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Geologic Note

A Temperature Probe Survey on the Louisiana Shelf: Effects of Bottom-Water Temperature Variations[1]

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ABSTRACT

A survey of temperature gradients in the uppermost sediments of the Louisiana continental shelf was done in 1983 by Gulf Oil Corporation, using a 5-m-long temperature probe. The survey covered 450 mi^2, with an average grid spacing of less than 1 mi. The purpose was to detect heat flow anomalies due to subsurface fluid flow. However, thermal perturbations due to seasonal variation of bottom-water temperature mask the temperature gradients due to geological heat flow. Bottom-water temperature variations similar to those recorded near the survey area in 1963–1965 explain most of the observed spatial and temporal changes in shallow temperature-depth profiles. The data set from this detailed survey has been donated to a publicly accessible scientific database, to spur research into heat flow measurement on continental shelves.

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[4]Chevron has donated the entire digital data set to Lamont-Doherty Geological Observatory, where it will accessible through the Earth Science Database System for Networked Computers (GEOBASE). Inquire care of Dr. R. N. Anderson, Head, Borehole Research Group, Lamont-Doherty Geological Observatory, Palisades, New York 10964.

We thank the Gulf Oil Corporation (now a part of Chevron) for supporting the temperature gradient survey, which was originated and directed by G. W. Zielinski. Lamont-Doherty Geological Observatory built the measuring and data reduction equipment under contract to Gulf. We thank W. Van Steveninck for his efforts in this regard. Omegalink International Ltd. performed the field survey. We thank M. A. Hobart for his contribution to field data collection, and I. Lerche for help during data acquisition and initial analysis. We are indebted to R. I. Mousseau for initial data reduction at Gulf. In 1984, D. E. Petroy analyzed the data further and recognized the dominance of bottom-water temperature variations. We also acknowledge the contributions of D. B. Jovanovich during this phase. The analysis in this paper was performed at Chevron Oil Field Research Company and presented as an internal memorandum by Cathles (1987). We thank Chevron Corporation for supporting this analysis and for allowing publication. We appreciate thoughtful reviews by M. H. Koelmel and W. H. Roberts III, and helpful discussions with G. W. Zielinski.

INTRODUCTION

Thermal measurements in sedimentary basins are potentially useful in petroleum exploration and development. Many oil and gas deposits have associated positive temperature anomalies (see for example, Roberts, 1981; Zielinski et al., 1985; McGee et al., 1989). These anomalies generally are attributed to lateral and upward movement of hot fluids in areas of petroleum accumulation. Thermal anomalies may also be caused by lateral changes in thermal conductivity (e.g., salt vs. sediment) and thus could be useful in prospect delineation. A knowledge of heat flow on a basin-wide scale is needed to constrain maturation models for petroleum source rocks.

The subsurface thermal regime is typically mapped using temperature data from wells (e.g., Vacquier, 1984), but this approach applies in densely drilled basins only. In appropriate circumstances, thermal anomalies in the sub-surface can be detected by accurately measuring the thermal gradient in the upper few meters of sediment. This is the basis of the temperature probe method of measuring heat flow in deep ocean basins (Langseth, 1965).

In 1983, Gulf Oil Corporation used the deep-sea probe technique in an attempt to measure thermal anomalies beneath the continental shelf of the Gulf of Mexico. This technique rarely had been applied in shallow seas (Matsubara et al., 1982) because seasonal variations in bottom-water temperature typically perturb the thermal regime near the sediment surface (Beck et al., 1985; Wang and Beck, 1987). To minimize the effects of bottom-water temperature variations, Gulf performed the survey near the edge of the continental shelf in water depths of about 70 m.

