Attachment 2
The Black Warrior Basin

The Black Warrior Basin covers an area of about 23,000 square miles in Alabama and Mississippi. The basin is approximately 230 miles long from west to east and approximately 188 miles long from north to south. Coalbed methane production in Alabama is limited to the bituminous coalfields of west-central Alabama, primarily in Jefferson and Tuscaloosa Counties.

Coalbed methane production in the Black Warrior Basin is among the highest in the United States. In 1996, approximately 5,000 coalbed methane wells were permitted in Alabama. In 2000, this number increased to over 5,800 wells (Alabama Oil and Gas Board, 2002). Coalbed methane well production rates range from less than 20 to more than one million cubic feet per day per well (Alabama Oil and Gas Board, 2002). Between 1980 and 2000, coalbed methane wells in Alabama produced roughly 1.2 trillion cubic feet of gas. According to the Gas Technology Institute (GTI), annual gas production was 112 billion cubic feet in 2000 (GTI, 2002).

2.1 Basin Geology

Coalbed methane production in the Black Warrior Basin (Figure A2-1) is contained within the Upper Pottsville Formation of Pennsylvanian age (300 million years). The depositional history along the ancient coastline of prehistoric Alabama was characterized by 8 to 10 "coal deposition cycles" of sea level rising and lowering. Each of these 10 geologic "coal deposition cycles" features mudstone at the base of the cycle (deeper water) and coalbeds at the top of the cycle (emergence) (Pashin and Hinkle, 1997).

The geologic structure of the Black Warrior Basin is complex. Due to erosion and structural uplift, not all of the coal zones are present at all locations (Pashin et al., 1991; Young et al., 1993). In general, however, most coalbed methane wells tap the Black Creek/Mary Lee/Pratt cycles, at depths that range from 350 to 2,500 feet deep (Holditch, 1990).

Alabama coalbeds are typically very thin, ranging from less than 1 inch in thickness to 4 feet (in rare cases they may be up to 8 feet thick in surface mines) (Horsey, 1981; Heckel, 1986; Eble et al., 1991; Carrol et al., 1993; Pashin, 1994) (Figure A2-2). In the area of coalbed methane development, the Pottsville Formation exists at or near the surface, and the depth to commercial coalbeds ranges from the surface outcrop to 3,500 feet, depending on location (Figure A2-3).

2.2 Basin Hydrology and USDW Identification

In the location where coalbed methane development is taking place in west-central Alabama, the Pottsville Formation is an unconfined aquifer. The matrix permeability of Pottsville rocks (e.g., mudstone, cemented sandstone) is low, but water is present and flows within an extensive system of faults, fractures, and joints. Flow patterns within the Pottsville Formation are strongly controlled by fault- and fold-related isotropic joints and fractures (Koenig, 1989). The close spacing and systematic pattern of cleats, however, make coalbeds the most productive aquifers within the Pottsville Formation (Koenig, 1989; Pashin et al., 1991; Pashin and Hinkle, 1997). In the early 1990s, several authors reported fresh water production from coalbed wells at rates up to 30 gallons per minute (Ellard et al., 1992; Pashin et al., 1991).

Most of the recharge to the Pottsville aquifer is precipitation that infiltrates from the surface, but some recharge occurs where streamflow enters the outcrop and moves laterally into the aquifer along folded anticlinal beds (Pashin and Hinkle, 1997) (Figure A2-4). Several researchers also propose upwelling of more saline waters from deeper zones, which takes place along vertical, fault-related, rubble zones (Pashin et al., 1991). Discharge from the Pottsville aquifer is primarily from the dewatering of coalbeds due to mining and coalbed methane production (Pashin et al., 1991).

Formation water produced from Alabama coalbed methane wells contains between less than 50 to over 10,000 milligrams per liter (mg/L) total dissolved solids (TDS) (Koenig, 1989; Pashin et al., 1991; Pashin and Hinkle, 1997). Some portions of the Pottsville Formation contain waters which meet the quality criterion of less than 10,000 mg/L TDS for an underground source of drinking water (USDW) (Figure A2-7). According to the Alabama Oil and Gas Board, some waters in the Pottsville Formation do not meet the definition of a USDW and have TDS levels which are considerably higher than 10,000 mg/L (Alabama Oil and Gas Board, 2002). Water quality generally decreases with increasing depth (Figures A2-7 and A2-8), and areally is related to the faulting pattern (Figure A2-9) (Pashin et al., 1991; Pashin and Hinkle, 1997). Waters exceeding 10,000 mg/L TDS can be found below 3,000 feet in areas near deep vertical faults, suggesting upwelling from deeper, more saline zones (Pashin and Hinkle, 1997).

2.3 Coalbed Methane Production Activities

Alabama coalbed methane wells are categorized into three distinct types. The first two types, "gob" wells and horizontal wells, are less common. Gob wells are associated with mines. The well is drilled to a depth above the mine roof, and when the mine is abandoned, the roof collapses. Gob wells produce coalbed methane from the fractured mine debris. A few horizontal wells are drilled from within mines to reduce coalbed methane concentration in advance of a working face. The third type, which includes 98 percent of all Alabama methane wells, includes vertically drilled wells that utilize mainstream oilfield technologies (Pashin and Hinkle, 1997). Because neither gob nor horizontal wells typically are hydraulically fractured, this discussion is limited to vertical wells.

According to literature, most coalbed methane wells are drilled using water or air rotary methods or water-based mud, due to lower cost and concerns that mud fluids will invade the coal. Wells in Alabama are completed with tubing. Water is pumped up the tubing for disposal, whereas gas is produced up the annulus. Wells are drilled to a depth 10 to 30 feet below the lowest coalbed to create a sump that collects coal fines and allows water to separate from the coalbed methane (Holditch, 1990).

About 95 percent of produced water is disposed by discharge into surface water, via Type II National Pollution Discharge Elimination System permits (O'Neil et al., 1989; O'Neil et al., 1993; Pashin and Hinkle, 1997). These permits require some water quality monitoring and limit instream water quality to 230 mg/L TDS (Pashin and Hinkle, 1997). Since 1991, about 5 percent of produced water has been injected for disposal into Class II injection wells (Pashin and Hinkle, 1997). Eight Class II wells are currently active (Alabama Oil and Gas Board, 2001), disposing coalbed waters into zones between 4,300 and 10,000 feet deep (Ortiz et al., 1993).

Most wells are completed in multiple coal zones using perforations. Some wells are completed in mudstones immediately below a coal zone, rather than within the coal ("limited entry" completions), and a few wells feature un-cased, open-hole completions. Each well is hydraulically fractured to allow communication with the thin coal seams outside of the casing, and most wells are fractured more than once as described below:

- In wells with multiple coal seams present, the hydraulic fracturing process may involve several or multiple stimulations, using 2 to 5 hydraulic fracture treatments per well (depending on the number of seams and spacing between seams); and,

- Many coalbed methane wells are re-fractured at some time after the initial treatment, in an effort to re-connect the wellbore to the production zones to overcome plugging or other well problems (remedial fracture-stimulation) (Holditch, 1990; Saulsberry et al., 1990; Palmer et al., 1991a and 1991b; Schraufnagel et al., 1991; Holditch, 1993; Palmer et al., 1993b; Spafford et al., 1993; Schraufnagel et al., 1993) (Figure A2-10).

