Attachment D Drilling Mud Dispersion Modeling

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Attachment D Drilling Mud Dispersion Modeling

D.1 Background

This appendix presents the results of far-field dispersion modeling conducted around Platform Irene. The modeling was conducted to determine the spatial extent of drilling mud deposition on the sea floor. Specifically, it determines whether the depositional footprint extends into State waters within the three-mile limit; and if so, whether the particulate concentration is likely to exceed water-quality standards.

Most past field investigations into the fate of drilling wastes have focused on the distribution of drilling solids in surficial sediments close (<0.5 km) to short–term exploration wells (e.g., O'Reilly et al., 1989, Boothe and Presley, 1989; Jenkins et al., 1989; and Neff et al., 1989a). Others have concentrated on heavier drill cuttings that are deposited immediately below platforms (Zingula and Larson, 1977; de Margerie, 1989). In contrast, this investigation examines the lighter fraction of drilling fluid that is carried by ambient currents and initially deposited at mid– and far–field distances (beyond 0.5 and 1.0 km from the source, respectively).

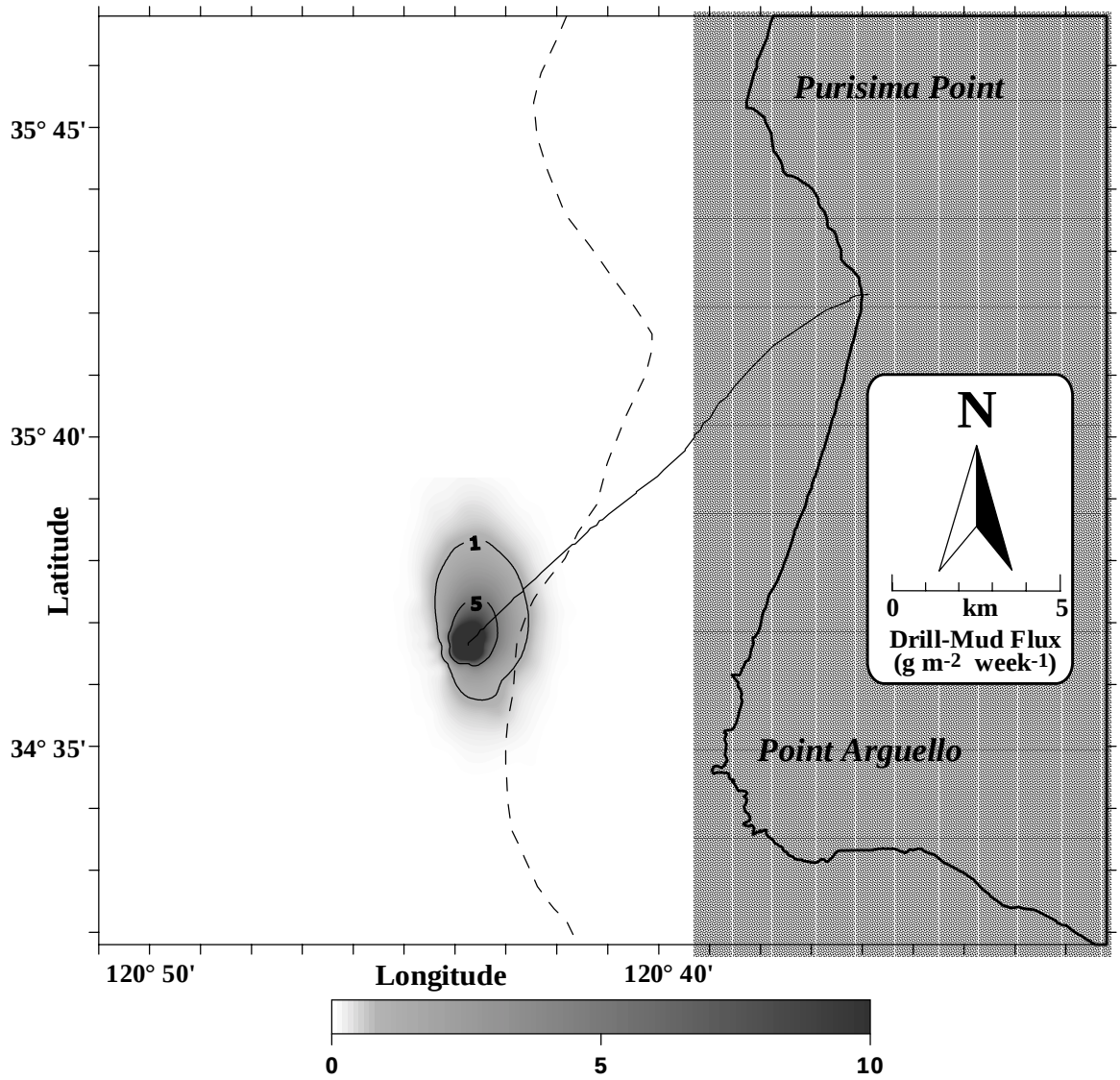
D.2 Model Description

Platform Irene lies six miles west of Point Pedernales in an oceanographically complex region. The mud model applied here was first applied in the same oceanographic regime near Point Arguello (Coats, 1994). The flow field in this region is complicated by the right angle change in the coastline orientation between the Santa Barbara Channel and the Santa Maria Basin (Figure D-1).

Processes that determine the ultimate fate of drilling–derived particulates in the marine environment are also complex. They include initial plume dynamics, passive current transport, wave–current resuspension, chemical weathering, bioturbation, burial, and biological uptake (National Research Council, 1983). Immediately upon discharge, dynamic plume processes dominate the dispersion of drilling particulates. These initial turbulent processes within the plume rapidly mix and dilute suspended particulates as gravitational forces deposit most of the drill cuttings and heavier aggregates of drilling material in the near–field, within about 0.5 km of platforms (Continental Shelf Associates, 1985). Lighter particulate material remains in the water column and is passively advected by ambient currents and deposited over greater distances. After deposition, long–term processes, such as resuspension, serve to further disperse drilling particles and expose benthic epibiota to low concentrations of drilling particles over extended periods.

This study focuses on the process of passive current transport, which initially distributes the particulates over wide areas and exposes benthic organisms to brief episodes of high drilling–particle concentrations within discharge plumes. It was this initial deposition that resulted in the significantly enriched barium signatures observed in sediment traps located at distances beyond 0.5 km from the Platform Hidalgo (Hyland et al., 1994).

Figure D-1 **Predicted Deposition of Drilling Particulates Discharged from Platform Irene**



