

## Relationship Between Gas and Water Production and Structure in Southeastern Deerlick Creek Coalbed Methane Field, Black Warrior basin, Alabama

R. H. Groshong, Jr. (The University of Alabama), Michael H. Cox (Science Applications International Corporation), Jack C. Pashin (Geological Survey of Alabama) and Marcella R. McIntyre (The University of Alabama)

### ABSTRACT

Map-scale structure exerts a significant control on the magnitude and distribution of fluid production in the Deerlick Creek coalbed methane field. In this area an exceptional gas producing well is usually an exceptional water producer but an exceptional water well is not necessarily an exceptional gas well. Of the 7 most productive gas wells, 5 (71%) are among the highest producing water wells. Gas production is generally poor in the southwestern part of the area where the maturation level of the coal is at the edge of or below the thermogenic gas window. Faults are zones of low water and gas production and segment the reservoir into blocks having significantly different productivity. The two most transmissive gas- and water-producing fault blocks are both half grabens, the eastern of which is the better gas producer, presumably because it is in an area of higher thermal maturity. The horst and full graben are the poorest producers of gas and water in the area where the coal is thermally mature. This suggests that moderate deformation (half grabens) may enhance fracture transmissivity relative to areas of no deformation (the horst), and that too much deformation (the full graben) reduces transmissivity.

### INTRODUCTION

This paper examines the relationship between the productivity of coalbed methane wells and map-scale structure. The coalbed methane fields of the Black Warrior basin (Figure 1) have long served as a test area for the relationship between the geology and methane production (Ellard et al., 1992; Sparks et al., 1993; Pashin et al., 1995; Smith 1995; Pashin and Hinkle, 1997; Pashin and Groshong, 1998; Cox, 2002; Pashin et al., 2003). The productivity of coalbed methane wells in the Black Warrior Basin ranges widely, even in small areas, and requires an explanation. Coal has very low permeability to methane and essentially zero permeability to water, so economic methane production and water production depend on the presence of transmissive fractures. The abundance, continuity, and openness of the fractures is potentially related to numerous factors including the coal stratigraphy, hydrology, map-scale geologic structure, thermal maturation, effective stress, and completion techniques.

In the fields of the Black Warrior basin, wells are completed by hydraulic fracturing across multiple coal zones (Lambert et al., 1987; Spafford and Saulsberry, 1993). Drilling and completion technique have not been found to be a major factor in the variability of production within a given area (Lambert et al., 1987; Sparks et al., 1993). For example, production can vary by a factor of more than ten in closely spaced wells that have undergone similar completion treatments (Malone et al., 1987). Wells are developed on an 80-acre spacing, which results in distances between wells of about 0.25 miles (402 m). Ellard et al. (1992) state that no production interference between wells has been documented, indicating that the controls on production variability are very local.

Stratigraphic factors, such as coal thickness, have surprisingly little significance in controlling the variability of methane production in the basin (Pashin and Hinkle, 1997). The amount of gas in place is largely a function of coal composition and maturity. The Black Warrior basin contains both thermogenic and late-stage biogenic methane (Clayton, 1993; Rice, 1993) with a maturity of  $R_0$  about 0.7 being the minimum for thermogenic methane formation. Within the mature area of the basin, the best wells have high gas in place and produce from shallow depths (Bodden, 1997) although local variation in the amount of gas in place exerts little control over production variations (Sparks et al., 1993; Bodden, 1997).

Coal has near-zero matrix permeability, yet direct measurements reveal that the coals are the most permeable units within the coal-bearing interval of the basin (Pashin et al., 1991; Ellard et al., 1992). This clearly indicates that open fractures enhance fluid flow (McKee et al., 1988; Pashin et al., 1999; Nelson, 2001). Coal cleat shows maximum development in low-volatile bituminous coal (Bodden, 1997). Permeability is normally best parallel to an open cleat direction. Because coal is a relatively soft material, the openness of the cleat is a function of the effective stress, which is related to the depth of burial, fluid pressure, and the tectonic stress (McKee et al., 1988; Sparks et al., 1993; Enever et al., 1999; Nelson, 2001). The magnitude of the least principal stress is equal to the fracture closure pressure measured prior to well stimulation by hydraulic fracturing. Permeability should be greater where the closure pressure is lower. Sparks and others [1993] have suggested that the in-situ stress is related to the map-scale structure.

Hydrology is a significant factor in gas production (Pashin et al., 1991). The basin water is recharged along the upturned southeastern edge of the basin where the Pottsville reservoir interval is exposed at the surface. This is indicated by a potentiometric high along the basin edge and by plumes of fresh water that extend to the northwest from the basin edge (Pashin et al., 1991; Ellard et al., 1992). In part of the recharge area in Cedar Cove field, the water pressure cannot be reduced enough to free significant quantities of gas (Sparks et al., 1993). The Deerlick Creek field (Figure 1) is a long distance from the basin-margin recharge area, however.

Map-scale structures (folds and faults) have been proposed as being significant factors in controlling production variability (Ellard et al., 1992; Sparks et al., 1993; Pashin et al., 1995; Pashin and Groshong, 1998). Bed dip has been indicated as one controlling factor (Malone et al., 1987), although the relationship was not specified. Enhanced natural fracturing near faults might be expected to lead to enhanced production in fault zones (Pashin and Hinkle, 1997), but Sparks et al. (1993) indicate that fault zones themselves are not as productive as the blocks between the faults. Thus, although structure has been clearly implicated as having a significant control on the productivity of the wells, the exact nature of the control has yet to be clearly determined.

In this study the relationships between map-scale structure and production are examined in the southeastern portion of Deerlick Creek field, an area previously discussed by Reeves et al. (1987) and Pashin et al. (1995). The new contribution here is to use a high-resolution 3-D model to re-evaluate the relationship between production and structure. The field has been completely remapped, new wells included, and borehole breakout data added. Breakouts are borehole expansions recorded by caliper logs that may indicate the intersection of the borehole with pre-existing fractures (Babcock, 1978) or the spalling of the borehole due to high differential stress (Bell and Gough 1979; Gough and Bell 1981, 1982; Blumling et al., 1983; Hyett et al., 1986; Plumb and Cox, 1987). Either factor could be related to in-situ fracture abundance or openness.