DATA COLLECTION AND REDUCTION[4]

Temperatures beneath the sea floor were measured at numerous locations in the survey area by a 5-m-long temperature probe. As shown in Figure 1, 42 north-south traverses (labeled 1–42 from west to east) were made, with 12 "drops" (labeled A–L from north to south) along each traverse. Between drops, the probe was

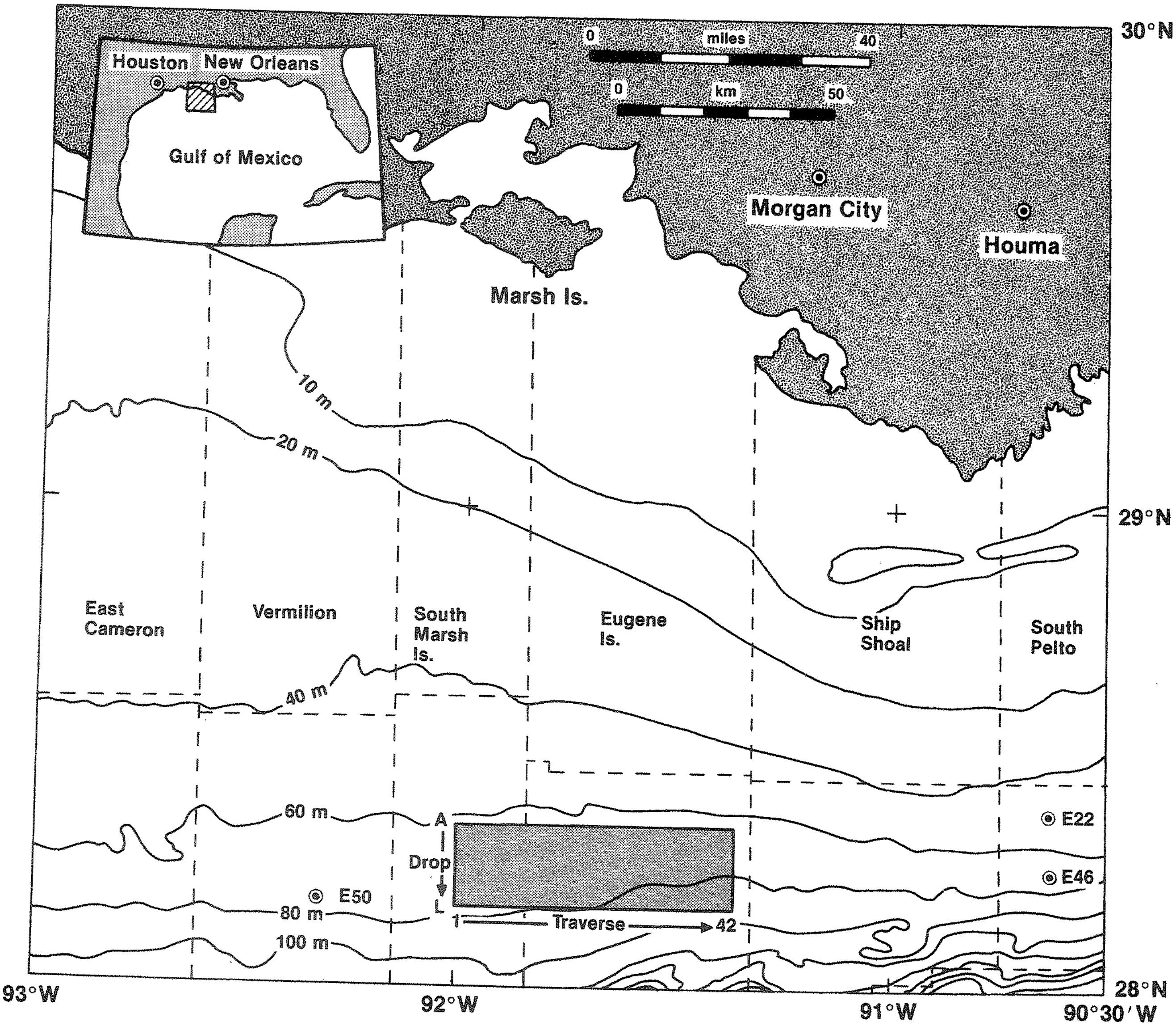

Figure 1—Location of the Gulf heat flow survey. Traverses are labeled 1–42, drops A–L. Water-temperature monitor stations near the survey area are shown (E50, E22, and E46). Water depth contours are in meters (20-m contour interval in unlabeled areas). The corners of the survey area are South Addition S. Marsh Island Area Blocks 130 and 162, South Addition Eugene Island Area Blocks 301 and 346.

