Geothermal heat flow in the northeast margin of the Gulf of Mexico

Seiichi Nagihara and Kelly Opre Jones

ABSTRACT

Eighty-two seafloor heat-flow measurements were recently obtained across the Mississippi Fan region in the deepwater northeastern Gulf of Mexico. These data display an abrupt transition in heat flow between an area near the center of Pleistocene deposition ($\sim$20 mW/m^2) and the eastern margin of the fan ($\sim$40 mW/m^2). Although deposition of fan sediments has very likely suppressed the shallow subseafloor thermal regime, causing lower seafloor heat-flow values near the center, the magnitude and abruptness of the heat-flow contrast cannot be fully accounted for by the mechanisms related to sedimentary deposition, which include radiogenic heat production in sediments, pore-fluid migration, and presence of salt structures. The most plausible explanation for the sharp heat-flow contrast is that the heat released from the igneous basement is significantly greater in the eastern margin of the fan. The zone of contrasting heat flow lies along a previously suggested boundary between the oceanic crust and the thin transitional crust in the northeastern Gulf of Mexico. The area of higher heat flow coincides with the suggested zone of transitional crust, which, because of its granitic origin, generates greater amounts of radiogenic heat than oceanic crust. This finding opens up the possibility that heat-flow data may be used in delineating crustal lithologic boundaries along continental margins.

INTRODUCTION

It has been accepted by many that much of the abyssal plain of the Gulf of Mexico (Figure 1) is underlain by oceanic crust (Buffler and Sawyer, 1985; Sawyer et al., 1991). No basement rock sample has been recovered, but three lines of indirect evidence suggest an oceanic setting. First, the total tectonic subsidence of the abyssal plain since its formation is so large that it can be explained only

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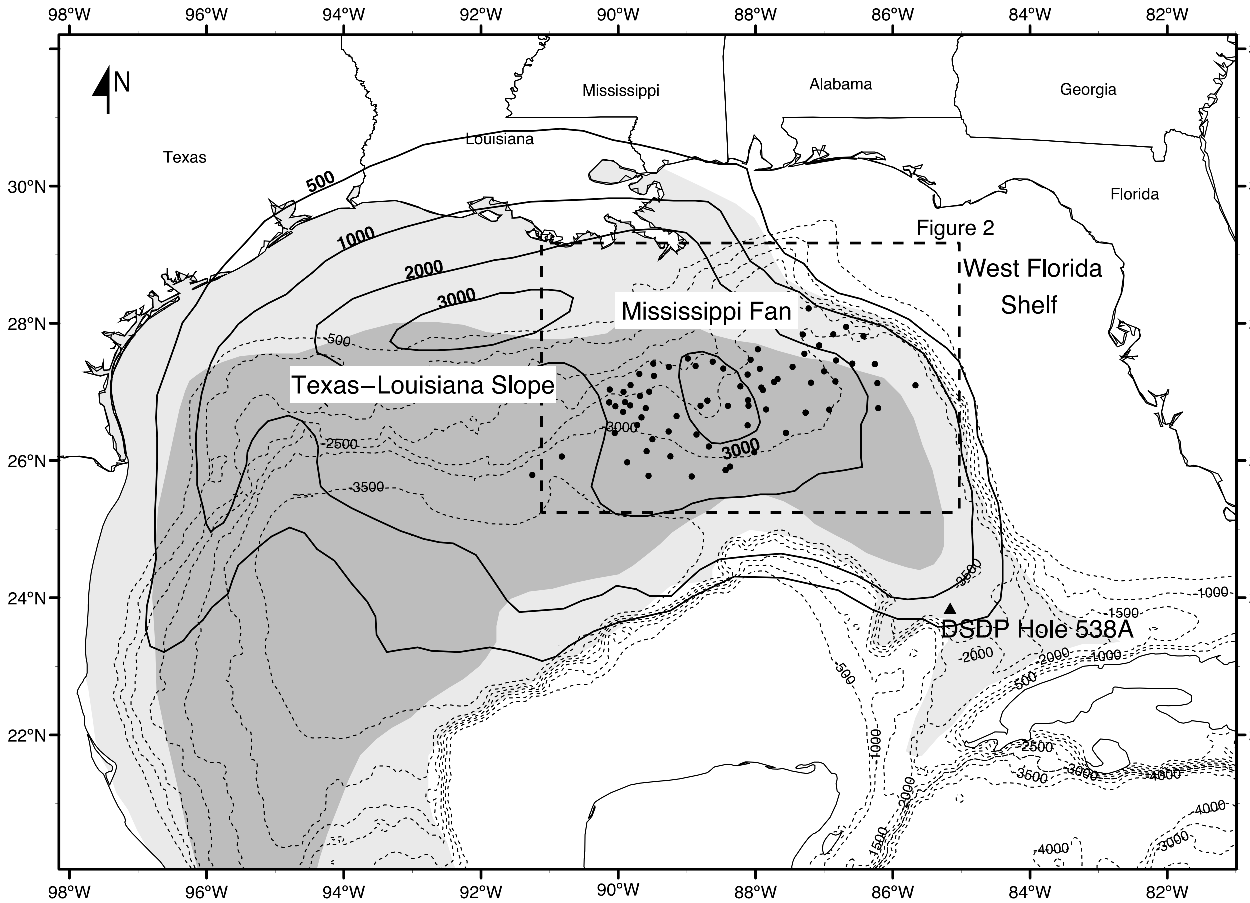

