

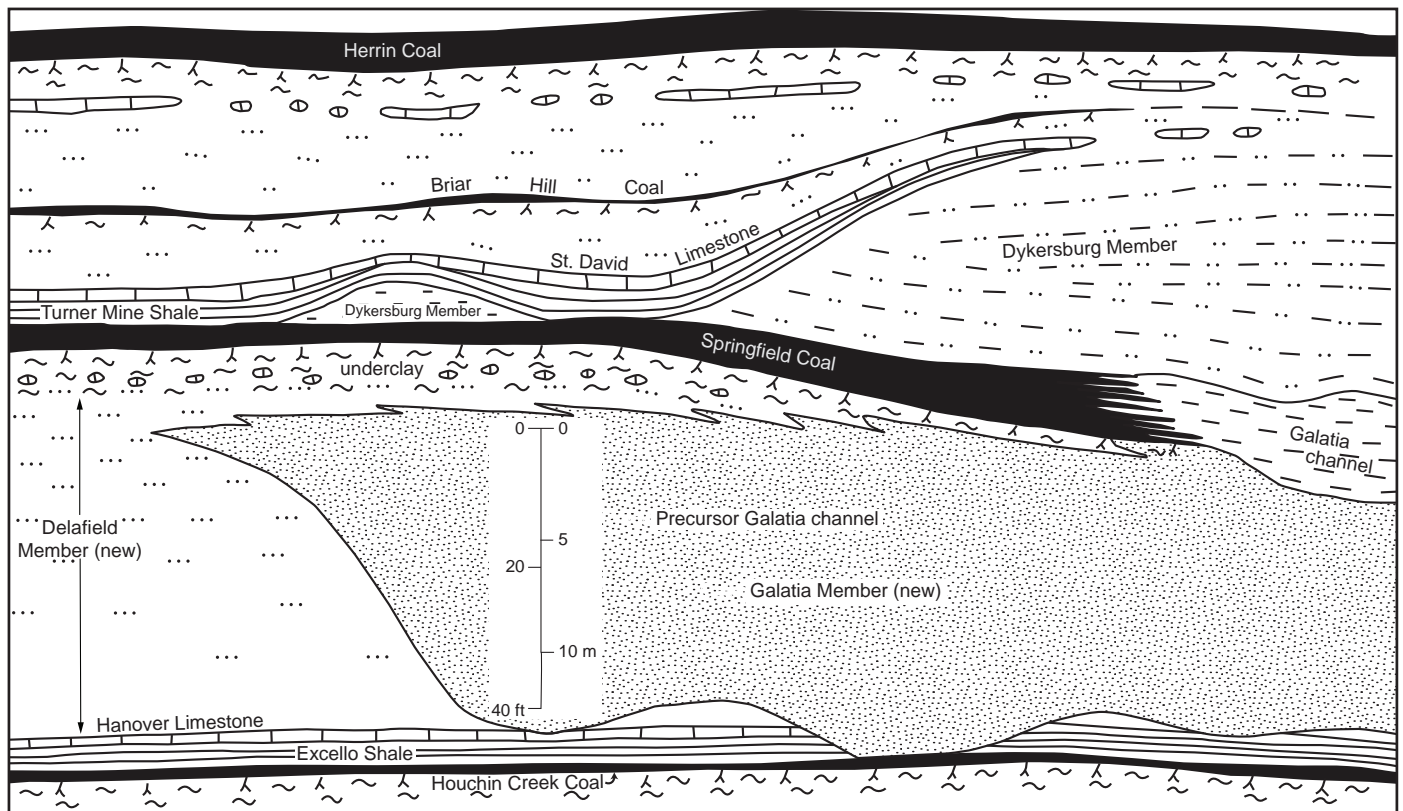
Evolution of a Peat-Contemporaneous Channel: The Galatia Channel, Middle Pennsylvanian, of the Illinois Basin

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Circular 605 2020

ILLINOIS STATE GEOLOGICAL SURVEY
Prairie Research Institute
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Front cover: *Diagram showing units between the Houchin Creek and Herrin Coals, including members newly named in this report.*

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ABSTRACT

For more than 40 years, geologists have understood that the thickness and quality of the Springfield Coal are intimately related to the Galatia channel, a paleochannel that existed contemporaneously with peat deposition. Early models envisioned a setting similar to the Mississippi delta, in which the river periodically breached its natural levees and carried crevasse splays of gray mud (Dykersburg Shale) into flanking peat swamps, shielding peat from a later influx of sulfur-bearing marine water and sediment. Using new findings and reinterpreting old maps, we present a new model for Galatia channel development. Before the formation of Springfield peat, falling sea levels exposed the Illinois Basin area to soil development and fluvial incision under a seasonal semiarid to wet subhumid climate. A “precursor” Galatia channel, carrying a bed load of sand, formed a meander belt several miles (kilometers) wide. Under a progressively more humid climate at glacial maximum, vegetation cover flourished and Springfield peat accumulation took place. As inferred under previous models, the thickest peat formed in lowlands flanking the channel. Dense, strongly rooted vegetation stabilized channel banks and restricted upstream sediment runoff. As a result, meanders became locked into place and the Galatia became a “black-water” stream that carried only fine suspended sediment. Some of this sediment was carried into peat swamps along the channel margins, creating belts of shaly coal a few hundred feet (meters) wide bordering the no-coal area.

At the end of the glacial episode, the sea level rose, drowning the peat swamp and turning the Galatia channel into a broad estuary flanked by mud flats. With concurrent changes in atmospheric circulation, the Illinois Basin climate shifted from year-round rainfall to a strongly seasonal, wet-dry (monsoonal) regime. This drier climate led to reduced vegetation cover and increased soil erosion and runoff in the Galatia drainage basin. Thus, the channel carried a heavy sediment load, largely silt and fine sand. Much of this was deposited in the estuary as the Dykersburg Shale, which rapidly buried the Springfield peat to a depth of more than 98 ft (>30 m). As envisioned by earlier geologists, this thick deposit of gray,

tidally influenced sediment shielded the peat from sulfur-rich marine water and sediment that invaded the area during maximum transgression. Large-scale rafting of peat during the initial stage of transgression produced “splits” and large coal-seam disruptions.

Other channels developed at the same time as the Galatia. The south-flowing Sullivan channel in Indiana is probably an upstream segment of the Galatia. A large southeast-flowing system in east-central Illinois, named the Effingham channel, was abandoned before Springfield peat formation. The Leslie Cemetery channel in southern Indiana began as a precursor tributary to the Galatia channel that was abandoned and then reoccupied during later stages of peat formation. The poorly understood Terre Haute channel may have a similar origin.

Channels and gray-shale clastic wedges similar to the Galatia channel and Dykersburg Shale affected the Murphysboro, Colchester, Herrin, Baker, and Danville Coals. Each of these presents variations on the theme, the Herrin example being most similar to the Springfield.

We interpret coal (peat) as having formed during glacial maxima, when the sea level was lowest and global cooling pinned the intertropical convergence zone near the equator. The resulting ever-wet climate in the tropics maintained the consistently high water table required for the production and preservation of peat. A warming cycle brought deglaciation, rapid sea-level rise, and a change to the seasonal wet-dry tropical climate, which in turn caused rapid drowning and burial of the peat deposit.

The impact of the Galatia channel and its analogues on coal thickness and quality has been understood since the 1960s. Our new findings and model of origin for these channels provide insights into the driving forces behind sedimentary cycles overlooked by most previous authors.

INTRODUCTION

Since the late 1960s, geologists working in the Illinois Basin have recognized that deposits of thick coal having a relatively low sulfur content (<2%) are associated with thick, nonmarine gray mudstone and siltstone overlying the coal.

Moreover, these thick, gray sediments are associated with paleochannels that existed during peat formation. Channels contemporaneous with the Herrin and Springfield Coals, the two most important economic seams in the basin, have been identified and mapped in detail. Similar relationships involving the Murphysboro, Colchester, Baker, and Danville Coals also have been documented (Treworgy and Jacobson 1979).

Previous authors have explained these relationships by using a model based on the modern Mississippi delta. They envisioned a channel that periodically broke through its natural levees and discharged sediment-laden water into flanking peat swamps. The resulting “crevasse splays” created clastic “splits” within the peat along the channel margins. However, no natural levees have been found along the paleochannels, significant evidence exists for tidal sedimentation, and further research has shown that the Mississippi delta is probably not a good analogue for Pennsylvanian coal deposits. Hence, the model needs revision.

This study describes and explains the Galatia channel, one of the best-known examples of a paleochannel contemporaneous with peat accumulation. Such paleochannels yield key insights into the ways eustasy and climate influence sedimentation, and they add complexity to generalized models of cyclic sedimentation. A new model is presented here, which takes in the complete history of development of the Galatia channel and the landscapes of which it was a part. This model is then applied to other paleochannels in the Illinois Basin, and likely can be applied in other basins.

Geologic Setting

The Illinois Basin, also called the Eastern Interior Basin, covers much of Illinois along with southwestern Indiana and part of western Kentucky in the east-central United States (Figure 1). The Illinois Basin is an interior cratonic basin that developed progressively throughout Paleozoic time (Leighton et al. 1991). During the Pennsylvanian Period, widespread tectonic deformation took place in the Illinois Basin in response to the Ancestral Rocky Mountains orogeny (McBride and Nelson 1998) and perhaps flexural interactions with the Allegheny orogeny

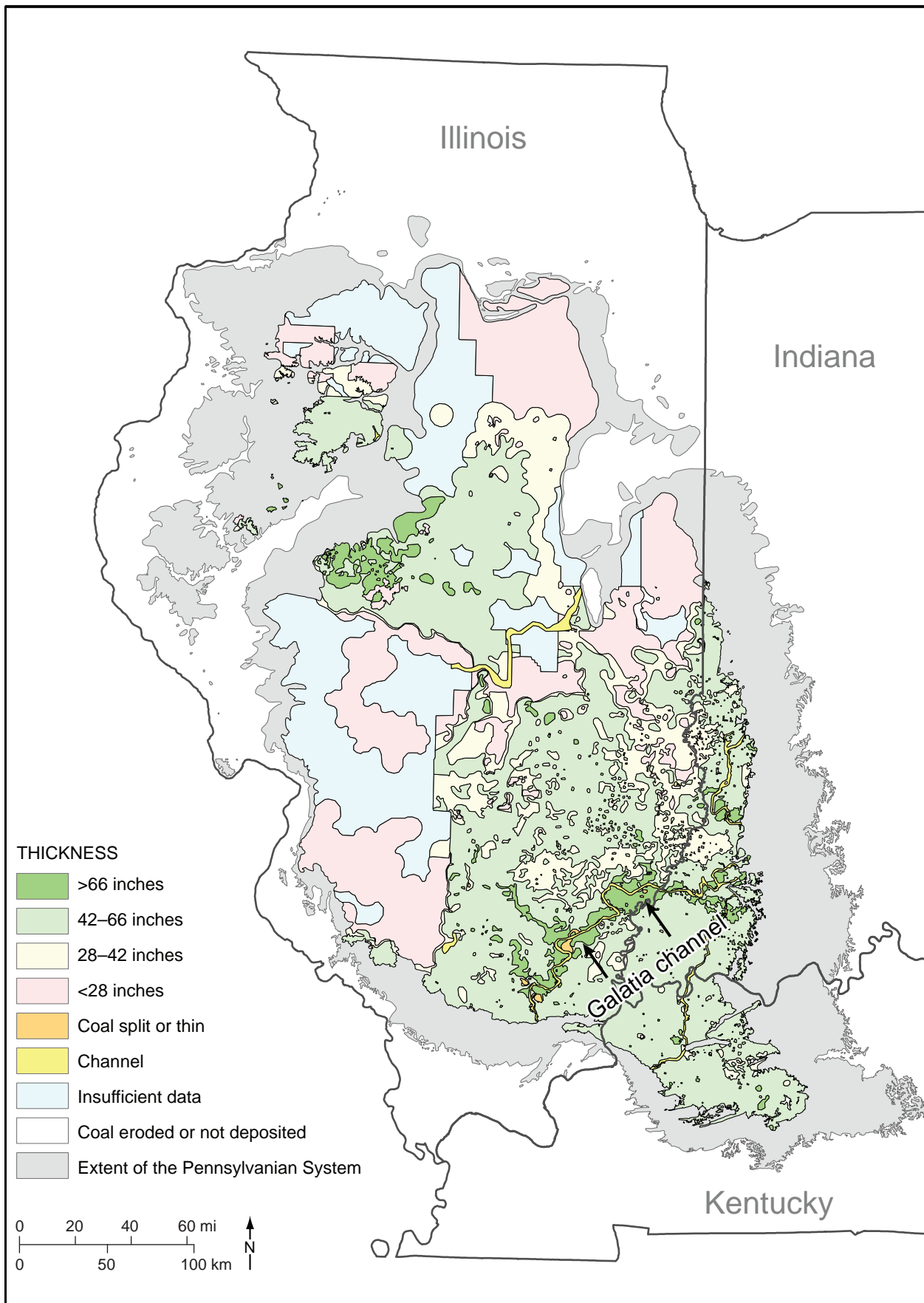


Figure 1 Map of the Illinois Basin showing the extent of Pennsylvanian rocks, thickness of the Springfield Coal, and channels interrupting the coal. From Finley et al. (2005). Straight lines separating polygons are artifacts of mapping protocol in original.

(Quinlan and Beaumont 1984). In Illinois, the La Salle Anticlinorium, Du Quoin Monocline, Salem and Loudon Anticlines, and numerous smaller structures all were active during the Pennsylvanian. In fact, the Springfield Coal thins where it crosses the Loudon Anticline and the southern part of the La Salle Anticlinorium (Plate 1), evidence that these structures were rising during peat accumulation.

On a global scale, assembly of the supercontinent of Pangaea was well underway by the Middle Pennsylvanian. Southwest of the Illinois Basin, plate collision had closed off the Arkoma Basin, and the Ouachita Mountains were rising (Houseknecht 1983). Tectonic activity was widespread throughout the Midcontinent, including the Illinois Basin (McBride and Nelson 1998). Plate reconstructions show the Illinois Basin close to, or slightly south of, the equator (Scotese 2010; Blakey 2011).

The Springfield Coal Member¹ of the Carbondale Formation is of late Desmoinesian age (Figure 2), which is equivalent to the Asturian (Westphalian D) of Western Europe and to late Moscovian on the global time scale (Davydov et al. 2012). It is informally known as No. 5 Coal in Illinois, Coal V in Indiana, and No. 9 Coal in western Kentucky. The Springfield is correlative with the Summit Coal of the Western Interior Basin and with the Middle Kittanning coal bed of the northern Appalachian Basin on the basis of physical stratigraphy (Wanless 1939), palynology of the coal (Peppers 1996), and conodonts (Heckel 2009) and ammonoids (Work et al. 2009) in associated marine rocks.

The Springfield accounts for about 29% of remaining identified Illinois Basin resources and has been the most extensively mined coal seam in the Illinois Basin (Hatch and Affolter 2002). The coal is high-volatile bituminous in rank and generally is bright-banded, having well-developed cleat and lacking significant clastic partings. Thickness varies from about 3.9 to 4.9 ft (1.2 to 1.5 m) in most areas where the coal has been mined. Thicker coal, locally exceeding 9.8 ft (3 m), is confined to the flanks of the Galatia channel.

Previous Research

With their eyes on industrial development, the scientists who made the first geological surveys of Illinois, Indiana, and Kentucky paid special attention to coal deposits. David Dale Owen first described what is now called the Springfield Coal in Indiana (1859) and in Kentucky (1856); Amos Worthen did the same in Illinois (1870). Gilbert H. Cady (1919, p. 21) may have been the first to remark on

a sandstone which occupies what seems to have been a channel running southward through the central part of the district in the west side of Raleigh and Harrisburg Townships (Ts. 8 and 9 S., R. 6 E.) [Saline County, Illinois]. This channel was apparently formed and filled before the deposition of No. 6 coal and probably during or after the deposition of No. 5 coal.

The extent of the channel north of Saline County in Illinois remained little known because the greater depth of the coal deterred mining. Over the next 50 years, other authors briefly remarked on aspects of what came to be known as the Galatia channel. Mining companies coped with channel-related features and recorded them on their maps. But until 1968, these features were known only as isolated phenomena.

Hopkins's (1968) report on resources of the Springfield Coal made a breakthrough. Using mainly electric logs from oil test holes, Hopkins mapped the coal in areas where no mining or coal exploration had taken place. Hopkins also employed the Illinois State Geological Survey's extensive database of coal quality analyses. His key findings remain essentially valid today:

- Clastic rocks replace the Springfield Coal along a southwest-trending, meandering tract across southeastern Illinois, averaging about 0.6 mi (1 km) wide. Hopkins (1968, p. 1) characterized this feature (then unnamed) as a channel "believed to be in part contemporaneous with the coal."
- Coal is abnormally thin or "split" with layers of rock close to channel margins.
- The thickest coal occurs close to the channel.

- Gray silty shale (Dykersburg Shale Member) directly overlies the coal along the channel.
- Where the Dykersburg is thicker than 19.7 ft (6 m), the Springfield Coal has a lower than normal sulfur content (2.5% or less).

Hopkins (1968) presented little geologic interpretation, aside from proposing that the channel existed during peat formation and that rapid burial by nonmarine gray mud (Dykersburg) shielded the peat from sulfur-bearing marine water and sediments.

A series of reports (Gluskoter and Simon 1968; Gluskoter and Hopkins 1970; Allgaier and Hopkins 1975; Hopkins et al. 1979; Jacobson 1983) rapidly followed, augmenting Hopkins's initial findings, developing an interpretive model, and outlining similar relationships for areas of low-sulfur coal bordering paleochannels in other Illinois coal seams. Hopkins et al. (1979, p. 148) proposed the name "Galatia channel," taking the name of a small community near the feature in Saline County, Illinois.

In Indiana, Donald L. Eggert (1978) was the first to recognize paleochannels contemporaneous with the Springfield Coal. A series of follow-up papers and reports (Eggert 1982, 1984, 1994; Eggert and Adams 1985) described the Galatia channel and related features in Gibson, Pike, and Warrick Counties. Together, these articles described relationships closely similar to those developed in Illinois, and they relied on the same interpretive crevasse-splay model.

Crevasse-Splay Model

Models applying modern deltaic processes to ancient rocks (e.g., Morgan and Shaver 1970) were in vogue when the Galatia channel was first recognized. Being close at hand and thoroughly investigated, the Mississippi delta commanded the attention of American geologists. Explicitly or otherwise, authors had the Mississippi delta in mind as they explained coal-contemporaneous channels in the Illinois Basin. Leading the way were Johnson (1972) and Allgaier and Hopkins (1975). Hopkins et al. (1979) referred to the Dykersburg and

¹Classification differs among the three state geological surveys. Indiana and Illinois regard the Springfield as a formal member, whereas Kentucky classifies all coals informally as beds.

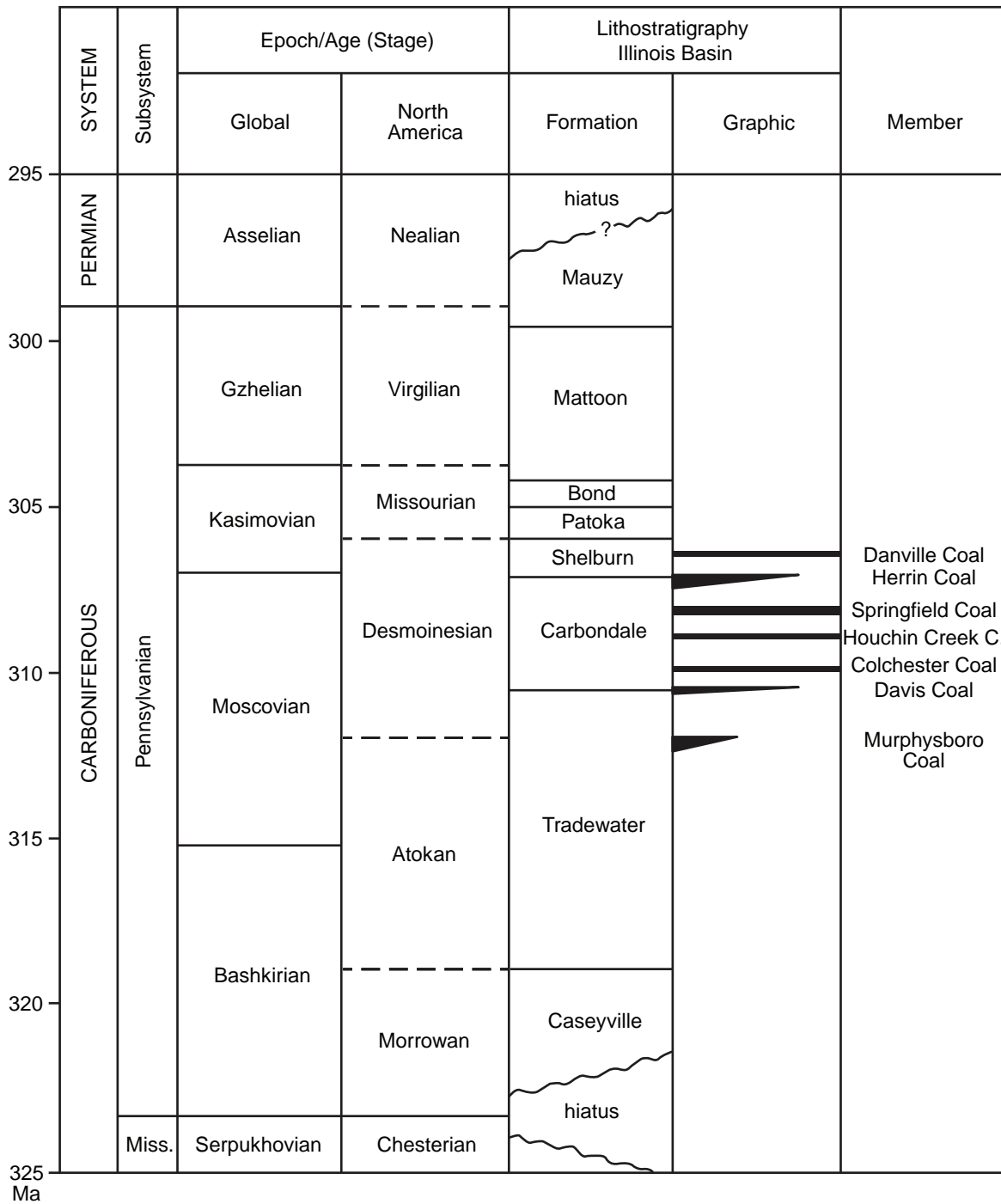


Figure 2 Correlation chart showing the positions of key units within the Pennsylvanian Subsystem. Global and provincial stage boundaries and ages in millions of years (Ma) are after Gradstein et al. (2012).

Energy Shales as crevasse-splay deposits derived from those channels. Summarizing earlier work, Nelson (1983, figure 8) illustrated Galatia channel environments, including levees, crevasse splays, and a bird-foot delta like that of the Mississippi

(Figure 3). Nelson et al. (1987, p. 12-14) departed slightly from previous scenarios, noting the lack of evidence for natural levees while continuing to place the coal and shale deposits within an overall deltaic setting. Similarly, Burk et al. (1987)

continued to interpret the origin of the Energy Shale in terms of deltaic crevasse splays.

Eggert (1982) and Eggert and Adams (1985) also explicitly related channel

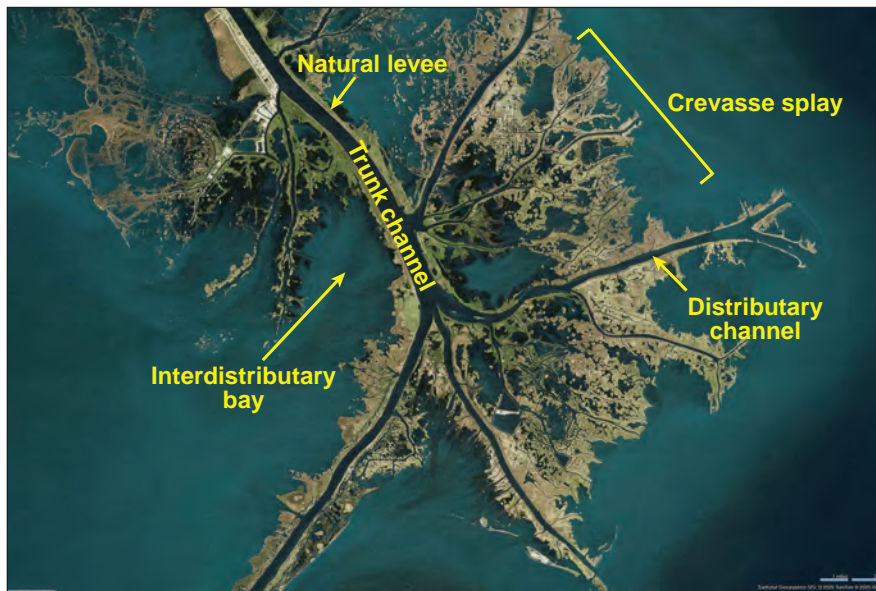


Figure 3 Satellite image of the mouth of the Mississippi River showing natural levees and crevasse splays. From Earthstar Geographic SIO, © 2020.

development in Indiana to the modern Mississippi delta. They envisioned the Galatia and associated channels as deltaic distributaries flanked by natural levees that frequently failed, spilling sediment-laden water into adjoining peat swamps. Eggert (1994) regarded the Galatia channel as part of a delta that prograded seaward during peat deposition (p. 14) and alluded to the Dykersburg Shale as lacustrine and overbank mud (p. 16).

Archer and Kvale (1993) and Archer et al. (1994, 1995) represent the first major departure from the deltaic model in the Illinois Basin. These authors recognized rhythmic lamination and other tidal signatures in Illinois gray shale associated with low-sulfur coal. Thus, they placed deposits such as the Dykersburg Shale into estuarine environments rather than fluvially dominated deltas.

Cyclicity and Sequence Stratigraphy

The Illinois Basin is the birthplace of the cyclothem. Udden (1912) recognized four cycles of deposition in Middle Pennsylvanian rocks near Peoria, Illinois; the oldest cycle included Coal No. 5 (Springfield). Weller (1930) introduced “cyclical formations”; Wanless and Weller (1932) coined

the term “cyclothem” based mainly on work in western Illinois. By this time, other workers had recognized Pennsylvanian cycles elsewhere in the United States. Among the driving mechanisms suggested were interrupted subsidence, tectonic movements, and autogenic processes such as channel avulsion and delta switching (Langenheim and Nelson 1992). Wanless and Shepard (1935, 1936) were the first to propose glacially driven eustatic changes of sea level as the driving process.

Sequence stratigraphy came into use within the oil industry in the 1970s and reached the broader geologic community with American Association of Petroleum Geologists’ Memoir 26 (Payton 1977). However, Sloss et al. (1949), who worked in Illinois, are acknowledged as pioneers. Basically, a sequence is an updated version of the cyclothem, with glacial eustasy viewed as the primary causative mechanism. A sequence is “a relatively conformable succession of genetically related strata bounded at its top and base by unconformities or their correlative conformities” (Mitchum 1977, p. 210) and represents a single cycle of sea-level rise and fall. Modern sequence stratigraphers recognize as many as five orders or levels of cyclicity and relate them to periodic changes in the earth’s climate caused by astronomical processes.

In the past 40 years, sequence stratigraphers have generated an immense amount of literature accompanied by a maze of terminology. A brief review revealed that different authors apply some of the same terms with different meanings. Ironically, sequence stratigraphy has yet to see much usage in its original homeland, the Illinois Basin. Full application of sequence concepts to Pennsylvanian rocks in this basin is beyond the scope of this report. Nevertheless, we wish to discuss rocks related to the Springfield Coal and Galatia channel in terms of their interpreted position in eustatic cycles. To avoid misunderstanding, we are using terms in the following fashion:

Lowstand: an episode when sea level was at its lowest, corresponding to the maximum extent of continental glaciers.

Transgression: an episode when sea level was rising in response to the melting of continental glaciers (deglaciation).

Highstand: an episode when sea level was highest, correlating to the maximum deglaciation.

Regression: an episode of falling sea level related to the growth of continental glaciers.

STRATIGRAPHY

This section describes, in ascending order, the rock units that enclose the Springfield Coal and Galatia paleochannel (Figure 4). To facilitate discussion of the new depositional model, two new members are proposed.

Houchin Creek Coal

Although the Houchin Creek Coal is thick enough to mine only in small areas, it is one of the most laterally extensive coal members in the Illinois Basin. With rare exceptions, the Houchin Creek is a single layer of bright-banded coal lacking significant clastic layers and resting on well-developed underclay. Pyrite content is normally 3% or higher. Thickness varies from a streak to as much as 5.9 ft (1.8 m), but coal thicker than 3.9 ft (1.2 m) is exceptional, and the usual thickness range is 7.9 to 23.6 in. (20 to 60 cm). The coal occurs throughout the

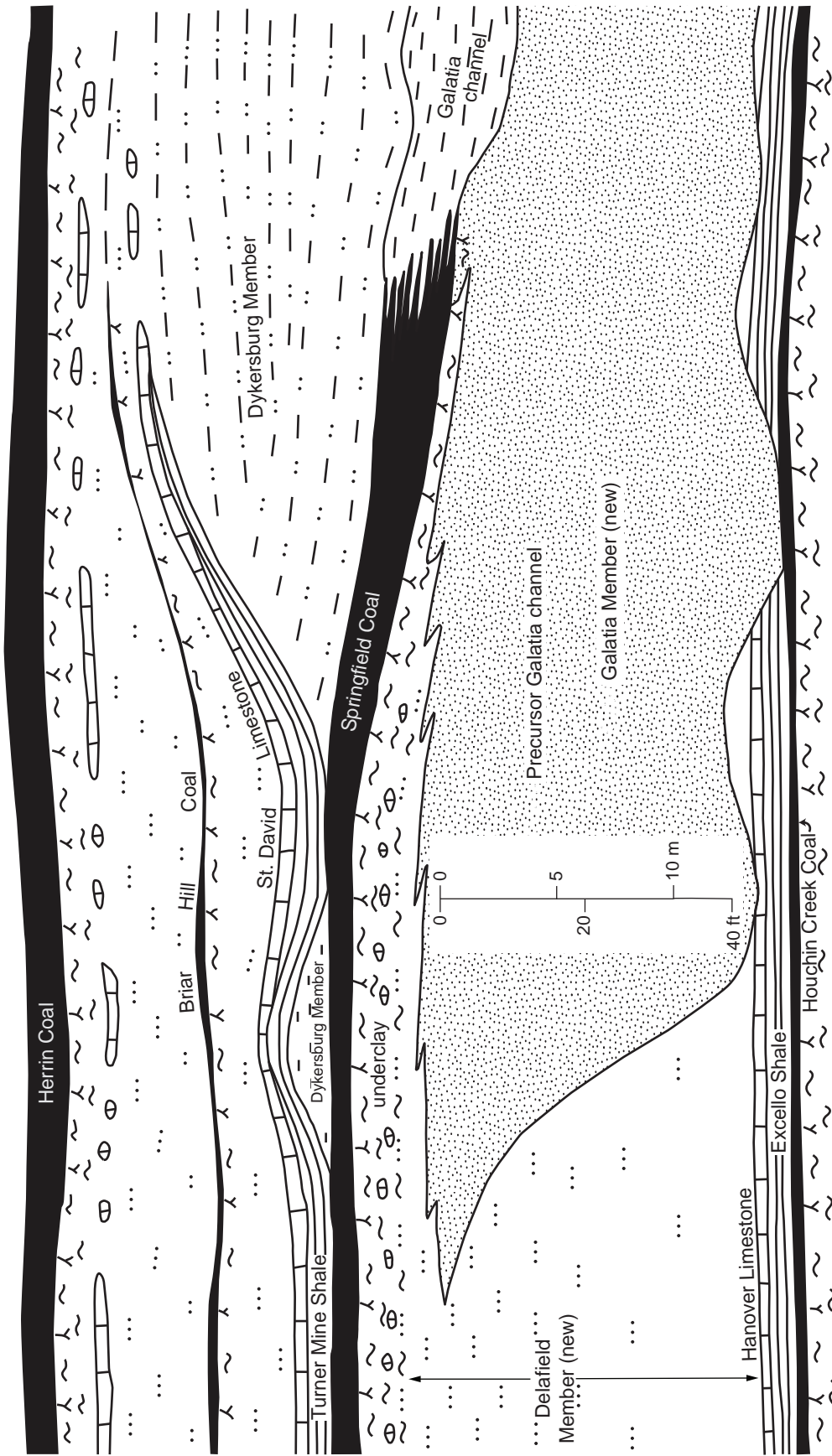


Figure 4 Diagram showing units between the Houchin Creek and Herrin Coals, including members newly named in this report.

Illinois Basin, except in a few small areas of nondeposition near the northern and western margins and in other small areas where the coal was eroded in paleochannels. With the overlying Excello Shale and Hanover Limestone, the Houchin Creek forms a package that is readily identified on nearly all types of well logs. A double-peaked, or “bird’s beak,” profile is characteristic on resistivity logs (Figure 5a). The Houchin Creek evidently represents an *in situ* peat deposit that developed on a virtually flat, tectonically stable coastal plain of great extent.

Excello Shale Member

The Excello Shale is the black, slaty, phosphatic shale that overlies the Houchin Creek/Mulky Coal across the Illinois and Midcontinent Basins. This member is typical among Middle and Upper Pennsylvanian black “sheety” phosphatic shale units of the Illinois and Western Interior Basins. It is hard, highly fissile, and well jointed, with a density lower than normal for shale because of a carbon content as high as 18.5%. Phosphatic laminae and bands of small lenses are common, as are large (to 3.3 ft [-1 m]) spheroidal dolomite concretions. The upper part of the Excello tends to be mottled, burrowed, and calcareous, grading into overlying limestone. Near its depositional limits on the western and northern basin margins, black sheety shale gives way to mottled gray, green, and olive mudstone that is weakly fissile (James and Baker 1972). The Excello carries a highly restricted marine fauna of inarticulate brachiopods, ammonoids, bivalves, fish remains, and conodonts. Articulate brachiopods have been found in their carbonate concretions (Wanless 1957, 1958). Burrows are rare, except near the upper contact. Like other black phosphatic shales, the Excello produces very high (typically off-scale) inflections on gamma-ray logs (Figure 5b). Thickness varies from a few centimeters to about 8.2 ft (2.5 m), with no regional trends evident. The Excello is nearly coextensive with the Houchin Creek Coal. The lower contact is sharp and shows evidence of erosion; in some cores, the coal is absent and the Excello rests directly on underclay.

Black shale such as the Excello clearly was deposited in marine water under anoxic reducing conditions, lacking cir-

ulation or agitation by waves and currents. Without taking account of eustasy, Zangerl and Richardson (1963) advocated deposition of black shale in shallow lagoons having floating mats of algae that impeded circulation. In contrast, Heckel (1977) placed black shale deposition during highstand under starved-basin conditions in water deep enough (330 ft [100 m]) that wind-driven circulation did not affect bottom waters. We favor Heckel’s model, but noting that he placed peat formation during transgression, we suggest that black shale developed during transgression to early highstand. Transgression was rapid (Archer et al., 2016) and often heralded by erosion or “ravinement” (Gastaldo et al. 1993). Sedimentation slowed and water circulation ceased in steadily deepening water. Peat on the sea floor consumed oxygen and contributed a great deal of carbon to bottom sediments. Rivers may have delivered additional carbon, carrying plant matter into the sea (James and Baker 1972; Banerjee et al. 2010; Holterhoff and Cassady 2012).

Hanover Limestone Member

The marine limestone member that directly overlies the Excello Shale is called the Hanover Limestone. The Hanover is regionally continuous but locally lenticular. In the deeper part of the basin, the Hanover ranges from fossiliferous shale a few inches (centimeters) thick to limestone averaging around 9.8 in. (25 cm) and rarely exceeding 19.7 in. (50 cm). The usual lithology is dark gray, very argillaceous, fossiliferous lime mudstone and wackestone. Fossils are chiefly brachiopods and echinoderm fragments, along with a few gastropods, bivalves, bryozoans, and ostracods. Shells are commonly unbroken and crinoid stems are partly articulated, indicating low depositional energy. The rock may be massive or show indistinct, wavy banding of fossil fragments and shale laminae. On the western side of the basin, the Hanover tends to be thicker (locally >9.8 ft [3 m]) and the rock is lighter colored, is less argillaceous, and contains more diverse fossils. The contact with the Excello Shale may be sharp and wavy or gradational.

The Hanover and its fauna record a return to normal marine water circulation, with near-normal salinity and oxygen content.

Bottom waters were intermittently agitated, likely below the normal wave base but within the storm wave base. Parts of the basin may have been too deep for carbonate production. Thicker and purer carbonate accumulated in shallower water on the Western Shelf. We interpret limestone deposition as occurring around highstand under a relatively dry, seasonal climate. Conversely, the switch from black shale to limestone might reflect stronger wind-driven circulation under climate otherwise unchanged (Cecil et al. 2003b).

Delafield Member (New)

Name and Definition

Between the Hanover Limestone and the base of the Springfield Coal is a thick, regionally extensive interval of shale, siltstone, sandstone, and mudstone that typically coarsens upward. The name Delafield Member is hereby proposed in reference to the community of Delafield in Hamilton County, southern Illinois.

Type Section

The type section of the Delafield Member is the core from the Energy Plus ME-13 borehole, which was drilled about 1.6 mi (2.5 km) southeast of Delafield (sec. 31, T4S, R6E, Hamilton County, county no. 25463). The member occupies the depth interval from 1,048.3 to 1,123.2 ft (319.5 to 342.4 m) in the core and is 74.9 ft (22.8 m) thick (Figure 6 and Appendix, part C). The entire core from the Energy Plus borehole is in permanent storage at the Illinois State Geological Survey (ISGS) Samples Library. The core description, a gamma-ray-density log, and other data on the borehole are on file at the ISGS Geologic Records Unit and available via the ISGS website.

Thickness and Distribution

Weiner (1961) produced a map showing the thickness of what is essentially the Delafield Member in the Illinois Basin. Wanless et al. (1963, figure 13) and Wanless et al. (1970, figure 4) published more legible versions. As reproduced here (Figure 7), the map shows that the Delafield Member thins westward from maximum values of more than 98.4 ft (>30 m) in southwestern Indiana and southeastern Illinois. The greatest known

a

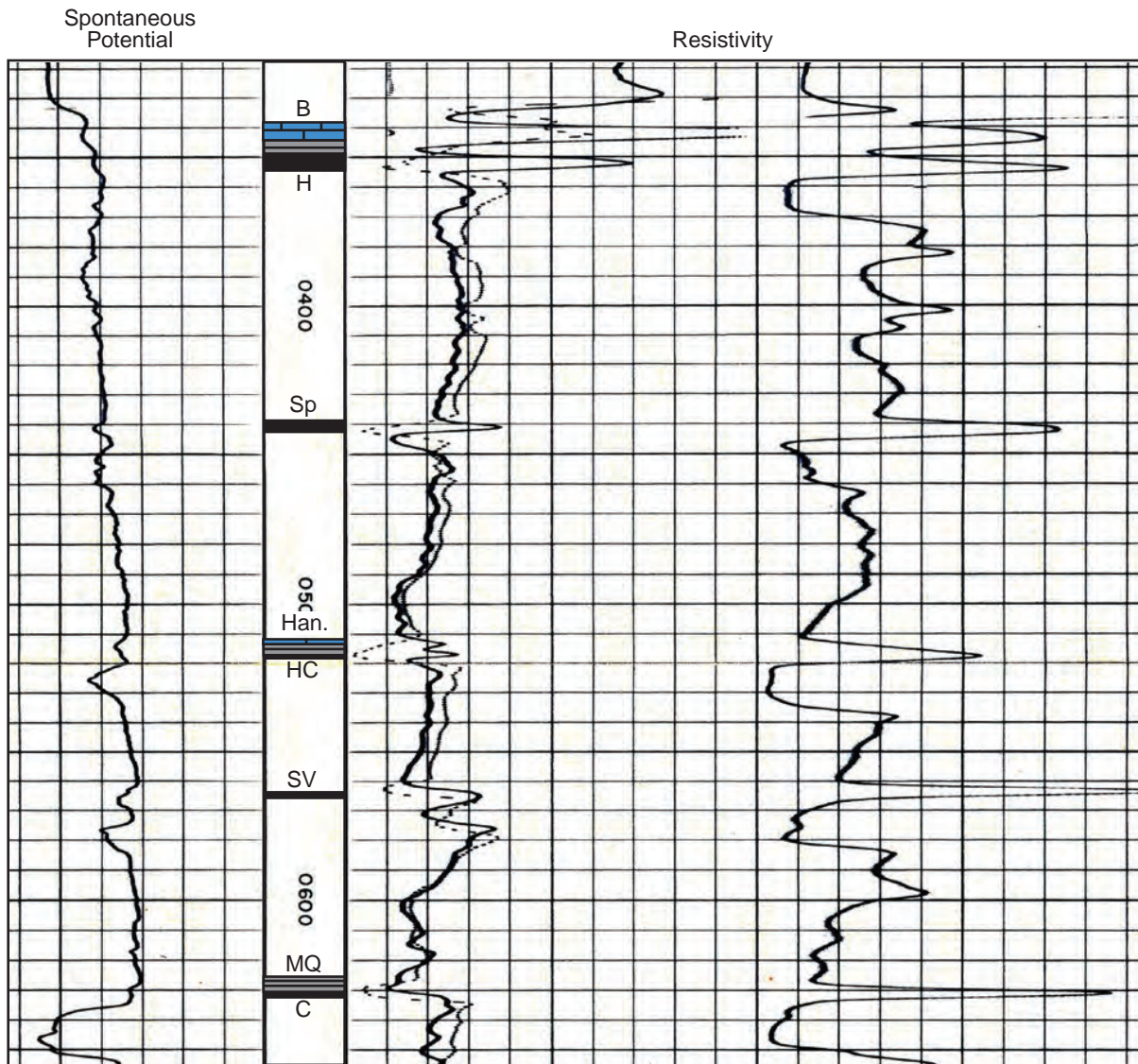


Figure 5 Wireline log illustrating the typical response of key units. (a) Electric log of Carter Oil No. 1 Beers well in sec. 28, T8S, R4E, Williamson County, Illinois (county no. 2107). B, Brereton Limestone; H, Herrin Coal; Sp, Springfield Coal; Han, Hanover Limestone; HC, Houchin Creek Coal; SV, Servant Coal; MQ, Mecca Quarry Shale; C, Colchester Coal. (b) Gamma-ray–resistivity log of Peabody Natural Gas No. 2 Short, in sec. 14, T7S, R7E, Hamilton County (county no. 25375). *Figure continues on p. 9.*

thickness is 124.7 ft (38 m) in eastern Wayne County, Illinois. The Delafield thins to less than 16.4 ft (<5 m) in much of western and northern Illinois, although the detailed pattern undoubtedly is more complex than shown in Figure 7.

Lithology

The Delafield consistently coarsens upward. Dark gray, sideritic clay-shale that contains abundant nodules and

bands of siderite is at the base. This grades upward through silty shale to siltstone and fine-grained sandstone. Shale, siltstone, and sandstone are commonly interlaminated in the upper Delafield. Structures include planar, wavy, ripple, and cross-lamination, along with slumped lamination. Definite neap-spring tidal bundles were displayed in one of the cores examined. At the top, siltstone grades upward to claystone or silty mudstone having paleosol features

(Springfield underclay). The upward-coarsening profile is evident on electric and other geophysical logs (Figure 5).