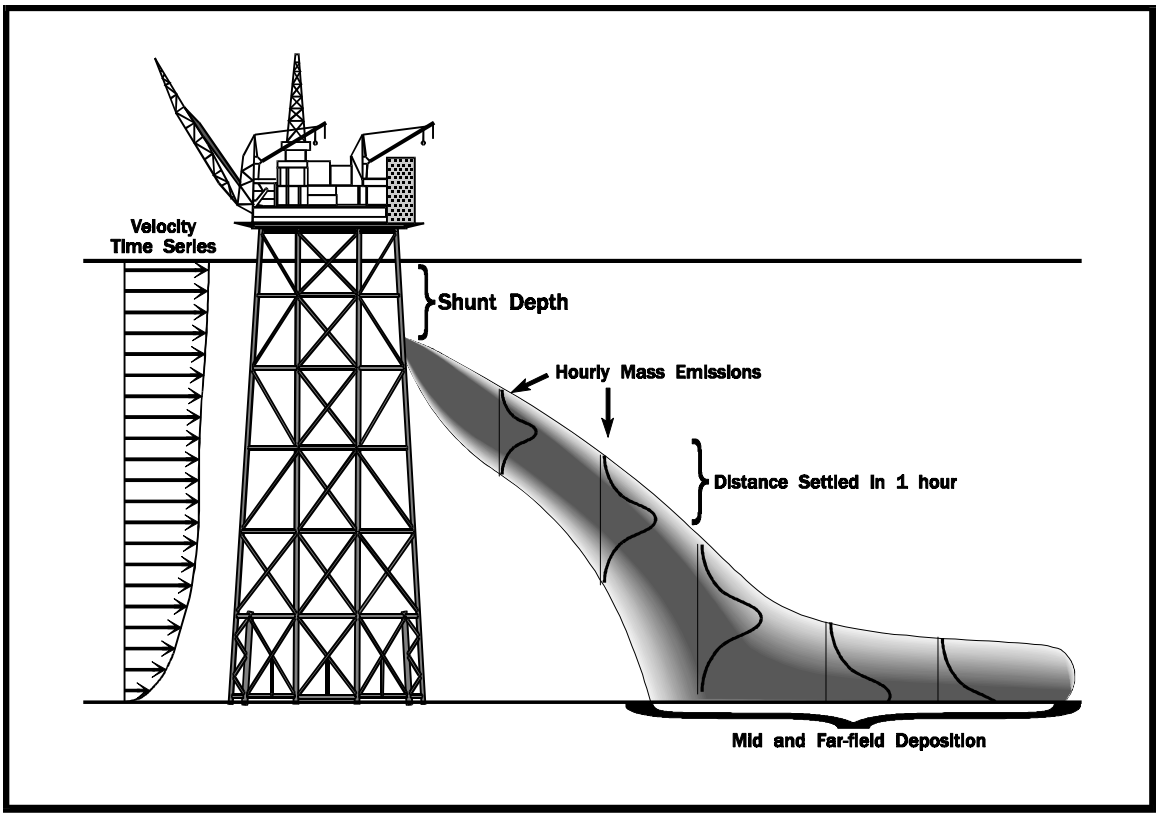
The numerical computation of initial deposition tracks plumes of drilling–fluid discharges as they settle and impinge on the benthos. The model was first applied to investigate mud deposition around Platforms Harvest, Hidalgo, and Hermosa (Coats, 1994). Subsequently, the model was applied to delineate additional discharges from these platforms (SAIC, 1995). Similar particle tracking analyses have been employed to evaluate other aspects of pollutant dispersion in the ocean (van Dam, 1982). Fry and Butman (1991) used a comparable approach to estimate depositional patterns resulting from disposal at the 106–mile dump site off the Atlantic coast.

D.2.1 Trajectory Computation

Although trajectory computations neglect initial plume dynamics and oceanic turbulence, they are capable of generating gross temporal and spatial patterns consistent with direct observations of particulate flux. Their success lies in the ability to integrate cumulative effects from many plumes over long periods. They indicate that, over the long–term, mid– and far–field depositional patterns are primarily controlled by the general circulation and geometry of the discharge sources.

The schematic shown in Figure D-2, illustrates the relationship among the principal parameters of the drilling–mud trajectory computation. For Platform Irene, a uniform hourly mass emission of particulates is computed from the total projected discharge volume over the life of the project. A total volume of 51,500 m^3 of drill mud will be discharged at a rate of 3.5 gpm over the 7.4 years of drilling. Although the daily discharge volume varies substantially, a uniform discharge rate is assumed for this computation. Short–term temporal variability in measured currents provides sufficient stochastic variability in the trajectories of individual plumes so long-term depositional patterns can be accurately represented.

Figure D-2 Schematic of the Depositional Model



The model assumes that about 10% of the discharge is deposited immediately below the platform as cuttings. The heavier coarse mud particulates are deposited in the near field during an initial phase of convective descent and dynamic collapse. These initial phases can be addressed in short–term near-field analyses incorporated in the Offshore Operators Committee model (Continental Shelf Associates, 1985). The depth of the plume of lighter material, remaining suspended at the edge of the zone of initial dilution, is largely determined by the 46-m shunt depth on Platform Irene.

The rate of plume settlement was one of the most sensitive parameters in the initial deposition analysis of open–ocean waste disposal (Fry and Butman, 1991). Fry and Butman's trajectory computations benefited from the results of numerous laboratory studies on the settling rates of sewage particulates. In contrast, only a few comprehensive laboratory investigations of drilling–mud settlement in seawater have been completed (Huang, 1992). Past studies into the behavior of clay–sized particles in seawater have revealed that settling behavior is complicated by their cohesive properties which result in the formation of light–weight aggregates or flocs. Consequently, settling speed is largely dictated by the properties of the flocs rather than the individual particles. For example, Stoke's Law specifies the terminal velocity of an individual spherically–shaped bentonite particle of diameter 0.005 cm and density 4.5 g cm^{-3} to be near 0.5 cm s^{-1}. Burban et al (1990), however, found that settling speed for clay aggregates are as much as 1000 times slower than that predicted by Stoke's law for a solid particle of equivalent size. They also found that the density of flocs, and hence their settling velocity, measurably increased with increasing ambient concentrations of suspended particulates and with increasing fluid shear, with the latter being the most influential.

