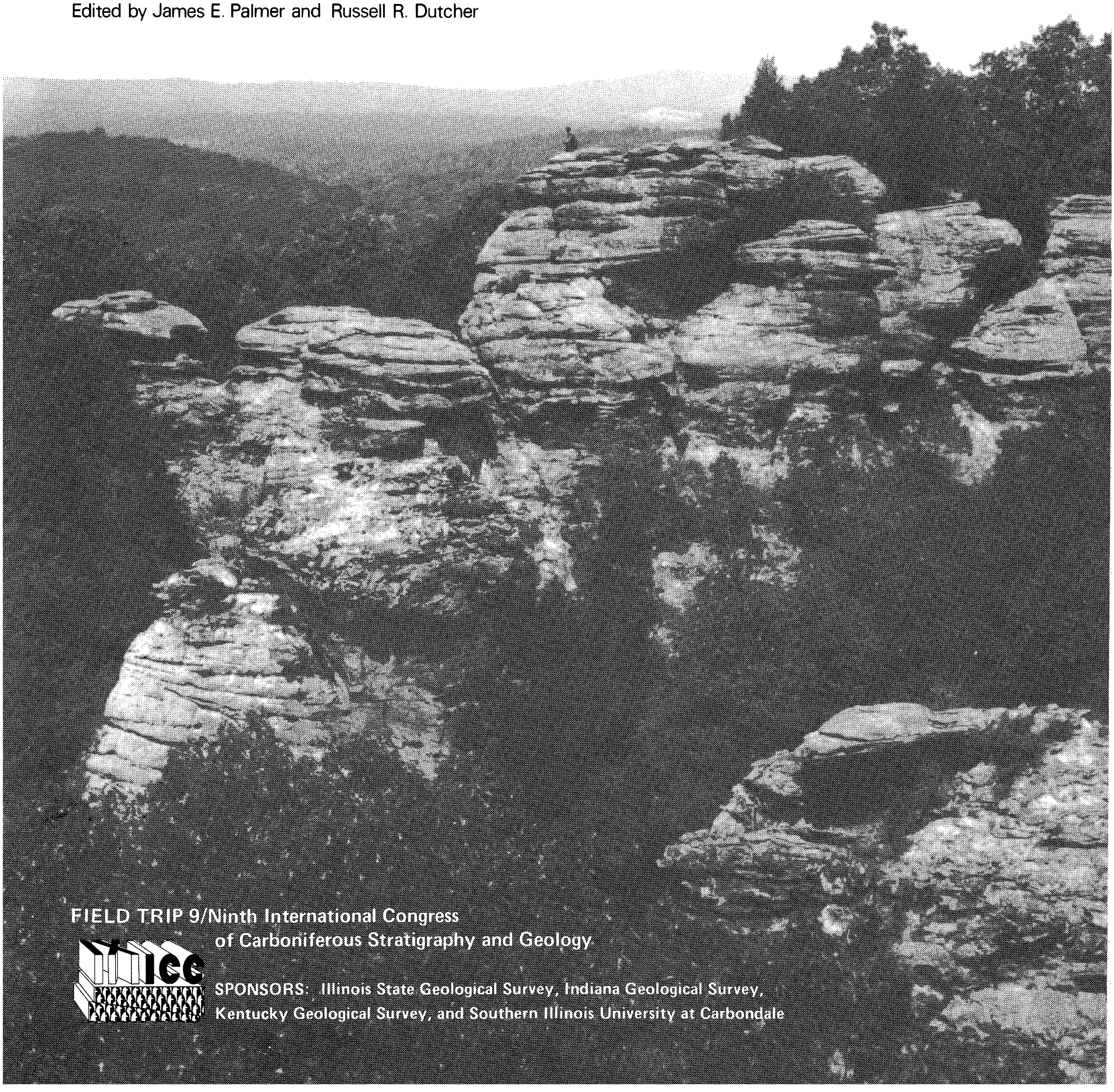
Depositional and structural history of the Pennsylvanian System of the Illinois Basin

Part 2: Invited papers

Edited by James E. Palmer and Russell R. Dutcher



FIELD TRIP 9/Ninth International Congress of Carboniferous Stratigraphy and Geology

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COVER PHOTOS

Front: Camel Rock (*far left*) and associated sandstone pinnacles, Garden of the Gods Recreation Area, Shawnee National Forest, Saline County, Illinois. Sandstone is of fluvial origin. Cut-and-fill structures, extensive cross-bedding, and steeply dipping joints are conspicuous. (Pounds Sandstone Member, Caseyville Formation)

Back: Circular, suboval, and irregular Liesegang banding. These iron-oxide-rich bands are believed to be the result of repeated uniform precipitation from colloidal suspension in porous and permeable sandstone. About one-third actual size. (Pounds Sandstone Member, Caseyville Formation)

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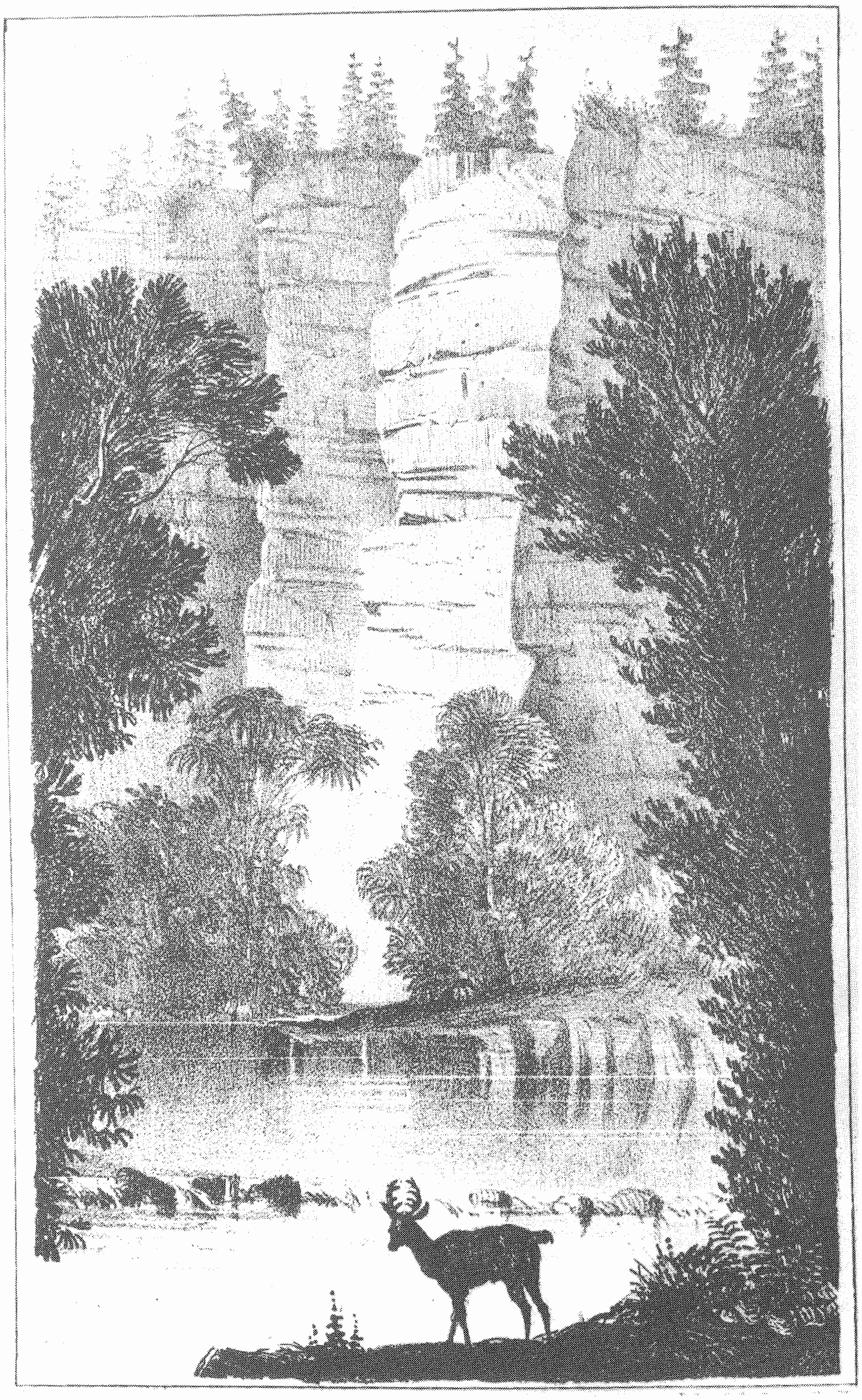

David Dale Owen's sketch of Kyrock Sandstone of Kentucky in 1856.

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PALEOCLIMATOLOGY AND PALEONTOLOGY

Pennsylvanian paleoclimate of the Illinois Basin

James M. Schopf
Dr. Schopf, formerly with the Department of Geology and Mineralogy, The Ohio State University, Columbus, Ohio, and the U.S. Geological Survey, died on September 15, 1978.

FLORISTIC INDICATIONS

The interpretation of paleoclimate is somewhat subjective. David White (1913a) has given an excellent review of the subject. He concluded that the Pennsylvanian floras indicated a tropical to subtropical climate. This conclusion still seems most acceptable with an important modification—continent displacement—which still is within the range of climate that he deduced.

White presumed a generally equable climate over the entire globe, but that model now seems unreasonable. Tropical climate, however, may be interpreted as marking an equatorial zone; this is the significance of the prolific Appalachian flora that Köppen and Wegener (1924) suggested. The belt of equatorial floras extended along the Appalachian trend, across Nova Scotia, to Britain, to the Ruhr, from Silesia to the Donetz basin, and must have continued eastward in accordance with the presently accepted doctrine of a zonal climate and continent displacement. The breadth of a tropical and subtropical zone may reasonably be extended to include the great Pennsylvanian-age coal-bearing regions of the earth. This point of view is presented in an article accompanying the paleotectonic map of the United States (Schopf, 1975).

White (1931) presented a more detailed and specific interpretation of the paleoclimate of the Carboniferous in the Illinois Basin. He noted climatic ameliorations and drier periods in comparison to climatic conditions in the Appalachian Trough. Such an interpretation agrees reasonably with the marginal, possibly partially subtropical, zone to which a Pangeatic reconstruction of the continents would assign it.

White's concepts still were somewhat generalized and probably did not include the variety of climate that existed. He scarcely took account of all the recurrent invasions of the sea, which must have had a profound effect on all marginal land areas. He regarded the fusain of coal beds as an indication of drought, but the incidence of fusain in Appalachian coals is about as great as that in Illinois coals. He did not consider the assemblages of Pennsylvanian plants that are now known to us from coal balls because most of this work has been accomplished since 1931. The plant remains that are known to us in coal balls show the same tropical and subtropical characteristics that I have summarized elsewhere (Schopf, 1975, p. 25). Plants from coal balls show less evidence of a climatic zonation than the occurrences of plants preserved as coalified compressions. We have, however, only one Appalachian occurrence of coal balls of Kanawha age (Lower, Middle Pennsylvanian), which has been reported extensively by Taylor (1967) and his students (Good and Taylor, 1970). More than 20 coal beds in the Interior Province have provided coal balls on which numerous studies have been completed. Facies assemblages have been recognized (Phillips, Kunz, and Mickish, 1977), but a phytosociologic (essentially topographic), rather than a climatic control, has been suggested to account for these differences. Thus far, there is no evidence available that differs from the tropical or subtropical interpretation advanced by White.

A great diversity of plant forms and types characterizes modern tropical plant assemblages. The inequalities of samplings of the fossil floras, however, renders suspect any attempt to summarize the fossil data statistically in terms of diversity. For example, the Mazon flora of northern Illinois, preserved by authigenic cementation, is one of the most diverse fossil assemblages that is known (Lesquereux, 1880-1884; Noé, 1925; Janssen, 1940; Stewart, 1950; Darrah, 1969). This single occurrence, however, is extensive and is one of the plant fossil localities most accessible to collectors (Schopf, 1978). The peculiarities of preservation have made these plant specimens exceptionally attractive to collectors.

To make any fair comparison of the Mazon flora with the abundance of plant fossils occurring in shale above most of the Appalachian coal beds is difficult. David White (1913b) published an extensive list of plants, which were known to him from West Virginia and were nearly all preserved as coalified compressions, but these lists are not appropriate for comparison with the one special well-known assemblage that is from the roof shale of a single coal bed in Illinois. Identical and closely related species of plants are present in both areas; therefore, floristic correlation is not in question. If the Mazon occurrence and coal-ball plants could be excluded, a more appropriate comparison of plants from the Illinois and Appalachian areas would be possible, but no such list of plants is available. The Appalachian plant fossils are so common and their preservation is generally fragile; thus, there are few collections from West Virginia or other Appalachian areas that are comparable to those of the Mazon fossils. On the basis of diversity, no fair comparison is possible.

Judged generally from the standpoint of abundance alone, the Appalachian plant fossils are clearly superior. White attributed this to climatic conditions that were less favorable for the preservation of abundant evidences of identifiable plants beyond the Appalachian belt in the Illinois Basin. Abundance of plant fossils may very well be an indirect result of climate and in accordance with the idea that more variable, less humid conditions prevailed in the Interior Basins than in the equatorial Appalachian region. The abundance of plant fossils also relates to the sedimentary regime and the greatly contrasting abundance of coal beds. Considered broadly, none of these features could occur without having either a direct or indirect climatic relationship.

Two general but conflicting theories have been advanced regarding paleoclimate. The older concept that a relatively equable global climate existed prior to the Pleistocene glacial periods, when a modification of our present zonal climate prevailed, does not satisfactorily explain earlier glacial periods.

The second concept regards zonal climate with solar control as the normal model for terrestrial climate; a conjunction of minor temperature fluctuations (for various causes) and shifts of storm tracks serves to account for glacial periods. Glacial periods depend on snowfall in excess of annual melting, and the perennial accumulation of snow depends on a ready source of moisture.

The indicators of paleoclimate may be displaced from their site of origin, either by continent displacement or by a shift of the earth's axis. If continents have been displaced, as seems probable, there is no means of determining whether or not axis displacement has been important, especially if projected over a long period of time. These uncertainties make it more necessary than ever to rely on indications from fossils for paleoclimatic interpretation.

RELATIONS TO CYCLOTHEMIC DEPOSITION

Some type or types of repetitive cyclical events are evidently responsible for cyclothemic deposition; this is particularly characteristic of the Pennsylvanian coal measures. This type of deposition may be explained by at least three kinds of control: (1) diastrophic causes, (2) isostatic fluctuation in sea level, or (3) variations in climate.

It seems unlikely that any of the three mediating agents can be eliminated from consideration. All of them probably contributed in conjunction, at least within particular areas. At one time or another any one of them may have played a more important part. The great difficulty, if not impossibility, of precisely dating any one diastrophic, eustatic, or climatic event and eliminating other conditions perhaps makes futile a search for specific causation. We should continue to rely on paleoclimatic indicators to suggest the importance of paleoclimate, but we must acknowledge that diastrophic and isostatic events also would have contributory, if not major, effects on any climatic regime. It does not seem likely that indicators of paleoclimate will provide a unique solution to the problem of cyclothemic control; however, few researchers will deny that climatic variation was a contributing factor.

Climate can be regarded as a major control of cyclothemic succession (Beerbower, 1961) if no marine beds are involved. The geographic extent of a repetitive alternation of marine and nonmarine hemicycles, however, shows at least that most Pennsylvanian cyclothems are characterized by an astonishing migration of the strand line. Weller (1957, appendix) relied upon tectonic effects almost exclusively to accomplish this effect. In view of the number of cycles and the small interval between many of the marine hemicycles, which must represent separate successive marine invasions, one may doubt that tectonic effects are entirely responsible. Wanless and Shepard (1936) originally relied upon glacial control for eustatic changes of sea level to accomplish repetitive marine invasions, in conjunction with climatic cycles to be responsible for cyclothemic alternation of deposition. Many of the objections to this theory by Weller (1937, 1956) seem valid. His latter paper should be referred to for a review of several alternative theories. Subsequently, Wanless and Cannon (1966) thoroughly analyzed the glacial possibilities but, in my opinion, with similarly inconclusive results. Glaciation is not the only possible source of eustatic variation, however.

Wanless was not oblivious to the difficulties in asserting solely a glacial eustatic control of Late Paleozoic sea level. He noted that **any** deformation of ocean basins would also have a eustatic effect (Wanless, 1967, p. 52). Although he continued to attribute local tectonic control of clastic wedges, possibly in deference to Weller, Wanless (1967, p. 48) stressed the close relationship of prodelta mud and local channel sandstones. The presence of the unconformity at the base of channel sandstones had generally seemed essential to the hypothesis of tectonic control. In an earlier paper, Wanless (1964, p. 604) had indicated that clastic wedges may be introduced into a basin from three or four different source directions during a single cyclothem. A tectonic hinge line operating from so many directions seems improbable. Increased erosion and sedimentation could more plausibly be accounted for by an increase of regional rainfall.

Any change that affects the capacity of ocean basins will have a eustatic result independent of terrigenous tectonism and in addition to normal tectonic effects. The varying heights of midocean ridges and depth of subduction troughs may be more effectual than glaciation in causing eustatic changes. Any extensive migration of the epicontinental strand line is bound to have a profound effect on the climate of adjoining regions. Such climatic effects, even more extreme than I would think necessary, have been discussed by Weller (1957, p. 357-359), although they were not mentioned in the appendix to his paper in which he considered tectonic control. Eustatic changes of relatively small amplitude sufficient to cause widespread flooding of extensive flat, swampy areas with clogged drainage systems seems more plausible than a postulation of tectonic uplift and subsidence for every widely correlated cyclothem. The efforts of both Weller and Wanless to explain the cyclical successions were formulated before the concept of ancillary effects of sea-floor spreading and its relationship to continent displacement was widely appreciated. Climatic effects must always be seriously considered; however, they always are superimposed on results achieved by either eustatic or tectonic agencies.

Neither tectonic nor eustatic effects could operate independently of climate. Both events must have produced major climatic results that are difficult to distinguish; climatic variations could achieve effects that are essentially independent of eustatic or tectonic controls. There are many uncertainties regarding the control of climate over comparably large areas; therefore, we are unable to state that a purely climatic control, in an area of a subsiding basin, would by itself be adequate.

SUMMARY

Pennsylvanian climate in the Illinois Basin was probably tropical or subtropical, as shown by morphological characteristics of the distinctive coal flora. In Illinois, a more varied climate than that of the Appalachian Trough is indicated by a generally less abundant representation of comparable plant fossils. Tropical diversity of some plant assemblages, however, may have been about equal. Many of the same plant species and closely related forms on which a biostratigraphic correlation may be based occur in both areas.

Climate is relative to cyclothemic sedimentation. The repeated occurrences of large, shallow, transgressive epicontinental seas must have had a moderating and humidifying effect on all the adjacent land areas. The unusually extensive region of low relief, continuing compaction, and more general subsidence caused the characteristically thin, and regionally persistent, occurrence of distinctive facies units in Pennsylvanian cyclothems. Marine transgressions and regressions needed only a relatively small amplitude to produce extensive geographic changes. Whether eustatic, tectonic, or other causes may have governed the movement of the strand line during Pennsylvanian time is difficult to determine. In any event, the varying effects of climate would be similar. In Appalachian areas farther east (southerly as displaced during the Pennsylvanian), climatic effects alone, as moderated by the intermittent existence of a large interior sea, may have been much more significant.

REFERENCES

BEERBOWER, J. R., 1961, Origin of cyclothems of the Dunkard Group (Upper Pennsylvanian-Lower Permian) in Pennsylvania, West Virginia, and Ohio: Geological Society of America Bulletin, v. 72, p. 1029-1050.

DARRAH, W. C., 1969, A critical review of the Upper Pennsylvanian floras of eastern United States with notes on the Mazon Creek flora of Illinois: privately published, 220 p.

GOOD, C. W., and T. N. TAYLOR, 1970, On the structure of *Cordaites felicis* Benson from the Lower Pennsylvanian of North America: Palaeontology, v. 13, pt. 1, p. 29-39.

JANSSEN, R. E., 1940, Some fossil plant types of Illinois: Illinois State Museum Scientific Papers, v. 1, 124 p.

KÖPPEN, W., and A. WEGENER, 1924, Die Klimate der geologischen Vorzeit: Verlag von Gebrüder Borntraeger, Berlin, 256 p.

LESQUEREUX, Leo, 1880 and 1884 (3 v.), 1879 (atlas), Description of the coal flora of the Carboniferous formation in Pennsylvania and throughout the United States: Second Geological Survey of Pennsylvania Report of Progress P, 977 p.

NOÉ, A. C., 1925, Pennsylvanian flora of northern Illinois: Illinois State Geological Survey Bulletin 52, 113 p.

PHILLIPS, T. L., A. B. KUNZ, and D. J. MICKISH, 1977, Paleobotany of permineralized peat (coal balls) from the Herrin (No. 6) Coal Member of the Illinois Basin, *in* P. H. Given and A. D. Cohen [eds.], Interdisciplinary studies of peat and coal origins: Geological Society of America Microform Publication 7, p. 18-49.

SCHOPF, JAMES M., 1975, Pennsylvanian climate in the United States, *in* E. D. McKee and E. J. Crosby [coordinators], Paleotectonic investigations of the Pennsylvanian system, Pt. II, Interpretative summary: U.S.G.S. Prof. Paper 853, p. 23-31.

SCHOPF, JAMES M., 1978, Mazon plants show a soft-sediment type of preservation: Abstracts with programs. North-Central Section Geological Society of America 12th Annual Meeting. Ann Arbor, Michigan, May 1-2, v. 10, no. 6, p. 283-284.

STEWART, WILSON N., 1950, Report on the Carr and Daniels collections of fossil plants from Mazon Creek: Illinois Academy of Science Transactions, v. 43, p. 41-45.

TAYLOR, T. N., 1967, On the structure of *Calamostachys binneyana* from the Lower Pennsylvanian of North America: American Journal of Botany, v. 54, no. 3, p. 298-305.

WANLESS, H. R., 1964, Development of the concept and interpretation of cyclic sedimentation, *in* D. F. Merriam [ed.], Symposium on cyclic sedimentation: State Geological Survey of Kansas, University of Kansas Bulletin 169, v. 2, p. 593-606.

WANLESS, H. R., 1967, Eustatic shifts in sea level during the deposition of Late Paleozoic sediments in the central United States: West Texas Geological Society Symposium on Cyclic Sedimentation in the Permian Basin, Oct. 20, 1967, p. 41-54.

WANLESS, H. R., and J. R. CANNON, 1966, Late Paleozoic glaciation: Earth-Science Reviews, v. 1, p. 247-286.

WANLESS, H. R., and F. P. SHEPARD, 1936, Sea level and climatic changes related to late Paleozoic cycles: Bulletin of the Geological Society of America, v. 47, p. 1177-1206.

WELLER, J. MARVIN, 1937, Comment on "Sea level and climatic changes related to Late Paleozoic cycles, by Wanless and Shepard": Bulletin of Geological Society of America, v. 47, p. 2011-2013.

WELLER, J. MARVIN, 1956, Argument for diastrophic control of Late Paleozoic cyclothems: American Association of Petroleum Geologists Bulletin, v. 40, no. 1, p. 17-50.

WELLER, J. MARVIN, 1957, Paleoecology of the Pennsylvanian Period in Illinois and adjacent states, Ch. 13, *in* H. S. Ladd [ed.], Treatise on marine ecology and paleoecology: The Geological Society of America Memoir 67, v. 2, Paleoecology, p. 325-364.

WHITE, DAVID, 1913a, Physiographic conditions attending the formation of coal, *in* David White and Reinhardt Thiessen, The origin of coal: U.S. Bureau of Mines Bulletin 38, p. 52-84.

WHITE, DAVID, 1913b, Fossil flora of West Virginia, pt. II, *in* C. F. Millspaugh and David White, Flora of West Virginia: West Virginia Geological Survey, v. V(a), p. 390-453.

WHITE, DAVID, 1931, Climatic implications of the Pennsylvanian flora: Illinois State Geological Survey Bulletin 60, p. 271-281.

Paleobotanical studies in the Pennsylvanian System of the Illinois Basin

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INTRODUCTION

Studies of Pennsylvanian-age plant compressions, coal palynology, and permineralized peats from the Illinois Basin have contributed significantly to the understanding of systematics, developmental morphology, reproductive biology, paleoecology, and evolution of land plants and to the biostratigraphy and correlation of coals. Some of the best-known Upper Carboniferous floras in Euramerica can be found in the Illinois Basin—the Francis Creek Shale (Mazon Creek biota) of northeastern Illinois (Darrah, 1969; Smith et al., 1970), the coal-ball floras of the Herrin and Calhoun Coal Members of southern Illinois, and the many palynological floras of the coals (Kosanke, 1950; Guennel, 1952, 1958; Winslow, 1959; Peppers, 1964, 1970). Among the older compression floras of particular interest are those representing Pennsylvanian upland floras in western Illinois (Leary, 1974; Leary and Pfefferkorn, 1977). There are 17 coals with coal balls, ranging in age from the Lower Block Coal (Atokan) of Indiana to the coal in the Shumway Cyclothem (Virgilian) of Illinois. The oldest coals occur along the eastern edge of the basin in Indiana, and the youngest are near the center (fig. 1).

Paleobotanical studies of the region were summarized, in part, by Canright (1959) and Darrah (1969) for compression floras, by Darrah (1941) and Andrews (1951) for coal-ball studies, and by Kosanke (1950) and Winslow (1959) for palynological studies. Phillips, Pfefferkorn, and Peppers (1973) have recounted the development of paleobotany in the Illinois Basin and have provided a comprehensive bibliography. This summary of paleobotanical progress, mostly during the past two decades, concerns coal-swamp studies.

COAL-SWAMP VEGETATION AND PATTERNS OF CHANGE

Studies of coal swamps of the Illinois Basin provide an overview as well as some of the most detailed information available on vegetational patterns and change in the Pennsylvanian. These observations probably reflect the same kinds of changes that occurred in many other paralic swamps across Euramerica; however, quantitative differences are to be expected.

Coal palynology

The palynological studies of Kosanke (1947, 1950) provided the first comprehensive framework in the United States for correlation of coals across an entire basin and through a thick sequence of strata. Together with the subsequent work, Peppers prepared quantitative profiles for the palynology of the Pennsylvanian coals in the basin (Peppers and Phillips, 1972). Most of the abundant spores and pollen from the coals are now assignable to at least major plant groups, and comparisons have been made between coal palynology and peat data (Phillips, Peppers, Avcin, and Laughnan, 1974). Data from the two sources are generally qualitatively or quantitatively corroborative (Phillips, Kunz, and Mickish, 1977).

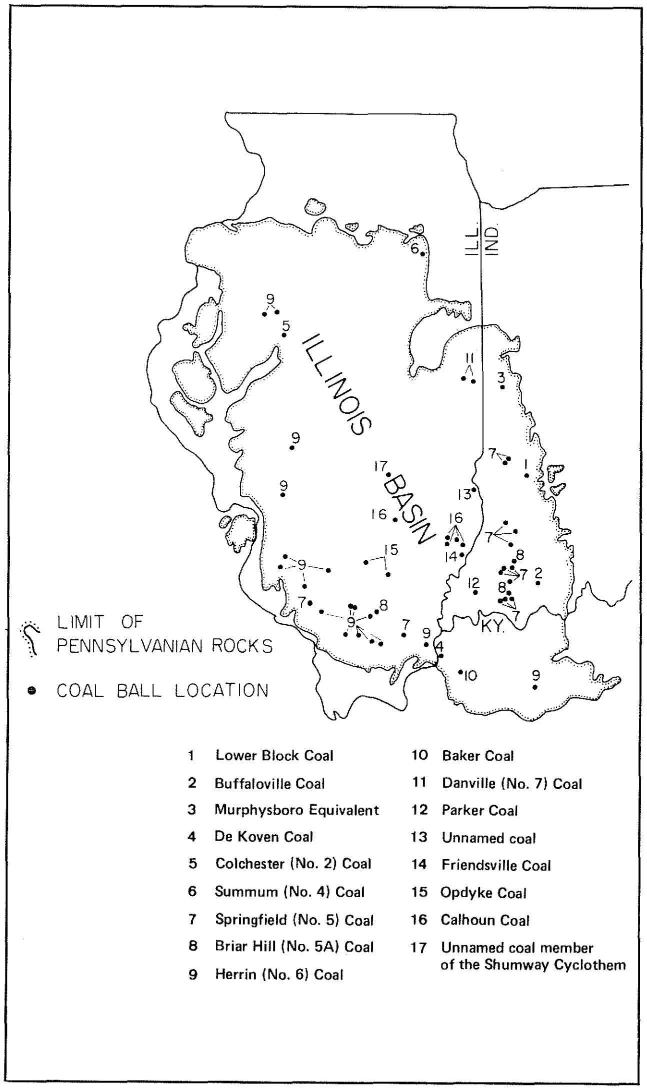

Figure 1. Occurrence of coal balls in the Illinois Basin.

Of particular importance to the interpretation of the above palynological studies is the correlation of in situ spores from megafossils with dispersed spores. Such relationships have been established by Brush and Barghoorn (1964), Taylor and Eggert (1969), Pfefferkorn, Peppers, and Phillips (1971), Millay and Taylor (1974), Courvoisier and Phillips (1975), and many others.

Coal balls and coal-swamp trees

The number of coal-ball occurrences, which spread stratigraphically across the middle and upper Pennsylvanian of the Illinois Basin, is unparalleled elsewhere in Euramerica. The coal balls from adjacent American coal basins and from Europe are complementary, and together they span the entire Upper Carboniferous. Thus, there are opportunities for comparisons of coal-ball data from many other coals from which swamp plants have been studied anatomically, and peats have been quantitatively analyzed. In briefly describing major vegetational patterns of Pennsylvanian coal swamps, it should be noted that many complementary quantitative data have been obtained from coal-ball peats in the Illinois Basin and western Europe since the report by Phillips et al. (1974). These data allow a clearer depiction of the history of some of the major types of swamp trees; however, no coal balls are known from the lower Pennsylvanian anywhere in the United States or from near the transition between the middle and upper Pennsylvanian (Westphalian-Stephanian) anywhere in Euramerica. Thus, coal palynology has been the major means of delineating the overall patterns of swamp change.

There are five major groups of swamp plants in the Pennsylvanian of Euramerica. Three are lower vascular plants: Lycophytina (lycopods), Filicophytina (ferns), and Sphenophytina (sphenopsids). The two gymnospermous types of seed plants are the Cordaitales (cordaites or *Cordaites*) and the Pteridospermales (seed ferns). Each of the five groups is largely represented in the peats and spore assemblages of coal swamps by one genus, or by only a few plant genera with an arborescent habit. The bituminous coals of the Pennsylvanian examined thus far derived from about 95 percent tree-peats; thus, trees are emphasized.

The lycopod trees, *Lepidophloios, Lepidodendron,* and *Sigillaria,* were the tallest (15 to 30 m); their shallow root systems are known as *Stigmaria.* The tree fern *Psaronius,* up to 7.5 m tall, was supported largely by buttressed root mantles, up to a meter across at the base. The seed fern *Medullosa* was even smaller but produced the largest seeds, pollen organs, and prepollen among Pennsylvanian plants. *Psaronius* and *Medullosa* had large complex fronds; the other types of trees had linear, undivided leaves. *Cordaites* and *Calamites* were probably intermediate in maximum height between lycopods and the frond-bearers; these two genera were the woody trees of the forests.

Vegetational patterns

Of the five types of swamp trees, lycopods, the largest trees, dominated most of the widespread habitats during the early and middle Pennsylvanian. They gave way only to seed plants of the Cordaitales in extreme coastal environments. The smaller swamp trees, *Psaronius* and *Medullosa,* largely dominated the late Pennsylvanian, with some *Calamites* and *Sigillaria.*

Between these two major vegetational patterns, the most significant change in the Pennsylvanian occurred, both in swamp and nonswamp floras. During the transition across the Desmoinesian-Missourian (at about the Westphalian-Stephanian boundary) the lycopod trees disappear from the swamps, except for *Sigillaria.* During the early and middle Pennsylvanian there were other important changes in swamp vegetation: *Cordaites* expanded into swamp environments, *Psaronius* evolved into robust forms that spread into the swamps, and the numbers of *Medullosa* and *Calamites* increased.

Coal balls that were formed in early Westphalian coal swamps of western Europe give direct evidence of swamp composition (Phillips, 1976) that is consistent with our regional coal palynology. *Cordaites* was restricted in occurrence, *Medullosa* trees were rare, and *Psaronius* was extremely rare. The relative abundance of *Calamites* was at its maximum in the early Westphalian and later in the Stephanian, but *Calamites* has not been established as dominant in the coal-ball peats of the Illinois Basin. In the Atokan there were major fluctuations in swamp environments; lycopod trees temporarily gave way to expansions of all other groups. *Psaronius* as a major community element appeared; *Cordaites* continued to expand into the early Desmoinesian swamps, second only to the lycopod trees in coal-ball peats of the Illinois Basin and dominating in coastal swamps westward. The rather abrupt diminution of occurrences of *Cordaites* in swamps occurred about midway through the Desmoinesian, between the Summum and Springfield Coal Members; in Kansas, it was between the Bevier and Iron Post Coal Members (Perkins, 1976). In the Illinois Basin this was followed by the development of vast and long-lasting deltaic swamps from which the Springfield and Herrin Coals were derived. *Psaronius* and *Medullosa* were the secondary elements of these swamps, apparently increasing in importance in some upper delta areas; with the loss of most of the lycopod trees, they became the most important trees of the late Pennsylvanian swamps.

SWAMP TREES—MORPHOLOGY AND ENVIRONMENTAL IMPLICATIONS

The dominant trees in various coal swamps during the Pennsylvanian were lycopods, tree ferns, and cordaites. Consequently, it is important to consider their growth, reproduction, and evolution—aspects which are relevant to interpretations of the environmental and vegetational changes of the Pennsylvanian. Anatomically preserved specimens from the Illinois Basin have contributed to such studies.

Lycopod trees—*Lepidophloios* and *Lepidodendron*

The discovery (Andrews and Murdy, 1958) and thorough documentation (Eggert, 1961) of determinate growth in the lycopod trees, *Lepidophloios* and *Lepidodendron,* indicate that after a series of branching, the apical growth of the trees ceased at a characteristic height. Analyses of large collections of stems depict apical growth of an unbranched trunk, of sizable diameter initially, with large leaf-cushions and long leaves. After attaining more than half its total height, the trunk underwent dichotomous branching and produced progressively smaller branchlets, leaf-cushions, and leaves—terminating ultimately with the differentiation of all apical tissues. The cones at the tips of branchlets exhibited the same determinate growth. A second, remarkable feature about lycopod trees is that despite their sizes they were essentially herbaceous plants, largely supported by cortex and persistent periderm (bark). Compared to woody trees, their growth must have been rapid.

The reproduction of lycopod trees is of considerable interest in view of their rather sudden demise (Brack-Hanes, 1978; Leisman and Phillips, in press; Phillips, in press). They had no known means for vegetative propagation, and survival depended on sexual reproduction. *Lepidophloios* (producing *Lepidocarpon*) and several species of *Lepidodendron* (producing *Achlamydocarpon*) had reproductive cycles highly adapted to aquatic environments. They dispersed their gametophytes in boat-shaped, seedlike units; fertilization took place while these units drifted in the swamp water. Abundant food reserves sustained the developing embryos, and the protected disseminules were further distributed by water. How frequently these plants produced cones is uncertain; in some plants, perhaps only once upon attaining determinate size; in others, several to many times as in *Sigillaria,* which survived the transition to late Pennsylvanian.

As swamp lands diminished, perhaps because of more extreme environmental fluctuations, the highly adapted, aquatic reproduction of lycopod trees concurrently declined and their loss from the swamps of Euramerica followed, except as noted. Their loss was accompanied by the loss of most of the less-specialized lycopod trees, which had been elements of the same community structure. *Lycospora* occurs in higher strata in Europe (particularly France) than in the Illinois Basin, but it is not clear whether the records are based on coal or shale. Stages in the life cycle of *Lepidocarpon,* including embryos and young sporophytes, have been reported from coal balls taken from the Illinois Basin (Phillips, Avcin, and Schopf, 1975). A comprehensive review of the Carboniferous Lepidodendraceae and Lepidocarpaceae has been prepared by Thomas (in press); DiMichele (in press) has monographed the American *Lepidophloios* trees.

Cordaites in coal swamps

The Cordaitales occupied many kinds of habitats during the Pennsylvanian—paralic and limnic swamps, as well as nonswamp environments. In contrast to their rarity in the lower Westphalian swamps of western Europe, *Cordaites* (or *Mesoxylon*) trees are the dominant elements in coal balls of numerous coals from Kansas and Iowa (Western Interior Coal Field) below the Iron Post Coal Member. We also find their complete assemblages in the coal balls of the Illinois Basin as the second most important group of plants in the lower Desmoinesian, below the Springfield Coal Member. The swamp cordaites of this age apparently occupied some habitats in brackish- to perhaps strongly saline-influenced environments. Such an interpretation is consistent with the suggestion of a mangrovelike (*Rhizophora*) habitat by Cridland (1964), of a tolerance for brackish or saline conditions by Wartmann (1969), and of their proximity to marine deposition by Neves (1958). Marine coal balls containing invertebrates are known to occur in certain of these coals (Mamay and Yochelson, 1962; Perkins, 1976). In the nonseasonal climatic conditions postulated for the Pennsylvanian coal swamps, the growth rings of the root systems of some cordaites (not in the stems) suggest some extreme fluctuations in their supposed mangrovelike habitats. Unlike the fate of major lycopod trees during the Desmoinesian-Missourian transition, when the cordaites almost disappeared from paralic swamp peats in mid-Desmoinesian, the cordaites were still well-represented in the nonswamp floras from which they came.

Tree ferns—*Psaronius*

Psaronius was the last major type of tree to expand into swamp environments; although the tree ferns were rare anywhere in the early Pennsylvanian, the genus was dominant in late Pennsylvanian swamps. The Illinois Basin has been the major American source of tree fern specimens from the Pennsylvanian. The stems of the middle (Desmoinesian only) and late Pennsylvanian psaronii are among the most complex types of all land plants. They are polycyclic and usually have many rows of fronds; the compression-cast form is *Caulopteris.* Details of their young sporophytes (Stidd and Phillips, 1968), stem development (Morgan, 1959), root system formation (Ehret and Phillips, 1977), frond anatomy (Stidd, 1971) and fructifications (Mamay, 1950; Stidd, 1974; Millay, 1976) have been recently summarized.

Pennsylvanian tree fern compressions and casts have also been studied recently (Pfefferkorn, 1976). The relationship between *Megaphyton* and *Psaronius* (anatomically preserved) has been uncertain because of the small stem size and two-rowed arrangement of frond scars in *Megaphyton.* The early evolutionary simplicity of *Psaronius* plants was not clearly established until the discovery of comparable, permineralized *Psaronius* stems with characteristic root mantle in the early Pennsylvanian of western Illinois (DiMichele and Phillips, 1977). Some *Megaphyton* plants are simply preservational forms of *Psaronius,* a genus that exhibited major evolutionary changes anatomically prior to the Desmoinesian. Coal palynology indicates abundant *Psaronius* in swamps beginning at about the middle of the Abbott Formation.

REFERENCES

ANDREWS, H. N., Jr., 1951, American coal-ball floras: Botanical Review, v. 17, no. 6, p. 430-469.

ANDREWS, H. N., Jr., and W. H. MURDY, 1958, *Lepidophloios*—and ontogeny in arborescent lycopods: American Journal of Botany, v. 45, no. 7, p. 552-560.

BRACK-HANES, S. D., 1978, On the megagametophytes of two lepidodendracean cones: Botanical Gazette, v. 139, no. 1, p. 140-146.

BRUSH, G. S., and E. S. BARGHOORN, 1964, The natural relationships of some Carboniferous microspores: Journal of Paleontology, v. 38, no. 2, p. 325-330.

CANRIGHT, J. E., 1959, Fossil plants of Indiana: Indiana Geological Survey Report of Progress 14, 45 p.

CRIDLAND, A. A., 1964, *Amyelon* in American coal-balls: Palaeontology, v. 7, pt. 7, p. 186-209.

COURVOISIER, J. M., and T. L. PHILLIPS, 1975, Correlation of spores from Pennsylvanian coal-ball fructifications with dispersed spores: Micropaleontology, v. 21, no. 1, p. 45-59.

DARRAH, W. C. 1941, Studies of American coal balls: American Journal of Science, v. 239, no. 1, p. 33-53.

DARRAH, W. C., I969, A critical review of the Upper Pennsylvanian floras of eastern United States with notes on the Mazon Creek flora of Illinois: Privately published, Gettysburg, PA, 220 p.

DiMICHELE, W. A., in press, Arborescent lycopods of Pennsylvanian age coals: *Lepidophloios:* Palaeontographica.

DiMICHELE, W. A., and T. L. PHILLIPS, 1977, Monocyclic *Psaronius* from the lower Pennsylvanian of the Illinois Basin: Canadian Journal of Botany, v. 55, no. 19, p. 2514-2524.

EGGERT, D. A., 1961, The ontogeny of Carboniferous arborescent Lycopsida: Palaeontographica, Abt. B, v. 108, p. 43-92.

EHRET, D. L., and T. L. PHILLIPS,1977, *Psaronius* root systems — morphology and development: Palaeontographica, Abt. B, v. 161, p. 147-164.

GUENNEL, G. K., 1952, Fossil spores of the Alleghenian coals in Indiana: Indiana Geological Survey Report of Progress, 40 p.

GUENNEL, G. K., 1958, Miospore analysis of the Pottsville coals of Indiana: Indiana Geological Survey Bulletin, no. 13, 101 p.

KOSANKE, R. M., 1947, Plant microfossils in correlation of coal beds: Journal of Geology, v. 55, no. 3, p. 280-284; Illinois State Geological Survey Circular 131, 5 p.

KOSANKE, R. M., 1950, Pennsylvanian spores of Illinois and their use in correlation: Illinois State Geological Survey Bulletin 74, 128 p.

LEARY, Richard, 1974, Stratigraphy and floral characteristics of the basal Pennsylvanian strata in west central Illinois: Septième Congrès International de Stratigraphie et de Géologie du Carbonifère, Compte Rendu, 1971, v. 3, p. 341-350.

LEARY, R. L., and H. W. PFEFFERKORN, 1977, An early Pennsylvanian flora with *Megalopteris* and *Noeggerathiales* from west-central Illinois: Illinois State Geological Survey Circular 500, 77 p.

LEISMAN, G. A., and T. L. PHILLIPS,in press, Megasporangiate and microsporangiate cones of *Achlamydocarpon varius* from the middle Pennsylvanian: Palaeontographica.

MAMAY, S. H., 1950, Some American Carboniferous fern fructifications: Missouri Botanical Gardens Annals, v. 37, no. 3, p. 409-476.

MAMAY, S. H., and E. L. YOCHELSON, 1962, Occurrence and significance of marine animal remains in American coal balls: U.S. Geological Survey Professional Paper 354-I, p. 193-224.

MILLAY, M. A., 1976, Synangia of North American Pennsylvanian petrified marattialeans: University of Illinois Ph.D. thesis [Urbana], 481 p.

MILLAY, M. A., and T. N. TAYLOR,1974, Morphological studies of Paleozoic saccate pollen: Palaeontographica, Abt. B, v. 147, p. 75-99.

MORGAN, E. J., 1959, The morphology and anatomy of American species of the genus *Psaronius:* Illinois Biological Monograph 27, University of Illinois Press, Urbana, Illinois, 108 p.

NEVES, R., 1958, Upper Carboniferous plant spore assemblages from the *Gastrioceras subcrenatum* horizon, North Staffordshire: Geological Magazine, v. 95, no. 1, p. 1-19.

PEPPERS, R. A., 1964, Spores in strata of late Pennsylvanian cyclothems in the Illinois Basin: Illinois State Geological Survey Bulletin 90, 89 p.

PEPPERS, R. A., 1970, Correlation and palynology of coals in the Carbondale and Spoon Formations (Pennsylvanian) of the northeastern part of the Illinois Basin: Illinois State Geological Survey Bulletin 93, 173 p.

PEPPERS, R. A., and T. L. PHILLIPS, 1972, Pennsylvanian coal swamp floras in the Illinois Basin [abstract]: Geological Society of America, v. 4, p. 624-625.

PERKINS, T. W., 1976, Textures and conditions of formation of Middle Pennsylvanian coal balls, central United States: Kansas University Paleontological Contribution Paper 82, 13 p.

PFEFFERKORN, H. W., 1976,Pennsylvanian tree fern compressions *Caulopteris, Megaphyton,* and *Artisophyton* gen. nov. in Illinois: Illinois State Geological Survey Circular 492, 31 p.

PFEFFERKORN, H.W., R.A. PEPPERS, and T.L. PHILLIPS, 1971, Some fern-like fructifications and their spores from the Mazon Creek compression flora of Illinois (Pennsylvanian): Illinois State Geological Survey Circular 463, 29 p.

PHILLIPS, T. L., 1976, Permineralized plants from the lower Westphalian A of Lancashire, England—Comparisons of floras [abstract]: Botanical Society of America, New Orleans, Louisiana, Allen Press, Lawrence, Kansas, p. 29-30.

PHILLIPS, T. L.,in press, Reproduction of heterosporous lycopods in the Mississippian-Pennsylvanian of Euramerica: Review of Palaeobotany and Palynology.

PHILLIPS, T. L., M. J. AVCIN, and J. M. SCHOPF, 1975, Gametophytes and young sporophyte development in *Lepidocarpon* [abstract]: Botanical Society of America, Corvallis, Oregon, Allen Press, Lawrence, Kansas, p. 23.

PHILLIPS, T. L., A. B. KUNZ, and D. J. MICKISH, 1977, Paleobotany of permineralized peat (coal balls) from the Herrin (No. 6) Coal Member of the Illinois Basin, *in* P. N. Given and A. D. Cohen [eds.], Interdisciplinary studies of peat and coal origins: Geological Society of America Microform Publication 7, p. 18-49.

PHILLIPS, T. L., R. A. PEPPERS, M. J. AVCIN, and P. F. LAUGHNAN, 1974, Fossil plants and coal: Patterns of change in Pennsylvanian coal swamps of the Illinois Basin: Science, v. 184, p. 1367-1369.

PHILLIPS, T. L., H.W. PFEFFERKORN, and R. A. PEPPERS, 1973, Development of paleobotany in the Illinois Basin: Illinois State Geological Survey Circular 480, 86 p.

SMITH, W. H., R. B. NANCE, M. E. HOPKINS, R. G. JOHNSON, and C. W. SHABICA, 1970, Depositional environments in parts of the Carbondale Formation—western and northern Illinois. Francis Creek Shale and associated strata and Mazon Creek biota: Illinois State Geological Survey Guidebook Series 8, 119 p.

STIDD, B. M., 1971, Morphology and anatomy of the frond of *Psaronius:* Palaeontographica, Abt. B, v. 134, p. 87-123.

STIDD, B. M., 1974, Evolutionary trends in the Marattiales: Missouri Botanical Gardens Annals, v. 61, no. 2, p. 388-407.

STIDD, B. M., and T. L. PHILLIPS, 1968, Basal stem anatomy of *Psaronius:* American Journal of Botany, v. 55, no. 7, p. 834-840.

TAYLOR, T. N., and D. A. EGGERT, 1969, Studies of spores from Carboniferous fructifications. Part 1. Introduction and preliminary survey utilizing the scanning electron microscope: American Microscopical Society Transactions, v. 88, p. 431-444.

THOMAS, B. A., in press, Carboniferous Lepidodendraceae and Lepidocarpaceae: Botanical Reviews.

WARTMANN, R., 1969, Studien über die papillen-förmigen Verdickungen auf der Kutikule bei *Cordaites* an Material aus dem Westfal C des Saar-Karbons: Argumenta Palaeobotanica, no. 3, p. 199-207.

WINSLOW, M. R., 1959, Upper Mississippian and Pennsylvanian megaspores and other plant microfossils from Illinois: Illinois State Geological Survey Bulletin 86, 135 p.

Development of coal-forming floras during the early part of the Pennsylvanian in the Illinois Basin

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INTRODUCTION

Interpretation of the paleoecology of Carboniferous floras, based on spore assemblages, is largely speculative because of the variable factors affecting the life habits of the plants, their deposition and preservation, and the sampling of fossil plants and spores (Cross, 1964; Funkhouser, 1969; Tschudy, 1969; Scott, 1977). A review of paleoecological studies of Pennsylvanian or Upper Carboniferous plant assemblages has been presented by Dorf (1964) and more recently by Scott (1977).

The prescribed pattern of evidence for interpreting the paleoecology of Pennsylvanian or Upper Carboniferous floras includes:

1. Sedimentological observations (Dragert, 1964; Habib and Groth, 1967; Scott, 1977; and others)
2. Investigations of morphology and anatomy of the plants (Frederiksen, 1972; Schopf, 1975; and others)
3. Examination of coal petrography (Smith, 1957, 1962, 1964a; Hacquebard and Donaldson, 1969; and others)
4. Study of physiographic features and geography (Peppers and Pfefferkorn, 1970; Leary, 1975)
5. Comparison with modern sedimentary environments (several papers in Dapples and Hopkins, 1969; Cohen and Spackman, 1972; and others)
6. Chemical analysis of coal (Niklas and Phillips, 1974)

An investigation of the palynology of coals in the Abbott and Spoon Formations (Atokan and early Desmoinesian) and equivalent strata in other parts of the Illinois Basin Coal Field was conducted for correlation purposes. The study indicated that several notable differences in the composition of the coal-forming floras occurred in the upper part of the Abbott Formation (fig. 1). Spore taxa were correlated, where possible, with major plant groups as outlined in Phillips et al. (1974) to show major changes in relative abundance of the various plant groups—lycopods, ferns, sphenopsids, and cordaites. As pointed out by Phillips et al. (1974), the relationship of pteridosperms is difficult to assess from palynology because *Schopfipollenites (Monoletes)*, the pollen of *Medullosa* (the major seed fern genus), is so large that it is seldom encountered in statistical analysis of miospore (small spore) assemblages.

The numbers of spore species that begin or end their stratigraphic range in each coal are shown in figure 1. The average number of taxa in each sample of the individual coals indicates the degree of diversity of the coal-forming floras.

MAJOR ENVIRONMENTAL CHANGES IN COAL-SWAMP FLORAS

During Morrowan time, coal-forming swamps were somewhat restricted in areas in the Illinois Basin, and the flora was essentially made up of arborescent lycopods dominated by *Lycospora*-bearing lepidodendrids, which probably grew most often in standing water. Erosion and sedimentation gradually leveled the topographic irregularities formed at the Mississippian-Pennsylvanian unconformity, and the peat swamps became fairly widespread. Late Atokan marks the beginning of the first major marine incursion with deposition of limestone in the Illinois Basin Coal Field. As changes in sedimentation occurred, along with perhaps a change to less precipitation, diverse groups of plants invaded the coal swamps in increasing numbers, beginning during late Atokan time. The increase in abundance of sigillarian lycopods followed by herbaceous lycopods could indicate a somewhat open flora, and later might have permitted other arborescent plants—marattiaceous ferns, pteridosperms, then sphenopsids and cordaites—to compete with the giant lycopods. The rise in the number of species of spores that begin or end their ranges in the individual coals also suggests that the floras were undergoing rather rapid evolution and migration. Plants growing along margins of relatively dry upland areas, which were being reduced in size and elevation, could have gradually migrated into adjacent lowland swamps that were undergoing periodic drying. Other studies of coal floras help support the conclusion that a change to slightly drier conditions may have prevailed. During early Desmoinesian time, perhaps because of a return to wetter conditions, *Lycospora*-bearing lepidodendrids regained dominance. Another episode of plant diversification took place during later Desmoinesian time; it followed almost the same sequence as the earlier episode except there was no increase of sphenopsids and cordaites before wetter conditions returned during deposition of the widespread Davis and De Koven Coal Members.

LYCOPODS

Except for a brief period during the latest Atokan and earliest Desmoinesian time (Phillips et al., 1974), lycopods dominated the Pennsylvanian coal swamp floras in the Illinois Basin until the beginning of the Missourian (Stephanian) Series. After the beginning of Missourian time, marattiaceous ferns and pteridosperms became most prevalent.

Endosporites

Endosporites globiformis (Ibrahim) Schopf, Wilson, and

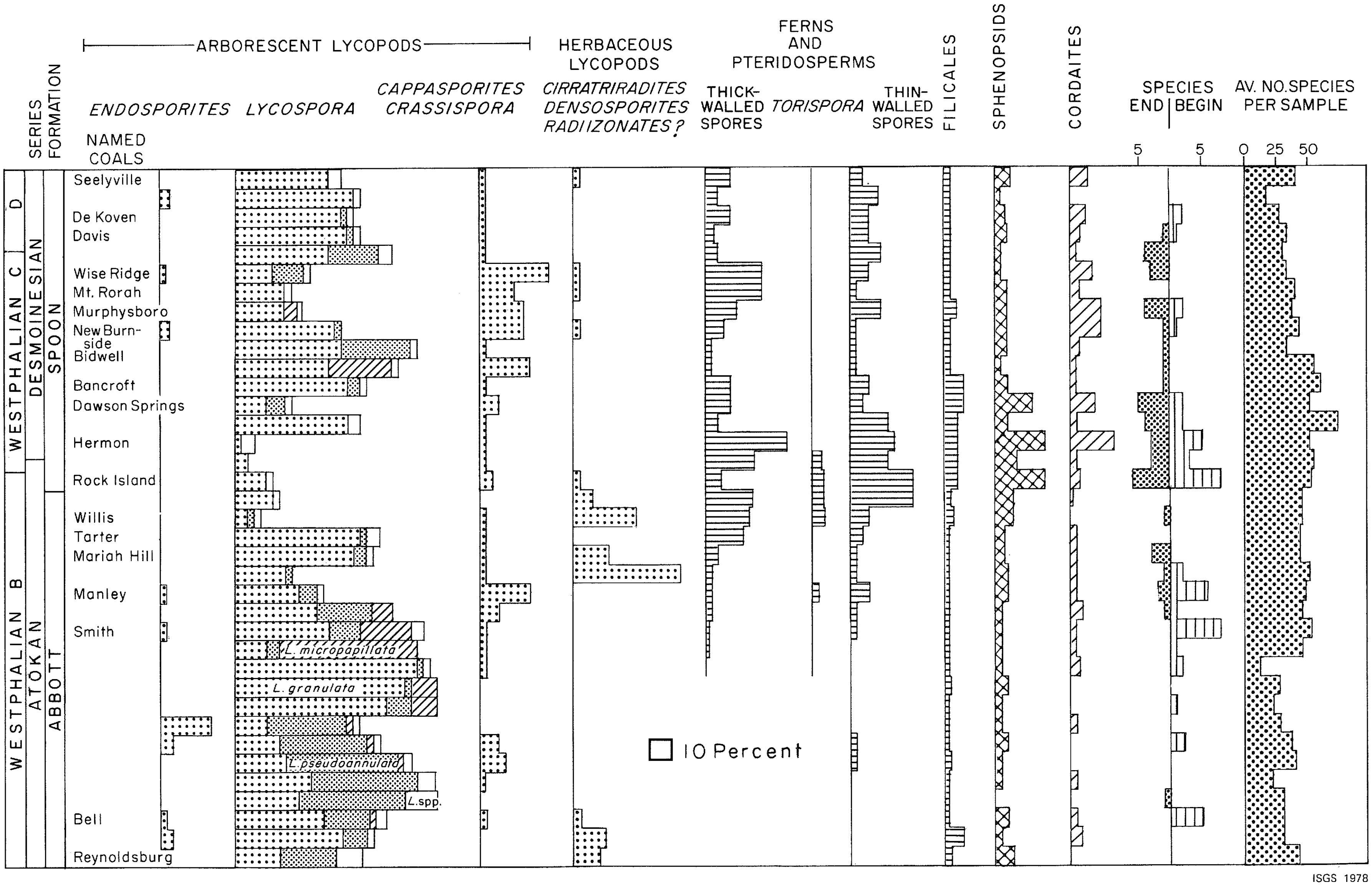

Figure 1. Relative abundance of major plant groups interpreted from assemblages in coals in the Abbott and Spoon Formations and equivalent strata in Indiana and western Kentucky (correlation with European time-stratigraphy according to Phillips, in press).