The geometry of hydraulic fractures in coalbed methane zones usually differs from that observed in conventional oil and gas scenarios. In conventional hydrocarbon zones, the gas and/or oil are physically "trapped" by the presence of an impermeable confining layer, usually shale. Shale formations may present a barrier to upward fracture growth because of the stress contrast between the coalbed and the higher-stress shale (see Appendix A). Therefore, for conventional fracturing, the vertical growth of fractures out of the target zone may be limited by the presence (i.e., stress contrast) of overlying shales. In conventional gas-well fracture environments, fracture half-length (200-1,600 feet from the well bore) almost always exceeds fracture height (10-200 feet above the perforations). In the Black Warrior Basin, however, the lithologic properties and stress fields of the coal cycles typically produce fractures that are higher than they are long ("length" refers to horizontal distance from the well bore) (Morales et al., 1990; Zuber et al., 1990; Holditch et al., 1989; Palmer and Sparks, 1990; Jones and Schraufnagel, 1991; Steidl, 1991; Wright, 1992; Palmer et al., 1991b and 1993a).

In the Black Warrior Basin of Alabama, hydraulic fractures created in coalbed methane deposits are able to grow much higher than some fractures in "conventional" gas reservoirs. There are three primary reasons for this phenomenon:

- Due to coal's low modulus of elasticity (i.e., brittleness, stiffness) and complex fracture geometries, high pressures are required to fracture coal hydraulically (500 to 2,000 pounds per square inch (psi), or 0.7 to 2.0 psi/ft), and high treatment pressure often causes preferential extension of the fracture in the vertical dimension (Jones et al., 1987; Reeves et al., 1987; Morales et al., 1990; Palmer et al., 1991a);

- The economics of coalbed methane production in this basin requires tall fractures that penetrate several coal seams. The coal seams are typically thin (1 to 12 inches) and economically viable production requires the drainage of as many seams as possible. Because coal seams may be vertically separated by up to hundreds of feet of intervening rocks, operators usually design fracture treatments to enhance the vertical dimension and might perform several fracture treatments within a single well (Ely, et al., 1990; Holditch, 1990; Saulsberry et al., 1990; Spafford, 1991; Holditch, 1993); and,

- The other rocks within the Pottsville coal cycles (jointed mudstone and sandstone) fracture much more easily than coal (Teufel and Clark, 1981; Saulsberry et al., 1990; Jones and Scraufnagel, 1991; Spafford, 1991). Because there are no significant barriers to fracture height (Simonson et al., 1978; Ely et al., 1990; Palmer et al., 1991a), vertical fractures in the Black Warrior basin typically penetrate several thin coalbeds and hundreds of feet of intervening rocks (Teufel and Clark, 1981; Hanson et al., 1987; Holditch et al., 1989; Ely et al., 1990; Palmer et al., 1991c; Schraufnagel et al., 1991; Spafford, 1991; Palmer et al., 1993b) (Figure A2-11).

Mined-through studies in the Black Warrior Basin identified many instances where thin (less than 1-foot thick) shales overlying targeted coalbeds were fractured. Penetration into layers above the coal was observed in more than 80 percent of the fractures intercepted by mines underground in the Black Warrior Basin (Diamond, 1987b). Some fractures continued completely through very thin shales (Diamond, 1987a and b). These studies did not conduct a systematic assessment of the extent of the vertical fractures through and above the roof rock shales.

Several researchers conclude (based on pressure behavior during fracturing and several examples where mines penetrated hydraulic fractures) that shallow fractures have a horizontal component as described below:

- Fractures that are created at shallow depth typically have more of a horizontal component and less of a vertical component. The vertical component is most likely due to the presence of vertical natural fractures (cleats and joints) as pre-existing planes of weakness from which vertical fractures can initiate.

- Fractures created at a greater depth can propagate vertically to shallower depth, and develop a horizontal component. In these “T-fractures”, the fracture tip may fill with coal fines and/or intercept a zone of stress contrast, which causes the fracture to “turn” and to develop horizontally.

As noted above, penetration of the layers above the coal was observed in more than 80 percent of the fractures intercepted by mines underground in the Black Warrior Basin (Diamond, 1987b), but, as coals become shallower, the potential for fracture height growth decreases. In general, horizontal fractures are most likely to exist at shallow depths (less than 1,000 feet). As depths increase, it is more likely that a simple vertical fracture will occur (Gas Research Institute, 1995).

Sand is the most common proppant used in coalbed methane treatments in Alabama. The amount of sand injected per fracture treatment ranges from 10,000 to 120,000 pounds (Holditch et al., 1989; Palmer et al., 1991b and 1993a). Fracture widths in the formation vary from 0.5 inches to closed (i.e., no proppant emplaced), depending on distance from wellbore and efficiency of the proppant displacement into the length of the fracture (Palmer and Sparks, 1990; Palmer et al., 1993a; Steidl, 1993).

Fracturing fluid (30,000 to 200,000 gallons per treatment) is injected at a rate of 5 to 50 barrels per minute (which equals 210 to 2,100 gallons per minute) at injection pressures ranging from 500 to 2,300 psi (Palmer et al., 1989 and 1993b; Holditch et al., 1989; Pashin and Hinkle, 1997). The most common constituent of fracturing fluid is plain water. Several researchers conclude that approximately 75 percent of all coalbed methane wells in Alabama were fractured using cross-linked gel fluids (Palmer et al., 1993a; Pashin and Hinkle, 1997).

According to service companies, diesel fuel is no longer used as a component of fracturing fluids in Alabama. In addition, additives that could introduce chemicals exceeding maximum contaminant levels (MCLs) are no longer used in fracturing fluids in Alabama.

Table A2-1 presents some data concerning the general chemical makeup of common fracturing fluids used in Alabama from literature published prior to the Alabama hydraulic fracturing regulation (Economides and Nolte, 1989; Penny et al., 1991). In addition, most gel fluids utilize a breaker compound (usually a borate or persulfate compound or an enzyme, at 2 lb/1,000 gal) to allow post-treatment thinning and easier recovery of gels from the fracture. Several researchers conclude that approximately 75 percent of all coalbed methane wells in Alabama were fractured using cross-linked gel fluids (Palmer et al., 1993a; Pashin and Hinkle, 1997).

According to Hunt and Steele (1992), environmental regulations restrict local disposal of used fracturing fluids, and fracturing fluids are transported to regulated disposal sites. Robb and Spafford (1991) reported that acids were used to fracture production zones as shallow as 400 feet deep.

In fracture treatments of wells in homogeneous formations in conventional gas fields, injection is temporary and the majority of fracturing fluid is subsequently pumped back up through the well when production resumes.

There are limited data in the literature concerning the volume of fracturing fluids subsequently pumped back to the well after stimulation has ceased. Palmer et al. (1991b) found that only 61 percent of fracturing fluids were recovered during production sampling of a coalbed well in the Black Warrior Basin of Alabama, and projected that 20 to 30 percent would remain in the formation.

2.4 Summary

Coalbed methane development and hydraulic fracturing in the Black Warrior Basin of Alabama takes place within a USDW, the Pottsville formation. Some portions of the Pottsville Formation contain waters which meet the quality criteria of less than 10,000 mg/L TDS for a USDW. Some waters in the Pottsville Formation do not meet the definition of a USDW and have TDS levels that are considerably higher than 10,000 mg/L (Alabama Oil and Gas Board, 2002).

