Discrete Fracture Network Models for Risk Assessment of Carbon Sequestration in Coal

FINAL TECHNICAL REPORT

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ABSTRACT

A software package called DFNModeler has been developed to assess the potential risks associated with carbon sequestration in coal. Natural fractures provide the principal conduits for fluid flow in coal-bearing strata, and these fractures present the most tangible risks for the leakage of injected carbon dioxide. The objectives of this study were to develop discrete fracture network (DFN) modeling tools for risk assessment and to use these tools to assess risks in the Black Warrior Basin of Alabama, where coal-bearing strata have high potential for carbon sequestration and enhanced coalbed methane recovery.

DFNModeler provides a user-friendly interface for the construction, visualization, and analysis of DFN models. DFNModeler employs an OpenGL graphics engine that enables real-time manipulation of DFN models. Analytical capabilities in DFNModeler include display of structural and hydrologic parameters, compartmentalization analysis, and fluid pathways analysis. DFN models can be exported to third-party software packages for flow modeling.

DFN models were constructed to simulate fracturing in coal-bearing strata of the upper Pottsville Formation in the Black Warrior Basin. Outcrops and wireline cores were used to characterize fracture systems, which include joint systems, cleat systems, and fault-related shear fractures. DFN models were constructed to simulate jointing, cleating, faulting, and hydraulic fracturing. Analysis of DFN models indicates that strata-bound jointing compartmentalizes the Pottsville hydrologic system and helps protect shallow aquifers from injection operations at reservoir depth. Analysis of fault zones, however, suggests that faulting can facilitate cross-formational flow. For this reason, faults should be avoided when siting injection wells.

DFN-based flow models constructed in TOUGH2 indicate that fracture aperture and connectivity are critical variables affecting the leakage of injected CO_2 from coal. Highly

transmissive joints near an injection well have potential to divert a large percentage of an injected CO_2 stream away from a target coal seam. However, the strata-bound nature of Pottsville fracture systems is a natural factor that mitigates the risk of long-range leakage and surface seepage. Flow models indicate that cross-formational flow in strata-bound joint networks is low and is dissipated by about an order of magnitude at each successive bedding contact. These models help confirm that strata-bound joint networks are self-compartmentalizing and that the thick successions of interbedded shale and sandstone separating the Pottsville coal zones are confining units that protect shallow aquifers from injection operations at reservoir depth.

DFN models are powerful tools for the simulation and analysis of fracture networks and can play an important role in the assessment of risks associated with carbon sequestration and enhanced coalbed methane recovery. Importantly, the stochastic nature DFN models dictates that they cannot be used to precisely reproduce reservoir conditions in a specific field area. Rather, these models are most useful for simulating the fundamental geometric and statistical properties of fracture networks. Because the specifics of fracture architecture in a given area can be uncertain, multiple realizations of DFN models and DFN-based flow models can help define variability that may be encountered during field operations. Using this type of approach, modelers can inform the risk assessment process by characterizing the types and variability of fracture architecture that may exist in geologic carbon sinks containing natural fractures.

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EXECUTIVE SUMMARY

Coal is potentially an important sink for the sequestration of carbon dioxide, and a software package called DFNModeler has been developed to assess the potential risks associated with carbon sequestration in coal. Natural fractures provide the principal conduits for fluid flow in coal-bearing strata, and these fractures present the most tangible risks for the leakage of injected carbon dioxide. DFN models are stochastic realizations based on the statistical properties of fracture networks. These models have been used successfully to assess leakage risks associated with hydraulic fracturing and coalbed methane production, and these models show promise for assessing risks associated with carbon sequestration in coal. The objectives of this study were to develop DFN modeling tools for risk assessment and to use these tools to assess risks in the Black Warrior Basin of Alabama, where coal-bearing strata of the Pennsylvanian-age Pottsville Formation have high potential for carbon sequestration and enhanced coalbed methane recovery.

DFNModeler software runs under Microsoft Windows operating systems and provides an interactive, user-friendly environment for the construction, visualization, and analysis of DFN models. The software is driven by a system of menus and dialog boxes that facilitates the input and editing of the parameters required to construct DFN models and enables users to customize the appearance of those models. DFNModeler employs an OpenGL graphics engine that enables real-time translation, zooming, and rotation of DFN models in three dimensions and further gives users control over scale, color, and transparency. Analytical capabilities in DFNModeler include color contouring of fracture polygons according to structural and hydrologic parameters, compartmentalization analysis, and fluid pathways analysis. DFN models can be exported as text files to third-party software packages, such as TOUGH2, for flow modeling.

DFN models were constructed to simulate fracturing in coal-bearing strata of the upper Pottsville Formation in the Black Warrior Basin. Geophysical well logs from the Jobson 24-14 #11 well, which is being used for the SECARB Black Warrior field test for carbon sequestration and enhanced coalbed methane recovery in Deerlick Creek Field, were used as the primary stratigraphic control for the models. Outcrops and wireline cores were used to determine the basic statistical scaling rules for fracture systems in the upper Pottsville, which include orthogonal joint systems, cleat systems, and fault-related shear fractures. Critical variables analyzed include the orientation, length, height, spacing, kinematic aperture, and cross-cutting relationships for each type of fracture. Results of fracture analysis indicate that the Pottsville Formation is dominated by strata-bound fracture networks. Fracture aperture tends to follow power-law distributions dominated by hairline fractures with kinematic aperture smaller than 0.05 mm. Highly transmissive fractures with aperture on the order of 1 mm, by contrast, form a small percentage of the fracture population.

A large DFN model simulating jointing in 96 beds of shale, sandstone, and coal was constructed. DFN models were also constructed to simulate cleating, faulting, and hydraulic fracturing. Analysis of transmissivity in cleats systems indicates that a strong permeability anisotropy is developed in shallow, permeable coal seams and that a loss of transmissivity contrast in deep, low-permeability seams makes anisotropy negligible. Compartmentalization analysis indicates that strata-bound fracturing compartmentalizes the Pottsville hydrologic system. First-order reservoir compartments envelop the major coal zones, and these compartments are separated by thick successions of interbedded shale and sandstone that help protect shallow coal seams that may be useful aquifers from operations at reservoir depth. Compartmentalization analysis of faulted DFN models, however, suggests that communication among joints and fault-related shear fractures can facilitate cross-formational flow, and so fault zones should be avoided when siting injection wells. Aligning production wells near faults, moreover, can help limit risk by forming pressure sinks between injectors and fault zones.

Flow models were constructed in TOUGH2 software to determine the impact of individual fractures and strata-bound fracture networks on the leakage of injected CO_2 from coal seams. Results of flow modeling in the Black Warrior Basin indicate that fracture aperture and connectivity are critical parameters affecting the leakage of injected CO_2 from coal. Highly transmissive fractures near an injection well have potential to divert a large percentage of an injected CO_2 stream away from a target coal seam. Therefore, highly transmissive fractures may impact the performance, efficiency, and predictability of sequestration and enhanced coalbed methane recovery operations. However, the strata-bound nature of Pottsville fracture systems is a natural factor that mitigates the risk of long-range leakage and surface seepage. DFN models indicate that the probability of direct communication between highly transmissive fractures in successive beds is low. Flow models indicate that cross-formational flow in strata-bound joint networks is low and is dissipated by about an order of magnitude at each successive bedding contact. These models help confirm that strata-bound joint networks are self-compartmentalizing and that the thick successions of interbedded shale and sandstone separating the Pottsville coal zones are confining units that protect shallow aquifers from injection operations at reservoir depth.

DFN models are powerful tools for the simulation and analysis of fracture networks and can play an important role in the assessment of risks associated with carbon sequestration and enhanced coalbed methane recovery. Importantly, the stochastic nature DFN models dictates that they cannot be used to precisely reproduce reservoir conditions in a specific field area. Rather, these models are most useful for simulating the fundamental geometric and statistical properties of fracture networks. Because the specifics of fracture architecture in a given area can be highly uncertain, multiple realizations of DFN models and DFN-based flow models can help define variability that may be encountered during field operations. Using this type of approach, modelers can inform the risk assessment process by characterizing the types and variability of fracture architecture that may exist in geologic carbon sinks containing natural fractures.

INTRODUCTION

Coal is a geologic sink in which large quantities of carbon dioxide can be sequestered while enhancing coalbed methane recovery (Reichle and others, 1999; Gentzis, 2000; White and others, 2003). Discrete fracture network (DFN) models have proven useful for assessing risks to shallow aquifers posed by coalbed methane operations (Pashin, Jin, and Payton, 2004), and these models have strong potential for assessing short- and long-term leakage risks associated with carbon sequestration in fractured strata. DFN models are 3-D computer simulations based on the statistical scaling properties of natural and induced fracture systems, and these models provide a basis for compartmentalization analysis, pathways analysis, and flow modeling in fractured media (Smith and Schwartz, 1984; Dershowitz and Einstein, 1988; National Research Council, 1996). Accordingly, DFN models can be used to assess the risks associated with carbon sequestration in coal by simulating fracture networks in coal-bearing strata, modeling hydrologic compartmentalization in these strata, defining the distribution and geometry of cross-stratal pathways for leakage of injected carbon dioxide from coal beds into adjacent country rock or to the surface, and quantifying the magnitude and timing of flow through fracture systems.

This report summarizes a three-year study that focused on the DFN modeling tools for coal-bearing strata and the application of those tools to assess leakage risks associated with carbon sequestration in mature coalbed methane reservoirs of the Black Warrior basin in Alabama (fig. 1). This study was conducted by the Geological Survey of Alabama in partnership with the University of Alabama and Jim Walter Resources, Incorporated. The software developed during this study is called DFNModeler and employs object-oriented programming to construct, visualize, and analyze DFN models. The basic approaches used in this study were (1) software development using commercial development tools, (2) characterization of fracture networks in the field and laboratory, (3) 3-D modeling and analysis of fracture systems using DFNModeler software, (4) flow modeling using TOUGH2 software, and (5) risk assessment based on model results.

Coalbed methane reservoirs in the Black Warrior basin of Alabama (fig. 1) are among the most intensely studied in the world and have strong potential for carbon sequestration and enhanced coalbed methane recovery (Pashin and others, 2001; Pashin and McIntyre, 2003; Pashin and others, in press). DFNModeler software was applied to assess risks associated with sequestration in this basin to demonstrate the real-world application of this software, and the Black Warrior Basin was chosen because of the large volume of data available and because of the authors' experience in the region. Pashin, Carroll, and others (2004) and Pashin and others (in press) determined that more than two decades of carbon dioxide emissions from coal-fired power plants in the basin may be sequestered in existing coalbed methane fields while increasing coalbed methane reserves by more than 20 percent. Coal-bearing strata in the Black Warrior basin and many other prospective coal basins have minimal matrix permeability, so the flow of water and gas is restricted primarily to fracture networks (e.g., Pashin and Hinkle, 1997; van

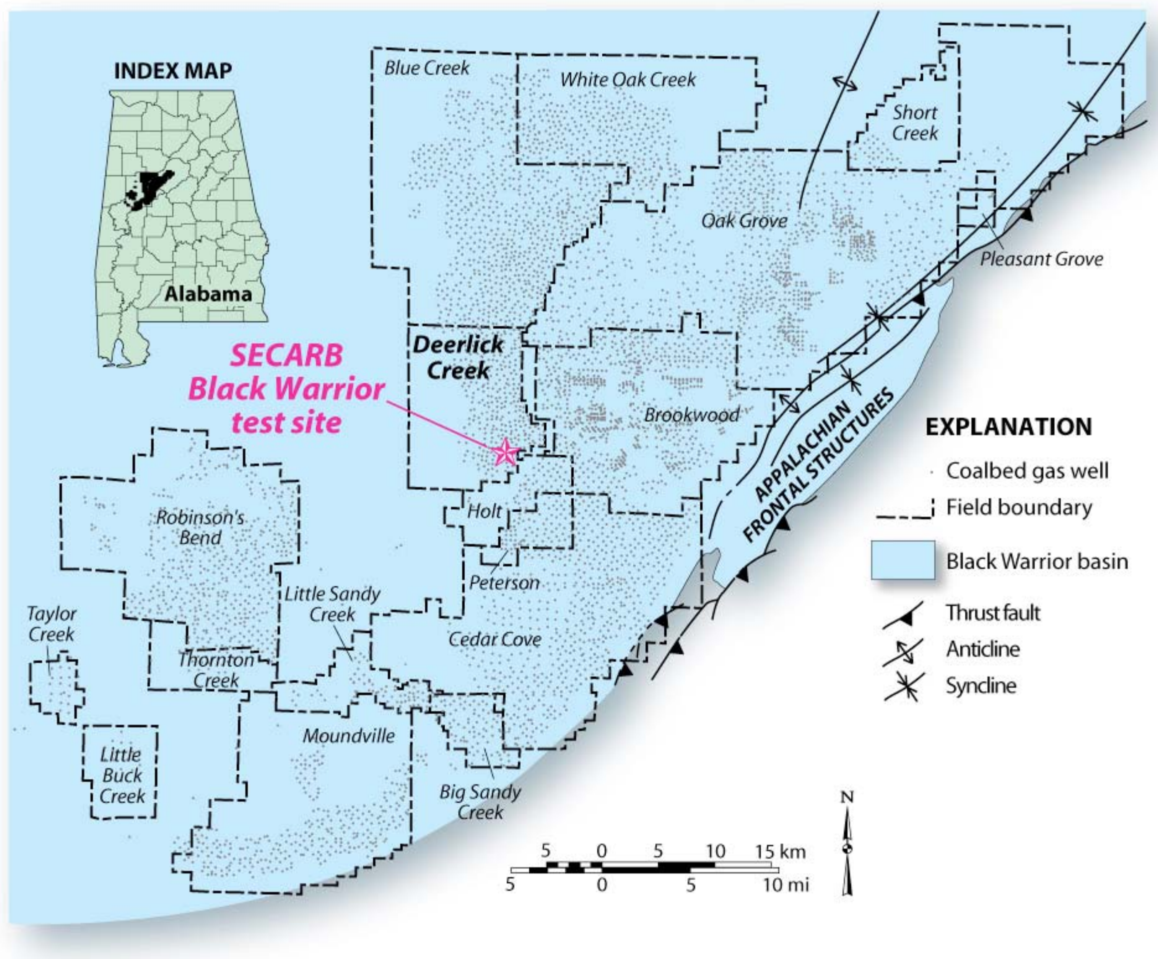


Figure 1.—Map of coalbed methane fields in the Black Warrior Basin showing location of the SECARB Black Warrior test site.

Bergen and others, 2006). For this reason, fracture networks pose the most tangible risks for leakage of injected carbon dioxide that need to be assessed. The Southeastern Regional Carbon Sequestration Partnership (SECARB) has established a field validation test site for the Black Warrior Basin in Deerlick Creek Field (Pashin and Clark, 2006; Pashin and others, 2007) (fig. 1), and some of the models constructed in this study are based on the geology of the SECARB Black Warrior test site.

This report begins with a detailed discussion of the analytical methods used in software development, geological characterization, geological modeling, and flow modeling. The report continues with documentation for DFNModeler software, which includes an overview of the software architecture and instructions for the use of the software. Next is a discussion of fracture systems and the application of DFNModeler software to the Black Warrior Basin and the SECARB Black Warrior test site. The report continues with a section on flow modeling using TOUGH2 software and concludes with an assessment of risks associated with carbon sequestration and enhanced coalbed methane recovery in the Black Warrior Basin.

ANALYTICAL METHODS

Developing DFNModeler software and applying it to fracture networks required a multidisciplinary approach that employed a broad range of analytical methods. This section contains detailed descriptions of the methods used to conduct this study and is subdivided into three parts. The first part summarizes software development, and the second discusses the field and laboratory techniques used to characterize and model fracture networks in the Black Warrior Basin. The third part describes the flow modeling and risk assessment techniques used during this investigation.

Software Development

DFNModeler software was written using the Visual C++ programming language and includes an OpenGL visualization engine. This software was developed using Microsoft Visual C++ and Microsoft Foundation Class (MFC) Library under the Visual Studio .Net 2005 programming environment. DFNModeler utilizes OpenGL graphic libraries for 3-D graphical rendering of DFN models. DFNModeler is implemented with an object-orientation programming (OOP) model to take advantages of the OOP design paradigm and to utilize the MFC document-view architecture to separate the data from presentations. All geological objects such fractures, faults, and compartments are abstracted as objects that encapsulate basic data. DFNModeler is therefore highly extensible and can be updated readily to refine existing capabilities and to add new functionality.

The look of the user interface when the DFNModeler application is started is shown in Figure 2. DFNModeler was designed to have five major functions: (1) input and editing of model data; (2) generation of discrete fracture networks; (3) analysis of compartmentalization and fluid migration pathways; (4) visualization DFN modeling results; and (5) export of model data and results. To provide this functionality, the software was designed with a modular architecture (fig. 3).

A brief technical overview of the functionality and logic behind the design of DFNModeler software is given here, and a user's guide for the software is given in the section on software documentation. A broad range of analytical methods and geological concepts were used to design and develop DFNModeler software and were required to develop a user-friendly software interface and to achieve fast computational performance.

The first step in model development is the definition of a region, which can also be referred to as a fracture region. Fracture regions represent physical geologic units; that is, a lithologic unit or a zone of fractures as may be associated with a fault. Fracture regions are of two types: rectangular box and slab (fig. 4). A rectangular region commonly represents a lithologic unit, whereas a slab region is used to represent a dipping rock formation or an inclined fracture zone. Each DFN model is composed of at least one region. Different rock units can be treated as

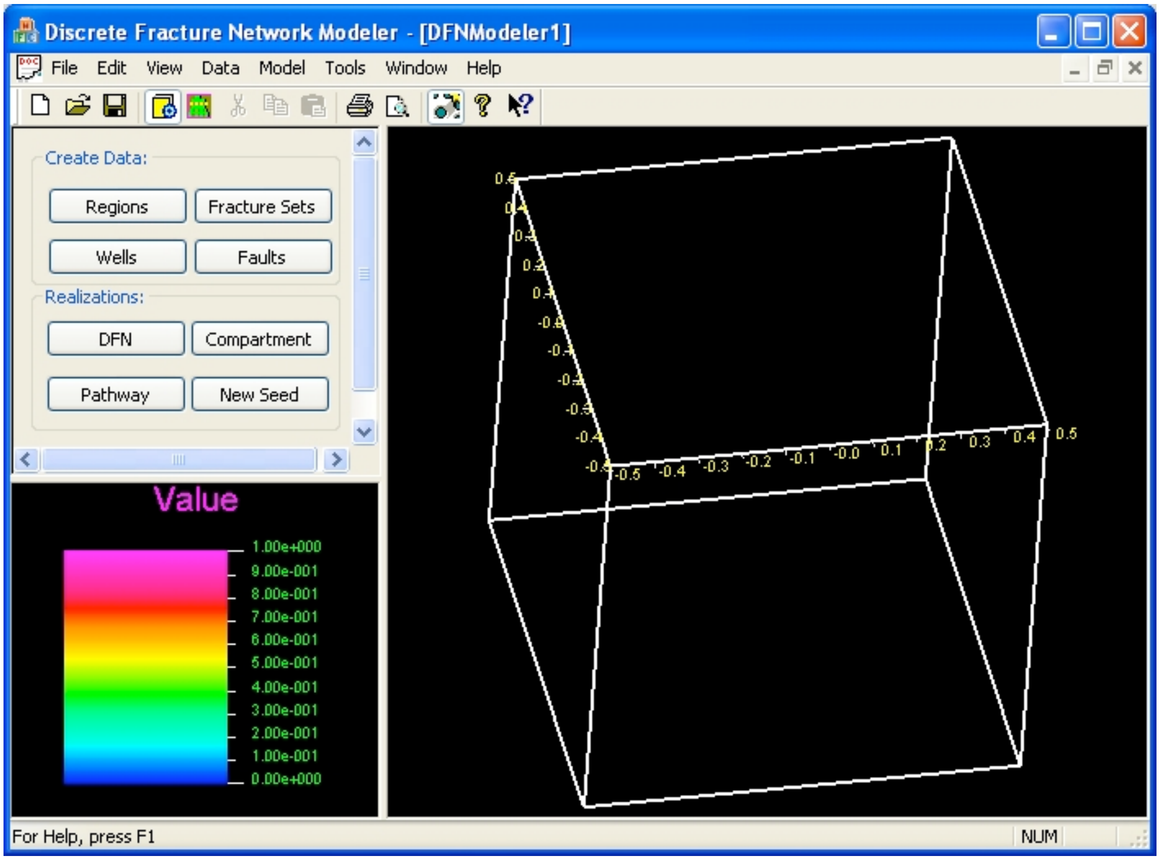


Figure 2.—Appearance of the DFNModeler software interface at launch.

multiple regions. Fracture regions conceptually represent physical rock units and fracture swarms from a geologist's point of view, and they also improve the efficiency of fracture generation in terms of computational geometry. In a DFN model, each fracture region can contain multiple fracture sets.

A fracture set represents a group of fractures that have a common origin and thus similar geological properties. Fracture sets are distinguished from one another by (1) the fracture region in which they occur, (2) orientation, and (3) geological origin. If any one of the above three factors is different, they should be included in different fracture sets. The geometric properties of a fracture set are defined statistically in terms of orientation, length, height, aperture, spacing,

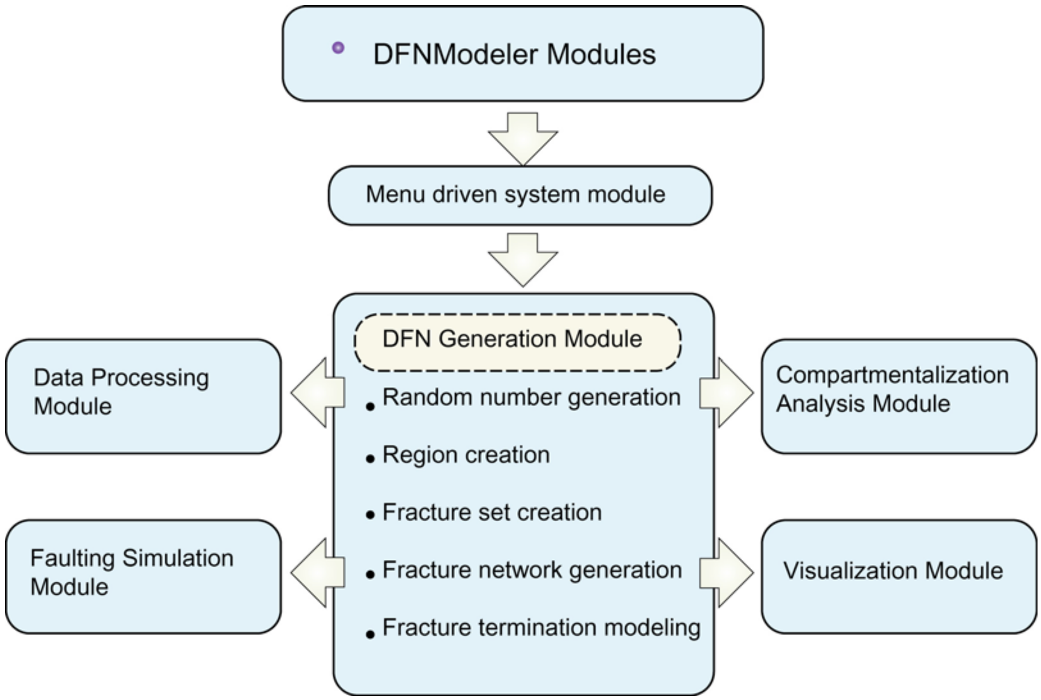


Figure 3.—Diagram showing modular architecture of DFNModeler software.

and the frequency with which fractures terminate at pre-existing structures (i.e., cross-cutting relationships). In DFNModeler, fracture regions and fracture sets are created by entering values for their properties into a set of dialog boxes. Each fracture set is mapped into a specific region to generate fractures based on its statistical properties. A fracture set can only be assigned to one fracture region, whereas a fracture region can contain multiple fracture sets (fig. 5).

In DFNModeler, fractures are generated based on statistical distributions derived from field and laboratory data. Once the fracture regions and sets are defined, there is enough information to generate DFN models. DFNModeler generates fractures using a hierarchical algorithm to ensure the efficiency and speed. Generation of fractures is computationally intensive given the thousands of fractures that a fracture set may contain. Because cleat spacing in coal can be at a centimeter scale, for example, there can be tens of thousands of fractures in a small area within a single bed. In order to efficiently generate fractures, a series of mathematical procedures have

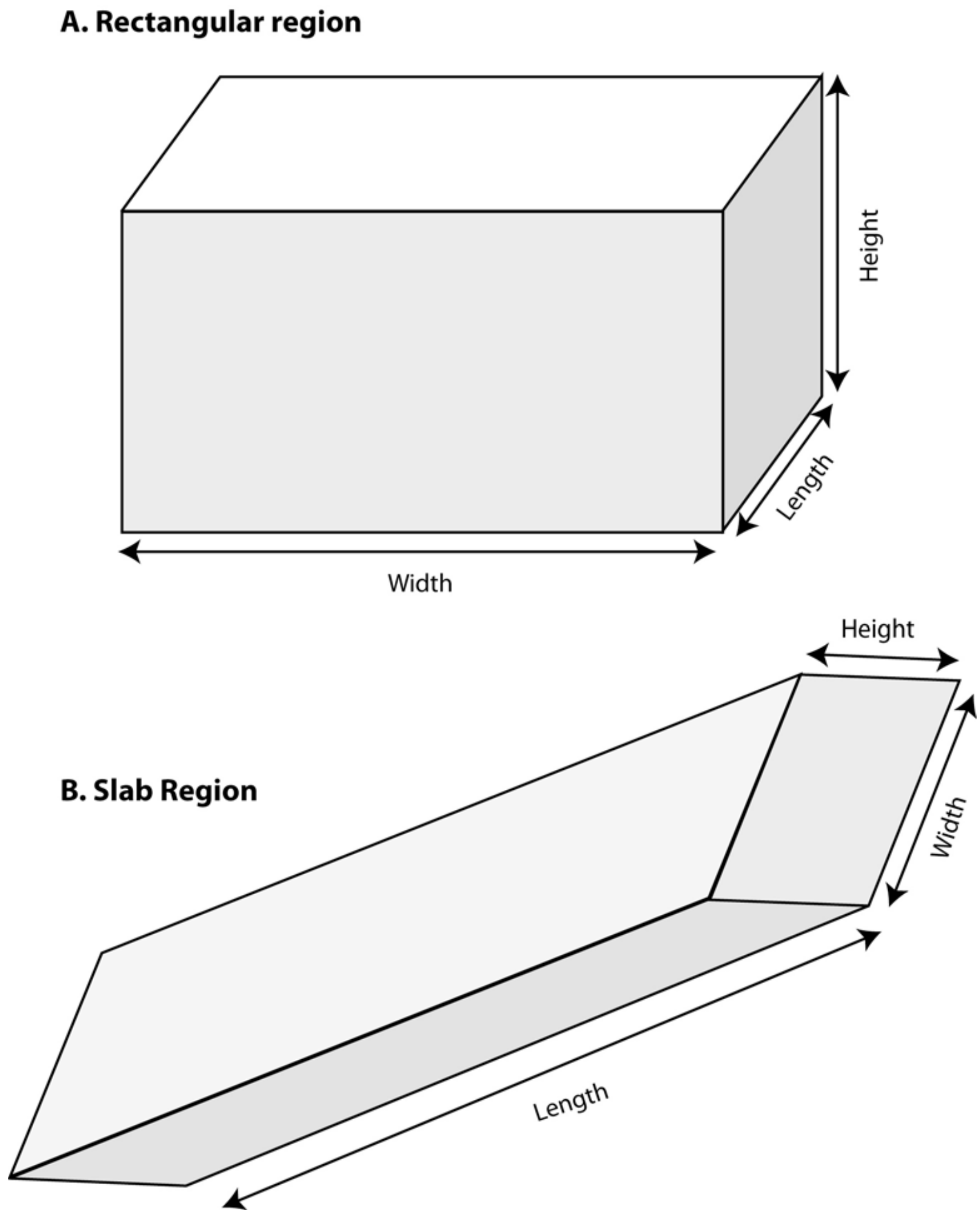


Figure 4.—Diagram showing different types of fracture regions.

been implemented and optimized that include (1) definition of fracture polygons and vertices, (2) rotation of polygons to simulate strike and dip, and (3) translation of the polygon to the proper location within the fracture region. Note that each parameter of the fracture is generated by its statistical distribution. The statistical distributions used for generating fractures are uniform,

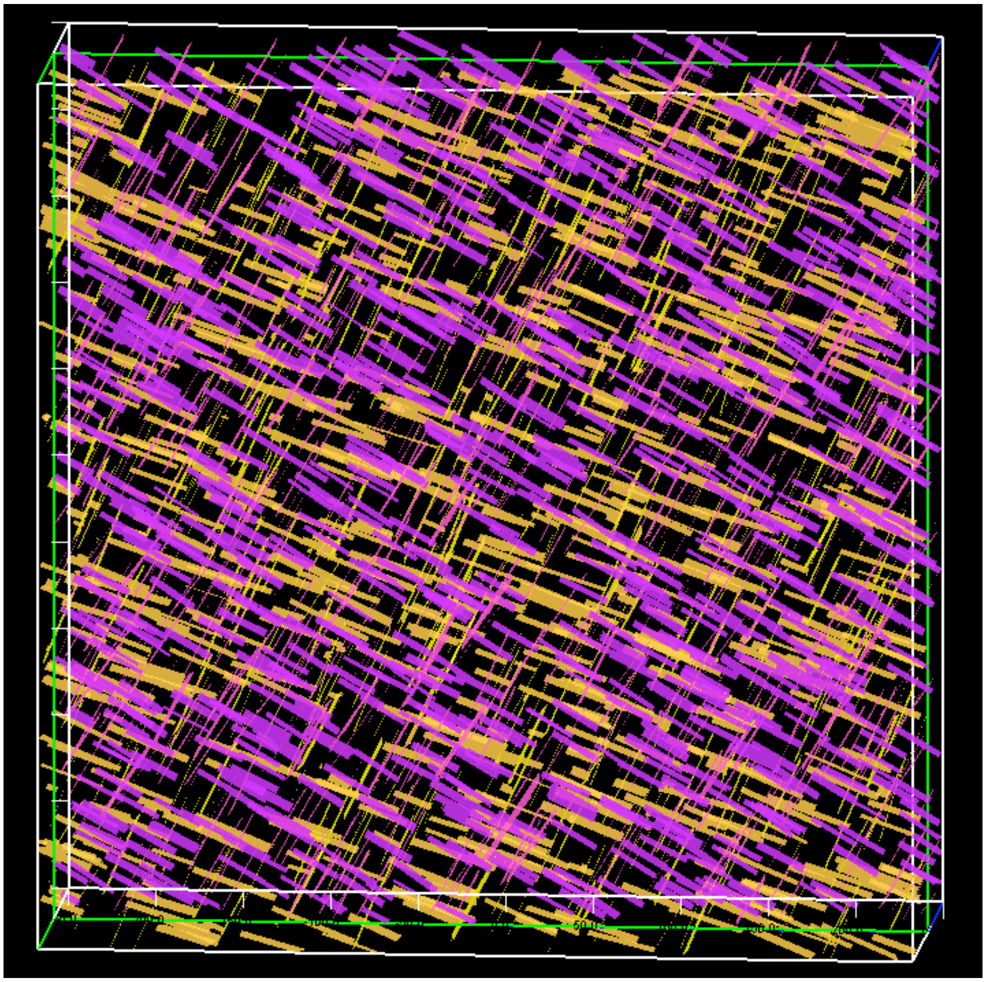


Figure 5.—Multiple fracture sets simulating orthogonal joints in two fracture regions. Systematic joints and cross-joints were modeled as individual fracture sets in each region. The two fracture sets in the lower region are displayed in orange, and those in the upper region are in magenta.

normal, log-normal, exponential, and Fisher distributions (Wood, 1994; Saucier, 2000). The Fisher distribution was implemented specifically for directional data used for fracture orientations in DFNModeler (Ulrich, 1984; Wood, 1994). All other distributions were used for scalar data, such as the dimensions of fractures.

Clipping of fractures at region boundaries and at intersections with pre-existing structures was a critical step in the design and implementation of DFNModeler software. Because the centers of fractures are generated using uniform random numbers, many fractures cross the region boundary and must therefore be clipped. In addition, fractures must be clipped where they intersect pre-existing structures to properly simulate cross-cutting relationships. Each fracture in DFNModeler is represented as a polygon, which in turn is represented by an array of directed vertices. To clip a fracture requires removing any vertices lying outside a region or beyond an intersected plane and inserting new vertices to honor region boundaries and geological relationships.

A key functionality of DFNModeler is the ability to simulate faults (fig. 6). Faults are simulated in DFNModeler by specifying the location, attitude, and slip of a plane. In all cases it is assumed that slip occurs only along a fault plane. Therefore, the slip direction can be defined by its pitch within the fault plane. Pitch can be any number from 0 to 360°. Pitch of 0 or 360° defines a normal (dip-slip) fault, whereas 90° or 270°defines a normal fault. A reverse fault has a pitch of 180°, and all other numbers specify oblique slip. The cross-cutting relationship between a fault and fractures is determined by the sequence in which a DFN model is built. Fractures generated before slip is applied to a fault plane will be cut by the fault and will be translated according to the pitch and slip of the fault. By contrast, fractures generated after slip can cut across a fault.

Compartmentalization analysis was included in DFNModeler to characterize the interconnectivity of fracture networks. A fracture compartment is defined as a convex polyhedron, or hull, that connects all vertices of intersecting fractures (fig. 7). Compartmentalization analysis determines if fractures intersect and how many fractures are interconnected to form a compartment. Compartment hulls define effective no-flow boundaries, and all fractures with vertices forming the hull are in hydraulic communication. The algorithms used for compartmentalization analysis rely on the compilation of tables of intersecting fractures.

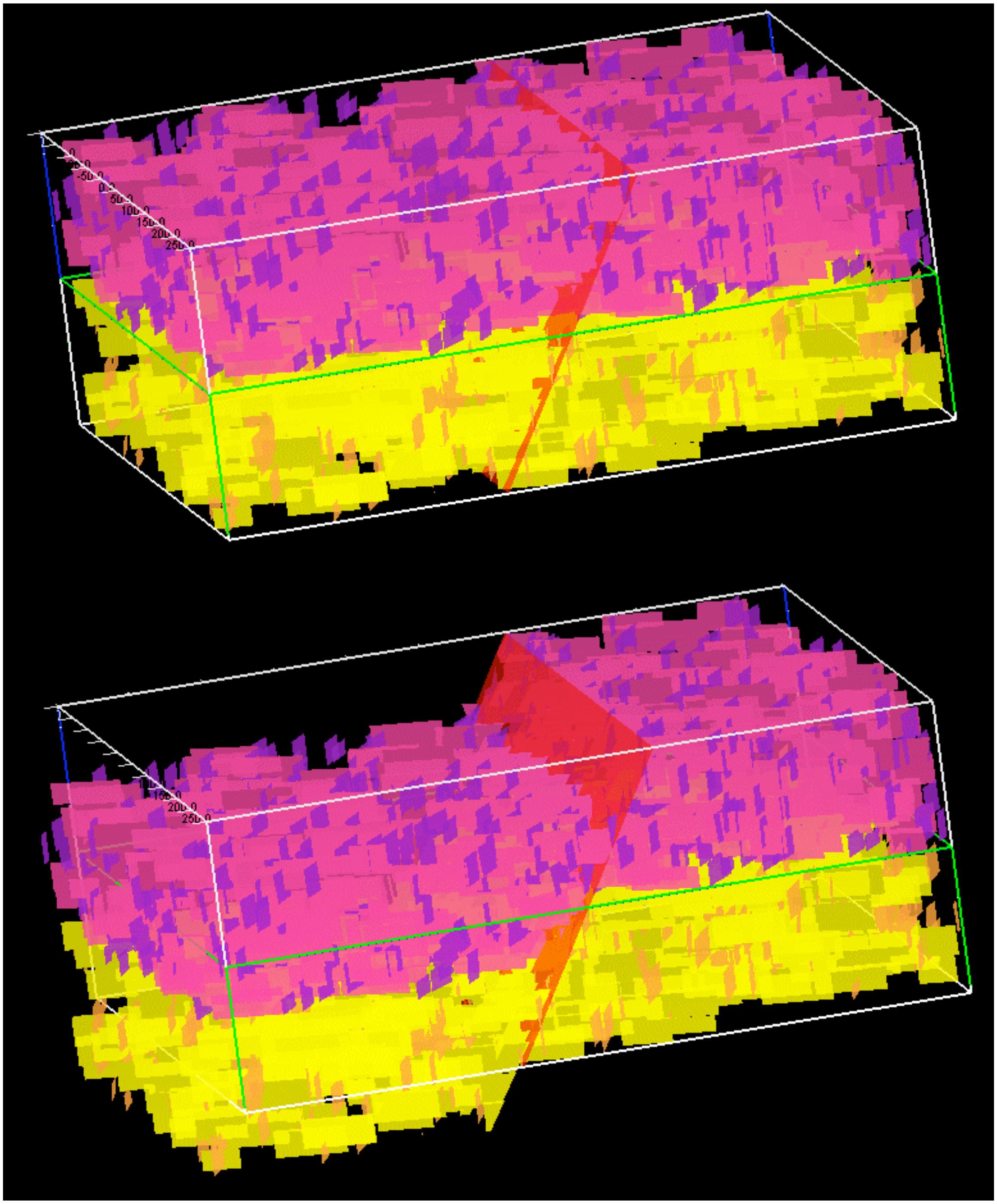


Figure 6.—Simulation of faulting in DFNModeler. Top: DFN model containing fractures (yellow and magenta) and a dipping fault plane (red) before slip is applied. Bottom: DFN model after normal fault slip is applied.

