the spoil disposal area, but not in the dredge channel. Because natural seasonal changes created drastic population fluctuations, late winter or early spring was probably the best time for dredging to produce the fewest effects on benthic populations.

Key Words: Industrial minerals; Scraping; Excavating; Geology; Physical oceanography; Benthos.

Entry Number: 0083.

Citation: Poopetch, T. 1982. Potential effects of offshore tin mining on marine ecology. In *Proceedings of the Working Group Meeting on Environmental Management in Mineral Resource Development*, Series No. 49:70-73.

Type(s) of Study: Review.

Geographic Location(s): Thailand.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Coastal.

Mineral(s): Mineral sands.

Type(s) of Mining Operation(s): Scraping.

Environmental Resource(s): Geology; Water quality; Plankton; Nekton; Benthos; Sensitive habitats; Commercial and recreational fisheries; Local economies.

Date(s) of Study: Not applicable.

Study Technique(s): This paper reviewed available literature on the potential environmental impacts of tin mining in Phuket, Thailand. Information was mainly based on unpublished data from the Phuket Marine Biological Center. A description of the turbidity plume generated during tin mining by dredge was provided.

Conclusion(s): Significant environmental effects of tin mining were observed. Suspended solid concentrations as high as 138 ppm and a Secchi disk depth of 0.5 m were reported within the plume from one large dredging operation. ^{14}C primary productivity was reduced to 12% of ambient values 1 km downstream of the dredge. Species composition and density were poorer in the dredged areas compared to undisturbed areas.

Key Words: Mineral sands; Scraping; Geology; Water quality; Plankton; Nekton; Benthos; Sensitive habitats; Commercial and recreational fisheries; Local economies.

Entry Number: 0084.

Citation: Pycha, R. L. 1968. *Effects of dumping taconite tailings in Lake Superior on commercial fisheries*. U.S. Department of the Interior, Bureau of Commercial Fisheries.

Type(s) of Study: Review.

Geographic Location(s): Lake Superior, United States.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Freshwater.

Mineral(s): Mineral sands.

Type(s) of Mining Operation(s): Excavating

Environmental Resource(s): Commercial and recreational fisheries.

Date(s) of Study: Not applicable.

Study Technique(s): This report summarized the findings of a review of fisheries data that was undertaken to determine if the discharge of taconite tailings into Lake Superior had negative effects on commercial fisheries. The author examined the available data for several fisheries within Lake Superior prior to and following the start of dumping, including data for fisheries in waters of Minnesota, Michigan, and Wisconsin.

Conclusion(s): The decline in the fisheries that were examined could not be attributed solely to the dumping of taconite into Lake Superior. The decline of these fisheries was already underway prior to the start of dumping (1956). There was already a decline in trout populations, thought to have been initiated by the introduction of the sea lamprey into the Great Lakes, before 1956. Likewise, the decline in the herring fishery was already underway, attributed to intensive fishing. Examination of fishing records from areas in Minnesota that were adjacent to the taconite dumping did not reveal any effects that could be attributed to the dumping. In contrast, smelt populations have been increasing. These increases could not be attributed to the taconite dumping because they began much earlier. Similarly, the increase in the chub fisheries was not tied to the taconite dumping but was a reflection of increased fishing pressure. The author also found that population records for whitefish were insufficient to provide any conclusive information on the effects of taconite dumping on this species.

Key Words: Mineral sands; Excavating; Commercial and recreational fisheries.

Entry Number: 0085.

Citation: Sharma, R., and A. Rao. 1991. Environmental considerations of nodule mining in Central Indian Basin. In *Proceedings, 23rd Annual Offshore Technology Conference*, 481-490.

Type(s) of Study: Review.

Geographic Location(s): Central Indian Basin, Indian Ocean.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Deep seabed.

Mineral(s): Metalliferous oxides.

Type(s) of Mining Operation(s): Scraping.

Environmental Resource(s): Geology; Physical oceanography; Water quality; Plankton; Nekton; Benthos.

