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APPLICATION OF DISCRETE FRACTURE NETWORK MODELS TO COALBED METHANE RESERVOIRS OF THE BLACK WARRIOR BASIN

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Abstract

Natural fracture systems in the upper Pottsville Formation of Alabama can be characterized by statistical scaling rules that facilitate the construction of discrete fracture network (DFN) models. DFN models are 3-D virtual realizations of fracture systems that provide a basis for compartmentalization analysis and flow modeling. The DFN models indicate that the upper Pottsville is a heterogeneous, compartmentalized hydrologic system. These models help explain the variable performance of coalbed methane wells and indicate that the likelihood of significant hydraulic communication between reservoir coal beds and shallow aquifers is minimal.

Introduction

Alabama ranks second nationally in cumulative coalbed methane production, but that production has been threatened by legal action related to alleged contamination of groundwater by hydraulic fracturing. In 1997, the 11th U.S. Circuit Court of Appeals in Atlanta, Georgia, ruled in favor of the Legal Environmental Assistance Foundation (LEAF) that hydraulic fracturing in coalbed methane wells is an underground injection procedure. Evidence for contamination of shallow aquifers is anecdotal, and indeed, few data exist that can be used to assess the impact of coalbed methane operations on domestic groundwater supplies.

A concern that is central to contamination issues is the degree to which flow is confined within coal beds of the upper Pottsville Formation (Lower Pennsylvanian) in the Alabama coalbed methane fields. Within the coalbed methane fields, upper Pottsville strata have effectively no matrix permeability to water, and virtually all flow of water is through natural fractures (Pashin et al., 1991; Pashin and Hinkle, 1997). Closely spaced cleats give coal the best aquifer and reservoir properties of any rock type in the upper Pottsville, and between coal beds, flow is restricted primarily to joints and fault-related shear fractures. Observations of fracture systems in core and outcrop can be extrapolated statistically to simulate regional fracture systems, and compartmentalization and flow can be modeled using discrete fracture network (DFN) software technology (e.g., Smith and Schwartz, 1984; Dershowitz and Einstein, 1988; National Research Council, 1996).

DFN technology has yet to be applied to coalbed methane reservoirs but is a promising approach that can be used to quantify and model the degree of interconnection between coalbed methane reservoirs and shallow supplies of domestic groundwater. In this paper, we present DFN models of natural fracture systems in the Pottsville Formation and use compartmentalization analysis to characterize the degree of hydraulic interconnection between reservoir coal beds and shallow aquifers. This paper summarizes part of a research project that is sponsored by the U.S. Environmental Protection Agency and is designed to assess risks that coalbed methane operations may pose to shallow groundwater resources.

Methods

DFN models are three-dimensional stochastic realizations of fracture architecture that incorporate statistical scaling rules derived from field and laboratory analysis (Dershowitz, 1984; Smith and Schwartz, 1984). DFN models are predicated on the assumption that fracture architecture and fluid flow can be predicted from statistical scaling rules. These scaling rules can further be used to generate virtual realizations of fracture networks in which fractures are given attributes as the conductive elements in compartmentalization and flow models.

The data required to develop DFN models include information on the stratigraphy of the host strata and the orientation, spacing, height, aperture, and cross-cutting relationships of the fractures contained therein. A well in Blue Creek Field, where the complaint resulting in the LEAF case originated, provided the basis for a stratigraphic model (figs. 1, 2). Data on the statistical properties of natural fractures in the Pottsville Formation were collected from nearby outcrops and from five cores from Brookwood Field that were donated by Jim Walter Resources, Incorporated (fig. 1).