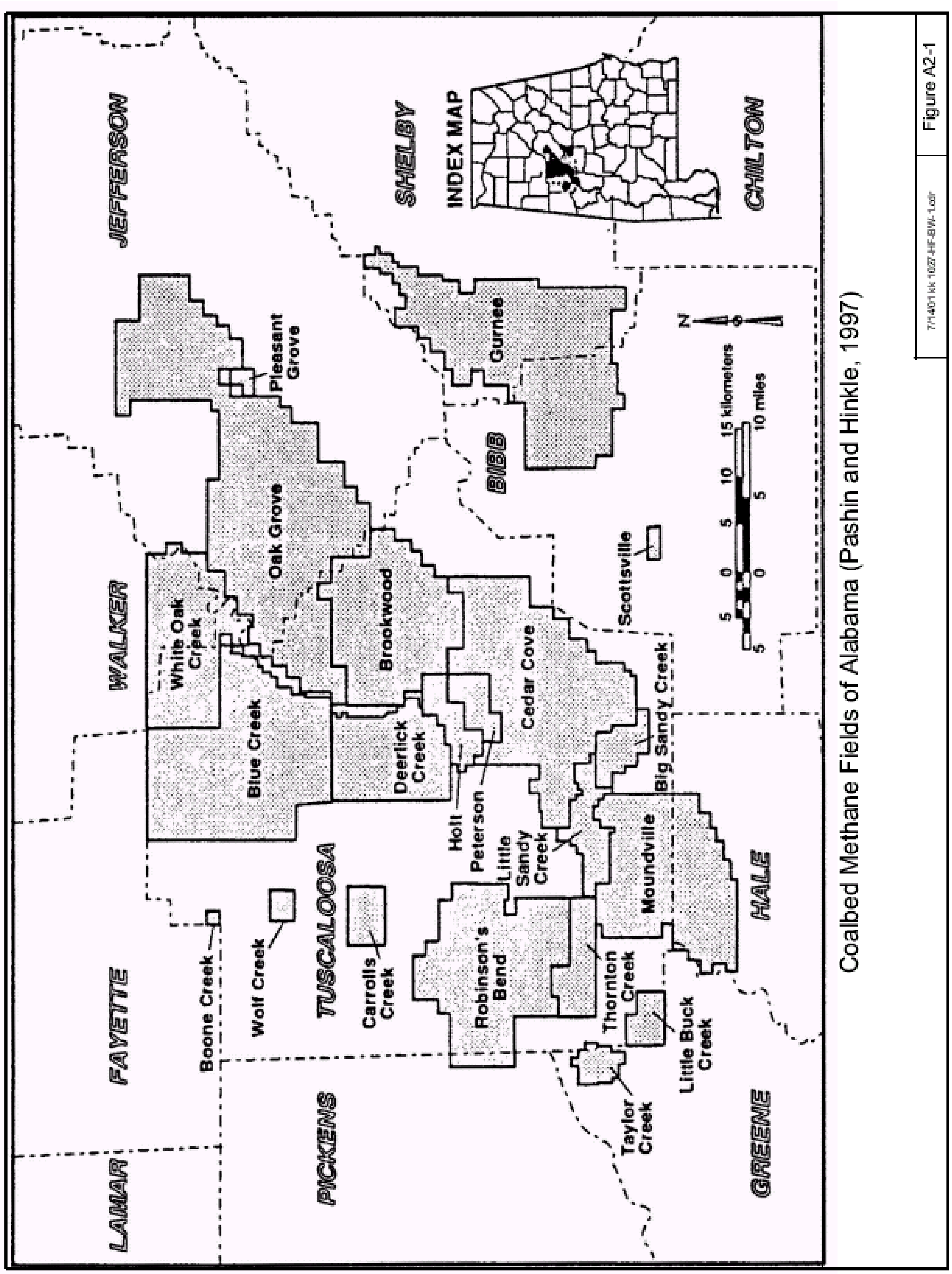
According to service companies, diesel fuel is no longer used as a component of fracturing fluids in Alabama. In addition, additives that could introduce chemicals exceeding MCLs are no longer used in fracturing fluids in Alabama.

In the Pottsville Formation, the lack of a significant vertical barrier can provide for extensive fracture height growth (Holditch et al., 1989; Lambert et al., 1989; Ely et al., 1990; Saulsberry et al., 1990; Palmer and Sparks, 1990; Spafford, 1991; Palmer et al., 1991a and 1993a; Spafford et al., 1993; Gas Research Institute, 1995). Mined-through studies in the Black Warrior Basin identified many instances where thin (less than 1-foot thick) shales overlying targeted coalbeds were fractured. Penetration into layers above the coal, which are typically shale, was observed in more than 80 percent of the fractures intercepted by mines underground in the Black Warrior Basin (Diamond, 1987b).

Table A2-1. Chemical Components Previously Used in Typical Fracturing/Stimulation Fluids for Alabama Coalbed Methane Wells