Date(s) of Study: Not applicable.

Study Technique(s): The authors reviewed available information on physical, chemical, and biological conditions in the Central Indian Basin to evaluate the potential impact of deep sea mining of ferromanganese nodules by suction dredges. Using available information to estimate mining activities on the commercial scale [i.e., 5,000 metric tons (mt) per day], the authors developed predictions on the potential effects on the sea bottom and discharge of sediments into the water column.

Conclusion(s): The authors suggested that, at commercial mining scales, these activities will lead to aberrations in the marine food chain and drastic variations in the physico-chemical environment of the mining area. Measures for minimizing impacts were proposed, including the separation of nodules from the sediment matrix at the sea bottom. The mining of nodules in strips separated by undisturbed areas was also proposed to provide sources for recolonization of adjacent mined areas.

Key Words: Metalliferous oxides; Scraping; Geology; Physical oceanography; Water quality; Plankton; Nekton; Benthos.

Entry Number: 0086.

Citation: Taylor, J. L., and C. H. Saloman. 1968. Some effects of hydraulic dredging and coastal development in Boga Ciega Bay, Florida. *Fish Bull.* 67(2):213-241.

Type(s) of Study: Field.

Geographic Location(s): Boca Ciega Bay, Florida, United States.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Coastal; Estuarine.

Mineral(s): Industrial minerals.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Geology; Physical oceanography; Water quality; Neuston; Plankton; Nekton; Benthos; Sensitive habitats; Commercial and recreational fisheries; Local economies; Regional economies.

Date(s) of Study: September 1963 to August 1964.

Study Technique(s): Six stations, representative of undredged and dredge/fill impacted sites, were selected from a pool of 31 sites sampled initially in Boca Ciega Bay, Florida. Sampling was conducted at three-month intervals for nine months. Four stations were sampled for biomass using shovels, bucket dredges, bottom drags, plug samplers, trawls, beach seines, and trammel nets. Infauna was sieved to 0.701 mm. Triplicate plug cores were used to calculate wet and dry plant weights and wet infauna weights from vegetated and non-vegetated sites. All stations were sampled for water temperature, salinity, pH, total phosphorous, dissolved oxygen, Secchi turbidity, chlorophyll a, primary productivity, and sediment composition and texture.

Conclusion(s): Dredge and fill operations had reduced the area of Boca Ciega Bay, Florida by 3,500 acres since 1950. Estimated annual standing crop destroyed was 1,133 metric tons (whole dry weight) of seagrass and 1,812 metric tons (dry weight) of associated infauna. Annual production loss of biological resources was estimated at a minimum of 25,841 metric tons of seagrass, 73 metric tons of fisheries products, and 1,091 metric tons of infauna, excluding meiofauna. The loss of value from eliminated estuary was estimated at $1.4 million annually. Inestimable secondary losses occur from sedimentation, turbidity, and domestic sewage.

Key Words: Industrial minerals; Scraping; Excavating; Geology; Physical oceanography; Water quality; Neuston; Plankton; Nekton; Benthos; Sensitive habitats; Commercial and recreational fisheries; Local economies; Regional economies.

Entry Number: 0087.

Citation: Tsurusaki, K., T. Iwasaki, and A. Masafumi. 1988. Seabed sand mining in Japan. *Mar. Min.* 7:49-67.

Type(s) of Study: Review.

Geographic Location(s): Japan.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Continental shelf; Coastal.

Mineral(s): Industrial minerals.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Geology; Physical oceanography; Water quality; Plankton; Nekton; Benthos; Sensitive habitats; Commercial and recreational fisheries; Local economies; Regional economies.

Date(s) of Study: Not applicable.

Study Technique(s): The paper reviews the historical development and environmental impacts associated with seabed sand mining in Japan. A description of the extent and distribution of marine sand resources, trends in the mining industry, and representative mining activities in Kyushu are provided. The environmental impacts of seabed sand mining activities, primarily with regard to seabed alteration and sedimentation, are described.

