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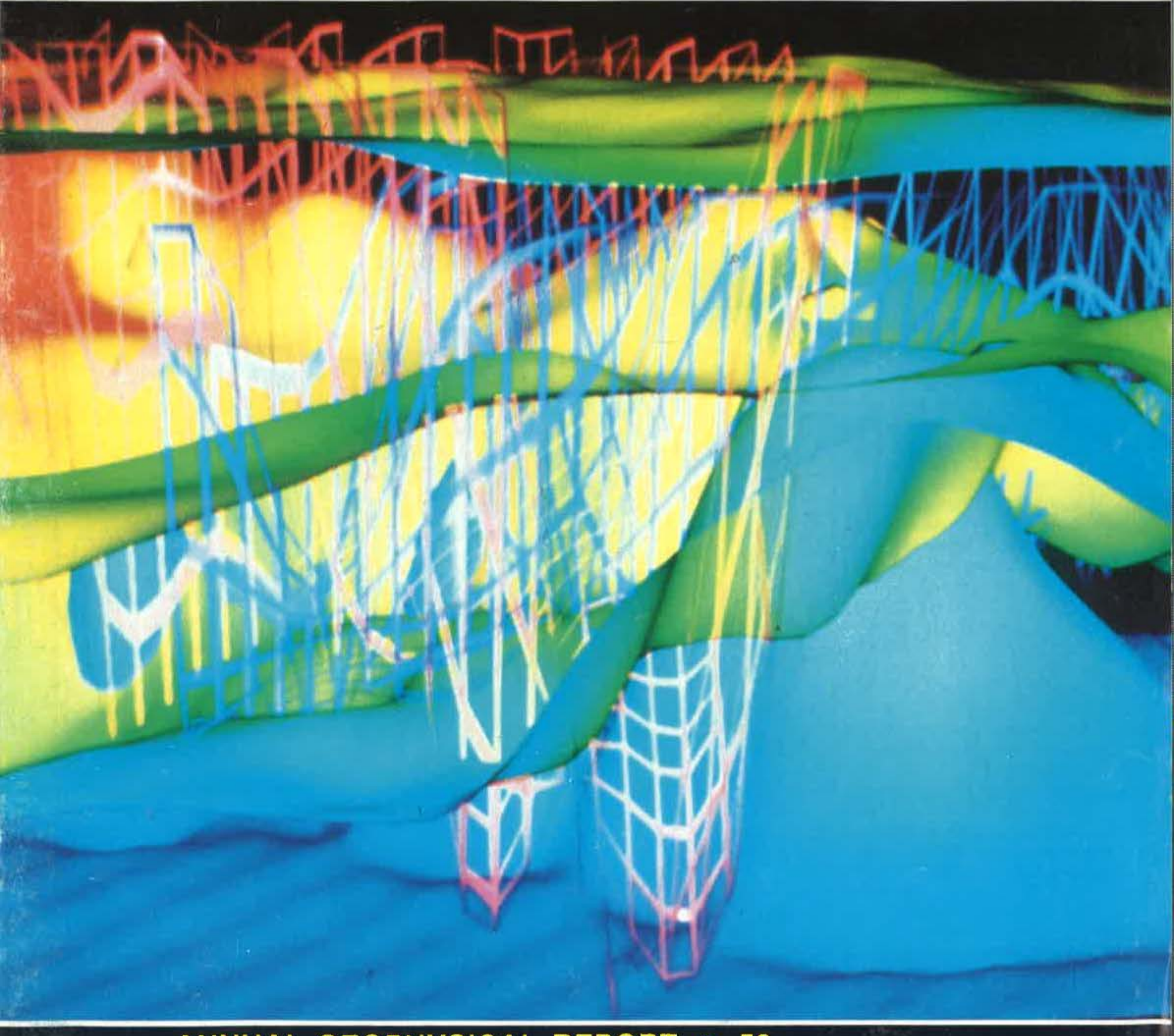

ANNUAL GEOPHYSICAL REPORT, p. 50

'Data cube' depicting fluid flow history in Gulf Coast sediments

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The search for hydrocarbons has been one of the costliest enterprises of the 20th Century, yet there is still no sure-fire method for accurately predicting the specific location of oil and gas without drilling. This is because there remains a poor understanding of how, why, and where oil and gas migrate within a sedimentary basin.

Addressing this issue, the Global Basins Research Network (GBRN) has constructed a "data cube" of the Plio-Pleistocene U.S. Gulf Coast that contains internally consistent geophysical, geochemical, and geological data relevant to fluid flow within a 60 km x 40 km x 10 km volume of Gulf Coast sediments.

