TESTA, STEPHEN M., Dames and Moore, Seattle, WA, and BENJAMIN N. AKPATI, Nigerian Inst. Oceanography and Marine Research, Lagos, Nigeria

Heavy-Mineral Distribution Along Coastline of Ghana, West Africa

As part of a natural resource appraisal of beach and shelf sediments of Ghana, the mineralogy and texture of beach sands along the Ghana coastline was studied. Precambrian (Dahomeyan) rocks rich in heavy minerals are widely distributed throughout Ghana, providing varied mineral suites along the coast. Most of the beach sediments studied were moderately well-sorted medium sands. Opaque and micaceous minerals constitute between 19 and 17% of the total heavy mineral suite, which on average comprises 46% of the sand. Five mineral provinces, based on relative frequency of the most abundant nonopaque and nonmicaceous heavy minerals, are recognized. (1) Tano province (between Half Assini and Esiama) is characterized by high staurolite (26%) and the least amounts of garnet (0.3% vs. an average of 8.3%) + amphibole (4.6%) + kyanite (1.6%) + epidote (1.8%) + pyroxene (1.3%). (2) Ankobra province (between Axim and Shama) is characterized by increased amphibole (15%) + staurolite (11%) + kyanite (2.7%) + epidote (2.6%). The marked increase in amphibole may be attributed to local outcrops of hornblende-rich Dixcove Granite. (3) Pra province (between the Pra and Densu Rivers) is characterized by increased staurolite (24%) + amphibole (11.3%) + kyanite (4.8%) + garnet (3.7%) + tourmaline (1.5%) + relatively high local occurrences of zircon. The Cape Coast Granite complex exerts a significant influence in this area. (4) Densu province (between the Densu River and Ada) is characterized by staurolite (26.8%) + garnet (16%) + amphibole (15.2%) + kyanite (3.5%) + epidote (3.2%), whose sources are the acidic division of Lahomeyan epidote-bearing hornblende schist and kyanite-bearing marble exposed near Accra. (5) Volta province (between Anyanui and Aflao) is characterized by garnet (17.5%) + staurolite (11.7%) + amphibole (9%) + kyanite (5%) + epidote (4.5) + pyroxene (3.8%). Except for rutile and zircon, heavy mineral content of the area appears to be independent of sedimentary texture. However, the distribution patterns of the heavy minerals reflect the dynamic conditions of the littoral drift in the dispersal of sediments along the coastline of Ghana.

THAYER, PAUL A., Amoco Production Co., New Orleans, LA

Diagenetic Controls on Reservoir Quality, Matagorda Island 623 Field, Offshore Texas

Matagorda Island 623 field is a large gas accumulation in overpressured, lower Miocene *Siphonina davisi* deltaic sandstones. Production is from fine, moderately well sorted sublitharenites deposited in distributary-mouth bars and channels. Reservoir depth is 10,000-14,000 ft (3,050-4,275 m) and bottom-hole temperatures approach 275°F (135°C). Pay-sand porosities range from 15 to 35% and permeabilities range from 10 to 3,000 md.

Between 60 and 85% of the porosity is primary intergranular. Porosity preservation is dependent upon the following: (1) early formation of chlorite grain coats, (2) a stable mineralogic framework, (3) overpressuring, and (4) entry of gas into the reservoir. Chlorite coats form as much as 8% of the rock and originated from a chemical decomposition of volcanic rock fragments (VRF). These coats inhibited quartz cementation and retarded compaction related to pressure solution.

Secondary porosity originated mainly from feldspar and VRF dissolution. Although calcite cement is locally common, evidence is lacking that calcite leaching formed significant porosity. Evidence against large-scale carbonate dissolution includes the following: (1) unaltered carbonate lithoclasts, (2) reworked Cretaceous foraminifers, (3) preservation of delicate chlorite crystal morphology, and (4) the absence of pitted or serrated surfaces on quartz overgrowths, which formed prior to calcite cementation.

THOMSON, ALAN, Shell Western E&P Inc., New Orleans, LA, and R. K. STOESSELL, Univ. New Orleans, New Orleans, LA

Nature of Secondary Porosity Created by Dissolution of Aluminum Silicates

Porosity enhancement in sandstone reservoirs cannot be due to dissolution of aluminum silicates without implying aluminum mobility. However, aluminum has yet to be reported in reservoir fluids at greater than trace concentrations. Predicted aqueous aluminum concentrations in subsurface fluids approach a level that Curtis has termed "a good approximation of zero."

