COALBED METHANE EXPLORATION IN THRUST BELTS: EXPERIENCE FROM THE SOUTHERN APPALACHIANS, USA

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ABSTRACT

Reservoir performance in the southern Appalachian thrust belt reflects a complex interplay among stratigraphic, structural, and hydrologic variables. Productive coal beds are distributed through more than 1,000 m of section, and in each well, between 5 and 20 coal beds ranging in thickness from 0.3 to 4 m are completed. Thrust-related folds in the southern Appalachian coalbed methane fields have steep forelimbs, gently dipping backlimbs, and contain multiple hinge zones. Fresh-water recharge is most effective in steep fold limbs, and fresh-water plumes extend from the outcrop to reservoir depth in thick, continuous coal beds. Late-stage bacterial methanogenesis within the fresh-water plumes facilitates high gas saturation in coal. Linear productivity sweet spots occur along fold hinges. Hinges in proximity to fresh-water recharge areas tend to be water-productive, whereas those that are distal to recharge contain sweet spots with exceptional gas production. Within broad, gently dipping fold limbs, linear gas- and water-production sweet spots appear to mark the positions of conjugate shear zones.

INTRODUCTION

Geologic structure is an important control on the performance of coalbed methane reservoirs because it is a major determinant of the distribution of permeability and basin hydrodynamics [e.g., 1-3]. To date, most coalbed methane development has been in large coal basins with gently deformed strata, such as the San Juan, Powder River, and Black Warrior basins [e.g., 4-6], but as these basins approach maturity and natural gas prices remain high, small basins with diverse structural styles are becoming increasingly attractive exploration targets. As exploration moves into regions with significant tectonic deformation, such as orogenic thrust belts, it is important to understand how geologic structures influence reservoir performance.

The southern Appalachian thrust belt of Alabama (fig. 1) has been the site of coalbed methane production since the infancy of the modern coalbed methane industry [7, 8], and the coal basins of the Alabama thrust belt remain the focus of intensive exploration and development [e.g., 3, 9-11]. Accordingly, experience with coalbed methane development in the southern Appalachians provides insight that facilitates the formulation of exploration and production strategies for deformed regions, and this paper summarizes the major stratigraphic, structural, and hydrogeologic information that are important to consider as exploration moves toward small, structurally diverse basins.

Economic coal-bearing strata in the southern Appalachian thrust belt are concentrated in the Lower Pennsylvanian Pottsville Formation of the eastern Black Warrior basin, the Cahaba synclinorium, and the Coosa synclinorium (figs. 1, 2). Coalbed methane is generally produced from the upper part of the Pottsville Formation in strata shallower than 1 km. The Black Warrior basin and Cahaba synclinorium have been the sites of intensive exploration and production activity [3, 9, 10], and coalbed methane reserves in these areas are thought to exceed 115 billion standard cubic meters [12]. Production has yet to be established in the Coosa synclinorium, and exploration efforts have focused on the northeastern part of the synclinorium [11, 13].

STRATIGRAPHY

The Pottsville Formation of the southern Appalachian thrust belt is of Lower Pennsylvanian (Westphalian A; Langsettian) age and is dominated by interbedded shale, sandstone, and coal. Coal