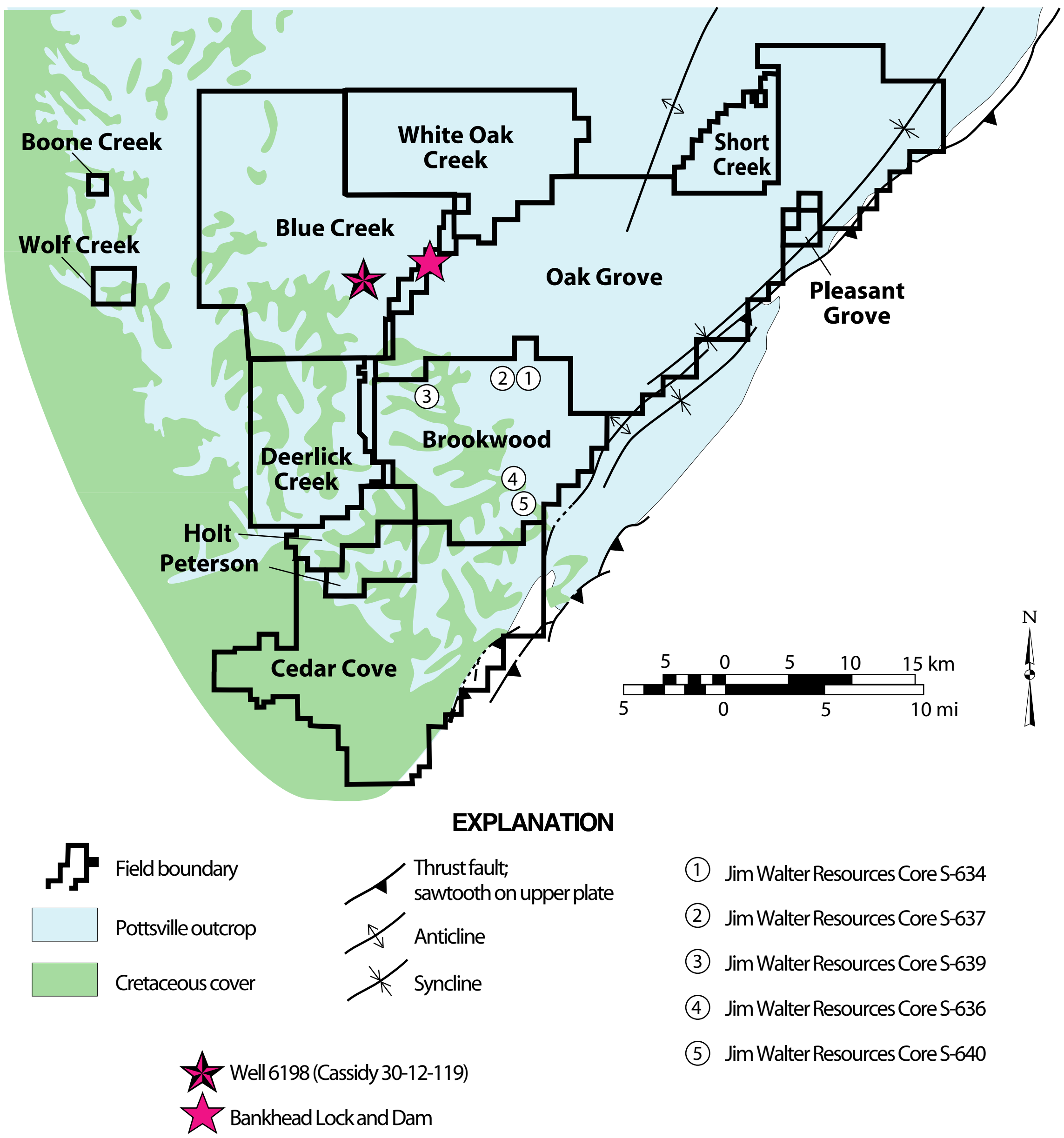

Figure 1. Index map showing coalbed methane fields where the Pottsville Formation serves as a coalbed methane reservoir and a shallow supply of domestic ground water and locations of key outcrops and cores used in this study.

Data on the orientation, spacing, height, and length of fractures were derived primarily from outcrop, whereas data on fracture aperture were derived from cores. After basic data were collected, the fracture systems were analyzed to determine the statistical scaling rules required for construction of DFN models using Golder Associates FracMan software. Upon completion of this task, the appropriate information was entered into FracMan, and two DFN models were built that simulate natural fracturing in one square kilometer using the procedures discussed by Dershowitz et al. (1997, 1999). The first DFN model contains exclusively joints and coal beds, whereas the second model includes a normal fault with a vertical separation of 30 m. Because cleats in coal are too numerous to incorporate in the large DFN models used in this study, coal beds were treated as single fractures with transmissivity and storativity determined from the permeability-depth relationship published by McKee et al. (1988).

After the DFN models were built, compartmentalization analysis was run using the FraCluster module of FracMan and using FracMax, which is an OpenGL visualization and analysis engine developed at the Geological Survey of Alabama by Guohai Jin. Compartmentalization analysis in FraCluster and FracMax constitutes the construction of polyhedral hulls around adjacent fractures. For example, if a group of fractures interconnects, a polyhedron is drawn connecting the vertices of those fractures, and the polyhedron can be considered an effective no-flow boundary around the conductive fractures. Compartmentalization was initially run on all fractures in the DFN models. Next, hairline fractures with kinematic aperture less than 0.2 mm were removed from the model to exclude fractures that are effectively non-transmissive at time scales of hydraulic fracturing and coalbed methane production. After these fractures were eliminated, compartmentalization analysis was again run to model the degree of interconnection between reservoir coal beds and shallow aquifers.

Model Stratigraphy

The upper Pottsville Formation contains interbedded shale, sandstone and coal that span more than 2,000 ft of section in Blue Creek Field (fig. 2). Pottsville coal beds occur in a series of stratigraphic clusters, or coal zones, separated by thick successions of shale and sandstone (e.g., McCalley, 1900; Gastaldo et al., 1993; Pashin, 1998). In the part of Blue Creek Field where the hydraulic fracturing complaint originated, coalbed methane is produced from the Black Creek and Mary Lee coal zones at a depth greater than 1,500 ft (fig. 2). The Pratt coal zone has not been completed in this area, but is productive in other parts of Blue Creek Field. Coal is thin or absent in the Cobb and Gwin coal zones in the complaint area and is thus not a target for coalbed methane production. A water well near the model well is open to the deepest of two coal beds in the Utley coal zone, and based on information on file at the Geological Survey of Alabama, water may also be produced from fractures in the adjacent strata to a depth of 165 ft. In all, 82 major shale, sandstone, and coal beds were logged in the model well, and all of these beds were incorporated into the DFN models.

Fracture Systems

Fractures in the upper Pottsville Formation include joints, cleats, and fault-related shear fractures, and the regional characteristics of these fractures have been discussed by Ward et al. (1984) and Pashin et al. (1991, 1999). In this section, we review the basic properties of these fracture systems that were used to construct the DFN models.

Joint systems are well exposed at the Bankhead Lock and Dam and in abandoned mine highwalls on the south side of Blue Creek. The joint systems consist of systematic joints and cross joints. The systematic joints are subvertical and strike with a vector mean azimuth of N. 47° E. in the highwalls, which is consistent with the regional joint system in the Alabama coalbed methane fields (Ward et al., 1984)., and the cross joints are roughly orthogonal to the systematic joints (fig. 3). Statistical analysis using three population tests (Baas, 2000) indicates that systematic joint orientation has a Gaussian distribution and that the orientation of the cross joints is more variable than that of the systematic joints.