Figure 1. Map of the Gulf of Mexico. Bathymetric contours are drawn as dashed lines at 500-m (1600-ft) intervals. The area shaded dark is underlain by oceanic crust according to Marton and Buffler (1994). The lightly shaded area is underlain by a thin transitional crust. Solid lines are thickness isopachs of Pleistocene sediments (Feng and Buffler, 1996). Black dots show the locations of the heat-flow measurements. The solid triangle shows the location of Deep Sea Drilling Project Hole 538A.

by the occurrence of seafloor spreading (Dunbar and Sawyer, 1987). Second, the seismic velocity structure of the basement is similar to those found in ocean basins (Ibrahim et al., 1981). Third, linear patterned-magnetic anomalies, a common feature in ocean basins, can be observed in the eastern abyssal plain (Hall and Najmuddin, 1994).

Aerial extent of the oceanic crust, however, is still much debated. If one can accept that seafloor spreading occurred soon after deposition of the Louann Salt in the Middle Jurassic (Salvador, 1991), the boundary between the oceanic crust and the surrounding transitional crust should follow the basinward edge of the autochthonous salt bed mapped by seismic profiling (Buffler, 1991). On the contrary, the magnetic anomaly lineations can be observed farther landward, at least in the eastern Gulf (Hall and Najmuddin, 1994). An interpretation primarily based on free-air gravity anomalies and crustal seismic-velocity structure data (Marton and Buffler, 1994) places the boundary somewhere in between (Figure 1). Delineation of the oceanic-continental transition zone is a key piece of information in reconstructing the early opening history of the Gulf.

The present study discusses a possibility in which geothermal heat-flow data may be used in delineating the crustal boundary in the northeastern Gulf of Mexico. Here, a clear distinction is made between the heat released from the top of the igneous basement and the heat flow through the top of the sedimentary cover because the two are not necessarily equal in any given location. The former is referred to as the basement heat flow, and the latter is referred to as the surface (seafloor) heat flow. Basement heat flow is primarily controlled by the mechanics of the basin-forming rift-extension event and the subsequent subsidence caused by the cooling of the lithosphere (McKenzie, 1978;

Sclater and Celerier, 1987). Heat flow decreases with time as the lithosphere gradually approaches a quasi-steady state (Sclater et al., 1980). Basement heat flow is also influenced by the heat generated through radioactive decay of unstable elements, such as uranium, thorium, and potassium, contained in the crustal rock (Beardsmore and Cull, 2001). In general, continental crust produces several tens of times more radiogenic heat than oceanic crust.

As heat travels upward through the sedimentary column, the column thickness is simultaneously increasing because of accumulation of new sediments. If speed of sediment accumulation is substantially faster than that of the upward heat flux through the sedimentary column, less heat would be released from the seafloor than was input from the basement (Von Herzen and Uyeda, 1963; Hutchison, 1985). Heat-producing elements are also present in sediments and would add to the total heat budget. In some abyssal plains where sedimentation rate is relatively low, the reduction in heat caused by sediment accumulation and the heat added by radioactivity may roughly cancel out (Nagihara et al., 1996). This is not the case in the Mississippi Fan, where the continental slope is in close proximity to the source of sediments. Therefore, surface heat flow tends to be less than basement heat flow because of the high accumulation rate.

Basement heat flow may be useful in delineating the crustal boundary, but it is impossible to measure directly in the Gulf of Mexico because of the thick sedimentary cover. One may still obtain reasonable constraints to the basement heat flow by measuring the surface heat flow and carefully evaluating the mechanisms that add to or reduce the heat flux through the sediments. The present study examines seafloor heat-flow data obtained in the northeastern Gulf, with the intention of identifying characteristics associated with the basement heat flow. Unlike the rest of the northern Gulf margin, this area is not heavily populated by shallow allochthonous salt structures. Thus, it presents a relatively unobstructed view into deep sediments and igneous crust for researchers using geophysical techniques.

HEAT-FLOW DATA

The heat-flow data used in this study were made available by TDI-Brooks International based in College Station, Texas. The company collected the data in the year 2000, using the standard marine heat-flow instrumentation capable of in-situ thermal conductivity measurement. The instrumentation and the data reduction scheme have been described in detail elsewhere (Hyndman et al., 1979; Lister, 1979) and thus are reviewed only briefly here. The instrument makes two separate measurements of geothermal gradient and thermal conductivity of the seafloor sediment by inserting a metal tube containing high-precision thermistors down to 4–5-m (13–16-ft) subbottom depth. Heat flow is obtained as the product of these two measurements. This type of instrumentation has been used for the last 25 yr by many researchers in deep ocean basins worldwide. Studies have shown that heat flow can be determined with 2–3% accuracy if environmental disturbance, such as thermal fluctuation of bottom water and fluid seeps on the seafloor, can be avoided (Villinger and Davis, 1987; Nagihara and Lister, 1993).