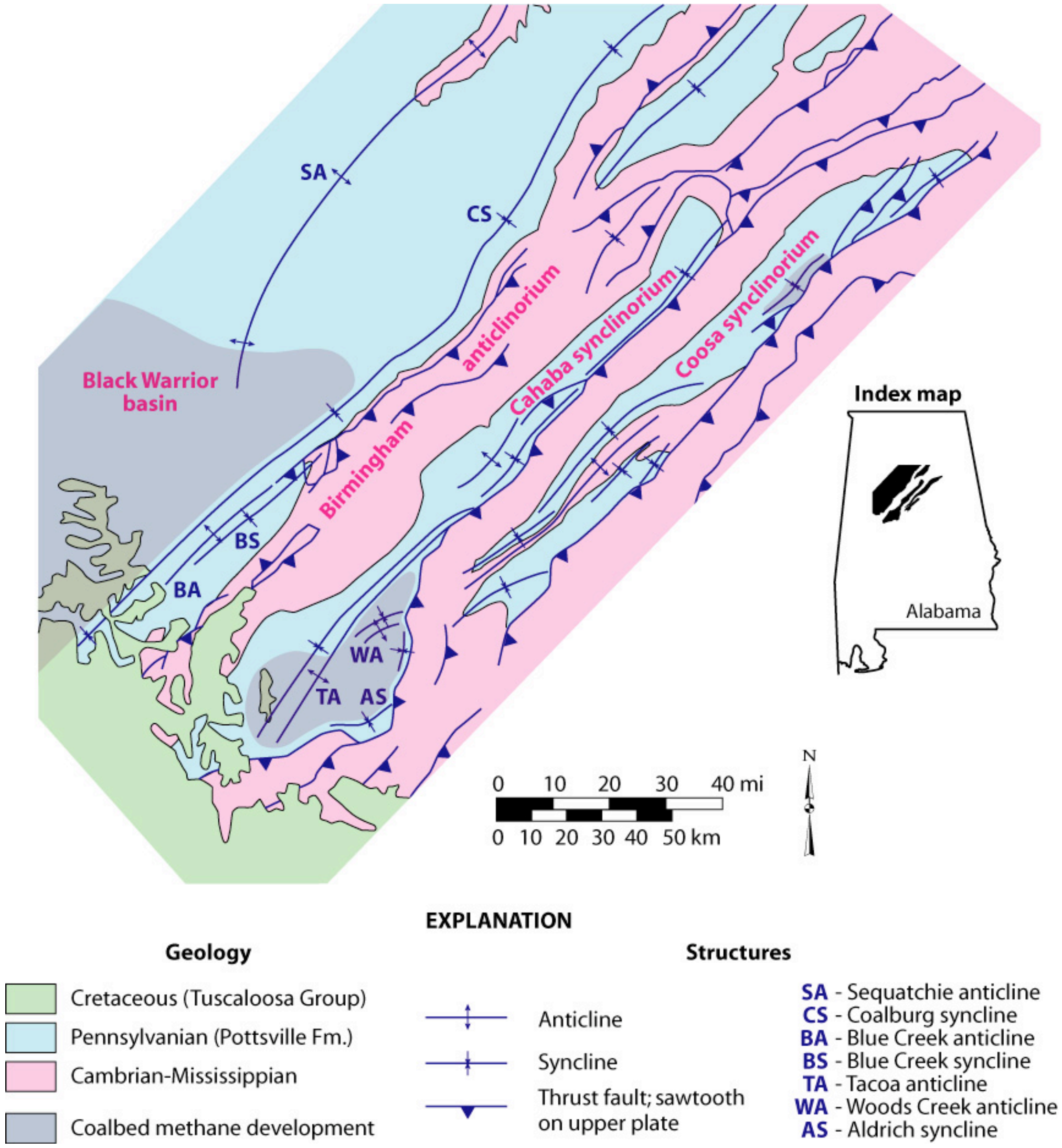

Figure 1.—Geologic map of the southern Appalachian thrust belt in Alabama showing major structures and areas of coalbed methane development. Geologic map modified from [37].

beds are distributed through up to 2.5 km of section (fig. 2), and individual coal beds are typically thinner than 3 m. Coalbed methane is produced from beds as thin as 0.3 m. In general, 5 to 20 coal beds are completed in Alabama coalbed methane wells, and most production is from the upper part of the Pottsville Formation in strata shallower than 1 km.

Numerous coal beds distributed through a thick stratigraphic section is a common characteristic of the Pottsville Formation throughout the study area, but the stratigraphic and depositional style of the Pottsville Formation in each area is different. The Black Warrior section (fig. 2) contains numerous stacked fluvial-deltaic depositional cycles that constitute 3rd- through 5th-order parasequences [14, 15], and coalbed methane is produced from multiple seams mainly in the Black Creek through Utley coal zones [16]. Accumulation of the thickest, most widespread coal beds that form the backbone of the Alabama coalbed methane and mining industries is thought to be associated with 5th-order base-level rises driven by glacial eustasy [14, 15].

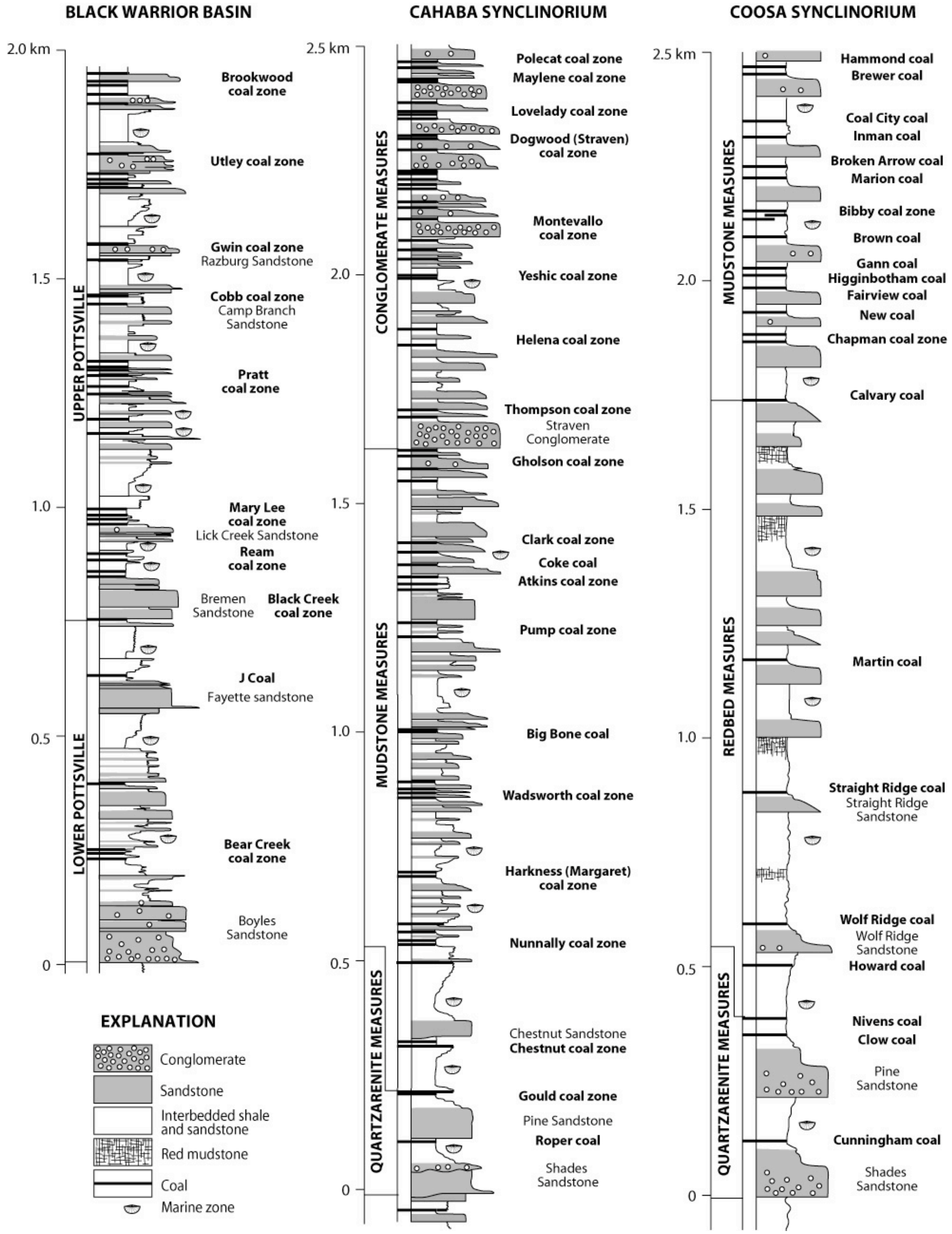

Figure 2.—Stratigraphic sections of the Pottsville Formation in the Black Warrior basin, Cahaba synclinorium, and Coosa synclinorium.