Bentall, 1944, which was correlated by Chaloner (1953a, 1958b) with *Polysporia mirabilis* Newberry 1873, was of rather minor overall importance in the miospore assemblage. *Endosporites globiformis* first appeared in the Illinois Basin just above the Reynoldsburg Coal Member and underwent only minor changes in relative abundance in the coals of the Abbott and Spoon Formations, except for an anomalous 24 percent of the spore assemblage in an unnamed coal in the lower part of the Abbott Formation.

Lycospora

Lycospora are spores of arborescent lycopods (Moore, 1946; Chaloner, 1953b; Felix, 1954; Sen, 1958; Abbott, 1963; Balbach, 1966; Hagemann, 1966; Courvoisier and Phillips, 1975). Arborescent lycopods that bore *Lycospora* were hydrophilous and probably grew in swamps having shallow brackish water (Smith, 1957, 1962, 1964b; Neavel, 1963; Alpern, Liabeuf, and Navale, 1964; Habib, 1966; Habib and Groth, 1967; Oshurkova, 1967; Peppers and Pfefferkorn, 1970; Phillips et al., 1974). This assemblage probably would be included in the "forest-moor" type of peat of Karmasin (1952) and Hacquebard and Donaldson (1969). Smith (1962, 1964b) and Smith and Butterworth (1967) distinguished between the presence of *Lycospora pusilla* (Ibr.) Schopf, Wilson, and Bentall, 1944 and *L. pellucida* (Wicher) Schopf, Wilson, and Bentall 1944, which they interpret from petrological studies as belonging mostly to the *Lycospora* phase of deposition, and *L. granulata* Kosanke 1950, which they thought indicated a transitional interval in which water in the peat swamp was shallower than it was during the *Lycospora* phase.

In the Illinois Basin Coal Field, *Lycospora pseudoannulata* Kosanke 1950, which may be a junior synonym of *L. pellucida*, was the most common species of spores since the beginning of the Pennsylvanian until deposition of the No. 2 coal bed of Kentucky, when *L. granulata* became the major species. According to Smith (1962, 1964b), a similar change in species dominance in Great Britain probably indicated that the water level in the coal swamps had become lower than before. In the Illinois Basin, shortly after this transition to a spore flora dominated by *L. granulata,* a sudden increase in abundance of *L. micropapillata* (Wilson and Coe) Schopf, Wilson, and Bentall 1944 took place. This small species was present (Felix, 1954) near the tips of *Lepidostrobus pulvinatus* Felix 1954, which also contained large species of *Lycospora* comparable to *L. pseudoannulata.* The sudden increase in population of *L. micropapillata,* which Felix interpreted as being abortive spores, suggests that the lycopods may have been experiencing adverse environmental changes and perhaps occasional dry periods.

Cappasporites and *Crassispora*

Cappasporites and *Crassispora,* which are morphologically similar, are present in most coals in the Abbott and Spoon Formations. *Crassispora* constitutes only about 3 percent of the total spores in any of the coals, but the abundance of *Cappasporites* increased twice during deposition of the Abbott Formation and again during deposition of the Spoon Formation. Shortly after the decline of *Lycospora pseudoannulata* and the rise in abundance of *L. micropapillata, Cappasporites* became a significant part of the spore flora in the Manley Coal Member. *Cappasporites distortus* Urban 1966 has been identified (Courvoisier and Phillips, 1975) from a specimen of *Achlamydocarpon varius* (Baxter) Taylor and Brack-Hanes 1976 (syn. *Achlamydocarpon* cf. *maslenii* [Jongmans] Schumacker-Lambry 1966). Spores resembling *Crassispora kosankei* (Potonié and Kremp) Sullivan 1964 were described from *Sigillariastrobus ciliatus* Kidston 1897 by Rettschlag and Remy (1954) and *Mazocarpon oedipternum* Schopf 1941 by Schopf (1941) and Courvoisier and Phillips (1975).

Achlamydocarpon (Cappasporites) proliferated at the expense of other lepidodendrids; perhaps this was due to a partial drying or a change in salinity in the coal swamps. According to Phillips (in press), aquatic dispersal may have played a necessary role in the reproduction of *Lepidophloios* and *Lepidodendron,* whereas the megasporangiate unit of *Achlamydocarpon varius* may have been well-dispersed by wind owing to its winged shape; thus, it would have had a greater chance of being deposited in small shallow pools of water. *Achlamydocarpon* and some of the lepidodendrids, however, unlike the *Sigillaria* that bore *Crassispora,* could not adjust to the major climatic changes that took place during the late Pennsylvanian and disappeared from the coal swamps in Illinois at the Desmoinesian-Missourian boundary. *Mazocarpon,* which bore *Crassispora,* produced small megaspores that were protected somewhat by portions of sporangial tissue. *Crassispora* became abundant in some coals in the Mattoon Formation (Phillips et al., 1974) in the upper Pennsylvanian.

Both *Cappasporites* and *Crassispora* are generally more common toward the top of coal seams in Illinois. *Crassispora* was reported (Peppers, 1970) as being more abundant in the Colchester (No. 2) and Summum (No. 4) Coal Members in the Carbondale Formation along the axis of the Ancona Dome than in the same coals off the flanks of the structure. (At that time I thought that specimens of *Cappasporites* were poorly preserved or over-macerated specimens of *Crassispora,* so both taxa were recorded as *Crassispora*.) The Ancona Dome is an anticlinal structure in Livingston and La Salle Counties, Illinois; and along the La Salle Anticlinal Belt. The dome is thought to have been a topographic and structural high; therefore, the peat swamp was drier or the water was less brackish than in adjacent areas.

Crassispora was included in the incursion phase of peat development by Smith (1962, 1964b). Butterworth (1964) found that *Crassispora kosankei* and *Cingulizonates loricatus* (Loose) Butterworth and Smith 1964, which is correlated with the lycopod *Porostrobus canonbiensis* (Chaloner) Chaloner 1962, are abundant in thin and bony coals along the margins of a coal basin in west-central England. She concluded that the spores were deposited during a transitional or incursion phase of deposition. Chaloner and Boureau (1967) proposed that *Porostrobus* was probably similar in stature to the herbaceous lycopod *Selaginellites.*

Cirratriradites

A sudden and significant increase in population of a group of lycopods, which were probably rather small in growth habit and some even herbaceous in part, occurs in the upper part of the Abbott Formation just above the Manley Coal. This group of plants in the Abbott Formation is represented by *Cirratriradites, Radiizonates,* and *Densosporites,* which are morphologically similar. The precise taxonomic relationships of some of the parent plants is not well understood. *Cirratriradites* has been identified (Chaloner, 1954; Hoskins and Abbott, 1956; Schlanker and Leisman, 1969) from specimens of the herbaceous lycopod *Selaginellites.*

Radiizonates

Most of the increase in what are thought to be spores of small, perhaps herbaceous lycopods is accounted for by *Radiizonates difformis* (Kosanke) Staplin and Jansonius 1964. The miospores of *Sporangiostrobus kansanensis* Leisman 1970 have been variously compared (*in* Leisman, 1970) to *Radiizonates rotatus* (Kosanke) Staplin and Jansonius 1964, *R. tenuis* (Loose) Butterworth and Smith 1967, or *R. difformis* by Butterworth and Smith; to *R. aligerens* (Knox) Staplin and Jansonius 1964 by Kosanke; and to *Vallatisporites* by Staplin. Courvoisier and Phillips (1975) also correlated the spores from a specimen of *Sporangiostrobus* cf. *kansanensis* from near Lovilia, Iowa, with *R.* cf. *difformis.* Leisman (1970) speculated that *Sporangiostrobus* might have been attached to small lycopods rather than to a plant like *Lepidodendron.*

Sporangiostrobus kansanensis had been described from the Weir-Pittsburgh coal bed of Kansas, which has been considered Desmoinesian in age and about equivalent to the middle of the Spoon Formation in Illinois; however, in Illinois *Radiizonates* does not extend into the Spoon Formation. A sample of Weir-Pittsburgh coal from four miles south of Cherokee, Kansas, was macerated, and no specimens of *Radiizonates* or *Vallatisporites* were observed in the 10 slides of residue examined. Perhaps the coal from which *S. kansanensis* derived is incorrectly identified.

Densosporites

Densosporites sphaerotriangularis Kosanke 1950 reaches its peak in abundance in approximately the same interval as that of *Radiizonates,* from just below the Mariah Hill Coal Bed of Indiana to the Rock Island (No. 1) Coal Member. Remy and Remy (1975) described *Sporangiostrobus puertollanensis* from Stephanian strata in Spain that contained spores that would be identified as *Densosporites sphaerotriangularis* if found isolated. The cones are closely associated with the stems, *Puertollenia sporangiostrobifera* Remy and Remy 1975, which has little or no secondary wood and a large cortex containing water-absorbent tissues. They felt that the plant "was fully accessible to insolation, far from subsoil water zones or was saliferrous."

Abundant specimens of *Sporangiostrobus* associated with *Scolecopteris,* pecopterids, sphenopterids, and *Cordaites* were recently discovered (Wagner and Spinner, 1976) in volcanic ash in a coal, also from the Stephanian of Spain. This plant community probably grew under drier conditions than were prevalent in coal swamps during Westphalian time.

The transitional phase of coal development according to Smith (1957, 1962, 1964b) corresponds to a period when the water of the peat swamp became increasingly more shallow. When the still wet surface of the peat was exposed to the atmosphere, aerobic decomposition took place. This marked the beginning of the *Densosporites* phase. Smith (1964b) believed that the changes in water level were due to changes in climate, rather than subsidence or uplift, and were responsible for changes in spore succession. Butterworth (1964) noted that the largest number of densospores in thick coals are found near the margins of deposition and decrease toward the center. In contrast, Habib (1966) found that *Densosporites* were most abundant toward the top of the Lower Kittanning coal of Pennsylvania and toward the center of the basin where the coal is overlain by marine shale. Habib (1966), Habib, Riegel, and Spackman (1966), and Habib and Groth (1967) thought that herbaceous lycopods (*Densosporites*) and ferns preferred more saline and deeper water than the arborescent lycopods (*Lycospora*) near the margins of the Appalachian Coal Basin. Kosanke (1973) noted an abundance of *Densosporites* at the top of the Princess No. 6 coal, which is considered equivalent to the Lower Kittanning coal, in an area of eastern Kentucky. He pointed out that there is no evidence that the roof shale is marine. Ravn (1977) noted a zone of *D. sphaerotriangularis* near the middle and near the top of a seam in the Cherokee Group of Iowa.

FERNS AND PTERIDOSPERMS

Spores related to marattiaceous ferns and perhaps some small pteridosperms are divided into two groups: (1) spores with thick exines—*Laevigatosporites globosus* Schemel 1951, *L. punctatus* Kosanke 1950, and *Thymospora pseudothiessenii* (Kosanke) Wilson and Venkatachala 1963; and (2) small, thin-walled, laevigate or finely ornamented spores—*Punctatisporites minutus* (Kosanke) Peppers 1964, *P. saetiger* Peppers 1964, *Fabasporites, Laevigatosporites minutus* (Ibrahim) Schopf, Wilson, and Bentall, *Apiculatisporis lappites* Peppers 1970. Shortly after the herbaceous lycopods began their major expansion into the peat-forming environment, the thick-walled fernlike spores rapidly increased in abundance in the upper part of the Abbott Formation. The second group of smaller fernlike spores appeared in the lower part of the Abbott Formation and became more abundant slightly after the first group of ferns became an important element in the peat-forming flora.

Laevigatosporites globosus commonly increases in abundance toward the top of coal seams (Smith, 1957, 1964a, 1964b; Habib, 1966; Habib, Riegel, and Spackman 1966). *Laevigatosporites globosus* became distinctly more frequent in several coals where the coals were deposited along the axis of the Ancona Dome than in adjacent areas (Peppers, 1970; Peppers and Pfefferkorn, 1970). The dome was probably a topographic high that caused a lower water table and a drier environment than that dominated by lycopods bearing *Lycospora.* An abundance of *Punctatosporites (P. minutus* and *Laevigatosporites globosus)* in dull coal, in contrast to an abundance of *Lycospora* in bright coal in the Harbour Seam of Canada, was interpreted by Hacquebard, Cameron, and Donaldson (1964) as representing a period of open forest (moor) swamp.

Torispora

The interval from the Willis Coal Member to an area just above the Rock Island Coal is the zone of maximum frequency of *Torispora* (fig. 1). The spore mass *Bicolaria* is characterized by an outer zone of specimens of *Torispora* that have a thickened pad or crassitude, which probably functioned as a protective layer against desiccation. Spores toward the inside of the spore mass lack the crassitude. Laveine (1969) described and illustrated specimens of *Torispora* from sporangia on several species of the fern foliage *Pecopteris.* As mentioned earlier, abundant pecopterids bearing *Torispora* were found in association (Wagner and Spinner, 1976) with sphenopterids, *Cordaites,* and *Sporangiostrobus* in a Stephanian assemblage in Spain.

Cuticles in an Indiana "paper coal," which also contain an abundance of *Torispora,* were reported by Neavel and Guennel (1960) to be associated with an abundance of the pteridosperm *Sphenopteris brandfordii* Arnold 1949. Abundant hairs on the cuticles were thought to indicate xerophytic or drying conditions. Navale (1963, 1964) found an inverse relationship in abundance between *Torispora* and *Densosporites* in durite zones in several Jura and Merlabach coals in France and Germany. Alpern, Leabeuf, and Navale (1964) observed that *Torispora* had an intermediate relationship between *Lycospora* and *Densosporites*—*Lycospora* represents relatively deep water and formation of vitrinite, and *Densosporites* represents a period of aerobic decomposition and formation of inertinite. A thin layer of dull coal rich in *Torispora* in the Harbour Seam of Canada was interpreted as indicative of relatively dry conditions (Hacquebard, Cameron, and Donaldson, 1964).

Punctatisporites

Research indicates that the climate was undergoing change toward less humid conditions in late Carboniferous time (Gothan and Grimm, 1930; White, 1931; Gothan and Remy, 1957; Frederiksen, 1972; Schopf, 1975; McKee, 1975). Near the base of the Missourian, where *Lycospora* essentially disappears from Illinois coals, marattiaceous ferns that produced small, thin spores became the dominant coal-forming plants in most of late Pennsylvanian time (Phillips et al., 1974). These small spores, including *Punctatisporites minutus* and *Punctatosporites minutus,* first became an important part of the miospores assemblages at the top of the Abbott Formation. Smith (1962, 1964b) and Smith and Butterworth (1967) included at least some *Punctatosporites minutus* of the small marattiaceous spores in the incursion phase of coal deposition.

FILICALES

Spores (*Granulatisporites, Lophotriletes, Verrucosisporites, Raistrickia,* and other genera) that derived, or probably derived, from the Filicales increased slightly in abundance in the lower half of the Spoon Formation.

SPHENOPSIDS

Sphenopsids represented by *Calamospora* (Arnold, 1944; Kosanke, 1955; Delevoryas, 1955; Baxter, 1963; Hibbert and Eggert, 1965; and others) *Vestispora* (Mamay, 1954; W. Remy, 1955; R. Remy, 1959; Brush and Barghoorn, 1962), and large species of *Laevigatosporites* (Reed, 1938; Baxter, 1950; Andrews and Mamay, 1951) did not undergo any significant increase in abundance in the swamp flora until about the Abbott-Spoon boundary, soon after the beginning of the expansion of marattiaceous ferns. Smith (1964b) placed the sphenopsids in the transition phase of coal development. The presence of sphenopsids may indicate frequent changes in water level and exposure to air (Elliott, 1969). According to Hacquebard and Donaldson (1969), sphenopsids grew mainly in a "reed-moor," which was transitional between open and forest "moors." They might have lived on wet coastal plains (Oshurkova, 1967) and required less moisture than in the *Lycospora*-rich environment (Peppers and Pfefferkorn, 1970). Sphenopsids are a common constituent in compression flora above coal strata and frequently may even replace pteridosperm or lycopod-dominated floras going upward into roof shales (Dragert, 1964; Pfefferkorn et al., 1975; Scott, 1977).

CORDAITES

Cordaites, represented by *Florinites* (Florin, 1936; Delevoryas, 1953; Wilson, 1960; Brush and Barghoorn, 1962; Millay and Taylor, 1974; and others), became a somewhat more important part of the peat environment in the Spoon Formation than in the Abbott Formation. *Cordaites* has been interpreted as essentially growing in areas marginal to the sea (Neves, 1958) or as having an upland habitat (Chaloner, 1958a, 1959; Peppers, 1964; Chaloner and Muir, 1968; Peppers and Pfefferkorn, 1970; Frederiksen, 1972; Scott, 1977). Smith (1964b) indicated that *Florinites* were brought into the coal swamp along with sediment by incursion of flood waters. At least some cordaites, however, probably grew in coal swamps and preferred somewhat saline, near-shore coastal plains (Peppers and Pfefferkorn, 1970)—an atmosphere in which cordaites was a physiological xerophyte (Wartman, 1969). *Cordaites* is fairly common in coal-ball assemblages in an Indiana coal equivalent to the Murphysboro Coal Member of Illinois (lower Spoon Formation) and in coal at several localities in lower Desmoinesian strata of Iowa (Phillips, personal communication).

SECOND CYCLE OF CHANGE

Near the beginning of Desmoinesian time and at the end of this succession of increasing diversification of peat swamp flora, a similar but less-pronounced cycle apparently began with a rise in frequency of *Lycospora micropapillata.* This was followed by a major increase in abundance of *Crassispora* and *Cappasporites* and *Densosporites.* Although the latter amounts to only a few percent, *D. sphaerotriangularis* is more abundant in this interval than any other time except in coals between the Mariah Hill and Willis Coals. Both groups of marattiaceous ferns also increased. No increase in abundance of sphenopsid and cordaitalean miospores is indicated in the Davis and De Koven Coals at the top of the Spoon Formation. These coals, which are widespread and rather uniform in thickness, may have formed when a wetter climate prevailed.

ABUNDANCE OF SPECIES

The number of species that appeared for the first time (fig. 1) increased markedly in the Smith coal bed of Kentucky, which is just above the maximum occurrence of *Lycospora micropapillata.* No new species were recorded from the Mariah Hill Coal to the stratum just below the Rock Island (No. 1) Coal, or approximately at the interval of peak development of herbaceous lycopods. The Rock Island Coal, however, shows the largest number of new species being introduced and species disappearing. Ranges of a relatively large number of species begin or end in coals in the lower part of the Spoon Formation; these species are characterized by an abundance of spores from marattiaceous ferns, sphenopsids, and cordaites. During deposition of the remainder of the Spoon Formation, disappearance of spore species from the coal swamps was more common than the introduction of new species.

The average number of species of spores in each coal seam increased in the middle of the Abbott Formation generally and reached a peak in the lower part of the Spoon Formation. The number then declined through the rest of the Spoon Formation.

REFERENCES

ALPERN, B., J. LIABEUF, and G.K.B. NAVALE, 1964, Beziehungen zwischen palynologischen und petrographischen Zonenfolgen in den Steinkohlenflözen: Fortschr. Geol. Rheinld. u. Westf., 12, p. 303-316.

ANDREWS, H. N. and S. H. MAMAY, 1951, A new American species of *Bowmanites:* Botanical Gazette, v. 113, p. 158-165.

ARNOLD, C. A., 1944, A heterosporous species of *Bowmanites* from the Michigan Coal Basin: American Journal of Botany, v. 31, no. 8, p. 466-469.

BALBACH, M. K., 1966, Microspore variation in *Lepidostrobus* and comparison with *Lycospora:* Micropaleontology, v. 12, p. 334-342.

BAXTER, R. W., 1950, *Peltastrobus reedae:* a new sphenopsid cone from the Pennsylvanian of Indiana: Botanical Gazette, v. 112, no. 2, p. 174-182.

BAXTER, R. W., 1963, *Calamocarpon insignis,* a new genus of heterosporous, petrified Calamitean cones from the American Carboniferous: American Journal of Botany, v. 50, no. 5, p. 469-476.

BRUSH, G. S., and E. S. BARGHOORN, 1962, Identification and structure of Cordaitean pollen: Journal of Paleontology, v. 36, p. 1357-1360.

BUTTERWORTH, M. A., 1964, Die Verteilung der *Densosporites sphaerotiriangularis* im Westfal B der westpenninischen Steinkohlenfelder Englands. Fortschr. Geol. Rheinld. Westf. 12, p. 317-330.

CHALONER, W. G., 1953a, A new species of *Lepidostrobus* containing unusual spores: Geological Magazine, v. 90, p. 97-100.

CHALONER, W. G., 1953b, On the megaspores of four species of *Lepidostrobus:* American Journal of Botany, v. 17, p. 263-293.

CHALONER, W. G., 1954, Notes on the spores of two British Carboniferous lycopods: Annual Magazine of Natural History, v. 7, p. 81-91.

CHALONER, W. G., 1958a, The Carboniferous upland flora: Geological Magazine, v. 95, p. 261-262.

CHALONER, W. G., 1958b, *Polysporia mirabilis* Newberry, a fossil lycopod cone: Journal of Paleontology, v. 32, p. 199-209.

CHALONER, W. G., 1959, Palaeoecological data from Carboniferous spores (Abstract): Ninth International Botany Congress, Proceedings, v. 2, University of Toronto Press, p. 64.

CHALONER, W. G., and E. BOUREAU, 1967, Lycophyta: *in* Traité de Paléobotanique, v. 2, Bryophyta, Psilophyta, Lycophyta: E. Boureau (ed.), Masson et Cie, Paris, 845 p.

CHALONER, W.G., and M. MUIR, 1968, Spores and floras, *in* D. Murchison and T. S. Westoll, [eds.], Coal and coal-bearing strata: Oliver and Boyd. Co., London, p. 127-146.

COHEN, A. D., and W. SPACKMAN, 1972, Methods in peat petrology and their application to reconstruction of palaeo-environments: Bulletin of Geological Society of America, v. 83, p. 129-142.

COURVOISIER, J. M., and T. L. PHILLIPS, 1975, Correlation of spores from Pennsylvanian coal-ball fructification with dispersed spores: Micropaleontology, v. 21, p. 45-59.

CROSS, A. T., 1964, Plant microfossils and geology: An introduction, *in* Cross, A.T. [ed.], Palynology in oil exploration: Special Paper No. 11, Society of Economic Paleontologists and Mineralogists, p. 3-13.

DAPPLES, E. C., and M. E. HOPKINS, eds., 1969, Environments of coal deposition: Geological Society of America Special Paper 114, 204 p.

DELEVORYAS, T., 1953, A new male cordaitean fructification from the Kansas Carboniferous: American Journal of Botany, v. 40, no. 3, p. 144-150.

DELEVORYAS, T., 1955, A *Palaeostachya* from the Pennsylvanian of Kansas: American Journal of Botany, v. 42, no. 6, p. 481-488.

DORF, E., 1964, The use of fossil plants in palaeoclimatic interpretations, *in* A.E.M. Nairn [ed.], Problems in Palaeoclimatology: John Wiley and Sons, London, p. 13-31.

DRÄGERT, K., 1964, Pflanzensoziologische Untersuchungen in den Mittleren Essener Schichten des nördlichen Ruhrgebietes: Forsch, Ber. Landes Nord Rhein-Westf. 1363, 295 p.

ELLIOTT, R. E., 1969, Deltaic processes and episodes: The interpretation of productive coal measures occurring in the East Midlands, Great Britain: Mercian Geologist, v. 3, p. 111-134.

FELIX, C. F., 1954, Some American arborescent lycopod fructifications: American Monthly Botanical Garden, v. 41, p. 351-394.

FLORIN, R., 1936, On the structure of the pollen-grains in the Cordaitales, Svensk. bot. Tidskr., v. 30, p. 624-651.

FREDERIKSEN, N. O., 1972, The rise of the Mesophytic flora: Geoscience and Man, v. 4, p. 17-28.

FUNKHOUSER, J. W., 1969, Factors that affect sample reliability, *in* R. H. Tschudy and R. A. Scott [eds.], Aspects of palynology: John Wiley and Sons, New York, p. 97-102.

GOTHAN, W., and O. GRIMM, 1930, Neurere Beobachtungen und Betrachtungen über die Flora des Rotliegenden von Thüringen: Arb. Inst. Paläobot. u. Petrogr. d. Brennsteine, v. 2, p. 39-74.

GOTHAN, W., and W. REMY, 1957, Steinkohlenpflanzen: Essen, Verlag Glückauf, 248 p.

HABIB, D., 1966, Distribution of spore and pollen assemblages in the Lower Kittanning Coal of western Pennsylvania: Palaeontology, v. 9, pt. 4, p. 629-666.

HABIB, D., and P.K.H. GROTH, 1967, Paleoecology of migrating Carboniferous peat environments: Palaeogeography, palaeoclimatology, palaeoecology, v. 3, p. 185-195.

HABIB, D., W. RIEGEL, and W. SPACKMAN, 1966, Relationship of spore and pollen assemblages in the Lower Kittanning Coal to overlying faunal facies: Journal of Paleontology, v. 40, p. 756-759.

HACQUEBARD, P. A., and J. R. DONALDSON, 1969, Carboniferous coal deposition associated with flood plain and limnic environments in Nova Scotia, *in* E. C. Dapples and M. E. Hopkins [eds.], Environments of coal deposition: Geological Society of America Special Paper 114, 204 p.

HACQUEBARD, P. A., A. R. CAMERON, and J. R. DONALDSON, 1964, Die Ablagerungsbedingungen des Flözes Harbour im Sydney-Kohlengebiet von Neuschottland (Kanada): Fortschr. Geol. Rheinld., Westf., u. 12, p. 331-356.

HAGEMANN, VON, Hans-Werner, 1966, Sporen aus kohlig erhaltenen Lepidophytenzapfen des Westfals, Beschreibung der Sporen in situ und eine statistische Analyse ihres Reifezustandes: Fortschr. Geol. Rheinld. u. Westf. 13, p. 317-338.

HIBBERT, F. A., and D. A. EGGERT, 1965, A new calamitalean cone from the middle Pennsylvanian of southern Illinois: Palaeontology, v. 8, pt. 4, p. 681-686.

HOSKINS, J. H., and M.L. ABBOTT, 1956, *Selaginellites crassicinctus,* a new species from the Desmoinesian Series of Kansas: American Journal of Botany, v. 43, p. 36-46.

KARMASIN, K. VON., 1952, Deutung des Fazieswechsels in den Flözen Erda und Ägir auf Grund mikropetrographischer Schlitzproben-Untersuchungen: Bergbau Archiv 13, p. 74-100.

KOSANKE, R. M., 1950, Pennsylvanian spores of Illinois and their use in correlation: Illinois State Geological Survey Bulletin 74, 128 p.

KOSANKE, R. M., 1955, *Mazostachys*—a new calamite fructification: Illinois State Geological Survey Report of Investigations 180, 37 p.

KOSANKE, R. M., 1973, Palynological studies of the coals of the Princess Reserve District in northeastern Kentucky: U.S. Geological Survey Professional Paper 839, 22 p.

LAVEINE, J. P., 1969, Quelques Pécopteridinees houillères à la lumière de la palynologie: Pollen et Spores v. XI, no. 3, p. 619-685.

LEARY, R. L., 1975, Early Pennsylvanian paleogeography of an upland area, western Illinois, USA. Bulletin Belg. Ver. Geol., v. 84, p. 19-31.

LEISMAN, G. A., 1970, A petrified *Sporangiostrobus* and its spores from the middle Pennsylvanian of Kansas: Palaeontographica, Abt. B, Bd. 129, p. 166-177.

MC KEE, E. D., 1975, Interpretation of Pennsylvanian history: Paleotectonic investigations of the Pennsylvanian System in the United States, part II, U.S. Geological Survey Professional Paper 853, p. 1-21.

MAMAY, S. H., 1954, A new sphenopsid cone from Iowa: Annals of Botany, v. 18, p. 229-239.

MILLAY, M. A., and T. N. TAYLOR, 1974, Morphological studies of Paleozoic saccate pollen: Palaeontographica, Abt. B, Bd. 147, p. 75-99.

NAVALE, G.K.B., 1963, Palynological studies in conjunction with petrographic structure: Palaeobotanist, v. 12, no. 3, p. 232-249.

NAVALE, G.K.B., 1964, Miospore assemblage pattern in the microlithotypes of Jura Coals: Palaeobotanist, v. 13, no. 1, p. 1-16.

NEAVEL, R. C., 1963, Coal III A and the Logan Quarry Coal, *in* R. Zangerl and E. S. Richardson, Jr., The paleoecological history of two Pennsylvanian black shale: Fieldiana, Geology, v. 4, p. 198-212.

NEVES, R., 1958, Upper Carboniferous plant spore assemblages from the *Gastrioceras subcrenatus* horizon, North Staffordshire: Geological Magazine, v. XCV, no. 1, p. 1-19.

NIKLAS, K. J., and T. M. PHILLIPS, 1974, Chemical analyses of a vertical sample of the Herrin (No. 6) Coal Member, Abstracts, American Journal of Botany, v. 61, p. 17.

OSHURKOVA, M. V., 1967, Paleophytological validation of the stratigraphy of the upper suites of the Carboniferous deposits in the Karaganda Basin: Izd-vo Nauka, Leningrad, 150 p.

PEPPERS, R. A., 1964, Spores on strata of the Late Pennsylvanian cyclothems in the Illinois Basin: Illinois State Geological Survey Bulletin 90, 89 p.

PEPPERS, R. A., 1970, Correlation and palynology of coals in the Carbondale and Spoon Formations (Pennsylvanian) of the northeastern part of the Illinois Basin: Illinois State Geological Survey Bulletin 93, 173 p.

PEPPERS, R. A., and H. W. PFEFFERKORN, 1970, A comparison of the floras of the Colchester (No. 2) Coal and Francis Creek Shale, *in* W. H. Smith et al., Depositional environments in parts of the Carbondale Formation—Western and northern Illinois: Illinois State Geological Survey Guidebook Series No. 8, p. 61-74.

PFEFFERKORN, H. W., H. MUSTAFA, and H. HASS, 1975, Quantitative Charakterisierung ober-karboner Abdruckfloren: N. Jb. Geol. Paläont. Abh., Bd. 150, p. 253-269.

PHILLIPS, T. L., in press, Stratigraphic ranges of permineralized Pennsylvanian swamp plants in the Euramerican Province, Memoir, Journal of Paleontology.

PHILLIPS, T. L., R. A. PEPPERS, M. J. AVCIN, and P. F. LAUGHNAN, 1974, Fossil plants and coal. Patterns of change in Pennsylvanian coal swamps of the Illinois Basin: Science, v. 154, p. 1367-1369.

RAVN, R. L., 1977, The palynology and paleoecology of a lower Cherokee (Pennsylvanian) Coal from Wapello County, Iowa: unpublished M.S. thesis, University of Iowa, 254 p.

REED, F. D., 1938, Notes on some plant remains from the Carboniferous of Illinois: Botanical Gazette, v. 100, p. 324-325.

REMY, R., 1959, Die Sporen von *Cingularia typica* Weiss: Mber. dt. Akad. Wiss. Berl. 1, p. 257-260.

REMY, W., 1955, Untersuchungen von kohlig erhaltenen fertilen und sterilen Sphenophyllen und Formen unsicherer systematischer Stellung: Abh. dt. Akad. Wiss. Berl. Jg., 1, p. 1-40.

REMY, W., and R. REMY, 1975, *Sporangiostrobus puertollanensis* n. sp. und *Puertollania sporangiostrobifera* n. gen., n. sp. aus dem Stefan von Puertollano, Spain: Argumenta Palaeobotanica, Heft 4, p. 13-29.

RETTSCHLAG, R., and W. REMY, 1954, Beiträge zur Kenntnis einiger paläeozoischer Fruktifikationen: Geologie, v. 3, p. 590-603.

SCHLANKER, C. M., and G. A. LEISMAN, 1969, The herbaceous Carboniferous lycopod *Selaginella fraiponti* comb. nov.: Botanical Gazette, v. 130, no. 1, p. 35-41.

SCHOPF, J. M., 1941, Contributions to Pennsylvanian paleobotany: *Mazocarpon oedipternum,* sp. nov., and sigillarian relations: Illinois State Geological Survey, Report of Investigations 75, 53 p.

SCHOPF, J. M., 1975, Pennsylvanian climate in the United States, *in* E. D. McKee and E.J. Crosby [eds.], Paleotectonic investigations of the Pennsylvanian System in the United States, Pt. 2, Interpretive summary and special features of the Pennsylvanian System: U.S. Geological Survey Professional Paper 853, p. 23-31.

SCHOPF, J. M., L. R. WILSON, and R. BENTALL, 1944, An annotated synopsis of Paleozoic fossil spores and the definition of generic groups: Illinois State Geological Survey Report of Investigations 91, 73 p.

SCOTT, A. C., 1977, A review of the ecology of Upper Carboniferous plant assemblages with new data from Strathclyde: Palaeontology, v. 20, pt. 2, p. 447-473.

SEN, J., 1958, Notes on the spores of four Carboniferous lycopods: Micropaleontology, v. 4, no. 2, p. 159-164.

SMITH, A.H.V., 1957, The sequence of microspores assemblages associated with the occurrence of crassidurite in coal seams of Yorkshire: Geological Magazine, v. 94, p. 345-363.

SMITH, A.H.V., 1962, The palaeoecology of Carboniferous peats based on the miospores and petrography of bituminous coals: Proceedings of Yorkshire Geological Society, v. 33, p. 423-474.

SMITH, A.H.V., 1964a, Zur Petrologie und Palynologie der Kohlenflöze des Karbons und ihrer Begleitschichten: Fortschr. Geol. Rheinld. u. Westf., v. 12, p. 285-302.

SMITH, A.H.V., 1964b, Palaeoecology of Carboniferous peats, *in* A.E.M. Nairn [ed.], Problems in Palaeoclimatology: John Wiley and Sons, London, p. 57-66.

SMITH, A.H.V., and M. A. BUTTERWORTH, 1967, Miospores in the coal seams of the Carboniferous of Great Britain: Special Paper No. 1, Palaeontology, 324 p.

TSCHUDY, R. H., 1969, Applied palynology, *in* R. H. Tschudy and R.A. Scott, [eds.], Aspects of palynology: John Wiley and Sons, New York, p. 103-106.

WAGNER, R., and E. SPINNER, 1976, *Bodeodendron,* le tronc associé a *Sporangiostrobus:* C.R. Academy of Science Paris, 282D, p. 353-356.

WARTMANN, R., 1969, Studie über die papillen-förmigen Verdickungen auf der Kutikule bei *Cordaites* an Material aus dem Westfal C des Saar-Karbons: Argumenta Palaeobotanica, no. 3, p. 199-207.

WHITE, DAVID, 1931, Climatic implications of Pennsylvanian flora: Illinois State Geological Survey Bulletin 60, p. 271-281.

WILSON, L. R., 1960, *Florinites pelucidus* and *Endosporites ornatus* with observations on their morphology: Oklahoma Geology Notes, v. 20, p. 29-33.

The distribution of fusulinids and their correlation between the Illinois Basin and the Appalachian Basin

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INTRODUCTION

This study is based on surface and well core samples from the Kentucky areas of the Illinois and Appalachian Basins. Supplementary surface samples from Illinois, Indiana, Ohio, and Pennsylvania were studied for correlation with other parts of the basins. An attempt was made to examine representative faunas from all fusulinid-bearing horizons in the two basins and from as wide a geographic coverage as practical.

The geographic area covered by this report is so large that a uniform stratigraphic nomenclature cannot be used throughout. The local names are used tentatively; comments on probable equivalents follow. The principal concern is to indicate how the fusulinid faunas correlate across the area rather than to suggest continuity of the stratigraphic units. Both basins have limited extent and rapid changes in facies near the margins. Most of the limestone beds—those in which the fusulinids are common—are discontinuous even within the basins.

The part of the Illinois Basin in western Kentucky will be used as the standard for reference in this paper because it has the greatest time spread represented by fusulinids and because it has been studied most intensely during the course of the investigation. Reports by Dunbar and Henbest (1942); Thompson, Shaver, and Riggs (1959); Thompson and Shaver (1964); and Shaver and Smith (1974) have summarized the known information on the fusulinids of the Illinois Basin. Reports by Thompson (1936) and Smyth (1957, 1974) summarized the fusulinids known from the Appalachian Basin.

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Most of the samples for this study were provided by C. L. Rice and T. M. Kehn of the U.S. Geological Survey, which worked in cooperation with the Kentucky Geological Survey, and by J. G. Beard of the Kentucky Geological Survey. Some core material was provided by the Institute of Mining and Mineral Research, University of Kentucky. Additional faunas were studied from collections in the U.S. National Museum of Natural History and were supplemented by collections I made in Ohio and Pennsylvania with the aid of C. H. Cheong and R. Ingavat. Thin sections for the study were prepared with great skill and dexterity by Richard Margerum.

The nomenclature used in this report is not necessarily that of the U.S. Geological Survey.

FAUNAL SUCCESSION (figs. 1 to 3)

Middle Pennsylvanian

Rocks of early Atokan age. The oldest beds containing fusuline foraminifers in western Kentucky are assigned to the Tradewater Formation. The fusulinid genus *Profusulinella* is present in the Lead Creek Limestone of Crider (1913) and occurs through more than 50 feet (15 m) of section in some wells. The member includes two limestone beds a few feet thick commonly containing small shale breaks that are separated by about 30 feet (10 m) of siltstone. The lower limestone was designated the Fulda Bed and the upper, the Ferdinand Bed by Shaver and Smith (1974) after exposures in southern Indiana.

In western Kentucky, both beds yield abundant *Profusulinella* associated with *Millerella.* Thompson and Riggs (*in* Thompson, Shaver, and Riggs, 1959, p. 776) described *Profusulinella kentuckyensis* from the upper beds of the Lead Creek Limestone as exposed in Butler County, Kentucky. A core hole in southeastern Ohio County, just a few miles away, penetrated both beds about 50 feet (15 m) apart, each containing common *Profusulinella.* Farther north in Daviess County and again in Hancock County, the two fusulinid-bearing limestones of the Lead Creek are about 30 feet (10 m) apart. Across the Ohio River in Spencer County, Indiana, the Fulda and Ferdinand Beds of the Lead Creek Limestone are reported to be separated by about 20 feet (5 m) of shale (Shaver and Smith, 1974, locality 28, p. 34).

No beds containing *Profusulinella* have been reported from Illinois, but they are known from rocks along the southern and eastern margin of the Illinois Basin from Christian County, Kentucky, to Warren County, Indiana. It would not be surprising to find this horizon in the subsurface of Illinois.

Correlation with the Appalachian Basin for beds of this age is difficult. The oldest fusulinid-bearing unit in eastern Kentucky is the Magoffin Member of the Breathitt Formation. The Magoffin contains *Millerella* sp. associated with other microfossils, but no *Profusulinella.* The Lost Creek Limestone (Morse, 1931; Wanless, 1939) of the Breathitt Formation is about 125 feet (40 m) above the Magoffin Member in its northwesternmost exposure and contains fusulinids that have attributes intermediate between *Profusulinella* and *Fusulinella.* This advanced *Profusulinella* or primitive *Fusulinella* has no specific equivalent in the Illinois Basin. Taxonomically it falls between the forms in the Lead Creek Limestone (Crider, 1913) and Curlew Lime-

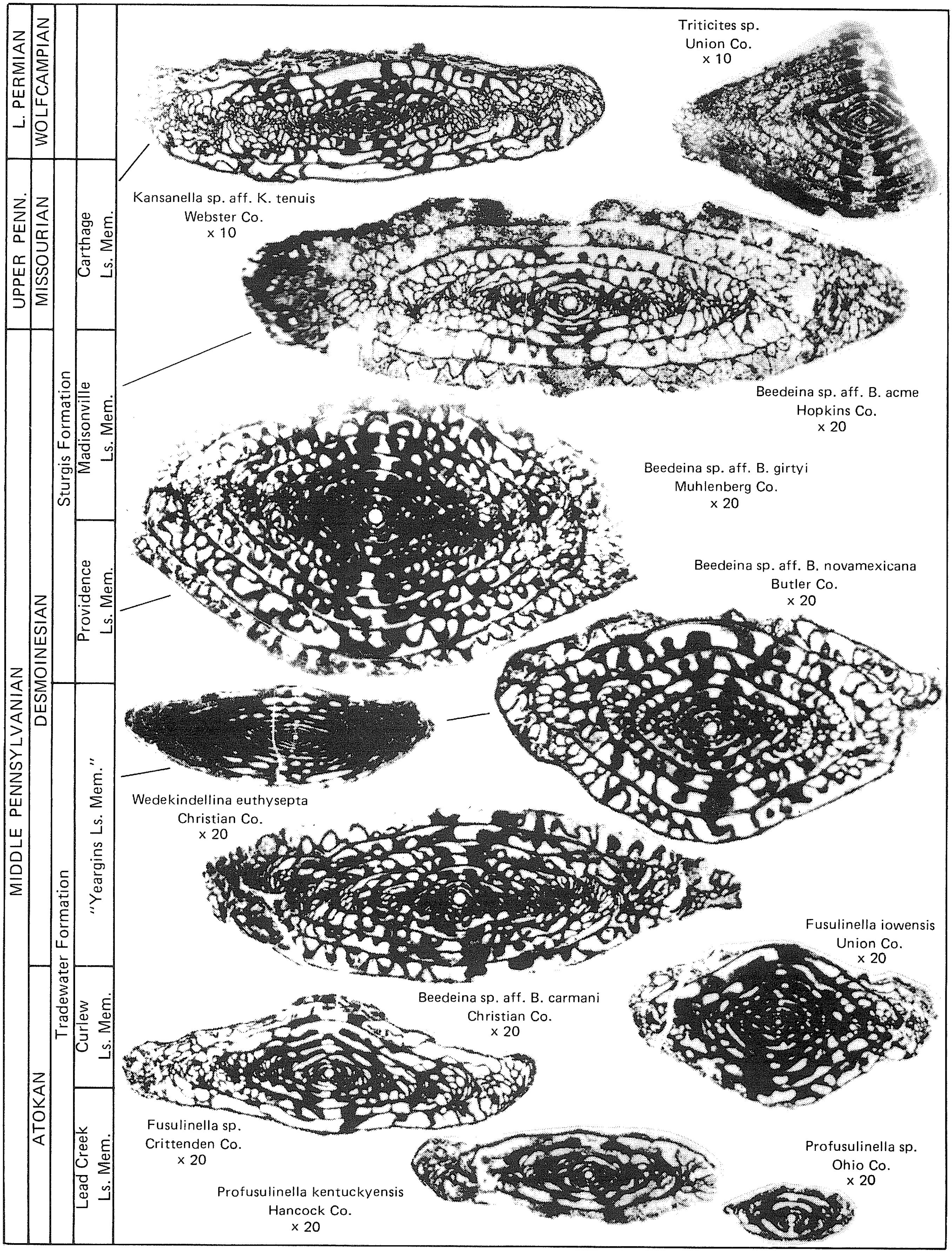

Figure 1. Representative fusulinids of Western Kentucky.

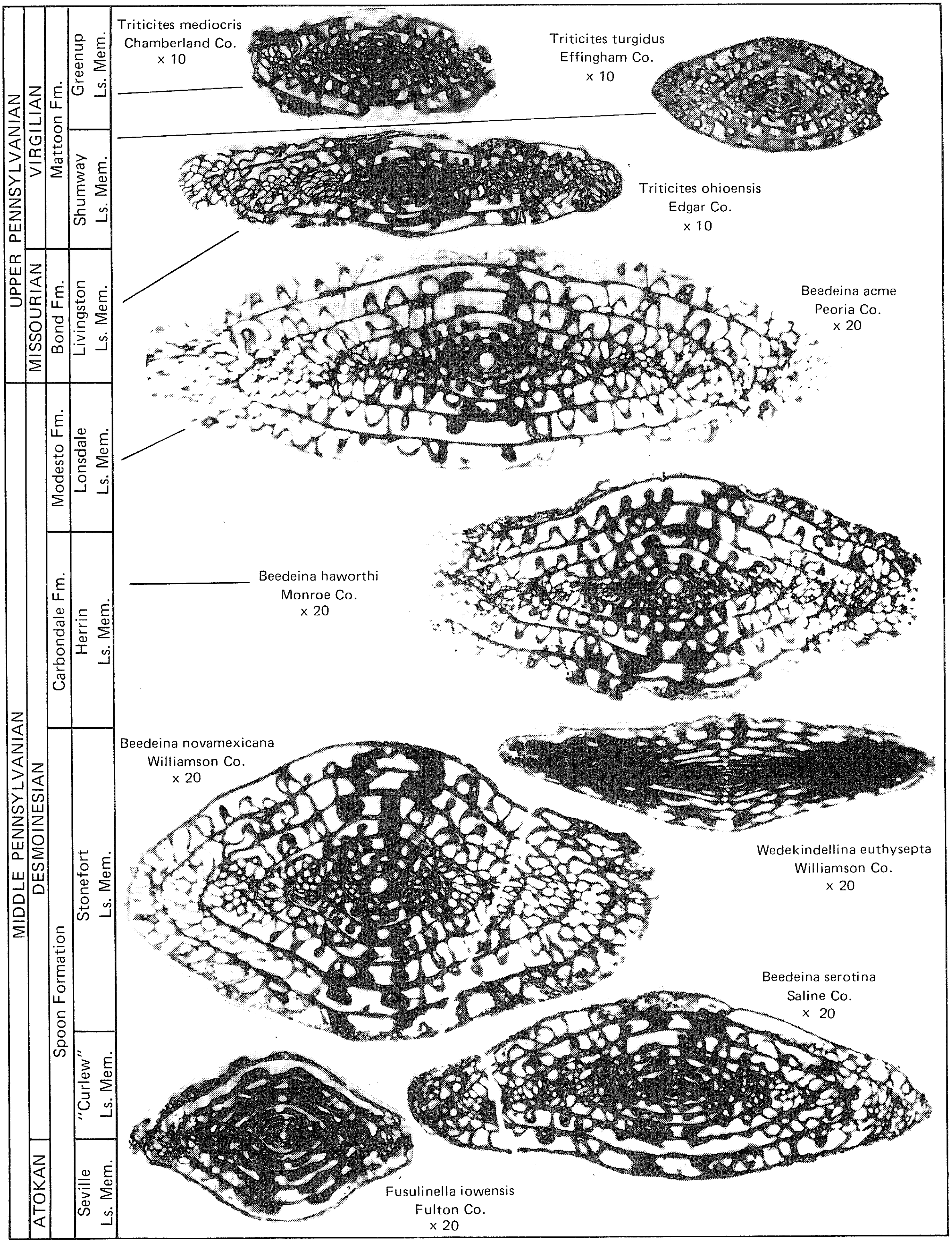

Figure 2. Representative fusulinds of Illinois.

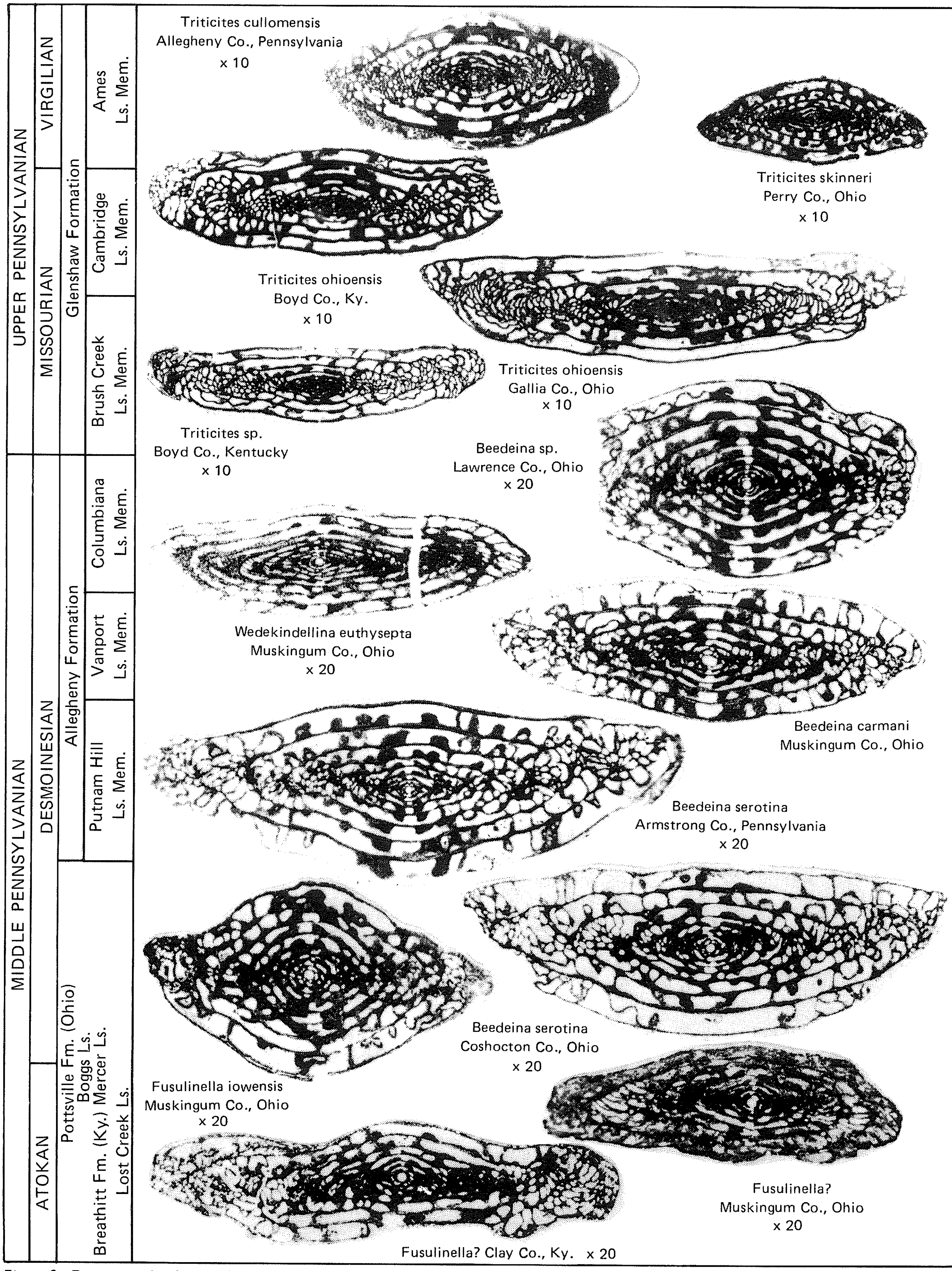

Figure 3. Representative fusulinids of eastern Kentucky, Ohio, and Pennsylvania.

stone Member of the Tradewater Formation in western Kentucky. Elsewhere in the Appalachian Basin, beds of this age apparently do not yield fusulinids.

Rocks of late Atokan age. The Curlew Limestone Member of the Tradewater Formation at its type locality in Union County, Kentucky, contains a fusulinid fauna of late Atokan age. Two limestones are present at the type locality, separated by about 30 feet (10 m) of siltstone. The lower limestone is about 3 feet (1 m) thick and yields most of the fauna. It includes species of *Fusulinella,* including *F. iowensis* and the form called *F. iowensis stouti* in addition to *Millerella* and other foraminifers. This fauna is known from the Seville Limestone Member of the Spoon Formation in Illinois and from the Perth Limestone Member of the Staunton Formation in Indiana.

Shaver and Smith (1974) discussed at length the series assignment for these beds and decided to include them with the Desmoinesian. They noted that others have considered the beds to represent late Atokan age. The limestones are the same age as the oldest fusulinid-bearing bed in Iowa and are essentially the same age as the upper part of the "Derryan" in New Mexico (Thompson, 1942, 1948).

In the Appalachian Basin, the rocks of equivalent age include the Boggs limestone unit and the lower and upper limestone units of the Mercer Member of the Pottsville Formation in Ohio. The Boggs Limestone Member is closely related to the Lost Creek Limestone Member (Wanless, 1939) of the Breathitt Formation in Kentucky, but it is slightly younger and more clearly assignable to the upper Atokan. The Mercer limestone units are typically late Atokan in age and are easily correlated to the Curlew Limestone Member of the Tradewater of western Kentucky and the Seville Limestone Member of the Spoon of Illinois.

Rocks of Desmoinesian age. The greatest diversity of fusulinid faunas in the Illinois Basin is present in beds of Desmoinesian age. In western Kentucky, the limestones commonly underlying the number 6 coal (tentatively called the "Yeargins Limestone Member" of the Tradewater Formation) yielded the first good Desmoinesian fusulinids, including *Wedekindellina euthysepta* and species of *Beedeina* (fig. 1). These limestone beds are the equivalent of the Creal Springs and Stonefort Limestone Members of the Spoon Formation in Illinois; the fauna from the Stonefort Limestone Member described by Dunbar and Henbest (1942) was taken from both these beds, which were not distinguished at that time.

A slightly older Desmoinesian horizon is present in Saline County, Illinois, where a limestone called the Curlew Limestone Member of the Spoon Formation contains a *Beedeina* identified as *Fusulina leei* Skinner by Dunbar and Henbest (1942). This "Curlew" of Illinois is younger than the type Curlew of Kentucky.

The upper part of the Desmoinesian Series in western Kentucky is included in the Sturgis Formation. Two limestone members contain abundant faunas of fusulinids. The Providence Limestone Member contains large obese *Beedeina* of the *B. girtyi* group, whereas the overlying Madisonville Limestone Member contains large elongate *Beedeina* of the *B. acme* group. Nomenclatorial problems remain to be solved for these fusulinids, but they are stratigraphically useful groupings.

In Illinois, the Herrin Limestone Member of the Carbondale Formation is the approximate equivalent of the Providence Limestone Member of the Sturgis. The Lonsdale or West Franklin Limestone Member of the Modesto Formation in Illinois is the approximate equivalent of the Madisonville Limestone Member of the Sturgis.

The Desmoinesian Series in the Appalachian Basin starts with the Putnam Hill Limestone Member of the Allegheny Formation. The member contains a *Beedeina* resembling that in the Illinois "Curlew" Limestone Member of the Spoon. This limestone and fauna are present in east-central Ohio and also have been recognized in Armstrong County, Pennsylvania, northeast of Pittsburgh (fig. 3), the easternmost known fusulinid locality in the U.S.A.

The Putnam Hill Limestone Member of the Allegheny in Ohio is overlain by the "Zalesky Member" and then the Vanport Limestone Member of the Allegheny Formation. The "Zalesky" Member may have fusulinids locally, and the Vanport commonly has scatter fusulinids including *Wedekindellina* and *Beedeina* that are similar to those found in the "Yeargins Limestone Member" of the Tradewater of Kentucky and the Creal Springs and Stonefort Limestone Members of the Spoon of Illinois. The Vanport Limestone Member, as used by Phalen (1912), is sparsely fossiliferous in eastern Kentucky, and only small indeterminate fusulinids have been found. In western Pennsylvania, remnants of the Vanport Limestone of the Allegheny Group are found around some of the abandoned coal pits; in Mercer County, a few pieces containing *Wedekindellina* have been found.

No abundant fusulinids are found in the younger Desmoinesian beds of the Appalachian Basin. Some rare specimens of *Beedeina* are found in the Columbiana Limestone Member (Sturgeon and DeLong, 1964) of the Allegheny Formation. Correlation with the Illinois Basin is uncertain, but a Carbondale equivalence is reasonable.

Upper Pennsylvanian

Rocks of Missourian age. The Carthage Limestone Member of the Sturgis Formation contains the first fusulinids of Late Pennsylvanian age in western Kentucky. A form referred to *Kansanella* sp. aff. *K. tenuis* is known from Webster, Union, and Hopkins Counties in western Kentucky (fig. 1). It is similar in general size and shape to many of the fusulinids referred to *Triticites ohioensis* from the Livingston or Millersville Limestone Members of the Bond Formation in Illinois.

In the Appalachian Basin, the Cambridge Limestone Member of the Glenshaw Formation of the Conemaugh Group in Ohio has a similar form and includes the type level for *Triticites ohioensis.* In eastern Kentucky, the Brush Creek Limestone Member underlying the Cambridge contains a smaller elongate *Triticites* sp. (fig. 3).

Rocks of Virgilian age. No fusulinids of definite Virgilian age have been recognized in western Kentucky; however, rocks of Virgilian age are probably represented by the uppermost beds of the Sturgis Formation in Union County. The Shumway and Greenup Limestone Members of the Mattoon Formation in Illinois contain species of *Triticites* of Virgilian age (fig. 2).

In the Appalachian Basin, species of *Triticites* of Virgilian age occur in Ohio in the Ames Limestone Member of the Glenshaw Formation of the Conemaugh Group. Beds of approximately the same age in Pennsylvania at Brilliant Cut in Pittsburgh contain rare specimens of *Triticites.* The overlying Gaysport Limestone Member of the Conemaugh Formation in Ohio also is reported to contain a Virgilian *Triticites* (Smyth, 1957), but I have not been able to verify this occurrence.

