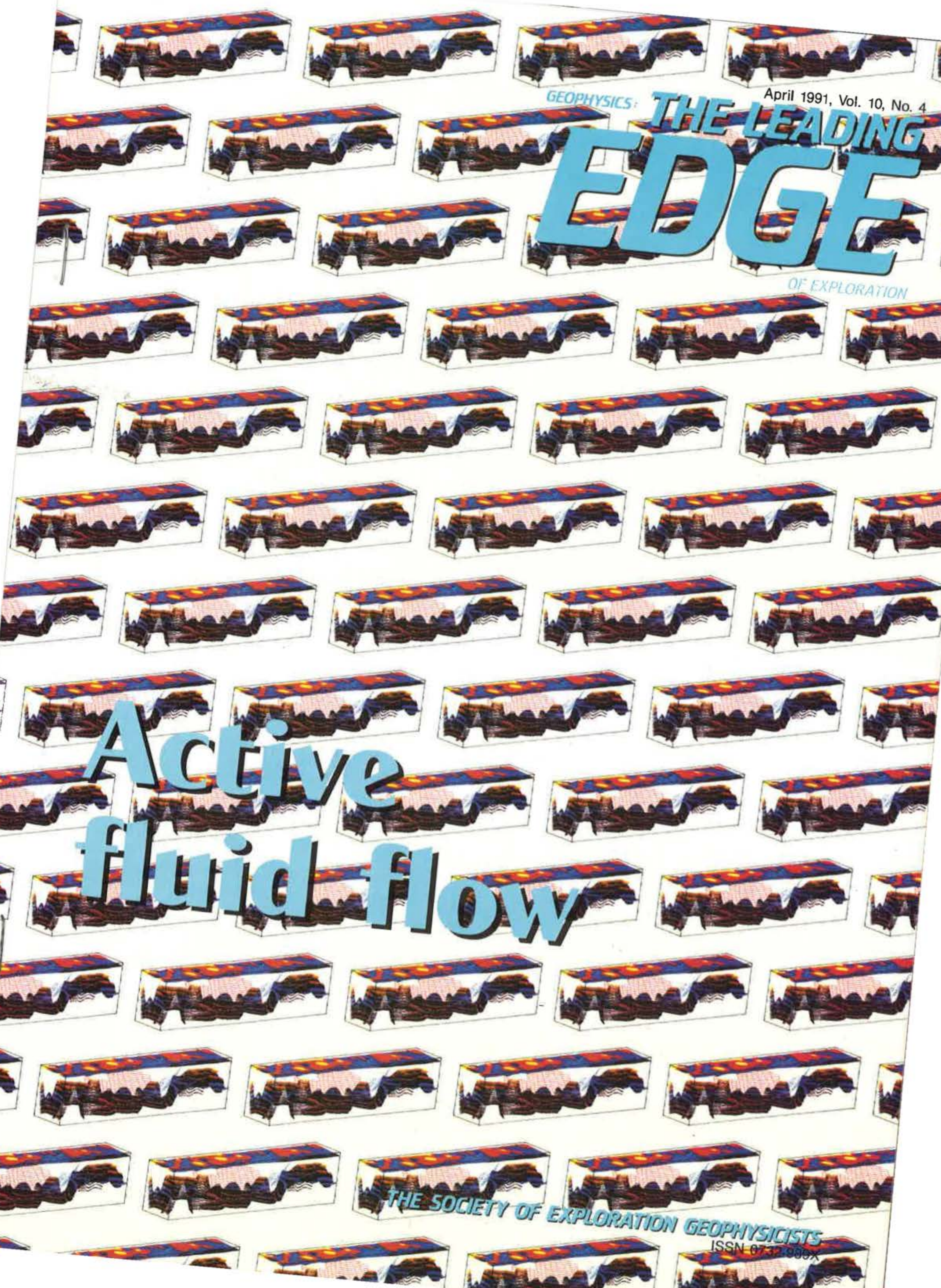

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Active fluid flow

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Active fluid flow
in the Eugene Island area, offshore Louisiana

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A sedimentary basin is a *thermochemical reactor;* i.e., a complex, dynamically interrelated system that is deformed and faulted by tectonic forces, modified by sedimentation and erosion, influenced by geopressuring and chemical reaction, and subjected to constantly changing temperature, pressure, and fluid composition and movement. We understand little about the *coupling* among these processes that comprise basin thermochemical reactors despite many recent advances in basin science and technology. However, we are certain that these processes are coupled so strongly that changes in one can completely alter the operation of all the others in a basin.