Contacts

The base of the Delafield Member is the top of the Hanover Limestone or, where the Hanover is absent, the top of the Excello Shale. This contact is sharp or gradational within an interval a few centimeters thick. The top of the Delafield is the

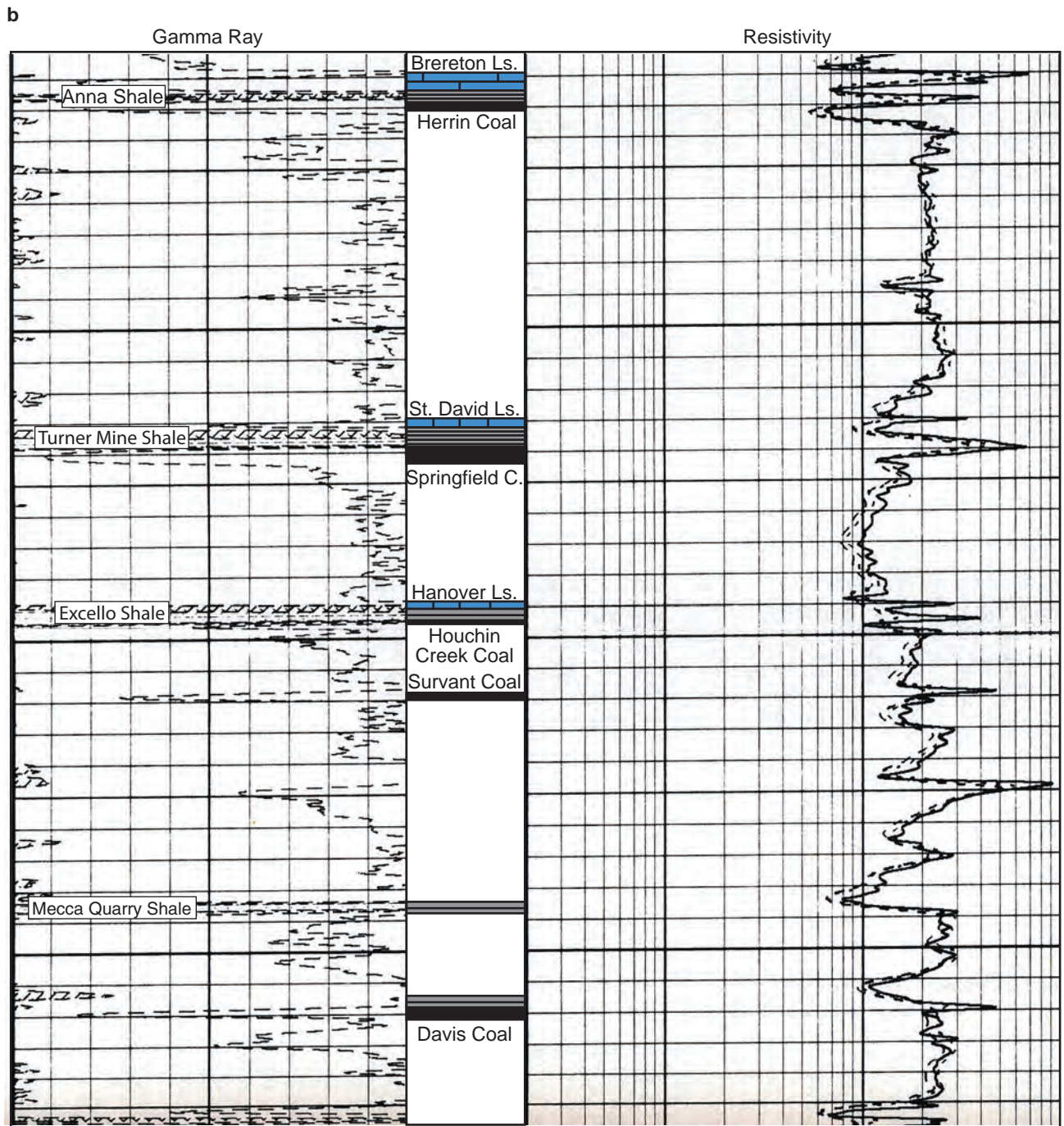


Figure 5 Continued.

base of the Springfield Coal or the base of the new Galatia Member. The contact to the coal is generally conformable but sharp, whereas the contact to the Galatia Member is erosive. Where the Galatia Member is absent, the underclay of the Springfield Coal is part of the Delafield Member.

Fossils

Fossils are scarce in the Delafield Member, but they record a transition from near-normal marine conditions at the outset of deposition to increasingly brackish water through time. Articulate brachiopods, crinoid fragments, and other marine forms occur at the base.

Above this are found rare pectenoid pelecypods, linguloid brachiopods, a single nautiloid cephalopod, and plant fragments. Burrows are present but not common. The type core contains the trace fossils *Teichichnus* and *Conostichus*, which have marine affinities.

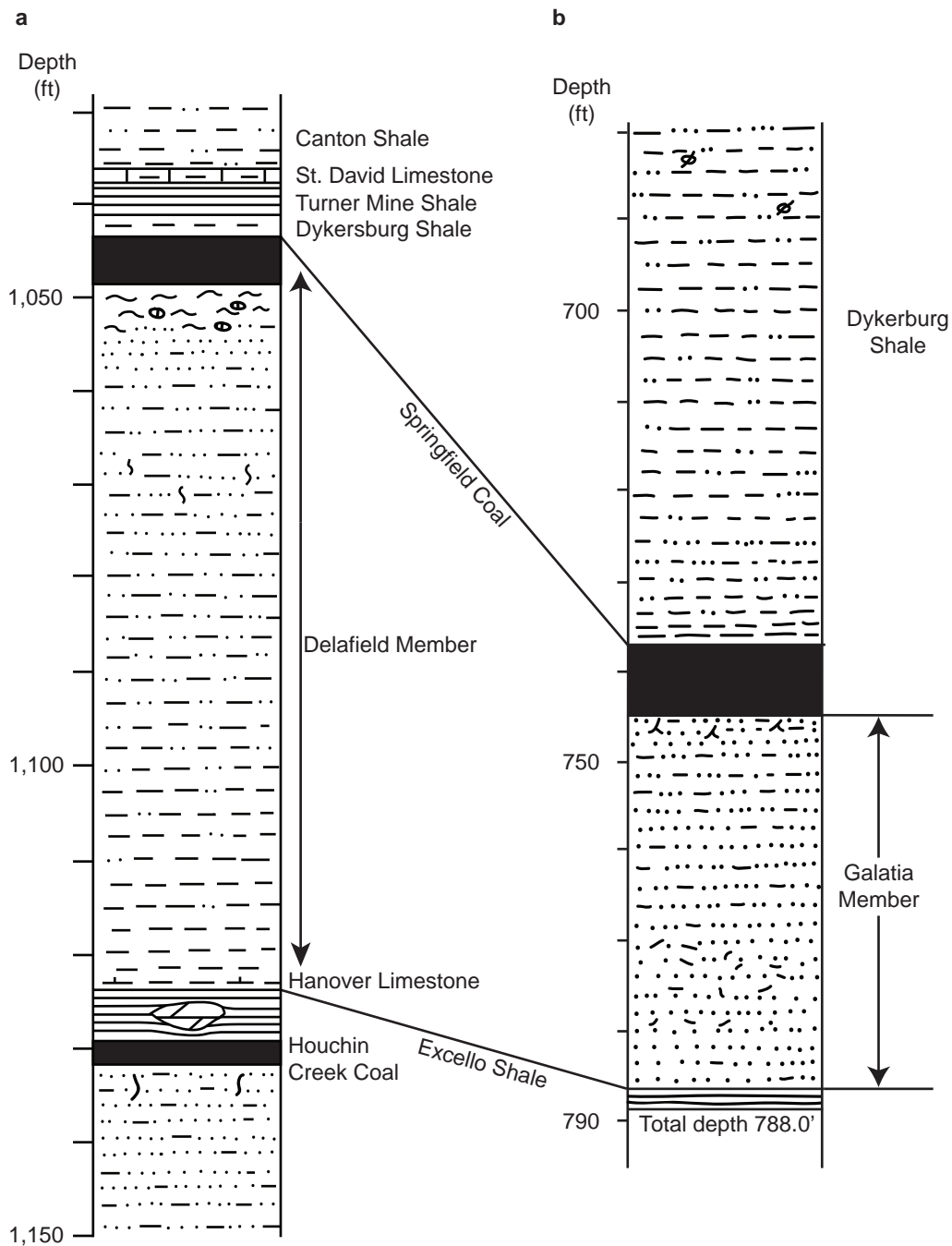


Figure 6 Graphic logs from cores serving as type sections of the newly named members: (a) Energy Plus borehole no. ME-13 in sec. 31, T4S, R6E, type section of the Delafield Member. (b) Kerr-McGee borehole no. 7629-16 in sec. 29, T7S, R6E, Saline County, type section of the Galatia Member.

Interpretation

The Delafield reflects a rapidly prograding shoreline. Deposition apparently took place in a complex of deltas and shoaling bays; normal marine salinity rapidly

gave way to brackish water. At the end of Delafield deposition, terrestrial clastics essentially filled the Illinois Basin as marginal marine sedimentation gave way to emergence and soil formation (underclay of Springfield Coal).

Galatia Member (New)

Name and Definition

Hopkins et al. (1979) named the Galatia channel, but the strata that fill the channel have not been formally named.

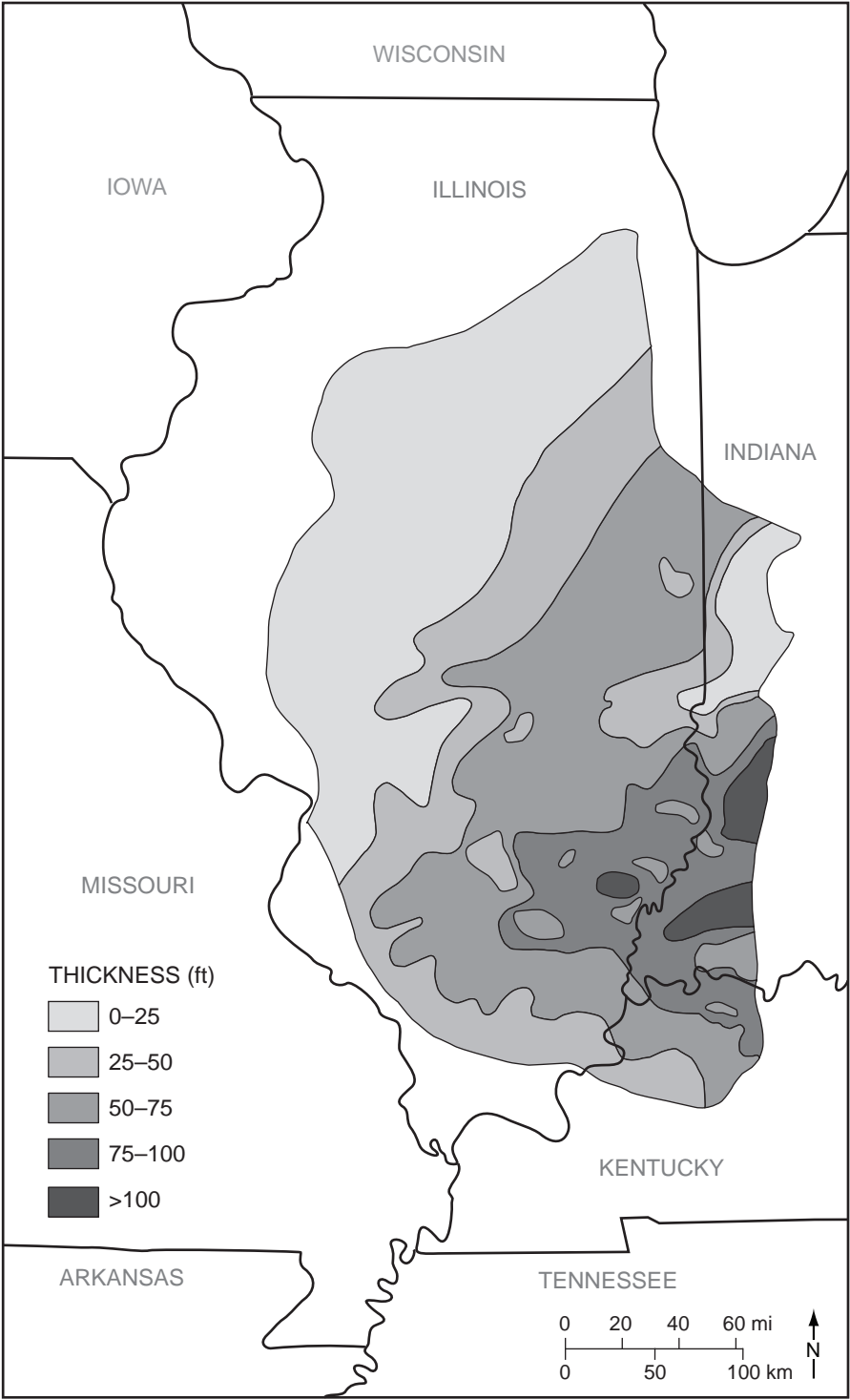


Figure 7 Isopach map of the Delafield Member. After Wanless et al. (1970). Thicknesses are in feet.

Having a name for these rocks simplifies discussion of the geology. Fortunately, the name "Galatia" is available and is hereby selected. The member takes its name from the town of Galatia in Saline County, Illinois, which is situated directly above the Galatia channel.

In this report, the Galatia Member of the Carbondale Formation is considered to comprise all rocks that fill channels that cut downward from near the top of the Delafield Member into older strata. These rocks are largely sandstone but also include siltstone, shale, heterolithic strata, and stringers of coal. Mapping discloses that the Galatia channel of Hopkins et al. (1979) is only one element in a network of paleochannels or incised valleys that traverse a large area of the Illinois Basin. Most of these channels were abandoned and filled prior to Springfield peat accumulation, but the Galatia channel itself remained as an open waterway throughout the time of peat formation. Thus, the Galatia Member is largely older than the Springfield Coal, but the upper part of the member is contemporaneous with the coal within the Galatia channel. Remaining unchanged is the Dykersburg Shale Member (Hopkins 1968), which comprises gray shale, siltstone, and sandstone lying above the Springfield Coal and beneath the black Turner Mine Shale.

Ledvina (1988, p. 638–646) used the name "Galatia Sandstone Member" for sandstone within the Galatia channel and also for lenses or tongues of sandstone within the Dykersburg Shale. However, because Ledvina's work was never published, it did not enter the U.S. Geological Survey stratigraphic lexicon, so it does not conflict with our definition of the Galatia Member. Lenses of sandstone within the Dykersburg are here considered simply part of the Dykersburg. Eggert (1982) named the fill of a paleochannel that splits the Springfield Coal in Indiana the Folsomville Member. As used by Eggert, the Folsomville is entirely within the Springfield Coal, whereas our Galatia Member is both older than and contemporaneous with the Springfield. In addition, Eggert's Folsomville Member is restricted to a single paleochannel, the Leslie Cemetery channel. Thus, the Folsomville and Galatia Members are separate entities. The Leslie Cemetery channel is discussed at greater length in a later section of this report.

Type Section

As a type section, the core from Kerr-McGee borehole no. 7629-16 is hereby selected. The hole was drilled about 4.0 mi (6.5 km) northeast of Galatia in sec. 29, T7S, R6E, Saline County (county no. 26537). Core from 7629-16 was logged by ISGS geologists and is stored in its entirety at the ISGS Samples Library in Champaign (storage number C-14933). Complete logs and other data for this hole are filed in the ISGS Geologic Records Unit and are available via the ISGS website. The Galatia Member in the type core extends from a depth of 745.4 to 786.0 ft (227.2 to 240.0 m), making the unit 40.6 ft (12.4 m) thick (Figure 6 and Appendix, part D).

Lithology

The Galatia Member is an upward-fining succession, commonly 65 to 100 ft (20 to 30 m) thick (Figure 6). The lower part is dominantly sandstone. As seen in cores, the sandstone is very fine to fine grained, locally medium grained, overall fining upward. Cross-bedding in the lower part gives way upward to rippled, wavy, and contorted or slumped laminations. Layers of shale-pebble conglomerate occur in the lower part. Also present are pebbles and fragments of siderite and stringers of coal. Upper channel filling consists of laminated to massive siltstone and silty shale or mudstone containing carbonaceous flakes and scattered plant fragments. Several cores showed rhythmic lamination, with probable neap-spring tidal cycles, near the top of the member. The uppermost part of the Galatia Member, lateral to the Springfield Coal, is largely dark, carbonaceous shale and claystone containing numerous ragged layers and stringers of coal.

Contacts

The lower contact is erosive, cutting into the Delafield Member and locally into older units, including the Houchin Creek Coal. This erosive basal contact is readily apparent in cores and in most geophysical logs. The upper contact with the Dykersburg Shale is at least locally erosive, as shown by drill cores and underground exposures in the now-abandoned Galatia Mine. Because upper Galatia and Dykersburg Members contain similar rock types, this contact can be difficult to pick

in well logs. Lacking lithologic evidence, the contact may be mapped at the elevation of the top of the coal adjacent to the channel.

Thickness and Distribution

Maps by Potter (1962, 1963), published before the Galatia channel was recognized, portray the thickness of sandstone between the Springfield and Houchin Creek Coals (Figure 8). The sandstone that Potter mapped is largely the Galatia Member of this report. Potter's 1962 map covers southeastern Illinois at a scale of about 1:250,000, whereas his 1963 map includes parts of Indiana and Kentucky at a smaller scale. An independently prepared map by Wanless et al. (1970, figure 6) shows a closely similar pattern of sandstone distribution. In addition, Hopkins (1968, plate 2) published two cross sections of the Galatia channel. Our own cross sections (Plates 2 and 3) show similar relationships.

Maps portray elongate bodies of sandstone having looping, arcuate boundaries and forming a dendritic pattern. Cross sections illustrate broad sand-filled channels or valleys that were eroded from near the top of the Delafield Member. These valleys have steep sides and broad, nearly flat bottoms.

Interpretation

Maps and sections portray a series of actively meandering, laterally migrating fluvial channels. Superimposed onto Potter's map of sandstone thickness, the Galatia channel of Hopkins (1968) coincides with a large, southwest-trending sandstone meander belt (Figure 8). Therefore, this meander belt appears to have been a direct precursor to the Galatia channel that flowed through the Springfield peat swamp. The Galatia precursor channel is the work of a river that flowed across the emerging coastal plain prior to peat accumulation. Eroding soft sediments on a low gradient, this river freely meandered and carried a large sediment load, derived partly from upland sources and partly from recycling its own banks and bed. A broad, sandy meander belt was rapidly established. Through time, the valley aggraded and stream energy declined, reducing the sediment load. Tidal influence became evident in the late stage of channel filling.

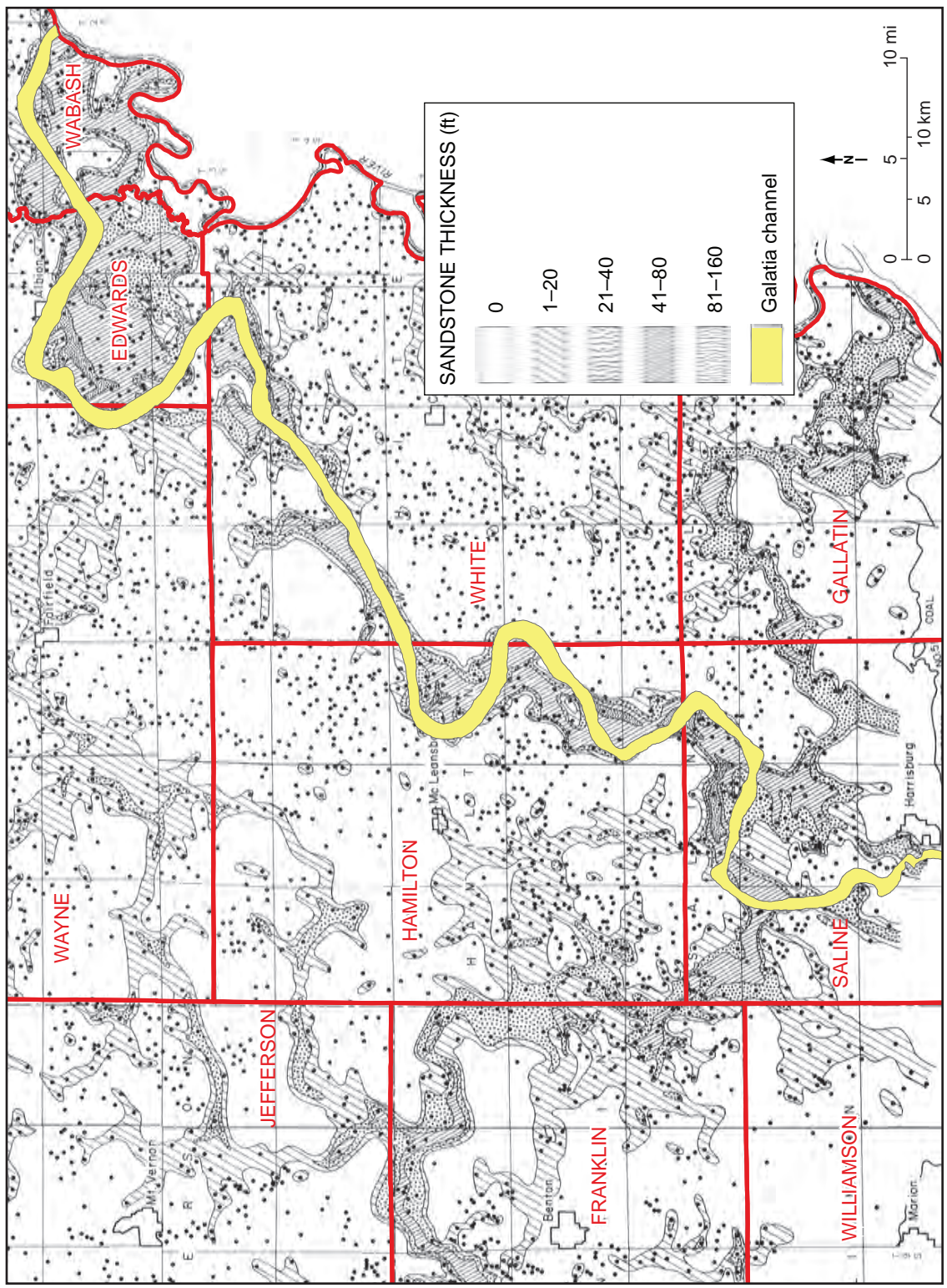


Figure 8 Map from Potter (1962) showing the thickness (in feet) of sandstone between the Houchin Creek and Springfield Coals, with the Galatia channel (from Hopkins 1968) superimposed.

Underclay of Springfield Coal

Like most coal beds in the Illinois Basin, the Springfield normally is underlain by nonfissile mudstone that miners call underclay. Features such as roots, slickensides, microscopic structures, and secondary carbonate nodules demonstrate that the underclay is a paleosol, the product of overprinting by soil development in previously deposited sediment. A paleosol is not a lithostratigraphic unit. From the stratigraphic point of view, the Springfield underclay is considered part of the Delafield Member except close to the Galatia channel, where the underclay is part of the Galatia Member.

Where the underclay is part of the Delafield Member, it is generally 4.9 to 9.8 ft (1.5 to 3 m) thick and in places reaches 13.1 ft (4 m). Black, organic-rich claystone commonly occurs at the top. The remainder is olive-gray to greenish-gray claystone that grades downward to siltstone or silty mudstone (Figure 9). All except the uppermost 1.0 to 2.0 ft (0.3 to 0.6 m) is generally calcareous and contains irregular nodules of limestone or dolomite. A solid layer of carbonate rock as thick as 3.3 ft (1 m) occurs in places. This is microgranular, argillaceous to silty, and lacks fossils other than root traces. The lower part of the paleosol is commonly riddled with irregular vertical fractures lined with siderite, calcite, and dolomite. These soils have characteristics of Calcisols and Vertisols.

Where underclay belongs to the Galatia Member, it is rarely thicker than 3.3 ft (1 m) thick and less strongly developed than in the Delafield Member. Root traces, slickensides, and granules or nodules of siderite are present, but carbonate nodules are rare and the rock is not calcareous. In places close to the Galatia channel, no paleosol is present, and the Springfield Coal grades downward to laminated, carbonaceous shale. Such soils have characteristics of Protosols.

The Springfield underclay exhibits a complex climatic history. Detailed examination (Rosenau et al. 2013) indicates that the soil formed mostly under a seasonally dry climatic regime, leading to vertic features. Late in its history, the soil underwent pronounced gleying, suggesting a change toward a much wetter climate. In places, the top of the paleosol grades into the base of the coal through a transitional

zone of organic-rich shale, suggesting the development of clastic swamps prior to the onset of peat formation.

Because the area away from the channel was topographically higher and better drained, soils developed during the entire interval of time while the Galatia precursor channel was being eroded and back-filled. Calcite nodules and caliche layers require a subhumid to semiarid climate, strongly seasonal with distinct wet and dry seasons (Cecil and Dulong 2003). In contrast, soil formation within the Galatia meander belt was frequently interrupted by lateral channel shifts. This low-lying, poorly drained, and frequently disturbed area did not permit long-term pedogenesis or caliche development. The youngest landscape, along the riverbanks, saw little or no soil development.

Springfield Coal

Thickness and Distribution

Many authors have mapped this major coal deposit. Comprehensive reports by Treworgy and Bargh (1984) and Treworgy et al. (2000) include statewide maps at 1:500,000 scale. Hatch and Affolter (2002) published (in digital form) a Springfield thickness map that covers the entire Illinois Basin.

Two large regions of thick Springfield Coal have been mapped (Figure 10). The larger of the two covers nearly all of the Fairfield Basin in Illinois, along with practically all of Indiana and western Kentucky within the coal outcrop. The coal is 39.4 in. (100 cm) or thicker across about 80% of this region, and it is consistently 47.2 to 59.1 in. (120 to 150 cm) across large areas. The thickest coal, locally exceeding 118.1 in. (300 cm), is found close to the margins of the Galatia channel. Coal thicker than 70.9 in. (180 cm) flanks the channel almost continuously in both Indiana and Illinois.

The second area of thick coal encompasses the part of north-central Illinois roughly bounded by Springfield, Decatur, Bloomington, and Peoria. Where it has been mined, the coal is generally 4 to 6 ft (1.2 to 1.8 cm) thick. The coal is thinner than 11.8 in. (30 cm) on most of the Western Shelf except for a small area near the outcrop in Perry and Randolph Counties (Figure 10).

Tectonic influence on coal thickness is evident. Not only the coal, but also the interval between the Springfield and Herrin Coals thins abruptly when crossing the Du Quoin Monocline from east to west. The Springfield also thins markedly across the Loudon Anticline and La Salle Anticlinorium, but not the Salem Anticline.

Focusing on the Galatia channel, coal thicker than 5.5 ft (1.7 m) closely corresponds to the limits of the precursor channel (Figure 10 and Plate 1). The floodplain atop the old meander belt clearly was conducive to forming and preserving peat. It is likely that peat formation commenced earlier on this floodplain than on adjacent higher ground.

Two narrow, sinuous belts of thick coal that intersect the main belt from the northwest in Hamilton County (Plate 1) probably represent small tributaries that joined the precursor channel. Potter's 1962 and 1963 maps do not show these features because Potter mapped sandstone thickness, not channels.

Hopkins (1968) mapped several areas of "thin and split" coal flanking the Galatia channel. Details of these areas are rather elusive because mines do not enter them and few cores have been drilled. One area where core drilling confirms abnormally thin coal is east of the channel in T8S, R6E, Saline County. Here, coal progressively thins from the edges inward and is absent or reduced to isolated stringers in the center. As the coal thins, the upper part becomes shaly, grading into gray shale above. Another such area, in western White County (Figure 10), has the arcuate shape of an oxbow lake.

These observations suggest that thin coal near the channel represents low-lying areas where standing water inhibited plant growth and peat production. Many such areas probably were meanders abandoned shortly before the onset of peat accumulation.

Shaly Coal Bordering the Channel

Bordering the entire length of the Galatia channel on both sides are belts of shaly coal several hundred feet (meters) wide. These exhibit a gradual lateral transition from coal without clastic layers to interlaminated coal and shale (Figure 11). Clastic layers steadily increase in



Figure 9 Photograph showing underclay of the Springfield Coal at American Coal's Galatia Mine, Saline County, Illinois. Field of view approximately 5 ft (1.5 m) square.

number and thickness toward the channel, although details differ from one place to another.

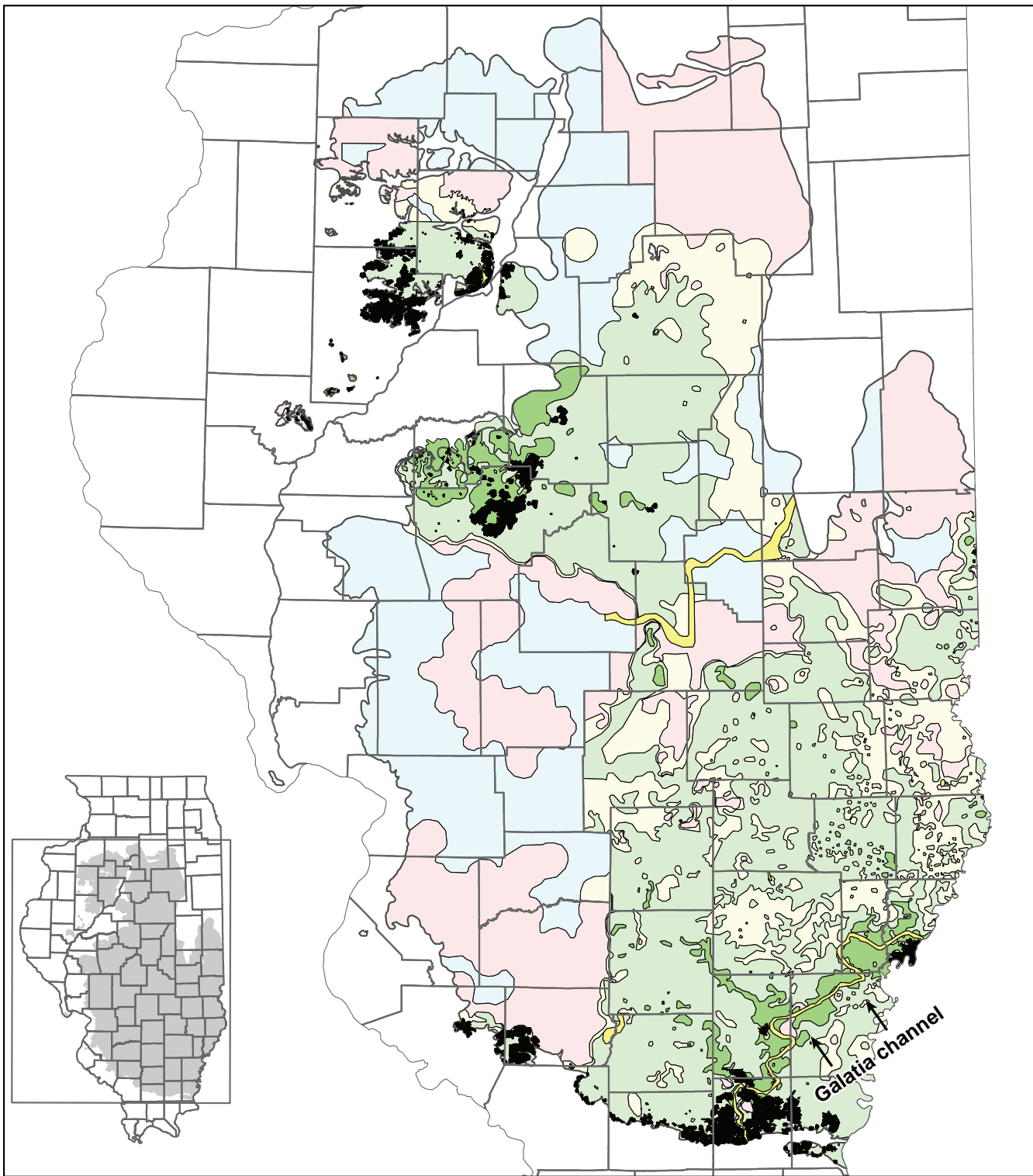
At American Coal's Galatia Mine, shale laminae first appear at the top of the seam. When approaching the channel, more and more shale layers appear, reducing the height of salable coal. Near the channel border is less than 1.6 ft (<0.5 m) of shale-free coal at the base of the seam, resting on underclay. Shale laminae are dark gray to black and loaded with carbonized plant remains, grading to dull or "bone" coal alternating with vitrain (bright coal) in laminae a few millimeters thick. Lamination is highly tabular, and the transition from bright coal to dull coal to shale is very gradual.

Cady (1919, p. 51) wrote of the old Galatia Colliery,

The lower 6 inches to nearly 3 feet [15 to 90 cm] of the coal contains layers of carbonaceous shale or "bone" that render that part of the bed unmarketable. The middle of the bed is generally fairly clean for a thickness of 3 to 5 feet [90 to 150 cm]. The upper part of the bed is again interbedded with shale, the partings increasing in number and thickness to the top of the bed, which in this mine is about 6 feet [180 cm] thick. The actual position of the top of the bed is rather difficult to ascertain because stringers of coal apparently leading out from the coal bed can be traced to as much as 5 or 6 feet [150 to 180 cm] above the coal, and in places

possibly as much as 10 feet [300 cm]. This shale contains a large amount of organic material, and impressions of leaves and stems are exceedingly numerous in the roof of the entries.

Similar conditions were encountered elsewhere in Saline County along both margins of the channel. Mines where shaly coal was encountered during the early to middle 20th century include the Galatia Colliery, Peabody No. 47, Sahara No. 16, and Sahara No. 14 west of the channel and Peabody No. 43 and Sahara No. 9 east of the channel. Several cored test holes also record shaly coal fringing the channel. In most cases, the shale partings are most numerous at the top of the seam, but in some places, they occur



Springfield Coal thickness (inches)

- | | |
|--|---|
| >66 | Insufficient data |
| 42 to 66 | Sandstone channel; no coal |
| 28 to 42 | Mined-out areas; Springfield Coal |
| 0 to 28 | Springfield Coal eroded; no coal |

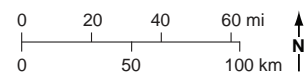


Figure 10 Map showing the thickness and mined areas of the Springfield Coal throughout Illinois. After Treworgy et al. (1999). Straight lines separating polygons are artifacts of mapping protocol in original.

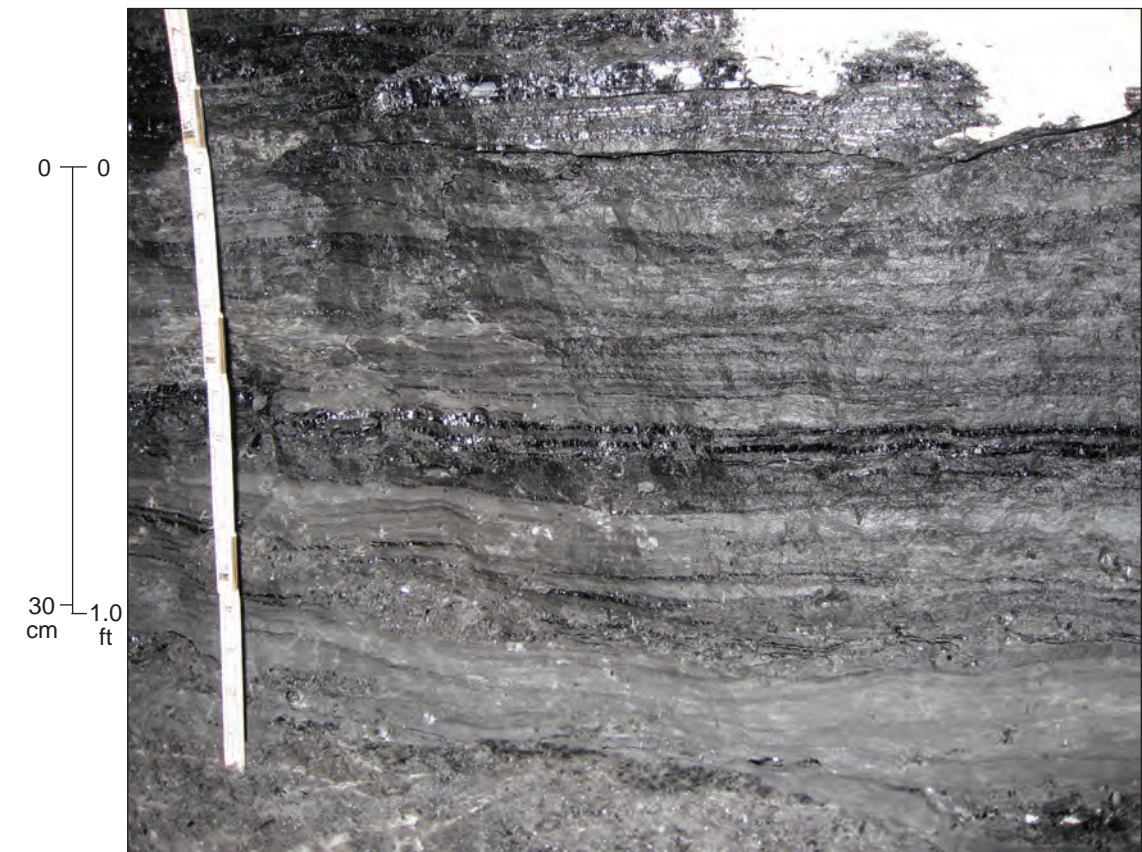


Figure 11 Photographs showing thinly interlaminated shale and dull to bright coal along margins of the Galatia channel at the Prosperity Mine in Gibson County, Indiana. The lower frame is a closer view of the upper. The ruler is graduated in 0.1-ft intervals

in the lower part as well. Where records are available, shaly coal rested on typical underclay (ISGS field notes, open files).

The transition from coal to shale at channel's edge was formerly well exposed in the Prosperity Mine of the Five Star Mining Company in Pike County, Indiana. In one area within 1,000 ft (300 m) of the channel, the seam was more than 10 ft (3 m) thick and shale laminae were confined to the uppermost 8 in. (20 cm). In another area of the mine, shale laminae appeared first near the base of the seam and made a vertical transition between the weakly fissile, rooted shale below through shaly coal to the normal coal above. The shaly zone thickened gradually toward the channel.

Belts of shaly coal record constant infiltration of water bearing fine suspended sediment into the peat swamp bordering the open-water channel. It is interesting that in the more than half a century since Hopkins (1968) proposed the crevasse-splay model, no natural levees have been found. The margins of the channel have been densely core-drilled because of the thick low-sulfur coal adjacent to the channel and for engineering design in underground mines. During our extensive studies in active mines and those by other geologists, no levee facies have been encountered in cores anywhere along the length of the channel. Being subaerial features, natural levees would display intensive rooting, burrowing, and probably evidence of weathering. Clastic layers within and above the Springfield Coal do not contain such features. Therefore, we surmise that vegetation flourished in standing water up to the margins of the flowing Galatia river. A buffer zone of clastic (non-peat-accumulating) wetlands lay between the channel and the peat. The plants and their interlocking roots filtered out fine clastic sediment derived from the channel. In addition, changes in acidity from peat mire through clastic wetlands to the active channel may have caused clays to flocculate along the channel margin rather than in the peat itself, following a model that has been proposed for other low-ash, low-sulfur coal deposits (Staub and Cohen 1979).

Relationship of Coal to the Channel

The path of the Galatia channel where the Springfield Coal is missing is consistently

about 0.6 mi (1 km) wide and describes a series of broad, simple, open meanders without significant cross-cutting of meanders or abandoned meanders (Plate 1). The lack of complexity indicates that the river did not migrate laterally while peat was forming or subsequent to peat formation. Evidently, interlocking roots of growing plants and tough, matted peat stabilized its banks. The river course, which freely migrated before peat began to form, was locked into place throughout the time of Springfield peat accumulation. In a similar fashion, modern domed peat deposits have partially encroached on an infilled valley that was incised during Late Pleistocene lowstand on the Rajang River delta of Sarawak, East Malaysia. One tributary, the Lassa, has been abandoned and overtopped with peat. Maps of coastal Sarawak show river bends, and in some cases individual meanders "locked" into place by peat deposits (Staub and Esterle 1993, 1994; Staub and Gastaldo 2003).

Previous authors generally depicted the Galatia channel as filled with sandstone. Drill holes that penetrate the channel encounter a variety of clastic rocks, ranging from shale and claystone to siltstone, sandstone, and conglomerate. Because the Springfield is absent, ascertaining which part of the channel-fill was deposited while peat formed is not easy. By far, the best record is from the Galatia underground mine in Saline County, Illinois. To facilitate underground haulage and ventilation, the company drove a set of mine entries, or "headings," completely across the channel. A detailed profile (Figure 12) is based on exposures in these headings, combined with closely spaced cores that were drilled to plan the channel crossing. In the heart of the channel, rhythmically laminated siltstone to very fine sandstone of the Dykersburg Member rests on dark, carbonaceous shale and claystone of the Galatia Member with an erosional contact. Near the north end of the crossing, the carbonaceous shale and claystone grade laterally into shaly Springfield Coal. The erosive contact between Dykersburg siltstone and Galatia dark shale was observed both in the mine and in drill cores (Figure 13).

These observations are consistent with the fact that along the entire length of the Galatia, the coal intergrades with shale or claystone rather than siltstone

and sandstone. Together, these findings indicate that during the time of peat formation, the Galatia river carried mostly (and possibly only) clay, rafted bits of peat and vegetation, and finely dispersed the organic matter. This light sediment load contrasts with the heavy bed load of sand in the "precursor" channel prior to peat formation. Thus, the Galatia during the time of peat accumulation may have been a "black-water stream" similar to many found in modern ever-wet, densely vegetated tropical wetlands (Cecil et al. 2003a, 2003b). Modern black-water rivers are restricted to regions having an ever-wet or perhumid climate, meaning that rainfall exceeds evapotranspiration the year around. Such a climate promotes lush vegetation growth, which stabilizes the landscape and inhibits soil erosion. In contrast, soil erosion and the fluvial sediment load peak under a monsoonal regime having prolonged alternating wet and dry seasons. A long annual dry season leaves much of the ground unprotected from severe gully erosion during the rainy season (Cecil 1990; Staub and Esterle 1993, 1994; Staub and Gastaldo 2003; Cecil and Dulong 2003; Cecil et al. 2003a). Therefore, climate change from a seasonally dry or monsoonal regime to ever-wet conditions likely heralded Springfield peat formation.

Dykersburg (Shale) Member

Definition

Hopkins (1968) assigned the name Dykersburg Shale (Figure 4) to the unit of gray clastic strata that lies between the Springfield Coal and Turner Mine Shale. As discussed here, the Dykersburg comprises a variety of rock types, ranging from true fissile shale to weakly fissile, laminated, and massive mudstone, siltstone, and sandstone. On this basis, the name "Dykersburg Member" seems more appropriate than "Dykersburg Shale." However, the latter term has been used by nearly all previous authors.

Chronologically, the Dykersburg is younger than the Springfield Coal, and it is younger than the Galatia Member and the channels it fills. Cores and exposures in underground mines show the Dykersburg in erosive contact with the Galatia Member. However, the Galatia and Dykersburg Members contain similar rock types and are difficult to distinguish



Figure 13 Photographs showing the ragged, erosive contact between the light-colored siltstone of the Dykersburg Member and the underlying coaly shale of the Galatia Member in the channel crossing at the Galatia Mine, Saline County, Illinois. (a) View of the east wall of the entry. Coaly shale of the Galatia Member grades laterally northward (left, out of view) to shaly Springfield Coal. The pick is approximately 2 ft (60 cm) long. (b) Close-up view on the west wall of the entry. The heart of the Galatia channel is south (left) of view. Notice how erosion undercut the clay below layers of tough, fibrous peat.

in well logs other than cores. In addition, wedges of Dykersburg locally split the Springfield Coal and separate the coal from its underclay. This is a seeming paradox—a younger unit within and beneath an older one. The unusual processes that caused this anomaly are addressed later in this report.

Thickness and Distribution

The Dykersburg is closely associated with the Galatia channel. As mapped by Hopkins (1968) and Eggert (1994), the Dykersburg occupies an irregular southwest-trending belt along the Galatia channel (Figure 14). This belt widens from about 9 to 12 mi (15 to 20 km) in Indiana to nearly 31 mi (50 km) in southern Illinois. Distribution of the shale relative to the channel is not symmetrical. Most of the thick shale is southeast of the channel in Indiana, whereas thick shale in southern Illinois is largely northwest of the channel. In places, the Dykersburg is missing right up to the channel margin. Maximum thickness of the Dykersburg increases from about 15 mi (24 m) in Indiana to as much as 24 mi (38 m) in Saline County, Illinois.