towed just above the sea bottom rather than bringing it onto the ship's deck (i.e., "pogo-stick" technique). The grid spacing was about 1 mi in both directions. Hurricane Alicia interrupted the survey. Most data were collected from July 28 to August 15, 1983, and the remainder during September 12–15, 1983. The mid-September data mainly filled in alternate north-south traverses in the western half of the survey area.

The 5-m-long probe was outrigged with eight thermistors, approximately equally spaced at depths ranging from 0.5 m to 5.0 m beneath the sea floor (exact thermistor depths varied at different times in the survey). During each drop, the probe was left in the sediment for at least 10 min to equilibrate thermally. The resistance of each thermistor was sampled every 30 sec and recorded in a data logger in the probe head. Thermistors were individually calibrated (resistivity vs. temperature) using a water bath. Measurement accuracy was estimated at approximately 0.01°C, with a resolution of approximately 0.001°C.

Penetration of a temperature probe causes a local transient increase in temperature due to frictional heat-

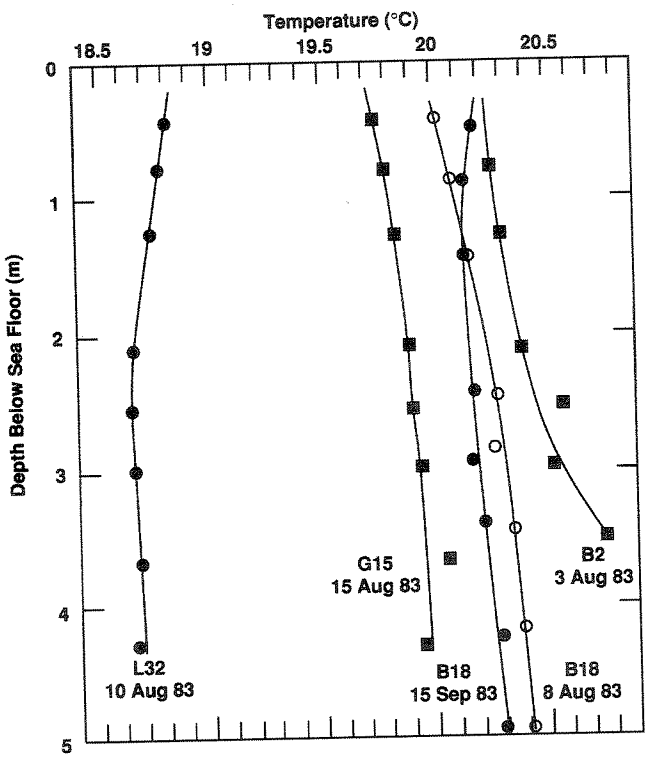

Figure 2—Typical temperature-depth profiles in August and September 1983 showing spatial variations across the survey area. Temporal variations from August to September are shown for Station B18.

ing. Thermistor temperatures are normally recorded at a number of times (called cycles) after the probe is dropped into the sediment. The temperature trend for each thermistor should ideally be extrapolated to steady state as described by Bullard (1954), but only last-cycle temperatures are presented here. All of the relationships discussed are closely similar for first-cycle and last-cycle data. Extrapolation should therefore not significantly alter the shape of individual profiles or the shape of anomalies shown in the contour maps.

TEMPERATURE-DEPTH PROFILES

Figure 2 shows representative temperature-depth profiles for various survey stations. During the first survey period (August), temperature-depth profiles change regularly across the survey area. In the northwest corner of the survey area, temperatures increase with depth parabolically, as indicated by the B2 profile. In the middle latitudes of the survey area, the temperature-depth profiles are flatter (e.g., G15). In the lowest latitudes (deepest water depths) temperatures decrease with depth near the sea floor (L32) and then flatten and increase slightly with depth. Note also the large decrease in average temperature from north (B2) to south (L32).

