Deep Sedimentary Thermal Regime of the Texas-Louisiana Continental Shelf, Gulf of Mexico (PO 35200)

FINAL REPORT – July 24, 2006

Seiichi Nagihara

Department of Geosciences
Texas Tech University
Lubbock, TX 79409-1053

seiichi.nagihara@ttu.edu

Introduction

The main goal of this study was to construct a database of present-day temperature distribution within deep sediments (2 to 7 km sub-seafloor) of the northern continental shelf of the Gulf of Mexico. The database will be helpful for researchers in assessing hazard risks associated with hydrogen sulfide (H_2S) gas generated by the thermo-chemical sulfate reduction (TSR) processes in deep reservoirs. The TSR is a series of chemical reactions partly controlled by the reservoir formation temperature. Mapping out or estimating the sediment temperature at depths prior to drilling is an important component in the risk assessment.

In constructing the database of sedimentary temperatures, we utilized bottom-hole temperature (BHT) data reported for previously drilled boreholes in federal waters of the continental shelf. A BHT is the maximum temperature recorded during a wire-line logging operation. The well bore temperature should increase with depth because the geothermal heat travels from deep earth to the surface, and thus the maximum temperature should be observed at the bottom of the hole. A BHT by itself does not represent the formation temperature at that depth. During drilling, circulation of drill fluid lowers temperature around the hole, and thus the BHT measurement can commonly be a few tens of degrees-C below the so-called virgin rock temperature (VRT) (Beardsmore and Cull, 2001). Most of the previous compilations of Gulf of Mexico BHT data (AAPG, 2001; Bebout and Gutierrez, 1981) either did not make any attempt to estimate VRTs from the BHT data or used BHT correction methods that were discounted by later studies (Deming, 1989).

For this project, we properly corrected individual BHTs for the drill fluid circulation effect. Theoretical models of the heat transport in and outside the borehole have been developed for some case studies and the VRT estimation methods based on such models are considered fairly reliable (Beardsmore and Cull, 2001; Hermanrud et al., 1990). Among them, the so-called Horner plot technique has been used by a number of geothermal heat flow researchers. The methodology requires that BHT be measured at multiple times at a fixed depth while the well is shut in. In other words, multiple tool runs must be made to the bottom of the hole while the well is shut in and before the hole can be drilled deeper. The BHT measurements obtained at different times should show the borehole temperature slowly recovering toward its pre-drilling state. An estimate of the VRT can be made by extrapolation of the observed temperature recovery trend to the infinite time (Lachenbruch and Brewer, 1959). More details on the BHT correction procedure for this study is described in an already published article (Nagihara, 2004), a copy of which is attached to this report.

Bottom-hole Temperature Data Used in This Study

Figure 1 shows the geographical locations of the wells examined for this study. BHTs from 1020 wells were compiled from their log headers. Only a small fraction of them were useful for VRT estimation, however, because of questionable reporting of BHTs from a number of wells and the requirement of multiple (at least 2) measurements made at a fixed depth. Quality control is a major issue in dealing with BHT data, as noted by many previous researchers (Beardsmore and Cull, 2001; Deming, 1989). The following measures were taken for data quality assurance. First, we excluded from consideration the wells that did not show any increase of BHT while multiple tool runs were made during a shut-in period. Numerous wells reported constant BHTs for more than a day while multiple tool runs were made. Such stability in temperature is highly unlikely, because BHT should begin to rise toward its pre-drilling state once the well has been shut. Second, we excluded the data if the well was circulated again between tool runs, because the BHT correction method cannot account for the disturbance caused by multiple circulation events. As a result, 567 VRT estimates were made from 365 wells. The depths of these estimates range from 1 km to 7 km (23,000 ft) sub-seafloor.

If four or five VRT estimates can be obtained at different depths of a single well, one could determine the geothermal gradient at that location with some confidence. However, as shown in Fig. 1, such cases are rare. Of the 1020 wells examined, only 20 yielded 4 or more VRT estimates. The vast majority of the wells yielded only one or no VRT estimate. Therefore, in this study, we first divided the VRT-yielding wells geographically into 34 groups, and then determined the geothermal gradient collectively for each group (Fig. 2), assuming that lateral heterogeneity in the geology is negligible within each.

Data Interpretation

The temperature-depth curve, or geothermal profile, obtained from the VRTs (corrected BHTs) show different shapes among different well groups. Figure 3 compares geothermal profiles obtained for 3 of the groups as examples. The difference reflects the regional variation in geologic history and structure, which affects the heat transport through the thick sedimentary column. We have already published two research articles discussing the variation of geothermal profile offshore Louisiana, Mississippi and Alabama (Nagihara and Smith, 2005, in press). Copies of these articles are also attached to this report.

