GLACIAL-EUSTATIC CONTROL OF COALBED METHANE RESERVOIR DISTRIBUTION (POTTSVILLE FORMATION; LOWER PENNSYLVANIAN) IN THE BLACK WARRIOR BASIN OF ALABAMA

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ABSTRACT

Subsurface maps and stratigraphic cross sections of Pennsylvanian-age strata in the Black Warrior basin provide new evidence for the origin of late Paleozoic depositional cycles and the stratigraphic controls on the distribution of coalbed methane reservoirs. Coal beds are concentrated in a series of 4th-order parasequences, or cyclothems, which are bounded by regionally extensive marine flooding surfaces. Each cyclothem represents about 0.4 my, which is equivalent to the long orbital eccentricity period. The cyclothems studied each contain three subordinate marine flooding surfaces defining 5th-order parasequences, which apparently are products of relative sea-level changes associated with the short eccentricity period (0.1 my). The first 5th-order parasequence in each cyclothem tends to be dominated by progradational deltaic deposits. The second and third 5th-order parasequences contain a higher proportion of aggradational deposits and include incised valley fills as deep as 100 ft overlain by widespread reservoir coal beds as thick as 10 ft. The fourth parasequence commonly contains transgressive tidal deposits. Although cyclothems provide an obvious basis for stratigraphic subdivision of Pennsylvanian strata in the Black Warrior basin, internal facies relationships suggest that major sea-level change was most effective in the short eccentricity band, as was the case during Pleistocene glaciation. Accordingly, rising base level in the second and third 5th-order parasequences of most cyclothems set the stage for widespread peat accumulation and preservation of the thickest and most widespread coalbed methane reservoirs in the Black Warrior basin.

INTRODUCTION

The geometry and distribution of coalbed methane reservoirs varies significantly among sedimentary basins. In Cretaceous and Tertiary strata of the western USA, for example, coalbed methane is produced from a single, thick (~10-100 ft) coal bed or from multiple thick seams within a single coal zone [e.g., 1, 2]. In Pennsylvanian strata of the eastern USA, by comparison, reservoir coal beds are relatively thin (~1-12 ft) and are in multiple zones distributed through a thick stratigraphic section [3-6]. In the upper Pottsville Formation of the Black Warrior basin, coal beds are in places dispersed through more than 4,000 ft of section, and gas has been produced from more than 20 coal beds in some wells (figs. 1, 2).

Distribution of Pennsylvanian coal beds through a thick stratigraphic section is largely the product of repetitive marine-terrestrial depositional cyclicity, and the origin of this cyclicity has been debated since the historic publications on cyclothems by Weller [7] and Wanless and Shepard [8]. Recent debate has focused on the tectonic and paleoclimatic implications of this cyclicity [e.g., 9-11], which is thought to be a product of basin subsidence associated with assembly of the Pangaean supercontinent, as well as eustasy driven by Gondwanan glaciation [12-14]. In the Black Warrior basin, close well spacing and a thick stratigraphic section facilitate investigation of stratal geometry and patterns of coal distribution in multiple depositional cycles [15-18]. This paper presents detailed subsurface maps and stratigraphic cross sections that provide new evidence for the origin of Pennsylvanian cycles and the geologic controls on the distribution of coalbed methane reservoirs.

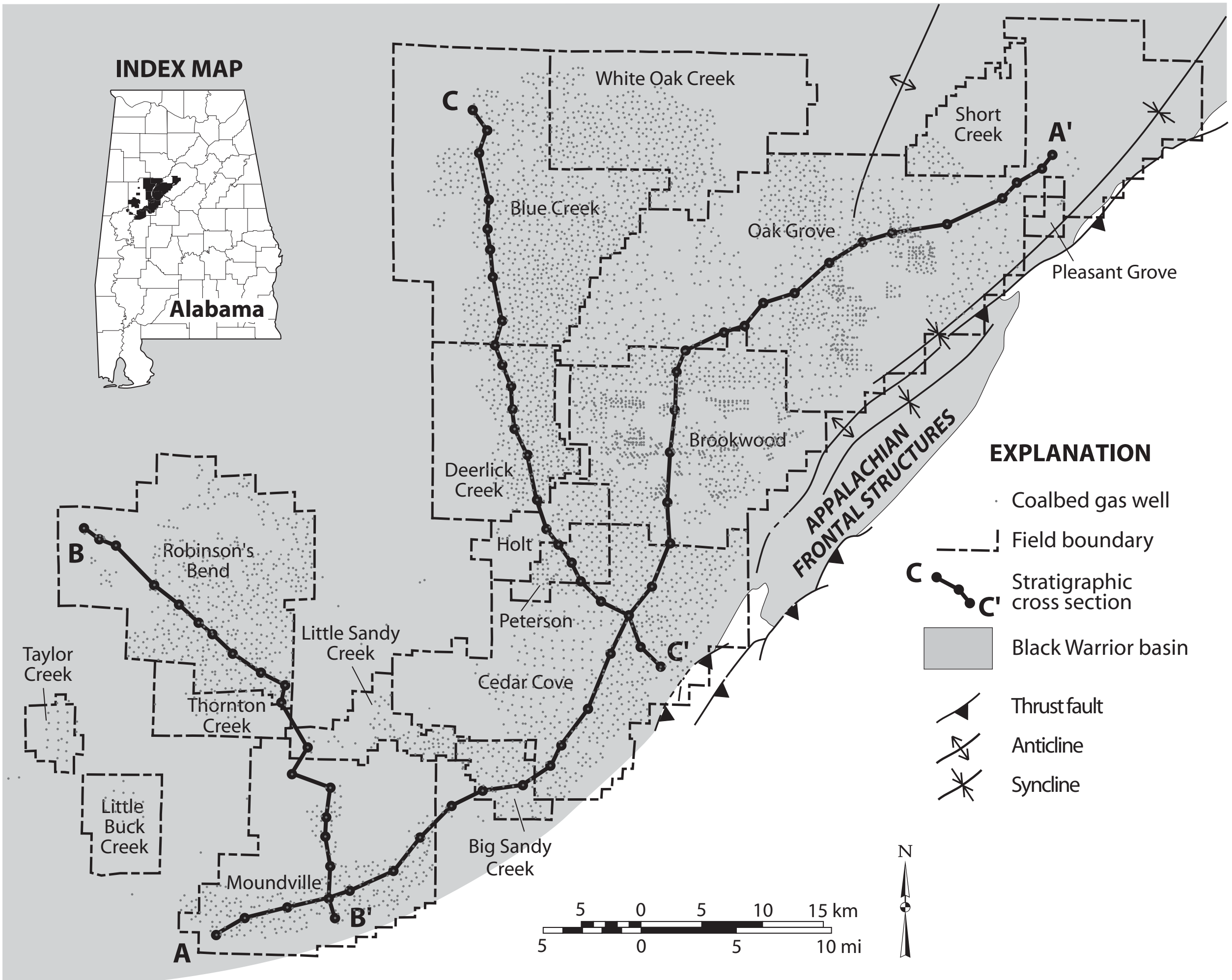

Figure 1. Index map showing locations of coalbed methane fields in the Black Warrior basin, well control, and lines of cross section used in this study.

Methods

More than 5,000 gamma-density logs and long cores were described and correlated to identify and classify stratigraphic markers, such as marine flooding surfaces; to identify and define sedimentary structures and lithofacies; and to determine the geometry and extent of sandstone bodies and reservoir coal beds (fig. 1). A series of stratigraphic cross sections was then constructed showing the stratigraphic architecture of the target coal zones (plates 1-3). Selected cross sections are presented in this paper, and a complete set is in Pashin et al. [19]. The cross sections depict gamma-density logs, major depositional cycles and marine flooding surfaces, subordinate parasequences, coal beds, and major sandstone units. Coal beds and associated organic-rich shale beds were classified according to thickness and density-log signature into primary resource targets, secondary resource targets, and thin marker beds. Primary resource targets are coal beds thicker than 2 ft and typically have a blocky log signature, whereas secondary resource targets are between 1 and 2 ft thick and have a pronounced spike signature (< 1.5 g/cc). Thin marker beds include coal and organic shale markers that are less than 1 ft thick and have a subdued spike signature (> 1.5 g/cc). After the coal beds were correlated, parasequences subordinate to the major depositional cycles were defined by correlating regionally extensive shale and coal markers.