Conclusion(s): The depletion of riverbed sand deposits in Japan drove the mining industry to exploit seabed deposits. Seabed sand mining off the Japanese coast has been conducted by approximately 540 relatively small vessels, mostly in waters off western Japan. These mining activities have contributed 20 to 25% of the total production of natural aggregate and 10% of all the aggregate used in recent years. Grab buckets and hydraulic dredges have typically been used. The main environmental impact noted was alteration of the seafloor. Sedimentation during dredging activities has also been reported to affect fishing and aquaculture. Recently, sedimentation has been mitigated by the use of an anti-turbidity overflow system. As the deposits in shallow areas are depleted, mining activities were expected to shift to deeper waters, a move which will likely further minimize environmental impacts.

Key Words: Industrial minerals; Scraping; Excavating; Geology; Physical oceanography; Water quality; Plankton; Nekton; Benthos; Sensitive habitats; Commercial and recreational fisheries; Local economies; Regional economies.

Entry Number: 0088.

Citation: U.S. Department of Commerce, National Oceanic and Atmospheric Administration (NOAA). 1981. *Deep seabed mining: Final programmatic environmental impact statement, Vols. I and II.* Washington, DC: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Office of Ocean Minerals and Energy.

Type(s) of Study: Review.

Geographic Location(s): Pacific Ocean.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Deep seabed.

Mineral(s): Metalliferous oxides.

Type(s) of Mining Operation(s): Scraping.

Environmental Resource(s): Air quality; Geology; Physical oceanography; Water quality; Neuston; Plankton; Nekton; Benthos; Birds; Marine mammals; Threatened and endangered species; Sensitive habitats; Commercial and recreational fisheries; Local economies; Regional economies; Human resources.

Date(s) of Study: Not applicable.

Study Technique(s): A literature review was conducted, with special emphasis on the Deep Ocean Mining Environmental Study (DOMES I & II), to assess the potential environmental impacts of exploration for and commercial recovery and processing of manganese nodules from the deep seabed. Marine and onshore environmental impacts were evaluated.

Conclusion(s): The Deep Seabed Hard Minerals Resources Act was adopted to regulate mining. Pilot scale nodule mining indicated a potential for several significant adverse impacts. Accordingly, NOAA decided to require monitoring of demonstration scale mining. Research was undertaken to determine the need for mitigation. NOAA would act as lead agency for review of environmental impacts (including environmental impact statement preparation for onshore facilities) and would work informally with other authorities to facilitate permit decisions.

Key Words: Metalliferous oxides; Scraping; Air quality; Geology; Physical oceanography; Water quality; Neuston; Plankton; Nekton; Benthos; Birds; Marine mammals; Threatened and endangered species; Sensitive habitats; Commercial and recreational fisheries; Local economies; Regional economies; Human resources.

Entry Number: 0089.

Citation: Wakeman, T. H. 1976. The biological ramifications of dredging & disposal activities. In *Dredging: Environmental Effects & Technology, Proceedings of WODCON VII*, 53-68. San Francisco, CA: Institute of Electrical and Electronic Engineers, Inc.

Type(s) of Study: Field; Laboratory.

Geographic Location(s): San Francisco Bay, California, United States.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Coastal; Estuarine.

Mineral(s): Industrial minerals.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Geology; Water quality; Plankton; Nekton; Benthos.

Date(s) of Study: 1972 to 1975.

Study Technique(s): The paper describes the results of a series of studies designed to investigate the effects of dredging and disposal activities on biological resources in San Francisco Bay. Investigations examined dredging and disposal effects on water quality, sediment heavy metal release, and benthic and pelagic organisms. Investigations involved both field observations and measurements and laboratory experiments. Laboratory experiments included studies of the role of temperature and dissolved oxygen in the effect of suspended solids on pelagic and benthic species.

