LUCAS, MARK, WARREN MANSPEIZER, and JOSEPH HULL, Rutgers Univ., Newark, NJ

En Echelon Folds: A Case History from Jacksonwald Syncline of Foreland Folds in Newark Rift Basins of Eastern North America

The Jacksonwald syncline of the Newark rift basin, like other en echelon folds in both the onshore and offshore Triassic-Jurassic basins, has characteristics typically found in foreland fold and thrust belts. The syncline, comprising Carnian to Sinemurian strata, is a shallow plunging synform (15° toward N55°W) with an axial surface dipping 83° toward S35°W. The fold has a subangular hinge with straight planar limbs, typical of buckle folds. Axial planar, spaced solution cleavage is well developed in siltstones. Although early clastic dikes in the border fanglomerates are rotated, the cleavage is unfanned and maintains a constant orientation. Quartz and calcite, dissolved along cleavage seams, were precipitated in extensional veins oriented perpendicular to the fold axis and to elongate mud cracks.

Conjugate shear fractures near the postulated border fault strike N79°W and N5°W, and show sinistral and dextral slip, respectively. Displacement along these shears indicates that sinistral slip is 5 times greater than dextral. Along the basin margin, tectonic layer-parallel shortening by pressure solution exceeds compaction shortening by 2:1. The fold is intruded by an undeformed Sinemurian diabase dike of Rossville composition, parallel to the extension veins.

The data show a consistent strain pattern, from the Upper Triassic through the Lower Jurassic, of northeast shortening and northwest extension, and suggest that en echelon folds formed along an east-trending sinistral shear couple. This stress field is consistent with dextral oblique slip along the Flemington fault, observed by Burton and Ratcliffe.

LUTZ, CHARLES T., and NICHOLAS B. WOODWARD, Univ. Tennessee, Knoxville, TN

Structural Complexity Associated with Transfer Zone: An Example from Southern Appalachians

Transfer zones provide a mechanism by which displacement is maintained across a fold and thrust belt where a single thrust terminates along strike. Commonly, the transfer is not simply a "lap joint" wherein en echelon thrusts, tied to a common sole fault, shift displacement; rather, these zones are structurally complex with intensified folding, fracturing, and, in some instances, cleavage. An example occurs in the Valley and Ridge of eastern Tennessee, northeast of Knoxville. There, the Beaver Valley thrust terminates into folded Middle Ordovician carbonates. To the southeast, the adjacent Saltville thrust increases in stratigraphic separation, coinciding with the Beaver Valley termination. The Saltville places Lower Cambrian strata on Mississippian units northeast of the fault termination, whereas the Lower Cambrian rests on Cambrian-Ordovician rocks only 20 km to the southwest.

Near its tip, the Beaver Valley thrust shows little displacement, but the loss of slip is accompanied by intensified folding. The folding traces an anticlinorium involving Middle and Upper Ordovician carbonates and shales. These folded rocks are broken by fractures and extensional veins, commonly filled with sparry twinned calcite, and ranging from 0.2 to 2.0 mm wide. One set of veins is generally normal to bedding with a second set oblique; in some cases, three sets cut the rock. Also, Middle Ordovician carbonates carry an axial planar solution cleavage, and catacalcites are locally developed, particularly in dolostones of the Cambrian-Ordovician Knox Group. A set of folds, the axes of which are oblique to transport direction, occurs across the transfer zone; they are often found in the footwall of a thrust.

The complex structural geometries in these thrust sheets suggest contradictory timing relationships. The contradiction is explained if the two faults are envisioned as propagating from initial breaks, then growing toward one another contemporaneously. This example demonstrates the potential complexity of a transfer zone, as well as the possibility of apparent local variation in fault sequence in a generally hinterland to foreland progression of emplacement.