Using a parallel supercomputer, the network is constructing a three dimensional (3D) model of the fluid flow history within the data cube, which will lead to the reconstruction of the fluid flow history of the volume. New dynamic technologies resulting from this method will perhaps predict the locations of vast quantities of undiscovered oil and gas.

Research network

Great strides have been made in the past 10 years in understanding the static processes of sedimentary basins in terms of their stratigraphic evolution, tectonics, and structure. However, sedimentary basins are beginning to be looked at as dynamic entities, as well.

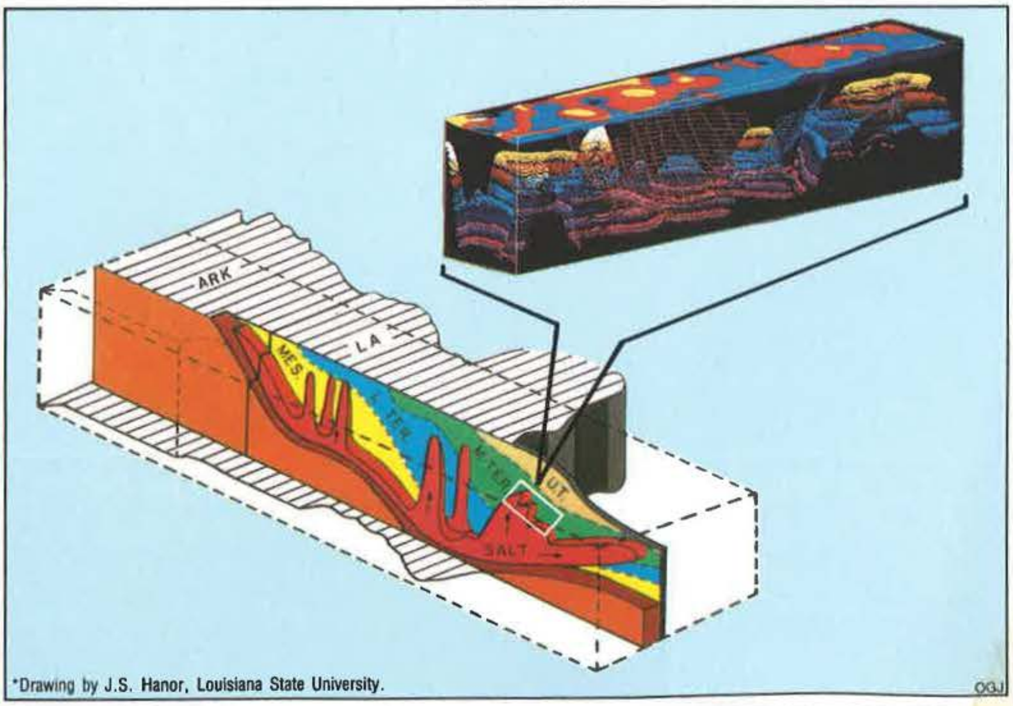
Basins are, in effect, thermochemical reactors—complex, interrelated systems, deformed and faulted by tectonic forces, modified by sedimentation, and dramatically influenced by fluid flow—which itself produces reactive chemical change. Indeed, it is fluid flow within basins that controls the concentration and location of oil and gas deposits, as well as most minerals.

A great deal is known about the specific processes that contribute to and affect the production and migration of hydrocarbons. However, good models do not exist to describe and predict the dynamic couplings between these major basin processes.

Building such models requires large numbers of people and technological resources. It is a task too big for any one university or corporate group. Thus, GBRN, a remotely linked, interactive research organization, joins uni-

Fig. 1

The data cube and Gulf Coast geology*



*Drawing by J.S. Hanor, Louisiana State University.

THE COVER

Computerized model portrays subsurface dynamics around Eugene Island Block 330 field off Louisiana. Colors—red is heat—show heat flux through four horizons, including the top of geopressure (second from top). The Annual Geophysical Report, p. 50, includes an article on the modeling project.

versity and industry scientists across the U.S. (and eventually worldwide).

Choosing a basin

Investigating and modeling coupled basin processes as a single, dynamic system requires the development of new methods and techniques to identify and map the time-dependence of fluid movement. The ideal location for developing such technologies is a basin with active maturation and expulsion of hydrocarbons. Thus, the Plio-Pleistocene Gulf of Mexico was chosen as the GBRN's initial research focus.