Systematic joints are too long to observe directly in outcrop, but the length is constrained by J-type intersections where one joint terminates against another. Cross joints are commonly sinuous but intersect the systematic joints at right angles. Cross joints typically terminate where they intersect systematic joints,

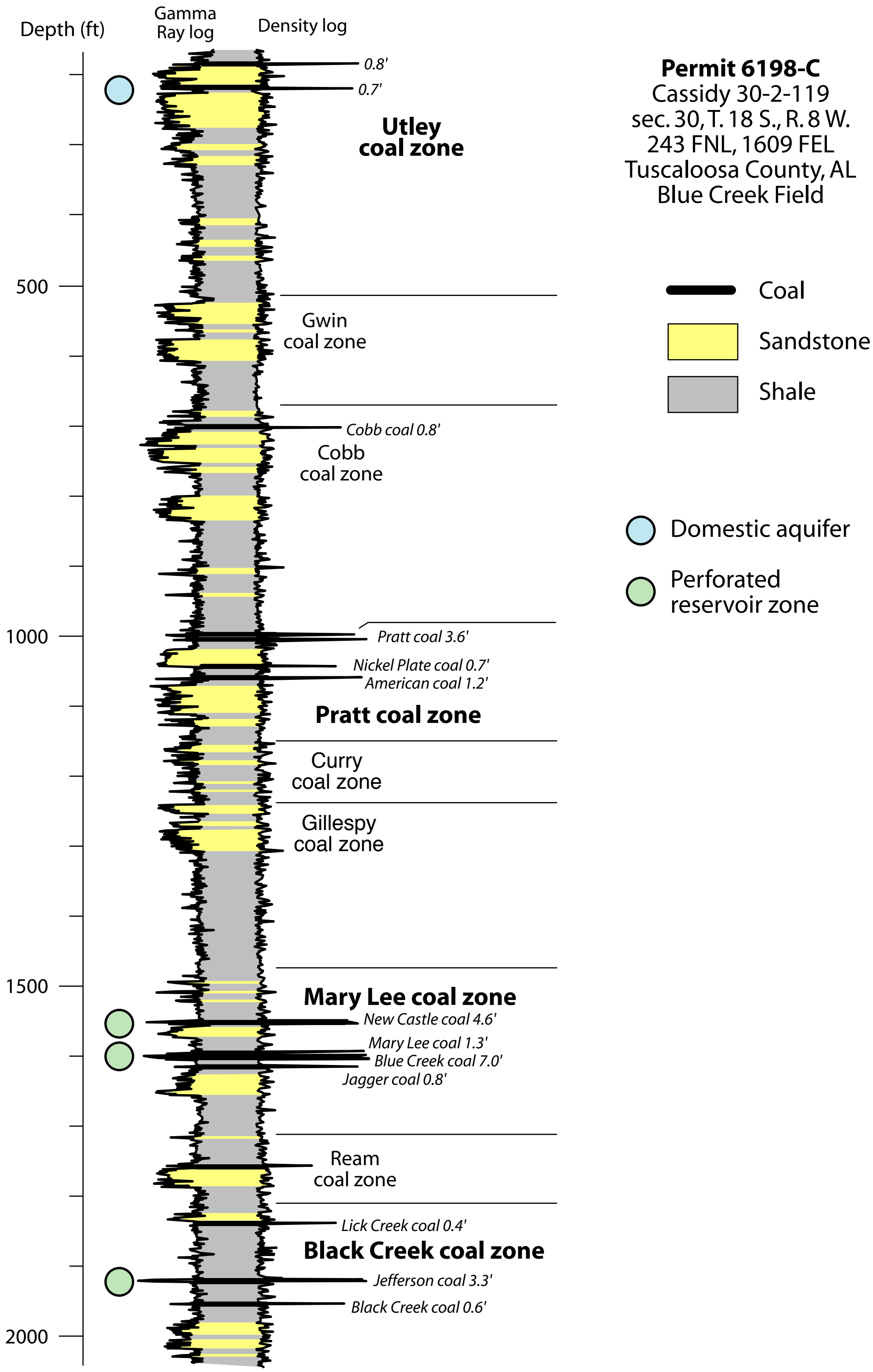

Figure 2. Geophysical well log showing the stratigraphic column, reservoir coal beds, and domestic aquifer used to construct DFN models.

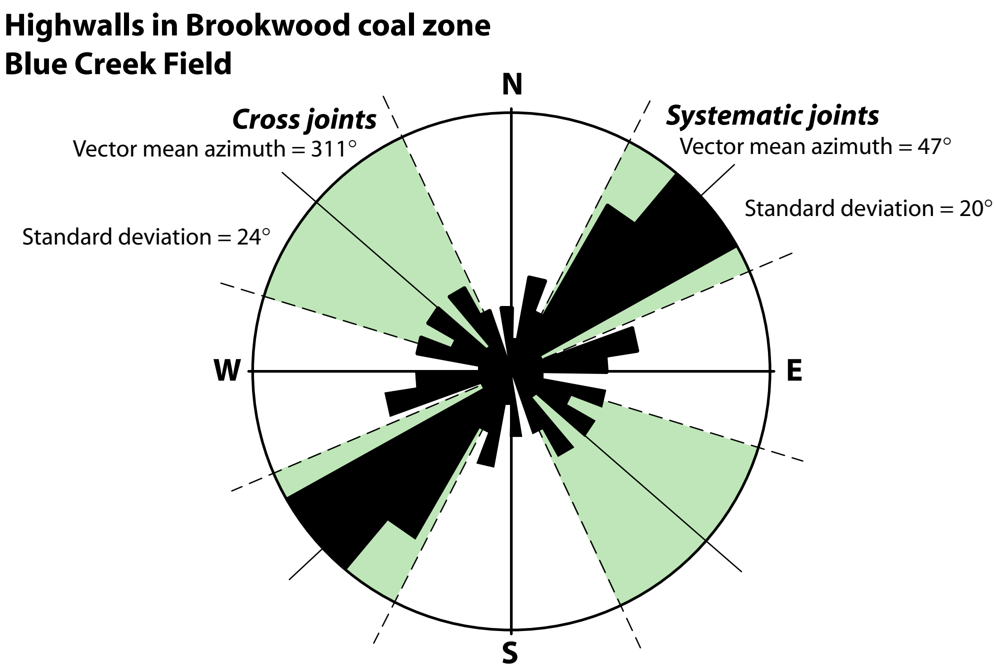

Figure 3. Rose diagram showing orientations of joints measured in abandoned mine highwalls in Blue Creek Field.

and termination percentages exceed 90%. Outcrops indicate that joints in shale and sandstone are dominantly strata-bound; that is, they terminate at or near bed contacts. Therefore, joint height effectively equals bed thickness, and to construct the DFN models, the joints were modeled as being 0.1 m thicker than the beds to simulate interconnection at stratigraphic boundaries.