These effects have been included in a global fate model developed for the Point Conception region by Pickens and Lick (1992). It addresses resuspension of drilling muds after deposition on the seafloor and incorporates settling rates applicable to the much denser flocs formed within high resuspended sediment concentrations generated by highly–sheared benthic flow. They represent settling speeds under a variety of flow conditions by empirically incorporating recent laboratory analyses of drilling–muds by Huang (1992). His work covers a broad range of flow conditions and particle concentrations.

In contrast to resuspension processes, the initial deposition of drilling particles from discharge plumes occurs at relatively low particulate concentrations and in the presence of low fluid shear. The average settling speed of 0.06 cm s^{-1} selected for this study falls well within the range of Huang's empirical results for drilling mud from the Point Conception platforms. He found settling rates as high as 0.1 cm s^{-1} for flocs that reached a steady–state diameter of 0.01 cm within 24 hours of release. The somewhat lower settling rate used in this study represents average conditions. Also, the selection of 0.06 cm s^{-1} is consistent with a diagnostic trajectory computation that was conducted to match sediment-trap flux measured during the MMS California Monitoring Program near Point Conception (Battelle Ocean Sciences, 1991; Coats, 1994). Specifically, the selected settling rate provides particulate accumulations within the 400 km^2 analysis grid that are on the same order as those measured by the traps. Material with a slightly lower settling rate (<0.04 cm s^{-1}) remained in the water column for periods greater than three days and was transported out of the study area before impinging on the seafloor, well away from the sediment traps.

Variation in settling speed about the average 0.06 cm s^{-1} is included to empirically account for a range of particulate sizes. This is modeled with a vertical distribution in the concentration of particulates. As indicated in Figure D-2, the particulate mass associated with each hourly discharge is spread over depth as a Gaussian distribution. This allows continuous deposition of particulates along the plume path. At a given position along the plume trajectory, the fraction of particulates adjacent to the seafloor is deposited within the underlying 1-km^2 grid cell. The amount of deposition within the cell depends upon the vertical spread in particulates and their mean depth as the plume settles with time. The vertical spread is assumed to span three standard deviations from the centroid of the distribution to the seafloor. Initially, this means that the plume is effectively suspended well off the seafloor and the early deposits constitute less than 1% of the total mass in the plume. As the particulate plume settles through the water column, increasingly larger fractions of material adjacent to the seafloor accumulate within underlying grid cells; until the distribution center is deposited. Thereafter, decreasing fractions are deposited within grid cells along the plume trajectory.

The flux of drilling–derived particulates within an individual grid cell is determined from

$$\boldsymbol{Flux} = \sum_{\substack{\text{Hourly}\\ \text{Discharges}}} \frac{\boldsymbol{M} \bullet \boldsymbol{F}(\Delta \boldsymbol{t}) \bullet \delta(\vec{\boldsymbol{X}}_{\text{cell}}, \vec{\boldsymbol{X}}_{\text{plume}})}{\boldsymbol{A} \bullet \boldsymbol{T}} \qquad \text{Equation A-1}$$

where $\boldsymbol{\delta=1}$ indicates that the plume at $\vec{\boldsymbol{X}}_{\text{plume}}$ is within the limits of the grid cell at $\vec{\boldsymbol{X}}_{\text{cell}}$, otherwise $\boldsymbol{\delta}$=0; A is the area of individual grid cells (1 km^2); $\boldsymbol{T}$ is the total duration of the seafloor deposition; $\boldsymbol{M}$ is the total particle mass in the plume; and $\boldsymbol{F(\Delta t)}$ is the fraction of mass adjacent to the seafloor $\boldsymbol{\Delta t}$ hours after discharge or,

$$\boldsymbol{F}(\Delta \boldsymbol{t}) = \frac{\boldsymbol{1}}{\sqrt{\boldsymbol{2x}}}\ \boldsymbol{exp}\left(-\frac{\boldsymbol{9}}{\boldsymbol{2}} \bullet \left(\boldsymbol{1} - \frac{\boldsymbol{2}\Delta \boldsymbol{t}}{\boldsymbol{t}}\right)^{\boldsymbol{2}}\right);\ \boldsymbol{0} \le \Delta \boldsymbol{t} \le \boldsymbol{1} \qquad \text{Equation A-2}$$

where $\boldsymbol{t}$ is the settling time from shunt to seafloor in hours.