Lower Permian

Rocks of Permian age. No rocks of Permian age have been recognized previously in the Illinois Basin. The Greenup Limestone Member of the Mattoon Formation is the youngest fusulinid-bearing bed reported. Limestone cored in a well in Union County, Kentucky, contains a few large *Triticites* sp of Early Permian age (fig. 1). Similar fossils have not been found in correlative surface exposures. In this area, the preservation of rocks of Permian age is probably related to the thickened sequence represented in the Moorman syncline and to the graben block that the sequence occupies within the Rough Creek fault system. Erosion may have removed beds of this age from other parts of the Illinois Basin.

REFERENCES

CRIDER, A. F., 1913, Economic geology of Tell City and Owensboro quadrangles: Kentucky Geological Survey, 4th ser., v. 1, pt. 1, p. 263-316.

DUNBAR, C. O., and L. G. HENBEST, 1942, Pennsylvanian Fusulinidae of Illinois: Illinois State Geological Survey Bulletin 67, 218 p.

MORSE, W. C., 1931, The Pennsylvanian invertebrate fauna of Kentucky, *in* Paleontology of Kentucky: Kentucky Geological Survey, ser. 6, v. 36, p. 293-348.

PHALEN, W. C., 1912, Description of the Kenova quadrangle Kentucky-West Virginia-Ohio: U.S. Geological Survey Geological Atlas, Folio 184.

SHAVER, R. H., and S. G. SMITH, 1974, Some Pennsylvanian Kirkbyacean ostracods of Indiana and Midcontinent Series terminology: Indiana Geological Survey Report of Studies 31, 59 p.

SMYTH, Pauline, 1957, Fusulinids from the Pennsylvanian rocks of Ohio: Ohio Journal of Science, v. 57, no. 5, p. 257-283.

SMYTH, Pauline, 1974, Fusulinids in the Appalachian Basin: Journal of Paleontology, v. 48, no. 4, p. 856-858.

STURGEON, M. T., and S. E. DELONG, 1964, Revision of some stratigraphic names between the lower and middle Kittanning coals of eastern Ohio: Ohio Journal of Science, v. 64, no. 1, p. 41-43.

THOMPSON, M. L., 1936, Pennsylvanian Fusulinids from Ohio: Journal of Paleontology, v. 10, no. 8, p. 673-683.

THOMPSON, M. L., 1942, Pennsylvanian System in New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 17, 92 p.

THOMPSON, M. L., 1948, Studies of American Fusulinids: University of Kansas Paleontological Contributions, Protozoa, Article 1, 184 p.

THOMPSON, M. L. and R. H. SHAVER, 1964, Early Pennsylvanian microfaunas of the Illinois Basin: Illinois State Academy of Science, Transactions, v. 57, no. 1, p. 3-23.

THOMPSON, M. L., R. H. SHAVER, and E. A. RIGGS, 1959, Early Pennsylvanian fusulinids and ostracods of the Illinois Basin: Journal of Paleontology, v. 33, no. 5, p. 770-792.

WANLESS, H. R., 1939, Pennsylvanian correlations in the eastern Interior and Appalachian coal fields: Geological Society of America, Special Paper 17, 130 p.

STRATIGRAPHY AND ENVIRONMENTS OF DEPOSITION

Depositional history of the Pennsylvanian System in the Illinois Basin–A summary of work by Dr. Harold R. Wanless and associates

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INTRODUCTION

From 1957 through 1968, the late Professor Harold R. Wanless of the University of Illinois directed a series of studies to determine the sequence of environments during different parts of the Pennsylvanian Period, as represented by Pennsylvanian rocks in the Illinois Basin, the Northern Appalachian Coal Basin, and the northern Midcontinent region. The purpose of these investigations was to determine the lateral extent of the variations within successive lithologic units, to examine the factors which determined the distribution pattern and caused variations in the units, and, finally, to draw conclusions about the environment in which the units were deposited.

The studies consisted largely of the preparation of a series of paleoenvironmental maps illustrating Middle Pennsylvanian beds in the Carbondale, Modesto, and Bond Formations in Illinois; the Carbondale and most of the Lisman Formations, western Kentucky; the Linton, Petersburg, Dugger, Shelburn, and Ditney Formations, Indiana; and equivalent units in the northern Midcontinent region. Those involved with Professor Wanless in the mapping of the Illinois Basin were A. Rocha-Campos; B. Dickson (M.S., 1965); J. C. Gamble (M.S., 1967); D. R. Gednetz; A. R. Glover (M.S., 1964); J. C. Horne (M.S., 1965, Ph.D., 1965); L. F. Kenny (M.S., 1968); C. Manos (Ph.D., 1963); D. E. Orlopp (M.S., 1962; Ph.D., 1964); R. Palomino-Cardenas (M.S., 1963); P. R. Trescott (M.S., 1964); J. B. Tubb, Jr. (M.S., 1961); J. L. Weiner (M.S., 1961); C. R. Wright (M.S., 1963; Ph.D., 1965); and R. S. Vail (B.S., 1965).

NATURE OF LITHOLOGIC UNITS UNDER STUDY

The Pennsylvanian sequence in the Illinois Basin is primarily composed of many very thin but laterally extensive units that are arranged in repetitive sequences. Figure 1 illustrates the full sequence of beds composing a typical or ideal cyclothem. The most commonly found units are the sandstone, underclay, coal, limestone (fig. 1, no. 9), and gray shale (fig. 1, no. 10), but regional variations exist. Sandstones, underclays, and coals are particularly well developed in the Illinois Basin.

PROCEDURE

The typical study interval consisted of the units of one cyclothem. Initially all stratigraphic sections for the region, both published and unpublished, that contained the cyclothem under consideration were assembled. The location of each section was plotted on a base map. Wherever possible, a control was established of one stratigraphic section per township. Sections were correlated by using the coal beds as datum planes; lithologic and paleontologic data were recorded for each unit on a preliminary map.

After the objective information on the preliminary maps had been examined and the distribution pattern of the rock types had been determined, the preliminary maps were interpreted in terms of the environment of deposition of each rock type. The final maps illustrate the geographical distribution of environments believed present during the time of accumulation of a particular stratum. It is assumed that the thin rock-stratigraphic units of the Pennsylvanian are equivalent to time-stratigraphic units.

The completed maps of the units in the cyclothem were examined in sequential order to interpret the depositional history of the cyclothem. Emphasis was given, not only to the data on individual maps, but also to the relationship between underlying and overlying maps.

STRUCTURAL SETTING

In Illinois, western Indiana, and western Kentucky, sediments were deposited in the shallow, subsiding Illinois Basin, bounded on the north by the Wisconsin Arch portion of the Canadian Shield, on the east by the Cincinnati Arch, on the southeast by the Nashville Dome, and on the southwest by the Ozark Dome. The Mississippi River Arch, located along the axis of the present-day Mississippi River, and the La Salle Anticline in northern Illinois sank more slowly than nearby basinal areas; rocks under study are relatively thin over these structures. (See page 106.)

PRINCIPAL DEPOSITIONAL ENVIRONMENTS

The principal environments in which the units under study in the Illinois Basin were deposited are briefly discussed below. A few examples of paleoenvironmental maps are given both to illustrate specific environments and to acquaint the reader with the general format of the maps.

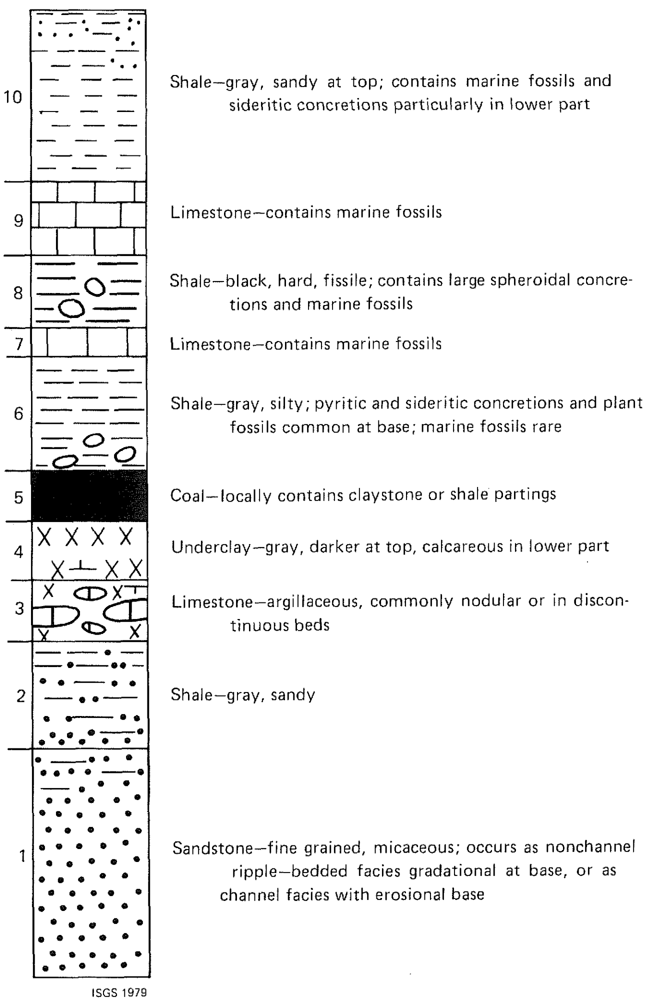

Figure 1. Lithologic units in a complete cyclothem. (After Willman, 1942, fig. 42, and Hopkins and Simon, 1975, fig. P-7).

Deltaic

Deposits in a typical delta complex. A large percentage of the total footage of mapped rocks originated in a deltaic environment (Wanless and others, 1970). Deltas formed consistently in the Illinois Basin, where sediments moved in from the east, southeast, and northeast.

The initial deposits in a developing delta were prodelta muds that were laid down in the early stages of deltaic sedimentation before distributary channels carrying coarser clastics had developed. The gray shale formed from these muds (fig. 1, no. 10) is generally 10 to 20 meters thick (up to 30 meters locally) and in many areas is the thickest member of the cyclic succession. In most places there is an abrupt and uneven erosional contact between the shale and overlying sandstone. In areas where the contact is gradational, the sandstone is fairly thin, generally less than 6 meters thick, and sheetlike in distribution; where the contact is erosional, the sandstone is coarse-grained, lenticular in cross section, generally more than 6 meters thick, and exhibits cut-and-fill structure. These two types of sandstone originated after distributaries had developed on the lengthening deltaic platform; the thicker lenticular sandstone originated in the distributaries themselves, and the finer sheet-sandstones in the interdistributary areas. Overlying the sandstone in many deltaic sequences is an underclay composed of silts and clays that were deposited in the final stages of deltaic sedimentation.

Studies of the areal extent, thickness, and sediment-sized distribution of the above sequence of shale, sandstone, and, in many cases, underclay, indicate that the rocks were originally a wedge of clastic sediments which thickened and became coarser in the direction of the source area.

Position of deltaic deposits in cyclic succession. Clastic wedges could develop at any stratigraphic position in the cyclic sequence, but the largest and most widespread wedges commonly formed at the base of a cyclothemic succession. The origin of clastic wedges found in this stratigraphic position is related to transgression-regression phenomena; they formed during a time of general regression. In many cyclothems, additional clastic wedges of deltaic sediments, whose origin is independent of the large-scale transgression-regression phenomenon, developed at other stratigraphic positions in the cyclic succession in response to minor tectonic activity in an adjacent source area.

Clastic wedges found at the base of a cyclothem are composed of the upper gray shale of the underlying cyclothem (fig. 1, no. 10) and the basal sandstone and underclay of the overlying cyclothem. Most of the widespread Pennsylvanian coals on the North American continent are found directly overlying the sequence of units described above. Clastic wedges composed of this sequence formed most of the platform on which developed the most widespread Pennsylvanian coal on the North American continent and possibly in the world (Wanless, 1975)—the Colchester (No. 2) of Illinois and equivalent coals (fig. 2). In the southeastern portion of the Illinois Basin, this coal is underlain by an extensive delta complex of shale, sandstone, and underclay derived from an eastern source area. (See Wright,

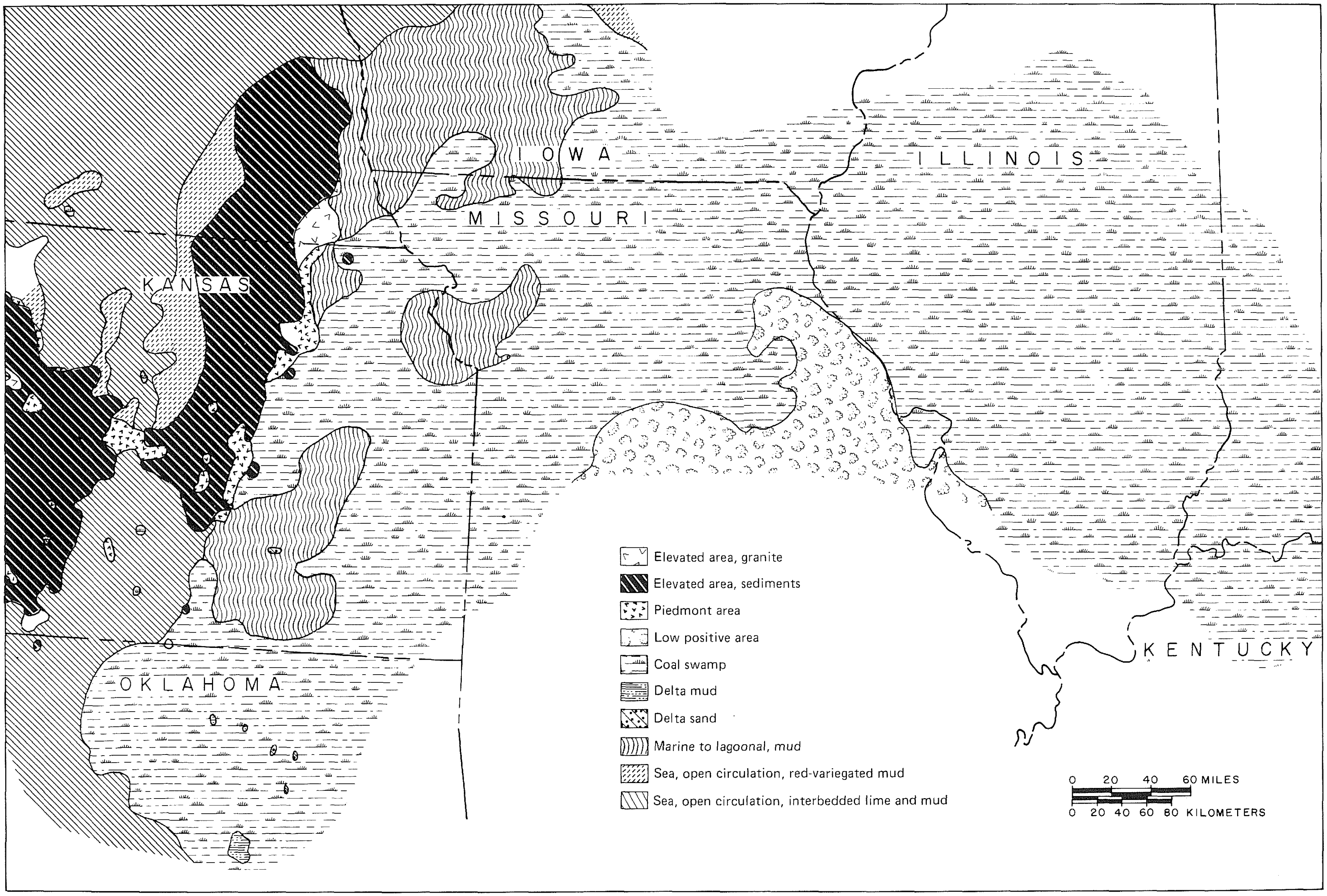

Figure 2. Environmental map of the Colchester (No. 2) Coal and equivalent coals (Wanless and Wright, in press).

1975, for a detailed description of the delta complex and the sequence of overlying units.)

An example of a clastic wedge of deltaic deposits that developed at a different stratigraphic position is the Francis Creek Shale (fig. 3) that overlies the Colchester (No. 2) Coal. It is a wedge-shaped deposit that thickens markedly to the east; in northeastern Illinois, up to 25 meters or more of Francis Creek Shale are found. The thickening of the wedge and the coarsening of sediments within it to the northeast indicate that the source area for the unit lay in that direction. The deposit is widespread over northern Illinois, but it is considerably thinner in northwestern Illinois. In eastern Missouri the deposit is represented by a thin gray shale bed, generally less than a half meter thick; it is probably the southernmost extension of the deltaic sediment deposited in the Illinois Basin. The Francis Creek wedge of clastics served as a barrier to encroaching marine waters from the west. The black shale (fig. 4) that overlies the coal in all other areas of the Illinois Basin is not found over the thickest portions of the Francis Creek Shale in northeastern Illinois.

Marine

The Ozark Dome served as a barrier to marine waters encroaching from the west and southwest, and the marine portion of a typical cyclothem in the Illinois Basin is consequently less well developed than the deltaic part. Many of the extensive, well-developed limestones that formed in the northern Midcontinent region are represented by thin, poorly developed Illinois Basin counterparts.

Black limes or muds accumulated locally in pockets on the sea floor where circulation was poor. Conditions of often-restricted circulation were not local, however, but widespread, and during these times black muds were deposited over most of the Illinois Basin and the northern Midcontinent region. In most cases, these black muds are now black fissile shales that are typically only ½ to 1 meter thick but are widespread and extend in many cases from northern Oklahoma to eastern Indiana and western Kentucky. One of the most widespread of these black shales is the Mecca Quarry Shale (fig. 4), which originated in the shallow marine transgressive waters that inundated the Colchester (No. 2) Coal swamp. It is found directly overlying the coal bed except where the Francis Creek Shale locally intervenes between the coal and black shale in northern and northeastern Illinois. Wanless (1975) suggested that the water in which the Mecca Quarry Shale was deposited may have been about 6 meters deep, because the black shale is not found in areas where the underlying Francis Creek Shale is more than 7 meters thick.

Fluvial

At times part or all of the Illinois Basin was emergent, and fluvial sediments were deposited. In some cyclothems the basal sandstone unit (fig. 1, no. 1) in the northern portion of the Illinois Basin accumulated in alluvial channels and on adjacent floodplain areas.

Lacustrine

Lakes developed at times on deltaic plains in the Illinois Basin. These lacustrine areas were generally the site of deposition of nodular freshwater limestones.

CONCLUSIONS

On the basis of an analysis of the paleoenvironmental maps prepared for the units under study, the following general conclusions were drawn. (For a detailed discussion of the conclusions, see Wanless and Wright, in press.)

1. Pennsylvanian rocks may be classified as thin, widespread units (underclays, coals, black shales, and limestones), and local, more variable clastic units composed of sandstone and shale.

2. The areal distribution of any given widespread unit is dependent upon one or more preceding pattern(s) of sediment distribution.

3. The sequences of thin, widespread units are interrupted by clastic wedges of sediment that thicken and become coarser toward source areas. Many clastic wedges are composed of the shale at the top of one cyclothem and the sandstone at the base of the overlying cyclothem. Such wedges originated during times of regression. Often additional clastic wedges developed at other positions within the cyclic succession. These clastic wedges developed in response to differential uplifts in highlands surrounding the depositional basins and are, therefore, excellent indicators of times of local tectonic activity.

4. The genesis of the principal rock types is as follows:

   Basal sandstone. The basal sandstone member of a cyclothem is deltaic, and its origin is related to that of the underlying gray shale in that they are both components of the same deltaic sequence.

   Underclay. Most underclays formed on deltaic platforms during the late stages of deltaic sedimentation, when the deposits were composed largely of clays. Some underclays were probably leached where they were deposited in alluvial valleys, on delta apexes, or where they were exposed following extensive marine regression. In most cases, however, the underclay was not sufficiently above ground level to favor any appreciable leaching.

   Coal. The geographical distribution of any given coal bed is dependent upon the immediately preceding patterns of sediment distribution. Coal beds were formed over extensive areas only where a suitable platform was present on which a coal swamp could develop. Most widespread coals accumulated on extensive platforms constructed by one or more deltas. If climatic conditions were favorable for the development of a coal swamp but a vast platform was not available, local coals formed where topographic and water-table conditions were appropriate—in estuaries, coastal lagoons, oxbow lakes, and in unfilled channels on either alluvial or deltaic plains. (For a detailed description of coals that formed in the above environments, see Wanless and others, 1969.)

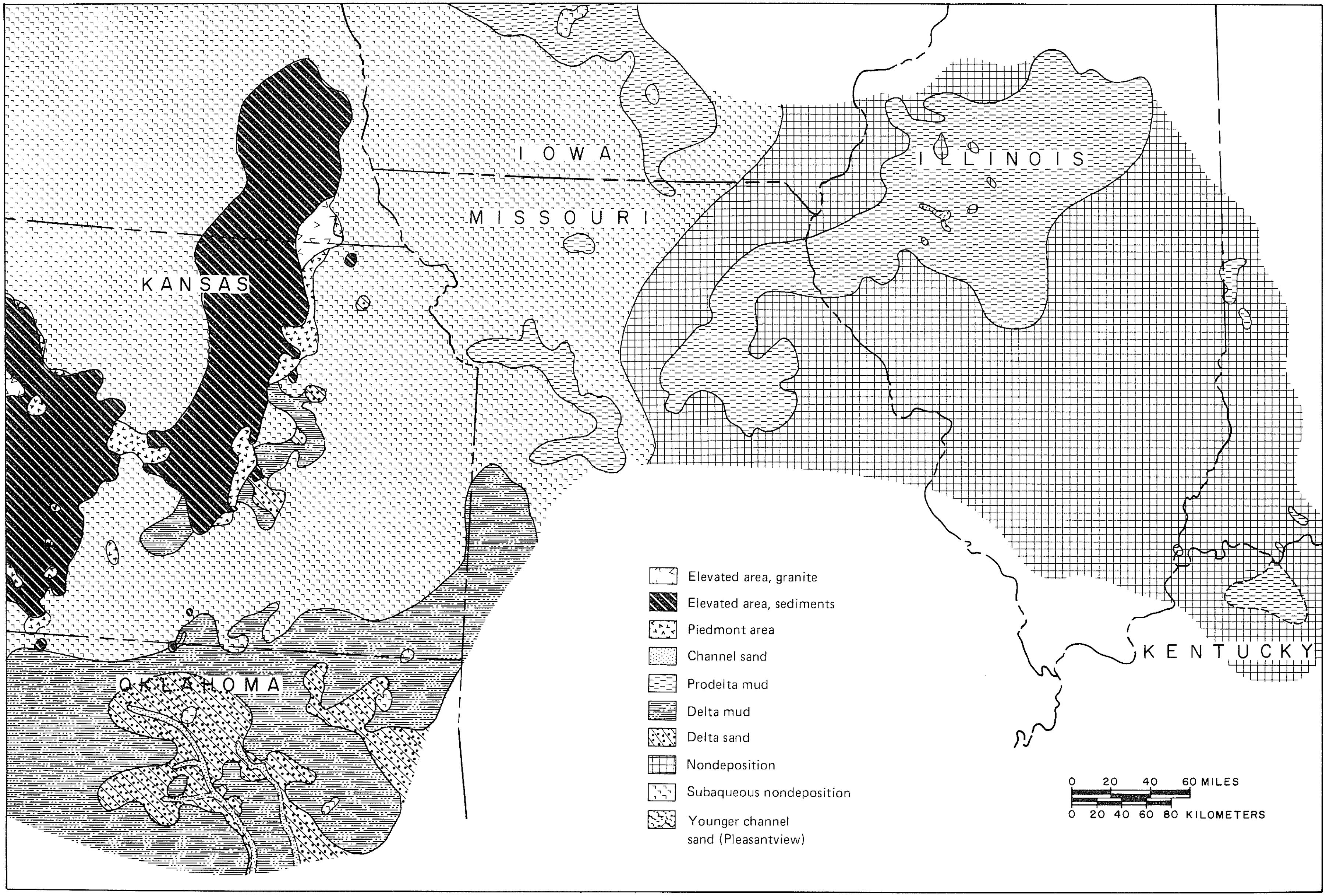

Figure 3. Environmental map of the Francis Creek Shale and equivalent strata (Wanless and Wright, in press).

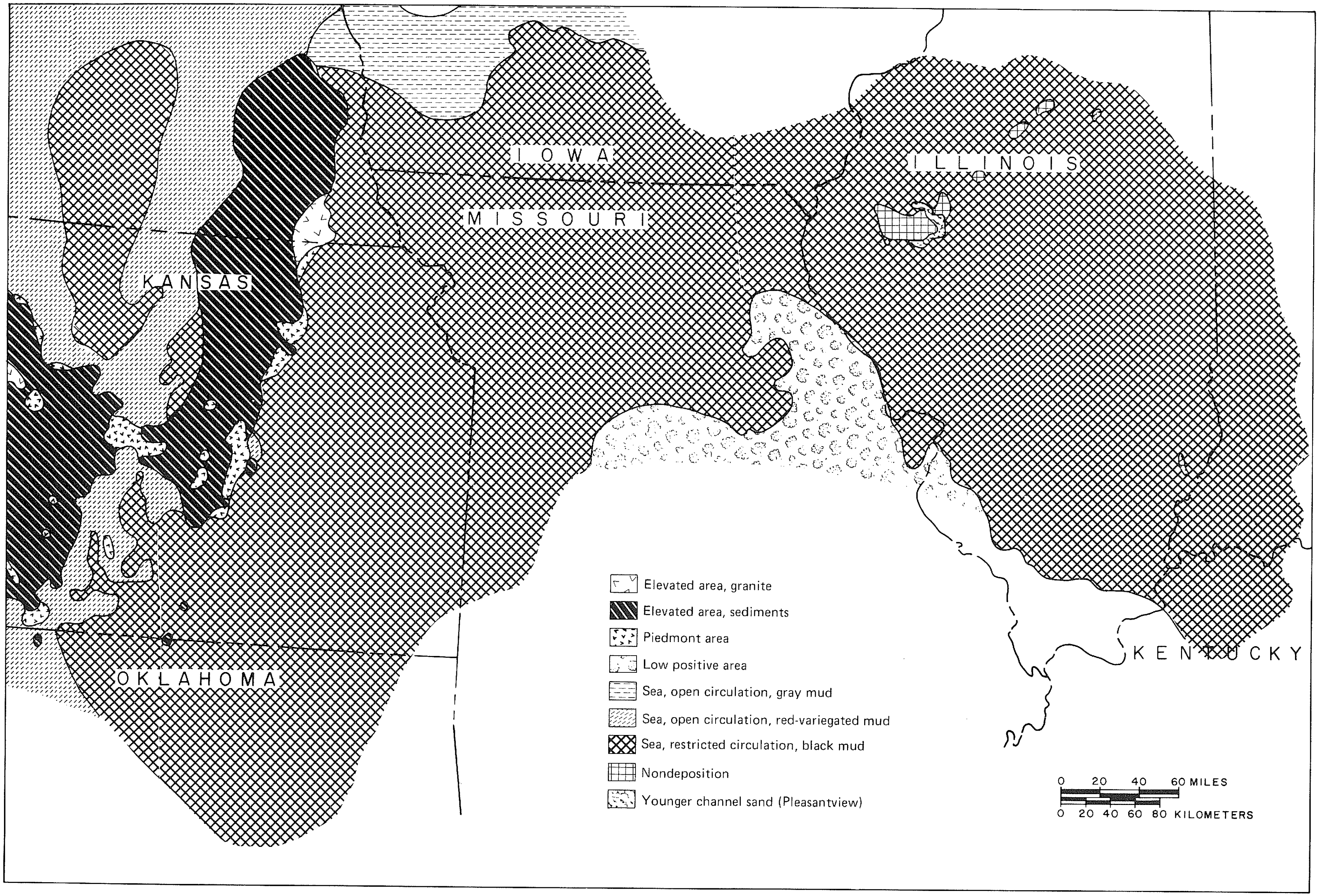

Figure 4. Environmental map of the Mecca Quarry Shale and equivalent shales (Wanless and Wright, in press).

Gray shale overlying coal. Several coals are overlain by a local wedge of gray shale that is deltaic in origin. These shale bodies are local or regional in distribution and formed in response to tectonic activity.

Black shale. Overlying the coal in many cyclothems is a black fissile shale. It is the initial unit deposited in transgressive marine waters that inundated the coal swamp. In most places this shale directly overlies the coal, but in some areas it overlies the wedge of gray shale described above that locally caps some coals. Generally in areas where the gray shale is unusually thick, the overlying black shale is not present; this suggests that the water in which the black shale was deposited was so shallow that it was able to encroach only part of the way up the delta front.

Marine limestone. Marine transgressions moved into the Illinois Basin from the west and southwest and are generally represented there by thin, argillaceous limestones that originated in shallower, less open waters than those of the northern Midcontinent region.

Upper gray shale. The lower portion of the gray shale that overlies the marine limestone in most cyclothems is marine and probably marks the end of the transgressive phase of the cyclothem. The upper portion is generally deltaic.

5. The numerous transgressions and regressions which took place during the time of deposition of the units under study seem to be the result of eustatic shifts in sea level that were perhaps caused by the alternate growth and wasting of continental glaciers in Gondwana areas (Wanless and Shepard, 1936). Superimposed on the general effect of eustatic sea level changes were local factors such as the rate of subsidence of a basin and the availability of sediments; these factors determined the quantity and type of deposit that accumulated during a particular transgressive-regressive interval.

REFERENCES

HOPKINS, M. E., and J. A. SIMON, 1975, Pennsylvanian System, *in* H. B. Willman et al., Handbook of Illinois stratigraphy: Illinois State Geological Survey Bulletin 95, p. 163-201.

WANLESS, H. R., 1975, Distribution of Pennsylvanian coal in the United States, *in* E. D. McKee et al., Paleotectonic investigations of the Pennsylvanian System in the United States, Pt. II, Interpretive summary and special features of the Pennsylvanian System: U.S. Geological Survey Professional Paper 853, p. 33-47.

WANLESS, H. R., J. R. BAROFFIO, and P. C. TRESCOTT, 1969, Conditions of deposition of Pennsylvanian coal beds, *in* E. C. Dapples and M. E. Hopkins [eds.], Environments of coal deposition: Geological Society of America Special Paper 114, p. 105-142.

WANLESS, H. R., J. R. BAROFFIO, A. ROCHA-CAMPOS, J. C. HORNE, D. E. ORLOPP, P. R. TRESCOTT, R. S. VAIL, and C. R. WRIGHT, 1970, Late Paleozoic deltas in the central and eastern United States, *in* J. P. Morgan [ed.], Deltaic sedimentation, modern and ancient: Society of Economic Paleontologists and Mineralogists Special Publication 15, p. 215-245.

WANLESS, H. R., and F. P. SHEPARD, 1936, Sea level and climatic changes related to late Paleozoic cycles: Geological Society of America Bulletin, v. 47, no. 8, p. 1177-1206.

WANLESS, H. R., and C. R. WRIGHT, in press, Maps of Pennsylvanian rocks, Illinois Basin and northern Midcontinent region: Geological Society of America Map and Chart Series.

WILLMAN, H. B., 1942, Stratigraphy of exposed formations, *in* H. B. Willman and J. N. Payne, Geology and mineral resources of the Marseilles, Ottawa, and Streator quadrangles: Illinois State Geological Survey Bulletin 66, p. 84-141.

WRIGHT, C. R., 1975, Environments within a typical Pennsylvanian cyclothem, *in* E. D. McKee, E. J. Crosby et al., Paleotectonic investigations of the Pennsylvanian System in the United States, pt. II, Interpretive summary and special features of the Pennsylvanian System: U.S. Geological Survey Professional Paper 853, p. 73-84.

Terrigenous sedimentation above unconformities

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INTRODUCTION

Terrigenous sedimentation above unconformities depends chiefly on the paleogeomorphology of the buried erosion surface, sediment supply, depositional environment, tectonic setting, and, to some degree, on paleoclimate. Not all of these factors are independent of one another (fig. 1). Tectonic setting is the most fundamental factor, because it directly determines whether the unconformity will be widespread or locally restricted to tectonically active highs. It also determines, to a very large degree, sediment supply—the volume and composition of the overlying detritus. Second in importance is the paleogeomorphology of the buried landscape itself—the drainage pattern and the relief of the buried landscape affect the overlying sedimentation. In some measure, the types of paleodrainage and relief depend upon the paleoclimate that prevailed during the development of the unconformity—for example, the development of karst topography or of a glacial landscape. Nor should sediment supply and the depositional environment be overlooked. Given the same buried landscape, overlying marine sandbodies will respond differently to it and thus will have a different spatial distribution than will fluvial-deltaic sandbodies.

This paper explores some of the above factors and their interrelationships, especially drainage pattern and density, relief, and paleoclimate, to provide a better understanding of the terrigenous sedimentation above the Mississippian-Pennsylvanian unconformity of the Illinois Basin. In addition, the characteristics of unconformities and their overlying sedimentation are briefly explored in three different tectonic settings.

A pioneer in the study of paleogeomorphology is Rudolph Martin, whose experience in the Alberta basin of western Canada provided the basis for the first statement of the principles of paleogeomorphology (1961 and 1966). The best paper to read is one written by Martin (1966). Another good discussion is given by Garner (1974, p. 640-666).

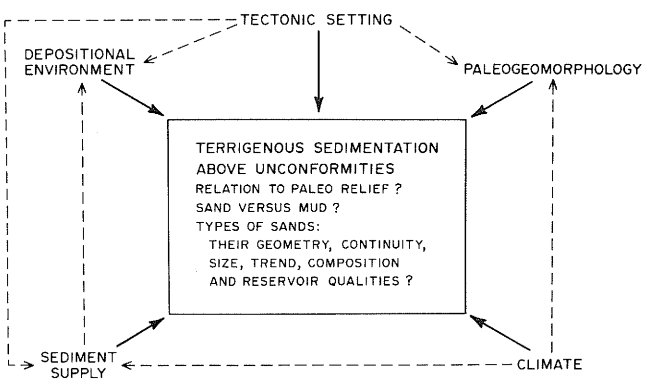


Figure 1. Interrelationships between the chief factors affecting terrigenous sedimentation above unconformities.

With few exceptions, buried landscapes are best studied and mapped in the subsurface. Outcrops are always helpful for supplemental control and usually are essential for observing details and relations that escape even close subsurface control. Exceptions to this generalization occur in high-relief plateau country, such as along some trailing-edge continental margins or in recently uplifted plateaus dissected by a major through-flowing stream (for example, the Grand Canyon of the Colorado Plateau). Data from well drillings are usually required, although seismic sections are being used more and more (Payton, 1977). Andresen (1962) has provided a short methodology paper presenting the main methods of mapping buried landscapes (table 1). A paleogeologic map in combination with an overlying isopach map provides a cast of the buried relief over which a map depicting the overlying sedimentation must be superimposed. The last map may be a sand-shale ratio map or, perhaps equally effective, a map made simply by shading the areas where sandstone is thicker than 20 meters, for example.

Several general references to unconformities explain how to recognize them and provide good background on their characteristics and significance. The classic paper by Krumbein (1942) on the subsurface recognition of unconformities is very worthy of reading. Weller (1960, ch. 11) presents a good general overview. An interesting discussion of unconformities is that by Levorsen (1954, p. 618-624). Chenoweth (1967) explains, in a comprehensive paper with many examples from North America, how offlap, overlap,

TABLE 1. Methods of mapping unconformities depicting their overlying sedimentation
(Modified from Andresen, 1962, table 1.)

Overlying isopach

Thickness of fill from an overlying datum to unconformity outlines paleorelief. Shows paleorelief independent of later structural warping and is especially useful when drilling stops at the unconformity or the unconformity is cut on massive basalts, granites, or thick diamictites. Use in combination with a paleogeologic map. When combined with a sand-shale map or shading, also shows the kind as well as the thickness of the overlying fill.

Cross sections

Successive cross sections at right angles to drainage are essential, especially to see relation of types of fill to paleorelief. Use either a level line above or below unconformity or make a structural section. Seismic cross sections are a new and most promising development.

Paleogeologic map

Most useful where paleorelief is developed in sediments with well-defined, thin, distinctive, and mappable stratigraphic units. Oldest unit is axis of paleovalley.

Underlying datum plane-valley floor isopach

Shows thickness of beds from an underlying datum to unconformity surface. Requires a sedimentary section with much control to a horizon below the unconformity. Shows paleorelief independent of later structural warping.

Seismic stratigraphy

Seismic cross sections readily identify sedimentary sequences and their discordant or concordant nature and to some degree the facies above discordances. A new type of cross section that gives a *continuous record,* one that works best on continental margins. One of the most exciting and promising developments in sedimentology in recent years.

Unconformity contour

Structure contour map of unconformity surface. Paleoriver followed low points. Rapid, and should always be done, but postunconformity deformation always complicates interpretation.

tilting, and truncation may be interpreted from unconformities.

The most modern ideas about unconformities concern their worldwide occurrence and synchroneity. Building on the initial ideas of Sloss (1963 and 1972), a good short summary is given by Gussow (1976). Payton (1977, pt. 1 to 11) gives details and documentation and much general methodology, mostly concerned with the interpretation of seismic sections.

PALEOGEOMORPHOLOGY

Drainage pattern and density

Nine basic types of drainage pattern (fig. 2), affect terrigenous sedimentation above unconformities. Early identification and definition of the type of paleodrainage and its density is essential. For example, sedimentation immediately overlying a Precambrian basement of complexly folded metamorphics implies a contorted drainage pattern, which is difficult to contour accurately if few data are available. If flat-lying sediments underlie the buried erosion surface, dendritic or parallel drainage is probable; such a pattern is rather easy to contour, even with limited control, once its origin and drainage density can be surmised. Drainage density is largely a function of the permeability of the rocks veneering the surface; for example, a shaly, flat-lying formation has a closely spaced network of streams, whereas drainage density would be much less for an unconsolidated sand or for karst topography. Commonly, the drainage density of a buried landscape can be correctly assessed only after mapping by using closely spaced subsurface control or after considerable experience with more open control.

Orientation of a drainage pattern can funnel and locally divert sediment transport of overlying clastics. The pattern commonly indicates the paleoslope of the overlying

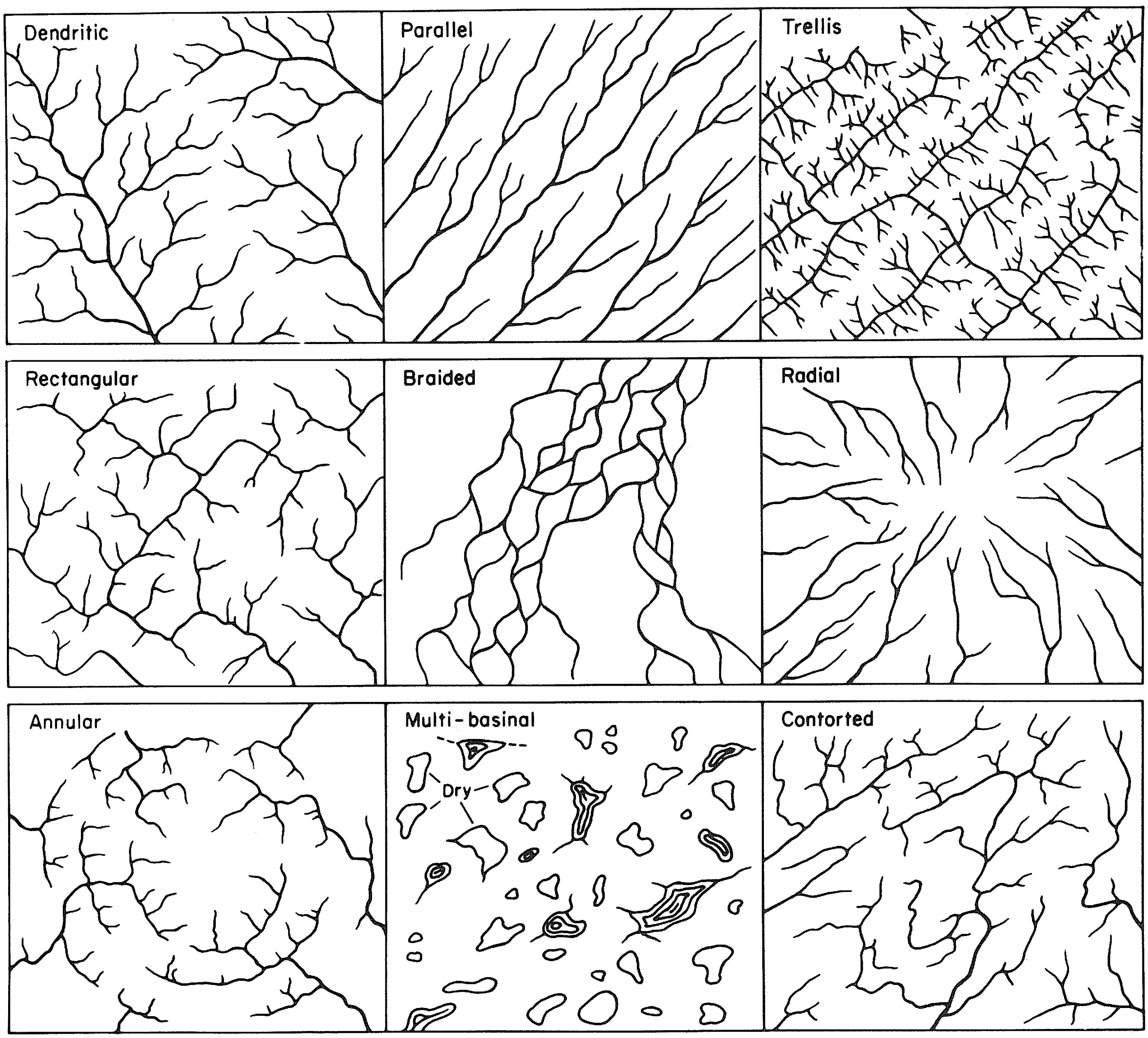


Figure 2. Nine basic types of drainage patterns. (Modified from Howard, 1967, fig. 3.)

sedimentation, especially for dendritic and parallel patterns and to a lesser degree for trellis and rectangular patterns. Moreover, the drainage pattern itself may locally determine where sand and mud will be deposited and the geometry of the deposited beds. For example, Martin (1966, fig. 24) shows an oil field where the trap is a clay-filled abandoned stream channel that occurs in a paleovalley about 5 miles (8 km) wide. A map of a paleodrainage pattern must take into account the possibility that it is partly localized by faulting or that it follows broad regional lows—river systems are very sensitive to penecontemporaneous subsidence or uplift (Potter, 1978).

The conditions under which different drainage patterns develop have been summarized by Howard (1967), who emphasized modern patterns. His ideas are adapted to paleodrainage patterns in table 2. Another excellent, more extended account of the control of rock type on drainage density and pattern is *Terrain Analysis* by Way (1973)—essential reading for one who maps buried land surfaces. Additional sources of information in the study of paleodrainage patterns, a field that is rapidly growing, are studies of drowned paleodrainage systems of continental shelves, systems that extended to the edge of the continental shelves before the most recent rise of sea level.

Dendritic and trellis drainage patterns. Of the nine basic types, the dendritic is the most common, followed by the trellis. Dendritic paleodrainage patterns prevail on flat-lying sedimentary rocks, and trellis patterns develop where broad buried cuestas crop out below the unconformity. Examples of dendritic patterns include much of the buried preglacial drainage that has been mapped in North America, the paleovalleys that have been mapped on many modern marine shelves (please see the excellent summary by Vanney, 1977, figs. 41, 81, and 87), and part of the pre-Pennsylvanian paleodrainage of the Illinois Basin (Bristol and Howard, 1971, pl. 1). Buried trellis patterns have been mapped in detail by DeGraw (1975, fig. 8) at the base of the Cretaceous Pierre Shale in Nebraska, locally recognized by McCubbin (1969) in northwest New Mexico, and widely recognized at the base of the Cretaceous in Alberta (Martin, 1966, fig. 15). Straight, long, apparently isolated paleovalleys have also been recognized on modern marine shelves (Vanney, 1977, figs. 71, 73, 75, and 78), and an unusual ancient example occurs in the Illinois Basin—the Bethel Sandstone of Mississippian age in western Kentucky and southern Indiana (Sedimentation Seminar, 1969).

Braided drainage patterns. Braided patterns have rarely been recognized on ancient landscapes, but may be more common than have been thought. They may largely be the product of catastrophic events—possibly when the Atlantic Ocean cascaded through the Strait of Gibraltar (Hsu, 1972), and certainly when the glacial dam broke in the eastern part

TABLE 2. Occurrence and origin of possible paleodrainage patterns
(Modified from Howard, 1967, table 1.)

Dendritic

Perhaps the most common pattern; very characteristic of cratons with their veneer of flat-lying sediments; also found on flood basalts and uniformly resistant crystalline rocks. Develop on gentle regional slopes with minor structural control and on fine-textured, easily erodable materials.

Braided

Not widely recognized in the subsurface, but may be much more common than is presently mapped. Most likely to develop from rapid (catastrophic?) changes in discharge associated with glaciation or rapid river diversion in mobile belts.

Multibasinal

To be expected with underlying carbonates (karst), especially where paleoclimate was humid to tropical. Also characteristic of youthful glacial topography resulting from differential scour and deposition, from deflation, and, possibly, from volcanism.

Parallel

Typical on moderate to steep slopes, but also produced by parallel landforms. A variety of dendritic drainage that appears to be especially common on continental shelves and slopes, on some ancient marine shelves, and possibly on some ancient coastal plains.

Trellis and rectangular

Develops in folded and gently dipping rocks that form buried cuestas, the latter being more prevalent below unconformities than below buried fold systems. Other causes include areas of parallel fractures, branching parallel and subparallel faults, and in beach ridge systems.

Radial and annular

Can occur over long-lived, buried highs and domes that have had one or more periods of emergence; also associated with volcanoes and erosional residuals.

Contorted

Contorted, coarsely layered metamorphics with dikes, veins, and migmatized bands, serving as resistant masses. Less regional orderliness than most other patterns and greater discontinuity of ridges and valleys.

of the state of Washington and the gigantic Missoula flood created a vast braided channel system (Bretz, 1969; Baker and Nummedal, 1978). Braided systems also have been suggested to have a noncatastrophic origin (Garner, 1968, fig. 15; and 1974, p. 656-659).

Relief

The local relief of unconformities varies from a few meters to hundreds of meters, depending upon the rock type, regional setting, and the geomorphic history of the buried landscape. Unconformities cut on coastal plains and cratons near sea level may have a local relief of only a few tens of meters. Mature pediplains developed in arid landscapes also can be virtually featureless except for a few residual monadnocks, which can be several hundred meters high. If a craton lacks a sedimentary cover, local relief can be much greater, reaching several hundred meters, especially if the area is far inland and pedimentation was not a major process or was not far advanced. An essay by Ambrose (1964) provides an insight into the preglacial relief of the Canadian Shield, which was locally appreciable. Beuf *et al.* (1971, p. 26-49) described the buried Precambrian landscape of southern Algeria, a pediplain that is notable for its flatness and low relief. Still another variation is a fault scarp of appreciable relief along an Atlantic type of continental margin. In southwestern Africa youthful paleovalleys—now filled with Cretaceous lava—have been found to have relief of over 1000 meters (Martin, 1975). Youthful submarine channels and canyons along continental shelves, ancient or modern, also provide examples of relief measured in hundreds of meters. Still another example is the alluvial or lava fill of a rift-controlled valley that was formerly occupied by a through-going stream that possibly connected a series of lakes.

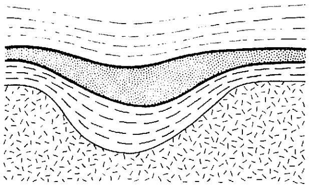
The elements of topographic relief on buried landscapes are universal—channels or valleys, upland or lowland flats, hills and ridges, sinkholes, and sharply defined glacial depressions. How they affect the overlying sedimentation depends upon the type of sedimentation that followed (table 3). For example, when mud is deposited above an unconformity, its behavior depends on its rate of deposition. If the rate of deposition is rapid, water expulsion is incomplete and the substrate is more susceptible to differential compaction than when sedimentation is slow and there is ample time for expulsion of water (fig. 3). Interbedded mud and sand deposition, especially in alluvial and deltaic deposits, is very sensitive to paleorelief because of the differential compaction of mud, which is estimated to be 50 percent greater than that of sand (Brown, 1975, p. 274). Glacial till is little affected by paleorelief—it is relatively homogeneous and seldom subject to later compaction; it is usually deposited under a heavy mass of ice, and interbedded, highly porous muds are not common as in alluvial and marine environments. Inundation by lava also would seem to be virtually unaffected by paleorelief except to channel its flow downdip.

Another aspect of paleorelief is neither erosional nor solutional, but *depositional.* Depositional relief is relief acquired during deposition and followed by a weak emergence so that it is but little modified by erosion. Good examples of this commonly are provided by glacial topography of constructional origin and by carbonate landscapes such as a barrier-lagoonal system, where the barrier defines the topographic highs and the lagoon defines the lows. Brown (1975, p. 278) cites such depositional carbonate relief as the principal factor determining the location of small, overlying deltas that prograded seaward over a carbonate shelf in the Pennsylvanian of northern Texas.

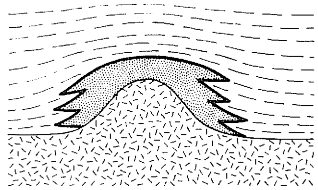
Two unresolved but important questions are, How far

TABLE 3. Effect on overlying sedimentation of different kinds of buried topography.

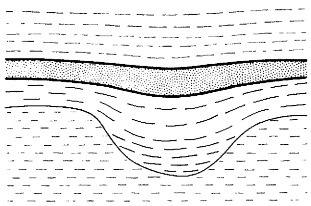
Topographic element	Effect on sedimentation
Channel or valley	*Collects and carries debris down paleoslope; if mostly filled with mud may have "compactional" syncline structure within it as well as "compactional" highs from isolated sandstone bodies. Also an overlying proximal sheet of sandstone may drape into the channel. Fill may be deep marine clays and sands, marine shelf clays and sand, fluvial sands and muds, and even glacial till and lava. Everywhere recognized by cutout beds that can be so abrupt as to suggest normal faulting, which in some tectonically active areas channels may indeed follow. Slump blocks may occur, especially when the channel was cut in a sandstone-shale or sand-mud sequence.*
Upland or lowland flat	Negligible effect, especially where underlying sediments are clastics. Discordance is difficult to recognize when there is a sandstone-sandstone or shale-shale contact free of paleosoil or enhancement by secondary porosity. May be seen on wire line logs and seismic sections by resistivity or density contrasts. Paleocurrents little affected.
Hill (unreduced erosional residual)	In marine or littoral environments will commonly be fringed by terrigenous or carbonate sands that may persist even after complete marine transgression because of differential compaction on flanks. When buried by fluvial sands or glacial tills, buried hills will not affect sedimentation.
Ridge	As above except associated facies changes and structures, if any, will be linear or gently curved in map pattern. When ridge is at right angles to paleoslope, there is major deflection and dispersion of paleocurrents.
Sinkholes and sharply defined glacial depressions	Depending on size, introduces complicated paleocurrent sedimentation patterns of sand and mud. Sinkholes can localize peats and, through groundwater level, affect type of cementation in sands. If sinkholes are suspected, try to estimate their size and relief. Basal sandstone bodies may drape over margins.



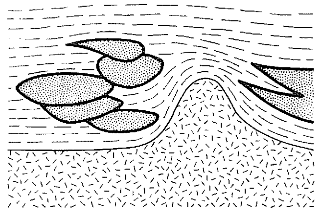
1. Sheet sandstone sags and thickens into poorly consolidated mud-filled channel or into sinkhole in consolidated bedrock.



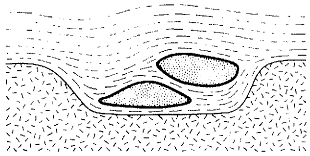
2. As in (1) but underlying mud was consolidated so that sag and differential thickness of sandstone are much less.



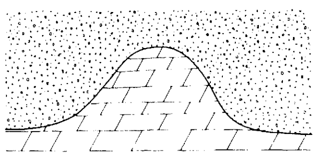
3. Differential compaction of mud around sandstone bodies in channel cut into consolidated bedrock.



4. Littoral sand fringe over hill develops during slow marine transgression.



5. Successive paleoalluvial channels avoid compactional bump over isolated hill (also rising diapirs).



6. Glacial till, sand deposited by braided river and lava or ignimbrites, but little influenced by isolated hill.

Figure 3. Six possible interactions between paleorelief and overlying sedimentation.

above an unconformity can the influence of its paleorelief extend, and what determines this distance? Penecontemporaneous tectonism can complicate both questions (Brown, 1975, p. 278-288).

PALEOCLIMATE

The paleoclimate during the formation of a buried landscape could have determined some aspects of its paleorelief and thus how it and the overlying sedimentation should be mapped. The limestones are important determinants of paleoclimate—Do they form resistant ridges and cuestas as in arid climates or do they form solutional sinkhole plains as in humid climates? Only careful mapping can reveal this, and hence special effort should be made to analyze the behavior of the limestones of a buried landscape. Judging from the literature, this is harder to do than might be expected.

Whether a well-defined, low-relief erosional surface is the result of peneplanation or pediplanation (the result of erosion in a wet versus dry climate) is essentially immaterial to the overlying sedimentation with one possible exception, the mineralogical composition of overlying sandstones. Locally derived sands from a low-relief erosion surface that was developed under tropical weathering will consist mostly of quartz arenites, whereas those from an arid climate can be expected to have a more variable composition, depending upon the local bedrock, and be lithic or even feldspathic arenites. It is unlikely that the composition of distally derived sand, however, will have little or any relation to the landscape buried beneath it.

What of buried soils of ancient landscapes? Normally these are very rare and play but a minor role in the overlying sedimentation. They should always be looked for, however, and one should always be alert to the difficulties of distinguishing between colluvium or "granite wash" above an unconformity developed on acid plutonic rocks and more far-traveled basal arkosic sandstones. Yaalon (1962) has recognized four stages of soil formation in earth history—protosoil in the early Precambrian, primitive soil during the late Precambrian and early Paleozoic, rudimentary soils (Devonian into Mesozoic), and fully developed soils (Cretaceous to present). If true, this evaluation may in part explain why the equivalents of modern soils have not been widely found at old buried landscapes.

UNCONFORMITIES AND OVERLYING SEDIMENTATION IN THREE TECTONIC SETTINGS

Cratons, synorogenic basins in fold and thrust belts, and tensional basins are the three major tectonic elements of the continents (fig. 4). Insofar as it is possible, table 4 provides a summary of unconformities in these three different tectonic settings and the terrigenous sedimentation that occurs above them. Much is known about cratons—from their many outcrops, from massive drilling projects, and from the abundance of thin, widespread, mappable units. On the other hand, Riba (1976) is one of the few who have published on unconformities in the synorogenic basins of fold and thrust belts, and little information has been marshaled for unconformities in tensional basins.

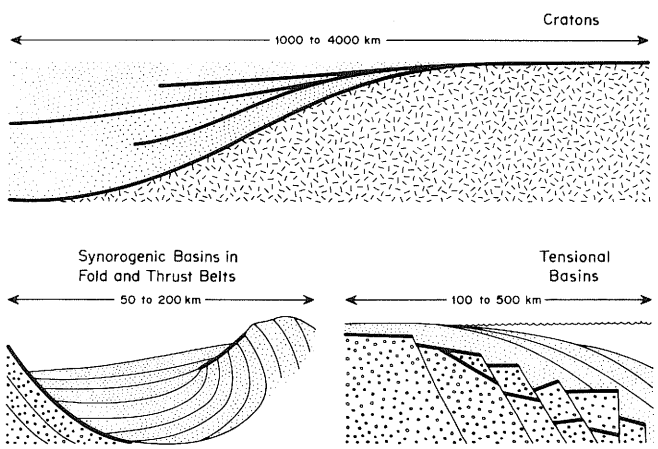


Figure 4. Diagrammatic cross sections of unconformities on cratons and in synorogenic and compressional tensional basins.

TABLE 4. Unconformities and overlying sedimentation in three tectonic settings

CRATONS

Morphology. Exceptionally widespread, ranging from thousands of square kilometers to virtually entire continents. Truncation of broad regional arches is typical, as is development of composite unconformities proximal to oldest cratonic cores. Local relief from a few meters (sinkholes and unreduced hills) to a few hundreds of meters in Precambrian massifs far from base level. Best studied in subsurface or possibly modern, drowned continental shelves.