The Pottsville section in the Cahaba synclinorium is subdivided into the quartzarenite measures, mudstone measures, and conglomerate measures (fig. 2), and coalbed methane is produced mainly from the mudstone and conglomerate measures [16]. The mudstone measures resemble the fluvial-deltaic parasequences in the Black Warrior basin, but the frequency of marine strata decreases upward in section. The conglomerate measures contain only one significant marine zone and are interpreted to contain mainly bedload-dominated and anastomosing fluvial deposits. Although changing base level in response to glacial eustasy may have affected deposition of the mudstone measures, it is unclear whether facies patterns in the conglomerate measures were sensitive primarily to eustatic events, tectonic events, or a combination thereof.

In the Coosa synclinorium, Pottsville strata are subdivided into the quartzarenite measures, the redbed measures, and the mudstone measures [17] (fig. 2). Few coal beds have been identified in the quartzarenite and redbed measures, so the coalbed methane potential of this part of the section may be limited. Strata in the quartzarenite and redbed measures of the Coosa synclinorium resemble strata in the Black Warrior basin and the lower part of the Cahaba section, although the redbed measures contains a red mudstone facies that is unique in the Lower Pennsylvanian of the eastern U.S. and has been interpreted as lateritic paleosols [17]. The mudstone measures in the Coosa synclinorium contain marine through terrestrial facies similar to those in the mudstone measures of the Cahaba synclinorium, and the abundant, closely spaced coal beds in this part of the section constitute the most attractive coalbed methane prospects in the Coosa synclinorium [11, 13].

STRUCTURAL GEOLOGY

The southern Appalachian thrust belt (fig. 1) comprises thin-skinned compressional structures that formed during the Carboniferous-Permian Alleghanian orogeny and were transported northwestward above a master detachment in Cambrian shale [e.g., 18, 19]. The Cambrian shale is a ductile layer that in places is deformed into thick, blind duplexes that form the cores of large anticlines, such as the Birmingham anticlinorium [20]. Above the ductile shale, a thick Cambrian-Devonian carbonate section forms a stiff layer that is deformed into a series of broad anticlines and synclines. The Carboniferous section, which includes the Pottsville Formation, contains a thick succession of synorogenic siliciclastic rocks that forms an upper weak layer. Consequently, multiple upper-level or secondary detachments are developed in the synorogenic stratigraphy [3, 19].

The Pottsville Formation is exposed at the surface throughout the eastern Black Warrior basin and is exposed in broad, northeast-elongate synclines in the Cahaba and Coosa synclinoria (fig. 1). The Pottsville Formation contains numerous folds and thrust faults throughout the study area, and the folds tend to be broad, open structures that verge northwest and southeast and have forelimbs that dip more steeply than the backlimbs. Within this general framework, the geometry of the folds is highly variable.

In the Black Warrior basin, the Sequatchie anticline forms the frontal structure of the Appalachian thrust belt (figs. 1, 3). The anticline in this area is an extremely subtle, open structure with about 120 m (400 ft) of structural relief and an interlimb angle of 178° [3, 21]. The anticline plunges southwest and terminates at a swarm of normal faults that forms a transtensional tear fault system. The anticline shares a common limb with the Coalburg syncline, which closely follows the southeastern margin of the Black Warrior basin. Strata dip most steeply in a crestal uplift near the axial trace of the Sequatchie anticline, and dip decreases noticeably along a hinge zone northwest of the Oak Grove Mine. Interestingly, a northeast-striking synclinal flexure is developed immediately northwest of the Oak Grove Mine at the southwestern end of the hinge zone.

Strata along the southeastern edge of the Black Warrior basin have been folded to form a steeply dipping basin margin in the forelimb of the Birmingham anticlinorium (figs. 1, 4). Thus, the Coalburg syncline is a footwall syncline that defines the southeastern margin of the Black Warrior basin. Structural style along strike of the Birmingham anticlinorium varies considerably [19, 20] (fig. 1). Pre-Pottsville strata contain an array of forward thrusts and backthrusts, and Pottsville strata exhibit a series of corresponding changes in structural geometry. For example, steeply dipping Pottsville strata in the southeast limb of the Coalburg syncline typically form the edge of the Black Warrior basin, but locally these strata have been folded into an anticline-syncline pair (Blue Creek anticline and syncline) (figs. 1, 4). Strata within the Black Warrior basin tend to be nearly flat lying, whereas the steep dip in the southeast limb of the Coalburg syncline brings reservoir coal beds to the surface (fig. 4), which has a significant impact on the hydrogeology and production characteristics of the coalbed methane reservoirs [4, 22, 23].