Several stations were resurveyed after the hurricane. As illustrated by profiles for station B18 (Figure 2), dramatic changes in temperature profile were observed. In contrast to the August profile, the September profile shows a decrease of temperature with depth near the sea floor.

BOTTOM-WATER TEMPERATURE VARIATIONS

Temple et al. (1977) measured seasonal temperature variations in the Gulf Coast water column for the period 1963–1965. There are no data for the period immediately preceding the 1983 Gulf survey. The 1963–1965 monitor stations nearest the survey area are E50, E22, and E46 (Figure 1). The water depths at E50, E22, and E46 are 73, 46, and 73 m, respectively. Monthly water temperatures were recorded for each station, at the sea surface, at the sea floor, and at 3, 11, 24, 43, and 70 m water depth.

The shape of the curve of the seasonal water temperature measured in the 1963–1965 survey changed little from station to station at any particular recording depth, but changed strongly with depth below the sea surface. The pattern of temperature variation was similar, but not identical, from year to year. Figure 3 shows some representative curves for depths of 11 and 70 m. Note in particular the following. (1) The annual average water temperature decreases linearly with depth. (2) The amplitude of the seasonal variation also decreases with depth, but remains large at 70 m depth (10 °C peak to peak). (3) The shape of the seasonal variation changes with depth. At 11 m depth, the variation is nearly sinusoidal, whereas at 70 m depth, the changes in temperature with time are more abrupt (due to large contributions from variations with 6- and 4-month periods). (4) The variations at depth lag those nearer the sea surface.

MODELED TEMPERATURE-DEPTH PROFILES

A sinusoidal temperature variation at the sea floor propagates into underlying sediment as an exponentially damped sinusoidal temperature wave (Carslaw and Jaeger, 1959). The wavelength and the rate of damping depend on the period of the temperature variation and the thermal diffusivity of the sediment. The shorter the period of the water temperature variation, the shorter the wavelength of the subsurface temperature wave, and the more rapid its exponential decay. A seasonal water-bottom temperature variation can be separated into Fourier components with periods of 1 year, 1/2 year, 1/3 year, 1/4 year, etc. that have the appropriate phase relationships. The total temperature disturbance in the sediment is obtained by summing the disturbances due to the individual Fourier components.

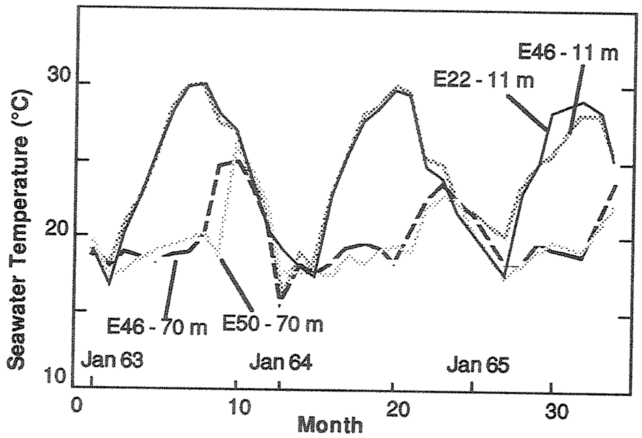

Figure 3—Annual temperature variations in Gulf waters depend mainly on water depth, but also change from year to year. The data shown are for 1963–1965, from Temple et al. (1977). Monthly temperature data are plotted in numerical order starting with January 1963. Thus, month 9 is September 1963, month 13 is January 1964, etc.

