bioturbated fossilferous wackestones and packstones; and pelmatozoan packstones and grainstones.

A complex diagenetic history has occluded virtually all primary porosity within the Viola. Petrographic evidence suggests that the following approximate sequence of diagenetic events has occurred; (1) microboring and subsequent micritization of bioclasts to form micrite envelopes; (2) very early submarine cementation that bound the loosely sorted allochems and partly occluded porosity, characterized by drusy overgrowths on trilobite and brachiopod fragments, bladed, void-filling cement, and turbid, inclusion-rich syntaxial overgrowths on pelmatozoan fragments; (3) initial compaction evidenced by local fracturing of elongate bioclasts; (4) neomorphism, including the inversion of aragonitic allochems to calcite and the recrystallization of micrite to microspar and pseudospar in the presence of low-salinity pore fluids; (5) freshwater cementation dominated by clear syntxial overgrowths on pelmatozoan fragments and pore-filling mosaic calcite that filled virtually all remaining pore space; (6) selective dolomitization; (7) silicification, including the formation of chert nodules and the replacement of bioclasts and calcite cements by microgranular quartz and/or lutecite; (8) compaction and pressure solution, probably due to deep burial, characterized by nonsutured seam stylolites, sutured seam stylolites oriented subparallel to bedding, and sutured grain boundaries; and (9) tectonically imposed pressure solution indicated by sutured seam stylolites oriented at high angles to bedding that developed during the late Paleozoic deformation of the Arbuckle Mountain.

The Viola Limestone is known as a reservoir rock and possible source unit for hydrocarbons throughout much of south-central Oklahoma. Thorough understanding of the nature and timing of diagenetic events is important for the further economic development of the Viola Limestone and other similar carbonate ramp deposits.

GRANTZ, ARTHUR, and STEVEN D. MAY, U.S. Geol. Survey, Menlo Park, CA

Geologic Framework and Petroleum Potential of United States Chukchi Shelf North of Point Hope, Alaska

A reconnaissance grid of 24-channel seismic-reflection data indicates that most of the United States Chukchi shelf north of Point Hope, Alaska, is prospective for petroleum. The prospective rocks, which consist of four stratigraphic sequences, rest on the Arctic platform, a regional erosional surface cut across mildly metamorphosed lower Paleozoic rocks in Late Devonian time. The Eo-Ellesmerian sequence, interpreted to contain mainly Mississippian nonmarine deposits, is 5+ km (16,500 ft) thick and fills local sags and faulted depressions in the Arctic platform. Mississippian to Neocomian stable shelf clastic and carbonate beds of the Ellesmerian sequence, 0 to 7.7+ km (25,000 ft) thick, underlie most of the shelf but are absent from Barrow arch and the outer shelf of the northeastern Chukchi Sea. Albian and Upper Cretaceous intradelta and prodelta deposits of the lower Brookian sequence, which thicken from 250 m (800 ft) on Barrow arch to 7.5+ km (24,500 ft) to the southwest, northwest, and north, underlie most of the shelf. The upper Brookian sequence, inferred to consist of marine and nonmarine clastic deposits of mainly or entirely Tertiary age, is 0 to 5.6+ km (18,500 ft) thick. It occurs only in Nuwuk and North Chukchi basins and locally as canyon fill beneath the central Chukchi shelf.

The northern Chukchi shelf contains seven provinces of contrasting tectonic origin and structural style. Nuwuk basin, a progradational clastic prism containing 12+ km (39,500 ft) of lower and upper Brookian strata and numerous growth faults, overlies a rifted margin of Neocomian age beneath the outer shelf and slope of the northeastern Chukchi Sea. North Chukchi basin, which underlies the outer shelf west of Nuwuk basin, contains Ellesmerian beds and 12+ km (39,500 ft) of lower and upper Brookian strata. It may also overlie a Neocomian rifted margin, but was deepened by Laramide extensional rifting. South of these basins, shelf structure is controlled by the geometry of the Arctic platform, which slopes gently southwest from a depth of 0.25 km (800 ft) on Barrow arch to about 13 km (42,650 ft) off Point Lay. In the central part of the shelf, the platform is somewhat faulted and folded and descends to a depth of 10+ km (33,000 ft) to form the north-trending Hanna trough. West of the trough the platform rises to within 1 km (3,300 ft) of the seabed and is broken by numerous normal faults. The southern part of the platform contains a thick lower Brookian section with numerous northwest-striking, northeast-verging detachment folds. The fold province is bounded on the southwest, off Cape Lisburne, by the northwest-striking Herald arch overthrust belt at which one or more southwestward-dipping thrusts brought Ellesmerian and older strata to the seabed.