A geothermal profile may not always be completely straight. Thermal conductivity of sediment varies depending primarily on its lithology and porosity. Along a vertical sedimentary column, sections with relatively low thermal conductivity tend to show high thermal gradient and vise versa so that the heat flow, which is the product of the thermal conductivity and the thermal gradient, is roughly maintained. Thermal conductivity of sediment also changes with time in the course of sediment accumulation due to compaction. In addition, changes in sedimentation rate influences the efficiency of upward heat transport through the sediment column (Hutchison, 1985).

Here we show an example of how changes in sedimentation rate affect temperature distribution in the sedimentary column. Figure 4 is a so-called thermal/burial history diagram for the vicinity of Viosca Knoll block 117 (Fig. 1). It shows how the sedimentary layers were added over time and how temperature distribution within them changed. Well #1 there penetrated down to the Jurassic Smackover formation at 7,620 m below sea level. Sediment cores recovered from the well have been dated and reported (Minerals Management Service, 2001), on which the burial history in Fig. 4 is based. Isotherms in the diagram were derived from a theoretical modeling of the heat transport process through the geologic history of the area (Dobson and Buffler, 1997; Sawyer et al., 1991). The VRT estimates from group 2, which include block 117, were used to constrain the model. The model calculation was performed using the software *BasinMod 1-D* of Platte River Associates, Inc.

According to the thermal/burial history diagram, during the period of rapid sedimentation, about 100 million years ago, isotherms were depressed, because the speed of upward geothermal heat transport could not catch up with that of sedimentation. However, several million years later, when sedimentation slowed, isotherms slowly recovered.

Regional Overview of the Sedimentary Thermal Regime

By geographically interpolating the geothermal profiles obtained for the 34 well groups, we have generated continuous maps of sedimentary temperature at 5 km sub-seafloor (Fig. 5) and thermal gradient at deep sedimentary interval (2 to 7 km sub-seafloor) (Fig. 6). Using the two sets of information, researchers can estimate sediment temperature at different depths. For example, in the Mobil lease area, sediment temperature at 5 km sub-seafloor is 158º C and thermal gradient is 0.027 K/m. Thus, temperature at 7 km sub-seafloor should be:

$158 + 0.027 \times (7000-5000) = 212.$

Using the attached the temperature database and the *ArcGIS* software of ESRI, it is possible to perform this type of calculations more precisely.

From the east to the west on the continental shelf, there are systematic variations in deep sedimentary temperature (Fig. 5). At 5-km sub-seafloor depth, temperature is 150 to 160º C offshore Alabama. It decreases westward and reaches a minimum near the mouth of the Mississippi, where temperature is 120º C or less. Along the eastern half of the Louisiana shore, temperature is generally low, especially toward the shelf break. In the western Louisiana to east Texas, a gradual increase of sedimentary temperature is clearly observed. Throughout the Texas shore, temperature at 5-km sub-seafloor depth is generally higher than 160º C. In the Mustang Island lease area, it is estimated be ~220º C. The wells there do not reach that depth (Group 30, Fig. 3) and the 5-km depth temperature has been extrapolated from the trend observed at shallower depths.

Figure 5 also shows the locations of previously occurrence of H_2S during drilling or production. Only those deeper than 4-km depth are shown, because they are more likely to be TSR-generated rather than of bacterial origin. The geographic correlation between hot sediment and H_2S occurrence is clear. No deep H_2S occurrence has been reported off eastern Louisiana where sediment is relatively cold.

Description of Attachments

The pages immediately following this main body of the report are reprints of previously published articles by Seiichi Nagihara and Michael A. Smith:

- Nagihara (2004) Transaction, Gulf Coast Association of Geological Societies
- Nagihara and Smith (2005) American Association of Petrolem Geologists Bulletin
- Nagihara and Smith (in press) Transaction, Gulf Coast Association of Geological Societies

Final pages of the report are a step-by-step instruction on how to manipulate the attached databases using the *ArcGIS* software.

Poster-size hard copies of Figures 4 and 5 are also attach to the report.

In attached CD-ROM, the PDF files of the main body of the final report, the reprints, and the step-by-step instruction mentioned above are included. If MMS is going to post the attached reprints on its website, it must obtain permission from the organizations who own the copyright. The article currently in press should not be posted until it is published in September 2006 and replaced by a reprint copy.