Stratigraphic and well-location data from all wells were compiled into a spreadsheet to facilitate subsurface mapping. Well locations were computed from surveyed line calls using the Wellbase module

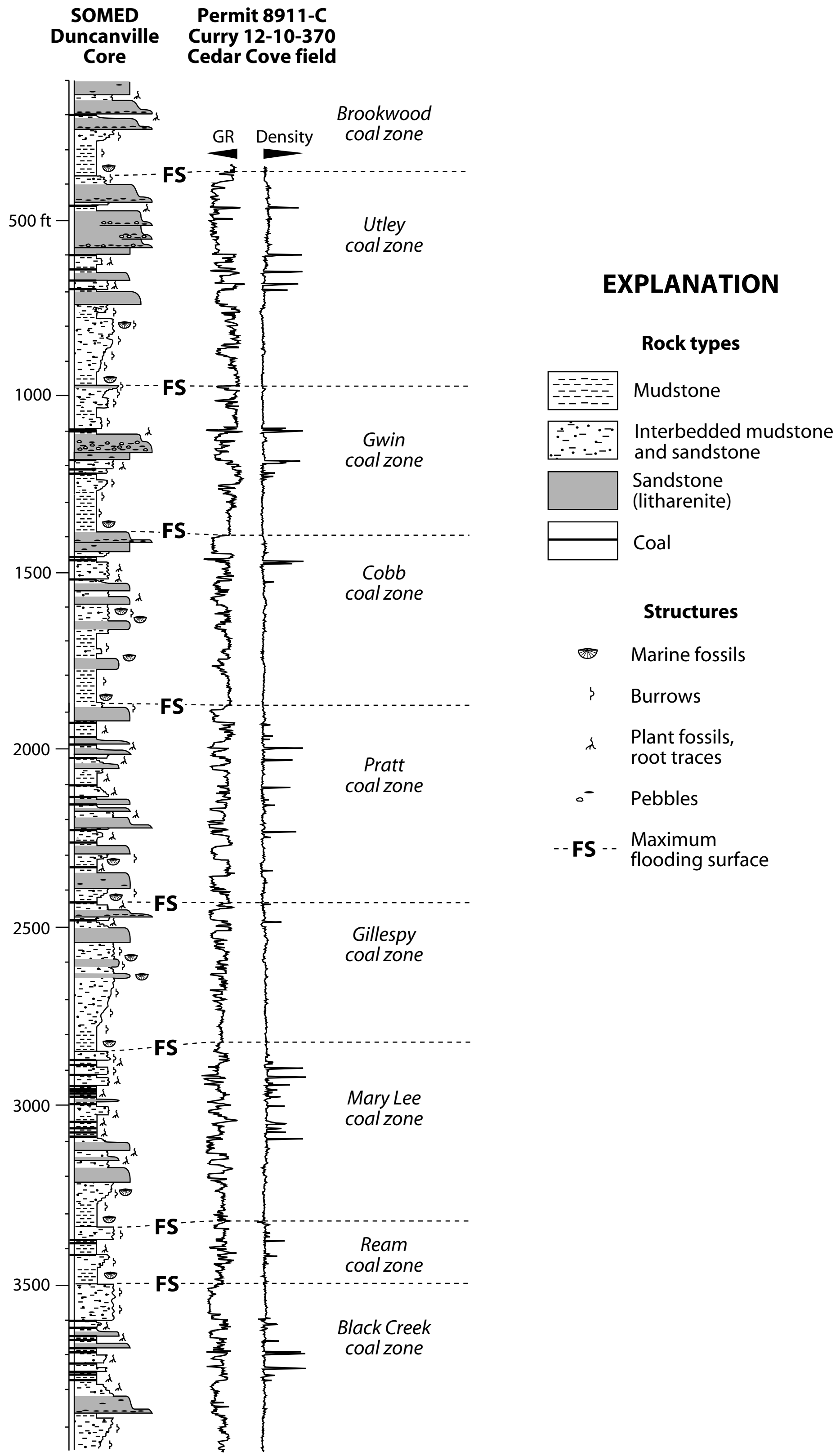

Figure 2. Core log and geophysical well log of the upper Pottsville Formation in Cedar Cove Field showing coal zones and 4th-order maximum flooding surfaces bounding cyclothems [after 18].

of the Geographix Exploration System. Stratigraphic data include the depth of each cycle boundary and net coal thickness in each coal zone. Coal thickness was determined using high-resolution density logs, which typically have a scale of 1 inch equals 25 ft. Coal beds thinner than 1 ft generally are not logged accurately, are seldom completed for gas production, and were thus excluded from the thickness determination. Maps of coal thickness were gridded and contoured using a minimum curvature algorithm in the Isomap module of Geographix. Net coal isolith maps were made for each target coal zone, and a net coal isolith map was made for the Black Creek through Brookwood coal zones.

Background

Coalbed methane reserves in the Black Warrior basin are concentrated in the upper Pottsville Formation (Lower Pennsylvanian; Langsettian), which comprises nine major coal zones and is dominated by siliciclastic rocks (fig. 2). More than 5,000 coalbed methane wells have been drilled, and more than 4,000 wells are currently producing. Cumulative gas production now exceeds 1.5 Tcf, and annual production has exceeded 110 Bcf since the mid 1990s. Coalbed methane resources are estimated to be between 10 and 20 Tcf [20, 21], and reserves are estimated to be between 2.5 and 4.6 Tcf [4, 22, 23].

The Black Warrior basin is a late Paleozoic foreland basin that formed at the juncture of the Appalachian and Ouachita orogenic belts [24-26]. The coalbed methane fields are in the eastern part of the basin adjacent to the frontal structures of the Appalachian orogen (fig. 1). Carboniferous strata in the Black Warrior basin thicken southwest, indicating that subsidence was dominated by thrust and sediment loading in the Ouachita orogen [27]. In the coalbed methane fields, however, upper Pottsville strata thicken southeastward, indicating superposition of an Appalachian flexural moat on the larger Ouachita foreland basin [15, 27, 28] (fig. 3). The area containing the thickest section in the coalbed methane fields is called the Moundville-Cedar Cove depocenter [19]. Net completable coal thickness in the upper Pottsville ranges from less than 10 ft in the northwestern part of the coalbed methane fairway to more than 70 ft in parts of the Moundville-Cedar Cove depocenter (fig. 4).

Stratigraphic grouping of Pottsville coal beds was observed by McCalley [29], and intercalated marine and terrestrial facies were recognized by Butts [30]. From the 1960s through the 1980s, the Alabama Pottsville formed a basis for facies models of Appalachian coal-bearing strata [25, 26, 31, 32]. During extensive natural gas exploration, regionally extensive depositional cycles were identified and mapped [3, 15, 28]. Recent workers [e.g., 18, 33, 34] have interpreted the upper Pottsville cycles as flooding-surface-bounded depositional units, or parasequences [see 35, 36]. The base of each parasequence is marked by a condensed section with abundant marine fossils. Above the condensed section is a thick interval (100-300 ft) of marine shale that coarsens upward into fluvial-deltaic sandstone. At the top of each parasequence is a lithologically heterogeneous coal zone that accumulated in a spectrum of marginal marine and terrestrial environments. Pashin [15, 16, 34] interpreted these parasequences to have been deposited at a frequency no greater than 0.4 my, which is equivalent to the Milankovitch long eccentricity period that is thought to have driven the formation of Pennsylvanian cyclothems [11, 13]. Accordingly, the major Pottsville parasequences analyzed in this study can be classified as cyclothems, or 4th-order parasequences.

POTTSVILLE PARASEQUENCES

Pottsville cyclothems are readily recognized in gamma-density logs (fig. 2; plates 1-3). Shale has radioactivity higher than 100 gammas, whereas sandstone has radioactivity lower than 100 gammas. The maximum flooding surface bounding each cyclothem is typically marked by elevated radioactivity at the bottom of a thick shale interval, and these surfaces can be traced throughout the study area. The basal shale units have a serrate log pattern and coarsen upward into sandstone, which is typical of progradational deposits. Framework sandstone has a blocky or fining-upward log signature, which is characteristic of aggradational deposits. Coal beds and associated organic-rich shale units are identified by low density, and coal beds thicker than 1 ft have low radioactivity similar to sandstone.

The cyclothems contain subordinate progradational intervals (fig. 2; plates 1-3). These intervals are best developed in the Gillespy through Gwin coal zones, and some minor flooding surfaces at the tops of these intervals can be correlated across the study area (plates 2, 3). These surfaces define the boundaries of high-frequency parasequences. Each cyclothem studied comprises four subordinate parasequences, suggesting sedimentation in the short eccentricity Milankovitch band (~0.1 my). Hence,