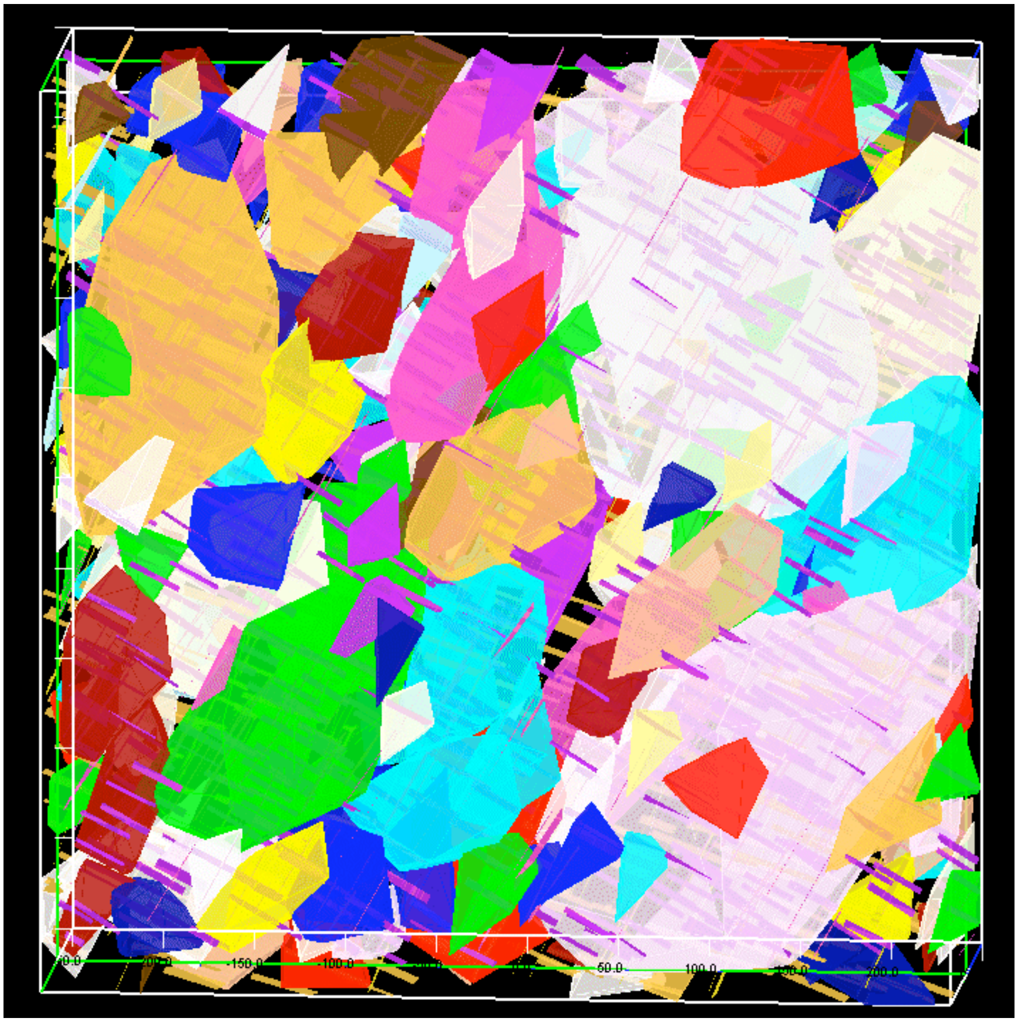


Figure 7.—Compartmentalization model based on the DFN model of joint networks that is shown in Figure 5. Colored polyhedra surrounding fracture polygons are compartment hulls.

Each fracture in a DFN model has its own table of interconnected fractures, and a compartment can be defined by performing a search of those interconnected fractures.

Additional functions built into DFNModeler include definition of well paths and identification of flow pathways. The location and trajectory of wells can be defined using a basic dialog box that can be accessed from the menu system. After a well path is defined and compartmentalization analysis is completed on a DFN model, pathways analysis can be performed. Pathways analysis is a technique that can be used to identify compartment hulls that are in communication with a well. When pathways analysis is performed in DFNModeler, all compartment hulls that intersect a well path are highlighted.

DFNModeler was designed to employ a broad range of OpenGL graphical functions. DFN models can be zoomed and rotated in real time. Users have a high degree of control over the color and transparency of virtually all model elements. In addition, fractures and compartment hulls can be color contoured according to a variety of parameters, including volume, aperture, and assigned hydrologic properties. Additional functionalities of DFNModeler are described in the section on software documentation, and the user is encouraged to explore the software to discover the full range of functionality and applicability to natural fracture systems.

Application to Black Warrior Basin

A broad range of field and laboratory techniques were employed to obtain the basic data necessary to develop DFN models of coalbed methane reservoirs in the Black Warrior Basin, and the methodology used in this study was similar to that employed by the earlier study of Pashin, Jin, and Payton (2004). The first step was to obtain data on the type, spatial relationships, and size of natural fractures in the Pottsville Formation. Orientation and spacing data were derived from outcrops and cores. In outcrop, the orientation of fractures was measured with a Brunton compass, and fracture spacing and fracture height were measured by tape. Fractures were then classified on the bases of orientation, spacing, and host rock. Outcrops also provide information on the height of fractures, which was also measured by tape. Most fractures are too long to determine horizontal fracture length directly, so orientation and cross-cutting relationships were used to estimate length.

Cores donated by Jim Walter Resources, Incorporated (fig. 8), provided critical information on fracture distribution, orientation, cementation, and aperture, and data were obtained from 2,615 joints and shear fractures in 15 cores. The dip of fractures was determined with a Brunton clinometer. Strike was not determined because the cores are not oriented. Aperture can be preserved where fractures are mineralized, and the width of mineralized fractures is typically referred to as kinematic aperture (Laubach and others, 1988; Stowell and others, 2001). A large proportion of the fractures in the Pottsville Formation are filled with calcite (Pashin and others, 1999; Pitman and others, 2003), and kinematic aperture was measured from 433 joints and shear fractures.

The statistical parameters required to construct DFN models were derived using a variety of spreadsheet, stereographic, and statistical software packages. The vector-mean azimuth and angular standard deviation of orientation data were determined using the equations of Krause and Geijer (1987). Dip modes of fractures were identified using stereoplots and histograms. A broad range of data on fracture orientation, spacing, size, and cross-cutting relationships were analyzed statistically, and population distributions were classified using the statistical tests of Baas (2000).

Numerous DFN models were constructed using DFNModeler software to simulate natural fracture networks and induced hydrofractures in the Black Warrior Basin. The SECARB Black Warrior test site is at the Jobson 24-14 #11 well (State Oil and Gas Board of Alabama permit 4001-C), which will serve as the injection well for the field test. Accordingly, the well logs and completion records from the Jobson well were chosen as the basis for stratigraphic control of the DFN models. Models were constructed to simulate joint systems in shale and sandstone, cleat systems in coal, and fault zones. Models were constructed at a variety of scales to display

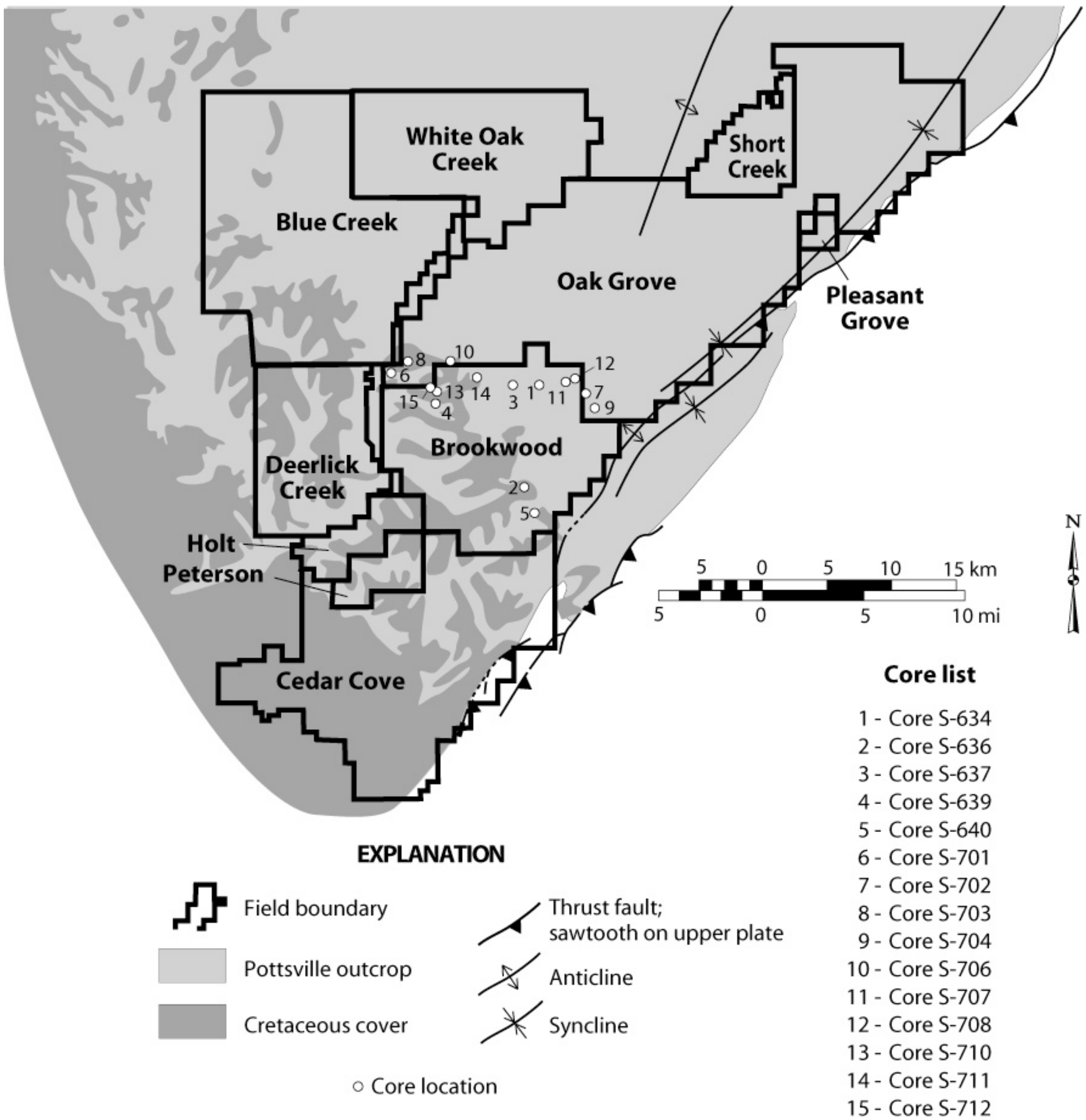


Figure 8.—Map showing locations of cores used to characterize fracture networks in coal-bearing strata of the upper Pottsville Formation.

fracture architecture and to support visualization and flow modeling. The largest of these models simulates fracturing over a 4 square-kilometer area to a depth of nearly 800 meters (m).

After the DFN models were completed, compartmentalization and pathways analysis were performed using the DFNModeler application. Compartmentalization analysis of DFN models enables delineation of interconnected fractures by testing for adjacency of fracture polygons

(Dershowitz and others, 1997). Where two or more fractures intersect, a hull (i.e., polyhedron) is constructed that connects the vertices of the fracture polygons. As such, a compartment hull can be considered as a no-flow boundary defining the limits of a reservoir compartment. Pathways analysis was used to identify the reservoir compartments that are contacted along specific well paths.

Flow Modeling and Risk Assessment

A flow model is a conceptual approximation of fluid flow processes in porous media using mathematical equations that include governing equations, boundary conditions, and initial conditions. These mathematical equations can be solved by numerical methods through the discretization of space and time. Because of the simplifying assumptions embedded in the mathematical equations and the many uncertainties in the data required by the flow model, a flow model must be viewed as an approximation and not an exact duplication of field conditions. However, even as an approximation, a flow model may be the only tool to predict, test, and compare a range of natural scenarios.

Prior to CO_2 injection operations, assessing the short- and long-term leakage risks associated with CO_2 sequestration is required to ensure that operations can be conducted safely and effectively. Simulating multiphase CO_2-H_2O flow provides a means by which to quantify possible leakage pathways, quantify the amount of leakage that can potentially take place, and to characterize the relationship of flow to fracture and matrix properties. As mentioned before, DFN modeling relies heavily on the basic concepts of stochastic simulation. Running CO_2-H_2O flow models based on different fracture network simulations is an effective way to characterize the uncertainty associated with injection into fractured media.

ECO2N is a fluid property module for the TOUGH2_MP simulator (Zhang and others, 2004; Pruess and Spycher, 2007) and was selected to model the flow of CO_2 and H_2O in selected DFN models that were generated during this study using an integral difference approach. TOUGH2_MP is the parallel processing version of TOUGH2, which is a general purpose numerical simulation program for the multi-dimensional flow of multiphase, multicomponent fluid mixtures in porous and fractured media (Pruess and others, 1999).

In TOUGH2, the continuum equation is discretized in space using the integral finite difference (IFD) method (Narasimhan and Witherspoon, 1976). The geometric parameters for the flow problem are grid block volumes V_n, the interface area between grid blocks *n* and *m* A_{nm}, distances D_n and D_m, and components g_{nm} of gravity acceleration in the direction of the line connecting nodal points *n* and *m* (fig. 9). A key advantage of the IFD technique for space discretization is that all geometric quantities are defined locally so there is no need to make reference to a global system of coordinates. A grid block *n* can be connected to many grid blocks *m* ($m = 1, 2$, etc.), and unstructured grids may be used. In addition, connected grid blocks do not need to be neighboring. These properties provide great flexibility when dealing with irregular features such as fractures in a flow model. Further details can be found in the TOUGH2 user's manual (Pruess and others, 1999).

ECO2N provides capabilities for modeling advection and diffusive flow and transport in multidimensional heterogeneous systems containing mixtures of H_2O, NaCl, and CO_2 (Pruess, 2005). In this study, only the flow of H_2O and CO_2 was modeled because the salinity of formation fluid in the study area is low (Pashin and others, 1991). Two phase conditions were modeled in ECO2N. One is an aqueous phase that is mostly water but may contain some dissolved CO_2, the other is CO_2-rich phase (gas or liquid) that is mostly CO_2 but may contain

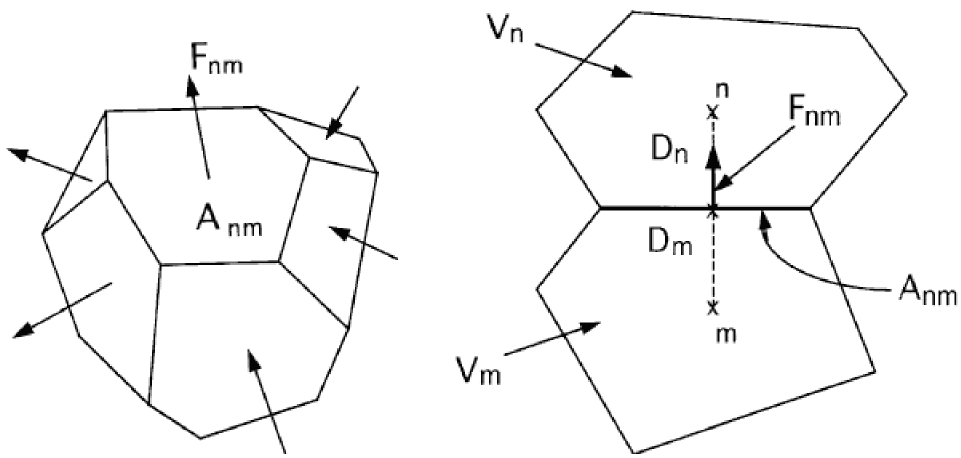


Figure 9.—Space discretization and geometry data in the integral finite difference method (modified from Pruess, and others, 1999).

some water. Importantly, H_2O is the wetting phase and CO_2 is non-wetting phase. Depending on pressure-temperature conditions, CO_2 was modeled as a gaseous or liquid phase.

Modeling flow in fractured reservoirs remains a challenge, although the basic behavior of fractured reservoirs has been modeled for many years (Warren and Root, 1963). Where fracture density is not high, some traditional methods like dual porosity and dual permeability may not be suitable. To properly represent DFN models, individual fractures need to be represented explicitly in the flow model. Flow can be modeled simultaneously along fractures and within rock matrix using the methods employed herein. In this study, discrete fractures were superimposed on porous rock matrix following the procedures of Zhang and others (2004). Thus, where fractures exist in a given domain, two kinds of grid blocks were used. One set of grid blocks was used to represent porous rock matrix, and the other set was used to represent fracture networks. The dual permeability concept was employed in this study to consider interactions within and between fractures and matrix.

The flow models developed in this study are based on multilayered models that simulate coal seams and joint networks. The DFN models were generated in DFNModeler and exported to ECO2N. The flow models were run using the methods discussed above, and the results were used to evaluate risks associated with the injection of CO_2 in coal-bearing strata. Key factors considered during flow modeling were the effects of individual fractures on leakage of injected CO_2 from coal, the effects of strata-bound fracture networks on reservoir leakage, and the nature and magnitude of risks associated with leakage of injectate.

Risk assessment was performed based on the results of DFN modeling, compartmentalization analysis, pathways analysis, and flow modeling. Key factors considered in risk assessment are the proximity of hydraulically conductive fractures to the injection point, the effects of strata-bound and trans-stratal fractures on fluid transport, and the effects of fault zones on reservoir continuity and cross-formational flow. An important goal of risk assessment was to evaluate the applicability of DFN models to carbon sequestration and enhanced coalbed methane recovery programs and to identify areas where DFN modeling tools can be improved.

SOFTWARE DOCUMENTATION

DFNModeler is a Windows application that can be used to generate and analyze discrete fracture networks. DFNModeler is designed to have 5 major functions: 1) input and editing of model data; 2) generation of discrete fracture networks; 3) analysis of compartmentalization and fluid migration pathways; 4) visualization of DFN modeling results; and 5) import and export of model data and results. A brief overview of these functions is given below:

Model Data

Data for DFN modeling are composed of fracture properties, fracture region properties, and rock matrix properties. Fracture properties commonly include statistical data on fracture orientation, cross-cutting relationships, fracture size and spacing, and hydrologic properties, such as aperture, transmissivity, and storativity. Fracture region properties include the geometry and orientation of the region containing a fracture system. A fracture region is defined as a geometric unit where fracture sets have the same statistical properties. Rock matrix properties include basic hydrologic properties, such as porosity, permeability, transmissivity, and storativity.

Generation of Discrete Fracture Networks

Once the data required to build a discrete fracture network have been entered, the next step is to generate a computer model of the fracture network. DFNModeler uses efficient algorithms to generate fracture populations and to simulate cross-cutting relationships between and among fractures. This allows the user to rapidly generate multiple realizations of fracture networks from a given set of input variables that can be used to characterize fracture architecture and to develop flow models.

Compartmentalization and Fluid Migration

Compartmentalization is an important measure of the interconnectivity among fractures. Compartmentalization analysis determines how far fractures at different stratigraphic levels can be interconnected and therefore provides us with information about how fluid can migrate and where effective no-flow boundaries may lie. A compartment is defined as a convex polyhedron, or <u>hull</u>, that connects the vertices of intersecting fractures. As the definition implies, fractures from different compartments are isolated from each other and thus fluid migration is hydrologically confined within the compartment boundaries.

Fluid pathway analysis is associated with wells penetrating different compartments. Fluid in one compartment can be transported into other compartments through a well which is open to multiple stratigraphic horizons or geologic structures, such as faults. Therefore, DFNModeler will determine if and how well placement may affect hydrologic communication among compartments that are separated geologically. All compartments that are connected to a well define the pathway of fluid migration from one compartment to another. For visual display, DFNModeler highlights compartments that are interconnected along a well path.

Visualization

DFNModeler enables visualization of modeling results with the help of OpenGL graphic rendering techniques. OpenGL allows real-time 3-D zooming, translation, rotation, and scaling of a DFN model. Apart from these standard visualization operations, DFNModeler can also color-contour fracture properties such as aperture, transmissivity, and storativity. In addition, variables such as color map and transparency can be customized.

Import and Export

Import and export functions are also implemented to enable DFNModeler to communicate with other modeling packages. Files can be imported from other DFN modeling software packages, such as Golder Associates FracMan. DFNModeler lacks flow modeling and solute transport capabilities, so data must be exported to other software packages for this purpose. The ECO2N module of TOUGH2 software was used for flow modeling in this study, and so the export function in DFNModeler translates fracture data into a text format that can be read by TOUGH2.

System Requirements

DFNModeler can be run on most modern personal computers and was designed with modest system requirements in mind. System requirements to run DFNModeler are as follows:

- A personal computer with the Microsoft Windows 2000 or Windows XP operating system installed (not tested with Microsoft Windows Vista).
- Microsoft Windows-compatible CPU with clock speed of 2.2 gigahertz or faster recommended.
- System RAM of 1.0 gigabytes or higher.
- OpenGL-capable graphics card with at least 32 megabytes of VRAM recommended (ATI Radeon X300 or better).

Menu Structure

DFNModeler employs a hierarchical menu system that provides users convenient access to all major software functions. The menu system is composed of seven main menu items that can be selected at the top of the main application window (fig. 2). Clicking on a menu item reveals a pull-down menu that displays specific software functions and sub-menus as is typical of software packages run under Microsoft Windows operating systems. A summary of each menu and its submenus is given below:

File Menu

The File menu allows users to create, open, close, or save any DFNModeler project (fig. 10). This menu also allows users to import fracture-related data and to export DFN models to TOUGH2 for flow modeling. Print functions, although listed in the menu, are currently not supported because there is no default support in the MFC library for OpenGL-rendered graphics. However, the user can take screen images of the modeling results by using the Print Screen function that is accessible directly from the keyboard of computers employing Microsoft Windows operating systems. At the bottom of the menu is the Exit item, which enables users to exit from DFNModeler into the main Windows operating environment.

View Menu

The View menu in DFNModeler serves a variety of purposes ranging from controlling the display of toolbars to manipulating the appearance of DFN models (fig. 11). The upper items in this menu can be used to toggle a toolbar that provides simple access to many file functions and a status bar that shows the state of the model display.

The DFN Model menu item enables display of model elements, such as fracture regions, fracture sets, and compartments. This item further enables color mapping and display of fracture attributes, such as aperture, transmissivity, and storativity. The Model Frame item provides control over the appearance of the model frame, which is the box bounding the DFN models.

Edit/View Mode toggles real-time manipulation and editing of DFN models. The lower part of the menu provides control over the appearance of DFN models and enables zooming, rotation, and vertical exaggeration of model realizations. The Home View item enables users to return to the default view that is used when models are initially displayed.

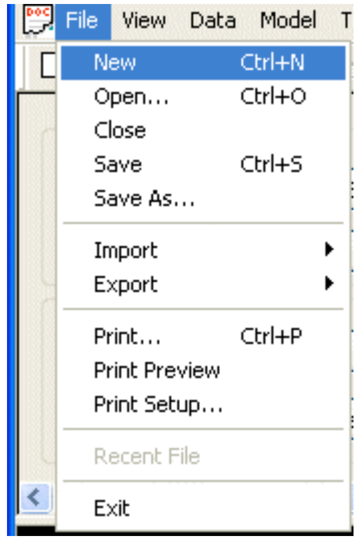


Figure 10.—Screen image of the File menu in DFNModeler.

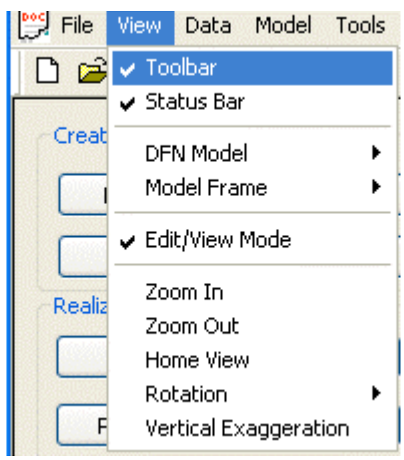


Figure 11.—Screen image of the View menu in DFNModeler.

Data Menu

The Data menu provides access to the basic tools for the construction and editing of DFN models (fig. 12). Parameters set under each menu item can be saved from within the data entry dialogs. The Model Definition menu item brings up a dialog box where users can define the boundaries and shape of a DFN model. The Region item brings up a dialog to define and parameterize fracture regions, and the Fracture Set item brings a dialog to define and

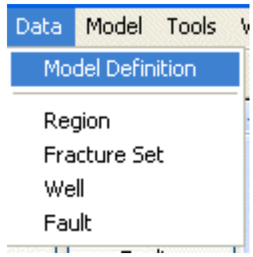


Figure 12.—Screen image of the Data menu in DFNModeler.

parameterize fracture sets. The Well menu item is used to define well paths, and the Fault item invokes a dialog box to define the orientation and slip of faults.

Model Menu

The Model menu (fig. 13) contains a set of menu commands that drive realization of a DFN model based on the parameters imported using the File menu or entered using the Data menu. The Initialize Seed menu item enables definition of a numerical seed that initializes a DFN model. To construct different realizations based on the same geologic parameters, users can enter different numerical seeds. Construction of models using the identical geologic parameters and numerical seeds will result in identical models.

The Realize menu item generates DFN models based on a given set of geologic parameters and a given numerical seed. Submenus under the Realize item enable realization of fractures, faults, and wells. After a model is realized, users can perform compartmentalization analysis and then fluid pathway analysis. Invoking the Compartment Analysis menu command results in the generation of compartment hulls in and around the DFN model. If well paths and compartment hulls have been generated, then the Pathway Analysis menu command can be used to highlight the compartments that are contacted by a well path.

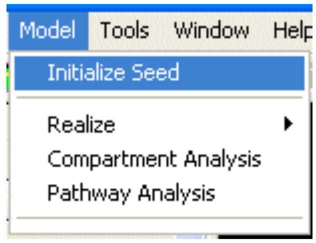


Figure 13.—Screen image of the Model menu in DFNModeler.

Tools Menu

The Tools menu facilitates customization of the appearance of the DFN models generated in DFNModeler (fig. 14). The Preferences menu item invokes a dialog box where default settings for lighting, color, and transparency can be assigned. The Lighting command enables definition of the type, intensity, and position of the virtual light sources that illuminate the DFN models. The Color Scheme command, by comparison, enables refinement of the color scheme used for model elements, such as regions, fracture sets, and compartment hulls.

Window Menu

The Window menu provides the standard window display options that are common to most applications running under Microsoft Windows operating systems (fig. 15). The upper part of the menu facilitates control over the arrangement of windows within the DFNModeler application. The bottom of the menu lists the windows that are open, and a check mark denotes the window that is currently active.

Help Menu

The Help menu (fig. 16) has been partially implemented in DFNModeler. The Help Topics item is currently inactive, and the user is therefore referred to this guide for information on the

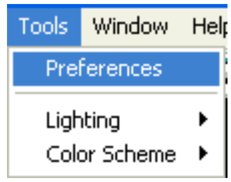


Figure 14.—Screen image of the Tools menu in DFNModeler.

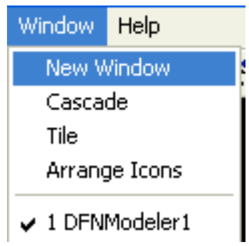


Figure 15.—Screen image of the Window menu in DFNModeler.

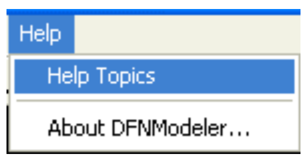


Figure 16.—Screen image of the Help menu in DFNModeler.

capabilities and used of DFNModeler software. The About DFNModeler item launches a window displaying the version information for the copy of DFNModeler that is running.

Data Entry and Editing

In DFNModeler, nearly all data entry and editing of data sets is performed through the Data menu (fig. 12). Each menu item invokes a dialog box where data can be entered and edited. This section focuses on the entry and editing of data using these dialog boxes.

Model Definition

The Model Definition menu item (fig. 12) invokes a dialog box where DFN models can be named and defined (fig. 17). A name can be applied to a DFN model in the Model Name field in the upper part of the dialog box. The size of the model, which is defined in units of meters, can be specified in the Model Size field. Clicking OK saves the model definition, whereas clicking Cancel dismisses the dialog box without saving the most recently entered information.

Defining Fracture Regions

The Region menu command (fig. 12) invokes a dialog box that enables the definition of fracture regions (fig. 18). Fracture regions are listed in the region list field in the upper-left part of the dialog box. New regions can be created by clicking the Create New Region button, which brings up an additional dialog box where the region can be named (fig. 19). Regions can be deleted by clicking the Delete Region button (fig. 18). Regions can be imported from existing data files using the Load Regions button. All changes made to the region list can be saved for future use by using the Save Regions button.

A stratigraphic name can be applied to a region in the Stratigraphy field in the upper part of the dialog box (fig. 18). Below this is a pull-down menu that can be used to assign the region as a box or slab region (see fig. 4). The remaining data entry fields are used to define the position, size, and orientation of the fracture region (fig. 18). Click the Update Region Properties button to save the data entered for each region. Clicking the OK button in the lower-left part of the dialog box will save all changes and dismiss the dialog box, whereas clicking Cancel will dismiss the dialog box without saving changes.

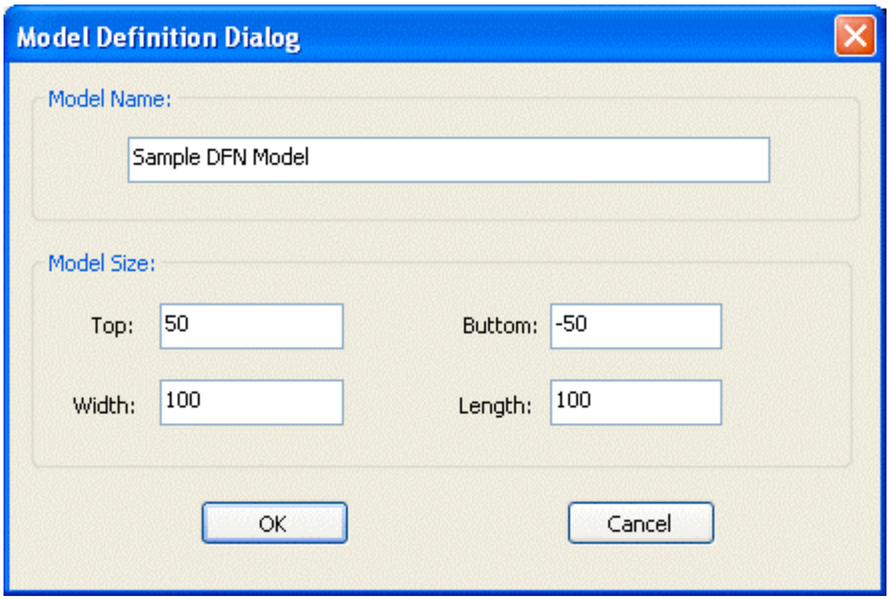


Fig. 17.—Model Definition dialog box.

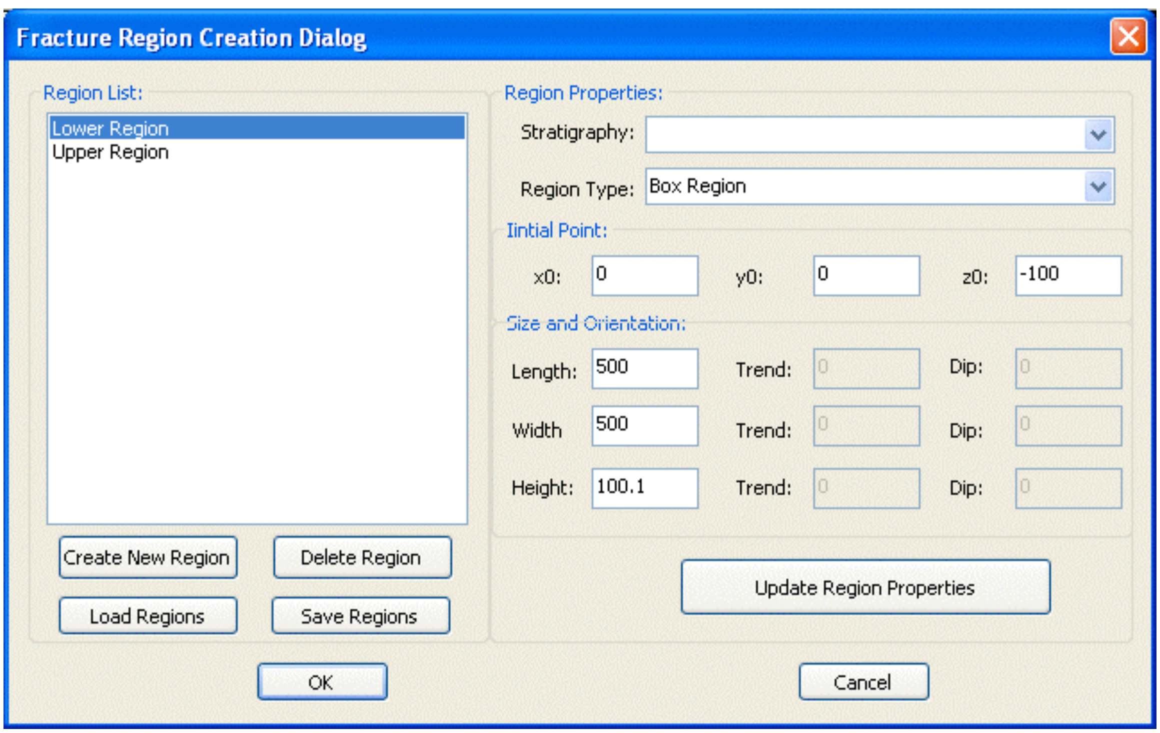


Fig. 18.—Dialog box used to create fracture regions.

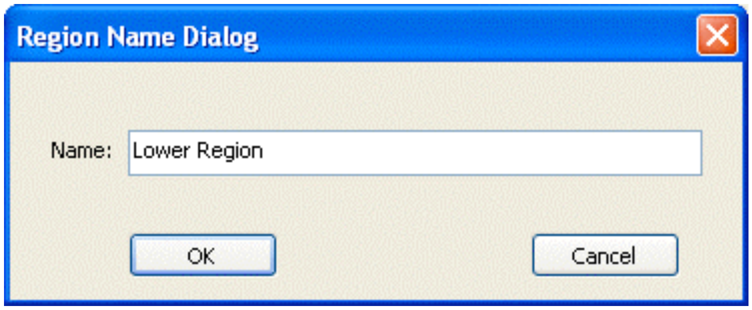


Figure 19.—Dialog box used to name fracture regions.

Defining Fracture Sets

Selecting the Fracture Set command in the Data menu (fig. 12) brings up a dialog box that enables the definition and parameterization of fracture sets. In the upper part of the dialog box is a list of available fracture sets (fig. 20). Clicking the Create button brings up a dialog box where a new fracture set can be named (fig. 21). Clicking the Load button (fig. 20) invokes a dialog box where existing fracture set files can be loaded. The Save Data button is used to save fracture sets defined during the current session.

The Location Model field in the upper-right part of the dialog box (fig. 20) is used to assign fracture sets to fracture regions. A fracture set must be assigned to a fracture region in order for it to be generated by DFNModeler. Clicking the Assign button brings up a list of available fracture regions. If an appropriate fracture region is not available, clicking the Create button brings up the region creation dialog box described in the previous section.

Fracture orientation is defined in the Orientation field. The user can enter trend (strike) and dip of any fracture set that can be selected from the Fracture Set List field. Fracture distribution can be uniform or can follow a Fisher (normal) distribution. If a Fisher distribution is selected, a concentration parameter (K1) must be entered. As the value of K1 increases, the orientation of

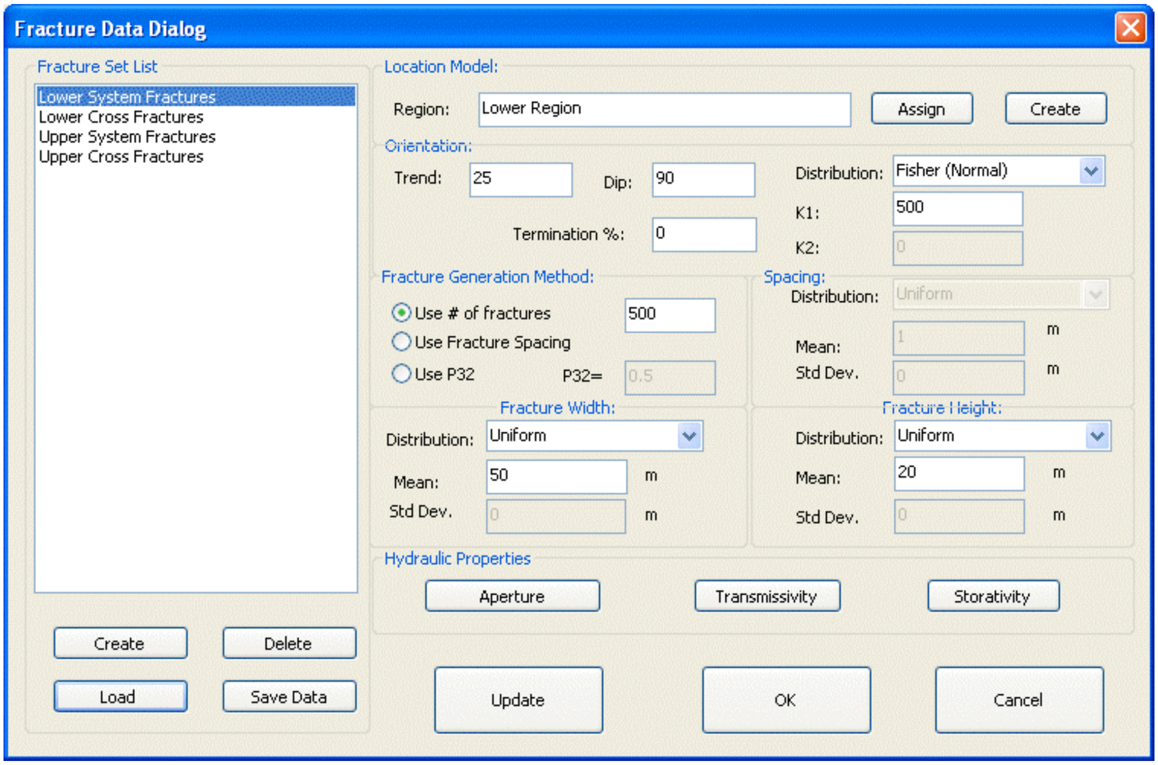


Figure 20.—Dialog box used to define and parameterize fracture sets.