Conclusion(s): Dredging and disposal activities were reported to have minimal effects on the upper water column. Plumes that were formed were of short duration and had minimal suspended solid concentrations. Significant impacts near the bottom were reported. Reduction in dissolved oxygen concentrations and increases in suspended solids were observed near the bottom at disposal sites. Nutrients, chlorinated hydrocarbons, and heavy metals were released into the water column from resuspended sediments. Salinity, oxygen concentrations, and biological activity interact with other physical and chemical factors which control the partitioning and sorption and desorption of heavy metals and toxic organic compounds. Suspended solid concentrations observed in the field did not affect adult benthic organisms at saturated oxygen conditions and at winter temperature. Significant mortality among benthic organisms was noted, however, at higher temperatures and reduced dissolved oxygen concentration. Similar observations were noted for pelagic species.

Key Words: Industrial minerals; Scraping; Excavating; Geology; Water quality; Plankton; Nekton; Benthos.

Entry Number: 0090.

Citation: Wilson, K. W., and P. M. Conner. 1976. The effect of china clay on the fish of St. Austell and Mevagissey Bays. *J. Mar. Biol. Assoc. U.K.* 56:769-780.

Type(s) of Study: Field.

Geographic Location(s): United Kingdom.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Coastal; Estuarine.

Mineral(s): Industrial minerals.

Type(s) of Mining Operation(s): Scraping; Excavating.

Environmental Resource(s): Water quality; Nekton; Benthos; Commercial and recreational fisheries.

Date(s) of Study: September 1970.

Study Technique(s): A trawling survey was conducted to determine the effects of china clay discharges on fish distribution in Mevagissey Bay, off Cornwall. A commercial trawling vessel was used to take three repetitive hauls from each of six sites where china clay was present. Similar hauls were completed at six additional sites where china clay was not present. All invertebrates and fishes collected were identified, sorted, and counted. Lengths of selected fish species were taken. Food habits of commercially important fishes (i.e., plaice, dabs) were examined.

Conclusion(s): The distribution of motile invertebrates and fishes was not greatly affected by the presence of china clay. However, certain fishing areas could not be sampled because large amounts of china clay fouled the trawl nets. The numbers of commercial species caught on the two different bottom types were approximately the same. The numbers of sedentary invertebrates were greatly reduced in the areas affected by china clay. In these areas, the fish shifted their diets and fed upon prevalent invertebrates. Mackerel and garfish were caught in water colored with suspended clay.

Key Words: Industrial minerals; Scraping; Excavating; Water quality; Nekton; Benthos; Commercial and recreational fisheries.

Entry Number: 0091.

Citation: Wyatt, T. 1972. Some effects of food density on the growth and behaviour of plaice larvae. *Mar. Biol.* 14:210-216.

Type(s) of Study: Laboratory.

Geographic Location(s): United Kingdom.

OCS Planning Area(s): Not applicable.

Type(s) of Environment(s): Continental shelf.

Mineral(s): Not applicable.

Type(s) of Mining Operation(s): Not applicable.

Environmental Resource(s): Plankton; Nekton; Commercial and recreational fisheries.

Date(s) of Study: Unavailable.

Study Technique(s): The effect of food density on the growth, survival, and swimming activity of plaice (*Pleuronectes platessa*) larvae was investigated under laboratory conditions. Larvae were placed in 5-L plastic tanks maintained at a constant temperature of 10 °C. Each tank was stocked with 50 larvae, then relative densities (i.e., 1, 0.5, 0.25, 0.125, and 0.0625) of prey (*Artemia* nauplii) were introduced. Effect of food density on relative growth was determined by an index based on the ratio of height of body musculature to body length. In another series of experiments, the effect of absence of food on survival and activity was assessed.

Conclusion(s): Experiments showed that suboptimal food densities affected the condition index and increased the amount of time searching for food. Older larvae were able to withstand much longer periods without food than young larvae. Based on these results, it was suggested that food limitation in a larval plaice population is likely to result in a concave mortality curve.

Key Words: Plankton; Nekton; Commercial and recreational fisheries.