In addition, the following digital files are included in the CD-ROM:

1. Digital databases and files generated for this project.

- Database on the locations and other attributes of the wells (API#, lease block#, etc.) of which bottom-hole temperature (BHT) data have been analyzed. *ArcGIS* format.
- Database of the corrected BHTs. *ArcGIS* format.
- PDF slide sets showing step-by-step how to manipulate the attached databases using the *ArcGIS* software.

2. Maps of geothermal gradient and sedimentary temperature at 5-km depth of the Gulf of Mexico continental shelf in two formats:

- Poster-size (33’ x 44’) PDF files

- *ArcGIS*-formatted raster data

3. An example of sedimentary thermal history analysis for the Viosca Knoll block 117 area using the VRT estimates, *BasinMod 1-D* format.

Note: *ArcGIS* is a product of ESRI. *BasinMod 1-D* is a product of Platte River Associates, Inc.

References Cite

AAPG, 2001, DP-AAPG DataRom: Tulsa, American Association of Petroleum Geologist.

Beardsmore, G. R., and J. P. Cull, 2001, Crustal Heat Flow: A Guide to Measurement and Modeling: Cambridge, UK, Cambridge University Press, 324 p.

Bebout, D. G., and D. R. Gutierrez, 1981, Geopressured geothermal resource in Texas and Louisiana --- geological constraints: 5th Conference, Geopressured - Geothermal Energy, p. 13-24.

Deming, D., 1989, Application of bottom-hole temperature corrections in geothermal studies: Geothermics, v. 18, p. 775-786.

Dobson, L. M., and R. T. Buffler, 1997, Seismic stratigraphy and geologic history of Jurassic rocks, northeastern Gulf of Mexico: Amer. Assoc. Petrol. Geol. Bull., v. 81, p. 100-120.

Hermanrud, C., S. Cao, and I. Lerche, 1990, Estimates of virgin rock temperature derived from BHT measurements: Bias and error: Geophys., v. 55, p. 924-931.

Hutchison, I., 1985, The effects of sedimentation and compaction on oceanic heat flow: Geophys, J. R. Astr. Soc., v. 82, p. 439-459.

Lachenbruch, A. H., and M. C. Brewer, 1959, Dissipation of the temperature effect of drilling a well in Arctic Alaska, Washington, United States Geological Survey, p. 109.

Minerals Management Service, 2001, Public Paleontological Information, CD-ROM.

Nagihara, S., 2004, Bottom-hole temperature data in the outer continental shelf off Alabama: Trans. Gulf Coast Assoc. Geol. Soc., v. 54, p. 523-530.

Nagihara, S., and M. A. Smith, 2005, Geothermal gradient and temperature of hydrogen sulfide-bearing reservoirs in the continental shelf off Alabama: Amer. Assoc. Petrol. Geol. Bull., v. 89, p. 1451-1458.

Nagihara, S., and M. A. Smith, in press, Deep sedimentary thermal gradient in the continental shelf off Alabama, Mississippi and Eastern Louisiana: Trans. Gulf Coast Assoc. Geol. Soc., v. 56.

Sawyer, D. S., R. T. Buffler, and R. H. Pilger, Jr., 1991, The crust under the Gulf of Mexico basin, *in* A. Salvador, ed., The Gulf of Mexico Basin: Geology of North America, v. J: Boulder, Geological Society of America, p. 53-72.