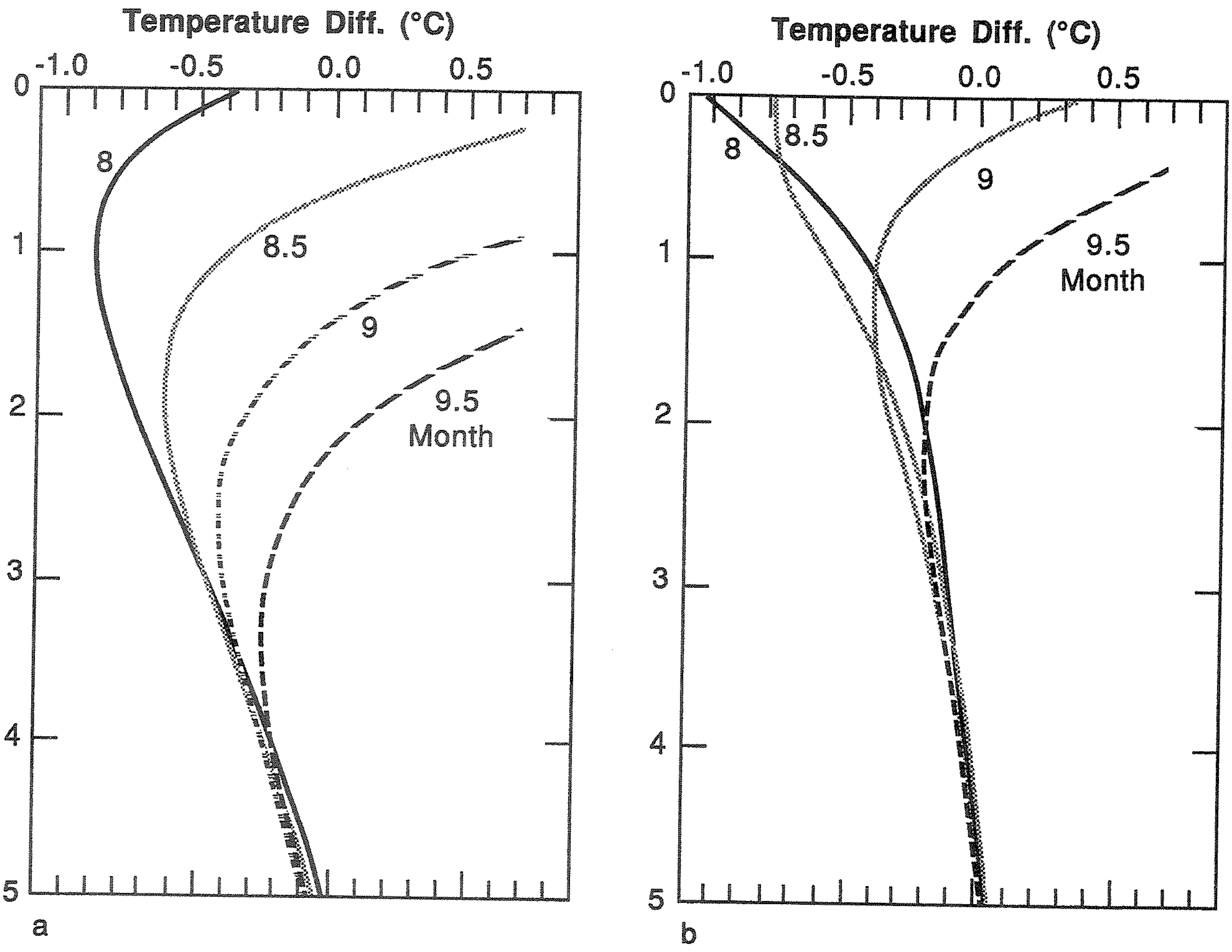

Figure 4—Temperature-depth profiles calculated for the water temperature variations for station E46 at 70 m water depth. The profiles are shown for various months of the year (e.g., 8 = August). The profiles change dramatically depending on the water temperature curve used. (a) Profiles based on 1963 water temperature data. (b) Profiles based on 1964 water temperature data. The profiles based on 1964 temperatures best match the profiles observed in the survey area. Physical parameters used in the models are appropriate for a Gulf Coast shale with a porosity of 0.6 (Cathles, 1987): thermal diffusivity, 4.1×10^{-3} cm^2/sec; thermal conductivity, 3.4 mcal/(cm sec °C). A background heat flux of 1 μcal/(cm^{2}sec) is assumed, which contributes a temperature gradient of only 0.03°C/m.