Beyond areas of thick, continuous Dykersburg, the member occurs as isolated pods and lenses that are typically 3.3 to 9.8 ft (1 to 3 m) thick and several tens of feet (meters) to roughly 328.1 ft (100 m) across. These are known mostly from exposures in underground mines. Including these lenses, the width of the Dykersburg tract is 49.7 to 55.9 mi (80 to 90 km) along the southern outcrop. The extent of Dykersburg lenses farther north is poorly known because less underground mining has taken place there.

Lithology

Medium to medium-dark gray silty mudstone and fine- to coarse-grained siltstone are the most prevalent rock types. Mudstone generally shows bedding or lamination but is weakly to moderately fissile. Much of the siltstone is nearly massive. Sandstone becomes common where the Dykersburg is thickest. The sandstone is light gray and very fine to fine grained, occurring as laminae, lenses, interbeds, and larger lens-shaped bodies. Volumetrically minor, dark gray fissile clay-shale (no silt) is mostly con-

finied to the basal part of the Dykersburg, in contact with the Springfield Coal.

Regular bands, nodules, and small concretions of siderite are common in finer grained facies of the Dykersburg. Small pyrite nodules occur in dark, carbonaceous shale, especially near the base of the member.

Sedimentary structures are mostly small scale. Planar, wavy, ripple, flaser, and cross-lamination are most common. Small load casts, ball-and-pillow structures, and deformed or contorted lamination (soft-sediment deformation) also are commonly seen. No cross-bedding in sets thicker than a few centimeters has been encountered.

Much of the lamination in the Dykersburg is strongly rhythmic. Specifically, bundles of thin clay-rich laminae alternate with bundles of thicker silt- or sand-rich laminae (Figures 15 and 16). This style of lamination is diagnostic of tidal settings with neap and spring tidal cycles (Archer and Kvale 1993; Archer et al. 1994, 1995). We have observed examples of tidal rhythmites through most of the geographic extent of the Dykersburg and at various levels in vertical profiles of the unit. The only places where rhythmites are not developed are at the thin edges of the Dykersburg, where the member is reduced to isolated lenses.

Large-scale (feet) inclined bedding has been encountered in underground mines close to the Galatia channel. Bedding of the Dykersburg intersects the top of the coal at angles as steep as 30°, although 15° to 20° is more usual (Figure 16). Such a structure signifies the lateral accretion of wedges of sediment.

Although sandstone occurs mostly in the upper part of the Dykersburg, it locally is found directly on the Springfield Coal. Sandstone bodies are lens shaped in cross section. Their lower contacts are erosive, truncating underlying shale and forming “rolls” in the coal (see below). Some sandstone bodies are convex upward, grading laterally to siltstone and mudstone.

Fossils

Fossil land plants are widely distributed. They are profuse and beautifully

preserved in the basal layers near the Galatia channel, where the Dykersburg is thickest. Fossils are preserved as compressions; that is, they are carbonized or coalified and stand out against the gray shale matrix (Figure 17). In many areas near the channel, fossil tree stumps occur in growth position (Figure 18). Invariably, these are rooted in the top of the Springfield Coal. Rare *Stigmaria* roots, with rootlets attached, have been found in the plant-rich basal part of the shale, suggesting that a few trees were able to grow during the initial stages of Dykersburg deposition.

The only invertebrate fossils are the inarticulate brachiopod *Lingula* and pelecypods, such as *Dunbarella*. Indicative of brackish water, these forms occur chiefly on the outer margins of the Dykersburg. Trace fossils are uncommon. The few examples we have seen are mostly from cores, in the upper part of the member. They are mostly vertical and inclined burrows, some such as *Teichichnus* with gutter stacking. Horizontal burrows are rare; no trails or feeding traces have been observed. Root traces are non-existent, except at the top of the Dykersburg directly beneath the Briar Hill Coal.

“Rolls”

Miners apply the term “rolls” to bodies of shale, siltstone, and sandstone at or near the top of a coal seam. Rolls filled with Dykersburg Shale are prevalent close to the Galatia channel, where the Dykersburg is thick and relatively coarse grained (siltstone, interlaminated shale, and sandstone). They are filled with rock identical to that overlying the coal at the same site. In map view, rolls are elongate and straight to sinuous and are locally branching. Rolls commonly occur in parallel sets or swarms. In cross section, they are roughly lens shaped, with “riders” or stringers of coal overlapping one or both margins (Figure 19). Widths range from 3 to 30 ft (0.9 to 9 m), lengths from tens to hundreds of feet (meters). Similar rolls disrupt the Herrin Coal elsewhere in west-central and southern Illinois (Krausse et al. 1979; Bauer and DeMaris 1982; Nelson 1983; DiMichele et al. 2007).

Rolls evidently formed during the early stages of drowning and burial of the peat deposit. At least some rolls appear to have

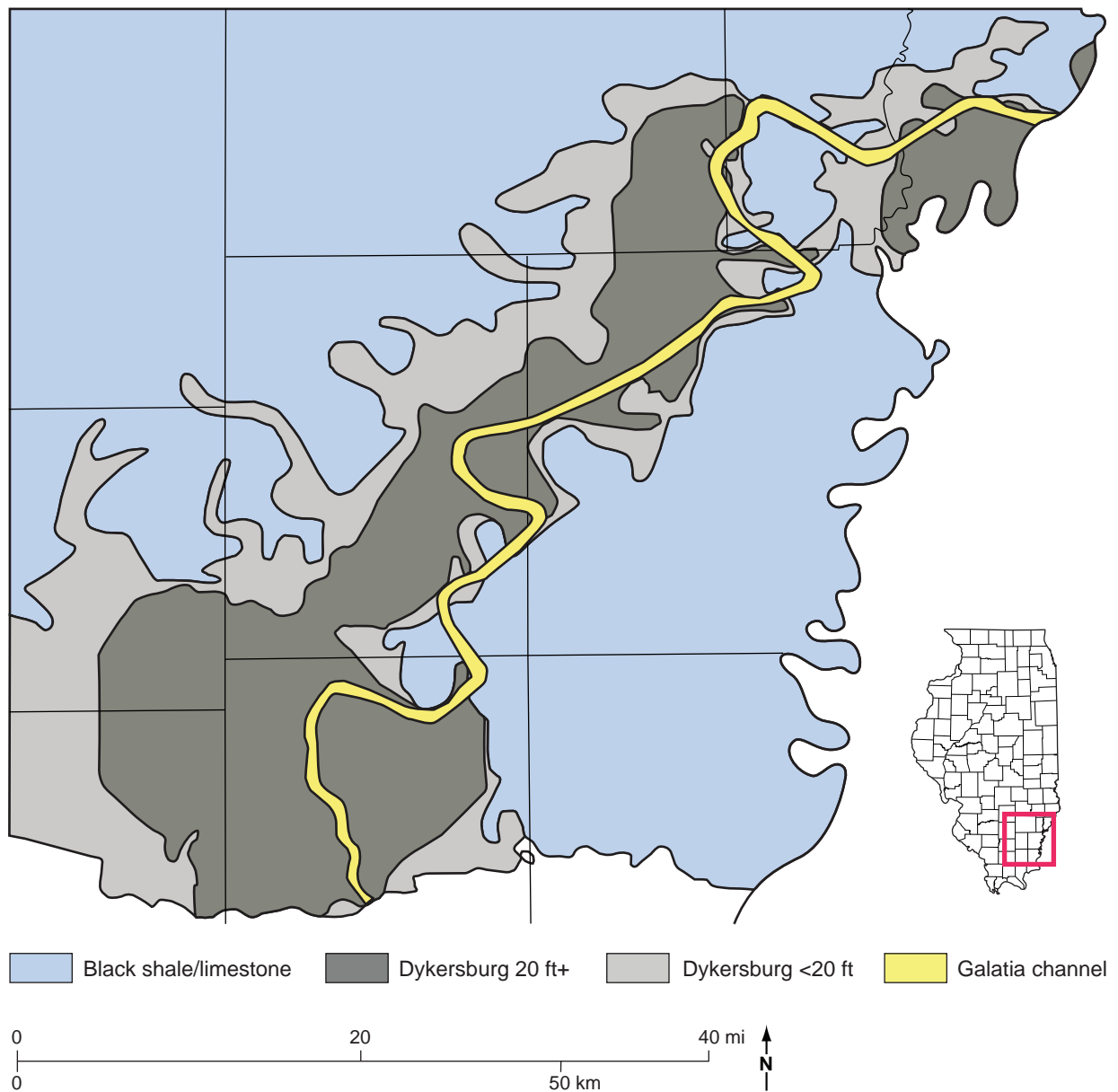


Figure 14 Map showing the thickness of the Dykersburg Member in the vicinity of the Galatia channel in southeastern Illinois. After Treworgy et al. (1999).

formed as tidal channels within the mud flats that developed along the flanks of drowning estuaries (e.g., DiMichele et al. 2007; Elrick et al. 2013). Currents scoured the peat, which, although tough and fibrous, was pliable and partially buoyant. Layers of peat were ripped out and clastic sediment filled the resulting voids. After burial, the roll filling compacted less than the surrounding peat, so the roll assumed a lens shape.

Coal “Splits”

Miners use the term “split” for a tabular or wedge-shaped layer of rock within a coal seam. Several types of splits occur in the Illinois Basin and have different modes of origin. Discussed previously are the thin layers of dark shale that are interlayered with the Springfield Coal at the margins of the Galatia channel. These simply represent sediment that washed into the peat swamp.

Markedly different are large splits in which the Dykersburg Member intrudes into the Springfield Coal. These splits are elongate lenses and tapering wedges of clastic rock that divide the coal along bedding planes. Thickness ranges from a feather-edge to more than 30 ft (9 m), with a lateral extent of up to several hundred feet (meters) in some cases. The lithology of splits closely resembles that of the Dykersburg Member overlying the

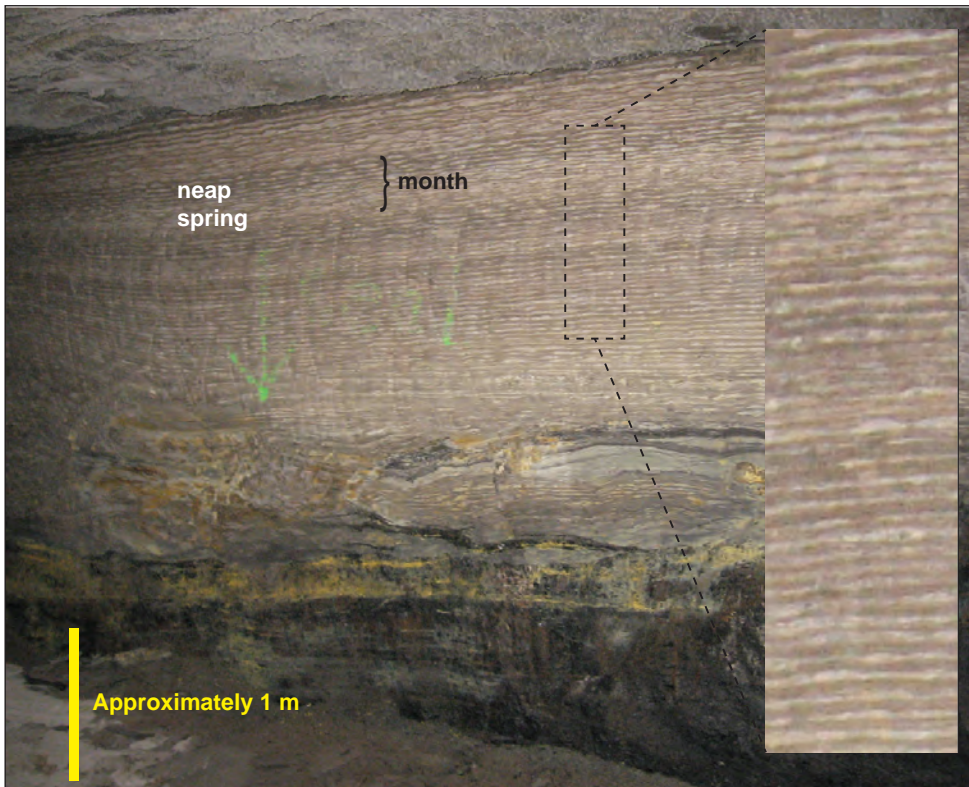


Figure 15 Photograph showing rhythmic lamination in sandy facies of the Dykersburg Member in American Coal’s Millennium Mine, Saline County, Illinois. Enlarged view at right. Reprinted from *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 487, p. 74, W.A. DiMichele, S.D. Elrick, and W.J. Nelson, Vegetational zonation in a swamp forest, Middle Pennsylvanian, Illinois Basin, U.S.A., indicates niche differentiation in a wetland plant community. Copyright 2017, with permission from Elsevier.



Figure 16 Photograph showing rhythmic lamination in sandy facies of the Dykersburg Member in the Millennium Mine, with lamination offlapping the top of the coal. Sediment thus was deposited in a wedge, prograding from left to right.



Figure 17 Photograph showing large, well-preserved fronds of fossil plant foliage (*Laevanopteris?*) in the Dykersburg Member at the Millennium Mine, Saline County, Illinois.



Figure 18 Photograph of an upright tree stump, rooted at the top of the coal and encased in mudstone of the Dykersburg Member, at American Coal's Galatia Mine in Saline County, Illinois.



Figure 19 Photograph of “rolls” at the top of the Springfield Coal, filled with Dykersburg sediments, at American Coal’s Millennium Mine in Saline County, Illinois. Ragged splaying of coal layers at the margins of rolls evokes fibrous peat layers ripped out by strong currents.

coal at the same locality. Most prevalent is medium gray, silty mudstone and siltstone, but some splits consist of very fine sandstone. The rock may be massive, or it may display indistinct horizontal to mildly contorted layering. Well-defined tidal lamination is rarely (if ever) seen.

A number of features of these splits are noteworthy and significant in interpreting their origin. Although ragged stringers and fragments of coal are abundant, identifiable plant remains are rare. No upright stems or trunks have been observed or reported. Roots and paleosol features are absent (Figures 20 and 21). “Riders” of coal detach into the clastic layer from both above and below. In some cases, coal stringers cross the clastic split

diagonally from the upper to the lower layer of coal (Figure 21). Splits of the type described here commonly occur hundreds of feet (meters) to more than 0.6 mi (>1 km) away from the Galatia channel and are surrounded by “normal” coal so that the splits lack a direct connection to the channel.

In the past, splits such as these were assumed to record clastic incursions into the swamp during the time of peat formation. Under the prevailing Mississippi Delta analogue, such splits were crevasse splays derived from breaches in natural levees along the main channel. But if clastic sediment was carried into a wetland with standing vegetation, we would expect upright stumps and other

plant remains to be preserved in the lower part of the split, as they are in the basal Dykersburg at the top of the Springfield seam. Moreover, when plant growth resumed above the split, roots should have penetrated the latter. The absence of stumps, plant remains, roots, and other soil features casts doubt on splits being crevasse splays.

As an alternative, we suggest that at least some of the siltstone splits near the Galatia channel resulted from rafting of peat layers during deposition of the Dykersburg. As rising waters drowned the peat, trapped air and self-generated gas made the upper layers buoyant. Agitated by tidal currents, the upper layers floated free of their substrate, separating



Figure 20 Photographs showing the Springfield Coal “split” by massive siltstone in the Millennium Mine. The lower view is a close-up of the upper view. Notice the ragged splaying of coal layers into the siltstone from both above and below, with one coal stringer crossing diagonally from the lower to the upper coal “bench.” Combined with the absence of roots beneath the upper bench, such geometry implies that the upper part of the peat deposit was rafted. Enlarged view at right. Brown and yellow stains resulted from iron-rich water seeping through the coal.





Figure 21 Photographs of siltstone “splits” in the Springfield Coal. (a) Upper “bench” of coal splitting into multiple layers, with ragged splaying of lower coal layers at the Millennium Mine. (b) Contact between the upper coal bench and a massive siltstone split in American Coal’s Millennium Mine, approximately 0.6 mi (1 km) west of the main Galatia channel. Notice the complete absence of root traces in the siltstone.

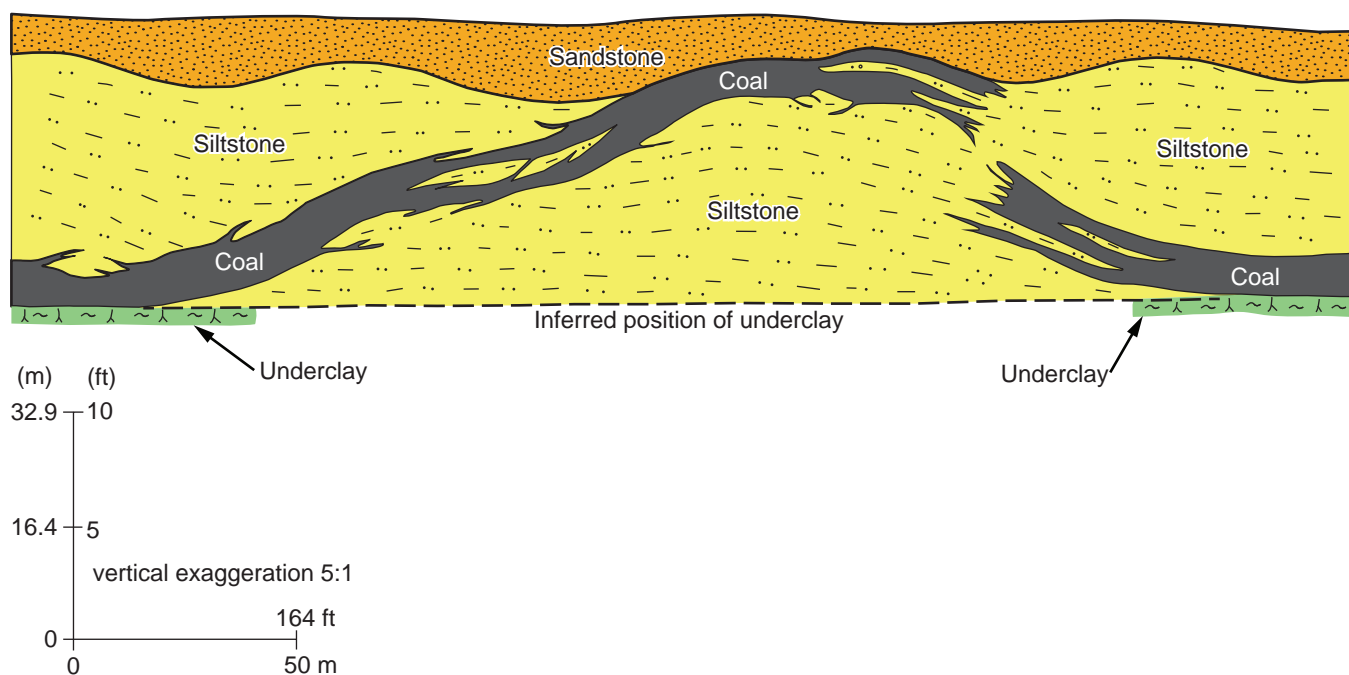


Figure 22 Profile view of the disturbance in Figure 21a in the Millennium Mine, Saline County, Illinois.

along weak bedding planes. Some of the floating layers drifted away, allowing sediment-laden water to enter beneath other peat rafts and deposit clastic layers. Obviously, no vegetation or roots grew in this setting. Stringers of peat could float upward, dangle downward, or occasionally cross from one floating peat mat to another. This activity could take place anywhere in the Dykersburg estuary, not being limited to margins of the channel that existed while the peat was forming.

Major Disturbances in Coal

Related to the planar “splits” are more dramatic disturbances of the Springfield Coal. In an example from the Millennium Mine in Saline County, Illinois (Figure 22), disturbed coal occupies an arcuate belt that is approximately 820 ft (250 m) wide and lies more than 0.6 mi (>1 km) west of the Galatia channel (as mapped by the absence of coal). There is no indication that the disturbance connects with the main channel. Within the disturbed area, the Springfield Coal rises abruptly, undulates strongly, and is torn asunder. The siltstone that underlies the coal within the disruption appears identical to siltstone overlying the coal. No roots or paleosol features occur below the coal

in the area where it rises. Normal rooted underclay (claystone) occurs below the coal outside the disturbance. The coal splays apart both above and below, and large lenses of siltstone occur within the seam. At the crest of the disturbance, the roof is water-bearing sandstone.

A smaller disturbance occurs near the slope bottom in the same mine. Completely surrounded by normal coal, the disrupted area is ovoid in map view, about 100 × 260 ft (30 × 80 m). In the central part of the disturbance, the coal is torn apart and arches upward on one or both sides. As shown by the sketch (Figure 23), in one place the torn edges overlap one another by about 33 ft (10 m) as if repeated by a thrust fault, although no fault is present. The upper end of the torn seam thins markedly, suggesting that the peat (still pliable) was stretched, accounting for the overlap.

Similar in many respects is disrupted coal encountered in the northeast part of the Sahara No. 20 Mine, also in Saline County. A map and field sketch portray part of the major disturbance (Figure 24). The entire Springfield Coal seam is torn apart, leaving ragged terminations. The southern end of the torn coal arches up, partly overlapping the northern end.

Separating the torn ends is “gray-brown, very hard massive silty mudstone or siltstone, similar to roof material” (John Nelson, field notes). Although the feature was not clearly exposed, the southern flap of coal appeared to truncate layering of the siltstone beneath. Notice on the map that the major disturbance is entirely surrounded by normal coal. Disturbances of lesser intensity lay north of the main one, surrounded on three sides by unaffected coal. These features lie several hundred feet (meters) west of the Galatia channel margin.

Also in Saline County, a large area of thin, absent, and disturbed coal interrupted the workings of the Dering Coal Company’s No. 2 Mine on the south side of the Galatia channel (Figure 25). The coal company drove entries across the disturbed area, and ISGS geologists Rolf Roley and Gilbert H. Cady sketched what they saw. By chance, an igneous dike intrudes into the coal at the eastern edge of the disturbance. On both margins, the coal splits against a blunt, rounded body of gray shale with “varve-like laminae” of light gray siltstone. The sketch indicates that coal and shale interfinger and that shale bedding is deformed in a manner suggesting forcible intrusion.

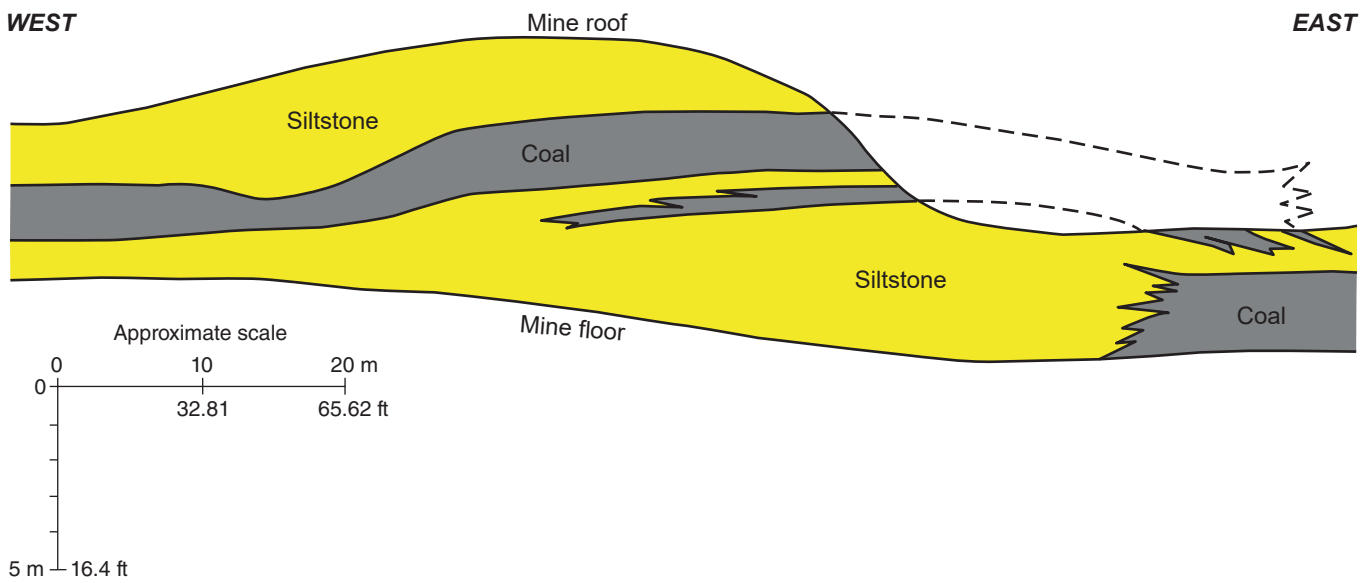
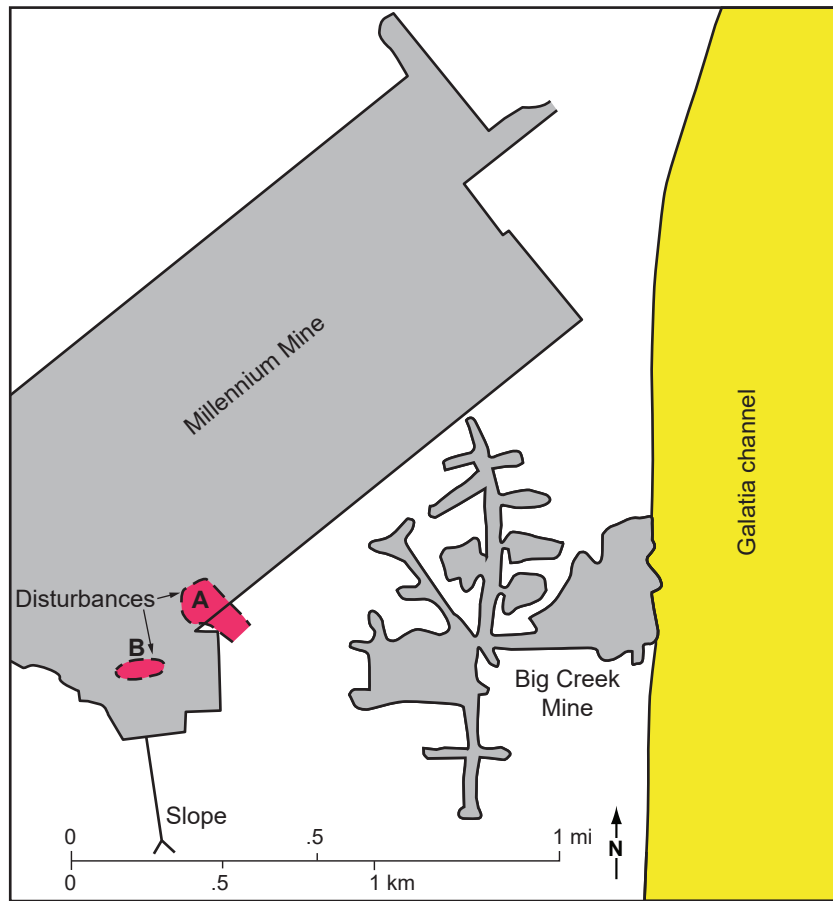


Figure 23 Profile view of the disturbance in Figure 21b in the Millennium Mine. The map shows the relationship to the Galatia channel. Location of profile is B on map.

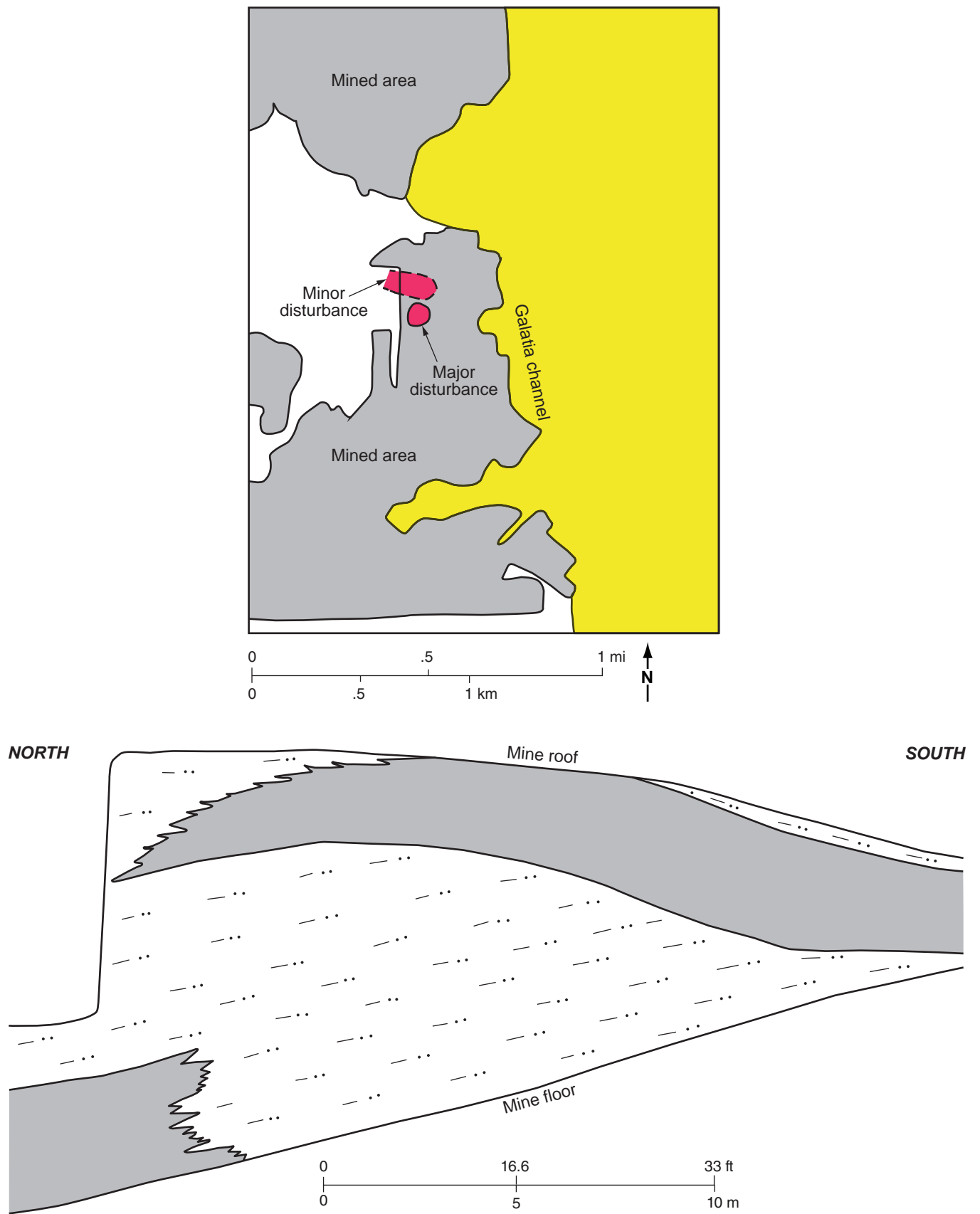


Figure 24 Map and cross section of the disturbance in the Sahara No. 20 Mine, Saline County, Illinois.

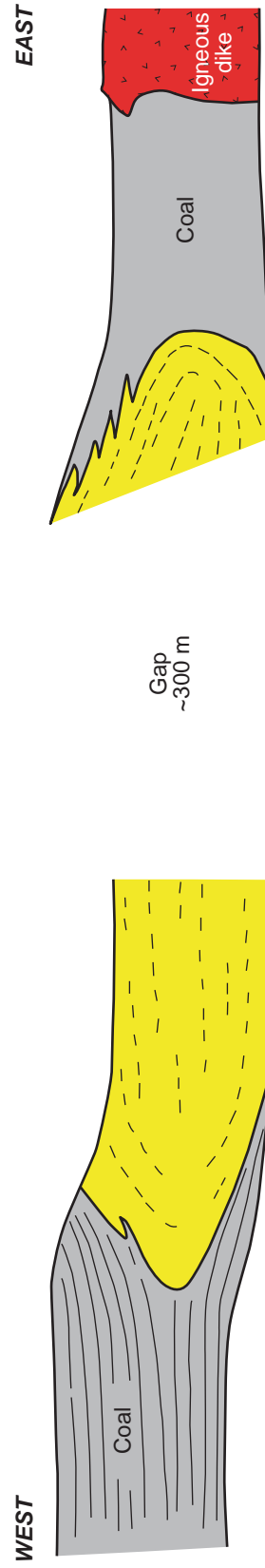
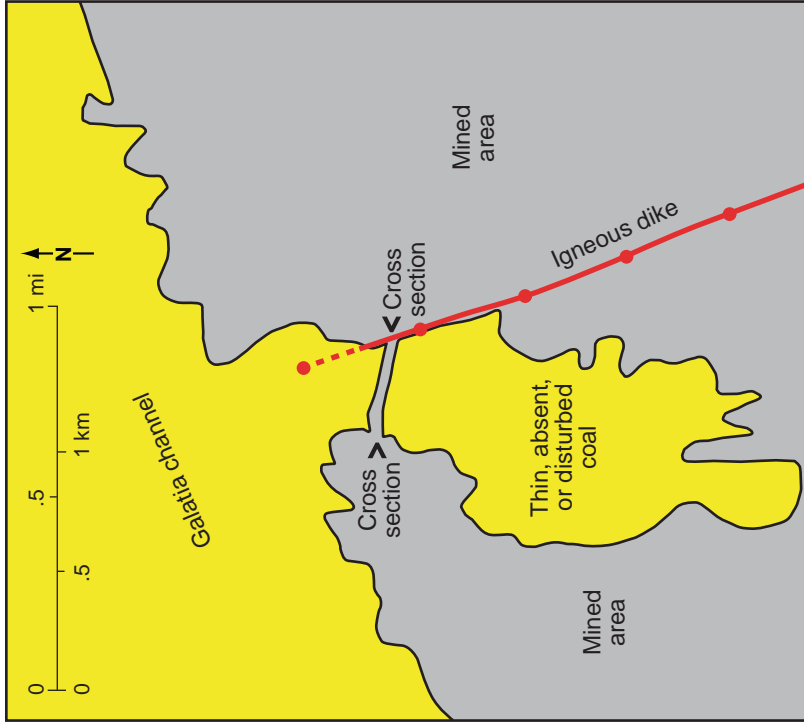


Figure 25 Map and cross section of the disturbance in the Dering Coal Company No. 2 Mine, Saline County, Illinois. Redrafted from field sketches by Rolf Roley and G.H. Cady in the ISGS archives.

Another major disturbance was encountered in the northern workings of the Wabash underground mine in Wabash County, Illinois. Meier and Harper (1981) described and illustrated the feature, supplemented by observations by ISGS geologists. Where crossed by mine entries, the disrupted area was about 656.2 ft (200 m) wide, flanked by normal coal on both sides, and lying at least 1,968.5 ft (600 m) south of the Galatia channel, as mapped by the absence of coal. Within the disturbance, the coal seam rises sharply, and the lower part is torn out in a highly irregular fashion (Figure 26). The rock that replaces and invades the coal is gray siltstone to fine-grained sandstone that is largely massive but that shows contorted lamination and contains many ragged stringers and chunks of coal. No roots or paleosol features were observed below the disrupted coal.

In the past, features such as these were generally interpreted as “splits” that formed when sediment was washed into the peat swamp, accompanied by currents that washed away some of the peat and perhaps an element of “slumping” to account for the observed deformation of layering. Specifically, Meier and Harper (1981, p. 14) invoked “wedges of fine-grained sediment, possibly a crevasse splay or overbank muds derived from the Galatia channel,” subsequently “thrown into a series of ridges and troughs, possibly by gravitational slumping on a slope formed by differential compaction.” Such models view “splitting” as contemporaneous with peat accumulation. But contemporaneous splitting cannot account for lifting the peat above its underclay, tearing it partly or entirely apart, and inserting a wedge of Dykersburg-like sediment between the coal and underclay. Explaining such geometry requires a new concept.

We propose that like the small planar splits, these dramatic disruptions formed when rising water rafted large masses of peat during the early stages of Dykersburg deposition. Rafting could involve just the upper layers or the entire thickness of the peat deposit. Agitated by tidal currents, floating peat mats frequently tore apart, admitting sediment-laden water beneath the peat. In this manner, thick wedges of mudstone and siltstone could have been

deposited within the seam and between the peat and the underclay. When currents stretched part of a torn peat mat, the ends of the mats could overlap. As the water level continued to rise, eventually the floating peat mats were completely encased in Dykersburg sediment. Differential compaction then deformed the sediment, perhaps squeezing some of it laterally. As an example, the major disturbance in the Wabash Mine is illustrated to show hypothetical ripping and rafting of peat (Figure 27).

Smaller disturbances that are completely surrounded by “normal” coal (e.g., Millennium slope and Sahara No. 20) probably began as blisters of floating peat that eventually burst, allowing sediment to infiltrate beneath. Some of the larger disruptions, such as the one in the Dering No. 2 Mine, seem to involve tidal channels that connect directly to the main Galatia channel.

Absence of Natural Levees

We have already shown that no natural levees flanked the Galatia channel while the Springfield peat was accumulating. Likewise, no levees existed during deposition of the Dykersburg Member, and this member and this unit appear to have been deposited in estuarine sedimentary environments rather than as crevasse-splay deposits, as proposed by previous authors.

Natural levees of the modern Mississippi Delta are seldom higher than about 6.6 ft (2 m) and are routinely overtopped by the floods that sustain them. Levees are composed of intermixed clay, silt, and sand exhibiting a variety of sedimentary structures, especially climbing ripples. These sediments are intensively rooted and burrowed, and they contain plentiful diagenetic iron carbonate (siderite) and iron oxide nodules (Coleman 1976). Inferred natural levees in Pennsylvanian rocks of eastern Kentucky likewise are mostly less than 5 ft (1.5 m) high and 500 ft (150 m) wide, although a few are larger. These comprise a poorly sorted, unevenly layered mix of claystone, siltstone, fine sandstone, and thin lenticular coal. Rooting is prevalent. Bedding typically dips gently away from the parent channels (Baganz et al. 1975; Horne et al. 1978).

Abundant continuous cores and underground mine exposures in the Dykersburg Member, including the continuous profile in the Galatia Mine, show no bioturbated strata that could be compared to modern natural levees. Crevasse splays cannot develop without natural levees. As Coleman (1976) explained, a crevasse splay is basically a small delta having its own distributary channels, delta front, and prodelta deposits. Crevasse splays are fan-shaped in map view and wedge-shaped in cross section. The coarsest sediments drop out close to the levee break; as the splay progrades into the bay or marsh, it develops an upward-coarsening profile. Although the Dykersburg Shale locally displays upward-coarsening sequences, in most cases the grain size is either uniform throughout the member or varies in a random fashion.

Origin of the Dykersburg Member

Many features of the Dykersburg Member point to rapid deposition in a tidal regime:

- Burial of tree stumps in the growth position
- Superb preservation of delicate plant fossils
- Sparse brackish-water invertebrate fauna
- Scarce burrowing and the absence of rooting
- Scouring of peat tops (rolls)
- Large-scale splits involving rafted peat
- Prevalent tidal rhythmites
- Common slump and load features
- Large-scale clinof orm bedding

The Dykersburg occurs in narrow bands on either side of the Galatia channel. Although the pattern is intricate, the Dykersburg belt overall widens toward the southwest, resembling a funnel in map view (Hopkins 1968). The pattern is consistent with an estuary, as Archer and Kvale (1993) proposed. This estuary developed when a rapid rise of sea level drowned the coastline. The Francis Creek Shale overlying the Colchester Coal and the Energy Shale overlying the Herrin Coal are close analogues to the Dykersburg, and they share nearly all the features listed above. Estuarine models have been proposed for both the Francis Creek (Kuecher et al. 1990; Baird 1997) and the Energy Shale (DiMichele et al. 2007).

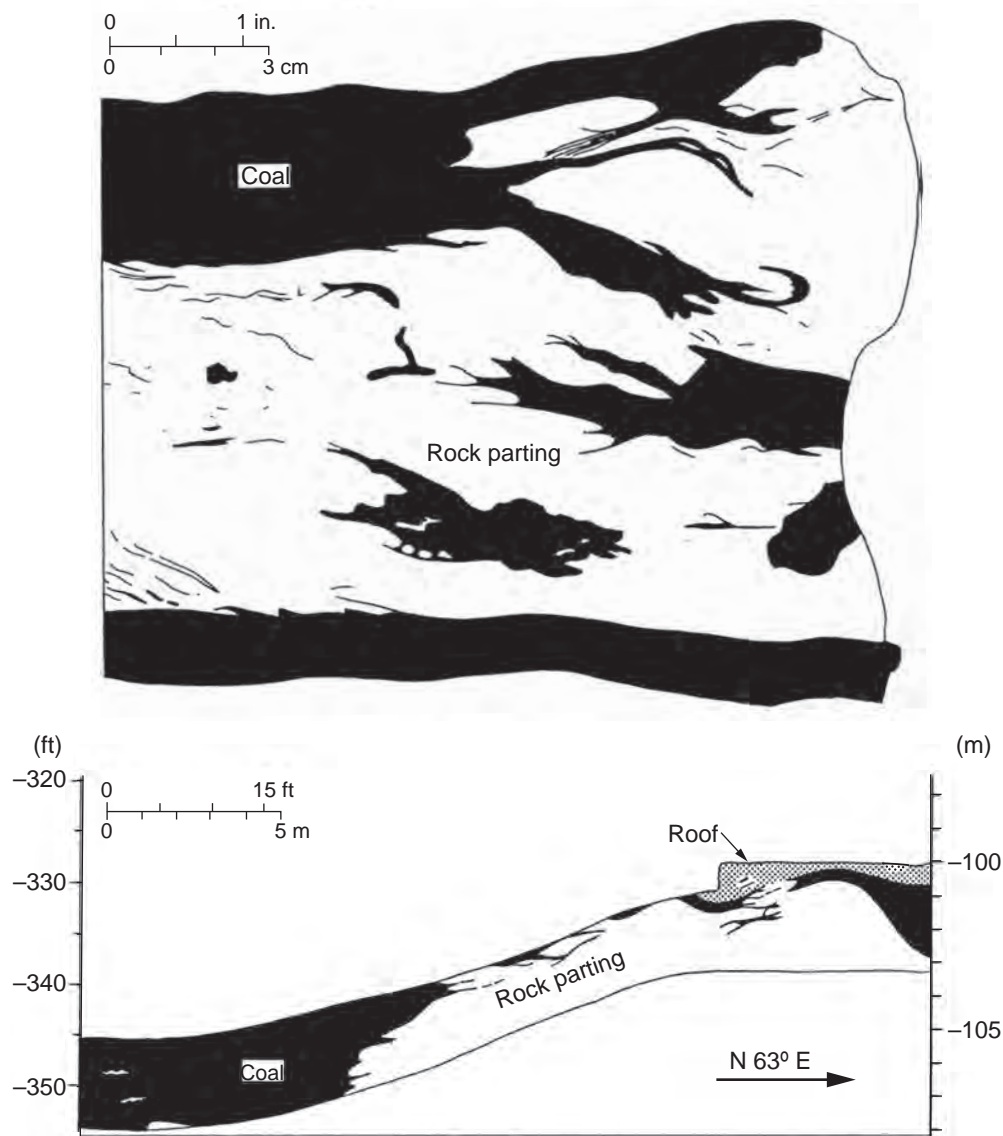


Figure 26 Drawings from Meier and Harper (1981) illustrating a major disruption of the Springfield Coal in AMAX Coal's Wabash Mine in Wabash County, Illinois.

The preservation of upright tree stumps and the packages of neap-spring tidal rhythmites indicate that Dykersburg sedimentation locally was rapid. Although we have not systematically measured and counted neap-spring cycles, they are commonly 0.4 to 2 in. (1 to 5 cm) thick, equating to deposition rates of about 3.3 ft (1 m) in 2 to 10 years. By analyzing rhythmites, Kuecher et al. (1990) determined that parts of the Francis Creek Shale were laid down at a rate of about 3.3 ft (1 m) per year. Of course, such findings do not show that the entire unit was laid

down at such a pace. Overall sedimentation rates were limited by the rising base level, tectonic subsidence, and compaction of peat and clastic sediment, which together typically account for millimeters per year. However, in tidal environments, if accommodation space is available, that space can be filled rapidly.