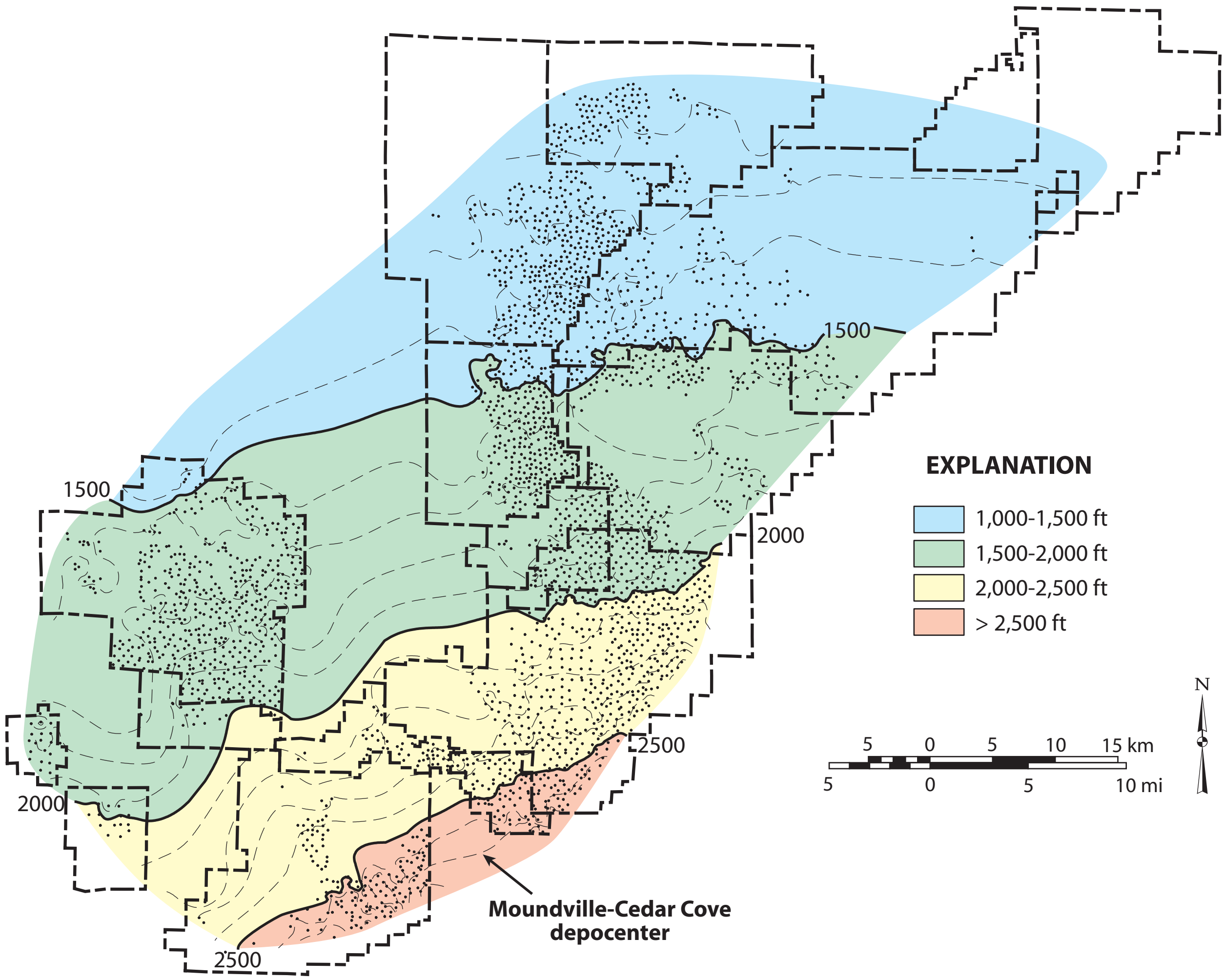

Figure 3. Isopach map showing thickness of the upper Pottsville Formation from the top of the Black Creek coal zone to the top of the Gwin coal zone.

the subordinate depositional units are interpreted as 5th-order parasequences. These parasequences are color-coded blue, green, yellow, and brown on the basis of their position within each cyclothem (plates 1-3). The progradational signature of the subordinate parasequences is most readily apparent in the blue and green color-coded intervals. In the green through brown parasequences, however, the progradational signature is commonly obscured or supplanted by aggradational sandstone and shale units. The tops of widespread coal beds commonly mark or correlate with marine flooding surfaces [36, 37] (plates 1-3), and flooding surfaces above regionally extensive coal beds in the study area were verified with core and outcrop data. The 5th-order parasequences contain three dominant lithofacies: (1) progradational shale and sandstone, (2) aggradational sandstone and shale, and (3) coal.

Progradational Shale and Sandstone

Progradational shale is very dark gray to dark medium gray and is silty or sandy. Marine fossils are most abundant in the lower parts of the shale units and include brachiopods, molluscs, echinoderms, and solitary corals [30, 38]. The shale typically contains horizontal burrows. Sandstone forms laminae to thick beds and is medium gray to light gray. The thickness, frequency, and grain size of these beds increases upsection. Sandstone beds in the lower parts of the progradational units are typically graded, and higher in section, graded sandstone beds can be traced laterally into clinoform foreset beds [39]. Near the tops of these intervals, crossbeds and scour fills are common. In the brown parasequences, graded bedding is absent, and marine body fossils are rare. These intervals are dominated by wavy-, flaser-, and lenticular-

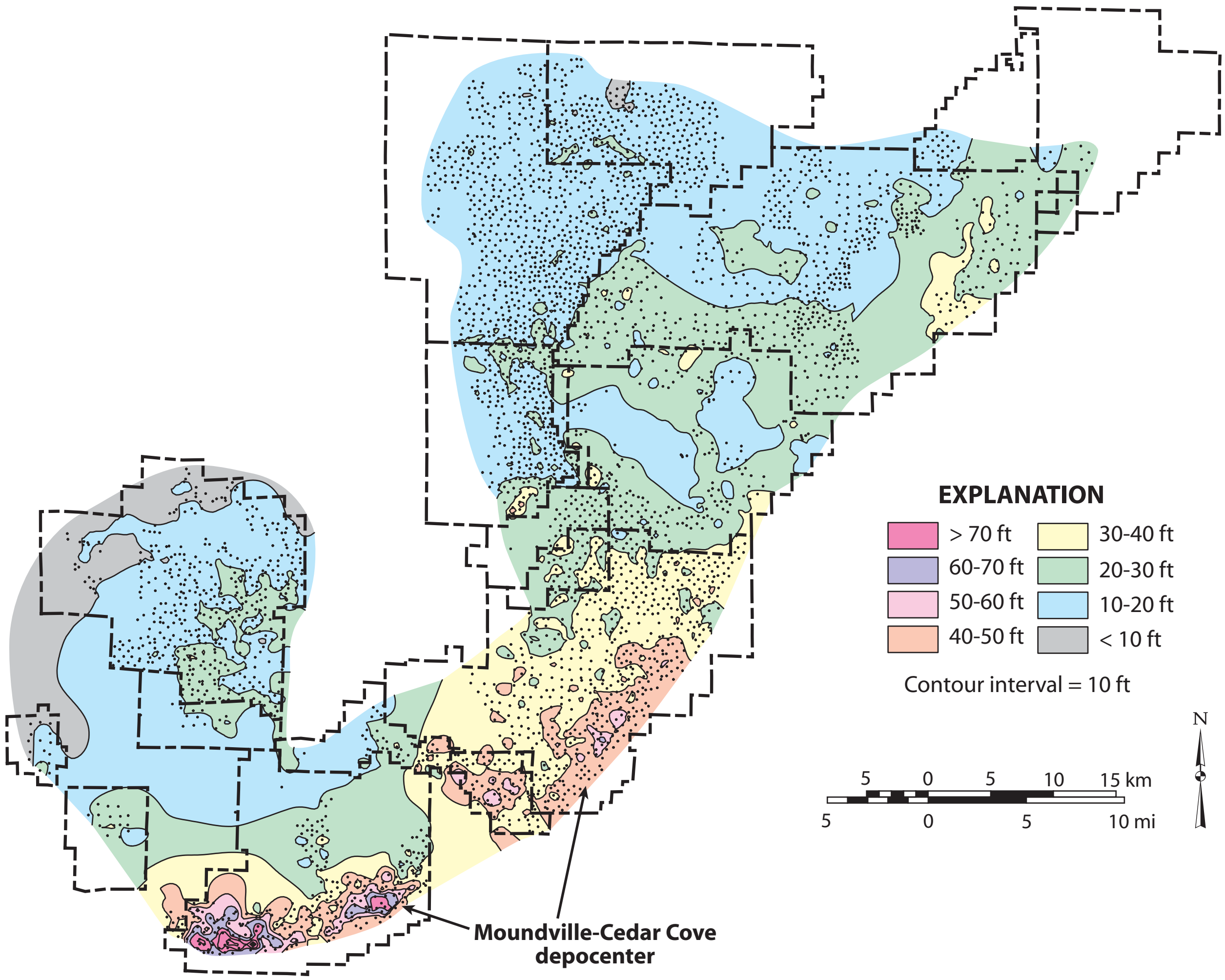

Figure 4. Net coal isolith map of the upper Pottsville Formation.

bedded shale and sandstone containing diverse trace fossils and are truncated by regionally extensive ravinements that underlie the condensed section of the next cyclothem [18, 40].

The deltaic character of the progradational shale and sandstone units has long been recognized [16, 18, 31, 33, 39]. In the blue and green parasequences, the basal parts of the progradational shale units are typical of prodeltaic deposits, whereas graded sandstone beds are typical of distal delta front deposits. Clinoform foreset bedding is common in distal to medial distributary mouth bars, whereas crossbeds and scour fills are characteristic of proximal mouth bars. Significantly, 5th-order flooding surfaces define northwest-dipping clinoforms in the lower parts of the Gillespy through Gwin coal zones (plates 2, 3). Wavy-, flaser-, and lenticular-bedded shale and sandstone in the brown parasequences, by contrast, are characteristic of tidal deposits [41, 42]. Pashin [17, 18] interpreted these strata as retrograding delta-destructive and estuarine facies that formed during the early stages of 4th-order marine transgressions. The ravinements capping the brown parasequences have been interpreted as transgressive surfaces that formed by shoreface erosion during regional inundation [18, 40].

Aggradational Sandstone and Shale

Aggradational sandstone bodies are abundant in the middle and upper parts of each cyclothem, and the thickness and continuity of these bodies is variable (fig. 2; plates 1-3). The sandstone is compositionally immature, is fine- to coarse-grained, and locally includes conglomerate. Isolith maps indicate that sandstone is thickest in the Moundville-Cedar Cove depocenter [3, 15]. The sandstone units have sharp bases, fine upward, and have gradational tops. Sedimentary structures include crossbeds, current-ripple cross laminae, horizontal laminae, scour-and-fill structures, and lateral accretion surfaces [3, 42, 43]. Biogenic structures range from plant fossils to invertebrate traces and, rarely, calcareous shells. Single-story sandstone bodies are most common in the blue and brown parasequences, and multistory sandstone bodies are most common in the green and yellow parasequences.