Sedimentation. Depending upon terrigenous sediment supply, overlying sediment may be either terrigenous or chemical and can range from rare, scattered, isolated, small, supermature sandstone bodies (marine or eolian) on a low-relief carbonate terrain to fluvial and deltaic sands (quartz and lithic arenites) and muds derived from afar. Sediment supply depends on uplift and possibly climate as far as 1000 to 2000 kilometers away. Continental glacial deposits are still another possibility. Normally there will be a close relationship between paleoslope, inferred from paleochannel systems and paleogeologic maps, and paleocurrents, measured in overlying and underlying sediments.

SYNOROGENIC BASINS IN FOLD AND THRUST BELTS

Morphology. Local and commonly limited to basin margins with angular unconformities most common; typically associated with rising folds and fault blocks, and penecontemporaneous, active highs. Depth of erosion may be hundreds of meters. Commonly difficult to correlate between intermontane basins; usually best studied in outcrop.

Sedimentation. Overlying sediment is almost always clastic and dominated by fanglomerates and coarse, immature lithic sandstones (fluvial as well as turbidite) with rare shales and less commonly arkosic sandstones, where uplifted granites locally prevail. The overlying clastics, unlike on cratons, may be very thick and the relation between paleoslope inferred from a paleogeologic map and overlying paleocurrents may vary greatly.

TENSIONAL BASINS

Morphology. Not well known, but probably local basin-margin unconformities having rectangular map patterns proximal to bounding faults, especially in rift systems and aulacogens, where correlation of unconformities between individual basins within the rift system is difficult. In the rifted basins of passive Atlantic continental margins, however, unconformities should be much more widespread and easier to correlate.

Sedimentation. Variable, depending upon type of tensional basin. Immature, thick fanglomerates, coarse lithic arenites and wackes, and even lavas in interior rift systems. Quartz and sublithic and subfeldspathic arenites are found on trailing continental margins, where commonly thin and widespread units predominate and tend to be closely associated with platform carbonates and shales.

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REFERENCES

AMBROSE, J. W., 1964, Exhumed paleoplains of the Precambrian shield of North America: American Journal of Science, v. 262, p. 817-857.

ANDRESEN, Marvin J., 1962, Paleodrainage patterns: Their mapping from subsurface data, and their paleogeographic value: American Association of Petroleum Geologists Bulletin, v. 46, p. 398-405.

BAKER, V. R., and Dag NUMMEDAL, eds., 1978, The Channeled Scabland: Washington, D.C., National Aeronautics and Space Administration, Planetary Geology Program, 186 p.

BEUF, Serge, Bernard BIJU-DUVAL, Oliver de CHARPAL, P. RAGNON, O. GARREL, and A. BENNAUF, 1971, Les grés du Paleozoique inférieur au Sahara: Paris, Editions Technip, 464 p.

BRETZ, J H., 1969, The Lake Missoula floods and the Channeled Scabland: Journal of Geology, v. 77, p. 505-543. (See also his papers extending back to 1923.)

BRISTOL, H. M., and R. H. HOWARD, 1971, Paleogeologic map of the sub-Pennsylvanian Chesterian (Upper Mississippian) surface in the Illinois Basin: Illinois State Geological Survey Circular 458, 14 p.

BROWN, L. F., Jr., 1975, Role of sediment compaction in determining geometry and distribution of fluvial and eolian sandstone, *in* G. V. Chilingorian and K. H. Wolf [eds.], Compaction of coarse-grained sediments I: New York, Elsevier Scientific Publishing Company, p. 247-292.

CHENOWETH, Philip A., 1967, Unconformity analysis: American Association of Petroleum Geologists Bulletin, v. 51, p. 4-27.

DeGRAW, H. M., 1975, The Pierre-Niobrara unconformity in western Nebraska, *in* W.G.E. Caldwell [ed.], The Cretaceous System in the Western Interior of North America: Geological Association of Canada Special Paper 13, p. 589-606.

GARNER, H. F., 1974, The origin of landscapes: New York, Oxford University Press, 734 p.

GARNER, H. F., 1968, Tropical weathering and relief, *in* R. W. Fairbridge [ed.], Encyclopedia of Geomorphology: New York, Reinhold Book Corp., p. 1161-1172.

GUSSOW, W. C., 1976, Sequence concepts in petroleum engineering: Geotimes, v. 21, p. 16-17.

HOWARD, Arthur D., 1967, Drainage analysis in geologic interpretation: A summation: American Association of Petroleum Geologists Bulletin, v. 51, p. 2246-2259.

HSU, K. J., 1972, When the Mediterranean dried up: Scientific American, v. 227, p. 27-36.

KRUMBEIN, W. C., 1942, Criteria for subsurface recognition of unconformities: American Association of Petroleum Geologists Bulletin, v. 26, p. 36-62.

LEVORSEN, A. I., 1954, Geology of petroleum: San Francisco, W. H. Freeman and Co., 703 p.

McCUBBIN, D. C., 1969, Cretaceous strike-valley sandstone reservoirs, northwest New Mexico: American Association of Petroleum Geologists Bulletin, v. 52, p. 2114-2140.

MARTIN, Henno, 1975, Structural and paleogeographical evidence for an Upper Paleozoic sea between southern Africa and South America, *in* K.S.W. Campbell [ed.], Gondwana Geology: Canberra, Australian National University Press, p. 37-59.

MARTIN, Rudolph, 1961, Principles of paleogeomorphology: Canadian Oil and Gas, October, p. 3-15.

MARTIN, Rudolph, 1966, Paleogeomorphology and its application to exploration for oil and gas (with examples from western Canada): American Association of Petroleum Geologists Bulletin, v. 50, p. 2277-2311.

MITCHUM, R. M., Jr., P. R. Vail, and J. B. Sangree, 1977, Seismic stratigraphy and global changes of sea level, part 6: Stratigraphic interpretation of seismic reflection patterns in depositional sequences *in* Charles E. Payton [ed.], Seismic stratigraphy—applications to hydrocarbon exploration: American Association of Petroleum Geologists Memoir 26, p. 117-133.

PAYTON, C. E., 1977, Seismic stratigraphy—applications to hydrocarbon exploration: American Association of Petroleum Geologists Bulletin, Memoir 26, 516 p.

POTTER, Paul Edwin, 1978, Significance and origin of big rivers: Journal of Geology, v. 86, p. 13-33.

RIBA, O., 1976, Tectogenese et sédimentation: deux modèles de discordances syntectoniques pyréneenes: Bulletin du Bureau de Recherches Geologiques et Minieres (France), ser. 2, sec. 1, v. 4, p. 383-401.

SEDIMENTATION SEMINAR, 1969, Bethel Sandstone (Mississippian) of western Kentucky and south-central Indiana, a submarine-channel fill: Kentucky Geological Survey, ser. X, Report of Investigations 11, 24 p.

SLOSS, L. L., 1963, Sequences in the cratonic interior of North America: Geological Society of America Bulletin, v. 74, p. 93-113.

SLOSS, L. L., 1972, Synchrony of Phanerozoic sedimentary-tectonic events of the North American craton and Russian platform: International Geological Congress, 24th session, sec. 6, p. 24-32.

VANNEY, Jean-René, 1977, Géomorphologie des plates-formes continentales: Paris, Doin Editeurs, 300 p.

WAY, D. S., 1973, Terrain analysis: Stroudsburg, Pa., Dowden, Hutchinson and Ross, 392 p.

WELLER, J. Marvin, 1960, Stratigraphic principles and practice: New York, Harper and Row, 725 p.

YAALON, D. H., 1962, Weathering and soil development during geologic time: Bulletin of the Research Council of Israel, sec. G, v. 116, p. 149-150.

The Mississippian-Pennsylvanian unconformity in the Illinois Basin–Old and new thinking

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INTRODUCTION

The unconformity between Pennsylvanian and older strata in the Illinois Basin has long been recognized. Tectonic development of the basin (that is, central downwarping and marginal uplift) has caused there to be a range in age of sub-Pennsylvanian strata (fig. 1) from Champlainian (middle Ordovician) St. Peter Sandstone along the northern rim of the basin to Grove Church Formation (uppermost Chesterian) in southern Illinois. Although the erosional contact at the base of the Pennsylvanian was evident to the early field geologist, the discovery in the late 1930s of prolific petroleum reservoirs within Mississippian strata in the deeper portions of the basin has permitted detailed regional examination of the unconformity. Exploratory drilling has provided a wealth of subsurface geologic data that includes many thousands of geophysical logs. Interpretation of these data has allowed insight into the morphology and evolution of the unconformity.

The published views of those who have studied the unconformity during the past 25 years show an evolution of ideas. The purpose of this paper is: (1) to review briefly the development of ideas concerning the nature and significance of the unconformity, and (2) to suggest the application of certain recently developed geomorphological concepts to the now reasonably well known physical configuration of the unconformity in the Illinois Basin.

MAJOR CONTRIBUTIONS TO STUDY OF THE UNCONFORMITY

Paleogeology and paleotopography

A major definitive study by Siever (1951) of the unconformity in southern Illinois was the first significant contribution to our knowledge of this surface. He showed that the unconformity is characterized by a drainage pattern of predominantly northeast-southwest-trending valleys up to 30 kilometers (20 mi) wide and 140 meters (450 ft) deep. Wanless (1955) enlarged upon Siever's work and published a generalized sub-Pennsylvanian geologic map of the entire Illinois Basin. The mapping by Siever and Wanless has been further generalized in figure 1 (Willman et al., 1975, fig. P-4).

Both Siever and Wanless proposed that the cessation of Mississippian sedimentation and the withdrawal of Chesterian seas from the Illinois Basin area was followed by two periods of uplift. During the first period the eastern, western, and northern borders of the basin were raised higher than its interior, and after a long period of subaerial erosion the whole region was reduced to a peneplain. During a second period of uplift and warping, rejuvenated streams cut deep valleys into the peneplain. Subsequent early Pennsylvanian aggradation of these valleys produced a relatively smooth surface once again.

During the 20 years following publication of Siever's (1951) work, thousands of geophysical logs from petroleum exploratory holes in the deeper portions of the basin became available. Bristol and Howard (1971, pl. 1) produced a detailed paleogeologic map of the sub-Pennsylvanian Chesterian surface in the Illinois Basin; they used data from all (more than 53,000) available electric logs of holes that crossed the Chesterian-Pennsylvanian boundary.

A generalized version of the paleogeologic map (fig. 2) by Bristol and Howard (1971) shows the relation of paleotopography, as deduced from the erosion pattern (fig. 2A), to tectonic features (fig. 2B). Wanless (1955) believed that

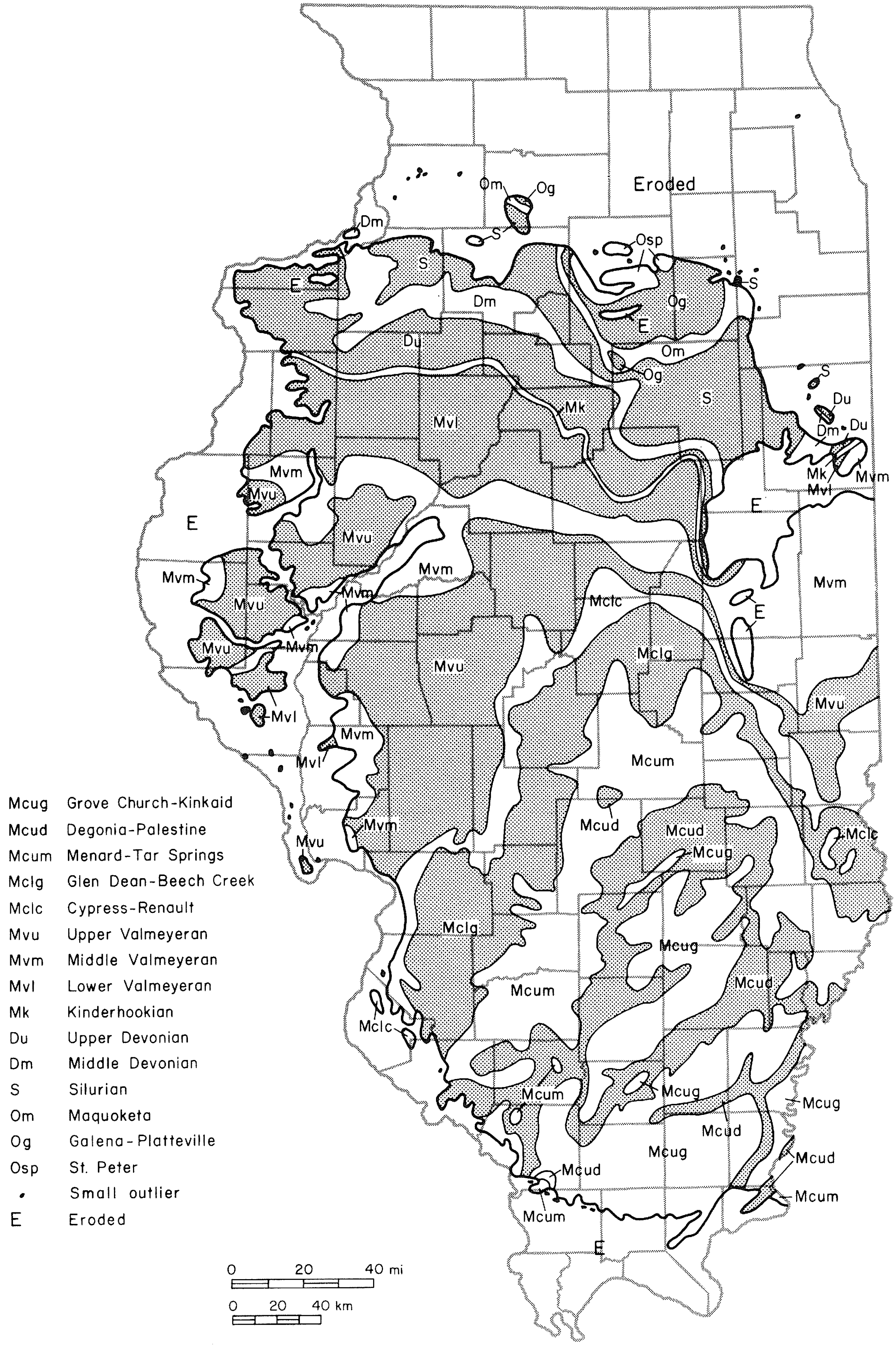

Figure 1. Geologic map of the sub-Pennsylvanian surface in Illinois. (From Willman et al., 1975, fig. P-4.)

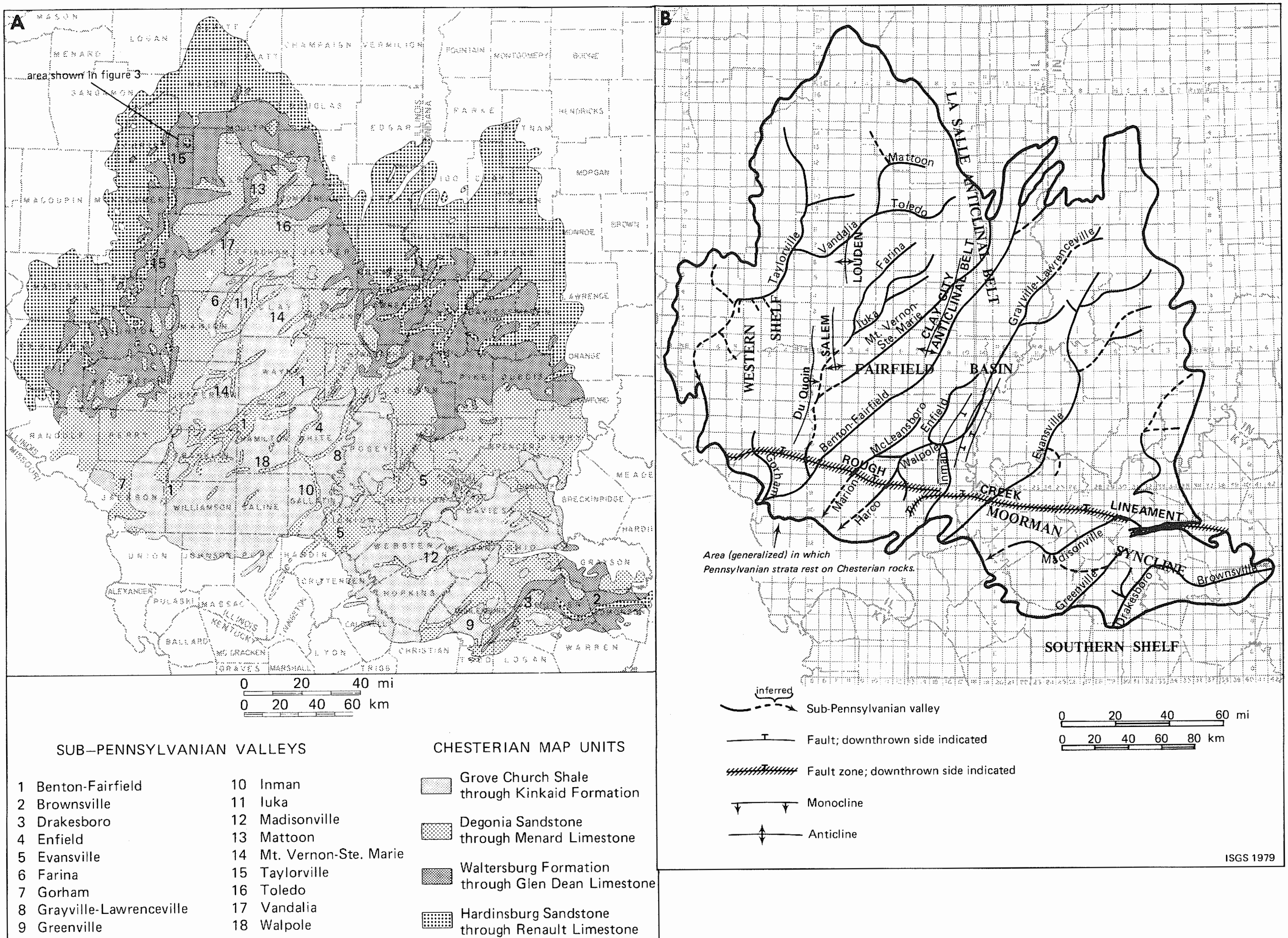

Figure 2. (A) Paleogeologic map of the sub-Pennsylvanian Chesterian surface in the Illinois Basin. (Modified from Howard, in press, fig. 3.) (B) Relationship of sub-Pennsylvanian valleys to tectonic features of the Illinois Basin. (Modified from Bristol and Howard, 1971, fig. 4.)

the La Salle Anticlinal Belt is not crossed by paleovalleys north of Crawford County, Illinois, and that southwesterly flowing streams were diverted southward around the belt; however, the influence of the La Salle Anticlinal Belt on valley orientation is negated by two major valleys—Benton-Fairfield and Mt. Vernon-Ste. Marie, which cross the La Salle Anticlinal Belt (fig. 2) in Clark County, immediately north of Crawford County. Similarly, Siever (1951, fig. 9) attributed the presence of Kinkaid Formation in the floor of Mt. Vernon-Ste. Marie Valley (fig. 2) to a tectonically induced drainage divide. It is much more likely, however, that a slight downwarping permitted some Kinkaid there to escape erosion.

With one exception—a rising Western Shelf with the Du Quoin Monocline at its eastern edge—there appears to have been no structurally related topographic obstruction to the development of a predominantly northeast-southwest-oriented drainage pattern across the basin (fig. 2). This does not preclude the evolution of structural features throughout the basin concurrent with valley erosion. As has just been shown, major paleovalleys cross anticlinal and synclinal axes in the same way. This likeness suggests that the drainage pattern was superimposed on either existing or developing folds. As shown in figure 3, a paleovalley crosses an anticline associated with the Assumption Consolidated Oil Field in Christian County, Illinois. If the paleovalley had not crossed the anticline (extant or developing), the existence of the paleovalley would not have been revealed by the pattern of paleo-geologic maps (figs. 2A and 3).

Unconformity reaffirmed

Several authors (Horne and Ferm, 1970; Ferm et al., 1971; and Horne, Ferm, and Swinchatt, 1974) have recently put forward a model of Mississippian-Pennsylvanian sedimentation in the Appalachian Basin that negates a Mississippian-Pennsylvanian unconformity. They suggest: (1) that some sediments that have been called Mississippian were deposited contemporaneously with sediments that have been called Pennsylvanian, and (2) that "Mississippian" offshore bars and marine clays intertongue with "basal Pennsylvanian" orthoquartzite beaches.

This revolutionary concept, though developed in the Appalachian Basin and mainly applied to strata there, has been considered by Ethridge, Leming, and Keck (1973) to have possible application to Mississippian-Pennsylvanian deposition in the Illinois Basin. Recent work in the Appalachian Basin by Dever (1973; personal communication, 1974) and Englund (1974), however, has led them to reaffirm the existence of an unconformity in this basin. Nevertheless, there are recognized areas locally in the basin in which sedimentation across the Mississippian-Pennsylvanian boundary was uninterrupted.

The inapplicability of the model within the Illinois Basin is conclusively demonstrated by the widespread

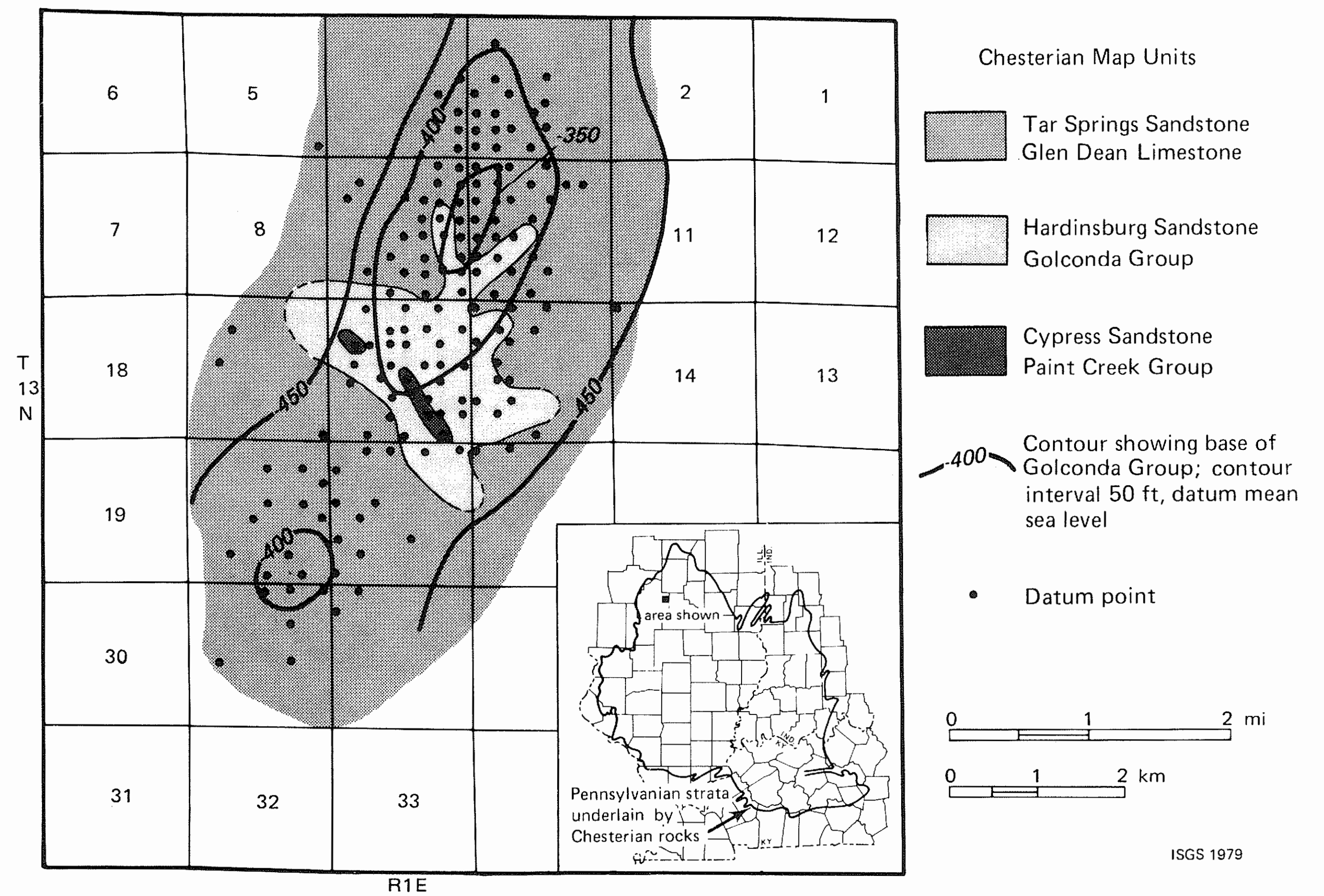

Figure 3. Sub-Pennsylvanian geologic map and Golconda structure map showing paleovalley crossing anticline associated with Assumption Consolidated Oil Field, T. 13 N., R. 1 E., Christian County, Illinois. See figure 2A for regional setting.

occurrence in the basin (Bristol and Howard, 1971, pl. 1) of Chesterian slump blocks incorporated in clastic units overlying undisturbed Chesterian strata (fig. 4). The basinwide abundance of these slump blocks, which may exceed 200 m (660 ft) in maximum horizontal dimension and 60 m (200 ft) in thickness, shows that lithified Chesterian strata were incorporated into basal Pennsylvanian sediments that filled the valleys of the unconformity.

Interpretations of the drainage pattern

Although the existence of the unconformity is well established, the geologic history of its evolution is not yet fully understood. An assertion by Siever (1951, p. 558) that the drainage pattern at the unconformity "resembles a normal dendritic development of tributaries and master streams" has been echoed in later studies (Potter and Siever, 1956; Potter and Pryor, 1961; Potter and Desborough, 1965; Sedimentation Seminar, in press) and, for the most part, has been unchallenged for 20 years. Recently, however, Bristol and Howard (1971; 1974) have pointed out that the configuration of the erosional pattern is essentially linear rather than dendritic. They (1974) also called attention to certain complex intravalley topographic features such as narrow, steep-walled valleys within wider valleys and complex intervalley relationships (Howard, in press) that appear to defy the simple explanation afforded by headward erosion of streams across an emerging coastal plain.

Especially puzzling is the evolution of certain valley intersections, such as the junction of Enfield, Grayville-Lawrenceville, Inman, and Walpole Valleys in southeastern Illinois (fig. 2A). Opposite directions of stream flow in Inman Valley were suggested by Siever (1951, fig. 9) and Potter and Desborough (1965, fig. 1); piracy of stream flow in Walpole and Grayville-Lawrenceville Valleys by Evansville Valley via its tributary Inman Valley was proposed by Bristol and Howard (1971). These diverse interpretations are based on the assumption that all the valleys are the product of a simple erosional history.

But what if the land surface was subjected to successive erosional episodes, each of which inscribed its own drainage pattern and was followed by a period of aggradation? This concept, suggested by Howard (in press), permits much less contrived explanations of complex intervalley and intravalley erosional phenomena and represents a significant departure from historically accepted views on the evolution of the unconformity. When one considers the impact of cyclicity on Carboniferous history, it would seem likely that the geologic processes that controlled cyclic deposition and erosion during both Mississippian and Pennsylvanian times were operating during the development of the unconformity that separates the two systems in the Illinois Basin.

The ancient Michigan River has been cited as the prime agent of deltaic deposition in the Illinois Basin area in both Chesterian (Swann, 1963) and Pennsylvanian (Pryor and Sable, 1974) times. The lateral shifts across the basin of the

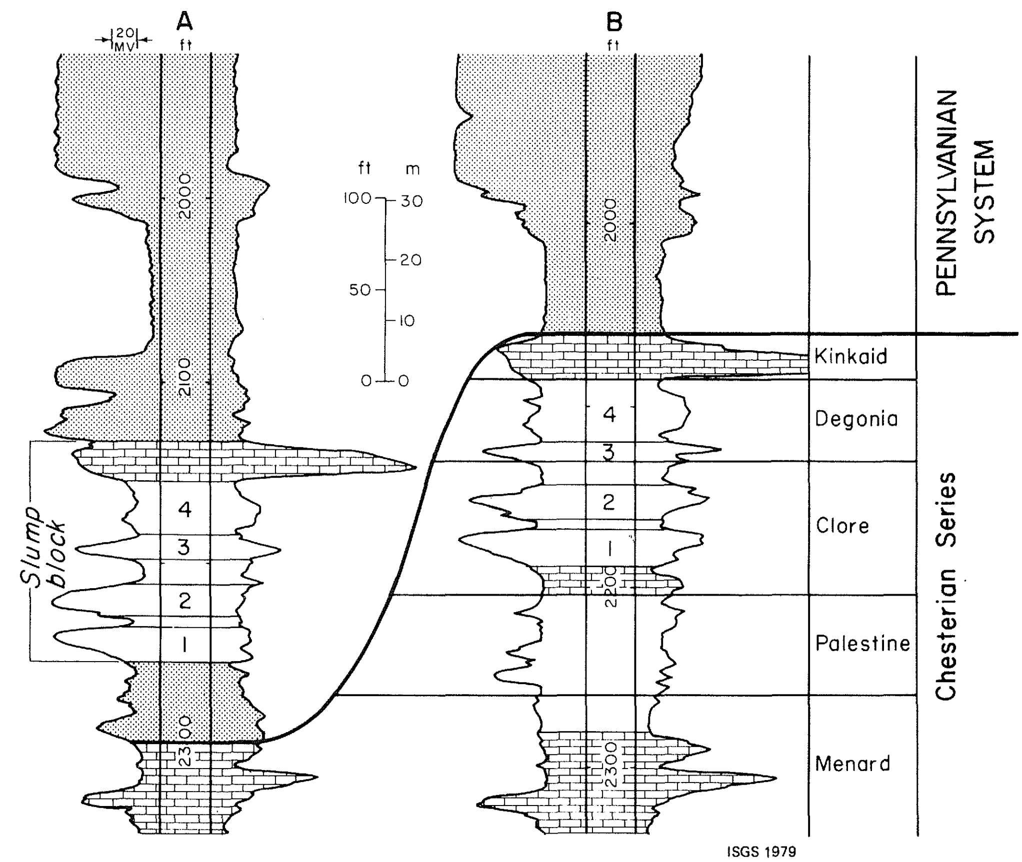

Figure 4. Electric logs of drill holes 200 m (660 ft) apart in Sec. 34, T. 1 N., R. 8 E., Wayne County, Illinois. A Chesterian slump block incorporated within Pennsylvanian strata is shown in log A. Some clastic units of the Degonia and Clore Formations are numbered. (After Howard, in press, fig. 6.)

generally southwestward course of the river may have continued during the interval following Chesterian deposition, at the time when the shoreline had shifted hundreds of miles to the southwest (Howard, in press). This lateral shifting, coupled with the continued response to cyclic changes in base level, might have caused the river system to alternately erode and aggrade valleys across the basin.

GEOMORPHIC MODEL FOR EVOLUTION OF THE UNCONFORMITY

Search for recent analogues

Subscription to the tenet of uniformitarianism leads to a search for recent or near-recent analogues of ancient geologic phenomena, whose imperfectly preserved record is under scrutiny. The study of an unconformity is especially difficult because a gap in the sedimentary record must be explained. The available geologic evidence consists only of (1) the paleotopography (deduced from paleogeology and structure) of the unconformity surface and (2) the sedimentary units covering that surface.

As shown earlier in this paper, evidence relating to the unconformity in the Illinois Basin has been examined in considerable detail during the last 25 years. Understanding of the unconformity has grown and continues to evolve. For example, the long-held viewpoint that the configuration of the basin-wide drainage pattern is generally dendritic and is the result of a single erosional episode is now effectively opposed by the concept of an essentially linear drainage pattern created by a succession of erosional episodes (Bristol and Howard, 1971, 1974; Howard, in press).

A geomorphic model that will allow the implementation of this concept is now beginning to emerge. Shawe and Gildersleeve (1969) were apparently the first to recognize the problems of attributing certain sub-Pennsylvanian erosional topography to the basic trunk-stream-tributary runoff pattern. The drainage pattern that they discussed is an anastomosing channel complex (fig. 5A) cut into Chesterian bedrock along the flanks of, and as much as 120 feet above, the Brownsville Valley (fig. 2) in western Kentucky. Subsequent mapping by Davis, Plebuch, and Whitman (1974) shows a similar anastomosing erosional pattern extending over several counties just west of Brownsville Valley. Although perplexed as to the origin of the channel complex, Shawe and Gildersleeve cited two somewhat similar drainage patterns: that of the present-day Rio Caroni in Venezuela (Garner, 1966b) and the Pleistocene erosional topography (fig. 5B) of the Washington Scablands (Bretz, Smith, and Neff, 1956).

These suggested analogues are crucial, not only in their possible applicability to western Kentucky, but in their implications regarding regional interpretation of the unconformity in the Illinois Basin. They are strikingly similar to the basin-wide erosional pattern shown in detail by Bristol and Howard (1971, pl. 1) and generalized in figure 2A.

If the hypothesis that the geomorphic history of the Caroni region is analogous to that of the Illinois Basin area of 300 million years ago is acceptable, then a thorough study of Caroni history is required. Fortunately, the exhaustive study of the Caroni region by H. F. Garner (1966a, 1966b, 1974) satisfies this requirement. A brief review of his ideas on the origin of landscapes, especially as those ideas relate to the evolution of the Mississippian-Pennsylvanian unconformity, is therefore in order.

Effect of climatic change on geomorphic history.

Garner believed that the geomorphic history of a landmass within 35° of the equator is profoundly influenced by the effects of climatic change upon its vegetation and drainage (fig. 6) over thousands of years. The most plausible mechanism to account for many such climatic fluctuations is a cooling and subsequent warming of the seas in association with the onset and termination of continental glaciation.

The conventional description of the growth of a river is "headward erosion," that is, the gradual lengthening of a valley upstream. According to Garner (1966a, p. 90), the evolution of rivers is explained more comprehensively by the erosional extension of channels downslope, which occurs when an increase of rainfall in uplands sends perennial runoff across a terrain previously modified by processes of aggradation and planation.

Application of the Rio Caroni geomorphic model to the Illinois Basin

The recorded geomorphic development of the Rio Caroni (fig. 7), throughout its history of environments that alternate from arid to humid, may well serve as a model for comparison with other modern and ancient drainages. The stabilization of anastomosing channel systems into a single drainage line (fig. 7, C-F) seems especially pertinent to the heretofore puzzling intersection of the four paleovalleys (Enfield, Grayville-Lawrenceville, Inman, and Walpole) mentioned earlier (fig. 2). One could easily assign these valley names to the channels in figure 7. Recent studies that I have made (not yet published) indicate that water once flowed southeastward from Enfield Valley into Inman Valley. I have also proposed that at one time Grayville-Lawrenceville Valley drained southwestward into Walpole Valley.

Corroboration of the view that the Rio Caroni geomorphic model can be useful in the study of the Mississippian-Pennsylvanian unconformity has recently come from H. F. Garner (personal communication, 1976), following his examination of my published and unpublished material. Following are some excerpts from his personal communication:

> I don't think there is any question about the repetitive nature of the erosional (and depositional) history of the Mississippian-Pennsylvanian unconformity . . . I think it most probable that you are dealing (at least in part) with a relict anastomosing channel system such as I described in Venezuela . . . .
>
> Illinois was alternately a site for aggradation and incision by channel networks . . . the incisional phases would tend to reduce the number of flow routes and lessen the complexity of runoff patterns. Aggradational phases would tend to cause "re-leveling" of the anastomotic channel bottoms . . . so that they would (or could) have been occupied by runoff and re-eroded several times . . . .
>
> Valleys that have undergone multiple alluviations and re-excavations . . . often display multiple talwegs separated by bedrock ridges beneath the fill material . . . I thought the Caroni channels had been "re-leveled" a number of times by alternating episodes of

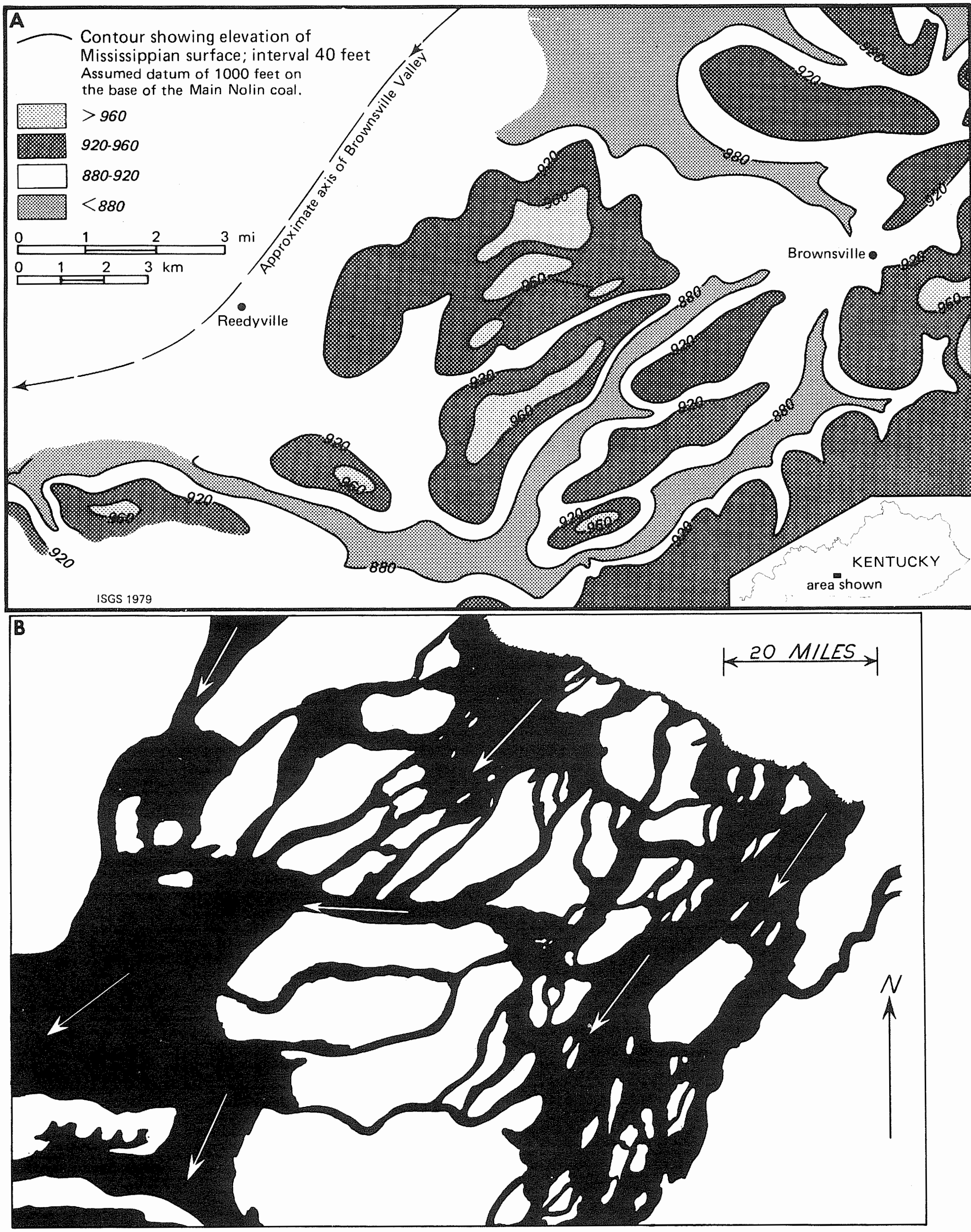

Figure 5. (A) Paleotopographic map of the Mississippian-Pennsylvanian unconformity showing anastomosing channel complex adjacent to Brownsville Valley (location shown in fig. 2) in western Kentucky. (Modified from Shawe and Gildersleeve, 1969, fig. 1.) (B) The anastomosing channel systems of the Washington Scablands, northwestern United States. Arrows show inferred directions of runoff during the several apparent inundations of the network caused by a series of ice-dam ruptures. (Reprinted with permission, from H. F. Garner, *The Origin of Landscapes* [New York: Oxford University Press, 1974], fig. 7.60.)

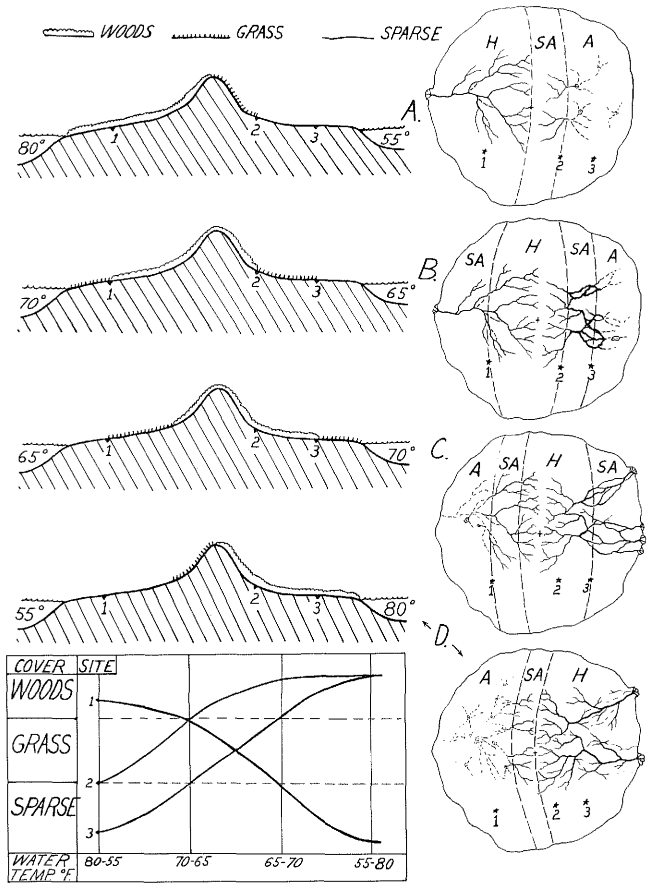

Figure 6. Effects of a climatic change extending over thousands of years upon vegetation and drainage of a hypothetical landmass just north or south of the equator. The region is shown in plan views (right) and in corresponding sections (left). Land environment shifts are related to changes in ocean-surface water temperatures adjusted to periodic glaciation. The drainage configurations adjust in relation to the areal extents of the humid and arid regions and correspondingly altered runoff volumes and continuities. In sequence (A), the land near the warm sea receives ample moisture, and forests begin at the strand; the opposite ocean is cold so that air masses are undersaturated, rise, and cool before precipitation can occur; there is a coastal desert; (B)-(D) The situations become climatically reciprocal as the ocean conditions reverse. In the bottom graph, three randomly located areas (1-3) record differing climatic and geomorphic histories during the same time span. (Reprinted with permission, from H. F. Garner, *The Origin of Landscapes* [New York: Oxford University Press, 1974], fig. 5.52.)

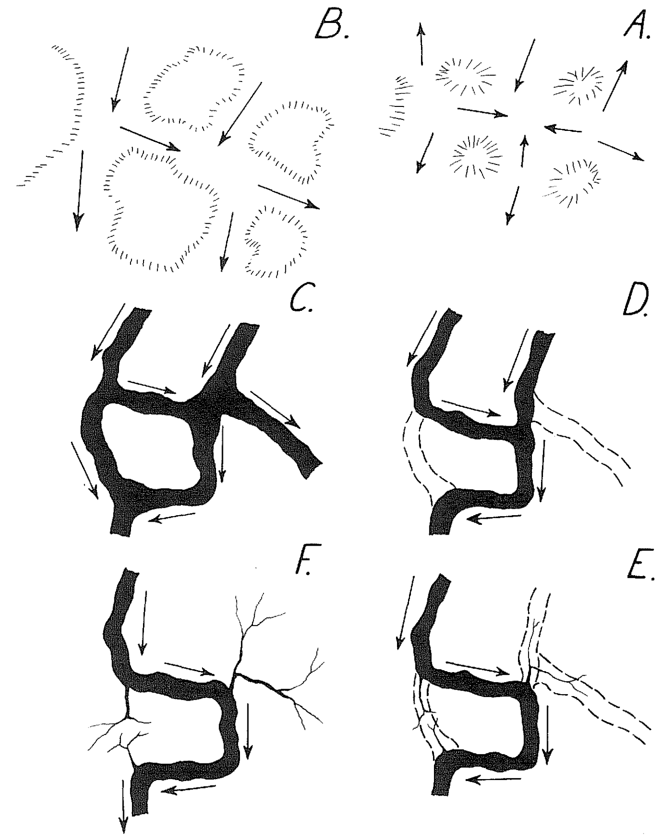

Figure 7. Diagram of channeled drainage development and stabilization under humid conditions as typified by the Rio Caroni, Venezuela. Initial express (A) is of ephemeral arid sheetfloods on an alluvial terrain of low relief and undrained depressions. Runoff modifications of (A) are expressed by (B) quasi-sheetflood transmission of runoff with minor confinement and ill-defined directions of flow to regional base level, (C) anastomosing channel system developed by incision of anabranches of quasi sheetflood, (D) network channel piracy through selective anabranch incision, (E) further channel piracy, local drainage reversals resulting in barbed tributaries and development of a single trunk channel drainage line, and (F) headward erosion and deepening of a river. (Reprinted with permission, from *Encyclopedia of Geomorphology,* Rhodes W. Fairbridge, ed., Dowden, Hutchinson & Ross, Inc., Stroudsburg, Pa.)

aggradation (under aridity) and incision (during humid times). This permits several discharge routes to be repeatedly reoccupied by discharge from the same general source instead of being selectively incised and abandoned as would be the case if there were a permanent climate change to humidity.

For his own purposes, namely, the determination of the source and transport mechanism of Prairie Grove (early Pennsylvanian) conglomerate in northern Arkansas, Garner (1974, p. 651-659) has been concerned with the genesis of the Mississippian-Pennsylvanian unconformity and its suprajacent sediments. Briefly stated, he concluded that the southern Canadian Shield region supplied the coarse quartzitic material to the Prairie Grove depositional sites via the anastomosing channel system (fig. 8A) described (although not in those terms, as has been shown earlier in this paper) by Potter and Siever (1956) and Bristol and Howard (1971).

According to Garner's analysis of drainage and environment, the coarse sediments of the Prairie Grove (Caseyville of Illinois) were apparently being prograded to the south from Canada under recurring arid conditions prior to Prairie Grove time (fig. 8B). A final arid-to-humid climate change brought deposition of the conglomeratic sediment in the Prairie Grove sea (fig. 8C).

Although the concept clashes with long-held assumptions concerning Pennsylvanian climate, Garner's suggestion

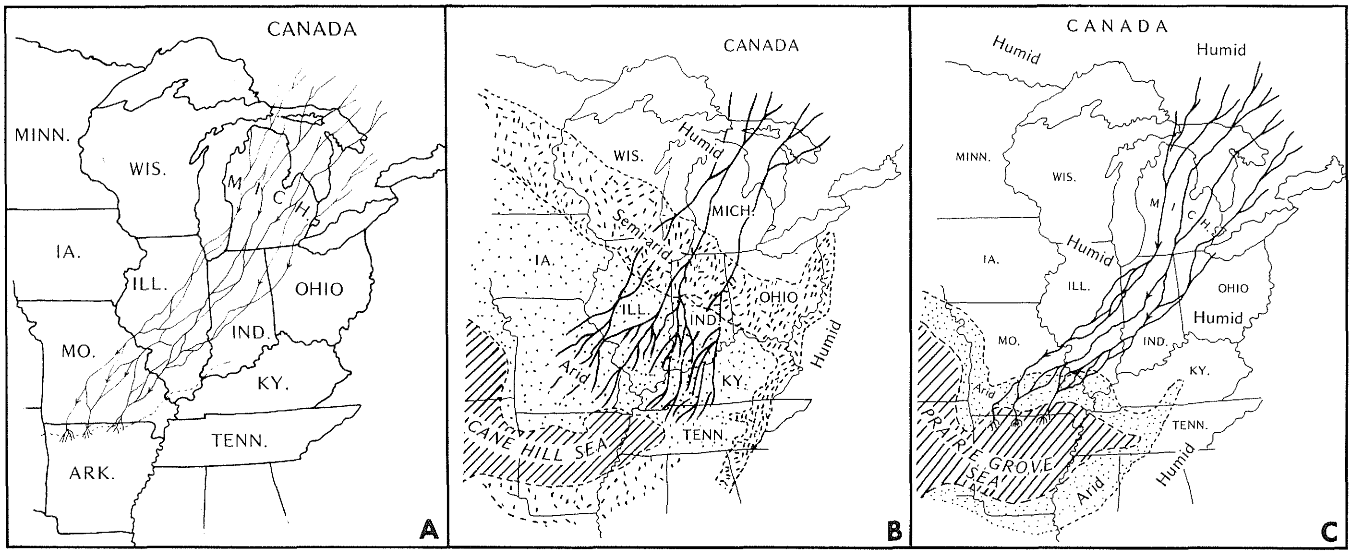

Figure 8. (A) Midcontinental drainage configurations developed intermittently during early Pennsylvanian time and capable of transporting quartzitic materials from Canada to Arkansas. (B) Paleoclimatic and drainage map of North American midcontinent during early Pennsylvanian Cane Hill (pre-Prairie Grove) time showing a restricted and probably cool sea bordered by extensive deserts. (C) Paleoclimatic map and drainage configurations of the North American midcontinent during Prairie Grove (early Pennsylvanian) time. Shown are a somewhat expanded and probably warm seaway adjacent to a narrowing coastal desert and an expanding humid upland to the northeast. (Reprinted with permission, from H. F. Garner, *The Origin of Landscapes* [New York: Oxford University Press, 1974], figs. 11.19, 11.20, and 11.21.)

that the Illinois Basin area was intermittently arid during part of early Pennsylvanian time should not be rejected out of hand. Sedimentation Seminar (in press) notes that the well-established fact that Chesterian limestones at the unconformity are commonly topographic bench formers "does not easily harmonize with a presumed warm, humid, subtropical climate as inferred from both the Pennsylvanian's coal beds and paleolatitude."

Additional support for the concept of climatically influenced geomorphic history comes from a discussion by Potter (1978) of ancient and modern big river systems, including the Michigan (ancient)-Mississippi (modern) River system. He notes that such a system "might dry up with a striking increase in aridity or, conversely, be initiated by enhanced rainfall" (1978, p. 16). Some paleobotanical support for the concept of early Pennsylvanian aridity, or at least semiaridity, can also be found in the literature. Schopf (1975, p. 29) reiterates White's (1931, p. 275) early view that during Caseyville time the climate of the Illinois Basin area was less humid than that of the Appalachian area. White stopped far short of embracing the idea of Pennsylvanian aridity, for he urged that xerophytic features in plants of the Caseyville Formation "be regarded as *pseudo-xerophytic* [italics mine] and as adapted to withstand the moisture-reducing effects of a dry season on a normally wet humic soil, rather than as indicating an environment approaching semi-aridity."

Tom L. Phillips has pointed out (personal communication, 1978), that paleobotanical records indicate that dur-Caseyville time there were some unusual swamp floras present with xerophytic characters. While such adaptations reflected either past or contemporary physiological water stress for the plants (ambiguities exist in interpretation), Phillips held that their xerophytic characters were consistent with semiaridity.

Although Garner's thesis of climatically controlled sedimentary and erosional patterns may be reluctantly accepted by some, I believe it may prove a landmark contribution to the study of early Pennsylvanian history. Garner provides a key to new interpretation of the Mississippian-Pennsylvanian unconformity in the Illinois Basin.

REFERENCES

BRETZ, J H., H.T.U. SMITH, and G. E. NEFF, 1956, Channeled scabland of Washington: New data and interpretations: Geological Society of America Bulletin, v. 67, p. 957-1050.

BRISTOL, H. M., and R. H. HOWARD, 1971, Paleogeologic map of the sub-Pennsylvanian Chesterian (Upper Mississippian) surface in the Illinois Basin: Illinois State Geological Survey Circular 458 (in cooperation with Indiana Geological Survey and Kentucky Geological Survey), 14 p.

BRISTOL, H. M., and R. H. HOWARD, 1974, Sub-Pennsylvanian valleys in the Chesterian surface of the Illinois Basin and related Chesterian slump blocks, *in* G. Briggs [ed.], Carboniferous of the southeastern United States: Geological Society of America Special Paper 148, p. 315-335.

DAVIS, R.W., R.O. PLEBUCH, and H.M. WHITMAN, 1974, Hydrology and geology of deep sandstone aquifers of Pennsylvanian age in part of the western coal field region, Kentucky: Kentucky Geological Survey Report of Investigations 15, ser. X, 26 p.

DEVER, G. R., 1973, Stratigraphic relationships in the Lower and Middle Newman Limestone (Mississippian), east-central and northeastern Kentucky: unpublished M.S. thesis, University of Kentucky, Lexington, KY, 121 p.

ENGLUND, K. J., 1974, Sandstone distribution patterns in the Pocahontas Formation of southwest Virginia and southern West Virginia, *in* G. Briggs [ed.], Carboniferous of the southeastern United States: Geological Society of America Special Paper 148, p. 31-45.

ETHRIDGE, F. G., S. L. LEMING, and D. A. KECK, 1973, Depositional environments of Lower Pennsylvanian detrital sediments of southern Illinois, *in* F. G. Ethridge, George Fraunfelter, and John Utgaard [eds.], Guidebook to depositional

environments of selected Lower Pennsylvanian and Upper Mississippian sequences of southern Illinois: 37th annual tri-state field conference, Carbondale, IL, p. 16-34.
FERM, J. C., J. C. HORNE, J. P. SWINCHATT, and P. W. WALEY, 1971, Carboniferous depositional environments in northeastern Kentucky, *in* Kentucky Geological Society Guidebook: Annual spring field conference, Lexington, KY, 30 p.
GARNER, H. F., 1966a, Rivers in the making: Scientific American, v. 216, no. 4, p. 84-94.
GARNER, H. F., 1966b, Derangement of the Rio Caroni, Venezuela: Revue de Géomorphologie Dynamique, no. 2, p. 50-83.
GARNER, H. F., 1974, The origin of landscapes: Oxford University Press, London, p. 646-667.
HORNE, J. C., and J. C. FERM, 1970, Facies relationships of the Mississippian-Pennsylvanian contact in northeastern Kentucky: Geological Society of America Abstracts with Programs (Southeastern Section), v. 2, no. 3, p. 217.
HORNE, J. C., J. C. FERM, and J. P. SWINCHATT, 1974, Depositional model for the Mississippian-Pennsylvanian boundary in northeastern Kentucky, *in* G. Briggs [ed.], Carboniferous of the southeastern United States: Geological Society of America Special Paper 148, p. 97-114.
HOWARD, R. H., in press, Carboniferous cyclicity related to the development of the Mississippian-Pennsylvanian unconformity in the Illinois Basin, *in* Proceedings of VIII International Congress on Carboniferous Stratigraphy and Geology, Moscow, USSR, 1975.
POTTER, P. E., 1978, Significance and origin of big rivers: Journal of Geology, v. 86, p. 13-33.
POTTER, P. E., and R. SIEVER, 1956, Sources of basal Pennsylvanian sediments in the Eastern Interior Basin: Journal of Geology, v. 64, p. 225-244.
POTTER, P. E., and W. A. PRYOR, 1961, Dispersal centers of Paleozoic and later clastics of the upper Mississippi Valley and adjacent areas: Geological Society of America Bulletin, v. 72, no. 8, p. 1195-1250.
POTTER, P. E., and G. A. DESBOROUGH, 1965, Pre-Pennsylvanian Evansville Valley and Caseyville (Pennsylvanian) sedimentation in the Illinois Basin: Illinois State Geological Survey Circular 384, 16 p.
PRYOR, W. A., and E. G. SABLE, 1974, Carboniferous of the Eastern Interior Region, *in* G. Briggs [ed.], Carboniferous of the southeastern United States: Geological Society of America Special Paper 148, p. 281-313.
SCHOPF, J. M., 1975, Pennsylvanian climate in the United States, *in* E. D. McKee and E. J. Crosby [coordinators], Paleotectonic investigations of the Pennsylvanian system in the United States, Part II.—Interpretative summary and special features of the Pennsylvanian system: United States Geological Survey Professional Paper 853, p. 23-31.
SEDIMENTATION SEMINAR, in press, Sedimentology of a paleovalley fill: Kyrock (Pennsylvanian) Sandstone in Edmonson and Hart Counties, Kentucky: Kentucky Geological Survey, Report of Investigations 21, ser. 10.
SHAWE, F. R., and B. GILDERSLEEVE, 1969, An anastomosing channel complex at the base of the Pennsylvanian System in western Kentucky: United States Geological Survey Professional Paper 650-D, p. 206-209.
SIEVER, R., 1951, The Mississippian-Pennsylvanian unconformity in southern Illinois: American Association of Petroleum Geologists Bulletin, v. 35, no. 3, p. 542-581; Illinois State Geological Survey Report of Investigations 152, 40 p.
SWANN, D. H., 1963, Classification of Genevievian and Chesterian (late Mississippian) rocks of Illinois: Illinois State Geological Survey Report of Investigations 216, 91 p.
WANLESS, H. R., 1955, Pennsylvanian rocks of Eastern Interior Basin: American Association of Petroleum Geologists Bulletin, v. 39, no. 9, p. 1753-1820.
WHITE, D., 1931, Climatic implications of Pennsylvanian flora: Illinois State Geological Survey Bulletin 60, p. 271-281.
WILLMAN, H. B., Elwood ATHERTON, T. C. BUSCHBACH, Charles COLLINSON, John C. FRYE, M. E. HOPKINS, Jerry A. LINEBACK, and Jack A. SIMON, 1975, Handbook of Illinois stratigraphy: Illinois State Geological Survey Bulletin 95, p. 170.