What caused the transition from the sediment-starved black-water channel during peat formation to a much greater load of coarser sediment is unknown. Although no evidence is available, some Dykersburg sediment may have been

transported up the estuary from offshore sources by flood tides. Alternatively, a large increase in fluvial runoff is suggested. A climate shift from ever-wet to a seasonally dry, monsoonal regime accompanied the global deglaciation that brought about sea-level rise. With long annual dry spells, less vegetation cloaked upland source areas. Therefore, the sediment load and transport in the Galatia river system dramatically increased in harmony with sea-level rise in the estuary. This process is consistent with the relationship observed between climate

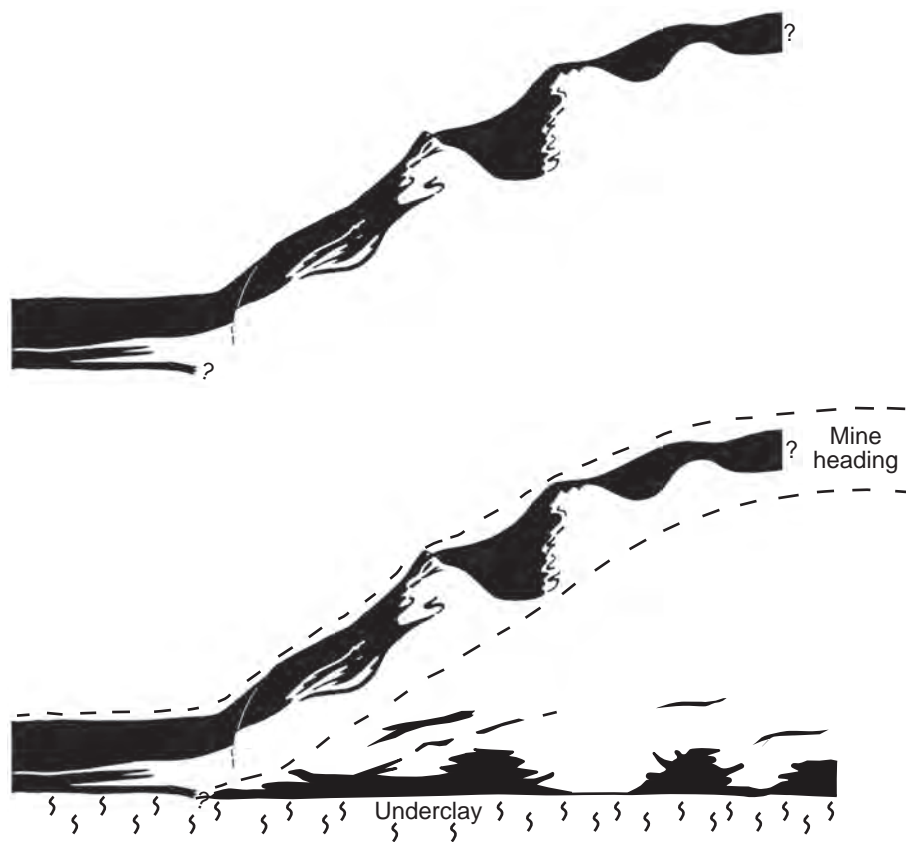


Figure 27 (Top) Image of the major disturbance in the Wabash Mine. From Meier and Harper (1981). (Bottom) The same drawing with interpretation added, depicting the peat deposit torn asunder, with the upper part floated away from the lower. The seam height at the left side of the diagram is approximately 9 ft (2.7 m).

and sediment transport in modern tropical river systems (Cecil and Dulong 2003; Cecil et al. 2003a) and with the potential for a rapid, pulse-like rise of sea level in association with deglaciation (Archer et al. 2016).

Turner Mine Shale Member

The Turner Mine Shale is the first marine bed to follow the Springfield Coal, the Dykersburg Shale, or both. It is black, fissile, and phosphatic and lies directly above the Springfield Coal throughout the Illinois Basin wherever the Dykersburg Member is absent. The Turner Mine also overlaps the Dykersburg (Figure 4) but typically pinches out where the Dykersburg reaches a thickness of 33 ft (10 m) or more. The Turner Mine averages about 3.3 ft (1 m) thick, ranging from less than 1 ft to 8 ft (0.3 to 2.4 m) thick. The Turner

Mine is readily identified by very high readings on gamma-ray logs (Figure 5) and low readings on density and neutron logs.

The contact between the Turner Mine and Dykersburg Shale varies from rapidly gradational to erosive. Unfortunately, few mines exposing this contact have been active within the last 40 years. In the Eagle No. 2 underground mine in Gallatin County, Illinois, Dykersburg Shale occurred in lenses less than 2 ft (60 cm) thick, grading into overlying Turner Mine Shale. Evidently, this mine lay at the eastern depositional limit of the Dykersburg. At the Willow Lake Mine in Saline County, closer to the Galatia channel, lenses of Dykersburg were more numerous and ranged up to 3.3 ft (1 m) thick. Here, the contact was clearly erosive, with the Turner Mine lying against truncated bedding of the Dykersburg.

The gray, nonmarine Energy Shale Member that overlies the Herrin Coal near the contemporaneous Walshville channel is a close analogue to the Dykersburg Shale. The contact of the Energy Shale to the overlying black, phosphatic Anna Shale has been observed and mapped in large areas of several underground mines. This contact is sharply erosive, cutting off Energy Shale bedding at angles as steep as 20°. The Energy Shale can be truncated from more than 15 ft (4.5 m) thick to zero in a lateral distance of 100 ft (30 m). Such erosion explains the highly irregular, lobate, and podlike distribution of gray shale as mapped in the mines (Bauer and DeMaris 1982; Nelson et al. 1987). Similar erosion evidently affected the Dykersburg prior to deposition of the Turner Mine Shale. The inferred origin of the Turner Mine Shale is essentially the same as that for the Excello Shale.

St. David Limestone Member

The St. David is marine limestone that overlies the Turner Mine Shale (Figure 4). Savage (1927) named the unit, whereas Wanless (1956) designated (but did not describe) a type section in Fulton County, western Illinois. The name "Alum Cave Limestone" has been used for the same unit in Indiana. Wanless (1939) was the first to use Alum Cave in its present sense. The name St. David therefore has priority and is used in this report.

The St. David is medium to dark gray, argillaceous, lime mudstone to wackestone containing an abundant normal-marine fauna of brachiopods, bivalves, gastropods, cephalopods, ostracods, crinoids, fusulinids, and bryozoans (Savage 1921; Wanless 1957; Shaver et al. 1986).

The member is practically coextensive with the Springfield Coal. In the Fairfield Basin and parts of western Kentucky, the limestone is less than 1 ft (30 cm) thick and consists of dark gray, argillaceous, fossiliferous lime mudstone to wackestone. On the Eastern Shelf in Indiana, the limestone is as thick as 10 ft (3 m) but more commonly 1 to 4 ft (0.3 to 1.2 m), in two layers separated by thin shale (Wier 1961). In northwestern Illinois, the unit is normally a few inches (centimeters) to about 2 ft (60 cm) thick but locally exceeds 6.6 ft (2 m; Wanless 1957). Thicker St. David, lighter colored and less argillaceous than that found in the basin, also occurs on areas of the Western Shelf where the Springfield Coal is thick enough to mine. Along with the Turner Mine Shale, the St. David pinches out where the Dykersburg Shale is thick (~32.8 ft [10 m] or more).

The limestone closely resembles the older Hanover Limestone and probably was deposited under similar conditions. Like the Hanover, the St. David appears to have developed better in the shallow waters at the margins of the Illinois Basin than in the deeper waters of the basin interior.

Canton Shale

Savage (1921) named the Canton Shale for the city of Canton in Fulton County, western Illinois. Little has been published about this unit. As depicted by Willman et al. (1975), the Canton Shale occupies the

interval between the St. David Limestone and the Briar Hill Coal (Figure 4). The following information is based on a cursory inspection of selected core records and observations in mines.

Generally, the Canton is an upward-coarsening succession of shale, siltstone, and fine-grained sandstone. Shale in the lower part contains numerous bands and nodules of siderite. Brachiopods and other marine fossils are common near the base. Sandstone in the upper Canton tends to be shaly and thinly layered. A few well records indicate a sharp contact between upper sandstone and lower shale, but deep channel incision is unknown. At the top of the Canton is the weakly developed underclay of the Briar Hill Coal. The thickness of the member is normally 10 to 50 ft (3 to 15 m), but the Canton reaches 82 ft (25 m) thick in Webster County, Kentucky.

Two problems arise in defining the Canton Shale. One problem, which does not concern this study, arises where the Briar Hill Coal is absent and the Canton cannot be distinguished from the unnamed clastic rocks overlying the Briar Hill position. The other difficulty is separating the Canton from thick Dykersburg Shale where the Turner Mine and St. David Members are missing. Core records indicate that the Canton thins to less than 9.8 ft (<3 m) where the Dykersburg is thicker than about 49.2 ft (15 m).

In depositional terms, the Canton Shale is more or less a repetition of the Delafield Member. The unit reflects the shoreline prograding into a shoaling basin during highstand to early regression.

Briar Hill Coal

The youngest unit considered in this report, the Briar Hill Coal (Figure 4) is thin but widely persistent in southeastern Illinois, southwestern Indiana, and western Kentucky. Glenn (1912) named the coal in Union County, Kentucky, whereas Butts (1925) extended the Briar Hill into southeastern Illinois. The same coal in Indiana has been called the Bucktown Coal Member (Shaver et al. 1970). Because Briar Hill has priority, usage of Bucktown should be discontinued.

The Briar Hill is confined to the southeastern part of the Illinois Basin in

approximately the same region as the southeastern area of thick Springfield Coal. It extends above the Galatia channel except where the Dykersburg Member approaches its greatest thickness. Generally, the Briar Hill is a single bench of bright-banded coal between 9.8 and 19.7 in. (25 and 50 cm) thick. The maximum known thickness is about 50 in. (130 cm) in Sullivan County, Indiana. Where the Briar Hill is thinner than 10 in. (25 cm), the coal commonly becomes shaly. The Briar Hill rests on a weakly developed paleosol, commonly little more than a thin, root-penetrated interval of laminated silty mudstone or siltstone. Above the coal is a shaly succession that typically coarsens upward. A thin layer of impure marine limestone or fossiliferous shale may occur at the base. No black phosphatic shale, comparable to the Excello or Turner Mine Shale, accompanies the Briar Hill Coal.

Summary

1. The Houchin Creek Coal formed as an *in situ* peat deposit on a vast, level, stable coastal plain.
2. The Excello Shale records rapid marine transgression to the point where bottom water became anoxic because of the absence of circulation and the abundance of plant-derived organic matter.
3. The Hanover Limestone reflects restoration of normal marine circulation in deep water offshore, probably under a seasonally dry climate.
4. The Delafield Member records progradation of the shoreline into brackish water under a falling sea level, essentially filling the basin with clastic sediment.
5. The Galatia Member fills an incised valley that was cut and filled during regression to early lowstand. The river meandered actively and carried a heavy load of sand, rapidly backfilling its meander belt.
6. Springfield peat formation commenced during lowstand (maximum glaciation) under an ever-wet climate that produced a perennially high water table. Vegetation stabilized meanders of the Galatia channel, which transitioned to a black-water stream that carried only fine-grained sediment. There were no natural

levees, but belts of laminated shaly coal flank the Galatia channel.

7. The Dykersburg Member records the onset of transgression, which converted the Galatia channel to an estuary and drowned the peat swamp. Vigorous tidal currents dislodged floating mats of peat, creating rolls, splits, and localized major disruption of the seam. As the climate became seasonally dry, the fluvial runoff and sediment load increased. Gray Dykersburg clastics rapidly entombed the peat.
8. Deposition of the marine Turner Mine black shale, St. David Limestone, and younger units completed the story.

The Galatia channel provides insights into events that are not recorded in most Carboniferous cyclothems. This example indicates, in conformance with some other studies (e.g., Cecil et al. 1985, 2003b, 2014; Eros et al. 2012; Horton et al. 2012; DiMichele 2014), that glacially driven sea-level fluctuations were linked to climate changes in the tropics. It also refines our understanding of when certain events (such as the development of peat) took place within the eustatic and climatic cycle. These themes are developed further in a later section of this report. For a more complete understanding of the Galatia channel, it is necessary to investigate other paleochannels related to the Springfield Coal.

OTHER CHANNELS RELATED TO THE GALATIA CHANNEL

Several paleochannels have been mapped that are similar to the Galatia channel in age and mode of formation. Previous authors have named some of these channels; others are named herein.

Sullivan Channel

A large paleochannel that interrupts the Springfield Coal in Sullivan and Knox Counties, Indiana (Plate 1), is here named the Sullivan channel. Several previous authors have mapped portions of the Sullivan channel and described some of its effects. Wier and Powell (1967) mapped two elongate areas where the Springfield Coal is absent in Knox County. Eggert

(1982, figure 2) showed on a small-scale map “known contemporaneous channels” in Knox and Sullivan Counties and suggested that they join the Galatia channel. Eggert and Adams (1985) discussed these features in more detail. Harper (1988) and Harper and Eggert (1995) presented further maps and information.

Combining information from these sources with newly acquired coal company data, we present a more complete picture of the Sullivan channel (Plate 1). The Sullivan channel is a nearly straight to strongly sinuous belt about 0.6 to 1.6 mi (1 to 2.5 km) wide where clastic rocks occupy the position of the Springfield Coal. Drilling indicates a “precursor” valley filled largely with sandstone and extending as deep as 215 ft (65 m) below the position of the Springfield. This channel truncates the Houchin Creek and Survant Coals, cutting within 15 ft (4.5 m) of the Colchester Coal. Channel filling generally fines upward, grading to siltstone or claystone at the level of the Springfield. These strata are basically identical to the Galatia Member as it occurs in the main Galatia channel.

Belts of interlaminated coal and carbonaceous shale, like those found along the Galatia channel, border the Sullivan channel. For example, at the eastern margin of the channel in the Oaktown Mine in Knox County, the Springfield Coal is thicker than 15 ft (4.5 m) but contains approximately 70% carbonaceous shale laminae (Figure 28). Fossil plant stems (*Sigillaria*) and foliage (*Pecopteris*, *Neuropteris*) are abundant in the shale layers. Shale content gradually diminishes eastward, yielding coal with no clastic layers about 5.6 ft (1.7 m) thick at 0.6 mi (1 km) from the channel. The floor also changes from a massive siltstone having few roots and slickensides close to the channel to a well-developed claystone paleosol away from the channel. Shaly coal also occurs along the western margin of the Sullivan channel in the Carlisle Mine, about 9 mi (15 km) north of Oaktown in Sullivan County (Figure 29). As in the Oaktown Mine, shale laminae contain abundant fossil plants, including *Calamites* stems and broken leaves of *Neuropteris* and *Macroneuropteris*. In this same area, the floor of the Springfield consists of laminated shale that contains abundant fossil plants and can be lifted

out in large sheets. Core drilling demonstrated that shaly coal borders both sides of the channel in Sullivan County.

Although details are sparse, previous authors (Kottlowski 1954; Wier 1954; Harper 1988; Harper and Eggert 1995) reported that numerous abandoned underground mines encountered areas of “dirty” or “shaly” coal, along with lenses of shale or sandstone, near the margins of the Sullivan channel.

Several sizeable tracts of thick, low-sulfur (0.4% to 1%) coal flank the Sullivan channel. Most of the thickest coal, ranging from 7 to 11 ft (2 to 3 m) thick, occurs in steep-sided structural depressions. As usual, low-sulfur coal is overlain by thick gray shale, siltstone, and sandstone of the Dykersburg Member. The largest of these areas is the Glendora district in northern Sullivan County (Plate 1), where the coal lies in a structural basin about 30 ft (9 m) deep and is topped by up to 30 ft (9 m) of Dykersburg shale and sandstone (Kottlowski 1954; Wier 1954; Harper 1988). Nearly surrounded by thin, shaly coal, the Glendora district appears to lie between branches of the Sullivan channel. The active Carlisle and Oaktown Mines both contain steep-sided troughs where the coal thickens markedly and has a gray, siliciclastic roof. However, in most areas of these mines, the Turner Mine Shale lies directly on the coal.

Thus, the Sullivan channel shares all the attributes of the Galatia channel. The Sullivan is either a direct northward continuation of the Galatia or a major tributary.

Effingham Channel

Across most of the basin, the upward-coarsening Delafield Member underlies the Springfield Coal. However, Potter's (1962, 1963) maps depict several large meandering and dendritic sand bodies, evidently paleochannels, that replace the Delafield Member below the Springfield Coal. The largest of these paleochannels trends southeast from central Illinois to southwestern Indiana (Figures 1 and 8, Plate 1). This feature is hereby named the Effingham channel after the city of Effingham, Illinois, which lies near its course. Comparing Potter's map (Figure 30) with those of Hopkins (1968), Treworgy and Bargh (1984), and Treworgy et al. (1999), we observed the following:

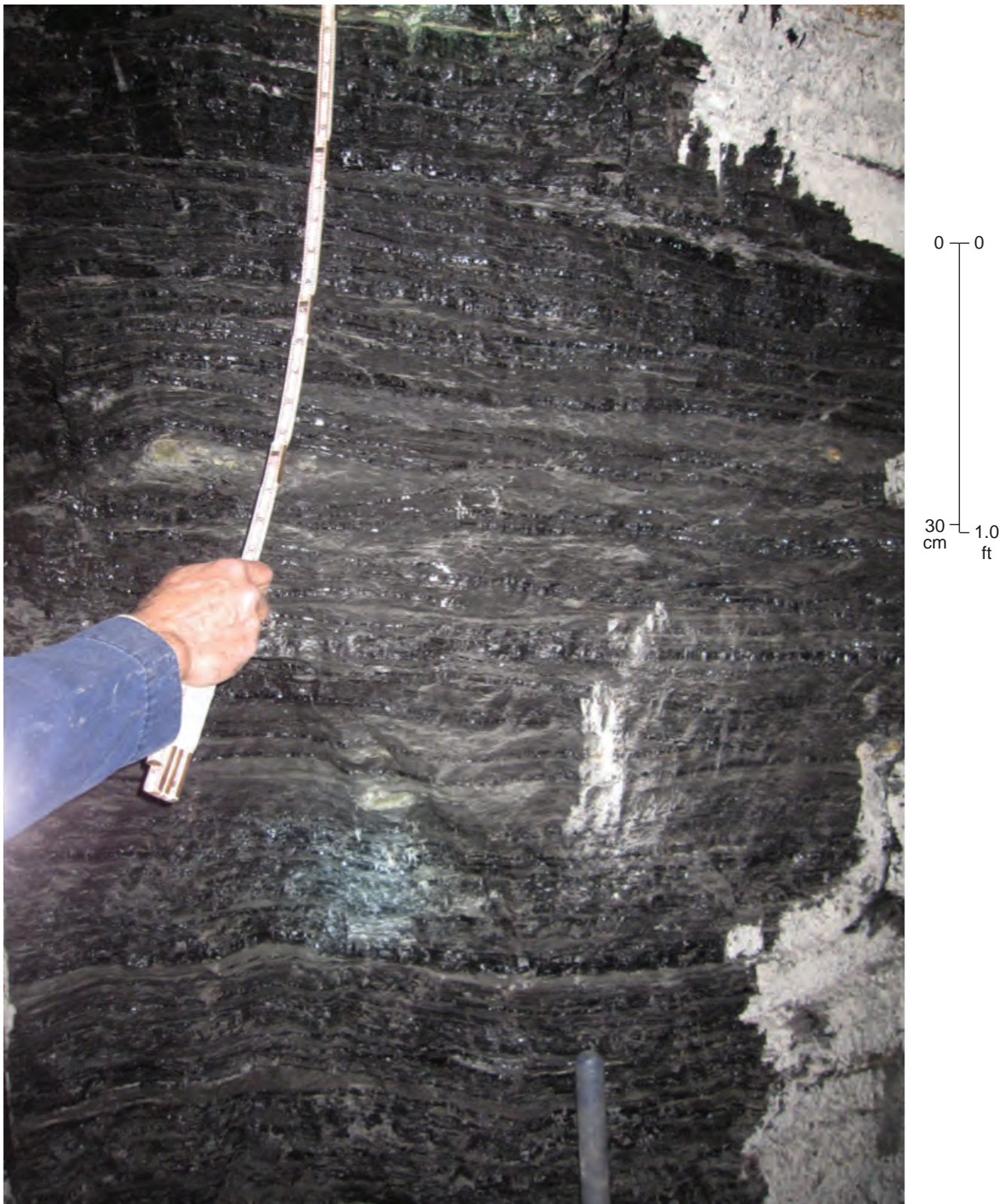


Figure 28 Photograph of interlaminated carbonaceous shale and bright to dull coal close to the margin of the Sullivan channel in the Oaktown Mine in Knox County, Indiana.

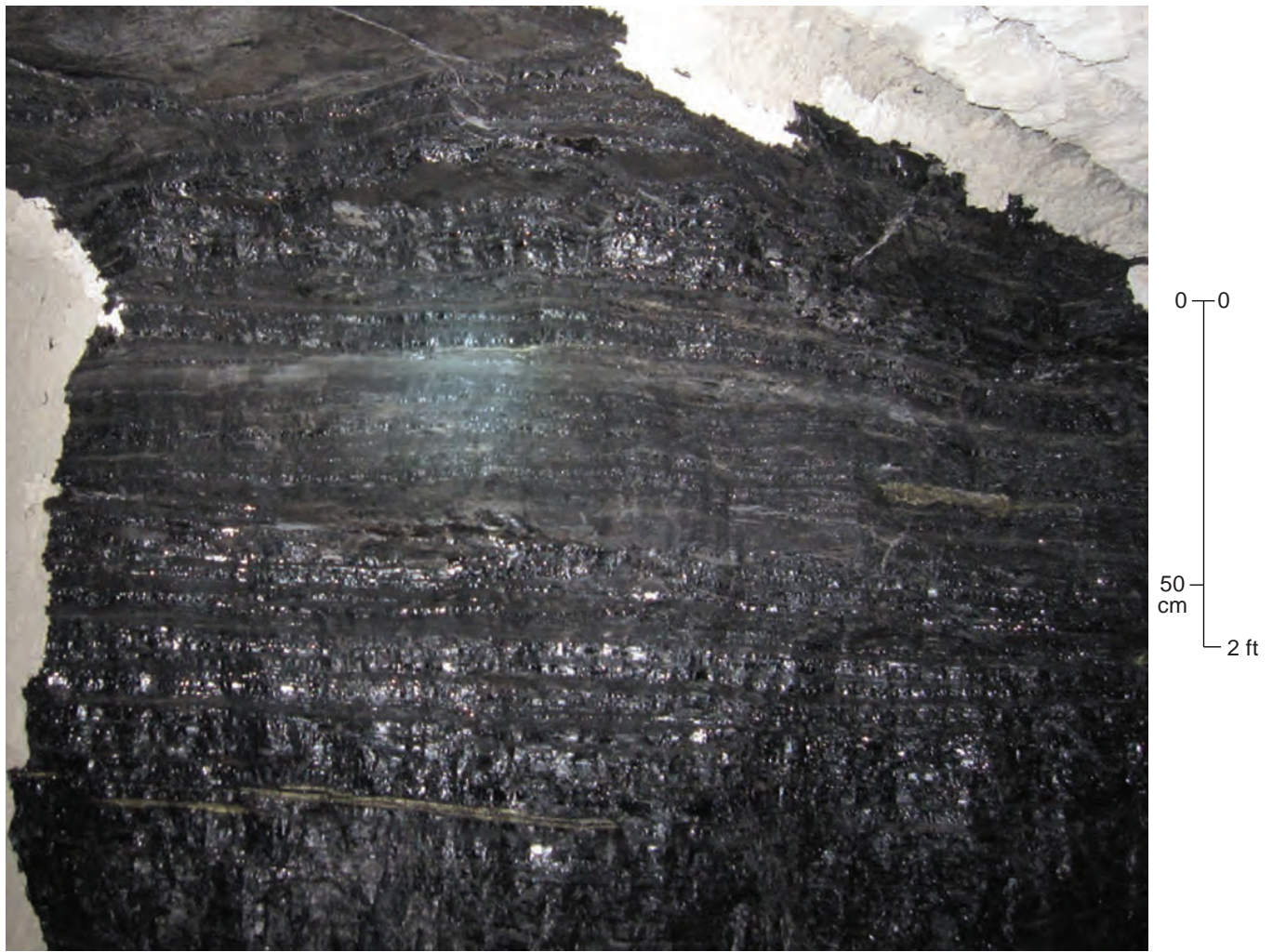


Figure 29 Photograph of interlaminated carbonaceous shale and bright to dull coal close to the margin of the Sullivan channel in the Carlisle Mine in Sullivan County, Indiana.

- The Effingham channel widens toward the southeast, and several tributaries are “barbed” toward the northwest. Thus, it evidently flowed southeast.
- The Effingham channel crosses the southwest-trending Galatia channel at a right angle.
- The Effingham channel does not interrupt the Springfield Coal, and the coal does not appreciably thicken along its margins.
- The Effingham channel exhibits meander-belt geometry (in map view) similar to the Galatia channel.
- No Dykersburg Shale is associated with the Effingham channel.

Cross sections (Plates 4 and 5) show that the Effingham channel, like the Galatia,

has a wide, nearly flat bottom and steep sides. The base is cut close to the Houchin Creek Coal. Many wireline logs indicate two sedimentary sequences filling the Effingham channel. The lower sequence is largely sandstone, fining upward and ranging from about 20 to 50 ft (6 to 15 m) thick. A few logs show a thin, highly resistive bed at the top of the lower sequence. A density–neutron log (Figure 31) from the Berry Petroleum No. 11-14 Pitcher well in Jasper County confirms that the resistive bed is coal. The upper sequence is 20 to 30 ft (6 to 9 m) thick and is mostly shale and siltstone. In some cases, the sequence fines upward from basal sandstone, but other logs show an upward-coarsening profile. The best record is continuous core from the ISGS No. 1 Elysium borehole in Richland County (Figure 32).

The lower sequence is about 15 ft (4.5 m) thick and is largely sandstone, fining upward from an erosive lower contact. Cross-bedding in the lower part gives way to planar lamination having well-developed neap–spring tidal couplets near the top. The upper sequence is 23 ft (7 m) thick and is largely sandstone, grading to blocky, rooted claystone at the top beneath the Springfield Coal.

The Springfield Coal locally thickens above the Effingham channel, as shown on the map by Treworgy et al. (2000). This is most obvious along the west branch of the channel in southern Shelby County (Plate 5), which suggests that the channel was incompletely filled, leaving a trough to be filled with thicker peat. There is no shaly coal or other evidence for an active

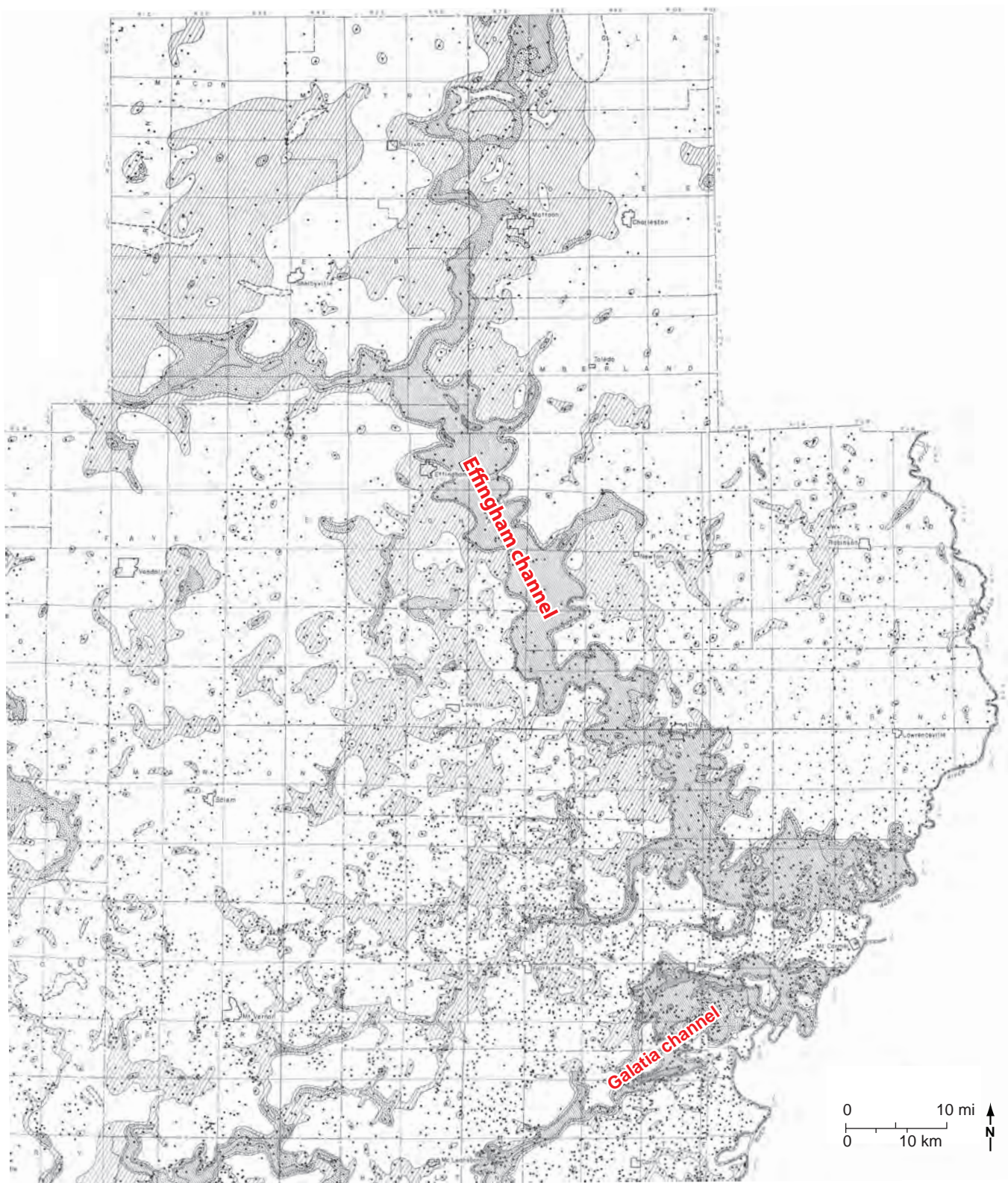


Figure 30 Map from Potter (1962) showing the Effingham channel as described in this report.

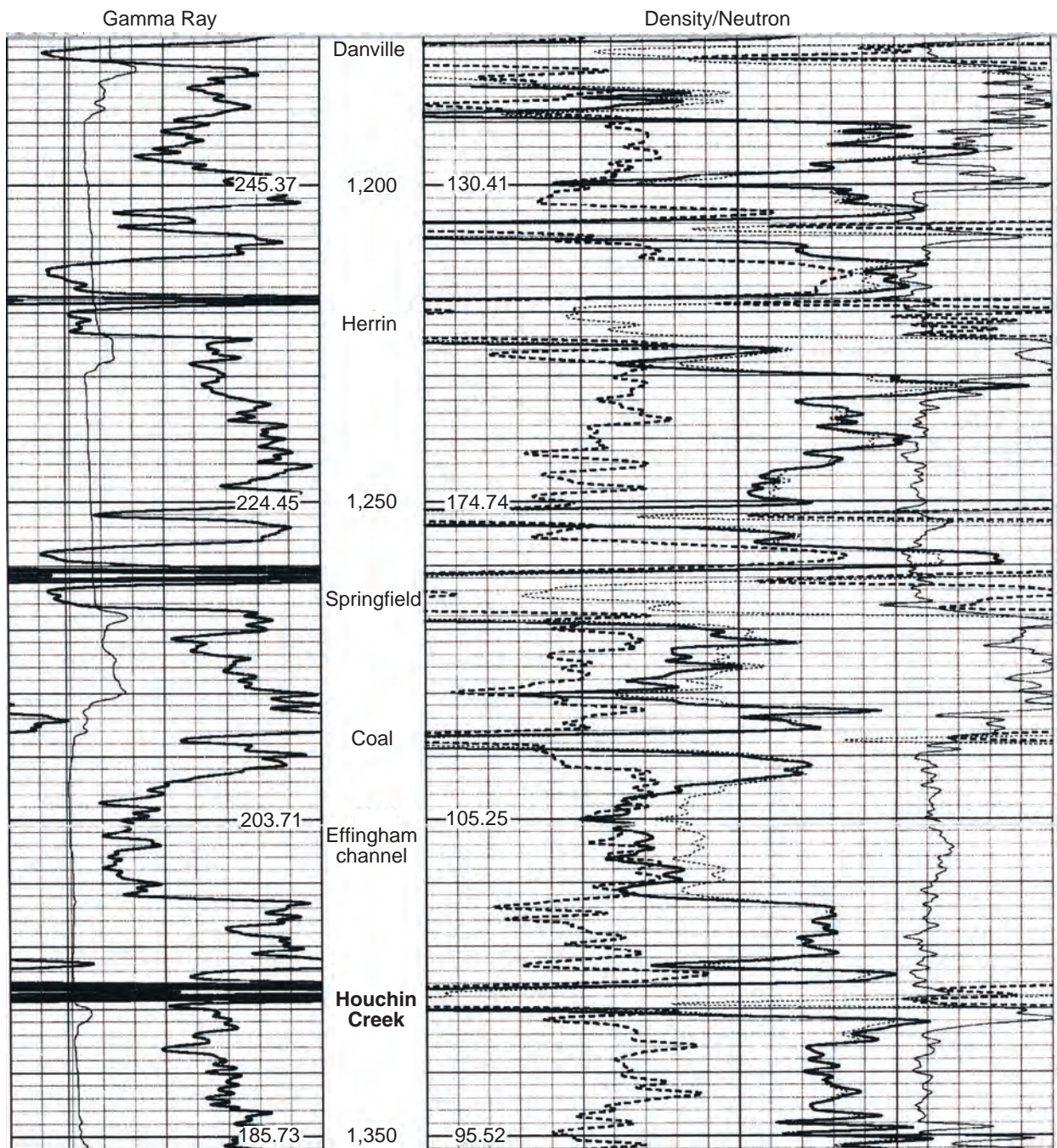


Figure 31 Gamma-ray–neutron log from the Berry Petroleum No. 11-14 Pitcher well in Jasper County, Illinois, indicating coal in the upper part of the Effingham channel fill.

stream occupying the channel during the time of peat formation.

Cross-cutting relationships indicate that the Effingham channel is older than the Galatia channel (Figure 33). After establishing its meander belt, the Effingham system was abandoned and backfilled with sediment. Locally, small peat depos-

its developed in the abandoned waterway before a second stage of fluvial activity completed backfilling of the channel.

This scenario introduces complications into how the Effingham channel fits into eustatic cycles. A possible solution is explored in the Discussion section.

Leslie Cemetery Channel

Eggert (1978, 1982, 1984, 1994), Eggert and Adams (1985), and Willard et al. (1995) described a belt of “split” Springfield Coal in southwestern Indiana and called this feature the Leslie Cemetery channel (Figure 34). Our observations in active surface mines and those of other

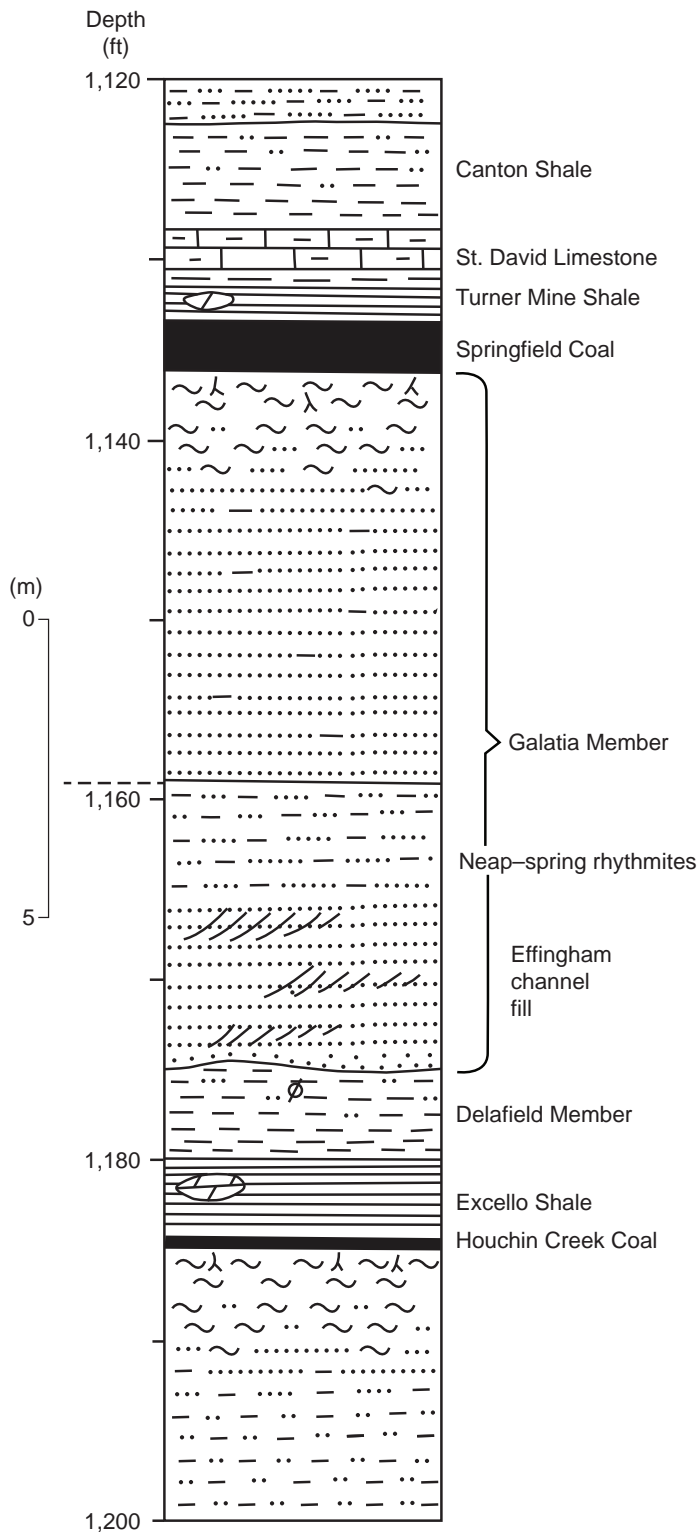


Figure 32 Graphic log of core from Richland County, Illinois, showing filling of the Effingham channel. The core shows two upward-fining sequences, the lower having tidal rhythmites in the upper part. The borehole is ISGS No. 1 Elysium (Hazel Farm) in sec. 27, T4N, R9E (county no. 25922).

ISGS geologists provided further information. A revised map of the channel (Figure 35) is based on newly available data from active mines and boreholes. In addition, a cross section (Plate 6) has been constructed using borehole data.

The Leslie Cemetery channel is slightly sinuous in map view and varies from about 0.9 to 3.7 mi (1.5 to 6 km) wide. It trends northwest from the outcrop in Warrick County into eastern Gibson County, where it intersects the Galatia channel. In sectional view (Plate 6), the Leslie is lens-shaped, reaching 65 ft (20 m) thick along its central axis. Unlike the Galatia channel, the Leslie Cemetery splits the Springfield Coal, with the upper “bench” of coal overriding the clastic rocks that fill the channel (Figure 36 and Plate 6). The Turner Mine Shale and St. David Limestone directly overlie the upper coal bench.

The lower bench of the Springfield Coal is generally 2 to 4 ft (0.6 to 1.2 m) thick and lacks clastic layers. Ash and sulfur content are moderate to low. In terms of petrography and palynology, the lower bench is similar to Springfield Coal elsewhere near the Galatia channel (Willard et al. 1995). The lower bench dips into a trough below the channel (Figure 36) and is nearly continuous, except in a few places where the channel truncates the coal.

Filling the Leslie channel is a succession of gray mudstone, siltstone, and fine-grained sandstone that Eggert (1982) named the Folsomville Member. Near the margins of the channel, the Folsomville consists largely of nonfissile, slickensided claystone and thinly laminated, organic-rich carbonaceous shale. As the Folsomville thickens, it changes to layered gray mudstone and siltstone containing laminae and lenses of sandstone along with siderite nodules and concretions. Toward the axis of the Leslie Cemetery channel, sandstone becomes more prevalent and commonly shows cut-and-fill features. Cross-bedding is unidirectional and indicates a paleocurrent toward the northwest; no indications of tidal sedimentation have been recognized (Willard et al. 1995). Fossil plants are locally abundant in the finer grained rocks, especially the prone stems and logs of lycosids and pteridosperm foliage, along with roots of lycosids, pteridosperms, and calamites. A rooted “seat earth” commonly occurs

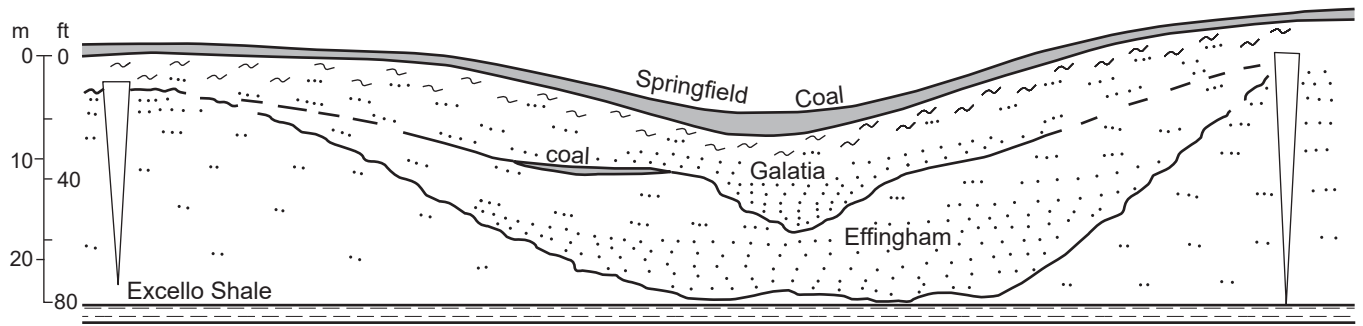


Figure 33 Interpretive cross section of the Effingham channel in Richland County, Illinois, showing two stages of infilling, with local coal at the top of the lower stage.