Shale is commonly interbedded with sandstone, and bedding styles range from pinstripe bedding to wavy, flaser, and lenticular bedding; rooted mudstone also is common. In places, thick, graded sandstone beds are common in the shale units, as are muddy channel fills. Fossils in the aggradational shale units range from erect plant assemblages to the burrows and trackways of invertebrates and vertebrates, as well as sparse brachiopod and mollusc shells [38].

The sandstone bodies have been interpreted to represent a spectrum of contributive, transitive, and distributive fluvial systems, as well as tidal channel systems [17, 18, 31, 43, 44]. Concentration of compositionally immature sandstone in the Moundville-Cedar Cove depocenter suggests a source in the Appalachian orogen [3, 15]. Some of the sandstone units in the coalbed methane fields, such as in the green parasequence of the Gwin coal zone (plate 3, C-C'), appear to have cut as deeply as 100 ft into the underlying shale units and can thus be interpreted as incised valley fills. The associated shale units appear to have been deposited in a broad array of interchannel environments and include overbank, crevasse-splay, bayfill, backswamp, and tidal-flat deposits [31, 39, 42, 43].

Coal

Pottsville coal is bright-banded and composed of vitrinite (70-95%) with lesser inertinite (5-30%) and liptinite (0-8%) [45]. Ash content is typically 5 to 19% and is dominated by detrital clay and quartz, and total sulfur content is typically 0.8 to 3.0% [19]. Net coal thickness in the upper Pottsville increases from less than 10 ft in the western coalbed methane fields to more than 70 ft in parts of the Moundville-Cedar Cove depocenter (fig. 4). In the Mary Lee and Pratt coal zones, net coal thickness exceeds 10 ft in several areas along the southeast margin of the Black Warrior basin (figs. 3, 5). In the Gwin and Utley zones, net coal thickness exceeds 5 ft mainly in the Moundville-Cedar Cove depocenter (figs. 3, 6).

Coal beds are most numerous in the Moundville-Cedar Cove depocenter (plates 1-3); they are rare in the blue parasequences and are most common in the green and yellow parasequences. Coal beds are sparse in brown parasequences, save for those above the Pratt coal bed (plate 3). Most upper Pottsville coal beds can be correlated for large distances (plates 1-3). Several thin marker beds and secondary resource beds appear to be truncated by aggradational sandstone bodies, and many appear to be in facies relationship with sandstone. In contrast, major resource beds and the correlative secondary resource beds and thin markers can be traced across large parts of the study area. Most of these beds have been named (see plates 1-3) and are the principal mining and degasification targets in the Black Warrior basin. Most named beds are at or are a short distance below flooding surfaces defining the boundaries of 5^{th}-order parasequences. Care must be taken, however, when associating coal beds with flooding surfaces. For example, it is tempting to place a parasequence boundary at the top of the upper Cobb bed based on log signature and the thickness of adjacent siliciclastic strata (plate 3). However, no correlative flooding surface can be identified in cross-section C-C'.

The vast majority of the coal beds are geometrically simple; that is, a single bed can be traced for large distances without splitting (plates 1-3). Where multiple beds merge, as is the case in the Mary Lee, Blue Creek, and Gwin beds of Big Sandy Creek and Moundville fields (plate 1, A-A'; plate 3, A-A'), individual coal beds tend to retain identity in density logs, and high-resolution well logs can be used for bench-scale correlation. A prominent example of bed splitting is in the Pratt seam, where a thick bed with multiple benches splits basinward toward a large multistory sandstone body (plate 2, C-C'). Channel-fill coal bodies are in the Blue Creek coal of Oak Grove Field (plate 1, A-A'). The channels are up to 60 ft deep, truncate Jagger coal, and form a dendritic network [17]. The coal thickens to more than 9 ft in the channels and is a primary target of longwall coal mining and mine-related degasification activities.

The Alabama Pottsville is part of the Euramerican coal belt, which formed as a widespread system of equatorial peat swamps during Pennsylvanian time [46]. High detrital ash content indicates that peat accumulated mainly in low-lying swamps, although some low-ash coal has been attributed to doming [47]. Sulfur content is higher than 2% in coal with marine roof strata [48, 49], and the broad range of sulfur content in the Pottsville reflects preservation of coal below marine through terrestrial roof facies.

The variable thickness and extent of Pottsville coal beds (plates 1-3; figs. 2-6) further points to diverse origins. Many of the thin, discontinuous beds arguably are the products of localized swamps that

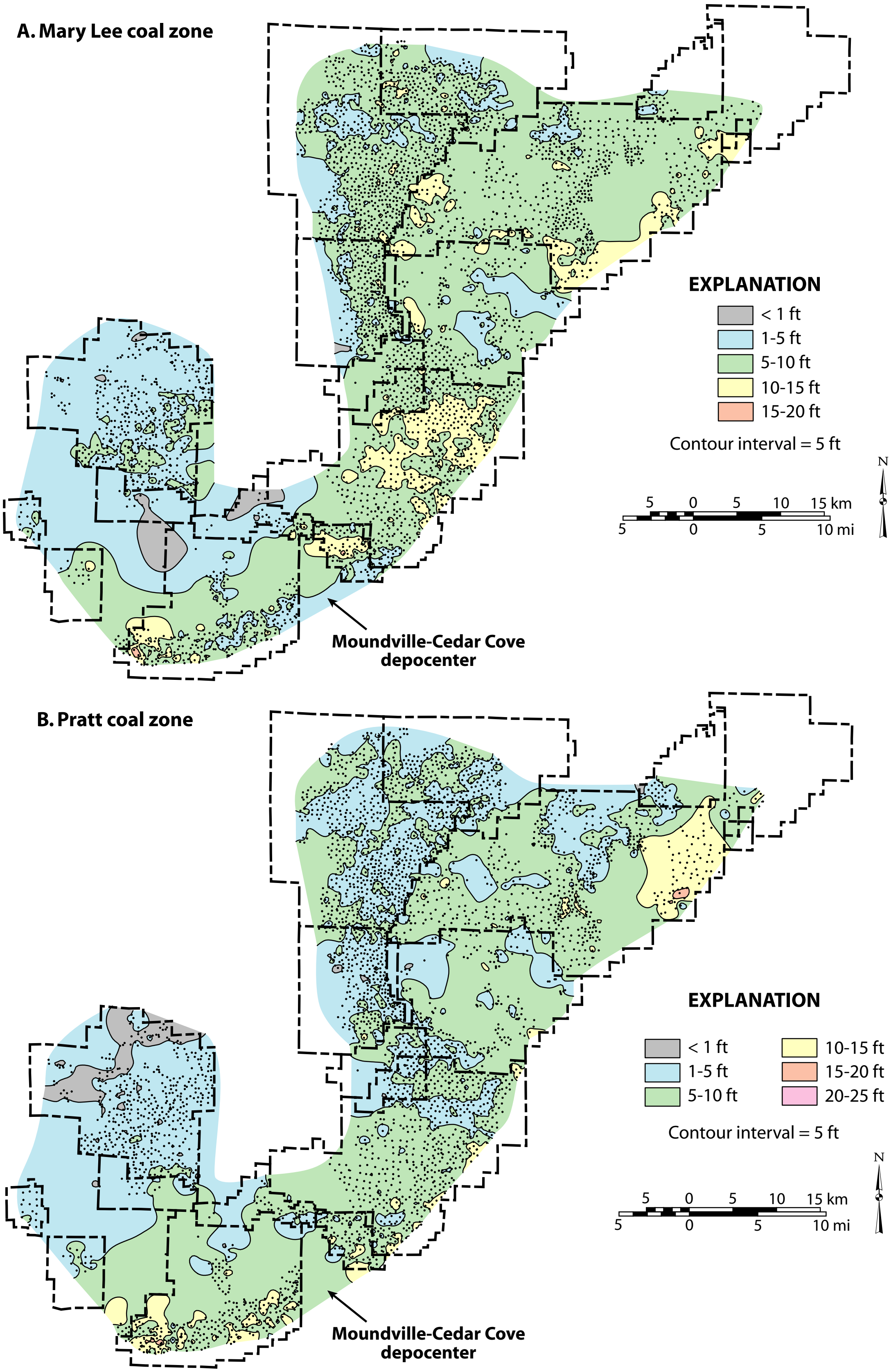

Figure 5. Net coal isolith maps of the Mary Lee and Pratt coal zones.