## GEOLOGIC SETTING

The Black Warrior basin is the foreland of the north- to northwest-verging Appalachian-Ouachita fold-thrust belt (Thomas, 1988). Regionally, strata in the basin dip 1-2° southwestward and generally thicken in the same direction, toward the buried Ouachitas (Whiting and Thomas, 1994). Strata in the coalbed-methane fairway thicken to the southeast toward the Appalachians (Pashin et al., 2002). The southeastern margin of the basin is formed by the Appalachian-Ouachita thrust front where units dip steeply and may even be overturned beneath the frontal thrust. The basin is broken by numerous northwest-trending normal faults forming horst, graben, and half-graben structures (Figure 1). Most of the faults dip to the southwest. Within the coalbed methane producing region, most of the normal faults are thin skinned and have displacements of 400 feet (122 m) or less. The lower detachment for the thin-skinned faults is generally in the lower part of the Pottsville Formation (Wang, 1994; Pashin and others, 1995). At least two faults in the coalbed-methane fields probably penetrate deep into the basement, specifically the major southwest dipping fault in Robinson's Bend field and the major northeast dipping fault in the Moundville field (Figure 1). Both faults have stratigraphic separations that exceed 1000 feet (305 m). All the faults in Deerlick Creek field have been interpreted to be thin skinned (Wang, 1994; Pashin and others, 1995).

The deposits of interest here belong to the coal-bearing Pottsville Formation of Early Pennsylvanian age. The formation is informally divided into upper and lower units, with the main economic coals belonging to the upper Pottsville. The coals are clustered in stratigraphic intervals called groups (McCalley, 1900; Bodden, 1997), or

zones (Gastaldo et al., 1993; Pashin et al., 2003). The entire column can be divided into flooding-surface-bounded depositional cycles, each of which contains a coal zone with one to seven coal beds, most of which are traceable throughout the study area. The cycles are coarsening-and-coaling upward sequences. A typical cycle consists of a basal marine mudstone that locally truncates the strata of the underlying cycle (Liu and Gastaldo, 1992). The basal mudstone is overlain by strata that grade upward into an open- to marginal-marine sandstone, which is overlain by marginal-marine and terrestrial sandstone, mudstone, and coal (Pashin, et al., 1991; Pashin, 1994, 1998). The cycle names in Figure 2 are those in common use in the basin, except that the interval between the Mary Lee and the Black Creek, previously unnamed or known as the Upper Black Creek (Pashin et al., 1991), is designated as the Ream cycle (Pashin, 1998).

## METHODS

In order to obtain an internally consistent 3-D structural interpretation, mapping has been done in 3-D utilizing nine cycle-bounding flooding surfaces. Accurately locating faults is the most difficult and time-consuming aspect of well-based map interpretation because, in general, faults are significantly undersampled. Mapping begins with the contouring of a cycle boundary. Then fault cuts in the wells are grouped into preliminary faults based on trend. Most faults in the area strike northwest, so this trend is used to identify wells that probably cut the same fault. Cycle thicknesses are generally very consistent across a field (unlike individual sandstone or coal thicknesses), and so thickness anomalies greater than about 25 ft (8 m) generally indicate fault cuts. Where three or more fault cuts can be assigned to the same fault, the fault surface is contoured and tested for realistic dip and fit to the elevation changes. Acceptable faults are relatively planar and have dips of 60° to 70° (normal faults). Faults are extrapolated laterally as far as perceptible elevation changes persist. The vertical extrapolation is from the just above the ground surface down to an elevation of generally -3000 ft (-914 m). The lower elevation places the base of the fault visibly below the lowest cycle top. If less than three fault cuts are available for a fault, a plane of appropriate strike, dip, and extent is constructed and inserted into the model. The cycle top is then projected along dip to the fault plane and the hangingwall and footwall intersection lines determined. The top is recontoured to include the intersection lines defining the faults. This process is repeated for each cycle top, then the result modified if necessary to ensure that cycle thicknesses remain a constant as possible, consistent with the data. The final interpretation is thus simultaneously based on all map horizons and on all fault planes. All mapping is done with the horizontal scale in UTM coordinates in meters and the vertical scale in feet. The 3-D illustrations all are shown at zero vertical exaggeration.

The production variables used here are the peak maximum daily production of methane and the peak maximum daily production of water. The values are obtained by dividing the peak monthly production amounts provided by the State Oil and Gas Board of Alabama by 30. Some previous investigators have used production rates at certain dates, or at certain fixed times since the beginning of commercial production. Initial production is very sensitive to desorption time (Sawyer et al., 1987) and desorption rates are quite variable (Bodden, 1997). Higher rank coals generally desorb gas faster than lower rank coals (Bodden, 1997), perhaps due to better development of cleat and microporosity at higher rank. The rate of methane production depends in part on how rapidly the water pressure drops. Pashin and Hinkle (1997) showed that peak rate is a good predictor of cumulative production. We reason that the peak values are the most closely related to the transmissivity of the coal. Deerlick Creek field has been producing long enough so that the peak months can be identified readily.

The presence of fractures in a well is also assessed through the use of borehole breakouts recorded by the caliper log. An average diameter for the well was determined from the caliper log and a breakout then defined as an increased diameter of more than 0.5 inches (1 cm) from the average. Coals, identified by their low density on the density log, always produce breakouts and are not recorded here. Sandstone and mudstone breakouts are presumed to indicate fractures or high stress. Midpoint elevations of all breakouts were recorded. If a breakout had a height greater than 3 ft (1 m), then the total height was recorded.

## STRUCTURE

Six faults divide the area into a horst, five half grabens and one full graben (Figure 3). Folding is minimal; beds in most fault blocks are nearly planar, except in the full graben where strata roll over into both faults.

Parallelism of beds has been verified by rotating and tilting the 3-D model. Methane is produced from coals zones ranging from the Pratt down to the Black Creek (Figure 2). The top of the Mary Lee is near the center of the productive coal interval and will be used as the reference horizon the subsequent data plots.