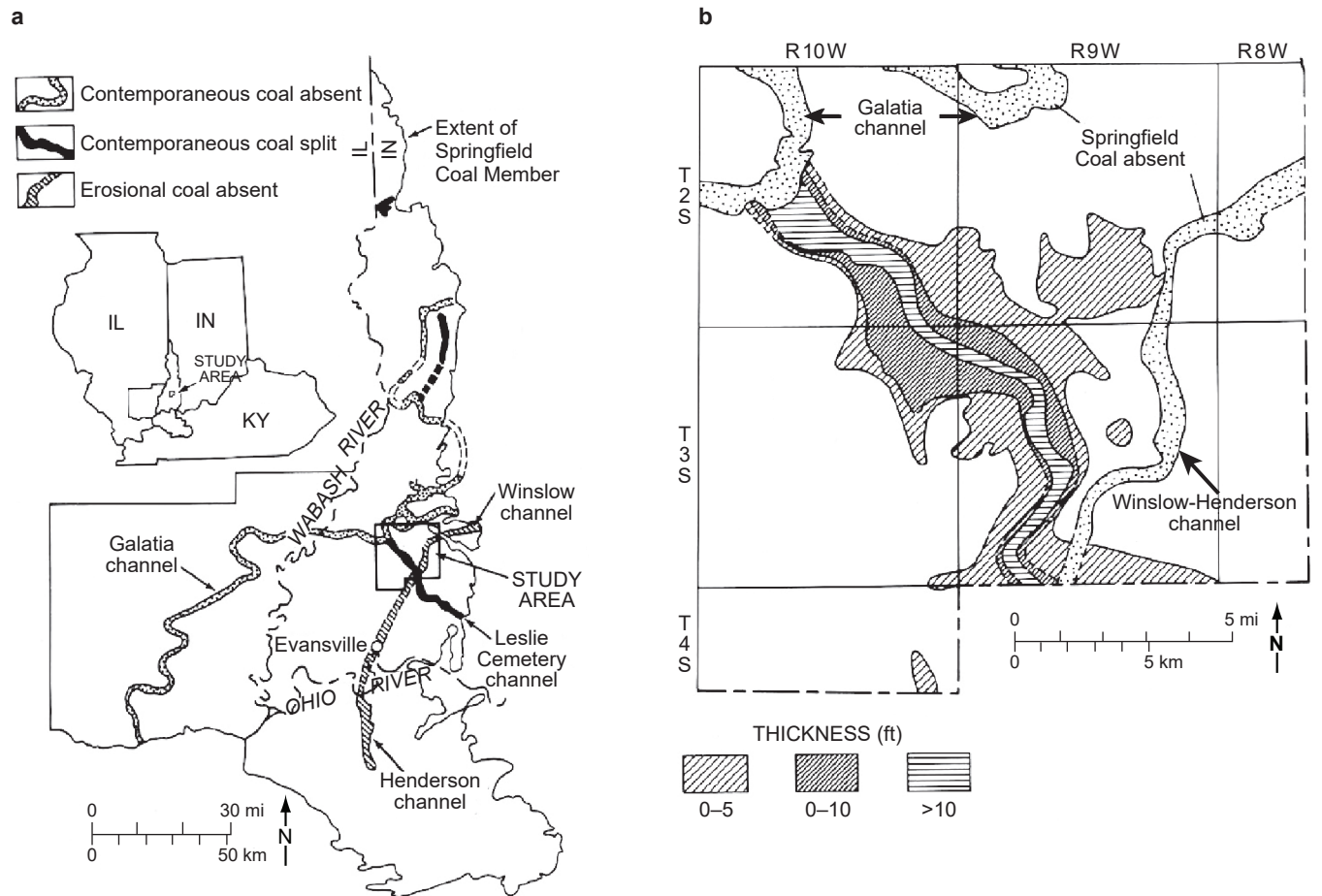


Figure 34 Maps of the Leslie Cemetery channel. (a) Regional map showing the relationship to other channels. (b) Map of the northern part of the Leslie Cemetery channel, with the thickness of the Folsomville Member. From Eggert (1984), *The Leslie Cemetery and Francisco distributary fluvial channels in the Petersburg Formation (Pennsylvanian) of Gibson County, Indiana, U.S.A.*, in R.A. Rahmani and R.M. Flores, eds., *Sedimentology of coal and coal-bearing sequences: International Association of Sedimentologists, Special Publication 7* p. 311, 313. Copyright © 1984 The International Association of Sedimentologists.

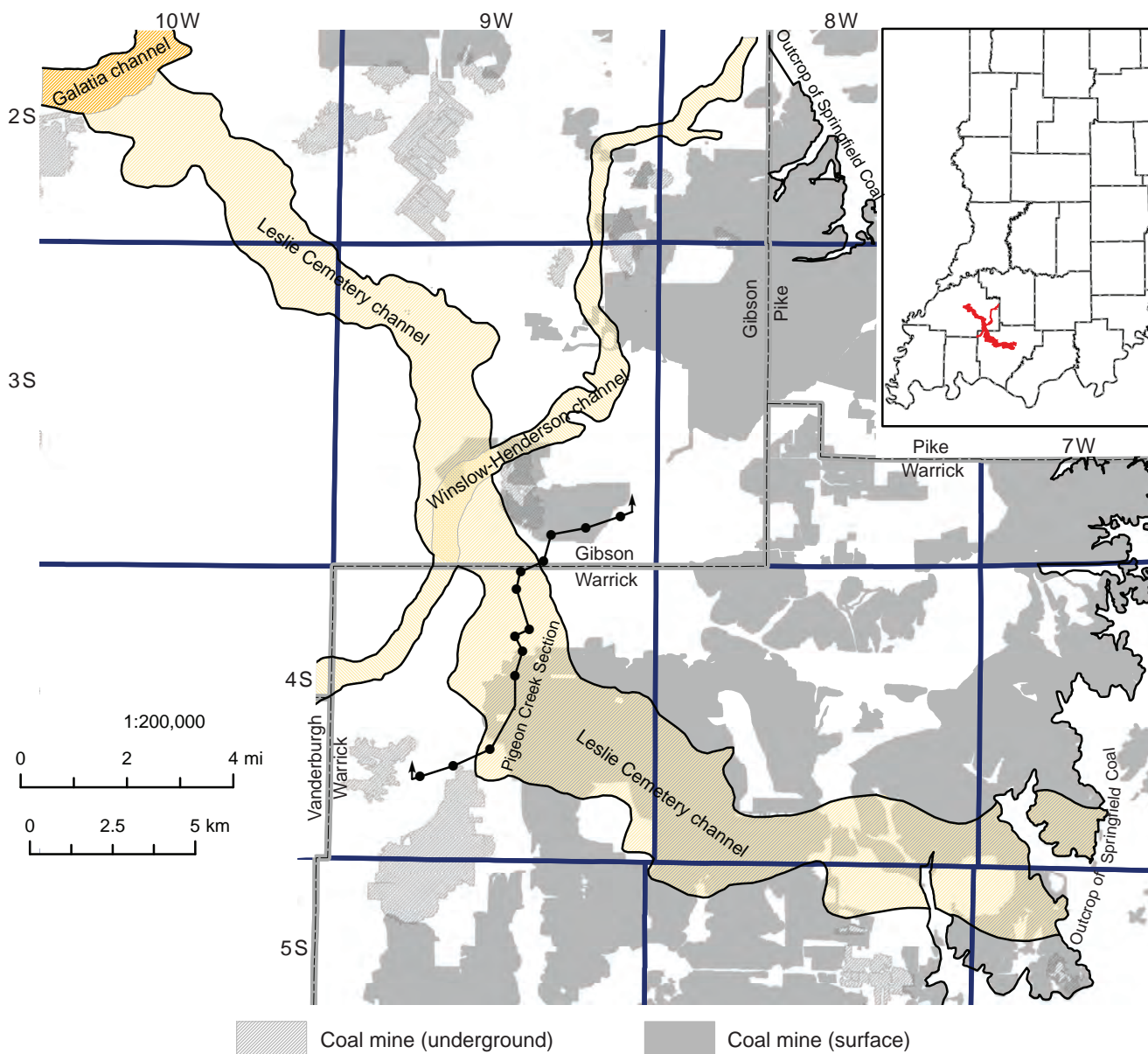


Figure 35 Map of the Leslie Cemetery channel prepared for this study, using information from boreholes and mines. Lines of section for Figure 36 and Plate 6 are shown.

below the upper coal bench (Willard et al. 1995). Eggert (1982) reported fossil tree stumps in growth position, and we observed several at the Cypress Creek Mine near the margin of the channel. These stumps were rooted in, or a short distance above, the lower coal bench. Spirorbid worm tubes, as reported by Willard et al. (1995), are the only invertebrates.

The upper bench of coal ranges from a few inches (centimeters) to 2.3 ft (0.7 m) thick and carries a much higher ash and sulfur content than the lower bench.

In places, the upper bench grades to carbonaceous shale or to thinly inter-laminated coal and shale (Figure 36). In some places, the upper coal is continuous above the channel, but in other sites, it pinches out. The flora is dominated by lycopsids accompanied by calamites, pteridosperms, and tree ferns, but ground-cover plants are uncommon (Willard et al. 1995). Calcareous coal balls occurred in the upper bench at both the Lemmon Brothers and Lynnville Mines, on opposite margins of the channel (Willard et al.

1995; Phillips and DiMichele 1998). Conodonts were recovered from coal balls near the top of the upper bench in the Lynnville Mine.

Like the Galatia channel, the Leslie Cemetery channel overlies an older “precursor,” which Eggert (1984) named the Francisco channel. The well-log cross section (Plate 6) illustrates this relationship. Underlying the Springfield Coal, the Francisco channel truncates the Delafield Member and is filled with an upward-

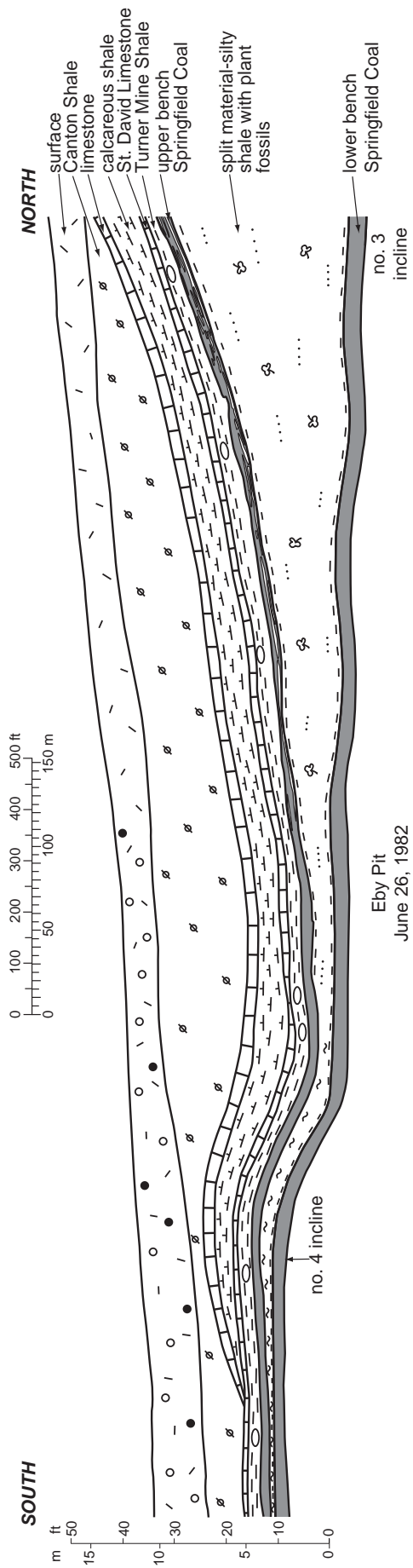
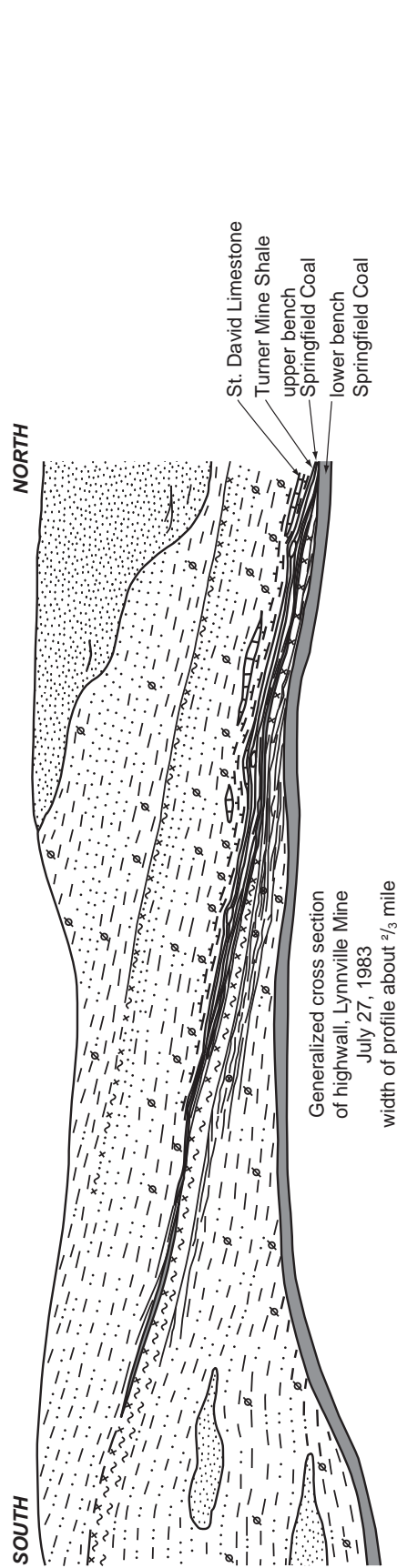


Figure 36 Generalized sketches illustrating opposite margins of the Leslie Cemetery channel, as exposed in surface mines in the eastern half of 9S, 4W, Warrick County, Indiana. The upper image is from Peabody's Lynnville Mine in July 1983, representing the northern half of the channel. The lower image is from Peabody's Eby Pit in June 1982, representing the southern half of the channel.

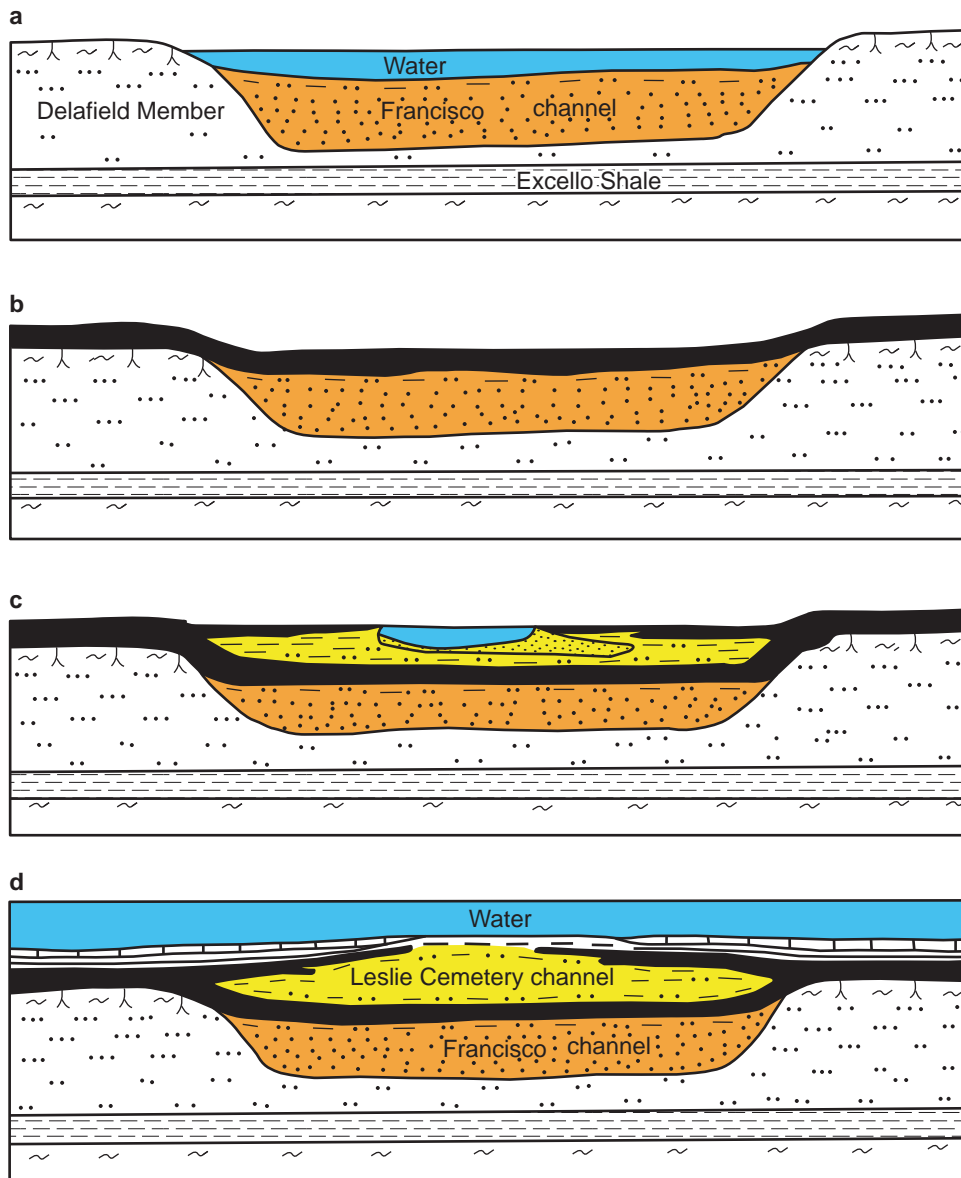


Figure 37 Interpretive diagram showing sequential development of the Leslie Cemetery channel. (a) The Francisco channel is eroded and filled with sediment, largely sand. (b) Springfield peat accumulates in swale left by the abandoned channel. (c) Flowing water reoccupies the channel during the later stages of peat accumulation. Peat encroaches from the margins as the channel migrates laterally. (d) A marine incursion downs the region and deposits black shale and limestone. Channel filling inverts the topography because of differential compaction.

fining succession of sandstone, siltstone, and shale. Borehole data (Eggert 1982) indicate that underclay is at least locally absent below the lower coal bench, which rests directly on sandstone. The Francisco channel is less deeply incised than the Galatia channel; the Francisco does not cut out the Houchin Creek Coal. Evidently, the Francisco was a tributary to the Galatia channel.

The observations outlined above suggest the Leslie Cemetery channel developed by the following sequence of events (Figure 37). The Francisco channel was a northwest-flowing tributary of the Galatia precursor channel. Prior to the onset of peat formation, the Francisco channel was filled with clastic sediments and abandoned (Figure 37a). The channel

course, however, remained as a trough through the peat swamp; the lower coal bench formed in this trough (Figure 37b). Partway through peat formation, flowing water reoccupied the trough, depositing clastic sediment in the Leslie Cemetery channel. The active channel migrated laterally, and plants grew in standing water along its margins. Peat and sediments

compacted, making space for more sediment. During later stages of Springfield peat development, the channel again was largely abandoned, and peat accumulated above channel sediments (Figure 37c). Marine transgression finally terminated peat formation. Coal balls developed, and the Turner Mine and St. David Members were deposited above the Leslie Cemetery channel (Figure 37d).

Other Channels

Potter (1962, 1963) mapped other channel-form sandstone bodies below the Springfield Coal that do not correspond to interruptions in the coal. These include a series of branching, strongly meandering channels in southern Illinois, largely Franklin, Hamilton, Saline, and Gallatin Counties (Figure 8). Widths are in the range of 0.6 to 1.9 mi (1 to 3 km). Portions appear dendritic with tributaries, but the overall drainage direction is unclear. These likely represent more than one channel; one segment appears to cross the Galatia channel at nearly a right angle. More channels mapped by Potter are in Bond, Clinton, Washington, and Perry Counties of southwestern Illinois. These sinuous features branch and rejoin but do not exhibit (as mapped) an integrated drainage. We have not investigated these channels and will offer no further comments.

Friedman (1956, 1960) mapped an area near Terre Haute, Indiana, where the Springfield Coal is split and partly replaced by sandstone and shale. He called this feature the Terre Haute channel. Friedman's map (Figure 38) shows a southwest-trending channel about 1,300 ft (400 m) wide, with several short branches joining from the southeast. In one area, the coal divides into a continuous lower bench and an upper bench that thins and pinches out toward the channel axis. In another area, shale layers occur in the coal along a linear trend, although the coal is not cut out. Sandstone is largely confined to the main channel. Maximum clastic thickness is about 40 ft (12 m). Harper (1985, p. 19-20) discussed the Terre Haute channel in relation to the Dresser underground coal mine but did not shed further light on the nature of the disturbance. Friedman (1956, 1960) inferred a dendritic fluvial system that was active during later stages of peat formation. The Terre Haute channel may be

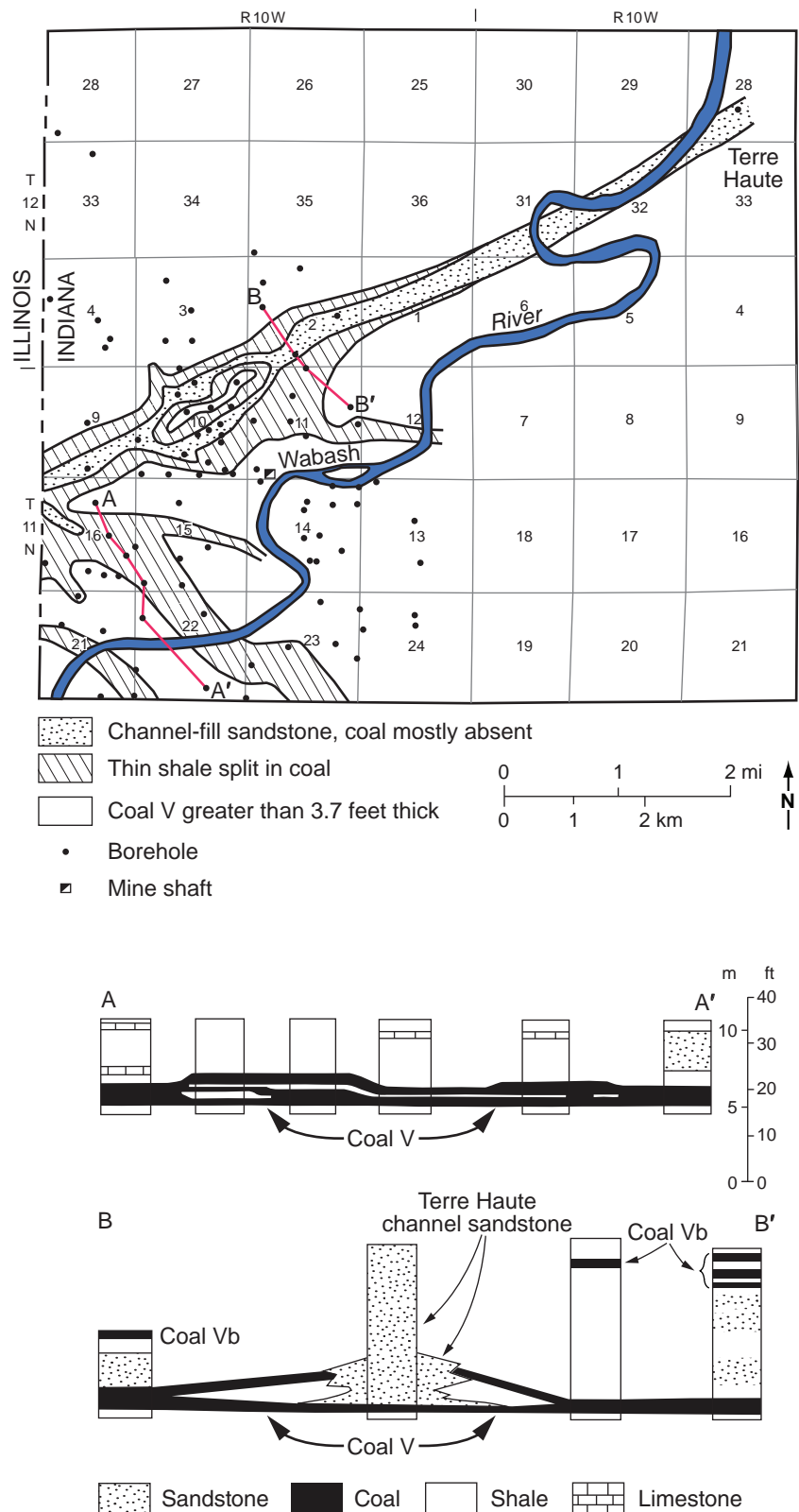


Figure 38 Map and cross section of the Terre Haute channel. From Friedman (1960). Courtesy of the Indiana Geological and Water Survey. Lines of cross section are shown on the map.

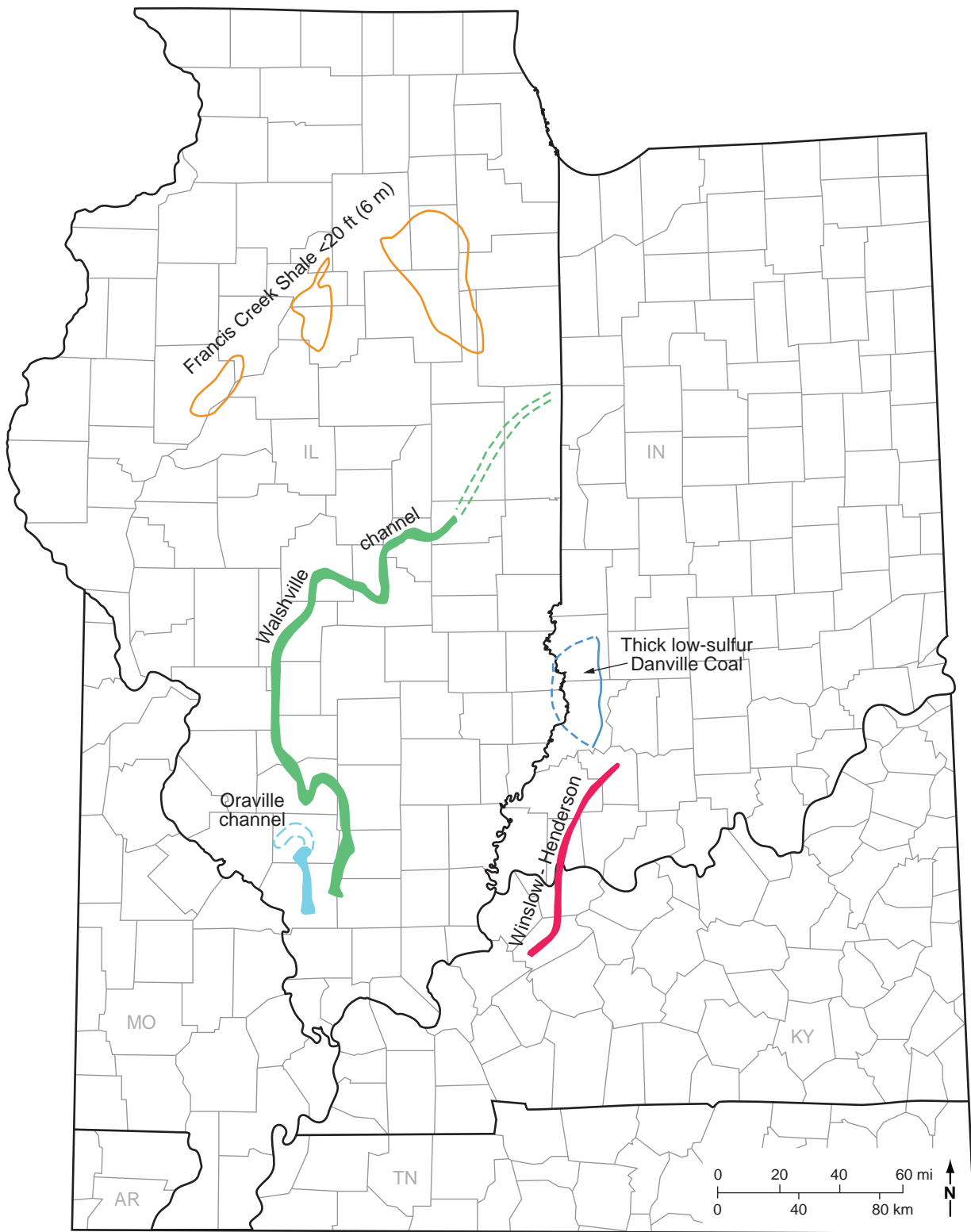


Figure 39 Map of the Illinois Basin showing channels and gray-shale wedges affecting the Murphysboro, Colchester, Herrin, Baker, and Danville Coals.

similar to the Leslie Cemetery channel, but not enough data are at hand to offer a theory of its origin.

SIMILAR CHANNELS AFFECTING OTHER COAL SEAMS

Several well-documented paleochannels in the Illinois Basin existed contemporaneously with peat deposits older and younger than the Springfield (Figure 39). The Galatia channel provides an apt model for comparison.

Colchester Coal and Francis Creek Shale

The Colchester Coal may be the most extensive coal bed in North America, if not the world (Wanless 1975; Greb et al. 2003). It correlates with the Lower Kittingham coal bed of the northern Appalachians and the Croweburg Coal of the Western Interior. Cecil et al. (2003b) characterized time-equivalent rocks throughout the continental United States.

In most of the Illinois Basin, the Colchester is too thin to mine (≤ 1.6 ft [≤ 0.5 m]) and is directly overlain by the black, phosphatic Mecca Quarry Shale, with the marine Oak Grove Limestone above that (Figure 40). In northern Illinois, the coal thickens to as much as 4.6 ft (1.4 m) and is overlain by the gray Francis Creek Shale, which ranges up to 34 m (112 ft) thick (Figure 41). Low-sulfur Colchester Coal is known from only two mines among the hundreds that formerly worked this seam. These mines had thick Francis Creek; however, many other mines having thick Francis Creek had high-sulfur coal (Gluskoter and Hopkins 1970).

The Francis Creek and Dykersburg Shales are closely similar in some respects and different in others. Both units encapsulate upright tree stumps and display beautifully developed tidal rhythmites (Kuecher et al. 1990; Baird 1997). The Francis Creek shows a more consistent upward-coarsening profile than the Dykersburg. The upper part includes rooted zones, impure coal, channel-form sandstone bodies, and features interpreted as crevasse splays and natural levees (Baird 1997). Most notably, the Francis Creek bears the famous Mazon Creek fossils, preserved in siderite concretions. These

include a remarkable fauna of soft-bodied organisms, some known nowhere else (Shabica and Hay 1997), along with a rich and diverse flora of land plants (Wittry 2006). These fossils have been divided into a “Braidwood assemblage” representing fresh to slightly brackish, tidally influenced water and an “Essex assemblage” of more saline but not fully marine conditions (Baird 1997). The Braidwood assemblage and thickest Francis Creek Shale are localized near the northeastern margin of the basin. The Dykersburg lacks a significant invertebrate fauna, and a marine to brackish transition has yet to be defined.

All these features point to extremely rapid sedimentation, at least locally. By counting tidal cycles and measuring their thickness, Kuecher et al. (1990) determined rates as rapid as 3.3 ft (1 m) per year.

No “split” Colchester Coal or channels contemporaneous with the coal have been identified. However, patterns of Francis Creek Shale distribution and enclosed biota suggest that river mouths lay a short distance northeast of the present Colchester outcrop (Baird et al. 1985a).

As with the Dykersburg Shale, early models placed the Francis Creek in a deltaic setting (Wright 1965; Shabica 1970). Later authors recognized an estuarine component and favored deposition during transgression of the peat-forming lowland (Baird et al. 1985a, 1985b). Archer and Kvale (1993) and Archer et al. (1995) further emphasized the tidal, estuarine aspect. We regard the Francis Creek as a series of tidally dominated deltas that accumulated in a broad, brackish embayment.

Herrin Coal, Energy Shale, and Walshville Channel

The gray, nonmarine Energy Shale and Walshville channel (Figures 42 and 43) are close analogues of the Dykersburg Shale and Galatia channel. Belts of thick Herrin Coal (up to 13 ft [4.3 m]) flank the channel, and shaly or “split” coal flanks channel margins. Away from the channel, the Herrin has a black shale-limestone roof and uniformly high sulfur content. Near the channel, wedges of the gray Energy Shale intervene between coal and black shale. The sulfur content of the coal

is moderate to low (0.5% to 2.5%) where the Energy Shale is thicker than about 20 ft (6 m; Johnson 1972; Allgaier and Hopkins 1975; Treworgy and Bargh 1984; Nelson et al. 1987).

The Energy Shale consists of gray mudstone, siltstone, and sandstone as thick as 120 ft (37 m). It is thickest and coarsest near the channel, becoming thin and lenticular at its outer limits. The sparse fauna comprises brackish-water forms such as *Lingula*, *Dunbarella*, *Myalina*, the brachiopod *Leaia tricarinata*, and rare cephalopods and eurypterids. Fossil land plants are abundant and well preserved, including stands of upright stumps (mainly lycopsids) rooted at the top of the coal (DiMichele and DeMaris 1987; DiMichele et al. 2007). Locally, the Energy Shale contains siderite concretions similar to those of Mazon Creek, containing fossils of plants and soft-bodied invertebrates (Gastaldo 1977; Baird et al. 1985b). Shared with the Dykersburg are features including tidal rhythmites (Archer and Kvale 1993; DiMichele et al. 2007), a variety of rolls (Edwards et al. 1979; Krausse et al. 1979; Bauer and DeMaris 1982; Nelson 1983), and a major coal disruption that suggests large-scale rafting of peat (Nelson 1983, p. 21–23). Away from the Walshville channel, the Energy Shale is eroded into pods beneath the black, fissile, marine Anna Shale. The Anna–Energy contact is clearly erosional, having locally more than 15 ft (4.5 m) of relief with bedding of the Energy Shale truncated at a 20° angle. Finally, the Anna and overlying marine Brereton Limestone onlap and pinch out against the tidally deposited, gray siltstone and sandstones that fill the core of the Walshville channel (Bauer and DeMaris 1982; DeMaris et al. 1983; DeMaris 2000). The Turner Mine Shale and St. David Limestone pinch out in similar fashion where the Dykersburg Member is thick.

Although no precursor Walshville channel has been mapped, core drilling in several areas confirms a deeply incised, sandstone-dominated valley fill below the belt of thick Herrin Coal. As with the Galatia, the precursor Walshville channel is considerably wider than the contemporaneous portion (as defined by the absence of Herrin Coal). Moreover, the Walshville channel, like the Galatia, exhibits looping meanders that did not migrate laterally.

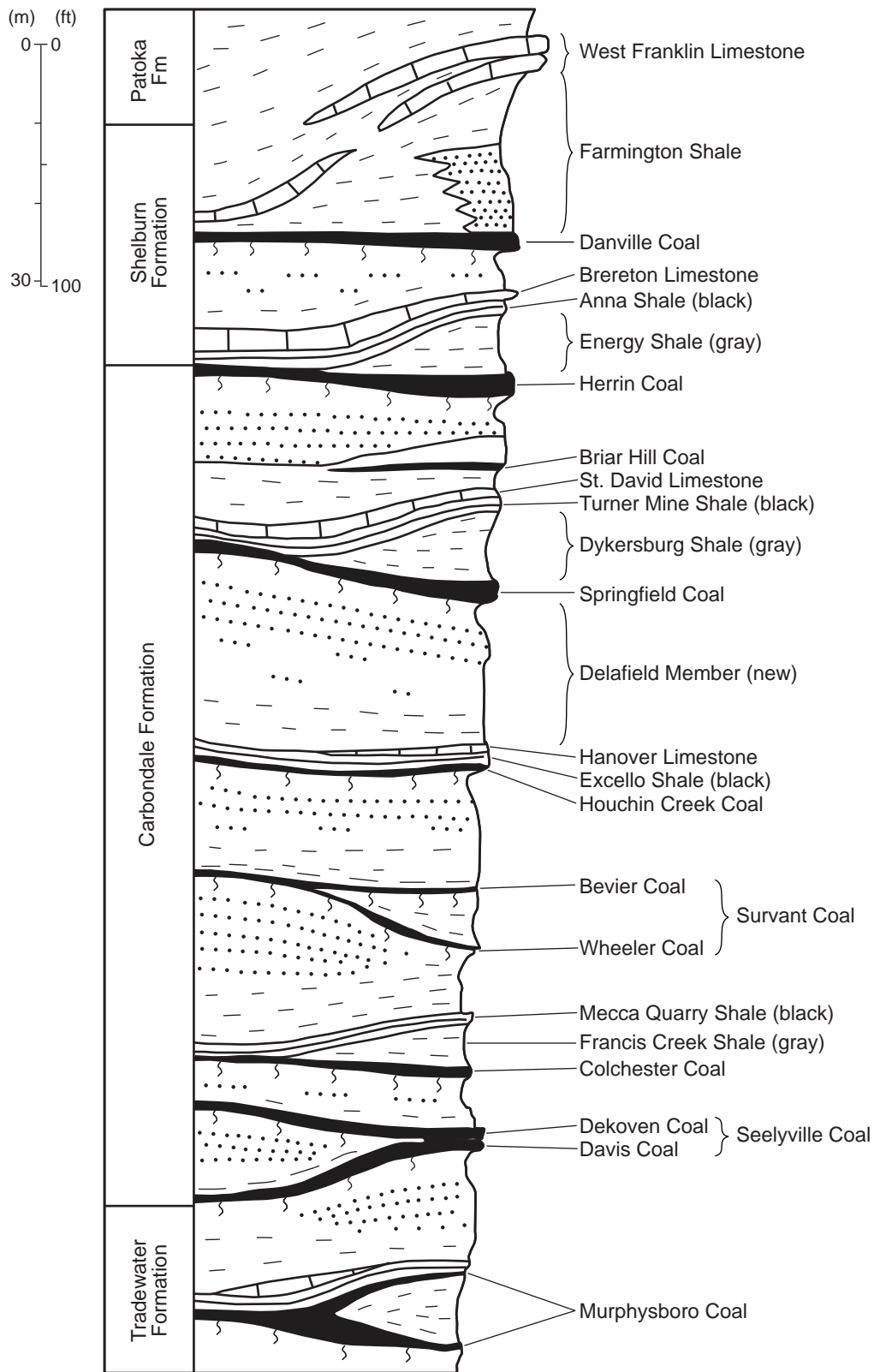


Figure 40 Stratigraphic column showing the units mentioned in the section on channels affecting coal seams other than the Springfield.

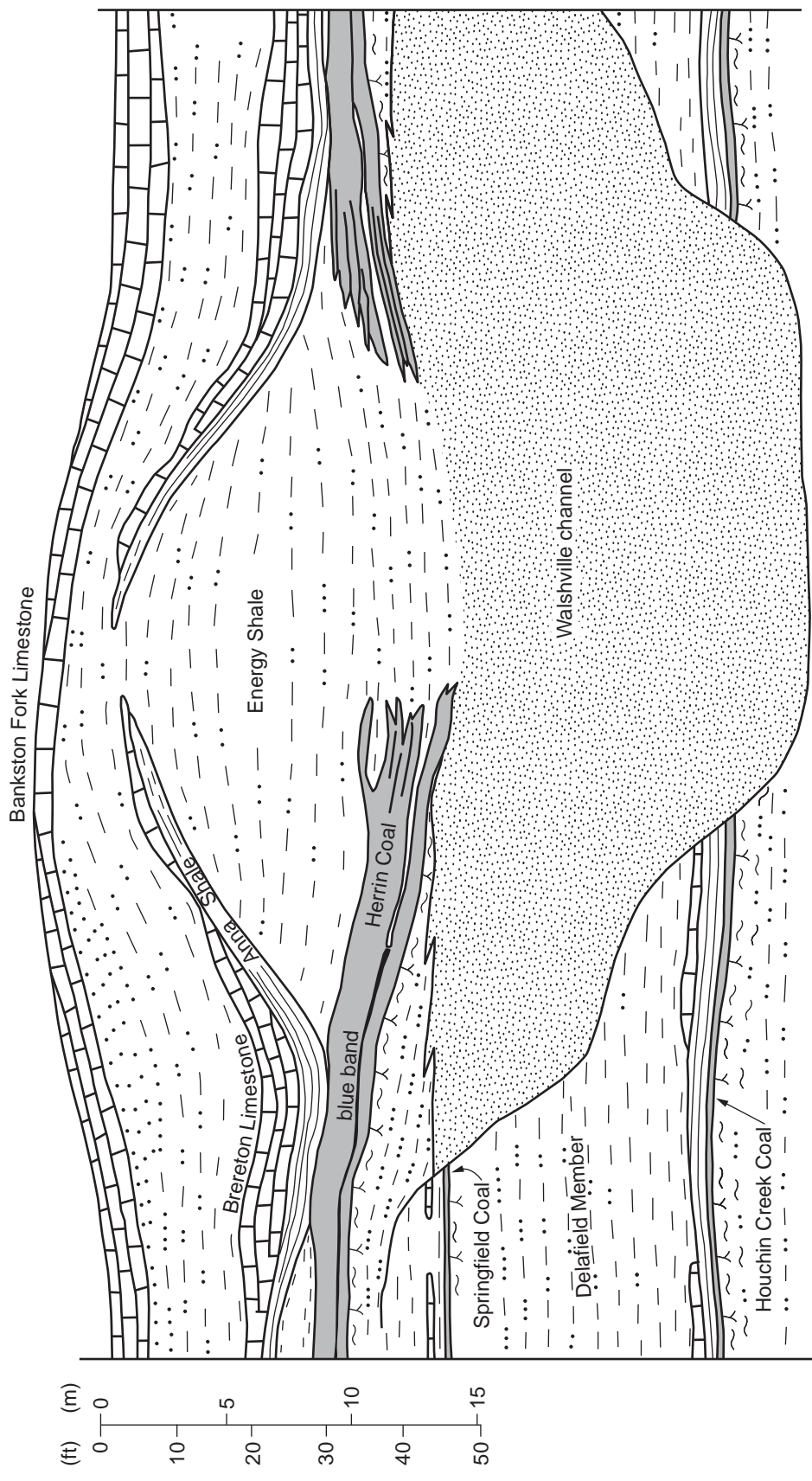
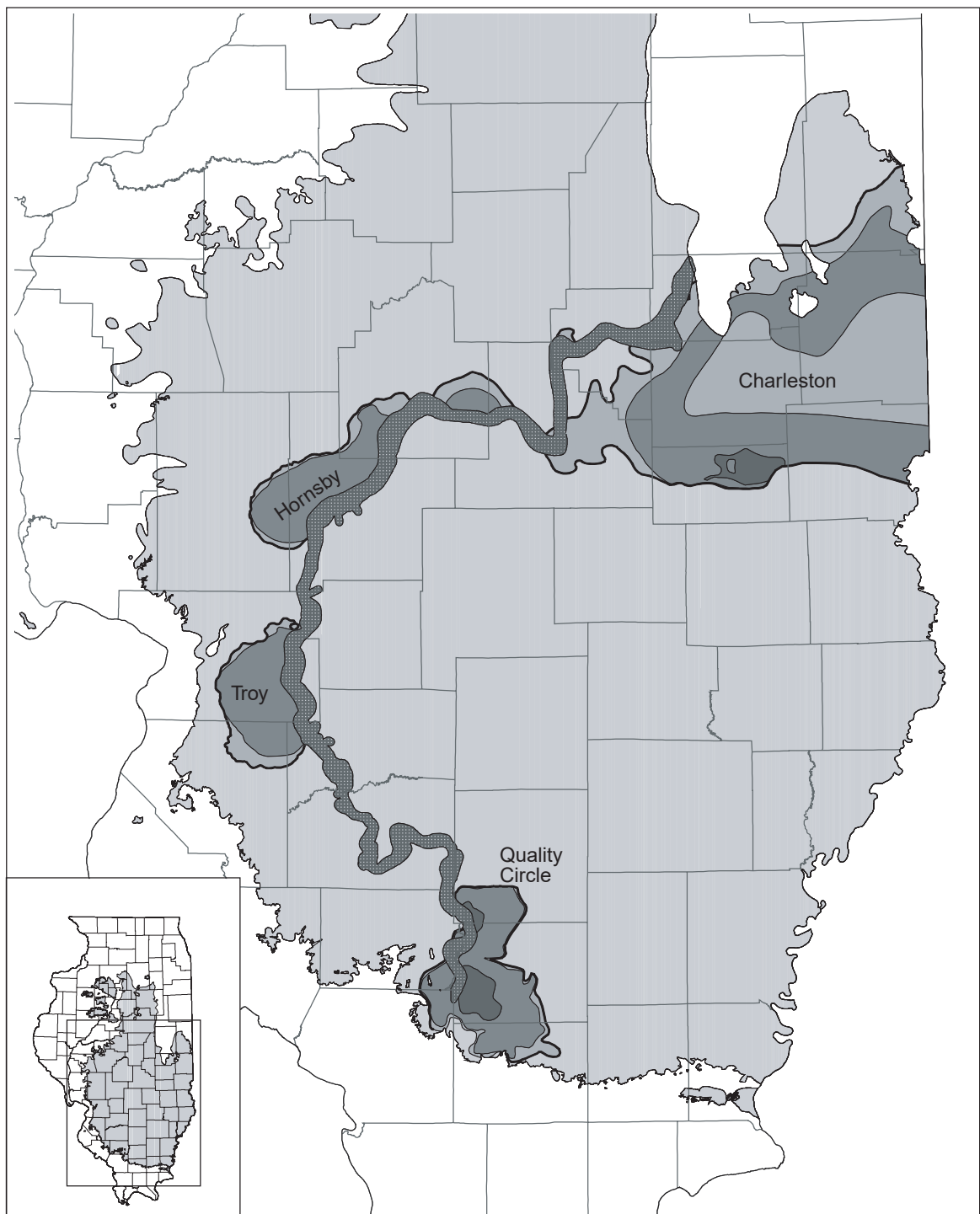
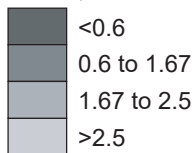


Figure 42 Interpretive cross section of the Herrin Coal, Walshville channel, and Energy Shale.