Heat-flow data from 82 sites in the northeastern Gulf are examined here (Figure 1). Because the data are proprietary, we are not able to show the exact heat-flow value for each site. Instead, we classify the heat-flow values using gray-scale color coding (Figure 2). More data are available farther north-northwest on the continental slope but are not used for the present study because they were obtained near or directly above shallow allochthonous salt structures. Salt is two to four times more thermally conductive than other sedimentary rocks, which causes deeply rooted diapiric salt structures to funnel geothermal heat and produce high-temperature anomalies in the overlying sediment (O'Brien and Lerche, 1988; Nagihara et al., 1992). Therefore, it is already known that the surface heat flow over shallow diapiric salt does not correlate well with basement heat flow. The salt map of Diegel et al. (1995) was used in locating salt structures in the area.

DATA INTERPRETATION

Seafloor heat flow in the study area ranges from less than 10 to about 50 mW/m^2 (Figure 2). Four factors primarily influence the flow of heat through sedimentary layers and, ultimately, to the seafloor. These include the rate and type of sedimentation throughout the burial history, radiogenic heat production in the sediments, subsurface fluid flow through sediments, and crust properties. These mechanisms have been individually studied to determine the possible cause or causes for the variance in surface heat flow.

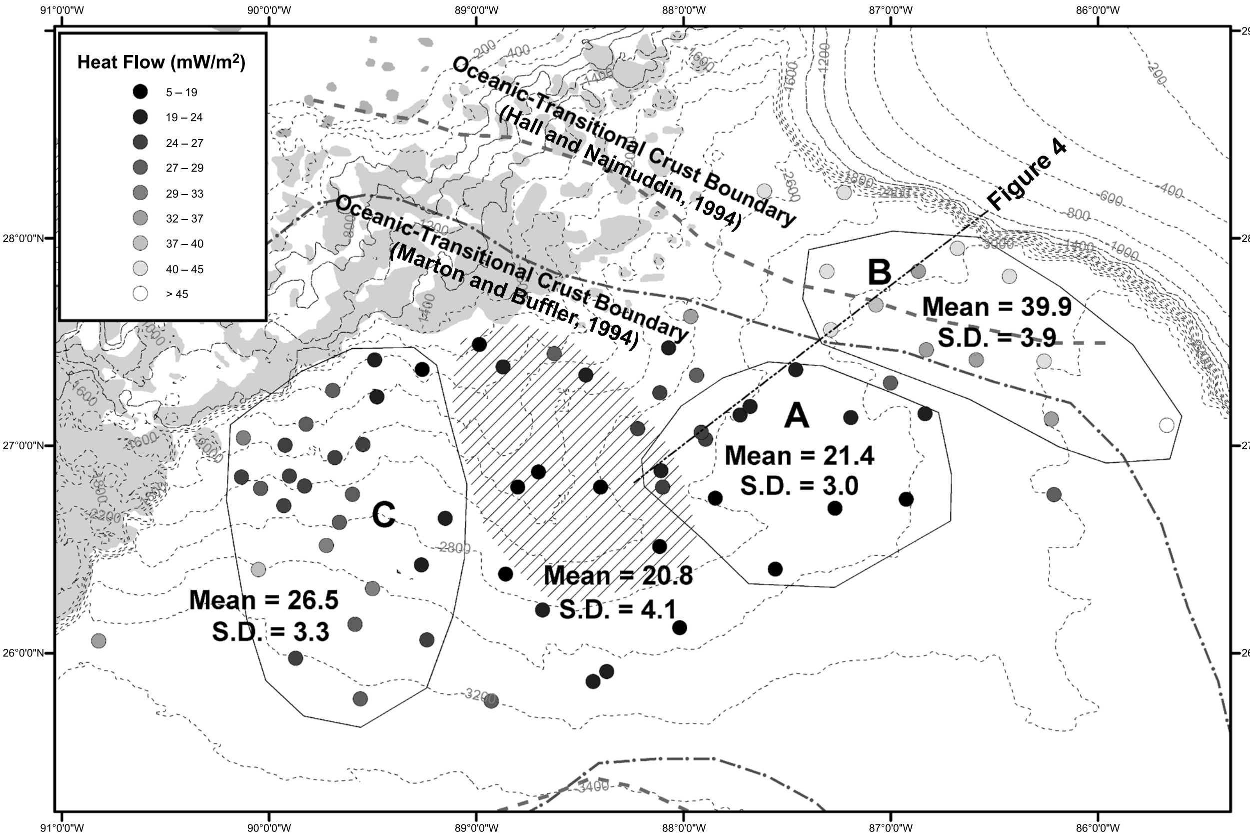

Figure 2. Map of the northeastern Gulf of Mexico. Bathymetric contours are drawn as dashed lines at 200-m (660-ft) intervals. Circles show the locations of the heat-flow measurements. Lighter colors indicate higher heat-flow values. Geographic extents of areas A, B, and C are indicated by solid lines. The boundary between oceanic crust and thin transitional crust according to Marton and Buffler (1994) and the one according to Hall and Najmuddin (1994) are delineated. The hachured area is where the Pleistocene sediments are thickest. Patches of gray shade in the northwest are the locations of shallow allochthonous salt structures according to Diegel et al. (1995). The heat-flow values along the dash-dot line crossing areas A and B are shown in Figure 4.

