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Structural controls on fractured coal reservoirs in the southern Appalachian Black Warrior foreland basin

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ABSTRACT

Coal is a nearly impermeable rock type for which the production of fluids requires the presence of open fractures. Basin-wide controls on the fractured coal reservoirs of the Black Warrior foreland basin are demonstrated by the variability of maximum production rates from coalbed methane wells. Reservoir behavior depends on distance from the thrust front. Far from the thrust front, normal faults are barriers to fluid migration and compartmentalize the reservoirs. Close to the thrust front, rates are enhanced along some normal faults, and a new trend is developed. The two trends have the geometry of conjugate strike-slip faults with the same σ_1 direction as the Appalachian fold-thrust belt and are inferred to be the result of late pure-shear deformation of the foreland. Face cleat causes significant permeability anisotropy in some shallow coal seams but does not produce a map-scale production trend.

1. Introduction

Fractures provide a tool for the study of regional tectonics in many areas, including the Appalachians (e.g. Nickelsen and Hough, 1967; Kulander and Dean, 1993; Engelder and Whitaker, 2006) and are recognized as being critical to the production of fluids from many reservoirs (e.g., Nelson, 2001). In the foreland of the southern Appalachian fold-thrust belt, the Black Warrior basin fractured coal beds serve as the reservoirs both for the commercial production of coalbed methane and, locally, some shallow coal beds serve as sources for domestic water. This basin is well suited for an examination of the connection between fracture-reservoir performance and structure because it is highly faulted, and because water and methane production data are available from thousands of coalbed methane wells. It will be shown that map-scale faults, fault-block geometry, and position relative to the Appalachian thrust front all contribute to reservoir behavior.

Map-scale structures of the Black Warrior basin have previously been proposed as being significant factors in controlling the production rates of coalbed methane wells (Malone et al., 1987; Pashin et al., 1991; Ellard et al., 1992; Sparks et al., 1993; Pashin et al., 1995; Pashin and Groshong, 1998). Enhanced natural fracturing associated with faulting and fault-related folding influences production locally (Pashin et al., 1991; Pashin and Hinkle, 1997). Faults in the Black Warrior basin have clearly provided conduits for fluid migration at geological time scales (Pashin et al., 1999), 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 Sparks et al. (1993) and Pashin et al. (2004) found that fault zones in many areas are not as productive as the blocks between faults, and Pitman et al. (2003) observed pervasive cementation of coal cleats within 10 m of normal faults in the basin, apparently precluding flow in coal along large parts of many faults.

Some of the previous results are seemingly contradictory, for example, that faults enhance fluid flow and that faults reduce fluid flow. Such contradictions could be the result of the different geographic locations of the studies. Hence a traverse from the basin up to the thrust front is examined. The specific questions addressed are: (1) the role of coal cleat in creating production trends; (2) the effect of faults; and (3) the effect of proximity to the thrust front. The first two questions are traditional issues in the interpretation of fractured reservoirs. The third, proximity to the thrust front, is newly identified here as being of considerable importance to the reservoir performance.

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2. Regional structure

2.1. Location

The Black Warrior basin is a Late Paleozoic foreland basin that formed adjacent to the junction of the Appalachian and Ouachita orogenic belts (e.g., Mellen, 1947; Thomas, 1985, 1988, 1995). The basin has a distinctive triangular plan and is bounded on the southeast by the Appalachian thrust belt, on the southwest by the Ouachita thrust belt, and on the north by the Nashville dome (Fig. 1). The basin is developed primarily in strata of Pennsylvanian age which contain virtually all of the economic coal and coalbed methane resources in the basin. These strata are exposed in the eastern third of the basin, and are concealed below the Mesozoic cover of the Gulf Coastal Plain in the western part (Mellen, 1947). The area of interest here is located in Alabama, beneath the eastern edge of the coastal plane overlap and to the east of it (Fig. 2).

2.2. Structure

Within the basin, numerous northwest-trending normal faults form horst, graben, and half graben structures (Fig. 2). The majority of the faults dip southwest. Faults in the eastern part of the basin terminate downward at a thin-skinned detachment in the lower part of the Pennsylvanian-age Pottsville Formation (Wang et al., 1993; Pashin et al., 1995; Cates and Groshong, 1999; Cates et al., 2004). To the west, faults that offset the Mississippian are present and many cut substantially deeper into the section, some penetrating basement (Hawkins et al., 1999).

All the faults shown in the coalbed methane fields (Fig. 2) are mappable across two or more well locations and generally have stratigraphic separations in the range of 30–122 m (100–400 ft). Wells are drilled on 16–32 ha (40–80 acre) spacings and are evenly distributed, not highly concentrated as they would be for conventional gas traps. Wells are approximately 402–569 m (1320–1867 ft) apart. A modest number of wells contain fault cuts of less than 24 m (80 ft) stratigraphic separation that are impossible to map into fault planes. We initially anticipated that most fault cuts with smaller separations would represent the tips of bigger faults. Any small fault cut that is contiguous and coplanar with a bigger fault has been mapped as part of the adjacent large fault. Nevertheless, there remain fault cuts with separations mostly in the 6–18 m (20–60 ft) range that cannot be mapped because only one well is affected and the marker-horizon elevations do not show a significant elevation change one well location away from the faulted well. They may represent deformation between the larger faults or may in places be small soft-sediment faults.

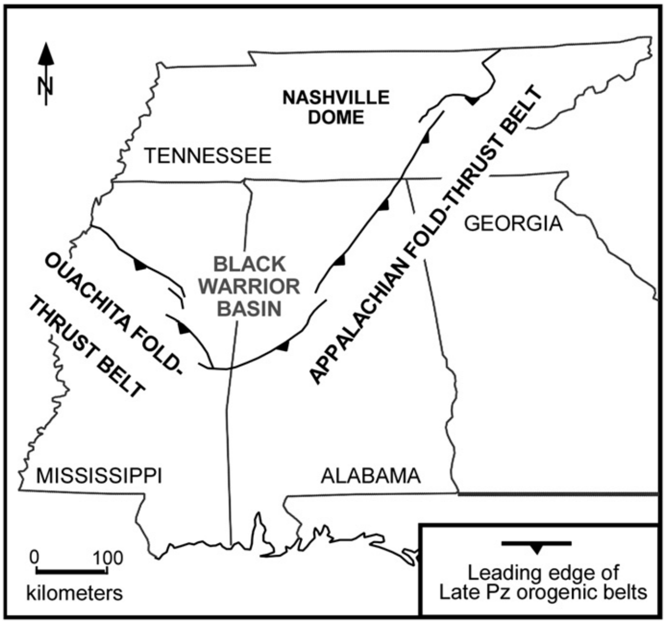

Fig. 1. Regional index map showing location of Black Warrior Basin (modified from Thomas, 1988).

2.3. Regional joint and cleat trends

In outcrops and underground coal mines, the siliclastic rocks of the basin are dominated by an orthogonal joint system consisting of ENE-trending planar systematic joints and orthogonal cross joints (Ward et al., 1984; Fig. 3). Planar systematic joints are relatively smooth-surfaced, parallel, and laterally and vertically persistent (Groshong, 1988). Cross joints are somewhat rough-surfaced, may be curved, are less persistent laterally and vertically (Pashin et al., 1999), and commonly terminate at planar joints. Planar systematic joints without associated cross joints have been observed in deep coal mines 610 m (2000 ft) below the surface (Ward et al., 1984), implying that the cross joints may form late, during uplift and erosion. Close to the Appalachian thrust front and extending across the Sequatchie anticline, a second orthogonal joint system is developed with the planar-systematic trend being NW, normal to the thrust front.

Cleat provides the major conduit for fluid flow in the coalbed methane reservoirs, and its trend might be expected to influence the flow of water and methane (e.g., Laubach et al., 1998). Cleat is a miner's term for closely spaced joints in coal. Cleat typically forms as an orthogonal system. The face cleat is equivalent to planar-systematic joints, and the butt cleat is equivalent to the cross joints. Face cleat is relatively smooth, planar, and extends for comparatively long distances; butt cleat is rougher and terminates at the face cleat. An ENE face cleat trend is present throughout the basin; close to the thrust front a NW face cleat trend is present as well (Fig. 3).