The amount of material accumulated within a particular grid cell is determined by the frequency with which plumes encounter that cell (viz. $\boldsymbol{\delta}$=1). Thus, the platform location and the ambient flow field largely dictate the long–term pattern of drilling particle flux. The plume movement is reminiscent of a progressive vector diagram where displacement relative to the release point is determined by temporal integration of current velocity.

D.2.2 Model Verification

The accuracy of the mud deposition model was originally verified during Phase II of the California Monitoring Program (CaMP; Coats, 1994). The verification was conducted near Platforms Harvest, Hermosa, and Hidalgo which are located offshore Point Conception a few miles south of Platform Irene. Subsequently, the model was successfully applied with slight

modifications to predict additional discharges from these platforms in Phase III of CaMP (SAIC, 1995). Model verification consisted of comparisons between predicted depositional flux rates with measured drill-mud flux rates within sediment traps deployed around the platforms. Sediment–trap arrays were deployed at distances ranging between 0.5 and 6.5 km from the northernmost platform and the depositional flux of drilling–derived particulates was estimated from elevated barium concentrations in trapped sediments. The maximum flux of drilling solids, near 500 mg m^{-2} day^{-1}, represented less than 2 percent of the total particulate flux into the traps. Furthermore, a substantial portion of these drilling solids originated from the two distant platforms located 3.5 and 6.8 km to the southeast. Particle trajectory computations indicated that ambient current flow carried discharges toward the northwest. Cessation of drilling on the platforms to the southeast accounts for the observed temporal decline in drilling–particulate flux measured near the northernmost platform. Although drilling mud has been discharged at a nearly constant rate over the sampling period, nearby sediment traps recorded lower flux rates when the platforms to south stopped discharging drill mud. This unexpected temporal decline in sediment-trap flux was successfully captured in the depositional model.

D.2.3 Model Input

For the most part, fluctuations in mid–depth current flow at subtidal periods dictate plume trajectories and depositional patterns. In the Platform Irene model, particulates were released 46 m below the sea surface and the discharge plumes required about 0.5 days to transit the remaining 28 m of water column at a mean settling rate of 50 m day^{-1} (0.06 cm s^{-1}). Continuous hourly emissions were tracked until deposition. Consequently, the trajectory computation reflected a climatological summary of subtidal current statistics and depositional patterns disclosed the relative likelihood of plume impingement on benthic communities. Again, this is a fundamental departure from other assessments which include the detailed short–term behavior of individual bulk discharges (e.g., O'Reilly et al., 1989). Similarly, it differs from long–term fate assessments which include resuspension processes (e.g., Pickens and Lick, 1992). Therefore, patterns determined for the trajectory computations are not necessarily synonymous with drilling–particulate distribution in surficial sediments. Nevertheless, performing the trajectory computation on a climatological basis is consistent with measurements provided by sediment traps since they integrate the initial depositional flux of platform–derived particulates over extended periods.

D.2.3.1 Flow Field

Differences in the prevailing mid-depth flow field near Platform Irene are largely responsible for the difference in the mud depositional pattern there. In particular, the depositional pattern around Platform Irene shown in Figure D-1 is skewed to the north along a major axis aligned with the north-south bathymetric trend (Figure 5.6-1). In contrast, the depositional pattern generated by drill-mud discharges from Platforms Harvest, Hermosa, and Hidalgo had a major axis aligned parallel to isobaths that trend toward the northwest at 324°T. The northward skew in the Platform-Irene depositional pattern is also in opposition to the southward transport determined in oil spill trajectory modeling shown in Figure 5.8-1. The difference in patterns results because oil spill trajectories are largely driven by surface processes, namely, southward directed winds and

surface currents. At depth, where the drill muds are discharged, the northward-directed Davidson current is largely responsible for net movement of water parcels.