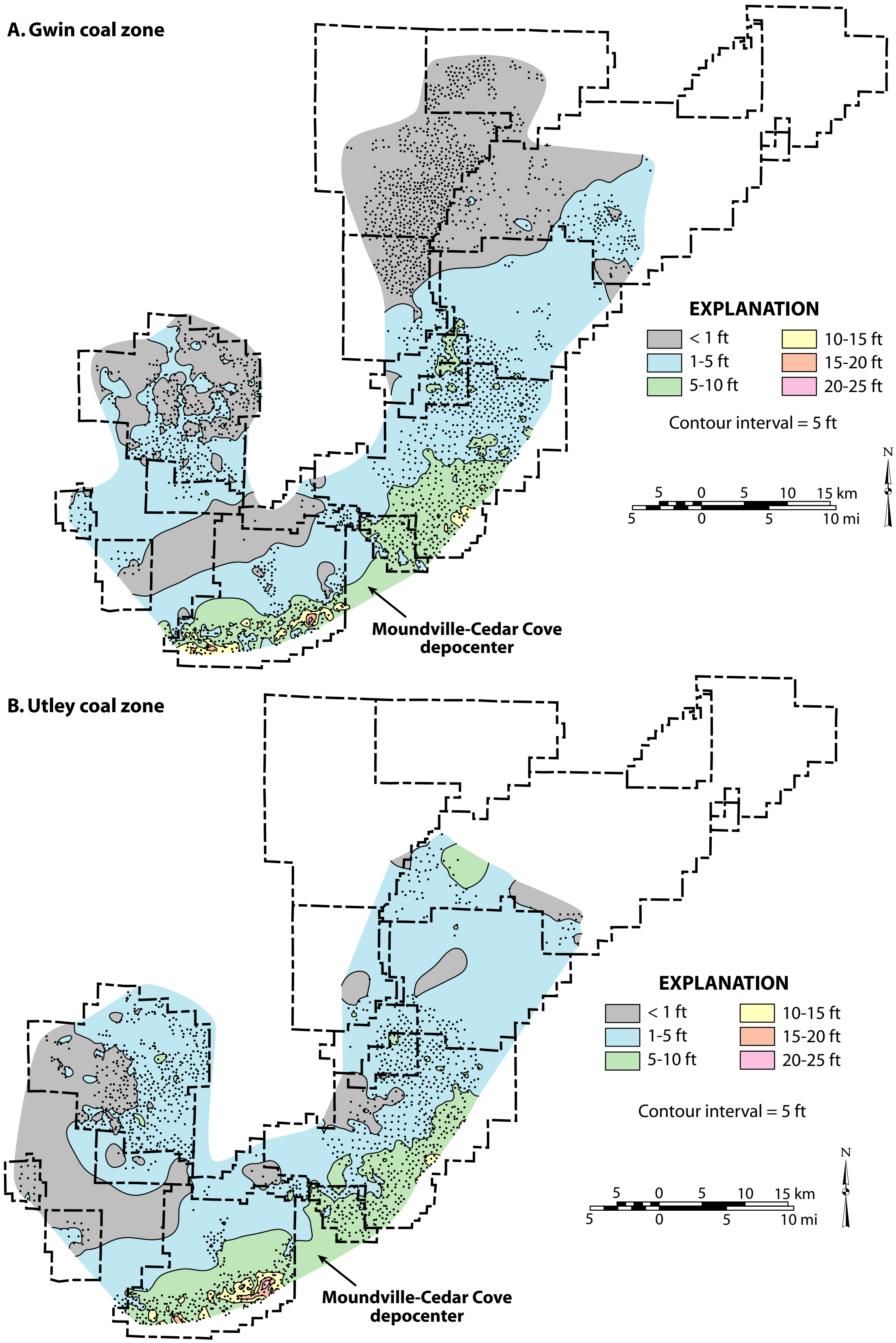

Figure 6. Net coal isolith maps of the Gwin and Utley coal zones.

were prone to erosion or pass laterally into contemporaneous siliciclastic sediment. At the other extreme, regionally extensive coal beds provide evidence for widespread paludification of the coastal plain [see 50]. Regional aggradation appears to have facilitated paludification. For example, Pashin [17] interpreted the channel fill coal of the Blue Creek bed (plate 1, A-A') to indicate infilling of an aggraded, dendritic paleovalley system with peat. Other widespread coal beds, like the Cobb and Gwin beds, accumulated after channel belts had aggraded and filled completely with siliciclastic sediment (plate 3). Interestingly, the Mary Lee-Blue Creek channel-fill coal is in the interior of a 5th-order parasequence (plate 1), whereas most other regionally extensive coal beds are at or a short distance below parasequence-bounding flooding surfaces (plates 1-3). As such, aggradation of sandy channel systems and accumulation of the Gwin bed was a prelude to a widespread marine flooding event. By contrast, progressive splitting of Pratt coal and interfingering with contemporaneous siliciclastic sediment (plate 2, C-C') suggests that some major swamp systems persisted through 5th-order flooding events.

PALEOCLIMATIC AND TECTONIC INTERPRETATIONS

Pennsylvanian cyclothems are commonly attributed to 4th-order changes of relative sea level in the long eccentricity band, although the mechanisms driving this cyclicity remain controversial [9, 11]. Berger and Loutre [51] showed that the intensity of insolation varied in concert with long eccentricity during Pleistocene glaciation (fig. 7A). However, Rial [52] demonstrated that glacial ice volume was regulated by short eccentricity and that long eccentricity modulated higher Milankovitch frequencies (fig. 7B). Regardless of the cause, 4th-order depositional cycles provide an obvious basis for stratigraphic subdivision of the upper Pottsville (fig. 2; plates 1-3).

The classic cyclothems of the North American midcontinent are much thinner than those in the Black Warrior basin, and correlative strata in the Appalachian basin contain major stratigraphic discontinuities [53]. Thus, interpretations of cyclicity in Pennsylvanian strata have been hampered by low stratigraphic resolution. The exceptional thickness of upper Pottsville cyclothems, coupled with close well spacing in the coalbed methane fields, facilitates the recognition of 5th-order parasequences (plates 1-3; fig. 8) and thus provides new insight into the depositional, climatic, and tectonic processes that operated during Pennsylvanian time. Taken together, the blue through green parasequences typically define progradational parasequence sets (fig. 8). The brown parasequences can represent continued progradational stacking, as is the case in the Gillespy and Pratt coal zones (plate 2). However, abundant marginal-marine deposits and limited sandstone and coal resources indicate retrogradation, as is the case in the brown parasequences of the Mary Lee and Gwin coal zones (figs. 2, 8; plates 1, 3).

The blue parasequences record major episodes of deltaic progradation and basin filling and thus constitute 4th-order highstand deposits (plates 1-3). Although the green and yellow parasequences can also contain progradational deltaic deposits, especially in the northwestern parts of the study area, these parasequences contain complex multistory sandstone bodies and some incised valley fills, suggesting that lowstand surfaces of erosion are present and that fluvial sedimentation had some sensitivity to base-level changes in the short eccentricity band. However, complex facies relationships within the 5th-order parasequences make lowstand surfaces difficult to trace. The incised valley fills in the green parasequence of the Gwin coal zone (plate 3, C-C') suggest that sea-level drops were about 100 ft, which is consistent with other estimates of glacial eustasy during the Early Pennsylvanian [54]. Although the stratigraphic expression of the brown parasequences is variable, retrogradation in some cyclothems indicates deposition during 4th-order marine transgressions.

Coal beds appear to be the products of interwoven autogenic and allogenic processes. The high abundance of coal beds in the Moundville-Cedar Cove depocenter reflects increased tectonic subsidence and persistence of terrestrial sedimentation in areas proximal to the sediment source. Within the depocenter coal beds, such as those above the Pratt seam (plate 3), can be too numerous to be explained solely by high-frequency Milankovitch processes, specifically obliquity (~40 ky) and precession (~20 ky). Autogenic processes that may have operated include channel avulsion and autocompaction of peat, which can cause rapid shifts in the locations of flood basins and swamps. Although more coal beds have been completed in the depocenter than in any other part of the Black Warrior basin, increased coal resources do not necessarily translate to large gas reserves or better well performance [3, 19].

Total effective subsidence rates in the Moundville-Cedar Cove depocenter during upper Pottsville deposition at times exceeded 1,500 ft/my [34, 55], so sediment compaction combined with tectonic processes driven by thrust and sediment loading may have also played an important role in the