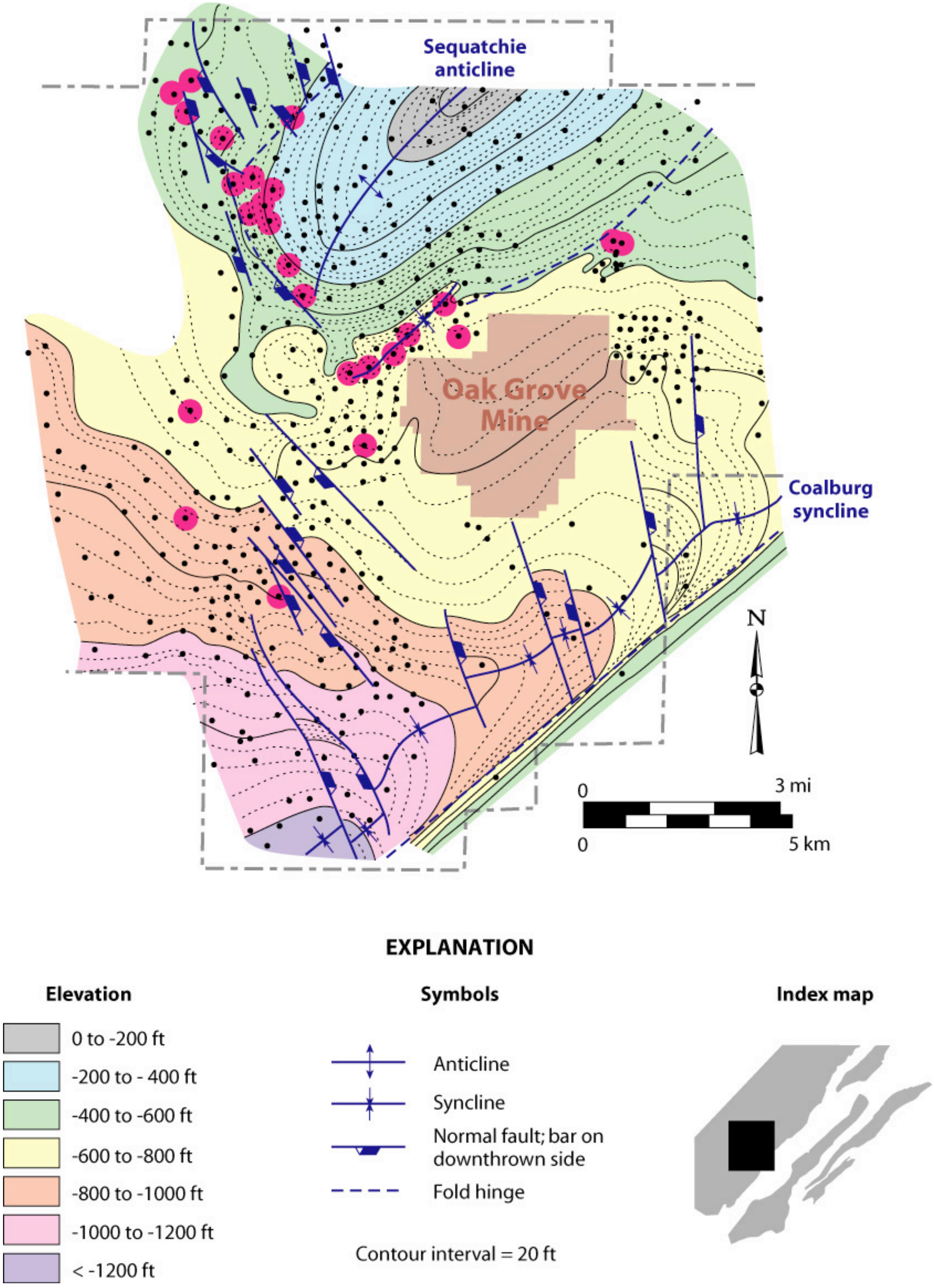

Figure 3.—Structural contour map of the top of the Mary Lee coal bed in the eastern Black Warrior basin showing the locations of exceptionally productive coalbed methane wells near the southwest terminus of the Sequatchie anticline (modified from [4]).

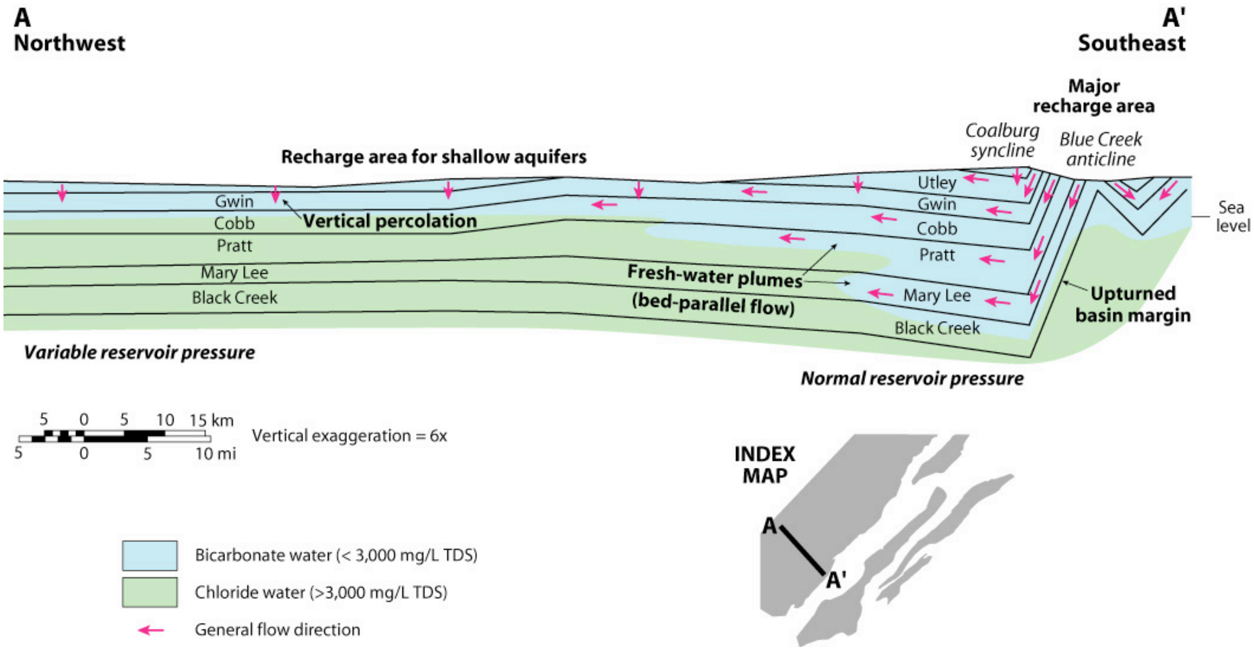

Figure 4.—Generalized structural cross section showing relationship of formation-water chemistry to the frontal structures of the Appalachian thrust belt (modified from [22]).

The Cahaba synclinorium is a northeast-elongate structure that is bounded on the northwest by the Birmingham anticlinorium and on the southeast by the Helena thrust fault (figs. 1, 5). Pottsville strata generally dip southeast at less than 20°and contain a series of open folds, including the Tacoa and Woods Creek anticlines (fig. 5). Folds and thrust faults in the Pottsville section are generally developed above upper-level or secondary detachments within the synorogenic stratigraphy [16]. In the area of coalbed methane development, the Tacoa anticline has a broad forelimb and backlimb, as well as a crestal uplift that verges southeast opposite the regional structural trend (fig. 5, cross-section B-B'). The overall structure appears to be detached below the Pottsville Formation, and the crestal uplift appears to be detached within the Pottsville. The Woods Creek anticline, by contrast, contains a thrust fault that is exposed in the crestal region and is developed above a detachment within the Pottsville Formation that may be a splay of the Helena thrust fault (fig. 5; cross-section C-C').