Sulfur (pounds per million Btu)



- Troy Mining District
- Walshville channel; no coal
- Transitional roof
- Extent of the Herrin Coal



Figure 43 Map showing the Walshville channel and sulfur content of the Herrin Coal. After Treworgy et al. (2000). The four named areas of low-sulfur coal are all associated with thick Energy Shale adjacent to the channel.

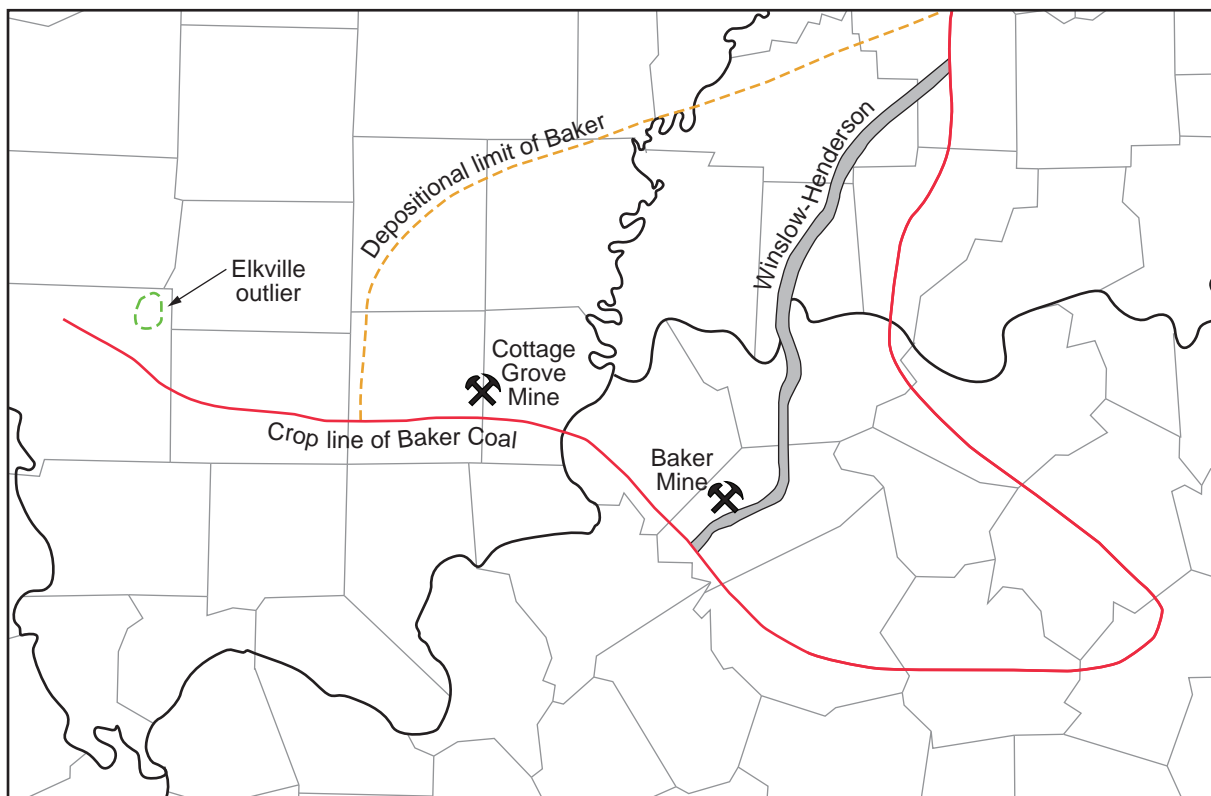


Figure 44 Map showing the Winslow-Henderson channel.

Thick Baker Coal is largely restricted to narrow belts along a paleochannel that was partly contemporaneous with peat formation (Figure 44). Friedman (1960) mapped this paleochannel in Pike County, Indiana, and named it the Winslow channel. Harper and Eggert (1995) and Eggert (1994) extended the Winslow channel farther south in the subsurface. Beard and Williamson (1979) mapped a paleochannel in Henderson and Webster Counties, Kentucky, and called it the Henderson channel. Because the Winslow and Henderson channels align directly at the state border, we recognize them as the same feature and use the compound name Winslow-Henderson channel.

Like the Galatia channel, the Winslow-Henderson comprises a broad, deeply incised valley that was filled largely with sand prior to peat development and a younger, narrower segment that was filled with finer grained sediments during the time of Baker peat formation (Figure 45). Borehole data and exposures in surface mines show that the channel cut downward from above the Bankston

Fork (upper Providence) Limestone a short distance beneath the Baker Coal. The channel carved a valley 2 to 8 mi (3 to 13 km) wide and as deep as 200 ft (60 m), removing units as old as the Springfield Coal. Sandstone of the lower valley fill displays large-scale lateral accretion on mine highwalls, signifying a meandering system. Sandstone grades upward to finer grained, heterolithic strata that bear tidal rhythmites. Approaching the Winslow-Henderson channel, the Baker Coal thickens to 10 ft (3.0 m) or more, and it has multiple laminae and thin interbeds of carbonaceous claystone. The Baker is absent or reduced to stringers within a meandering belt that varies from about 1 to 3 mi (1.5 to 5 km) wide.

The principal difference between the Springfield and the Baker is that the latter lacks marine roof strata and has no gray shale wedge analogous to the Dykersburg. Covering the Baker is a succession of fluvial and floodplain deposits, including mudstone, thin lenticular sandstone, thin coal, and paleosols. Lenses of gray shale a few feet (meters) thick bear fossil plants, including upright tree stumps.

Brackish to marine strata did not appear until after the next younger major peat deposit, the Danville Coal. These observations suggest that (1) preserved Baker Coal developed farther up the coastal plain than did preserved Springfield Coal, or (2) the sea level did not rise much following Baker peat accumulation.

Danville Coal

The Danville (Figures 2 and 40) is the next major coal bed above the Baker. It is the youngest widespread, economically important seam in the Illinois Basin. The Danville is thin and rather patchy in western Illinois, reaching 3.3 ft (1 m) thick in small areas. Coal thick enough to mine (generally 4 to 6 ft [1.2 to 1.8 m] thick) is largely confined to a belt running north-northwest along the east side of the basin from Gibson County, Indiana, into northern Illinois. Coal-thickness patterns (Korose et al. 2002) indicate that much of the thickest coal has been eroded east of the present outcrop. Most Danville Coal has a high sulfur content, but low-sulfur (locally <0.5%) coal occurs in Knox and

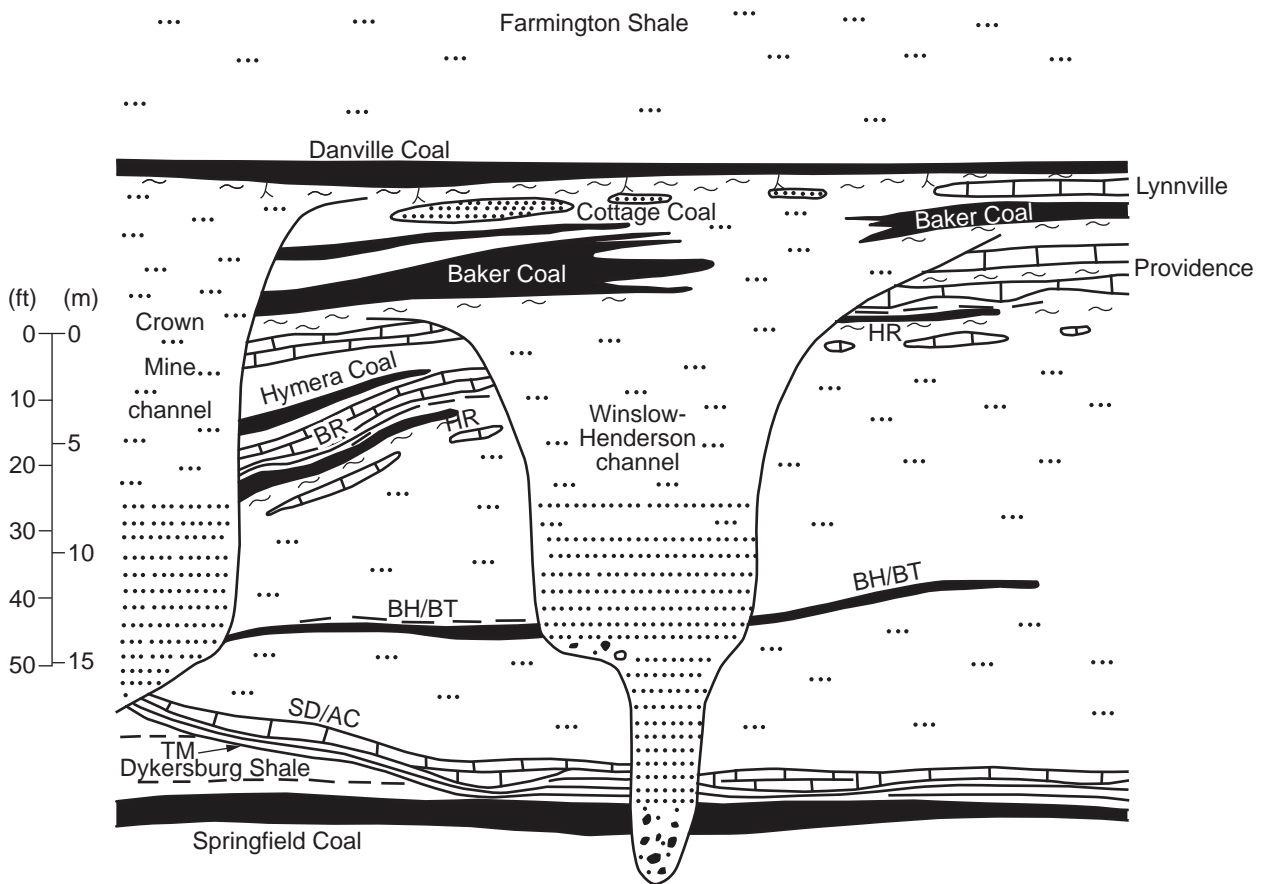


Figure 45 Interpretive cross section of the Winslow-Henderson channel. BR, Breerton Limestone; HR, Herrin Coal; BH/BT, Briar Hill/Bucktown Coal; SD/AC, St. David/Alum Cave Limestone; TM, Turner Mine Shale.

Sullivan Counties, Indiana, and in the bordering part of eastern Illinois (Harper 1988; Harper and Eggert 1995; Korose et al. 2002).

Overlying the Danville is a complex succession of gray clastic rocks that thickens from less than 3.3 ft (<1 m) in parts of western Illinois to as much as 230 ft (70 m) in the central Fairfield Basin of southeastern Illinois. Where it is thin, the shale is dark colored and, in places, is black, fissile shale similar to the Excello and Turner Mine Shales. Eastward, the interval changes to gray mudstone, siltstone, and sandstone arranged in multiple upward-coarsening cycles. The coarsest facies occur in Knox County, Indiana, coinciding with the only known area of low-sulfur Danville Coal. Abundant fossil plants, tree stumps in growth position, and tidal rhythmites are much in evidence in underground mines here. Rolls are also common, as are wedge-shaped siltstone splits and a large-scale coal-

seam disruption that probably involved peat rafting (Figure 46). However, no channels contemporaneous with the Danville have been encountered.

Evidently, Knox County lay near the mouth of a large estuary that discharged sediment onto the Danville peat from the east. Rapid burial under freshwater to slightly brackish conditions resulted in low-sulfur coal. Tidal currents agitated the peat near the estuary mouth, whereas deeper in the basin, the peat was quietly buried under fine mud.

Murphysboro Coal and Oraville Channel

The Murphysboro Coal, in the upper Tradewater Formation, presents some similarities to the Colchester, Springfield, Herrin, and Danville Coals in that thick, low-sulfur coal is associated with a gray shale "wedge" and a contemporaneous channel. However, the Murphysboro is

highly lenticular and has been less thoroughly studied than the other examples, so the relationship of coal to gray shale and the channel is not completely understood.

Jacobson (1983) documented that thick, low-sulfur Murphysboro Coal in southwestern Illinois flanks a feature that he named the Oraville channel (Figures 39 and 47). In fact, coal of mineable thickness (up to 8.2 ft [2.5 m]) is confined to a small area near the channel. Sulfur content is low to moderate (1% to 2.5%) near the channel where thick, nonmarine gray mudstone (unnamed) overlies the coal. Elsewhere, the coal is topped by marine black shale and limestone, and its sulfur content is greater than 3% (Jacobson 1983). Away from the Oraville channel, the Murphysboro has a highly patchy distribution (Treworgy and Bargh 1984). Only small, isolated areas of thick coal are known. Little significant mining has taken place away from the channel.



Figure 46 Disruption of the Danville Coal, with the seam “split” by a thick wedge of mudstone. Note the ragged splaying of coal into mudstone, with a thin coal stringer crossing diagonally from the lower to upper “bench.” The site is the box cut at a portal of the Prosperity Mine in Gibson County, Indiana.

The Murphysboro undergoes dramatic splitting near the Oraville channel margins, where underclay is absent or weakly developed (Figure 48). Upright lycopsid tree stumps are common above the lower coal bench. The gray mudstone exhibits tidal rhythmites and bears a prolific, well-preserved flora dominated by *Macroneuropteris scheuchzeri*, a plant believed to have been tolerant of coastal, perhaps brackish-water, conditions (Falcon-Lang 2009). The Oraville channel follows the downthrown side of a monocline that was active during deposition of the Murphysboro Coal (Nelson et al. 2011).

Ostensibly, the Oraville is another fluvial channel that became an estuary, like the Galatia and Walshville channels. However, nothing is known of the presumed fluvial “precursor” channel, and the

nature of “splitting” coal is poorly understood. Further study of the Murphysboro is required to integrate this unit into a general model.

DISCUSSION

Observations from mines and boreholes through the Galatia channel and related features, as well as similar channels associated with older and younger coal beds, indicate that the old model of a Mississippi-style delta having natural levees and crevasse splays is due for revision. Combined with a better understanding and climate influences not available to earlier workers, these observations led to a new model of channel development that has connotations for larger concepts of cyclic sedimentation.

Model of Channel Development

Our model is presented in 10 illustrated stages (Figures 49 to 58).

Stage 1: Prograding Deltas During Early Regression

To set the stage, the Houchin Creek Coal, Excello Shale, and Hanover Limestone sediments were laid down on a tectonically stable platform from lowstand (underclay and peat) through rapid marine transgression to highstand (black shale and limestone). During late highstand to early regression, clastic sedimentation resumed. A series of deltas were built into the basin, yielding upward-coarsening sediments of the Delafield Member (Figure 49). This part of the model is similar to past cyclothem models in the Illinois Basin.

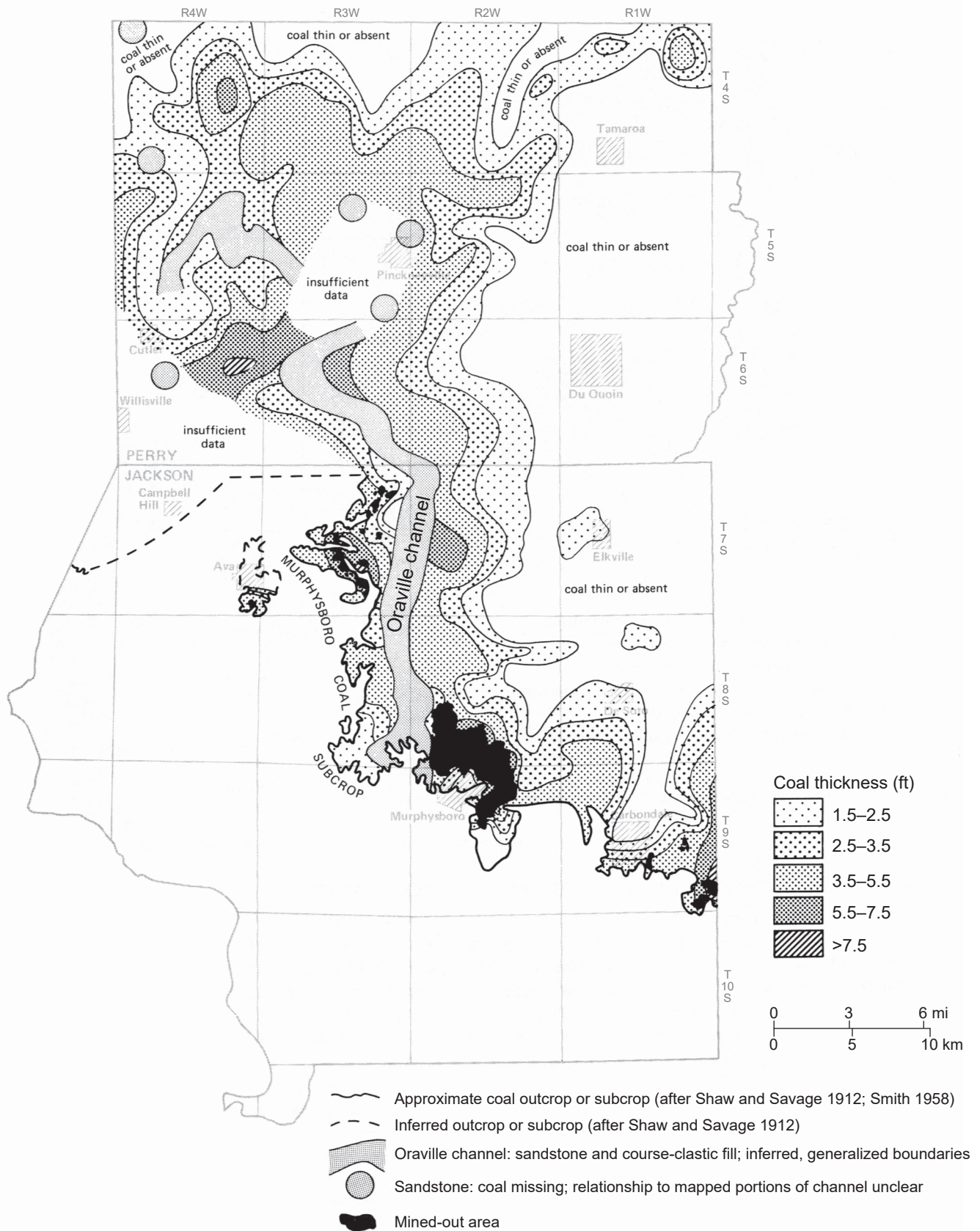


Figure 47 Map showing the thickness of the Murphysboro Coal near the Oraville channel in Jackson and Perry Counties, southwestern Illinois. From Jacobson (1983).

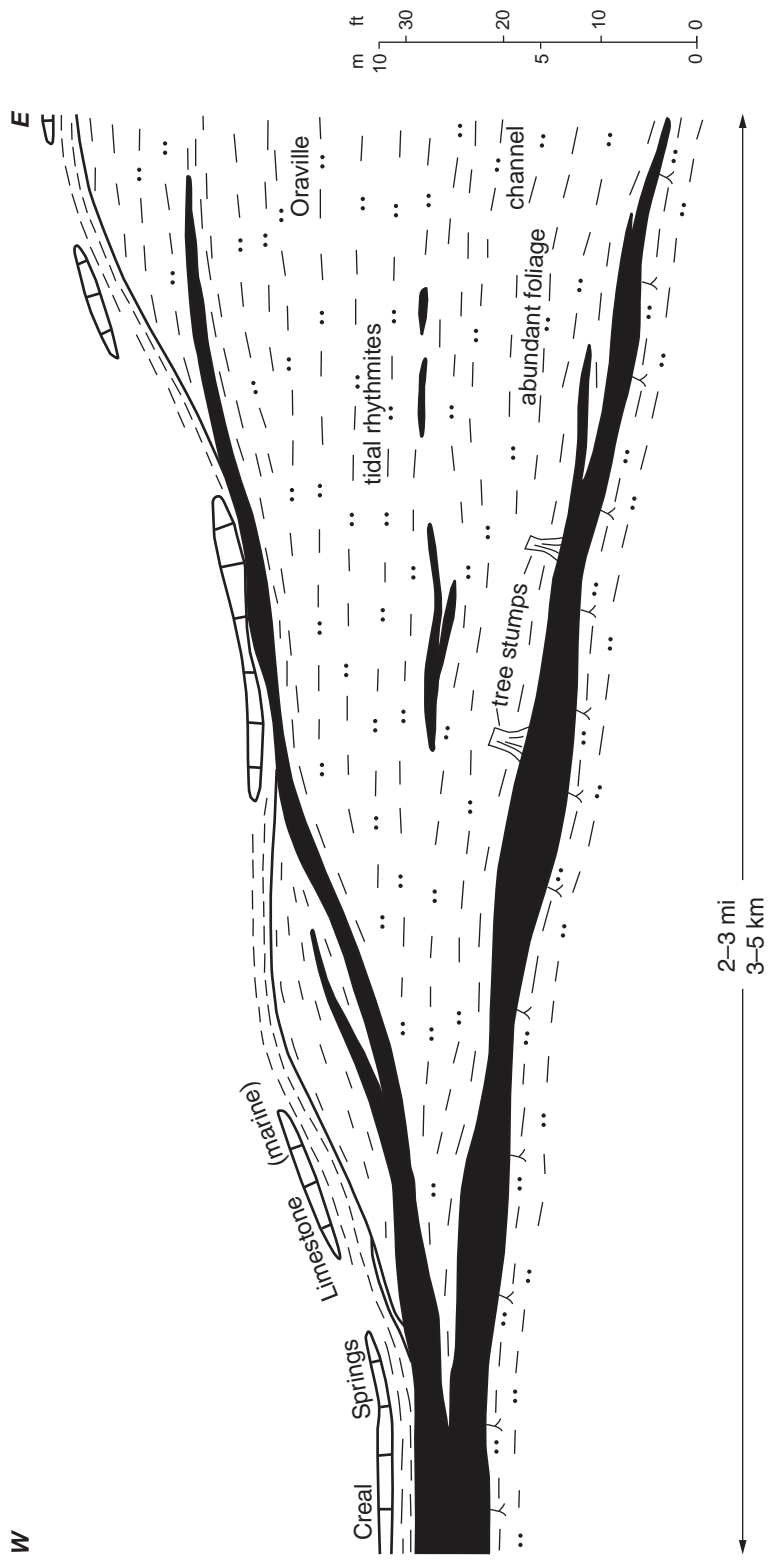


Figure 48 Interpretive cross section of the Oraville channel.

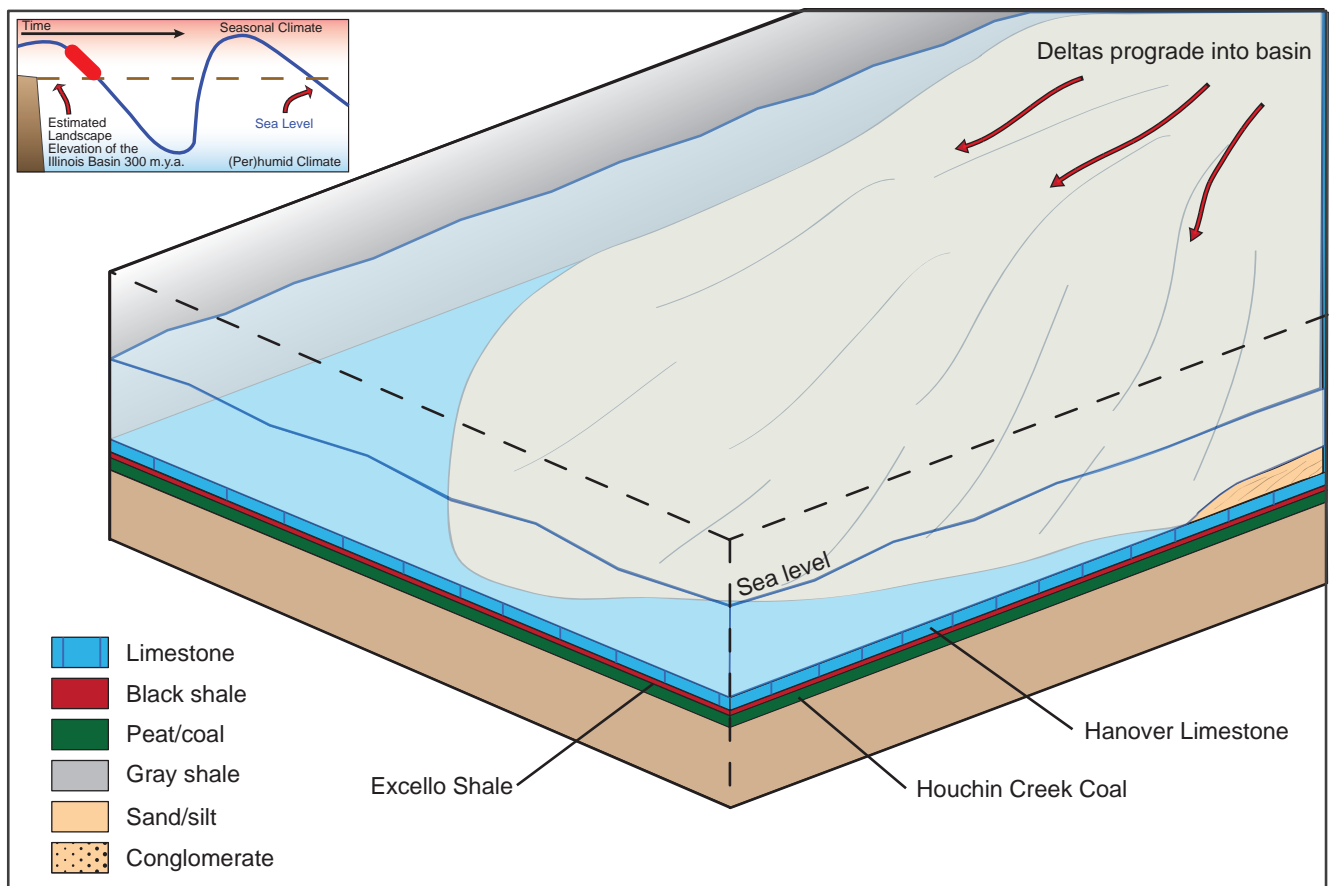


Figure 49 Stage 1: Deposition of the Delafield Member as a series of coalescing deltas during the onset of a glacial stage as the sea level began to fall. The product is a thick succession of clastic rocks that coarsen upward.

Stage 2: Valley Incision and Soil Development During Regression

Delafield sediments rapidly filled available accommodation space in the basin. With continuing marine regression, the delta platform became exposed. Rivers cut downward to base level, creating entrenched valleys. Given the extremely low gradient and the substrate of recently deposited sediments, these streams actively meandered. Outside of valleys, soil development was underway (Figure 50). Previous models (e.g., Potter 1962, 1963) placed channels in a deltaic setting and mostly did not take account of eustasy, although Hopkins (1958) interpreted channels as being cut subaerially during regression and backfilled during transgression.

Stage 3: Aggradation and Gleying During Late Regression

Channels developed broad meander belts. As soon as the channel bottoms were cut below sea level, suspended sediment (largely sand) began to drop out. Rivers reworked their own sandy deposits. Valleys aggraded rapidly approaching maximum lowstand, yielding an upward-fining profile (Figure 51). Approaching maximum glaciation, climate in the Illinois Basin became increasingly humid. This fostered vegetation growth, reducing soil erosion and sediment transport. Increased rainfall leached iron from soils, gleying much of the upper soil profile (Rosenau et al. 2013). Because of the lack of time and persistently wet conditions, little or no soil formation took place

within the Galatia meander belt. This part of the new model is similar to previous models, although most treated paleosols in a cursory fashion.

Stage 4: Peat Initiation and Paludification at Early Lowstand

Approaching glacial maximum or lowstand, climate in the basin became humid. Constant rainfall produced lush, dense vegetation, reducing sediment flux and creating black-water rivers of mostly plant tannin, clay, and perhaps a small bed load. Peat began to develop earliest in low-lying areas on the landscape, such as abandoned meanders. Vegetation lining the banks of the Galatia channel stabilized the banks, locking meanders into place for the duration of lowstand.

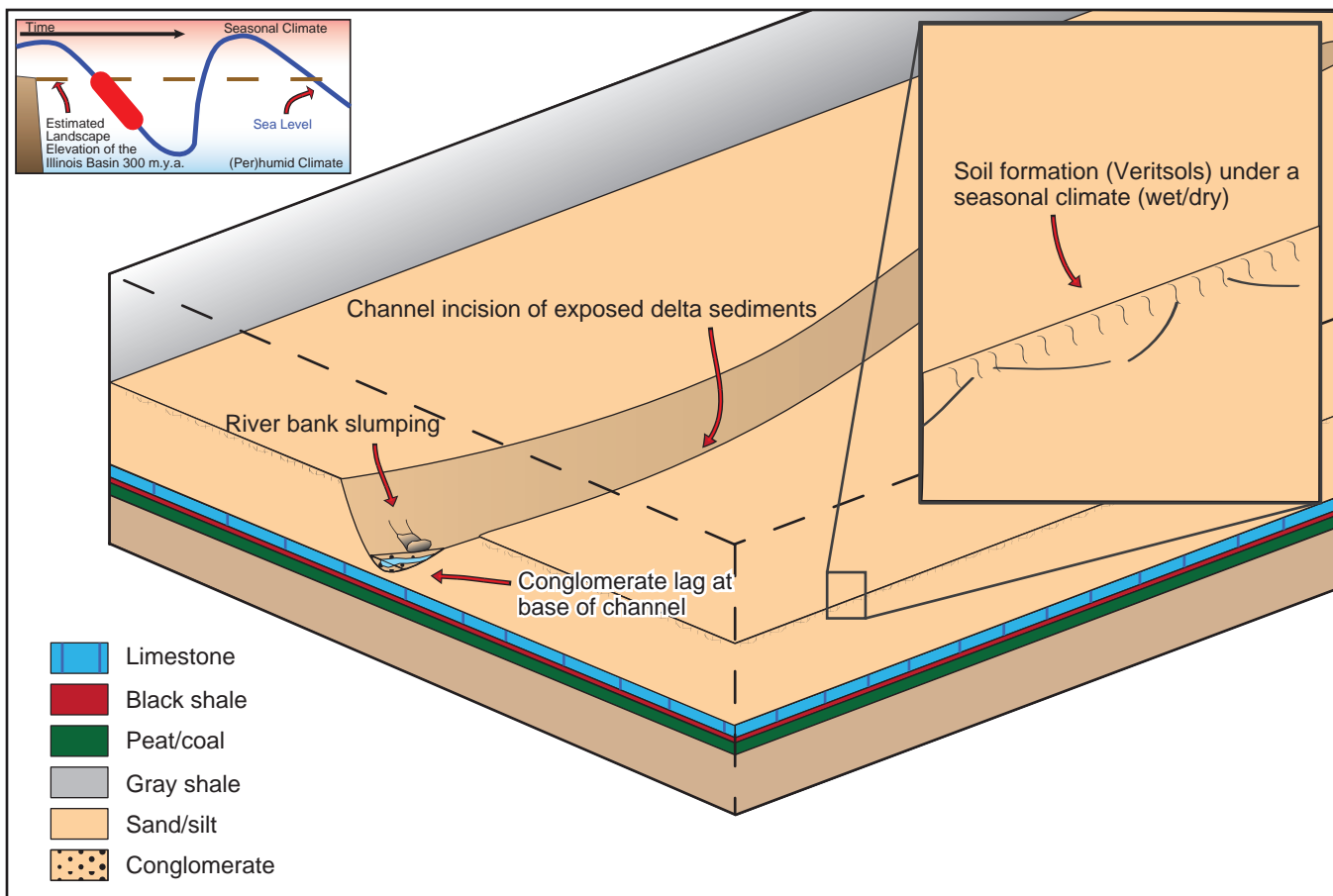


Figure 50 Stage 2: Channel incision of delta sediments.

Along the channel margins, fine clastics infiltrated the peat swamp, perhaps by flocculation of clay in vegetated areas along channel margins. The result was shaly coal in these channel-margin settings (Figure 52). Previous Carbondale cyclothem models did not incorporate syndepositional channels.

Stage 5: Widespread Peat Accumulation at Lowstand

Peat development overspread the basin except for active channels and well-drained tectonic highs (Figure 53). Naturally, the thickest peat accumulated in the lowlands flanking the Galatia channel. Periodic floods brought fine silt and clay out into the swamp, creating clastic laminae in the peat close to the channel. This process is taking place today along the Rajang River in Sarawak, Malaysia, where domed peat deposits fringe the river under a tropical, ever-wet climate (Staub

and Esterle 1993). Tectonic subsidence and concurrent peat compaction created space for thick (albeit nondomed) peat deposits along the Galatia channel. Placing coal at lowstand is conceptually different from many peat or coal depositional models and is elaborated on in the following section.

Stage 6: Peat Rafting and Splitting During Initial Transgression

Glaciation ended abruptly as the polar climate warmed. During the initial stages of sea-level rise, the lower part of the Galatia channel was subjected to increasingly vigorous tidal ebb and flow (Figure 54). Buoyed by trapped air and self-generated methane, large mats of peat floated free of the substrate. At the same time, the climate shifted from ever-wet to wet-dry seasonal. This led to less vegetation cover in inland source areas and a consequent increase in runoff and sedi-

ment load. Silt carried down the Galatia channel was deposited beneath floating peat layers, creating splits and major seam disruptions.

Stage 7: Estuarine Flooding During Early Transgression

Melting induced rapid, pulse-like transgression, drowning the Springfield peat swamp first along the Galatia channel, which became an estuary (Archer et al. 2016). The tropical climate became drier and more seasonal, which reduced the vegetation cover upstream, enhancing runoff, erosion, and fluvial sediment transport. A heavy load of gray silt (Dykersburg Shale) rapidly overwhelmed the peat, entombing tree stumps and other plant remains in place (Figure 55). Some Dykersburg sediment might have been derived from offshore and carried up the estuary by tidal currents, as is happening today in the Kampar River of Sumatra,

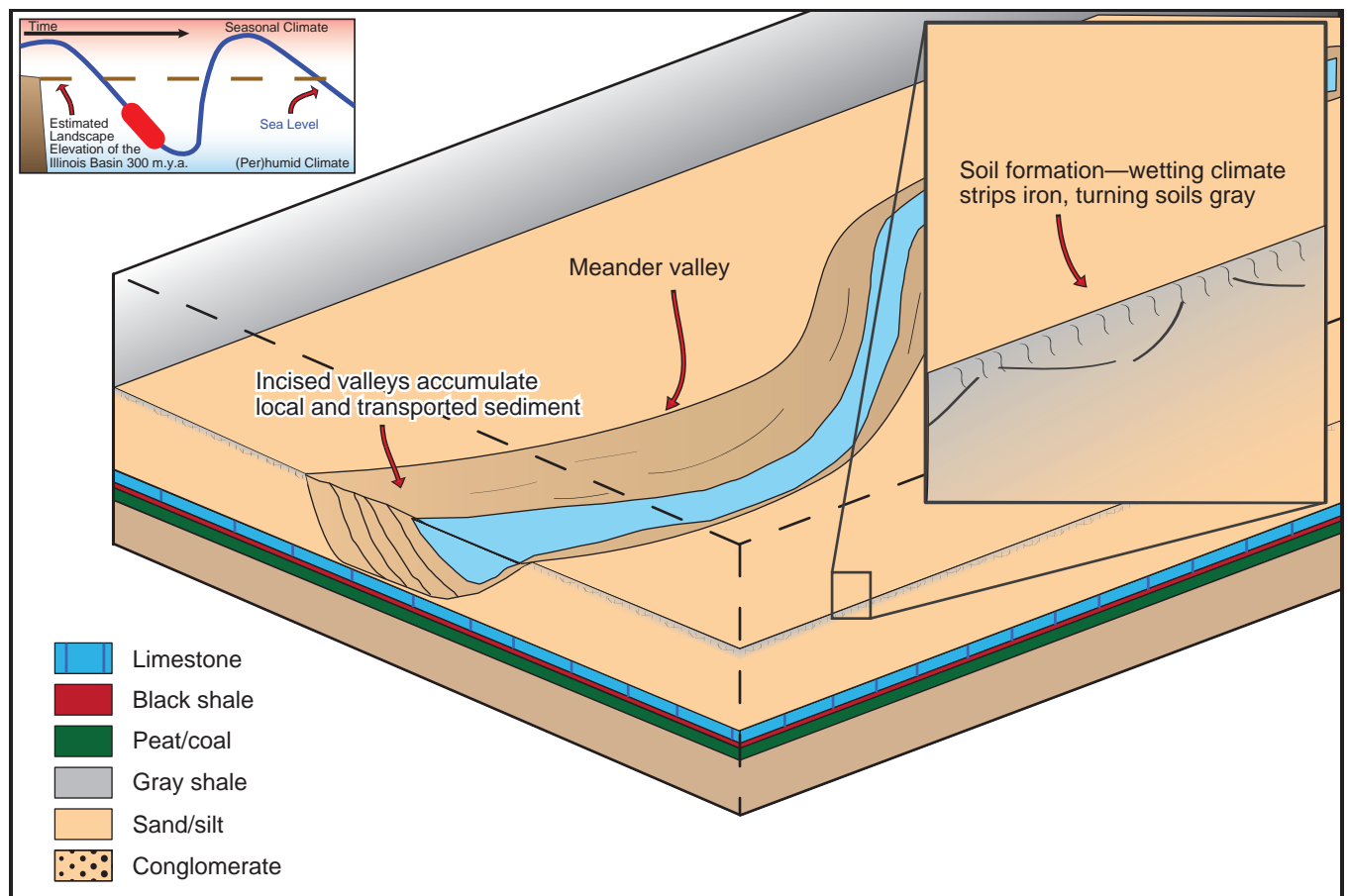


Figure 51 Stage 3: The Galatia channel developed a meander belt.

which is located just north of the equator under perhumid conditions. The upper Kampar has a deep channel and tea-colored water that carries practically no bed load or suspended sediment. Cecil et al. (2003a, p. 32) wrote, “The lower 85 km [52.8 mi] is exceedingly shallow and difficult to navigate even in small boats of very shallow draft” because of the sediment carried up the estuary by the tides. Placing the Dykersburg in a tidal-estuarine facies puts this relatively new concept into the larger cyclothem model and emphasizes the coastal-estuarine rather than the deltaic nature of this part of the cycle.

Stage 8: Estuary Advances Inland as Regression Continues

Loaded with sediment, peat compacted rapidly, making space for more sediment. Basin subsidence, sea-level rise, and peat compaction worked in concert until more than 98.4 ft (>30 m) of Dykersburg Shale was in place (Figure 56). The process

ended when the basin area became so deep and far offshore as to be beyond the realm of coastal processes.

Stage 9: Black Shale of Late Transgression and Highstand

The Turner Mine Shale records rapidly deepening water. The water column stratified, bottom circulation ceased, and the Illinois Basin became sediment starved. Fine sediment that filtered down resulted in black, phosphatic shale (Figure 57). Our model is similar to previous ones, such as those of Heckel (1977, 1986, 1994).

Stage 10: Limestone Deposition at Highstand to Early Regression

At maximum deglaciation, the sea level crested and the climate was seasonally dry. During highstand, bottom circulation became reestablished. Because the climate was seasonally dry, evaporation

was high and carbonate deposition took place as the St. David Limestone (Figure 58). Continued clastic influx during highstand led to delta progradation (Canton Shale), ending carbonate production and beginning the next cycle. This process is similar to those in previous models.

Linkage of Climate and Eustasy

We have alluded to changes in climate, together with fluctuating sea level, as being instrumental in the evolution of the Galatia channel and its related features. The recurrent glacial episodes that induced sea-level changes affected climate in the tropical realm of peat production as well as in the polar and temperate realms. Here we explore how and why climate and sea-level changes were linked.

Earth’s climate belts of today are the products of unequal solar energy to the earth’s surface. Solar radiation is most intense in the tropics, where the sun is

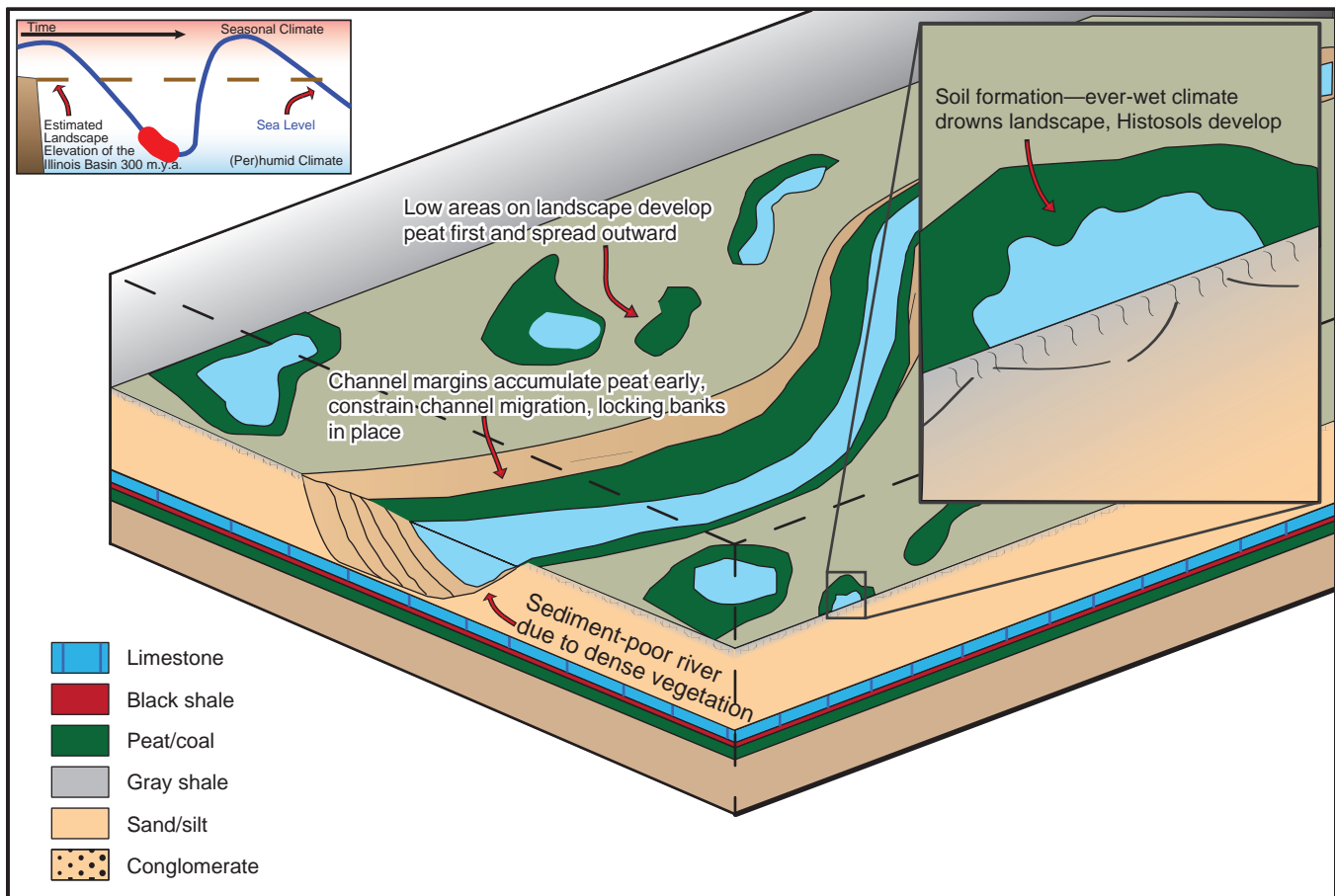


Figure 52 Stage 4: The change to a humid climate caused the Springfield peat to begin to form.

directly overhead. Hot air rises in a belt that girdles the earth roughly parallel to the equator. Rising air, heavily laden with moisture, cools as it rises, producing clouds and heavy rainfall. This rainy tropical belt of rising air is called the intertropical convergence zone (ITCZ). In more familiar terms, this is the doldrums, that zone of light and fickle winds where sailing ships often lay becalmed for weeks at a time. The ITCZ is also a belt of low pressure that draws air from both north and south, setting up persistent winds that angle toward the equator—the trade winds. Beyond them lie the horse latitudes, which, like the doldrums, are belts of persistent high pressure, light and variable winds, and dry weather (Figures 59 and 60). Most of the earth's largest deserts fall in the horse latitudes.