Joints and cleats in the basin are commonly mineralized. Calcite, pyrite and quartz are the dominant fracture-filling minerals in shale and sandstone, pyrite and calcite are common in coal (Pashin and Hinkle, 1997; Pashin et al., 1999, 2004; Pitman et al., 2003; Laubach and Gale, 2006). Fracture-filling minerals generally have patchy distributions and seldom completely fill the macrofractures.

3. Stratigraphy and reservoir properties

3.1. Stratigraphy

Economic coal and coalbed methane resources are concentrated in the upper part of the Pottsville Formation, which is of Early Pennsylvanian age. The Pottsville Formation consists principally of shale, sandstone and coal, and is locally more than 1800 m (6000 ft) thick (Thomas, 1988). It forms a series of basinwide coarsening- and coaling-upward depositional cycles, or parasequences, of fluvial-deltaic origin (Fig. 4; Pashin et al., 1991; Pashin, 2004). Map units are defined on the basis of the cycle-bounding flooding surfaces. Flooding surfaces are easily correlated across the basin using geophysical well logs, whereas individual coal and sandstone units are not. Parasequence thicknesses vary smoothly across the basin. Shale, sandstone, and coal are easily distinguished in gamma-density logs. Shale can be identified as intervals with gamma count higher than 100 API units, whereas sandstone has a gamma count lower than 100 API units. Coal beds and associated organic shale beds form distinctive low-density markers and can also have a low gamma count similar to sandstone. Cycle-bounding flooding surfaces are interpreted to be at the base of the first high-gamma peak

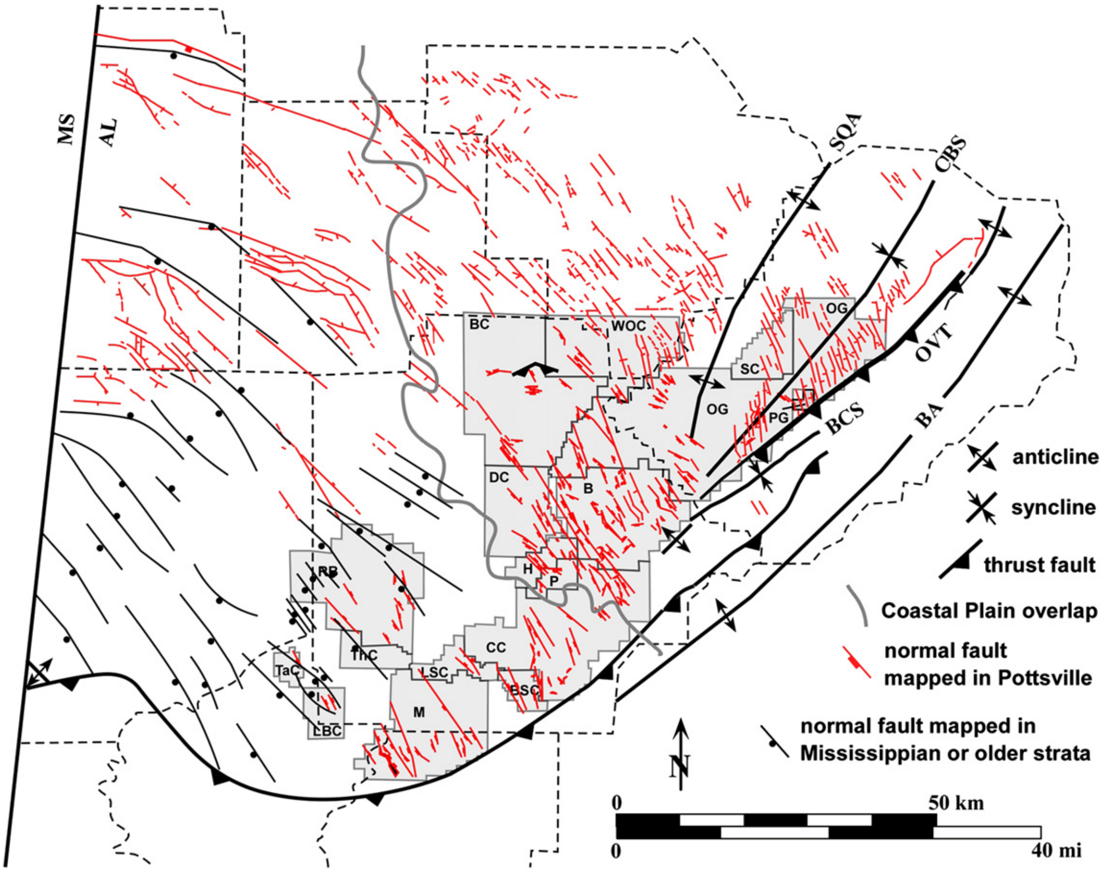

Fig. 2. Tectonic map of the Black Warrior basin in Alabama showing location of coalbed methane fields. Faults are compiled from records of the Geological Survey and the State Oil and Gas Board of Alabama (Pashin, 1991). Faults that cut Mississippian have been mapped from oil and gas wells (Pashin, 1993) and seismic reflection profiles (Hawkins et al., 1999; Cates et al., 2004). Within the coalbed methane fields (shaded) faults are from Groshong et al. (2003a). Coalbed methane fields are: B, Brookwood; BC, Blue Creek; BSC, Big Sandy Creek; CC, Cedar Cove; DC, Deerlick Creek; H, Holt; LBC, Little Buck Creek; LSC, Little Sandy Creek; M, Moundville; P, Peterson; PG, Pleasant Grove; RB, Robinson's Bend; SC, Short Creek; TaC, Taylor Creek; ThC, Thornton Creek; WOC, White Oak Creek. Named structures are: BA, Birmingham anticlinorium; BCS, Blue Creek syncline; CBS, Coalburg syncline; OVT, Opossum Valley thrust; SQA, Sequatchie anticline. Dashed lines are county boundaries.

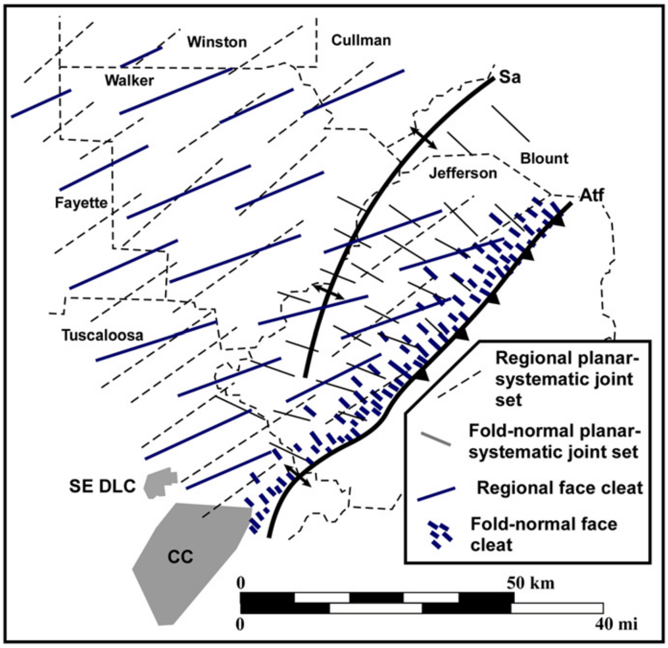

Fig. 3. Regional joint and cleat trends (after Pashin et al., 1991; Pitman et al., 2003). Sa, Sequatchie anticline; Atf, Appalachian thrust front; SE DLC, southeast part of Deerlick Creek coalbed methane field; CC, Cedar Cove and Peterson coalbed methane fields. Dashed lines are county boundaries with the counties named.

in the lower parts of thick marine shale intervals. The logs are recorded in feet, and for accuracy and consistency the same units are used here. Commercial production of methane is primarily from coals in the Black Creek through Pratt cycles.