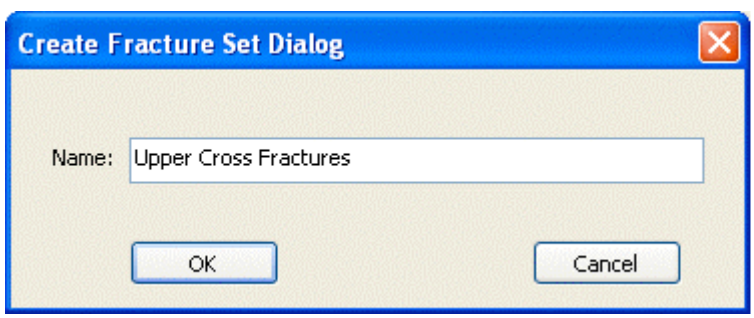


Figure 21.—Dialog box used to name a fracture set.

individual fractures will vary less. If a uniform distribution is selected, all fractures will have the same orientation.

Fractures can be generated by three methods. Selecting Use # of Fractures will assign a specific number of fractures to a given fracture set within a fracture region. Using Fracture Spacing will distribute fractures throughout the model based on fracture spacing. The third option uses the P32 parameter of Dershowitz and others (1999). Only the first method is currently implemented in DFNModeler, and the other methods will be implemented in future versions.

The Fracture Width and Fracture Height fields can be used to define the basic dimensions of fractures within a fracture set. Width, also known as length, can be used to specify the horizontal dimension of fractures parallel to trend or strike, and height can be used to specify the vertical dimension of fractures. The Distribution fields can be used to specify the appropriate statistical distributions for width and height, specifically uniform, log normal, exponential, and power-law. Appropriate parameters, such as the mean and standard deviation of the statistical distribution can be entered below the Distribution field.

The aperture, transmissivity, and storativity of fracture networks can be assigned using the three appropriate buttons in the Hydraulic Properties field in the lower part of the dialog box. Clicking each button brings up a dialog box that enables the definition of these hydraulic properties according to a series of statistical parameters.

The user must click the Update button to save all changes made to each fracture set during the current session. The OK button can be used to dismiss the dialog box while accepting changes to the fracture set that is currently displayed, whereas the Cancel button can be used to or dismiss the dialog box without accepting changes.

Defining Wells

Choosing the Well item from the Data menu (fig. 12) launches a dialog box that enables users to define well paths (fig. 22). Wells can be named in the Name field in the upper part of the dialog box. The Well Location field enables users to determine the position of the well within in

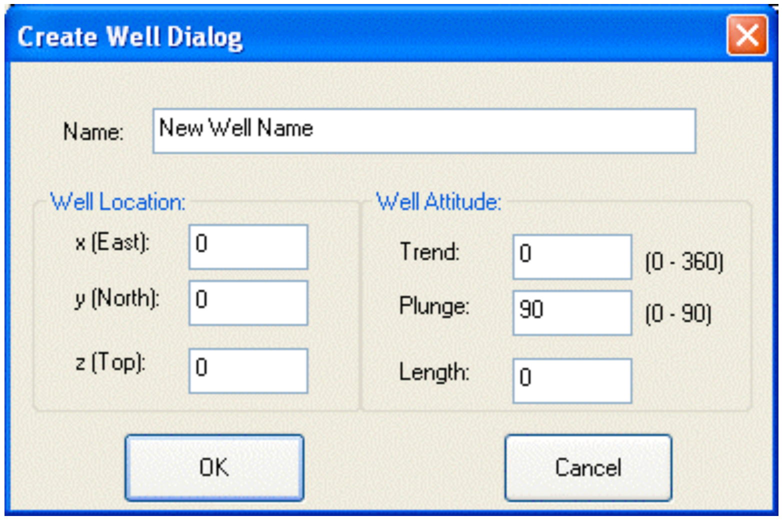


Figure 22.—Dialog box to define well paths in DFNModeler.

the DFN model. The Well Attitude field enables users to specify the trend (bearing), plunge, and length of the well path.

Complex well paths can be simulated as a series of straight wells using this dialog. For example, a curved well path can be simulated by defining a series of wells in which plunge decreases with depth. In many circumstances, it is desirable to simulate a complete wellbore length for the purpose of visualization and to simulate only the parts of the well that are open to a reservoir when conducting pathways analysis, which is discussed later in this documentation in the section on modeling and analysis.

Defining Faults

Choosing the Fault item from the Data menu (fig. 12) invokes a dialog box that enables definition of fault parameters (fig. 23). At the top of the dialog is the Name field, which can be used to name and identify faults. The location and attitude of the fault plane can be specified in the middle part of the dialog box. Fault location is defined on the basis of x, y, and z coordinates

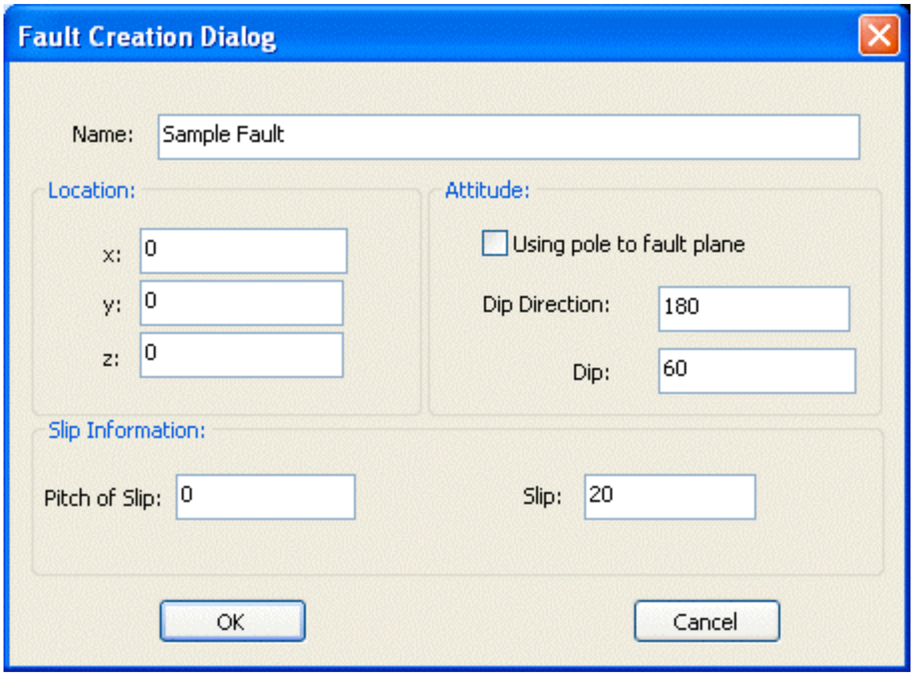


Figure 23.—Dialog box used to define faults.

as expressed in meters, and fault attitude is defined in terms of dip direction (azimuth) and dip as expressed in degrees. Users further have the option of defining fault attitude using the pole to the fault plane.

In the lower part of the dialog box is the Slip Information field, which defines fault slip in terms of the angle of pitch in degrees and the magnitude of slip in meters. Clicking the OK button saves the information in the dialog box and dismisses the box, whereas clicking Cancel dismisses the dialog box without saving the changes.

Import and Export

Data can be imported to and exported from DFNModeler by choosing Import or Export from the File menu (fig. 24). Three types of data can be imported into and exported from DFNModeler. Fracture set data from DFNModeler and FracMan can be imported as .fab files,

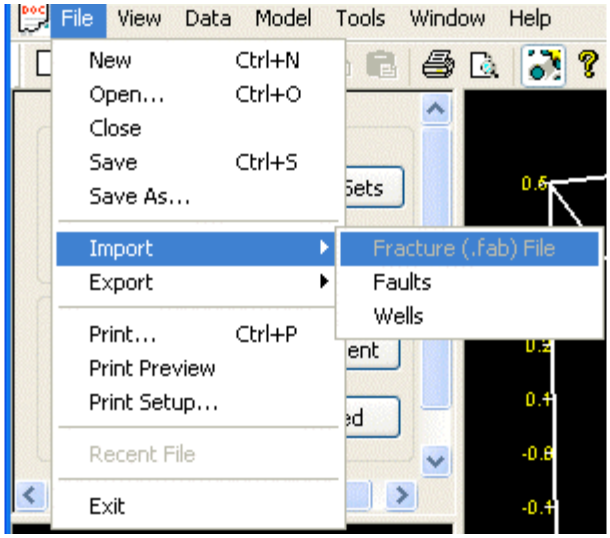


Figure 24.—Screen image showing import functionality in DFNModeler.

which are in a format defined for FracMan software by Dershowitz and others (1999). In addition, fault data and well data developed in DFNModeler can be imported. All data are exported as binary data files. These import and export functionalities enable DFNModeler to communicate with other DFN modeling software packages, such as FracMan and with flow modeling packages like TOUGH2.

Visualization Tools

DFNModeler makes use of an advanced OpenGL visualization engine and provides with a diverse set of visualization tools that can be used to manipulate and customize DFN models. Most visualization functions can be accessed through the View menu (fig. 25). Alternatively, the functions of the View menu can be accessed through the contextual menu system with a right-click of the mouse.

The first step in visualization is to use the Realize functions of the Model menu (fig. 13). The Realize menu item leads to a submenu in which key model elements, such as regions, fracture

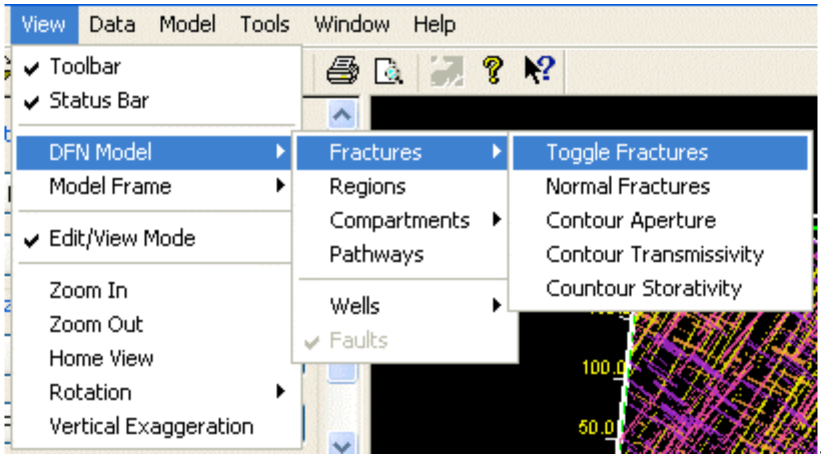


Figure 25.—Menu choices for displaying DFN models.

sets, faults, and wells, can be displayed. Upon selection of the items in the submenu, model elements are drawn in the model display area in the right-hand side of the DFNModeler application interface (fig. 2).

After model elements are realized, the appearance of those elements can be controlled by using the DFN Model menu item of the View menu (fig. 25). The DFN Model menu command leads to a hierarchical set of submenus that controls key model attributes. The Fractures submenu enables toggling and color contouring of fracture sets. Toggling fractures on and off is useful when viewing complex DFN models where fractures may clutter the view of key model elements, such as fracture compartments, faults, and well paths. The Normal Fractures command displays fractures with specified colors and transparency. This command is useful for restoring fracture sets to their original appearance after color contouring fractures according to attributes, such as aperture or transmissivity. To color contour fractures by attributes, such as aperture (fig. 26), transmissivity, or storativity, simply select the Contour Aperture, Contour Transmissivity, or Contour Storativity command from the Fractures submenu (fig. 25).

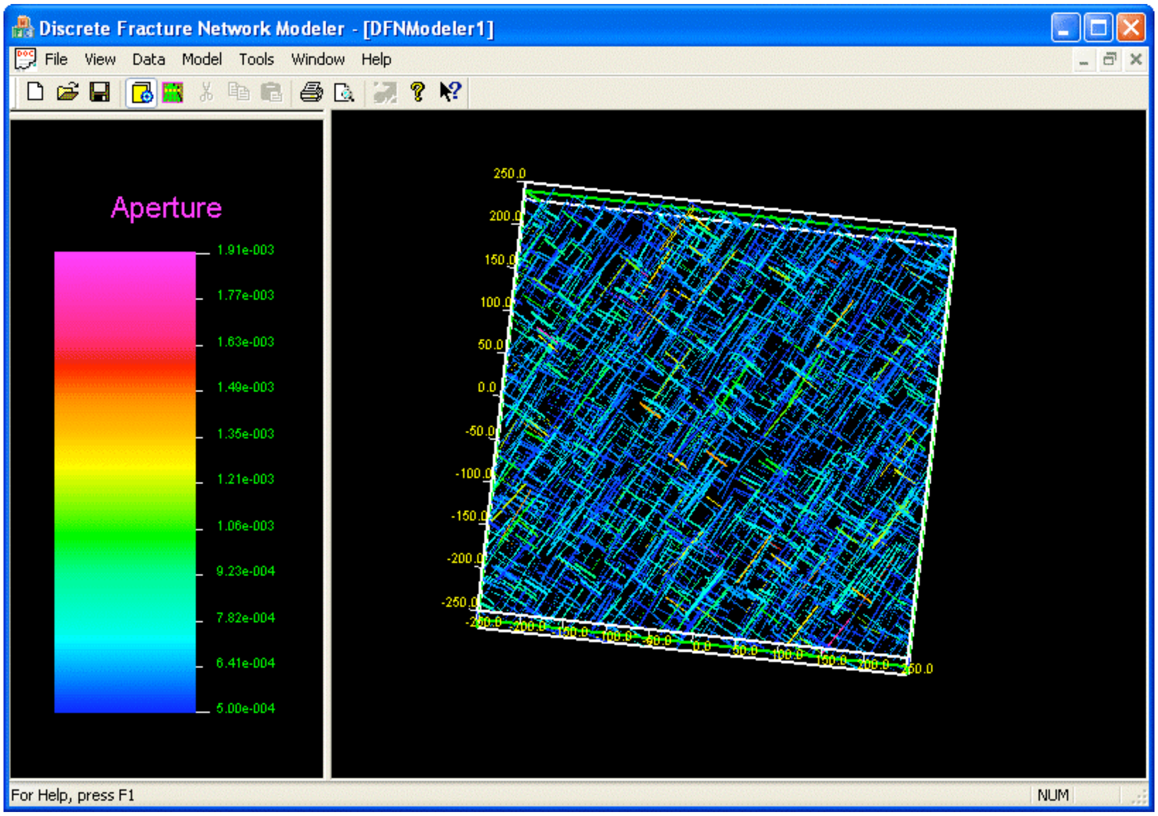


Figure 26.—DFN model contoured by fracture aperture

The Regions submenu allows users to set preferences for the display of fracture regions. This command launches the Object Display dialog box, which contains numerous options for customizing model elements (fig. 27). The DFN Object Type field contains a pull-down menu that lists the types of model elements, such as fracture regions, fracture sets, and compartments, that can be manipulated using this dialog box. In this case, fracture regions are selected, and a list of available fracture regions is listed in the Fracture Regions field. Fracture regions can be selected for manipulation directly by using the mouse, and all regions can be selected using the Select All button. The Refresh button can be used to deselect all items in the Fracture Regions field.

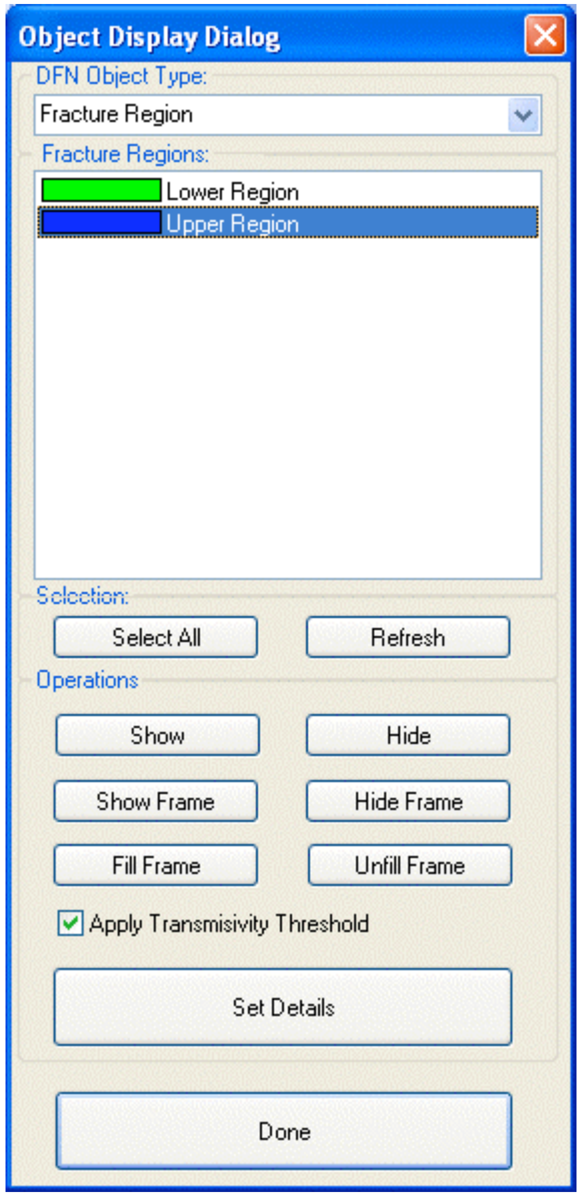


Figure 27.—Object Display dialog box.

A large number of operations can be performed using the buttons in the lower part of the Object Display dialog box (fig. 27). Selected fracture regions can be displayed by clicking the Show button or can be hidden using the Hide button. The Show Frame button is to display a frame outlining selected regions, and the Hide Frame button will hide the frames of selected regions. The Fill Frame button fills selected regions with a specified color, and the Unfill Frame button can be clicked to remove the fills. The Apply Transmissivity Threshold check box can be selected to display only fractures with transmissivity above a given threshold. This enables users to omit low-transmissivity fractures from DFN models and can further be used to reduce the number of fractures prior to the calculation of reservoir compartments, which can be time-intensive in extremely large DFN models. The Set Details button launches a dialog box that enables users to define the transmissivity threshold and to assign color and transparency to each region. Through the Set Details dialog or the Tools menu, users can access another dialog box to specify the color and transparency of selected DFN model components by using a color picker or sliding RGB color and transparency controls (fig. 28). Clicking the Done button will dismiss the Object Display dialog box (fig. 27).

Options available under the Compartments submenu of the DFN Model menu item are similar to those available under the Fractures submenu (fig. 25). For example, compartment hulls can be toggled on and off. A key feature is the ability to color contour compartments by volume. Using the Normal Compartment command restores the color-contoured compartment hulls to the original colors. DFNModeler further provides control over the appearance of fluid pathways and wells using tools similar to those discussed above.

The easiest way to translate, zoom, and rotate DFN models is with the mouse and keyboard. To translate a DFN model within the model window, position the pointer within the window, press and hold the left mouse button, and move the mouse. To zoom in and out, press and hold the right and left mouse buttons simultaneously and move the mouse. Moving the mouse forward zooms in, whereas moving in backward zooms out. Models can be rotated by pressing and holding the left mouse button while pressing and holding the CTRL key and moving the mouse.

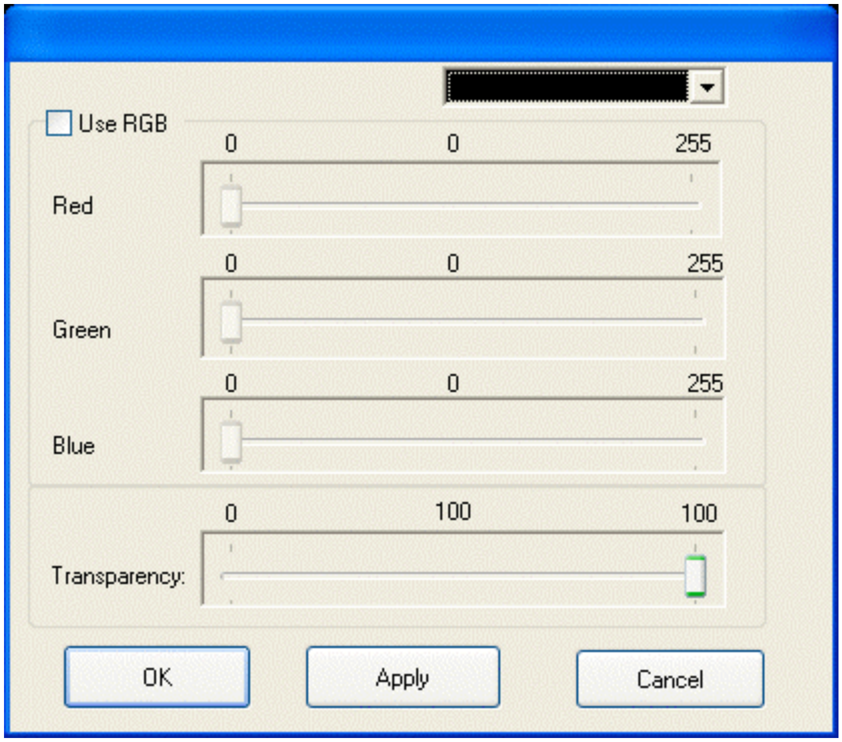


Figure 28.—Color Selection dialog box.

The user can combine the above operations to visualize any part of the model at the desired detail.

Controls for the zoom, rotation, and vertical exaggeration of DFN models are also available in the lower part of the View menu (fig. 25). Selecting the Zoom In and Zoom Out menu items can be used to control zoom in pre-set increments. The Home View menu command returns the size and orientation of the DFN model to default parameters. Rotation can be specified manually relative to X, Y, and Z components in degrees, and the Vertical Exaggeration command brings up a dialog box where the vertical exaggeration of a DFN model can be specified.

Modeling and Analysis

DFNModeler provides an array of tools for the modeling and analysis of fracture networks, and much of this functionality can be accessed through the Model menu (fig. 13). Key modeling and analytical functions available in DFNModeler include the construction and visualization of DFN models, compartmentalization analysis, and pathways analysis.

The Initialize Seed menu item (fig. 13) enables definition of a numerical seed that initializes a DFN model. To construct different realizations of DFN models based on a single set of geologic parameters, users can enter different numerical seeds. Construction of models using the identical geologic parameters and numerical seeds will result in identical models.

The Realize menu item (fig. 13) generates DFN models based on a given set of geologic variables and a given numerical seed. Submenus under the Realize item enable realization of fractures, faults, and wells. After a model is realized, users can perform compartmentalization analysis and then fluid pathway analysis. After a model is realized, users have access to the full suite of analytical tools described earlier in the section on visualization tools. Some important analytical capabilities, such as the color contouring of fractures by aperture, transmissivity, and storativity can be accessed through the View menu (fig. 25).

After a DFN model is realized, advanced functions, such as compartmentalization analysis can be performed. To perform compartmentalization analysis, simply go to the Model menu and select the Compartmentalization command (fig. 13). A progress bar will appear showing the status of the compartmentalization analysis, and compartment hulls will be drawn in the DFN model after the progress bar disappears (figs. 7, 29). Before performing compartmentalization analysis, be sure that all desired model elements are shown in the visualization window.

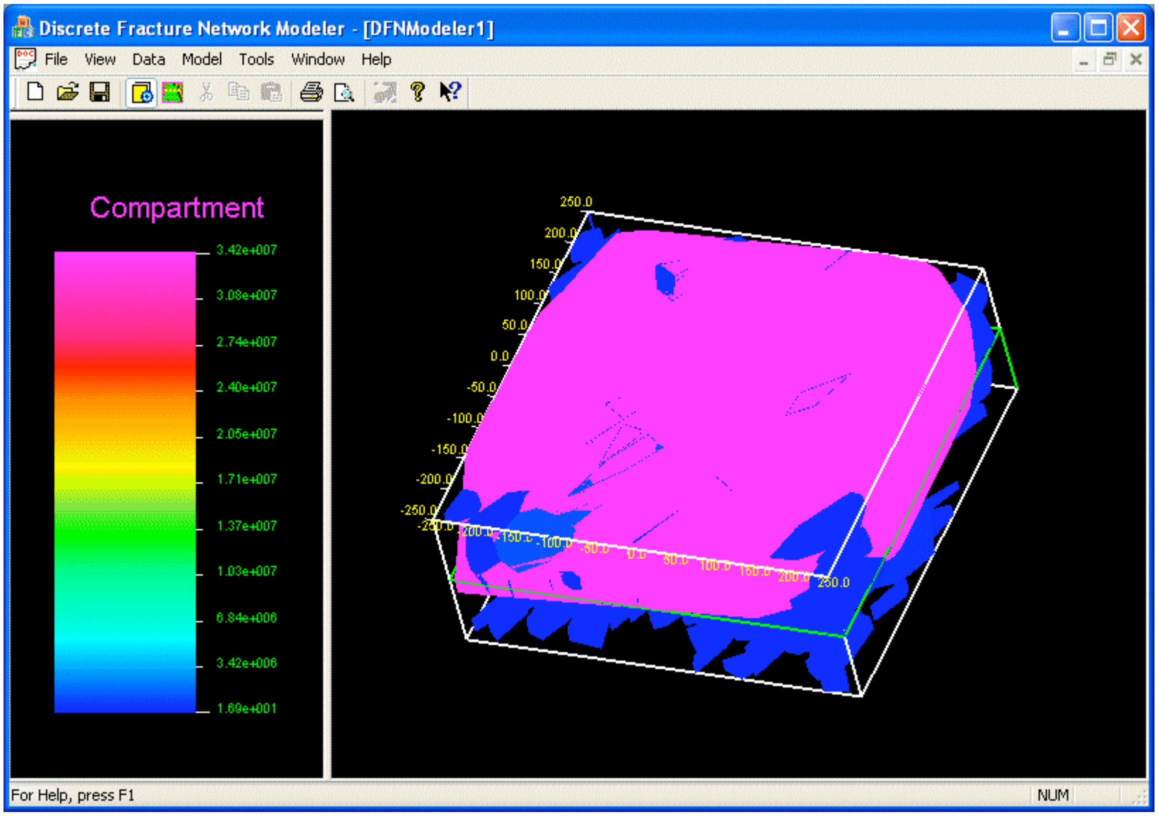


Figure 29.—Compartmentalization model with compartment hulls color contoured by volume.

Compartmentalization analysis can be performed on a completed DFN model or a partial DFN model. One approach that may be useful is to perform Compartmentalization on a complete DFN model to analyze the degree of structural interconnectivity in a fracture network and then apply a series of transmissivity thresholds using the Object Display dialog box (fig. 27) to analyze hydraulic interconnectivity. After hulls are drawn, users can customize color and transparency using the Object Display dialog box or can color contour the hulls according to volume using the submenus of the View menu (fig. 25).

Fluid pathway analysis is performed by selecting the Pathway Analysis function in the Model menu (fig. 13). Importantly, pathway analysis can be performed after compartmentalization analysis and only on DFN models containing at least one well. After the Pathway Analysis function is selected, a dialog box will appear that contains a list of available wells and some view options. Simply select a well, and the compartment hulls in contact with that well will be highlighted (fig. 30). The model can then be zoomed and rotated to examine intersections of highlighted compartment hulls with other wells. Selecting additional wells, moreover, helps determine if wells share common flow pathways or if they are in hydraulic communication with unique reservoir compartments.

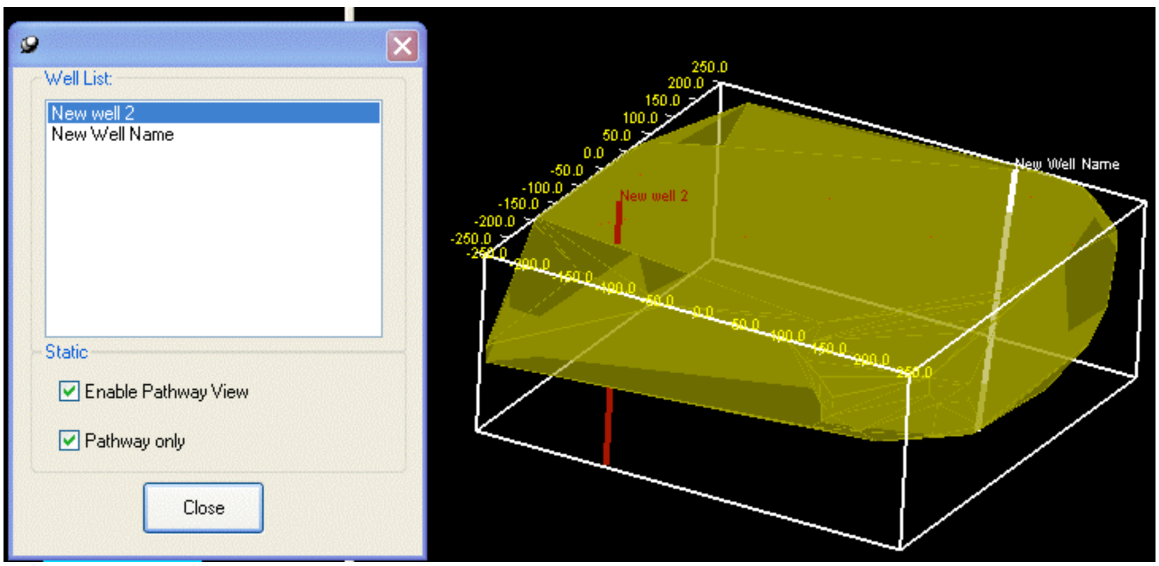


Figure 30.—Dialog box and DFN model showing results of pathways analysis.

APPLICATION TO BLACK WARRIOR BASIN

This section reviews the application of DFNModeler software to coalbed methane reservoirs of the Black Warrior Basin and the SECARB Black Warrior test site. Throughout this section, readers are encouraged to consider the techniques used in this study and how they can be adapted and applied to other sedimentary basins with coalbed methane and carbon sequestration potential. The discussion begins with an analysis of the geology and statistical properties of the fracture networks that form the basis of the DFN models. Next, the discussion turns toward simulation of the SECARB test site using DFNModeler software. Following this, the discussion concludes with compartmentalization analysis and pathways analysis of the DFN models.

Pottsville Fracture Networks

Economic coal resources in the Black Warrior Basin are concentrated in the upper Pottsville Formation (Lower Pennsylvanian), and coalbed methane production is restricted to the eastern part of the basin in Alabama (fig. 1). The upper Pottsville constitutes a succession of shale, sandstone, and coal that ranges in thickness from 600 to more than 1,400 m (fig. 31). Coal beds are generally thinner than 3 m, and beds as thin as 0.3 m are targets for coalbed methane production (e.g., Pashin and Hinkle, 1997; Pashin, 1998, 2007). Pottsville coal beds are clustered in coal zones, and each coal zone caps a marine-terrestrial depositional cycle (e.g., McCalley, 1900; Pashin, 2004). Coalbed methane is most commonly produced from the Black Creek, Mary Lee, and Pratt coal zones, although younger coal zones are productive in parts of the basin. Upper Pottsville coal zones are separated by coarsening-upward intervals of interbedded shale and sandstone that are between 10 and 120 m in thickness.

Pottsville strata in the eastern Black Warrior basin are folded, faulted, and fractured, and these types of geologic structures have a significant impact on reservoir properties (e.g., Semmes, 1929; Pashin and Groshong, 1998). The Pottsville Formation forms a structural homocline that dips southwest and contains numerous superimposed folds and faults (Semmes, 1929; Thomas, 1988) (fig. 32). Folds of the Appalachian thrust belt are superimposed on the southeast margin of this homocline. The axial traces of these folds strike northeast and include the Sequatchie anticline, the Coalburg syncline, and the Blue Creek anticline. The southwest-dipping homocline is broken by a multitude of normal faults that generally strike northwest.

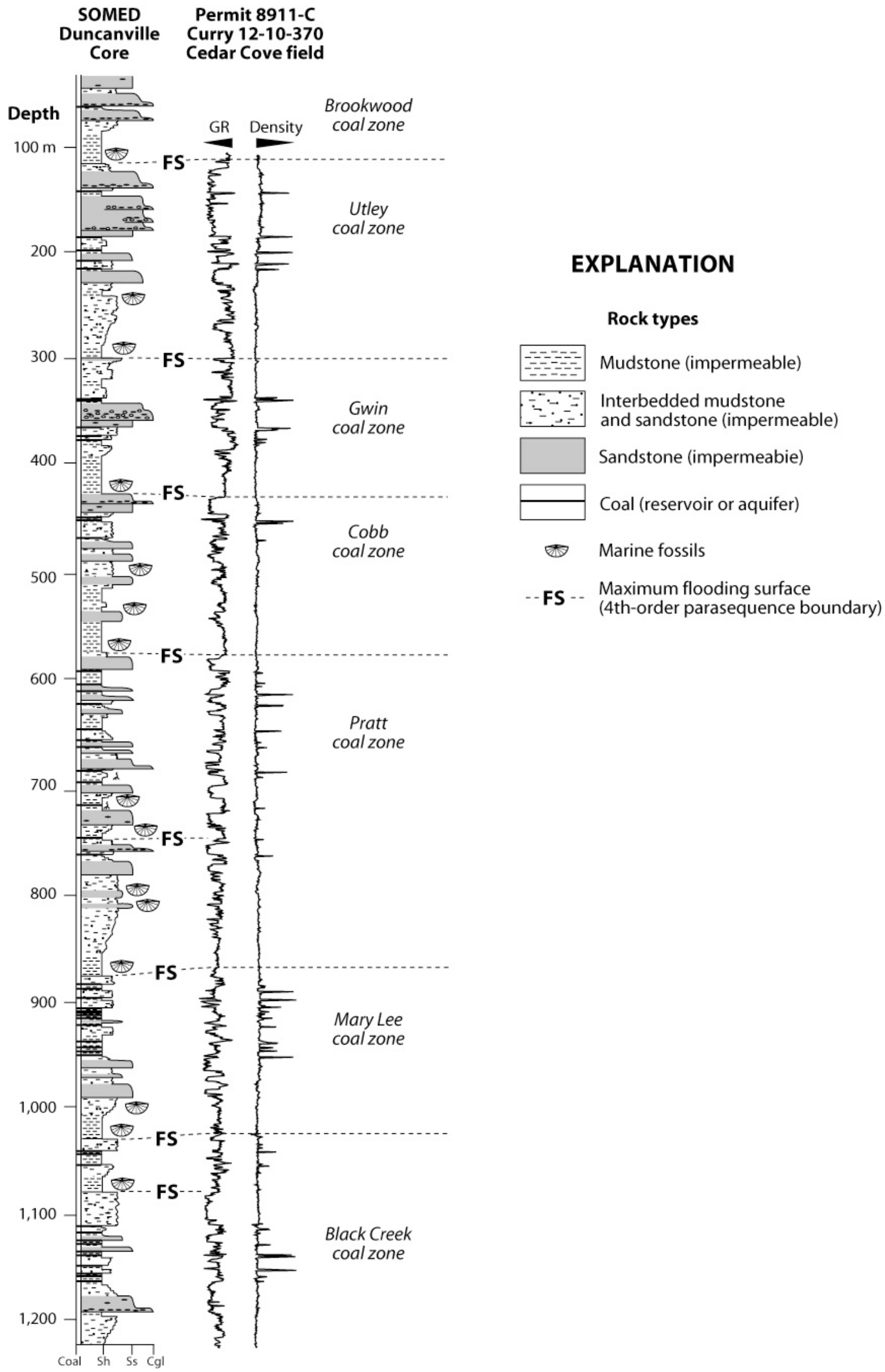


Figure 31.—Core log and geophysical well log showing the stratigraphic section of the upper Pottsville Formation in the Black Warrior coalbed methane fields (modified from Pashin and Hinkle, 1997).