In order to build a general understanding of one such thermochemical reactor, the Global Basins Research Network (see box) is beginning the synthesis of current geophysical exploration results and observations of the physical and chemical parameters that control the dynamic processes of fluid flow in the Louisiana Gulf Coast (Figure 1). As a beginning, we have assembled seismic, surface heat flow, cutting and log information within a 60 km (long) by 12 km (wide) by 10 km (deep) segment of the Eugene Island area of offshore Louisiana into a three-dimensional, volumetric description of the subsurface which we call a "data cube" (cover design and Figure 1). We demonstrate below that fluid flow is presently active within this data cube by comparing the areal distribution of surface heat flow with the topography of the top-of-salt-surface and with the structure of biostratigraphically defined horizons above the salt.

A 12-minute videotape "visualization" of the Eugene Island data cube is available from the senior author. The video, entitled *Sedimentary Basins as Thermochemical Reactors*, was prepared for the IEEE-sponsored conference, "Supercomputing '90," held in November 1990 in New York. The tape, which also describes the Global Basins Research Network, was made at the Cornell National Supercomputer Facility (the Theory Center) by Wayne Lytle. A $10 fee is charged to cover reproduction and mailing costs. Checks should be made payable to "The Trustees of Columbia University."

The Eugene Island area. The Louisiana Gulf Coast is an important part of the dominant hydrocarbon-producing province of the conterminous US. It is one of the best studied and most extensively sampled (but not yet synthesized) subbasins in the world and, as such, is the source of a vast collection of geophysical and geochemical observations.

The Eugene Island province of offshore Louisiana provides an excellent locale within this area to investigate coupled basin processes because its sediment dynamics have not been affected greatly by recent basement tectonics. Significant sedimentation was delayed until well after the Jurassic rifting that opened the Gulf of Mexico. Abundant terrigenous sedimentation began only after the Laramide orogeny and the uplift of the Rocky Mountains. The delivery of the Laramide erosional products was further delayed by the lower Cretaceous barrier reef system that developed along the hinge zone of the Gulf. This reef prevented most erosional sediments from reaching the offshore basin and, as a result, organic-rich marine sediments were deposited without much dilution. The Laramide sediments finally breached the reef in the Tertiary, and the ancestral Mississippi River delta system rapidly dumped an enormous thickness of sediments into the Gulf Coast basin.