As in the Black Warrior basin, steeply dipping strata are commonly developed in the southeast limb of a footwall syncline that is associated with the Helena thrust fault (figs. 1, 5). However, footwall synclines in the Cahaba synclinorium tend to be discontinuous, and some wells have penetrated a thick Pottsville section below the Helena fault [24]. In general, the thickest steeply dipping sections are adjacent to embayments of the Helena thrust, and a prominent example is in the southwestern part of the synclinorium where a nearly complete Pottsville section has been overturned in the southeast limb of the Aldrich syncline.

Overall, the structural style of the Coosa synclinorium resembles that of the Cahaba synclinorium, although the Coosa section tends to dip more steeply and be more intensely folded and faulted [25, 26]. A series of structural cross sections have recently been published by Bearce [26] and Osborne [13]. Coalbed methane development in the northeastern part of the synclinorium is in a footwall syncline that has been overridden by the Eden fault, which juxtaposes intensely deformed Mississippian shale on top of the Pottsville Formation. Pottsville strata dip gently adjacent to the Eden fault [25], although steeply dipping strata have been preserved adjacent to other thrust faults in synclines that have yet to be explored.

Much of the literature on coalbed methane reservoirs focuses on orthogonal cleat system, but coal is a weak rock type that is sensitive to shear stress associated with flexural slip during folding and can thus contain a diverse array of shear fractures in addition to cleats [27, 28]. In strata that are nearly horizontal, such as in the backlimb of the Sequatchie anticline, a northeast-trending face-cleat orientation is

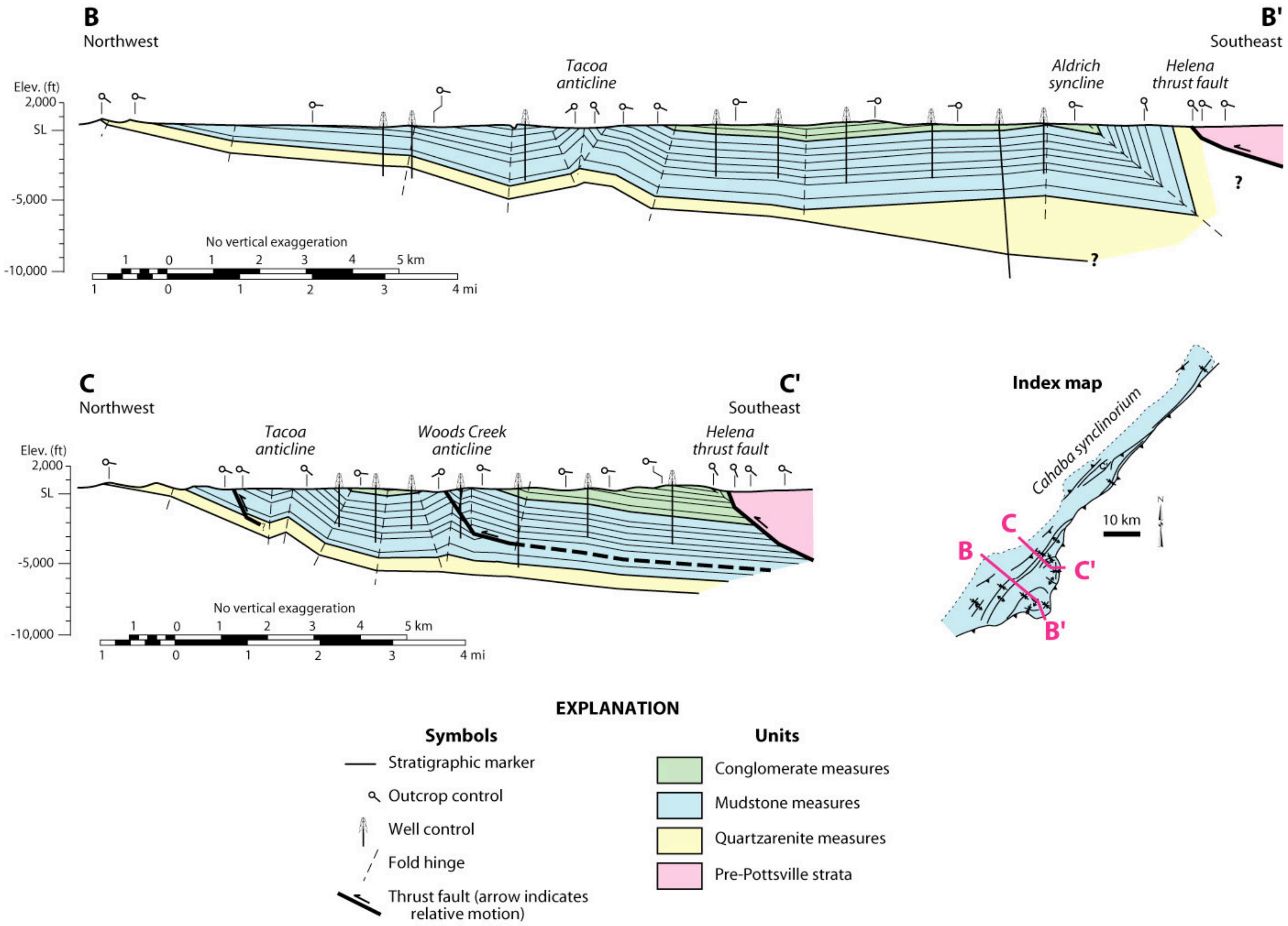

Figure 5.—Structural cross sections of the Pottsville Formation in the Coosa synclinorium (modified from [16]).

consistent with regional cleat patterns that extend far beyond the thrust belt (fig. 6). In fold limbs dipping steeper than 10°, such as in the northwest flank of the Cahaba synclinorium, face cleats tend to strike northwest, or perpendicular to fold axes, indicating that stresses associated with folding determined cleat orientation. Shear fractures are curvilinear and tend to be oriented along the strike of bedding. The shear fractures can be extensional or compressional structures, and geometries range from small-displacement normal faults, thrust faults, and conjugate fractures to mélange-like shear zones. Interestingly, one outcrop of a coal bed can contain mainly compressional fractures, whereas a nearby outcrop of the same coal can contain mainly extensional fractures. This suggests significant strain partitioning within fold limbs during deformation, and Pashin and others [28] suggested that irregularities in the contacts between coal and more competent beds can function as restraining and releasing fault bends during flexural slip (fig. 7).