3.2. Coal as a reservoir

Coal is a dual porosity reservoir in which adsorption within the microporous coal matrix is the principal storage mechanism for gas. Within the coal matrix diffusional flow of gas dominates whereas Darcian flow of gas and water occurs in the cleat system. Accordingly, fracture networks play a crucial role in coalbed methane production, because cleat systems are the principal source of permeability required to achieve commercial rates of gas and water production. Producible methane is adsorbed onto the large surface area inherent in the microporous organic matrix of coal and is held in place by a combination of van der Waal's forces and hydrostatic pressure. In order to produce the methane, the hydrostatic pressure must be lowered, thus wells typically produce both water and methane. Desorption and Darcian flow provide the initial methane production, while diffusion of methane from the matrix into the fracture system allows the wells to produce commercially for decades.

Coal is the source as well as the reservoir for the methane it contains. Vitrinite reflectance is a measure of the thermal maturity of the coal. A reflectance of $R_0 = 0.8\%$ approximates the degree of maturation required for the generation of thermogenic methane

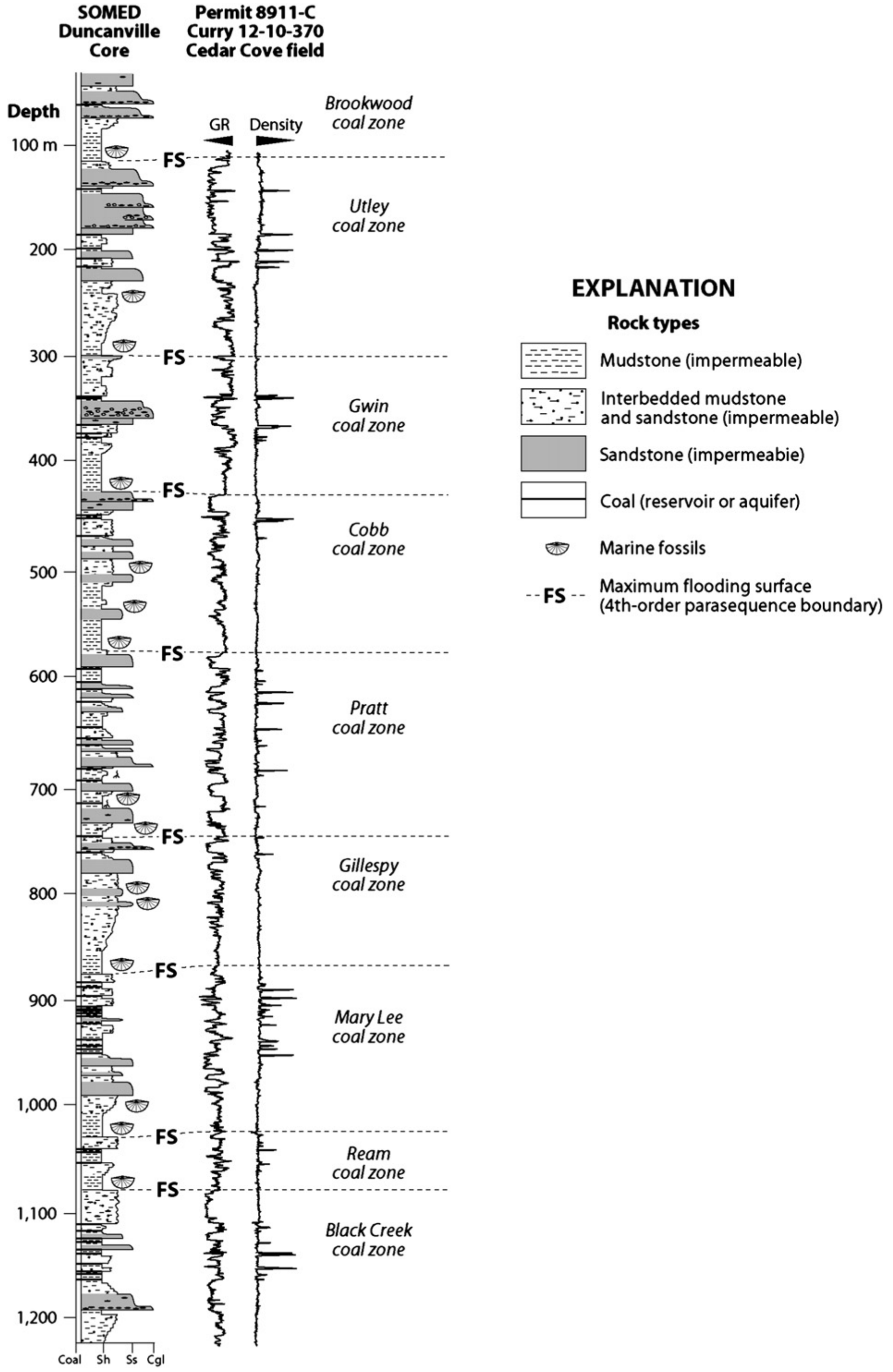

Fig. 4. Coal zones of the Pennsylvanian upper Pottsville Formation within the coalbed methane fields. Typical core log and geophysical logs for Cedar Cove field (modified from Pashin and Hinkle, 1997). A younger Sipsey cycle and additional unnamed cycles occur in the subsurface to the southwest (Telle et al., 1987).

from coal (Jüntgen and Klein, 1975; Stach et al., 1982; Dow and O'Connor, 1982). At any given location, migrated thermogenic and late-stage biogenic gas may also be present (Scott et al., 1994). A substantial biogenic component has been found to be present in the Black Warrior basin (Rice, 1993; Pitman et al., 2003; Pashin, 2007).

Cleat begins to develop as the coal devolatilizes and shrinks and becomes more intense as rank increases (Ammosov and Eremin, 1960; Law, 1993; Laubach et al., 1998). Low-volatile bituminous coal shows maximum coal cleat development in the Black Warrior basin (McFall et al., 1986; Pashin et al., 1999; Bodden, 1997). Where seen, the spacing between adjacent fractures is on the order of 1–2.5 cm (0.5–1.0 inch) or less. The cleat spacing is substantially less than the thickness of the producing coal beds (0.3–3 m, 1–9 ft). Pashin et al. (1999) suggest that the edge of the thermogenic gas window ($R_0 = 0.8\%$) marks the threshold for significant (i.e., cm-scale) cleat development. The in situ formation of methane would reduce the effective confining pressure which could lead to the enhanced fracturing. Coalbed methane reservoirs are classified as continuous, unconventional-type reservoirs in which the producible resource is distributed across a large area.

Wells in the coalbed methane fields are characterized by heterogeneous production rates. Production-rate differences of up to three orders of magnitude have been documented among closely spaced wells in the basin (Malone et al., 1987). At any given depth, the permeability can vary by more than an order of magnitude (McKee et al., 1988). Studies have shown that the variability of gas production is unlikely to be the result of stratigraphic factors such as coal thickness (Pashin et al., 1991; Pashin and Hinkle, 1997) or local variations in the amount of gas in place (Sparks et al., 1993; Bodden, 1997). Pashin et al. (2004) found that apertures in partially cemented joints and minor slip surfaces in cores from a local coalbed methane field have an exponential size distribution, indicating that most of the flow will be concentrated in relatively few fractures. The success of an individual well in finding a wide, partially cemented fracture or fracture swarm (Laubach et al., 1998) may explain the local heterogeneity of production rates. Completion practice varies considerably in the Black Warrior basin and can affect the production performance of individual wells (e.g., Lambert et al., 1987; Pashin, 2007). However, completion techniques do not vary systematically with respect to geologic factors and can be considered more as a source of noise than a dominant control on map-scale production patterns (Sparks et al., 1993; Pashin et al., 1991; Pashin, 2007).

4. Methods

We have no direct observations of fractures within the wells. But the transmissivity of coal and the intervening strata is due to open fractures, and so we use peak daily production of both gas and water from coalbed methane wells as proxies for the degree and openness of fracturing in the vicinity of the wellbore. Typically a well reaches peak water production within the first 6 months, followed by peak gas production in a few months to as much as 4 years. Within the basin, reservoir pressures range from normal to extremely underpressured (Pashin and McIntyre, 2003), hence, water is pumped to the surface at a rate controlled primarily by the transmissivity of the coal and the power of the walking-beam or cavity pump. The production of water and methane are reported to the Alabama Oil and Gas Board in monthly increments; we divided by 30 to find the peak daily production, which therefore represents a peak that has been sustained over an entire month. All the wells in this study were in production for a year or more at the conclusion of data collection, thus production peaks have certainly been achieved for water in all wells and for gas in most wells. There are multiple reasons why a well may fail to produce gas, ranging from the gas not having been generated or retained at that location to a lack of open fractures. Hence both water- and gas-production maxima provide information on the degree of in situ fracturing, with water production being the more consistent of the two within the study area.