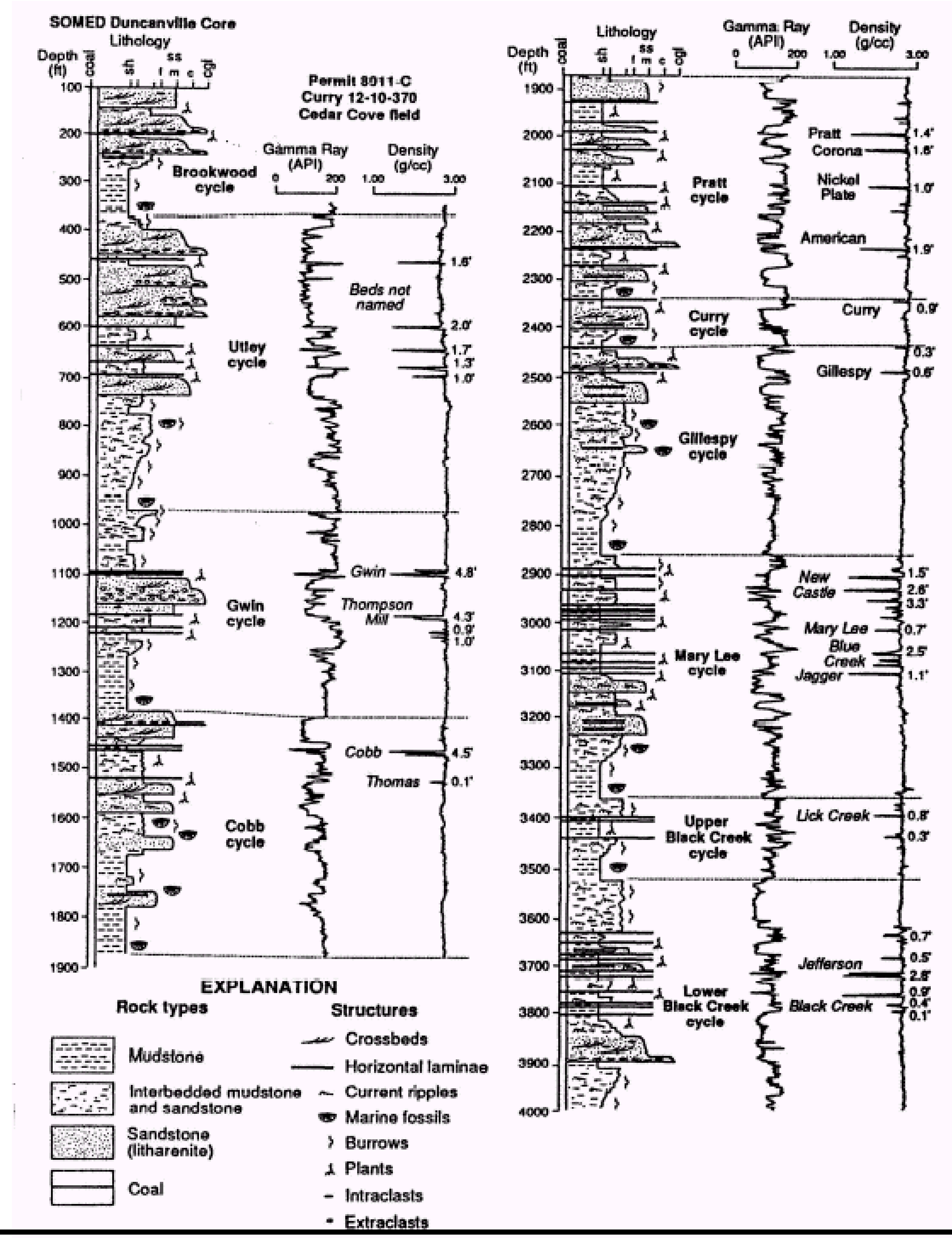
Type of Stimulation Fluid	Composition	pH
Fluids		
Hydrochloric acid	15% HCl water solution	<1-3
"Slick" water	water-soluble solvent as viscosity reducer (% unknown)	NA
Diesel oil	NA	NA
Gels[1]		
R-F	3% resorcinol, 3% formaldehyde, 0.5% KCl, 0.4% $NaHCO_3$	6.5
Pfizer Flocon 4800	0.4% xanthan, 154 ppm Cr^{3+} (as $CrCl_3$), 0.5% KCl	4.0
Marathon MARCIT	1.4% polyacrylamide (HPAM), 636 ppm Cr^{3+} (as acetate), 1% NaCl	6.0
DuPont LuDox SM	10% colloidal silica, 0.7% NaCl	8.2
CPAM crosslinked with Pfizer Floperm 500	0.4% cationic polyacrylamide (CPAM), 1520 ppm glyoxal, 2% KCl	7.3