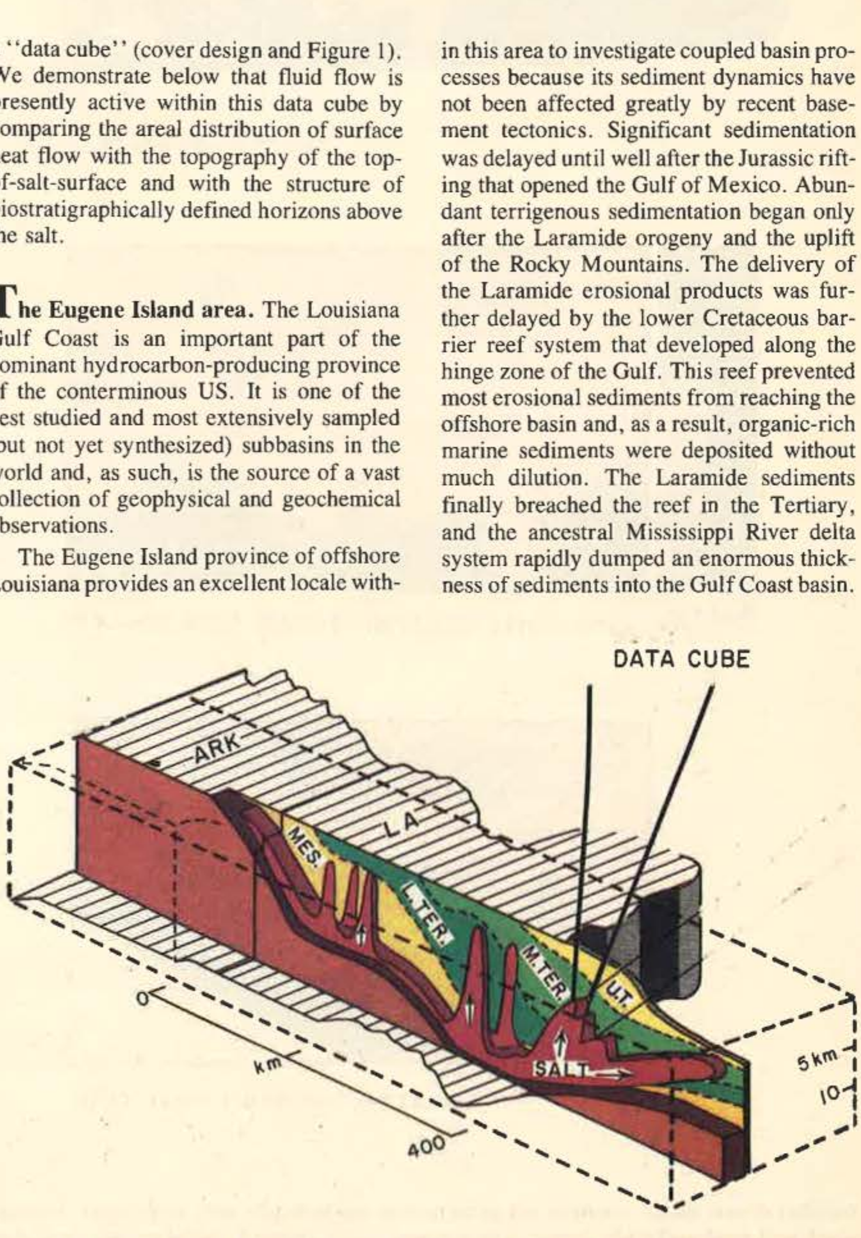

Figure 1. Data cube and surface heat flow survey in the Eugene Island area of offshore Louisiana are located within the subsurface geology of the southern Gulf Coast (from an original drawing by J.S. Hanor).

The pre-Tertiary sediments were buried, loaded, and heated with unusual rapidity. This rapid loading triggered the migration of the Louann salt, the increase in pore pressures within the deeper sediments to far greater than hydrostatic (geopressures), and the generation and migration of large volumes of hydrocarbons. All of these processes continue to this day.

Large-scale hydrodynamic processes are coupled with the ongoing deposition of the massive sedimentary load. Convection is occurring in all three of the major hydrological regimes active in the Louisiana Gulf Coast. At shallow depths, meteoric flow, controlled by topography and directed toward the shelf, mixes with upward moving connate water and diagenetic fluids from deeper in the basin. At middepths, considerable dissolution of salt occurs which produces an unstable layer of heavy, dense, and highly saline pore fluids. In the deepest portion of the basin, metamorphism and hydrocarbon maturation reactions release large volumes of high-temperature, geopressured, extremely buoyant fluids. Thermal build-up and restricted fluid flow are associated with this geopressured zone which dominates the deeper compactional system within the basin. Hydrothermal fluids are known to migrate both laterally and vertically for considerable distances in the Louisiana Gulf Coast.

In addition to these subsidence and chemically driven hydrodynamic forces, the mountainous topography of the salt itself results in tremendous thermal, as well as hydraulic, gradients over very short subsurface distances. The high thermal conductivity of the salt relative to the surrounding sediments (8–10 W/m°K for rock salt, compared to 1–3 W/m°K for Gulf Coast shales and 2–4 W/m°K for sandstones) causes the refraction of significant quantities of heat away from the deep basin and toward the salt highs. Isotherms can even become subvertical near salt columns.

The form and magnitude of this hydrothermal fluid flow is controlled by both the buoyancy forces acting on the fluids (temperature, pressure, chemical gradients, and fluid densities), and the permeability pathways available to the fluids. As in most geologic situations, the convecting fluid in the Gulf Coast is predominantly water (though oil, gas, and significant brine are variously included).

The rate and duration of fluid movement is not always slow and steady-state; it may be extremely rapid and transient. Compaction and hydrocarbon generation can create geopressures large enough to cause hydraulic fracturing which, in turn, releases bursts of large volumes of oil, gas, and water into overlying sediments. Similar transient release of fluids from deep within the geopressured depths of a basin is thought to occur in many other hydrocarbon-producing provinces elsewhere in the world.

A more complete description of the dynamic forces driving fluid movement is required before we can fully understand the thermal and pressure evolution that resulted in the current distribution of hydrocarbons in the Gulf Coast. By developing new *dynamic* exploration techniques, perhaps we can identify vast new reserves awaiting discovery in the Louisiana Gulf Coast, an area that most explorationists would classify as a mature hydrocarbon exploration province.

Surface heat flow as an exploration technique. A high-density, surface heat flow survey was conducted over the Eugene Island data cube area during Gulf Oil Company's *Elva Bruice* cruises I and II. This unique dataset, since donated to the Lamont-Doherty Geological Observatory by the Chevron Corporation, provides a new and important dynamic observation for the investigation of the relationships among structure, tectonics, heat flow, and fluid flow in the Gulf Coast. The heat flow surveying technique consists of lowering a vertical lance equipped with thermometers (thermistors) into the seafloor at periodic intervals. The thermistors measure the thermal gradient over the upper boundary layer of the basin (the upper few meters). When