The velocity field at the depth of the plume centroid is interpolated from velocity measured at various current-meter moorings near Platform Irene. Their locations are shown in Figure 5.6-1. They include flow measurements collected at NDBC Buoy 46023 and at moorings deployed during the Santa Barbara Channel – Santa Maria Basin Coastal Circulation Study (SBC-SMB; Hendershott and Winant, 1996). Although the SBC-SMB moorings that are located offshore Point Arguello are closest to Platform Irene, they lie within the different bathymetric regime described above. The mid-shelf SBC-SMB mooring between Point Sal and Purisima Point provides a more suitable flow history for determining the fate of drill-mud discharged from Platform Irene. The mooring is also located near the 100-m isobath, which is comparable to Platform Irene's water depth. While the annual mean surface flow at this mooring is strongly to the south (Hendershott, 2001), the mid-depth prevailing flow carries drilling particulates to the north.

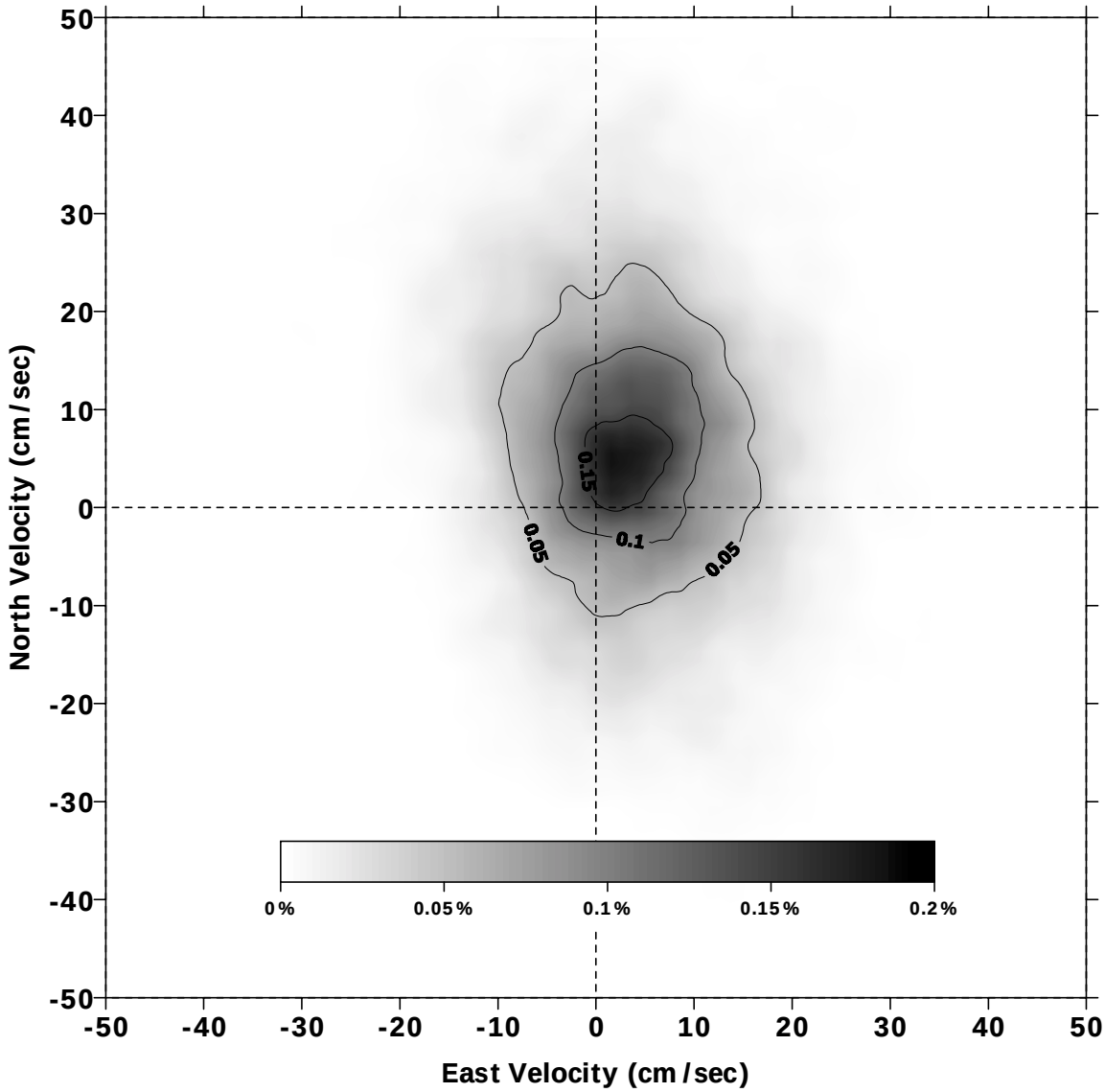
The northward mean flow at depth is evident in flow statistics computed from the 45-m current meter shown in Figure D-3. It shows the probability (%) of observing a particular velocity value within a 1 cm s^{-1} square. For example, the northward mean velocity of (5.2 cm s^{-1}) is almost three times more likely to occur ($P \approx 0.19\%$) than an equivalent speed to the south ($P \approx 0.07\%$). Similarly, cross-shore velocities of the same magnitude are only about half as likely to occur ($P \approx 0.10\%$). The increased likelihood of northward directed flow at mid-depth is largely responsible for the northward elongation of the drill-mud depositional pattern shown in Figure D-1.

