

shales are in the range of  $10^{-7}$  to  $10^{-12}$  cm/sec. The change in permeability, with void ratio is expressed as  $\Delta \log k = \Delta e/C_v$ . The parameter  $C_v$  is directly related to the void ratio. For clays, values of  $C_v$  range from 0.5 to 4. For shales, the  $C_v$  values are in the range of 0.02 to 0.5.

Permeability of fissile shales is expected to be highly anisotropic as compared to massive shales that have a more random fabric. However, permeability anisotropy in shales has not been extensively investigated. At shallow depth, the permeability of shale formations is strongly influenced by discontinuities such as fissures and joints.

PEVEAR, D. R., Western Washington Univ., Bellingham, WA (present address: Exxon Production Research Co., Houston, TX)

#### Illite/Smectite Diagenesis: Relation to Coal Rank in Tertiary Sediments of Pacific Northwest

Bentonite partings formed by alteration of air-fall tephra interbedded with coal in three Eocene coal basins (Tulameen, British Columbia; Chuckanut and Centralia, Washington) record the nature of arc volcanism and subsequent diagenesis and metamorphism. Euhedral feldspar phenocrysts, embayed quartz, and relict glass shards demonstrate volcanic provenance, whereas the absence of muscovite, microcline, and other nonvolcanic minerals indicates lack of epiclastic detritus. At Tulameen, abundant sanidine and biotite indicate rhyolitic tephra; at Centralia, plagioclase and absence of quartz and K-spar indicate dacite. Absence of K-spar from Chuckanut deposits may be due to its destruction by metamorphism, since quartz phenocrysts are present, suggesting rhyolite.

Alteration of glassy tephra to bentonite has taken place in two or three steps. (1) Leaching (weathering) in the swamp may have formed allophane or halloysite, but much glass remained unaltered. (2) Early diagenesis at temperatures below 60°C (suggested by vitrinite  $R_o = 0.40\%$ ) formed, by reaction of non-phenocrystic components with pore fluids within individual partings, one of five assemblages depending on degree of prior leaching: zeolite-smectite-cristobalite, smectite-cristobalite, smectite, smectite-kaolinite, kaolinite. Na-smectite at Centralia inherited interlayer Na from original glass. Delicate vermicular kaolinite may also have formed during this stage. (3) Thermal metamorphism has transformed smectite in some Tulameen and all Chuckanut partings to regularly interlayered illite/smectite (I/S). At Tulameen ( $R = 1$  ordered I/S with 55% I + kaolinite), the source of potassium for the reaction was solution of phenocrystic sanidine and mica;  $R_o = 0.9\%$  suggests 130 to 200°C. The Chuckanut bentonites ( $R = 1$  and  $R \geq 3$  ordered with 65 to 90% I + chlorite) show  $R_o = 3\%$  suggesting temperatures exceeded 300°C; some potassium may have been derived from outside the parting, and more complete illitization may have been inhibited by lack of potassium and by calcium released during albitization of plagioclase.

QUIREIN, J. A., J. S. GARDNER, and J. T. WATSON, Schlumberger Well Services, Houston, TX

#### Combined Natural Gamma Ray Spectral/Litho-Density Measurements Applied to Clay Mineral Identification

The utilization of well log data to provide a lithologic description of complex formation is well-evidenced. Historically, however, most approaches assume fixed, known, and distinct lithologies for analyst-specified zones. The proposed approach attempts to alleviate this restriction by estimating the

"probability of a model" for the most likely models suggested by the reservoir geology. Lithologic variables are then simultaneously estimated from response equations for each model and combined in accordance with the probability of each respective model.

The initial application of the proposed approach has been the recognition of clays in the presence of calcite, quartz, dolomite, feldspar, anhydrite, or salt. This application has been realized through utilization of natural gamma-ray spectra, photoelectric effect, bulk density, and neutron porosity information.