Several studies of secondary pore systems formed by aluminum silicate dissolution demonstrate that aluminum is conserved on a scale of a few inches, in the form of diagenetic clay minerals—notably kaolinite. Our examinations indicate that the products of dissolution of aluminum silicate grains (which include feldspar and many rock fragments) can be accounted for in thin section primarily by the presence of adjacent pore-filling kaolinite and possibly authigenic quartz and albite. At high temperatures, the diagenetic mineral is often illite.

Secondary porosity formed by dissolution of aluminum silicate grains should not necessarily be construed as adding to total porosity, but should rather be thought of as a "rearrangement" of porosity already present. Indeed, the process may actually be harmful, inasmuch as the newly formed clay minerals can greatly reduce permeability. Calcite resorption remains the principal means of adding to total porosity through a dissolution process.

TIEH, THOMAS T., Texas A&M Univ., College Station, TX

Occurrences of Sphalerite in Reservoir Rocks of North Texas and Gulf Coast

Chemical evolution of pore fluids during diagenesis is important to oil and gas origin and migration and mineral deposits. Authigenic sphalerite, a potential geochemical indicator, has been found in reservoir rocks that include the following: (1) Mississippian Osage formation, (2) the Pennsylvanian Strawn Formation, (3) the Jurassic "Gray" sandstones (Smackover), (4) the Jurassic Cotton Valley Formation, and (5) the Cretaceous Hosston Formation. These and two previously reported occurrences in the Smackover suggest a widespread occurrence of sphalerite in subsurface pre-Tertiary sedimentary rocks of north Texas and the Gulf Coast.

Preliminary examinations reveal the following two modes of sphalerite occurrence: (1) as finely crystalline patches of cement in sandstones or limestones, and (2) as individual crystals in ooids or in the cement of oolitic limestones. In some sections, formation of sphalerite appears to be early, with zinc and reduced sulfur derived from nearby shales. In others, late formation and distant sources seem to be most likely. Further studies of the chemistries of sphalerite and fluid inclusions, associated host rock alterations, and temporal and spatial distribution of sphalerite may lead to improved understanding of pore-fluid chemistry during hydrocarbon origin and migration.

TILLMAN, R. W., Cities Service Research, Tulsa, OK

Spectrum of Ancient Shelf Sandstones

Processes that have operated on the seabed of the shelves of the world in the past include waves, storms, permanent currents, subtidal currents, and turbidity currents. As a result of the wide variety of processes, sand bodies with different geometries have resulted, and they commonly contain different sedimentary structures or different sequences of sedimentary structures. On ancient shelves the most common sedimentary structures in current-deposited sandstones are planar-tangential to *planar-tabular cross-beds, and current ripples. Wave-deposited sand*stones are characterized by horizontal to subhorizontal laminations and symmetrical ripple forms. One of the most common shelf sequences reflects upward-increasing energy. However, a sequence reflecting upward-increasing energy and consequent increase in grain size is not unique to shelf sandstones.

Shelf sandstones may be classified on the basis of their position on the shelf (shoreface-attached, inner shelf, middle shelf, outer shelf) and on the basis of whether they are deposited during a transgression, regression, or a stillstand. Both vertical and lateral sequences of lithologies vary with position on the shelf, processes of deposition, and position within transgressive-regressive spectra.

Cretaceous sandstones used to characterize a variety of these processes, geometries, and shelf locations include the "Gallup" (Tocito), Shannon, Fales, and Frontier sandstones.

TOBIN, RICK C., Amoco Production Co., Houston, TX, and WAYNE A. PRYOR, Univ. Cincinnati, Cincinnati, OH

Cincinnatian Series—Model for Cyclic and Episodic Deposition of Carbonates and Shales on a Storm-Dominated Ramp

Upper Ordovician (Cincinnatian) strata in Ohio, Indiana, and Kentucky were deposited as cyclic sequences. Three types of cycles are represented: thin, graded storm cycles, moderately thick megacycles (carbonate to shale sequences), and thick shoaling-upward cycles (shale-rich, grainstone-poor facies that grade upward into shale-poor, grainstone-rich facies).