#### METHANE AND WATER PRODUCTION RELATED TO STRUCTURE

The most productive gas wells in this area yield a maximum of about 750 Mcf/day of methane (Figure 4), placing them in the top 5% of all producing wells in the basin. Gas production is poor in the southwestern part of the area where the vitrinite reflectance is less than 0.8. The immature coal southwest of the 0.8 line evidently lacks methane. Faults clearly segment the reservoir into blocks having significantly different production maxima.

The peak daily water is plotted together with peak gas in Figure 4. Wells with more than 725 bbl/day water are in the top 20% in the basin. Peak production of the most productive water well is about 1,500 bbl/day. Visual correlation in Figure 4 indicates that a good gas well is usually a good water well, but that a good water well is not necessarily a good gas well. Of the 7 best gas wells, 5 (71%) are among the best water wells. On the other hand, in the hangingwall of fault 5 (Figure 4), two of the biggest water producers in the area are very poor gas producers. Both gas and water production are low southwest of the estimated location of the 0.8 reflectance contour (Pashin et al., 1999a, 2003), implying that methane generation is necessary for optimal fracturing.

The two best gas and water producing fault blocks (Figure 4: between faults 2 and 5, and between faults 7 and 8) are both northeast-dipping half grabens. The implication is that these blocks have the highest fracture transmissivity. The eastern block (between faults 7 and 8) is the best of the two, perhaps because the coal is the most thermally mature. The full graben between faults 6 and 7 (Figure 4) is the poorest producer of gas and water within the thermally mature region. The difference between the blocks could be related to the amount of internal deformation required to accomplish the deformation. A half graben can form primarily by rigid-block rotation with only a little internal deformation except near the lower detachment. The narrow full graben with shallow detachment in Figure 4 must have a significant amount of internal deformation (Groshong, 1994; Groshong et al., 2003). The double rollover is additional evidence for increased internal deformation in the full graben. This suggests that a little deformation (a tilt-block half graben) may enhance fracture transmissivity, whereas more deformation (the full graben) might reduce it. The horst block (between faults 5 and 6) is also a poor producer of both gas and water. This block is relatively horizontal, except for the southeast regional dip and therefore is the least deformed location within the study area. The horst is in the thermally mature area, and so the lack of fracture transmissivity suggests that no deformation is less favorable for fracturing than mild deformation. Fault 6 ends within the map area and the wells near the tip (Figure 4) do not show enhanced production, indicating that if a fault-tip damage zone is present here, it does not extend far enough to enhance the fracturing.

The direct effect of a fault on well productivity is illustrated by two representative examples (Figure 5). Faults clearly form abrupt boundaries between blocks having different producing characteristics. Wells that penetrate faults have generally low productivity of both water and gas. Productivity of wells in the hangingwall of fault 5 increase toward the fault (Figure 5a) but productivity drops off sharply in the faulted wells. One well in the footwall of fault 5 (Figure 5a) shows slightly enhanced productivity. The excellent producing wells that cut fault 7 (Figure 5b) are no better than the other wells in the adjacent footwall block. Of the 29 wells that cut faults in the map area, only 2 show either gas or water production that is greater than that in the adjacent block

Most wells contain one or more borehole breakouts (Figure 6). The breakouts should represent locations of enhanced natural fracturing or in-situ stress-related fracturing of the borehole. Nearly all the breakouts occur in or above the Mary Lee cycle, coinciding with the part of the drilled stratigraphy that contains the most sandstone beds (Figure 2). Except for that, the breakouts seem to be distributed relatively randomly, both vertically and in map view. Some breakouts occur at faults, but most do not. It is not possible to pick out the most productive fault blocks based on the breakout abundance.

## DISCUSSION

Faults in the Black Warrior basin have clearly provided conduits for fluid migration at geological time scales (Pashin et al., 1999a) and are frequently conduits for near-surface fluid flow as evidenced by water inflows into coal mines and by the presence of springs and gas seeps along faults (Clayton et al., 1994). Yet in southeast Deerlick Creek field (Figure 5), the faults have no direct effect on the maximum production of either gas or water, other than to separate the field into blocks having different production behavior (Figure 4). In fact, many wells that cut faults are less productive than other wells in the same block. The faults act as barriers in the subsurface, not conduits. Either the preferential cementation of fault zones or the cross-fault juxtaposition of transmissive beds against non-transmissive beds can explain why the faults act as barriers. Fracture-filling calcite has been found to be particularly abundant in coal cleat within 10 meters of fault zones (Pashin et al., 1999b). Both factors may be important here.

Locations with high transmissivity appear to be sporadically located both in outcrop and in the subsurface. For example, Clayton et al. (1994) sampled outcrops of three faults in the methane fields and found a significant gas seep at only one location. In the subsurface, some wells that cut faults are exceptional producers of gas or water, but most are not (Figures 4, 5). Within the productive fault blocks, the most productive wells are sporadically distributed (Figure 4). Zones of enhanced fracturing indicated by borehole breakouts (Figure 6) appear to be randomly distributed. This behavior is consistent with models of the Pottsville Formation showing significant compartmentalization, because only a small percentage of the joint population is capable of transmitting significant amounts of fluid (Jin et al., this volume). Where a well is close to significantly transmissive fractures, the production may be affected. Where transmissive fractures interconnect near the ground surface, a seep may form. The apparently random distribution of breakouts in 3-D (Figure 6) implies that gas seeps are not deep-sourced but rather local fracture enhancements that conduct gas from shallow coal beds. The black arrow in Figure 6 points to the only well in the study area that has enough breakout locations along its length to even suggest the possibility of vertical transmission of gas from the commercial methane-producing interval to the surface. The peak production of both gas and water from this well is relatively low, however (55 mcf/day methane, 178 bbl/day water), arguing against significant connectivity between the different zones of fracturing. Vertical gas chimneys have been recognized on seismic reflection profiles from conventional gas basins (Aminzadeh and Connolly, 2002) and the technique could be applied here to determine whether any significant vertical migration of gas occurs in the basin.