D.2.3.2 Mud Discharge

Although the mud dispersion model can process a time-varying mud discharge, a constant discharge was assumed. When the drilling schedule is accurately known, or when mud-log records are available after the fact, the model can combine the mud-discharge time history with the time-varying measured currents to predict drill mud dispersion more accurately. This is particularly useful when the discharge occurs over a brief time; for example, within a single oceanographic season when current flow may depart from the average conditions reflected in Figure D-3. However, the directional drilling that will be used to develop the Tranquillon Ridge Field will occur over many years. Consequently, the discharges are likely to encounter the full range of seasonal variation and the assumption of a uniform discharge rate provides a reasonably accurate depositional pattern.

The model computations are based on a total discharge of 51,500 m^3 over a period of about 7.4 years. The discharge duration was computed assuming 90 days of discharge for each of 30 wells. The discharge volume was estimated from a discharge rate of 3.5 gpm (19 m^3 day^{-1}) over the 7.4 years of discharge. At an average mud density of 1450 kg m^{-3}, the total mass discharged would be about 75,000 metric tons. This discharge mass equals the integral of the flux over the area shown in Figure D-1 multiplied by the discharge duration.

Figure D-3 **Joint Probability Distribution for Current Velocity Measured at 45 m on the Mid-Shelf Point-Sal Mooring from the SBC-SMB Study**



D.3 Model Results

The modeling results shown in Figure D-1 demonstrate that despite the large total discharge, most of the material is deposited close to Platform Irene. Over half of the mud is deposited within the 5-g-m^{-2}-week^{-1} contour, which covers a 9-km^2 area within about 1.7 km of the Platform. The remaining material is dispersed over wide areas where the flux of particulates is negligible. Over 80% of the mud is deposited within the 1-g-m^{-2}-week^{-1} contour, which covers a 40-km^2 area within about 3.6 km of the Platform. Less than 0.4% travels farther than 10 km before being deposited on the seafloor.

Based on the depositional pattern, drill mud plumes would rarely extend into State Waters, which are delineated by the dashed line in Figure D-1. This is partially due to the along-shore alignment of the major depositional axis and preferential transport to the north by mid-depth currents as reflected in Figure D-3. Maximum drill mud deposition rates within the small portion of State Waters encompassed by the 1-g-m^{-2}-$week^{-1}$ contour are negligible compared to the deposition rates of ambient particulates. Fallout of detrital and terrigenous material in the upper water column ranges from 4.2 to 17.5 g m^{-2} $week^{-1}$ (Jackson et al., 1989). When sediment resuspension is included, total ambient particulate flux to the seafloor averages 175 g m^{-2} $week^{-1}$ in this region of the continental shelf (Coats, 1994). In the presence of these natural processes, diffuse drill-mud plumes contributing 1g m^{-2} $week^{-1}$ to the seafloor flux would neither tangibly increase water column turbidity nor measurably contaminate seafloor sediments.

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