Effects of the Mississippi Fan Sedimentation

Previous researchers have proposed theoretical models describing how sedimentation influences surface (seafloor) heat flow (Von Herzen and Uyeda, 1963; Hutchison, 1985; Wang and Davis, 1992). All agree on an inverse relationship between sedimentation rate and seafloor heat flow (i.e., faster sedimentation rate, lower heat flow, and vice versa). These models also suggest that the most recent depositional events have the greatest influence on surface (seafloor) heat flow. The general trend observed in the northeastern Gulf is consistent with these model predictions. The systematic, large-scale variation in heat-flow values is easily seen because of the wide distribution of data points across the Mississippi Fan (Figures 1, 2). The average Pleistocene sedimentation rate at the center of deposition is about 2000 m/m.y., whereas it is about 1100 m/m.y. in the eastern margin of the fan (Jones and Nagihara, 2003). Sedimentation rates prior to the Pliocene were much lower (less than 200 m/m.y.) and were more uniform in the study area. Sediment thickness information was obtained from Feng and Buffler (1996). In the center of Pleistocene deposition (Figures 1, 2), heat-flow values are lowest (<20 mW/m^2). Away from it, especially toward the east, heat flow increases to almost 50 mW/m^2. The correlation with Pleistocene sediment thickness is seen in the graph presented in Figure 3.

Although heat flow does decrease with increasing sedimentation rate near the Mississippi Fan, the actual amount of change with distance does not correlate well across the study area. As seen in Figure 2, the heat-flow data have been divided into several areas of similar value. The area of thickest Pleistocene sediments (>3000 m; >10,000 ft) is hachured. The average heat-flow value for measurements in this area is 21 mW/m^2. An area immediately to the east from the

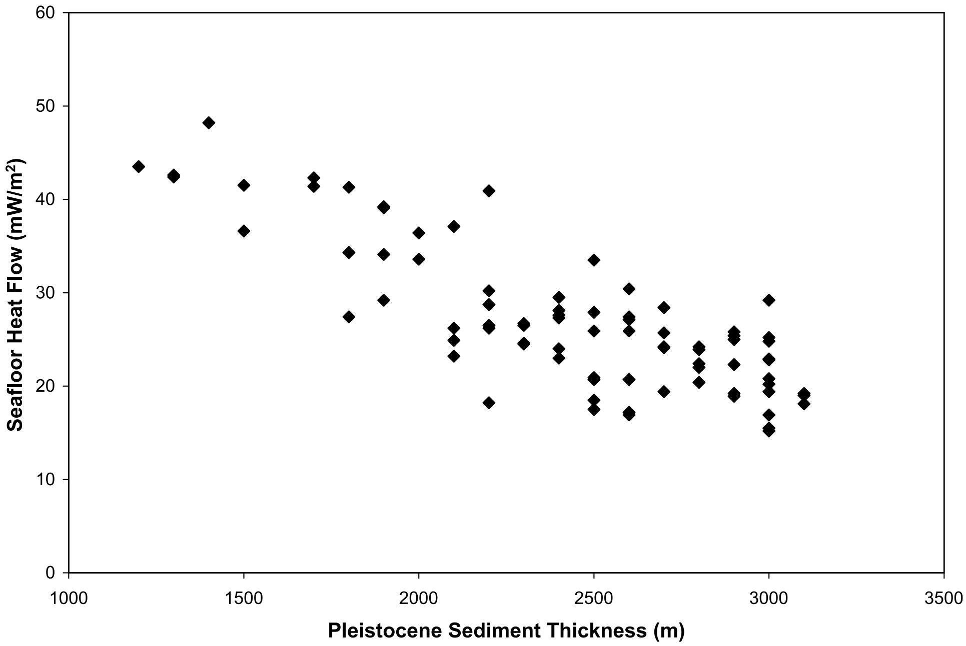

Figure 3. A plot of seafloor heat-flow values vs. thickness of Pleistocene sediments as obtained from Feng and Buffler (1996).

center of deposition is designated as A in Figure 2. Sixteen measurements there show that heat flow is remarkably uniform at about 21 mW/m^2. Thus, there is practically no increase in heat flow eastward from the center of deposition to area A, although the Pleistocene sediment becomes considerably thinner in the same direction. In contrast, in an area farther east (designated B in Figure 2), toward the Florida escarpment, the heat-flow values are almost twice as high at 40 mW/m^2. The eastward increase of heat flow between areas A and B occurs abruptly near 87.2°W, 27.2°N, as shown in the southwest-northeast profile in Figure 4.

Westward from the center of Pleistocene deposition, heat flow also increases. In an area designated as C, the average is about 26 mW/m^2. The westward increase (~5 mW/m^2) is gradual, and its magnitude is much smaller than the difference in heat flow between areas A and B (~19 mW/m^2).

The thermal models of sedimentation (Hutchison, 1985; Wang and Davis, 1992) predict that the recent events have stronger impacts to the seafloor heat flow than older events. Here, the youngest lobe of the fan represents the most recent sedimentary accumulation trend. Figure 5 compares the thickness isopachs of the youngest fan lobe (Bouma et al., 1985) with the heat-flow values. Areas B and C are mostly outside the extent of the lobe and can be expected to have experienced slower sedimentation. That may explain the 5-mW/m^2 westward increase from the center of deposition to area C. However, why is the eastward increase from area A to area B much greater (~19 mW/m^2)?