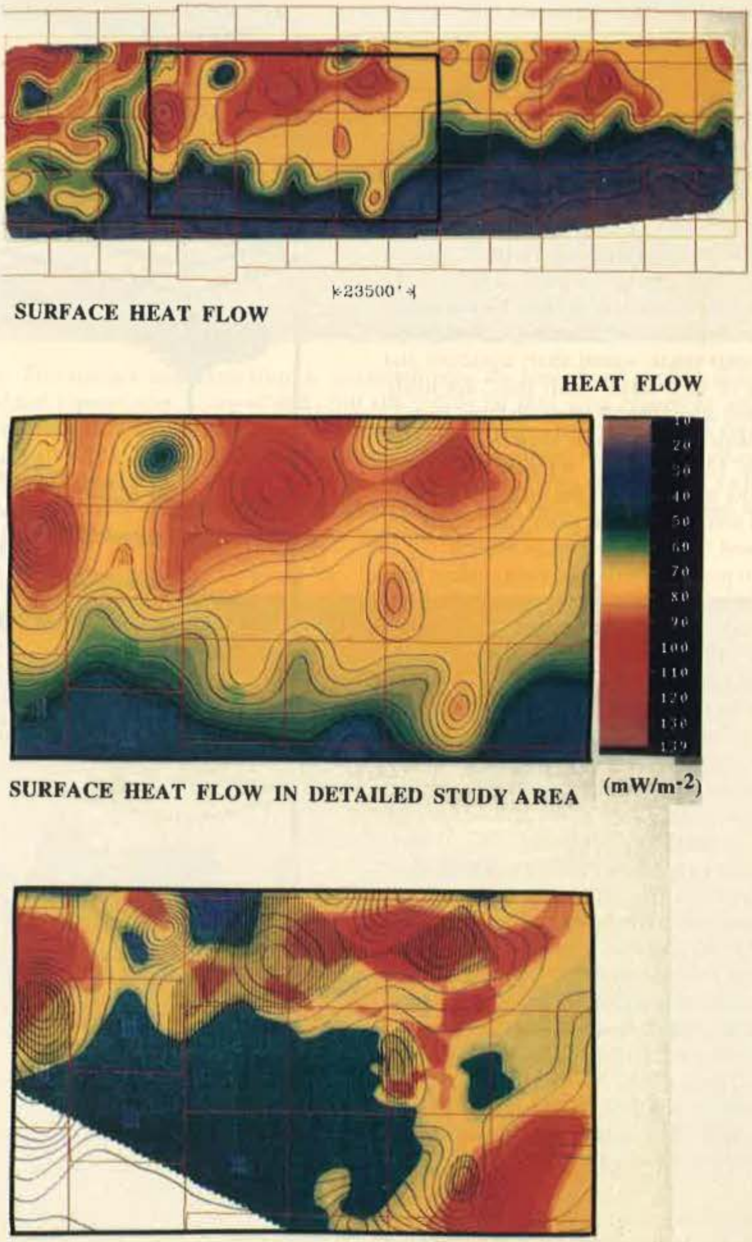

Figure 2. (top) Heat flow distribution measured at the seafloor. Black box is detailed study area shown below. (center) Color image and contours of surface heat flow from box located above. (bottom) Color images of heat flow calculated from depth to 80° C isotherm, with overlay of surface heat flow contours from above. Hatching indicates high heat flow anomalies. North is up.

combined with measurements of the thermal conductivity of the surface sediments, the heat flux from deeper in the basin can be determined (by the product of thermal gradient and conductivity).

L.M. Cathles and A.G. Nunns (in a paper recently published in the AAPG *Bulletin*) correctly identified a predominant component of the heat flow signal from the *Elva Bruice* survey to be from bottom-water temperature changes on the Louisiana continental shelf. That is, oceanographic effects provide a strong overprint onto the geologic flux we are trying to observe. In order to determine the heat flow from deeper in the basin from this dataset, we added two further processing steps to the sequence done by Cathles and Nunns. They determined temperature gradients from the last "cycle" of temperature recorded by the device while in the seafloor. We followed the more traditional analysis technique of correcting each temperature observation for transients by using "Hoerner Plots", 1/time extrapolations to thermal equilibrium. Second, we isolated relative temperature changes across anomalies observed in the heat flow field by normalizing the multiple temperature gradient measurements made within short distances and times of each other—and, thus, not likely to have encountered large changes in bottom-water temperatures between measurements. In this manner, we were able to isolate the magnitude of the heat flux coming from within the basin from that clearly associated with oceanographic effects.

To prove the validity of the surface heat flow measurements, we compared the locations and magnitudes of the surface anomalies with heat flow calculated from a compilation of temperatures measured in 300 wells from a detailed study area within the data cube by J.B. Leedy (*Fluid migration study, South Marsh Island—Eugene Island area,* Pennzoil Exploration and Production Company) (Figure 2). We calculated heat flow by assuming a constant value of thermal conductivity and determining the thermal gradient from the depth to the 80° C isotherm from the Leedy study. Considering the likelihood of variable thermal conductivity structure and convective fluid flow within the sediments of the upper 5000 ft, the correspondence between surface and subsurface heat flow anomalies is remarkable (Figure 2). As can be seen in both data sets, there are several anomalies present with heat flow values higher than 100 mW/m-2 (cover and Figure 2).