The doldrums (ITCZ), trade winds, and horse latitudes follow the sun through the seasons, migrating north during the

summer² and south in winter. The result is that many areas of the tropics receive distinct wet and dry seasons. Wet seasons or monsoons, characterized by torrential downpours, take place when the ITCZ is overhead. Monsoons alternate with hot, dry seasons when little rain falls. Depending on the local geography, areas of the tropics may receive either one or two annual monsoons, whereas other places have an ever-wet (or perhumid) climate, under which rainfall exceeds evapotranspiration every month of the year.

In the modern world, cold, dense air settles over the poles and flows outward, displacing warm, moist air and generating storms in the middle latitudes. During the "ice ages," the polar realm expanded greatly, compressing the earth's other climate belts toward the equator. As a result, the ITCZ did not migrate as freely with the seasons as it does during the current interglacial episode. With the ITCZ nearly

fixed in place during glacial episodes, much of the equatorial region experienced an ever-wet climate.

Plate-tectonic reconstructions indicate that during the Pennsylvanian, the coal-forming regions of the Illinois and Appalachian Basins, maritime Canada, Western Europe, Russia, and the Ukraine were all aligned close to the equator. Thus, a number of authors (Cecil et al. 2003a, 2003b; Peyser and Poulsen 2008; Eros et al. 2012; Horton et al. 2012) deduced the following equation:

$$\text{Maximum glacial ice} = \text{Low sea level} = \text{Ever-wet climate} = \text{Maximum peat production.}$$

Conversely, during the interglacial episodes, the sea level rose and a monsoonal regime of pronounced wet and dry seasons took hold. Less vegetation stabilized the landscape because fewer plants could tolerate the extended annual droughts. Hence, soil erosion and the sediment

²For simplicity, seasons are discussed in northern hemisphere terms.

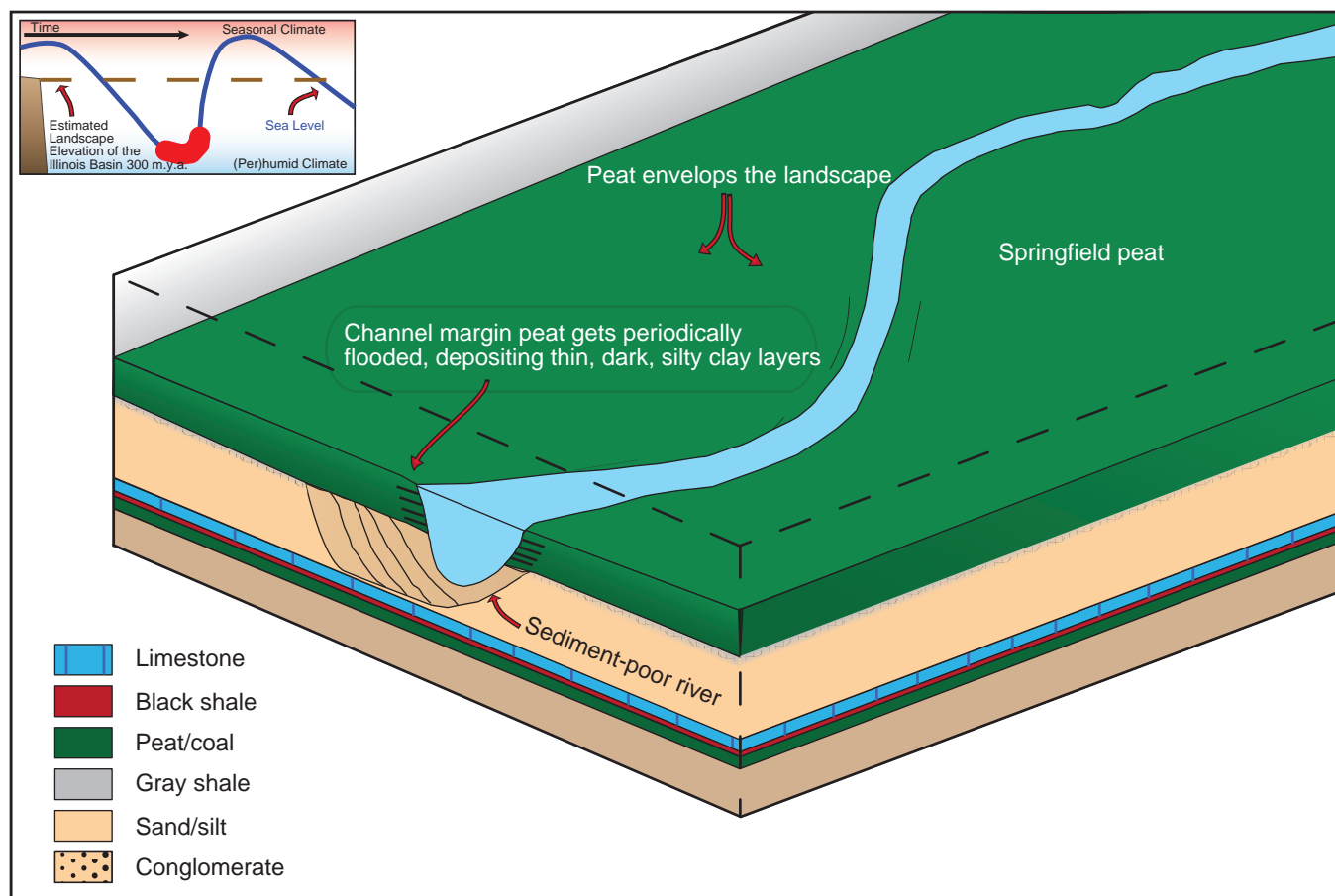


Figure 53 Stage 5: Springfield peat accumulates across a large area of the basin.

load in streams increased dramatically compared with the episodes of ever-wet climate, when plants carpeted the landscape:

Minimum glacial ice = High sea level
 = Strong wet-dry seasonal climate =
 Maximum erosion and runoff.

Peat Developed at Lowstand

Our model calls for the Springfield Coal (and, by implication, other Pennsylvanian coal seams) to be formed during eustatic lowstand under ever-wet conditions. Some previous authors, such as Flint et al. (1995), Bohacs and Suter (1997), and Heckel (2008), maintained that peat developed during transgression. According to their view, preserving a thick peat deposit requires a rising water table because otherwise peat is oxidized and lost. Flint et al. (1995) further held that most economic coal deposits devel-

oped in domed or raised mires, which excluded clastic sediment derived from nearby rivers.

However, evidence from coal-body geometry, coal petrography, geochemistry of coal and enclosing strata, and fossil-plant patterns strongly suggests that Desmoinesian coal in the Illinois Basin developed as planar, not domed, peat deposits (Cecil et al. 1985; Eble et al. 2001; Greb et al. 2002, 2003; Neuzil et al. 2005). Thus, peat accumulated at grade with the Galatia channel, with plants filtering clastics through the flanking belts now preserved as shaly coal. The Galatia was a river without banks or natural levees. Perennial flooding from the channel, coupled with an ever-wet climate, ongoing basin subsidence, and ongoing compaction of underlying sediment, maintained a consistently high water table throughout the duration of Springfield peat accumulation.

Rapid Transgression, Gradual Regression

Evidence from the Pleistocene, particularly the most recent deglaciation, indicates that melting can be surprisingly rapid, even “catastrophic.” Blanchon and Shaw (1995, p. 4) inferred, based on drowned reefs in the Caribbean and Gulf of Mexico, “three catastrophic, metre-scale sea-level-rise events during the last [Pleistocene] deglaciation.” Gregoire et al. (2012) calculated that a sea-level rise of 45.9 to 59.0 ft (14 to 18 m) took place within a span of about 350 years close to 14,000 years ago, and a rise of 29.5 ft (9 m) took place within 500 years about 8,200 years ago. Data from Greenland ice cores indicate two remarkably sudden Late Pleistocene warming events. One at 11,700 years B.P. lasted 60 years, and an earlier event at 14,700 years ago spanned a mere 3 years (Steffensen et al. 2008). Other evidence and examples may be

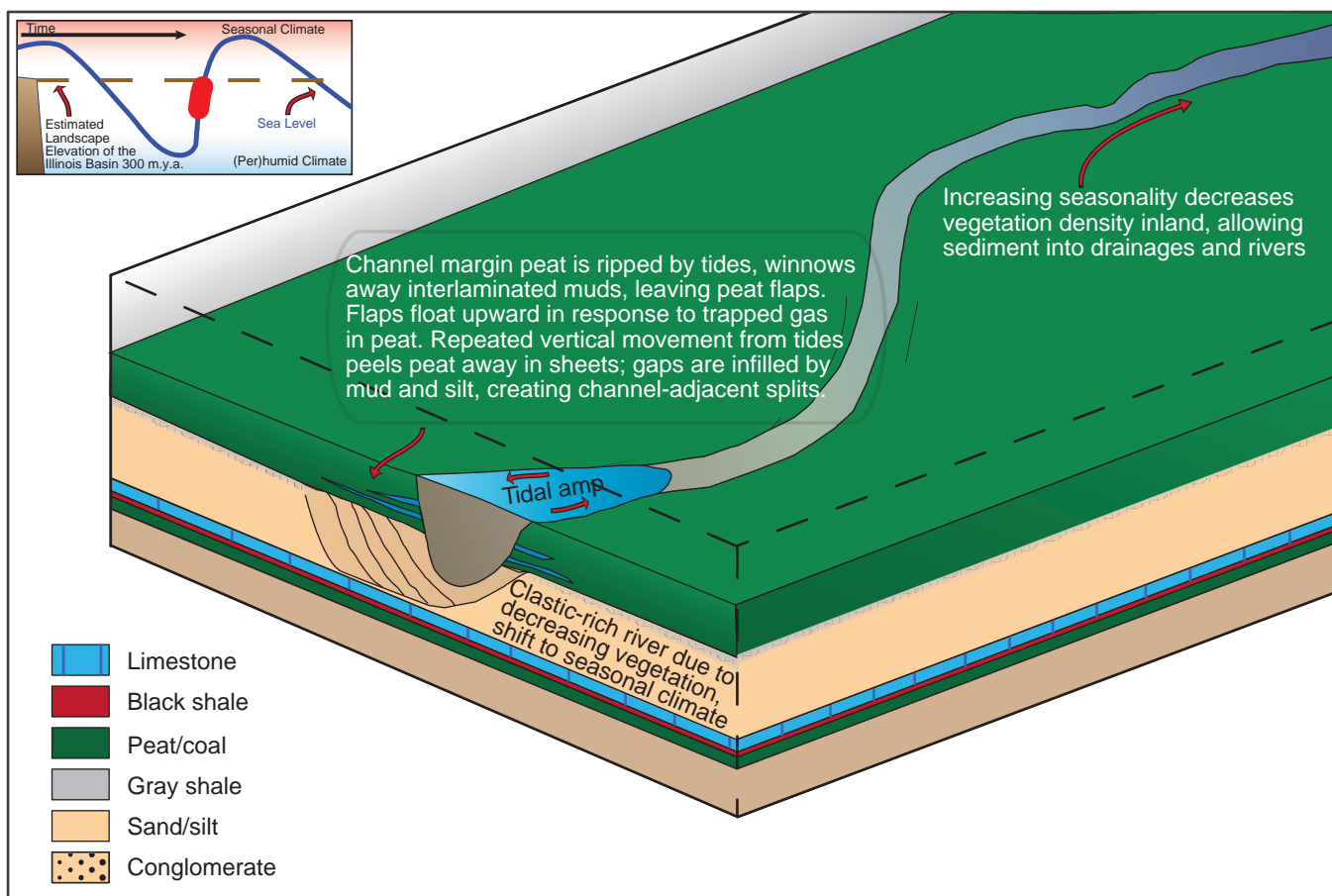


Figure 54 Stage 6: A warming climate brought rapid melting of the glaciers and a sea-level rise. The Galatia channel became an estuary, subject to strong tidal currents.

found in Webster et al. (2004), Wright et al. (2009), Bird et al. (2010), and Törnqvist and Hijma (2012). In contrast, the growth of a continental ice cap requires a much longer interval of time, measured in thousands to tens of thousands of years (Muhs et al. 2011; Dutton and Lambeck 2012).

The authors cited above suggest that any triggering event that raises the sea level may set off a chain of events leading to the rapid destruction of ice caps. The trigger could be the onset of a warmer climate or the failure of ice dams that hold back large bodies of fresh water, such as glacial Lake Agassiz and Lake Missoula. The rising sea breaks up floating ice sheets and releases fleets of icebergs, which melt in warmer waters and raise the sea level further. Moreover, the loss of sea ice changes the ocean and atmospheric circulation, leading to more melting. In contrast, the growth of conti-

ental glaciers is “glacially slow” because snow and ice can accumulate only so fast. In fact, the global cooling required to bring on an ice age reduces the capacity of the atmosphere to hold water vapor and yield snow.

The rapid drowning and burial of the Springfield peat swamp has counterparts in other late Paleozoic deposits. Ravinement surfaces are reported from other coals, such as the Herrin Coal of Illinois (DeMaris et al. 1983), which also has a buried autochthonous flora adjacent to the Walshville paleochannel (DiMichele and DeMaris 1987). Lower Permian carbonate cycles of Kansas commonly begin with a thin transgressive lag of fish bones, ostracods, and intraclasts, implying abrupt, erosive transgression (Miller et al. 1996). The rapid marine transgression that terminated peat accumulation repeats throughout the Pennsylvanian in the Illinois Basin among coal beds that

lack channels and a gray shale roof. Most commonly, the coal is sharply overlain either by offshore black, phosphatic black shale or by marine limestone; at the contact, coal laminations are generally truncated, indicating some erosion of the top of the peat body. At the base of black shale, a thin pyritic shell breccia may be present (Zangerl and Richardson 1963). Where nonmarine gray shale overlies low-sulfur coal, *in situ* tree stumps and tidal rhythmites are commonly in evidence. We have logged examples, including the Lower Block, Murphysboro, Colchester, Herrin, and Danville Coals in addition to the Springfield.

Conditions of rapid, pulse-like sea-level rises likely also occurred during the Pennsylvanian ice age (Archer et al. 2016). Such considerations further militate against the notion of “keep up” time-transgressive peat swamps created by rising base level and driven across the

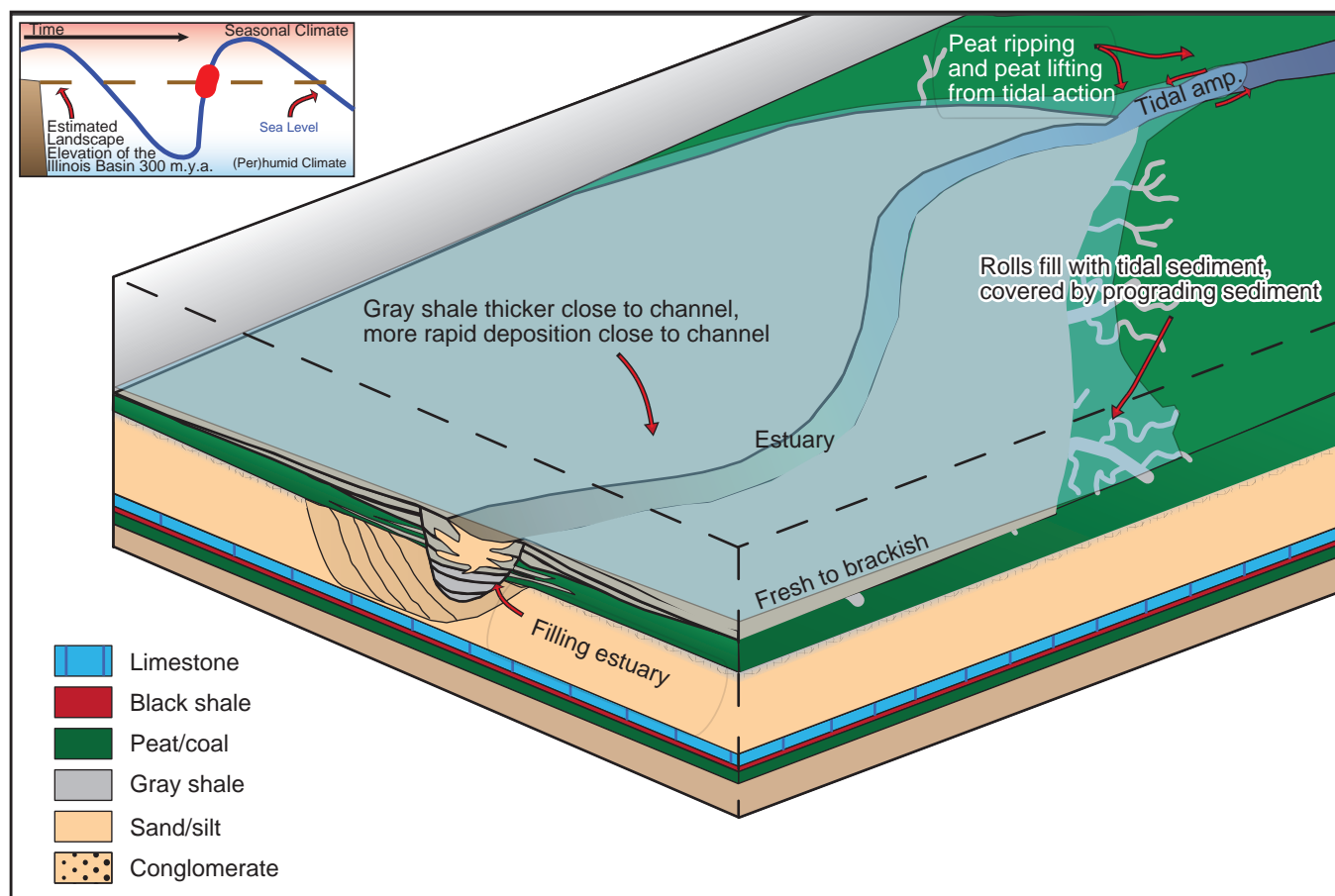


Figure 55 Stage 7: Peat swamps drowned as the estuary became an embayment. Dykersburg sediments rapidly buried the peat.

landscape by sea-level rise (e.g., Heckel 1995). Peat formed much too slowly to keep up with the abrupt sea-level rise of a typical deglaciation.

Relationship of the Effingham and Galatia Channels

The Effingham channel clearly was cut, filled, and abandoned prior to development of the Galatia channel. In fact, the Galatia channel crosses the Effingham at a right angle. Thus, the two channels represent separate cycles of sedimentation. Previously, all strata between the Houchin Creek and Springfield Coals were assumed to belong to a single cycle (Sumnum cyclothem), reflecting a single episode of marine transgression and regression.

In the Midcontinent Basin, the correlative interval contains two cyclothem. The minor Upper Blackjacket Creek cycle

(Figure 61) falls between the major Lower Fort Scott (Excello Shale) and Upper Fort Scott (Little Osage Shale, correlative with Turner Mine Shale) cycles (Heckel 1994, 2002, 2013). As Heckel (2002, p. 110) stated, “The upper part of the Blackjacket Creek Limestone extends as a bed into the upper part of the Morgan School Shale in Iowa, where it contains moderately abundant conodonts [and] thus apparently represents a minor transgression.” Heckel further noted that “the Lower Fort Scott cyclothem loses both its lower and upper bounding paleosols a short distance south of the Kansas border in northern Oklahoma [see Heckel 2013, figure 11, p. 20]. This supports the idea that the lower part of the Midcontinent shelf in southern Kansas and northern Oklahoma was at a lower Pennsylvanian elevation than the entire Illinois Basin” (P.H. Heckel, written communication to W.J. Nelson, June 6, 2014).

We propose the following scenario: During late highstand and early regression of the major Lower Fort Scott cycle, deltaic sediments of the Delafield Member essentially filled the Illinois Basin. As the sea level continued to fall, the Effingham channel became incised and established a meander belt. Then came the minor Upper Blackjacket Creek transgression, drowning the Effingham channel and backfilling it with sediment. When sea level again declined, a new fluvial system—the Galatia channel—became established on the exposed shelf. No limestone or marine fossiliferous shale marks the Upper Blackjacket Creek event in this basin because the sea-level rise was relatively brief and low in amplitude. Tidal rhythmites in the upper Effingham channel fill in the Elysium core, and local, thin coal in other boreholes points to estuarine conditions, not fully marine.

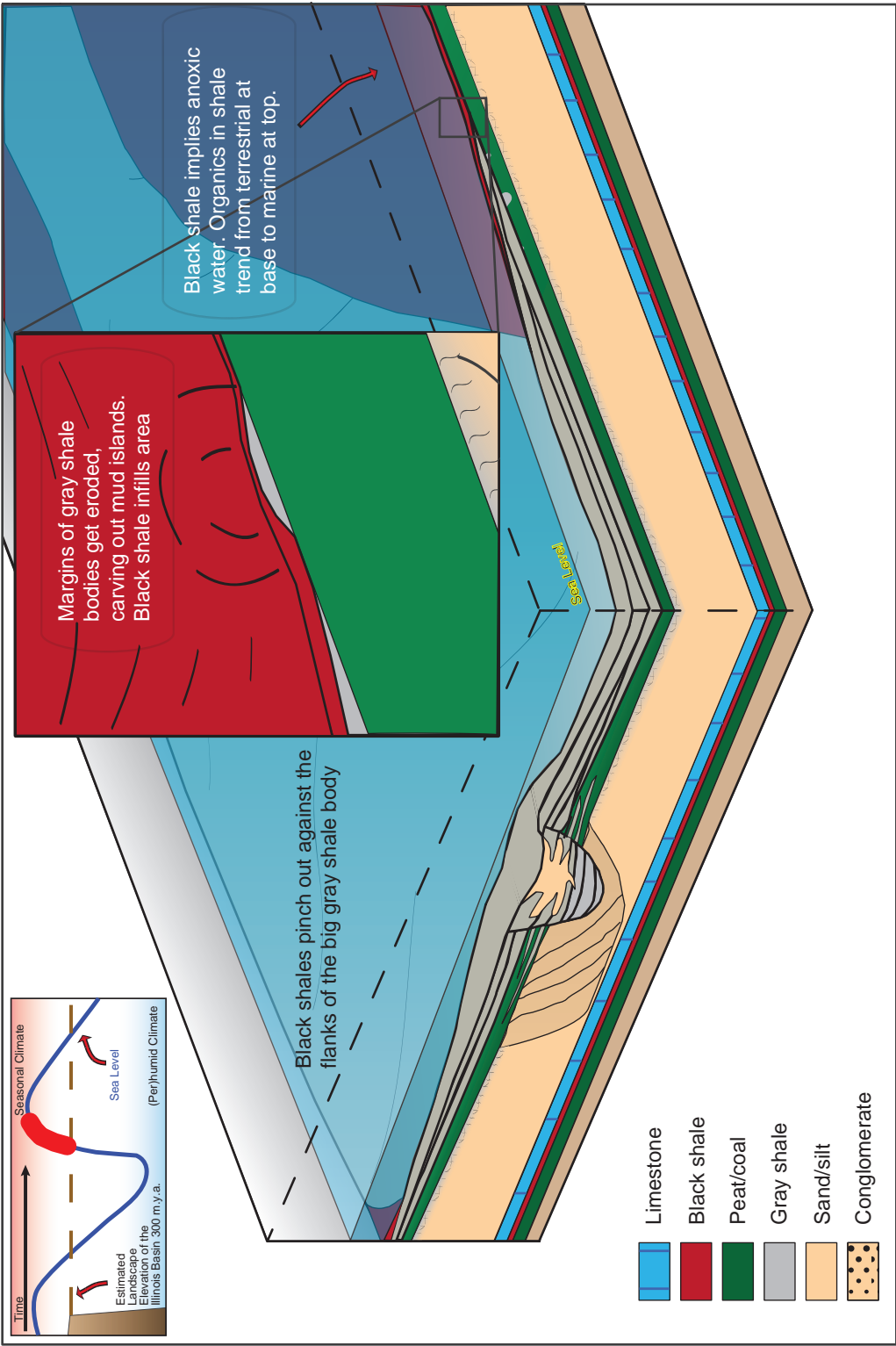


Figure 56 Stage 8: As the transgression continued apace, the entire basin area was submerged in deep water, which became stratified and anoxic, and black mud (Turner Mine Shale) was deposited.

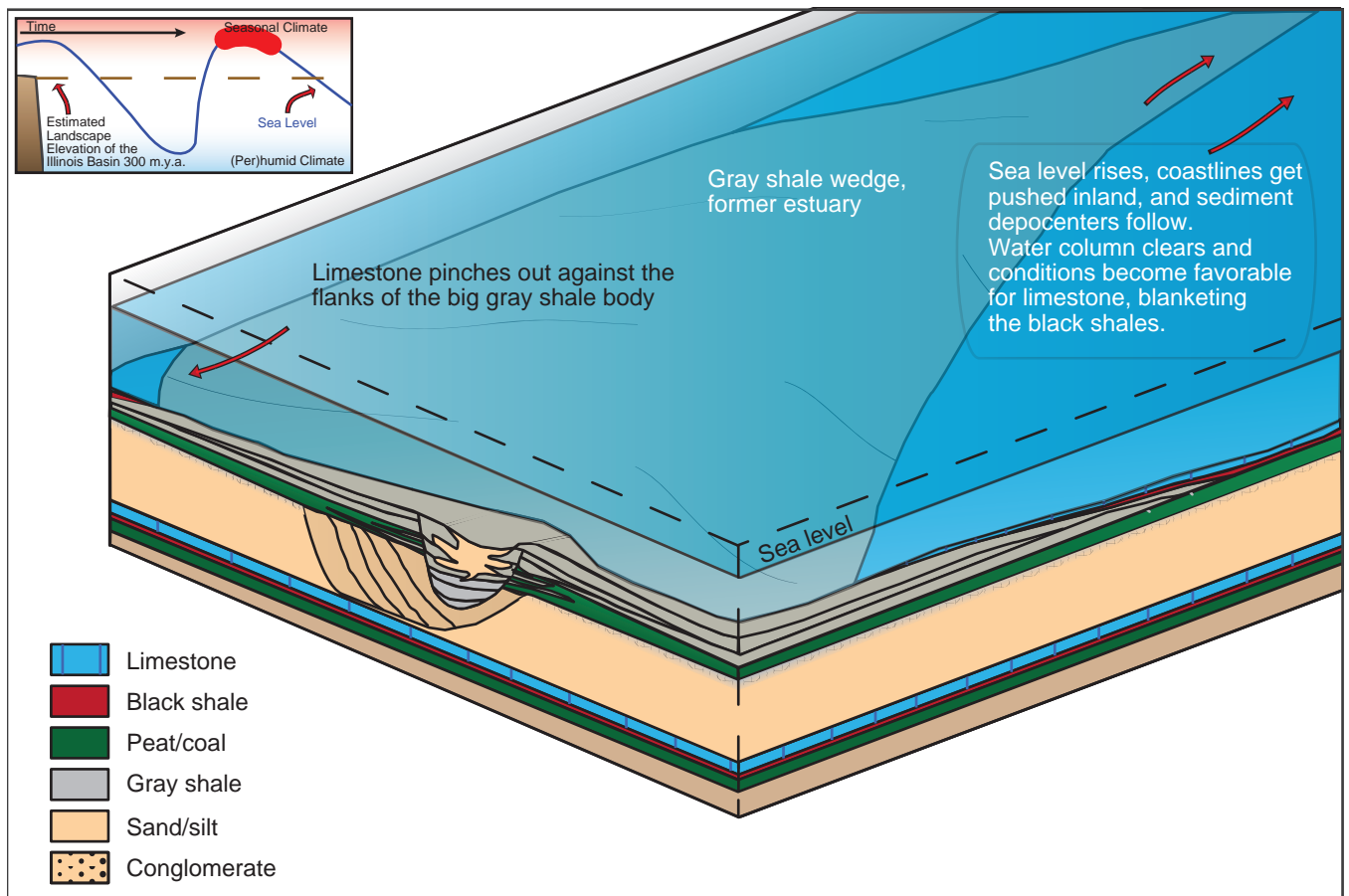


Figure 57 Stage 9: Normal marine circulation resumed near the apex of an interglacial stage (marine highstand), bringing a brief interlude of carbonate sedimentation (St. David Limestone).

As an alternate hypothesis, an autocyclic process or tectonic movement in the basin might have led to the abandonment of one channel (Effingham) and the establishment of another (Galatia) during a single eustatic cycle. Earth movements might have changed the regional gradient from southeast to southwest, inducing a change in channel orientation. This idea is not farfetched because both the Springfield and Herrin Coals thin across the La Salle Anticlinorium and other basin structures, indicating syndepositional tectonism. The channel-forming process clearly was complex and required a substantial amount of time.

CHANNELS AND CYCLOTHEMS: A SUMMARY MODEL

Wanless and Weller (1932) introduced the term “cyclothem” to describe appar-

ently repeating sequences of lithologies in coal-bearing rock sections of Pennsylvanian age (Langenheim and Nelson 1992). These authors tied such successions to sea-level fluctuations driven by the waxing and waning of polar glaciers during the Pennsylvanian, a model that has proven remarkably robust and continues in use today (e.g., de Wet et al. 1997; Heckel et al. 2007; Heckel 2008; Eros et al. 2012; Waters and Condon 2012). Challenges to the cyclothem concept reflect various attempts to outright discredit it (e.g., Wilkinson et al. 2003), to demonstrate control by local, coastal sedimentary processes (e.g., Horne et al. 1978; Ferm and Cavaroc 1979) or by structural geological movements (e.g., Ferm and Weisenfluh 1989), or to subsume it terminologically within sea-level-driven sequence stratigraphic models (e.g., Bohacs and Suter 1997). The recurrent patterns discussed here, in relation to the Galatia channel and

similar features in other coals, only serve to strengthen the argument for a periodically repeating class of natural phenomena as drivers of lithological sequences in Pennsylvanian cratonic coal-bearing rock sequences. The relatively recent additions of climate (e.g., Cecil et al. 2003a, 2003b; Horton et al. 2007; Peyser and Poulsen 2008; Bishop et al. 2010) and of the ties between climate and sedimentation patterns (Cecil and Dulong 2003) provide a more complete framework for explaining cyclothem patterns in space and time, particularly those permitting escape from an either-or focus on allocyclic versus autocyclic underlying controls (in the terminology of Beerbower 1964) while recognizing the role and context of each.

The modern cyclothem concept takes full account of sequence stratigraphy, including autocyclic processes, such as the formation of deltas, within a framework of sea-level change. The proximate

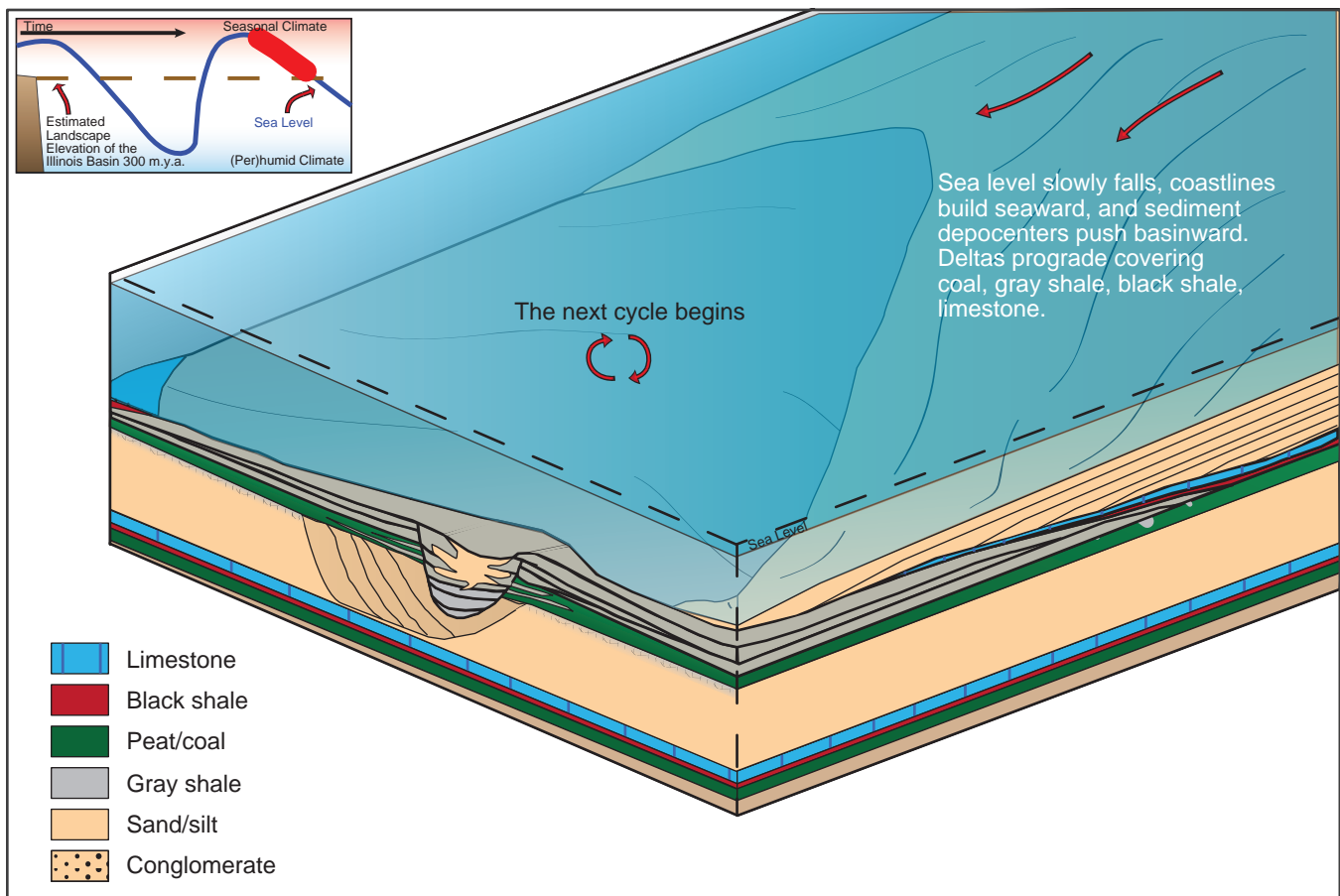


Figure 58 Stage 10: Marine regression begins the next cycle.

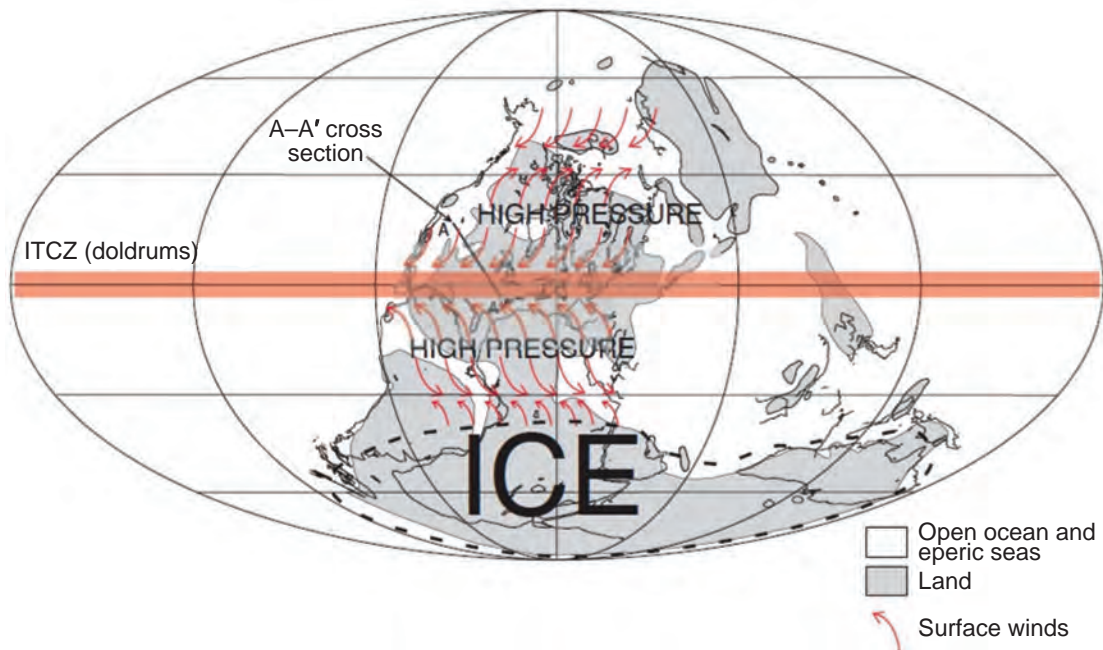


Figure 59 Conceptual model of Pangea during a glacial episode of the Pennsylvanian. From Cecil, C.B., F.T. Dulong, R.R. West, R. Stamm, B. Wardlaw, and N.T. Edgar, 2003b, Climate controls on the stratigraphy of a Middle Pennsylvanian cyclothem in North America, in C.B. Cecil and N.T. Edgar, eds., Climate controls on stratigraphy: SEPM Special Publication 77, p. 151–180. Copyright © 2003, used with permission of SEPM; permission conveyed through Copyright Clearance Center, Inc. ITCZ, inter-tropical convergence zone.

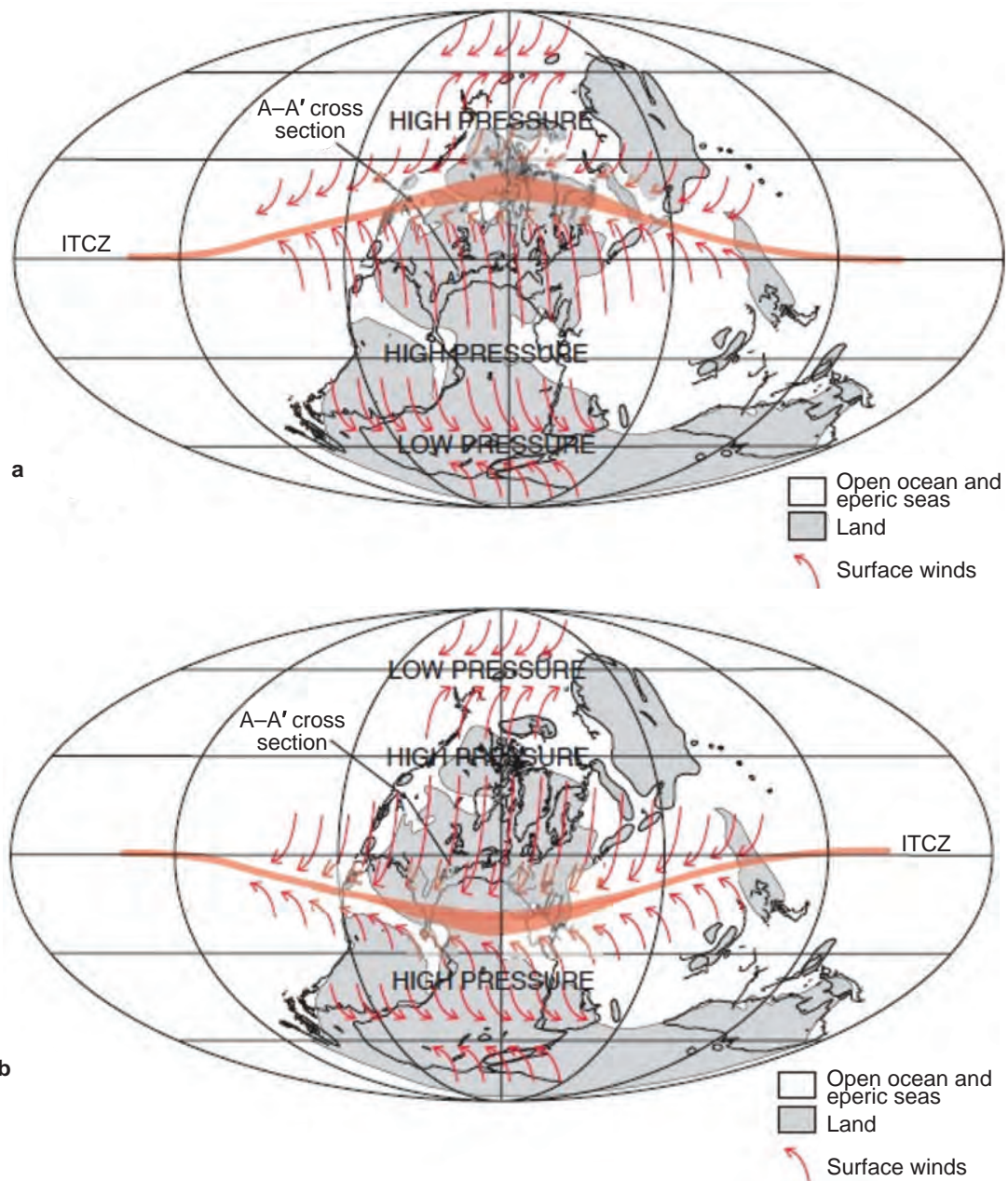


Figure 60 Conceptual model of Pangea during an interglacial episode of the Pennsylvanian. From Cecil, C.B., F.T. Dulong, R.R. West, R. Stamm, B. Wardlaw, and N.T. Edgar, 2003b, Climate controls on the stratigraphy of a Middle Pennsylvanian cyclothem in North America, in C.B. Cecil and N.T. Edgar, eds., *Climate controls on stratigraphy: SEPM Special Publication 77*, p. 151–180. Copyright © 2003, used with permission of SEPM; permission conveyed through Copyright Clearance Center, Inc. ITCZ, intertropical convergence zone.

driving force of Pennsylvanian and Early Permian sea-level change still appears to be changes in grounded ice volume, mainly in the south polar and mountainous regions of Gondwana. However, questions have been raised about the sufficiency of the volume of ice (Isbell et al. 2003; Horton and Poulsen 2009; Henry

et al. 2010) and whether it was present at all (Fielding et al. 2008; Gulbranson et al. 2010) during some intervals of the Pennsylvanian (such as the Kasimovian; e.g., see Gulbranson et al. 2010), during which cyclothem sequences nonetheless continue to be found in the equatorial regions of central and west-central

Pangaea. We will take as a given that cyclothem sequences reflect covariant changes in sea level, climate, and sediment transport volume linked to variations in ice volume (Horton et al. 2007, 2012).