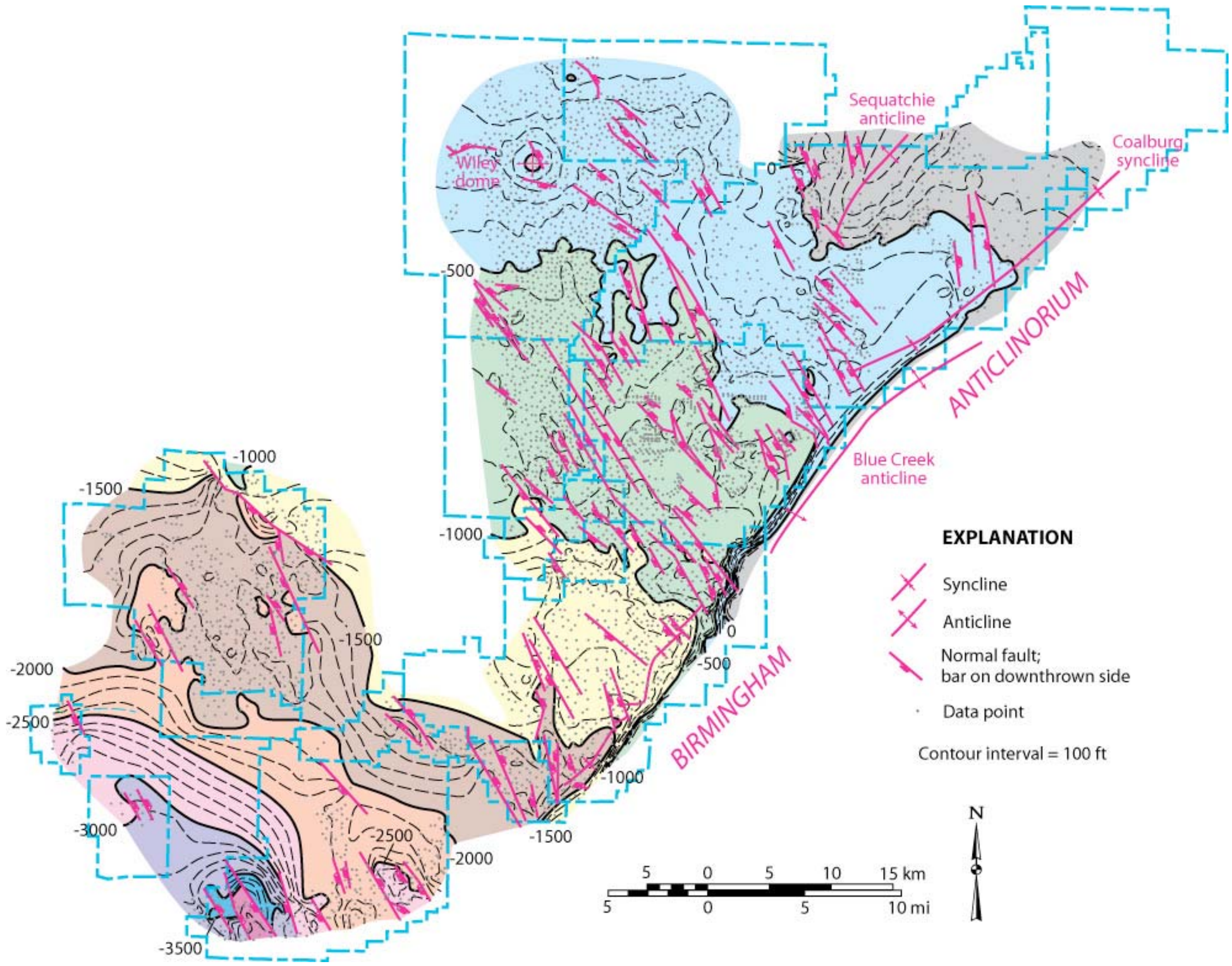


Figure 32.—Structural contour map of the top of the Pratt coal zone in the Black Warrior coalbed methane fields (modified from Pashin, Carroll, and others, 2004).

Trace length of the subsurface-mappable faults ranges from about 1 to 13 kilometers (km). Strike of the faults averages about N. 30° W. and ranges from N. 7° W. in the backlimb of the Sequatchie anticline to N. 54° W. in farther west in the interior of the basin. The faults constitute a horst and graben system, and dip of the faults is generally between 50 and 70°.

The shale, sandstone, and coal of the upper Pottsville in the Black Warrior coalbed methane fields have effectively no matrix permeability to water (Pashin and Hinkle, 1997). Accordingly, natural fractures are the primary hydrologic conduits in these strata. Fracture networks in the upper Pottsville include joints, cleats, and fault-related shear fractures (Ward and others, 1984; Pashin, Jin, and Payton, 2004) (fig. 33). Cleat systems are the principal source of permeability in coal, whereas joints and fault-related shear fractures in the intervening strata potentially provide avenues for cross-stratal flow. Each type of fracture has distinctive geologic and statistical attributes, and these attributes are discussed in detail below.

Joints

Joints are widespread in shale and sandstone and are typically spaced between 0.5 and 10 m. Joint systems in the Pottsville Formation form orthogonal sets of near-vertical fractures composed of systematic joints and cross joints (Ward and others, 1984; Pashin and others, 1999; Pashin, Jin and Payton, 2004) (fig. 34). Systematic joints are planar and can have surface traces on the order of 100 m. Cross joints are shorter than systematic joints, tend to strike perpendicular to systematic joints, and commonly terminate at intersections with systematic joints.

Systematic joint systems can maintain consistent orientations in the eastern Black Warrior basin (Ward and others, 1984) (fig. 35). Joints in sandstone and shale have been subdivided into a regional joint system and a localized joint system that is restricted to the area containing Appalachian folds (fig. 35A). Systematic joints of the regional joint system strike with a vector mean azimuth of N. 47° E., whereas systematic joints of the fold-related system strike with a vector mean azimuth of N. 64° W. Observations from underground coal mines indicate that the regional joint systems persist at reservoir depth (Ward and others, 1984), and these joint systems are the primary focus of this study. The regional joint system apparently formed in a basinwide stress field stress-release fractures, whereas the localized joint system formed in response to stresses within Appalachian folds (Ward and others, 1984; Pashin and others, 1999). In addition

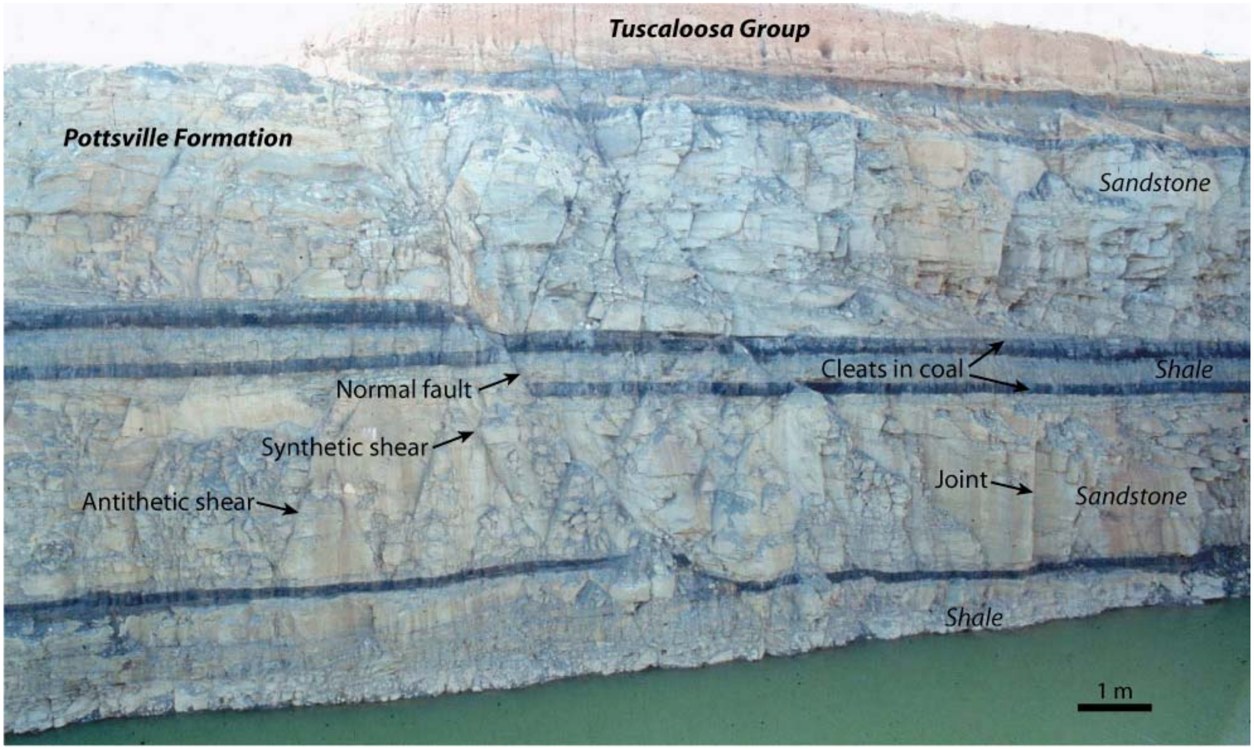
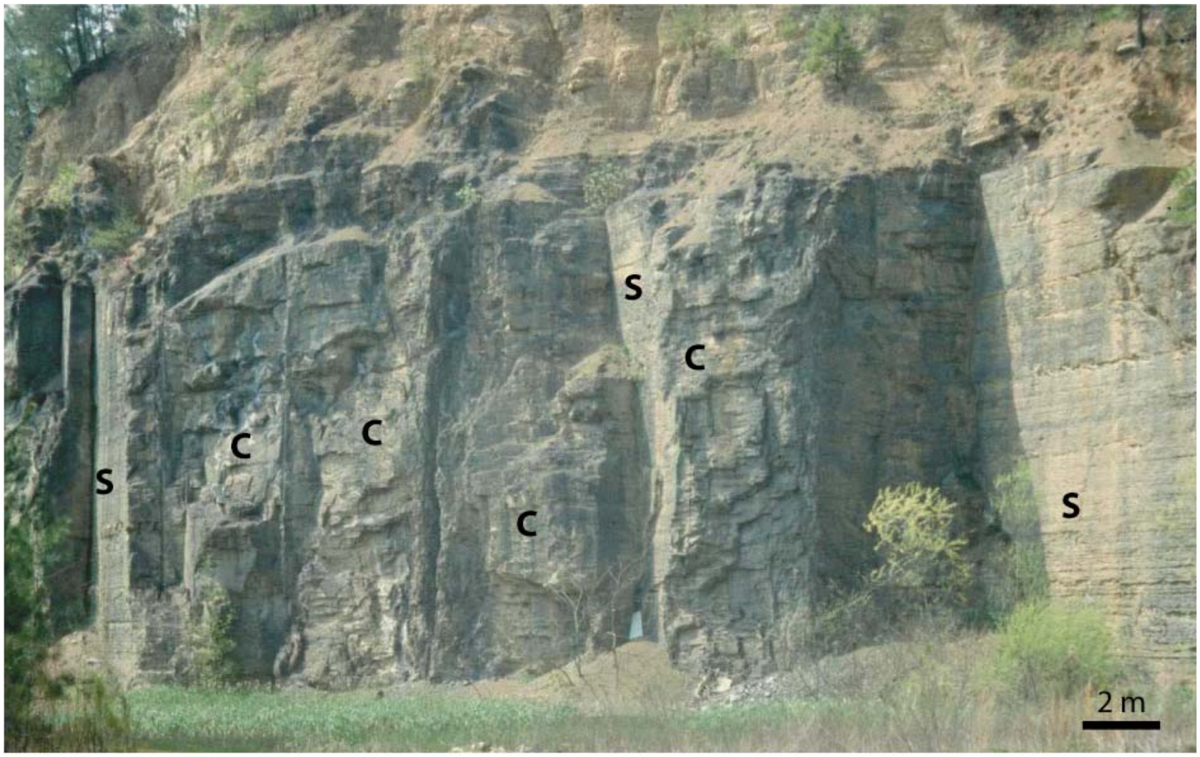


Figure 33.—Photograph of a mine highwall showing relationships among cleated coal seams, jointed shale and sandstone, and a normal fault with associated fault-related shear fractures.

to regional and fold-related joint systems, near-surface joint systems and bed-parallel partings that are associated with local topography have been identified in the Black Warrior Basin (Pashin, Jin and Payton, 2004). These shallow fracture systems are not considered in the current study because they apparently do not reach reservoir depth.

A series of abandoned mine highwalls (secs. 30 and 31, T. 18 S., R. 8 W.) in the Brookwood coal zone north of the SECARB Black Warrior test site was used to constrain joint orientation. Fractures in the highwalls are dominated by systematic joints that strike with a vector-mean azimuth of N. 47° E., which is consistent with the regional joint system (fig. 36). Systematic joint orientation has a Gaussian distribution with a standard deviation of 20°. Cross joints are relatively sparse in the highwalls and have an angular standard deviation of 24°.



S - Systematic-joint surface
C - Cross-joint surface

Figure 34.—Photograph of mine highwall showing systematic joints and cross joints in a thick marine mudstone interval.

Joints in the Pottsville Formation dip steeply (figs. 34, 37). Analysis of the dip of 715 joints in the 15 cores analyzed shows a strongly skewed distribution with a mean dip of 85° and a standard deviation of 5° (fig. 37). These fractures can indeed be considered geologically vertical, considering that the median dip is 87° and the modal value is 90°. Variability of joint dip is interpreted in part to represent curvature of joint surfaces, and core data are biased by the probability that drilling will intersect dipping joint segments rather than vertical segments.

Height, length, spacing, and cross-cutting relationships are critical variables for the simulation of joint networks. Where the full height of joints in the Pottsville Formation can be observed, they tend to be strata-bound; that is, they terminate at or near bedding contacts (fig. 38). Of the 723 joints analyzed in core, 197 (27 percent) had length sufficient to determine the

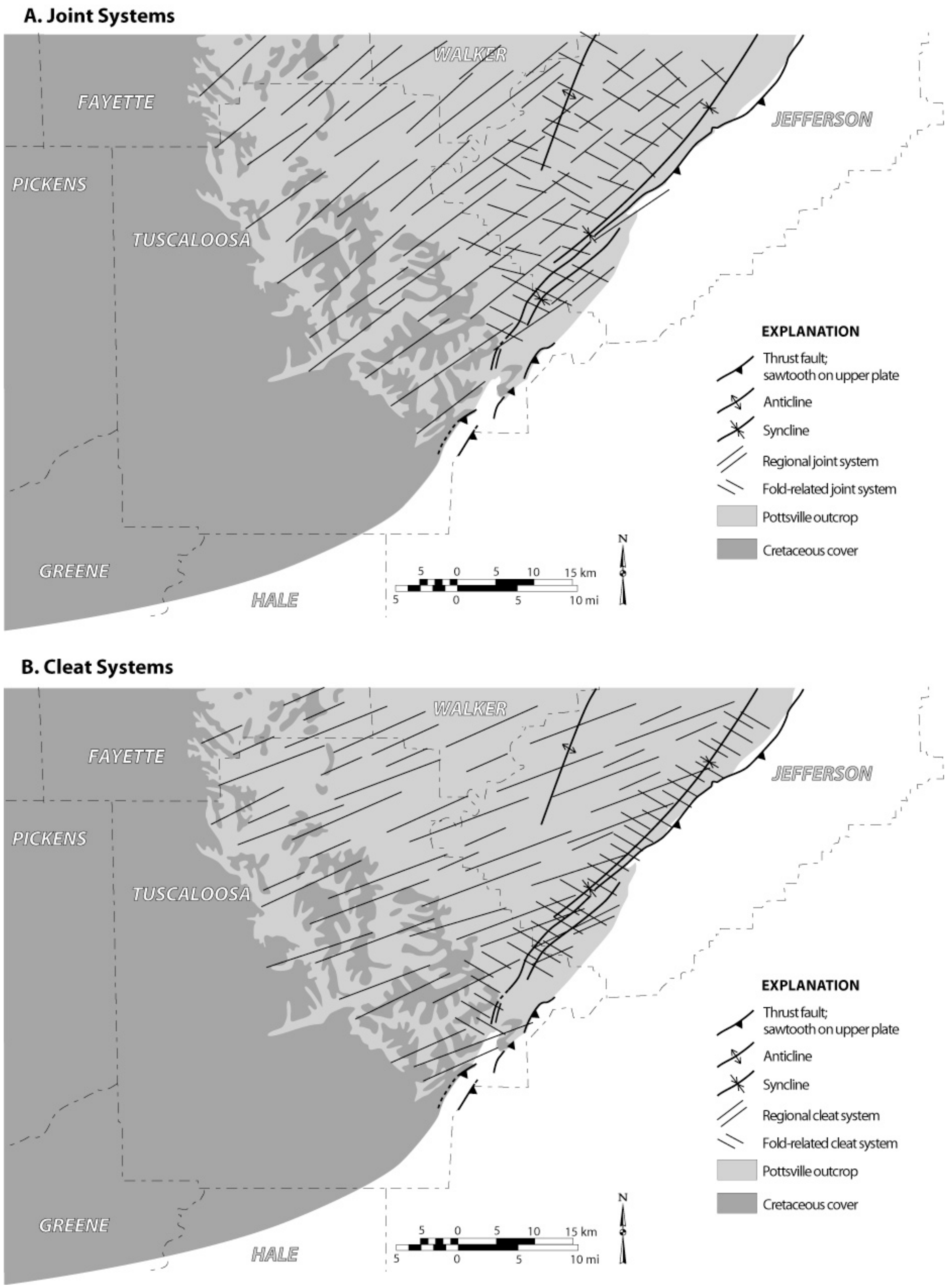


Figure 35.—Generalized map showing joint and cleat systems in the Pottsville Formation (modified from Pashin and others (1991).

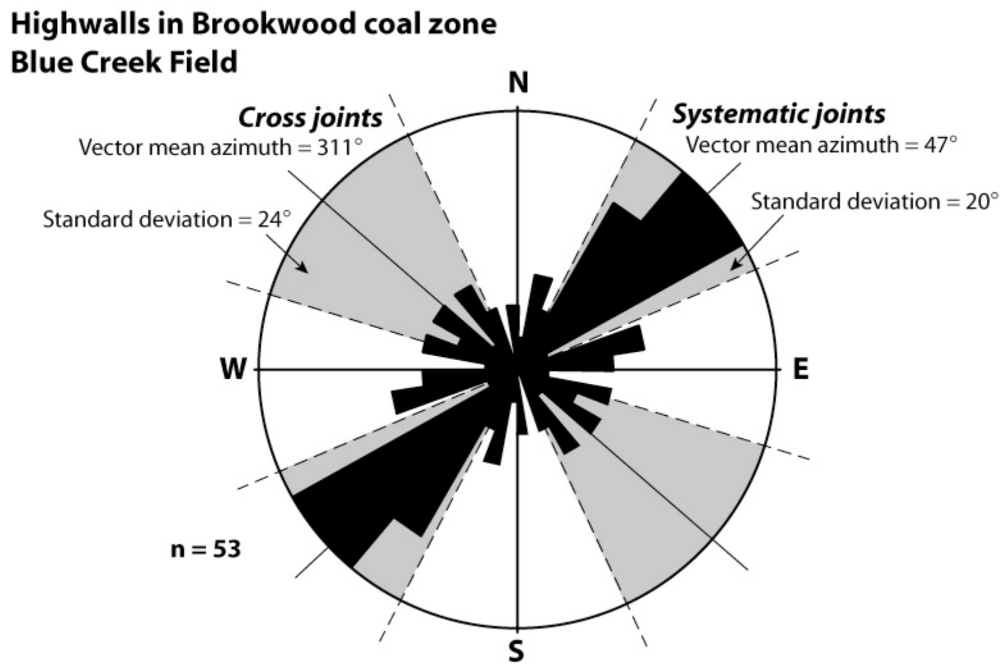


Figure 36.—Rose diagram showing orientation of systematic joints and cross joints in mine highwalls in Blue Creek Field.

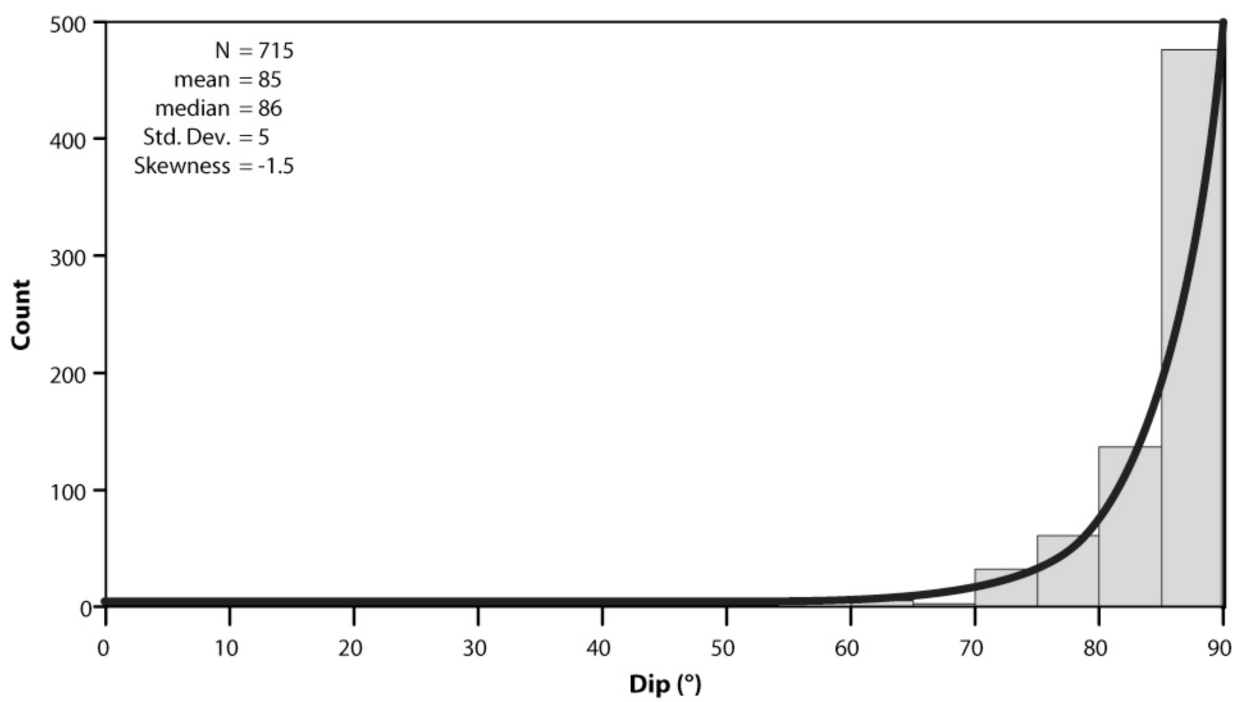


Figure 37.—Histogram showing dip of joints measured in wireline cores.

Figure 38.—Photograph showing strata-bound joints in flaggy sandstone beds. Note that joint spacing increases with bed thickness.

relationship to bedding and other fractures. Of these, 178 joints (90 percent) are contained within individual shale or sandstone beds, and only 16 joints (8 percent) cross bedding contacts. Only 3 joints (1.5 percent) terminate at fracture intersections. Strata-bound joint systems are common in sedimentary rocks and indicate that beds were fractured with a degree of mechanical independence as dictated by their individual geomechanical properties (Pollard and Aydin, 1988). Considering the predominance of strata-bound joint systems in the Pottsville Formation, the equivalence of joint height to bed thickness is a baseline hypothesis that can be used to construct DFN models.

Most joints are too long to determine length directly, but cross-cutting relationships can be used to estimate joint length. Fracture intersections can be classified as X-type where they cross, T-type where one fracture intersects at another at a high angle, and J-type where one fracture curves to intersect another with similar orientation (Pashin, Jin, and Payton, 2004) (fig. 39). About 90 percent of the joint intersections observed in the area of the Black Warrior Basin

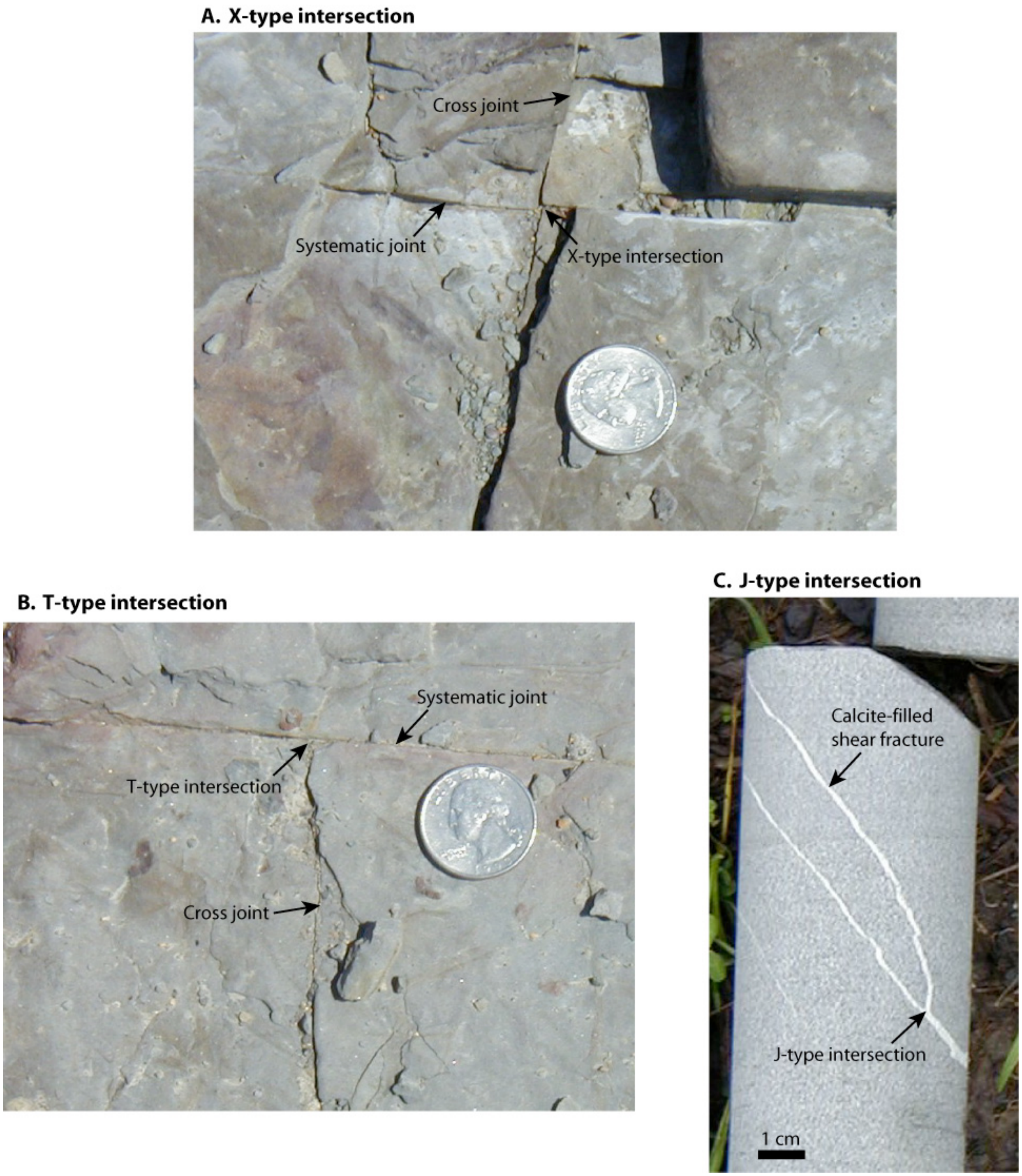


Figure 39.—Photographs showing types of fracture intersections.

containing only the regional joint system are T-type intersections. Therefore, cross-joint length tends to equal systematic joint spacing. Systematic joints are closely aligned and were not observed to cross in the study area. Instead, where closely aligned joints approach, either one fracture will curve and terminate against another to form a J-type intersection, or a fracture will simply terminate within the rock mass without intersecting another fracture. Accordingly, systematic joint length can be constrained by spacing, angle of approach, and the frequency of simple termination within the rock mass.

Limited exposure and a scarcity of bed-parallel fracture pavement makes rigorous analysis of joint spacing difficult. However, an exceptional data set from a siderite bed at the Bankhead Lock and Dam (SE 1/4, sec. 22, T. 18 S., R. 8 W.) suggests that the spacing of joints within individual beds can be modeled using log-normal distributions (fig. 40A). Median joint spacing typically increases with increasing bed thickness (Verbeek and Grout, 1984). Based on observations from 26 beds in various outcrops in the eastern Black Warrior Basin, joint spacing has a logarithmic distribution (fig. 41). A consequence of this distribution is that joint spacing is substantially greater than bed thickness in thin beds, which gives the beds a flaggy appearance (fig. 38), and is substantially less than bed thickness in thick beds, which imparts a columnar appearance (fig. 34). One shortcoming of this study, however, is that limited sampling opportunities do not permit the derivation of separate spacing-thickness relationships for sandstone and shale.

Mineral cement was observed in 30 percent of the joints studied in core. Calcite is the dominant fracture-filling cement in Pottsville joint systems (e.g., Pashin and others, 1999; Pitman and others, 2003) and was identified in 98 percent of the mineralized fractures (fig. 42A). Pyrite and clay (kaolinite) are accessory fracture-filling minerals. Cement covers more than 80

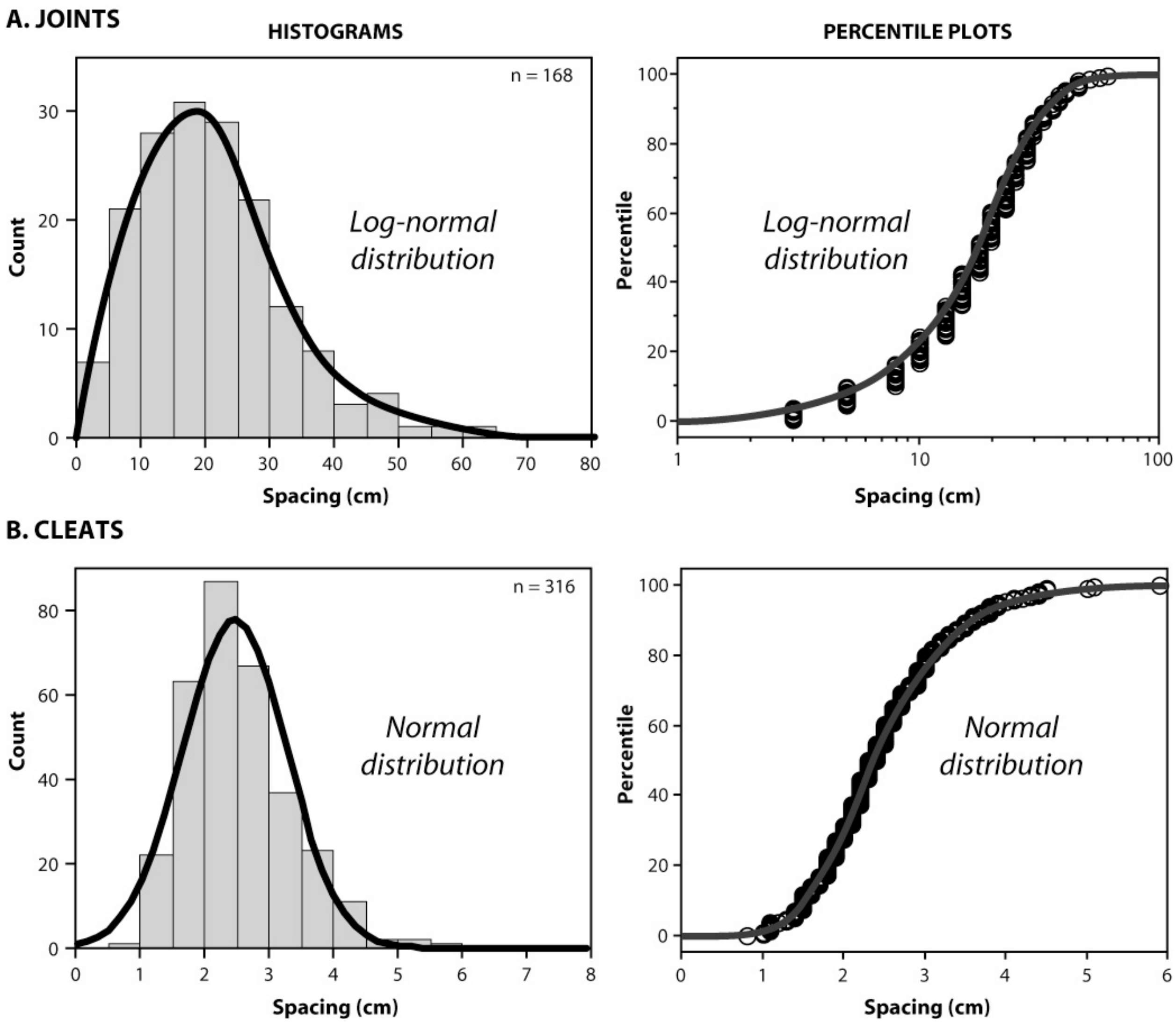


Figure 40.—Histograms and percentile plots demonstrating statistical properties of joint and cleat spacing.

percent of fracture surfaces in most mineralized segments of joints (fig. 43A), indicating that mineralization can limit flow within joint systems. However, about 40 percent of the mineralized fractures have cement coverage between 1 and 80 percent, indicating that significant porosity exists within many mineralized joint segments. Based on the observations from core, it appears cement has a patchy distribution in Pottsville joint networks and that, provided aperture exists along nonmineralized segments, most joints have capability to support flow.

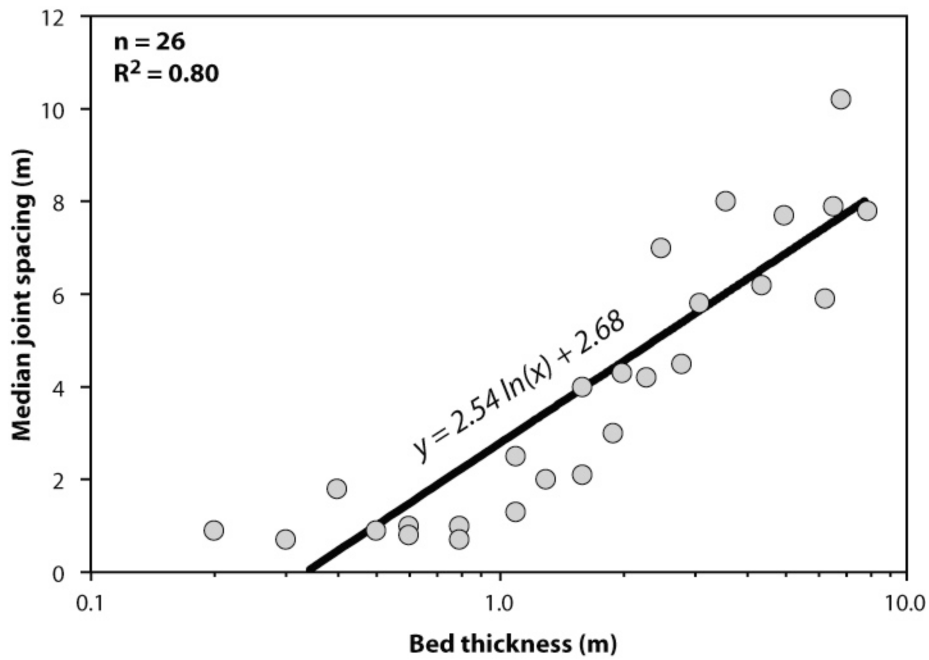


Figure 41.—Scatterplot showing logarithmic relationship between joint spacing and bed thickness in outcrops of the Black Warrior Basin.

Most calcite fracture fills in the Pottsville are simple and been interpreted as the product of a single post-kinematic mineralization event that preserves fracture aperture (Pitman and others, 2003; Pashin, Jin, and Payton, 2004). Indeed, the multiple crack-seal textures and fracture-filling breccia that are characteristic of polyphase fracturing and mineralization were observed only in 7 joints. Percentile plots of kinematic aperture, as interpreted from the thickness of simple joint fills, can be characterized using exponential or power-law statistical distributions (Pashin, Jin, and Payton, 2004) (fig. 44).