5. Deerlick Creek field

5.1. Structure

The southeastern portion of the Deerlick Creek field (Fig. 5) provides a detailed example of the relationship between structure and reservoir properties at a significant distance from the Appalachian thrust front. Numerous well penetrations clearly define the locations of the faults. The main producing interval is from the Pratt to the Black Creek coal zones.

5.2. Production rates

Production rates of both water and gas are shown on a map of the top of the Mary Lee coal zone (Fig. 6) which is in the approximate center of the producing interval (Fig. 5). All wells have been completed, and so all symbols of peak daily production of water and methane, even the very small ones, represent production rate magnitudes, not just well locations. Some wells, especially on the east side of block C, show substantial rates of water production with little methane but no well shows a large production rate of methane without water. This is consistent with the hypothesis that the entire reservoir contains water but not necessarily methane, and that a lack of both water and methane production means a lack of open fractures. To the west of the 0.8% reflectance line (blocks A, B and the western part of C) the thermal maturation is less, and the lack of significant production of either water or methane suggests a lack of fractures. High water and/or gas production to the east of the 0.8% reflectance line implies more intense fracturing. There are no obvious linear production trends. Noteworthy is the absence of an ENE trend parallel to the face cleat. Production rates are not enhanced around the southeast tip of fault 6, the location of which is constrained by wells that do not contain fault cuts.

5.3. Effect of faults

Faults divide the region into blocks having different production characteristics (Figs. 6, 7; Pashin et al., 1995; Pashin and Groshong, 1998). East of the 0.8% vitrinite reflectance line, blocks D and E

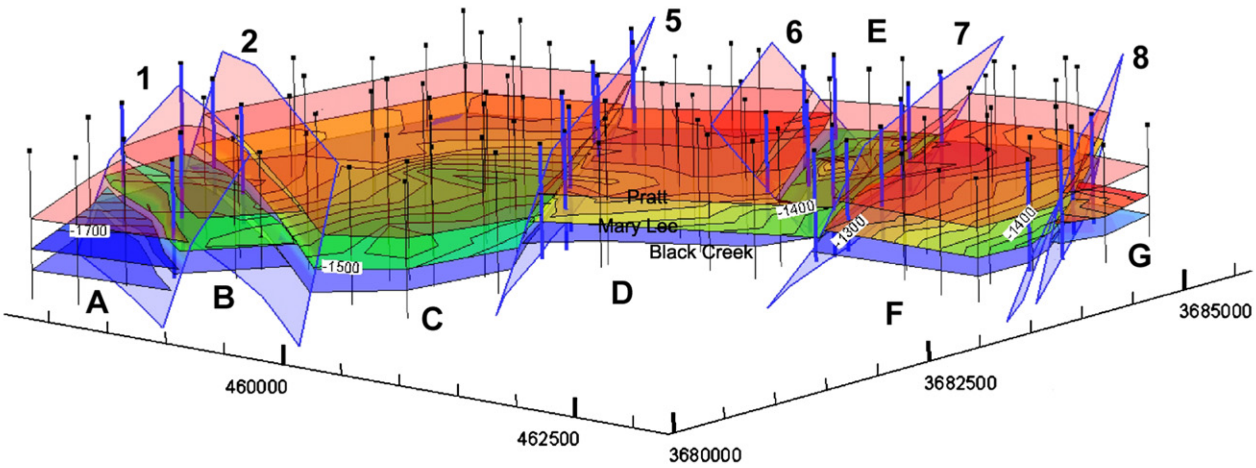

Fig. 5. 3-D volume interpretation of the southeastern Deerlick Creek coalbed methane field showing producing interval and all wells, oblique view to NW (after Groshong, 2004). Vertical lines are wells, horizontal scale UTM in meters, no vertical exaggeration. Faults are numbered, fault blocks are lettered. Location shown in Figs. 2 and 3.

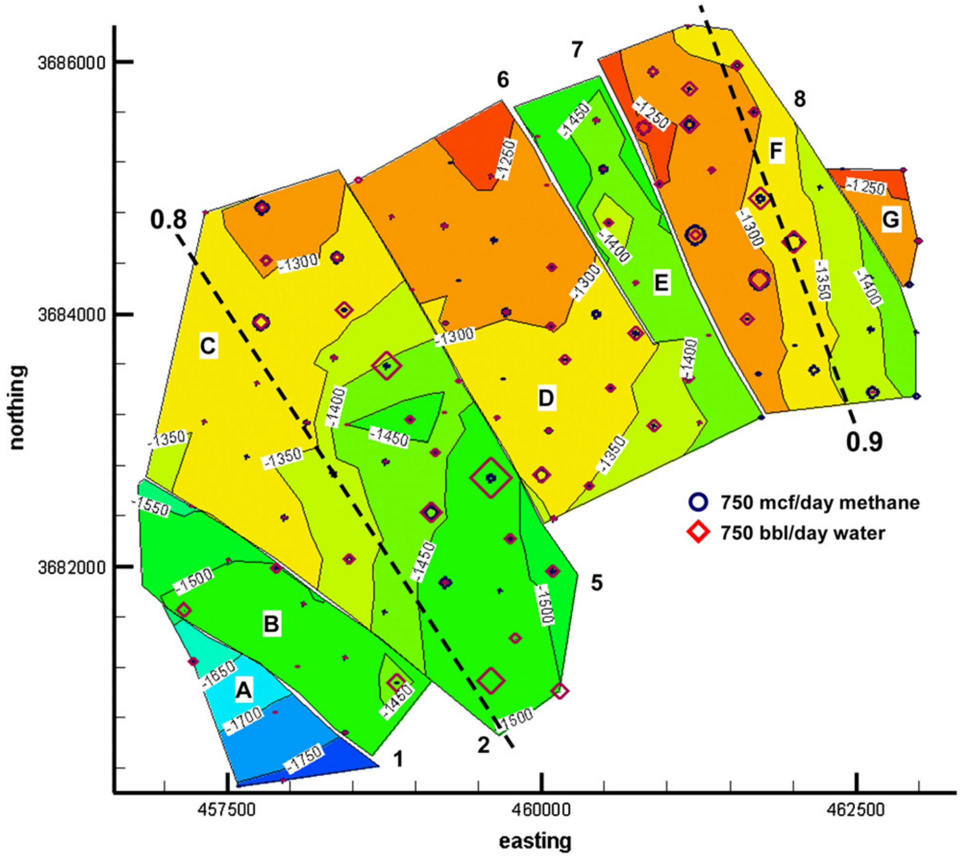

Fig. 6. Structure contour map of the top Mary Lee coal zone showing peak daily production of methane and water. Easting and northing in meters; contour interval 50 ft (15 m). All production bubbles represent producing wells: circles are peak mcf/day methane; diamonds are peak bbl/day water production. The thick dashed lines are approximately located contours of vitrinite reflectance from Winston (1990). Modified from Groshong et al. (2003a) and Groshong (2004).

show generally low production rates of both water and gas, yet the adjacent parts of blocks C and F are substantially more productive of both. Thus the faults separate blocks with different permeability. The most productive blocks are half grabens. The least productive blocks within the region of methane generation are the horst (block D) and the adjacent graben (block E). We suggest that this relationship indicates that there is an optimum amount of deformation in the half grabens for the formation and preservation of open cleat. In principle, for extension above a detachment, the horst block would be undeformed or have the least deformation, the graben block would have the most deformation, and a tilted fault block would have an intermediate value (cf. discussion of requisite strain in Groshong, 2006).