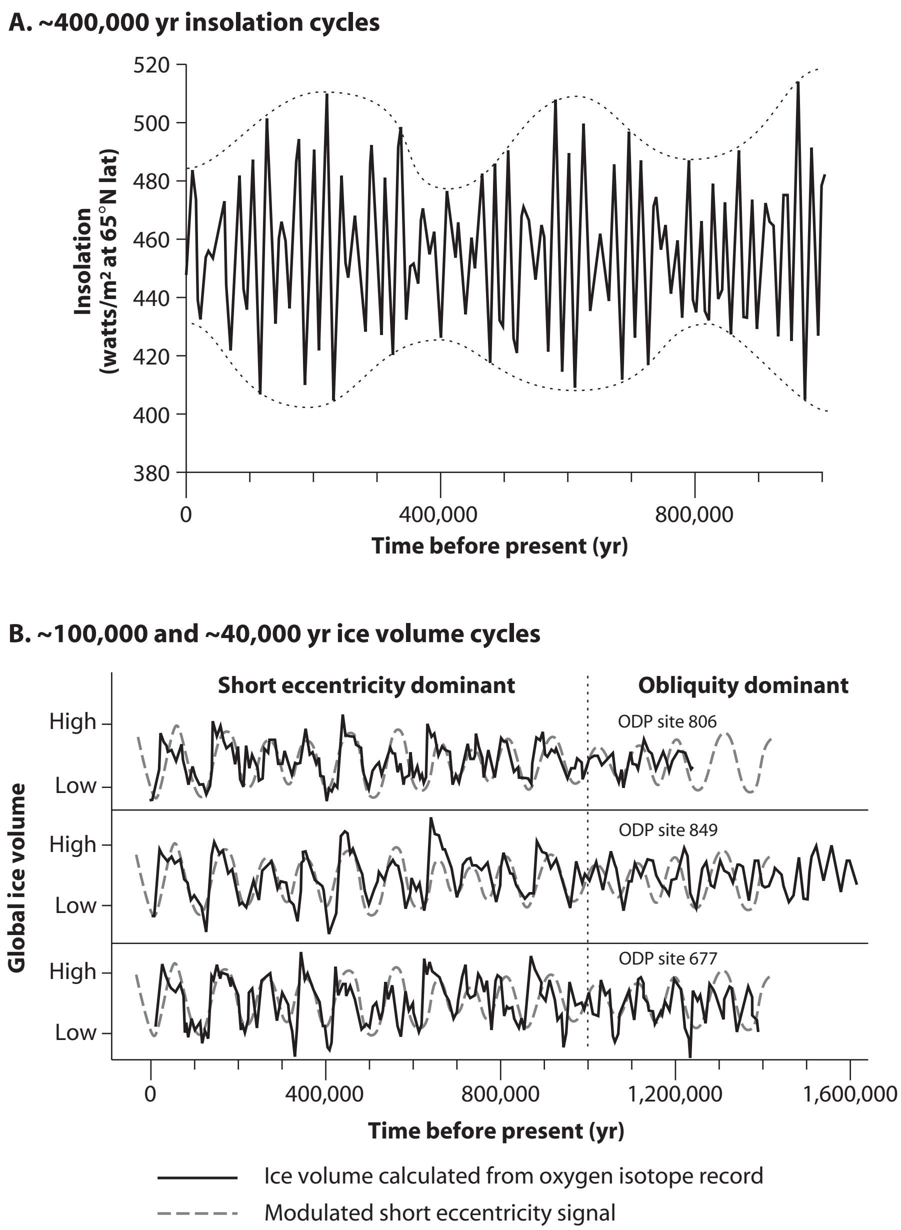

Figure 7. Insolation and ice-volume curves showing the impact of the long (~0.4 my) and short (~0.1 my) eccentricity signals on climate during Pleistocene time [after 51, 52]. These same factors may have regulated glacial eustasy and the development of cyclothems during the Pennsylvanian.

preservation of coal and the intervening siliciclastic rocks. Gastaldo et al. [56] argued that catastrophic subsidence events explain the preservation of standing forests in which erect plants extend upward through more than 20 ft of aggradational shale. Rapid subsidence events also may help explain the alternation of geometrically simple coal beds with siliciclastic strata in the interiors of many 5th-order parasequences. Furthermore, rapid subsidence apparently kept upper Pottsville fluvial systems close enough to grade to favor the development of single-story and poorly confined multistory sandstone bodies over well-confined paleovalley fills in most parasequences.

Although many processes affected peat accumulation, base level changes appear to have played a fundamental role in the formation of the thickest and most widespread coal beds, which are the principal targets for gas production, as well as underground and surface mining. The common association between widespread coal beds and 5th-order flooding events suggests that regional aggradation driven by high-

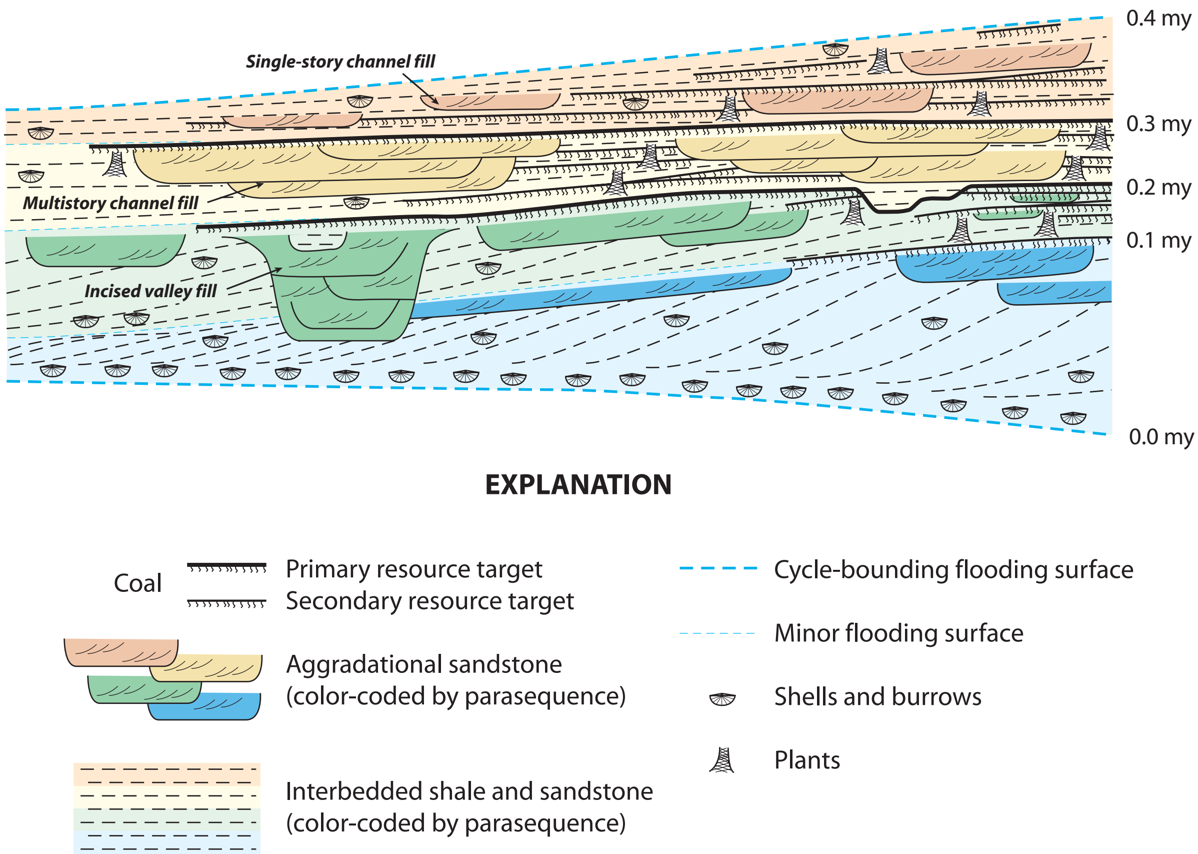

Figure 8. Idealized stratigraphic model showing facies relationships and flooding surfaces in upper Pottsville cyclothems of the Black Warrior coalbed methane fields.

frequency glacial eustasy helped curb siliciclastic sediment flux and subdue topography, thereby laying the groundwork for the growth of regionally extensive peat swamps. Although aggradation prior to marine flooding favored the development of major swamps, the thick valley-fill coal of the Mary Lee-Blue Creek subzone (plate 1) suggests that subsidence coupled with the earliest stages of eustatic sea-level rise could raise water tables enough to promote the formation of a major resource bed in the interior of a 5^{th}-order parasequence.

SUMMARY AND CONCLUSIONS

Coalbed methane reserves in the upper Pottsville Formation are distributed among multiple 4^{th}-order depositional cycles, or cyclothems, that in places span more than 4,000 ft of section. Upper Pottsville strata thicken southeastward into a prominent foreland flexure adjacent to the Appalachian orogen. Coal beds and resources are most abundant in this flexure, and isolith maps indicate that the impact of tectonic subsidence on coal thickness patterns increased through time during Pottsville sedimentation.

Each cyclothem studied comprises four 5^{th}-order parasequences, suggesting control of sedimentation by glacial eustasy. The first of these parasequences is dominated by deltaic deposits and contains limited coal resources. The second and third parasequences contain thick, aggradational sandstone, including incised valley fills. The thickest and most widespread coal beds are within these parasequences, and together, the first three parasequences exhibit progradational stacking. The character of the fourth parasequence is variable, indicating continued progradation or retrogradation. This parasequence commonly contains transgressive tidal facies and generally lacks major coal resources.

Most upper Pottsville coal beds are geometrically simple; that is, individual beds can be traced without splitting. However, some beds include channel-fill coal bodies or progressive bed splits adjacent to contemporaneous siliciclastic facies. Regionally extensive coal beds are associated with 5^{th}-order base-level rises. These base-level rises facilitated aggradation of fluvial systems, smoothing of topography, and reduction of sediment flux, thereby setting the stage for paludification of the coastal plain and accumulation of the most important reservoir coal beds and mining targets in the basin.

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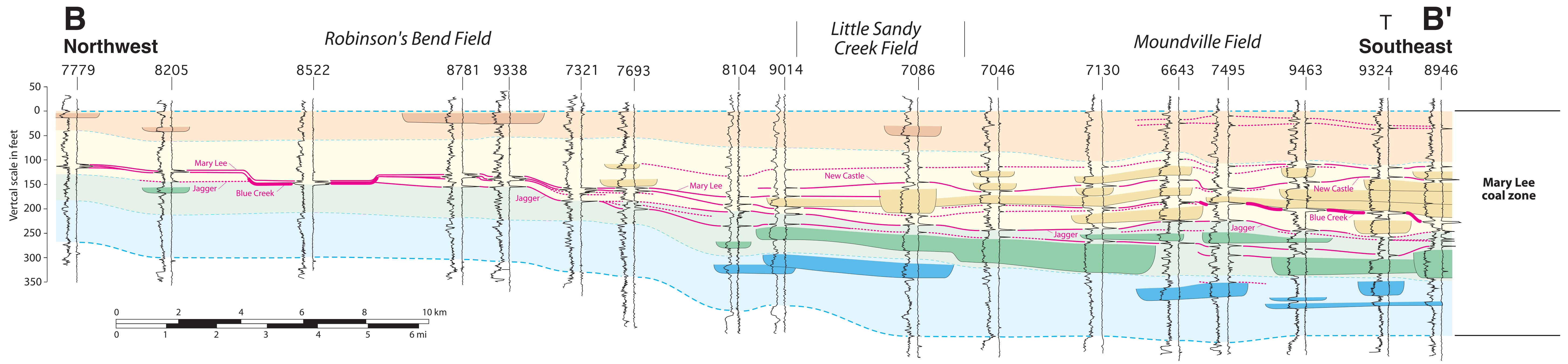