Data cube compilation. Three subsurface horizons were identified from seismic reflection profiles, cutting analyses, and log data. These and the surface heat flow were then used to construct the Eugene Island data cube. From the surface downward (in Figure 3), the four horizons represent: a) the surface heat flow distribution; b) the Angulogerina or Ang (B) surface (which is 1.5 Ma and forms the top of the sand-shale sequence); c) the Lenticulina (1) surface (which is 2.5 Ma and the base of the sand-shale sequence); and d) the top-of-salt surface (which was verified with gravity observations).

The structure within the data cube is dominated by the extremely high relief of the salt topography which is overlain, in turn, by thick sequences of Plio-Pleistocene sediments. Massive sands predominate from the seafloor to the Ang (B) surfa and geopressured shales are found from th base of the Lent (1) surface to the salt. Tw of the many normal faults (predominantl east-west trending) are shown by the re and blue meshes in the top cube o Figure 3.

Relation of high heat flow anomalies t

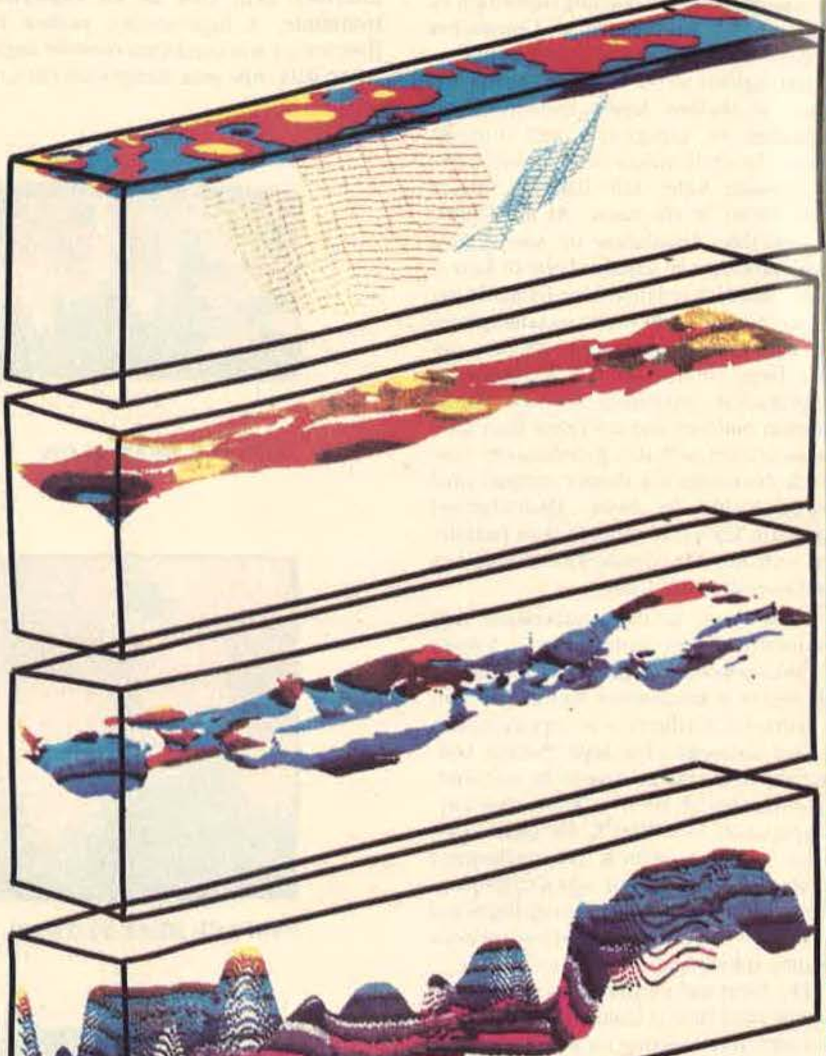

Figure 3. The data cube is composed of the distribution of surface heat flow (to along with log- and cutting-verified biostratigraphic horizon maps of the shallowe occurrence of Angulogerina (B) (second from top), Lenticulina (1) (third from top and the topography of the top-of-salt (bottom)which were determined via seismic dat Also shown are two normal faults with obvious thermal anomalies associated wi them (the red and blue faults, top). The vertical scale is in milliseconds of two-wa traveltime (except for the heat flow surface, where yellow is greater than 2 HFU an dark blue is less than 0.5 HFU). North is to the upper left in this view.

salt topography. Surface heat flow has proved to be an effective tool for interpreting subsurface fluid movements in scientific and geothermal exploration. In the Eugene Island data cube, we wish to test if high heat flow anomalies found along the upper boundary layer of the data cube were caused by upwelling within an active fluid flow system. More specifically, we wish to determine whether the high heat flow anomalies observed in the surface heat flow survey are related spatially to the salt topography (with its very high thermal conductivity) or has the convective flow of hot fluids away from the salt displaced the thermal anomalies.