Joint spacing within single beds follows log-normal statistical distributions, as exemplified by cross joints in a siderite bed at the Bankhead Lock and Dam (fig. 4). In shale and sandstone, median joint spacing increases linearly with bed thickness, as is typical in sedimentary rock (Verbeek and Grout, 1984), and can be approximated with the equation:

$$S = 0.43\,T - 0.08,$$

where S is median joint spacing and T is bed thickness. The predominance of strata-bound joint systems in the Pottsville Formation indicates that individual beds fractured with a high degree of mechanical independence.

Fracture aperture is the principal determinant of transmissivity, and the kinematic aperture (i.e., distance between fracture or vein walls; Stowell, 2000) of partially mineralized fractures was determined from core using a graphical comparator. A percentile plot indicates that joint aperture can be characterized as an exponential population (fig. 5). More than 40 percent of the fractures studied have kinematic aperture at or below the lower limit of observation (0.05 mm), and more than 60 percent of the fractures have a kinematic aperture of 0.20 mm or less and are thus effectively non-transmissive.

Normal faults are abundant in the Alabama coalbed methane fields (e.g., Semmes, 1929; Pashin and Groshong, 1998). A well-exposed normal fault at the Bankhead Lock and Dam (fig. 1) provided much of the information used to model faults in this investigation, and additional data were obtained from core. At this locality, a fault strikes N. 28° W. and dips 66° NE. Deformation is expressed as a swarm of mutually crosscutting synthetic and antithetic shear fractures that are developed mainly in sandstone of the footwall block of the fault. The shear fractures strike with the fault plane and have a Gaussian distribution about a vector mean azimuth of N. 30° W (fig. 6). The poles to the synthetic shears are broadly

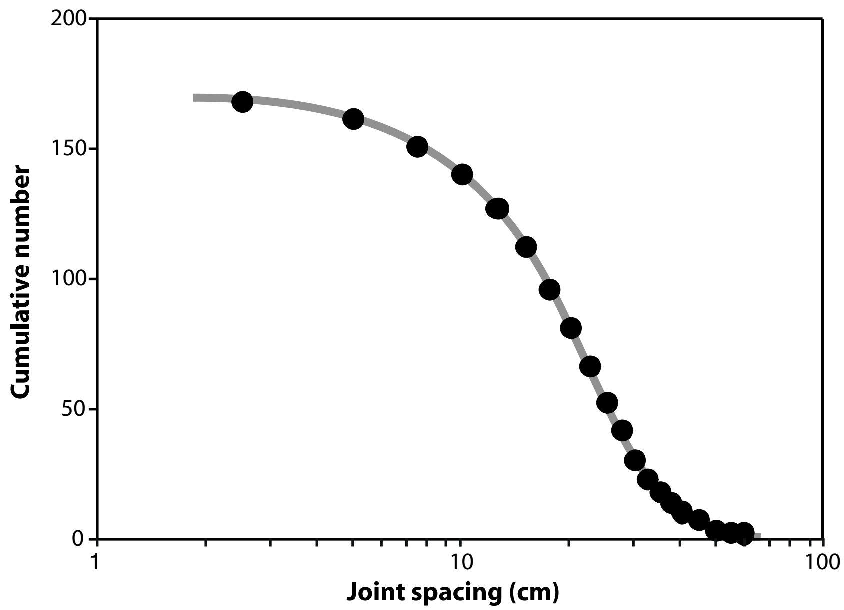

Figure 4. Cumulative plot showing positively skewed, log-normal distribution of the spacing of strata-bound joints in a siderite bed at the Bankhead Lock and Dam.

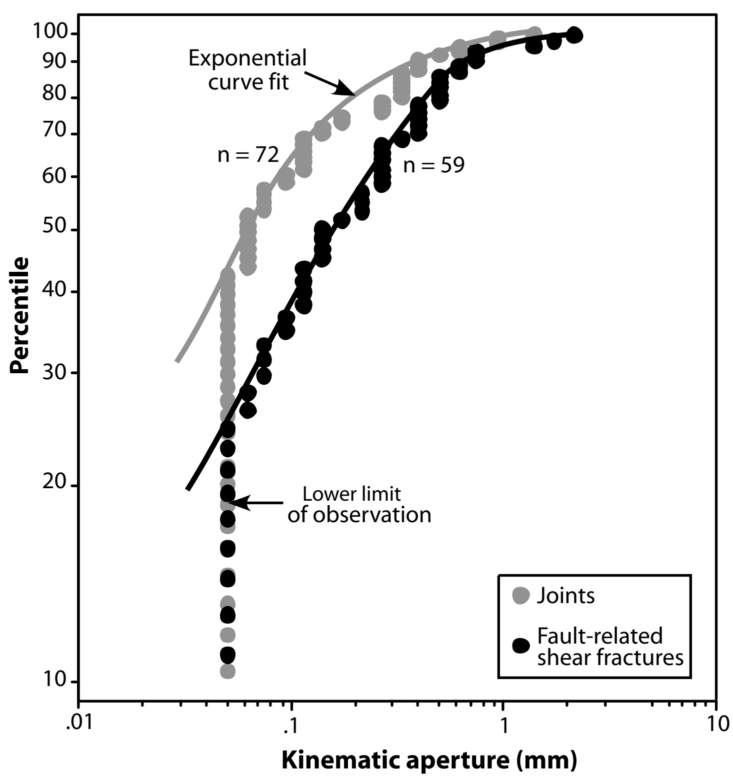

Figure 5. Percentile plots showing exponential distribution of kinematic aperture in fractures from five cores in Brookwood Field.