There also are elements that, although varying through time, must be treated

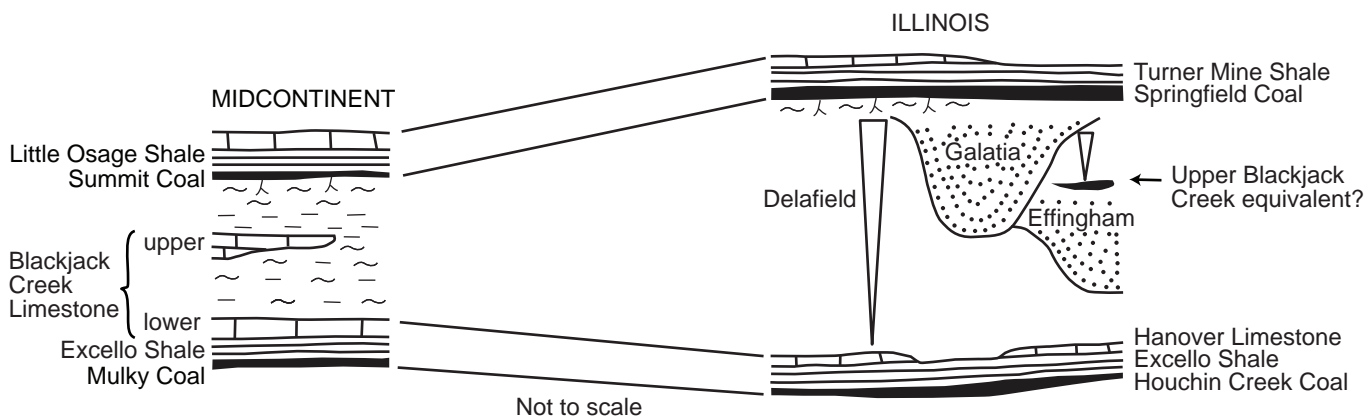


Figure 61 Diagram illustrating the possible relationship of the Effingham and Galatia channels to Midcontinent cyclothem.

as constants because (1) they are not linked causally to the set of variables tied to cyclic global change, and (2) their effects and timing are often obscure. The most prominent of these is tectonics. It is understood that accommodation space is needed to preserve sediments as part of the geological record. However, remarkably robust correlations have proven possible between cyclothem, glacial-interglacial cycles in the cratonic basins of the American Midcontinent (Western Interior), Illinois (Eastern Interior), and Appalachian regions (Heckel et al. 2007; Falcon-Lang et al. 2011), correlative with a nearly identical cycle sequence in the Donets Basin (Heckel et al. 2007; Heckel 2008; Eros et al. 2012; Schmitz and Davydov 2012; Davydov et al. 2012), based on marine microfossils, palynology, and radiometric dating. These correlations reveal that nearly every major cycle and many minor cycles are preserved in all these basins. This high degree of correlation leads to the conclusion that the creation of accommodation space was sufficient to be treated, on average, as a constant, even though there clearly are local effects on the thickness or areal extent of any given bed, as discussed above.

The “Typical” Cyclothem on a Cratonic Platform

A Midcontinent North American cyclothem, at its simplest, consists of a terrestrial and a marine portion. The rock units representing these markedly different settings are, in most cases, not interdigitated. The great flatness and large areal extent of the central-western equa-

torial Pangaea cratonic surface allowed for widespread, nearly synchronous deposition of many marine units and equally for the widespread development of soils on exposed surfaces, including Histosols (peats), under conditions of widespread, aseasonal to weakly seasonal patterns of high rainfall.

The terrestrial portion of a cyclothem consists primarily of a mineral paleosol, developed on normal marine or near-shore marine deposits, followed by patchy to widespread mineral swamp deposits, represented by organic-rich shales and terminated by a Histosol, developed in a peat-forming environment. The contacts between these units can be sharp or gradational. The basal paleosol, particularly in the later Middle Pennsylvanian and Late Pennsylvanian, and in some places, earliest Permian, shows strong evidence of a complex origin. Such paleosols are vertic and often calcic, evidencing a seasonal climate and well-drained conditions during their early formation. These initial patterns are overprinted by evidence of decreasing seasonality and increasing moisture, during which the soil was gleyed to various degrees. Mineral soil formation terminates with surface flooding, locally with the development of clastic swamps and finally with the onset of peat formation (Joeckel 1995, 1999; Miller et al. 1996; Cecil et al. 2003a, 2003b; Hembree and Nadon 2011; Catena and Hembree 2012; Rosenau et al. 2013).

The contact between the terrestrial and marine portions of the cyclothem is marked by an often-cryptic erosional sur-

face (a ravinement surface). Above this surface, there may be discontinuously distributed phosphate nodules (Heckel 1977), signifying a period of sediment starvation under marine water cover, or a thin, discontinuous marine bed, often just a shell hash (Bauer and DeMaris 1982), what Heckel (1986) has called the transgressive limestone. Above the ravinement surface, and transgressive limestone, if present, is generally a widespread, sheeted black shale that, where it has been examined, has a terrestrial organic signature in its lower half and a marine signature in its upper half (James and Baker 1972; Banerjee et al. 2010). This black shale often contains marine invertebrates throughout. Succeeding and in sharp contact with the black shale is a marine limestone that contains a normal marine fauna. Above this limestone, variably developed is a sequence of mixed gray shales and sandstones that generally coarsen upward and rarely can contain thin, discontinuous layers or beds of organic-rich shale or coal. In most cases, these deposits appear to be of deltaic origin and strongly reflect autocyclic controls on local characteristics. The paleosol at the base of the terrestrial portion of the next sequence is developed upon these marine to brackish-water deposits. The parent material of the soil may vary considerably, reflecting the landward extent and depth of the transgression that accompanied the previous interglacial and associated sea-level highstand.

This characterization of a cyclothem is a generalization. Details of how this series of terrestrial-marine environments is represented in the rock record depend

strongly on vagaries in a number of physical variables. These include the extent of marine transgression, the maximum water depth, the volume of sediment and location of sediment delivery points, the rate of sea-level rise and fall, the length of the exposure period of the craton during falling sea-level stages and at lowstand, the length of time and extent over which the tropical climate was suitable for peat formation during lowstand, and, of course, the rate amount of and areal variability in the creation of accommodation space. That regular cycles can be recognized at all, given the many variables, shows the strong influences of the most basic drivers, climate and eustasy, which overprint the entire record, allowing for the creation of accommodation space.

Cyclothem Models Do not Address Contemporaneous Channels

The traditional cyclothem model leaves out the channel deposits that form contemporaneously and continuously through the interval of paleosol development, peat formation, and early sea-level rise. Also left out along with these channels, and of particular interest here, are the gray-shale wedges that lie immediately above, and in gradational contact with, the coal bed along the channel flanks, the splits in the coal bed that form contemporaneously with final channel filling, and the dark shales interbedded with the coal close to the channel. These deposits, which reflect the complex interaction of allocyclic (sea level and climate in particular) and autocyclic processes, are key indicators of the timing of peat or coal formation during a glacial-interglacial cycle. Such deposits appear to have existed contemporaneously with every major coal bed, to have been expressed differentially depending on the many factors described briefly above, and to have been known or understood to different degrees in each instance depending on the availability of exposures, both natural and created, by mining and road construction or in drill core.

Perhaps the most important aspect of the channel deposits is their long duration, within the framework of a glacial-interglacial cycle. As can be seen from the examples discussed above, stream downcutting began as soon as the craton

was exposed during sea-level fall, in the early stages of glacial advance. As a consequence, the development of paleosols and floodplain deposits likely began under the strongly seasonal subhumid climates to, in some instances, even semi-arid climates that characterized sea-level highstands and falling stages (Cecil et al. 1985, 2003a, 2003b; Peyser and Poulsen 2008; Tabor and Poulsen 2008; Horton et al. 2012). The flatness of the craton in the Midcontinent through the Appalachian Basin must be kept in mind here. By the late Atokan, land-surface irregularities created by the Mississippian-Pennsylvanian sea-level drop had filled such that the surface of the craton, deeply incised at the end of the Mississippian (Howard 1979; Kvale and Archer 2007), had become much flatter (Waters and Condon 2012). This flatness is the major factor that led to beds of huge areal extent, contemporaneous throughout their extent, most notably coals (e.g., Greb et al. 2003) but also open marine environments (Heckel 2008) and fossil soil horizons (Cecil et al. 2003a, 2003b). Consequently, with the shelf edge of the mid-Pangaeian equatorial craton in the modern-day Arkoma Basin region of Oklahoma by later Middle Pennsylvanian (Desmoinesian/Moscovian), slopes on the surfaces leading inland from that point may have been much less than 6.3 in./mi (<10 cm/km). As a consequence of this low slope, exposure of the cratonic surface during sea-level fall, or its flooding during sea-level rise, was likely rapid. Once the slow process of ice buildup began during the early phases of a glacial interval, small changes in sea level would have had large effects on the depth of water coverage on the craton and the timing and extent of surface exposure.

The channels and associated deposits discussed here are those that were initiated on the exposed cratonic surface during falling stages of sea level and that continued uninterrupted through early stages of sea-level rise. Attempts to incorporate dynamics into the cyclothem model often place channels throughout the entire sequence (e.g., Baird and Shabica 1980; Jacobson 2000), relying on a strictly autocyclic, deltaic model of deposition for an entire cyclothem under an invariant climate (e.g., Horne et al. 1978). Gray shale clastic wedges covering coal beds, and associated with channel deposits,

have been explained as reflections of tectonism, again holding climate constant (e.g., Wanless 1964). There certainly are channels at many portions of any glacial-interglacial cycle, but these must not be confused as being of a single type or all reflecting deposition under a common set of circumstances.

Lowstand channels are partially contemporaneous with the paleosols that underlie coal beds, and these paleosols are indicators of the climatic conditions under which the precoal channels and floodplains formed (Feldman et al. 2005; Falcon-Lang et al. 2009). Such paleosols may have thicknesses of up to several feet (meters) and characteristics that include indicators of seasonality of moisture or rainfall (vertic features), even considerable periods when evapotranspiration exceeded rainfall (the development of soil carbonates—which, in older literature, often were referred to as “fresh-water” carbonates and envisioned to have formed in lakes, laterally equivalent to marine limestones offshore; e.g., see Wanless 1964). The climate signature of these sorts of paleosols stands at odds with the coal beds that immediately supersede them stratigraphically. Formed as Histosols, the coals are indicative of perhumid to humid climates (humid during the later Middle and Late Pennsylvanian; perhumid during much of the earlier Pennsylvanian—see Cecil et al. 1985; Cecil and Dulong 2003). As the glacial maximum was approached (sea-level lowstand), the climatic seasonality under which these soils initially developed began to diminish, resulting in an overprint of a wetter climate state (Cecil et al. 2003a, 2003b; Hembree and Nadon 2011; Rosenau et al. 2013). This late-stage increase in rainfall and decrease in seasonality, while soils were still well drained, led to the initiation of organic buildup on the soil surface, with the attendant formation of weak organic acids and the subsequent intense gleying that characterizes so many Pennsylvanian paleosols in coal-bearing sequences (Joeckel 1995, 1999; Cecil et al. 2003a, 2003b; Driese and Ober 2005; Hembree and Nadon 2011; Rosenau et al. 2013).

With continued high rainfall and greater uniformity of moisture distribution throughout the year, the formation of swampy surface conditions ensued across much of the low-gradient, widely exposed

craton, leading to the development of peat swamps. The coal beds resulting from these peat swamps were not time transgressive; they did not form as narrow belts, moving inland ahead of rising sea level, as is often portrayed (e.g., Heckel 1995; Bohacs and Suter 1997), but were time equivalent over large areas (Greb et al. 2003), as indicated by such evidence as ash partings (Greb et al. 1999), widespread clastic partings that fall at consistent levels within the coal bed over its whole extent, or partings that separate benches of coal with distinct petrographic characteristics throughout their areal extents (Eble et al. 2006). As discussed above, channels already present on the landscape were considerably narrowed by the development of erosion-resistant peat deposits on their floodplains and along their banks. In addition, intense plant rooting acted to stabilize the local substrate and greatly reduce sediment input to streams throughout the drainage basins on these very flat landscapes. Channels such as the Galatia channel, the Walshville channel, the Oroville channel, and others share the common characteristic of being significantly narrower and showing no evidence of the dynamic character of their precursors on clastic floodplains. In addition, at this stage the rivers appear to have carried little sediment other than very fine grained material or dissolved organic matter. Floods carrying this material into the adjacent peat swamps created the abundance of fine, dark, thin laminae of clastic material that is found in coal beds adjacent to the coal-contemporaneous channels, suggesting low-sediment to black-water river conditions.

In their final stages, the coal-contemporaneous reaches of cratonic river systems appear to have become estuarine and tidally influenced (e.g., Archer and Kvale 1993; Tessier et al. 1995) and to have widened considerably through disruption of the peat bodies along their flanks. The channels were rapidly filled with clastic material, initially clays and silts but ultimately sands, and were flanked by mudflats and a network of tidal channels. We propose that this final portion of channel life history is a reflection not only of ice melting and sea-level rise, but also of the coupling of these factors to climate change (e.g., Cecil et al. 2003a, 2003b; Peyser and Poulsen 2008; Tabor

and Poulsen 2008) and the relationship between climate and sediment transport patterns (Cecil and Dulong 2003). The filling of the main channel course with clastic material is accompanied also by the erosion of the margins of the peat body, resulting in a series of floating peat mats (Elrick et al. 2008), between which clastic material was deposited, resulting in the “splits” that line the contact between the coal body and the contemporaneous, now estuarine, and strongly tidally influenced channel.

The Gray-Shale Wedge and Its Relationship to the Channel

It is important to recognize that economically mineable, low-ash, and low- to moderate-sulfur blanket coals intrinsically have nothing to do with sea level as the driving force of their formation (Cecil et al. 1985). The peats from which these coal beds formed reflect the climate, specifically humid to perhumid climatic conditions (terminology from Cecil and Dulong 2003) covering large areas of the paleotropics. Such climatic conditions can occur, hypothetically, at any point in space and time. However, because of the various extrinsic drivers, most proximately related to ice volume and atmospheric CO₂ (Horton et al. 2012), the peat swamps that became coals are mainly confined to the lowstand phase of the covariant, linked sea-level and climate cycles (Cecil et al. 2003a, 2003b), thus around the time of maximum glacial conditions.

For interpretation of the position of coal within a sea-level rise-fall cycle, the rate of sea-level rise, and the timing of sediment emplacement within the channel, the gray-shale wedge is probably the single most important feature within a cyclothemic sequence.

As discussed above, we believe the empirical evidence strongly suggests that peat accumulated under a humid to perhumid climate and that no empirical support can be adduced for rising sea level as the principal driver. In brief, if rising sea level induces peat formation, modern coastlines and coastal shelves around the world should be covered by peat swamps. These peat-accumulating environments should be advancing ahead of widespread, now flooded, trailing areas of time-transgressive blanket peat

deposits, reflecting the rising sea levels of the current interglacial. Additionally, it should be considered that during the Pennsylvanian, there was no peat or coal in vast expanses of the western Pangaeon tropical or equatorial regions, which many climate proxies indicate was under a strongly seasonal climate regime too dry for peat formation. Were sea level the driver, peat should be equally present throughout all coastal belts across the Pennsylvanian and Permian world, regardless of the prevailing climate. This is clearly not the case.

This model is supported further by evidence for low-sediment to black-water conditions in major peat-contemporaneous drainages. Sediment transport within channel systems is, of course, tied directly to the entry of sediment into drainage systems. As discussed by Cecil and Dulong (2003), on the basis of empirical observations in modern tropical environments, high rainfall distributed throughout the year results in densities of plant cover that stabilize soils and drastically cut back on sediment movement into streams. With the melting of ice during the glacial-interglacial transition, major changes in atmospheric circulation patterns (e.g., Cecil et al. 2003a, 2003b; Peyser and Poulsen 2008; Horton et al. 2012) led to increasing seasonality in the tropics (Kvale et al. 1994). This change led directly to a reduction in vegetational cover, particularly in those areas surrounding the coastal peat-swamp ecosystems, resulting in an influx of clastics into drainages. This clastic influx is thus coincident with rising sea level and the initial conversion of river drainages into estuarine environments. Under this model, the sediment that blanketed peat swamps adjacent to major drainages originated coincidentally with rising sea level, melting ice, and climate changes from humid-perhumid to wet subhumid, and progressively to dry subhumid. Carried to the lower areas of river systems, this sediment was pushed out of the channels with flooding caused by the rising base level. It was pushed outward over the swamp and moved progressively inland as the locus of such flooding moved with the sea-level rise.

During this rising phase of sea level, the channel was converted to an estuary, subject to regular tidal action. This can be seen in the nature of the sediments that

constitute the gray-shale wedge, particularly in the channel adjacent to the coal or peat body and in those parts of the gray-shale wedge that cover the surface of the coal bed. Such sediments bear clear evidence of rhythmicity typical of tidal deposits (Archer and Kvale 1993; Archer et al. 1995). These sediments vary in character, some evidently deposited in mud flats (Archer et al. 1994; Kvale and Mastalerz 1998) and others in tidal channels, with the rate of deposition varying across the top of the peat locally. Also associated with this phase is the development of a system of tidal channels in areas immediately adjacent to the main river channel. Called “rolls” in mining parlance, these features are of limited lateral extent, have erosional bases and irregular to sinuous courses, and can contain plant fossils, often differing significantly from those buried at the top of the coal bed.

Throughout the area adjacent to the channel, abundant plant material appears to have been buried rapidly in place. The sediment surrounding these plants is the finest of the gray-shale wedge, largely claystone to fine siltstone; it is very finely laminated but preserves evidence of tidal rhythmic deposition. In addition, a transitional zone of organic shale less than 0.4 in. (<1 cm) to tens of inches (centimeters) in thickness often occurs between the top of the normally bright-banded coal and the bottom of the gray-shale roof, indicating an early flooding stage that was accompanied by the onset of death of the vegetation. This transitional zone often contains abundant fallen stem material, including large lycopside trunks that are not sediment filled, thus indicating decay in an environment where sediment input was low, even if flooding was taking place. These observations reflect the earliest phases of gray-shale wedge deposition in areas adjacent to the channel and show clearly that the gray-shale wedge was emplaced during the early stages of sea-level rise. It is at this stage that we envision the development of extensive mud flats along the margin of the channel, probably colonized by the most flood-resistant vegetation. The most dramatic evidence of the rapid early burial of vegetation is the presence of upright tree bases, nearly always of arborescent lycopsids, extending tens of inches (centimeters) to 3.3 ft or more (≥ 1 m) into the roof shales and rooted in the coal body.

The gray shale onlaps the tree bases, and in some instances, laminae in the enclosing sediments can be traced from outside a stump through the shales that filled its hollow interior. Stigmarian rooting organs of these trees, identifiable by their distinctive external patterns, have been identified as much as 3.9 in. (10 cm) deep in the coal bed, filled with roof-shale sediments, indicating that the hollows in the standing lycopside trunks extended down into the peat and were filled as muds were deposited in and around the tree bases. In some instances, prostrate lycopside trunks have been found still attached to standing tree stumps (e.g., DiMichele and DeMaris 1987). Prostrate vegetation is abundant, and stems with hollow central cavities, such as those found in calamitaleans and lycopsids, are often partially to completely filled with the roof sediment that encloses them, indicating little or no transport. Models of mud-cast logs (Gastaldo et al. 1989) demonstrate that these develop in place on the surface of the substrate. Delicate plant parts, such as the stems and foliage of tree ferns and pteridosperms, are abundantly preserved. Moreover, spatial patterns of original vegetation are preserved. All these factors point to rapid burial of the peat surface by flood-borne sediments.

Accompanying conversion of the channel to a tidal estuary, the peat body along the channel margins began to erode and be torn apart, most likely initially along the fine layers of dark clay partings in the peat in areas immediately adjacent to the channel. This probably was exacerbated by the action of daily tides against the peat margin. In addition, modern studies have shown that flooding of peats leads to an increase in methane production in the peat body, which can result in flotation of the peat. In-mine evidence of peat flotation has been found associated with channels in several different coal bodies (Elrick et al. 2008). This evidence includes the following:

1. Peat or coal “flaps,” in which the detachment of peat leads to an abundance of flaps along the peat margin in contact with the channel, varying in thickness from a few inches (centimeters) to 3.3 ft (1 m) or more.
2. Clastic sediment deposited between these peat flaps, leading to the “splits”

in the seam along the channel margin, and clastic wedges up to several feet (meters) in thickness and lateral extents of a few feet (meters) to a few hundred feet (meters) or so, measured orthogonally to the channel axis. The sediment filling these splits is identical to that constituting the roof rock that lies in gradational contact with the top of the coal bed.

3. Detachment of the coal body from the seat earth. Adjacent to the channel are areas where the coal bed is detached from the seat earth and bent and stretched or torn. The interval between the top of the seat earth and the base of the coal is filled with rock identical to the rock that fills the channel and covers the coal adjacent to the channel.
4. Sharp contacts occur between peat flaps and the underlying gray shales. In areas of suspected floating peat mats, the basal contacts of the coal with the top of the underlying gray shale are sharp, entirely lacking rooting of any kind, which would be expected were these splits to have been splays. Splays are usually recolonized by vegetation, and with peat sitting immediately on such splits, there absolutely should have been rooting from the peat into the shale had the peat been deposited after the shale. We know of no case, among the hundreds of exposures of such splits we have observed, where any rooting occurs. Thus, the gray mudstones appear to have been deposited within the splits and not subject to recolonization by vegetation after deposition of the muds in a flood.
5. Stringers of coal cross gray shales within splits. Dozens of examples have been observed wherein thin stringers of coal pass from the coal bench below to the coal bench above the gray shale split between such benches. Exhumation of these stringers shows that they are not roots but generally vitrain sheets or thicker sheets of normally bright-banded coal. This is effectively incontrovertible evidence that the mudstones of the splits were emplaced following some kind of disruptive ripping apart of the peat body.

6. Vegetation is in the upright position upon tilted peat flaps. Upright, buried stumps of lycopsid trees have been observed above the uppermost peat flaps but are tilted so that their vertical axes are orthogonal to the upper surface of the coal bed, despite its inclination. These stumps are buried in the same siltstones and claystones as the roof in areas where the coal lies horizontally and in attachment to its seat earth. They indicate that the peat was floated and distorted during sediment filling above the peat and injection into the spaces between floating flaps.

Tidal deposition continued in the gray-shale wedge throughout its thickness of as much as 98.4 ft (30 m) in areas adjacent to the channel. Brackish-water invertebrates appear in the higher levels, primarily inarticulate brachiopods and pelecypods of various types. At the same time, plant fossil content decreases sharply several feet (meters) above the top of the coal. The plants become increasingly scrappy and appear to be entirely allochthonous, perhaps reflecting some transport of organic matter from the shoreline, which was moving rapidly inland, flooding and drowning coastal vegetation. Evidence of normal marine salinities is very restricted in the gray-shale wedges and appears to be confined to those parts that may represent the most offshore reaches, such as that represented by the so-called Essex fauna in the Francis Creek Shale, above the Colchester Coal (Johnson and Richardson 1966). Evidence of a once greater lateral extent of the gray-shale wedge is represented particularly by finer grained siltstone in erosional remnants many miles (kilometers) from the main channel. The erosional remnant nature of these gray deposits is indicated by the remnants of marine shell-hash lags and the overlying and onlapping nature of the marine black shale with the erosional basal contact, as well as the still greater extent and onlap of the marine limestone above the black shale. All these combine to place the gray-shale wedge and its once continuous outliers below the marine transgression that ultimately covered the peat swamp.

CONCLUSIONS

The Galatia channel and similar paleochannels in the Illinois Basin yield valuable insights into patterns of climate and eustasy that controlled Pennsylvanian sedimentation. A dry, seasonal climate at peak interglacial highstand facilitated erosion and sediment transport from distant source areas. Deltas prograded rapidly into the Illinois Basin and filled nearly all accommodation space. At the onset of a glacial episode, the sea level began to fall, exposing the delta plain. Following a tectonic trough, the Galatia river incised a deep valley. Having a low gradient and traversing soft sediments, the river meandered actively. Away from the river, calcic Vertisols developed under a continuing dry, strongly seasonal climate.

Approaching the peak of a glacial episode, the climate in the basin changed from seasonally dry subhumid to ever-wet humid. Lush vegetation hemmed in the channel banks and inhibited the river from migrating laterally. The Springfield peat developed first in low places, then broadly across the lowlands. Sediment flux dropped dramatically, and the Galatia became a black-water stream. Periodic floods carried fine sediment into the peat swamp as thin clastic splits.

With an abrupt climate shift, glaciers melted and the sea rose, drowning the peat swamp. The Galatia channel became an estuary, now carrying a large load of suspended sediment (whether from upstream or offshore is uncertain). Gray mud buried the peat, entombing tree stumps and other plant material. With continued transgression, offshore deposition of marine black shale and limestone ended the cycle.

The Walshville channel, contemporaneous with the younger Herrin Coal, is closely similar to the Galatia channel. The Colchester and Danville Coals have thick, low-sulfur deposits overlain by gray shale, but no channels because the preserved coal lay offshore from the river mouths. The Baker Coal lay farther inland than the other examples, and no significant transgression followed peat accumulation. Thick, low-sulfur Murphysboro Coal flanks an estuary controlled by active tectonism.

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APPENDIX: TYPE AND REFERENCE SECTIONS OF NAMED UNITS

A. Principal Reference Section of the Houchin Creek Coal Member, Carbondale Formation

From an unpublished manuscript by Wier (1961, locality 6): Highwall on the north side of an abandoned strip mine, SE NE SW, sec. 3, T3S, R7W, Pike County, Indiana. Map by Wier and Stanley (1953) identifies the site as the Blackfoot Mine.

TOP

- 4.0' Shale, light to medium gray, thin- to medium-bedded
- 1.5' Shale, dark gray to black, slightly calcareous, scattered crinoid columnals and small brachiopods, nodules and thin lenses of gray to tan, finely crystalline limestone
- 0.9' Shale, black, fissile
- 1.2' **Hanover Limestone Member** (Stendal Limestone of Wier 1961), black, dense, argillaceous, few fossils (not named), contains lenses of dark gray to tan limestone that is fossiliferous. Unit is lenticular, varies from 0 to 2 ft (0 to 0.6 m) thick.
- 2.2' **Excello Shale Member**, black, fissile, alternating hard and soft layers
- 0.5' **Houchin Creek Coal Member**, bright banded
- 5.3' Claystone, light gray, scattered rootlets
- 4.0' Shale, light gray, weathers brown, sandy
- 1.2' Sandstone, medium gray, silty, calcareous, single bed
- 28.0' Sandstone, light gray, fine grained, shaly, mostly thin- to medium-bedded, interlaminated gray sandy shale contains siderite bands. Base under water, close to top of **Survant Coal Member**, which was mined. Wier and Stanley (1953) reported average Survant Coal thickness of 2.4 ft (0.7 m) at this mine.

Total section 48.8 ft (14.9 m).

B. Type Section of the Hanover Limestone Member

Field notes by S.E. Ekblaw, September 8, 1930: Ravine south of the road east of Hanover School, SW NW SE and NE SW SE, sec. 27, T10N, R11W, Greene County, Illinois. Illinois State Geological Survey, Map Room, open files.

TOP

- 4'± **Hanover Limestone Member**, brownish to bluish gray, nodular structure with brecciated character, massive, in one or two beds. Abundant blue-gray to black nodules in places. Fossils include crinoids, *Composita*, *Squamularia*, fusulinids.
- 8" Shale, greenish gray, slightly calcareous
- 2'± Covered
- 6" Clay-shale, bluish gray, noncalcareous
- 2" Shale, coaly
- 2½" Clay shale, dark bluish gray, noncalcareous, poorly bedded, very slickensided, no fossils
- 1'6"-2'8" **Houchin Creek Coal Member**
- 1' Claystone, black, shaly, leafy
- 2" Claystone, gray, noncalcareous
- 2' Shale, gray, noncalcareous, evenly bedded, fern leaf and stem impressions

C. Type Section of the Delafield Member (New)

From continuous core of Energy Plus borehole No. ME-13, drilled 2,605 ft (794 m) from south line, 1,274 ft (388 m) from west line, sec. 31, T4S, R6E, Hamilton County, Illinois. Core described by W. John Nelson, January 4–5, 2007.

Table A1 Type section of the Delafield Member (new)

Thickness (ft)	Top depth	Bottom depth	Rock description
4.6	1,043.7	1,048.3	Springfield Coal Member , bright banded, partly removed by company; depths from company log.
4.7	1,048.3	1,053.0	Top of Delafield Member , claystone (underclay), nearly black at top, changing downward to dark gray, olive gray in lower half. Blocky, thoroughly slickensided, lower 3 ft (0.9 m) calcareous, with scattered small limestone nodules. Lower contact gradational.
6.3	1,053.0	1,059.3	Sandstone, medium gray, very fine grained, micaceous, lithic arenite. Brecciated at the top with zigzag fractures extending downward and irregular masses of dark gray dolomite(?) at top. Dark gray siltstone laminae become more numerous downward, outlining wavy and ripple lamination. Lower contact gradational.
35.7	1,059.3	1,095.0	Sandy siltstone and shale, medium gray, mostly planar laminated, some ripples and horizontal burrows in sand-rich interval, possible tidal rhythmites. Interlaminated light gray sandstone is 10% to 30% of rock, reaching a maximum at 1,068–1,076 ft (325.5 to 328.0 m) and decreasing below that point. Trace fossils <i>Teichichnus</i> and <i>Conostichus</i> identified by J.A. Devera. Lower contact gradational.
22.0	1,095.0	1,117.0	Shale, medium-dark gray, silty, becoming darker and finer downward, laminae of very fine sandstone confined to upper part. "Pyrite trails" common, siderite bands and lenses occur in lower 14 ft (4 m). Lower contact gradational.
6.2	1,117.0	1,123.2	Shale, dark gray, contains little or no silt, very fissile; "pyrite trails" and siderite lenses numerous. Lower contact rapidly gradational, base of Delafield Member.
0.4	1,123.2	1,123.6	Hanover Limestone Member , calcareous shale, grayish black, contains scattered echinoderm and fossil shell fragments; lenses of dark gray, micritic limestone occur near base; lower contact rapidly gradational.
8.4	1,123.6	1,132.0	Excello Shale Member , black, low-density, fissile; phosphatic lenses and pyrite nodules. Concretion of black microgranular dolomite occurs at 1,126.0 to 1,127.7 ft (343.2 to 343.7 m). Lower contact appears erosive; Houchin Creek Coal is absent.
3.0	1,132.0	1,135.0	Sandstone, medium greenish gray, very fine grained, micaceous, lithic arenite.

D. Type Section of the Galatia Member (New)

Core from Kerr-McGee Corp. borehole No. 7629-16 (sec. 29, T7S, R6E, Saline County, Illinois). This core is in permanent storage at the Samples Library of the Illinois State Geological Survey in Champaign (storage number C-14933).

Table A2 Type section of the Galatia Member (new)

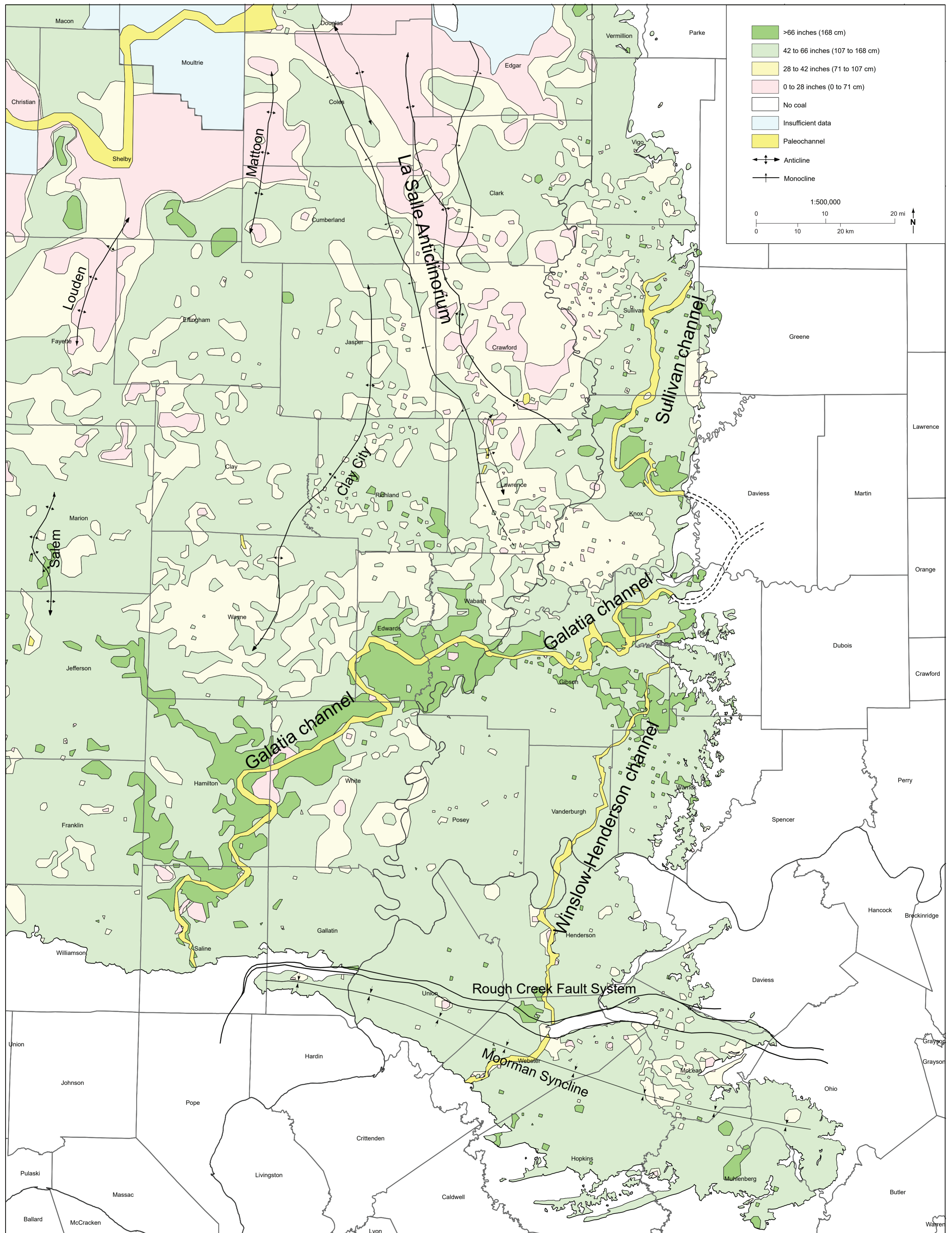
Thickness (ft)	Top depth	Bottom depth	Rock description
8.7	736.5	745.2	Springfield Coal (core removed by company; depths from other logs).
0.2	745.2	745.4	Coal and shale interlaminated, lower contact sharp and uneven.
3.6	745.4	749.0	Top of Galatia Member , sandstone, light olive gray, very fine grained, argillaceous; root traces throughout, masses of granular siderite near base. Lower contact gradational.
5.0	749.0	754.0	Siltstone, light olive gray, coarse (almost sandstone), moderately fissile, lenses and nodules of siderite common. Lower contact gradational.
8.5	754.0	762.5	Sandstone, medium to light gray, very fine grained, sublitharenite; portions show faint wavy silt and clay laminae, a few siderite lenses. Lower contact gradational.
6.5	762.5	769.0	Siltstone and sandstone, interlayered, lithologies as above. Lamination mostly lenticular and wavy, locally contorted. Rip-up clasts of siltstone in sandstone matrix become more numerous downward. Irregular masses of siderite common. Lower contact gradational.
17.0	769.0	786.0	Sandstone, light gray, very fine to fine grained, litharenite, micaceous. Shale-pebble conglomerate common in upper 11 ft (3.4 m). Plant fossils in siltstone at 770.0–770.9 ft (234.7–235.0 m). Basal 6 ft (1.8 m) is clean, massive sandstone. Lower contact erosional. Base of Galatia Member (thickness 40.6 ft).
2.0	786.0	788.0	Excello Shale Member, black, hard, thinly fissile, phosphatic lenses and laminae; dense dolomite concretion in mid to lower part.
	788.0		End of core, total depth.

EVOLUTION OF A PEAT-CONTEMPORANEOUS CHANNEL: THE GALATIA CHANNEL, MIDDLE PENNSYLVANIAN, OF THE ILLINOIS BASIN

Plate 1: Map of the Southeastern Part of the Illinois Basin Showing the Thickness of the Springfield Coal, Channels That Affect the Coal, and Major Structural Features

W. John Nelson, Scott D. Elrick, William A. DiMichele, and Philip R. Ames

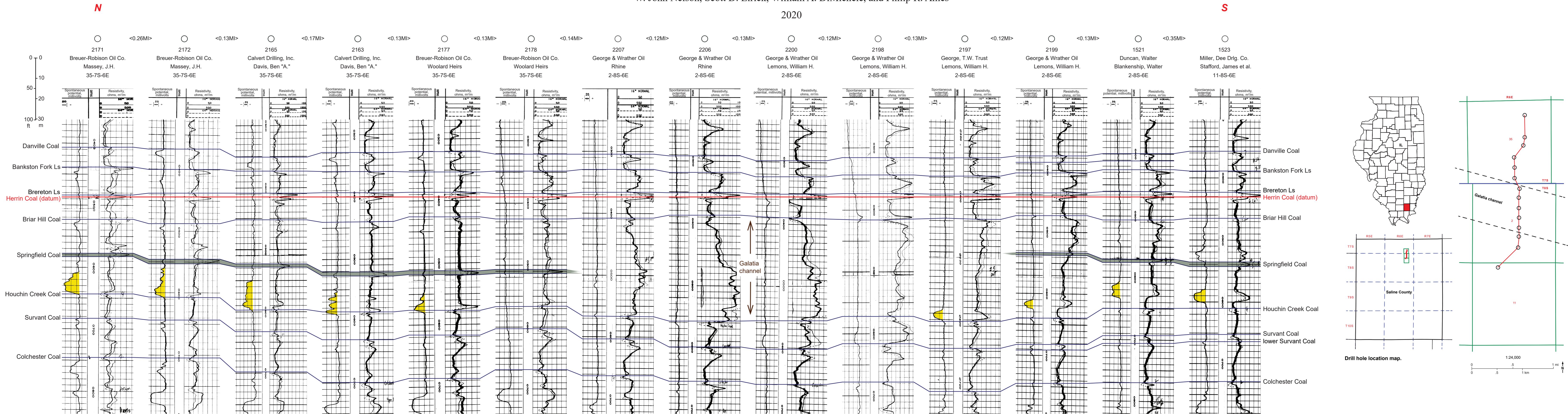
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EVOLUTION OF A PEAT-CONTEMPORANEOUS CHANNEL: THE GALATIA CHANNEL, MIDDLE PENNSYLVANIAN, OF THE ILLINOIS BASIN

Plate 2: Cross Section of the Galatia Channel in the Raleigh Area, Saline County, Illinois

W. John Nelson, Scott D. Elrick, William A. DiMichele, and Philip R. Ames

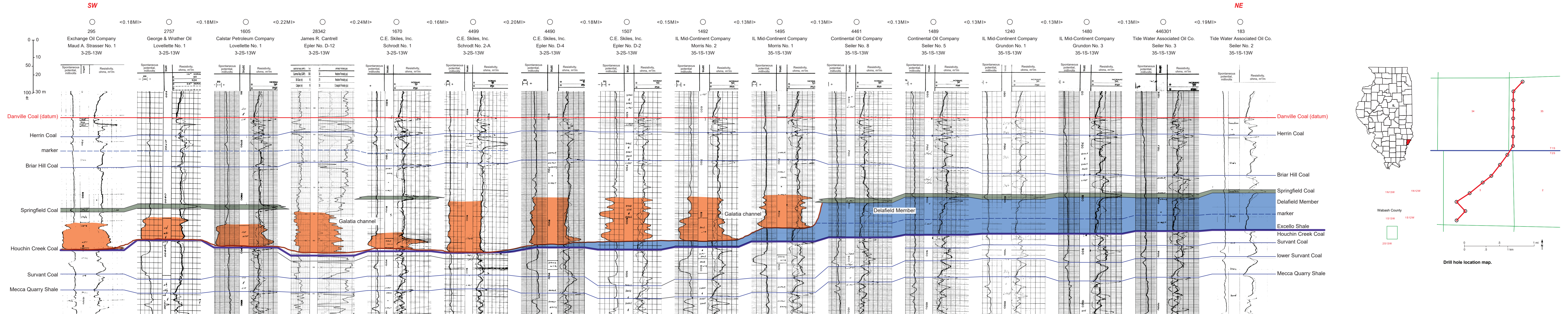


EVOLUTION OF A PEAT-CONTEMPORANEOUS CHANNEL: THE GALATIA CHANNEL, MIDDLE PENNSYLVANIAN, OF THE ILLINOIS BASIN

Plate 3: Cross Section of the Galatia Channel in Wabash County, Illinois

W. John Nelson, Scott D. Elrick, William A. DiMichele, and Philip R. Ames

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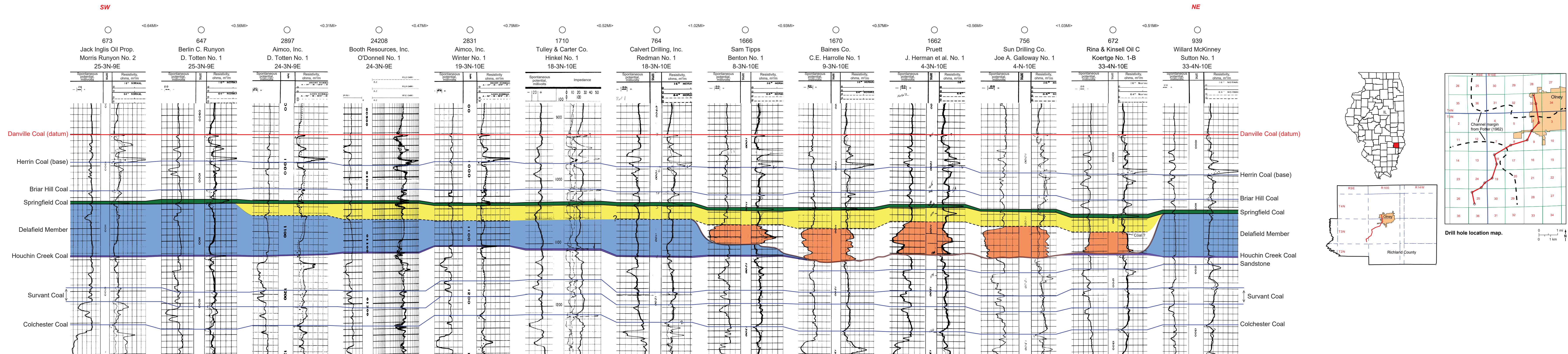


EVOLUTION OF A PEAT-CONTEMPORANEOUS CHANNEL: THE GALATIA CHANNEL, MIDDLE PENNSYLVANIAN, OF THE ILLINOIS BASIN

Plate 4: Cross Section of the Effingham Channel in the Olney Area, Richland County, Illinois

W. John Nelson, Scott D. Elrick, William A. DiMichele, and Philip R. Ames

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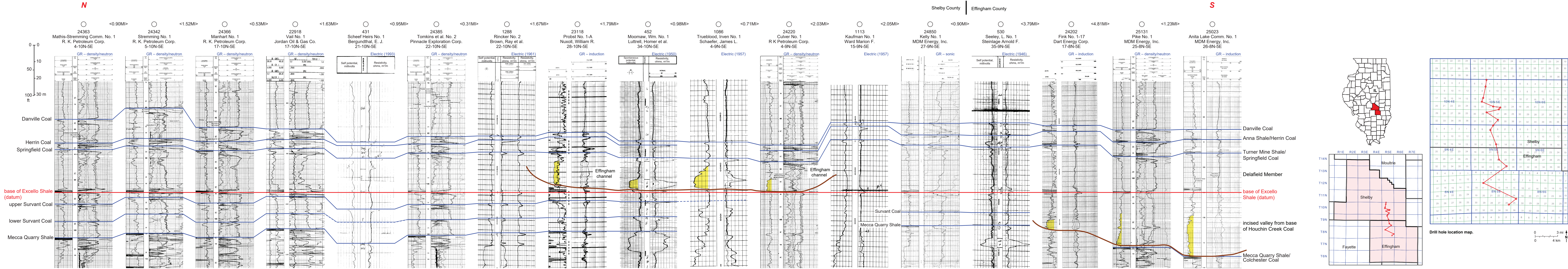


EVOLUTION OF A PEAT-CONTEMPORANEOUS CHANNEL: THE GALATIA CHANNEL, MIDDLE PENNSYLVANIAN, OF THE ILLINOIS BASIN

Plate 5: Cross Section of the Effingham Channel in the Stewardson Area, Shelby and Effingham Counties, Illinois

W. John Nelson, Scott D. Elrick, William A. DiMichele, and Philip R. Ames

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EVOLUTION OF A PEAT-CONTEMPORANEOUS CHANNEL: THE GALATIA CHANNEL, MIDDLE PENNSYLVANIAN, OF THE ILLINOIS BASIN

Plate 6: Cross Section of the Leslie Cemetery Channel, Warrick and Gibson Counties, Indiana

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