As the dominant hydrocarbon producing province in the U.S. Lower 48, the gulf has yielded a wealth of geophysical and geochemical data. Well over $100 billion has been spent on gulf exploration and development in the last 20 years.

However, because of comparatively recent movements of its phenomenal salt structures, the massive pile of sediments contributed by the Mississippi River in the last few million years, and the relatively late maturation of its oil and gas, the U.S. gulf basin is extremely active. Much remains to be known about it.

South Eugene Island

Before attempting to understand the dynamics of the gulf basin as a whole, the GBRN chose a small sector for the initial modeling effort. It is now establishing a 3D understanding of the physical and chemical parameters controlling dynamic processes of fluid flow in the South Eugene Island region off Louisiana.

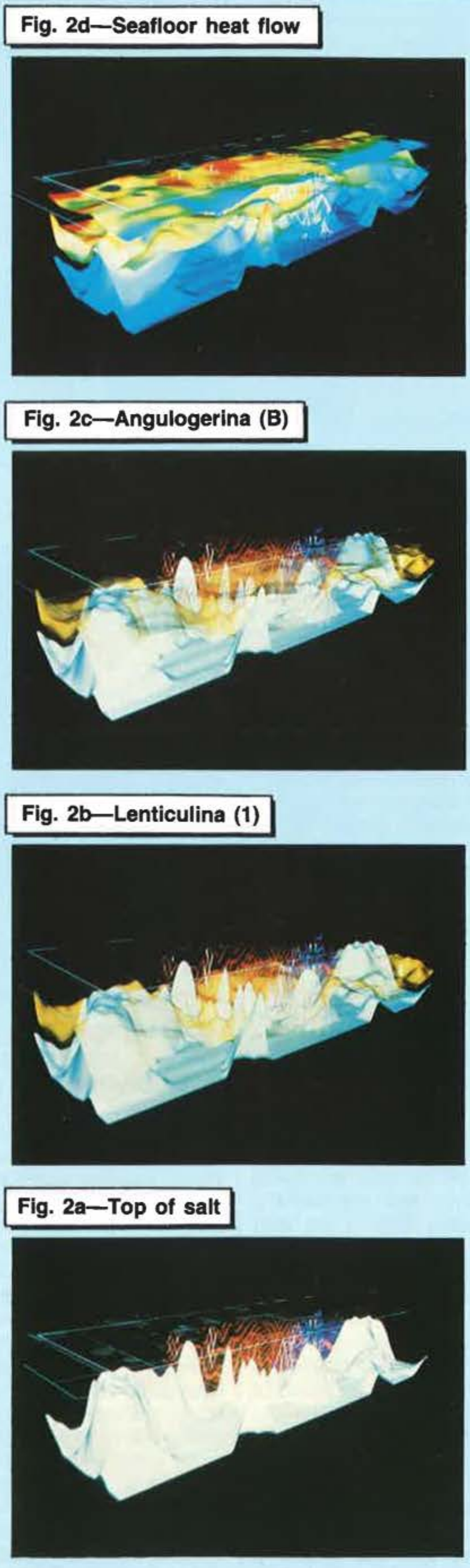
This area contains the largest offshore oil field in the U.S. It is one of the best studied, most extensively sampled (but not yet synthesized) subbasins in the world.

Specifically, the GBRN is assembling seismic, surface heat flow, temperatures, pressures, fluid compositions, cuttings and log information for the South Eugene Island area. These data are being synthesized into a 3D volumetric description of the subsurface—a data cube (Fig. 1).

This collection of internally consistent data will facilitate a description and definition of the dynamic processes controlling fluid flow, which will, in turn, shed light on where additional oil and gas are located and why.

Fig. 2

Eugene Island area subsurface horizons



Geological background

The geophysical evolution and structure of the Eugene Island area is well understood.

The region's 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. Delivery of 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; as a result, organic-rich marine sediments were deposited without much dilution.

The Laramide sediments finally breached the reef during the Tertiary, when the ancestral Mississippi Delta system dumped an enormous thickness of sediments into the Gulf Coast basin.

The pre-Tertiary marine sediments were buried, loaded, and heated with unusual rapidity. This rapid loading triggered the dramatic migration of the Jurassic Louann salt, which developed into some of the most rugged subsurface topography on Earth. The relief of the Gulf Coast salt is the greatest on the planet, with the exception of cumulonimbus clouds and associated thunderheads.