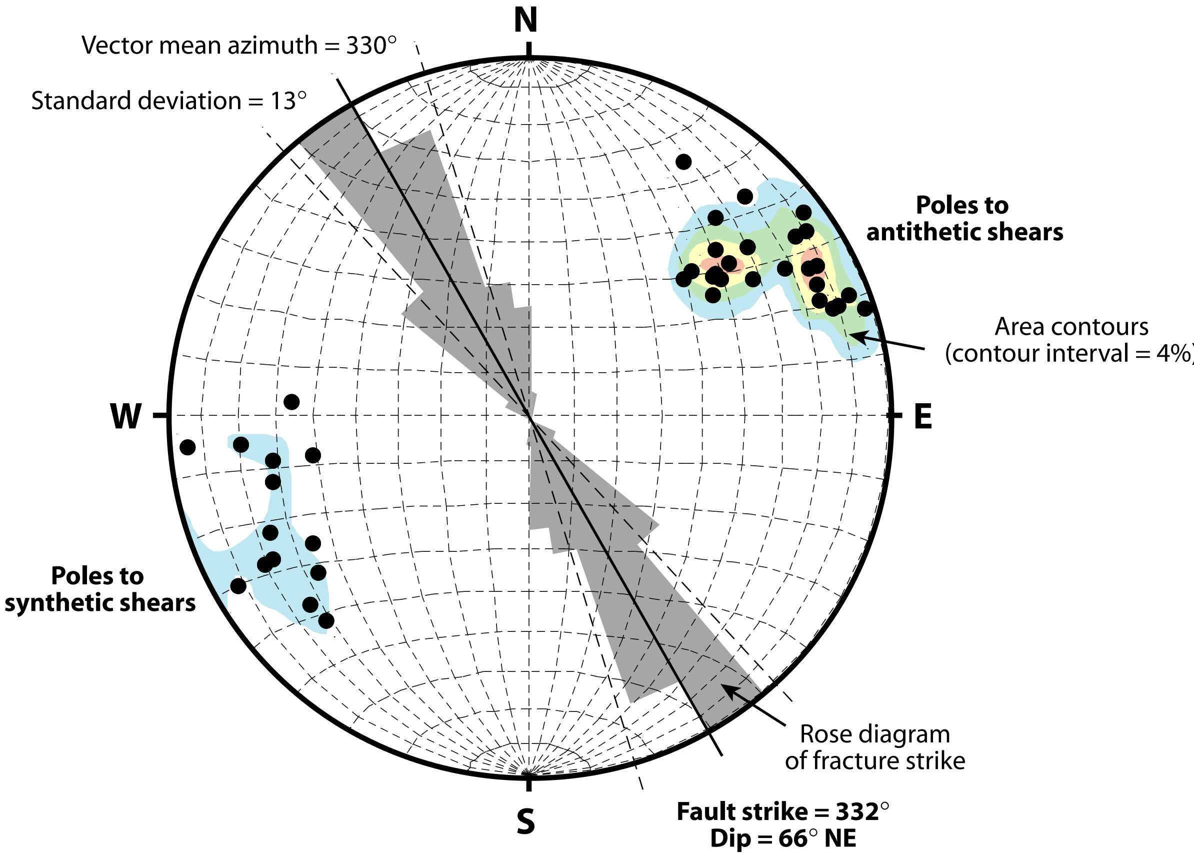

Figure 6. Stereoplot and rose diagram showing the orientation of fault-related shear fractures at the Bankhead Lock and Dam.

distributed, whereas poles to the antithetic shears have a bimodal distribution, clustering about dips of 50 and 78°.

Fracture spacing increases exponentially away from the fault plane for the first 10 m and is fairly uniform farther away from the fault. The complete width of the footwall fracture system is about 60 m. Analysis of cores indicates that fault-related fractures tend to be concentrated in shear zones about 10 m wide, and that the broad zone of deformation observed in outcrop is relatively uncommon. The population distribution of the kinematic aperture of fault-related shear fractures can be characterized by an exponential function, and about 60% of the shear fracture population has kinematic aperture greater than 0.2 mm (fig. 5). Accordingly, kinematic aperture tends to be significantly larger for fault-related shear fractures than for joints.

DFN Models and Compartmentalization Analysis

Developing DFN models with the statistical and spatial attributes described above shows that fracture architecture and compartmentalization within the Pottsville Formation is extremely complex. This discussion begins with characterization of a simple two-bed joint model (fig. 7) and continues with discussion of the complete jointed and faulted DFN models (figs. 8, 9).

A simple DFN model includes joints modeled from a shale bed that is 40 m thick and an underlying sandstone bed that is 3 m thick (fig. 7A). Each bed contains a series of systematic joints and cross joints that follow the scaling relationships discussed in the previous section. Coloring the fractures according to aperture shows that nearly half of the joints are hairline fractures with aperture less than 0.05 mm (dark