LUTZ, RICHARD D., and RAMESH VENKATAKRISHNAN, Old Dominion Univ., Norfolk, VA

Lineaments in Richmond Triassic Basin Area, Virginia: A Kinematic Model

A lineament study from various sources was conducted to develop a conceptual kinematic model for the Richmond Triassic basin area in Virginia. The procedure involved mapping at different scales: color infrared U-2 photos (1:130,000), Landsat MSS images (1:1,000,000), and rectified drainage maps (1:250,000). The lineaments were digitized and subjected to a correlation package that compared the statistically significant peaks (>95%) and troughs (<5%) within 5 km^2 grid cells. Spatially filtered significant 10° trends were contoured according to length-weighted frequencies to obtain lineament zones. These lineament zones were compared to mapped structures, outcrop patterns, Triassic diabase dikes, and aeromagnetic alignments and gradients.

Correlations of lineament zones with mapped structures and geophysical gradients strongly support the interpretation that they represent the surface expressions of boundaries of subsurface structural domains. The basin is bounded on the west by the northeast-trending Hylas fault zone, and the eastern margin is cut by 60°-70° northeast-trending lineament zones that segment the basin into discrete blocks. Numerous ± 15° north-trending lineaments correlate remarkably well with the north-trending diabase dikes, yet none of the mapped dikes apparently cut across the basin margins as other Triassic basins do in Virginia and elsewhere.

Detailed analysis of lineament patterns appears to indicate left-handed strike-slip movement along the Hylas fault. At this time, the dikes intruded the basin, but were refracted into the fault zones despite pervasive north-trending fractures. Present-day expression of lineaments is probably due to Cenozoic reactivation of preexisting fractures.

The kinematic model postulated here is entirely compatible with existing models for Mesozoic tectonism in the Virginia coastal plain.

LYONS, PAUL C., WILLIAM F. OUTERBRIDGE, and M. DEVEREUX CARTER, U.S. Geol. Survey, Reston, VA

Correlations of Coal Beds near Allegheny-Conemaugh Contact in Tri-State Area of Ohio, Kentucky, and West Virginia

The top of the Upper Freeport coal bed marks the contact between the Allegheny Formation (Middle Pennsylvanian) and the Conemaugh Formation (Upper Pennsylvanian) at their type area in western Pennsylvania. The position of the Upper Freeport is uncertain in the tri-state area of Ohio, Kentucky, and West Virginia because of lack of continuity and apparent miscorrelations of coal beds. Our stratigraphic analysis of coal-bed correlations with respect to our identification of the Brush Creek Limestone Member, the lowest marine member of the Conemaugh Formation, indicates probable miscorrelations of coal beds by previous workers in this area. In Lawrence County, Ohio, Condit identified the Mahoning coal bed as 46 ft below the Brush Creek Limestone and 24 ft above the Upper Freeport coal bed. Northward along the Ohio River in southeastern Ohio, the Brush Creek Limestone–Mahoning interval is about 30 ft. Wanless correlated the Princess 9 coal bed of Kentucky with the Upper Freeport of Ohio and Pennsylvania. Huddle et al indicated that in eastern Kentucky the Princess 9 is in the Conemaugh Formation, about 45 ft below the Cambridge Limestone Member (correlated with the Brush Creek Limestone Member) and about 35 ft above the Upper Freeport. Thus, the Mahoning coal bed of Ohio appears to correlate with three units in eastern Kentucky—the Princess 9 of Huddle et al, the uppermost Princess 9 of Connor and Flores, and the Brush Creek coal bed of Sharps—and with the Brush Creek coal bed in parts of the adjoining areas of West Virginia. This stratigraphic analysis indicates that the true Brush Creek Limestone–Upper Freeport interval is about 70-110 ft in the tri-state area, which is consistent with the same stratigraphic interval to the north.