New data collected during this study indicate that the kinematic aperture of fractures in the Pottsville Formation can be characterized most simply and consistently using power-law functions, and separate functions were derived for joints and shale and sandstone (fig. 44). The lower limit of visual observation of kinematic aperture is 0.05 millimeters (mm), thus the dataset is truncated below this value. About 35 percent of the joints measured have kinematic aperture at

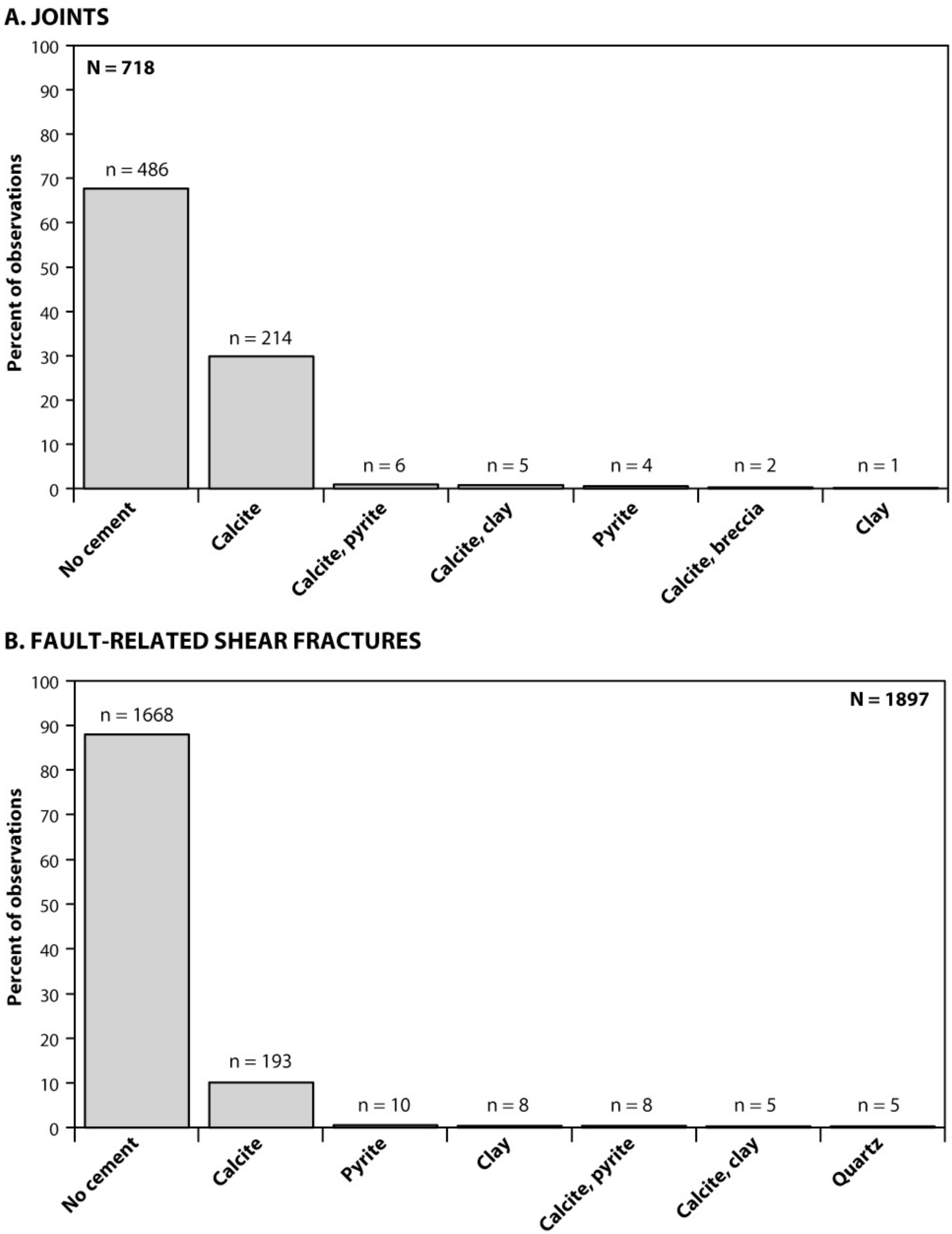


Figure 42.—Histograms showing frequency and mineralogy of cement fills in joints and fault-related shear fractures in the Black Warrior Basin.

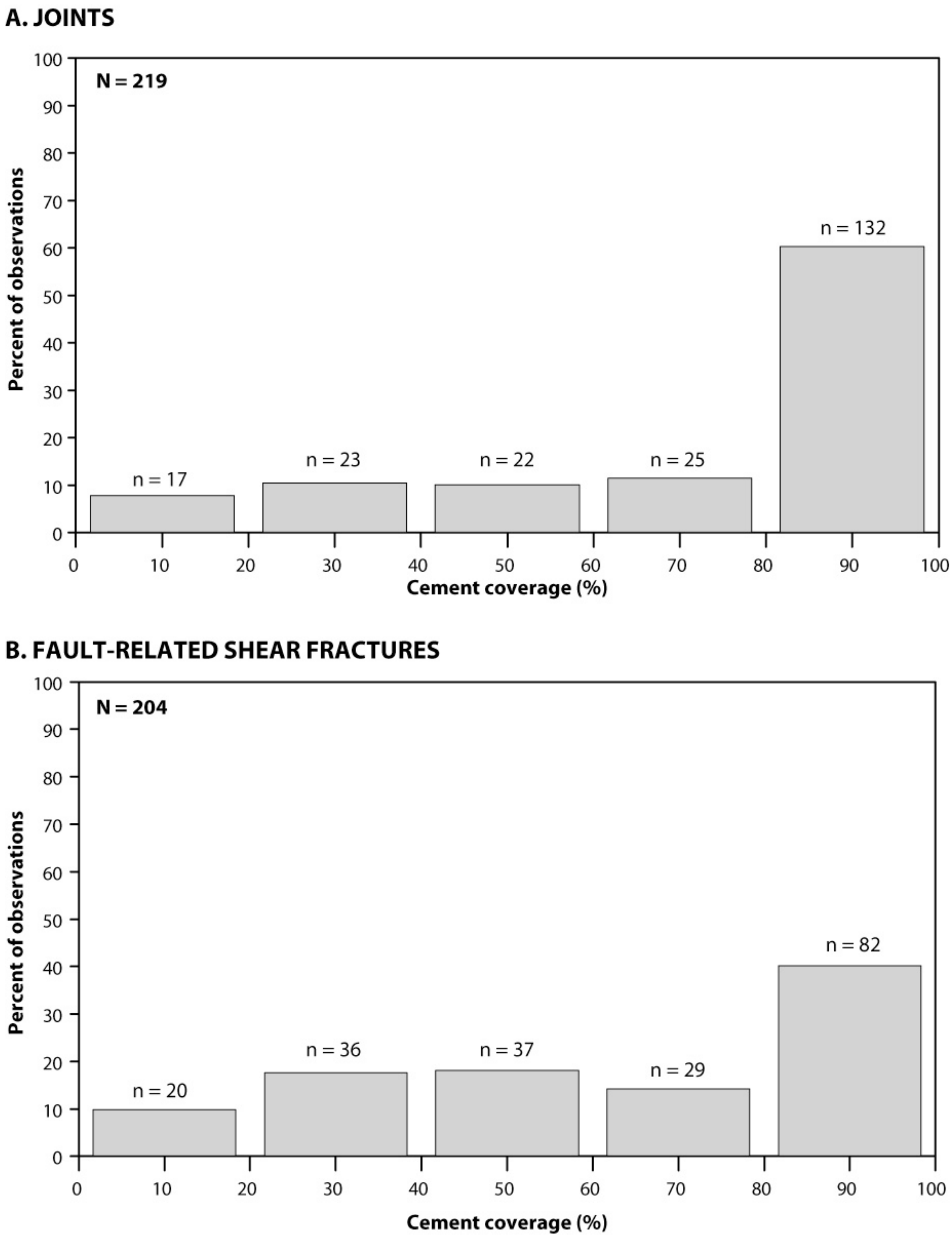


Figure 43.—Histograms showing percent of cement coverage in joints and fault-related shear fractures of the Black Warrior Basin.

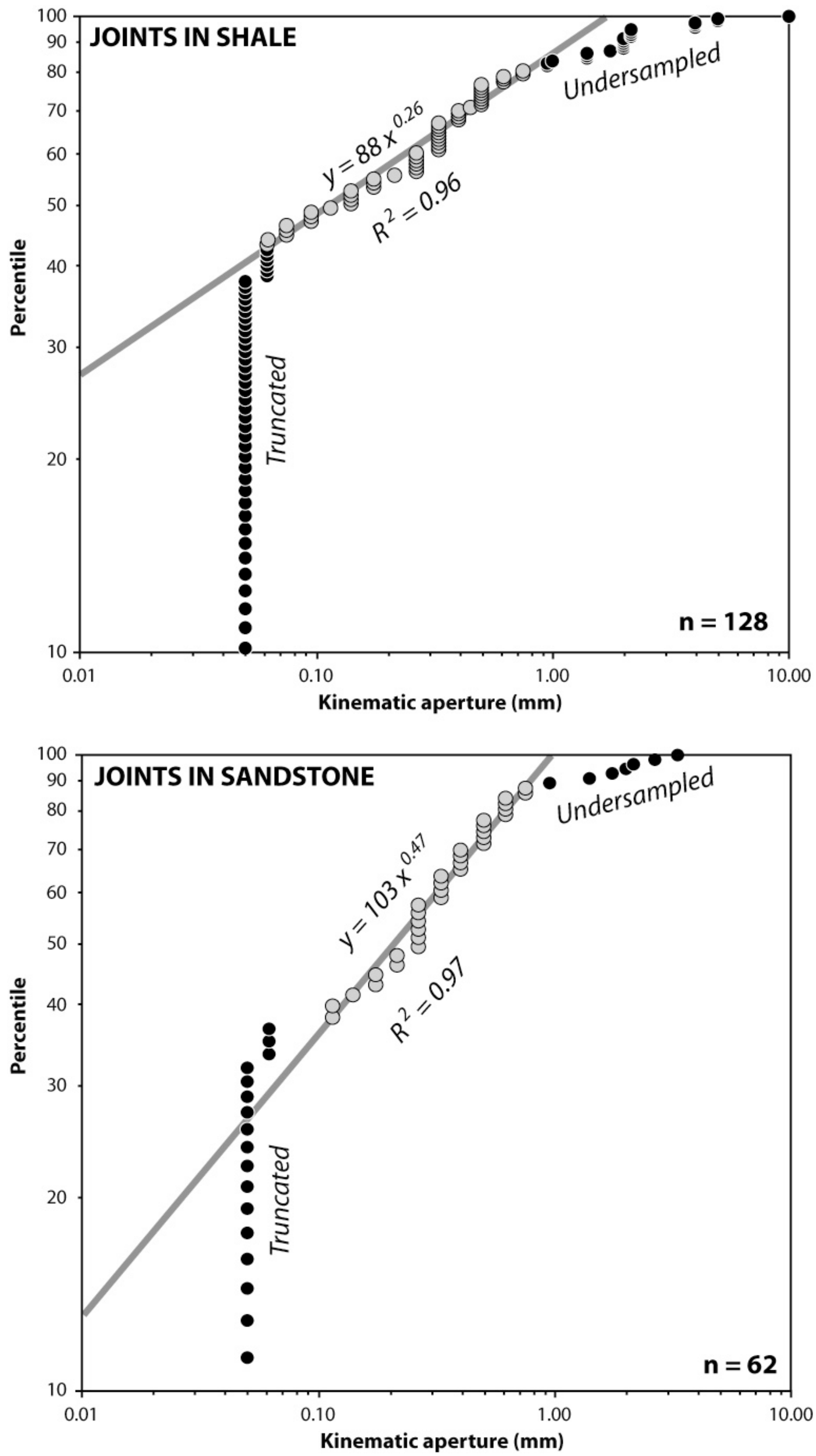


Figure 44.—Percentile plots showing exponential distribution of kinematic aperture in mineral-filled joints hosted by shale and sandstone.

or below the lower limit of observation. Fractures with kinematic aperture between 0.07 and 0.80 mm plot along a nearly straight line in a log-log plot that can be used to define a power-law function. Divergence of large-aperture fracture fills from that line reflects undersampling. The results of this analysis indicate that weakly transmissive hairline fractures dominate the joint population and that highly transmissive joints with large aperture are relatively rare. Joints in sandstone tend to have larger kinematic aperture than those in shale and thus appear to be capable of transmitting larger volumes of fluid.

Cleats

Coal in the Black Warrior Basin is extremely well-cleated (fig. 45), and close spacing of the cleats gives the coal the ability to support commercial flow rates. Cleat systems are orthogonal networks of vertical fractures that are composed of systematic fractures and cross fractures. In coal, face cleats are equivalent to systematic joints, and butt cleats are equivalent to cross joints. In the Pottsville Formation, butt cleats almost universally terminate at intersections with face cleats.

As with joints, cleat systems can be subdivided into a regional fracture system and a localized system that is restricted to the southeast margin of the Black Warrior basin (Ward and others, 1984) (fig. 35B). Face cleats of the regional cleat system strike with a vector mean azimuth of N. 62° E., which is 15° east of the regional systematic joints. Face cleats in the localized fracture system along the southeast margin of the basin strike with a vector mean azimuth of N. 36° W. The orientation of the regional cleat system has been interpreted as the product of an Appalachian-wide stress field that formed during Pennsylvanian time (Engelder

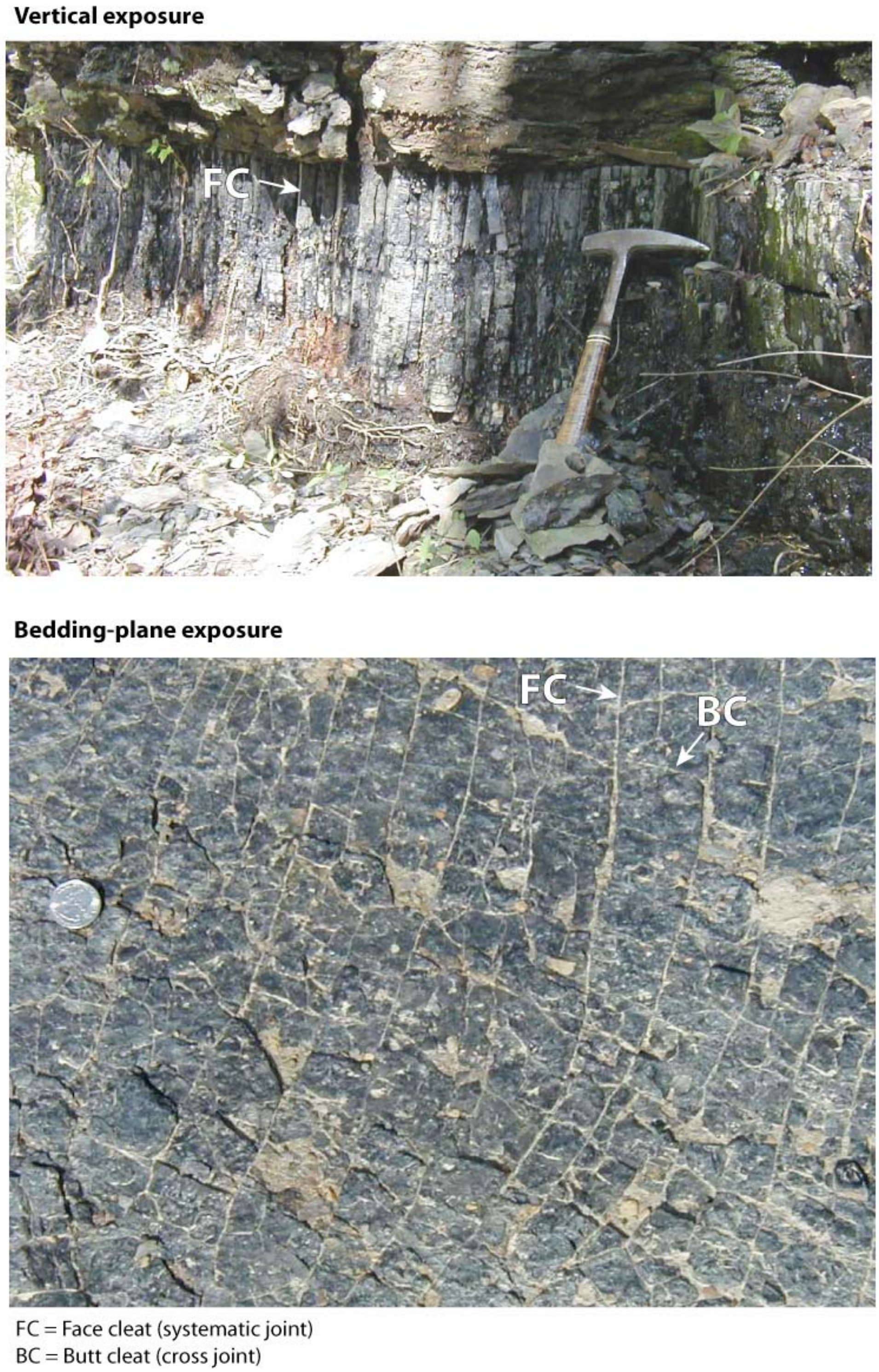


Figure 45.—Photographs of cleated coal in outcrop showing face cleats and butt cleats.

and Whitaker, 2006), whereas the localized cleat systems reflect local stresses associated with Appalachian folding (Ward and others, 1984; Pashin and others, 1999).

Devolatization and shrinkage of matrix during coalification is a source of stress that is thought to contribute to the formation of cleats in coal (e.g., Law, 1993; Laubach and others, 1998). Pashin and others (1999) pointed out that the regional change in orientation between face cleats systematic joints reflects different mechanisms of fracturing, different timing of fracturing, and rotation of the regional stress field. The cleat direction was probably established during major coalification, which occurred during active burial (Telle and Thompson, 1987; Carroll and others, 1995), whereas joints probably formed later as stress was released by post-orogenic unroofing and cooling.

Cleat spacing decreases substantially as coal rank increases in the Black Warrior Basin (McFall and others, 1986; Pashin and others, 1999) (fig. 46). In high volatile B and lower rank coal, for example, primary cleats can be spaced on the order of a decimeter, whereas in low volatile bituminous coal, millimeter-scale cleat spacing is common. Whereas joint spacing has a log normal distribution, cleat spacing follows a normal distribution (fig. 40). Outcrops and cores establish that coal in the Black Warrior Basin is dominated by primary cleats with height equivalent to bench or bed thickness. Accordingly, primary cleats define strata-bound fracture networks that are even better developed than those in jointed shale and sandstone (fig. 45). Secondary cleats, which are contained within benches or beds, form a minor part of the cleat population, whereas tertiary cleats, which are restricted to individual vitrain bands, can be abundant and are spaced an order of magnitude more closely than primary cleats.

Measuring cleat aperture in coal can be difficult. Calcite and pyrite cleat fills are common in the Black Warrior Basin, but these fills typically display displacive petrographic fabrics

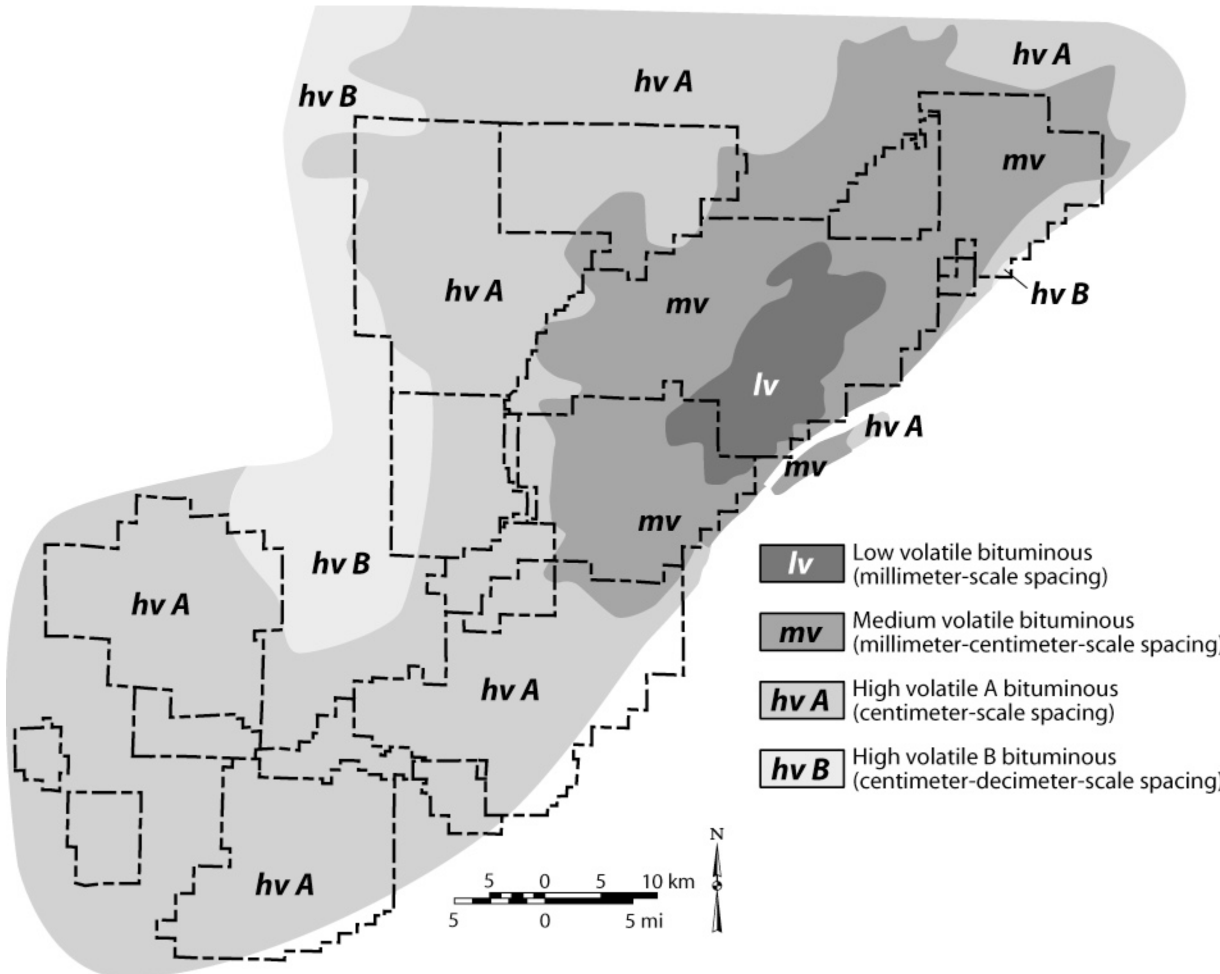


Figure 46.—Map showing general relationship between cleat spacing and coal rank in the Black Warrior Basin (modified from McFall and others, 1986; Pashin and others, 1999).

indicating that they are not meaningful indicators of kinematic aperture. Coal is an extremely stress-sensitive rock type, so aperture measured at surface pressure is not representative of aperture at reservoir depth. However, if the statistical distribution of apertures is known, then the distribution can be scaled to simulate fracture properties under reservoir conditions. Literature provides contrasting information on cleat aperture. Laubach and others (1998) indicated that apertures in coal can follow a power-law scaling rule similar to that shown here for joints, whereas Mazumder and others (2006) suggested that cleat aperture can be normally distributed (fig. 47).

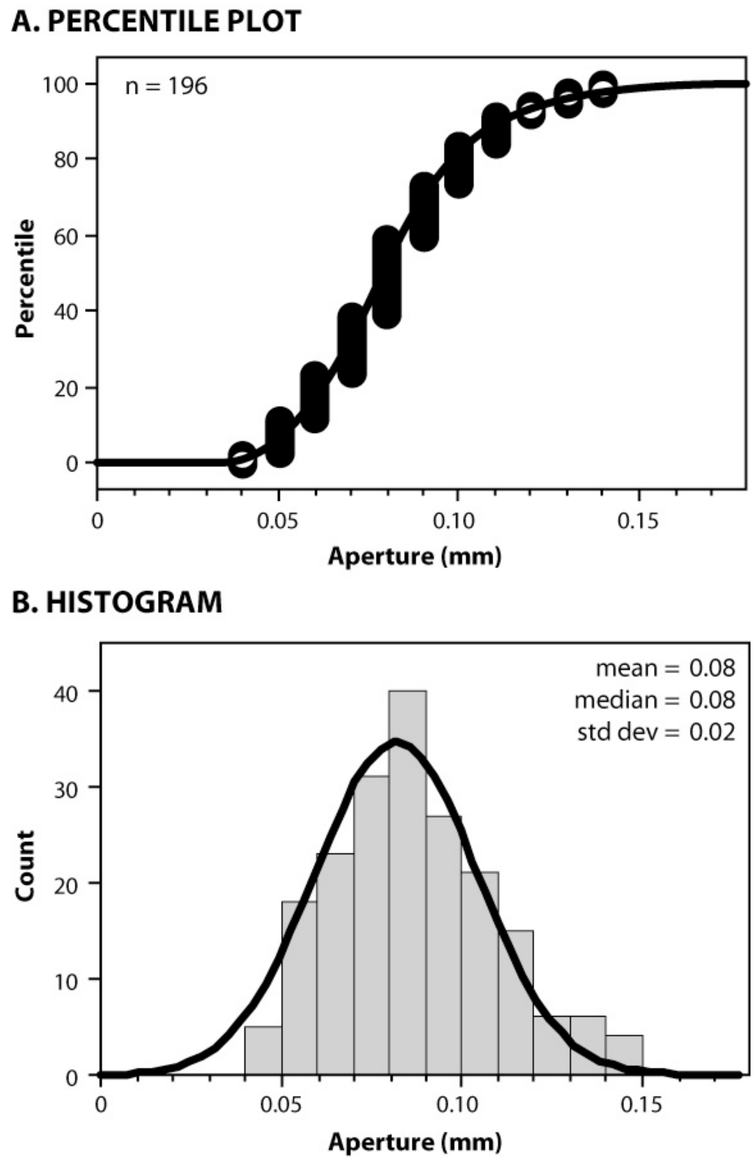


Figure 47.—Percentile plot and histogram showing normal distribution of cleat aperture in coal (based on data in Mazumder and others, 2006).

Close fracture spacing precludes the incorporation of cleats in large DFN models, thus it can be advantageous to model coal in terms of bulk porosity and permeability. If aperture and spacing are known, porosity and permeability can be expressed as a function of cleat spacing and cleat aperture, such that

$$\phi = 100 \cdot 2a/s, \quad (1)$$

where ϕ is porosity, a is aperture, and s is cleat spacing, and

$$k = a^3/12s, \quad (2)$$

where k is permeability (Harpalani and Chen, 1995). Well test data indicate that porosity and permeability decrease substantially with depth in the Black Warrior Basin (McKee and others, 1988). Under reservoir conditions, cleat aperture generally ranges from 0.03 to 0.40 mm, and porosity is typically less than 0.1 percent (Laubach and others, 1988). Permeability decreases exponentially with depth in the Black Warrior Basin such that coal can have permeability on the order of 100 to 1,000 mD near the surface and on the order of 1 to 10 mD below a depth of 300 m (fig. 48). Accordingly, it is common for coalbed methane reservoirs to span more than three orders of magnitude of permeability in a single coalbed methane well.

Shear Fractures

Faults cut across bedding and thus may avenues for leakage of injected CO_2. Indeed, Clayton and others (1994) investigated a number of exposed normal faults in the Black Warrior Basin and found a significant gas seep along one fault in Oak Grove Field. Dipping fractures are a key component of fault zones in the Black Warrior basin and consist of crossing synthetic and antithetic shears (Pashin and others, 1991; Pashin, 1998) (fig. 33). Synthetic shears dip with the associated fault, whereas antithetic shears dip opposite to the fault.

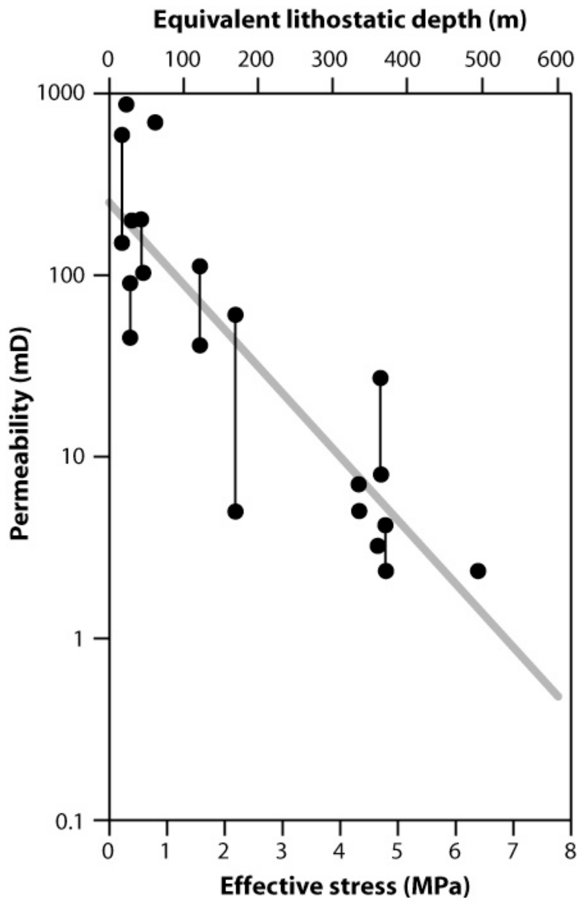


Figure 48.—Permeability-depth plot showing exponential decrease of permeability in coal of the Black Warrior Basin with increasing lithostatic stress.

An exceptional exposure of a normal fault at the Bankhead Lock and Dam facilitates the analysis of shear fractures (fig. 49). The fault strikes N. 28° W. and dips 66° NE. A thick sandstone unit is well exposed in the hanging wall block, and shale is exposed in the footwall block. The shale is intensely and chaotically sheared within 2 m of the fault plane and contains few fractures farther from the fault. In the sandstone, shear fractures strike nearly parallel to the fault plane and have an angular standard deviation of only 13°. Of the 44 fractures measured, 14 (32 percent) of the fractures are synthetic shears, and 30 (68 percent) are antithetic shears. Dip of the shear fractures ranges from 48 to 87°. Dip of the synthetic shears is scattered, whereas dip of the antithetic shears is bimodal with peaks at 50° and 78°. Most of the shear fractures cross,

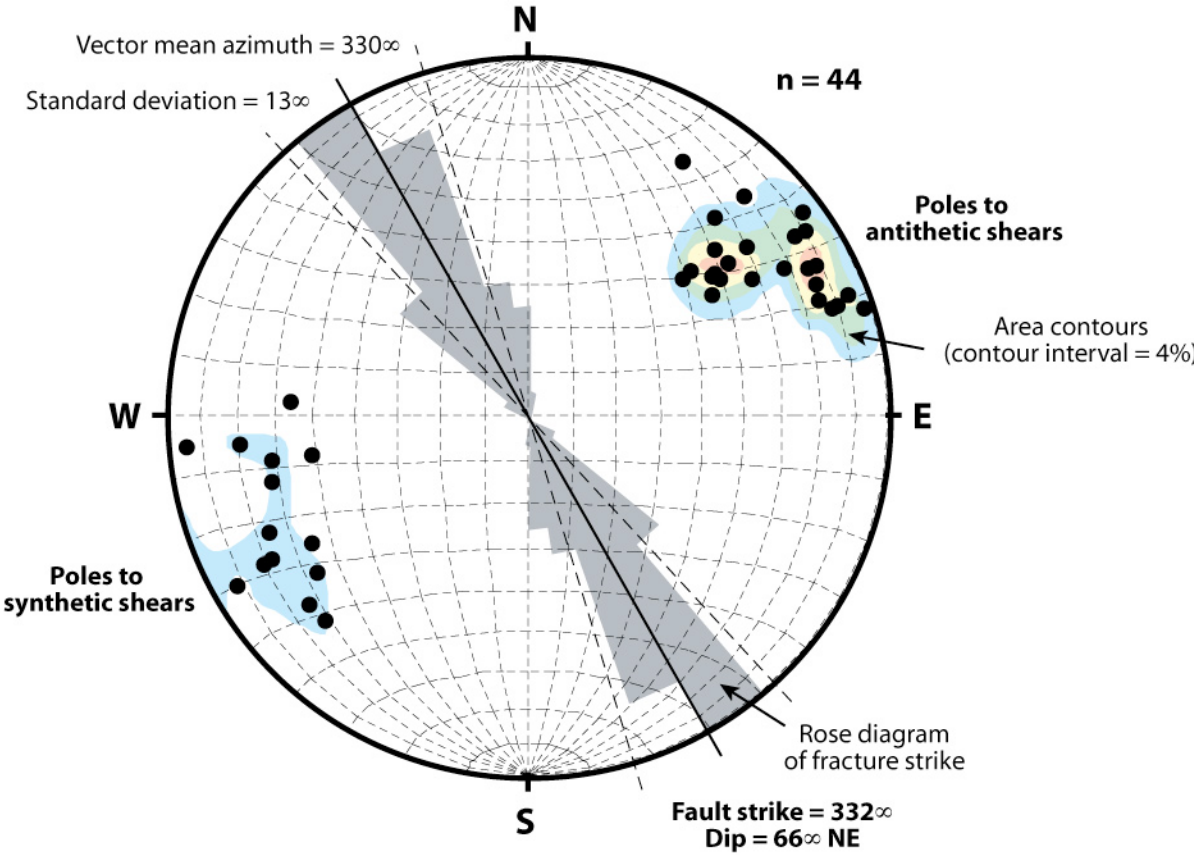


Figure 49.—Rose diagram and stereoplot showing orientation of synthetic and antithetic shears associated with a normal fault in the Black Warrior Basin.

forming X-type intersections, but where fractures of similar orientation approach, one fracture abuts the other, thus forming a J-type intersection. Fracture spacing increases exponentially away from the fault for about 22 m, but farther away, shear spacing is fairly uniform (fig. 50).

Eleven of the cores analyzed intersect normal faults and associated shear fractures. Of 1,897 fractures analyzed, 80 percent are in shale, and the remainder are in sandstone. Importantly, fractures in shale were undersampled because of locally intense shearing and friability. Indeed, an important outcome of outcrop and core analysis is that shear fractures have fundamentally different distributions in shale and sandstone. In shale, shear-zone deformation predominates in which fractures are concentrated in bands narrower than 3 m. In sandstone, by contrast, shear

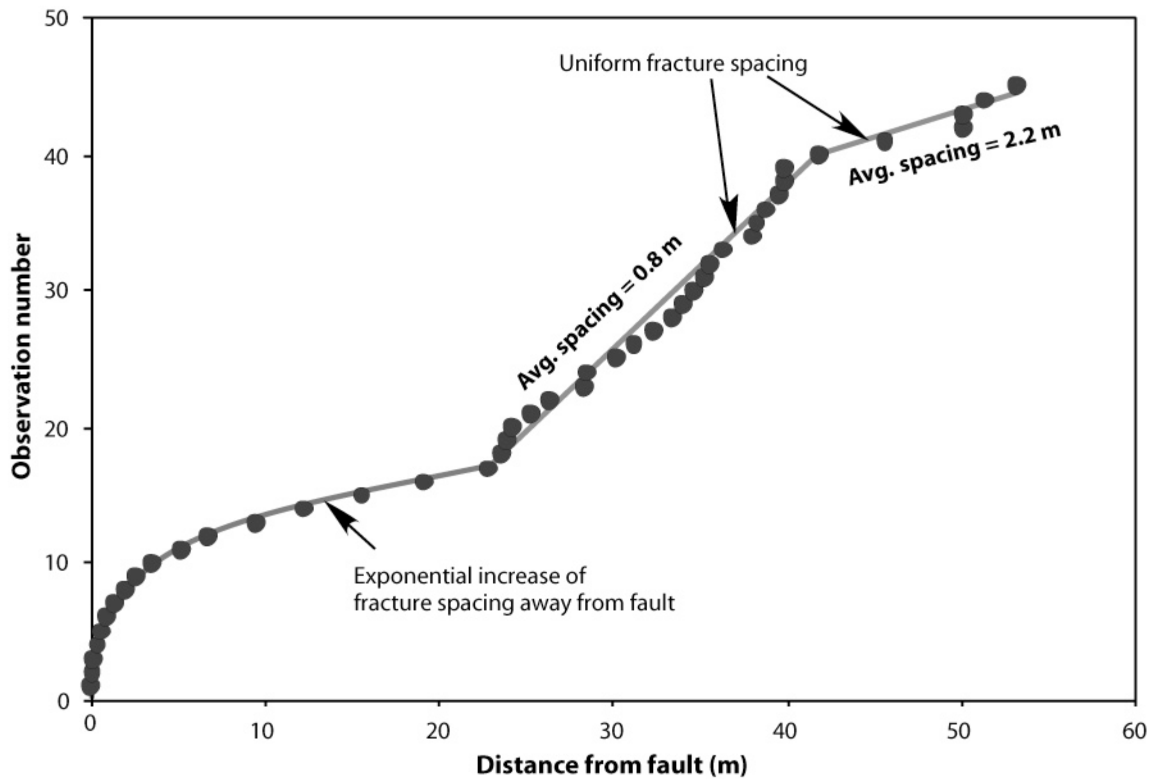


Figure 50.—Plot of fracture spacing versus distance from a normal fault in the Black Warrior Basin.

fractures are broadly distributed and have been observed as far as 100 m from fault planes. These relationships indicate significant stratigraphic control on shear behavior, with shear-zone deformation in mechanically weak shale and distributed deformation in mechanically stiff sandstone. Where like rock types are juxtaposed across a fault, fracturing about a fault plane is predicted to be relatively symmetrical, but where shale and sandstone are juxtaposed, as at the Bankhead Lock and Dam, fracture distribution can be highly asymmetrical. Indeed, examination of mine highwalls indicates a significant strata-bound component to shear fracturing (fig. 33).