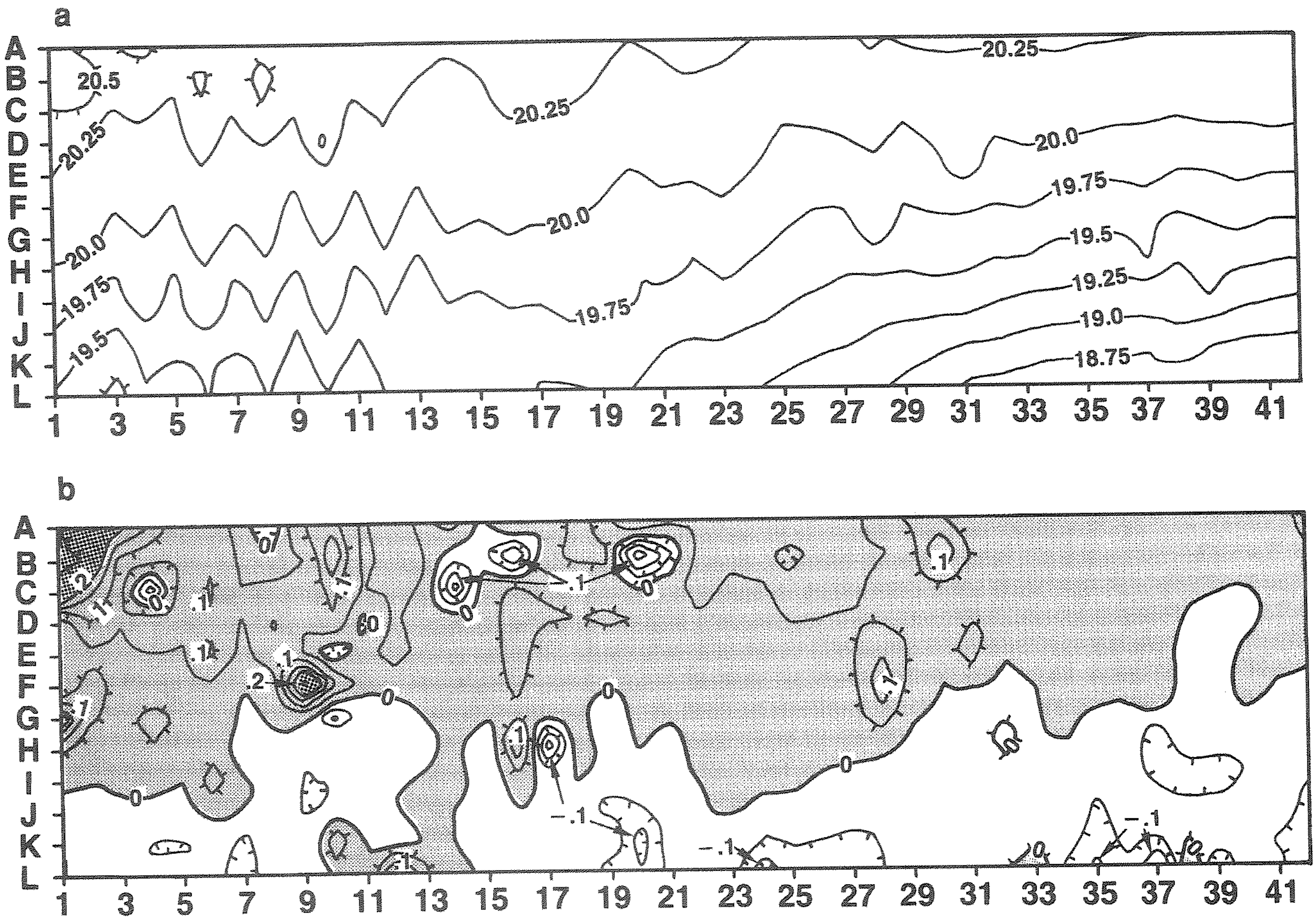

Figure 5—(a) Contours of temperature at 3.5 m depth. (b) Contours of temperature gradient at 3.5 m depth. Temperature-depth data were reduced by fitting last-cycle temperatures from the five deepest thermistors to a second-order polynomial with respect to depth. If the χ^2 of the fit was greater than 0.01, data from each of the five thermistors were dropped in turn, and a new fit made. The fit with the minimum χ^2 was retained, provided that χ^2 was less than 0.01. The polynomial coefficients were then used to determine the temperature and vertical temperature gradient at 3.5 m depth. In (b), areas of positive temperature gradient (temperature increasing downward) are shaded and areas of negative temperature gradient are unshaded. The contour interval in (b) is 0.05 °C/m.

Using this approach, the temperature profiles that would be produced in the top 5 m of sediment were modeled. Figure 4 shows the result based on the water temperatures at 70 m depth for station E46. In Figure 4a, we have used the 1963 water temperature measurements; in Figure 4b, the 1964 measurements. At more than 1 m depth, the modeled curves are dominated by the contributions of the annual and semi-annual harmonic components of the water temperature variation. The curves in Figure 4 show calculated profiles for various times during the year (month 8 = beginning of August). Comparison of the profiles in Figure 4a, b shows that considerable changes in the shape of the thermal disturbance are to be expected from year to year. Consequently, the 1963–1965 data have qualitative value only.

The 1964 model profiles nevertheless match many of the observed profiles. The month 8 and 8.5 profiles match the G15 profile in Figure 2. The change in modeled profile shape between months 8 and 9 corresponds with the observed changes at station B18 (Figure 2). The shape change is due to the downward propagation of the rapid rise in water temperature that occurs in the summer months. The shape of the observed profile L32 (typifying the deeper parts of the survey area) better matches the month 8 profile for 1963. Relatively small changes in the phase of the water temperature variation across the survey area could easily cause the changes in profile shape.

The profiles in the northwestern corner of the survey area (typified by B2) are harder to explain. To the first order (rapid increase of temperature with depth), the