MAKI, MARK U., and ALAN H. COOGAN, Kent State Univ., Kent, OH

Subsurface Stratigraphy and Structure of Sauk Sequence of Northern Ohio

The lower Paleozoic Sauk sequence of northern Ohio represents a carbonate and clastic sedimentary sequence deposited during the late Late

Cambrian Saint Croixan and early Early Ordovician Canadian. It is bounded below by the unconformity on the Precambrian basement and above by the Knox unconformity. The Sauk sequence was deposited throughout the study area of northern Ohio, which includes the western portion of the Appalachian basin, the Ohio-Indiana platform to the west, and the southernmost portion of the Michigan basin northwest of the Ohio-Indiana platform. The major lithostratigraphic units, all in the subsurface, are the Cambrian Mount Simon Sandstone, Shady Dolomite, Eau Clair Formation, Rome Formation, Conasauga Formation, and Kerbel Formation, and the Cambrian-Ordovician Knox Group.

Stratigraphic interpretations generally show that the Sauk sequence begins with clastic deposition occurring in the north-central and western portions of Ohio and predominantly carbonate and open-marine clastic deposition occurring in eastern and south-central Ohio. The location of the present Cincinnati arch marks a transition zone between the two sedimentary regimes. The final stage of Sauk sequence deposition was marked by a major marine transgression that resulted in deposition of the Knox Dolomite over the entire study area.

Producing reservoirs occur in four stratigraphic-structural settings. The Copper Ridge Dolomite (Knox Group) on the eastern edge of the Ohio-Indiana platform has oil production from glauconitic sandstone reservoirs.

Basinward, the Cambrian dolomitic Rose Run Sandstone Member occurs at the top of the Copper Ridge Dolomite. Mainly gas has been discovered in the Rose Run in secondary reservoirs formed during erosion of the Knox unconformity. Middle Ordovician shales and impermeable limestones are the seals.

The majority of hydrocarbon production from the Knox Dolomite is located in central Ohio's Morrow County where erosional remnants of vuggy dolomite on the Knox unconformity form paleotopographic highs with Middle Ordovician shale as the seal. Other small pools consist of vuggy dolomite reservoirs with small structural closures.

Although no significant amounts of hydrocarbons have been discovered below the Copper Ridge Dolomite, high porosities and permeabilities in the Mount Simon Sandstone and Eau Claire Formation lend potential to these rocks for liquid waste disposal.

MARTIN, ANTHONY J., WAYNE D. MARTIN, and JOHN K. POPE, Miami Univ., Oxford, OH

Genesis of Phosphatic Sediments in Cincinnatian Series (Upper Ordovician), Southeastern Indiana and Southwestern Ohio

Few workers have considered the origin of lower Paleozoic phosphate-rich strata, especially in the light of recently proposed phosphorite depositional models. Selected samples of limestones and shales from the Cincinnatian Series have been examined to determine the environmental factors contributing to the accumulation of phosphatic sediments.

The conditions of phosphate accumulation have been interpreted from a detailed description of the stratigraphic sequence, sedimentary structures, textures, and fossil content of each locality. Microfacies analysis of the limestones revealed that phosphate is largely confined to intragranular pores of bioclasts (echinoderm debris, juvenile mollusks, bryozoan zooecia). The phosphatized bioclasts are concentrated as basal lag deposits above discontinuity surfaces, as starved ripples within shale beds, and as burrow infillings. The zones of phosphatic concentration directly overlie bioclastic wackestones.

The original phosphatization process probably occurred within the sediments that formed the bioclastic wackestones. The ichnofossils (and, in part, the body fossils) indicate that there was a low rate of sedimentation, high organic input, high initial water content ($> 50\%$), normal oxygen concentrations, and pervasive bioturbation of a muddy substrate. The confining microenvironments necessary for the reducing conditions of phosphate precipitation were the intragranular pores of bioclasts, such as bryozoans, filled with organic-rich muds. Early diagenesis of phosphate took place within the pores, and these relatively denser allochems were subsequently winnowed from the unconsolidated muddy substrate by episodic high-energy events. The resultant deposits were phosphatic sands that also underwent biogenic disturbance and further physical redeposition.