Drilling Specialties HE-100 Crosslinked	0.3% HPAM-AMPS, 100 ppm Cr^{3+} (as acetate), 2% KCl	5.0

[1] Gels are typically mixed at a ratio of 40 lbs. per 1000 gal. water; compositions shown are "as mixed".



Coalbed Methane Fields of Alabama (Pashin and Hinkle, 1997)

Figure A2-1



Coal Cycles of the Pottsville Formation in the Black Warrior Basin (Pashin and Hinkle, 1997)

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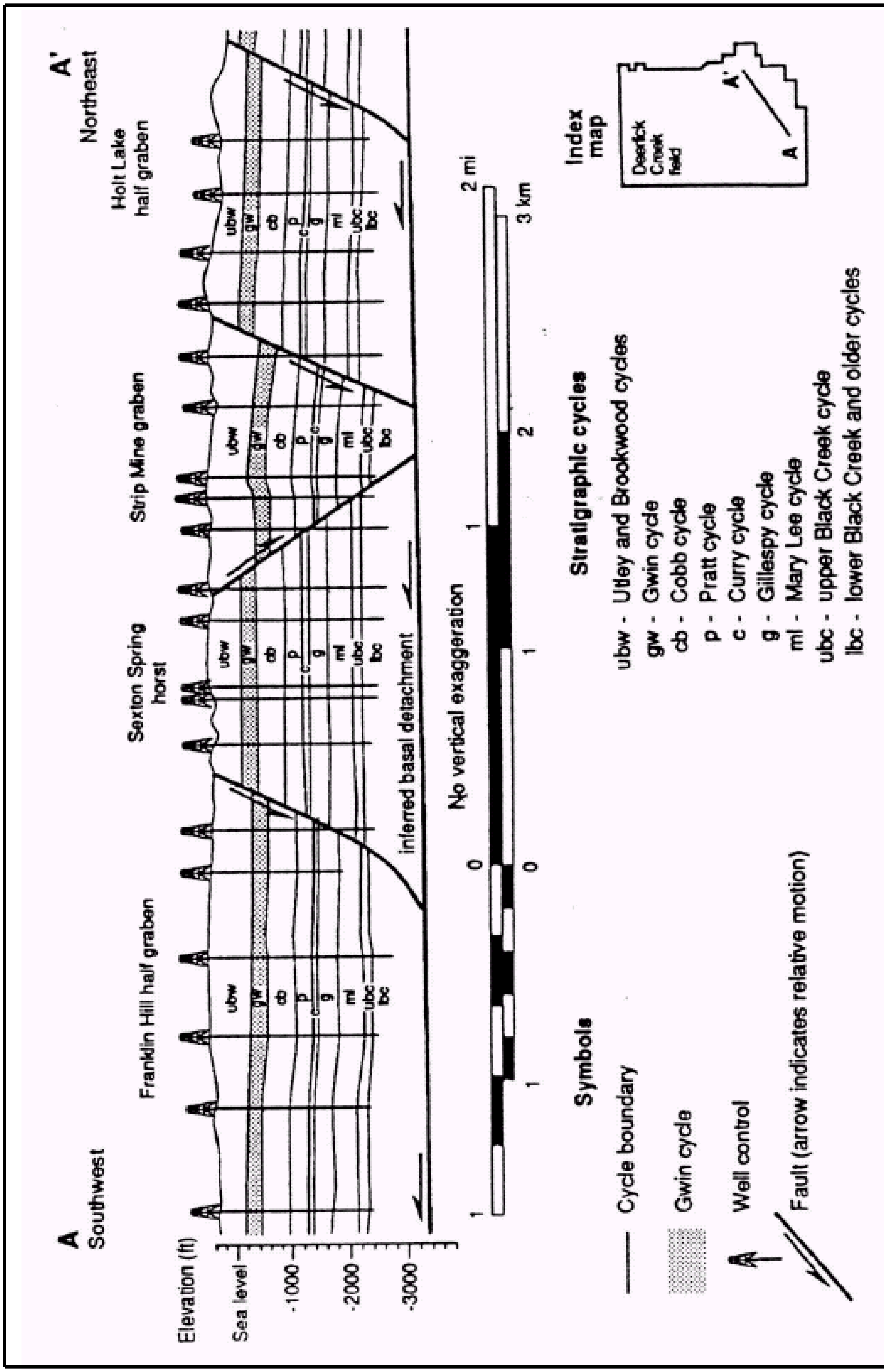
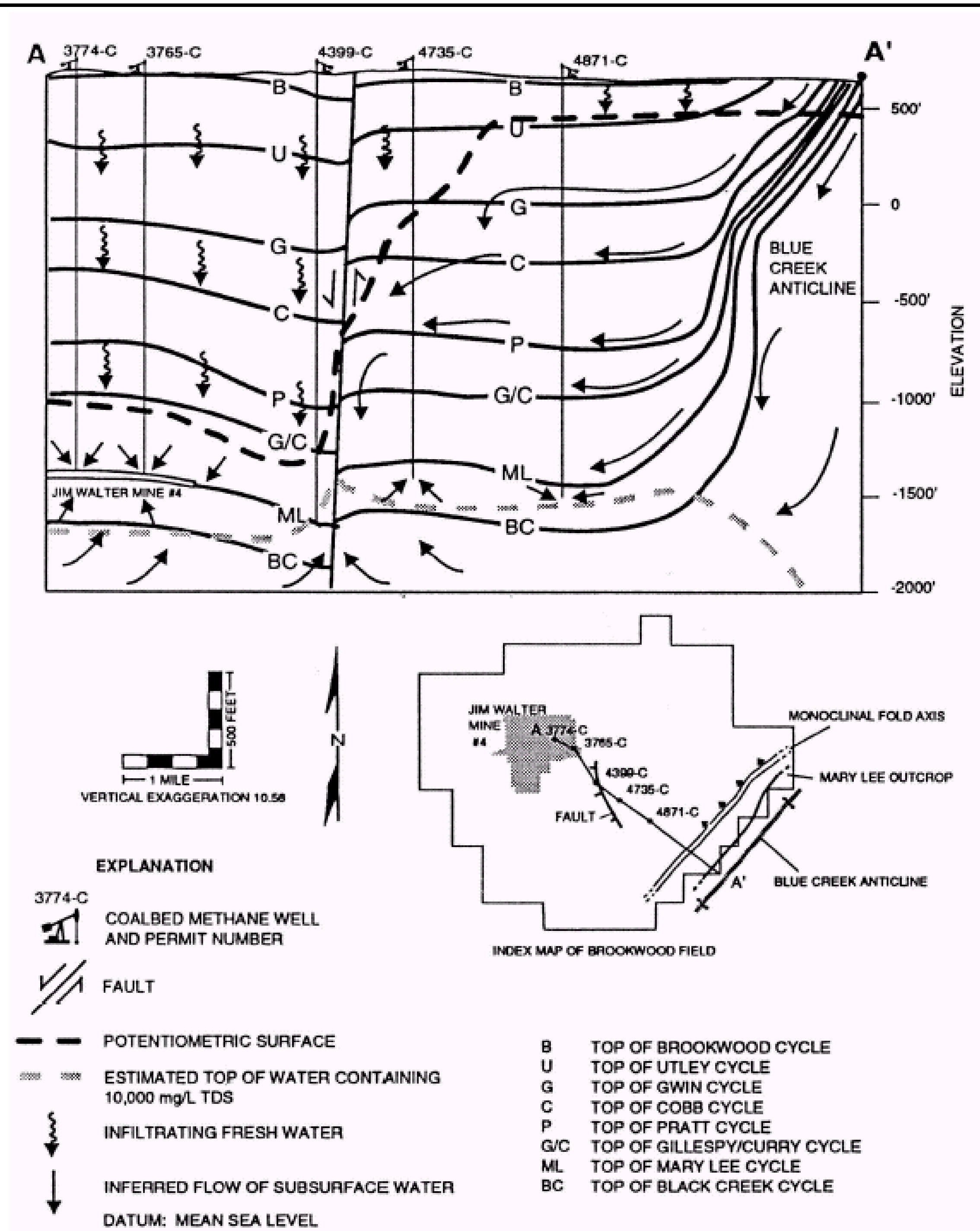
Figure A2-2