Interference injection testing at the Rock Creek test site in Oak Grove field (Koenig, 1989) identified higher permeability in the face cleat direction of the Pratt coal, no anisotropy in the Mary Lee and Blue Creek coal beds, and higher permeability approximately in the butt cleat direction in the Black Creek coal. The average regional face cleat direction is N. 62° E. (Pashin et al., 1999b). In the nearby Cedar Cove field, the average induced hydraulic fracture trend, which is perpendicular to the in-situ least principal stress, is N. 77° E. (Sparks et al., 1993), thus the in-situ stress direction would favor opening of the face cleat trend. Sparks et al. (1993) suggested that some high production trends in Cedar Cove field are parallel to the face cleat direction, but in southeastern Deerlick Creek field, no productive trend can be recognized in the N. 60°-77° E. direction.

Lower production of methane can be the result of either a lack of fracturing, a lack of methane, or both. The 0.8 vitrinite reflectance contour (location estimated from Pashin et al., 2003) separates the field into productive (>0.8) and poorly productive (<0.8) regions. The poorly productive region produces little methane or water. It has been recognized elsewhere that thermogenic methane generation and cleat formation peak in the reflectance range of 0.7-0.8, indicating that methane formation may be required for cleat formation (Pashin et al., 1999b). This is consistent with the concept of cleat formation by hydraulic fracturing of the coal with gas being the fluid. Areas with low methane production but that contain good fractures, as indicated by high water production, might be excellent targets for CO<sub>2</sub> sequestration, even though they are not attractive from the methane production point of view. Faults clearly divide the reservoir into compartments and must be accurately located prior to CO<sub>2</sub> injection in order to be certain that all the wells involved are in communication and to avoid possible leakage. In the subsurface of the Deerlick Creek field, the faults generally appear to be sealing with respect to methane and thus do not create an extra risk factor for CO<sub>2</sub> escape. The borehole breakout zones, interpreted as zones of enhanced fracturing, might indicate the locations of possible leaks from a highly pressured reservoir. Only one well in the southeastern Deerlick Creek field has an unusual vertical concentration of borehole breakouts that might produce a vertical escape zone for methane or injected gas.

## CONCLUSIONS

The estimated location of the 0.8 vitrinite reflectance contour separates the field into productive ( $>0.8$ ) and poorly productive ( $<0.8$ ) regions. Within the productive area, faults segment the reservoir into blocks in which wells have significantly different rates of production. The half grabens significantly outperform the full graben and the horst. This result agrees with previous studies indicating structural control on production (Pashin et al., 1991; Ellard et al., 1992; Sparks et al., 1993; Pashin et al., 1995; Pashin and Hinkle, 1997; Cox, 2002). The significance of dip (Malone and others, 1987) is confirmed. This result is consistent with the interpretation that a moderate amount of deformation enhances transmissivity, but that not enough deformation (the horst) causes no enhancement, and that too much deformation (the full graben) reduces any previous enhancement.

Wells that cut faults commonly exhibit a slight reduction of productivity. Generally, the faulted wells have the same productivity as those in the adjacent fault block. The faults act simply as discontinuities, without necessarily changing the properties of the reservoir rock on either side.

Most wells contain borehole breakouts, nearly all of which occur in or above the Mary Lee cycle. No obvious correlation exists between the breakouts and gas or water production. Some breakouts occur along faults, but most do not. The sporadic occurrence of breakouts in 3-D, together with the sporadic distribution of the best-producing wells in the productive fault blocks suggests that both are controlled by something other than the mapped structure. Zones of enhanced jointing and/or joint intersections could provide such a control.

## ACKNOWLEDGMENTS

This research was prepared with the support of the U.S. Department of Energy under Award no. DE-FC26-00NT40927 through the Geological Survey of Alabama (Subcontract No. 01C035301). However, any opinions, findings, conclusions, or recommendations expressed herein are those of the authors and do not necessarily reflect the views of the DOE.

## REFERENCES CITED

- Aminzadeh F. and Connolly D., 2002: "Looking for Gas Chimneys and Faults"; AAPG Explorer, V 23, No. 12, p. 20-21.
- Babcock E.A., 1978: "Measurement of Subsurface Fractures from Dipmeter Logs"; American Association of Petroleum Geologists Bulletin, V. 62, p. 1111-1126.
- Bell J.S. and Gough D.I., 1983: "The Use of Borehole Breakouts in the Study of Crustal Stress, in Hydraulic Fracturing Stress Measurements, Zoback M.D. and Haimson B.C., eds., Washington, D. C., National Academy Press, p. 201-209.
- Bell J.S. and Gough D.I., 1979: "Northeast-Southwest Compressive Stress in Alberta; Evidence from Oil Wells", Earth and Planetary Science Letters, V. 45, p. 475-482.
- Blumling P., Fuchs K. and Schneider T., 1983; "Orientation of the Stress Field from Breakouts in a Crystalline Well in a Seismic Active Area", Physics of the Earth and Planetary Interiors, V. 33, p. 250-254.
- Bodden W.R III, 1997: Coalbed Methane Production and Desorption Testing in the Black Warrior Basin of Alabama: Ph.D. Dissertation, Columbia, University of South Carolina, 237 p.
- Cox M.H., 2002: Relationship Between Fracture Transmissivity and Structure in Coalbed Methane Fields of the Eastern Black Warrior Basin, Alabama: M.S. Thesis, Tuscaloosa, University of Alabama, 95 p.
- Ellard J.S., Roark, R.P. and Ayers W.B. Jr., 1992: "Geologic Controls on Coalbed Methane Production: An Example from the Pottsville Formation (Pennsylvanian Age), Black Warrior Basin, Alabama, U.S.A.", Symposium On Coalbed Methane Research And Development In Australia, Townsville, James Cook University, p. 45-61.
- Enever, J., Casey, D. and Bocking, M., 1999: "The Role of In-Situ Stress in Coalbed Methane Exploration", in Mastalerz, M., Glikson, M., and Golding, S., eds., Coalbed Methane: Scientific, Environmental and Economic Evaluation: Dordrecht, Netherlands, Kluwer Academic Publishers, p. 297-303.