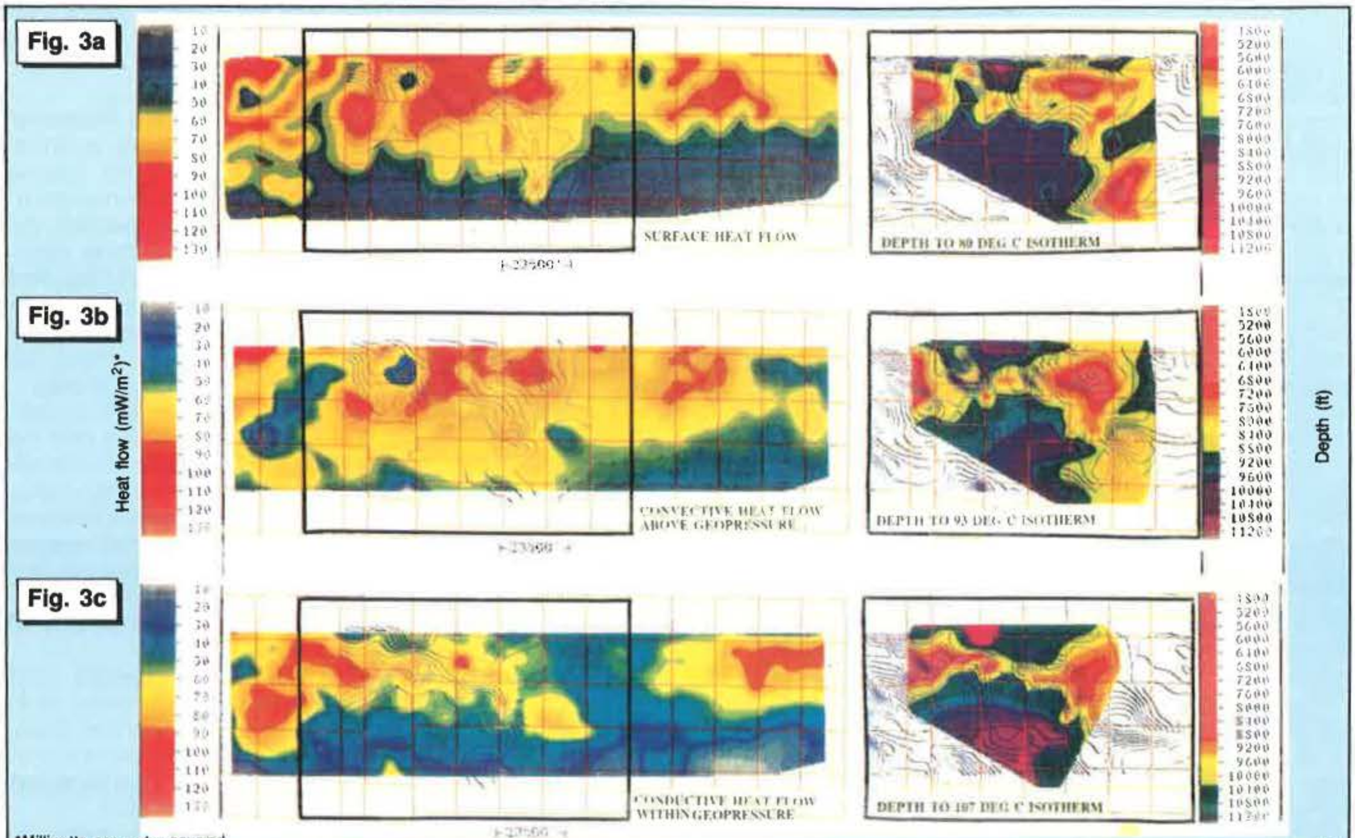
The massive dumping of all this sediment prevented normal compaction and increased pore pressures within the deeper sediments to far greater-than-hydrostatic (geopressures), causing the delayed maturation and migration of large volumes of hydrocarbons, which continue to this day.

Hydrodynamics

Drilling data suggest that large-scale hydrodynamic processes are coupled with the

Fig. 3

Subsurface heat flow, temperature comparisons



*Milliwatts per meter squared.

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ongoing deposition of voluminous sediments along the Gulf Coast. In the deepest portion of the basin, compaction and hydrocarbon maturation reactions release large volumes of high-temperature, geopressured, extremely buoyant fluids.

Thermal buildup and restricted fluid flow are associated with the top of the geopressured zone, which hydraulically isolates the deeper compactional system within the basin. Hydrothermal fluids periodically expelled from the geopressured "chambers" are known to migrate both laterally and vertically for considerable distances.