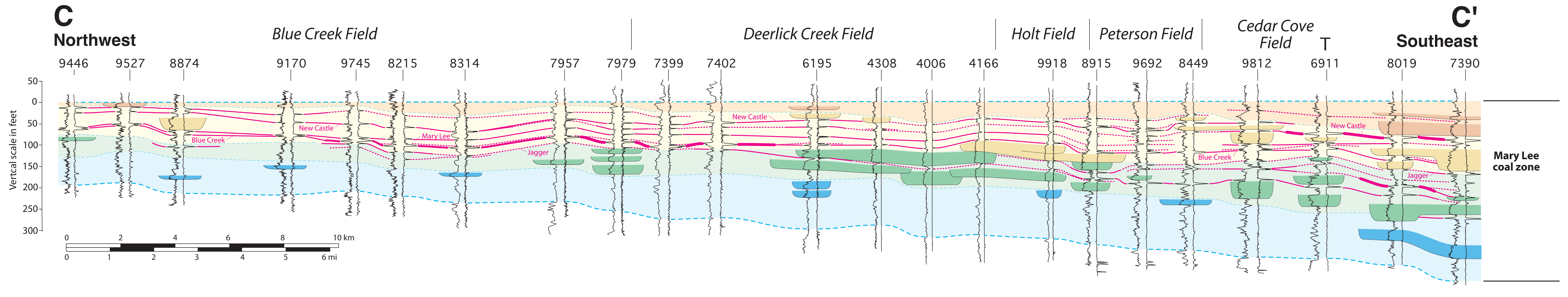

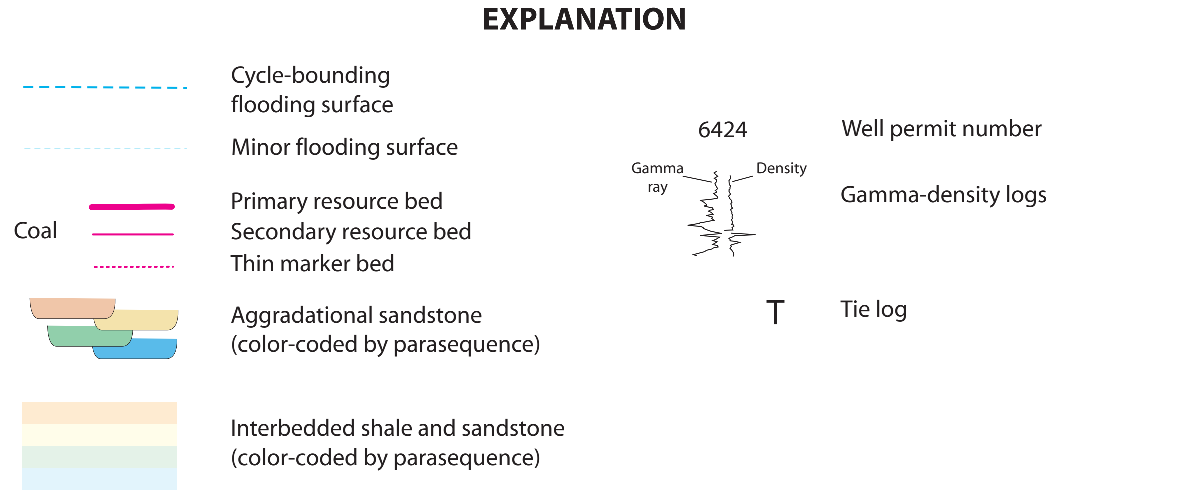

STRATIGRAPHIC CROSS SECTIONS OF THE MARY LEE COAL ZONE IN THE BLACK WARRIOR COALBED METHANE FIELDS, ALABAMA

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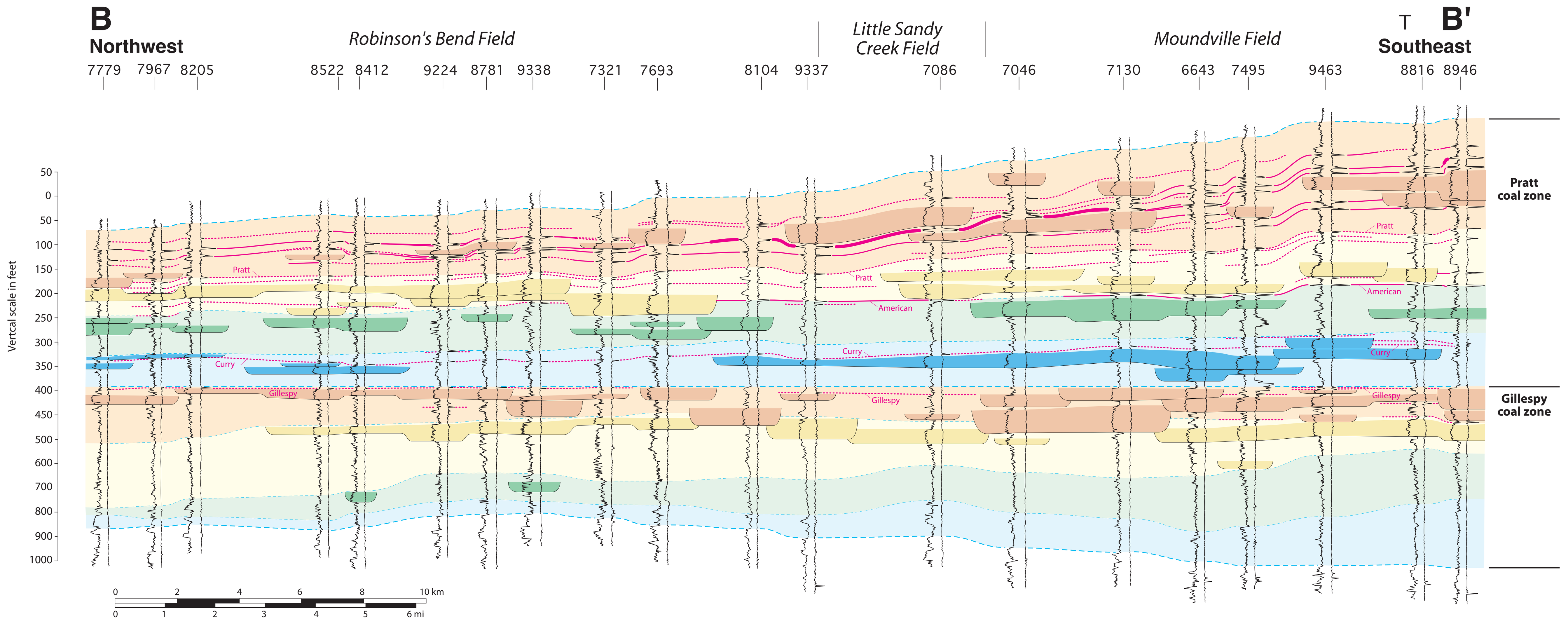
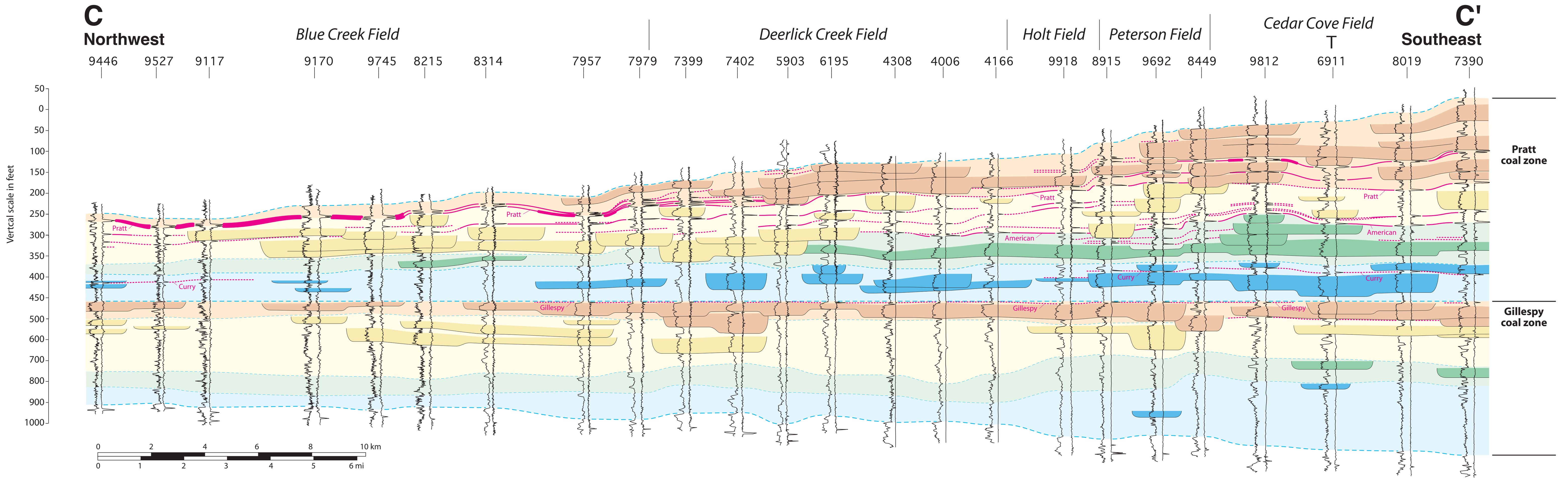
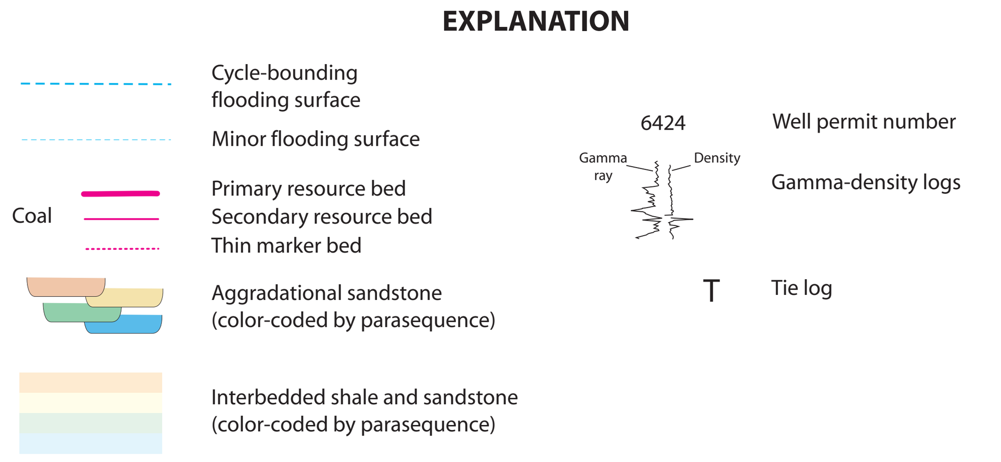
2004