Wells that penetrate faults (Fig. 7) do not show an increase in production rate compared to those in the block in which they are completed. One well in the footwall of fault 5 may be an exception, but that well cuts the fault significantly above the producing interval and so is unlikely to be affected by the fault-zone properties. In this area, the production rates in wells that penetrate fault zones are either the same as or less than the production rates of wells

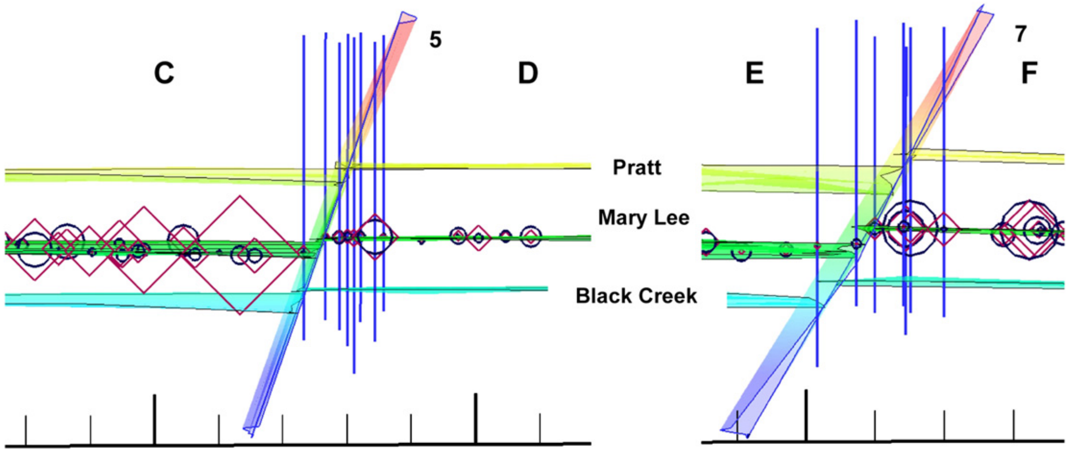

Fig. 7. Effect of faults on production rates, southeastern Deerlick Creek field. Side views parallel to the fault strike, approximately to the NW. Fault numbers and block letters correspond to those in Figs. 5 and 6. Only wells with fault cuts are shown. Circles are peak mcf/day methane; diamonds are peak bbl/day water production. The interval between the Pratt and the Black Creek is 1000 ft (305 m).

outside the fault zones. Neither methane nor water appears to move across the faults during production. For example, the numerous low-volume producers in the footwall of fault 5 do not pull water from the adjacent water-producing hangingwall. The latter observation indicates that, at the present time, the fault acts as a barrier to fluid flow. The fault may be a barrier either because of the juxtaposition of impermeable units against the coal or because of cementation of the coal cleat. Calcite cementation along fault zones has been observed in coal mines close to the thrust front as well as on the northern flank of the basin where the coals are again close to the surface (Pitman et al., 2003; Pashin et al., 1999, 2004), thus cementation along fault zones is likely in the Deerlick Creek area as well.

6. Cedar Cove and Peterson fields

6.1. Structure

The contiguous Cedar Cove and Peterson fields (Fig. 8) provide an example of the relationship between structure and reservoir properties at the Appalachian thrust front (Fig. 2). Strata along the southwestern margin of the field tilt upward in the footwall of the leading Appalachian thrust fault. Most of the normal faults trend NW to NNW, as seen elsewhere in the basin. Two WNW normal faults occur close to the thrust front, a trend otherwise absent in the eastern part of the basin.

6.2. Production rates

In contrast to the production-rate map of Deerlick Creek, numerous linear production trends are present in Cedar Cove field. The most prominent trends are found on the map of peak water production (Fig. 9a), which most directly reflects the fracture permeability of the coal reservoir. One trend is NW and is subparallel to that of the majority of the normal faults. A strong WNW trend is also present in the production-rate data.

As in the Deerlick Creek field, the cleat trends (NW and NE) are not obvious on the production-rate map (Fig. 9). Cleat-related permeability anisotropy is nevertheless present. Pressure buildup tests in the Oak Grove field, close to the thrust front to the northeast (Fig. 2), show permeability that is significantly greater parallel to the regional face cleat direction (Fig. 4) in a shallow (Pratt) coal zone (Koenig, 1989). This is only about 20° NW of the contemporary in situ σ_1 direction (N 80° E, Sparks et al., 1993) and is thus the mechanically favored direction to be open. In intermediate-depth coal seams (Mary Lee and Blue Creek), the permeability is nearly isotropic (Koenig, 1989), an observation interpreted by Pashin et al. (2004) to be the result of the closure of cleat with depth in the coal. Production rates are generally higher in the Cedar Cove area (~1640 bbl/day and above) than in the Deerlick Creek area (~750 bbl/day). The presence of two cleat systems near the Appalachian front (Fig. 4) should increase the fracture intensity and explain the greater magnitudes of the fluid flow rates. Similarly, in the San Juan basin of Colorado and New Mexico the greatest gas production rates are in the area where two face cleat trends are present (Laubach et al., 1998; Ayers, 2002).

6.3. Effect of faults

Some of the faults in the Cedar Cove field lie along trends of increased production rates (Fig. 9b). Most notable is the NW trend in the southwestern part of the field. The trend of enhanced

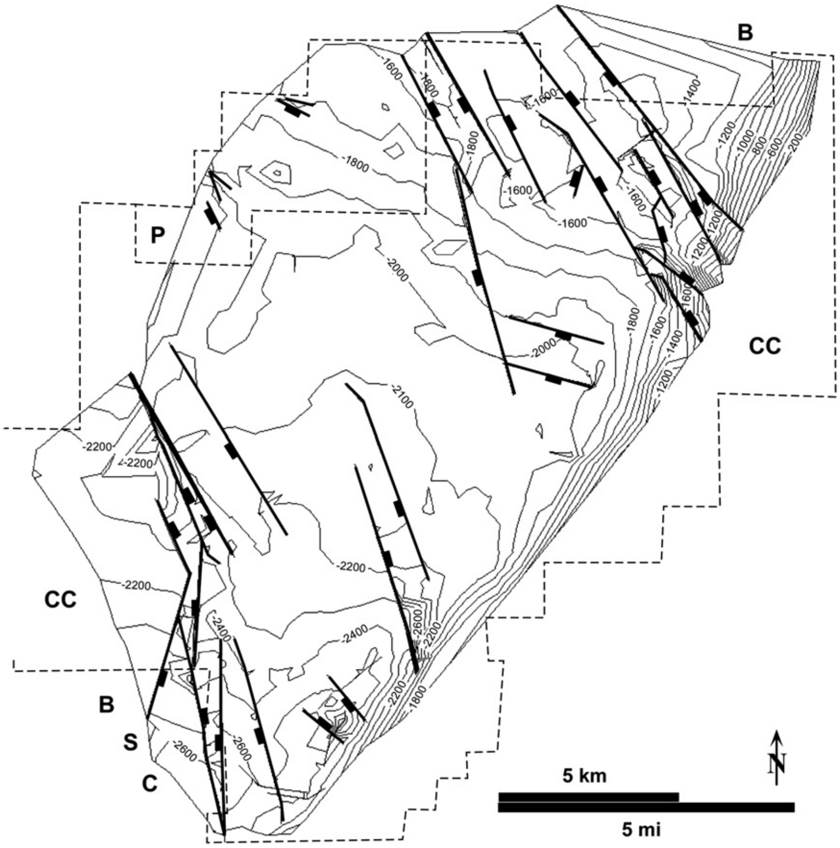

Fig. 8. Structure contour map of Cedar Cove, Peterson, and parts of adjacent fields (after McIntyre et al., 2003). Structure contours on the top of the Mary Lee zone. Contour interval 100 ft (30 m). Location in the basin given in Figs. 2 and 3. Coalbed methane fields are: B, Brookwood; BSC, Big Sandy Creek; CC, Cedar Cove; P, Peterson.