Table 1. Temperature Data for Northwestern and Southeastern Corners of Survey Area

	Water Depth	Temperature (°C) at 3.5 m Below Sea Floor*	Average Annual Bottom-Water Temperature (°C)**
Northwest Corner	62 m (34 fathoms)	20.6 °C	20.4 °C
Southeast Corner	96 m (52.5 fathoms)	18.5 °C	17.8 °C

*Based on temperature probe survey.
**Based on data of Temple et al. (1977) with extrapolation to 96 m.

profiles match the model profile for month 8 of 1964, but the observed concave-up shape is enigmatic.

MAP OF TEMPERATURE AND TEMPERATURE GRADIENT

Contour maps of temperature and temperature gradient at 3.5 m depth were prepared using data from each survey location (Figure 5). The maps are analogous to those typically prepared from well data to delineate subsurface thermal anomalies. The contour maps display several trends and irregularities. Temperatures at 3.5 m depth decrease markedly to the south, with some north-south banding, particularly in the western third of the survey area. The temperature gradients also decrease to the south and show a muted north-south banding. Many large positive and negative gradient anomalies are evident. Most of these anomalous features are due to the effects of bottom-water temperature variations and individual thermistor errors.

The regular north-south decrease in temperature can be explained as follows. The temperature at 3.5 m depth below the sea floor closely matches the average annual temperature of the bottom water throughout the year. The north-south decrease in temperature correlates with the decrease in average annual water temperature (Figure 5). Table 1 illustrates this correlation for the northwest and southeast corners of the survey area.

The north-south banding of the temperature data in the western half of the survey area relates to the time of data collection. In particular, transverse 3, 5, 7, 9, 11, and 13 were measured during the second survey period in September. These traverses produce the cool "bands" in the temperature plots of Figure 5. Sediments at 3.5 m depth were evidently cooler in September than in August. These changes are also evident in the few locations that were measured in both survey periods (e.g., B18 in Figure 2). The magnitude of the decrease in temperature is about 0.13°C. The modeling results for 1964 predict a decrease of about 0.05°C at 3.5 m depth between months 8 and 9.5, whereas the 1963 results predict an increase of about 0.1°C over the same period.