In addition to these subsidence and chemically driven hydrodynamic forces, the mountainous topography and movement of hot salt result in tremendous thermal as well as hydraulic gradients over very short distances in the subsurface.

The thermal conductivity of the salt is five times that of shale, so its location and movement will dominate the deep thermal structure of the basin. The high thermal conductivity of the salt relative to the surrounding sediments causes the refraction of tremendous quantities of heat away from the deep basin shales and toward the salt highs. Isotherms can even become subvertical near salt columns.

The form and magnitude of this hydrodynamic fluid flow are controlled by both the buoyancy forces of the fluids (temperature, pressure, chemical gradients, and fluid densities) and the permeability pathways available to the fluids. As in most geological situations, the predominant convecting fluid in the Gulf Coast is water—though oil, gas, and saline brines are variously included.

The rate and duration of fluid movement in such a dynamic sedimentary basin is not slow and steady-state but is transient and can be extremely rapid. Compaction and hydrocarbon generation create geopressures large enough to cause repeated hydraulic fracturing of the geopressured chambers.

In turn, this releases bursts of large volumes of water accompanied by oil and gas up the large growth faults and into overlying sediments. Similar transient releases of fluids from deep within geopressured chambers are thought to occur in many other hydrocarbon producing basins elsewhere in the world.

Constructing the cube

From seismic reflection profiles, cutting analyses, and log data, salt topography and subsurface stratigraphic horizons were constructed. These, together with the seafloor heat flow, were used to construct the Eugene Island data cube (Fig. 2).

The base is the top-of-salt surface (Fig. 2a), which was mapped from seismic profiles and verified by gravity observations. The complex red and blue grids are major normal fault systems, associated with oil and gas accumulation. Fig. 2b depicts the addition of a prominent sedimentary horizon above the salt.

The Lenticulina (1) biostratigraphic surface—dated 2.5 million years before present (ma)—is the base of the sand/shale sequence that is the primary hydrocarbon producer in the area. The top of this productive interval, the Angulogerina (B) biostratigraphic surface (1.5 ma) is shown in Fig. 2c, and the upper boundary layer of the data cube, the distribution of surface heat flow, is shown in Fig. 2d.

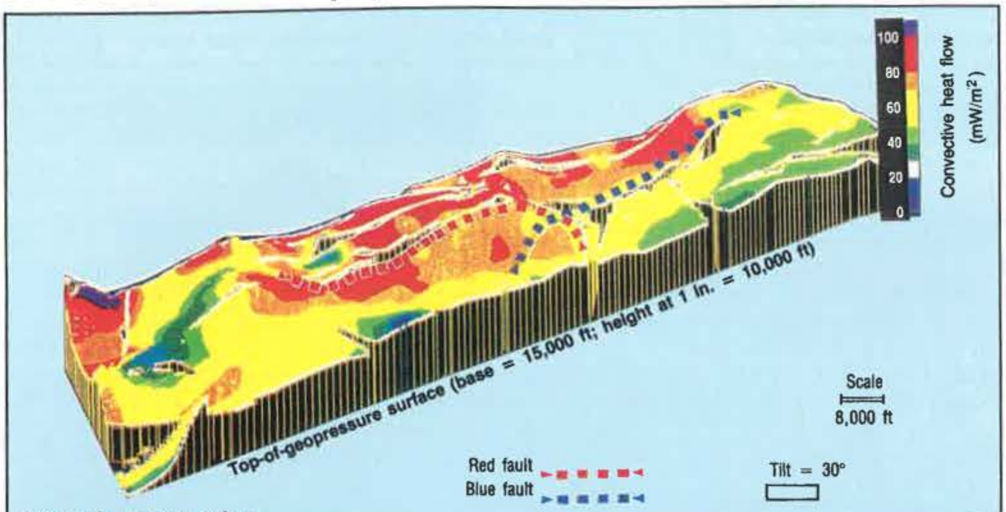
Massive sands predominate from the seafloor to the Ang (B) surface, and geopressured shales are found predominantly from the base of the Lent (1) surface to the salt.

The plumbing system is complex. It distributes oil and gas rising along the faults from the geopressured shales into the lower-pressured sand intervals within the sand-shale sequence. Water accompanies the hydrocarbons upward and moves into the even more permeable sands higher up the section.

The plumbing is actually upside down in that the most buoyant substances, the oil and gas, are trapped by the

Fig. 4

Convective heat flow projection*



*Onto top-of-geopressure surface.