Cincinnatian strata were deposited on a gently sloping, shallow-marine carbonate ramp. Sedimentation was episodic; periods of in-situ carbonate accumulation were frequently interrupted by storm events. Tropical storms affected sedimentation and benthic ecology in seven ways by: (1) eroding sediments; (2) transporting allochthonous clays and silts onto a carbonate ramp; (3) winnowing, transporting, and redistributing carbonate sediments; (4) generating downslope gravity flows; (5) mixing benthic fauna from different communities; (6) periodically interrupting the process of community succession; and (7) creating favorable conditions for the evolution and success of opportunistic species.

Because of the excellent preservation of episodic storm events and their influence on sedimentation and paleoecology, the Cincinnatian Series is recognized as an example of an ancient storm-dominated, carbonate ramp. The following characteristics are diagnostic of storm domination in the rock record: (1) abundant storm sequences occur in all facies; (2) storm sequences are variable; (3) inner shelf facies have thin, discontinuous bedding; (4) rudites dominate in inner shelf facies; (5) fine grainstones are concentrated in outer-shelf facies; (6) textural inversions are common; (7) carbonate rock types are widely variable; (8) storm-generated structures occur in all facies; (9) in-situ faunal communities are rare; and (10) most beds contain a mixture of fossil-preservational states.

TOBIN, RICK C., Amoco Production Co., Houston TX

Reservoir Development in Ellenburger Group of West Texas—a Diagenetic Jambalaya

Porosity and permeability in the Ellenburger Group of west Texas result from a complex interaction of early to late diagenetic processes. Porosity formation occurred in at least seven stages: (1) early marine phreatic calcite cementation, (2) fabric-selective (mixing-zone?) dolomitization, which created intercrystalline porosity, (3) episodic subaerial exposure and karstification, which created vuggy, cavern, solution-channel, moldic, fenestral, breccia, and fracture porosity, (4) mineralogy-selective meteoric phreatic or mixing-zone silicification, which preserved existing porosity by preventing further carbonate cementation, (5) deep-burial xenotopic dolomite recrystallization, which destroyed nearly all of the precursor intercrystalline porosity, (6) deep-burial dolomite, calcite, and anhydrite cementation of some vugs and fractures, and (7) late-stage tectonic fracturing, which created most of the reservoir permeability.

The Ellenburger Group consists of numerous vertically stacked subaerial exposure cycles 1-20 ft thick. Porosity within each cycle is laterally discontinuous and patchy. The complete cycle is composed of four zones (from top to bottom): (1) glauconitic shale, which is interpreted to be a paleosoil horizon, (2) brecciated dolomite, cherty dolomite, or chert, which formed from solution collapse, (3) nonbrecciated dolomite containing abundant dissolution-generated porosity, and (4) nonporous dolomite, which was largely unaffected by karstification. Zones 1 and 4 are nonporous with very low permeability; zones 2 and 3 have high porosity and permeability. The presence of subaerial exposure cycles throughout the Ellenburger Group has resulted in numerous vertical permeability barriers, which may be the cause of reservoir stratification in some fields.

TREVENA, A. S., and R. A. CLARK, Union Oil Science and Technology Division, Brea, CA

Diagenesis of Miocene Gas Sands in Pattani Basin, Gulf of Thailand

Diagenesis of early Miocene sandstones in the Pattani basin resulted in rapid cementation and degradation of reservoir quality with increasing depth of burial. These subquartzose sandstones provide an example of accelerated burial diagenesis in an area of unusually high geothermal gradient. Burial compaction, progressive cementation by quartz overgrowths, and development of authigenic kaolinite and illite have substantially reduced porosity and impaired permeability at depth. Abundance of quartz overgrowths increases with depth, indicating continuous or episodic silica cementation. Kaolinite occurs as a pore-filling cement between depths of 4,500 and 10,000 ft (1,375-3,050 m). Illite is common as pore-linings and also bridges pores in deeper zones (8,000-10,000 ft or 2,450-3,050 m). Minor cements include calcite, dolomite, siderite, pyrite, mixed-layer illite-smectite, and chlorite. Feldspars display textures that indicate progressive dissolution with increasing burial depth. Large intergranular pores are present in permeable sandstones between 3,000 and 7,500 ft (925-2,275 m). In low-permeability sandstones from deeper zones (7,500-10,000 ft or 2,275-3,050 m), porosity is largely restricted to voids within detrital feldspar grains. Many of these secondary pores are partly filled by authigenic kaolinite and illite, and their pore apertures are usually smaller (1-15 $\mu$m diameter) than intergranular pore apertures (10-75 $\mu$m diameter). Good reservoir properties in the Pattani basin are generally restricted to sandstones above 7,500 ft (2,275 m) that contain large intergranular pores. Abundant secondary porosity below 7,500 ft (2,275 m) is generally associated with poor reservoir properties; however, favorable reservoir properties may occur locally where large feldspars have been leached from coarse-grained sands.