HYDROGEOLOGY

Strata associated with coalbed methane production in the Alabama Pottsville have effectively no matrix permeability to water, so closely spaced cleats and shear fractures make coal the most permeable rock type, and hence, the best aquifer and reservoir rock in the coalbed methane fields [16, 28]. Well testing in the backlimb of the Sequatchie anticline indicates that permeability in coal can have a varied expression in thrust belts [29, 30]. The permeability of coal in this area is highly stress-sensitive and decreases exponentially from as much as 1 darcy at the surface to about 1 millidarcy at depths exceeding 700 m [29]. In shallow, well-cleated coal beds, pressure-buildup testing indicates that permeability is strongly anisotropic and that flow is favored in the face-cleat direction [30]. In deep, low-permeability coal beds, however, permeability is weakly anisotropic, and flow is favored in the systematic joint direction, indicating that flow is difficult to isolate in tight coal deeper than 700 m. The Blue Creek coal of the Mary Lee coal zone (fig. 1) is sheared within the backlimb of the anticline, and well test results indicate that permeability is anisotropic in this bed.

These results indicate that significant permeability exists in sheared coal in thrust belts. The maximum horizontal compressive stress in the Black Warrior basin is directed east-northeast [31], which favors flow in the northeast-striking cleats and shear fractures in the southern Appalachian thrust belt. Importantly, cleats and extensional shear fractures were probably conductive of fluids during deformation, but compressional fractures may have been closed and functioned mainly as slip planes during folding. Thus, compressional shear fractures may not be sources of permeability in thrust belts where the stress field has not been reoriented following orogenic deformation.

At a larger scale, fold limbs can play an important role in fluid flow, the development of the pressure regime, and late-stage gas generation [2, 23, 32]. In the Black Warrior basin, reservoir coal beds are exposed at the surface in the southeast limb of the Coalburg syncline where they can accept meteoric recharge (figs. 4, 8). Sodium bicarbonate formation waters with total dissolved solids (TDS) content less than 3,000 mg/L occur at reservoir depth adjacent to the southeast basin margin, whereas sodium chloride waters with higher TDS content occur at reservoir depth in the interior of the basin, indicating that recharge is dominated by the southeast limb of the Coalburg syncline. Mapping TDS content of the Mary Lee coal zone defines a series of fresh-water plumes that extend northwestward from the basin margin (fig. 8). Importantly, normal faults strike at a high angle to the southeast basin margin and thus do not block recharge. Recharge supports a normal hydrostatic pressure regime as far as 20 km northwest of the basin margin, whereas reservoirs tend to be underpressured farther northwest [23]. Fresh to weakly saline water at reservoir depth is thought to host bacterial consortia that facilitate late-stage bacterial methanogenesis, and a combination of thermogenic and late-stage biogenic gases helps explain the geochemistry and high gas content of the Pottsville Formation in the eastern Black Warrior basin [32].

Whereas the hydrologic system in the Black Warrior basin is dominated by steeply dipping strata at the southeast basin margin, the structure of the Cahaba synclinorium indicates that the hydrologic system in the interior parts of thrust belts can be more complex and include multiple recharge areas (fig. 5). For example, steeply dipping strata in footwall synclines, such as the southeast limb of the Aldrich syncline, may facilitate recharge similar to that observed in the Black Warrior basin (fig. 5; cross-section B-B’). But in other areas, footwall synclines are not present or are sheltered by the Helena thrust fault (fig. 5; cross-section C-C’), indicating that meteoric recharge along the southeast margin of the Cahaba synclinorium is discontinuous. In addition, dipping strata on the northwest margin of the Cahaba synclinorium may also facilitate meteoric recharge, and additional sources of recharge probably exist on fold limbs within the synclinorium. Although reservoir pressure and water chemistry data are few in the Cahaba synclinorium,

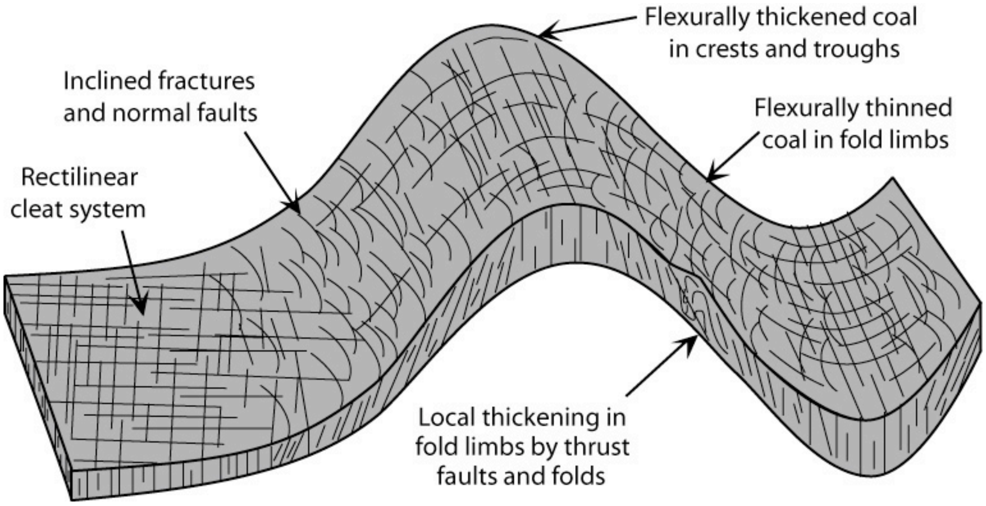

Figure 6.—Generalized model of fracturing in folded coal beds (modified from [16]).

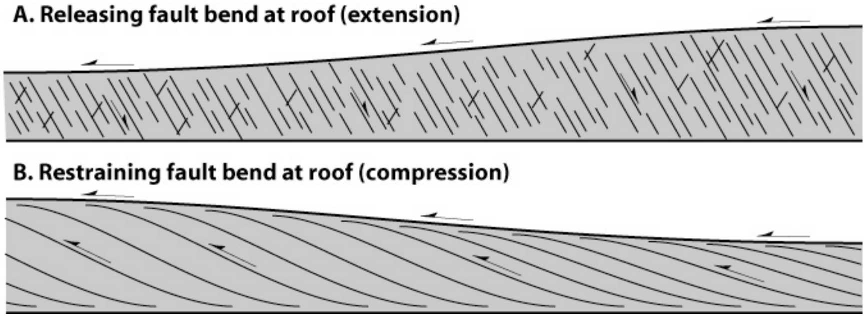

Figure 7.—Relationship of extensional and compressional shear structures in coal to irregularities of roof geometry (modified from [28]).

multiple sources of recharge may introduce fresh water into deep coalbed methane reservoirs, and considering the small size of the synclinorium relative to the Black Warrior basin, recharge can be predicted to support a normal hydrostatic pressure regime over large areas.