Wells Examined and the Number of VRT Estimates Yielded for Each

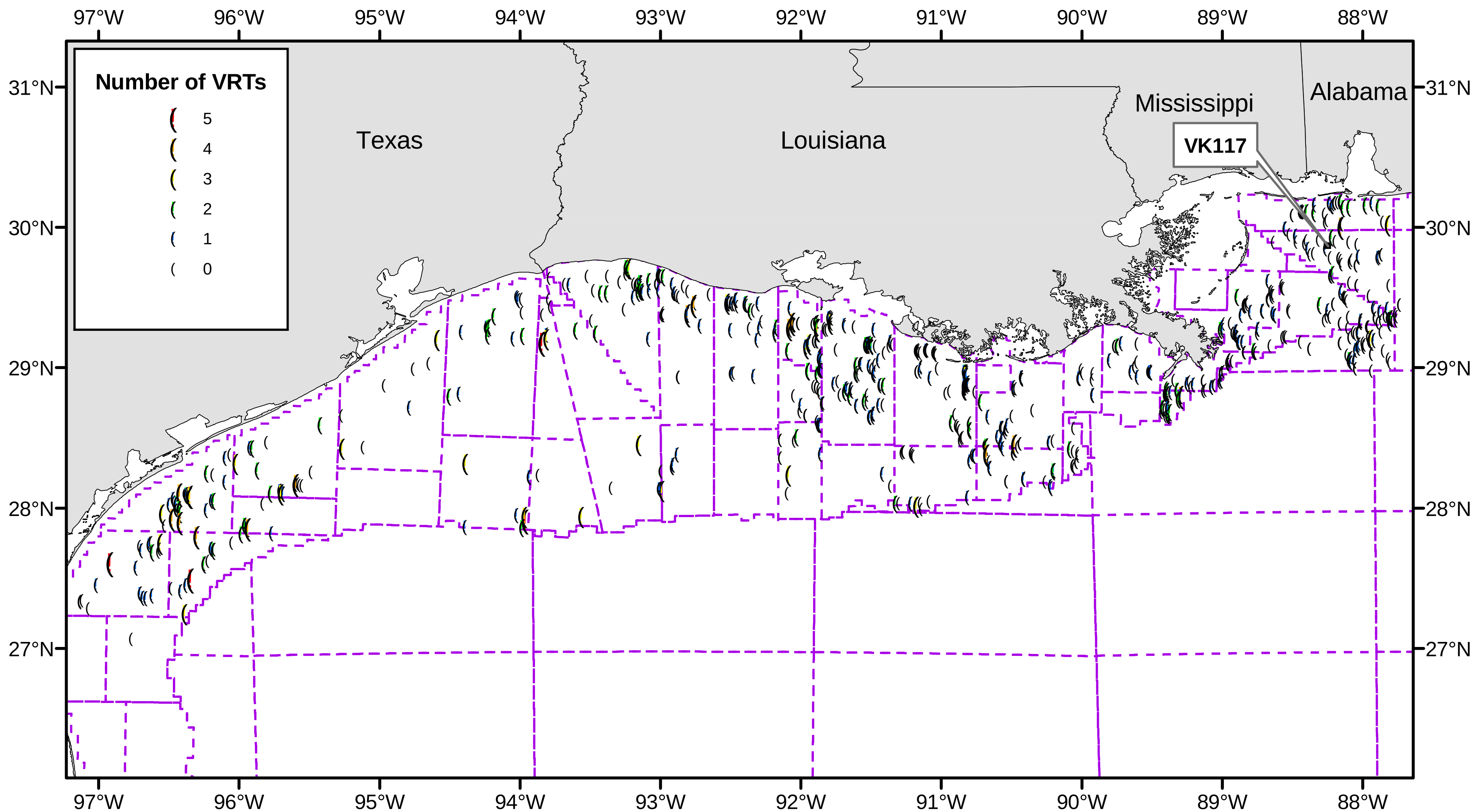

Figure 1 Each dot represents the location of a well examined for this study.
The dots are color coded according to the number of VRT estimates they yielded.

