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

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A B S T R A C T

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.

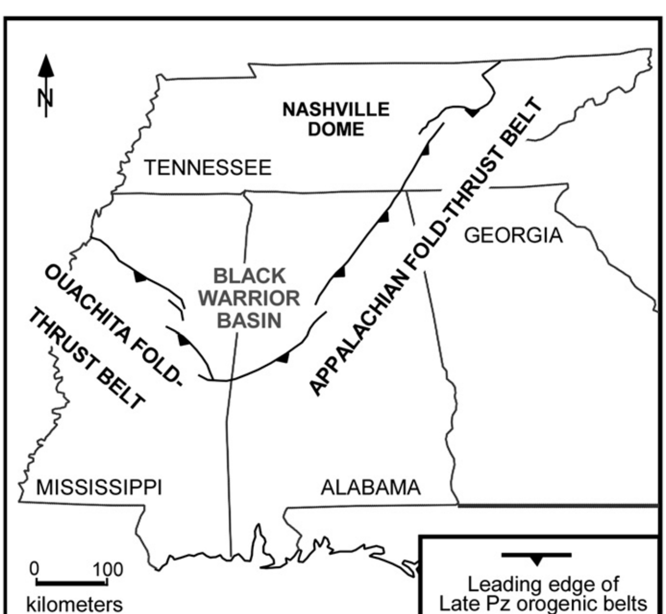

Fig. 1. Regional index map showing location of Black Warrior Basin (modified from Thomas, 1988).

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.

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