TDI-Brooks International also provided with us the mean values of the sedimentary thermal conductivity data at the heat-flow measurement sites. Using the data, we found that the average thermal conductivity for the sites in area A is greater than the average for area B by 7%, which is the opposite in the way heat flow varies. The difference in average thermal

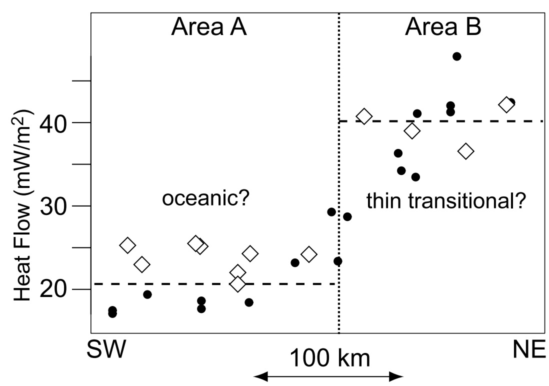

Figure 4. Heat-flow values in areas A and B plotted along the southwest-northeast profile line shown in Figure 2. The heat-flow sites that are right on the profile line are shown as diamonds. For all the other sites, which are shown as open circles, their positions have been projected onto the profile line. Note the abrupt change in heat flow that occurs at the boundary of the two areas especially for those indicated by diamonds. Dashed lines show the average heat flow in each area.

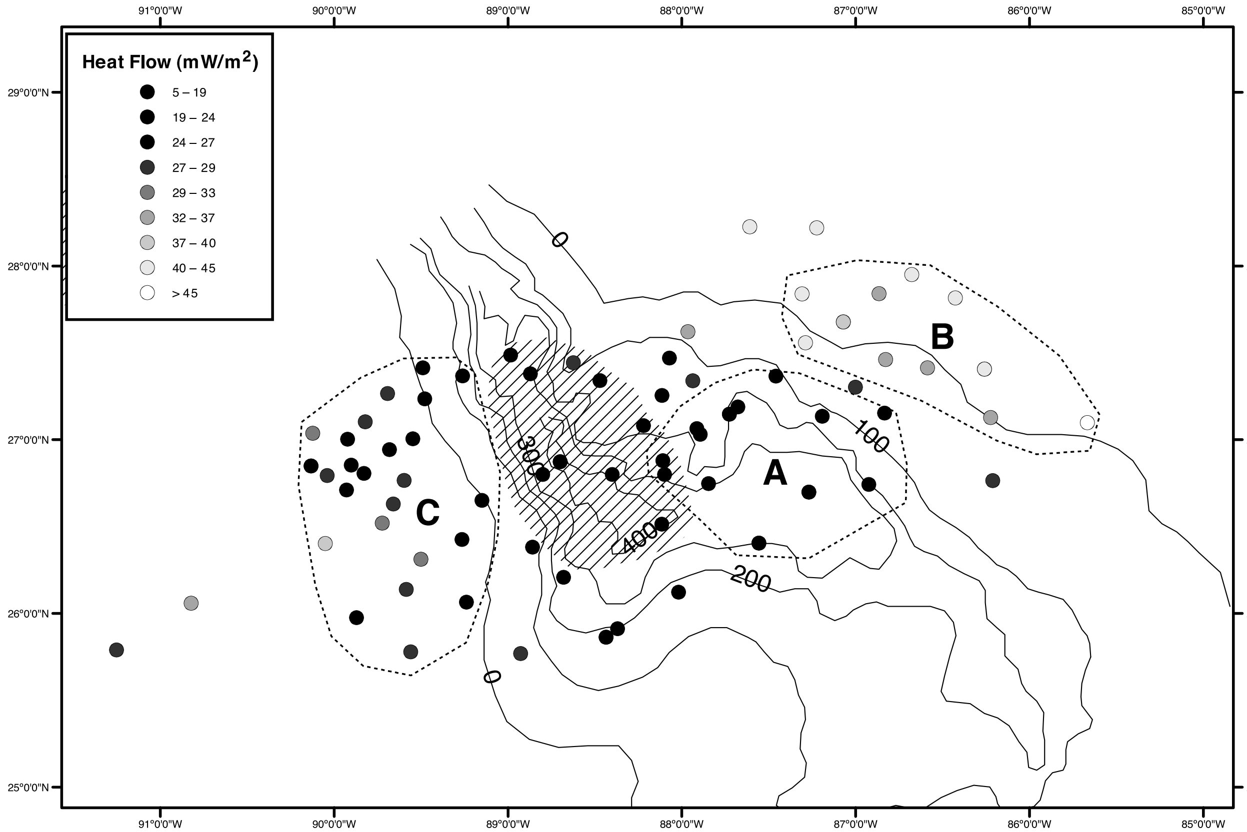

Figure 5. Map showing the thickness isopachs of the youngest lobe of the Mississippi Fan (modified from Bouma et al., 1985). Contours interval is 200 m (660 ft). The hachured area is the center of Pleistocene deposition according to Feng and Buffler (1996). Circles denote the locations of the heat-flow measurements. Dashed lines delineate areas A, B, and C.

conductivity is not statistically significant, because in each area, individual thermal conductivity values show variances of similar magnitudes. The similarity in thermal conductivity between the two areas rather implies that uppermost sediments have similar physical properties (e.g., porosity, bulk density, etc.) and accumulation trends.

No abrupt change is observed in older sedimentary sequences in Pleistocene or units below as seen in the seismic sequences previously mapped (Buffler, 1991; Feng and Buffler, 1996) at the boundary between areas A and B. Thus, the thermal effect of sedimentation alone does not explain the difference in heat flow between the two areas.