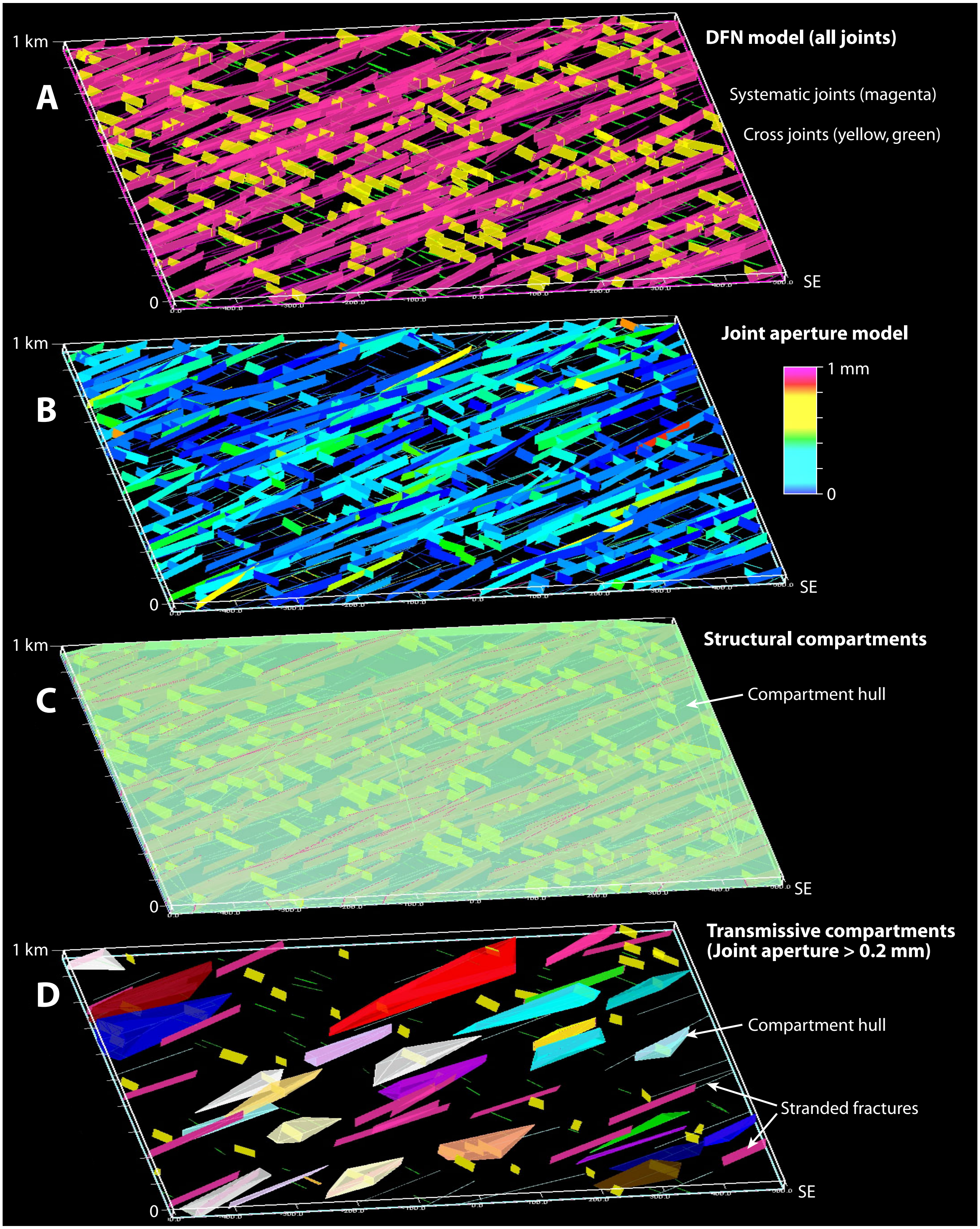

Figure 7. Simple DFN models showing fracture systems, joint aperture, and compartmentalization in two beds.