- Gastaldo R.A., Demko, T.M. and Liu, Y., 1993: "Application of Sequence and Genetic Stratigraphic Concepts to Carboniferous Coal-Bearing Strata; An Example from the Black Warrior Basin, USA", *Geologische Rundschau*, V. 82, p. 212-226.
- Gough D.I. and Bell J.S., 1981: "Stress Orientations from Oil-Well Fractures in Alberta and Texas", *Canadian Journal of Earth Sciences*, V. 18, p. 638-645.
- Gough D.I. and Bell J.S., 1982: "Stress Orientations from Borehole Wall Fractures with Examples from Colorado, East Texas and Northern Canada", *Canadian Journal of Earth Sciences*, V. 19, p. 1358-1370.
- Groshong, R.H., Jr., 1994: "Area Balance, Depth to Detachment, and Strain in Extension", *Tectonics*, V. 13, p. 1488-1497.
- Groshong, R.H., Jr., Pashin, J.C., Chai, B. and Schneeflock, R.D., 2003: "Predicting Reservoir-Scale Faults with Area Balance: Application to Growth Stratigraphy", *Journal of Structural Geology*, in press.
- Hyett A.J. Dyke C.G. and Hudson J.A., 1986: "A Critical Examination of Basic Concepts Associated with the Existence and Measurement of In Situ Stress", in Stephansson. O., ed., Stockholm, *Proceedings of the International Symposium on Rock Stress and Rock Stress Measurements*, p. 387-396.
- Jin, G., Pashin, J. and Payton, J.W., 2003: "Application of Discrete Fracture Network Models to Coalbed Methane Reservoirs of the Black Warrior Basin", this volume.
- Koenig, R.A., 1989: "Hydrologic Characterization of Coal Seams for Optimal Dewatering and Methane Drainage", *Quarterly Review of Methane From Coal Seams Technology*, V. 7, p. 30-31.
- Lambert S.W., Niederhofer J.D. and Reeves S.R., 1987: "Multiple Coal Seam Completion Experience in the Deerlick Creek Field, Black Warrior Basin, Alabama", paper 8721, *Proceedings of the 1987 International Coalbed Methane Symposium*, Tuscaloosa, Alabama, p. 81-82.
- Liu Y. and Gastaldo R.A., 1992: "Characteristics of a Pennsylvanian Ravinement Surface"; *Sedimentary Geology*, V. 77, p. 197-213.
- Nelson, C.R., 2001: "Geologic controls on effective cleat porosity variation in San Juan Fruitland Formation coalbed reservoirs", paper 0108, *Proceedings of the 2001 International Coalbed Methane Symposium*, Tuscaloosa, Alabama, p. 11-19.
- Pashin J.C., 1991: *Regional Analysis of the Black Creek-Cobb Coalbed-Methane Target Interval, Black Warrior Basin, Alabama*: Tuscaloosa, Alabama Geological Survey 145, 127 p.
- Pashin J.C. and Hinkle, F., 1997: *Coalbed Methane in Alabama*: Tuscaloosa, Alabama Geological Survey Circular 192, 71 p.
- Pashin J.C. and Sarnecki J.C., 1990: *Coal-Bearing Strata Near Oak Grove and Brookwood Coalbed-Methane Fields, Black Warrior basin, Alabama*: Geological Society of America Southeastern Section Guidebook, Field Trip 5: Tuscaloosa, Alabama Geological Survey Guidebook Series 3-5, 37 p.
- Pashin, J.C. and Groshong, R.H., Jr.: 1998, "Structural Control of Coalbed Methane Production in Alabama", *International Journal of Coal Geology*, V. 38, p. 89-113.
- Pashin, J.C., Ward, W.E., II, Winston, R.B., Chandler, R.V., Bolin, D.E, Richter, K.E., Osborne, W.E. and Sarnecki, J.C., 1991: *Regional Analysis of the Black Creek-Cobb Coalbed-Methane Target Interval, Black Warrior Basin, Alabama*: Alabama Geological Survey Bulletin 145, 127 p.
- Pashin J.C., Groshong R.H., Jr. and Wang S., 1995: "Thin Skinned Structures Influence Gas Production in Alabama Coalbed Methane Fields. Tuscaloosa, Alabama", paper 9508, *Intergas '95*, Tuscaloosa, Alabama, p.15-32.
- Pashin, J.C., Carroll, R.E., Hatch, J.R. and Goldhaber, M.B., 1999a: "Interplay Among Cleating, Maturation, and Mineralization in Coalbed Methane Reservoirs of the Black Warrior Basin", paper 9942, *Proceedings of the 1999 International Coalbed Methane Symposium*, Tuscaloosa, Alabama, p. 367-375.
- Pashin, J.C., Carroll, R.E., Hatch, J.R. and Goldhaber, M.B., 1999b: "Mechanical and Thermal Control of Cleating and Shearing in Coal: Examples from the Alabama Coalbed Methane Fields, USA", in Mastalerz, M., Glikson, M., and Golding, S., eds., *Coalbed Methane: Scientific, Environmental and Economic Evaluation*: Dordrecht, Netherlands, Kluwer Academic Publishers, p. 305-327.
- Pashin, J.C., Carroll, R.E., Groshong, R.H, Jr., Raymond, D.E., McIntyre, M. and Payton, J.W., 2003: "Geologic Screening Criteria for Sequestration of CO<sub>2</sub> in Coal: Quantifying Potential of the Black Warrior Coalbed Methane Fairway, Alabama", *Annual Technical Progress Report*, U.S. Department of Energy, National Energy Technology Laboratory, contract DE-FC-00NT40927, 190 p.
- Malone P.G., Briscoe F.H. and Camp B.S., 1987: "A Study of Coalbed Methane Production Trends as Related to Geologic Features", paper 8762, *Proceedings of the 1987 International Coalbed Methane Symposium*, Tuscaloosa, Alabama, p. 293.
- McCalley, H., 1900: *Report on the Warrior coal basin*: Tuscaloosa, Alabama, Geological Survey Special Report 10, 327 p.