Cross-Section of the Pottsville Formation in the Deerlick Creek Field (Pashin and Hinkle, 1997)

Figure A2-3



Hydrogeologic Cross-Section of the Pottsville Formation in the Brookwood Field
(see Figure 2-1 for Field Location) (Pashin and Hinkle, 1997)

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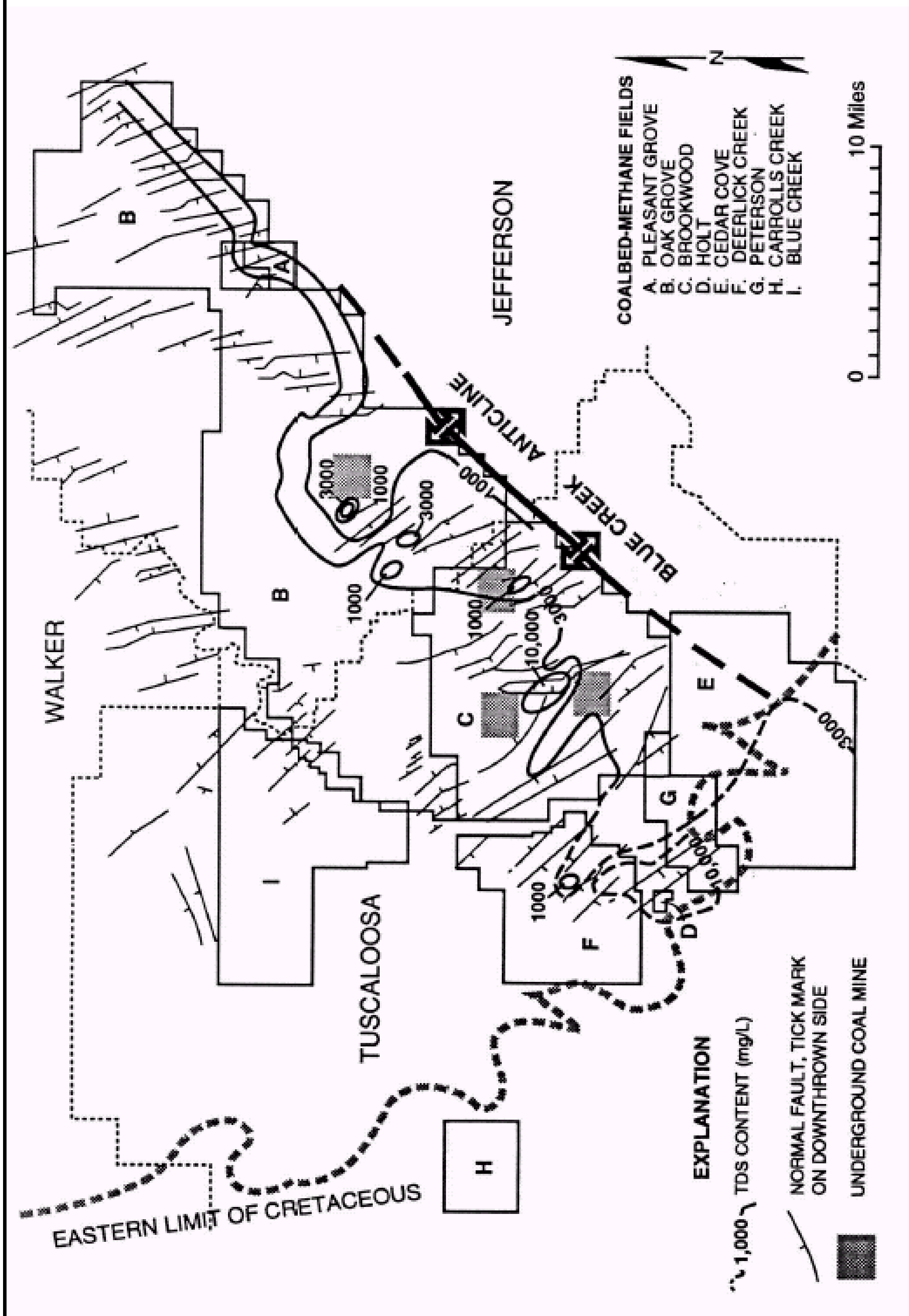
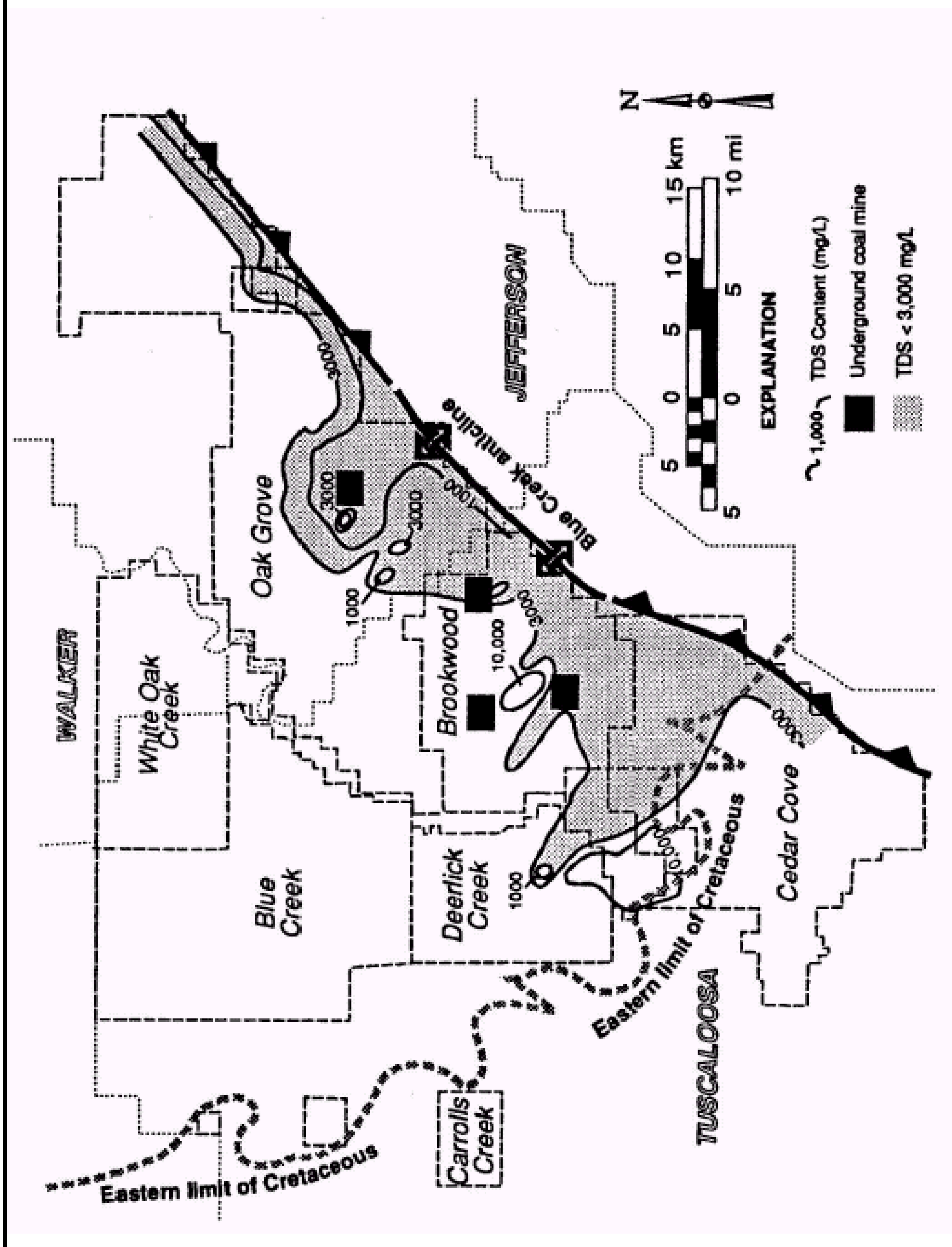
Figure A2-4



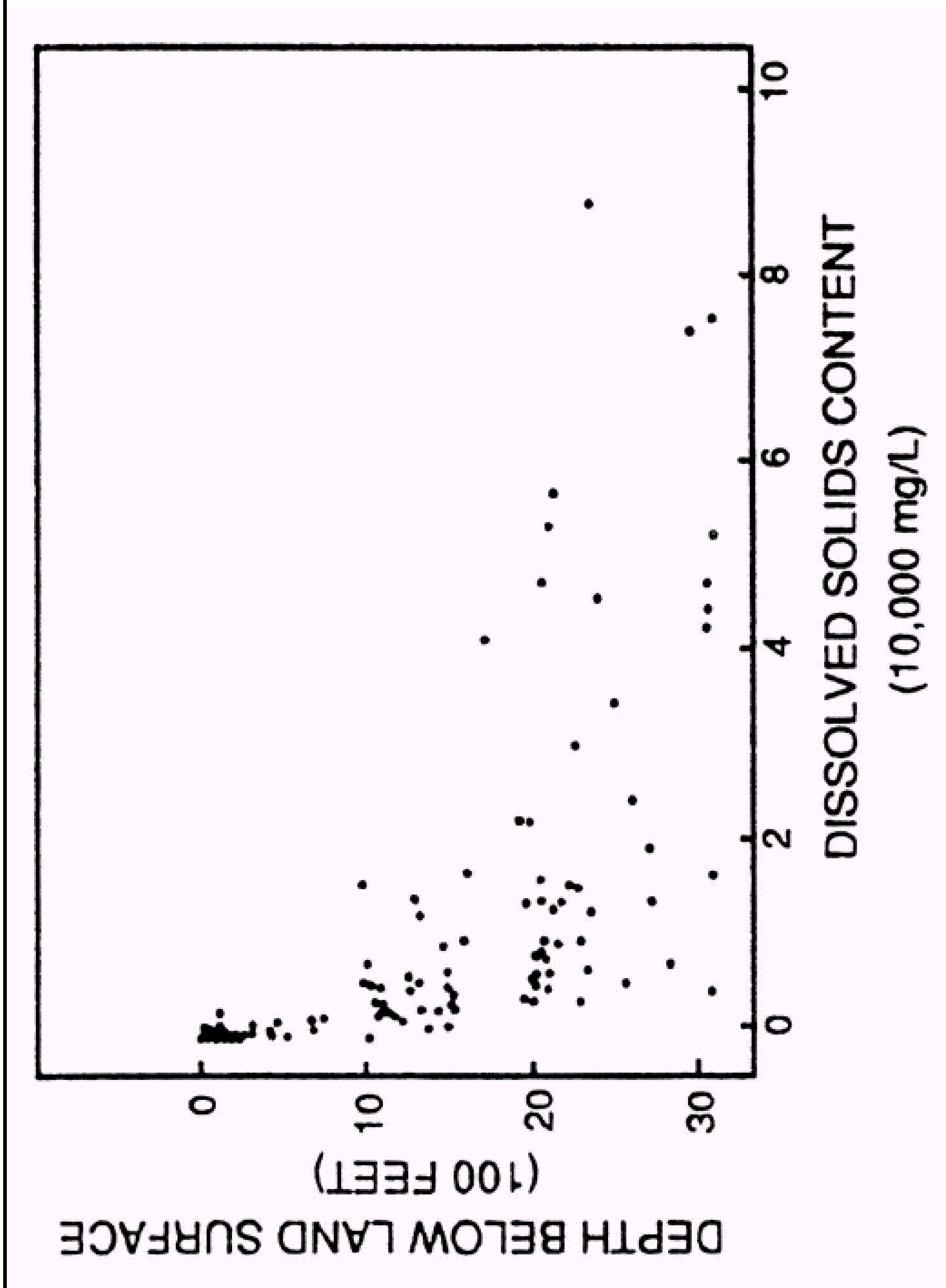
TDS concentration of Pottsville Aquifer, Black Warrior Basin, Alabama (Pashin and Hinkle, 1997)