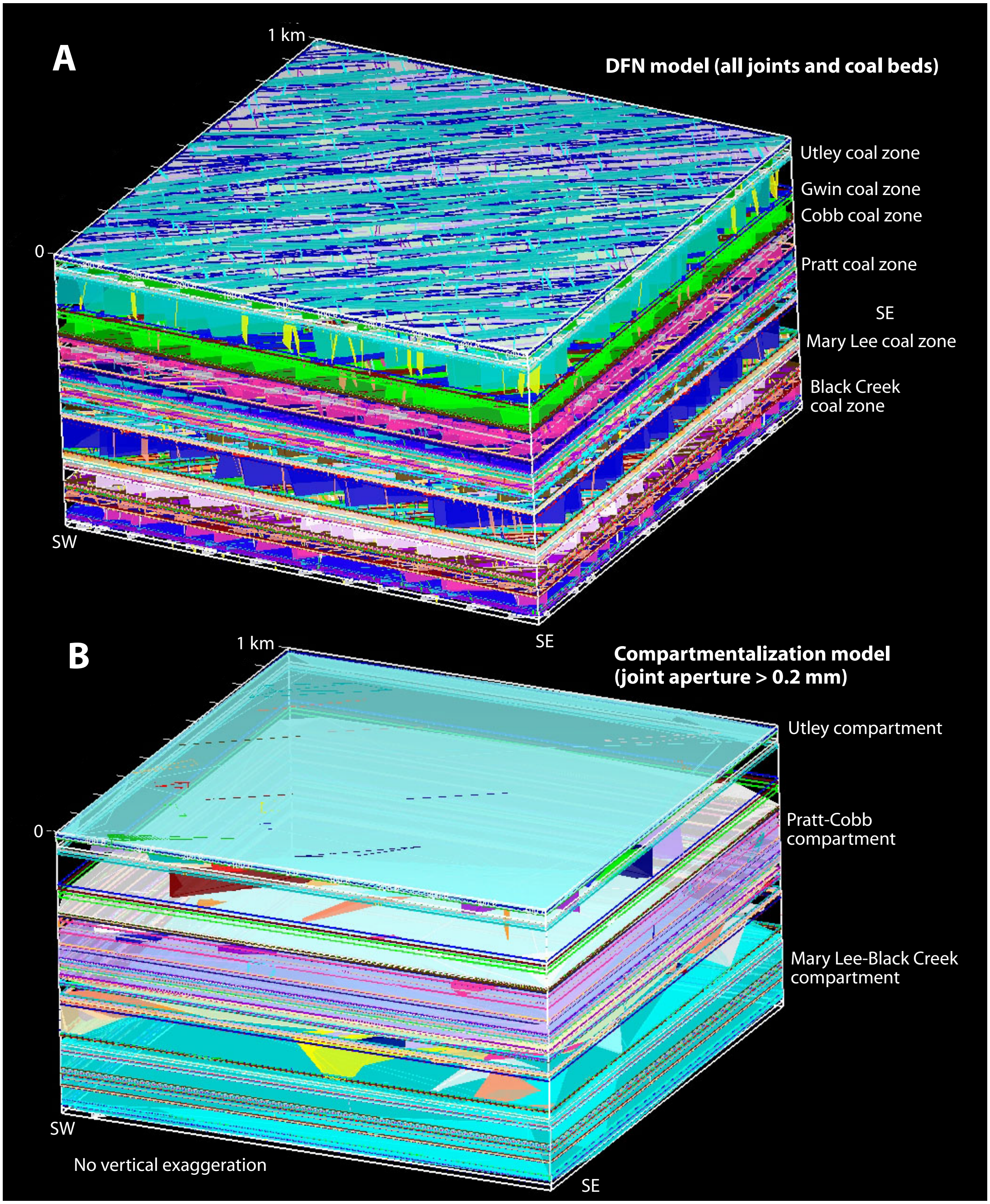

Figure 8. DFN and compartmentalization models of jointed strata in the upper Pottsville Formation.

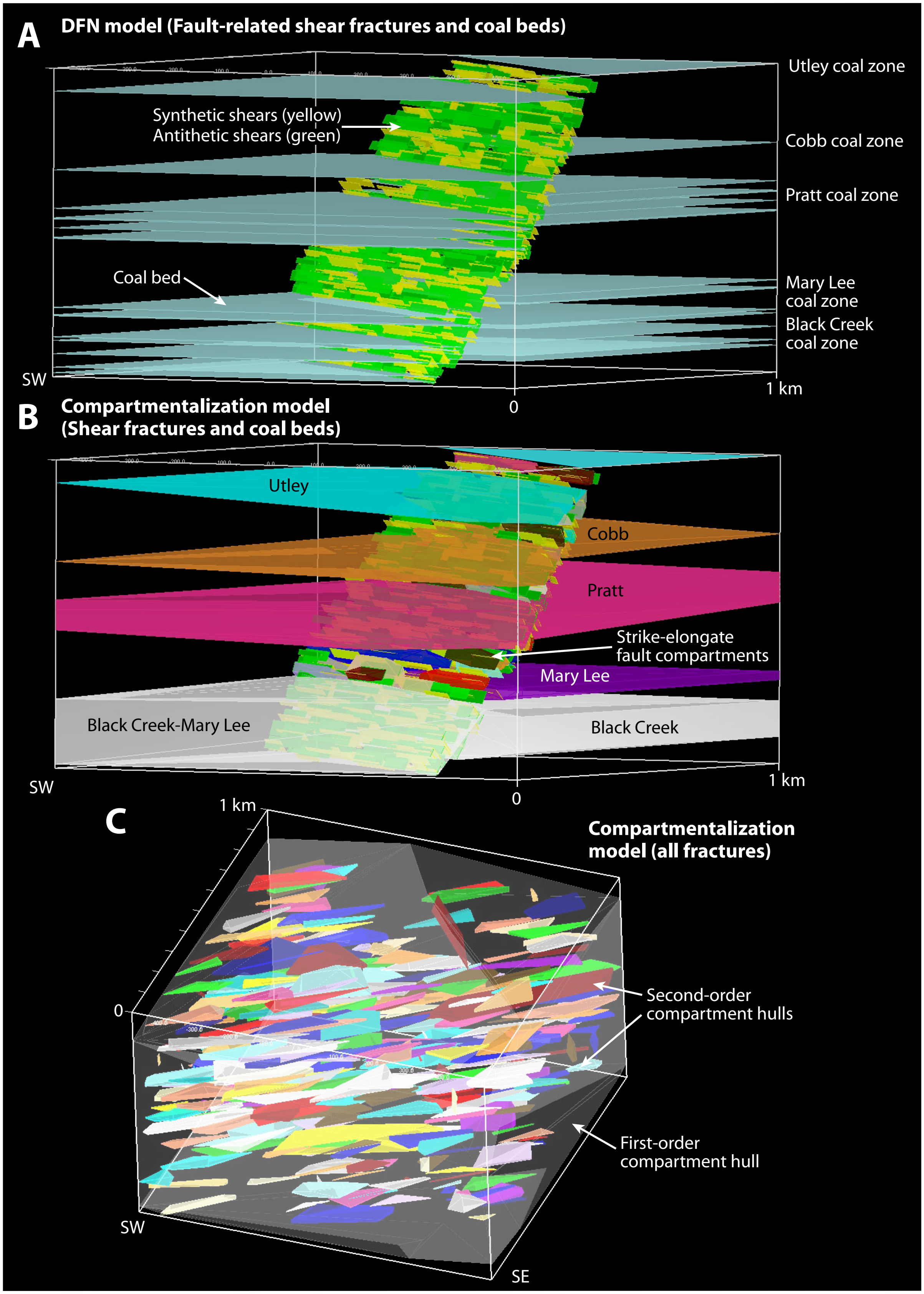

Figure 9. DFN and compartmentalization models of faulted strata in the upper Pottsville Formation.

blue) and that few joints have aperture greater than 0.50 mm (yellow and red) (fig. 7B). Running the compartmentalization analysis on the complete DFN results in development of a single polygonal hull encompassing all the fractures (fig. 7C). This result suggests that the joint network is structurally interconnected. Eliminating the effectively non-transmissive fractures (aperture < 0.2 mm) results in a model with numerous small compartment hulls and stranded fractures, indicating that hydraulic communication within the joint system is limited (fig. 7D).

A larger DFN model simulates strata-bound joint systems in 68 shale and sandstone beds and incorporates 14 horizontal fractures to simulate coal beds (fig. 8A). This model depicts a preponderance of thin shale and sandstone beds with closely spaced joints within the upper Pottsville coal zones and thick shale beds with widely spaced joints between the coal zones.