- McKee, C.R., Bumb, A.C. and Koenig, R.A., 1988: "Stress-Dependent Permeability and Porosity of Coal and Other Geologic Formations", Society of Petroleum Engineers Formation evaluation, March, 1988, p. 81-91.
- Plumb R.A. and Cox J.W., 1987: "Stress Directions in Eastern North America Determined to 4.5 km from Borehole Elongation Measurements", Journal of Geophysical Research, V. 92, p. 4805-4816.
- Reeves S.R., Lambert S.W. and Zuber M.D., 1987: "A Field Derived Inflow Performance Relationship for Coalbed Gas Wells in the Black Warrior Basin", paper 8744, Proceedings of the 1987 International Coalbed Methane Symposium, Tuscaloosa, Alabama, p. 207-215
- Rice, D.D., 1993: "Composition and Origins of Coalbed Gas" American Association of Petroleum Geologists Studies in Geology 38, p. 159-184.
- Sawyer W.K., Zuber M.D., Kuuskraa V.A. and Horner D.M., 1987: "Using Reservoir Simulation and Field Data to Define Mechanisms Controlling Coalbed Methane Production", paper 8763, Proceedings of the 1987 International Coalbed Methane Symposium, Tuscaloosa, Alabama, p. 295-307.
- Smith J., 1995: Normal Faults in Holt and Peterson Coalbed Methane Fields, Black Warrior Basin, Alabama: M.S. Thesis, Tuscaloosa University of Alabama, 76 p.
- Spafford S.D. and Saulsberry J.L., 1993: "Field verification of Fracture Height Growth Associated with a Restricted Access Completion", paper 9375, Proceedings of the 1993 International Coalbed Methane Symposium, Tuscaloosa, Alabama, p. 139-144.
- Sparks D.P., Lambert S.W. and McLendon T.H., 1993: "Coalbed Gas Well Flow Performance Controls, Cedar Cove Area, Warrior Basin, U.S.A.", paper 9376, Proceedings of the 1993 International Coalbed Methane Symposium, Tuscaloosa, Alabama, p. 529-547.
- Thomas, W. A., 1988: The Black Warrior basin, in Sloss L.L., ed., Sedimentary Cover-North American Craton: Geological Society of America, The Geology of North America, v. D-2, p. 471-492.
- Wang S., 1994: Three-Dimensional Geometry of Normal Faults in Southeastern Deerlick Creek Coalbed Methane Field, Black Warrior basin, Alabama: M.S. Thesis, Tuscaloosa, University of Alabama, 77 p.
- Whiting, B.M. and Thomas, W.A., 1994: "Three-Dimensional Controls on Subsidence of a Foreland Basin Associated with a Thrust-Belt Recess: Black Warrior basin, Alabama and Mississippi; with Supplementary Data 9437", Geology, V. 22, p. 727-730.

FIGURES

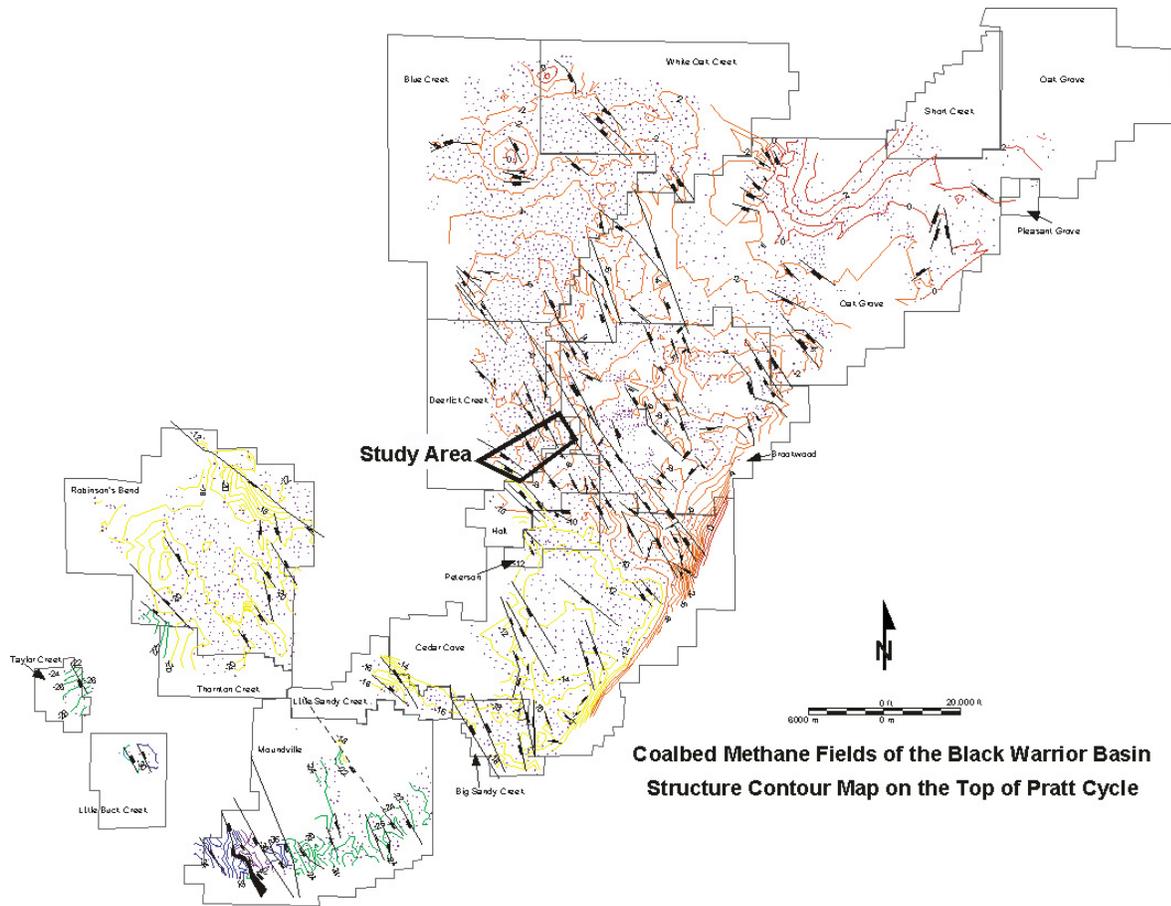


Figure 1. Index map to southeastern Deerlick Creek field area. Contour interval = 100 feet x100 (30 m x 100), every fifth contour is accented. Small dots are well locations used in mapping.