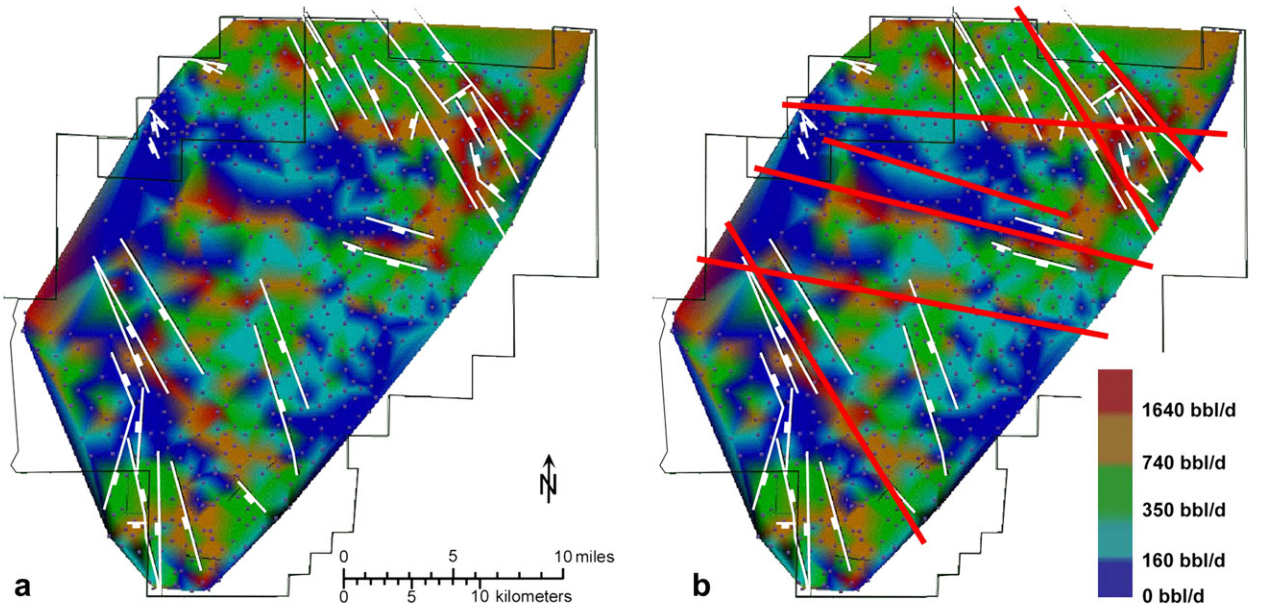

Fig. 9. Maximum daily water production (bbl/day) from Cedar Cove and Peterson fields (after McIntyre et al., 2003; Cates et al., 2004). Faults (white) are superimposed from Fig. 8. (a) Uninterpreted. (b) Interpreted linear production trends (red lines).

production rate extends well beyond the mappable fault tips. The large production-rate maximum in the northeastern corner of the map coincides with a swarm of normal faults and partly reflects their trend. In addition, this area is the trough of the syncline where the basin dip reverses. In the middle of the field close to the thrust front, the new WNW fault trend is parallel to a production-rate trend, although the production trend extends far beyond the tips of the faults.

6.4. Interpretation

The water production-rate trends in Cedar Cove field have the geometry of conjugate shears bisected by a NW-SE trending maximum compressive stress, σ_1 (Fig. 10). The inferred σ_1 direction is perpendicular to the adjacent Appalachian fold axes and thrust trends and so we interpret the features to be conjugate shears formed as Appalachian deformation encroached into the foreland. The NW production-rate trend parallels the strike of the normal faults that are distributed throughout the basin (Fig. 2). Normal faults close to the thrust front are inferred to have been reactivated with a small component of left-lateral strike slip. Stress concentrations should develop at the fault tips, leading to increased fracturing and the propagation of the fracture trend beyond the fault tip. Only a few faults have been so enhanced, however.

The WNW trend appears to be unique to the region close to the thrust front. Faults on this trend are seen only in Cedar Cove field. Clearly defined water production-rate trends with the same west-northwest direction extend far beyond the tips of the mapped normal faults and traverse regions where no faults have been mapped. We interpret this trend to be the result of incipient to very small right-lateral strike-slip faults. Small strike-slip faults are not likely to produce enough stratigraphic separation to be recognized in the well logs from this area, so we do not consider the lack of mapped faults along the production trends to contradict this inference. Pashin et al. (1999) reported outcrop-scale strike-slip faults associated with the Alleghanian σ_1 direction in the Blue Creek syncline, close to Oak Grove field (Fig. 2). In the underground Oak Grove mine McDaniel (1986) reported horizontal slickensides on small (3 m, 10 ft) displacement normal faults. We envisage the enhanced-permeability zones to consist of misalignments across original dip-slip-parallel corrugations on existing normal faults, and new trends characterized by enhanced fold-normal tension fractures and/or zones of cleat-block rotation with spaces formed between the blocks. The latter features are recognized along exposed strike-slip faults elsewhere (e.g. Ramsay and Huber, 1987; Groshong, 1988). The presence of pervasive cm-scale, cleat-bounded blocks makes strike-slip block rotations very likely.

The Appalachian thrust front is linear in this area, thus the expected deformation in the foreland as the thrust front propagates into it would approximate pure shear. The normal faults have the

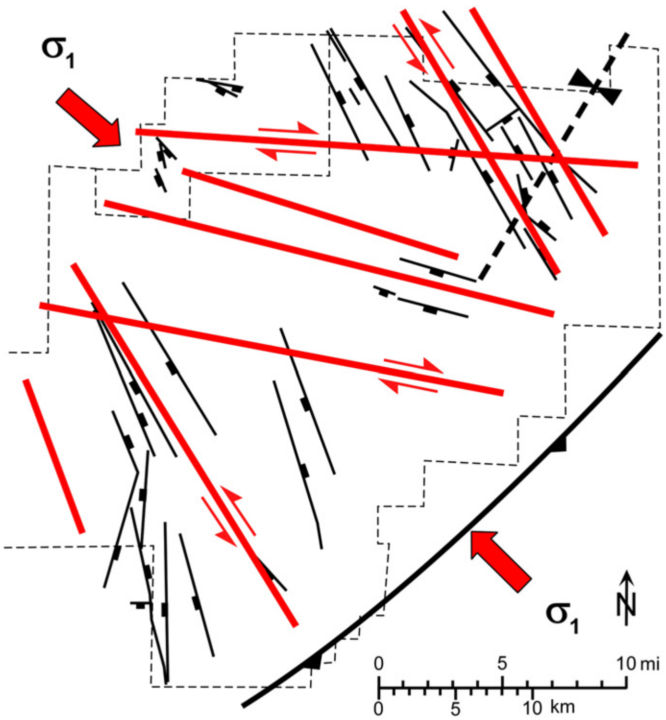

Fig. 10. Interpreted tectonic map of Cedar Cove and Peterson fields (after Cates et al., 2004). Water production-rate trends (red) from Fig. 9b.

correct orientation to be reactivated by the northwest-southeast shortening. In order to maintain the pure shear geometry with this shortening direction, the conjugate trend is required (Ramsay and Huber, 1987). Within Cedar Cove field only select, widely spaced zones show enhanced production rates. This is reminiscent of the fault patterns that develop in analog physical (i.e. clay or sand) models. Even where the stress field is uniform, visible faults form with a characteristic spacing that probably depends on the material properties and the width and thickness of the section involved (e.g., Wolf et al., 2003). While some fraction of the total shortening in the field and in the models may be penetrative or close to it, at the map scale the faults form with a significant distance between members of the same set.

7. Stress regimes

Southeastern Deerlick Creek and Cedar Cove coalbed methane fields show significantly different production-rate patterns, which are attributed here to differences in stress history. Differences are manifested by the presence or absence of fault-related production trends. Southeastern Deerlick Creek is interpreted to represent a reservoir beyond the influence of the Appalachian thrust front. The behavior of this field preserves the original properties of the cleat and faults. Cedar Cove field is interpreted as having been overprinted by the main Appalachian orogenic stress field (Alleghanian). The Alleghanian stress is inferred to have caused minor strike-slip displacements along favorably located normal faults, enhancing the open fracturing, and to have produced a conjugate trend of enhanced fracturing with stratigraphic separations too small to map from well logs. Cedar Cove field is interpreted to lie in the Appalachian stress regime whereas Deerlick Creek field lies in the far-field stress regime where it is unaffected by the Appalachian stresses (Fig. 11).