Radiogenic Heat Production in Sediments

One other mechanism related to sedimentation that influences seafloor heat flow is radiogenic heat production. Clastic sediments, particularly shale, are rich in radiogenic heat-producing elements, namely, thorium, uranium, and potassium. The effect of radiogenic heat is cumulatively added to the heat flux traveling upward through the sedimentary column. The contribution of radiogenic heat to seafloor heat flow should be roughly proportional to the total sedimentary thickness. Between areas A and B (Figure 2), total sedimentary thickness is approximately the same (Sawyer et al., 1991), although area B has relatively thinner clastic layers and thicker carbonate layers. Because carbonate sediments produce significantly less heat than clastic sediments (Nagihara et al., 1996), the total effect of radiogenic heat production in the sediments should elevate the seafloor heat flow in area A relative to area B. However, the opposite is observed.

Deeply Buried Salt Structures

Because the mechanisms directly related to the sediment accumulation in this region cannot explain the large contrast in surface heat flow between areas A and B, other potential causes for the difference must be examined.

This study area is located outside the allochthonous salt province on the Texas–Louisiana slope (Figure 2). Deeply buried, autochthonous salt deposits are present in the northeastern Gulf, but they have not been mapped in much detail. Some diapirs pierce out of the autochthonous Jurassic bed deposits and reach the Oligocene strata, which are 1–2 km (0.6–1.2 mi) below the seafloor. However, such diapirs occur farther upslope than areas A and B (Dobson and Buffler, 1997; Pyles et al., 2001; Bouroullec et al., 2004). Southeast along the outer perimeter of the west Florida shelf break, autochthonous bed deposits overlying the basement have been seismically imaged in some areas, but no obvious diapiric feature has been identified on them (Dobson and Buffler, 1997). No published seismic profiles crossing area B are available, but those immediately to the southeast show a laterally extensive salt bed overlying the basement (Buffler et al., 1993). The bed is about 1.5 km (0.9 mi) thick and overlain by sediments totaling 6 km (3.7 mi).

Generally speaking, salt-induced heat-flow anomalies are primarily controlled by two factors (O'Brien and Lerche, 1984; Corrigan and Sweat, 1995). The first is the depth of burial. The second is the thickness (height) of the salt body relative to its width. A tall, piercing diapiric plug that almost reaches the seafloor or surface, for example, the Sigsbee Knolls (Epp et al., 1970), would cause a large heat-flow anomaly, whereas a deeply buried, laterally extensive, bedded salt would produce no anomaly. Diapir-induced heat-flow anomalies are localized directly above the salt body (Nagihara et al., 1992).

In this study area, there may be a few isolated autochthonous diapirs buried under 1–2 km (0.6–1.2 mi) of sediment cover (Dobson and Buffler, 1997; Pyles et al., 2001), but if they cause any anomaly, it would only be locally. Away from the salt, heat-flow values in area B should be similar to those in area A. That is not the case here. In addition, estimates from previously published heat-conduction models (O'Brien and Lerche, 1988) indicate that a diapir buried under 1–2 km (0.6–1.2 mi) of sediment cover would elevate the surface heat flow by only 20–30%. In this study, heat flow in area B is nearly 100% greater than that in area A (Figures 2, 4).

It is possible that area B is underlain by a laterally extensive, autochthonous salt bed. A previously published heat-conduction model for a slab of salt 2 km (1.2 mi) thick, 20 km (12 mi) wide, and buried under a sediment cover of 3-km (1.8-mi) thickness shows no detectable surface heat-flow anomaly (Yu et al., 1992). The salt bed imaged off the west Florida shelf just southeast of area B (Buffler et al., 1993) is much wider and buried much deeper than the above-stated example and can therefore be assumed to also show no detectable surface heat-flow anomaly.

Fluid Flow through Sediments

Vertical migration of pore fluid and seeps on the seafloor can perturb nearby sedimentary thermal regimes. If heat-flow measurements are made near the path of upward migration or seeps, the values may be significantly greater than those surrounding it (Anderson et al., 1991). Flow-related thermal anomalies are localized near migration paths and exist only when the flow is active. Thus, they would not yield a uniform, shallow subseafloor thermal structure in large areas like those present in areas A and B. Alternatively, there can be widespread diffusive flow processes that occur in association with sediment compaction in the Mississippi Fan. However, such flow is very slow because the fluid budget is limited to pore space still available in the compacting sediments. Therefore, this type of fluid flow does not produce large anomalies (Hutchison, 1985).

Igneous Crust and Lithosphere

In the course of the analysis thus far, it is increasingly evident that although the sedimentation cooling effect can account for part of the large-scale trend in seafloor heat flow (Figure 3), it cannot explain the sharp contrast between areas A and B (Figures 2, 4). Thus, mechanisms not directly related to sedimentation and sedimentary structure must be influencing heat flow in areas A and B. The only remaining possibility is that there is a difference in the basement heat flow of the two areas.

Basement heat flow has two components. The first is the heat released from the mantle. In a continental margin setting, mantle heat flow is primarily controlled by the amount of horizontal extension (stretching), which the lithosphere has experienced during the initial stage of basin formation (Sclater and Celerier, 1987). A greater lithospheric extension results in a higher mantle heat flow. Seafloor spreading is theoretically equivalent to the lithosphere extending to infinite length. In any case, mantle heat flow decreases with time as the lithosphere cools.