Geology of the Springfield Coal Member (V) in Indiana—A review

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INTRODUCTION

This review provides a background for participants in the IX-ICC postcongress field trip on the Springfield Coal Member (V) of the Petersburg Formation, which will be visited during the first day of the trip in Indiana. We selected the Springfield for inspection and review because it is the most important economic coal in Indiana and because it typifies coal development on a broad shallow shelf of a cratonic basin, such as the Illinois Basin during Pennsylvanian time. Probably more is known about the Springfield in Indiana than any other coal because of its widespread development and its exposure in numerous mines throughout southwestern Indiana.

The maximum thickness of Pennsylvanian rocks in Indiana is about 1,500 feet (475 m), but only the middle 500 feet (150 m) or so (the Desmoinesian Series) contains most of the principal minable coals. The Springfield, as mapped along the eastern margin of the Illinois Basin from Vermillion County southward to the Ohio River, a distance of more than 100 miles (160 km), has a characteristic set of physical and chemical properties and sedimentary rock associations. Similar lithologies and rock associations can also be observed in western Kentucky and Illinois.

GEOLOGIC SETTING

After deposition of Mississippian sediments, the Illinois Basin underwent a period of uplift that resulted in a gentle southerly tilting of the basin. Because of increased erosion in the northern part of the basin, progressively older Mississippian rocks are found beneath the Mississippian-Pennsylvanian unconformity northward from the Ohio River. Slow subsidence of the basin during Pennsylvanian time reinitiated Paleozoic sedimentation.

Throughout Pennsylvanian time the Illinois Basin, one of several intracratonic basins flanking the Canadian Shield, received sediment from a complex river system to the northeast. Repetitions of marine and fluviatile sediments attest to the progradation of large delta systems southwestward onto a shallow marine platform. Shifting of the delta from time to time resulted in numerous vertical changes in lithology and cyclic associations. There is about twice as much shale as sandstone in the middle and upper parts of the Pennsylvanian System in the Illinois Basin, but the reverse is true in the lower part. Limestone and coal, the other basic lithologies, constitute about 2 percent each of all rocks deposited in Indiana during Pennsylvanian time. Only the marine limestones and shales and the coal beds have extensive lateral continuity.

After Pennsylvanian deposition, broad uplift and erosion occurred, giving the rocks in the Indiana part of the Illinois Basin a southwesterly dip of about 35 feet to the mile (7 m/km). At present about 6,500 square miles (16,800 km^2) of Indiana's total area—36,291 square miles (93,995 km^2)—remains covered by Pennsylvanian rocks. No evidence of younger Paleozoic or Mesozoic deposition, if it ever occurred, remains in the rock record of Indiana.

REGIONAL STRATIGRAPHY

Petersburg Formation

The term Petersburg Formation was first applied by Fuller and Ashley (1902). They included the coal that they named Petersburg, the Springfield Coal Member (V) of current usage, and the overlying rocks to the base of the Millersburg Coal, the Danville Coal Member (VII) of current usage (fig. 1). Wier (1950) restricted the Petersburg Formation to the rocks between what he interpreted as unconformities at the top of Coal IV (Survant Coal Member) and the top of the Alum Cave Limestone Member. Wier and Gray (1961) further emended the Petersburg to a more workable definition by including the rocks from the top of the Survant Coal Member (IV) to the top of the Springfield Coal Member (V).

The Houchin Creek Coal Member (IVa) lies at about the middle of the Petersburg Formation (fig. 1) and marks the base of the interval reviewed here. This coal is commonly 0.2 to 3.5 feet (.06 to 1.1 m) thick and is typically overlain by black fissile shale 1 to 4 feet (.3 to 1.2 m) thick. This shale is overlain by dark dense argillaceous limestone 1 to 3 feet (.3 to .9 m) thick. The widespread black shale unit has not been named, but the overlying limestone was named the Stendal Limestone Member by Burger and Wier (1970) in accordance with the nomenclature suggested by Wier.

A variable interval frequently described as "sandstones and shales" lies between the top of the Stendal Limestone Member and the base of the Springfield Coal Member (V). Friedman (1961) noted that 25 feet (8 m) of shale with siderite nodules lies at the base of this interval and that at several places in northern Vigo County the entire interval is replaced by massive or crossbedded sandstone. In a few places, such as at the abandoned Dresser Mine in Vigo County, the entire Petersburg is a massive sandstone (Friedman, 1954).

Dugger Formation

The Dugger Formation (fig. 1) is the uppermost formation of the Carbondale Group. Its lower units compose the upper part of the study interval. Wier (1950) first applied the term Dugger Formation to the rocks lying between what he interpreted as unconformities at the top of the Alum Cave Limestone Member and the top of the Danville Coal Member (VII); thus he further emended the revision by Fuller and Ashley (1902) of the Petersburg and Millersburg Formations that had been proposed by Cumings (1922). Wier and Gray (1961) adopted the current definition of the Dugger Formation that places the base of the formation at the top of the Springfield Coal Member (V) of the Petersburg Formation and places the top of the formation at the top of the Danville Coal Member (VII).

Typically, the lowest units of the Dugger Formation are black fissile shale 1 to 6 feet (.3 to 2 m) thick overlain by the Alum Cave Limestone Member. In places, however,

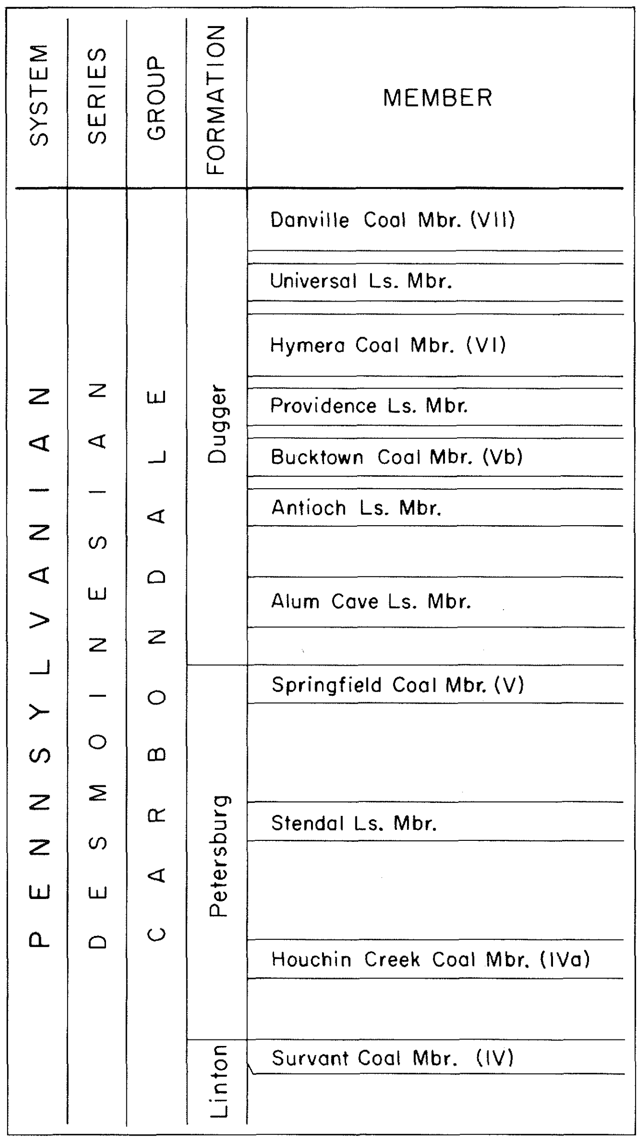

Figure 1. Stratigraphic relationships of the Springfield Coal Member (V) and associated units.

the basal unit of the Dugger Formation consists of a thick wedge of gray shale, shaly sandstone laterally grading into channel-fill sandstones, or a thin bed of limestone, 0.1 to 1 foot (0.3 to .3 m) thick, and pyrite containing abundant pyritized brachiopods and wood fragments (Wier, 1952). The black fissile shale that normally forms the base of the Dugger Formation typically contains large calcareous and ferruginous concretions, 0.1 to 3 feet (.03 to .9 m) in diameter, in its lower part (Hutchison, 1958). These project down into the underlying Springfield Coal Member (V).

The Alum Cave Limestone Member (fig. 1) overlies the basal black shale of the Dugger Formation and is best developed close to its outcrop in Sullivan and Greene Counties. The Alum Cave limestone has been traced into northern Vigo County and southward into Pike and Warrick Counties, where it is represented by calcareous shales with marine fossils. The Alum Cave typically is separated into two limestone beds by a thin calcareous shale.

The Antioch Limestone Member is a conglomeratic or brecciated limestone that directly underlies the underclay of the Bucktown Coal Member (Vb) and is separated from the Alum Cave limestone by a 20-foot (6-m) interval of sandstone and shale that may include a thin unnamed coal bed. The Antioch limestone is best developed in Sullivan and Greene Counties and has been traced as far north as Vermillion County, but has not been traced south of Knox County.

The Bucktown Coal Member (Vb) and its underclay lie immediately above the Antioch limestone and form the top of the interval reviewed (fig. 1). The coal ranges from 0.1 to 3.6 feet (.03 to 1 m) in thickness in Indiana and has been identified from Vermillion County to Warrick County. Some coals in Pike and Warrick Counties that have been assigned to the Bucktown Coal Member (Vb) may actually be benches of the Springfield where it splits in proximity to contemporaneous channel-fill deposits. The Bucktown Coal Member (Vb) is normally overlain by dark-gray shale that contains siderite bands and marine fossils.

CHARACTERISTICS OF THE COAL AND ADJACENT ROCKS

Petrography

The Springfield Coal Member is generally a banded coal, consisting of alternating bright vitrain bands and duller clarain and durain bands. It is generally brighter than the closely associated Hymera and Survant. The distribution and ratio of the different lithotypes in the Springfield are more variable with location than are other coal beds. Broadly speaking, the upper half of the seam is more variable and contains more dull coal than the lower half (Neavel, 1961). The lithotypes consist of about 20 percent vitrain, 75 percent clarain and durain, 2 percent fusain, and 3 percent mineral matter (Pickering, 1953). The mineral matter consists mainly of clay minerals (kaolinite, illite, mixed-layer minerals, and occasional minor chlorite), quartz, pyrite, and occasional carbonates. Diagenetic or secondary minerals, such as pyrite, kaolinite, calcite, gypsum, and limonite, have been found in places filling vertical cleats, horizontal partings, and irregular fissures in the coal. Pyrite is generally more abundant in the topographically higher areas of coal seams (Khawaja, 1975). After weathering, iron sulfides in the coal may partly alter to secondary sulfate minerals, such as white powder and tiny acicular rozenite. Yellowish clayey films of jarosite are also found in some places.

The clay minerals in the argillaceous rocks above the Springfield Coal Member consist mainly of kaolinite, illite, and mixed-layer clay (illite > smectite). Chlorite has been found in some places as a minor component; it is more common in the black shale and dark-gray shale than in other lithologic types. Generally speaking, the gray mudstone and shale contain greater amounts of kaolinite than illite, although the black shale contains more illite than kaolinite. Mixed-layer clay appears to be more abundant in the underclay.

The Springfield Coal Member is variably underlain by underclay (silty mudstone and claystone), siltstone, and sandy shale and is rarely underlain by fine-grained sandstone. The argillaceous rocks consist mainly of clay minerals (kaolinite, illite, and mixed-layer clay) and subordinate nonclay minerals, including quartz, calcite, dolomite, siderite, and pyrite. Although these muddy rocks generally slake in water, they do not cause appreciable swelling or heaving in mining because they are commonly silty in texture and contain only limited amounts of water-expandable minerals.

Palynology

Guennel (1952) published the only palynologic study of the microflora of the Springfield Coal Member in Indiana. On the basis of eight samples, the following microflora assemblage was identified: *Laevigatosporites,* 62 percent; *Lycospora,* 26 percent; *Punctatisporites,* 6 percent; *Endosporites,* 3 percent; *Calamospora,* 2 percent; and *Granulatisporites,* 1 percent. Since this study there have been many significant changes in palynologic nomenclature. Both Guennel (1952) and Peppers (1970) indicated that monolete *Laevigatosporites* and (or) *Thymospora* spores combined are dominant over cingulate *Lycospora* spores in the Springfield Coal Member (Harrisburg Coal Member of Illinois). Thus, the marattialian tree ferns were the dominant members, and the arborescent lycopods were the subdominant members of the plant community that formed the Springfield.

Rank and analyses

Springfield coals typically have 7 to 10 percent moisture, 40 to 42 percent volatiles, and 39 to 42 percent fixed carbon on an as-received basis. They are ranked as high-volatile bituminous coals (B or C, according to ASTM designation), containing moderately high sulfur and ash (table 1). Washability studies that simulate the cleaning processes of modern coal preparation plants have shown that about half of the pyritic sulfur can be removed from the Springfield (Wier and Hutchison, 1977).

DEPOSITIONAL ENVIRONMENT

Recent investigations of coal-bearing strata in the Illinois Basin have shifted from climatic or base-level cyclic interpretation to a genetic reconstruction of depositional environments. It is now widely believed that the sediments

TABLE 1. Range and average values of ash, sulfur, and Btu content of 231 samples from the Springfield Coal Member (V) in Indiana, calculated on a moisture-free basis.

	Range		Average value	
	Minimum	Maximum	Mean	Median
Ash, percent	3.9	30.1	11.0	10.5
Sulfur, percent	0.7	8.9	3.8	3.8
Heating value, Btu per lb	9,700	13,990	12,693	12,793
(Calorie per gm)	(5,389)	(7,773)	(7,052)	(7,108)

between the Houchin Creek Coal Member (IVa) and the Springfield Coal Member were deposited during the progradation of a delta into a shallow inland sea where near-tropical climatic conditions prevailed. The coal-forming peat accumulated between fluvial channels in a swamp environment, one of the several environments of deposition that were associated with the delta. Marine beds that overlie the coal in many places were deposited after abandonment and subsidence of the delta platform. Thus, the environment of deposition of the Springfield is closely interrelated with other depositional environments.

The interval between the Houchin Creek and the Springfield was studied by Wanless and others (1963, 1969, and 1970) and was found to contain sediments representing a major delta distributary channel complex that was traceable from southwestern Indiana through southeastern Illinois. Such channel complexes built the deltaic platform on which the Springfield peat was deposited. A peat deposited on a deltaic platform must be associated with some active aggrading fluvial channels, and several such channels are now known to have been present in Indiana and Illinois during deposition of the peat (fig. 2). The contemporaneous channels in the Springfield were first mapped by Friedman (1956 and 1960) in Vigo County, Indiana. Hopkins (1968) found that the channel complex described by Wanless and others was in part contemporaneous with the Springfield Coal Member in southeastern Illinois. Adams (in preparation) and Eggert (in preparation) have mapped additional fluvial channels contemporaneous with the Springfield in Sullivan and Warrick Counties, Indiana. Eggert has found that the channel complex mapped by Wanless and others (1963, 1969, and 1970) in Gibson and Pike Counties was in part contemporaneous with the Springfield and that channel cutouts mapped in Pike, Gibson, and Knox Counties by Wier and Stanley (1953), Friedman (1954, 1960), Wier and Powell (1967), and Brittain (1975), and considered erosional by them, represent channel deposits contemporaneous with the deposition of the Springfield. He believes that these channel-fill deposits represent interconnected principal and secondary fluvial distributary channels of a major delta lobe.

Direct determination of the ecologic setting of the Springfield Coal Member is not possible, but paleoecologic variation can be inferred by studying changes in coal thickness, chemistry, palynology, paleobotany, and coal petrography. Most of the coal adjacent to the contemporaneous distributary channels is low in sulfur and significantly thicker than the coal that is distant from the channels; these differences probably reflect the influence of the freshwater environment.

Palynologic data (1952) shows that the Springfield flora varies between near and far from the channel. Although Neavel's petrographic study (1961) shows some variation between coal samples near and far from the distributary channel, more detailed coal petrographic work is

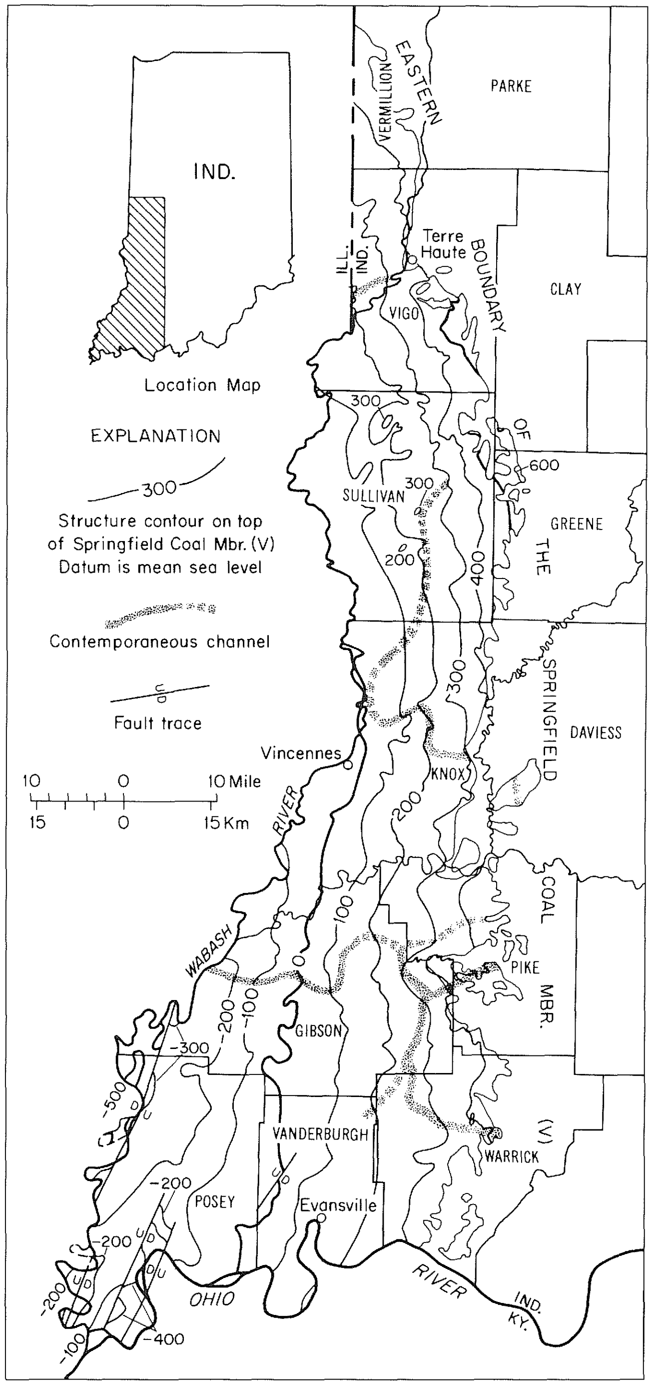

Figure 2. Structure, extent, and locations of contemporaneous channels of the Springfield Coal Member (V) in southwestern Indiana. Contour interval: 100 ft.

needed. Geochemical studies of trace elements and mineral matter in the Springfield Coal Member in Indiana have been inconclusive. The evidence now available indicates that the distributary channels were the principal ecologic factors controlling the deposition of the coal.

The Springfield Coal owed its development to the delta platform on which peat flourished. When the delta lobe was abandoned, the peat swamps were eventually choked out by marine advance as compactional and tectonic subsidence continued. The brackish to marine environment that covered the swamp produced the black shales and limestones that in most places overlie the Springfield. Prodelta and deltaic deposits that overlie the marine beds of the Dugger represent the development of the next deltaic advance into southwestern Indiana.

ECONOMIC GEOLOGY

History of mining

Thirty-five percent of the more than 25 million short tons (23 million t) of coal produced annually in Indiana is from the Springfield Coal Member; it has been the most widely mined coal in Indiana. The Springfield and other coals exposed near the Ohio River in southwestern Indiana have been mined since before 1800, when the coals were first put to domestic use by pioneer settlers.

One of the first commercial mines reported, probably in the Springfield, was opened about 1818 near the Ohio River in Warrick County, but this mine was soon abandoned for financial reasons. Later, as Welsh, English, and other European immigrants with mining experience arrived, numerous shallow shaft and slope mines were opened along the outcrops. By the mid 1800s, steamboats on the Ohio and Wabash Rivers were using Indiana coal, and some coal was being exported from the state to markets down the Ohio River.

Coal production in Indiana increased rapidly after about 1900. In 1918, production, mainly from underground mines, reached 30.7 million tons (28 million t), a level that has not been reached since. Production slackened after World War I, and mining technology changed. Large draglines and other mining machinery made stripping of thick overburden feasible, and coal could be produced cheaper by strip mining than by expensive, labor-intensive underground mining. World War II provided another boom for the coal industry; new underground mines were opened, and strip-mine production, much of it from the Springfield, increased dramatically. After the war, production again dropped because coal could not compete favorably as a fuel with the cleaner and cheaper oil and gas. The increasing use of coal for generating electricity, however, saved the day for the coal industry. Today 97 percent of electrical generation in Indiana is by coal.

After World War II, most underground mines were abandoned, even though efficient underground mining machinery had increased production per man-hour worked and had decreased the cost of producing the coal. Underground-mined coal still cannot compete with the less expensive strip-mined coal for most markets. Of the 116 mines operating in Indiana today, only four are underground mines, and three of these produce coal from the Springfield Coal Member.

Reserves

Total original reserves of the Springfield Coal Member were 12.9 billion short tons (12 billion t) (table 2). This figure represents about 39 percent of the total original reserves of coal in Indiana. Most of the tonnage was in Gibson, Posey, Sullivan, Vigo, Warrick, Knox, Vanderburgh, and Pike Counties.

As of January 1978, almost 1.2 billion short tons (1.1 billion t) of the Springfield had been mined or lost in mining in 13 of the 14 counties of southwestern Indiana where this coal occurs. No Springfield coal has been produced in Posey County. Major production from this coal seam has been in Pike, Vigo, Warrick, Knox, Vermillion, Gibson, Sullivan, and Greene Counties. Remaining reserves total 11.7 billion short tons (11 billion t), of which about 6.1 billion short tons (5.5 billion t) can be considered recoverable by current mining technology. Most of these reserves are in Gibson, Posey, Sullivan, Vanderburgh, Vigo, Knox, Warrick, and Pike Counties.

Strippable reserves. To date, 482 million short tons (437 million t) of Springfield coal has been strip mined or lost in mining in Indiana (table 2). This leaves reserves of 748 million short tons (679 million t). At 85-percent recovery, nearly 636 million short tons (577 million t) of reserves are available with a maximum of 90 feet (27 m) of overburden. The biggest production of strip-mined coal has been in Pike, Warrick, and Sullivan Counties, and the most strippable reserves are in Warrick, Pike, Vigo, Sullivan, and Greene Counties.

Deep minable reserves. Slightly more than 702 million short tons (637 million t) of Springfield coal has been mined or lost in mining in underground mines in Indiana (table 2). This leaves a reserve of nearly 11 billion short tons (10 billion t). At 50-percent recovery, almost 5.5 billion short tons (5 billion t) of these reserves are recoverable by current mining techniques. Most of the deep-mined coal has been produced in Vigo, Knox, Gibson, and Vermillion Counties, and most of the underground minable reserves are in Gibson, Posey, Sullivan, Vanderburgh, Knox, Vigo, Warrick, and Pike Counties.

Mining possibilities

Indiana's coal industry is gearing for increased production. Estimates indicate that production will at least double during the next 20 years. Not only the large coal companies, but also many smaller operators, are involved in this upswing, and the number of operators is increasing almost daily.

Strip mining. Most of Indiana's coal production is from strip mines. While it is true that most, if not all, of the large blocks of strip-minable coal are currently being worked, the increased number and size of the stripping machines that are being installed at currently active mines are not only

TABLE 2. Coal reserves of Springfield Coal Member (V) in Indiana, in thousands of short tons.

County	Original reserves	Mined and lost			Remaining reserves			Recoverable reserves		
		Underground	Strip	Total	Underground	Strip	Total	Underground	Strip	Total
Clay	19,682	5,092	1,236	6,328	—	13,354	13,354	—	11,351	11,351
Daviess	65,567	19,003	—	19,003	12,879	33,685	46,564	6,440	28,632	35,072
Gibson	2,950,657	110,078	1,242	111,320	2,839,337	—	2,839,337	1,419,669	—	1,419,669
Greene	146,910	34,669	16,483	51,152	3,348	92,410	95,758	1,674	78,549	80,223
Knox	1,090,598	112,022	5,137	117,159	932,414	41,025	973,439	466,207	34,871	501,078
Parke	1,618	1,053	—	1,053	—	565	565	—	480	480
Sullivan	1,743,338	30,072	78,254	108,326	1,558,890	76,122	1,635,012	779,445	64,704	844,149
Vanderburgh	1,047,740	19,006	—	19,006	1,028,734	—	1,028,734	514,367	—	514,367
Vermillion	257,081	106,385	6,874	113,259	129,185	14,637	143,822	64,593	12,441	77,034
Pike	911,710	38,226	215,453	253,679	502,297	155,734	658,031	251,149	132,374	383,523
Posey	2,327,695	—	—	—	2,327,695	—	2,327,695	1,163,848	—	1,163,848
Spencer	675	540	—	540	—	135	135	—	115	115
Vigo	1,232,707	184,633	20,750	205,383	931,716	95,608	1,027,324	465,858	81,267	547,125
Warrick	1,098,423	41,509	137,053	178,562	695,182	224,679	919,861	347,591	190,977	538,568
Total	12,894,401	702,288	482,482	1,184,770	10,961,677	747,954	11,709,631	5,480,841	635,761	6,116,602

increasing coal production but also are increasing strippable reserves. The calculated strippable reserves (table 2) contain only coal with a maximum 90 feet (27 m) of overburden. But additional and larger-sized stripping machines will make possible coal reserves having overburden of more than 90 feet (27 m) to perhaps as much as 150 feet (46 m) or more. Reserves of strippable coal could thus be increased by as much as 50 percent. Probably such expansion will be controlled by economics; that is, the point at which the cost of strip-mining becomes greater than the cost of underground mining. An additional factor will be government regulation, such as that forbidding stripping of prime farmland.

Underground mining. Because deep minable reserves are tenfold or more greater than strippable reserves, it is apparent that eventually deep mining will again become the method by which most of Indiana's coal is produced. Several large blocks of deep-lying coal are being prospected and engineered for development by large coal producers. Smaller business groups are also directing their attention toward deep mining. In fact, two new small underground mines began operating in Indiana in 1978.

REFERENCES

ADAMS, S. A., in preparation, Roof strata associated with low-sulfur Springfield coal in Sullivan County, Indiana.

BRITTAIN, A. E., 1975, Geometry, stratigraphy, and depositional environment of the Springfield coal and the Dugger Formation (Pennsylvanian) north of Winslow, Pike County, Indiana: Unpublished M.S. thesis, Bloomington, Indiana University, 64 p.

BURGER, A. M., and C. E. WIER, 1970, Stendal Limestone Member *in* R. H. Shaver and others, Compendium of rock-unit stratigraphy in Indiana: Indiana Geological Survey Bulletin 43, p. 229.

CUMINGS, E. R., 1922, Nomenclature and description of the geological formations of Indiana, *in* W. N. Logan, Handbook of Indiana geology: Indiana Department of Conservation Publication 21, pt. 4, p. 403-570.

EGGERT, D. L., in preparation, A contemporaneous fluvial channel associated with the Springfield Coal Member in northeastern Warrick County, Indiana: Indiana Geological Survey.

FRIEDMAN, S. A., 1954, Distribution, structure, and mined areas of coals in Gibson County, Indiana: Indiana Geological Survey Preliminary Coal Map 4.

FRIEDMAN, S. A., 1956, Split and channel sandstone cutout in Coal V in the Dresser area, Vigo County, Indiana: Indiana Academy of Science Proceedings for 1955, v. 65, p. 165-168.

FRIEDMAN, S. A., 1960, Channel-fill sandstones in the Middle Pennsylvanian of Indiana: Indiana Geological Survey Report of Progress 23, 59 p.

FRIEDMAN, S. A., 1961, Geology and coal deposits of the Terre Haute and Dennison quadrangles, Vigo County, Indiana: U.S. Geological Survey Coal Investigations Map C-44.

FULLER, M. L., and G. H. ASHLEY, 1902, Description of the Ditney quadrangle: U.S. Geological Survey Geological Atlas, Folio 84, 8 p.

GUENNEL, G. K., 1952, Fossil spores of the Alleghenian coals in Indiana: Indiana Geological Survey Report of Progress 4, 40 p.

HOPKINS, M. E., 1968, Harrisburg (No. 5) coal reserves of southeastern Illinois: Illinois Geological Survey Circular 431, 25 p.

HUTCHISON, H. C., 1958, Geology and coal deposits of the Seelyville quadrangle, Vigo County, Indiana: U.S. Geological Survey Coal Investigations Map C-27.

KHAWAJA, I. K., 1975, Pyrite in the Springfield Coal Member (V), Petersburg Formation, Sullivan County, Indiana: Indiana Geological Survey Special Report 6, 24 p.

NEAVEL, R. C., 1961, Petrographic and chemical composition of Indiana coals: Indiana Geological Survey Bulletin 22, 81 p.

PEPPERS, R. A., 1970, Correlation and palynology of coals in the Carbondale and Spoon Formations (Pennsylvanian) of the northeastern part of the Illinois Basin: Illinois Geological Survey Bulletin 93, 173 p.

PICKERING, R. J., 1953, An analysis of selected Indiana coals by the particle count method: Indiana Geological Survey Report of Progress 6, 23 p.

PRYOR, W. A., and E. G. SABLE, 1974, Carboniferous of the Eastern Interior Basin, *in* Garrett Briggs [ed.], Carboniferous of the southeastern United States: Geological Society of America Special Paper 148, p. 281-313.

WANLESS, H. R., and others, 1963, Mapping sedimentary environments of Pennsylvanian cycles: Geological Society of America Bulletin, v. 74, p. 437-486.

WANLESS, H. R., and others, 1969, Conditions of deposition of Pennsylvanian coal beds, *in* E. C. Dapples and M. E. Hopkins [eds.], Environments of coal deposition: Geological Society of America Special Paper 114, p. 105-142.

WANLESS, H. R., and others, 1970, Late Paleozoic deltas in the central and eastern United States, *in* J. P. Morgan and R. H.

Shaver [eds.], Deltaic sedimentation, modern and ancient: Society of Economic Paleontologists and Mineralogists Special Publication 15, p. 215-245.
WIER, C. E., 1950, Geology and mineral resources of the Jasonville Quadrangle, Indiana: A.M. thesis, Bloomington, Indiana University, 44 p.; Indiana Geological Survey Bulletin 6, 34 p., 1952.
WIER, C. E., 1952, Distribution, structure, and mined areas of coals in Vigo County, Indiana: Indiana Geological Survey Preliminary Coal Map 1.
WIER, C. E., and H. H. GRAY, 1961, Geologic map of the Indianapolis 1° x 2° quadrangle, Indiana and Illinois, showing bedrock and unconsolidated deposits: Indiana Geological Survey Regional Geologic Map [1].
WIER, C. E., and H. C. HUTCHISON, 1977, Reduction of sulfur in Indiana coal by washability techniques: Indiana Geological Survey Bulletin 55, 61 p.
WIER, C. E., and R. L. POWELL, 1967, Distribution, structure, and mined areas of coals in Knox County, Indiana: Indiana Geological Survey Preliminary Coal Map 12.
WIER, C. E., and J. T. STANLEY, 1953, Distribution, structure, and mined areas of coals in Pike County, Indiana: Indiana Geological Survey Preliminary Coal Map 3.

Sedimentology of a paleovalley fill: Pennsylvanian Kyrock Sandstone in Edmonson and Hart Counties, Kentucky

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REGIONAL SETTING

Paleovalleys at the base of the Pennsylvanian System in the Illinois Basin have been recognized in outcrop and subsequently have been mapped in subsurface. Notable subsurface studies include those by Shiarella (1933), Siever (1951), Wanless (1955), Potter and Desborough (1965), and most recently by Bristol and Howard (1971). Bristol and Howard have produced a spectacular and very detailed basin-wide map (fig. 1).

These paleovalleys are best exposed in outcrop in Kentucky and Indiana. Along the eastern outcrop of the Illinois Basin, from its southeastern corner northward into Indiana, outcrop mapping has revealed four major paleovalleys (table 1). The most spectacular is the Brownsville paleovalley (Bristol and Howard, 1971, table 2) that extends across portions of Edmonson and Hart Counties, Kentucky (fig. 2); scattered remnants occur as far east as Larue County, Kentucky. Additional residual Pennsylvanian debris, which may have been part of the Brownsville paleovalley, occurs in scattered, irregular patches along the Muldraugh Escarpment across the Cincinnati Arch. Early accounts of this paleovalley have been given by Miller (1910), Burroughs (1923), and Weller (1927, p. 151-158). It was David Dale Owen (1856), writing in *Report of the Geological Survey of Kentucky during the years 1854 and 1855,* who first recognized the Brownsville paleovalley at the junction of Dismal Creek and the Nolin River, just south of the present Nolin Dam (an original drawing by Owen of this exposure is reproduced as the frontispiece). His description and interpretation still merit consideration (p. 154-166):

> A remarkable feature in the geology of Edmonson County is witnessed at the mouth of Dismal Creek . . . . One hundred and fifty-five feet of pebbly sandstone and conglomerate appears here in vertical escarpment, . . . resting on Archimedes limestone . . . and occupying, therefore, the place of the alternations of limestone, sandstone, chert, marly shales . . . . We are led to infer, from this local modification of the order of superposition, either that the horizontal continuity of the strata of deposition was interrupted at the mouth of Dismal Creek, and some very local cause operated to produce an entirely different sediment from that accumulating to the south, or, what is perhaps more probable, powerful local currents, sweeping over this point, first carried away some one hundred and fifty feet of the original material forming the ocean's bed, the denuded space being subsequently filled in with sand and gravel, when the force of the rushing waters was in some measure retarded. The very local position of the conglomerate, at the base of our Coal Measures, and its prevalence in the vicinity of the principal water courses, in valleys along which we might expect ancient currents to have been directed, lends probability to this latter conclusion.

STRATIGRAPHY

In the area of figure 2, basal Pennsylvanian sediments generally lie on Chesterian formations ranging from the Leitchfield to the Golconda (fig. 3). About 66 meters (200 ft) of the Chesterian sediments have been eroded, and the excavation is filled by the Kyrock Sandstone, first named by McFarlan (1943, p. 109) for exposures near Kyrock, Edmonson County, Kentucky (21-J-39, Bee Spring quadrangle). This unit has a maximum thickness of about 46 meters (150 ft) and consists principally of coarse- to medium- to fine-grained, cross-bedded, commonly pebbly sandstone and some local lenses of quartz pebble conglomerate. Its lower part is more consistently pebbly and coarser than is its upper part. This division is easily recognized throughout most of the study area shown in figure 2, especially in the eastern part (fig. 4).

A detailed transverse structural cross section across the paleovalley also shows these two portions of the fill (fig. 5). In addition, this section demonstrates how quickly the Kyrock Sandstone can change its thickness along the margins of the paleovalley—from as little as 5 meters (15 ft) to more than 20 meters (60 ft) in only 131 meters (400 ft) laterally.

BURIED TOPOGRAPHY

In Edmonson and Hart Counties, in the Bee Spring, Nolin Reservoir, and Cub Run geologic quadrangles where we

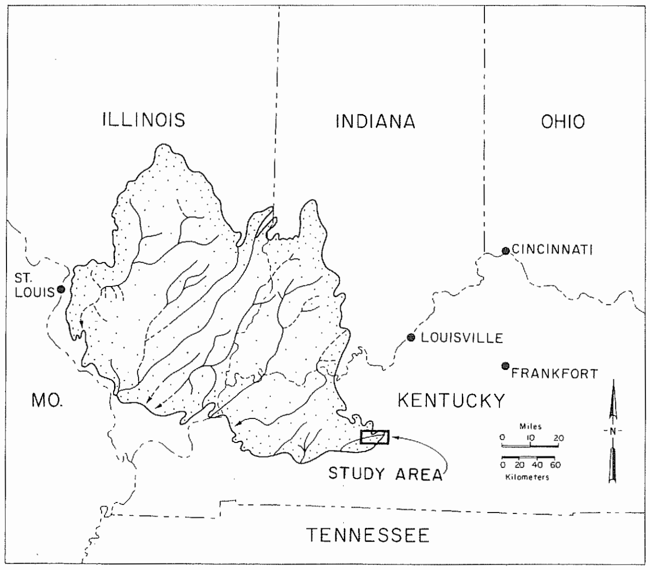

Figure 1. Pre-Pennsylvanian paleovalleys in the Illinois Basin. (After Bristol and Howard, 1971, fig. 1.) Note southwestern orientation of paleovalleys.

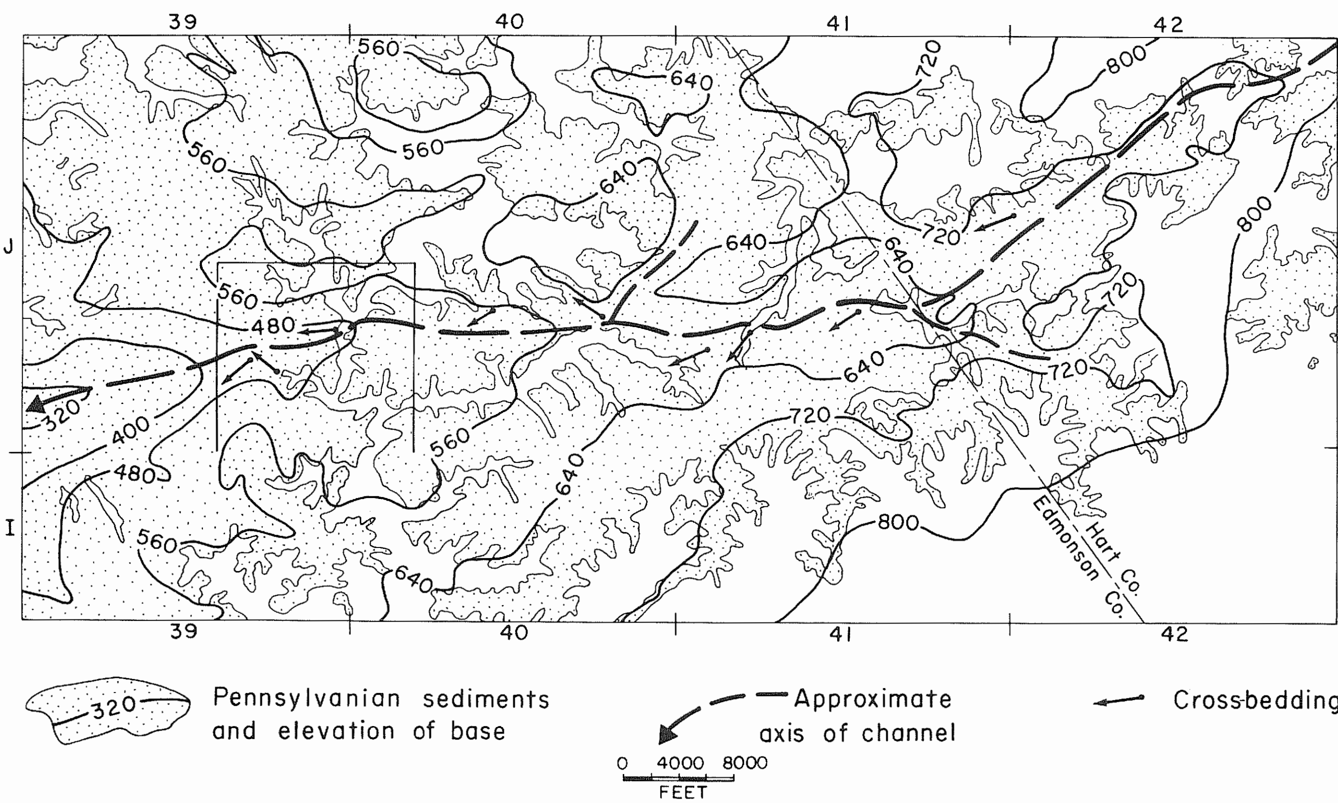

Figure 2. Pennsylvanian sediments and generalized structure at their base in portions of Edmonson and Hart Counties, Kentucky. Structure contours based on more than 300 elevations taken from published geologic quadrangle maps. Note close correlation between orientation of cross-bedding and axis of Brownsville paleovalley. Contour interval: 80 ft.

TABLE 1. Notable Pre-Pennsylvanian paleovalleys on east side of Illinois Basin.

Location	Salient features	References
Edmonton and portions of Butler and Hart Counties, Kentucky.	Most spectacular of all paleovalley outcrops in Illinois Basin; traceable for over 83 km (50 mi). As much as 66 m (200 ft) of Chesterian sediments eroded at base. Width varies from 3 to 5 km (2 to 3 mi). Mostly thick bluffs of pebbly, cross-bedded sandstone. Parts of paleovalley have core islands. Strikes S70W and S30W. Paleocurrents to southwest. Named Brownsville paleovalley (Bristol and Howard, 1971, fig. 4).	Owen (1856), Miller (1910), Burroughs (1923), Weller (1927, p. 151-158), Potter and Siever (1956, fig. 6), Klemic (1963), Sandberg and Bowles (1965), Gildersleeve (1965, 1968, 1971), Shawe and Gildersleeve (1969), Miller (1969), and Moore (1973).
Hawesville, Hancock and Perry Counties, Kentucky and Indiana.	Over 41 m (125 ft) of eroded Chesterian sediments. Striking bluffs of pebbly, cross-bedded sandstone. Near-vertical paleovalley wall south of Indian Lake on Cannelton quadrangle. Probably part of Madisonville paleovalley (Bristol and Howard, 1971, fig. 4).	Malott (1950, p. 240), Spencer (1964), and Bergendahl (1965).
Indian Springs and Shoals, Indiana.	At Indian Springs contours on pre-Pennsylvanian show 46 m (140 ft) of relief; paleovalley strikes S45W and S30W. Dendritic paleoflow to southwest. Indian Springs paleovalley probably connects with the one at Shoals. Part of Evansville paleovalley (Bristol and Howard, 1971, fig. 4).	Malott (1931, p. 229-231) and Potter and Olson (1954, fig. 6).
Huron, Lawrence County, Indiana.	Structure map of unconformity outlines a paleovalley about 0.8 km (0.5 mi) and 33 to 39 m (100 to 120 ft) deep. Paleovalley trends S20W and S45W; probably connects with paleovalley at Shoals. Both part of Evansville paleovalley (Bristol and Howard, 1971, fig. 4).	Gray, Jenkins, and Wiedman (1960, p. 29-35).
Budda outlier, Lawrence County, Indiana.	Very friable, pebbly Pennsylvanian sandstone exposures about 16 km (10 mi) east of the main outcrop. Rests on St. Louis Limestone; basal contact may be much modified by solution. Probably connects with paleovalley at Huron.	Malott (1946).

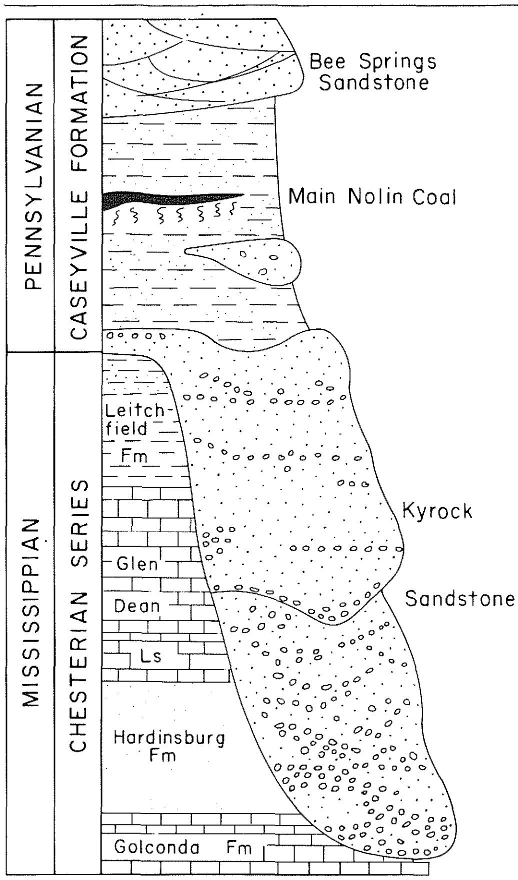

Figure 3. Generalized stratigraphic section of Pennsylvanian and Mississippian sediments near Nolin Reservoir, Edmonson County, Kentucky.

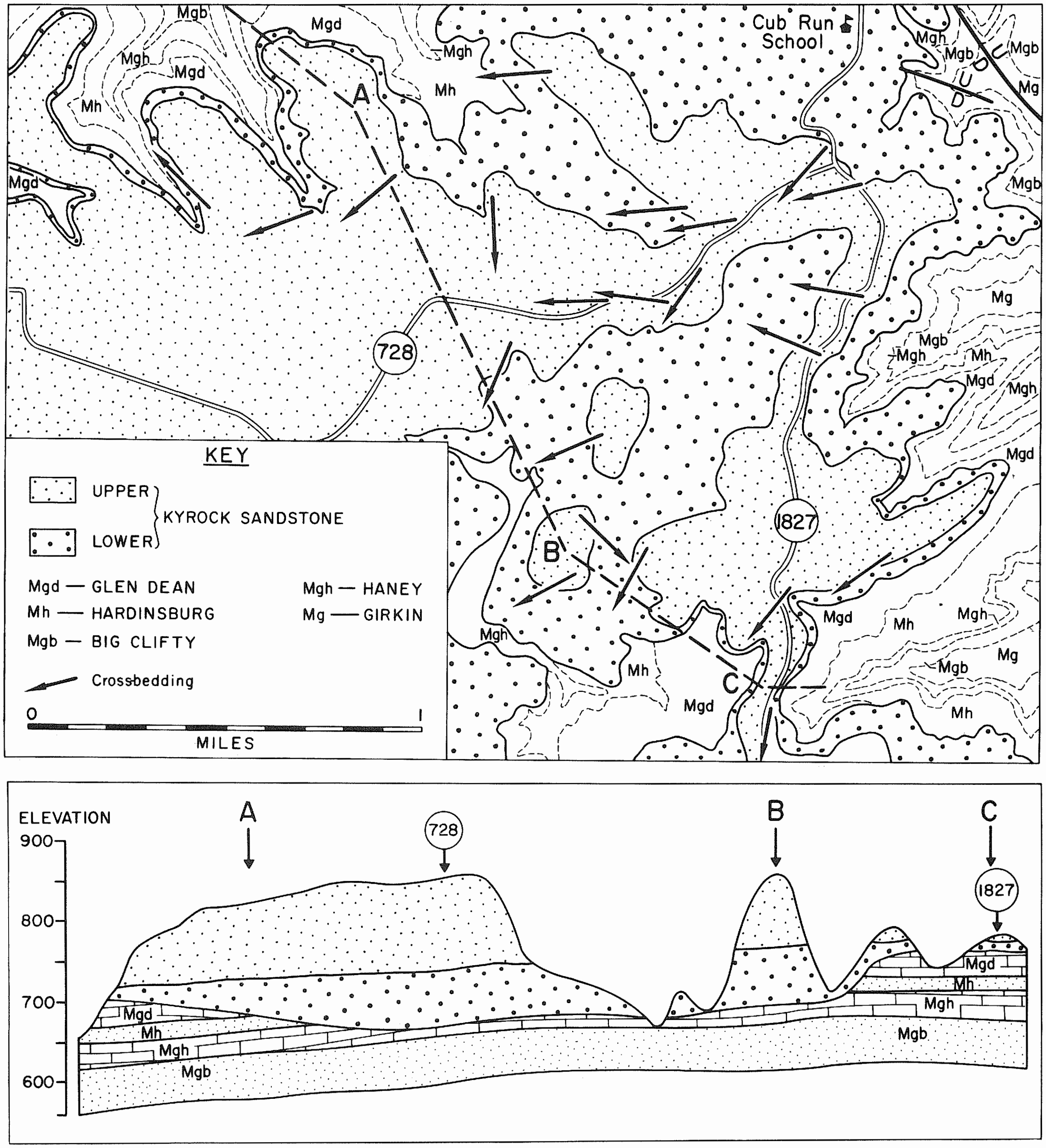

Figure 4. Paleocurrent map and cross section of lower pebbly and upper part of Kyrock Sandstone near Cub Run, Hart County, Kentucky. Chesterian contacts taken from Cub Run quadrangle (Sandberg and Bowles, 1965).

worked, the Brownsville paleovalley varies from a maximum width of almost 5 kilometers (3 mi) near its western outcrop along the Nolin River to a minimum of somewhat less than 3 kilometers (2 mi) on the eastern border of the Cub Run quadrangle (fig. 2). Thus, over a distance of 30 kilometers (18 mi), the paleovalley appears to widen only a small amount.

On the generalized structure map (fig. 2), an overall dendritic pattern prevails. Tributary paleovalleys generally join the main paleovalley at an angle of about 60 degrees.

A feature noted by Shawe and Gildersleeve (1969, p. 206-207) and confirmed by us is that the sides of the Brownsville paleovalley are terraced or stepped. This mapping suggests that the paleovalley has two parts: a sharply

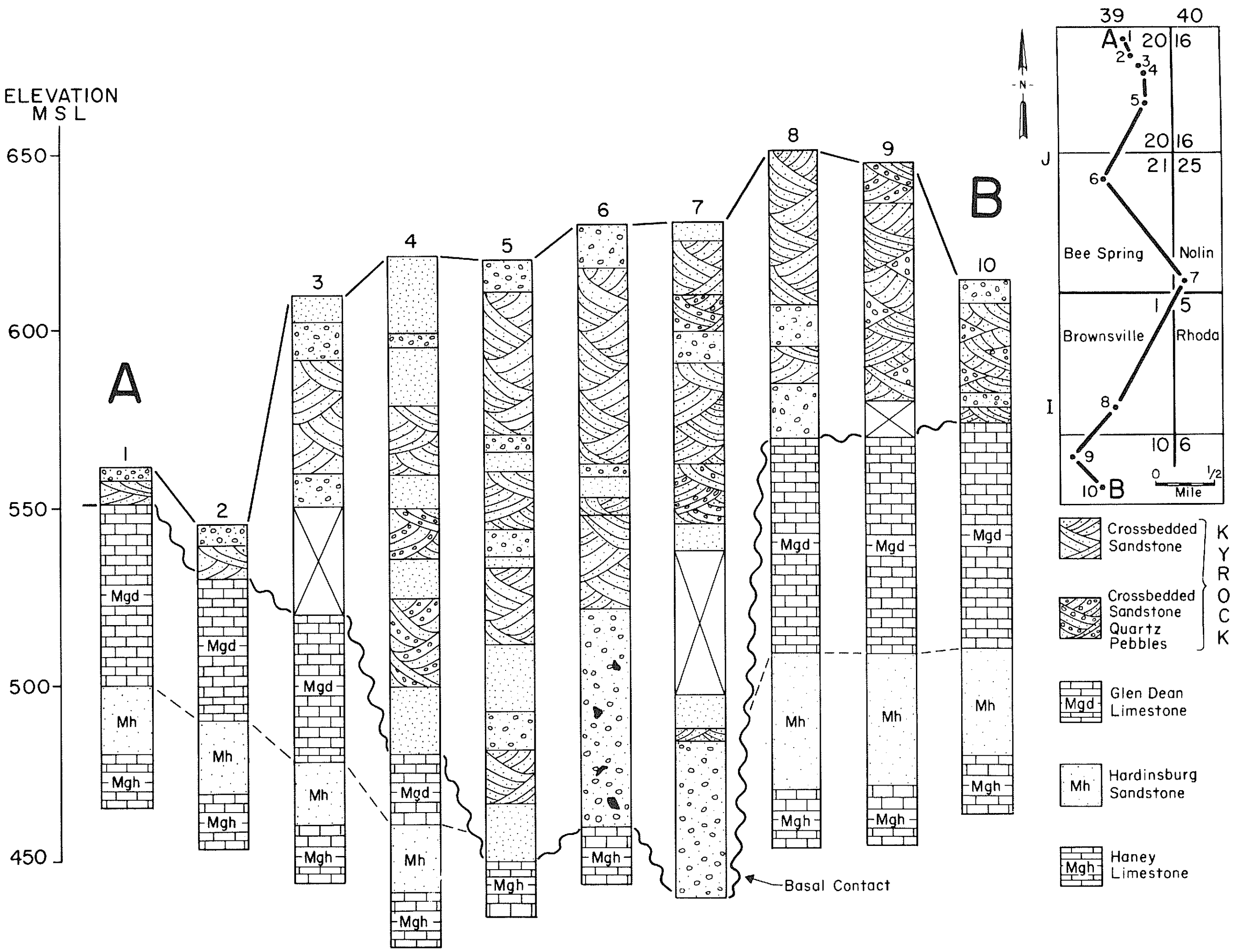

Figure 5. Outcrop cross section approximately at right angles to Brownsville paleovalley in portions of Bee Springs, Nolin, and Brownsville quadrangles. Locations of sections: (1) 1000 FNLx2000 FEL, 20-J-39; (2) 1800 FNLx2000 FEL, 20-J-39; (3) 2400 FNLx1600 FEL, 20-J-39; (4) 2600 FNLx1500 FEL, 20-J-39, (5) 2400 FSLx1400 FEL, 20-J-39; (6) 1300 FNLx1400 FWL, 21-J-39; (7) 500 FWLx500 FSL, 25-J-40; (8) 1700 FWLx1600 FSL, 1-I-39; (9) 600 FWLx1100 FNL, 10-I-39; and (10) 1600 FWLx2000 FNL, 10-I-39.

entrenched inner valley that is bordered by shallowly entrenched, outer margins. At the Nolin Dam, the boundary between these two parts descends 33 meters (100 ft) in little more than 131 meters (400 ft) (fig. 6). Shawe and Gildersleeve (1969, p. 207) and Siever (1951, p. 574) noted that Chesterian limestones are commonly the bench formers—a fact that does not easily harmonize with a presumed warm, humid, subtropical climate as inferred from both the coal beds of the Pennsylvanian and paleolatitude (Frederiksen, 1972).

Wherever we saw the Mississippian-Pennsylvanian contact, it was sharp and did not have a weathered zone below it. With few exceptions, there is little Chesterian rubble at the contact.

The present gradient of the paleovalley, which includes the original gradient and later structural warping to the west, is about 7.2 meters per kilometer (22 ft/mi).

The buried Mississippian paleotopography has a youthfully dissected surface devoid of deep weathering. In contrast, the Brownsville paleovalley has sharply defined walls and is fairly straight, and commonly has turns of only 15° to 25°. Several tributaries enter the main paleovalley at about 60°, and some core islands appear to be present.

MAJOR FACIES OF THE FILL

The two major divisions of the fill of the paleovalley are a pebbly, restricted lower sandstone and a more widely spread upper sandstone. Table 2 summarizes most characteristics of the two divisions. The exposures at the east side of the dam show well the two sandbodies and the overlying shale (fig. 7).