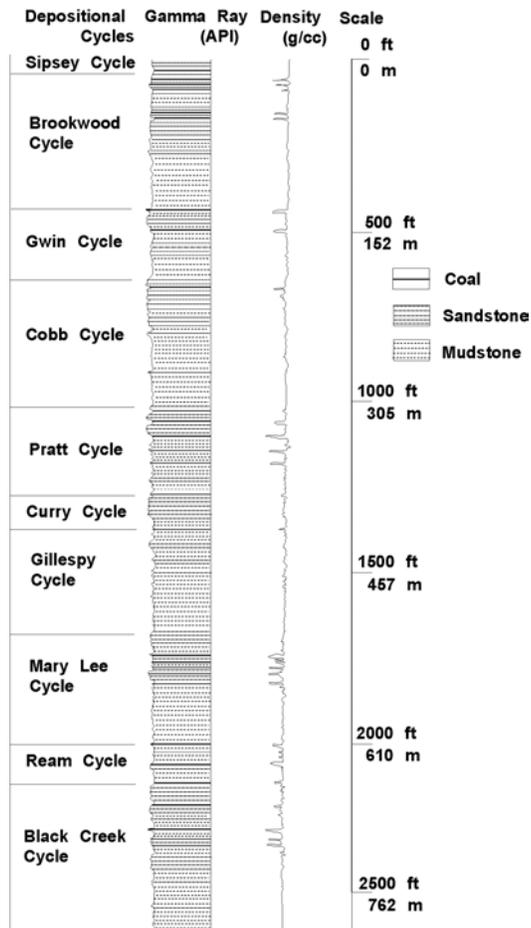


Fig. 2. Pottsville coal cycles and a typical log response (composite of wells 5693 and 5615). From Cox, 2002, after Wang, 1994.

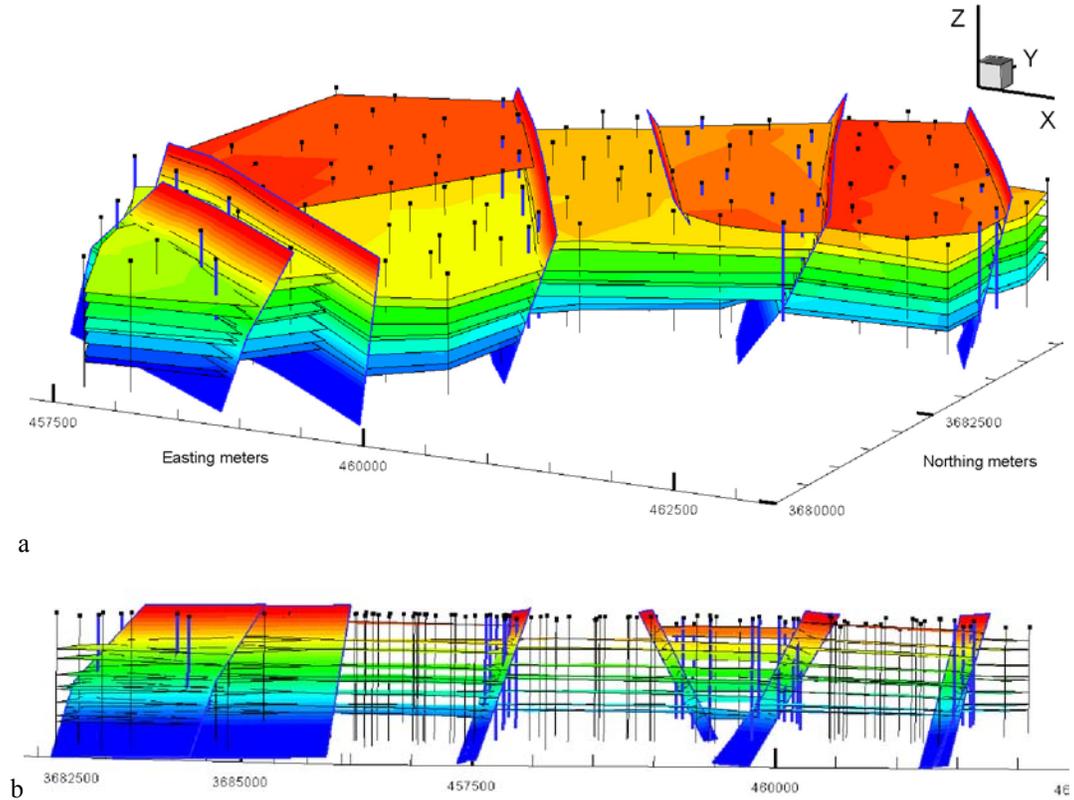


Figure 3. 3-D interpretation of southern Deerlick Creek field. All 9 cycle tops, all mappable faults, and all wells shown. The upper cycle top (Utley) is not present in all wells. The blue wells contain fault cuts. Black lines on faults are bed intersection lines. Coordinates are UTM, one small scale division is 200 m. a. Oblique view from southeast to the northwest. b. Horizontal view from southeast to northwest.

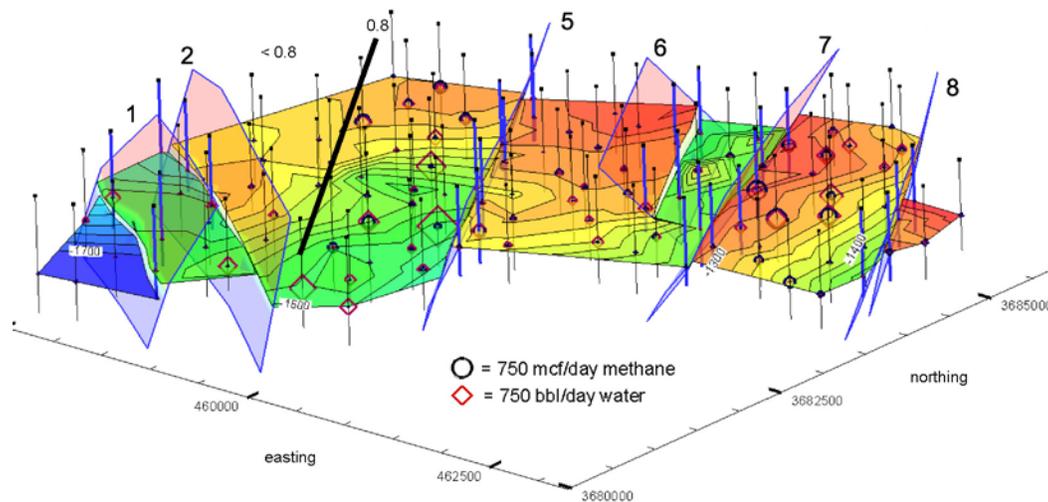


Figure 4. Methane and water production superimposed on the top Mary Lee surface, viewed to the northwest. The contour interval is 20 ft (6 m). Blue represents deeper elevations and red represents higher elevations. Faults are numbered. The heavy line marked 0.8 is a vitrinite reflectance contour. One small scale division is 200 m.