The boundary between the two stress regimes lies between the southeastern edge of Deerlick Creek and the northwestern edge of Cedar Cove (Fig. 11). Here the boundary coincides with the northwestern edge of the NW-oriented face cleat domain and lies close to the outer margin of the zone of NW jointing in other lithologies, as extrapolated to the southwest. Results from previous studies (Pashin et al., 1991; Pashin and Groshong, 1998; Pashin, 2005) suggest that the Alleghanian stress regime extends to the northeast, at least to Oak Grove field (Fig. 2) where production-rate enhancement is seen along pre-existing structures, for example, in a small syncline on the backlimb of the Sequatchie anticline and along the normal faults that define the southwest end of the anticline. We propose that the stress-regime boundary continues to the northeast. We tentatively place the boundary along the outer edge of the NW joint zone in order to include the entire Sequatchie anticline in the Alleghanian stress zone. Coal is, however, a very weak rock type, and may not be an effective transmitter of horizontal stress. Thus the location of the stress-regime boundary might depend on lithology and extend farther into the basin in sandstone and brittle shale than in coal. It is possible that the stress-regime boundary for production rates more closely follows the outer edge of the NW cleat zone.

8. Stress history

Here we place the structural events of the Black Warrior basin into a time sequence and suggest the stress fields responsible. The basin is defined by the great local thickness of Pottsville Formation coal-bearing sediments of lower Pennsylvanian Morrowan age (Fig. 12), deposited in the foreland of the Appalachian–Ouachita orogen. The depth of the basin is the result of flexural downwarping in front of both the Appalachian and Ouachita fold-thrust belts (e.g., Thomas, 1988). Regional dip is toward the Ouachita front (Fig. 1;

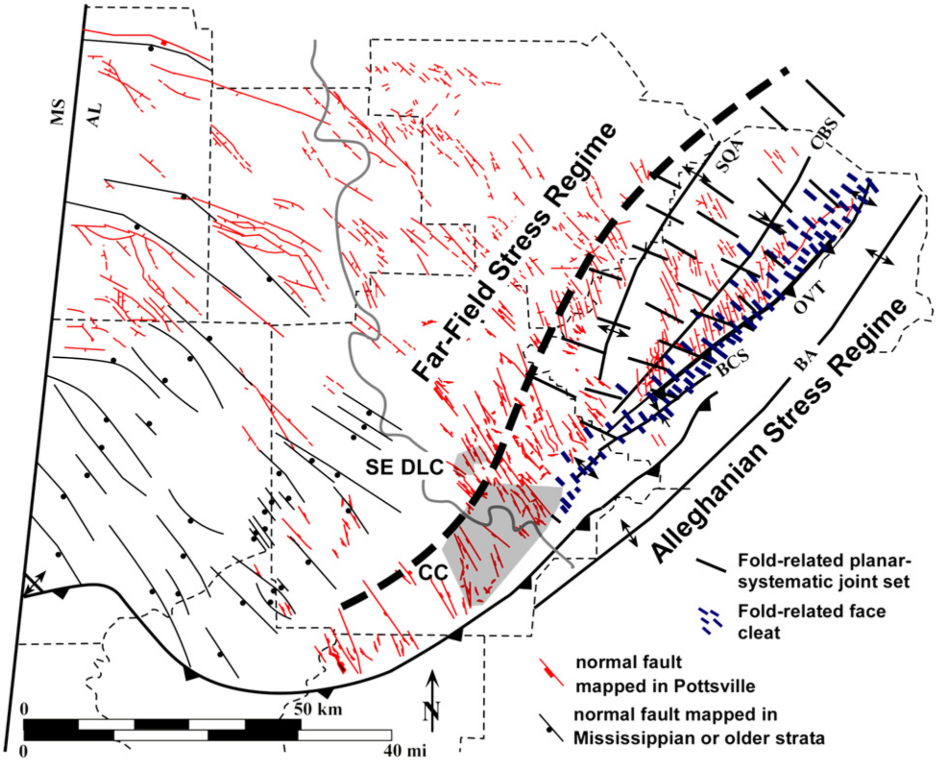

Fig. 11. Regional stress regimes in the coal of the Black Warrior basin. Data compiled from Figs. 2 and 3. Southeastern Deerlick Creek (SE DLC) and Cedar Cove-Peterson (CC) coalbed methane fields are shaded. Wide dashed line is the approximate boundary between the Alleghanian and far-field stress regimes. BA, Birmingham anticlinorium; BCS, Blue Creek syncline; CBS, Coalburg syncline; OVT, Opossum Valley thrust; SQA, Sequatchie anticline.

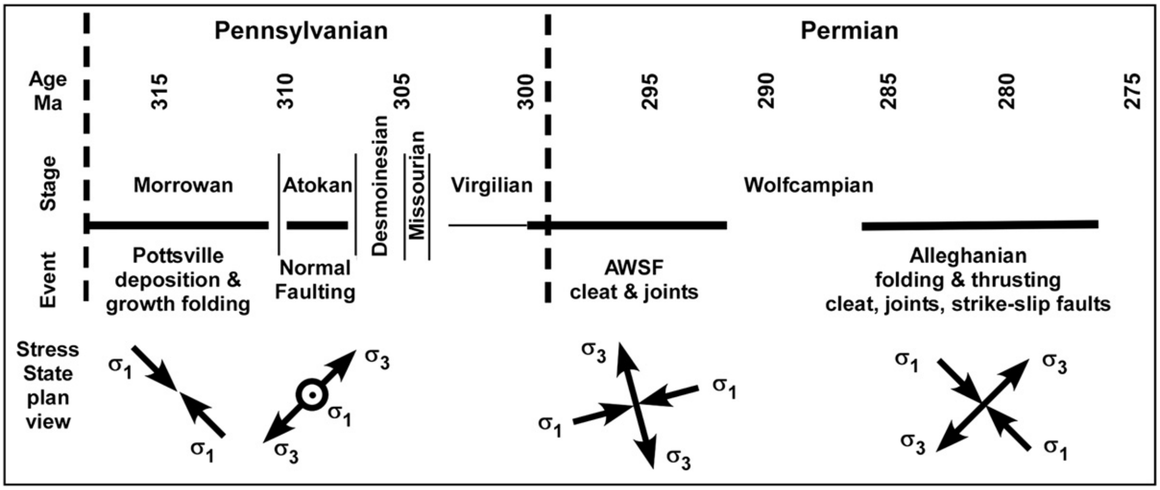

Fig. 12. Structural time line for Black Warrior basin modified from Engelder and Whitaker (2006). AWSF is Appalachian-wide stress field.

Pashin, 1994b). Regional isopachs indicate general thickening toward the Ouachita trend with a thickening toward the Appalachian trend within the coalbed methane fields (Pashin et al., 2004). The oblique collision of Gondwana with the Laurentian margin of North America produced a transpressional uplift that is inferred to have been the source of the Pottsville sediments (e.g., Engelder and Whitaker, 2006).

8.1. Syndepositional deformation

Both normal faults and compressive anticlines began to grow at the basin margins during Pottsville deposition. Soft-sediment normal faulting has been recognized in outcrop in the Brookwood field (Fig. 2) based on the ductile texture of the zone and the absence of grain deformation or breakage in thin section (Ben Ferrill, personal communication, 1984) and in underground coal mines nearby (Gary Owen, personal communication, 2003). In the adjacent thrust belt Thomas (1986) demonstrated outcrop-scale faulting contemporaneous with deposition based on hangingwall growth stratigraphy. We have encountered small normal faults in a few coalbed methane wells which cannot be connected to any map-scale fault and which may therefore be local contemporaneous faults. The soft-sediment normal faults could be tectonic in origin or could be the result of slumping related to local topography.