Pebbly lower sandstone

This medium- to coarse-grained, friable sandstone typically has median sizes between 0.6 to 0.4 mm and is dominantly cross-bedded. Thickness ranges up to 20 meters (60 ft). As far as we could determine, the pebbly lower unit is limited to the inner, deeply entrenched portion of the paleovalley

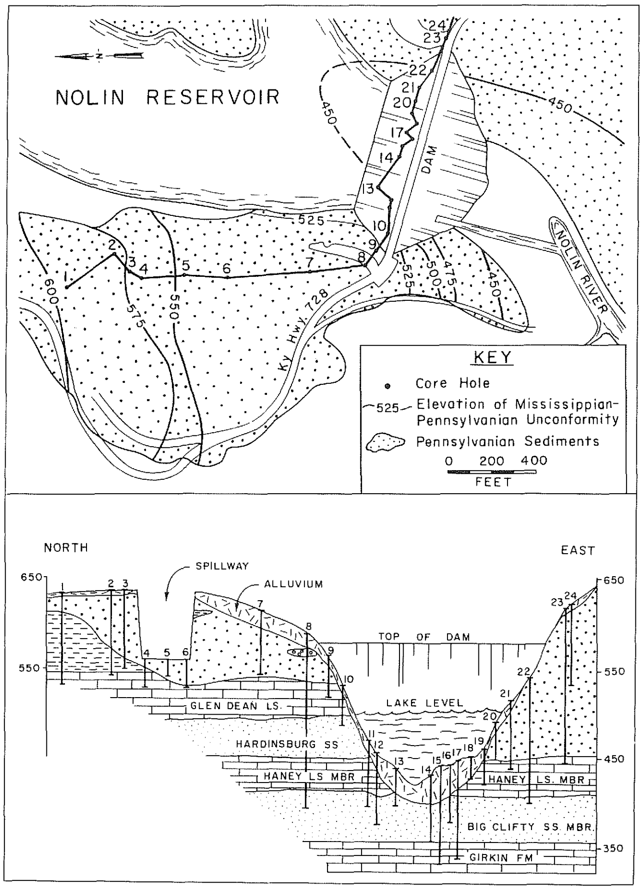

Figure 6. Kyrock Sandstone, elevation of base and cross section. Map based on coreholes described by U.S. Army Corps of Engineers. Map and cross section show "inner" and "outer" boundaries of northwest side of Brownsville paleovalley.

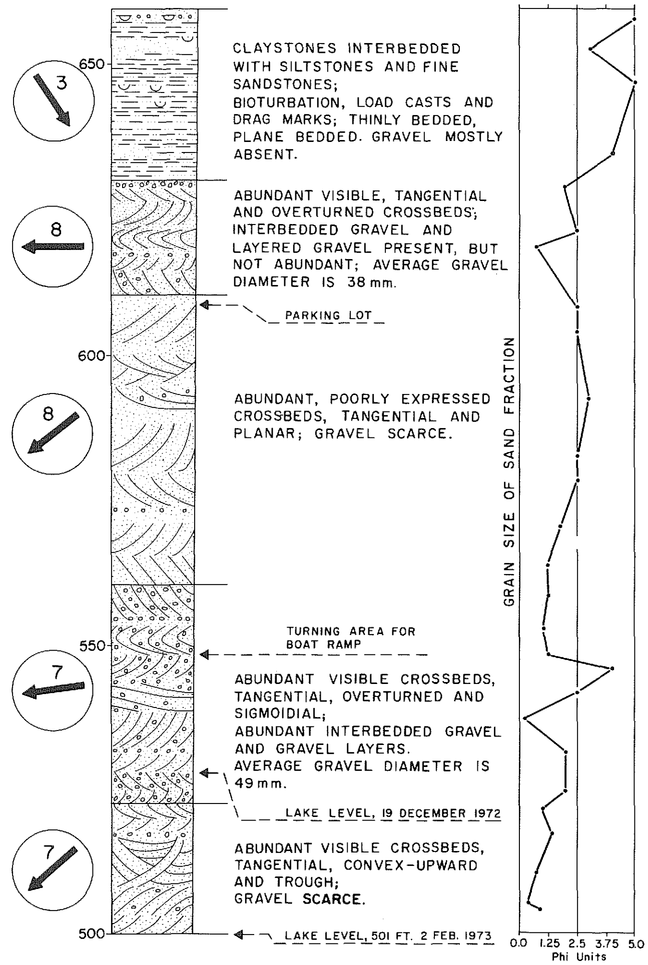

Figure 7. Stratigraphic section, paleocurrents, and modal grain size immediately east of Nolin Dam along access road to landing ramp and state route 728.

TABLE 2. Essential characteristics of Kyrock Sandstone.

Configuration

Dimensions—A large erosional valley about 3 mi wide, as much as 66 m (200 ft); continuously traceable in outcrop for over 56 km (35 mi); scattered outcrops extend to 80 km (50 mi). Largest paleovalley outcropping in basin.

Orientation—Paleovalley trends S 40° to 70° W perpendicular to local depositional strike of basin in Pennsylvanian time.

Position in basin—At southeastern corner of Illinois Basin; one of several paleovalleys that entered from the east and therefore crossed the exposed axis of the Cincinnati Arch.

Bounding units

Basal contact—Sharply disconformable with underlying Chesterian rock of which locally approximately 66 m (200 ft) have been eroded (Litchfield to Golconda Formations).

Upper contact—Commonly an abrupt transition to an overlying shale that contains the Nolin Coal.

Internal characteristics

Sedimentary structures and bedding—Tabular and trough cross-beds, mostly between 20 and 60 cm thick, are predominant; well-oriented paleoflow is parallel to channel axis to southwest. Thickest units most common at base. Some apparently massive bedding plus generally thin zones of flat bedding. Minor ripple bedding and soft sediment deformation. Some large channel scours and fills near top.

Constituents—Mostly subangular to well-rounded grains of unit quartz and some polycrystalline quartz and minor detrital muscovite, clay matrix, and rock fragments. Well- to sub-rounded quartz granules and pebbles are conspicuous at many outcrops. Also present are a few chert pebbles and a few, very rare dolomitic ones. A thin, but locally persistent, pebble band occurs at the top of the sandstone body. Locally derived clay galls are common.

Texture—Mostly fine to medium, well-sorted sandstone with a general, but weak, tendency to fine upward. Good outcrop-induced porosity.

Fossils—Almost totally absent except for a few plant remains, some of which are concentrated along major scour surfaces.

Organization

Two major sandstone units, each about 33 m (100 ft) thick, fill the paleovalley. Lower unit has more gravel than upper unit. Upper unit is commonly well expressed on topographic maps. Upper unit has 3 or more fining upward cycles defined by cross-bedding → flat bedding → disconformity. Lateral continuity of bedding appears to be limited except for pebble band at very top. Complex multistory sandstone body.

and perhaps forms, by volume, about 20 to 30 percent of the Kyrock. The granules, pebbles, and cobbles of the lower sandstone are its most striking feature. Locally, beds of conglomerate are as thick as 2.0 to 3.8 meters (6 to 12 ft).

The median size of the quartz pebble conglomerate near the dam is typically 4.8 mm to 2.8 mm. Sand less than 2 mm commonly accounts for about 30 to 40 percent of the conglomeratic beds.

Cross-bedding is characteristic of the pebbly sandstone body (table 3). About 70 to 80 percent of the lower body is visibly cross-bedded, and planar cross-bedding predominates. Cross-beds usually range from 10 cm to more than a meter. Maximum length is 21 meters (65 ft) and maximum width is 11 meters (33 ft). A few cross-beds have overturned foresets. Quartz granules and pebbles may be scattered throughout a bed, but are more common as lags along scour surfaces at their tops and bottoms. Virtually no shale laminations occur within the sandstone body, nor are vertical variations in bedding types apparent. Most of the true conglomeratic beds are massive, but pebbles exposed on their bedding planes usually show a weak orientation. All paleocurrents are unidirectional and show little dispersion; in general, they conform closely to the axis of the paleovalley (figs. 2, 4, and 8). Lateral continuity of lithic units, including the conglomeratic beds, is limited. No invertebrate fossils of any kind nor any bioturbation were observed.

Upper sandstone body

In all observations, the upper sandstone body overlies the lower body, is two to four times wider, and extends to the outer limits of and beyond the paleovalley. Thickness ranges from more than 32 meters (100 ft) to as little as 3 meters (10 ft); thinning is particularly abrupt near the limits of the paleovalley, where only ledges or small cliffs are present (fig. 5, sections 1 and 2).

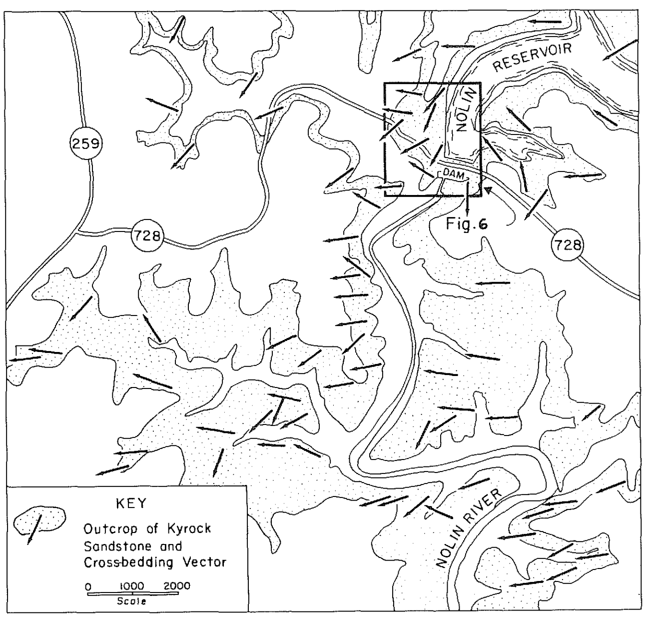

Figure 8. Outcrop of Kyrock Sandstone and its paleocurrents. Note flow to southwest.

TABLE 3. Structures and bedding in upper and pebbly Kyrock Sandstone.

Upper	Pebbly
Bedding types—Planar and tangential cross-beds, ripple mark, parting lamination, small slumps and massive beds; some shale and shaly beds.	Planar and tangential cross-beds; ripple mark and parting laminations rare; shale virtually absent.
Prevalence—Planar and tangential cross-beds predominate; ripple mark and parting lamination minor.	Planar cross-bedding more abundant than tangential.
Distribution—Clearly defined fining-upward cycles of about 5 to 7 m (15 to 20 ft); thick planar beds at base pass to trough cross-beds upward, followed by parting lamination and ripple mark.	No vertical sequence.

Grain size typically ranges from 0.30 mm to 0.137 mm, and standard deviations are commonly between 0.4 and 0.7 phi, so that the sandstone is mostly moderately well sorted. Siliceous pebbles and granules, mostly quartz, are present, but are much less abundant than in the lower sandstone body. Only a few conglomerate beds are present; most of the siliceous pebbles and granules are concentrated on widely scattered bedding planes and at the base of fining-upward sequences. Some clay-ironstone pebbles are also present. Shale-clay galls are, however, more abundant than in the lower body principally because of the greater abundance of shale laminations and beds, especially in the upper 13 meters (40 ft). Most of these shale beds appear to occur as channel fillings. Some small shaly slumps and slides also are present; some are associated with the shale interbeds. The spillway section of the dam has the best exposures of the upper sandstone body. Here, medium- to dark-gray, silty shale containing some plant debris occurs at several levels, usually near the tops of fining-upward cycles defined by decrease in grain size, change in sedimentary structures, and basal conglomerates that are principally composed of ironstone pebbles and concretions.

Three fining-upward cycles are present, and a probable fourth is exposed in the floor of the spillway (fig. 9). The thickness of each cycle is about 5 to 6 meters (15 to 20 ft); the top is usually truncated. Similar cycles probably exist throughout the upper sandstone body.

The sedimentary structures of the upper body are more diverse than those of the lower body. In addition to more abundant planar and trough cross-bedding, parting lamination and ripple marks are fairly common, especially at the tops of fining-upward cycles. Cross-bedding type varies from the position in the cycle ranging from mostly planar at the base of a cycle, to trough near the top. Thickness of cross-bedding decreases upward in the cycle; median thickness is about 30 cm. Overall, cross-beds probably form from 40 to 70 percent of the upper body. Some overturned cross-beds are present and scour surfaces are abundant.

Paleocurrents are generally to the southwest as in the lower sandstone body, but with a somewhat greater deviation (fig. 8). As in the lower body, bimodal cross-bedding

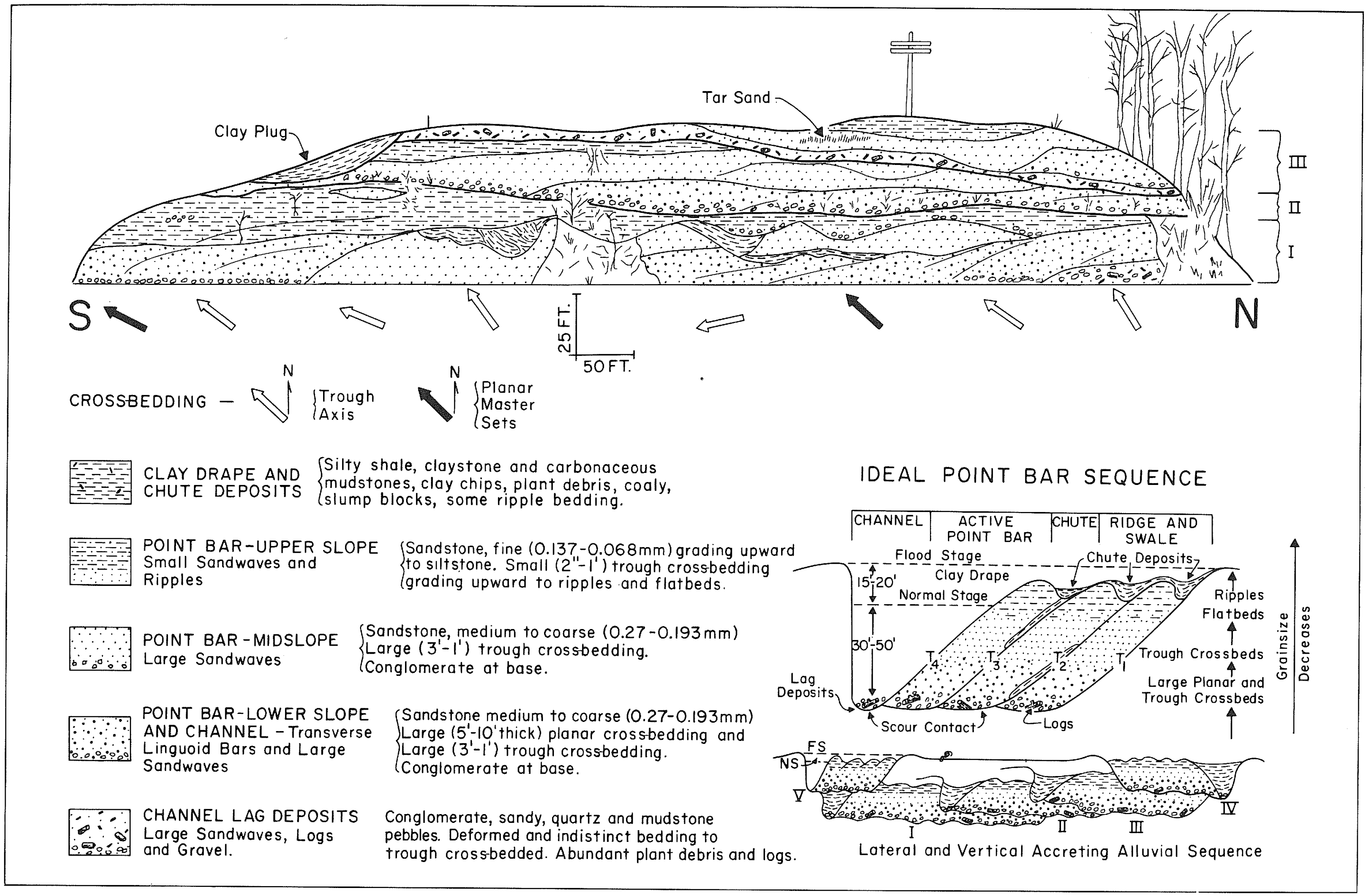

Figure 9. Spillway at Nolin Dam is best outcrop to see details of upper sandstone.

is absent. Fossil invertebrates are absent, but fossil logs are present, especially at the base of fining-upward cycles; bioturbation is rare.

Overlying post-Kyrock shale.

This unit is poorly exposed, but appears to consist of medium- to dark-gray silty shale, interlaminated siltstone, and a few small sandstone bodies, some of which are channel fills. Some bioturbation is present, but we found no marine fossils. Several thin, but minable coals, the Nolin Coals, occur in this shale. The best exposure of the shale is in the roadcut on Kentucky 728 east of the dam.

PETROGRAPHY

The typical Kyrock Sandstone is a moderately well sorted, 0.4 to 0.7 phi, subangular to subrounded, typically fine- to medium-grained, porous quartz-arenite ($Q_{95}F_{tr}L_5$) containing scattered granules and pebbles of rounded and well-rounded quartz.

Quartz is subangular to subrounded and consists of about 7 percent polycrystalline and 77 percent unit quartz. Rock fragments, which are mostly argillaceous, are subrounded or deformed and are commonly stained by limonite and hematite. Some contain quartz silt. Feldspar of all kinds is rare, but may be present as a trace. Only a few detrital muscovite grains are present. The principal transparent heavy minerals are zircon and tourmaline. The clay minerals of the Kyrock are chiefly kaolinite, illite, and some chlorite.

We also studied the thin-section petrography of the granules in the Kyrock. Our classification (table 4) has five varieties of quartz plus sandstone, siltstone, and chert. Three types of polycrystalline quartz were recognized: polycrystalline granules having crystals of markedly unequal "bimodal" sizes; those having well-oriented, elongate crystals, generally with strongly sutured contacts; and those consisting of a unimodal "well-sorted," anhedral mosaic. Unit single-crystal quartz also is present and is of two types: granules that have single, uniform extinction and those having a pseudo-fracture pattern.

Quartz granules are overwhelmingly predominant. Moreover, polycrystalline varieties are twice as abundant as unit quartz (table 4). Granules of sandstone and siltstone form 9 percent of the total. There is a trace of chert, and one recrystallized dolomite fragment was noted.

INTERPRETATION

We separated our interpretation into two parts: the local depositional environment and the broader, regional aspects. As in most studies, the one complements the other.

Local depositional environment

Observations and data from field and laboratory show that Kyrock Sandstone was deposited as the fluvial fill of a preexisting, subaerially excavated river valley. The most convincing evidence for the fluviatile origin of the Kyrock Sandstone occurs in the upper sandstone body, where three or more well-developed fining-upward sequences (fig. 9), which are typical of high sinuosity, river point-bar accumulations (Reineck and Singh, 1973, p. 225-263) are superimposed (table 4). The point-bar sequences are fairly complete; basal thalweg lag and pebble lag deposits are present on a scoured surface and are laterally accreted, and lower point-bar sands fine upward and are generally moderately to moderately well sorted. Cross-bedding shows the wide dispersion that is typical of high-sinuosity meandering river systems. There is no evidence, however, of the bimodal cross-bedding that is typical of many tidal deposits. The thickness and lateral extent of each complete sequence suggest meandering streams 5 to 9 meters (15 to 25 ft) deep and from about 196 to 328 meters (600 to 1000 ft) wide from bank to bank. Average current velocities, deduced from our data on grain size and from the modified Hjulstrom Curve (American Society of Civil Engineers Committee on Sedimentation, 1966, fig. 2), were probably on the order of 30 to 75 cm per second (1.0 to 2.5 ft/sec); maximum velocities were on the order of 121 cm per second (4.0 ft/sec), and discharge was estimated to be 25,000 cubic feet per second. This estimate of discharge is, of course, conjectural and is based on our collective field experience in the lower Wabash River valley of southwestern Indiana, whose channel dimensions, sediment load, and discharge characteristics are thought to be similar to that of the upper Kyrock.

The lower sand body exhibits some features typical of low-sinuosity braided stream systems (table 5): the bimodal textural characteristics of the pebbly sands are especially significant; low dispersion of the cross-bedding directions (generally parallel to the trend of the enclosing valley walls); lack of well-developed silt-clay units; abundance of planar cross-bedding; narrow lateral extent of the individual bedding units; and numerous reactivation surfaces.

Most geologic data, field and laboratory, strongly suggest a fluvial origin for the Kyrock fill of the Brownsville Valley. The early fill was deposited in a rapidly aggrading, low-sinuosity, braided stream system and was followed by the deposition from an aggrading, high-sinuosity, meander-

TABLE 4. Petrographic types of granules (245 granules).

Pebble type	Percentage	
Quartz		
Monocrystalline	27	
Single extinction		23
Pseudofracture		4
Polycrystalline	64	
Unimodal		23
Bimodal		38
Parallel-stretched		3
Sandstone	8	
Siltstone	1	
Sedimentary		trace
Recrystallized		1
Dolomite	trace	
TOTAL	100	

TABLE 5. Characteristics of meandering braided streams.

Characteristic	Meandering stream	Braided stream
Cyclical sequence	Prominent fining-upward cycles	Commonly absent or very poorly developed
Floodplain facies	Well-developed	Absent
Silt and clay	Much	Little
Plant material	Can be appreciable; may include peats and coals	Little
Cross-bedding	Abundant	Abundant
Variability of cross-bedding	Little to appreciable, depending upon sinuosity	Little to moderate
Channel scours	Moderate to abundant	Commonly abundant
Gravel	Absent to some	Some to appreciable

ing stream of moderate dimensions. The block diagram of figure 10 summarizes these interpretations. We consider that environment of the upper sandstone to be firmly established, whereas the environment of the pebbly lower sandstone is less certain and represents an opportunity for future study. The absence of marine fossils, bioturbation, and the nondevelopment of typically marine shoreface or tidal, estuarine and deltaic sedimentary sequences eliminates these possible depositional environments from consideration. Judging from the presence of coal beds and paleolatitude interpretations (Frederiksen, 1972), the climate of this region was humid subtropical to tropical with an extensive plant cover.

Because the lower sandstone body was probably deposited by a rapidly aggrading stream system, the depositional processes clearly were not the same processes responsible for cutting the Brownsville Valley. Hence, it must have been excavated earlier by a somewhat different fluvial system. This conclusion is even more obvious if a shale-filled valley such as that described nearby from the subsurface (Shiarella, 1933) is considered.

Regional analyses of basal Pennsylvanian sedimentation that are particularly relevant to the Brownsville paleovalley are those of Siever and Potter (1956, p. 331-333), Bristol and Howard (1971, pl. 1), and Pryor and Sable (1974, p. 301-302 and fig. 17). From these and other studies, we suggest the following. Broad regional uplift marked the close of Mississippian time in the Eastern Interior Basin. During the time period between deposition of the latest Chester and the earliest Pennsylvanian sediments, the deltaic environments were probably only present to the southwest in and near the Ouachita Trough. In early Pennsylvanian time, a westerly and southwesterly inclined coastal plain existed and formed a well-developed linear drainage pattern. The Brownsville Valley system was one of the southernmost major westerly drainage courses through which sediments were introduced into the Ouachita Trough. With renewed subsidence of the Eastern Interior Basin in Mid-Morrowan time (mid-early Pennsylvanian), the depositional base level migrated eastward and northward up the paleoslope, taking with it first the alluvial plain and then deltaic environments. The through-flowing streams changed from dominantly erosional to aggrading systems. In the Brownsville Valley, the lower sandstone body represents the headward encroachment of a stream system characterized by an upper alluvial valley and a high discharge-high sediment load; the upper sandstone body represents the further encroachment of base level up the paleoslope, and the deposition of a lower alluvial valley and possibly some delta plain sedimentation.

A modern analogue to this is in the late Pleistocene-early Holocene history of sedimentation in the Mississippi Valley (fig. 11). During the last low stand of sea level, the Mississippi River entrenched its valley, and base level stood at the edge of the continental shelf. In the early Holocene, eustatic sea-level rise shifted base level up-slope; the result was deposition of low-sinuosity stream deposits of pebbly sands having glacial outwash origin in the entrenched valley until present sea level was reached. The high-sinuosity meander system then developed and migrated up-valley over the pebbly sands. Whereas the tectonic causes of the base-level shift in late Mississippian-early Pennsylvanian time in the Eastern Interior Basin were different from that of the late Pleistocene-early Holocene Mississippi River system, the results of base-level shift and change in sediment load on alluvial sedimentation are strikingly similar.

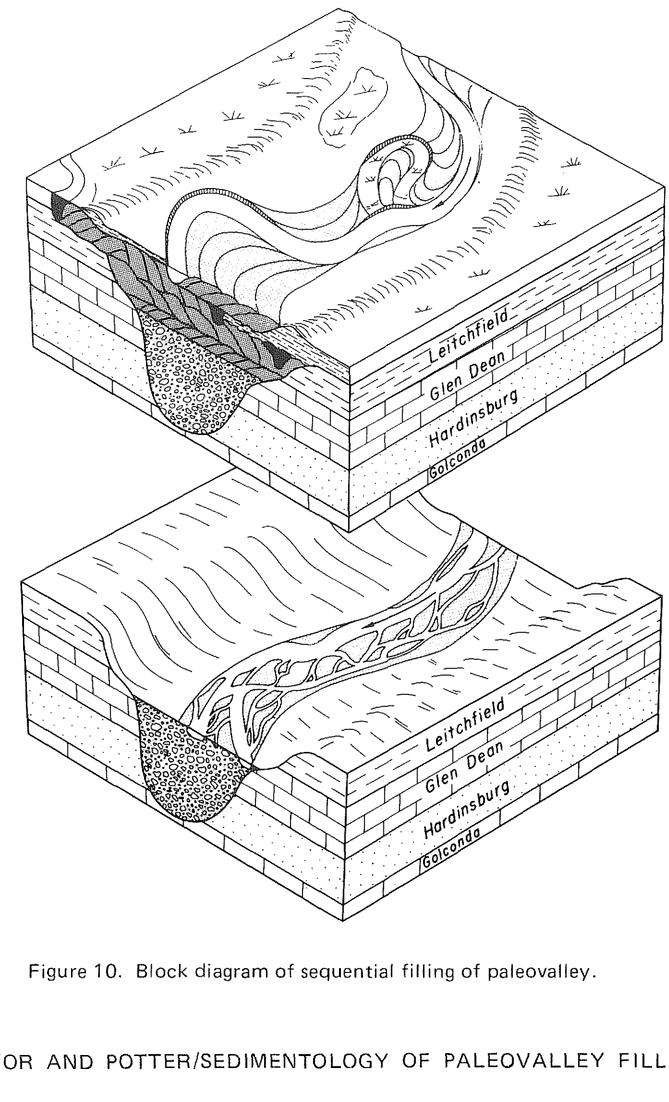

Figure 10. Block diagram of sequential filling of paleovalley.

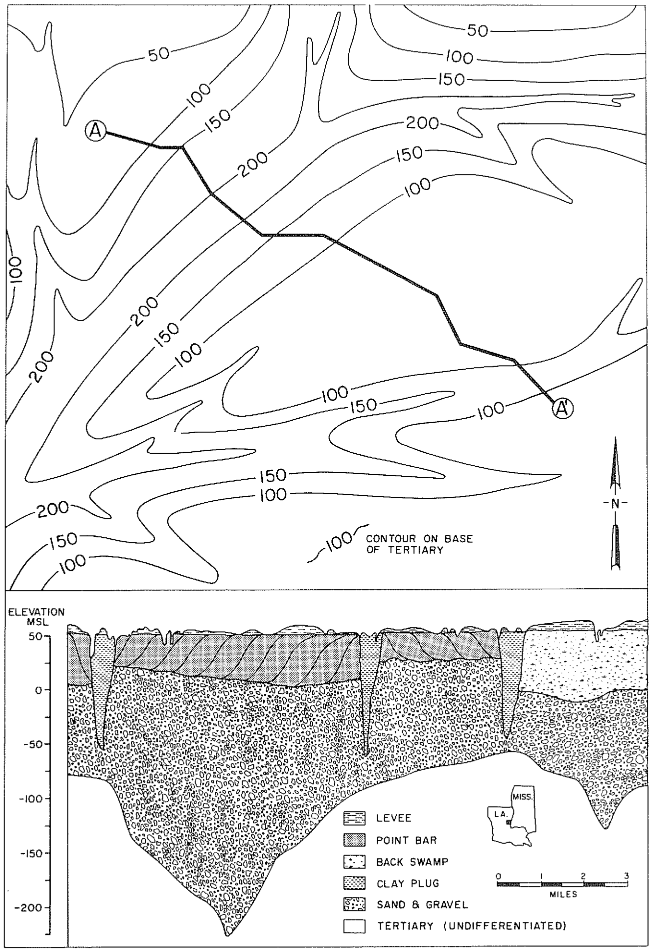

Figure 11. Pleistocene valley and its two types of fill on the Ferriday quadrangle, Mississippi-Louisiana. Simplified from Saucier (1967). Contour interval: 50 ft.

Paleodrainage and provenance

The course of the Brownsville paleovalley is fairly continuous to its present limits in Hart County, but east of this point it is difficult, if not impossible, to determine. The paleovalley could have continued directly northeast, or it could have turned sharply to the north and perhaps have crossed the axis of the Cincinnati Arch far to the north. Detailed mapping of the basal Pennsylvanian exposed along the western edge of the Appalachian Basin in Kentucky has not yet revealed a clearly matching paleovalley of comparable size and corresponding paleocurrents.

From the petrography of the quartz granules and pebbles, it is fully clear, however, that the stream that first cut and then filled the Brownsville paleovalley carried siliceous pebbles that could only have come from east of the Cincinnati Arch (fig. 12).

The tight, nonporous fabric of the sandstone and siltstone pebbles indicates that they were not derived from underlying Mississippian sandstones, but probably from an incipiently folded terrain, most probably one consisting of the middle or lower Paleozoic sandstones of the Appalachian geosyncline. The recrystallized siltstones suggest a similar conclusion as does the single recrystallized dolomitic granule. Supporting evidence for this conclusion of a confining pressure greater than that of Phanerozoic tectonic environments of the craton is provided by the parallel-oriented polycrystalline quartz and the parallel-fractured monocrystalline quartz. The unimodal and bimodal polycrystalline quartz is more difficult to interpret, except it does indicate derivation from quartz veins that are typical of folded, medium- to high-rank metamorphic terrains or from some acid plutons. Blatt (1967, p. 407) thought that bimodal polycrystalline quartz of sand size was indicative of a metamorphic origin. Siever and Potter (1956, table 5) also concluded from study of thin section that the bulk of the pebbles were indicative of a metamorphic terrain. We fully recognize that some of these quartz pebbles may have been reworked from the Mississippian, Devonian, Silurian, and possibly even the Ordovician and Cambrian, as well as perhaps some direct combinations from the Canadian Shield from Ontario and Quebec. Certainly, quartz pebbles and granules, because of their mechanical and chemical durability, are among the most durable of sedimentary materials at the earth's surface. Hence they can be recycled again and again exactly as many of those from the Caseyville have been reworked, first into the Plio-Pleistocene and subsequently into the Recent terrace deposits of the Mississippi Embayment. We also recognize that because of their durability, some of these quartz pebbles may have had an ultimate origin on a continent other than North America—perhaps northwestern Africa, for example.

The evidence from the sand fraction is fully consistent with that from the quartz granules and pebbles. The subangular, fairly mineralogically mature sand was multi- but

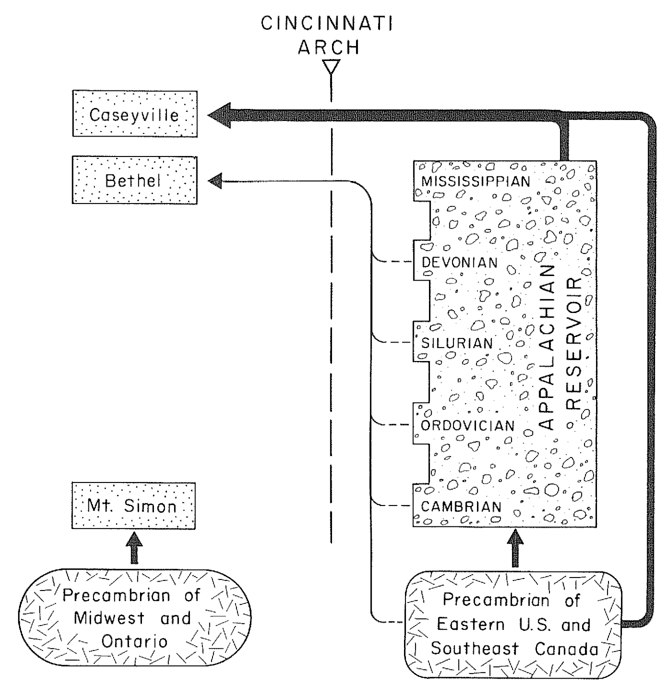

Figure 12. Inferred provenance of quartz pebbles in Paleozoic sandstones of Illinois Basin. Quartz pebbles of the Cambrian Mt. Simon Sandstone are abundant and derived from the Precambrian basement. From the Mt. Simon to the Mississippian Bethel Formation no quartz pebbles are present. Those in the Bethel are few in number and came from the northeast, probably from much the same source as those in the Caseyville and Mansfield Formations.

not many-cycled, just as would be expected if it were derived from an incipiently deformed, geosynclinal basin and coupled source area that was exposed to tropical and subtropical weathering.

The Kyrock Sandstone and its eastward extending remnants occur midway between the Illinois Basin and the western Appalachian Basin and form a physical connection between the two basins. How then do our interpretations fit with those interpretations put forward by workers in the basal Pennsylvanian of the western Appalachians in eastern Kentucky?

Ferm et al. (1971) and Horne, Ferm, and Swinchatt (1974) interpret the basal Pennsylvanian Lee Sandstones (eastern equivalents of the Kyrock Sandstone) to have been deposited as marine barrier bars and islands. Both works also interpret the Lee Sandstone to be of barrier bar origin and in conformable relationship with the underlying shallow marine sequence of Chesterian age. Neither Ferm et al. (1971) nor Horne, Ferm, and Swinchatt (1974) recognized the unconformity between basal Pennsylvanian and upper Mississippian rocks in eastern Kentucky, which Siever (1951) and Bristol and Howard (1971 and 1974) have mapped in the Illinois Basin.

Our studies of the Kyrock in Edmonson County, Kentucky, show without question (figs. 3, 4, 5, and 6) that there is a major unconformity between the basal Pennsylvanian and upper Mississippian sequences. In central Kentucky, this unconformity very probably extends eastward into the Appalachian Basin and locally is in the form of a major, deep (over 60 m) alluvial valley system. We have shown this valley to be filled with Pennsylvanian sediments of freshwater, riverine origin. The unidirectional cross-bedding and lithic similarity of other basal Pennsylvanian channels described in the basin (table 1) similarly indicate a fluvial fill. There are no data to indicate that these basal Pennsylvanian sediments are of either shallow marine or tidal origin. Clearly, then, if the Kyrock Sandstone is the western down-paleoslope equivalent of the Lee Sandstone, it is paleogeographically incompatible for the up-paleoslope Lee Sandstones to be marine-barrier bar equivalents of the alluvial Kyrock Sandstone. Seen in broadest perspective, the Brownsville Channel is a paleovalley that is part of a much larger paleodrainage system that transported gravel, sand, and mud across a stable platform to a major, linear Pennsylvanian trough to the south and west (fig. 13).

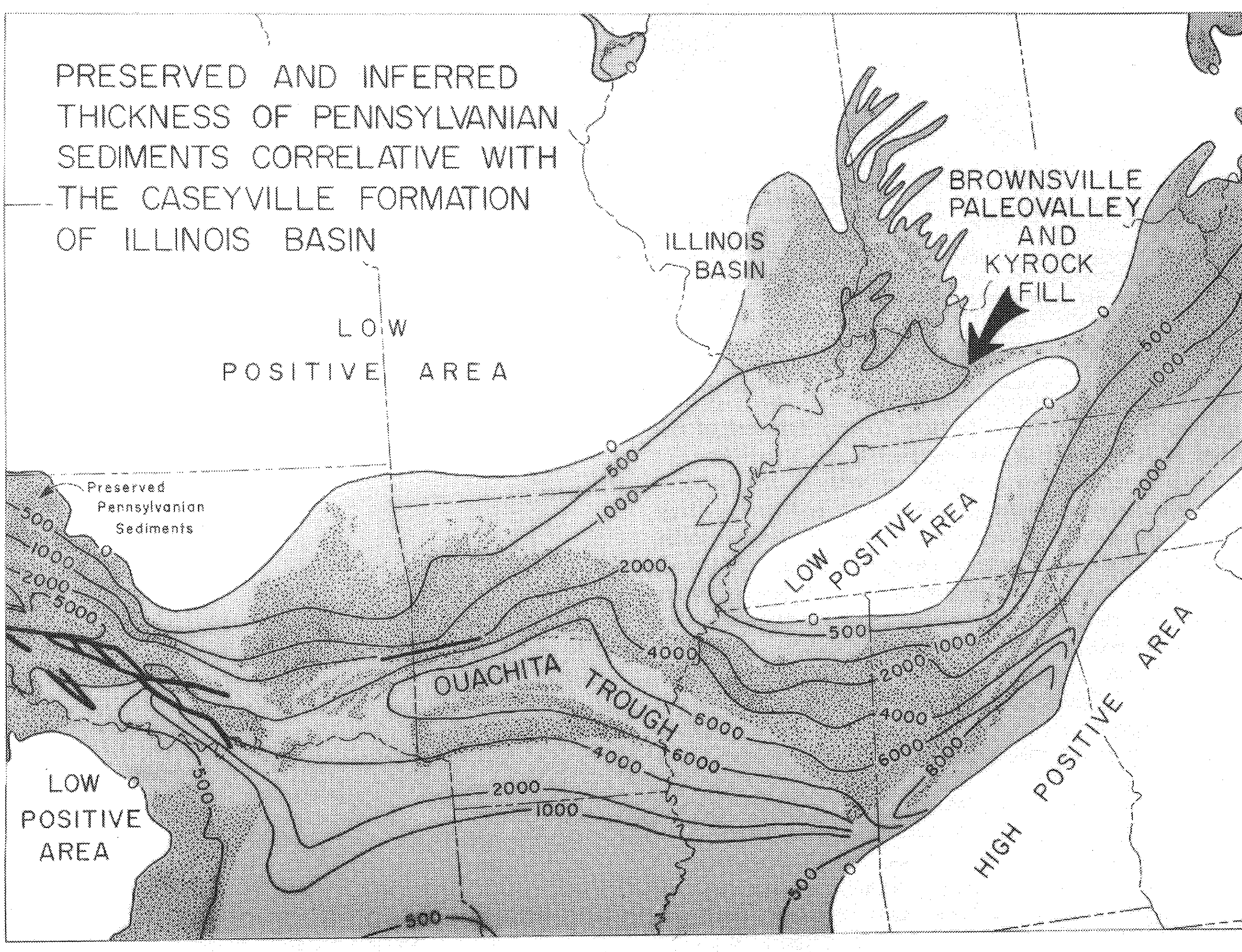

Figure 13. Reconstruction of Lower Pennsylvanian in Illinois Basin and location of Brownsville paleovalley. (Redrawn from McKee, 1975, pl. 15A, fig. 1.) (Contour interval in feet.)

TAR SANDS

Tar sands also occur in the Pennsylvanian and Chesterian sandstones of Kentucky, most notably in Edmonson County and nearby areas (fig. 14). The tar sands have been described by Jillson (1927) and recently by McGrain (1976 and 1979). Currently, they are used for road materials by the Highway Safety Materials Company of Brownsville, Kentucky. Most of the pits are in the south part of the Bee Spring quadrangle and are in the Bee Spring and younger sandstones. In addition, there is a large pit in sec. 2-I-39 and a small one in sec. 19-I-38 of the Brownsville quadrangle, the latter pit being in the Kyrock. Outcrop mapping reveals many scattered thin beds of asphalt-impregnated sandstone such as those exposed in the Kyrock Sandstone in the spillway, the Nolin Dam (fig. 9).

The bituminous content of the basal Pennsylvanian asphaltic sandstones usually ranges from 7 to 8 percent (Jillson, 1927, p. 101). In the mid 1950s the Gulf Oil Corp. evaluated certain extraction techniques using asphaltic sandstones from Edmonson County.

A recent memoir on oil sands (Hills, 1974) includes mention of the Kyrock by Walters (1974, p. 248-249), who suggested that the Devonian Chattanooga Shale, locally about 1100 feet below the Kyrock, was the source of its oil. As discussed above, however, closer underlying marine Chesterian units seem much more probable as the oil source. On the other hand, Walter's view (p. 242) that most of the world's major oil sands occur in fluvial and deltaic environments along the margins of sedimentary basins, certainly fits well the Kyrock and other nearby occurrences in Chesterian and Pennsylvanian sandstones (fig. 14). Oil sand occurrence in fluvial and deltaic sands along basin margins appears to be the result of fluvial erosion on uplifted basin margins causing fluvial and deltaic sands to be superimposed on marine source rocks; such newly exposed source rocks release oil to the up-dip outcrop via the conduits of their overlying fluvial and deltaic sands.

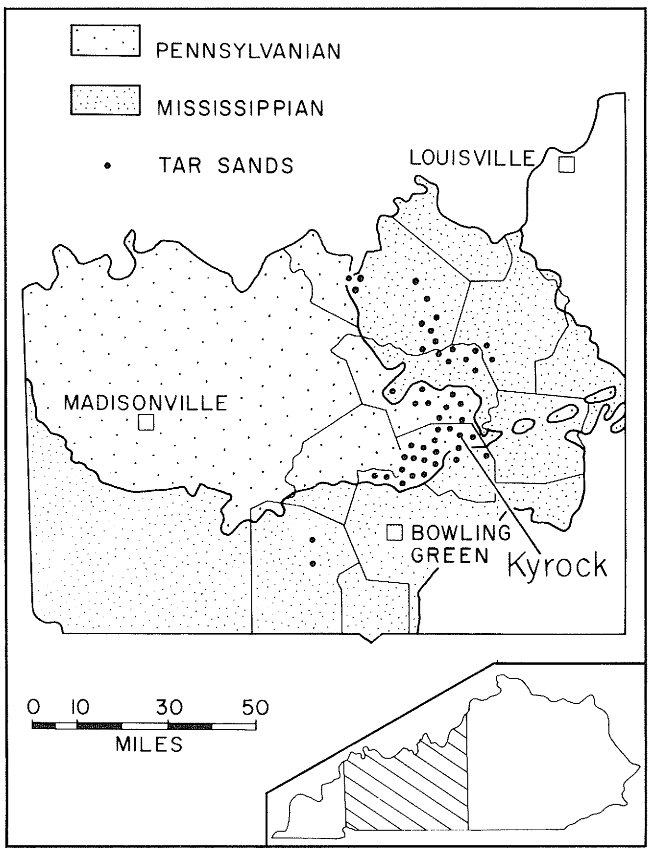

Figure 14. Known occurrences of tar sands in the southeastern corner of Illinois Basin, according to McGrain (1976).

REFERENCES

AMERICAN SOCIETY OF CIVIL ENGINEERS COMMITTEE ON SEDIMENTATION, 1966, Sediment transport mechanics: Initiation of motion: American Society of Civil Engineers Proceedings Journal, Hydraulics Division 92, Paper 4738, p. 291-314.

BERGENDAHL, M. H., 1965, Geology of the Cloverport quadrangle, Kentucky-Indiana and the Kentucky part of the Carrolton quadrangle: U.S. Geological Survey GQ-273.

BLATT, Harvey, 1967, Original characteristics of clastic quartz grains: Journal of Sedimentary Petrology, v. 37, no. 2, p. 401-424.

BRISTOL, H. M., and R. H. HOWARD, 1971, Paleogeographic map of the sub-Pennsylvanian-Chesterian (Upper Mississippian) surface in the Illinois Basin: Illinois State Geological Survey Circular 458, 14 p.

BRISTOL, H. M., and R. H. HOWARD, 1974, Sub-Pennsylvanian valleys in the Chesterian surface of the Illinois Basin and related Chesterian slump blocks *in* Garret Briggs [ed.], Carboniferous of the southeastern United States: Geological Society of America Special Paper 148, p. 315-335.

BURROUGHS, W. G., 1923, A Pottsville filled channel in the Mississippian: Kentucky Geological Survey Series 6, v. 10, p. 115-126.

FERM, J. C., J. C. HORNE, J. P. SWINCHATT, and P. W. WHALEY, 1971, Carboniferous depositional environments in northeastern Kentucky: Guidebook of the Geological Society of Kentucky spring field conference, 30 p.

FREDERIKSEN, N. O., 1972, The life of the mesophytic flora: Geoscience and Man, v. 4, p. 17-28.

GILDERSLEEVE, Benjamin, 1965, Geologic map of the Brownsville quadrangle, Kentucky: U.S. Geological Survey GQ-411.

GILDERSLEEVE, Benjamin, 1968, Geologic map of the Bee Spring quadrangle, Edmonson and Grayson Counties, Kentucky: U.S. Geological Survey Map GQ-757.

GILDERSLEEVE, Benjamin, 1971, Geologic map of the Nolan Reservoir quadrangle, western Kentucky: U.S. Geological Survey map GQ-895.

GRAY, H. H., R. D. JENKINS, and R. M. WEIDMAN, 1960, Geology of the Huron area, south-central Indiana: Indiana Geological Survey Bulletin 20, 78 p.

HICKEN, A., E. IRVING, L. K. LAW, and J. HASTIE, 1972, Catalogue of paleomagnetic directions and poles: Publications Earth Physics Branch, Department of Energy, Mines, and Resources, v. 45, 135 p.

HILLS, L. V., ed., 1974, Oil sands—fuel of the future: Canadian Society of Petroleum Geologists Memoir 4, 263 p.

HORNE, J. C., J. C. FERM, and J. P. SWINCHATT, 1974, Depositional model for the Mississippian-Pennsylvanian boundary in northeastern Kentucky *in* Garrett Briggs [ed.], Carboniferous of the southeastern United States: Geological Society of American Special Paper 148, p. 97-114.

JILLSON, M. R., 1927, Kentucky rock asphalt *in* Topography of Kentucky and other papers: Kentucky Geological Survey Series 6, v. 30, p. 95-103.

KLEMIC, Henry, 1963, Geologic map of the Rhoda quadrangle, Kentucky: U.S. Geological Survey GQ-219.

MALOTT, C. A., 1931, Geologic structure in the Indian and Trinity Springs locality, Martin Co., Indiana: Indiana Academy of Science, v. 40, p. 217-231.

MALOTT, Clyde A., 1946, The Budda outlier of the Mansfield sandstone Lawrence County, Indiana: Proceedings of the Indiana Academy of Science, v. 55, p. 96-101.
MALOTT, C. A., 1950, Variations in the stratigraphic position and character of the base of the Mansfield sandstone in southern Indiana: Proceedings of the Indiana Academy of Science, v. 60, p. 239-246.
McFARLAN, A. C., 1943, Geology of Kentucky: Lexington, University of Kentucky, 531 p.
McGRAIN, Preston, 1976, Tar sands (rock asphalt) of Kentucky—A review: Kentucky Geological Survey, Series X, Report of Investigations 19, 16 p.
McGRAIN, Preston, 1979, Bitumen-impregnated Carboniferous sandstones along the southeastern rim of the Illinois Basin, *in* James E. Palmer and Russell R. Dutcher [eds.], Depositional and structural history of the Pennsylvanian System of the Illinois Basin: Ninth International Congress of Carboniferous Stratigraphy and Geology, Guidebook for field trip no. 9, part 2; p. 62-65.
McKEE, Edwin D., and others, 1975, Paleotectonic investigations of the Pennsylvanian System in the United States: Geological Survey Professional Paper 853, pl. 15A, fig. 1.
MILLER, A. M., 1910, Evidence of former connection between eastern and western coal fields across central Kentucky: Geological Society of America Bulletin, v. 20, p. 621-624.
MILLER, Robert C., 1969, Geologic map of the Canmer quadrangle, Hart Co., KY: U.S. Geological Survey Map GQ-816.
MOORE, Samuel L., 1973, Geologic map of the Munfordville quadrangle, Hart County, KY: U.S. Geological Survey map GQ-1055.
OWEN, David Dale, 1856, Report of the Geological Survey in Kentucky: A. G. Hodges, State Printer, Frankfort, KY, 416 p.
POTTER, Paul Edwin, and Jerry S. OLSON, 1954, Variance components of cross-bedding direction in some basal Pennsylvanian sandstones of the Eastern Interior Basin: Geological application: Journal of Geology, v. 62, p. 50-73.
POTTER, Paul Edwin, and Raymond SIEVER, 1956, Sources of basal Pennsylvanian sediments in Eastern Interior Basin: Part I—Cross-bedding: Journal of Geology, v. 64, p. 225-244.
POTTER, Paul Edwin, and G. A. DESBOROUGH, 1965, Pre-Pennsylvanian Evansville valley and Caseyville (Pennsylvanian) sedimentation in the Illinois Basin: Illinois State Geological Survey Circular 384, 16 p.
PRYOR, W. A., and Edward G. SABLE, 1974, Carboniferous of the Eastern Interior Basin *in* Garrett Briggs [ed.], Carboniferous of the southeastern United States: Geological Society of America Special Paper 148, p. 281-313.
REINECK, H. E., and I. B. SINGH, 1973, Depositional sedimentary environments: Springer-Verlag, New York, 439 p.
SAUCIER, R. T., 1967, Geological investigation of the Boeuf-Tensas Basin: Ferriday, Mississippi-Louisiana maps a and b: U.S. Army Engineers Waterways Experiment Station Technical Report No. 3-757, Vicksburg, Miss.
SANDBERG, C. A., and C. G. BOWLES, 1965, Geologic map of the Cub Run quadrangle, Kentucky: U.S. Geological Survey GQ-386.
SHAWE, Fred R., and Benjamin J. GILDERSLEEVE, 1969, An anastomosing channel complex at the base of the Pennsylvanian System in western Kentucky: U.S. Geological Survey Professional Paper 650-D, p. 206-209.
SHIARELLA, N. W., 1933, Typical oil producing structures in the Owensboro Field of Western Kentucky: Bureau of Mineral and Topographic Survey Bulletin No. 3, University of Kentucky, Lexington, Kentucky, p. 12-13.
SIEVER, Raymond, 1951, The Mississippian-Pennsylvanian unconformity in southern Illinois: American Association of Petroleum Geologists Bulletin, v. 35, p. 542-581.
SIEVER, Raymond, and Paul Edwin POTTER, 1956, Sources of basal Pennsylvanian sediments in Eastern Interior Basin. Part II—Sedimentary petrology: Journal of Geology, v. 64, p. 319-335.
SPENCER, Frank D., 1964, Geology of the Tell City quadrangle, Kentucky-Indiana: U.S. Geological Survey Map GQ-356.
WANLESS, H. R., 1955, Pennsylvanian rocks of Eastern Interior Basin: American Association of Petroleum Geologists Bulletin, v. 39, p. 1753-1820.
WELLER, J. M., 1927, Geology of Edmonson Co.: Kentucky Geological Survey Series 6, Bulletin 28, 246 p.

Bitumen-impregnated Carboniferous sandstones along the southeastern rim of the Illinois Basin

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INTRODUCTION

Bitumen-impregnated sandstones of Early Pennsylvanian and Late Mississippian ages are present in Kentucky along the southeastern rim of the Illinois Basin (fig. 1). The Kentucky deposits have been referred to as tar sands, oil sands, bitumen-bearing rocks, rock asphalt, and natural rock asphalt. Where it naturally occurs in outcrop, it has been called "black rock" by some Kentucky natives; this descriptive term found its way into some of the geologic literature of 60 years ago. At one time its use as a surfacing material was so widespread that the trade name, "Kentucky rock asphalt" was adopted. When completely saturated, the rock may "bleed," particularly during hot weather (fig. 2). Some of the sites where "bleeding" sandstones are present have been designated locally as "tar springs."

LOCATION

The area containing the largest and best-known bitumen-bearing sandstones in Kentucky extends from Breckinridge County on the Ohio River south and southwest around the rim of the Illinois Basin to Logan County (fig. 1). The largest rock asphalt quarries, all in Pennsylvanian strata, are located in west-central Edmonson County (Gildersleeve, 1965, 1968).

Stratigraphically, the bitumen-bearing rocks of western Kentucky are principally the Kyrock and Bee Spring conglomeratic sandstones of Early Pennsylvanian age and the Big Clifty (Cypress of many earlier writers), Hardinsburg, and Tar Springs Sandstones of Late Mississippian age (fig. 3). Thick-bedded sandstones generally appear to be richer in bitumen than thin-bedded ones. The largest deposits have

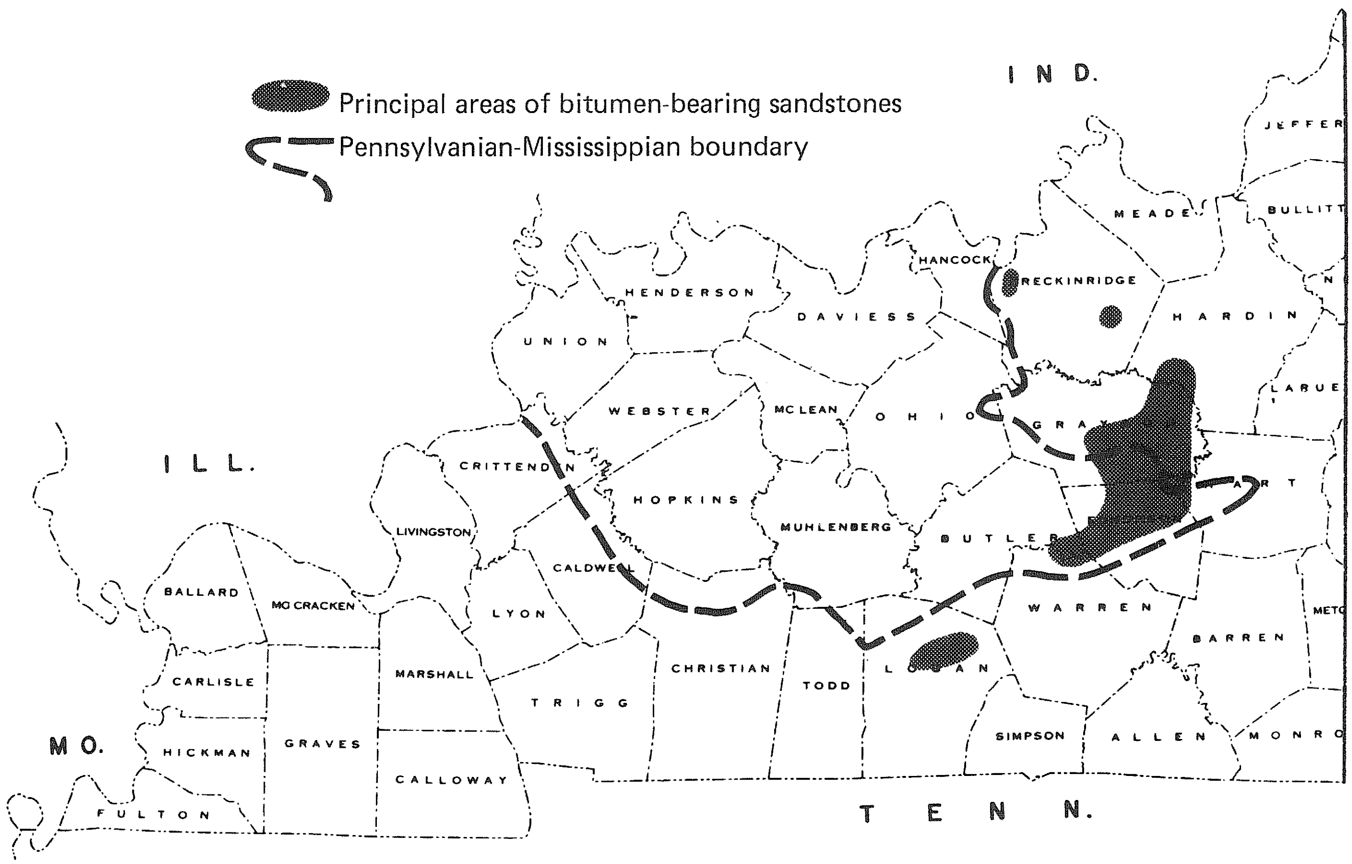

Figure 1. Principal areas of occurrence of bitumen-bearing Carboniferous sandstones in western Kentucky.

been found in the Bee Spring, Big Clifty, and Kyrock; all of the above sandstones have been recognized by the petroleum industry as potential reservoir rocks for oil and gas, and all have been productive in a number of localities in the Illinois Basin.