The temperature gradient map is more complex. Gradients at 3.5 m depth range from more than +0.25 °C/m to less than −0.1°C/m. The gradients in the northern part of the survey are generally positive; those in the south are generally negative. The positive temperature gradients outweigh by an order of magnitude the approximately 0.03°C/m gradients expected from regional heat flow in the Gulf, but are of the same order as those expected from bottom-water temperature variations. Figure 6 shows computed gradients based on the 1963 and 1964 data for 70 m water depth. These models predict positive gradients of 0.1–0.25°C/m in August, with a shift to gradients near zero in September. Temperature-depth data were plotted at all survey locations (not shown). These plots showed that many of the isolated "bulls eye" gradient anomalies probably are due to intermittent inaccuracies in individual thermistors. An effort was made to screen measurement errors (as described in the Figure 5 caption) but because there were few thermistors on the probe, this procedure could not identify all bad data. The large positive anomaly in the northwest corner of the area may have a geologic origin, or it could be due to anomalous bottom-water temperature variations in this vicinity.

DISCUSSION

The survey is the most extensive shallow temperature gradient survey ever done on the Gulf Coast. We conclude that the data are dominated by the effects of bottom-water temperature variations, which have produced temperature gradients at 3.5 m depth that are an order of magnitude greater than those expected from regional heat flow. Our analysis is preliminary, and we hope that Chevron's donation of the data to an accessible database will encourage additional treatment of the data. Simultaneous inversion of all the data could conceivably yield information on bottom-water temperature variations as a function of water depth, horizontal and vertical variations in thermal diffusivity of sediments, and spatial variations in subsurface heat flow (cf. Lee, 1977). The amplitude and phase of the semi-annual bottom-

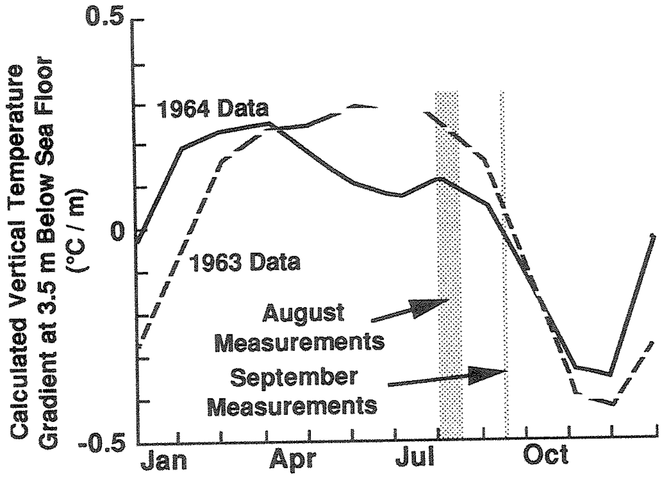

Figure 6—Temperature gradients at 3.5 m depth calculated from the bottom-water temperature variations shown in Figure 3 (Station E46, 70 m water depth).

water temperature variation will be important in any such inversion.

We believe that heat flow surveys on continental shelves will prove useful in petroleum exploration. We recommend monitoring bottom-water temperature variations at numerous sites across a survey area for several years prior to and during the survey (Allis and Garland, 1976). Probes should be as long as possible (ideally more than 12 m long) and should be capable of measuring temperatures at numerous points closely spaced in depth. Thermal properties should be measured in-situ as a function of depth (Hyndman et al., 1979) at numerous locations over the survey area. In-situ measurements should be confirmed using closely spaced cores, which are also necessary to determine the local sedimentation rates (Von Herzen and Uyeda, 1963). At several sites, multiple temperature profiles should be obtained over a period of at least three months (Wang and Beck, 1987).

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