The second component to basement heat flow is the cumulative radiogenic heat production in the igneous crust. A typical continental crust made of granitic rock is richer in heat-producing elements than oceanic crust. In addition, continental crust tends to be thicker than the typical oceanic crust. Therefore, the cumulative flow resulting from radiogenic heat is much greater for continental crust (Sclater et al., 1980).

The simplest explanation for the sharp contrast in heat flow between areas A and B is that the two are underlain by different types (or thicknesses) of igneous crustal rock and that the crust under area B yields a greater amount of radiogenic heat. This would explain both the elevated heat flow in the east and the sharp change occurring between the two areas (Figure 4). If the crust under area A is nonheat producing (e.g., basalt and gabbro) and that under area B is heat producing (e.g., granite and diorite), radiogenic heat production in the latter could account for the difference in heat flow. For example, if the crust beneath area B is 8 km (5 mi) thick, an average heat production rate of 1.875 $\mu W/m^3$ would elevate the heat flow in area B by 15 mW/m^2 relative to area A. This is well within the typical heat production rates reported for granitic rock samples vs. oceanic crust material (Beardsmore and Cull, 2001).

There is some evidence, at least in the southeastern Gulf of Mexico, that the transitional crust is indeed of granitic origin. Hole 538A of the Deep Sea Drilling Project (DSDP) Leg 77 (Figure 1) drilled into the Catoche Knoll and reached the crystalline basement. Some samples of gneiss, metamorphic rock that commonly originates from granite, were recovered (Dallmeyer, 1984).

Sedimentary Thermal Models

Figure 6 shows model predictions of present-day temperature vs. depth and heat flow vs. depth relationships calculated for areas A and B. These were derived from hydrocarbon maturation models generated previously by Jones and Nagihara (2003). The models reconstructed the sediment accumulation and lithospheric cooling history since the opening of the gulf and include the mechanisms discussed above (i.e., sedimentation cooling effect, radiogenic heat production in sediments, and diffusive fluid migration caused by sediment compaction). For area B, radiogenic heat production in a granitic crust is also considered. The software package BasinMod 1-D of Platte River Associates was used for the calculations. Details of model construction are described in Jones and Nagihara (2003).

These models are helpful in understanding the major difference between the two areas. In area A, basement heat flow is approximately 28 mW/m^2. From there upward, heat flow increases slightly because of radiogenic heat production in the sediments. Above the Pliocene strata, heat flow decreases because of the sedimentation cooling effect. In area B, basement heat flow is much greater ($\sim$45 mW/m^2). The curvature of the heat-flow profile in the sedimentary column is similar to that for area A, but the magnitude of the heat-flow reduction in the Pleistocene is less because of the slower sedimentation rate. Some model parameters are not very tightly constrained because there is little well control in these areas. However, using reasonable bounds for key parameters (sedimentation rate, radiogenic heat production in sediments, etc.), it is difficult to produce a model of area B that will yield a surface heat flow as high as what was measured without assuming higher basement flow.

DISCUSSION AND CONCLUSIONS

Based on the series of analyses above, it is most reasonable to conclude that basement heat flow should be significantly higher in area B. In the ocean-continent transition zone of any continental margin, basement heat flow can vary, depending on the amount of lithospheric stretching, crustal thickness, lithology, and the time passed since the formation of the basin. In a relatively old (>150 Ma) oceanic basin, such as the Gulf of Mexico, mantle heat flow should be similar in the continental and oceanic areas as heat flow through the lithosphere approaches quasi-steady state. In such a setting, the continental areas would yield greater basement heat flow because there is more radiogenic heat production in the crust.

As a comparison, we describe here the previous heat-flow observation made in the ocean-continent transition zone off the Iberian Peninsula (Louden et al., 1997). The data showed heat-flow values of 45–50 mW/m^2 in the area underlain by oceanic crust and 55–70 mW/m^2 over the continental crust. The margin was formed in the Early Cretaceous ($\sim$130 Ma), and the thermal structure of the lithosphere should be approaching quasi-steady state. The margin is also relatively starved of sediments. Thus, variation in surface heat flow is most likely attributable to the radiogenic heat production in the igneous crust and not to factors associated with sedimentation. The magnitude of the heat-flow contrast between the continental and oceanic areas of the Iberian Peninsula is comparable to what is observed in the northeastern Gulf.