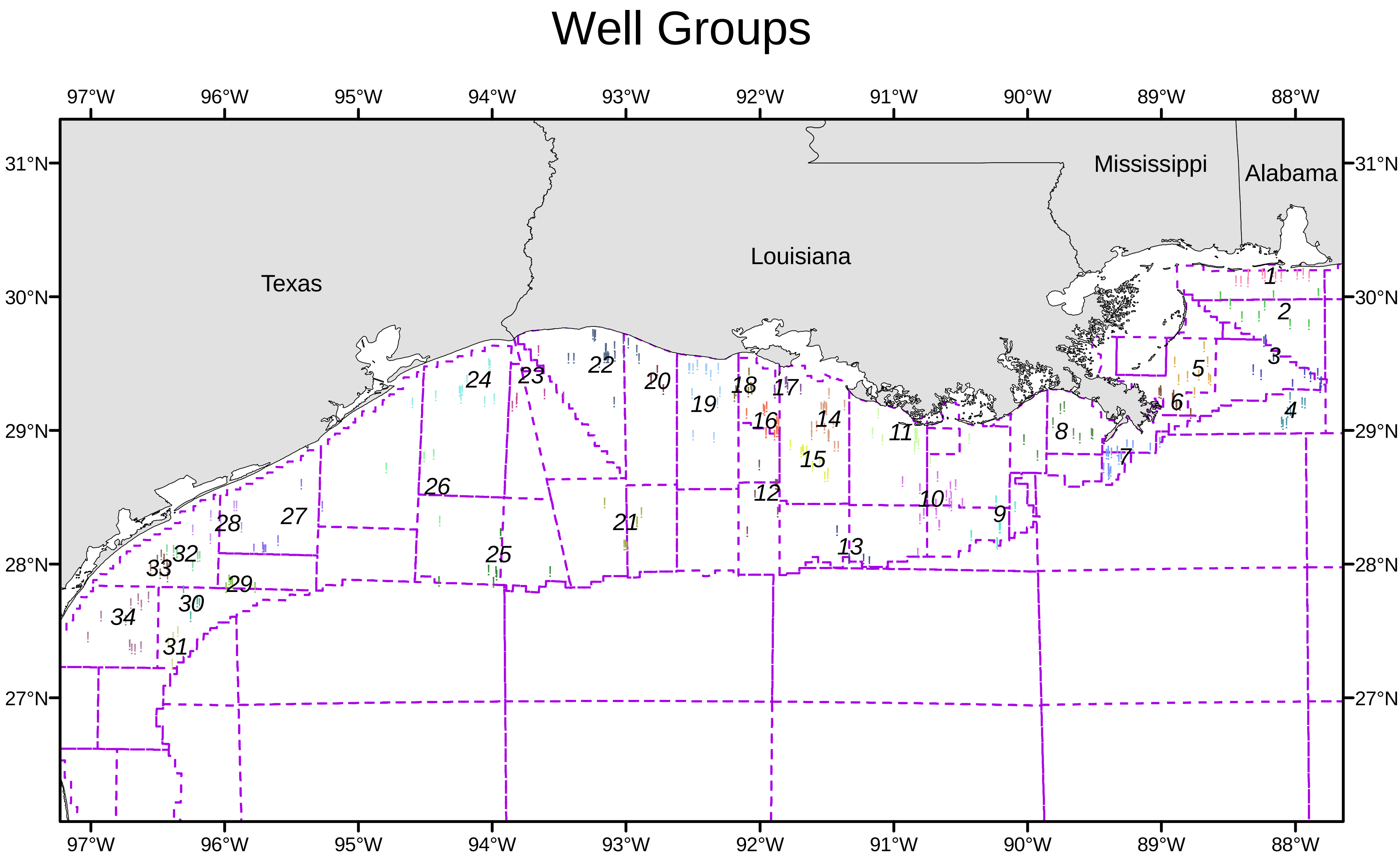

Figure 2 Each dot represents the location of a well that yielded at least one VRT estimate. These wells have been divided geographically into 34 groups. The wells in each group are in the same color.