For each specified model, response equations and parameter selections are obtained through utilization of the thorium versus potassium crossplot and the apparent matrix density versus apparent volumetric photoelectric cross-section crossplot. The thorium and potassium response equations are used to estimate the volumes of clay and feldspar. The apparent matrix density and volumetric cross-section response equations can then readily be corrected for the presence of clay and feldspar. However, a test is applied to ensure that the clay correction lies within limits consistent with the assumed lithology model. If inconsistency is detected, either the estimate of clay volume or the lithology model, or both, are changed.

A computer program has been written to test the proposed approach. Initial field testing in the U.S.A. and Canada has been completed and the program appears to recognize, with minimal analyst intervention, illite, chlorite, and a third clay which is considered to be a kaolinite-montmorillonite mixture. Results from the field are presented for an assortment of wells with varying lithologies.

ROBERSON, HERMAN E., State Univ. New York, Binghamton, NY, and BRUCE SASS, State Univ. New York, Binghamton, NY (present address: Washington State Univ., Pullman, WA)

#### Al-Hydroxy Smectite: An Intermediate Between Smectite and Mixed-Layer Illite/Smectite Formed in Burial Diagenesis of Pelitic Sediments?

Reaction mechanisms for the reaction smectite → mixed-layer illite/smectite are proposed based on experimental results. Pure smectite (100% expandable) in NaCl-Na<sub>2</sub>CO<sub>3</sub> solutions was heated in sealed gold capsules to 180 and 350°C for periods of 7 and 28 days. The solutions used for this initial hydrothermal treatment were kept  $K \neq$  free to prevent the formation of non-expanding illite layers, a condition which would have made it difficult to characterize the exchange properties of expanding layers undergoing transition.

A series of cation exchange experiments using chloride solutions of Na<sup>+</sup>, K<sup>+</sup>, and Mg<sup>++</sup> were carried out at 25°C to determine the effect of the heat treatment described above on  $K \neq$  selectivity and total cation exchange capacity. Data obtained from these experiments show that the hydrothermally treated clays become *less selective* for K<sup>+</sup> with increasing temperature and length of run. Data also show that the total CEC *appears to decrease* with increasing temperature and length of run. We suggest that this apparent decrease in total CEC as well as the difference of  $K \neq$  selectivity is caused by the inability of the exchange cation (Ba<sup>++</sup> in these experiments) to replace tightly held Al, which diffused to exchange sites from tetrahedral and octahedral positions when the clays were heated.

These results lead us to propose that a smectite-interlayer Al-hydroxy complex may be an important intermediate in the smectite → mixed-layer illite/smectite transformation often observed in buried pelitic sediments. Further study of the rate and mechanisms involved in the formation and ultimate destruction of the Al-hydroxy interlayer material should be

instructive in predicting the behavior of fluid movement during burial diagenesis/metamorphism of pelitic sediments.

SAVIN, SAMUEL M., Case Western Reserve Univ., Cleveland, OH

Oxygen Isotopic Studies of Diagenetic Clay Minerals: Implications for Geothermometry, Diagenetic Reaction Mechanisms, and Fluid Migration

Oxygen isotope ratios of diagenetically formed minerals in shales and sandstones can provide information about temperatures of diagenesis, mechanisms of clay mineral reactions, degree of openness of the rocks to the movement of water during diagenesis, and sources of water involved in reactions.

The isotopic approach has proven especially effective in studying the shales of the United States Gulf Coast in which the predominant diagenetic reaction involving clays is the conversion of smectite layers to illite layers in mixed-layer illite/smectite. Clay minerals affected by this reaction appear to undergo oxygen isotope equilibration with the ambient water. A byproduct of the smectite-illite transition is quartz. When the diagenetically formed quartz can be isolated for isotopic analysis, oxygen isotope fractionations between coexisting quartz and clay are indicative of diagenetic temperatures when temperatures are higher than 70 or 80°C. There is some evidence that at temperatures above 180°C clay-size detrital quartz may exchange isotopically with pore fluids and other rock constituents, perhaps permitting the determination of maximum burial temperatures of shales even in the absence of the smectite-illite conversion reaction.