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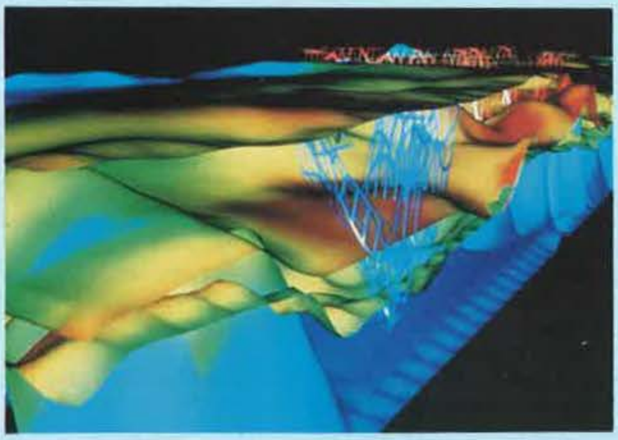
Fig. 5

Eugene Island data cube*



*Viewed from northeast corner along Blue fault. Red is heat from an undiscovered oil field.

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deepest permeable layers, whereas the water moves upward to flood the shallower sands. This stripping of the hydrocarbons is related to geopressure offsets across the major growth faults.

Heat, fluid flow

The locations of oil and gas fields in the Eugene Island area are well known, but the controlling fluid flow forces that put them there are not well understood.

The data cube horizons give a static view of how the structure and stratigraphy might relate to fluid flow and to the movement of oil and gas. However, the physical and chemical dynamics involved still need to be defined. As a start, the GBRN has been mapping thermal and pressure surfaces and analyzing their relationships to each other and to the stratigraphy.

Surface heat flow has proved to be an effective tool in scientific and geothermal exploration for interpreting subsurface fluid movements, but the technique has not been used at all in the oil industry. Fortunately, a high-density surface heat flow survey was conducted in years past over the Eugene Island data cube area by Gulf Oil Co. with the support of Lamont-Doherty Geological Observatory.

This unique data set, since donated to Lamont by Chevron Corp., 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 (Fig. 3).

To identify the convective movement of heat in the subsurface, the locations and magnitudes of the surface anomalies were checked against a compilation of temperatures measured in 300 wells from a detailed study area within the data cube.

Conductive heat transfer

Studying the measured surface heat flow anomalies more closely, the GBRN sought to determine if the upper boundary thermal anomalies were caused by upwelling within an active fluid flow system. More specifically, the group wanted to determine the spatial relationship of these surface heat flow anomalies to the salt topography (with its very high thermal conductivity) and whether the convective flow of hot fluids above the salt had displaced the thermal anomalies.

Conductive heat transfer theory predicts a strong spatial correlation between the tops of such massive salt bodies of extreme relief and high heat flow. (Within the data cube the salt topography has up to 20,000 ft of relief.)

GBRN participants calculated the magnitude of the 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 (bottom surface of Fig. 3c).

The difference between the surface heat flow (top surface, Fig. 3a) and the conductive heat flux likely to be exiting the geopressured Lent (1) layer was then calculated (center surface, Fig. 3b). This difference is assumed to be from convective heat flow occurring just above the top-of-geopressure and represents the heat transfer that cannot be explained by conduction.

The authors...

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He received a BS in petroleum geophysics from the University of Oklahoma, wrote a master's thesis at Woods Hole Oceanographic Institution, and earned a PhD in earth sciences from Scripps Institution of Oceanography, University of California.

Lawrence M. Cathles III is a professor of geology at Cornell University and codirects the Global Basins Research Network. During 1982-86 he was senior research scientist at Chevron Oilfield Research Co., La Habra, Calif., and during 1978-82 was professor of geosciences at Pennsylvania State University. Before that he directed Kennecott Copper Corp.'s mineral technology operation at its Ledgemont Laboratory.