Conductive heat transfer theory predicts a strong spatial correlation between the tops of massive salt bodies of extreme relief and high heat flow. Within the study area, the salt topography has from 1-6+ s of relief. However, in a projection of surface heat flow data onto the topography of the top-of-salt surface (Figure 4), the high heat flow anomalies (yellow) are offset from the salt peaks—with one exception. Over the salt dome in the extreme northwest corner of the study area, a large surface heat flow anomaly occurs directly over a salt dome, as predicted by theory. All other heat flow anomalies in the area are found on the flanks of the salt topography. Consider, for example, the large salt ridge in the northeastern quadrant of the data cube. The surface heat flow anomaly in this area is located over the northwestern flank of the ridge, not over the location of the shallowest salt. Likewise, a large, high heat flow anomaly occurs over a saddle between two prominent peaks in the salt ridge that runs from the south-center of the data cube area toward the northwest. Paradoxically, some salt peaks are located over the lowest heat flow anomalies, as is the case of the peak just west of the previously discussed heat flow high.

When surface heat flow is projected onto the base of the sand-shale sequence, the Lent (1) horizon, much of the high heat is correlated with structural closure (Figure 5). That is, the largest surface heat flow anomalies are located over the portions of this horizon with the greatest upward slope, not at the tops of the structures themselves. The heat flow anomaly located over the saddle in the central salt ridge lies downdip from a large normal fault that itself dips to the south along the edge of the salt ridge (the red fault in Figure 3). This observation suggests that movement of hot fluids surrounding the salt topography is likely to be a significant redistributor of heat in the area.

Next, we calculate the magnitude of heat flow likely to be conducted through the top-of-salt and geopressured shales, and into the base of the sand-shale interval, the Lent (1) horizon (the bottom surface in Figure 6). The difference between the surface heat flow (top, Figure 6) and the conductive heat flux exiting the geopressured, Lent (1) shale layer (bottom, Figure 6) is

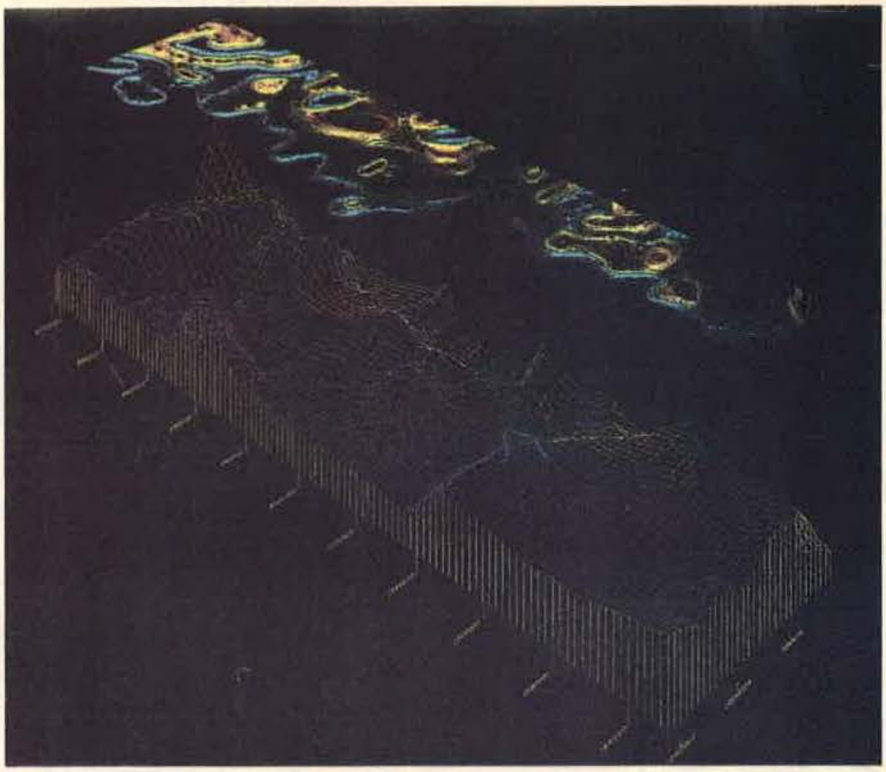

Figure 4. The surface heat flow (top) is projected onto the top-of-salt surface (below). The gridded topography is top-of-salt, but the colors on that grid represent surface heat flow. Note that the largest heat flow anomalies (orange) are not located directly above the salt highs, as would be required from thermal conduction theory (except in the far left-hand corner). Thermal convection must be occurring as fluid flow redistributes the heat above the salt surface to displace the high heat flow anomalies away from the salt highs. North is to the upper right in this view.

