tion, and decline curves each characterized by fitting to a sum of up to three exponential decay curves (adjusting for those wells in which a later cleanup occurred), are also interpolated onto the grid.

We are then using contingency tables to study the degree of correlation between different geologic and flow parameters. For example, final open flows show a much higher correlation with structure or with its curvature along the major fracture trend than they do with the slope of the structure normal to the fracture trend.

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Petrology and Depositional Environments of Boyle Dolomite (Middle Devonian) in East-Central Kentucky

The Middle Devonian Boyle Dolomite is a sequence of dolomite, dolomitic limestone, limestone, chert, and shale which has been deposited on a regional unconformity that truncates successively older units toward the axis of the Cincinnati arch. The Boyle varies in thickness (0 to 11 m) and crops out in a 40-km-wide, northeast-trending, arcuate belt on the eastern margin of the Blue Grass region.

The Boyle Dolomite is divided into the following four lithofacies: Kiddville, Winston (Boyle limestone), Casey, and Duffin. The basal Kiddville is a quartzose dolomicstone with abundant fish remains and represents the slow accumulation of a lag deposit in a platform environment. The Winston (Boyle limestone) is a crinoidal grainstone-packstone and indicates a full marine transgression with high-energy winnowing action on the shelf. The Casey is a cherty dolomicstone with a sparse fauna and represents continued transgression of carbonate mud environments. The Duffin is an interbedded dolomicstone and shale with an abundant and diverse trace-fossil assemblage and marks the transition between carbonate and clastic deposition in Middle to Late Devonian time.

An upward decrease in fossil abundance, diversity, and detrital clastics corresponds to an increase in the percentage of dolomite. Iron substitution in the dolomite crystal lattice increases upward and suggests an influence of reducing diagenetic environments. Trace-fossil analysis reveals a shelf to slope assemblage in the Boyle.

The Boyle Dolomite represents the marine transgression in the western margin of the basin during Middle Devonian time. The transition between open-marine carbonate and anoxic black shale is a shelf to slope carbonate mud with a predominant infaunal assemblage.

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Hydrothermal and Uplift Histories of Northern Appalachian Basin

Geochemical and structural analysis techniques were integrated in an investigation of epigenetic mineralization on fault zones to develop an evolutionary model for the post-Paleozoic history of the northern Appalachian basin. Analysis of faults in outcrop, excavations, and oriented drill cores revealed the occurrence of strike-slip and dip-slip faults which are representative of a fabric which is persistent in style, orientation, and magnitude across New York State. The elements of this fabric do not decrease in frequency with distance from the Allegheny structural front nor do they fan around the centers of deformation as do the Allegheny structures. Indeed the west-northwest trends of the normal faults and the acute bisectrix of the conjugate strike-slip faults are parallel with the short axis of the Appalachian basin. Their formation is attributed to the stresses produced during the asymmetric uplift of the basin in post-Paleozoic time.

Mississippi Valley-type epigenetic mineralization was deposited along these fault zones where they served as the dominant channels for circulating fluids within the well-cemented sandstones. Homogenization of fluid inclusions in vein minerals revealed an intermittent range of depositional temperatures from that typical of the peak of diagenesis in deep sediments, 170°C, to as low as 70°C. The higher temperatures may reflect waning of an elevated heat-flow regime produced by dehydration during diagenesis. The temperatures between 112 and 70°C are attributed to cooling during uplift.

Strike-slip faulting was initiated at temperatures near 170°C as indicated by syntectonic deposition of high-temperature calcite. Normal faulting did not occur until the hydrothermal brines had cooled to 112°C. Minor deformation and entrapment of secondary fluid inclusions continued to 70°C. The timing of tectonic events can be estimated by several techniques which generally indicate a late Paleozoic to early Mesozoic age for strike-slip faulting and a late Mesozoic to Cenozoic age for normal faulting.

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Patterns of Species Diversity in Helderberg Group of West Virginia and Virginia

Twenty-five outcrops of the Lower Devonian Helderberg Group in West Virginia and Virginia were analyzed for stratigraphic, petrographic, and paleontologic variations to interpret depositional environments. Fossil counts, by species, were made along 260 line-transects of standard sampling lengths in 14 of the 25 outcrops.

The stratigraphic study suggests that Helderberg sediments were deposited in the Virginias during an overall Early Devonian transgressive phase of deposition, and that formations comprising the Helderberg Group in the study area are rock-stratigraphic rather than time-stratigraphic units.

Thirty-three interspecific fossil associations involving 10 of 34 species of New Scotland invertebrate macrofossils were identified using a chi-square test for independence. Species showing significant associations were grouped into a primary recurrent group and a related secondary recurrent group by the Fager method. There is a direct relation between the number of interspecifically associated strophomenids in a sample and the percentage of fine-grained sediment.