The Sequatchie anticline is a regional-scale detachment fold at the leading edge of the Appalachian fold-thrust belt and has its southwestern terminus within the map area. Stratigraphic thinning in Oak Grove field (Fig. 2) indicates that the anticline grew slightly during deposition of the Pottsville. Growth within the preserved Black Creek–Pratt interval accounts for about 10% of the total dip (Pashin, 1998). A few northwesterly trending map-scale normal faults near the terminus of the anticline were active during deposition of the Mary Lee–Pratt cycles (Pashin, 1994a) with the total growth also being a small fraction of the total displacement. The faults may have functioned as a transtensional lateral ramp at the termination of the anticline. Near the southwestern boundary of the map (Figs. 2 and 11) a NW-trending detachment fold also shows stratigraphic growth during Pottsville. Because of the paucity of data, the trend of the anticline is only an approximation. As seen on a proprietary seismic line, the Black Creek–Pratt cycles onlap the anticline, indicating growth during this interval (Groshong et al., 2003b). The Cobb maintains a constant thickness and is essentially unfolded, indicating cessation of growth of the anticline. A NW-SE directed σ_1 fits the proto-Sequatchie anticline (Fig. 12) and could fit the southwestern fold if it is related to a lateral ramp. More data are needed before the transport direction of the southwestern fold and its stress state can be determined.

8.2. Map-scale normal faulting

Most of the displacement on the map-scale normal faults (Fig. 11) postdates the youngest Pottsville sediments but predates the main folding and thrusting of the Alleghanian orogeny. The normal faults have their maximum displacements in the youngest preserved units, indicating substantial post-Pottsville slip. In outcrop, the map-scale normal faults have the brittle deformation features characteristic of deformation after lithification (Groshong, 1988; Clayton et al., 1994). Within the coalbed methane fields, virtually all the normal faults are detached in the lower Pottsville. Along the northeastern flank of an anticline just southeast of the Brookwood coalbed methane field (Fig. 2), the detachment is folded and exposed at the surface (Cates and Groshong, 1999; Cates et al., 2004). In the same area, thrust faults cut normal faults in outcrop (Cates et al., 2004).

The normal faulting is inferred to have been caused by a stress field with σ_3 oriented NE-SW (perpendicular to normal-fault strike), σ_1 vertical and σ_2 NW-SE. The extension direction is down the regional dip toward the buried Ouachitas and is in the principal curvature direction for Ouachita-related flexure (Cates et al., 2004). Both downdip gravity glide and flexural extension (Bradley and Kidd, 1991) could have contributed to the stress state. Because the faults appear to be part of a trend that is well documented in the Ouachita orogenic belt, they may have the same age. Dramatic thickening of Atokan sediments occurs across the normal faults in the frontal Ouachita foreland (e.g., Thomas, 1989) which is here inferred to represent the most likely age of the normal faults in the eastern Black Warrior basin (Fig. 12).

8.3. ENE joints and cleat

The regional ENE joint and cleat set (Figs. 3 and 11) has recently been recognized to be part of an Appalachian-wide trend (Engelder and Whitaker, 2006). The Appalachian-wide stress field (AWSF) that caused the fracturing developed in the early stages of convergence between Gondwana and Laurentia (Engelder and Whitaker, 2006) with the shortening direction ENE, parallel to the convergence direction. The ENE joints and cleat are rotated by the Appalachian folds, indicating that they predate the main Alleghanian folding event and the fold-associated NW-oriented joints and cleat. It is inferred that the ENE joint-cleat set formed when cleating first became possible, approximately the time of maximum burial (Late Pennsylvanian to Early Permian: Telle et al., 1987; Carroll et al., 1995; Engelder and Whitaker, 2006). The joints and cleat require σ_3 to be oriented NNW-SSE (Fig. 12).

8.4. Large-amplitude folding and thrusting

Appalachian folds exposed in outcrop both southeast and northeast of the area in Figs. 2 and 11 have forelimbs in which the Pottsville Formation is vertical to overturned. Growth folding during Pottsville deposition accounts for only a few degrees of limb rotation. Thus the main folding event postdates Pottsville deposition. The main fold deformation clearly affected lithified rocks, not soft sediments. Small amounts of crystal-plastic grain deformation, including in the cements, are widespread in the Pottsville (Wu and Groshong, 1991) as expected for the deformation of lithified sedimentary rocks. Twinned calcite in Mississippian limestone from the core of the Sequatchie anticline northeast of the study area indicates low-temperature crystal-plastic (i.e., lithified rock) deformation related to folding. Twin strain measurements indicate that the maximum shortening direction is at a low angle to bedding and perpendicular to the fold axis (Cherry, 1990), indicating that σ_1 was oriented NW-SE.

The NW cleat system (Figs. 3 and 11) is perpendicular to Appalachian fold axes, indicating contemporaneity with large-amplitude folding and thrusting (e.g. Srivastava and Engelder, 1990). This joint trend is found only in the higher-grade coal, close to the Appalachian thrust front and within the fold-thrust belt, implying that it occurred during or after maximum burial (Early Permian: Pitman et al., 2003). The compressional folding and thrusting, together with NW joint and cleat set, are interpreted to have formed in the main Alleghanian orogeny in the Permian (late Wolfcampian; Engelder and Whitaker, 2006). The joint and cleat set requires σ_3 to be oriented NE-SW.

The inferred strike-slip faults share the same σ_1 direction as the folds and the same σ_3 direction as the NW joint and cleat sets (Fig. 10). This is a common pattern in some areas, notably in the Jura fold belt (e.g., Guillaume et al., 1972; Laubscher, 1979) and has been produced in the laboratory (Dubey, 1980). In the Dubey (1980) experiment, and presumably also in the Jura, the strike-slip faults are associated with a significant amount of extension parallel to the fold axis. Axis-parallel extension may be enhanced in the study area relative to the rest of the Appalachians because it is at the southern end of the trend where the fold-thrust belt can stretch into the Ouachita foredeep. The complete fold, fault and joint pattern could have been caused by a triaxial stress field with σ_1 oriented NW-SE-horizontal (perpendicular to fold trend), σ_3 oriented NE-SW-horizontal (parallel to fold trend), and σ_2 vertical (Fig. 12).

9. Conclusions

The coals of the Black Warrior basin represent nearly pure fractured reservoirs because unfractured coal has negligible permeability to water. The peak daily production rate of water produced by coalbed methane wells thus provides a measure of the fracture permeability at the well bore.

Comparison of map-scale structure to production rate indicates that the nature of the relationship depends primarily on the distance from the Appalachian thrust front. In the far-field stress regime (southeastern Deerlick Creek field), fault zones segment the reservoir into blocks with different production characteristics but do not themselves enhance production rates. Tilted fault blocks are the most transmissive. In the Alleghanian stress regime (Cedar Cove field), some faults show enhanced production rates, although most do not. A second, west-northwest trend of enhanced production-rate is developed in the Alleghanian regime and is mainly independent of mappable faults. The two productive trends are interpreted as being conjugate shears produced by the Alleghanian σ_1 direction. The left-lateral trend consists mainly of reactivated normal faults and the right-lateral trend is probably zones of enhanced tension fracturing or cleat-block rotation. Where it is best documented, the Alleghanian stress zone extends about 20 km into the foreland basin from the outcrop of the first large Appalachian thrust fault.

Even though nearly all the permeability to water in the coal is due to the cleat, the cleat orientation does not form production-rate trends at the scale of the field. Joint and cleat orientations are not dominant controls on production – it is the map-scale structures that influence the abundance and openness of fractures.

The Black Warrior basin records evidence of orogen-scale strain partitioning. In agreement with the results of Engelder and Whitaker (2006), we find an AWSF with an ENE σ_1, followed by a NW, fold-normal σ_1. We also have evidence of an early fold-normal σ_1, producing growth folds, and a subsequent extensional bending stress, producing normal faults. The occurrence of a fold-normal σ_1 in Early Pennsylvanian and again in Early Permian may indicate a ca. 40 my long transpressional collision with strain-partitioned events. Complete partitioning between strike-slip and convergence may have been the general rule with an interruption for the AWSF in which the orogen-oblique σ_1 was transmitted to the whole Appalachian region. The normal faults, which are so important to the fluid production from the basin, appear to represent crustal bending of the Ouachita foreland, not an Appalachian feature.

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