of the whole North Sea basin shows that the mean gradients rarely exceed 40°C/km and are rarely lower than 20°C/km. In broad outline, the gradient pattern seems to reflect the major structural elements. The positive geothermal anomalies are explained in terms of convective heat transport within an actively subsiding basin. Major fault systems serve as conduits for fluid flow. Salt pillows and salt diapirs are centers of hot areas caused by heat conduction. Isothermal maps of key structural horizons and geoisothermal maps are presented to support these interpretations.

The importance of constructing thermograms is emphasized. In the North Sea basin, variations in interval geothermal gradients are explained by a combination of differences in lithology-related conductivity and subsurface fluid flow. Locally, interval gradients twice as high as the mean gradients are observed.

This investigation does not support the idea that geothermal anomalies are uniquely associated with oil or gas accumulations and hence could be used as an exploration tool. Rather, it seems that detailed mapping of geotemperatures can help explain the pattern of subsurface fluid flow of which water (and not hydrocarbons) constitutes the major part.

FERRELL, R. E., Louisiana State Univ., Baton Rouge, LA

Clay Mineral Evidence for Movement of High Temperature Subsurface Fluids

The study of geopressured formations has provided considerable information on the probable pathways for subsurface fluid movement. The fluids have been traced and associated with structure, pressure distribution, salinity of formation waters, various organic and inorganic diagenetic effects, as well as local changes in the geothermal gradient and the temperature of formations. The temperature changes may be measured directly or inferred from the presence of temperature-controlled reaction products such as the modification of illite/smectites.

Clay mineral changes are detected initially at temperatures as low as 50°C and may extend to temperatures in excess of 300°C. The smectite-illite conversion is most pronounced in the range from 50°C to about 160°C. Significant changes in kaolinite and chlorite occur between 75°C and 250°C.

In shales from the Gulf Coast, the smectite-illite conversion is readily recognized, while kaolinite-chlorite reactions are most apparent in associated sands. In several places the development of kaolinite in sandstones is directly linked to the movement of high temperature fluids and the subsequent blocking of secondary porosity. Kaolinite is most abundant in those zones which experienced maximum flushing.

GATENBY, G. M., JR., Union Oil Co., of California, Lafayette, LA

Temperature Anomalies and Gulf Coast Structures

Temperature anomalies associated with various structures in the Gulf Coast are interpreted to be the result of fluid migrations from depth. Pressure and salinity data are also part of an exploration model where hot, fresh, hydrocarbon-laden waters are believed to be migrating up faults. Traps in the vicinity of these migrations are of special interest to the explorationist because they are more likely to be charged with hydrocarbons.

The part of southeastern Louisiana studied has twelve areas of possible subsurface fluid migrations. Eight hydrocarbon fields are in the vicinity of these migrations. The areas of migration are most likely to occur at areas of structural expansion, i.e., grabens, crests of diapirs, and most importantly, intersections of faults.

HITCHON, BRIAN, Alberta Research Council, Edmonton, Alberta, Canada

Relations Between Hydraulics, Temperatures, and Crude Oil and Natural Gas Composition in Some Upper Devonian Reefs of Alberta, Canada

The Upper Devonian Woodbend Group and Beaverhill Lake Formation of Alberta contain numerous crude oil and natural gas occurrences pooled in several carbonate reef chains, which are hydraulically distinct with small but subtle differences in present reservoir temperature. Regionally, these hydrocarbon occurrences exhibit typical trends from immature gases in the shallower pools, sometimes associated with biodegraded crude oils, to deeper mature crude oils. Examination of the composition of the natural gases and the broad general characteristics of the crude oils suggests that there is imposed on these typical maturation trends differences in the fluid compositions and reservoir temperatures which are related to the different hydraulic systems and the position of each system within the low fluid-potential drain which essentially channels flow within the thick sequence of highly permeable Upper Devonian and Carboniferous carbonate rocks in the medium-depth part of the Alberta basin.

HODSON, MARK W., Marathon Oil Co., Houston, TX, and JOHN M. SHARP, JR., Univ. Missouri-Columbia, Columbia, MO

Rocks, particularly those formed from clayey sediments, are capable of retaining pore fluids at pressures greater than hydrostatic. Such pressures are frequently encountered while drilling for oil and gas, and consequently the phenomenon of excess fluid pressure has been studied extensively. Anomalous temperature changes with depth have been observed associated with overpressured zones and these anomalies have themselves been the object of considerable thought. However, few studies have attempted to model simultaneously the generation of overpressuring and the associated temperature patterns. Such a model has been constructed, with an equation describing one-dimensional flow through a porous medium at its heart. Through a computer program, this equation describes the vertical movement of fluids and heat through accumulating sediments and the resultant densities, pressures, and temperatures. This program was applied to an accumulating thickness of "mud" and sand approximating a generalized Gulf Coast section. The resultant plots of pore pressure, porosity, and temperature versus depth are similar to those typifying the drilled areas of the Gulf Coast. These characteristic profiles can be viewed as a consequence of the Gulf Coast overpressured environment.

HOUBOLT, J. J. H. C., and P. R. A. WELLS, Shell Exploratie en Produktie Laboratorium, The Netherlands

Estimation of Heat Flow in Oil Wells Based on Relation Between Heat Conductivity and Sound Velocity

Based on published data, it is assumed that the ratio of sound velocity to thermal conductivity exhibits a linear relation with formation temperature for most sedimentary rocks.