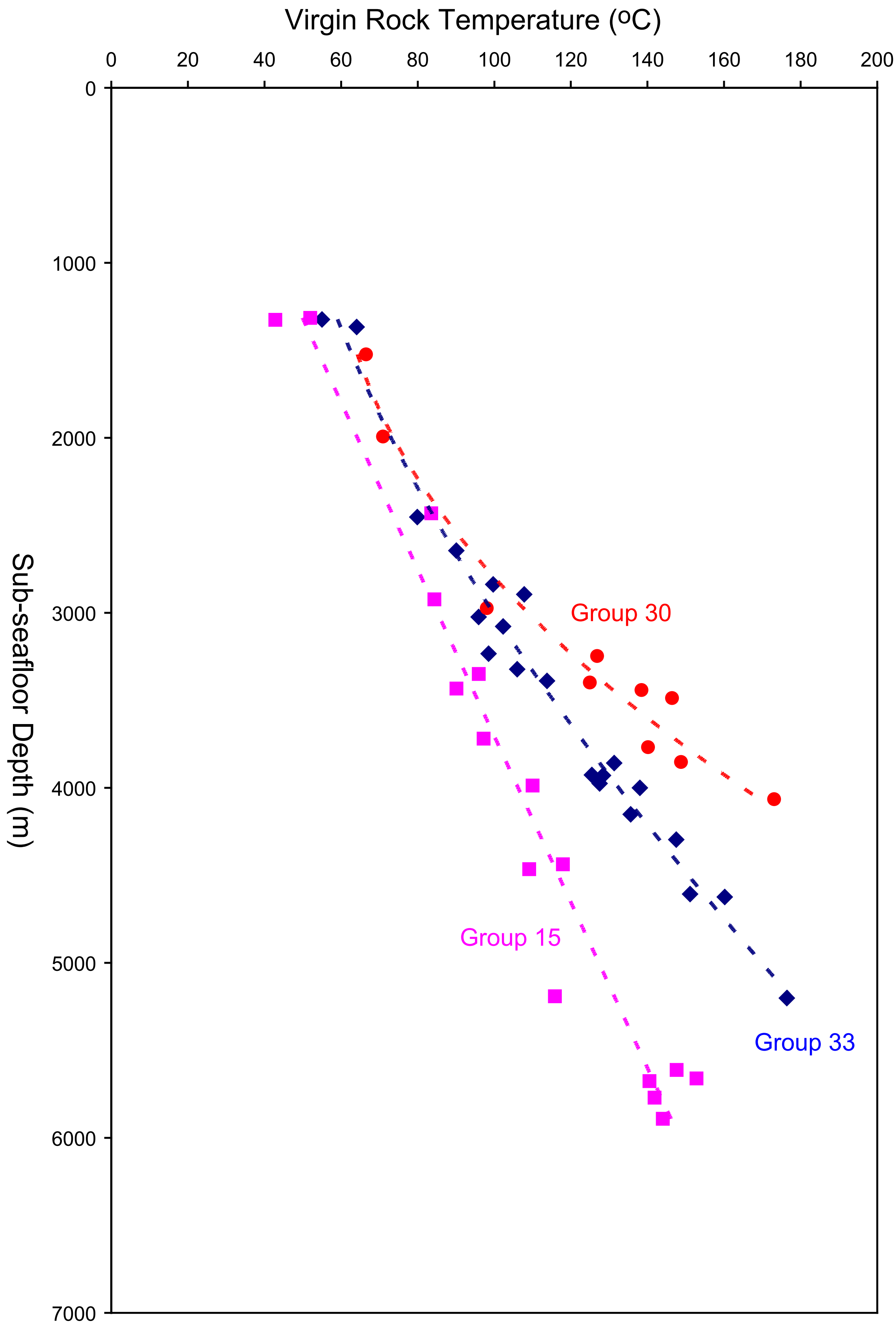

Figure 3 Geothermal profiles of three well groups (15, 30, and 33). are compared. Point symbols are the VRT estimates for the groups and dashed curves are polynomial fits.