TYPES OF DEPOSITS

The bitumen-bearing deposits in Kentucky are mineral aggregates consisting of natural mixtures of sandstone and residues of petroleum. Texturally, they range from fine-grained sandstone to conglomeratic sandstone with pebbles up to 0.5 inch (1.3 cm) in diameter. The predominant component is quartz in the form of angular, subangular, or rounded particles. Silica generally constitutes 80 to 90 percent, or more, of the weight of the rock. The bitumen impregnation is not homogeneous; bitumen content ranges from 0 to approximately 15 percent by weight. The crude hydrocarbon material occurs generally as intergranular deposits. Occurrences also have been recognized in fractures and other openings, with concentrations at irregular intervals. These deposits appear to represent the residual material of oil sands whose lighter and more volatile constituents have dissipated because of proximity to the surface or direct exposure to the atmosphere. The bitumen is highly viscous and is not recoverable in its natural state by conventional oil-field methods.

The bitumen-bearing sandstones are not restricted to any particular stratigraphic unit in a district, nor are they restricted to a particular zone within a formation. Outcrop

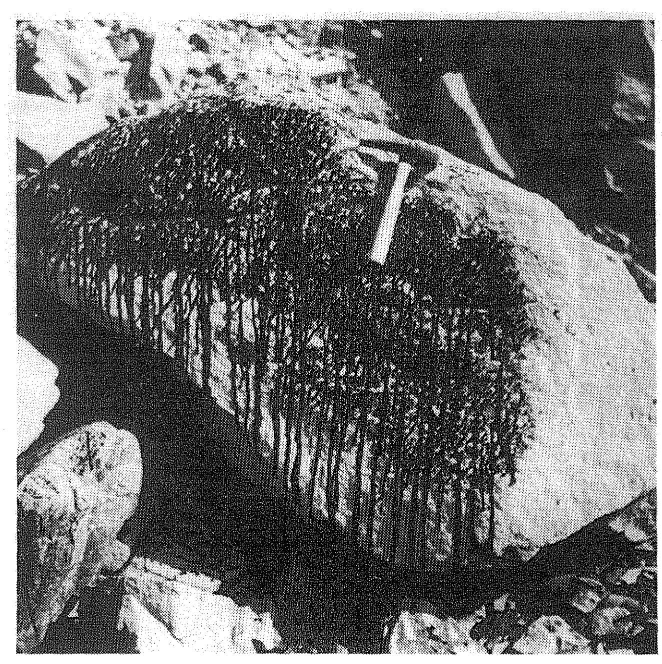

Figure 2. Block of bleeding and bleached bitumen-bearing Pennsylvanian sandstone, Edmonson County, Kentucky. Heat from the sun lowers the viscosity of the asphaltlike material so that it seeps from within the rock. Sunlight also bleaches the outer surfaces of the rock to a light gray. (After McGrain, 1976, fig. 1.)

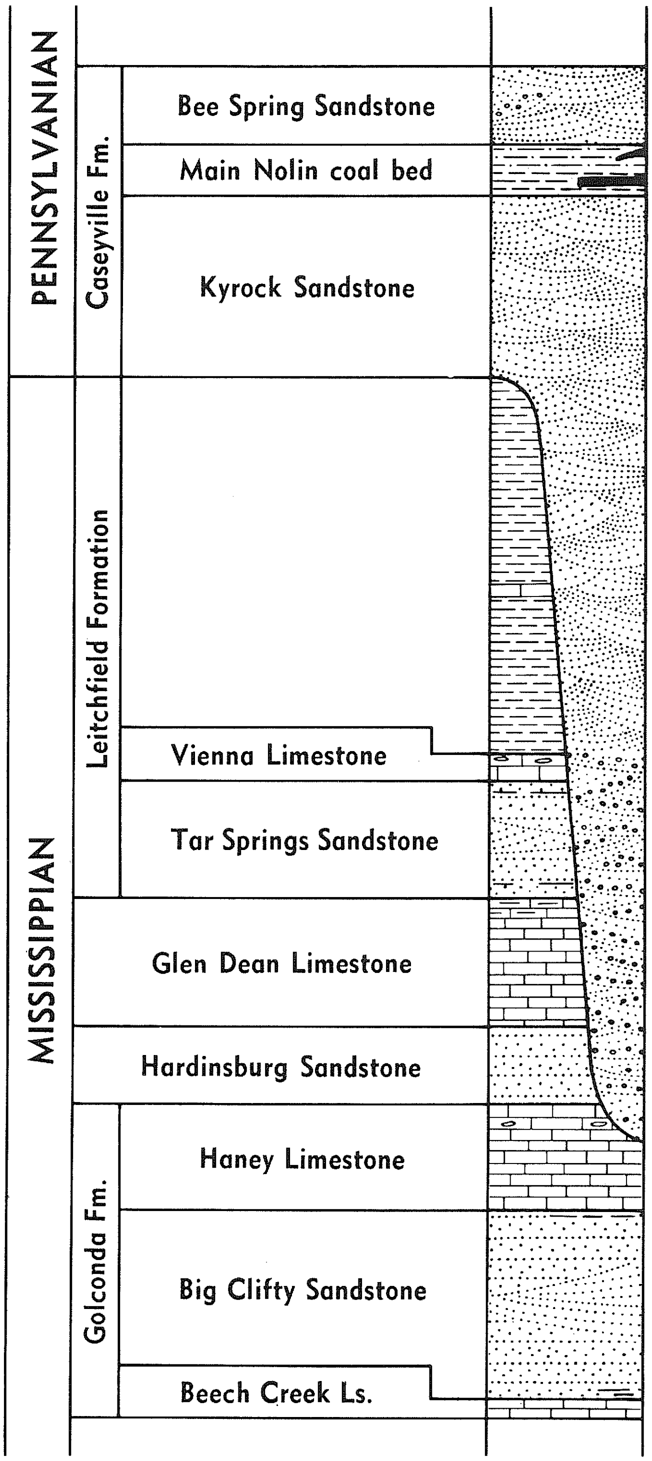

Figure 3. Generalized geologic section for the Western Kentucky rock asphalt district. The Bee Spring, Kyrock, and Big Clifty Sandstones are the principal sources of bitumen-bearing rock in the district. (After McGrain, 1976, fig.3.)

thicknesses of the asphaltic beds generally range from a few inches to 30 feet (10 cm to 10 m), although greater thicknesses have been reported. Variations in thickness of the impregnated rock and in concentration of bitumen characterize the deposits. Although highly petroliferous at a number of localities, the sandstones are not consistently so; barren areas may be present within the bounds of a designated asphaltic rock area.

The sandstones and conglomeratic sandstones of the Pennsylvanian are complexly cross-bedded. There has been cementation locally by iron oxide, silica, or calcium carbonate along both horizontal bedding planes and the plane of cross-bedding; movement by hydrocarbons through the rock thus is restricted and causes irregularities in the extent of impregnated zones. In numerous instances there is no apparent change in porosity, either horizontally or vertically, and it appears that lack of pressure prevented further impregnation. The Mississippian sandstones are thin-bedded to massive, are cross-bedded in places, and exhibit similar irregular patterns of hydrocarbon impregnation. The best places to inspect these deposits are in man-made prospects, pits, quarries, and roadcuts (fig. 4).

The largest deposits are found in northern Edmonson County, in the area bounded by the Nolin River on the east, the Green River on the south, and the Bear Creek on the west. The Kyrock and Bee Spring Sandstones are the principal exposed bitumen-bearing rocks. The two sandstones are generally separated by a shaly zone containing one or more thin coal beds referred to as Nolin coals. Sandstone strata above the Bee Spring Sandstone are locally impregnated with bitumen, but the deposits are generally small. The largest rock asphalt quarries, all in Pennsylvanian strata, were in the Brownsville and Bee Spring areas (Gildersleeve, 1965, 1968). Bitumen occurrences in Edmonson County, as in other areas along the southeastern rim of the Illinois Basin, are erratic, thicken and thin abruptly, and vary in viscosity; rich deposits are separated by lean or barren sandstone. The Big Clifty Sandstone (Mississippian) contains significant deposits of bitumen-bearing rock in Logan and parts of Grayson and Hardin Counties.

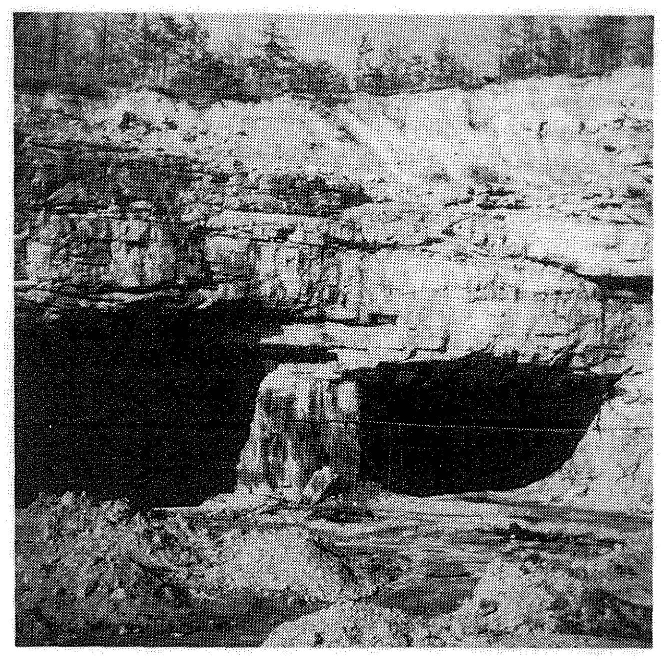

Figure 4. Rock asphalt quarry and mine in Pennsylvanian Kyrock Sandstone near Sweeden, Edmonson County, Kentucky. (After McGrain, 1976, fig. 4.)

ORIGIN

Many questions about the bitumen-bearing sandstones remain unanswered. No satisfactory explanation has been advanced as to why the deposits are concentrated along the southeastern rim of the Illinois Basin and are not present elsewhere around the perimeter in comparable number or size.

A majority of those who have written on the Kentucky deposits refer to the bitumen-impregnated deposits as fossil oil fields. In a paper at the 1975 annual meeting of the Kentucky Oil and Gas Association, however, W. O. Bement, University of Cincinnati, proposed that the absence of asphaltic limestones in the area of the tar sand deposits suggests that the bitumen-bearing sandstones do not represent exhumed pools (fossil oil fields), but rather the direct migration of hydrocarbons through unsealed reservoirs to the surface.

CONCLUSIONS

No single geological environment will explain the localization of the Kentucky deposits. In the Homer area of Logan County (Gildersleeve, 1966), northern Warren County (Shawe, 1966), northern Grayson County (Swadley, 1962), and elsewhere, the proximity of deposits to known faults suggests structural control and orientation. Locations of some of the larger pits in Edmonson County appear to be related to a deep sand-filled paleovalley (Gildersleeve, 1965; Sedimentation Seminar, in press; Weller, 1927). Other deposits can be explained only as stratigraphic traps or local porous zones in the enclosing rock. Much detailed subsurface information is needed to provide the answers.

REFERENCES

BALL ASSOCIATES, LTD., 1965, Surface and shallow oil-impregnated rocks and shallow oil fields in the United States: U.S. Bureau of Mines Monograph 12, 375 p.

GILDERSLEEVE, Benjamin, 1965, Geology of the Brownsville quadrangle, Kentucky: U.S. Geological Survey geologic quadrangle map GQ-411.

GILDERSLEEVE, Benjamin, 1966, Geologic map of the Homer quadrangle, Kentucky: U.S. Geological Survey geologic quadrangle map GQ-549.

GILDERSLEEVE, Benjamin, 1968, Geologic map of the Bee Spring quadrangle, Edmonson and Grayson Counties, Kentucky: U.S. Geological Survey geologic quadrangle map GQ-757.

McGRAIN, Preston, 1976, Tar sands (rock asphalt) of Kentucky—A review: Kentucky Geological Survey, Report of Investigations 19, ser. 10, 16 p.

SEDIMENTATION SEMINAR, in press, Sedimentology of a paleovalley fill: Kyrock Sandstone (Pennsylvanian) in Edmonson and Hart Counties, Kentucky: Kentucky Geological Survey, Report of Investigations 21, ser. 10, 24 p.

SHAWE, F. R., 1966, Geologic map of the Reedyville quadrangle, western Kentucky: U.S. Geological Survey geologic quadrangle map GQ-520.

SWADLEY, W C, 1962, Geology of the Big Clifty quadrangle, Kentucky: U.S. Geological Survey geologic quadrangle map GQ-192.

U.S. ARMY, CORPS OF ENGINEERS, 1951, The synthetic liquid fuel potential of Kentucky: New York, Ford, Bacon & Davis, Inc., Engineers (Report for U.S. Bureau of Mines), 347 p.

WELLER, J. M., 1927, The geology of Edmonson County, Kentucky: Kentucky Geological Survey, ser. 6, v. 28, 248 p.

Stratigraphy of the lower part of the Pennsylvanian System in southeastern Illinois and adjacent portions of Indiana and Kentucky

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INTRODUCTION

The Caseyville, Abbott, and Spoon Formations in the lower part of the Pennsylvanian System have their thickest development, about 1200 feet (365 m), in the southeastern part of Illinois (fig. 1). Caseyville strata are separated from the underlying Mississippian System by a major unconformity. The upper boundary of the Spoon Formation is conformable with the Carbondale Formation. Sandstones constitute about 60 percent of the three formations, and the remainder consists of siltstone and shale, and, to a lesser amount, coal and limestone. The succession of rocks can be characterized as having been deposited in a fluvial-deltaic environment with occasional marine incursions in a gently subsiding basin (Wanless et al., 1963). Clastic sediments were generally transported from the north, northeast, and east, and, to a lesser extent, from the northwest (Potter, 1963; Simon and Hopkins, 1966; McKee, 1975) across the Illinois Basin, which was open toward the Ouachita Geosyncline to the south during Pennsylvanian time. The Cincinnati Arch and Nashville Dome, to the east and southeast (see p. 106), served as positive features and supplied little if any sediment to the Illinois Basin.

PALEOCLIMATE

The climate during the Pennsylvanian has been the subject of considerable discussion and has been reviewed by Schopf (1975, 1979). A reconstruction of the position of the land masses during the Pennsylvanian indicates that Midcontinent and Appalachian regions of the United States, western Europe, North Africa, and the Donets Basin were within tropical or subtropical regions near the paleo-equator (Köppen and Wegener, 1924; Wegener, 1966; Clark and Stearn, 1968; Larson and LaFountain, 1970). Most workers agree that the climate in the Illinois Basin and Europe, at least before the Missourian (Stephanian), was warm and humid, and rainfall was fairly abundant (White, 1931; Noé, 1931; Kräusel, 1964; Chaloner and Creber, 1974; McKee, 1975; Schopf, 1975). Frederiksen (1972) thought that although the major Carboniferous coal basins were close to the equator, the climate was cooler than the present tropics because of Carboniferous continental glaciation. Alternating periods of aridity and humidity are suggested by Howard (1979) as an explanation for the anastomosing drainage pattern of the Mississippian-Pennsylvanian unconformity.

PALEOBOTANY

Read and Mamay (1964) divided the upper Paleozoic of the United States into 15 floral zones. Zone 6 (*Neuropteris tennesseeana* and *Mariopteris pygmaea*) is represented in the Caseyville Formation (Westphalian A) of Illinois. Some of zone 5 (*Mariopteris pottsvillea* and common occurrence of *Aneimites*) may occur in the earliest Caseyville strata. The Abbott Formation (Westphalian B) lies in zone 7 (common occurrence of *Megalopteris*) and zone 8 (*Neuropteris tenuifolia* zone), and the Spoon Formation (Westphalian C and D) is included in zone 9 (*Neuropteris rarinervis*).

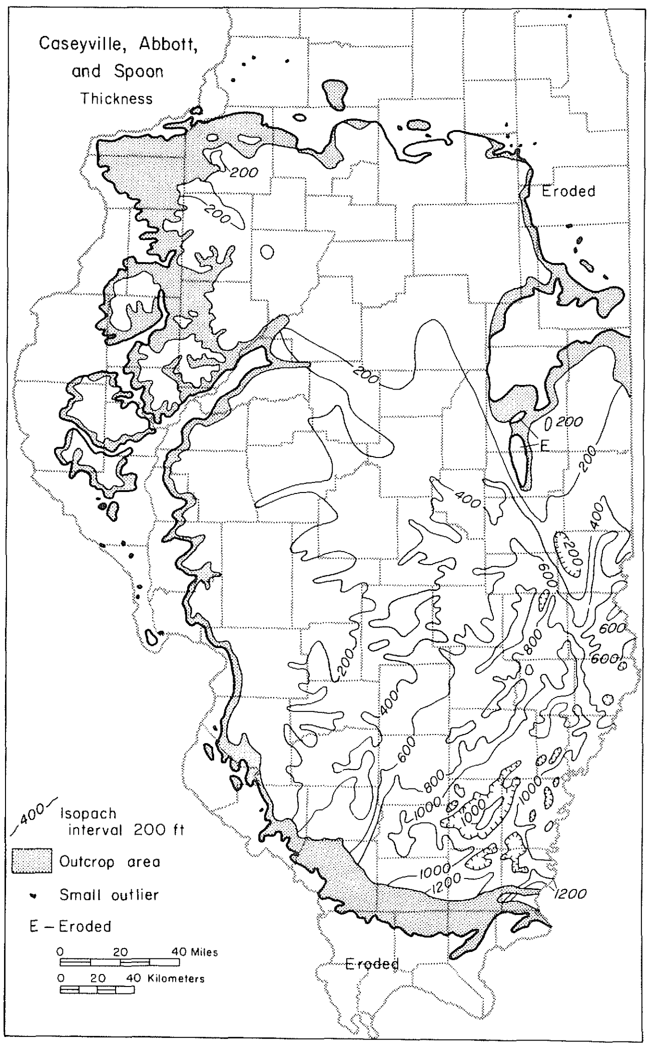

Figure 1. Combined thickness of the Caseyville, Abbott, and Spoon Formations. (After Wanless, 1955.)

Quantitative studies (Peppers and Pfefferkorn, 1970; Pfefferkorn, Mustafa, and Hass, 1975) indicate that pteridosperms, ferns, and sphenopsids are the most common plants in compression floras found in shale overlying coal in the Illinois Basin. No major compression floras of Missourian or Virgilian age have been found in Illinois. In the Illinois Basin there has been only one palynological study of the Pennsylvanian strata other than coal (Peppers, 1964).

The main elements of the coal swamp flora in the Illinois Basin as revealed by palynological studies (Kosanke, 1950; Winslow, 1959; Peppers, 1964, 1970; Phillips et al., 1974) and coal-ball studies (Phillips et al., 1974; Phillips, personal communication) were lycopods, ferns, pteridosperms, sphenopsids, and cordaites, in decreasing order. Lycopods, especially those that bore *Lycospora*, were most prolific in the lower part of the Pennsylvanian (Morrowan to Desmoinesian, Namurian to Westphalian D). Ferns, especially marattiaceous ferns, and pteridosperms replaced lycopods as the most abundant group of plants after the Desmoinesian.

PALYNOLOGICAL CORRELATION OF COALS

A palynological investigation of coals in the Spoon and Abbott Formations of Illinois and equivalent strata in Indiana and Kentucky was made (Peppers, in preparation) to help resolve some correlation problems in the lower part of the Pennsylvanian. Correlation of coals and other strata by physical evidence has been difficult because of abrupt changes of facies and discontinuity of units, an insufficient number of exposures and drill holes, and relatively little mining of the coals in comparison to coals in the overlying Carbondale Formation. Palynology has been a useful means of correlating the coals.

Caseyville Formation

The Caseyville Formation includes strata from the base of the Pennsylvanian to the top of the Pounds Sandstone Member (Willman et al., 1975, p. 178) and is up to 150 meters thick. The Caseyville Formation is discussed in detail elsewhere in this guidebook (Koeninger and Mansfield, 1979; Potter, 1979). In southern Illinois, the Caseyville varies abruptly in thickness because the relief of the unconformable surface on which it was deposited varies about 100 meters extending from valley bottoms to the flat upland divides (Siever, 1951; Wanless, 1955; Bristol and Howard, 1971; Howard, 1979; Pryor and Potter, 1979).

The sandstones in the Caseyville Formation are mineralogically mature, consisting of quartz, clay minerals, and minor amounts of detrital heavy minerals (Potter and Glass, 1958). Although quartz pebbles are present in small amounts throughout the formation, the sandstones are generally medium to fine grained and are well sorted. The source area was probably in the Canadian Shield or uplands in the northern Appalachian area. The sediments were transported across a low-lying plain and marine shelf. Variable rates of basin subsidence produced an abundance of local depositional environments and resulted in establishment of the fluvial stream channel systems. Potter and Desborough (1965) interpreted the Caseyville sediments of southeastern Illinois to be the product of stream deposition during times of relative emergence of the basin; interpretation was based on the regional patterns of sand bodies and cross-bed orientation.

The Caseyville in southeastern Illinois was deposited within a deltaic fluviatile environment as shown by Simon and Hopkins (1966) and Wanless (1975, p. 77). Their studies document a fluviatile environment by evidence of primary structure such as large-scale cross-bedding, current ripple marks, flute marks, and mudstone-pebble conglomerates and by evidence of the geometry of sandstone bodies (Wanless, p. 77, 1975; Potter, 1963, p. 27-49). The "Caseyville Delta" has been characterized by Ethridge, Leming, and Keck (1973) and Ethridge and Fraunfelter (1976) as a highly constructive, lobate delta, depositing sediment in shallow water and prograding rapidly onto a slowly subsiding shelf. The only marine limestone recognized in the Caseyville is the Sellers Limestone Member (Fraunfelter, 1979), which is known from a very small area in Hardin County along the Ohio River. The formation contains several coals that are rarely as much as 1 meter thick and that are difficult to trace laterally for any appreciable distance because they are lenticular and are distributed irregularly within a section dominated by massive sandstones (Smith, 1957).

Abbott Formation

The Abbott Formation, which overlies the Caseyville, extends from the top of the Pounds Sandstone Member to the top of the Bernadotte Sandstone Member (Kosanke et al., 1960, p. 30). The Abbott Formation has a maximum thickness of 90 to 110 meters in southeastern Illinois. It is similar to the Caseyville Formation in being composed primarily of detrital rocks (fig. 2), but it differs from the Caseyville in containing thicker, more widespread coals and in the characteristics of the sandstones (Willman et al., 1975). The sandstone members in the Abbott Formation and equivalent strata are separated by intervals of shale, siltstone, or thin-bedded sandstone. The sandstones of this formation are more argillaceous and micaceous, and generally finer grained, than those of the Caseyville. Ferruginous cementing material is more common than in the Caseyville. The shales and thin-bedded sandstones are commonly carbonaceous and micaceous. Plant fossils are common in the shales. Most of the siltstones and shales have flaggy bedding; black fissile shales are not common. Marine fossils may be present in the siltstones and sandstones between the massive sandstones (Baxter and Desborough, 1965).

Correlation of Abbott sandstones of western Illinois with those of southern Illinois is difficult. In western Illinois, fairly reliable stratigraphic control is present; in southern Illinois sandstones usually were named and defined from outcrops where they are prominent channel deposits and where other more correlative units such as coal and limestone are lacking. The sandstones change abruptly from channel to sheet facies and are difficult to differentiate according to composition and texture. Stratigraphic sections made up entirely of shale are difficult to correlate with sections that are predominantly sandstone. Several of the coal seams in the Abbott Formation, which have been relied upon as aids in sandstone correlations, have been incorrectly correlated (Searight, 1974).

The sandstones of the Abbott are thicker and compose a larger part of the formation along the eastern and southern borders of the basin than in the western part; this difference suggests an eastern or northeastern source for the detrital sediments. The inferred source of sediments for the equivalent sandstones in western Illinois is thought to have a northerly or northwesterly origin (Wanless, 1975).

The sandstones of the Abbott Formation appear to have both channel and sheetlike forms. The channel sands probably filled fluvial channels and distributary channels of deltas. The Grindstaff Sandstone Member might be an example of the transition of fluviatile to deltaic sandstone (Wanless, 1975). The sheetlike sandstones may be floodplain accumulations, interdistributary sands of a delta or shallow marine sands. Some of the dark-gray mudstones contain abundant clay ironstone concretions and probably formed in brackish-water lagoons or bays. Influxes of detritus that formed these sandstones and associated mudstones may have been initiated by uplifts in source areas or by climatic changes that increased stream flow.

Some kaolinitic clays below coal seams are widespread and probably accumulated slowly, perhaps on or marginal to deltas in late stages of growth. Relief on the pre-Pennsylvanian topography was subdued by infilling during Caseyville deposition, and thus fairly widespread coal swamps formed during Abbott and Spoon deposition (Wanless, 1975).

Limestones are rare in the Abbott Formation, but several marine limestones occur in strata equivalent to the upper part of the formation in Indiana and western Kentucky. Coals are more abundant, generally thicker, and more widespread in the Abbott Formation than in the Caseyville (figs. 2 and 3).

Named Members. The Reynoldsburg Coal Member is the oldest named unit in the Abbott Formation (fig. 3). It is as much as 1 meter thick near Reynoldsburg, Johnson County, Illinois, where it has been mined on a small scale. The coal locally grades upward and laterally into a canneloid black shale. It has been identified in a relatively small area in Johnson and Jackson Counties, Illinois, along the outcrop.

The No. 1b (Bell) coal bed, probably about 15 meters above the Reynoldsburg Coal, is extensive and has been traced palynologically from its type area in Crittenden County, Kentucky, into southeastern Illinois, and into Indiana, where it is known as the St. Meinrad Coal Bed (fig. 3). The coal is as much as 1.6 meters thick and was mined extensively around Cannelton in southern Indiana in the nineteenth and early part of the twentieth centuries. The canneloid coal was much in demand and some was exported to Great Britain.

The Finnie Sandstone Member of Kentucky is separated from the underlying No. 1b coal bed by a gray shale about 6 meters thick. The Finnie is probably equivalent to the Grindstaff Sandstone Member of southern Illinois, the Babylon Sandstone Member of western Illinois, and an unnamed sandstone in the Mansfield Formation in Indiana. The Grindstaff Sandstone is present throughout much of

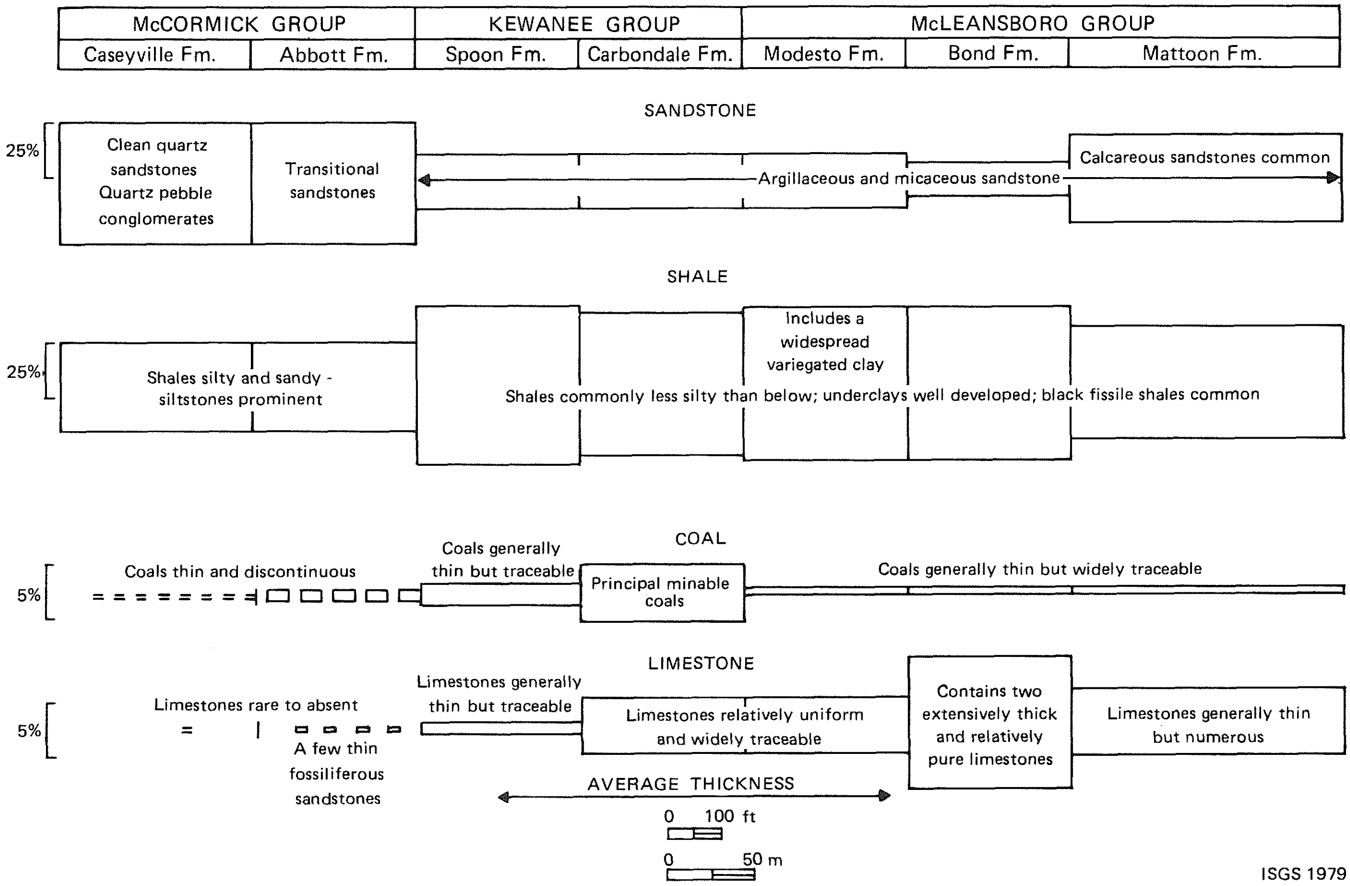

Figure 2. Distribution of the four principal lithologies in Pennsylvanian strata of Illinois. (From Kosanke et al., 1960.)

southern Illinois but is best developed east of the Du Quoin Monocline. The Finnie Sandstone in the area of the Tradewater River in Crittenden and Union Counties, Kentucky, reaches a thickness of 30 meters. The Grindstaff and Finnie Sandstones are normally as much as 20 meters thick and are thickest where deposited in fluvial channels. The thickest succession of strata in the lower part of the Tradewater Formation of Kentucky (Abbott Formation of Illinois) is in an area where at least eight discontinuous coals are interbedded in shaly portions of the Finnie Sandstone (Peppers, 1977). The sandstones are fine grained and contain a small amount of mica and rarely some quartz pebbles—their lithology may resemble sandstones in the Caseyville. In places the sandstone is calcareous and contains marine fossils.

The Smith coal bed is just above the Finnie Sandstone in the area of the Tradewater River in Kentucky; in a few places it extends into the subsurface of southeastern Illinois and the eastern part of western Kentucky. The coal was mined locally in Crittenden County, Kentucky, where its thickness is slightly more than 1 meter.

The Manley Coal Member (formerly called Babylon Coal) is discontinuous, but rather widely distributed, in western Illinois. A coal equivalent to the Manley has been identified by spore correlation in southwestern Illinois and western Kentucky. In a few places in western Illinois where it has been mined, the coal is as much as 1 meter thick and is somewhat canneloid in places.

Coal and limestone equivalents to the Dunbar coal of Kentucky and the Mariah Hill Coal Bed of Indiana and the overlying Lead Creek Limestone Member of Kentucky and Indiana have not been identified in Illinois. The Mariah Hill Coal Bed and Dunbar coal are semiblocky and are as much as 1.5 meters thick where they have been strip-mined locally. The Lead Creek Limestone, a few centimeters to several meters above the coal, consists of at least two benches of dense, massive to shaly, fossiliferous limestone. The upper bench is commonly cherty. The Lead Creek Limestone is the oldest widespread Pennsylvanian limestone in the Illinois Basin that has been studied in some detail for its microfossil content (Thompson, Shaver, and Riggs, 1959; Thompson and Shaver, 1964; and Shaver and Smith, 1974).

The Tarter Coal Member in the northwestern part of the Illinois Basin is equivalent to the Lower Block Coal Member of Indiana (fig. 3), but has not been recognized in southern Illinois. It has been extensively mined in Indiana. The Tarter Coal has a maximum thickness of about 35 centimeters. The Lower Block Coal is generally dull-banded, slabby or blocky, and may be boney toward the top or bottom. A coal known locally as the "4A coal" occupies the position of the Lower Block Coal in parts of western Kentucky.

The Willis Coal Member of southern Illinois is correlated with the Pope Creek Coal Member of northwestern Illinois, the Upper Block Coal Member of Indiana, and the No. 3 (Ice House) coal bed of western Kentucky. The Willis

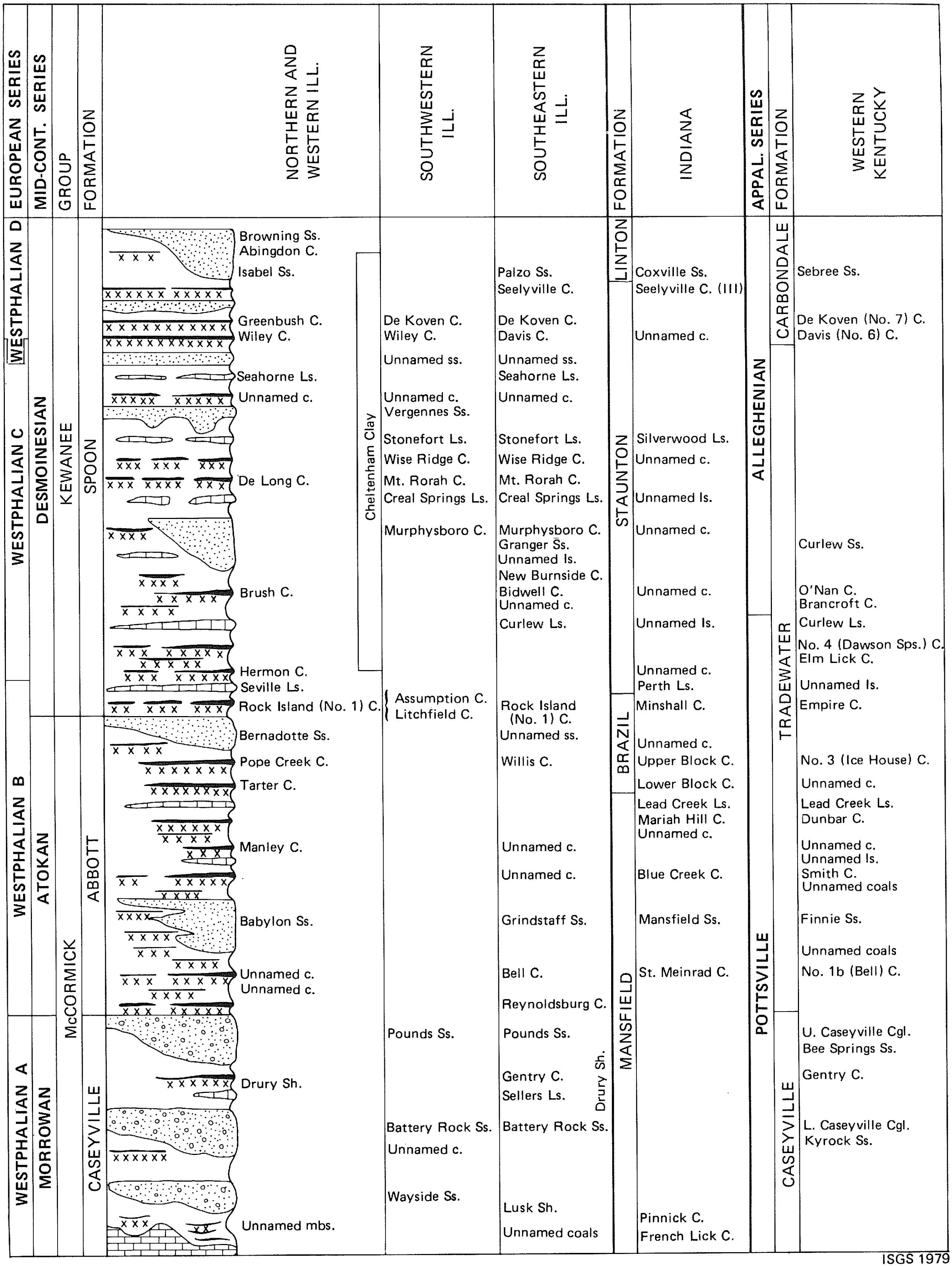

Figure 3. Correlation of formations and major stratigraphic members and beds in the lower part of the Pennsylvanian in the Illinois Basin Coal Field. (Adapted from Kosanke et al., 1960, and Willman et al., 1975, p. 163-201.)

Coal has been mined in Gallatin County, Illinois, where it is slightly more than 1 meter thick and can be traced in the subsurface into several counties in southeastern Illinois. It is somewhat like a cannel coal in appearance. The Upper Block Coal is a dull, blocky coal and is more than 1 meter thick where it is mined. The Pope Creek Coal is widespread in western Illinois but is generally only about 35 centimeters or less thick.

In southern Illinois a sandstone, referred to in the past as the Finnie Sandstone, overlies the Willis Coal or equivalent coals. On the basis of correlation of the Willis Coal with the No. 3 (Ice House) coal (Peppers, 1977), this sandstone, which is as much as 12 meters thick, is younger than the Finnie Sandstone of Kentucky and is probably equivalent to the Bernadotte Sandstone of western Illinois. Accordingly, it defines the upper boundary of the Abbott Formation in southern Illinois.

Spoon Formation

As defined by Kosanke et al. (1960, p. 30), the Spoon Formation consists of strata from the top of the Bernadotte Sandstone to the base of the Colchester (No. 2) Coal Member. It is as much as 110 meters thick in southern Illinois. The formation is characterized by less sandstone and more coal and limestone than the Abbott and Caseyville Formations and by less limestone and coal than the overlying Carbondale Formation (fig. 2). In general, cycles of sedimentation (cyclothems) are better developed in the Spoon Formation than in the Abbott and Caseyville Formations. Sandstones are well developed in both channel and sheet facies, but do not constitute as much of the total section as they do in the lower formations. The sandstones of the Spoon Formation show the general upward increase in the amount of argillaceous matrix and mica flakes that first appeared in the sandstones in the Abbott Formation, from which they differ only slightly. The formation contains the youngest widespread limestones and coals; they are thinner than those in the overlying Carbondale Formation, but thicker and more extensive than those of the lower formations. The shales are commonly less sandy than those in underlying strata; underclays beneath the coals and black shales above the coals are generally better developed.

The composition of sandstone in the Spoon Formation (and in the overlying Carbondale Formation) contrasts with that in the Abbott and Caseyville, which contain higher proportions of quartz and less mica, feldspar, interstitial clay, and unstable heavy minerals than the Carbondale sandstones (Wanless, 1975). The sandstones in the lower part of the Spoon are subgraywackes and contain much larger percentages of detrital matrix and mica than do sandstones in the Abbott Formation (Searight, 1974 and 1979). Like those in the Abbott and Caseyville Formations, sandstones occur in elongate deposits as much as 40 meters thick and in sheet deposits that may be 0.3 to 0.6 meters thick. Only the Granger and the Vergennes Sandstone Members occur in prominent elongate bodies. The latter sandstone might actually be equivalent to the Palzo Sandstone Member (Searight, 1974). One unnamed sheet sandstone below the Davis Coal is widespread and a significant unit (Searight, 1974).

Named members. The Rock Island (No. 1) Coal Member is the basal named member of the Spoon Formation; it is known as the Litchfield and Assumption Coal Members in southern Illinois and the Minshall Coal Member in Indiana (fig. 3). The Rock Island Coal is tentatively correlated by use of spores with a coal locally known as the "Empire coal bed," in western Kentucky. Two benches of coal separated by a few centimeters to several meters of clay or shale are commonly present. The Rock Island and Minshall Coals are bright to dull.

The Seville and Perth Limestone Members that overlie the Rock Island and Minshall Coals, respectively, are discontinuous and contain diverse marine faunas and chert at some localities. Thickness of the Seville Limestone varies considerably but is greatest in the narrow zones where the Rock Island Coal is also of maximum thickness. An unnamed limestone in western Kentucky is present in the same stratigraphic position as the Perth Limestone.

The No. 4 coal bed (Mining City Coal), which is extensively mined in western Kentucky, has been traced by use of palynology into the subsurface of southern Illinois. The coal is almost 2 meters thick in places, is bright, blocky, and in parts of Kentucky is canneloid.

The Curlew Limestone Member overlies the No. 4 coal bed and is thin, gray, fine grained, and cherty in places. It contains abundant open marine fossils, including ostracods and fusulinids, which have been investigated by Dunbar and Henbest (1942); Thompson, Shaver, and Riggs (1959); and Thompson and Shaver (1964).

The Bidwell Coal Member and the New Burnside Coal Member a few meters above the Bidwell are overlain by a thin, discontinuous limestone that resembles the Curlew Limestone. The Bidwell Coal is fairly extensive and is correlated with the O'Nan Coal Member of southeastern Illinois and an unnamed coal in Indiana. The Bidwell Coal is as much as 1.5 meters thick, whereas the New Burnside Coal locally is somewhat thicker.

The Granger Sandstone Member of Illinois and the Curlew Sandstone of western Kentucky are found in the subsurface in a large area of southern Illinois and western Kentucky. They are characterized as having channel and sheet facies. The sandstones are fine grained, have some partings, and become massive, coarser grained, and locally conglomeratic toward the base. They are as much as 30 meters thick.

The Murphysboro Coal Member, which is as much as 2 meters thick in Jackson County where it was mined as early as 1810, contains several shale bands or benches away from the area of thick occurrence where it was mined. The coal is discontinuous and has been recognized at only a few places in the Illinois Basin outside Jackson County. Where it is thick and overlain by gray shale, the coal contains less sulfur than elsewhere.

The Creal Springs Limestone Member is discontinuous, but rather widespread, in southern Illinois and is no more than about 70 centimeters thick. It is gray, argillaceous, and cherty in places and contains an open marine fauna.

The Mt. Rorah and Wise Ridge Coal Members are between the Creal Springs and the next higher limestone, the Stonefort Limestone Member. Both coals are thin, but the Mt. Rorah Coal is thick enough to have supported some small mines near Stonefort, Williamson County. It usually has a shale band, which is several centimeters thick and is about one-third the distance from the bottom. The Mt. Rorah Coal is correlated with the De Long Coal Member of western Illinois. The Wise Ridge Coal is thinner than the Mt. Rorah but is apparently the more widespread of the two. It is correlated with an unnamed coal in Indiana and is usually overlain by a black fissile shale.

The Stonefort Limestone Member extends through most of southern Illinois and is equivalent to the Silverwood Limestone Member in Indiana. It is less than 1 meter thick, is gray and fine grained, and contains a diverse marine fauna.

The unnamed coal that underlies the Seahorne Limestone Member is most commonly less than 30 centimeters thick. In southwestern Illinois and western Kentucky, it locally attains a thickness of more than 1 meter. The Seahorne Limestone Member is best developed in western Illinois, where it varies from a discontinuous nodular zone to a limestone as much as 2 meters thick. It is easily recognized in areas where it is conglomeratic or brecciated. The limestone consists mostly of brachiopods in dark-gray limestone that are surrounded by light-gray limestone with gastropods. The presence of another fauna elsewhere, including *Spirorbis* and ostracods, indicates that the limestone is probably nonmarine.

The Davis and De Koven Coal Members in southern Illinois and western Kentucky are separated by about 3 to 12 meters of shale and are correlated with the Wiley and Greenbush Coal Members, respectively, of western Illinois. In places the De Koven Coal is split into two benches by as much as several meters of shale. The Davis and De Koven Coals have been mined in several areas of southern Illinois and in western Kentucky. They are relatively widespread, usually persistent coals in areas where they are recognized.

The Seelyville Coal Member, which was deposited in the eastern part of the Illinois Basin, especially in Indiana, occurs between the De Koven and Colchester Coals. The Seelyville Coal is as much as 2 meters thick and has been mined extensively in Indiana. The Seelyville and De Koven Coals are difficult to distinguish from each other palynologically and by physical evidence, especially where the De Koven and Davis Coals split into two or more benches and approach the stratigraphic position of the Seelyville Coal. The two coals have not been differentiated in the same section, so they might be at least partly equivalent.

The Palzo Sandstone Member of southern Illinois, the Sebree Sandstone Member of western Kentucky, and the Coxville Sandstone Member of Indiana are at least approximately equivalent to each other and are widespread. They have channel and sheet facies and are as much as 15 meters thick. The sandstones contain less quartz and more mica and feldspar than other sandstones in the Spoon Formation.

The Browning Sandstone Member is confined to western Illinois and is the youngest recognized member in the Spoon Formation. It is a sheet type or channel sandstone; where it is the latter, it is up to 25 meters thick. It grades upward from sandstone to siltstone or shale. An equivalent unit is not recognized in southeastern Illinois.

REFERENCES

BAXTER, J. W., and G. A. DESBOROUGH, 1965, Areal geology of the Illinois fluorspar district, Pt. 2—Karbers Ridge and Rosiclare quadrangles: Illinois State Geological Survey Circular 385, 40 p.

BRISTOL, H. M., and R. H. HOWARD, 1971, Paleogeologic map of the sub-Pennsylvanian Chesterian (Upper Mississippian) surface in the Illinois Basin: Illinois State Geological Survey Circular 458, 14 p.

CHALONER, W. G., and G. T. CREBER, 1974, Growth rings in fossil woods as evidence of past climates, *in* D. H. Tarling and S. K. Runcorn [eds.], Implications of continental drift to the earth sciences: Academic Press, London, v. 1, p. 425-437.

CLARK, T. H., and C. W. STEARN, 1968, The geological evolution of North America: Ronald Press, New York, 570 p.

DUNBAR, C. O., and L. G. HENBEST, 1942, Pennsylvanian fusulinidae of Illinois: Illinois State Geological Survey Bulletin 67, 218 p.

ETHRIDGE, F. G., and G. FRAUNFELTER, 1976, Variability within a high constructive lobate delta: The Pounds Sandstone of southeastern Illinois: Great Lakes Section, 6th Annual Field Conference, Society of Economic Paleontologists and Mineralogists, 76 p.

ETHRIDGE, F. G., S. L. LEMING, and D. A. KECK, 1973, Depositional environments of Lower Pennsylvanian detrital sediments of southern Illinois, *in* F. G. Ethridge, George Fraunfelter, and John Utgaard [eds.], Depositional environments of selected Lower Pennsylvanian and Upper Mississippian sequences of southern Illinois: Guidebook, Thirty-seventh Annual Tri-State Field Conference, 158 p.

FRAUNFELTER, G. H., 1979, Lower Pennsylvanian limestones in southern Illinois, *in* James E. Palmer and Russell R. Dutcher [eds.], Depositional and structural history of the Pennsylvanian System of the Illinois Basin: Guidebook for field trip no. 9, part 2, Ninth International Congress of Carboniferous Stratigraphy and Geology, p. 73-75.

FREDERIKSEN, N. O., 1972, The rise of the mesophytic flora: Geoscience and Man, v. 4, p. 17-28.

HOWARD, Richard H., 1979, The Mississippian-Pennsylvanian unconformity in the Illinois Basin—Old and new thinking, *in* James E. Palmer and Russell R. Dutcher [eds.], Depositional and structural history of the Pennsylvanian System of the Illinois Basin: Guidebook for field trip no. 9, part 2, Ninth International Congress of Carboniferous Stratigraphy and Geology, p. 34-43.

KOENINGER, C. Allen, and Charles F. MANSFIELD, 1979, Earliest Pennsylvanian depositional environments in central southern Illinois, *in* James E. Palmer and Russell R. Dutcher [eds.], Depositional and structural history of the Pennsylvanian System of the Illinois Basin: Guidebook for field trip no. 9, part 2: Ninth International Congress of Carboniferous Stratigraphy and Geology, p. 76-81.

KÖPPEN, W. P., and A. L. WEGENER, 1924, Die Klimate der geologischen Vorzeit: Verlag von Gebrüder Borntraeger, Berlin, 256 p.

KOSANKE, R. M., 1950, Pennsylvanian spores of Illinois and their use in correlation: Illinois State Geological Survey Bulletin 74, 128 p.

KOSANKE, R. M., J. A. SIMON, H. R. WANLESS, and H. B. WILLMAN, 1960, Classification of the Pennsylvanian strata of Illinois: Illinois State Geological Survey Report of Investigations 214, 84 p.

KOSANKE, R. M., 1969, Mississippian and Pennsylvanian palynology, *in* R. H. Tschudy and R. A. Scott [eds.], Aspects of palynology: John Wiley and Sons, New York, p. 75-87.

KRÄUSEL, R., 1964, Introduction to the palaeoclimatic significance of coal, *in* A.E.M. Nairn [ed.], Problems in palaeoclimatology: Interscience, New York, p. 53-56.

LARSON, E. E., and L. LaFOUNTAIN, 1970, Timing of the breakup of the continents around the Atlantic as determined by paleomagnetism: Earth and Planetary Science Letters, v. 8, p. 341-351.

McKEE, E. D., 1975, Interpretation of Pennsylvanian history, *in* E. D. McKee and Eleanor Crosby [coordinators], Paleotectonic investigations of the Pennsylvanian System in the United States, Pt. 2, Interpretive summary and special features of the Pennsylvanian System: U.S. Geological Survey Professional Paper 853, p. 1-21.

NOÉ, A. C., 1931, Evidences of climate in the morphology of Pennsylvanian plants: Illinois State Geological Survey Bulletin 60, p. 283-289.

PEPPERS, R. A., 1964, Spores in strata of Late Pennsylvanian cyclothems in the Illinois Basin: Illinois State Geological Survey Bulletin 90, 89 p.

PEPPERS, R. A., 1970, Correlation and palynology of coals in the Carbondale and Spoon Formations (Pennsylvanian) of the northeastern part of the Illinois Basin: Illinois State Geological Survey Bulletin 93, 173 p.

PEPPERS, R. A., 1977, Palynology and correlations of some coals in the Tradewater Formation (Pennsylvanian) in western Kentucky and in the Abbott Formation in southeastern Illinois [abstract]: North-central Section Annual Meeting, Geological Society of America, p. 640-641.

PEPPERS, R. A., and H. W. PFEFFERKORN, 1970, A comparison of the floras of the Colchester (No. 2) Coal and Francis Creek Shale, *in* W. H. Smith, Roger B. Nance, and M. E. Hopkins, Depositional environments in parts of the Carbondale Formation—western and northern Illinois: Illinois State Geological Survey Guidebook 8, p. 61-74.

PFEFFERKORN, H. W., H. MUSTAFA, and H. HASS, 1975, Quantitative Charakterisierung ober-Karboner Abdruck-floren: Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen, v. 150, p. 253-269.

PHILLIPS, T. L., 1977, Stratigraphic ranges of permineralized Pennsylvanian swamp plants in the Euramerican Province [abstract]:Journal of Paleontology, v. 51, Supplement to no. 2, North American Paleontological Convention II, Abstracts of Papers.

PHILLIPS, T. L., in press, Stratigraphic ranges of permineralized swamp plants in the Euramerican Province: Journal of Paleontology, Memoir.

PHILLIPS, T. L., R. A. PEPPERS, M. J. AVCIN, and P. F. LAUGHNAN, 1974, Fossil plants and coal: Patterns and change in Pennsylvanian coal swamps of the Illinois Basin: Science, v. 184, p. 1367-1369.

POTTER, Paul Edwin, 1963, Late Paleozoic sandstones of the Illinois Basin: Illinois State Geological Survey Report of Investigations 217, 92 p.

POTTER, Paul Edwin, 1979, Terrigenous sedimentation above unconformities, *in* James E. Palmer and Russell R. Dutcher [eds.], Depositional and structural history of the Pennsylvanian System of the Illinois Basin: Guidebook for field trip no. 9, part 2, Ninth International Congress of Carboniferous Stratigraphy and Geology, p. 27-34.

POTTER, P. E., and G. A. DESBOROUGH, 1965, Pre-Pennsylvanian Evansville Valley and Caseyville (Pennsylvanian) sedimentation in the Illinois Basin: Illinois State Geological Survey Circular 384, 16 p.

POTTER, P. E., and H. D. GLASS, 1958, Petrology and sedimentation of the Pennsylvanian sediments in southern Illinois—A vertical profile: Illinois State Geological Survey Report of Investigations 204, 60 p.

PRYOR, Wayne A., and Paul E. POTTER, 1979, Sedimentology of a paleovalley fill: Pennsylvanian Kyrock Sandstone in Edmonson and Hart Counties, Kentucky, *in* James E. Palmer and Russell R. Dutcher [eds.], Depositional and structural history of the Pennsylvanian System of the Illinois Basin: Guidebook for field trip no. 9, part 2, Ninth International Congress of Carboniferous Stratigraphy and Geology, p. 49-62.

READ, C. B., and S. H. MAMAY, 1964, Upper Paleozoic floral zones and floral provinces of the United States with a glossary of stratigraphic terms by G. C. KEROHER: U.S. Geological Survey Professional Paper 454-K, p. 1-35.

SCHOPF, J. M., 1975, Pennsylvanian climate in the United States, *in* E. D. McKee and E. J. Crosby [eds.], Pt. 2, Interpretive summary and special features of the Pennsylvanian System: U.S. Geological Survey Professional Paper 853, p. 23-31.

SCHOPF, J. M., 1979, Pennsylvanian paleoclimate of the Illinois Basin, *in* Depositional and structural history of the Pennsylvanian System of the Illinois Basin: Guidebook for field trip no. 9, part 2, Ninth International Congress of Carboniferous Stratigraphy and Geology, p. 1-3.

SEARIGHT, Thomas K., 1974, Stratigraphy and sedimentation of the Abbott Formation and the lower part of the Spoon Formation (Pennsylvanian) in Illinois: Unpublished manuscript, Illinois State Geological Survey.

SEARIGHT, Thomas K., 1979, The stratigraphy and sedimentation of the Abbott and lower portion of the Spoon Formation in the outcrop belt of southern Illinois, *in* James E. Palmer and Russell R. Dutcher [eds.], Depositional and structural history of the Pennsylvanian System of the Illinois Basin: Guidebook for field trip no. 9, part 2, Ninth International Congress of Carboniferous Stratigraphy and Geology, p. 81-86.

SHAVER, R. H., and S. G. SMITH, 1974, Some Pennsylvanian Krikbyacean ostracods of Indiana and Midcontinent Series terminology: Indiana Geological Survey, Report of Progress 31, 59 p.

SIEVER, Raymond, 1951, The Mississippian-Pennsylvanian unconformity in southern Illinois: American Association of Petroleum Geologists Bulletin, v. 35, no. 3, p. 542-581.

SIMON, J. A., and M. E. HOPKINS, 1966, Sedimentary structures and morphology of late Paleozoic sand bodies in southern Illinois: Illinois State Geological Survey Guidebook Series 7, American Association of Petroleum Geologists Annual Meeting, 67 p.

SMITH, W. H., 1957, Strippable coal reserves of Illinois, part 1—Gallatin, Hardin, Johnson, Pope, Saline, and Williamson Counties: Illinois State Geological Survey Circular 228, 39 p.

THOMPSON, M. L., and R. H. SHAVER, 1964, Early Pennsylvanian microfaunas of the Illinois Basin: Illinois Academy of Science Transactions, v. 57, p. 3-23.

THOMPSON, M. L., R. H. SHAVER, and E. A. RIGGS, 1959, Early Pennsylvanian fusulinids and ostracodes of the Illinois Basin: Journal of Paleontology, v. 33, p. 770-792.

WANLESS, H. R., 1955, Pennsylvanian rocks of Eastern Interior Basin: American Association of Petroleum Geologists Bulletin, v. 39, p. 1753-1820.

WANLESS, H. R., 1975, Illinois Basin Region, *in* E. D. McKee and E. J. Crosby [eds.], Paleotectonic investigations of the Pennsylvanian System in the United States, pt. 1, Introduction and regional analyses of the Pennsylvanian System: U.S. Geological Survey Professional Paper 843, 349 p.

WANLESS, H. R., J. B. TUBB, Jr., D. E. GEDNETZ, and J. L. WEINER, 1963, Mapping sedimentary environments of Pennsylvanian cycles: Geological Society of America Bulletin 74, p. 437-486.

WEGENER, A., 1966, The origin of continents and oceans, J. Biram [trans.]: Dover Publications Inc., New York, 246 p.