PRODUCTION TRENDS

A series of distinctive production trends can be related to structure in the southern Appalachian thrust belt. Exceptionally productive wells with peak production exceeding 300 Mcfd form linear trends associated with the Sequatchie anticline (fig. 3). Five exceptionally productive wells are distributed along the small syncline immediately northwest of the Oak Grove Mine, and this trend was originally identified by Pashin and others [4]. Another linear trend of exceptionally productive wells extends northwest from the southern terminus of the Sequatchie anticline into the en echelon tear fault system. Most of the wells in these two trends are aligned along fold hinges. Increased well productivity in fold hinges suggests that flexure has enhanced fracturing, thus increasing permeability and making the reservoir easier to depressurize. Increased water production has been identified locally along the axis of the Coalburg syncline [3, 33]. Importantly, the Coalburg syncline is proximal to the main area of meteoric recharge, whereas the Sequatchie anticline is distal to the main recharge area. One possibility is that fracturing in

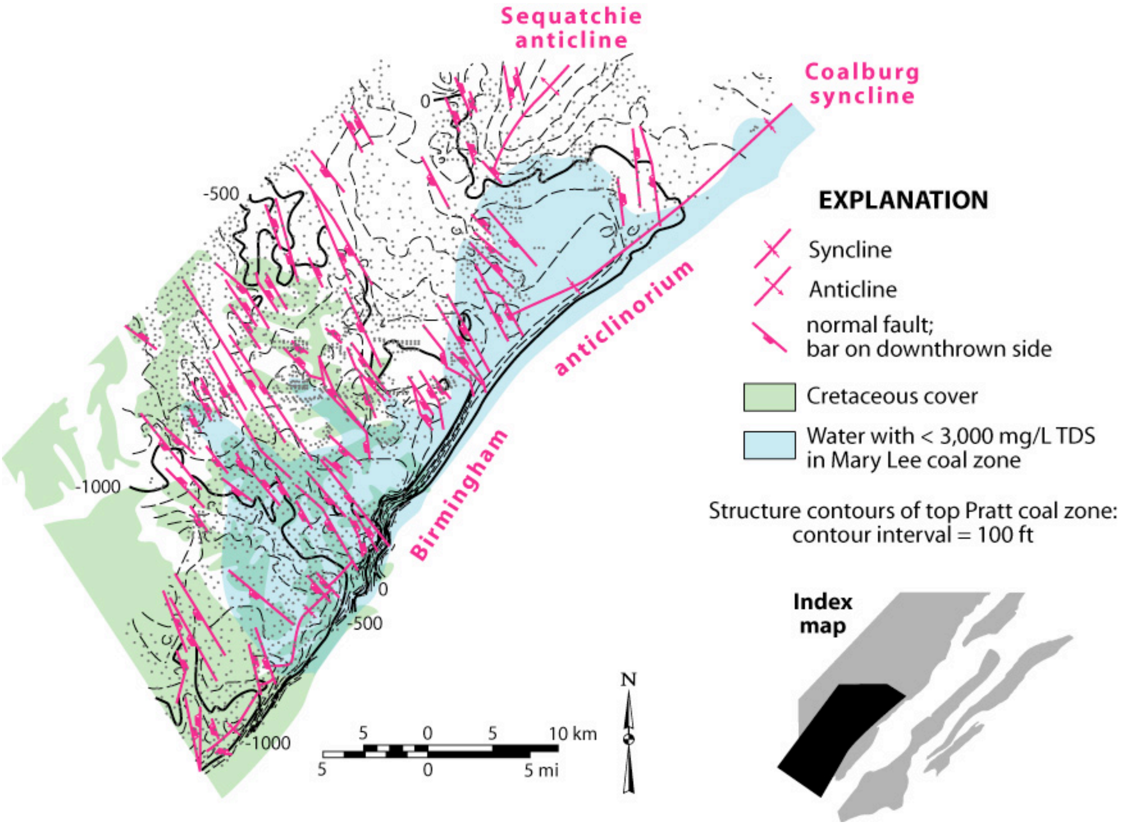

Figure 8.—Map showing position of fresh-water plumes relative to the Appalachian frontal structures in Alabama (modified from [23]).

fold hinges near recharge areas result in increased water production, whereas hinges that are removed from active recharge areas show better promise for the development of gas-productive sweet spots.

In the Cahaba synclinorium, Pashin and Groshong [3] observed that production rates were locally higher on folds like the Woods Creek anticline, suggesting locally increased permeability in folds. However, wells with the highest production rates are located in the gently dipping strata between the Tacoa anticline and the Helena thrust. Productivity appears to be influenced by tectonic stress [34], and an explanation for increased productivity in weakly deformed strata is that residual stresses are reduced in weakly deformed strata between the major folds.

In the Cedar Cove area of the Black Warrior basin, strong linear production anomalies are developed adjacent to the Appalachian frontal structures [35, 36] (fig. 9). A structural contour map of the top of the Gwin coal zone shows a strong fold hinge that trends northeast along the basin margin and is broken by a series of north- to northwest-striking normal faults (fig. 9A). Mapping peak gas and water production reveals a series of linear production trends that are oblique to some normal faults and are parallel to others (figs. 9B-9E). Cates et al. [36] interpreted the linear trends as the products of conjugate shear zones that developed in response to compressional stresses associated with Appalachian folding (fig. 9F). Parallelism of some of the linear trends to normal faults may also indicate that the orientation of the normal faults was also influenced by conjugate shear stress in the Cedar Cove area. However, the precise structural expression of the conjugate shear zones remains unclear.