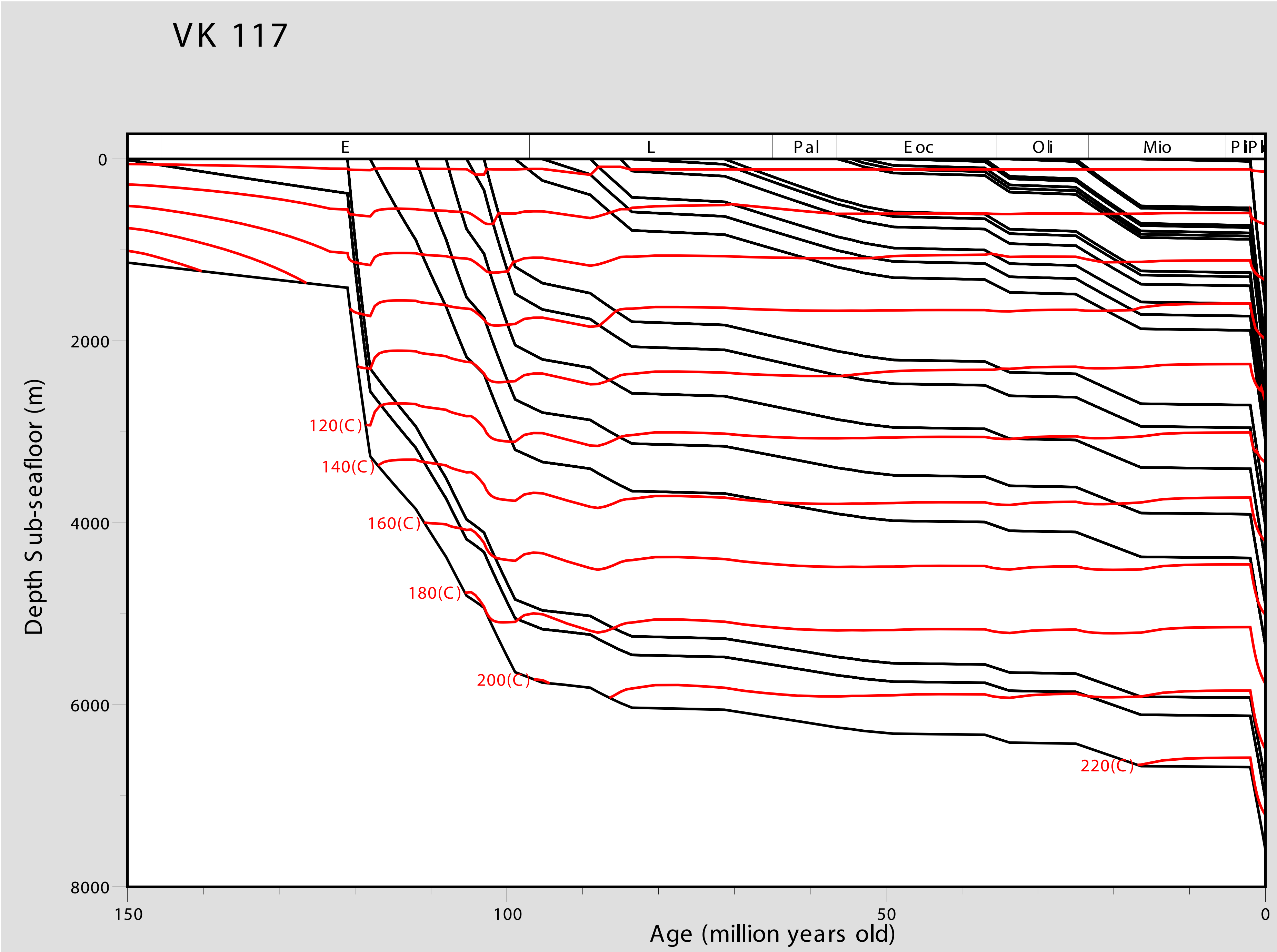

Figure 4 An thermal/burial history diagram generated for a geologic history model for the Viosca Knoll block 117 area. The biostratigraphy data from well #1 in the same area and the VRT estimates from group 2 are used in constraining the model.

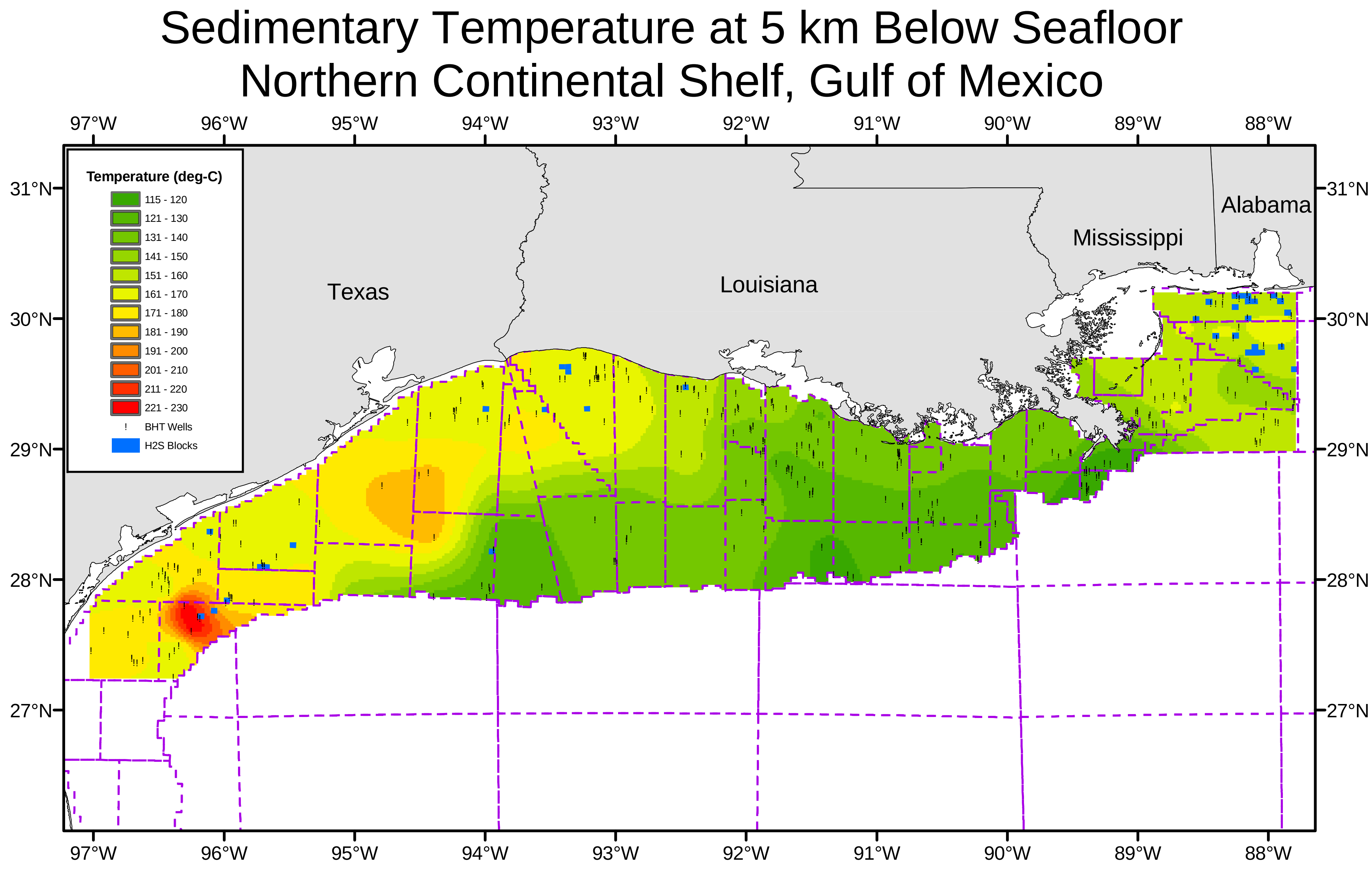

Figure 5 Geographically interpolated estimates of sedimentary temperature at 5 km sub-seafloor. Dots show the locations of the VRT-yielding wells. Blue squares show the locations of previously reported hydrogen sulfide occurrence deeper than 4 km.