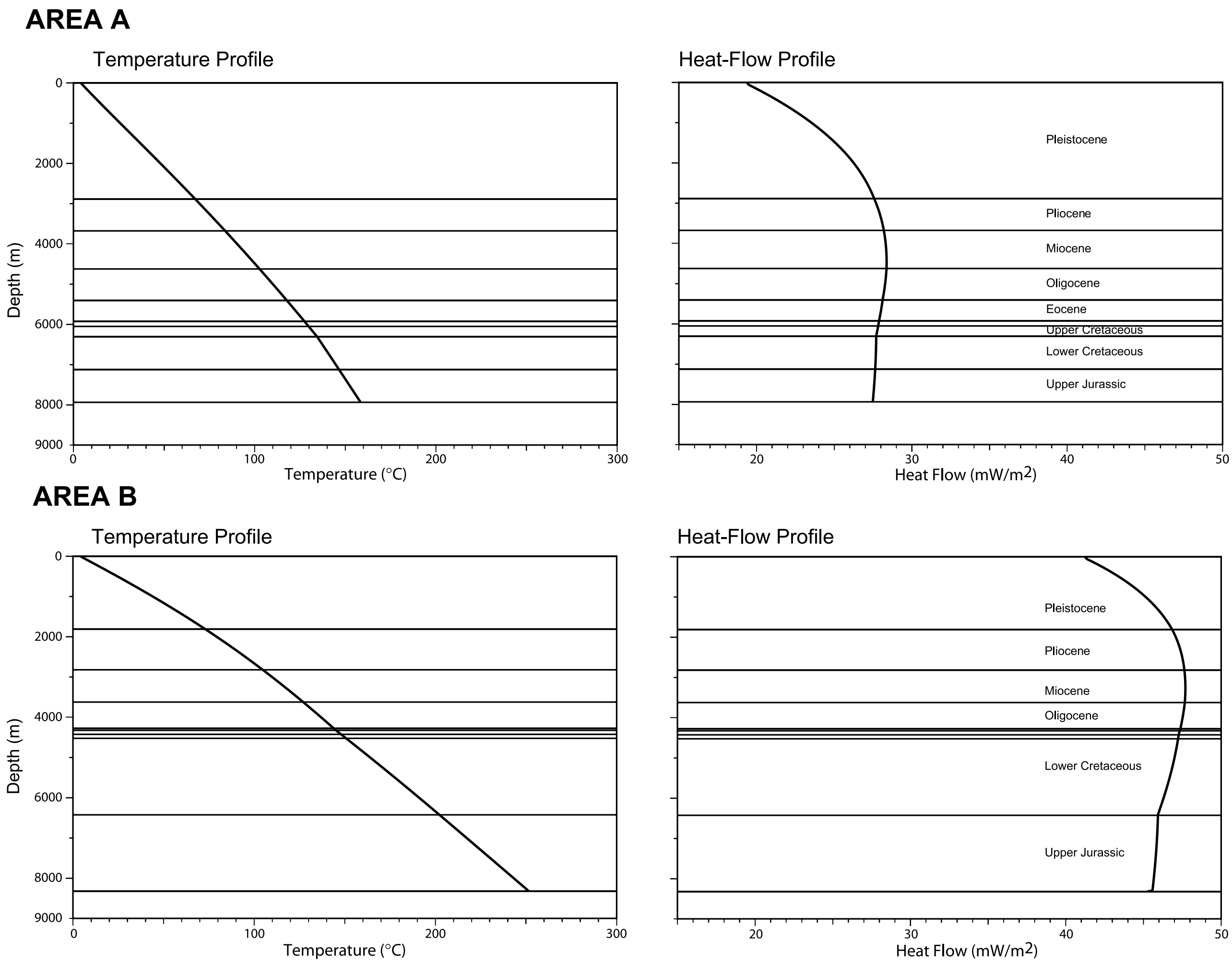

Figure 6. Temperature vs. subseafloor depth profiles (left) and heat flow vs. depth profiles (right) for areas A (top) and B (bottom) based on the thermal models generated by Jones and Nagihara (2003).

Despite the similarity of contrasting thermal regime, actual heat-flow values from the Iberian margin are considerably greater than those found in the northeastern Gulf. This can be explained by the lower rates of sedimentation and younger age of the Iberian margin. The heat-flow values in the oceanic area of the Iberian margin are consistent with what is predicted by the standard oceanic lithospheric cooling model of comparable age (Sclater et al., 1980). The basin thermal model constructed for area A (Figure 6) used the same lithospheric thermal parameters, and the model-predicted surface heat flow matches measured values.

In the northeastern Gulf of Mexico, there are two possible mechanisms for area B to yield greater radiogenic heat than area A. First, the composition of the basement is different between areas A and B, with that of area B containing a greater amount of radiogenic heat-producing elements. Second, the composition may be similar, but the thickness is different, with that of area B being greater. We believe that the first is more likely because both areas experienced roughly the same amount of total tectonic subsidence (Sawyer et al., 1991). If there was a significant difference in igneous crust thickness, the area with thinner crust should have subsided to a noticeably greater depth according to the principle of isostacy.

The abrupt transition in heat flow between the two areas occurs in the vicinity of the previously proposed boundary between the oceanic crust and the so-called thin transitional crust (Figure 2). The heat-flow transition zone lies almost exactly along the crustal boundary proposed by Marton and Buffler (1994) based on their seismic and gravity data compilation. Therefore, the most straightforward interpretation is that area A overlies oceanic crust, and that area B overlies thin transitional crust. The thin transitional crust is basically a stretched continental crust as suggested by the findings from the DSDP Hole 538A (Dallmeyer, 1984) and thus should be rich in heat-producing elements.

It is still debatable whether the samples from Hole 538A widely represent the rest of the transitional crust zone. If studies in other passive continental margins are any indication, the crustal composition and structure can be highly complex depending on the prior tectonic history (Whitmarsh and Wallace, 2001). However, the findings from this study suggest that acquisition of additional high-quality heat-flow data in areas farther southeast and northwest would be a useful next step. If we can verify that a linear boundary between high and low basement heat flow truly exists in this part of the Gulf of Mexico, that will be further, more conclusive evidence for the occurrence of the oceanic to transitional crust boundary. Those data would be in addition to those inferred from the magnetic and seismic studies, which already suggest the presence of just such a boundary.

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