Combination of this assumption with Fourier's heat-flow law yields

$$q^* = \ln \frac{T_L + c}{T_u + c} \cdot \frac{1}{A(t_L - t_u)}$$

where T_L and T_u are the subsurface temperatures at the top and the bottom of an interval, respectively, t_L and t_u the sound travel times, and q^* is the heat flow. This relation has been tested in the case of 10 wells, for which accurate data were available. The relation generated satisfactory fits with the measured data for siliciclastic and carbonate rocks. The parameters a and c take respective values of 1.039 and 80.031; heat flow (q^*) is expressed relative to the heat flow in the standard well Bolderij-1 in the Groningen gas field Bolderij Unit (BU).

A method for estimating the relative heat flow from bottomhole tempeatures as observed during logging operations, and sound-travel times from well-shoot in combination with sonic-log data, has been developed and tested in the Viking and Central grabens of the UK sector of the North Sea. In this region the mean relative heat flow using data from 120 wells is 0.601 BU, with a standard deviation of 0.055 BU.

Comparisons of calculated relative heat-flow values in BU, with heat-flow values in Si-Units conventionally obtained suggests that the Bolderij Unit is equivalent to about 77 mWm^{-2}.

JONES, PAUL H., Consultant, Baton Rouge, LA

Geothermal and Hydrocarbon Regimes in Northern Gulf of Mexico Basin

Geotemperature transients and the phenomena of heat flow define the fluid hydrocarbon regime in petroliferous sedimentary basins. The redistribution of heat and the thermo-physical properties of the rocks are mainly determined by the hydrogeology. As the temperature thresholds of smectite dehydration and kerogen diagenesis are passed, endothermic chemical changes convert solid rock mineral matter to fluids, reducing the net volume of mineral solids in each unit volume of rock and thereby increasing its porosity. As this occurs the pore-fluid pressure rises markedly in response to the loss of load-bearing strength in the altered rock. Simultaneously, the aqueous solubility of fluid hydrocarbons is enhanced and the hydraulic permeability of the altered rock is greatly increased. Pore water carrying dissolved hydrocarbons moves through the altered rock and into adjacent aquifers, driven by steep hydraulic gradients. Subsequently, mass movement of water from the geopressure zone to the hydropressure zone migrates the dissolved hydrocarbons to traps, near which a sharp pressure drop causes exsolution.

The threshold temperature of smectite dehydration generally occurs a short distance below the top of the geopressure zone. The 100°C isothermal surface closely approximates the top of the geopressure zone, except where water loss from the geopressure zone is in progress. At depths where temperature exceeds 150°C, petroleum occurrences are rare indeed. The abundance of natural gas, however, in both vapor phase and in aqueous solution, increases with pressure and temperature—and thus with depth—probably as a result of progressive natural cracking of petroleum residues in the rocks with deepening burial.

JONES, TERRY, and AMOS NUR, Stanford, Univ., Stanford, CA

Effect of Temperature and Pore Pressure on Velocity and Attenuation of Seismic Waves in Rocks: Applications to Crustal Exploration

Compressional seismic wave velocities have been used with much success in defining structural features likely to serve as hydrocarbon reservoirs. Recent advances in data collection and processing and, as we will describe, a greater understanding of the factors governing wave propagation in rocks indicate much additional information regarding the in-situ temperature, degree of saturation, and pore pressure may be obtained if data are available on seismic attenuation and shear velocity in addition to compressional velocity.

Both velocity and attenuation are strongly temperature dependent. In dry sandstones, velocity increases rapidly with temperature to 100°C then levels off. V_p/V_s increases with tempeature. Shear and extensional attenuations increase rapidly with temperature from a Q of about 90 at room temperature to over 500 at 225°C. Shear attenuation is less than extensional attenuation below 200°C; the opposite is true above 200°C. In rock with a small amount of free water, thermal fracturing of rocks becomes dominant above 170°C decreasing velocities because of the increased porosity and increasing attentuation due to additional surface area in contact with water. In partly saturated rocks at elevated temperatures (200°C) attenuation is high in bulk compression and about half as great in shear. In fully saturated rocks, shear attenuation is high and bulk attenuation is low. Compressional velocity is greater in a fully saturated rock than in a dry or partly saturated rock. Shear velocity is less in a saturated rock than in a dry rock. Velocity and attenuation roughly follow an effective stress law.

KHARAKA, YOUSIF K., MICHAEL S. LICO, and LEROY M. LAW, U.S. Geol. Survey, Menlo Park, CA

Subsurface Temperatures Calculated by Chemical Geothermometers Applied to Formation Waters from Northern Gulf of Mexico and California Basins

Twelve chemical geothermometers based on the concentrations of silica and proportions of sodium, potassium, calcium, and magnesium in water from hot springs and geothermal wells are used successfully to estimate the subsurface temperatures of the reservoir rocks. These twelve geothermometers together with a new geothermometer based on the concentrations of lithium and sodium were used to estimate the subsurface temperatures of more than 200 formation-water samples from about 40 oil and gas fields in coastal Texas and Louisiana and the Central Valley, California. The samples were obtained from reservoir rocks ranging in depth from less than 1,000 m to about 5,600 m.

Quartz, Na-K-Ca-Mg, and Na-Li geothermometers give concordant subsurface temperatures that are within 10°C of the measured values for reservoir temperatures higher than about 75°C. Na-Li, chalcedony, and a modified Na-K geothermometers give the best results for reservoir temperatures between 40°C to 75°C. Subsurface temperatures higher than about 75°C calculated by chemical geothermometers are at least as reliable as those obtained by conventional methods. Chemical and conventional methods should be used where reliable temperature data are required.

KUMAR, MADHURENDU BHUSHAN, Louisiana State Univ., Baton Rouge, LA

Geothermal Trends in Petroliferous Regions of Louisiana