Dip of the shear fractures in core is highly variable (fig. 51). In sandstone, mean fracture dip is 53°, which is similar to fault dip, and has a normal distribution. In shale, however, mean dip is substantially lower at 38°, and the distribution of dip is positively skewed. The weak central

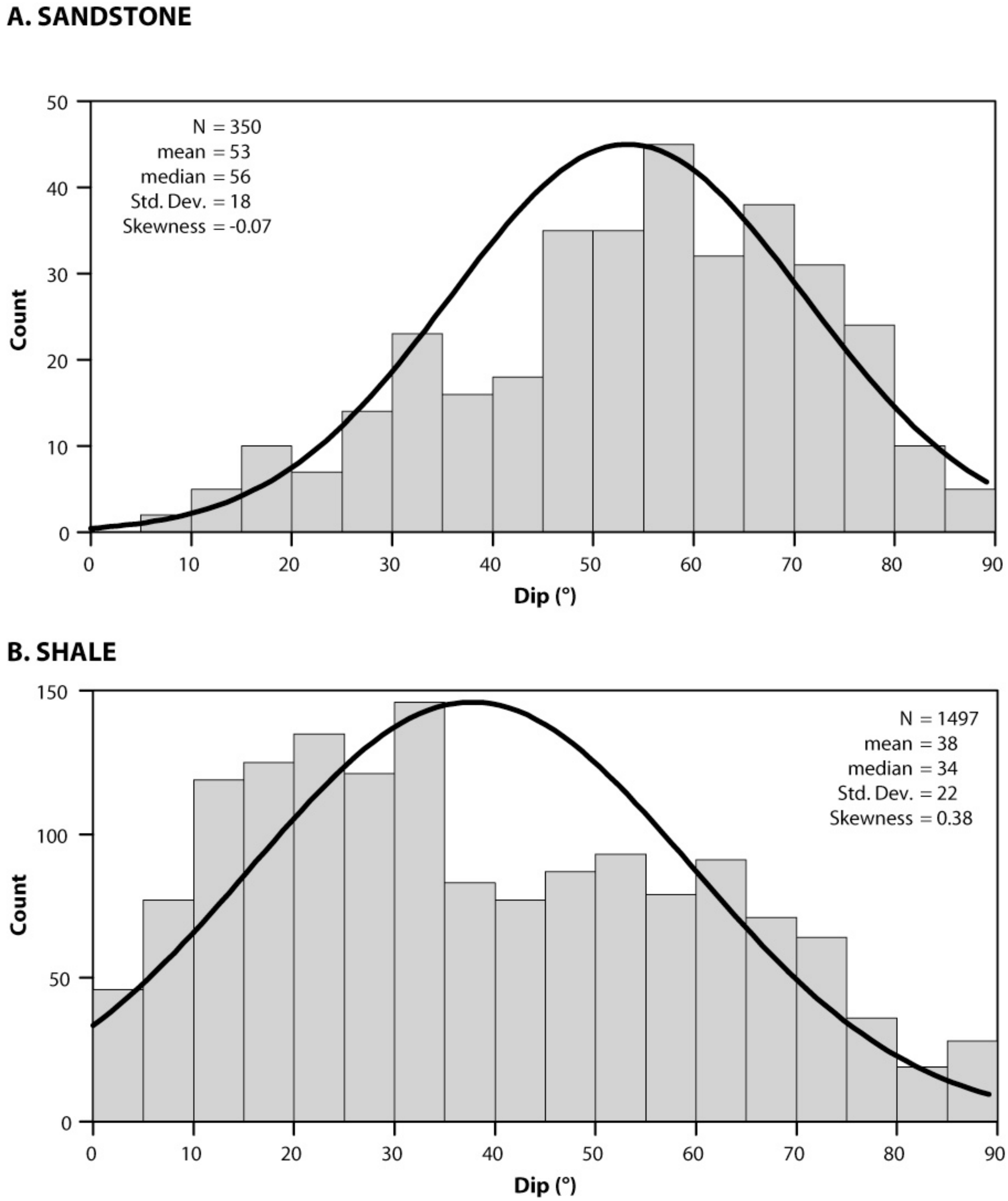
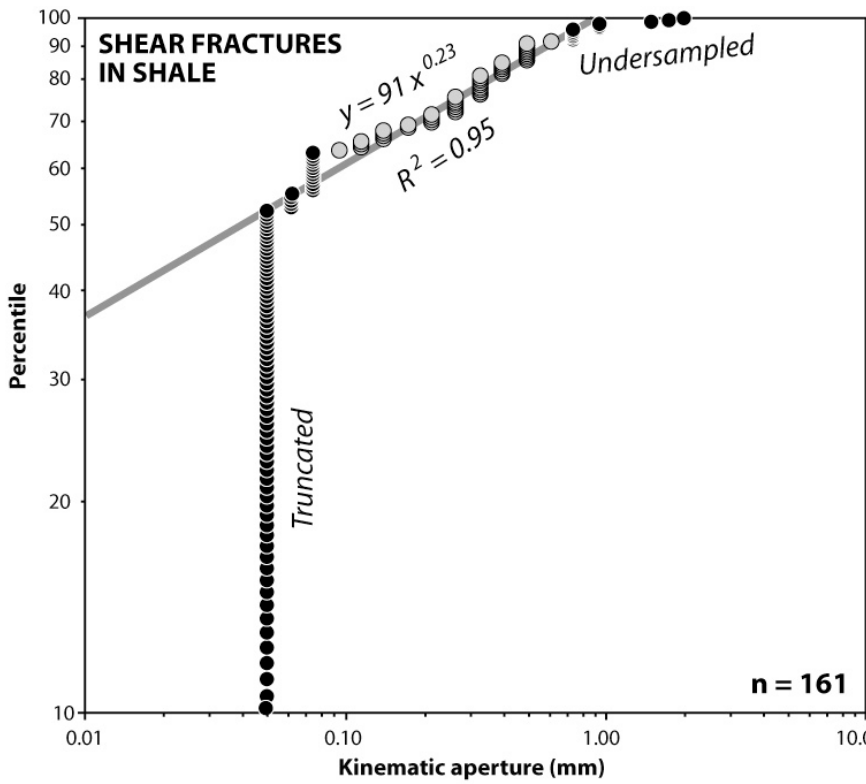


Figure 51.—Histograms showing dip of fault-related shear fractures measured in cores from the Black Warrior Basin.

tendency of dip values in shale relative to sandstone reflects the chaotic nature of shear-zone deformation in shale.

Mineral cement was observed in only 12 percent of the shears studied in core (fig. 42B). As in joints, calcite is the dominant fracture-filling cement in fault-related shear fractures. Calcite was identified in 84 percent of the mineralized fractures, and pyrite, clay, and quartz are accessory fracture-filling minerals. Cement covers more than 80 percent of fracture surfaces in a minority of the mineralized shears (fig. 43B). About 60 percent of the mineralized fractures have cement coverage between 1 and 80 percent, indicating that significant porosity exists along mineralized shear fractures. As in joint networks, cement has a patchy distribution in fault-related shear fractures. If the nonmineralized shears are open, they can support flow and should be considered carefully when developing carbon sequestration and enhanced coalbed methane recovery programs.

Like joints, nearly all shear fills are simple and can be used to determine kinematic aperture, and percentile plots of kinematic aperture can be characterized using power-law statistical distributions (fig. 52). More than 50 percent of the shears measured in shale have a kinematic aperture equal to or less than 0.05 mm, whereas only about 30 percent of the shears measured in sandstone fall in this range. As in joint networks, weakly transmissive hairline fractures dominate the shear population, and highly transmissive shears with large aperture are relatively rare. Shears in sandstone tend to have larger kinematic aperture than those in shale and thus appear capable of transmitting larger volumes of fluid.



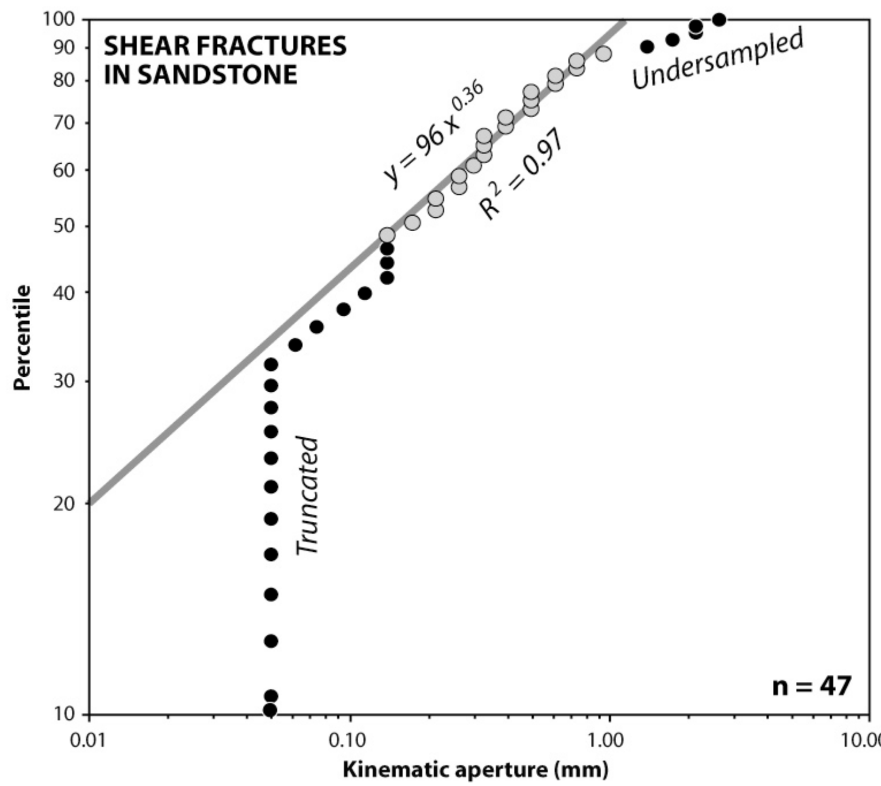


Figure 52.—Percentile plots showing exponential distribution of kinematic aperture in mineral-filled, fault-related shear fractures hosted by shale and sandstone.

Simulation Based on SECARB Test Site

Background

The SECARB Black Warrior field test will center on injection of about 907 tonnes (1,000 short tons) of CO_2 into a mature production well in Deerlick Creek Coal Degasification Field (fig. 1), where technical feasibility and the potential for commercial application of carbon sequestration technology are considered to be high (Pashin, Carroll, and others, 2004). Coalbed methane in the test area is produced from multiple seams with diverse reservoir properties that are distributed through a thick stratigraphic section (fig. 53). Multiple seam completion technology was developed to recover gas from coal seams with a broad range of reservoir properties (Graves and others, 1983; Schraufnagel and others, 1991; Young and others, 1993), and injection procedures will need to be optimized to realize the sequestration and CO_2-enhanced recovery potential offered by multiple coal seams. Additionally, procedures need to be developed and optimized that will provide for safe and permanent storage of CO_2 in coal seams. Accordingly, the SECARB Black Warrior field verification test is the first step in this optimization process.

As is typical of wells in Deerlick Creek Field, the J. D. Jobson 24-14 #11 well is completed in the Black Creek, Mary Lee, and Pratt coal zones (fig. 53). The well has a total depth of 792 m (2,460 feet). Beds in the Pratt and Mary Lee coal groups were perforated through casing adjacent to coal beds. A coal bed at the top of the Black Creek group was similarly perforated, and the prominent Black Creek bed was completed in open hole between 2,470 and 2,488 feet. A sand plug was placed in the well from 2,488 feet to total depth prior to hydrofracturing. Completion records indicate that the well was hydrofractured in multiple stages to ensure each coal zone could be effectively isolated and stimulated. The Jobson well is historically an above average

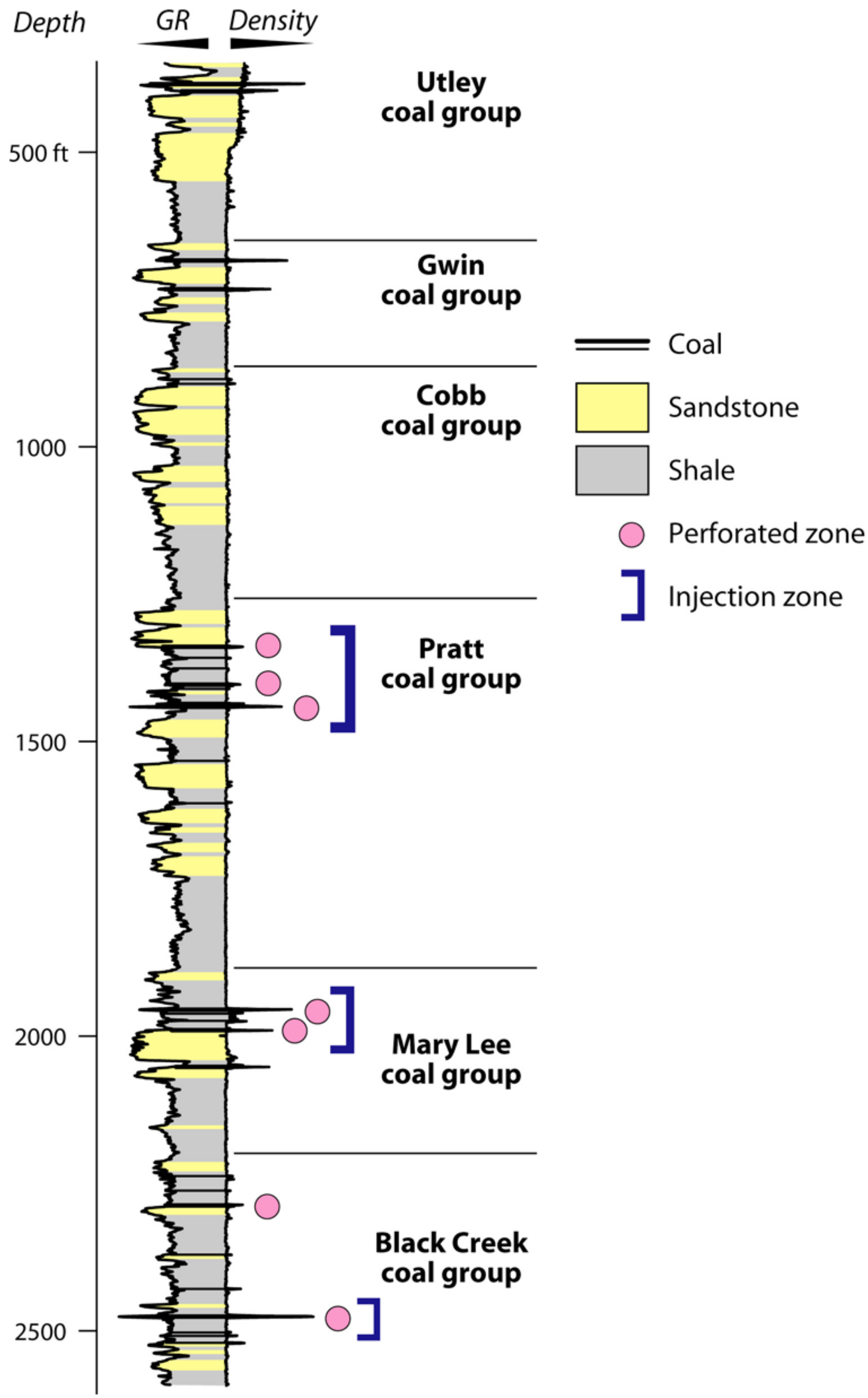


Figure 53.— Geophysical well log of the J. D. Jobson 24-14 #11 well (State Oil and Gas Board of Alabama permit 4001-C) showing perforated coal beds and injection zones to be used in the SECARB Black Warrior field verification test.

producer of both gas and water, but production has declined to the point where the well can be considered as a candidate for plugging and abandonment (fig. 54).

Southern Deerlick Creek Field has been an area of intensive geological investigation (e.g., Wang and others, 1993; Pashin and others, 1995; Pashin and Groshong, 1998; Groshong and others, 2003). Pottsville strata in this area are nearly flat-lying and are cut by normal faults defining a horst-and-graben system (fig. 55). The test site sits in a structural low in the hanging-wall block of a normal fault having about 45 m of vertical displacement. A three-dimensional structural model indicates that the fault dips southwest toward the Jobson well but does not intersect the well (fig. 56). Wells intersecting the fault within the Black Creek-Pratt production interval have produced only minor quantities of water and gas, which suggests that the fault forms an effective seal (Groshong and others, 2003; Pashin, Jin, and Payton, 2004). Based on the volumetric analysis of Pashin, Carroll, and others (2004), coal in the area of the test site has the capacity to sequester about 1,580 tonnes (1,740 short tons) of CO_2 per acre at a modest pressure of 2.41 MPa (350 psi). Therefore, the field verification test is expected to affect only the area immediately surrounding the injection well.

Detailed synopses of injection and monitoring activities are available in Pashin and Clark (2006), Pashin and others (2007), and McIntyre and others (2008), and a brief summary is given here. Testing in the Jobson well will comprise a series of production-buildup and injection-falloff tests (fig. 57). All injection is to be conducted below the critical point for CO_2 (31°C, 7.4 MPa). First, a production-buildup test (T1) will be used to determine the time it takes for pressure to stabilize in the well and to determine the stabilized shut-in pressure. Next, injection-falloff tests will be performed using CO_2. An initial slug of 40 short tons of CO_2 (T2) will be injected into the Black Creek coal to determine baseline injectivity and to help estimate the pressure and rate at

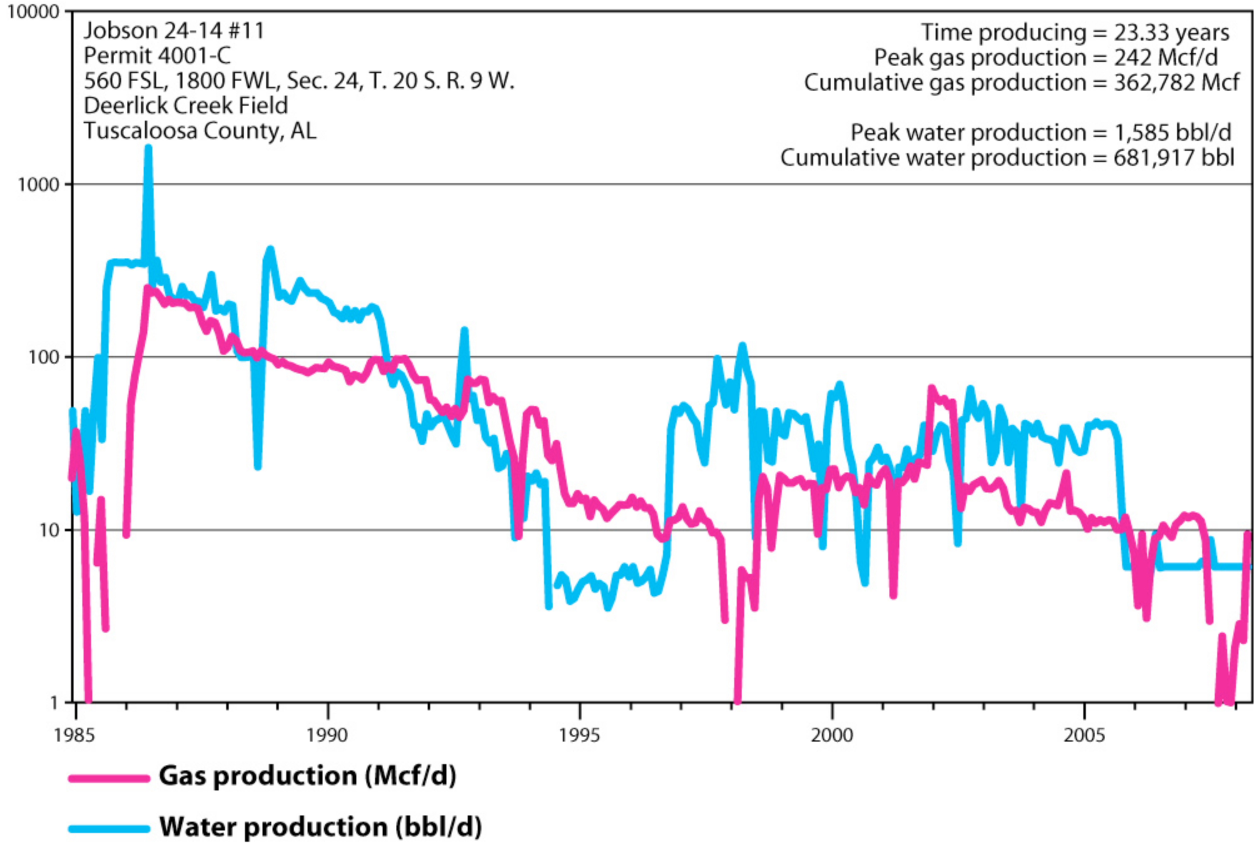


Figure 54.—Production curves showing long-term decline of gas and water production from the J. D. Jobson 24-14 #11 well in southern Deerlick Creek Field.

which a larger quantity of CO_2 can be injected. After pressure stabilizes, a larger slug of up to 280 short tons of CO_2 (T3) will be injected to determine longer term changes of injectivity and pressure response. After pressure stabilizes in the Black Creek coal, these tests will be repeated at higher stratigraphic levels (T4-T7). After the injection-falloff tests are completed, another production-buildup test will be performed to determine if reservoir properties have changed (T8).

The monitoring program has been designed to ensure the safety and effectiveness of the field verification test and includes several subsurface and surface techniques. Deep subsurface monitoring will be conducted using the three observation wells that will be drilled through the Black Creek coal (figs. 58, 59). Inflatable packers will be installed to isolate the target coal beds, and pressure transducers and fluid samplers will be placed in the wells. Pressure data will

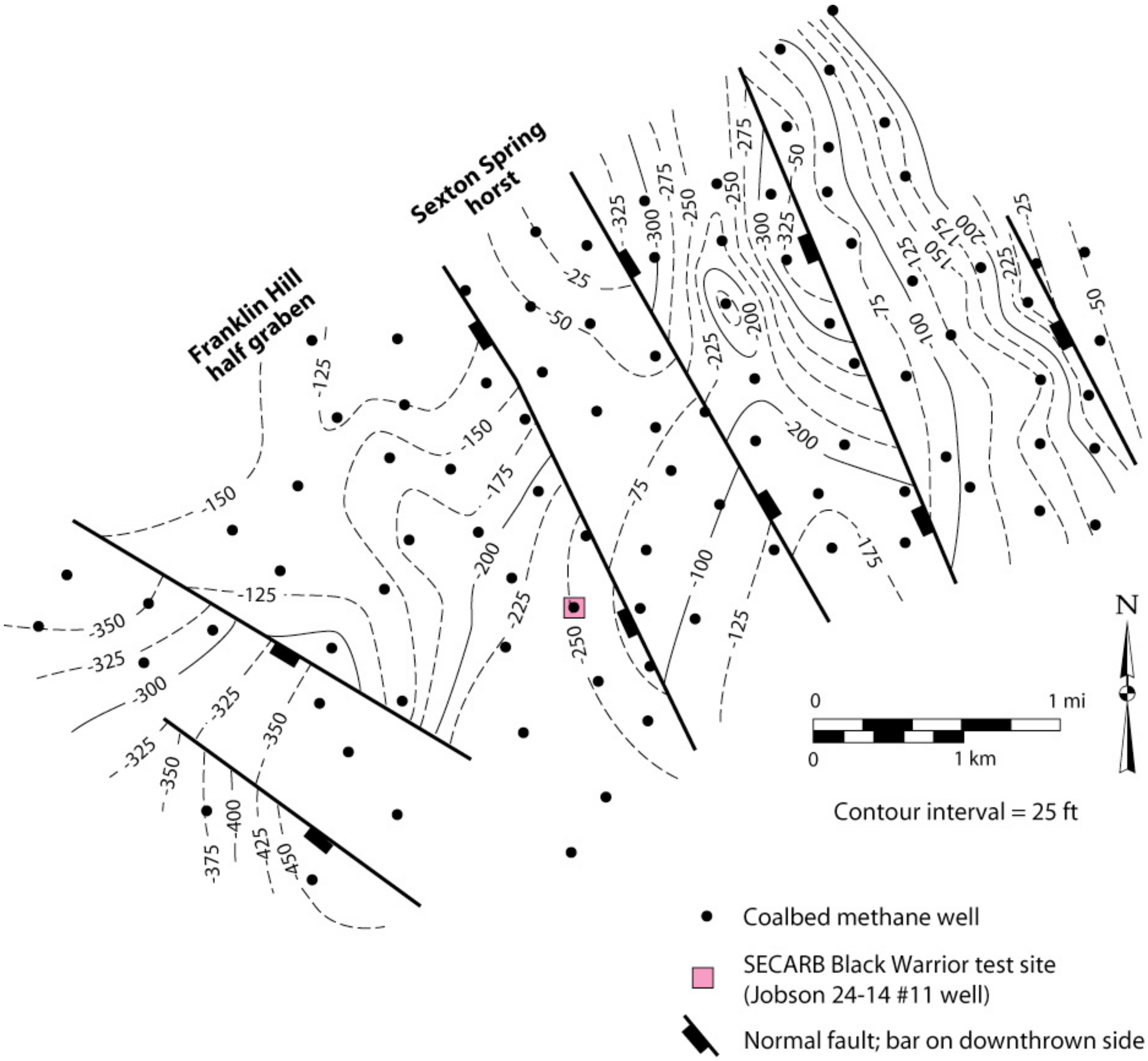


Figure 55.—Structural contour map of the top of the Gwin coal zone in southeastern Deerlick Creek Field showing location of the SECARB Black Warrior test site in the Franklin Hill half graben (modified from Pashin and Groshong, 1998)

provide a basis for analysis of interference, permeability anisotropy, and the effect of hydrofractures. Simultaneous monitoring in multiple coal groups will be useful for determining if significant cross-communication exists between the coal zones and will be useful for verifying the DFN models, flow models, and risk assessment offered herein. To further ensure that field operations are safe and effective, water quality will be monitored in a shallow well, and the composition and flux of soil gas are being monitored (McIntyre and others, 2008).

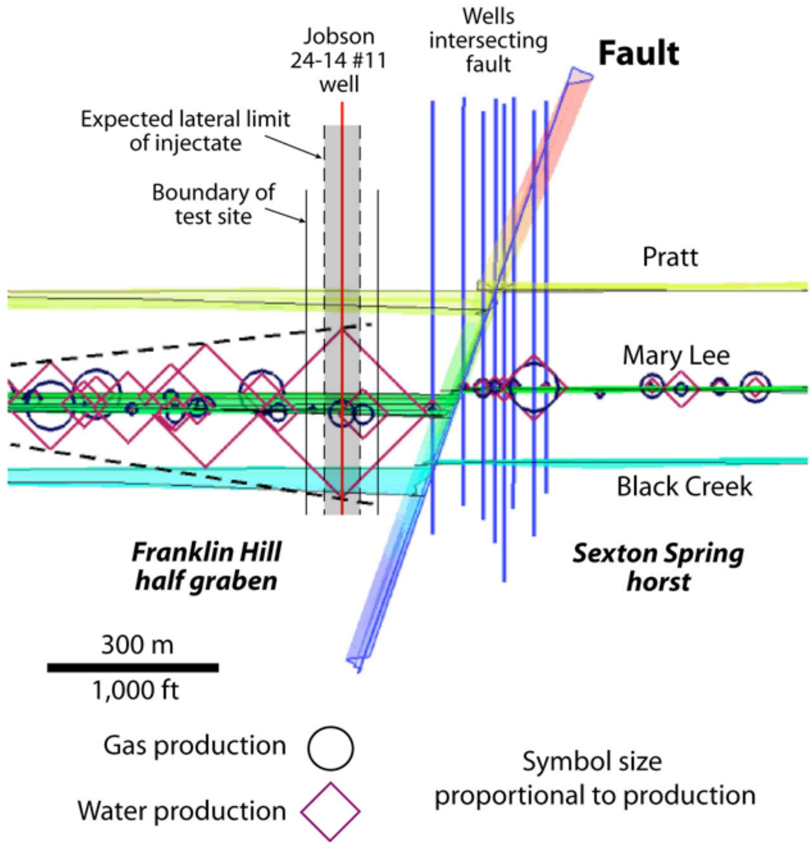


Figure 56.—Three-dimensional structural model showing relationship of the J. D. Jobson 24-14 #11 well and the SECARB field verification test site to a normal fault separating the Franklin Hill half graben from the Sexton Spring Horst (modified from Groshong and others, 2003).

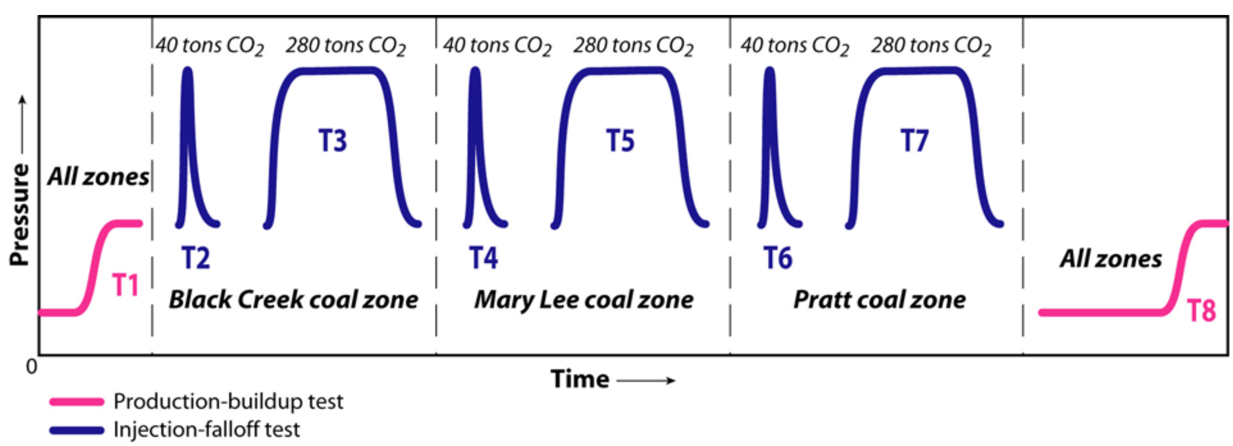


Figure 57.—Sequence of production-buildup and injection-falloff tests to be performed in the J. D. Jobson 24-14 #11 well.

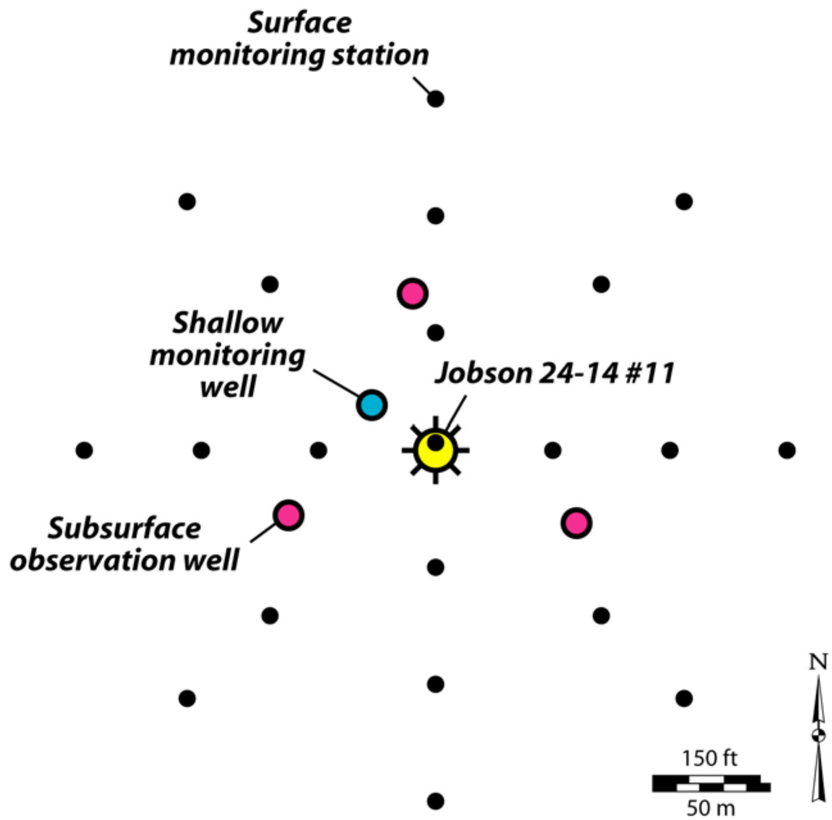


Figure 58.—Diagrammatic layout of observation wells and surface monitoring stations at the SECARB Black Warrior field verification test site.

DFN Models

Fracture networks in the upper Pottsville Formation have statistical properties that are readily quantified and are therefore suited for the development of DFN models. This section reviews selected DFN models that were developed during this project, which include models of joint systems, cleat systems, fault-related shear fractures, and induced hydraulic fractures. Results presented here also include a discussion of compartmentalization and pathways analysis in selected DFN models. As mentioned previously, these models are offered not only as tools to evaluate the carbon sequestration and enhanced coalbed methane recovery potential of the Black

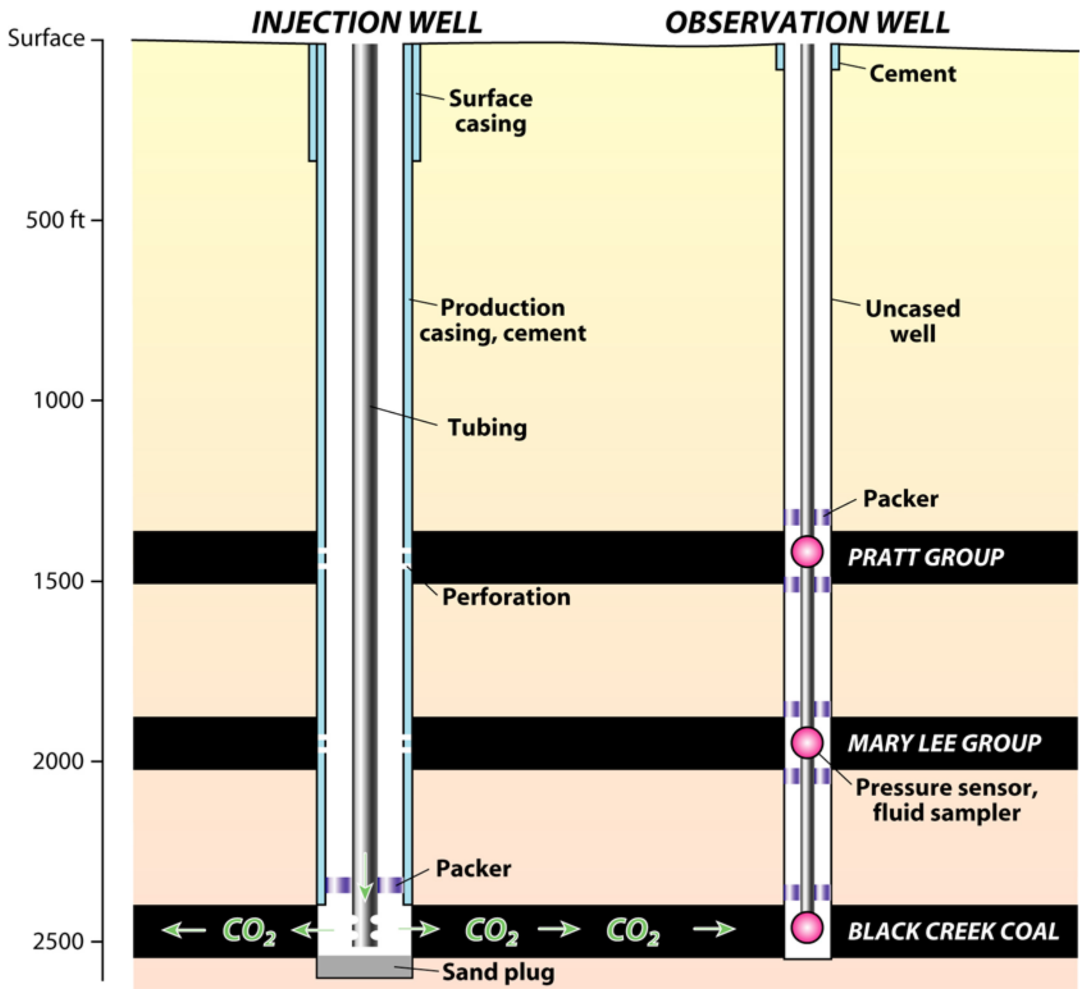


Figure 59.—Generalized diagram showing injection and multi-zone subsurface monitoring scheme to be employed at the SECARB Black Warrior test site.

Warrior Basin, but to provide users with ideas that can be used to apply DFN models to other prospective geologic carbon sinks that contain natural fractures.