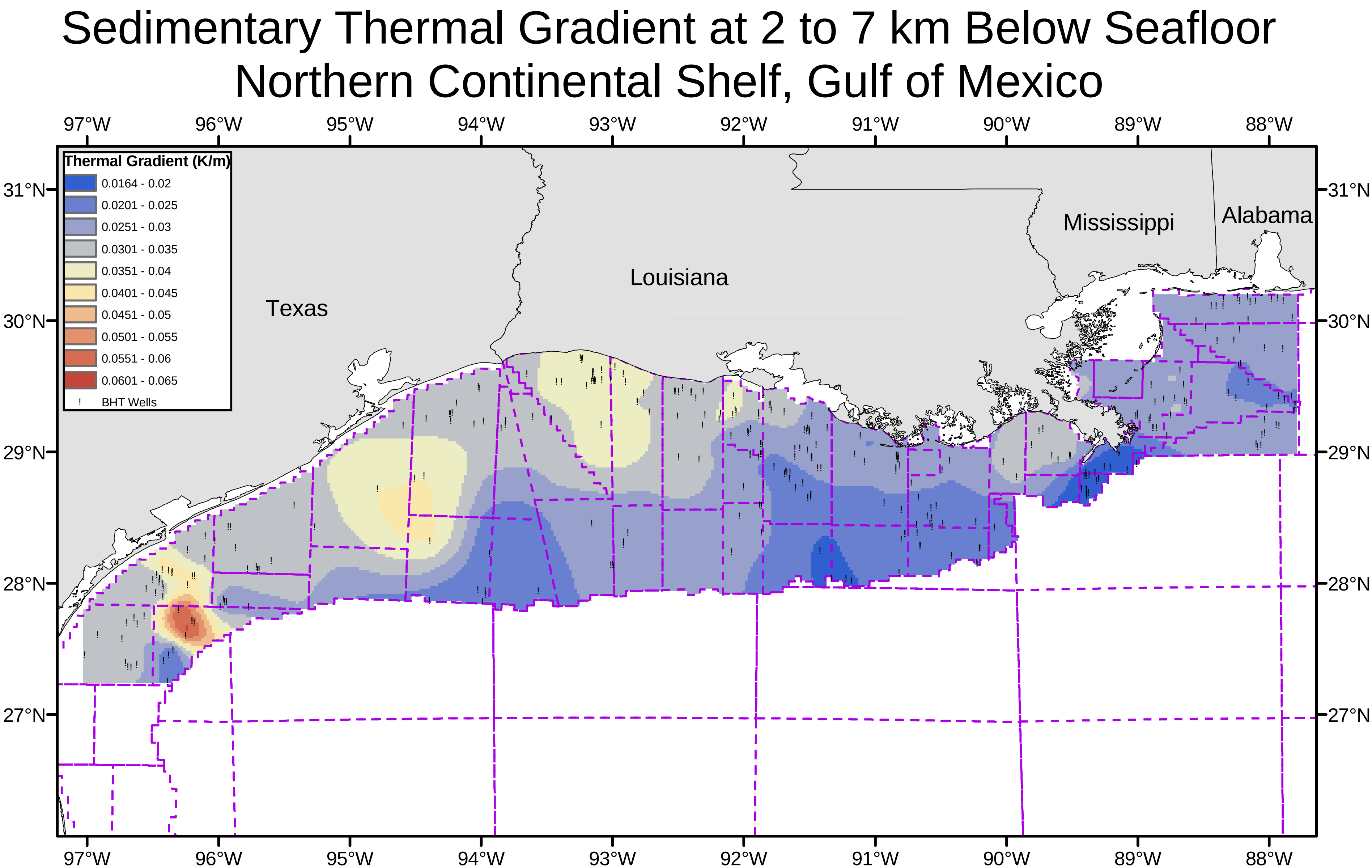

Figure 6 Geographically interpolated estimates of geothermal gradient in a depth interval of 2 to 7 km sub-seafloor. Dots show the locations of the VRT-yielding wells.