Figure 5. The surface heat flow is projected onto the geopressured base of the sand-shale sequence, the Lent (1) surface. The largest heat flow anomalies (again in orange) are located above the stratigraphic closures on the flanks of topographic highs, again reflecting redistribution of heat by fluid flow away from the salt highs. North is to the upper right in this view.

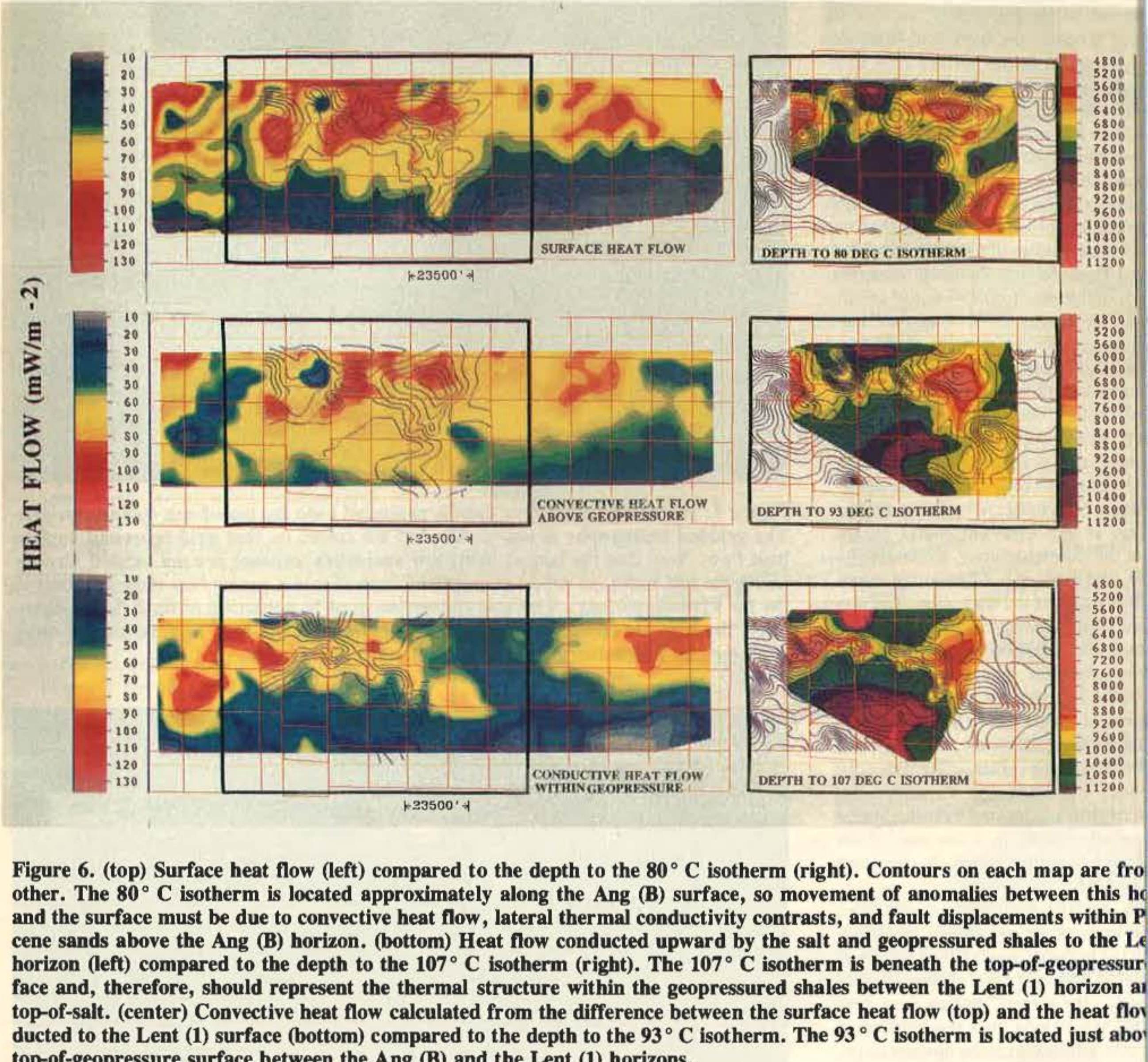

Figure 6. (top) Surface heat flow (left) compared to the depth to the 80° C isotherm (right). Contours on each map are fro other. The 80° C isotherm is located approximately along the Ang (B) surface, so movement of anomalies between this ho and the surface must be due to convective heat flow, lateral thermal conductivity contrasts, and fault displacements within P cene sands above the Ang (B) horizon. (bottom) Heat flow conducted upward by the salt and geopressured shales to the Le horizon (left) compared to the depth to the 107° C isotherm (right). The 107° C isotherm is beneath the top-of-geopressur face and, therefore, should represent the thermal structure within the geopressured shales between the Lent (1) horizon an top-of-salt. (center) Convective heat flow calculated from the difference between the surface heat flow (top) and the heat flow ducted to the Lent (1) surface (bottom) compared to the depth to the 93° C isotherm. The 93° C isotherm is located just abo top-of-geopressure surface between the Ang (B) and the Lent (1) horizons.