The first step in modeling the SECARB test site was to develop a DFN model based on the stratigraphic section recorded in the geophysical log of the Jobson 24-14 #11 well (fig. 53). Accordingly, a DFN model was constructed that simulates fracturing in 96 layers of shale, sandstone, and coal in an area of four square kilometers (fig. 60). To give a feel for scale relative to well spacing in the Black Warrior Basin, the DFN model was constructed with four vertical wells spaced at 40 acres. The model was constructed on a bed-by-bed basis according to the

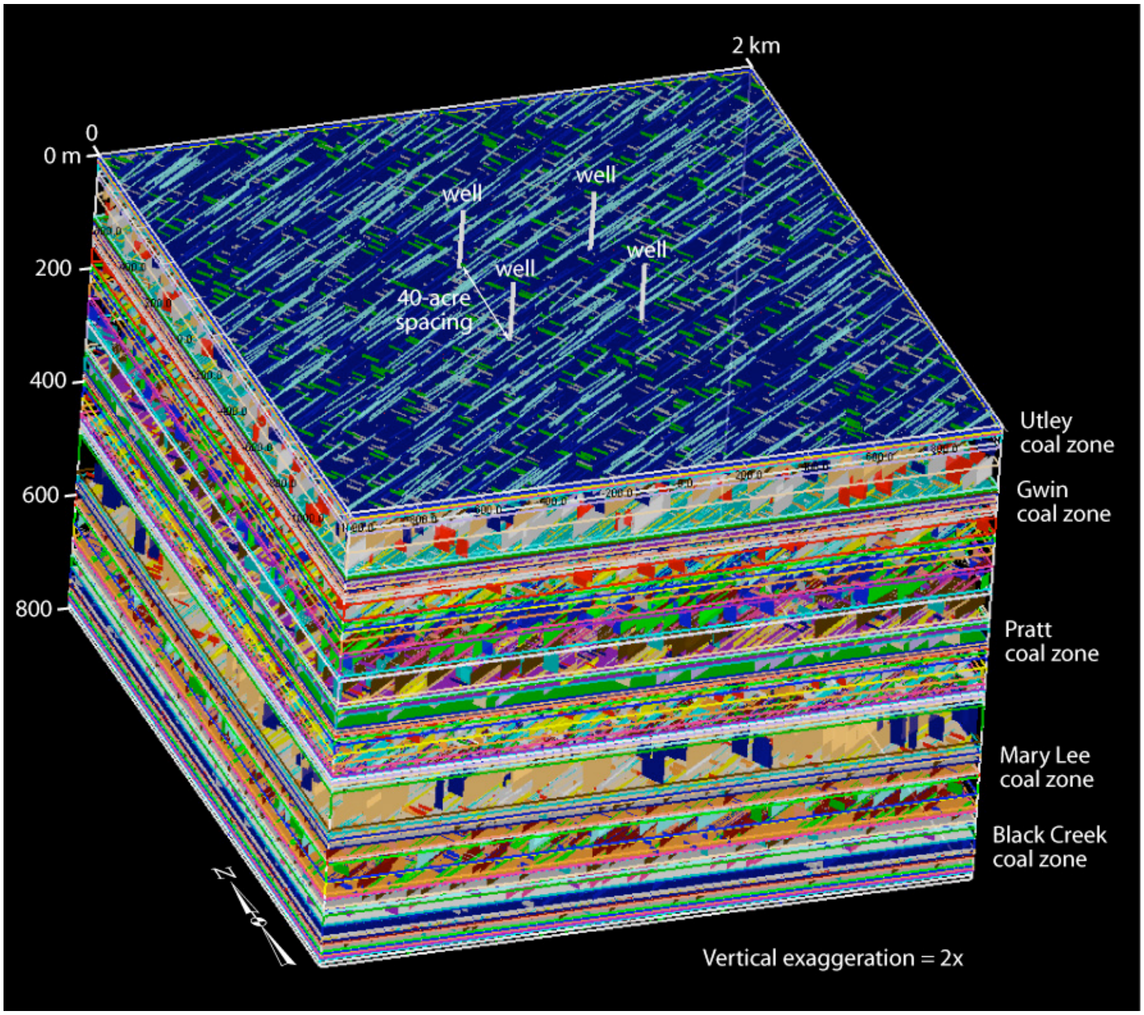


Figure 60.—Jointed DFN model based on stratigraphic relationships in the Jobson 24-14 #11 well and observations of fractures in core and outcrop.

statistical properties of Pottsville fracture networks described above earlier in this report. For each shale and sandstone bed, networks of joints and cross joints were simulated. For example, a DFN model of a joint network in a sandstone bed is color-contoured by fracture aperture (fig. 61). This model honors the power-law distribution of fracture aperture, which indicates that joint networks are dominated by poorly transmissive hairline fractures and that highly transmissive fractures with aperture greater than 1 mm are few. The complete DFN model contains 16 coal beds, which were modeled as horizontal porous strata parameterized with permeability,

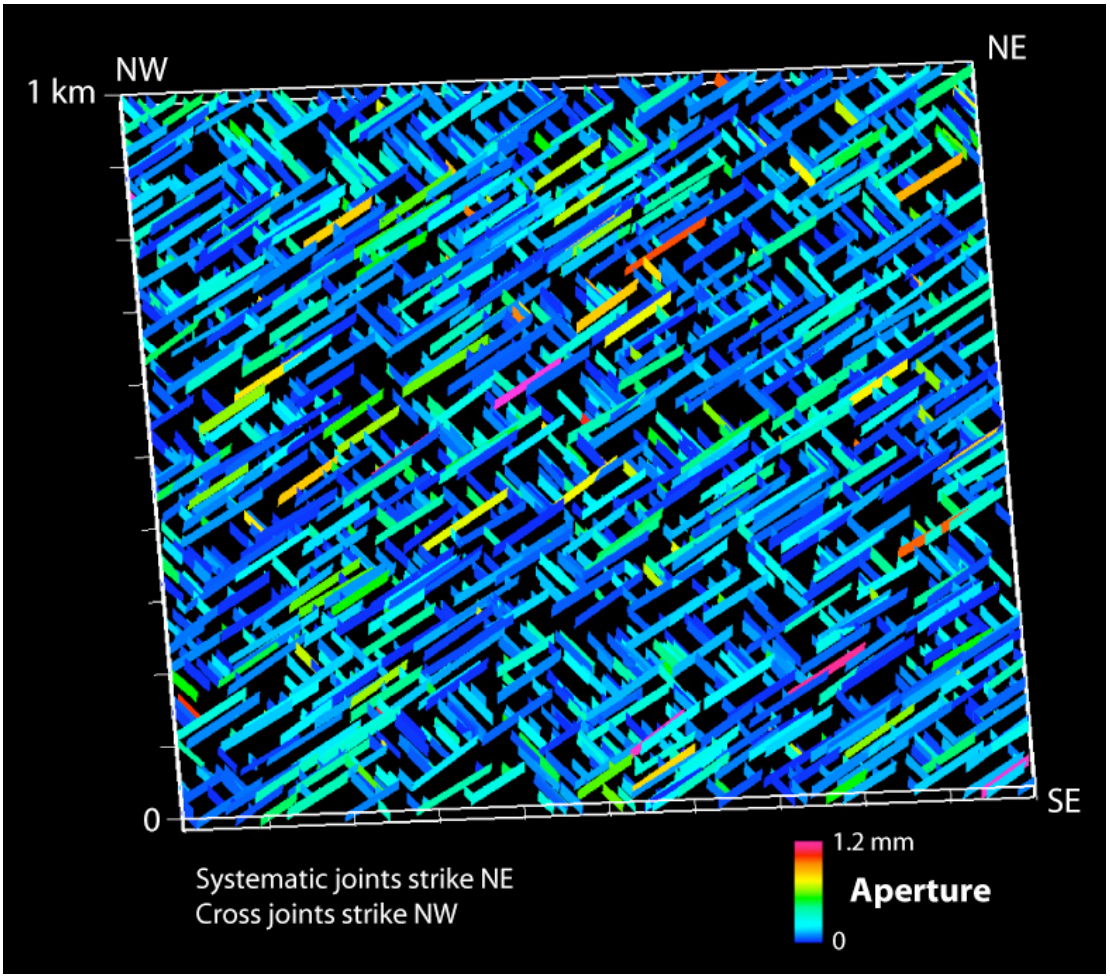


Figure 61.—DFN model of a joint network in a sandstone bed. Note that joint network is dominated by hairline fractures.

transmissivity, and storativity values based on the well-test data of McKee and others (1988) (fig. 62).

To better understand the impact of cleating on reservoir heterogeneity in coal, data on cleat spacing and aperture (figs. 40B, 47) were used to construct a simple DFN model (fig. 63). The cubic law function of Harpalani and Chen (1995) was used to scale the cleat apertures to simulate coal with bulk permeability of 100 mD, 10 mD, and 1 mD, which is representative of the range of permeability observed in most coalbed methane wells in the Black Warrior Basin. Color contouring the DFN models by storage and transmissivity reveals significant contrast

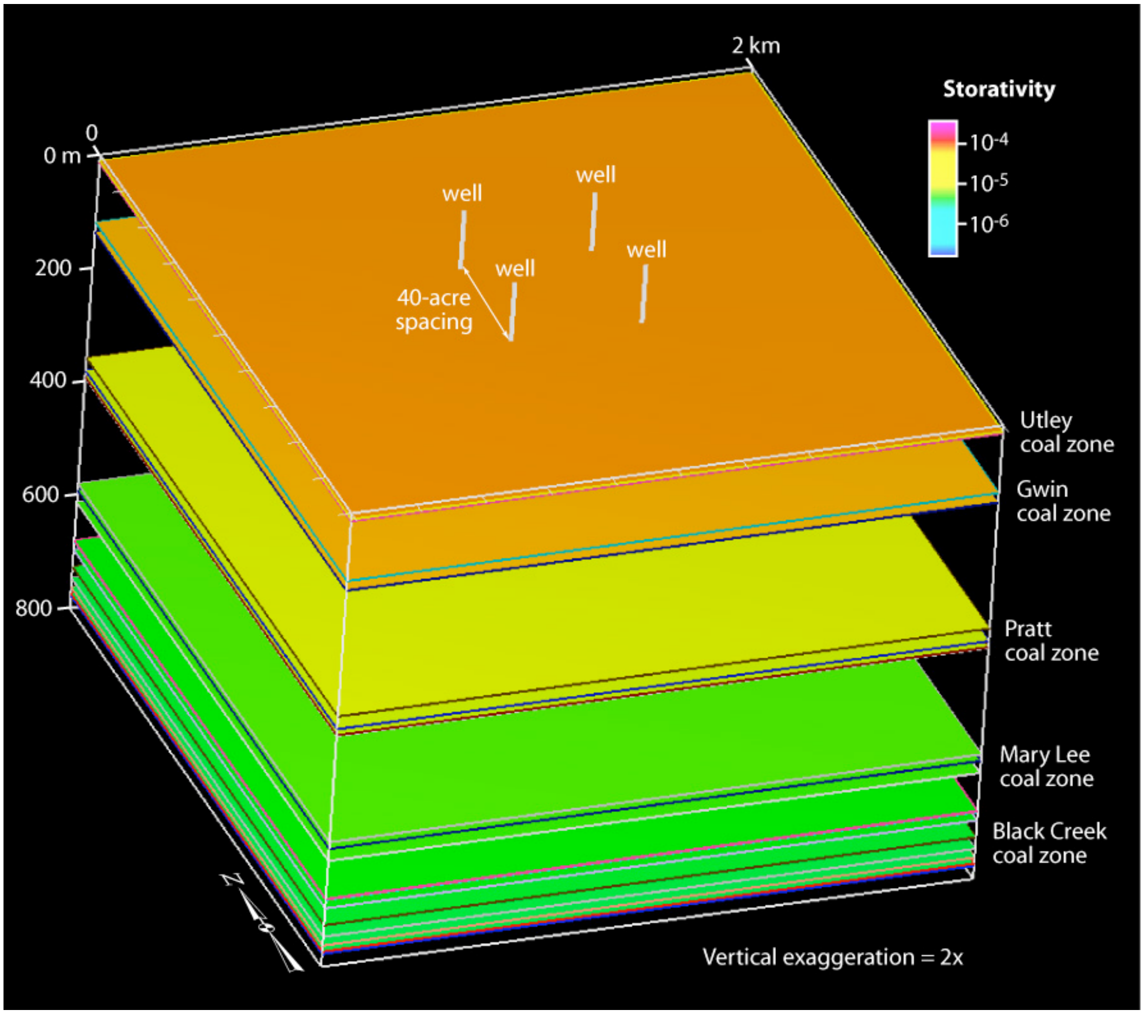


Figure 62.—Storativity model of coal beds in the Jobson 24-14 #11 well.

between shallow, permeable and deep, tight coal seams (fig. 64). The storativity model shows a loss of storage capacity that corresponds to the decrease of fracture aperture with decreasing permeability. Transmissivity is a function of permeability and layer thickness and so shows the effect of cubic law on reservoir properties. What is especially notable is the extreme transmissivity contrast at 100 mD and the general lack of contrast at 10 mD or less. This result is consistent with interference test results from the Black Warrior Basin that show extreme permeability anisotropy favoring flow the face cleat direction in the shallow, highly permeable

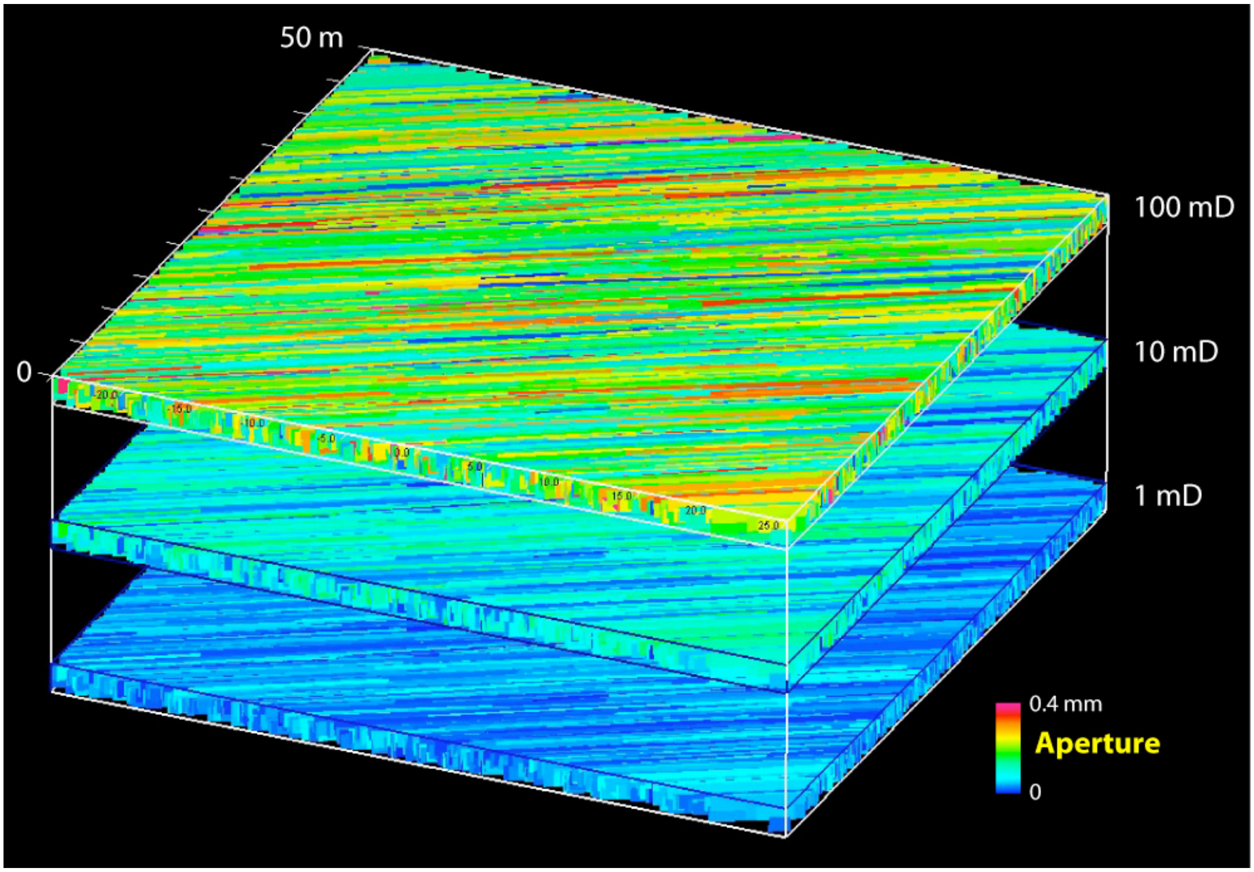


Figure 63.—DFN model of cleat systems with fractures color contoured by aperture. Vertical exaggeration = 5x.

coal of the Pratt zone and limited or negligible anisotropy in deep, less permeable coal of the Mary Lee and Black Creek zones (Koenig, 1989).

DFNModeler is also capable of modeling hydraulic fractures (fig. 65). The example shown here is based on models of hydrofractures that operators submit to the State Oil and Gas Board as part of their hydraulic fracturing programs (summarized in Pashin, Jin and Payton, 2004). The DFN models incorporate the hydraulic fractures as elliptical structures that extend laterally for an average of 93 m and vertically for an average of 24 m. Induced fractures tend to propagate parallel to the maximum horizontal compressive stress, which in the Black Warrior Basin is directed at about N. 75° E. (Zoback and Zoback, 1989; Steidl, 1993). Hydrofractures are propped

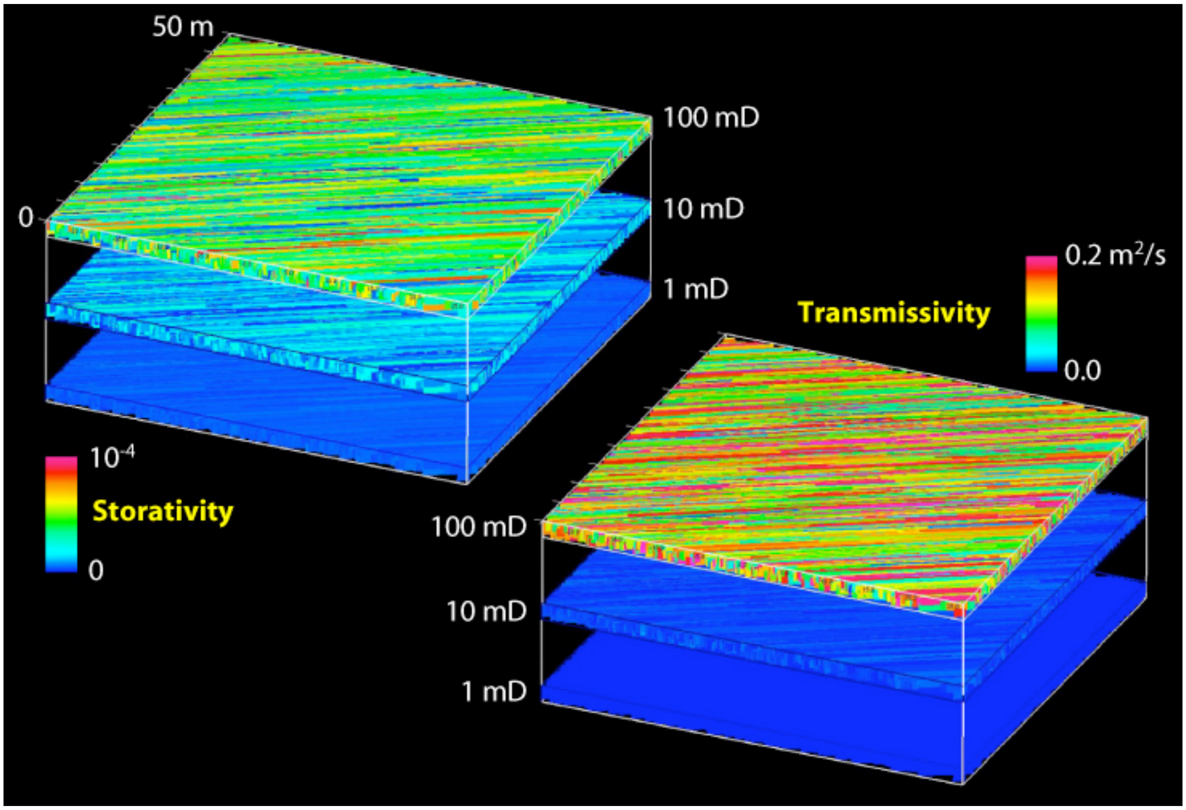


Figure 64.—DFN models of cleat systems with fractures color contoured by storativity and transmissivity. Vertical exaggeration = 5x.

that some hydraulic fractures are solitary structures, although hydrofractures within the same coal zone can grow into each other.

Simulation of faults and fault-related shear fractures in the Black Warrior Basin proved challenging. The original faulted DFN models of Pashin, Jin, and Payton (2004) modeled normal faults with a symmetrical swarm of shear fractures developed around a fault plane. However, analysis of cores and outcrops indicates that shale and sandstone beds fracture in fundamentally different ways and that networks of fault-related shear fractures contain distinctive strata-bound elements (figs. 33). In shale, fault-related are concentrated within 10 m of the fault plane and form shear zones in which the orientation of individual fractures is highly variable. In sandstone, by comparison, shear fractures are organized into a well-defined network of synthetic and

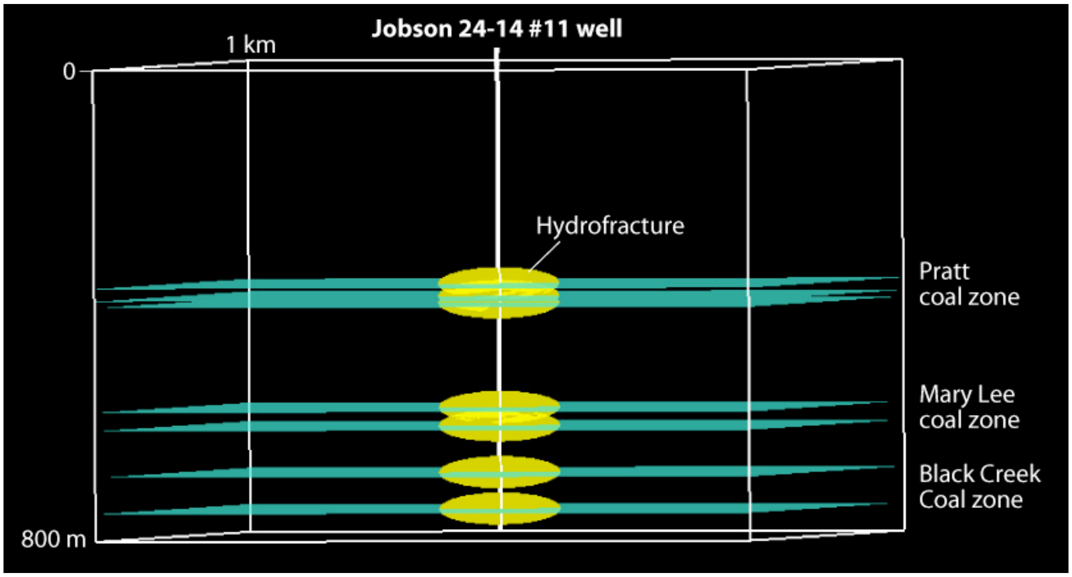


Figure 65.—DFN model of coal seams and hydraulic fractures in the Jobson 24-14 #11 well. No vertical exaggeration

by 20 to 40 mesh sand and thus have aperture between 0.4 and 0.8 mm. The DFN model shows antithetic shears and are distributed in a wide zone that can extend up to 100 m from the fault plane (fig. 50). These differences result in an extremely complex fracture architecture that is controlled by the juxtaposition of different rock types at the fault plane (fig. 66). Where like rock types are juxtaposed, fracturing around the fault plane is fairly symmetrical. Where different rock types are juxtaposed, fracturing about the fault plane is highly asymmetrical.

Compartmentalization analysis was performed on the major DFN model based on the Jobson 24-14 #11 well (fig. 53) and indicates that strata-bound fracturing in the Pottsville Formation facilitates compartmentalization of the hydrologic system (fig. 67). Closely spaced coal beds that are interconnected by joints and hydraulic fractures fall within the same hydrologic compartments. Accordingly, the Mary Lee and Black Creek coal zones constitute a deep reservoir compartment, the Pratt coal zone constitutes an intermediate reservoir compartment, and the Gwin and Utley coal zones constitute a shallow compartment. Interestingly, Pashin, Jin

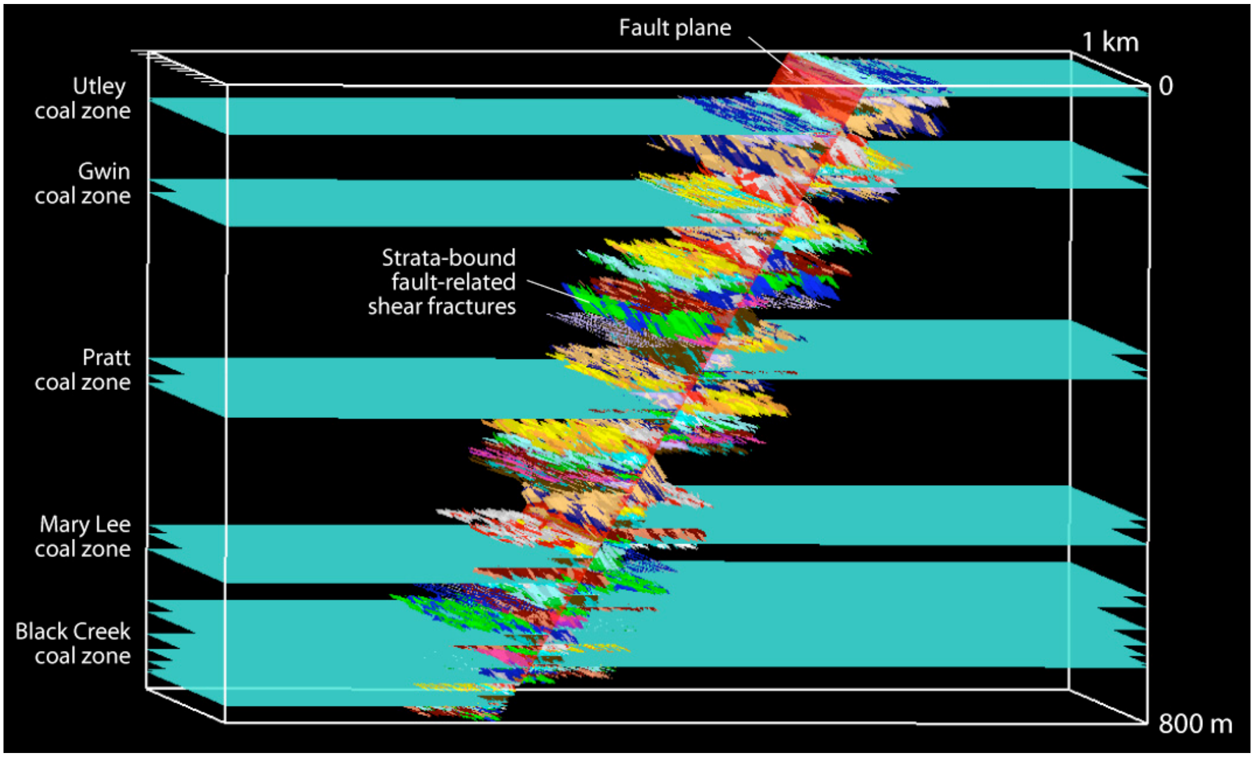


Figure 66.—DFN model of coal seams, a normal fault, and fault-related shear fractures. No vertical exaggeration.

and Payton (2004) reported nearly identical results when performing compartmentalization analysis on a similar DFN model based on a different well. These three major compartments are separated by thick intervals of interbedded shale and sandstone, which contain numerous second-order compartments. These second-order compartments represent stranded clusters of interconnected joints that are not in hydraulic communication with the coalbed methane reservoirs. Stacking of numerous shale and sandstone units with separate strata-bound joint networks is the principal mechanism of compartmentalization. Pathways analysis based on the four wells in the DFN model simply highlights the first-order compartments, which contain coal seams that extend across the model.

Compartmentalization analysis of faulted DFN models indicates that fault zones can form significant conduits for cross-formational flow. DFN models containing only coal seams and

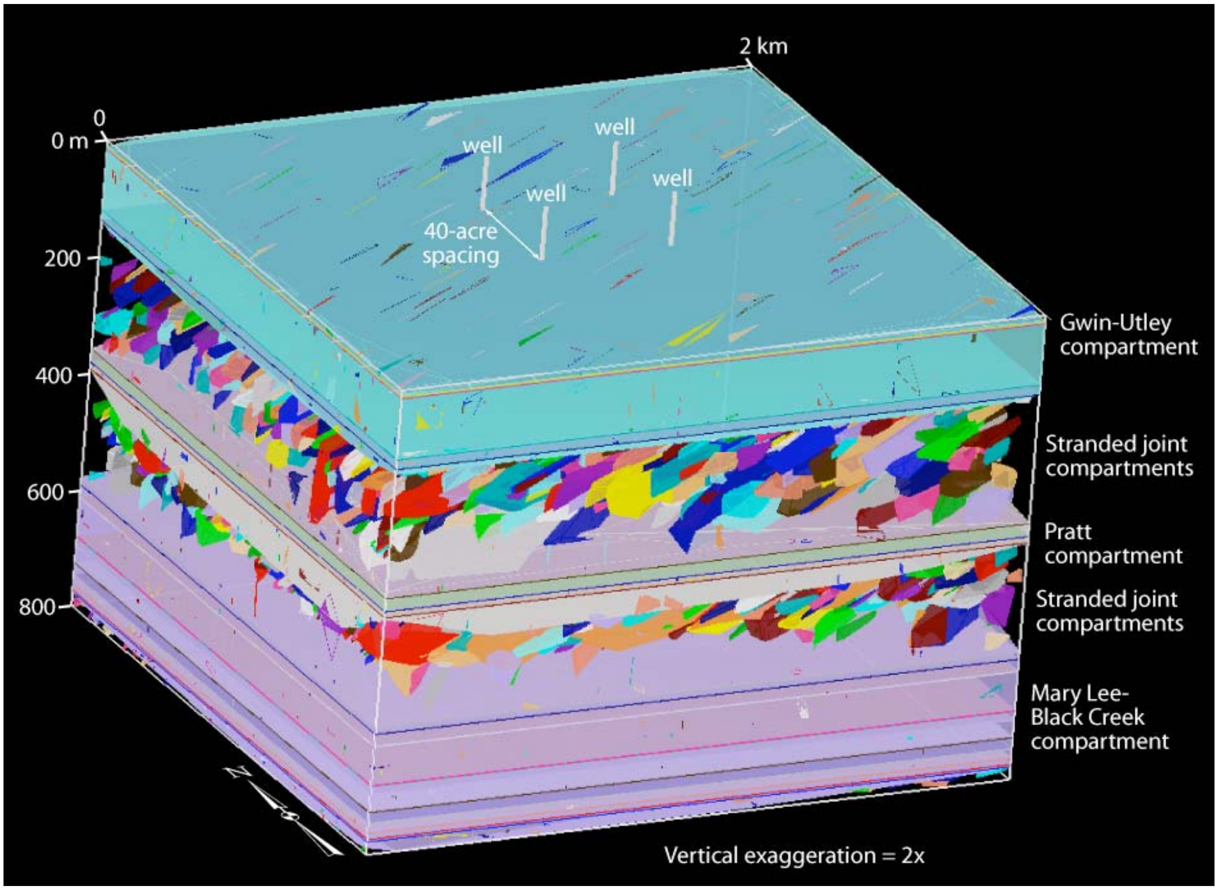


Figure 67.—Results of compartmentalization analysis. Note that shallow coal zones are in a compartment that is separate from the reservoir coal zones and that small, stranded joint compartments are stranded between the major reservoir compartments.

fault-related fractures maintain a high degree of compartmentalization that is similar to that observed in the jointed DFN models (fig. 68). In the faulted models, shale-shale juxtapositions within the thick mud-rich intervals separating the major coal zones act as bottlenecks that help compartmentalize the system. Complete models incorporating joints, however, do not contain major compartments separating the major coal zones (fig. 69). Instead, a first-order compartment envelops the entire DFN model, and contains numerous second-order compartments containing stranded joint networks. The results of compartmentalization analysis indicate that communication among joints and fault-related shear fractures can facilitate cross-formational

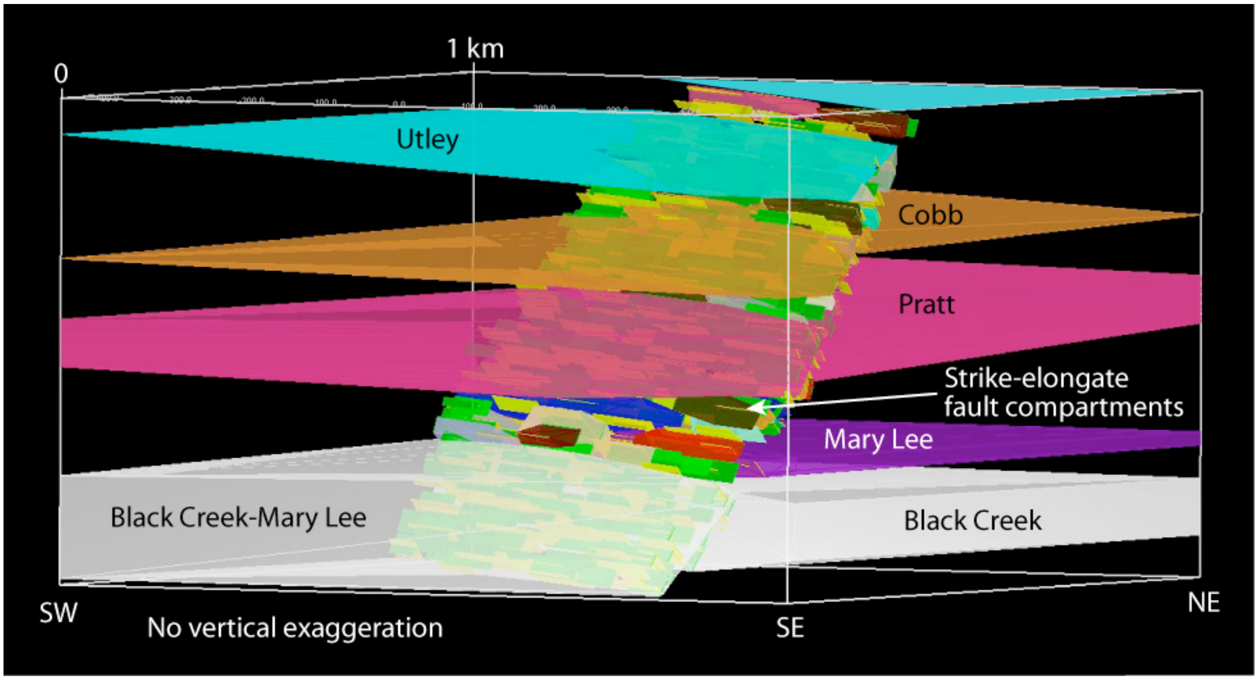


Figure 68.—Compartmentalization analysis of a DFN model containing coal-seams and fault-related shear fractures. Note the development of first-order compartment hulls enveloping coal zones and second-order compartment hulls that are elongated along strike of the fault.

flow. The requirement for communication among joints and shears to break down the major reservoir compartments further indicates that significant cross-formational flow should occur only in close proximity to fault zones.

FLOW MODELING

Having developed and analyzed DFN models of fracture networks of Pottsville, flow models can then be constructed. Flow modeling software packages, such as TOUGH2, are too computationally intensive to model flow within extremely large DFN models with tens of thousands of fractures. However, flow models can be constructed using subsets of the large DFN models to test hypotheses and identify critical controls on subsurface flow in fractured media. Discussion of these flow models begins with a review of key model parameters, continues by

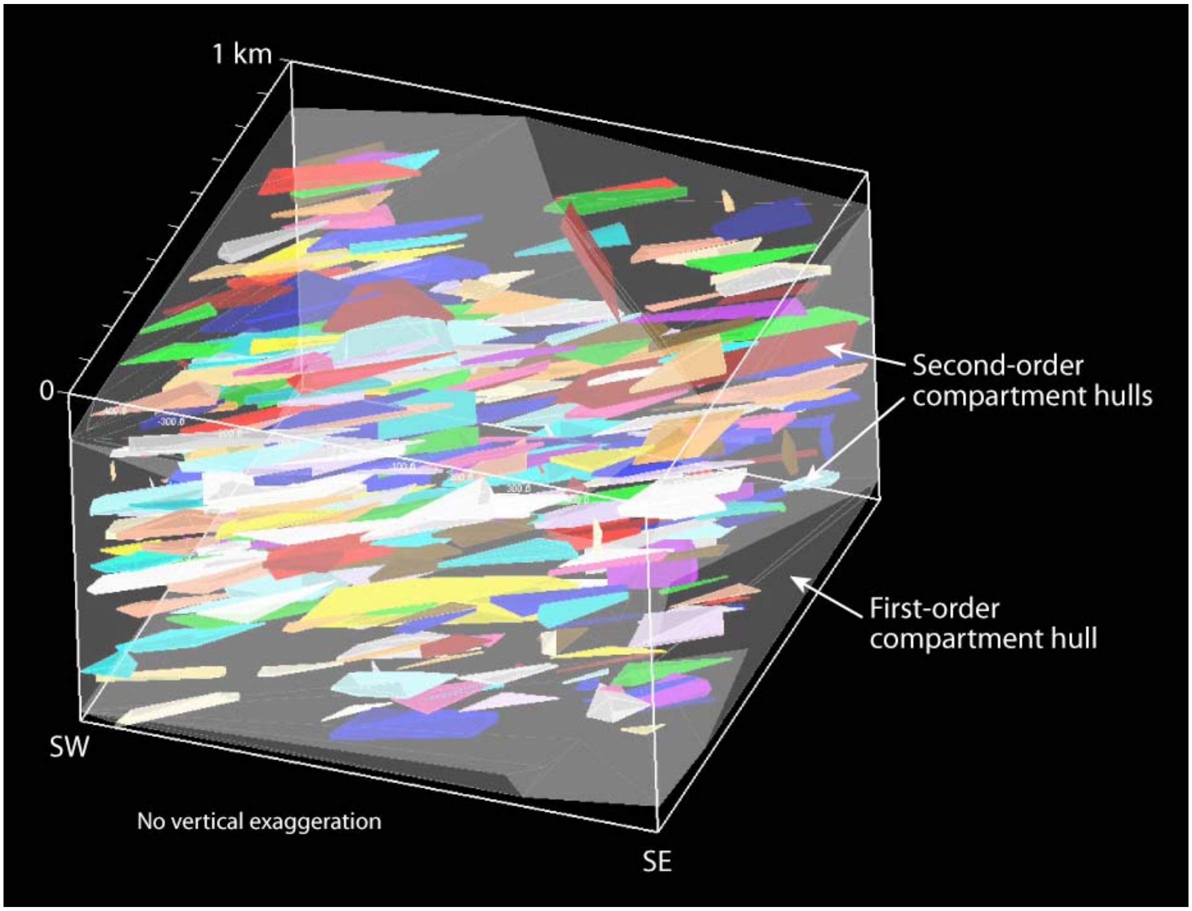


Figure 69.—Compartmentalization analysis of a faulted DFN model that includes joint networks. Note that a first-order compartment hull envelops the complete DFN model and contains numerous second-order hulls.

considering the impact of fractures on the flow of injected CO_2, and concludes by modeling the impact of strata-bound fracture networks on fluid flow.