MARTIN, D. W., A. H. COOGAN, R. SHADRACH, B. A. URIAN, and A. WIECKOWSKI, Kent State Univ., Kent, OH

Depositional Trends of Clinton Section in East-Central Ohio

The Lower Silurian Clinton section in east-central Ohio is a clastic wedge of sandstones, shales, and carbonates. Previous studies have shown that the Clinton section was deposited as a delta prograding westward over reworked clastics of the Ordovician Queenston Shale.

Geophysical log data were used to construct total Clinton sandstone and sandstone cleanliness maps of the delta margin. Clean-sand maps show the distribution of sand and shale in an offshore bar system in west-central Holmes County. Similar studies in adjoining counties indicate an extension of this bar system, which coincides with the Newburg pool in southern Medina County. Stratigraphic cross sections show the intertonguing relationship of sand, shale, and carbonate lithosomes typical of a deltaic system. The clastics of the upper Cabot Head grade westward into calcareous sands and thickening carbonates. Slice maps show the distribution of these deposits during time.

Production of oil and gas in Holmes County has been concentrated along the north-trending thick sands of the delta-margin bar system. Sand isopach maps, cross sections, and a porosity foot map show the distribution of thinner fluvial and fluvial delta-margin sands in western Holmes County.

MATTHEWS, R. DAVID, Inst. of Gas Technology, Chicago, IL

Relationship of Fracture-Induced Gas Reservoirs to Stratigraphic Controls in Eastern Devonian Shales

A new exploration method is advanced based on the hypothesis that some fractured shale reservoirs are related to a stratigraphic-type trapping mechanism at lithofacies boundaries where gray shales grade laterally into dark, radioactive shales having different physical and chemical characteristics. Hydrocarbons are postulated to move through these indurated, fine-grained shales as they do during late primary migration. Whatever mechanisms are operating at shale lithofacies, facies changes are systematic depositional events that can be mapped using conventional subsurface geologic methods. Shale gas fields associated with the mapped position of shale facies changes are found in all three eastern basins.

Gas occurrences from 139 wells were projected into a stratigraphic test section in Kentucky and West Virginia. Several facies changes and 232 gas occurrences are documented; they show a trend of gas occurrences near shale facies changes. For example, the middle Huron, more than 200 ft (61 m) thick, changes from 88% black to 2% within 17.2 mi (28 km); 87% of reported gas in the unit occurs in that same distance. Of 66 major shows or increases (> 100 mcf or 2,830 m^3) in the Ohio Shale, 88% fall within the 17.2 mi (28 km) in which the total unit changes from 86% black to 16%.

Facies changes appear to define trends of shale gas potential within specific beds; thus, a new element has been added to shale gas exploration methodology. The methods developed can be used to test the applicability of the hypothesis to the eastern basins.

MAXWELL, TIMOTHY C., and RICHARD SMOSNA, West Virginia Univ., Morgantown, WV

Sedimentology, Diagenesis, and Porosity Development of Middle Silurian Lockport Dolomite, Johnson County, Kentucky

A complete core of the Lockport Dolomite reveals the presence of five distinct lithofacies. Proceeding upsection from the underlying littoral Keefer Sandstone, these units are: (1) extensively burrowed and sparsely fossiliferous mudstone-wackestone (initial transgression); (2) thinly bedded, crinoidal packstone-grainstone (open shelf); (3) stromatoporoid-coral-crinoidal packstone (open shelf); (4) oolitic-peloidal packstone-grainstone (shoal); and (5) finely laminated mudstone (tidal flat). The middle to upper sections reflect a shoaling-upward sequence that grades into the overlying Salina Formation sabkha sediments.

Original rock textures have been veiled for the most part by dolomitization. Petrographic analysis indicates that dolomite occurs in two forms: (1) as a fine to medium crystalline replacement mineral, and (2) as a coarse crystalline cement (including saddle dolomite) filling vugs and fractures. The first variety is eogenetic, having formed primarily as a result of freshwater/seawater mixing during occasional subaerial exposure of sediments. The coarser dolomite is of late (mesogenetic) origin.

Historically, the Lockport has been an important oil and gas producer in eastern Kentucky. Secondary porosity development is significant and