STRATIGRAPHIC CROSS SECTIONS OF THE GILLESPY, CURRY, AND PRATT COAL ZONES IN THE BLACK WARRIOR COALBED METHANE FIELDS, ALABAMA

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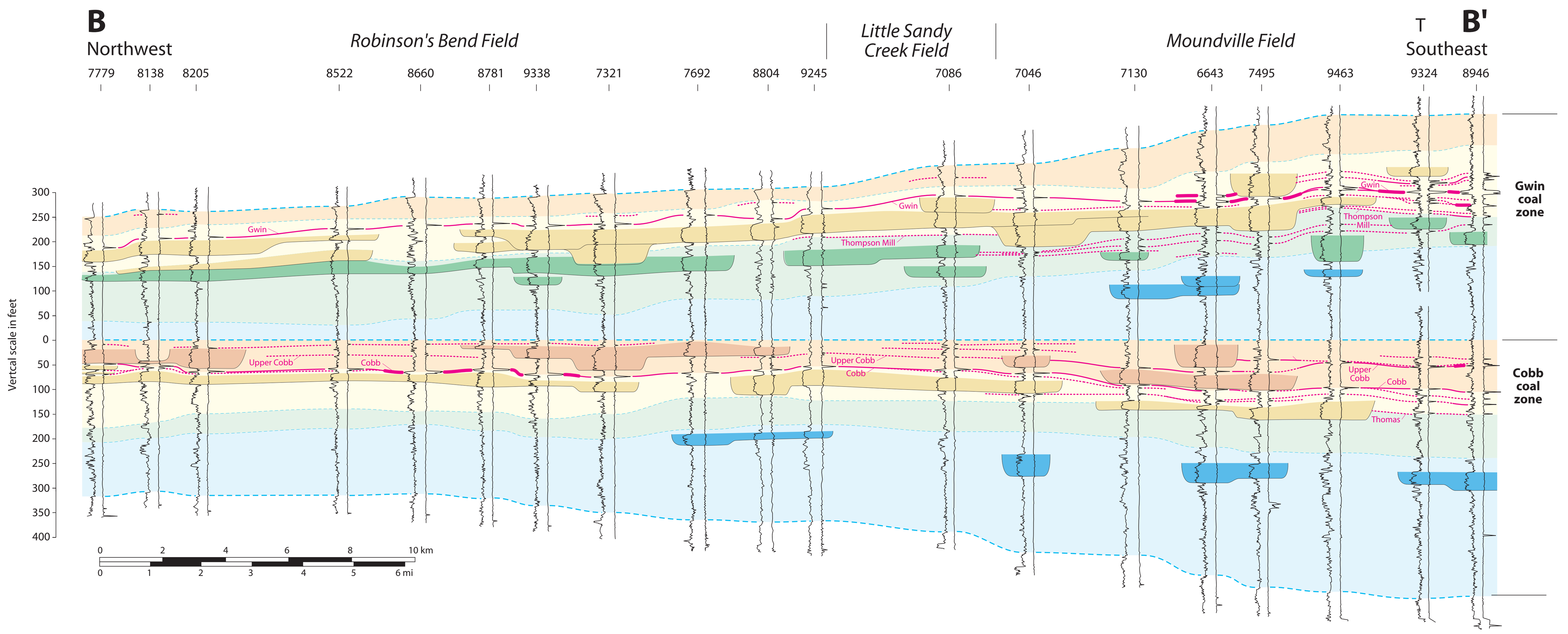

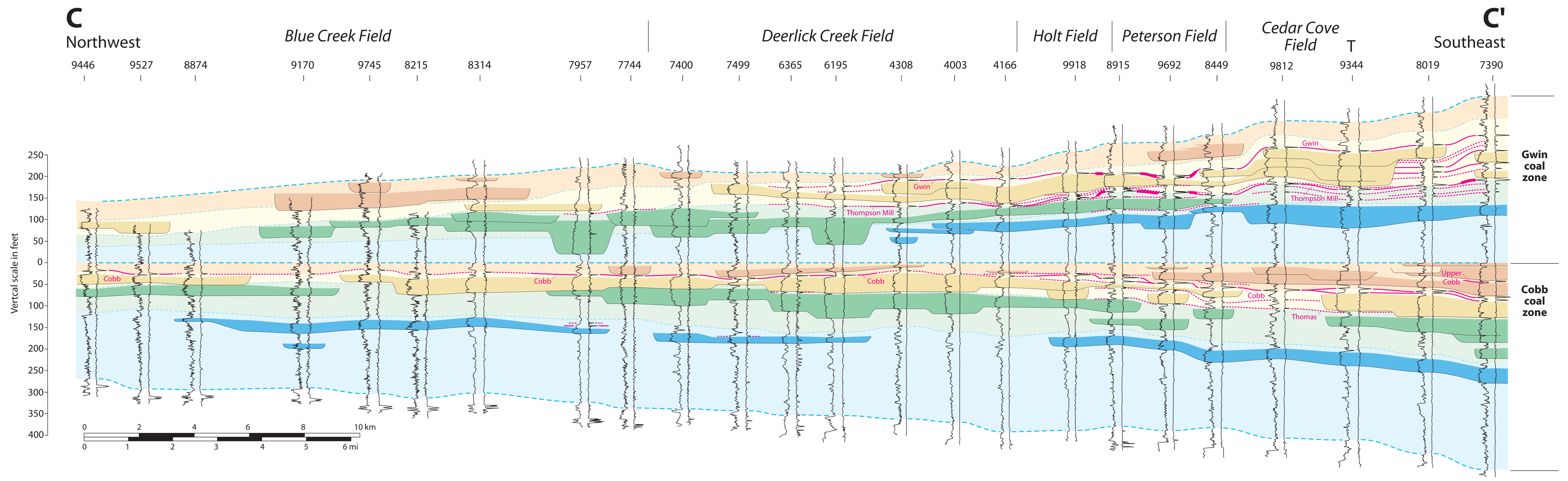

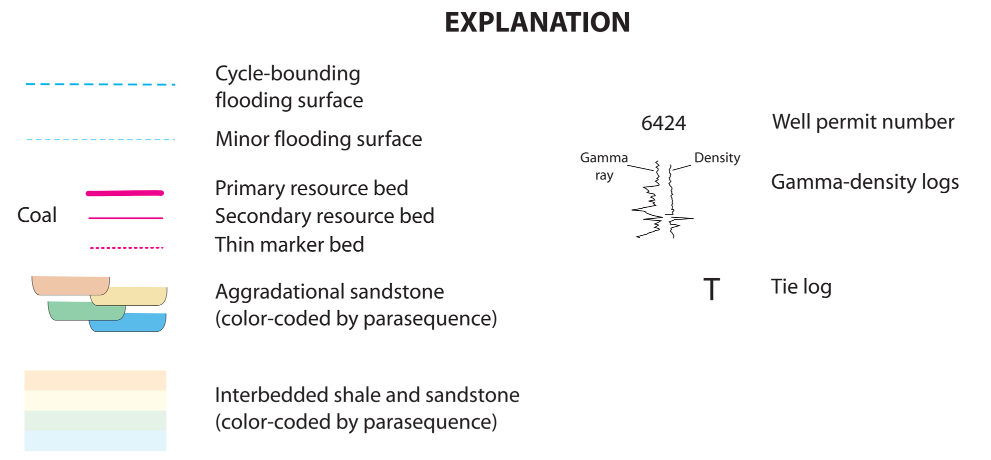

STRATIGRAPHIC CROSS SECTIONS OF THE COBB AND GWIN COAL ZONES IN THE BLACK WARRIOR COALBED METHANE FIELDS, ALABAMA

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