Ten coalbed methane wells were drilled in the Coosa synclinorium, but to date, no commercial production has been established. Gas content estimates based on desorption of well cuttings indicate that the coal contains between 6.7 and 20.9 cc/g (214-670 scf/t) of gas [11, 13]. Although core analysis is more reliable than cuttings analysis, these numbers indicate that commercial production potential exists.

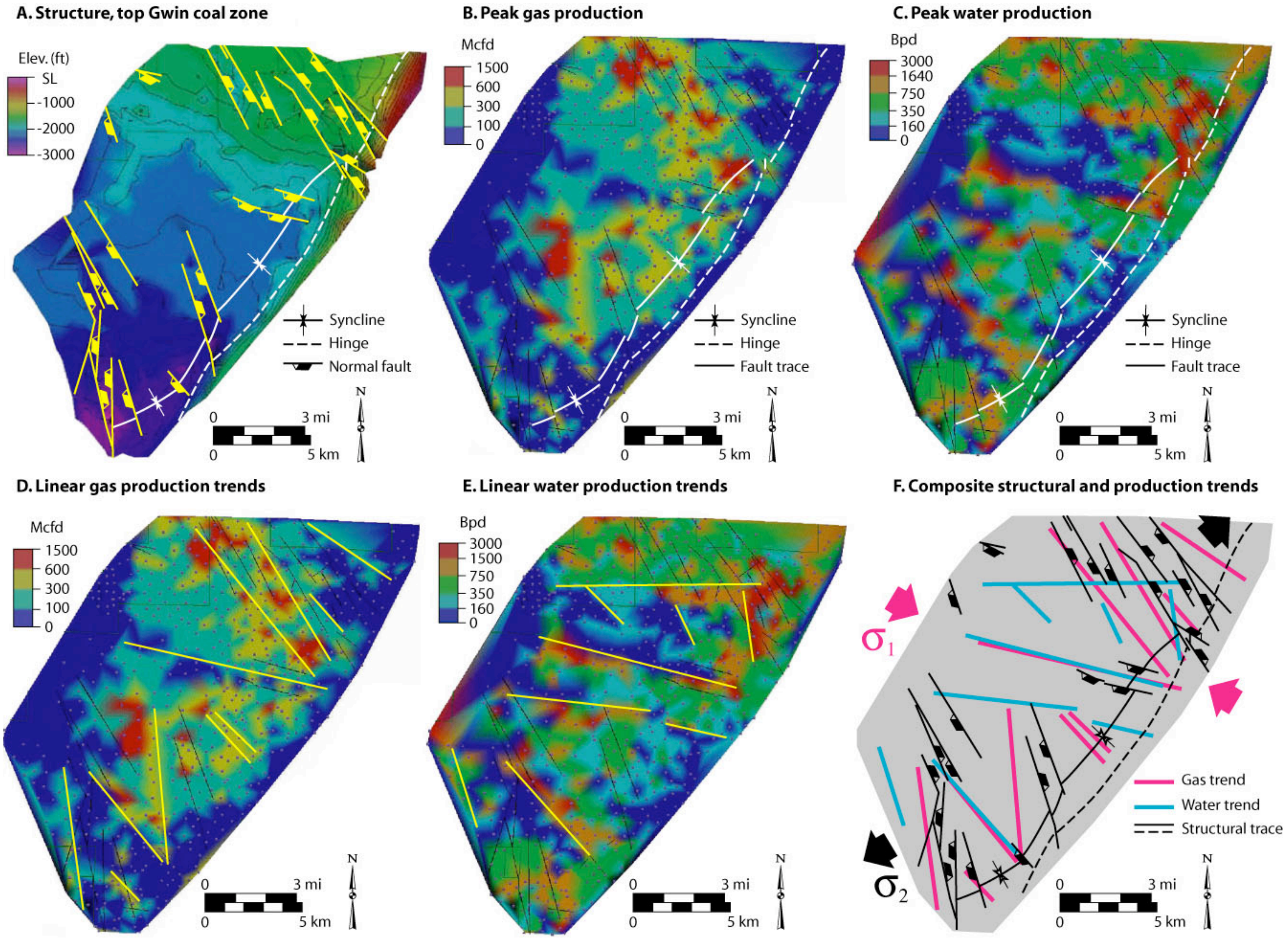

Figure 9.—Maps showing structure and linear gas and water production trends in the Cedar Cove area of the Black Warrior basin (modified from [36]). Linear trends of gas and water production are interpreted to mark the positions of conjugate shear zones adjacent to the southern Appalachian thrust belt.

With the sustained high price of natural gas, reevaluation of the coalbed methane potential of the Coosa synclinorium would be timely.

SUMMARY AND CONCLUSIONS

Numerous coalbed methane wells have been drilled in the southern Appalachian thrust belt of Alabama, and geologic and fluid production data from this area provides important insight into coalbed methane exploration strategies for thrust belts. In the southern Appalachian coalbed methane fields, reservoir performance reflects a complex interplay among stratigraphic, structural, and hydrologic variables. Productive coal beds are of Lower Pennsylvanian age, are distributed through more than 1,000 m of section, and are of high volatile A bituminous to low volatile bituminous rank. Completed coal beds range in thickness from 0.3 to 4 m.

Thrust-related folds in the southern Appalachian coalbed methane fields typically have steep forelimbs, gently dipping backlimbs, and contain multiple hinge zones. Meteoric recharge is most effective in steep fold limbs, and fresh-water plumes extend from the outcrop to reservoir depth in thick, continuous coal beds. Late-stage bacterial methanogenesis within the fresh-water plumes facilitates high gas saturation in coal, and the fresh-water plumes help maintain a normal hydrostatic pressure regime in parts of basins proximal to recharge areas.

Economic coalbed methane production is proven in the Black Warrior basin and the Cahaba synclinorium. Production has yet to be established in the Coosa synclinorium, but limited gas content data indicate that the economic potential of coal in the Coosa synclinorium should be reevaluated. Linear productivity sweet spots for gas and water are associated with geologic structures in the southern Appalachian thrust belt. Fold hinges that are proximal to fresh-water recharge areas tend to be zones of exceptional water production, whereas those that are distal to recharge areas host sweet spots with exceptional gas production. In weakly deformed strata between major fold hinges, linear gas- and water-production sweet spots appear to mark the positions of vertical conjugate shear zones. However, the precise geologic expression of the shear zones remains unclear.

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