Figure A2-5



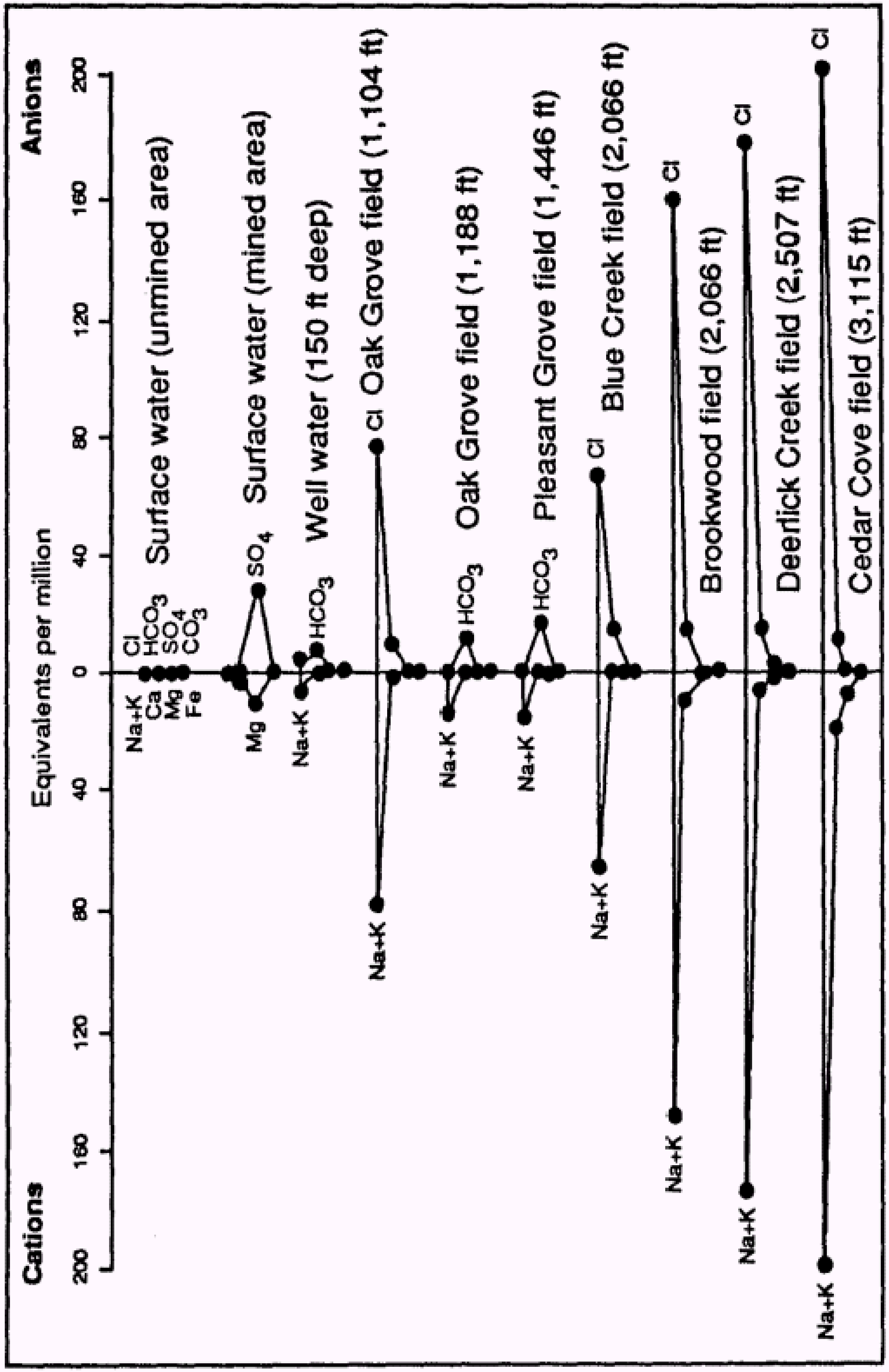
TDS Concentration of the Mary Lee Coal Seam of the Pottsville Aquifer in the Eastern Part of the Black Warrior Basin, Alabama (Pashin et al., 1991)

Figure A2-6



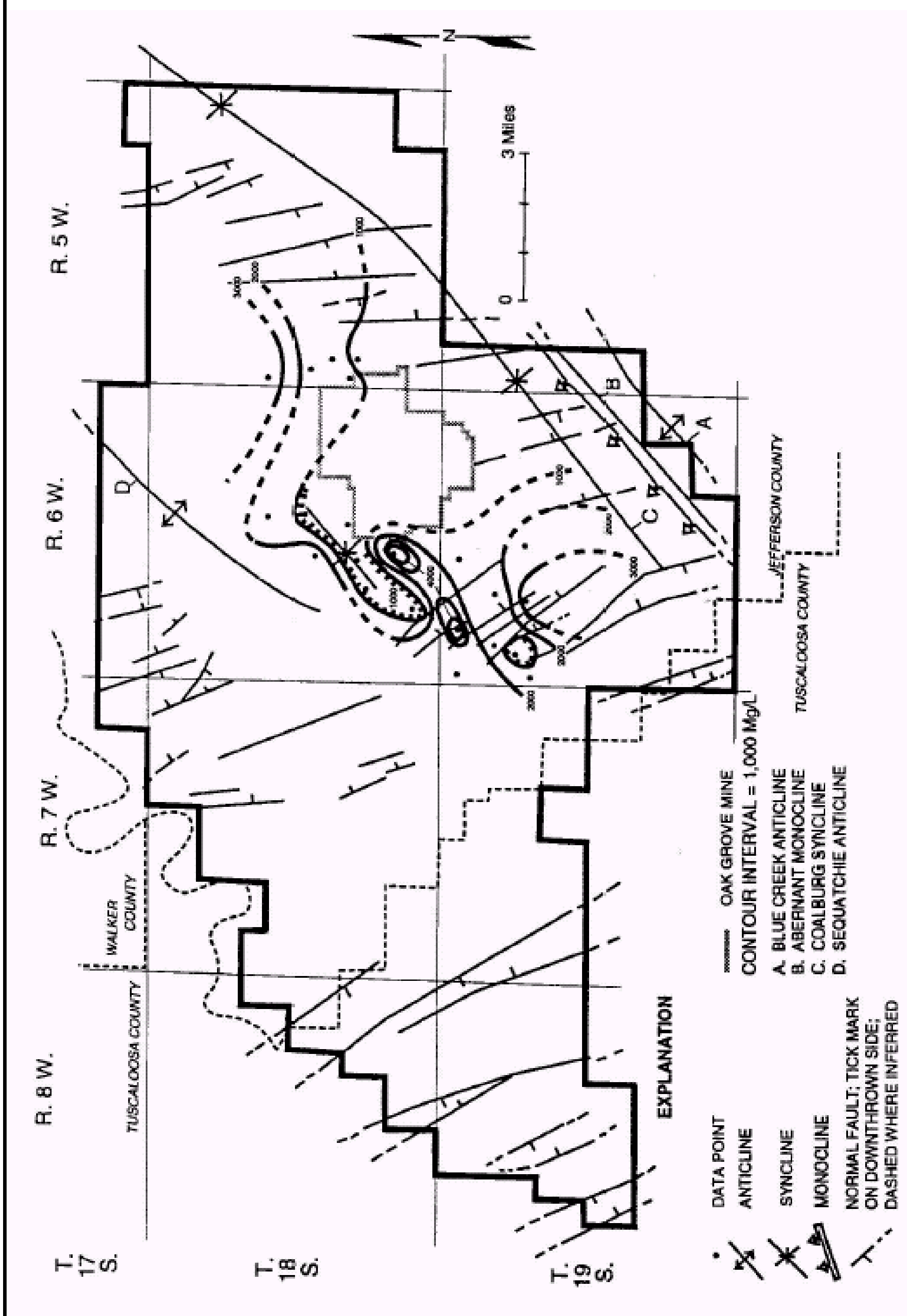
Generalized Increase in TDS Concentration with Depth in the Pottsville Aquifer
Black Warrior Basin, Alabama (Pashin et al., 1991)