During diagenesis the shales studied approximate closed systems, the isotopic composition of the diagenetic waters being determined largely by isotopic exchange with the rocks. Water lost from the shale sequences during diagenesis apparently moves outward or upward along cracks, passing out of the system without isotopically affecting overlying shales.

Diagenetic minerals in sandstones, like those of shales, reflect temperatures and isotopic compositions of pore waters. While few isotopic studies of minerals from sandstones have been done to date, those by Land and his coworkers indicate that this is a very promising approach for unraveling and understanding complex histories of diagenetically altered sandstones.

SHARP, JOHN M., JR., Univ. Texas, Austin, TX, and MICHAEL H. KORTENHOF, Univ. Missouri, Columbia, MO

Numerical Model of Shale Compaction, Aquathermal Pressuring, and Hydraulic Fracturing

Clastic sediments, which are fine-grained or clayey, are capable of retaining fluids at pressures considerably greater than hydrostatic. The excess pressures can be induced by any of several mechanisms. A numerical model is developed which considers simultaneously the effects of compaction disequilibrium and aquathermal pressuring. Energy transport by conduction only is used to provide temperature profiles. The pressure and temperature dependency of isobaric thermal expansivity and isothermal compressibility are integrated in the solution. Simulations were conducted for a variety of heat flux, permeability, stratigraphic, and sedimentation conditions.

It is shown that, while compaction disequilibrium itself explains the general pressures in Gulf Coast sections, aquathermal pressuring can lead to fluid pressures greater than lithos-

tatic. Fluid release by hydraulic fracturing must then occur. This combination of processes provides an explanation for the observed variations in shale bulk density, excess pressure, and thermal gradient. A Mohr failure diagram, using a two-part failure envelope combined with horizontal versus vertical stress data provides a means of determining when fracturing is initiated and the orientation of the fractures. A variety of stress conditions that result in both horizontal and vertical fractures are considered. The depth of fracture initiation is highly dependent on the sedimentation rate, the sand versus shale ratio of the sediments, and on the tensile strength and hydraulic conductivity of the shale.

UNGERER, Philippe, Institut Francais du Petrole, Rueil-Malmaison, France

Importance of Physical Properties of Clays in Oil Formation and Migration

Many source rocks have argillaceous matrixes. Until recently, only chemical interactions between clay minerals and organic matter (catalytic effect) have been given serious consideration. It appears now that the physical or physico-chemical properties of clays also play a key role in the processes of primary migration of oil. Among these properties are (1) microstructure of clays which influences the porosity and permeability in both the water and oil phase, (2) mechanical behavior of clays which may contribute to the microfracturing processes thus allowing the expulsion of oil from source rocks, and (3) physico-chemical properties of adsorption and wettability of clays which act strongly because of the high specific area of clay minerals. This property may influence the permeability of clay shales. In addition, adsorption is selective toward various components generated by organic matter, thus explaining major differences observed between the composition of source rock extracts and reservoir oils.

On a larger scale, such as anticlinal structures, clays are commonly the origin of fluid pressure anomalies. High pressures modify the flow system, since fluids are drained preferably by the tops of structures. The flow of water due to natural convection eventually may cause the alteration of clay minerals and enhance the permeability of the overpressured sections beneath the pressure seal. This process contributes to the modification of geothermal conditions in undercompleted rocks where poor thermal conductivity conditions exist.

These combined effects influence both the nature and spatial distribution of hydrocarbons trapped in reservoirs. Therefore, a better knowledge of the physical properties of clays should lead to a better understanding of the role of clays in the formation and migration of oil and gas and thus lead to better exploration practices.

VELDE, B., Laboratoire de Geologie, Ecole Normale Supérieure, Paris, France

Effect of Bulk Composition on Clay Mineralogy: Examples from Jurassic Sandstones of North Sea

It is now common to estimate diagenetic grades of claystones and shales using the composition of interstratified dioctahedral minerals. It is also well known that sandstones commonly have mineralogies which are different from those in associated shales. It has, therefore, been proposed that solution composition of formation waters can play an important role in determining the clay mineralogy of sandstones.

Chemigraphic analysis of clay minerals present under conditions of deep burial can be used to determine the key assem-