TRUMBLY, NANCY I., and JOHN D. PIGOTT, Univ. Oklahoma, Norman, OK

Origin and Diagenesis of Beachrock, Discovery Bay, Jamaica

From in-situ pore water and rock analyses of a lithified Holocene beach deposit in Jamaica (1,240 ± 50 yr B. P. at 22 cm depth, 670 ± 50 yr B. P. at 14 cm depth, 0 yr B. P. at surface), we propose a geochemical model for intertidal carbonate cementation. The beachrock unit is laterally and vertically discontinuous with unconsolidated beach sands surrounding it. The unit dips seaward at an angle of 10° and contains localized open orthogonal fractures that are oriented parallel and normal to the shore line. Three distinct cement types are found in Jamaican beachrock: (1) equant and bladed high-Mg calcite (12-29 mole % $MgCO_3$), (2) low-strontium fibrous aragonite (1,700-3,100 ppm SrO), and (3) micritic high-Mg calcite envelopes. These cements vary both laterally and with depth in the unit, and accurately reflect the changes in time and space of the chemistry of the interstitial water; the cements are produced in stoichiometric equilibrium with the pore-water chemistry. The high-Mg calcite cements are precipitated when $CO_2$ degases ($P_{CO_2} = 10^{-5.1}$) through agitation in the surf and consequently raises the pH to a maximum of 8.4 during the higher tides. During these times, the pore waters are saturated with respect to the precipitating Mg calcite containing 15-29 mole % $MgCO_3$. During low tide, when the agitation of the surf is minimal, the $CO_2$ does not degas, increasing the $P_{CO_2}$ to a maximum of $10^{-4.0}$. Continued precipitation aids in the increase in $CO_2$ levels, the decrease in pH to a minimum of 7.9 and the lowering of saturation states of Mg calcites. Phreatic fresh water flows seaward during low tide, preferentially through the open fractures, lowering strontium levels and saturation states in the pore waters. Thus, at low tide, lower Mg calcites of 12-15 mole % $MgCO_3$ are precipitated where fresh water has not invaded (maximum Cl = 22‰). Models of Sr partitioning show low-strontium aragonite is produced from the neomorphism of high-Mg calcites near the open fractures in mixed meteoric and marine interstitial waters (Cl = 11.05-13.48‰). Our data suggest that $P_{CO_2}$ is the master variable and that beachrock cements are not static but ever-changing in mineralogy and chemistry.

TSUI, TIEN-FUNG, and CLIFTON F. JORDAN, Mobil Research and Development Corp., Dallas, TX

Fluid Inclusions and Porosity Development in Arun Gas Field, Indonesia

The Arun gas and condensate field in northern Sumatra is a large Miocene coral-algal reef complex. The Arun limestone is rich in lime mud throughout the section, and low to moderate-energy paleoenvironments are indicated. The reservoir facies are strongly affected by diagenesis and display several secondary porosity types, including moldic, vuggy, breccia, and fracture porosities. Without the diagenetic alteration of otherwise tight muddy limestones, reservoir facies would not have developed at Arun. To put constraints on the timing of porosity development in Arun field, fluid inclusions were examined in coarse calcite cements which partially or completely filled some of the secondary pores. The fluid within the inclusions is brackish with an equivalent of 2.5 wt. % NaCl.

Homogenization temperatures, after pressure correction, suggest that the cementation began close to the maximum burial depth and as recently as 5 Ma. Since the cement postdates the formation of secondary pores, it is conceivable that secondary porosity could have developed not only in the shallow subsurface (i. e., the vadose zone), but also in moderate to deep burial conditions. Shales surrounding the Arun reef are overpressured as a result of dewatering during smectite-illite conversion and have expelled water into the Arun limestone. This process may contribute to