Figure A2-7



"Stiff" Diagram of Water Salinity (Pashin et al., 1991). The diagram indicates that most water samples contain less than 10,000 mg/L TDS (except near a few faults), and the salinity generally increases with depth in the Pottsville Aquifer, Alabama. Note that as mg/L of NaCl, the "Equivalent per Liter (epm)" units of the table correspond to 2337 mg/L (40 epm), 4675 mg/L (80 epm), 7012 mg/L (120 epm), 9350 mg/L (160 epm), and 11,688 mg/L (160 epm). NaClis, by far, the dominant species of most Pottsville water samples, and mg/L as NaCl closely approximates mg/L TDSs

Figure A2-8



Relationship of Water Salinity to Structural Features in the Oak Grove Field, Black Warrior Basin, Alabama (Pashin and Hinkle, 1997).
In general, water containing more than 3,000 mg/L TDS is related to upwelling of saline water near a few geologic faults

Figure A2-9

Field*	Number of Producing Groups	Coal Group	Depth Range (ft)	Number of Separate Stimulations
Oak Grove	2 or 3	Pratt Mary Lee** Black Creek	500–2500	2 or 3
Deerlick Creek (Lambert et al., 1987, 1990)	3		1000–3000	3
Cedar Cove (Sparks and Richardson, 1991)	4	Cobb Pratt Mary Lee** Black Creek	2000–3500	4
Moundville (Ely et al., 1990)	Up to 6 or 7†	Brookwood Utley Gwin Cobb Pratt Mary Lee** Black Creek	3000–5000	3–6

Productive Coal Seams and the Typical Number of Stimulations Per Well as of 1993, Black Warrior Basin, Alabama (Palmer et al., 1993)

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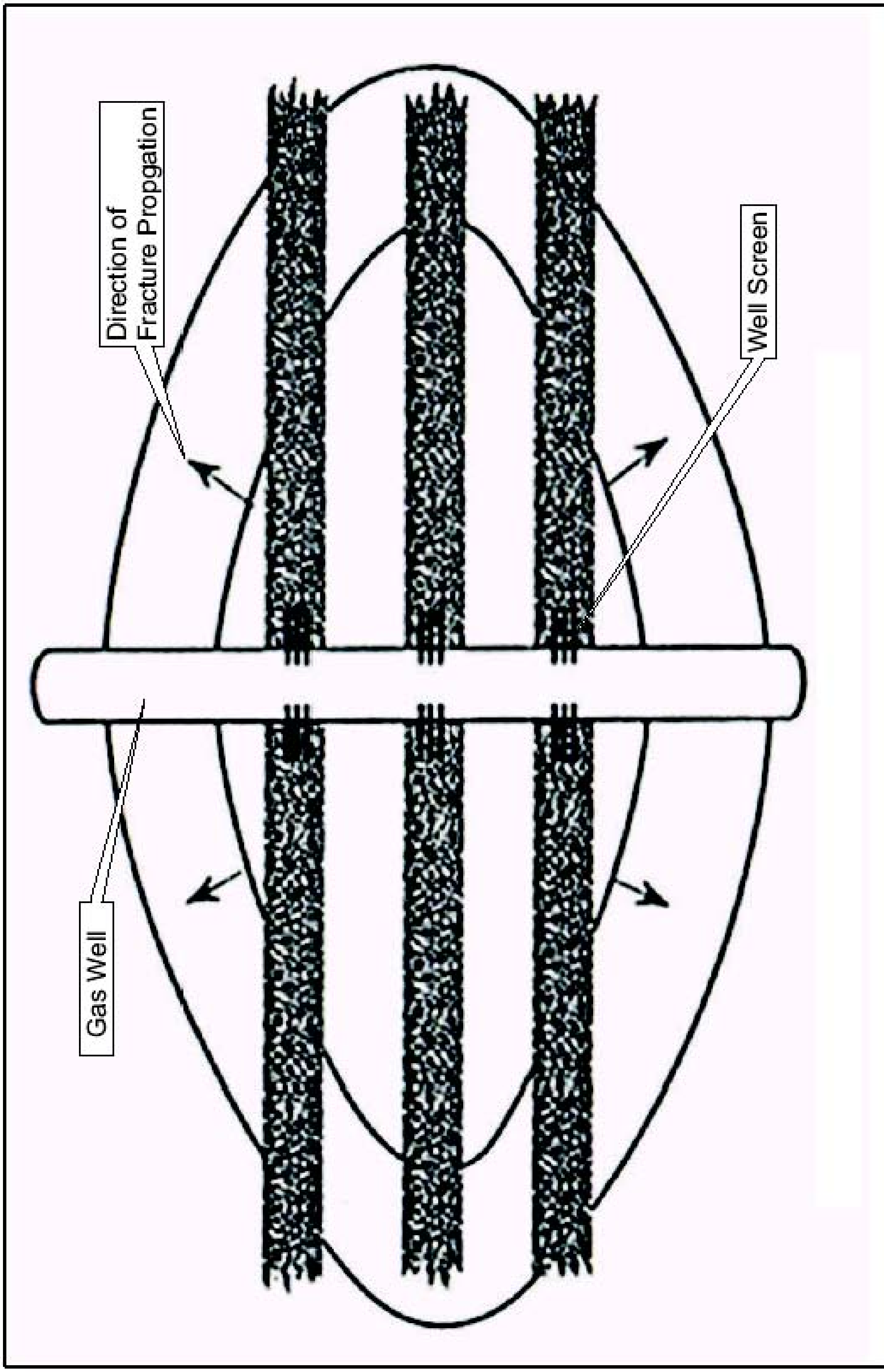
Figure A2-10



Sketch of a Vertical, Unconfined Fracture Typical of the Black Warrior Basin (Palmer et al., 1991)

Figure A2-11

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SPE = Society of Petroleum Engineers

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