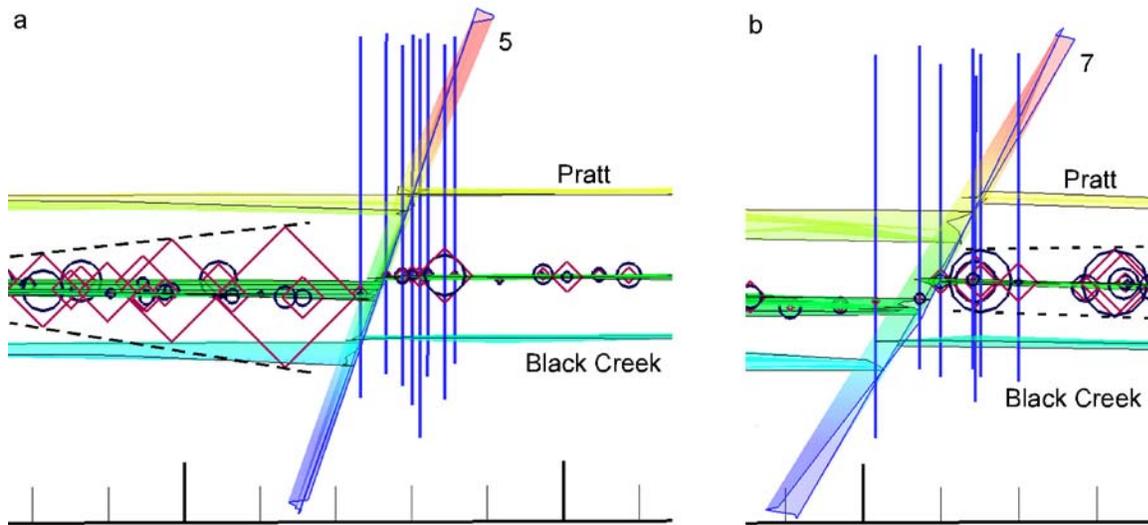


Figure 5. Methane (circle) and water (diamond) production near faults 5 (a) and 7 (b). Approximately horizontal, 3-D view to the northwest, parallel to the fault. Wells cut by the mapped fault are shown. Pratt and Black Creek cycle tops are labeled. The center horizon is the top Mary Lee. The dashed lines are extrapolations of the maximum production values in the block adjacent to the fault. Small scale divisions are 200 m. No vertical exaggeration.

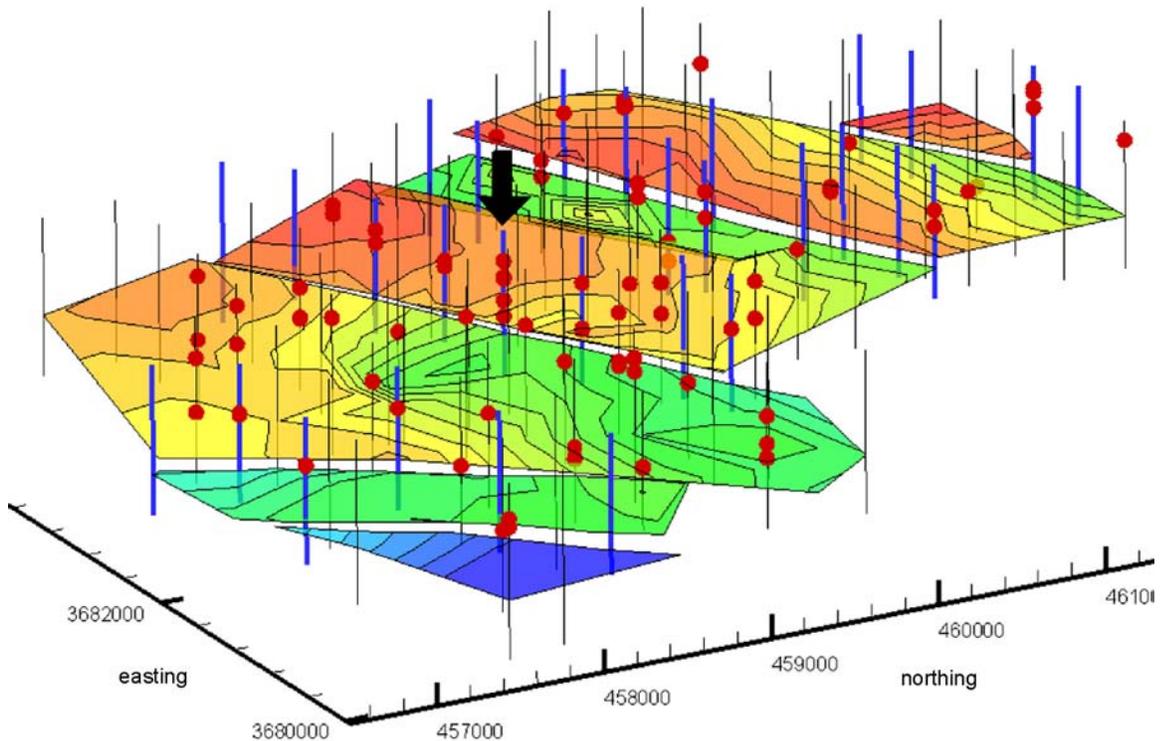


Figure 6. Borehole breakouts (red dots) within and above the methane producing interval, plotted at the breakout location. The map horizon is the top of the Mary Lee, viewed toward the northwest, fault planes omitted. Small scale divisions are 200 m. Blue wells (thicker) contain fault cuts. Black arrow indicates a well with an unusual concentration of breakouts.