The seismic and extrapolated onshore data suggest that Nuwuk and North Chukchi basins, Hanna trough, and the Arctic platform east and west of the trough could contain significant deposits of oil or gas. The potential of the fold belt, however, is modest, and of Herald arch slight. Small areas on Barrow arch and the Arctic platform west of Hanna trough lack potential because they are underlain by less than 1 km (3,300 ft) of prospective section.

GREGG, WILLIAM J., Michigan Technological Univ., Houghton, MI, and T. H. MROZ, Morgantown Energy Technology Center, U.S. Dept. Energy, Morgantown, WV

Mechanical Factors Affecting Stimulation Design in Devonian Gas Shale

Oriented core samples from 23 Devonian gas shale wells in the Appalachian basin were used to determine microscopic and mesoscopic fracture patterns. The specific objectives were to note the preferred direction and nature of natural microcracks, to determine the preferred fracture propagation direction in laboratory mechanical testing, and to outline areas in the basin that are characterized by a high natural fracture density in the gas shales. This information provides a necessary background for the development of the in-situ stimulation technology which would most effectively connect natural fracture systems to a single well bore.

Mechanical tests under zero confining pressure conditions included point load, indirect tensile, laboratory hydrofracturing, and directional ultrasonic testing. Natural fractures were measured prior to testing. The preferred orientation of both induced and natural fractures throughout the basin was generally parallel to the trend of Paleozoic tectonic structure. This parallelism, as well as the details of the microfabric, suggests an "incipient cleavage" origin for the natural crack arrays. It thus appears that the residual effects of in-situ stresses do not influence the orientation of the induced fractures in laboratory tests. Tests under zero confining pressure are therefore not useful for determining the orientation of $\sigma_{Hmax}$ as other workers have previously suggested, nor is the orientation of the fractures produced in these tests necessarily the same as that of an induced hydrofracture in the field.

The trajectory maps for in-situ stresses in the basin clearly illustrate the lack of parallelism with the mechanical fabric of the shale. However, analysis of the two patterns has been used to outline local areas in the basin where $\sigma_{Hmax}$ is parallel to the natural microcrack system. In these areas the natural crack array would be oriented so as to facilitate induced crack propagation.

Combined with an analysis of hydrocarbon potential and the location of detachment zones related to basement deformation, these relationships offer a useful rationale for targeting areas for future unconventional gas recovery programs. In addition they provide a framework for understanding the behavior of the rock mass in response to hydrofracture stimulation in less promising areas of the basin.

GREGORY, A. R., and R. A. MORTON*, Bur. of Econ. Geology, Austin, TX

Enhanced Gas Recovery From Watered-Out Reservoirs

Major additions to future gas reserves will depend partly on development of resources that are presently unconventional. Recently, coproduction of gas and water has been proposed as a method to increase ultimate gas recovery from reservoirs that have begun to water out or were abandoned because of high water production. The enhanced recovery method involves producing large volumes of water and reducing reservoir pressure to the point where dispersed gas, trapped in the water-invaded zone, is mobilized and flows to the well bore. Research involving the coproduction method was funded by the Gas Research Institute.