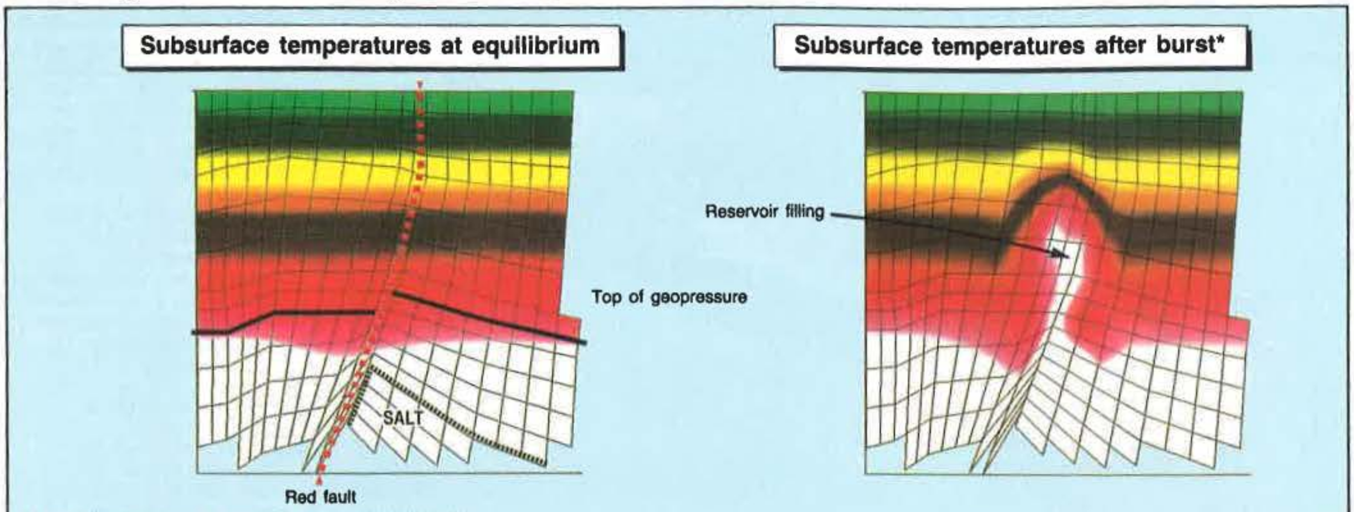
He received AB and PhD degrees in geophysics from Princeton University.

H. Roice Nelson Jr. is on the management council of the Global Basins Research Network. He is one of the founders, in 1982, of Landmark Graphics Corp., where he is involved in long range planning and development of advanced interpretation products. He also has founded two firms not directly related to the oil industry. During 1980-82, Nelson was general manager of the Applied Geophysics Laboratory at the University of Houston and before that exploration geophysicist for Mobil Oil Corp.

He received a BS in geophysics from the University of Utah and an MBA degree from Southern Methodist University.

Fig. 6

Modeling fluid burst along fault zone*



*Of fluid upward along a fault from deep, geopressured shales.

The convective heat flow surface quantifies the magnitudes and directions of fluid flow required to move the heat conducted from locations centered on the salt highs to the locations at the seafloor surface, where the heat flow anomalies were measured. Thus, the very displacement of the surface heat flow anomalies relative to the locations of the salt highs is a strong indicator that active fluid flow is presently occurring within the data cube.

While a great deal of heat rises up the salt, the shales overlying the base of salt have remarkably low heat flow (the purple area in Fig. 3). In effect, the heat flow has bypassed those shales, leaving them colder than they should be at that depth. This has important implications for the delayed timing of hydrocarbon maturation.

Top of geopressure

The most important dynamic boundary in the Gulf of Mexico is the top-of-geopressure surface. The transition zone from hydrostatic pressures above to those approaching lithostatic contains most of the hydrocarbon accumulations in the gulf. This transition zone varies in thickness from a few hundred feet to several thousand feet and is not a flat surface. In fact, it has been shown from well logs, mud weights, and drill stem tests to have several thousand feet of relief in the data cube area.

Using a novel seismic reflection strength mapping technique, the GBRN has shown the surface to be offset across the hydraulically important growth faults (Fig. 4).

More importantly, the convective heat flow anomalies from the completely independent geothermal data set correlate strongly with both the locations of major offsets in the top-of-geopressure surface and the major locations of oil and gas accumulation in the data cube area (in Fig. 4, the red areas are high heat flow oil and gas fields). This suggests that the movement of hot fluids from the geopressure chambers upward along the faults is likely to be a significant distributor of heat and hydrocarbons in the area.

Geopressured shales

Darcy fluid flow velocities of up to several meters per year, sustained over a few hundred years, are required to account for the magnitudes of temperature anomalies observed along the faults within the data cube (Figs. 5 and 6 and cover).

Also, the volumes of fluid transport required to sustain the thermal anomalies are too great for steady state dewatering. Therefore, the fluid flow must have occurred episodically, as "bursts" from the geopressured shales deep within the data cube area. That is, these very high fluid flow velocities can be maintained only with episodic opening of very high permeability pathways along the growth faults as a result of hydraulic fracturing.