Compartmentalization analysis of all fractures results in construction of a single compartment hull around the entire model, which again indicates structural interconnection. Eliminating effectively non-transmissive fractures, however, gives a more complex result in which first-order compartment hulls are developed around the major coal zones (fig. 8B). One first-order hull envelops the Mary Lee and Black Creek coal zones, which contains the reservoir coal beds (fig. 2). Another hull envelops the Pratt and Cobb coal zones, which are not completed, and a third envelops the Utley coal zone, which contains the domestic aquifer (figs. 2, 8B). Each first-order hull contains numerous second-order hulls, indicating that significant heterogeneity exists within the major compartments. In addition, numerous isolated compartments were modeled in the intervals between the major compartments enveloping the coal zones.

Another DFN model incorporates a fault with a vertical separation of 30 m (fig. 9). The fault is modeled as a shear zone with synthetic (yellow) and antithetic (green) fractures (fig. 9A). Compartmentalization analysis of the transmissive fault-related fractures and coal beds results in numerous strike-parallel compartments within the fault zone and large compartments around the coal beds that join with the fault zone (fig. 9B). In the footwall block, compartments envelop each coal zone, and in the hanging-wall block, the Black Creek and Mary Lee zones are united in a single compartment. Incorporating joints results in development of a first-order hull around the entire model (fig. 9C). However, a multitude of second-order compartments are developed within the first-order hull, suggesting that hydraulic communication within the model is extremely complex.

Discussion

The DFN models indicate that a high degree of compartmentalization exists in the upper Pottsville Formation (figs. 7-9). In areas lacking normal faults, joints provide the principal conduits for hydraulic communication between coal beds. The modeling technique used in this investigation dictates that coal beds are in hydraulic communication with all transmissive joints in the roof and floor beds. Thus, where coal beds are closely spaced and are separated by only one or a few beds of shale and sandstone, large reservoir compartments can be expected (fig. 8). By contrast, the thick successions of interbedded shale and sandstone between major coal zones facilitate development of numerous, isolated compartments, and multiple no-flow boundaries have thus been modeled between the reservoir coal beds in the Mary Lee and Black Creek coal zones and the shallow aquifer in the Utley coal zone. On the basis of this model, the chances of contamination of shallow aquifers through hydraulic fracturing and other operational activities appear remote.

Fault zones cut across bedding throughout the upper Pottsville and are therefore possible conduits for cross-formational flow (fig. 9). However, compartmentalization analysis indicates that flow is extremely complex within fault zones and that any flow paths to the surface may be highly tortuous and require interplay between fault-related shear fractures, joints, and coal beds (compare figs. 9B and 9C). Published reports confirm that the role of faulting in the Pottsville Formation is diverse. For example, Clayton et al. (1994) documented a gas seep along a normal fault, and McIntyre et al. (this volume) suggested that fluid production is enhanced along other faults. Conversely, Pashin and Groshong (1998) suggested that faults segment coalbed methane reservoirs into structural panels with differing production characteristics, and Groshong et al. (this volume) presented evidence that some faults are sealing. These interpretations indicate that flow is extremely complex in faulted coalbed methane reservoirs and that uncontrolled factors like shale smearing and mineralization make characterization difficult.

In all, the results of compartmentalization and heterogeneity presented in this paper are consistent with the observations and findings of previous studies. For example, Koenig (1989) determined that the distribution of pressure around a single production well differs significantly among coal beds, which suggests that vertical communication is limited. Pashin and McIntyre (this volume) presented evidence for a bimodal pressure regime in the Pottsville Formation, which is characteristic of compartmentalized sedimentary basins (Bradley and Powley, 1994). Pashin (1998) and Pashin and Groshong (1998), moreover, attributed extreme variation of production performance among neighboring wells to hidden interwell heterogeneity that is related to the abundance and openness of natural fractures. Indeed, the exponential distribution of kinematic aperture (fig. 5) dictates that flow is concentrated in a small percentage of the total fracture population, and this may be the key source of interwell heterogeneity in the coalbed methane reservoirs of Alabama.

Summary and Conclusions

Natural fracture systems in the upper Pottsville Formation have spatial relationships and obey statistical scaling rules that provide a robust basis for developing DFN models. Joint systems in the Pottsville are dominantly strata-bound fracture networks, whereas fault zones can be characterized as swarms of synthetic and antithetic shear fractures that cut across bedding. Kinematic aperture data for joints and shear fractures can be characterized with exponential functions. These functions indicate that hairline fractures predominate and that a small percentage of the fracture population is capable of transmitting significant amounts of fluid.

The DFN models indicate a high degree of structural interconnection among joint systems in the upper Pottsville Formation. However, analysis of transmissive fractures indicates that upper Pottsville strata are hydrologically compartmentalized. Major compartments envelop intervals with closely spaced coal beds, whereas small, isolated compartments were modeled in thick shale-sandstone successions lacking coal. According to this model, multiple no-flow boundaries separate reservoir coal beds from shallow domestic groundwater supplies. Therefore, the chance of contamination of water wells through hydraulic fracturing of coalbed methane reservoirs appears remote.

Fault systems bridge the major reservoir compartments, and according to the DFN model, significant cross-formational flow requires a complex interplay among joints, shear fractures, and coal beds. Even though cross-formational flow is facilitated by fault zones, compartmentalization analysis indicates that the Pottsville Formation is extremely heterogeneous and that flow paths are highly tortuous. Indeed, production data and seep information indicate that some fault zones transmit fluid, whereas others are effectively sealing. Multiple lines of evidence indicate that the upper Pottsville Formation is a heterogeneous, compartmentalized hydrologic system. Moreover, the exponential distribution of fracture aperture is a critical source of interwell heterogeneity that helps explain this compartmentalization and the variable production performance of neighboring wells.

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