Integration of geological and engineering studies indicates that the Port Arthur field in Jefferson County, Texas, is a prime area for research to test the coproduction techniques. Prior to abandonment, the field produced from lower Hackberry (Oligocene) sandstones at depths less than 12,000 ft (3,600 m). The field contains 11 reservoirs with a maximum net sandstone thickness of over 450 ft (135 m). Individual sandstones are 10 to 120 ft (3 to 36 m) thick, but gas columns are usually less than 20 ft (6 m) thick. The reservoirs are relatively narrow and elongate and are oriented nearly perpendicular to the local structure, a simple rollover anticline. These reservoirs, interpreted as submarine channel and fan deposits, are internally heterogeneous owing to the vertical imbrication and dip-alignment of the sand lenses. Optimum reservoir facies occur as thick, massive sandstones with uniformly high porosities and permeabilities that average 28% and 60 md, respectively. Reservoir quality is more variable and diminishes somewhat away from the channel axes in the more thinly bedded sandstones with intercalated shales. Upward decreases in porosity and permeability characterize the zones of gas accumulation.

The "C" sandstone was selected for detailed investigation because of high abandonment pressure, excellent reservoir quality, high productivity, and good lateral continuity. Reservoir simulation studies suggest that 5.5 bcf of gas and some condensate could be recovered from the "C" sandstone under natural flow conditions by producing slightly more than 9 million bbl of water over a 5-year period. Brine disposal would be accomplished by injection into thick Miocene sandstones that occur at shallow depths. If successful, the recovery efficiency of the "C" sandstone would be increased from 42% (primary) to 53% of the original gas in place.

An economic analysis of the enhanced recovery project indicates a favorable payout under prevailing gas prices. Project economics are even more attractive if gas prices increase or if gas production from other abandoned reservoirs is commingled with production from the "C" sandstone.

GROTZINGER, J. P., Virginia Polytechnic Inst. and State Univ., Blacksburg, VA, and P. F. HOFFMAN, Geol. Survey of Canada, Ottawa, Ontario, Canada

Quantitative Paleobathymetry of Early Proterozoic (1.9 B.Y.) Continental Slope, Rocknest Formation, Wopmay Orogen, N.W.T., Canada

The Rocknest Formation is an early Proterozoic (1.9 b.y.) westward-facing, rimmed carbonate shelf that evolved from a ramp developed on quartzites of the underlying Odjick Formation. Shelf interior facies are cyclic peritidal dolomites; shelf edge facies are reefal stromatolitic boundstones and intraclast/ooid grainstones, and slope facies are turbidites, slope breccias, and shelf edge breccias. The carbonates are overlain by black shales and graywackes of the Recluse Group.

Facies that represent the shelf edge-to-slope transition of the Rocknest Formation are well exposed for almost 200 km (125 mi) along the strike length of the major north-south trending syncline. At the southern end of the syncline, the Rocknest Formation comprises 230 m (755 ft) of slope deposits on the west limb and 660 m (2,165 ft) of shelf edge deposits on the east limb. The difference in the decompacted thickness of the Recluse Group on both sides of the syncline, as measured from the top of the Rocknest Formation to a marker bed in the Recluse, is 590 m (1,935 ft), which represents the total paleobathymetric relief. However, the difference in thickness of the Rocknest Formation, 430 m (1,410 ft), is less than the total paleobathymetric relief, which indicates that most, but not all of the total paleobathymetric relief was produced by constructional aggradation of the shelf edge. The remaining relief, 160 m (525 ft), was inherited from a preexisting slope at the top of the Odjick Formation and therefore represents the initial relief of the Rocknest slope.

Average inclinations of the Rocknest slope can be calculated given the distance between sections (approximately 4,500 m, 15,000 ft). The initial average inclination of the slope is 2°, and the final average inclination of the slope is 7°.

The sedimentologic and stratigraphic evidence strongly suggests a depositional model involving a ramp that evolves into a steep, marginal escarpment passing seaward into a shallow-dipping slope. As such, the geomorphic development of the Rocknest slope is considered to be analogous to the slopes of many Phanerozoic rimmed shelves, implying that similar evolutionary processes were operative during the early Proterozoic.