then calculated (center, Figure 6). Again, these heat flow surfaces correlate well with the 93° C isotherm's topographic relief just above top-of-geopressure and the depth to the 107° C isotherm just within the geopressured chamber, from the Leedy study (Figure 6). This "convective" heat flow surface represents the heat transfer that cannot be explained by conductive heat transfer. The convective heat flow surface quantifies the magnitudes and directions of fluid flow required to move the heat from locations centered on the salt highs to the locations at the surface, where the high heat flow anomalies were measured. Thus the displacement of the surface heat flow anomalies relative to the location of the salt highs is a strong indicator that active fluid flow is presently occurring within the data cube.

Further, fluid flow velocities of several meters-per-year are required to account for the magnitudes of some of the high heat flow anomalies observed in the data cube area. The intergranular permeability of sandstones in the Gulf Coast cannot support steady-state, porous media flow this high. Therefore, the fluid flow have occurred episodically, as bursts the geopressured shales deep withi data cube. That is, these very high flow velocities can be maintained only episodic opening of very high permea pathways along faults like the red and (Figure 3). Preexisting normal fault be hydraulically opened when geopres build to values greater than the least cipal stress. The faults may quickly again, but large volumes of hot flui have been released into the sand/shale sequence above. Further, the rapid thermal decay of transient heat flow events requires that the fluid flow bursts responsible for the high heat flow anomalies must have occurred within the last 200 000 years (at the extreme). It is entirely possible that some fields may be filling now. A search should be made for anomalous production histories in the area.

Summary. Because of the geophysical constraints imposed by the observed offset between the locations of the largest surface heat flow anomalies and the shallowest salt structures, active fluid flow must be an important mechanism for the transfer of heat in the subsurface of the Eugene Island data cube. Furthermore, the magnitudes of the high heat flow anomalies require that the subsurface thermal structure be affected by thermal transients, likely caused by bursts of hot fluids exiting the geopressured shales when the fracture reopening pressures of large normal faults are periodically exceeded.

A more quantitative understanding of the thermal structure of this data cube requires 3-D numerical modeling. Such models must consider the numerous coupled processes that affect the buoyancy of fluids in sedimentary basins. Basins begin to fill with fluid and sediment at rifting. As time progresses, the coupled effects of sedimentation, compaction, heating, tectonism, and chemical alteration turn these water-filled sediments into rock with the accompanying maturation and expulsion of oil and gas (as well as the displacement of much water). Interdependently, the permeability structure evolves with time and is affected not only by changes in primary rock properties (porosity, mineralogy, lateral continuity of facies) but also by secondary changes such as diagenesis, faulting, and hydraulic fracturing.

In the future, data from all available geophysical and geochemical sources must be brought to bear upon this problem in order to accurately describe the subsurface processes that control the movement and accumulation of oil, gas, and water in a basin. Additional technologies that map the dynamic forces active in basins—such as surface heat flow, thermal and geochemical logging, and long-term temperature and pressure monitoring of wells—will be required to accurately characterize subsurface fluid flow and, hopefully, to locate additional, undiscovered oil and gas deposits in the thermochemical reactors that are sedimentary basins.

Suggestions for further reading. The article by Cathles and Nunns which is cited in the text is *A temperature probe survey on the Louisiana shelf: Effects of bottom-water temperature variations* (1991, AAPG *Bulletin*). Other recent articles dealing with the subject, and upon which some of our points are based, include *Evidence for the large-scale vertical and lateral migration of formation waters, dissolved salt, and crude oil in the Louisiana Gulf Coast*, by J.S. Hanor and R. Sassen (in *Proceedings* of the 1988 Gulf Coast Section SEPM Reservoir Conference, "The Geochemistry of Gulf Coast Crude Oils and Gases"); *The generation of petroleum from abnormally pressured fluid compartments*, by J.M. Hunt (1990, AAPG *Bulletin*); *Shallow drilling in the Salton Sea region: The thermal anomaly*, by R.L. Newmark et al. (1988, *Journal of Geophysical Research*); and *Diagenetic Processes in Northwestern Gulf of Mexico Sediments*, by J.M. Sharp et al. (1988, *Elsevier*). For additional references, contact *TLE* staff. LE

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