Preexisting fault zones can be hydraulically opened only when geopressures build to values that exceed the fracture reopening pressure in the data cube (the minimum compressive stress magnitude). Rapid bleeding off of the geopressure quickly closes the faults again, but large volumes of hot fluid will have been released into the sand-shale sequence above, thus the correspondence between hot spots and faults (Fig. 5 and cover).

As the water, oil, and gas, accompanied by heat, move upward, the oil and gas are stripped off into the first available space within the more normally pressured sands abutting the growth faults. The water keeps on moving upward, until it reaches aquifers in the sands. The heat continues to conduct and convect right up to the surface, where it can be measured.

Finite element modeling

The data cube horizons give a dynamic view of how the structure and stratigraphy relate to fluid flow and to the movement of oil and gas. But the physical and chemical equations involved still have not been defined. An explanation of how these coupled processes evolve also is needed. Specifically, the flow has not yet been modeled.

Basins begin to fill with fluid and sediment at rifting. With time, 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 of the water.

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 secondary fracturing. GBRN's success in firmly connecting observed subsurface fluid flow to geopressures and episodic thermal convection within the data cube make it clear that precise modeling of the flow of oil- and gas-saturated fluids is now possible.

The coupled equations describing fluid flow, temperature change, fault movement, and chemical change, among others, have been cast in material coordinates and solved at the Cornell National Supercomputer Center by a sophisticated 3D finite element code. The code is unusual in that the differential equations that it solves are input as short (40-100 line long) input files called templates.

Component models (such as fluid flow or temperature) can be described by separate templates and solved in parallel, with the terms that couple the equations then calculated at each iteration or time step.

To date, templates have been developed that describe and couple changes in 1) sea level; 2) sedimentation; 3) compaction, diapirism, and faulting; 4) compactively, convectively, or topographically driven fluid flow; and 5) temperature. In the next year, salinity changes, inorganic chemical alteration, and organic maturation component models will be added.

These changes should enable the complete description of the processes occurring in the Eugene Island data cube. For example, the difficult numerical task of describing transient bursts of fluid up a fault zone has already been modeled in 2D (Fig. 6).

Outlook

Goals of the GBRN are to compile comprehensive data on a representative portion of the Gulf of Mexico basin and to make this data available on-line to all the GBRN research institutions on modern workstations.

The workstations are the tools that allow construction, visualization, and interpretation of the data cube. They also allow the interaction of model results and observations in the complex, multidisciplinary combinations that represent geologic reality in actual basins.

Over the next year or so, the GBRN will work with the data cube to simulate the fluid flow history of the South Eugene Island area with increasing complexity.

When the model is running, results will be transmitted to all the collaborating institutions and displayed on workstations using an X-Windows interface. In this way, the model runs can be closely monitored in real time. If parts go astray, the run can be aborted or corrected in midcourse.

In the largest sense, the GBRN is pioneering the use of a network organization for carrying out scientific research. If a significant contribution to the understanding of how fluids flow in a basin can be made, the efficacy of a networked research organization will be demonstrated.

Meanwhile, GBRN's scientific aim is to deliver a "proof of concept" demonstration that specific subbasins can be modeled in sufficient detail to reconstruct the history of fluid movements and the locations of mineral and hydrocarbon resources. In fact, the development of dynamic exploration and production technologies perhaps portends the discovery of a whole new generation of oil and gas in the thermochemical reactors called sedimentary basins.

Acknowledgments

A 12 min videotape "visualizing" the Eugene Island data cube and giving further details about GBRN is available from Lamont-Doherty.

Besides Columbia University's Lamont-Doherty Geological Observatory and Cornell University's Department of Geological Sciences, other Global Basins Research Network centers are located at Louisiana State University (Jeff Nunn), Woods Hole Oceanographic Institution (Jean Whelan), Michigan Technological University (Jim Wood), and the University of Tennessee (Paul Manhardt).

GBRN work is supported by corporate affiliates including Amoco, ARCO, BP, Canadian Hunter, Conoco, Elf, Exxon, Mobil, Shell, Texaco, and Union.

Corporate partners include Computational Mechanics, Halliburton, IBM, and Dynamic Oil & Gas Corp. These corporate affiliates are making the new technologies described available to the oil and gas industry.

The images in this article were created from horizon files exported from a Landmark Graphics workstation to an IBM 3090-600E parallel supercomputer running Wavefront Technologies software. ▪