An index of species diversity was calculated for each outcrop using the Fisher, Corbert, and Williams loga-

rithmic series equation, d = (s-1)/1nN where S is the number of species showing significant associations and N is the number of individuals. A species diversity map constructed by contouring the computed indices of diversity reveals that at least three fossil communities existed in the Helderbergian sea throughout the study area. The boundaries of these communities are undulatory and subparallel with the axis of the Appalachian basin. Areas with lower species diversity are interpreted as deeper water environments.

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Petrologic Evaluation of Significance of Natural Fractures in Low-Porosity Shale Gas Reservoirs—Results of Investigation in Upper Devonian of Virginia and West Virginia

Economic production of gas from the Devonian shales of the Appalachian basin is dependent on the presence of natural or induced fracturing. Investigation of natural fractures in five cored wells of varying productivity, located in areas of regional fracturing and not crestally located on folds, indicates that fracture frequency alone is not the sole control of well productivity. A one-to-one relation between natural fractures seen in the core and gas shows indicated by temperature and sibilation logs is not present. This is attributed to degrees of permeability enhancement by different fracture types and the presence of favorable shale lithotypes for recharging the fracture system. No system of abundant microfractures was documented after petrographic study of nearly 400 shale samples by radiography, thin section, and SEM. Thus, only macroscopic fractures are of importance.

Horizontal to subvertical slickensided fractures, even with frequencies of 2 to 3 per ft, are not associated with gas shows in organic-rich, laminated shales. Examination of their surfaces by SEM at 30,000× shows complete obliteration of grain-to-grain boundaries and a uniform, glassy surface of low permeability. Stimulation by hydraulic fracturing of a well dominated by slickensided fractures resulted in production equal to that of a well (same formation thickness and porosity) that possessed only one fracture (slickensided). Presence of slickensided fractures does not greatly influence open flow or final flow after fracturing of a shale reservoir.

High-angle vertical fractures, associated with higher gas productivity, retain some openness and permeability in the subsurface due to mineralization and slight movement between fracture surfaces characterized by coarse twist hackles. Mineral-filled fractures, commonly 1 to 2 mm in width, were seen in thin section to be tightly mineralized by dolomite with little intercrystalline porosity. SEM observation reveals that many seemingly unmineralized fracture surfaces have minor mineralization. Tightly and partially mineralized vertical fractures in nonproductive portions of the shale sequence were associated with organic-poor, nonlaminated shales which have less potential for recharging the meager fracture porosity present.

The most productive well, final open flow of 1,007 MCFGD, possessed high-angle vertical fractures in its pay zone of organic-rich, laminated shale. These fractures have coarse twist hackles which show evidence of later vertical movement. Slight offsetting along these hackles opened widths up to 28 mm. This well is not located near photolineaments. Vertical fractures with no mineralization or indication of offsetting along hackles are interpreted as being closed at depth and do not contribute to shale productivity.

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Upper Niagaran and Lower Cayugan Stratigraphy and Depositional Environments of Central Appalachian Basin

Data from geophysical logs and sample descriptions of 677 wells were used to prepare nine cross sections and 38 maps that illustrate upper Niagaran and lower Cayugan stratigraphic relations and environmental constructions within the central Appalachian basin of New York, Pennsylvania, West Virginia, Ohio, Maryland, and Ontario. Ten basin-wide stratigraphic intervals (genetic sequences of strata) were correlated and mapped on the basis of interpreted time-stratigraphic markers. Fourteen lithofacies, which are repeated in several of these intervals, were recognized in the subsurface on the basis of characteristic radioactivity-log patterns supplemented with sample descriptions. Four of the lithofacies occur in dolomite, either with or without sulfates, three in limestones and shales, and two each in halite and sandstone.

Stratigraphic and lithofacies analysis reveals that the Lockport Formation in the northern and western parts of the basin is a rock-stratigraphic unit consisting of reefal, shallow-water, and carbonate tidal-flat facies that undergoes a complete gradation eastward into transitional marine and continental clastics within the first five intervals of the study. The remaining intervals were dominated by restricted evaporite basins, carbonate mud flats, and carbonate-sulfate mud flats (sabkhas) over the northern and western parts of the basin, whereas less restricted shallow-marine to intertidal environments were present in the southeast.

Detailed correlations indicate several inconsistencies in past correlations of Upper Silurian strata, most notably the miscorrelation of the Williamsport and Newburg sandstones that has resulted in considerable confusion in nomenclature and correlation in the Silurian of West Virginia.

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Recovery of Energy from Michigan Antrim Shale by In-Situ Process

A 12-member team at Dow Chemical Co. has completed 3 years of a 4-year, $14 million contract with DOE to assess the feasibility of recovering energy from Antrim oil shale. The contract has four specifically identified tasks: (1) shale characterization; (2) in-situ fracturing and assessment; (3) in-situ extraction trials; and (4) environmental, public policy, and legal assess-