Model Parameters

Sandstone and shale in the coalbed methane fields have extremely low matrix permeability. For example, upper Pottsville sandstone is litharenite with permeability below 0.06 mD (Pashin and Hinkle, 1997), and conventional core analyses indicate that permeability is below the limits of detection of standard permeameters. In the flow models, the permeability of shale and sandstone was modeled as being on the order of a microdarcy, or 1 x 10^{-18} m^2. Porosity values for shale and sandstone were assigned as 2 percent and 15 percent, respectively.

The average permeability of coal was modeled as decreasing with depth following the well-test results of McKee and others (1988). The permeability of the shallowest coal zone (Utley) is estimated to be 233mD (2.3 x 10^{-13} m^2), whereas that of the deepest zone (Black Creek) is estimated to be about 1 mD (9.87 x 10^{-16} m^2). Permeability can vary more than one order of magnitude at any given depth, and so well-test data are desirable for constraining permeability in coalbed methane reservoirs. Though coal is typically considered as a dual continuum consisting of coal matrix and cleats, it is modeled as single continuum that averages matrix and cleat properties here. Permeability anisotropy due to the coal cleat systems was incorporated into the models. The porosity of coal decreases with depth and has been modeled as ranging from 5 percent at the surface to less than 1 percent at reservoir depth (Pashin, Jin, and Payton, 2004).

Capillary pressure and liquid relative permeability values were selected using van Genuchten functions (van Genuchten, 1980). The Corey function (Corey, 1954) was used to calculate the relative permeability of CO_2. The parameters for Genuchten functions and Corey function used in this study follow examples given in the ECO2N manual (Pruess, 2005). Injection pressures and rates were modeled using a variety of values based on known reservoir pressures and likely injection pressures to be used during sequestration and enhanced recovery operations.

Effect of Fractures and Rock Matrix

Several 3-D, two-phase CO_2 injection models were constructed to simulate the effect of discrete fractures. In all runs, model length and width were 1 km, and model height was 45 m. Each model consists of five layers of shale, sandstone, and coal. Vertical grid size is a maximum of 10 m, depending on bed thickness, and horizontal grid blocks were 10 x 10 m. A sandstone bed above coal was modeled as containing four discrete fractures with the same aperture (fig. 70). The fractures are arranged in a rectilinear pattern with the center of each fracture located 50 m from a well (fig. 70B).

Injection of CO_2 is modeled as taking place in the center of the coal layer (fig. 70B). Injection rate was modeled at 0.05 kilograms per second (kg/s), or 4.32 tonnes per day, which is consistent with the injection rate planned for the SECARB Black Warrior field test. In this model, rock matrix was discretized into 16,425 grid blocks. Boundary conditions for the model include zero CO_2 saturation prior to injection, hydrostatic reservoir conditions, and a reservoir temperature of 25°C.

Seven simulations were performed using different fracture apertures to determine the effect of fracture aperture on the leakage of injected CO_2 from coal into fractures in the overlying sandstone (fig. 71). Fracture apertures used for the models range from 0.001 mm to 1 mm. Simulating 4,000 days, or more than a decade, of continuous injection indicates that fracture aperture has a major influence on leakage of injected CO_2 from coal into adjacent strata. Leakage is negligible through hairline fractures having aperture of 0.05 mm or smaller (fig. 71, table 1).

By comparison, large aperture fractures with aperture greater than 0.1 mm pose significant leakage risks (fig. 71, table 1). Moreover, fractures with aperture on the order of 1 mm can form major leakage pathways, and the pattern of four fractures modeled in this study can capture 20 to 40 percent of the injected CO_2 during continuous injection operations lasting longer than 1,000 days. For short-term experiments lasting less than 30 days, like the SECARB Black Warrior field test, however, these leakage risks are limited by the small volume of CO_2 that will be used.

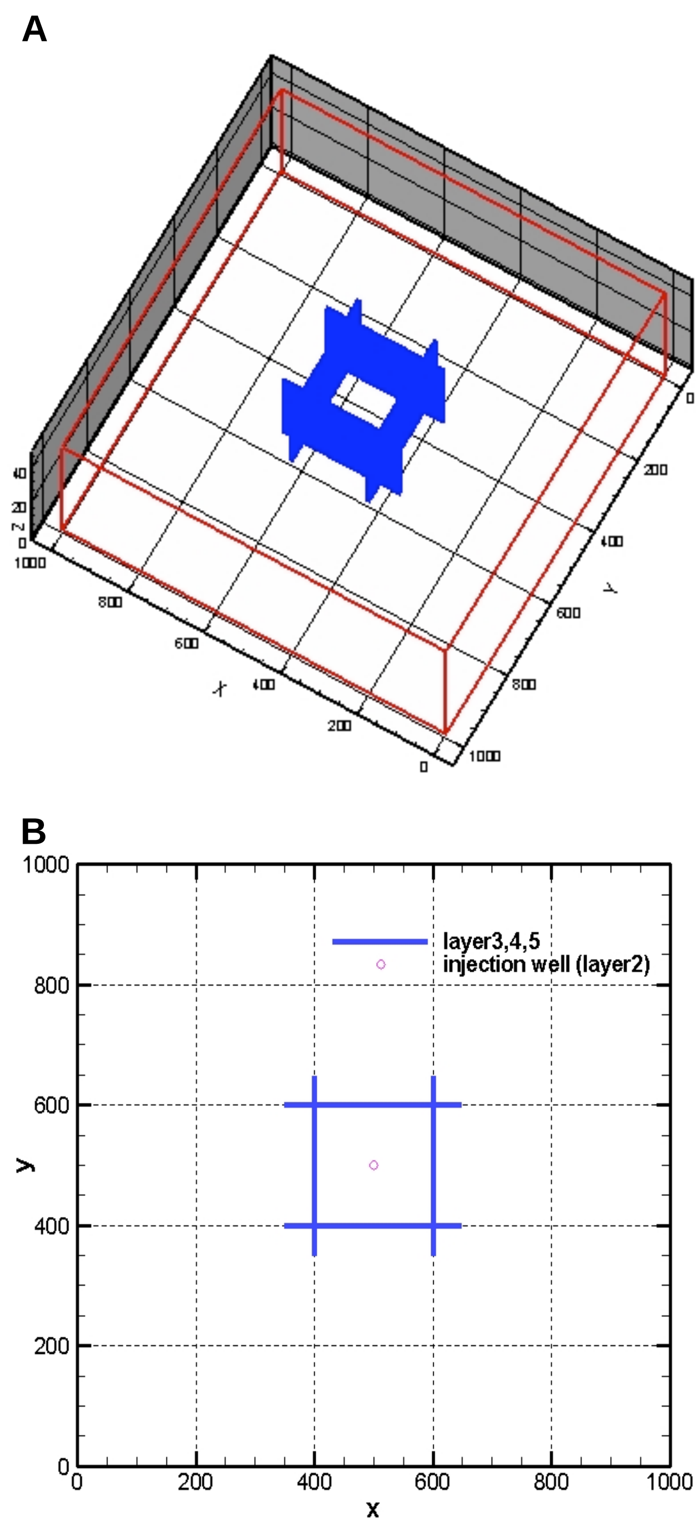


Figure 70.—Locations of fractures and injection well in flow models testing influence of individual fractures on leakage of injected CO_2. A) Overview of model. B) Plan view.

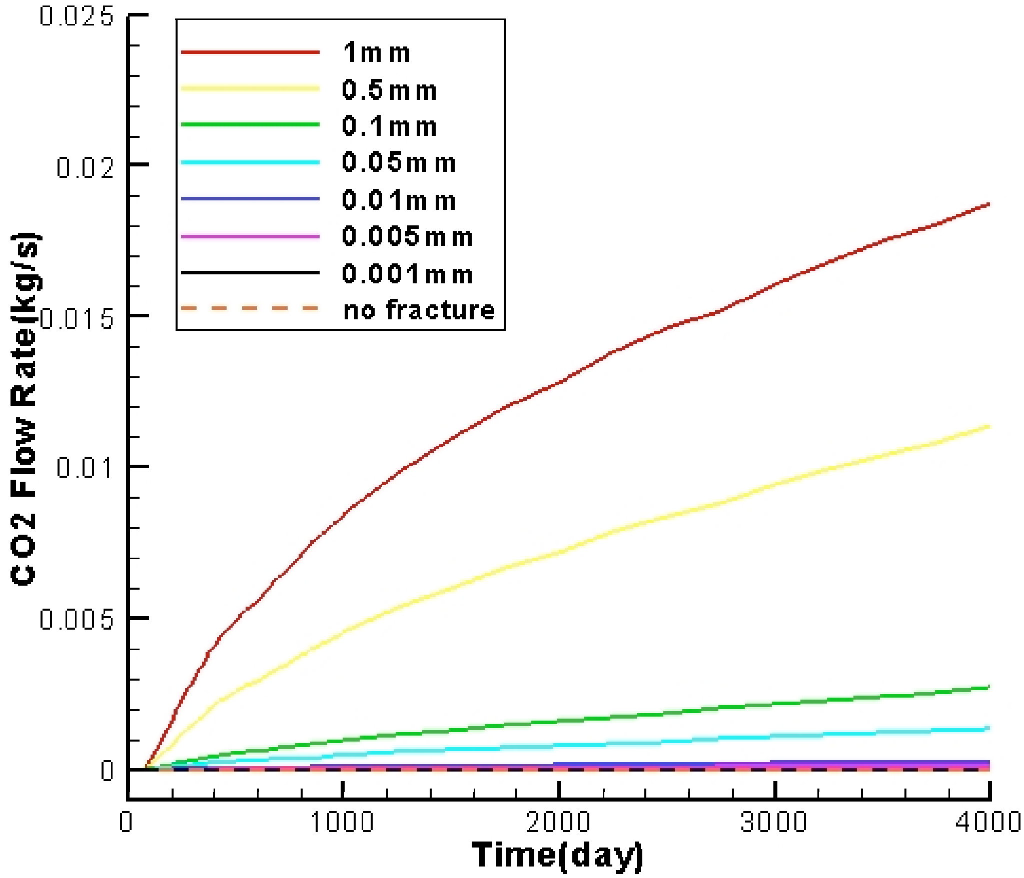


Figure 71.—Flow modeling results showing the effect of fracture patterns with different aperture on leakage of injected CO_2 from coal into joints in sandstone.

Table 1. Calculated leakage for different fracture apertures of injected CO_2 based on flow modeling of a pattern of four rectilinear fractures located 50 m from an injection well.

Aperture (mm)	Leakage (%)
1.0	23.70
0.5	13.55
0.1	3.05
0.05	1.55
0.01	0.29
0.005	0.12
0.001	0.003

Three additional flow models were made using a fracture aperture of 0.5 mm to investigate the effect of microdarcy-class matrix permeability on leakage of injected CO_2 through fractures. In these models, sandstone permeability was investigated at 5 x 10^{-18} m^2 (high), 1 x 10^{-18} m^2 (middle) and 5 x $10^{-19}$$m^2$ (low) (fig. 72). Results indicate that increased matrix permeability, even at the microdarcy level, can help reduce leakage of injectate through fractures during multi-year injection operations. Accordingly, permeable streaks in sandstone beds appear to be advantageous during sequestration operations provided that bounding shale units have sufficient sealing capacity.

Effects of Strata-Bound Fracture Networks

Whereas the preceding discussion considers the leakage of injected CO_2 from coal, this section considers the effect of strata-bound fracture networks on trans-stratal flow and leakage. To characterize the impact of strata-bound fracture networks, three realizations of a DFN model containing four stratigraphic units were constructed in DFNModeler. The area of the model is 500 m^2, and the height of the model is 19.5 m, and the model simulates two coal beds, a bed of shale, and a bed of sandstone (fig. 73).

One challenge for modeling fluid flow in fractured media is incorporating discrete fractures. Although TOUGH2 provides a way to grid unstructured features for flow model, there is no procedure on directly gridding the discrete fracture networks. As part of this study, a procedure was developed to characterize the connectivity of fractures within layers and among layers and to generate grid blocks four TOUGH2 that accurately represent fracture location and connectivity in the original DFN model. Because joints and cleats are effectively vertical, 3-D DFN realizations of individual beds can be projected into two dimensions without losing significant

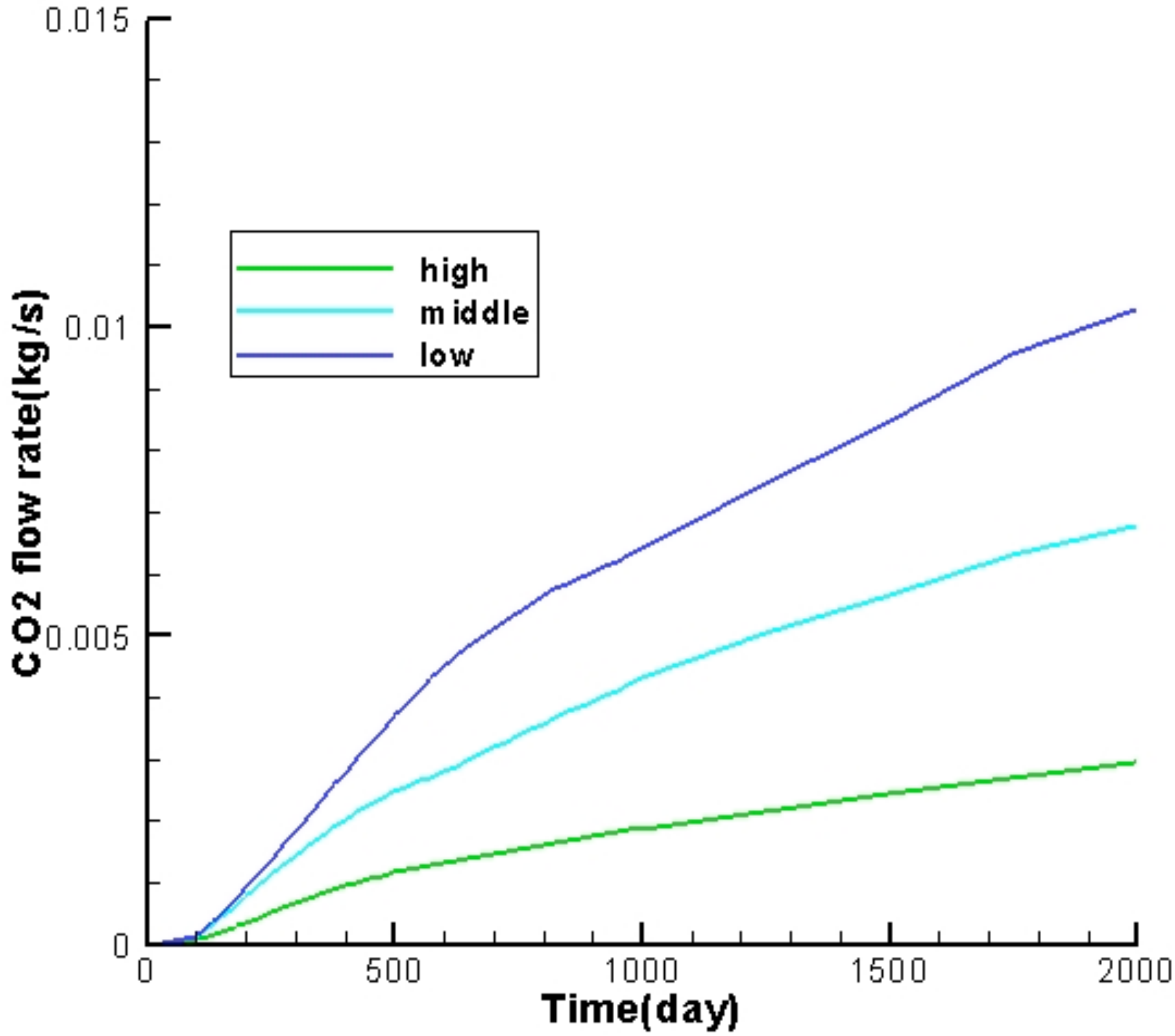


Figure 72.—Flow modeling results showing the effect of microdarcy-class matrix permeability in sandstone on the leakage of injected CO_2 through fractures.

information (fig. 74). Interconnectivity of the fractures can further be characterized using a hierarchical box diagram (fig. 75). Based on the distribution of fractures in each bed, fracture grid blocks are defined and superimposed on a grid of rock matrix properties.

In all realizations based on the DFN models, CO_2 is modeled to be injected in the center of the lower coal layer. The injection rate was modeled at 0.01 kg/s (0.86 tonnes per day). Parallel to bedding, the matrix grid blocks represent an area of 10 m^2. The number of grid fracture grid

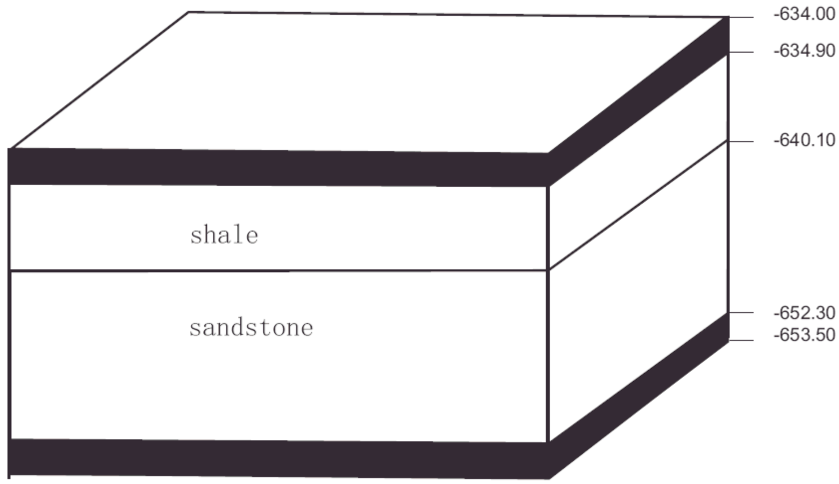


Figure 73.—Simple diagram showing stratigraphic framework consisting of coal (black), shale, and sandstone that was used to model flow in strata-bound fracture networks.

blocks used in each realization is variable and depends on the number of intersections that exist between the matrix grid and the fracture grid. In the first realization run, for example, 1,780 fracture grid blocks are required to accurately simulate the DFN model. Boundary conditions for the flow models are the same as those discussed earlier for the models of leakage into fractures and matrix.

An important result of flow modeling is that the strata-bound nature of the fracture system causes major dissipation of flow from a coal bed into successive overlying beds (fig. 76). Hydraulic communication between strata-bound joint systems is restricted to narrow pore throats where joints of differing orientation intersect at bed boundaries. Because only small segments of joints can communicate across major bedding contacts, the dissipation of flow into successive beds is substantial. Moreover, the odds of linkage between two large-aperture fractures in successive beds appears to be remote. In the model shown here, the rate of leakage decreases by about an order of magnitude from bed to bed. The other realizations modeled in this investigation

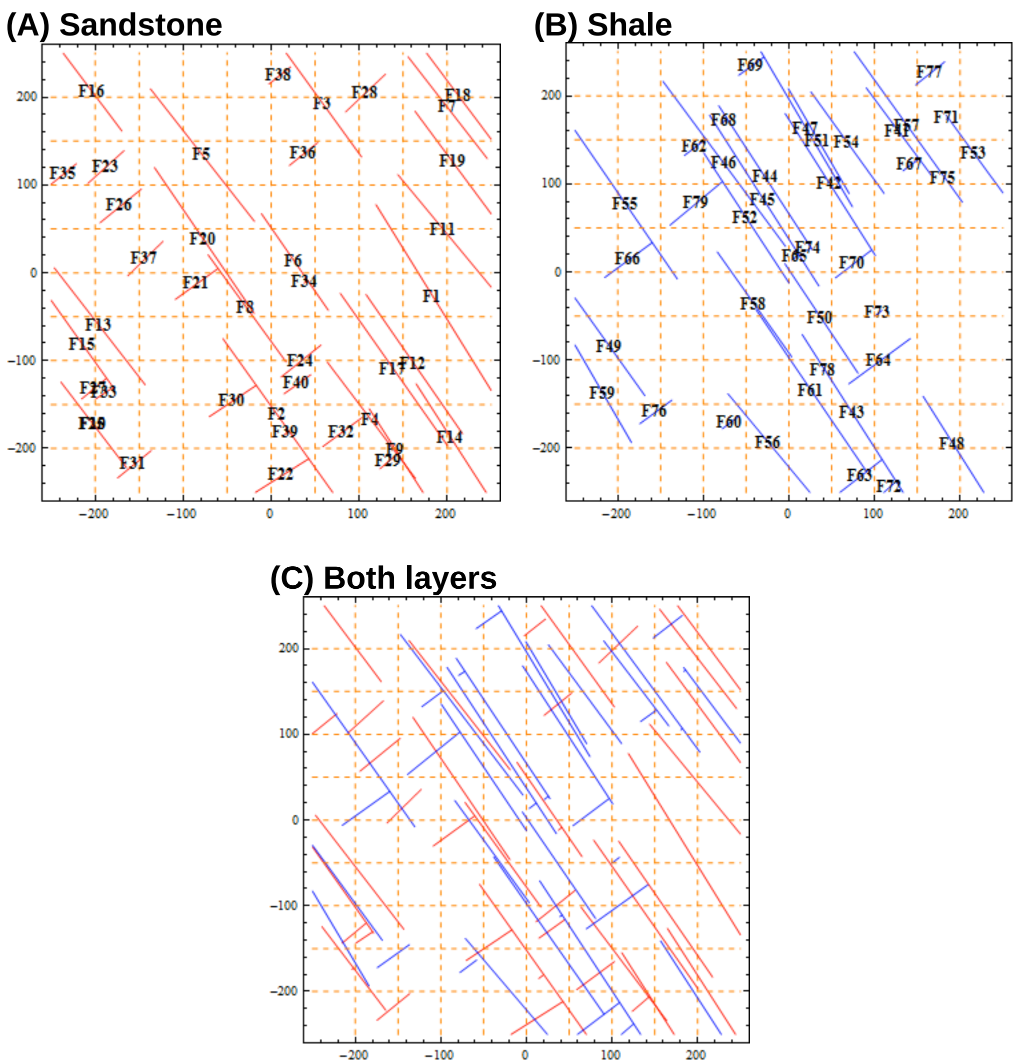


Figure 74.—Two-dimensional plan-view representations of DFN models of joint networks in two successive beds of (A) sandstone and (B) shale and (C) a composite of the two models.

show similar results, although the magnitude of leakage is influenced significantly by differences in fracture architecture.

RISK ASSESSMENT

DFN models have been used to assess risks associated with hydrofracturing and other coalbed methane operations in the Black Warrior Basin (Pashin, Jin and Payton, 2004), and DFN models can similarly be used to assess risks associated with carbon sequestration and enhanced coalbed methane recovery. This section considers the utility of DFN models and DFN-

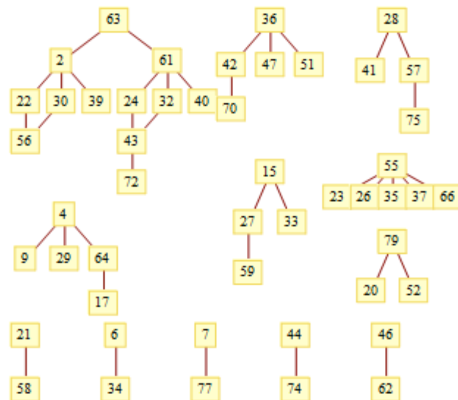


Figure 75.—Diagram showing linkages among fractures in the sandstone and shale bed shown in Figure 74.

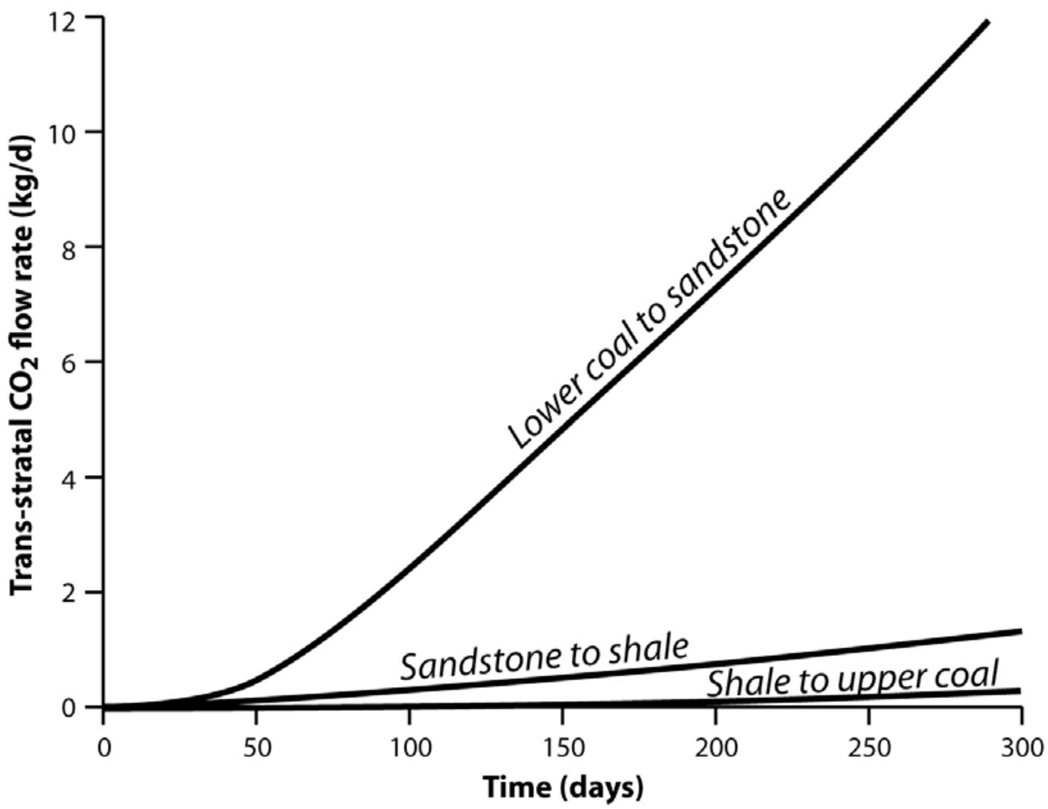


Figure 76.—Plot showing modeled magnitude of leakage of injected carbon dioxide from coal into overlying strata containing strata-bound joint networks.

based flow models for assessing risks associated with sequestration in coal-bearing strata. Critical points that are emphasized throughout the discussion are the applicability of these models to the Black Warrior Basin and the advantages and shortcomings of these models as risk assessment tools.

DFN models are powerful tools for the simulation and analysis of fracture networks (figs. 60-69). However, the stochastic nature DFN models dictates that they cannot be used to precisely reproduce reservoir conditions in a specific field area because high-transmissivity fractures are likely to be realized where they do not exist in nature. For this reason, DFN models cannot be used reliably for the development of history matched reservoir models. Rather, the role of these models is to help develop and test hypotheses by simulating the fundamental geometric and statistical properties of fracture networks. Using this type of approach, modelers can inform the risk assessment process by characterizing the way these basic relationships affect the behavior of aquifers, hydrocarbon reservoirs, and geologic carbon sinks.

Pottsville coalbed methane reservoirs have been interpreted on the basis of reservoir pressure and water chemistry as part of a highly compartmentalized reservoir system that favors bed-parallel flow in coal (e.g., Pashin and McIntyre, 2003; Pashin, 2007). The results of DFN modeling and compartmentalization analysis corroborate this finding and indicates that the predominance of strata-bound joint networks limits the probability of surface seepage (figs. 60, 67). However, these models indicate that substantial communication may occur among closely spaced coal seams through large-aperture fractures and hydrofractures.

Although communication among coal seams does not appear to pose a safety hazard, it is a source of operational risk that may reduce the efficiency of sequestration and enhanced gas recovery efforts. Simulation of the SECARB Black Warrior test site, for example, indicates that some hydraulic communication through natural fractures and hydrofractures may exist between the Black Creek and Mary Lee coal zones during injection, but no significant communication should take place between the Pratt coal zone and the other coal zones (fig. 67). Formation of first-order reservoir compartments around the major reservoir coal zones reflects the predominance of bed-parallel flow with coal seams and predicts that shallow aquifers should be protected from injection operations in the Black Creek through Pratt coal zones.

Trans-stratal joints exist in the Pottsville Formation but are not abundant enough to characterize statistically and therefore were not included in the DFN models. Indeed, one shortcoming of DFN models is that they rely on the identification of geometric and statistical relationships that can be quantified, so any factors that exist in the reservoir that are beyond the realm of observation and quantification can potentially invalidate a model. The principal risk posed by trans-stratal fractures is that, where they occur, little is known of their vertical extent or their relationship to the strata-bound networks that dominate the Pottsville Formation. For this reason, careful well testing and monitoring is important, not only to corroborate the models offered here, but to ensure the safety of sequestration operations in the field.

Faults provide the most obvious trans-stratal discontinuities in the Pottsville Formation (figs. 33, 66) and thus appear to be a significant source of risk. DFN models indicate that interaction among fault-related shear fractures and joints breaks down the first-order reservoir compartments enveloping the major coal zones and thus poses the greatest risk for leakage in fault zones (figs. 68, 69). Examination of production data, however, shows that the performance of coalbed methane reservoirs is affected strongly by the hydrogeologic setting of fault systems (Groshong and others, 2003; McIntyre and others, 2003; Pashin, Jin, and Payton, 2004). Near a major recharge zone along the southeastern margin of the Black Warrior Basin, wells penetrating normal faults can produce anomalously high volumes of water, which indicates that faulting may have enhanced permeability. Distal to recharge in the interior of the basin, coal seams adjacent to faults tend to be cemented with calcite and are associated with exceptionally low gas and water production.

Variable well performance in fault zones indicates that faults should be considered seriously when designing sequestration and enhanced coalbed methane recovery programs. From a practical standpoint, faults are fundamental discontinuities that limit the amount of reservoir that can be contacted by an injection well. In addition, formation of carbonic acid during injection of CO_2 can dissolve calcite cement and thus degrade the integrity of fault seals. Therefore, risk can be minimized and efficiency can be optimized if injection wells are kept away from faults. When designing five-spot programs, locating production wells between injectors and faults will limit risk by creating pressure sinks that ensure that CO_2 flows away from fault zones.

DFNModeler is capable of constructing extremely complex DFN models simulating tens of thousands of fractures (figs. 61-66), but these models are far too large for flow modeling using computational intensive software packages like TOUGH2. Because of this, flow models need to be constructed for subsets of larger DFN models and must be designed to test specific aspects of fracture architecture. In general, DFN-based flow models are subject to the same limitations as DFN models and are best used as tools to test fundamental geologic relationships and to aid in the testing and formulation of hypotheses related to risk. Testing multiple realizations of DFN models, moreover, helps add depth to this type of assessment because multiple realizations help constrain the variability that is inherent in naturally fractured reservoir systems.

Results of modeling in the Black Warrior Basin indicate that fracture aperture and connectivity are critical parameters affecting the leakage of injected CO_2 from coal (figs. 71, 74, 76). The vast majority of joints and fault-related shear fractures are hairline fractures with negligible transmissivity. However, fractures with aperture larger than 0.1 mm can capture a significant amount of injected CO_2, and highly transmissive fractures with aperture on the order of 1 mm have potential to divert a large percentage of an injected CO_2 stream away from a target coal seam (fig. 71). Hence, the location of transmissive fractures relative to a wellbore may have a strong impact on the performance, efficiency, and predictability of sequestration and enhanced coalbed methane recovery operations. This risk appears to be greatest within coal zones where seams are closely spaced and are separated by few beds of shale and sandstone.

Although highly transmissive fractures may divert a significant amount of CO_2 from a target coal seam, the strata-bound nature of Pottsville fracture systems is a natural factor that mitigates the risk of long-range leakage and surface seepage. The probability that highly transmissive fractures are connected in successive beds is low, and communication between strata-bound joints can occur only through narrow throats at bedding contacts where fractures of different orientation overlap (fig. 74). The result of this configuration is that cross-formational flow is dissipated by about an order of magnitude from bed to bed (fig. 76). In this respect, strata-bound joint networks are self-compartmentalizing, and the thick successions of interbedded shale and sandstone that separate the Pottsville coal zones are interpreted as confining units that protect shallow coal zones from injection operations in reservoir coal zones.

SUMMARY AND CONCLUSIONS

Coal is potentially an important sink for the sequestration of carbon dioxide, and a software package called DFNModeler has been developed to assess the potential risks associated with carbon sequestration in coal. Natural fractures provide the principal conduits for fluid flow in coal-bearing strata, and these fractures present the most tangible risks for the leakage of injected carbon dioxide. DFN models are stochastic realizations based on the statistical properties of fracture networks. These models have been used successfully to assess leakage risks associated with hydraulic fracturing and coalbed methane production, and these models show promise for assessing risks associated with carbon sequestration in coal. The objectives of this study were to develop DFN modeling tools for risk assessment and to use these tools to assess risks in the Black Warrior Basin of Alabama, where coal-bearing strata of the Pennsylvanian-age Pottsville Formation have high potential for carbon sequestration and enhanced coalbed methane recovery.

DFNModeler software runs under Microsoft Windows operating systems and provides an interactive, user-friendly environment for the construction, visualization, and analysis of DFN models. The software is driven by a system of menus and dialog boxes that facilitates the input and editing of the parameters required to construct DFN models and enables users to customize the appearance of those models. DFNModeler employs an OpenGL graphics engine that enables real-time translation, zooming, and rotation of DFN models and further gives users control over scale, color, and transparency. Analytical capabilities in DFNModeler include color contouring of fracture polygons according to structural and hydrologic parameters, compartmentalization analysis, and fluid pathways analysis. DFN models can be exported as text files to third-party software packages, such as TOUGH2, for flow modeling.

DFN models were constructed to simulate fracturing in coal-bearing strata of the upper Pottsville Formation in the Black Warrior Basin. Geophysical well logs from the Jobson 24-14 #11 well, which is being used for the SECARB Black Warrior field test for carbon sequestration and enhanced coalbed methane recovery in Deerlick Creek Field, were used as the primary stratigraphic control for the models. Outcrops and wireline cores were used to determine the basic statistical scaling rules for fracture systems in the upper Pottsville, which include orthogonal joint systems, cleat systems, and fault-related shear fractures. Critical variables analyzed include the orientation, length, height, spacing, kinematic aperture, and cross-cutting relationships for each type of fracture. Results of fracture analysis indicate that the Pottsville Formation is dominated by strata-bound fracture networks. Fracture aperture tends to follow power-law distributions dominated by hairline fractures with kinematic aperture smaller than 0.05 mm. Highly transmissive fractures with aperture on the order of 1 mm, by contrast, form a small percentage of the fracture population.

A large DFN model simulating jointing in 96 beds of shale, sandstone, and coal was constructed. DFN models were also constructed to simulate cleating, faulting, and hydraulic fracturing. Analysis of transmissivity in cleats systems indicates that a strong permeability anisotropy is developed in shallow, permeable coal seams and that a loss of transmissivity contrast in deep, low-permeability seams makes anisotropy negligible. Compartmentalization analysis indicates that strata-bound fracturing compartmentalizes the Pottsville hydrologic system. First-order reservoir compartments envelop the major coal zones, and these compartments are separated by thick successions of interbedded shale and sandstone that help protect shallow coal seams that may be useful aquifers from operations at reservoir depth. Compartmentalization analysis of faulted DFN models, however, suggests that communication among joints and fault-related shear fractures can facilitate cross-formational flow, and so fault zones should be avoided when siting injection wells. Aligning production wells near faults, moreover, can help limit risk by forming pressure sinks between injectors and fault zones.

Flow models were constructed in TOUGH2 software to determine the impact of individual fractures and strata-bound fracture networks on the leakage of injected CO_2 from coal seams.

Results of flow modeling in the Black Warrior Basin indicate that fracture aperture and connectivity are critical parameters affecting the leakage of injected CO_2 from coal. Highly transmissive fractures near an injection well have potential to divert a large percentage of an injected CO_2 stream away from a target coal seam. Therefore, highly transmissive fractures may impact the performance, efficiency, and predictability of sequestration and enhanced coalbed methane recovery operations. However, the strata-bound nature of Pottsville fracture systems is a natural factor that mitigates the risk of long-range leakage and surface seepage. DFN models indicate that the probability of direct communication between highly transmissive fractures in successive beds is low. Flow models indicate that cross-formational flow in strata-bound joint networks is low and is dissipated by about an order of magnitude at each successive bedding contact. These models help confirm that strata-bound joint networks are self-compartmentalizing and that the thick successions of interbedded shale and sandstone separating the Pottsville coal zones are confining units that protect shallow aquifers from injection operations at reservoir depth.

DFN models are powerful tools for the simulation and analysis of fracture networks and can play an important role in the assessment of risks associated with carbon sequestration and enhanced coalbed methane recovery. Importantly, the stochastic nature DFN models dictates that they cannot be used to precisely reproduce reservoir conditions in a specific field area. Rather, these models are most useful for simulating the fundamental geometric and statistical properties of fracture networks. Because the specifics of fracture architecture in a given area can be highly uncertain, multiple realizations of DFN models and DFN-based flow models can help define variability that may be encountered during field operations. Using this type of approach, modelers can inform the risk assessment process by characterizing the types and variability of fracture architecture that may exist in geologic carbon sinks containing natural fractures.

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