WHITE, David, 1931, Climatic implications of Pennsylvanian flora: Illinois State Geological Survey Bulletin 60, p. 271-281.

WILLMAN, H. B., Elwood ATHERTON, T. C. BUSCHBACH, Charles COLLINSON, J. C. FRYE, M. E. HOPKINS, J. A. LINEBACK, and J. A. SIMON, 1975, Handbook of Illinois Stratigraphy: Illinois State Geological Survey Bulletin 95, 261 p.

WINSLOW, M. R., 1959, Upper Mississippian and Pennsylvanian megaspores and other plant microfossils from Illinois: Illinois State Geological Survey Bulletin 86, 135 p.

Lower Pennsylvanian limestones in southern Illinois

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INTRODUCTION

Only two isolated marine limestone units of lower Pennsylvanian age, namely, the Sellers Limestone Member of the Caseyville Formation and the "Boskydell" limestone interval in the Grindstaff Sandstone Member of the Abbott Formation, are known to occur in southern Illinois. Desborough (1959), Wanless (1939), and Hopkins and Simon (1975) have published reports concerning the Sellers and "Boskydell."

THE GRINDSTAFF SANDSTONE

The Grindstaff Sandstone Member of the Abbott Formation was named by Charles Butts in 1925 from outcrops in Grindstaff Hollow in Gallatin County, Illinois (NE corner Sec. 28, T. 10 S., R. 8 E.) (fig. 1). The Abbott Formation belongs to the McCormick Group and the Atokan Series (fig. 2). The Grindstaff is in general a fine- or medium-grained, slightly micaceous quartz sandstone. In places in the western part of the southern Illinois outcrop belt, it contains quartz granules and pebbles; the Grindstaff, for the most part, contains fewer granules and pebbles than the underlying Caseyville sandstones. The Grindstaff Sandstone attains a maximum thickness of 60 feet and is thickest and coarsest where it was deposited in local distributary or fluvial channels. In southern Jackson County, south of Carbondale (NE Sec. 8, T. 10 S., R. 1 W.) (fig. 1), a very impure, sandy argillaceous, clastic limestone or calcareous sandstone containing marine fossils occurs near the middle of the Grindstaff Sandstone Member. This fossiliferous interval was formerly referred to as the Boskydell Marine Zone (Desborough, 1959). The fossils contained in this interval include solitary and colonial corals; *Composita* sp., *Wellerella* ? sp., Spiriferid, Productid, and other brachiopods; trilobites; trepastome bryozoans; gastropods; crinoid stem segments; and sharks' teeth (*Pterodus occidentalis*). Coalified plant fragments are also present. The Grindstaff Member overlies and grades laterally into gray, silty, sandy, or limy shale, the unnamed shale member. The Grindstaff Sandstone is best developed east of the Du Quoin Monocline. The Grindstaff Sandstone is part of a fluvial-deltaic sequence. The underlying unnamed shale member (A in fig. 3) contains interbedded thin beds of white, medium-grained, quartz sandstone bearing linguloid ripple marks and interbedded medium bluish-gray, very fine-grained, argillaceous, thin limestone beds bearing numerous plant fragments. This unnamed shale member probably represents delta front sedimentation. In addition, the Reynoldsburg Coal is present in many places near the middle of the unnamed shale, the latter representing swamp or marsh sedimentation. The overlying basal Grindstaff sandstones (B), which are pebbly at the base and contain large cross-bed sets, probably represent distributary channel sedimentation. The sandstones near the middle of the Grindstaff (C) exhibit multidirectional cross-bedding, perhaps bimodal, and are interbedded medially with argillaceous partings and argillaceous thin limestones. Above the latter units are calcareous, coarse-grained sandstones and thin, interbedded, sandy to argillaceous limestones that contain numerous fragmented and worn marine fossils, especially crinoid stem segments, and large-scale cross-beds. The sandstones and limestones are pebbly, especially at the base. These units may represent a period of channel abandonment characterized by reworking of the distributary channel sands by tidal- or wave-produced currents and by the deposition of thin limestones and shales. The upper sandstones of the Grindstaff (E), slightly pebbly sandstones that bear large-scale cross-bed sets, probably represent the reestablishment of distributary channel sedimentation.

No microfossils were found associated with any of the above described sedimentary units.

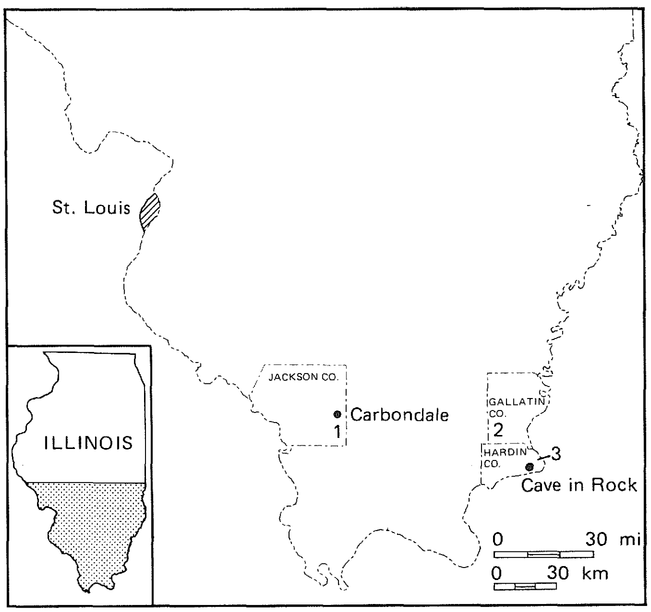

Figure 1. Site of (1) Grindstaff Sandstone Member containing the "Boskydell" Limestone, (2) type section of the Grindstaff Sandstone Member, and (3) type section of Sellers Limestone Member.

THE SELLERS LIMESTONE

The Sellers Limestone Member of the Caseyville Formation was named by Wanless (1939) from an exposure in the west bank of the Ohio River about one-third of a mile south of Sellers Landing in Hardin County, Illinois (SE NW SE NE SE Sec. 21, T. 11 S., R. 10 E.) (fig. 1). The Caseyville Formation is part of the McCormick Group and the Morrowan Series. The Sellers Limestone Member is known only

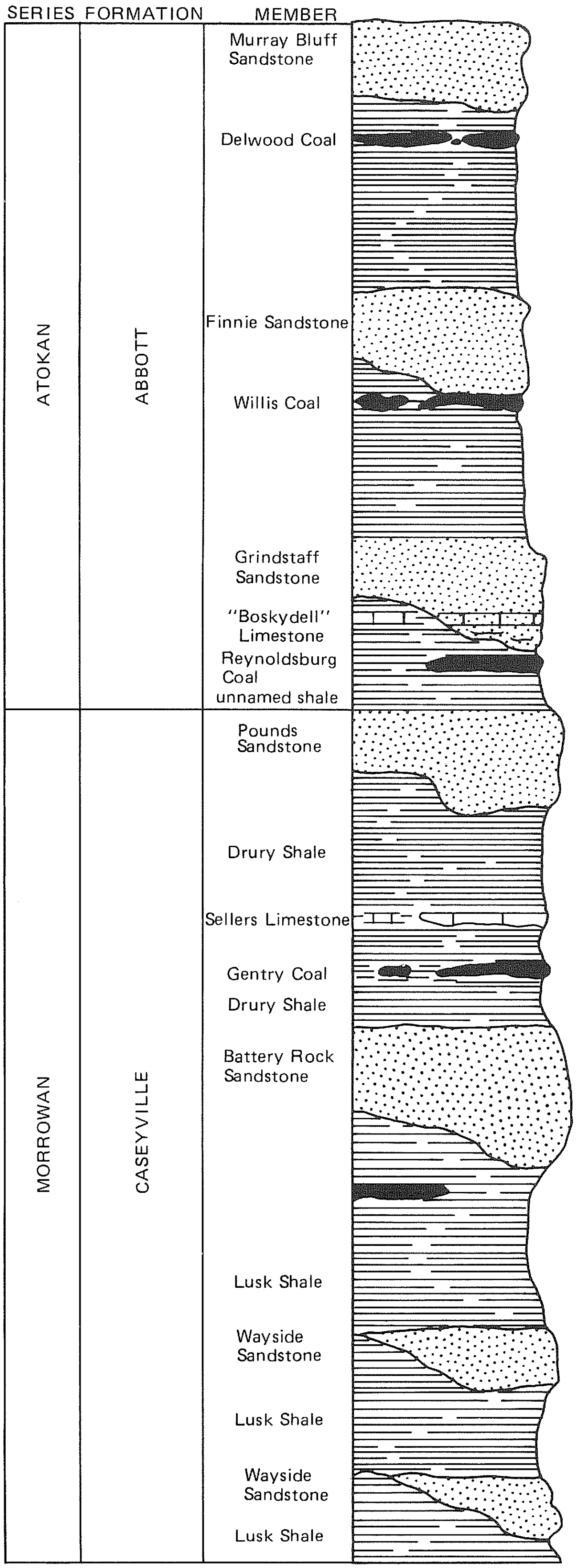

Figure 2. Columnar section, lower Pennsylvanian strata, southern Illinois. (Modified from Hopkins and Simon, 1975.)

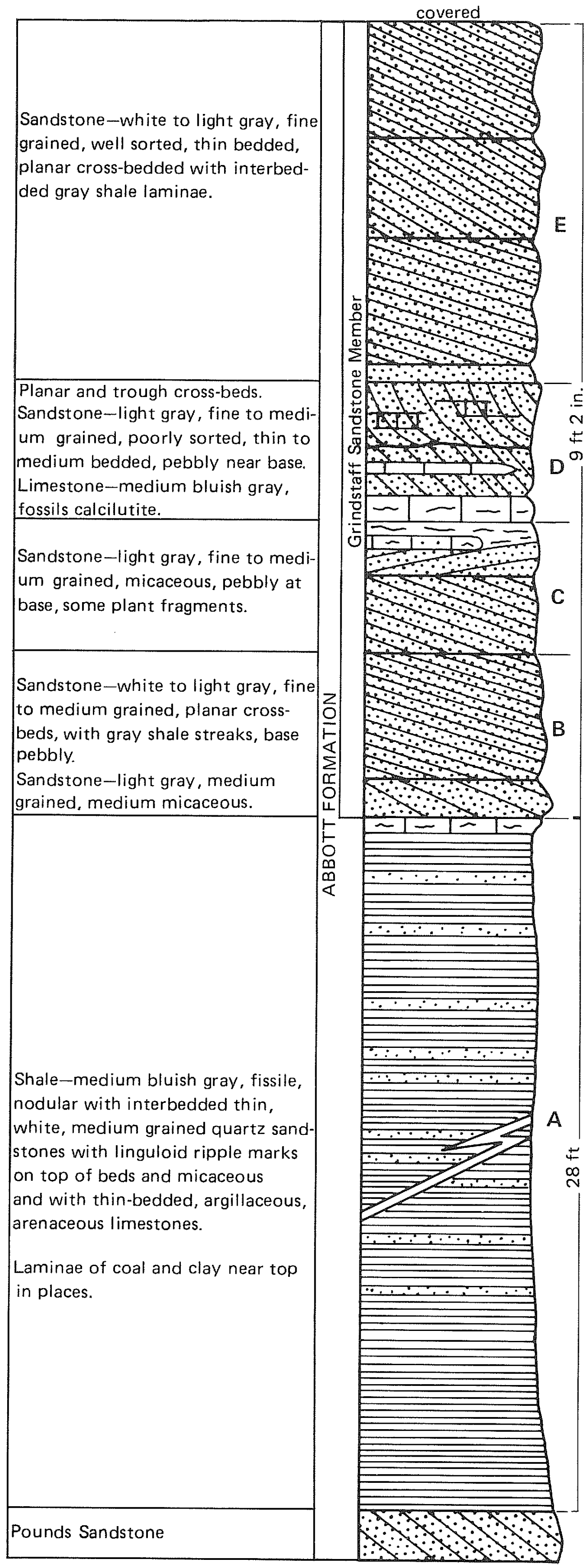

Figure 3. Columnar section, Grindstaff Sandstone Member with "Boskydell" lime. (Modified from Desborough, 1959.)

from the type locality. This limestone is in part coarse-grained, silty, and slightly argillaceous; weathers thin-bedded; and contains an abundant marine fauna. The coarse-grained part of the Sellers grades laterally into very fine-grained, thin beds of argillaceous, nonfossiliferous limestones and calcareous siltstones that are interbedded with gray shales. The Sellers reaches a thickness of about 10 feet and is overlain, underlain, and grades laterally into the Drury Shale Member of the Caseyville Formation (fig. 4).

The contained marine fauna consists of gastropods, trilobites, pelecypods, blastoids, and sharks' teeth. Nearly 100 species have been identified by M. W. Fuller (Wanless, 1939).

The Sellers Limestone is part of a complex fluvial-deltaic sequence. The underlying Drury Shale consists of interbedded siltstones and shales, which probably represent interdistributary bay deposition. Near the middle of the latter shale, the Gentry Coal is usually present. The Gentry probably represents swamp or marsh deposition on the delta plain. The Sellers Limestone contains randomly distributed whole or nearly whole fossils as well as "lenses" of fossil "hash" and consists of biomicrite at the base which grades upward into calcareous siltstones. The latter are nonfossiliferous. The Sellers may represent bay-mouth bar sedimentation. The upper part of the Drury Shale is more silty than the lower part and consists of interbedded shales and siltstones. These beds probably represent delta front sedimentation. The overlying Pounds Sandstone, which is pebbly and contains large-scale cross-bedding, probably represents distributary channel sedimentation.

No microfossils were found associated with any of the above described sedimentary units.

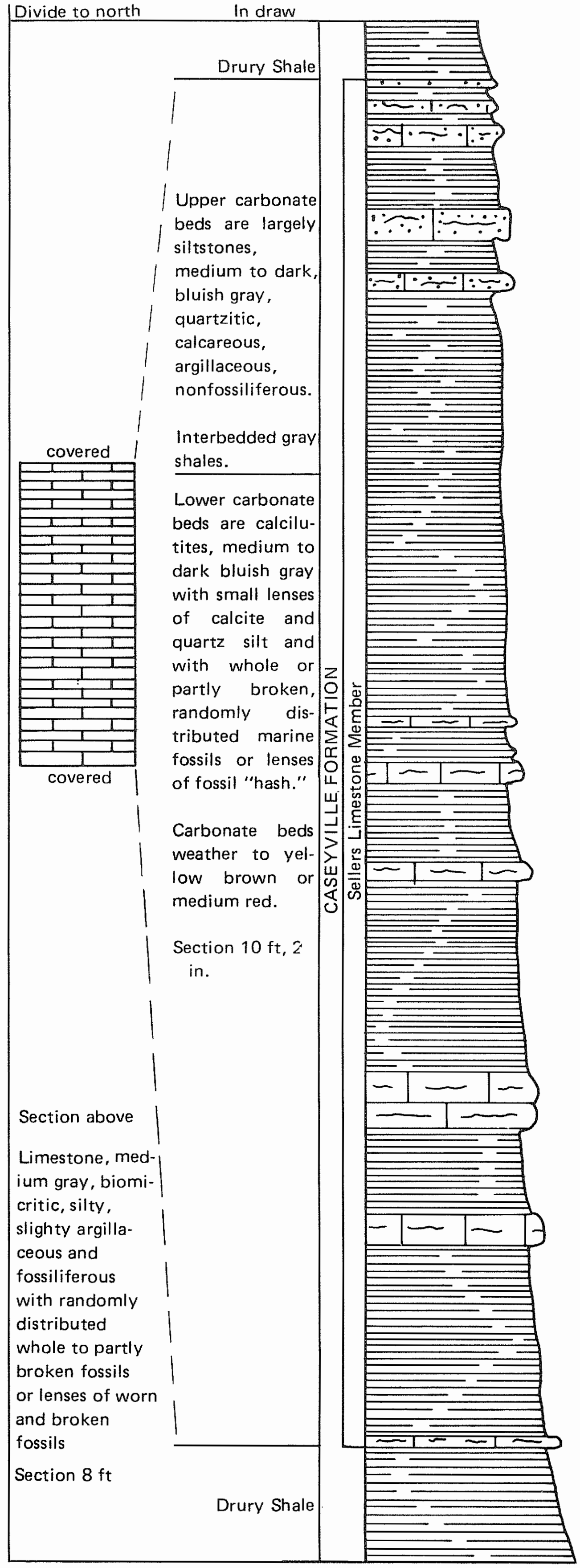

Figure 4. Columnar section, type section of the Sellers Limestone.

BIBLIOGRAPHY

BROUSSARD, M. L., 1975, Deltas, models for exploration: Houston Geological Society, 455 p.

BUTTS, Charles, 1925, Geology and mineral resources of the Equality-Shawneetown area: Illinois State Geological Survey Bulletin 47, p. 44.

DESBOROUGH, G. A., 1959, Correlation of the Boskydell Sandstone in southwestern Illinois: American Association of Petroleum Geologists Bulletin, v. 43, no. 11, p. 2720-2724.

ETHRIDGE, F. G., George FRAUNFELTER, and John UTGAARD, 1973, Depositional environments of selected Lower Pennsylvanian and Upper Mississippian sequences of southern Illinois: 37th Annual Tri-State Field Conference Guidebook, Southern Illinois University at Carbondale, p. 63-78.

HOPKINS, M. E., and J. A. SIMON, 1975, Pennsylvanian System, *in* H. B. Willman, Elwood Atherton, T. C. Buschbach, Charles Collinson, John C. Frye, M. E. Hopkins, Jerry A. Lineback, and Jack A. Simon, Handbook of Illinois Stratigraphy: Illinois State Geological Survey Bulletin 95, p. 165, 181, and 182.

KOSANKE, R. M., J. A. SIMON, H. R. WANLESS, and H. B. WILLMAN, 1960, Classification of the Pennsylvanian strata of Illinois: Illinois State Geological Survey Report of Investigations 214, p. 84.

MORGAN, J. P., 1970, Deltaic sedimentation, modern and ancient: Society of Economic Paleontologists and Mineralogists Special Publication no. 15, p. 312.

SIMON, J. A., 1960, Measured section at Sellers Limestone type section: Unpublished field notes, Illinois State Geological Survey, Urbana, Illinois.

WANLESS, H. R., 1939, Pennsylvanian correlations in the Eastern Interior and Appalachian coal fields: Geological Society of America Special Paper 17, p. 36, 101.

Earliest Pennsylvanian depositional environments in central southern Illinois

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INTRODUCTION

The lowest part of the Pennsylvanian System in central southern Illinois (fig. 1) consists of sandstones, siltstones, and shales of the Caseyville Formation. The lower Pennsylvanian caps a disconformity between Mississippian and Pennsylvanian strata in the Illinois Basin—a disconformity that becomes more pronounced farther north. The Caseyville Formation is approximately 110 meters thick and comprises deltaic, nearshore marine, and possibly shallow marine facies. In south-central Illinois, the Caseyville has been divided into four members by Willman et al. (1975): a lower shale (Lusk Shale Member), an intervening sandstone (Battery Rock Sandstone Member), an upper shaly interval (Drury Shale Member), and an upper sandstone (Pounds Sandstone Member).

The sandstones of the Caseyville are supraquartzose with a concomitant lack of feldspar and lithic fragments. Studies by Koeninger (1978), Gopinath (1972), and Sliva (1972) indicate that most sandstones in the Caseyville are quartz-rich arenites with some minor occurrences of lithiquartzose arenites and wackes, as classified according to the system proposed by Mansfield and Ahlbrandt (1978a, 1978b). Caseyville sandstones are cemented principally by silica from pressure solution of the predominantly quartz framework; there are patchy occurrences of later calcite cement.

Studies of cross-bedding and petrology (Potter and Siever, 1956; Siever and Potter, 1956) indicate that the source was to the north/northeast of the present location of the basin. The primary source was probably sedimentary strata in the northern Appalachian Mountains; a subsidiary source may have been deeply eroded crystalline rocks of the Canadian Shield. Abraded quartz overgrowths (Koeninger, 1978) and rounded grains of tourmaline and zircon in Caseyville sandstones (Koeninger, 1978; Gopinath, 1972) indicate recycled and reworked sediments.

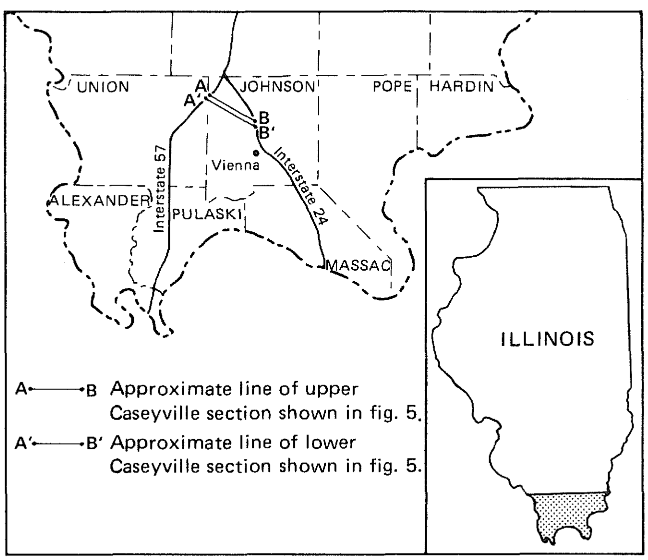

Figure 1. Area of study.

The Caseyville Formation was deposited in what is here termed the Illinois Embayment of an epeiric sea that extended at least as far west as Kansas and as far south as northern Arkansas, where it joined the Ouachita Trough. The Illinois Embayment was bounded on three sides by low, positive elements. To the west lay the Ozark shoals area; this was a positive structural element, although not necessarily above sea level during deposition of the Caseyville. To the northwest, northeast, and east, the Kankakee, Findlay, and Cincinnati Arches, respectively, formed positive elements (King, 1977), which evidently were not effective barriers to sediment transportation from the inferred northeastern source area (Potter and Siever, 1956).

The Illinois Basin was subsiding during Early Pennsylvanian (Wanless and others, 1970), although the uniformity in rate of subsidence is a point of controversy. This controversy centers around the still uncounted number of deltaic progradations and marine transgressions as well as possible eustatic changes in sea level during the Pennsylvanian.

The possibility of a major transgression between periods of delta-lobe formation during earliest Pennsylvanian is indicated by the shaly interval between the upper and lower Caseyville outcrops along both Interstate 57 (I-57, northeastern edge of Union County) and Interstate 24 (I-24, central Johnson County). This interval is 20 to 30 meters thick and is formed by the Drury Shale; the thickness compares well with postcompactional thicknesses of modern Mississippi River prodelta clays reported by Coleman (1976). If the Drury Shale does represent a marine transgression, it correlates well with the Sellers Limestone, which is a marine limestone separating the Battery Rock Sandstone Member from the Pounds Sandstone Member in southeastern Illinois (Potter and Desborough, 1965).

The Caseyville was deposited in an area that, according to Schopf (1975), was a few degrees north of the Early Pennsylvanian equator that, in terms of modern geography, trended northeast-southwest. In addition, Schopf (1975) described the climate as humid, subtropical to tropical.

SUBENVIRONMENTS OF THE CASEYVILLE FORMATION

Distributary channel deposits (figs. 2a and 2b) in the Caseyville Formation are commonly cut into interdistributary bay, marsh, swamp, abandoned channel, and older point

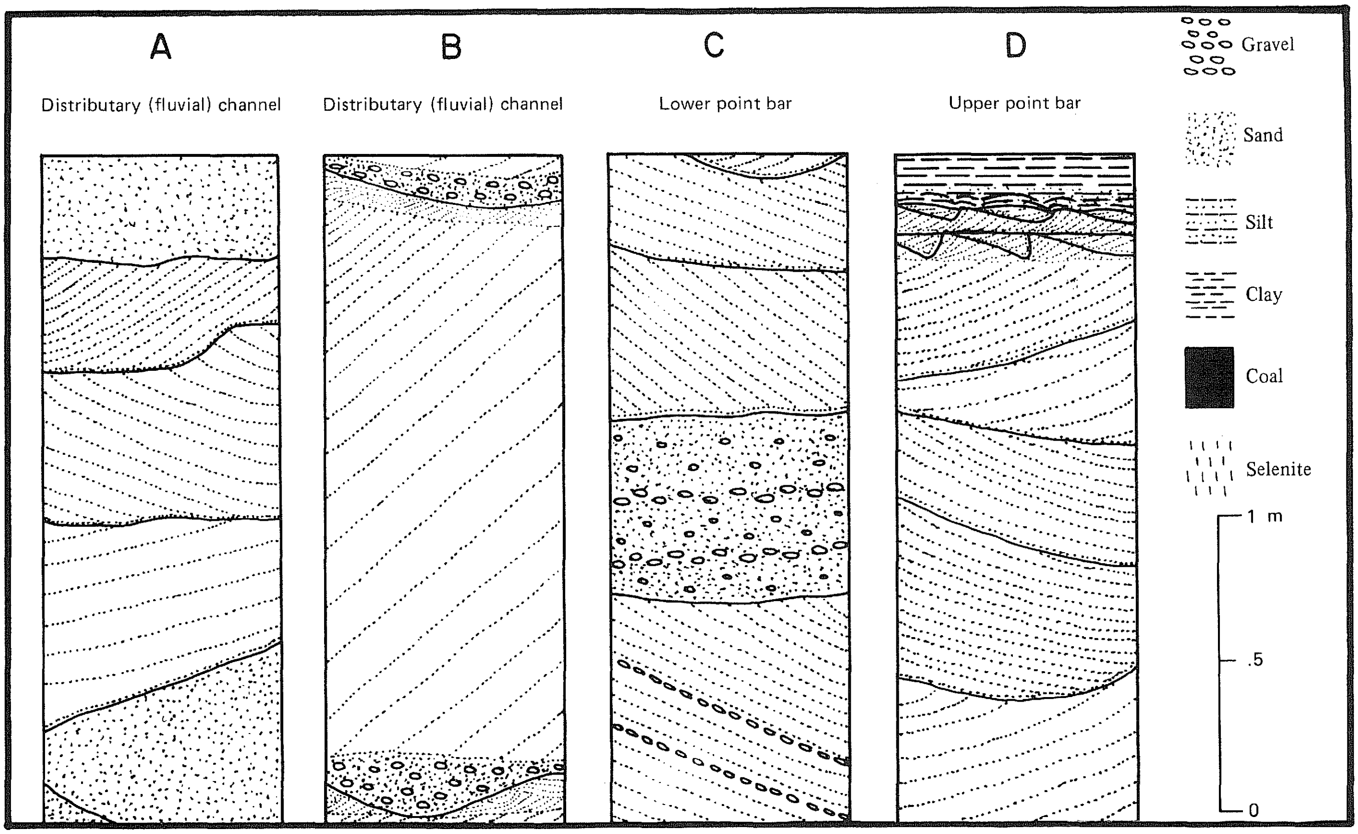

Figure 2. Active channel facies.

bar deposits. These distributary channel fills commonly grade upward into tidally influenced abandoned channel, marsh, interdistributary bay, and swamp deposits, and may be scoured by younger point bar or distributary channel deposits.

These distributary channel deposits are predominantly medium-grained and fine-grained sandstone with infrequent stringers of gravelly, coarse-grained sandstone and some layers of shale. Principal sedimentary structures include planar and trough cross-beds, erosional truncation, casts of plant fragments, and disrupted bedding. Fluvial facies described by Harms et al. (1975) are found in various combinations in each of the Caseyville distributary channel deposits. Recent distributary channel and channel deposits of the Mississippi River delta, described by Coleman and Gagliano (1965), are similar to those in the Caseyville.

Point bar deposits (figs. 2c and 2d) in the Caseyville Formation commonly overlie and may cut into interdistributary bay, marsh, swamp, and abandoned channel facies. Conversely, point bar deposits may be overlain conformably by marsh and floodplain deposits, or may be scoured by younger distributary or fluvial channels.

Point bar deposits in the Caseyville are predominantly gravelly, coarse-grained sandstone and medium-grained sandstone. Sedimentary structures include planar and trough cross-beds, major scour channels, and erosional truncation (fig. 2c). Rocks generally become finer upward within each channel fill; siltstone/mudstone drapes commonly cap each channel fill (fig. 2d). Where several point bars are stacked, the rocks also become finer upward overall. Fluvial facies, described by Harms et al. (1975), that are commonly present in Caseyville point bar deposits include: facies A, which is coarse and pebbly sandstone with poorly defined trough cross-beds; facies E, which is composed of large scours filled with sandy cross-beds that conform to scour shape; and facies G, which is a very low-angle cross-bedded sandstone. Point bar deposits in the Caseyville Formation are similar to those described by McGowen and Garner (1970) from the Amite River in southwestern Louisiana.

Interdistributary bay deposits (fig. 3b) commonly overlie distributary channel and abandoned channel deposits and may overlie marsh and swamp deposits. Conversely, bay deposits may pass upward into marsh deposits, but in many locations are in scour contact with overlying point bar or distributary channel deposits.

The interdistributary bay deposits are dominantly shale, siltstone, and fine-grained sandstone. The siltstones and sandstones are lenticular in shape and are encased by shale. These thin to very thin lenses are scoured into the shale and contain small-scale trough cross-beds and ripple marks with associated ripple-drift lamination. The shales contain wavy bedding and rare burrows; in deposits that contain coarser detritus, lenticular laminations are common. Interdistributary bay fills of the Caseyville Formation are similar to those of the Mississippi River delta described by Coleman and Gagliano (1965).

Abandoned distributary channel deposits (figs. 3a and 3c) conformably overlie distributary channel deposits. These abandoned channel-fill units frequently pass upward into interdistributary bay and marsh deposits and may be scoured by younger distributary channels.

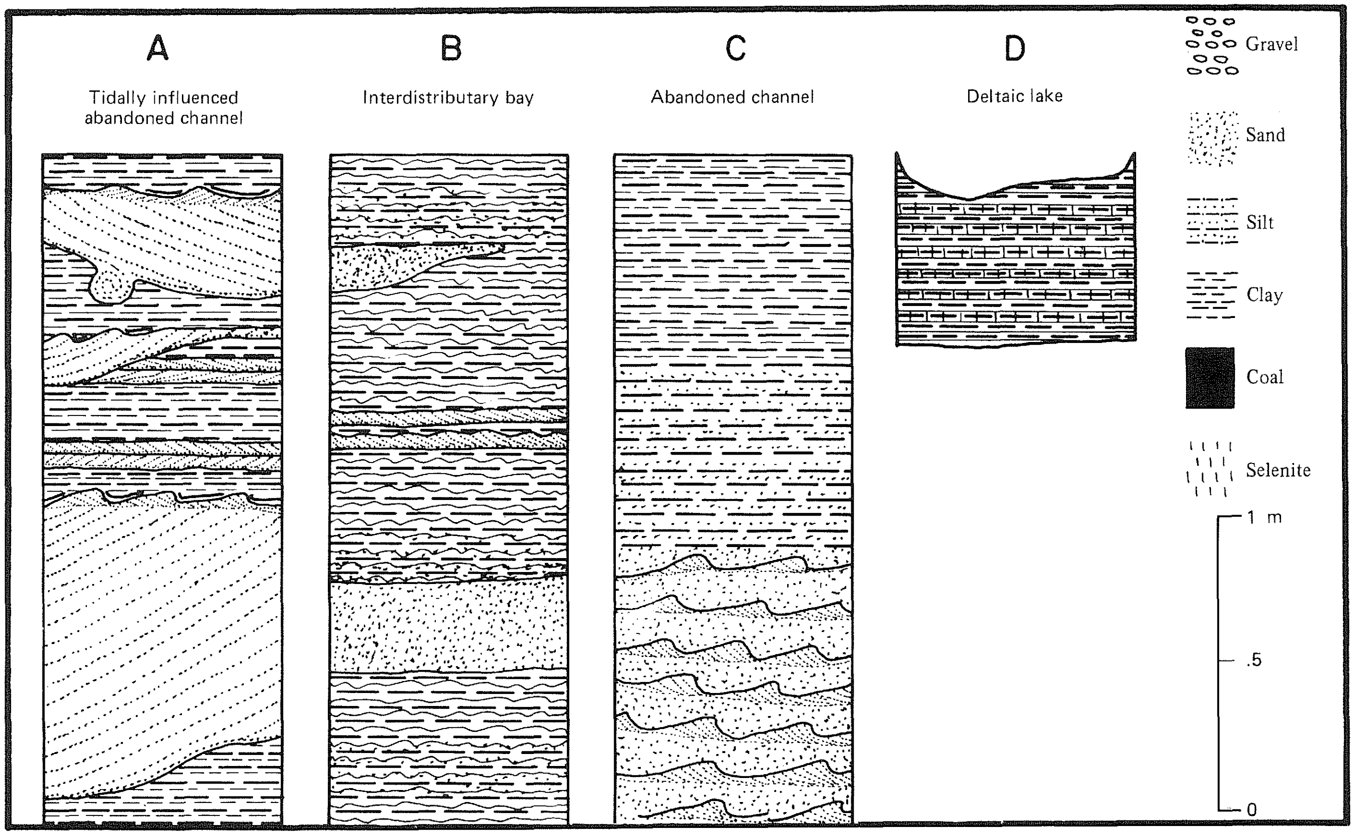

Figure 3. Interdistributary facies.

Abandoned distributary channel deposits in the Caseyville are characterized by shale and enclosed lenticular bodies of medium- to fine-grained sandstone. Tidally influenced abandoned channel deposits (fig. 3a) contain thin to thick lenses of small-scale trough cross-bedded sandstone; these lenses are commonly capped by ripple marks formed by flow in a direction opposite to that suggested by the underlying trough cross-beds. Flaser beds are also present in these tidally influenced deposits. On the other hand, abandoned channel deposits not directly influenced by tidal action (fig. 2c) are characterized by ripple-marked fine-grained sandstone that grades upward into horizontally bedded siltstone and shale. These abandoned channel-fill deposits, lacking apparent marine or tidal influence, are similar to those of the Mississippi delta, described by Coleman (1976).

An example of a deltaic lake deposit (fig. 3d) lies in the Caseyville Formation. This unit conformably overlies an interdistributary bay fill deposit and is scoured by a distributary channel. The lake deposit contains rhythmically interbedded black mudstone and a gray, silty mudstone, which is interesting in that it also contains layers of vertical selenite crystals. Bedding is uniformly very thin and laterally persistent, resulting in the varvelike appearance of the deposit, similar to deltaic lake deposits described by Coleman and Gagliano (1965) on the modern Mississippi River delta. The selenite layers indicate seasonal (?), high-evaporative conditions and occasional marine washover.

Marsh deposits (fig. 4a) in the Caseyville Formation overlie distributary channel, point bar, and interdistributary bay deposits. These marsh deposits may grade upward into swamp and interdistributary bay deposits and are commonly cut into by distributary channels.

Marsh deposits may laterally interfinger with swamp deposits. Marsh deposits in the Caseyville are predominantly black shale with interbedded, thin lenses of sandstone. Laminae of carbonaceous material are common along parting planes in the shale and along bedding planes in the sandstone lenses. These marsh deposits are similar to those of the Mississippi River deltaic plain described by Coleman and Gagliano (1965).

Floodplain deposits (fig. 4b) of the Caseyville Formation overlie point bar deposits and are scoured by younger distributary channels. These deposits contain color-banded shale, which indicates subaerial exposure. Furthermore, the shales enclose rhythmically interbedded, uniformly thick, ripple-marked siltstone lenses, which were probably deposited by seasonal floods. Although these marshes were probably intermittent and patchy, they were likely more widespread and abundant than the remaining deposits indicate.

Swamp deposits (fig. 4c) and related coals are not well represented in the Caseyville Formation. Where present, these deposits are normally associated both laterally and vertically with marsh deposits and may be scoured by fluvial or distributary channels.

CASEYVILLE FACIES RELATIONSHIPS

Lower Caseyville strata exposed in the lower roadcut on I-24 were deposited in an environment that was dominantly fluviatile; the right side of the lower half of figure 5 illustrates this deposition. The thick sequence of point bar deposits indicates the absence of marine influence, and the domination of the upper third of the outcrop by marsh and overbank deposits indicates relatively stable conditions which allowed vegetation to become established. Lower Caseyville rocks along I-24 probably were deposited on what Allen (1970) calls the upper delta plain.

On the other hand, lower Caseyville strata exposed in the lower roadcut on I-57 (fig. 5, lower left side) were deposited on that part of the delta which was much more influenced by marine processes. Evidence of reworking, flaser bedding, and the absence of marsh deposits suggest that marine influence was stronger and conditions were more transitory than the conditions that existed at the I-24 outcrop. Lower Caseyville strata exposed along I-57 were probably deposited on a lower deltaic plain (after Allen, 1970).

Comparative sedimentology, paleocurrent indicators, and progressively finer grain size westward indicate that the lower Caseyville delta prograded in a west/southwestwardly direction. The shoreline during deposition of the lower Caseyville was located to the west/southwest of the present outcrop belt. Dominance in the upper third of the lower roadcut on I-57 by distributary and marsh deposits suggests that the delta was also building up as it prograded west/southwestwardly.

Upper Caseyville strata exposed in the upper roadcut on I-24 (fig. 5, upper right side), like lower Caseyville strata in the lower roadcut, were deposited in an environment dominated by fluvial/terrestrial processes. A thick channel-fill sandstone forms the uppermost unit of the upper Caseyville and is overlain by marsh, swamp, and distributary channel deposits of the overlying, lowermost part of the Abbott Formation.

Conversely, like lower Caseyville strata in the lower roadcut, upper Caseyville strata exposed in the upper roadcut on I-57 (fig. 5, upper left side) were deposited on a part of the delta that was much more influenced by marine processes. Tidally influenced deposits and a thick interdistributary bay-fill unit indicate that strata exposed in the upper roadcut on I-57 were deposited seaward of those in the upper roadcut along I-24; the shoreline probably was situated to the west/southwest of the present outcrop belt. The swamp and marsh deposits overlying the Caseyville in the eastern portion of the area under consideration suggest that the delta was building up as well as prograding to the west/southwest. The braided-stream character of upper Caseyville sandstones in eastern southern Illinois (Hardin and adjoining counties) further suggests that the delta that prograded across the Illinois Embayment may have been a braided-stream delta which was not unlike the Ganges portion of the Ganges-Brahmaputra delta as described by Morgan (1970).

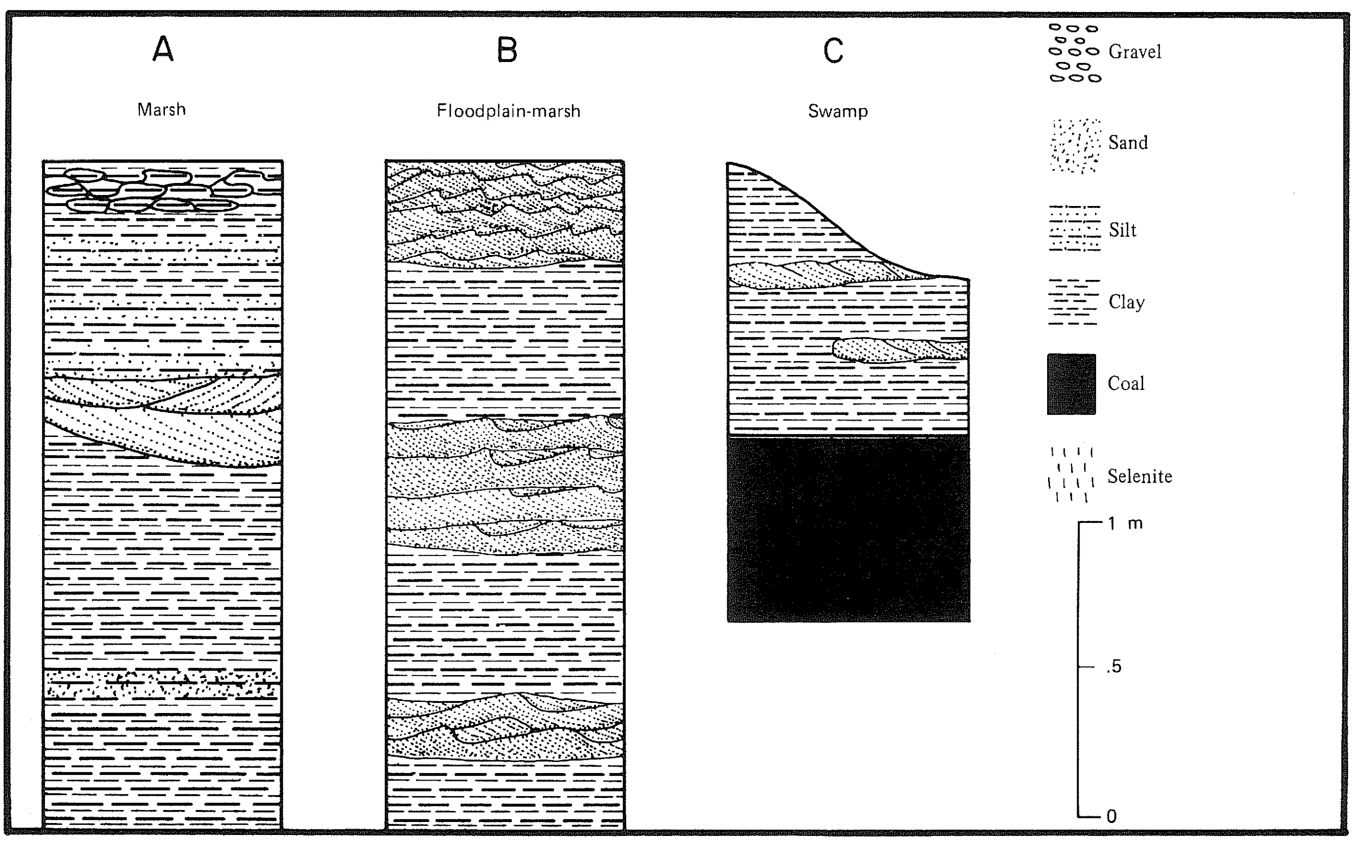

Figure 4. Overbank facies.

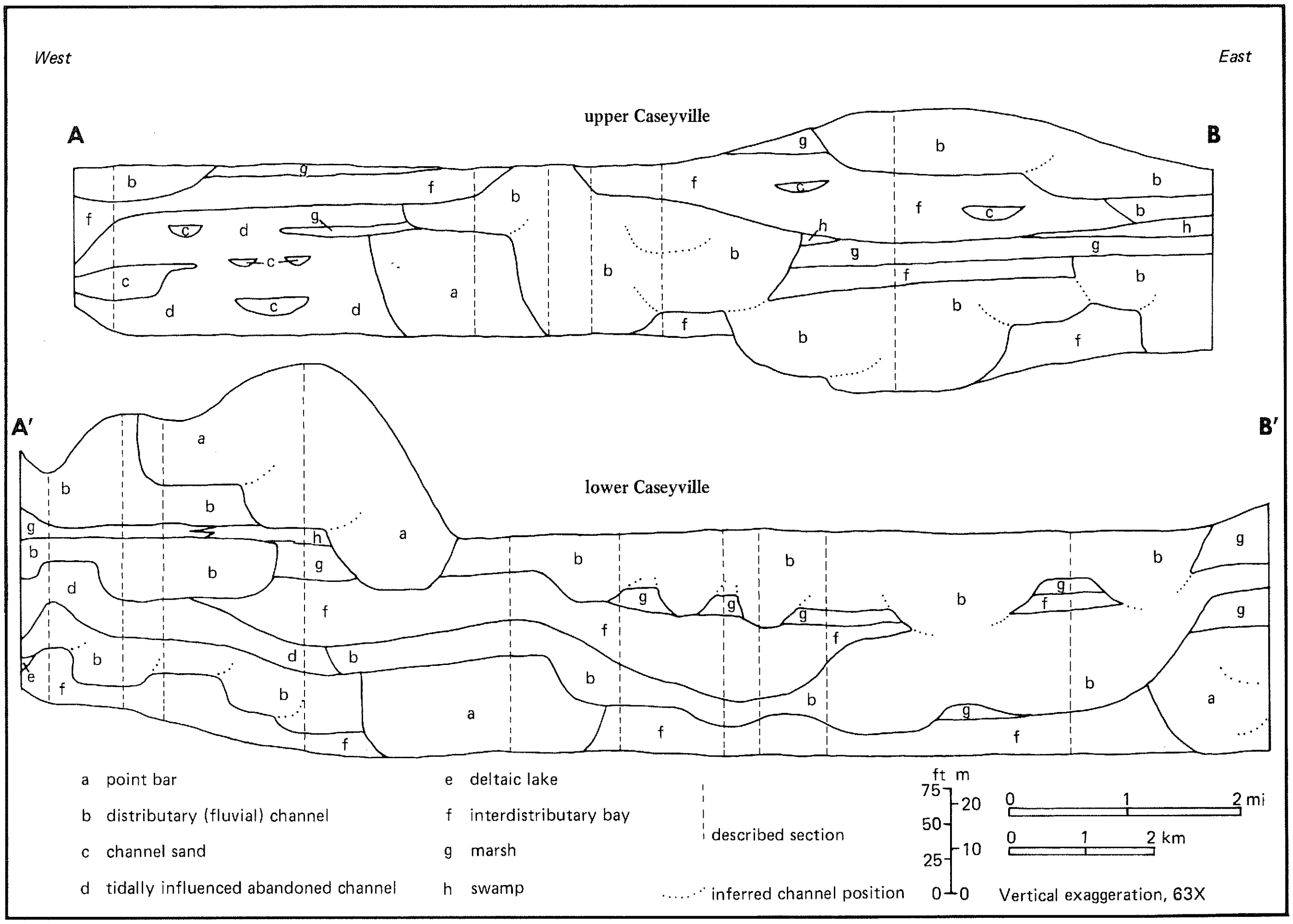

Figure 5. Facies relationships. (See figure 1 for location.)

REFERENCES

ALLEN, J.R.L., 1970, Sediments of the modern Niger delta: a summary and review, *in* J. P. Morgan [ed.], Deltaic sedimentation, modern and ancient: Society of Economic Paleontologists and Mineralogists Special Publication 15, p. 138-151.

COLEMAN, J. M., 1976, Deltas: processes of deposition and models for exploration: Continuing Education Publication Company, Inc., Champaign, Ill., 102 p.

COLEMAN, J. M., and S. M. GAGLIANO, 1965, Sedimentary Structures: Mississippi River deltaic plain, *in* G. V. Middleton [ed.], Primary sedimentary structures and their hydrodynamic interpretation: Society of Economic Paleontologists and Mineralogists Special Publication 12, p. 133-148.

GOPINATH, T. R., 1972, Upper Caseyville (Lower Pennsylvanian) deltaic sedimentation: Jackson, Union, and Johnson Counties, Illinois: Unpublished M.S. thesis, Southern Illinois University, Carbondale, 84 p.

HARMS, J. C., J. B. SOUTHARD, D. R. SPEARING, and R. G. WALKER, 1975, Depositional environments as interpreted from primary sedimentary structures and stratification sequences: Society of Economic Paleontologists and Mineralogists Short Course No. 2, 161 p.

KING, P. B., 1977, The evolution of North America: Princeton University Press, Princeton, NJ, 198 p.

KOENINGER, C. A., 1978, Regional facies of the Caseyville Formation (Lower Pennsylvanian), south-central Illinois: Unpublished M.S. thesis, Southern Illinois University, Carbondale 124 p.

McGOWEN, J. H., and L. E. GARNER, 1970, Physiographic features and stratification types of coarse-grained point bars: modern and ancient examples: Sedimentology, v. 14, p. 77-111.

MANSFIELD, C. F., and T. S. AHLBRANDT, 1978a, A descriptive classification for detrital sandstones: Geological Society of America Abstracts with Programs, v. 10, no. 6, p. 260.

MANSFIELD, C. F., and T. S. AHLBRANDT, 1978b, A detrital sandstone classification for petrologists: Wyoming Geological Association Earth Science Bulletin, v. 11, no. 3, p. 1-11.

MORGAN, J. P., 1970, Depositional processes and products in the deltaic environment, *in* J. P. Morgan [ed.], Deltaic sedimentation, modern and ancient: Society of Economic Paleontologists and Mineralogists Special Publication 15, p. 31-47.

POTTER, P. E., and G. A. DESBOROUGH, 1965, Pre-Pennsylvanian Evansville Valley and Caseyville (Pennsylvanian) sedimentation in the Illinois Basin: Illinois State Geological Survey Circular 384, p. 1-15.

POTTER, P. E., and Raymond SIEVER, 1956, Sources of basal Pennsylvanian sediments in the Eastern Interior Basin: Part 1—Crossbedding: Journal of Geology, v. 64, p. 225-244.

SCHOPF, J. M., 1975, Pennsylvanian climate in the United States, *in* Paleotectonic investigations of the Pennsylvanian System in the United States, Part II: U.S. Geological Survey Professional Paper 853, p. 23-31.

SIEVER, Raymond, and P. E. POTTER, 1956, Sources of basal Pennsylvanian sediments in the Eastern Interior Basin: Part 2—Sedimentary petrology: Journal of Geology, v. 64, p. 317-335.

SLIVA, T. W., 1972, Lower Caseyville (Lower Pennsylvanian) depositional environments: Union and Johnson Counties, Illinois: Unpublished M.S. thesis, Southern Illinois University, Carbondale, 47 p.

WANLESS, H. R., J. R. BAROFFIO, J. C. GAMBLE, and seven others, 1970, Late Paleozoic deltas in the central and eastern United States, *in* J. P. Morgan, [ed.], Deltaic sedimentation, modern and ancient: Society of Economic Paleontologists and Mineralogists Special Publication 15, p. 215-245.

WILLMAN, H. B., Elwood ATHERTON, T. C. BUSCHBACH, Charles COLLINSON, J. C. FRYE, M. E. HOPKINS, J. A. LINEBACK, and J. A. SIMON, 1975, Handbook of Illinois stratigraphy: Illinois State Geological Survey Bulletin 95, p. 163-183.

The stratigraphy and sedimentation of the Abbott and lower portion of the Spoon Formations in the outcrop belt of southern Illinois

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INTRODUCTION

The Abbott and Spoon Formations crop out in a belt extending from Monroe County to eastern Gallatin County, Illinois (fig. 1). Southern Illinois was part of, and adjacent to, a northeast-southwest-trending embayment, which was open to the southwest during deposition of these strata. The Campbell Hill Anticline (fig. 1) was a hinge separating the more rapidly subsiding eastern portion of the area from a more stable shelf to the northwest. The Illinois Basin was closed after deposition of the Abbott and Spoon Formations. Movements during the closure of the basin produced the several structures and structural belts shown in figure 1.

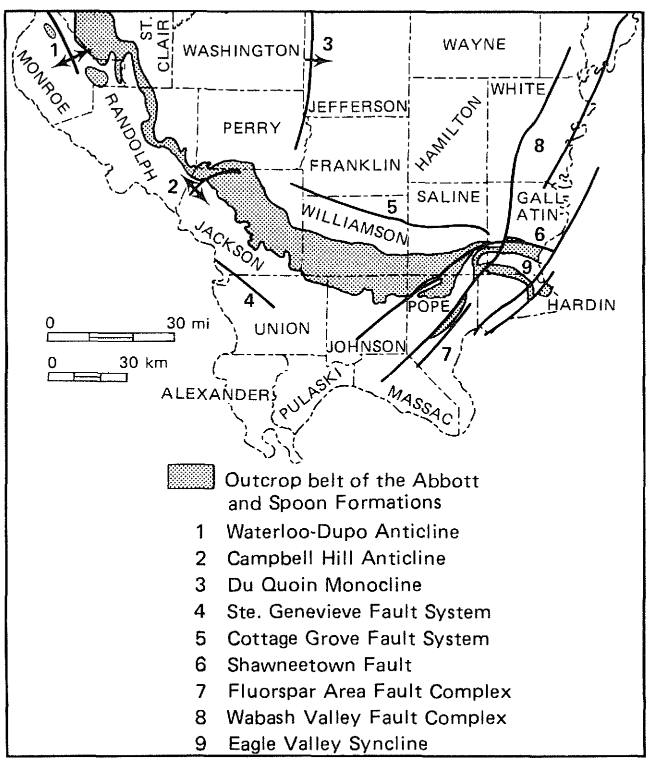

Figure 1. Outcrop belt of the Abbott and Spoon Formations and principal structures in southern Illinois.

STRATIGRAPHY

A number of stratigraphic units in the Abbott and Spoon Formations have been given formal names (fig. 2). The derivation of the names of these units and their type localities are discussed by Kosanke et al. (1960) and by Hopkins and Simon (1975). Several named units recognized by the Illinois State Geological Survey are considered here to be equivalents of other named units and have been omitted from this discussion.

McCormick Group

The McCormick Group includes the strata from the base of the Pennsylvanian to the top of the Murray Bluff Sandstone and comprises the Caseyville (lower) and Abbott (upper) Formations. The sedimentary cycles that characterize much of the Pennsylvanian are less evident in the McCormick Group, in which relatively clean quartz sandstones, sandy shales, and siltstones predominate. Coals are generally thin and nonpersistent, although palynologic studies have permitted correlation of several coals across portions of southern Illinois and with equivalents elsewhere. Carbonates are almost entirely restricted to local calcareous zones in sandstones and shales.

Abbott Formation

The Abbott Formation includes the strata between the top of the Pounds Sandstone Member of the Caseyville Formation and the Murray Bluff Sandstone Member (fig. 2). The Abbott thins from east to west across southern Illinois from approximately 350 feet (107 m) in Gallatin and Saline Counties to less than 10 feet (3 m) in Monroe County. The rate of thinning is fairly uniform from Saline County to the Campbell Hill Anticline in northwestern Jackson County (fig. 3), where the Abbott thins abruptly from approximately 140 feet (43 m) to 35 feet (11 m). The base of the Abbott is readily established in areas where the Reynoldsburg Coal is present, but is somewhat arbitrary elsewhere. In much of southern Illinois the Abbott is underlain by the thick quartz-bearing Pounds Sandstone Member of the Caseyville Formation. Although quartz pebbles are not

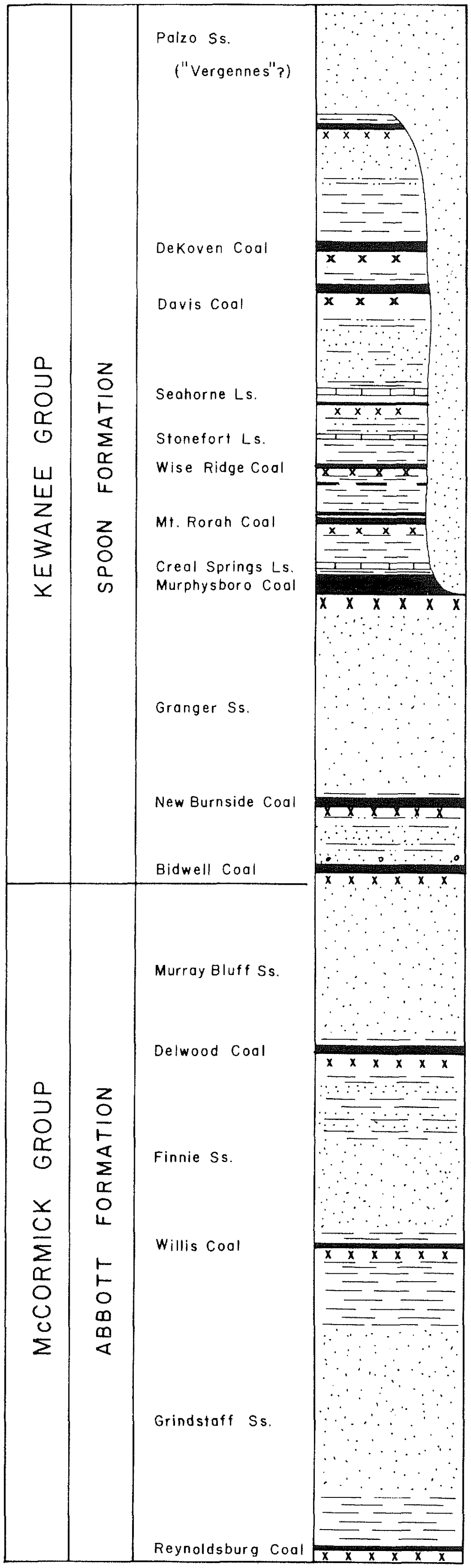

Figure 2. Columnar section of the Abbott and Spoon Formations.

restricted to the Caseyville, they are most characteristic of it, and the highest sandstone having abundant quartz pebbles is generally the upper member of the Caseyville. The Abbott is overlain by the Spoon Formation of the Kewanee Group which also overlaps it northwest of the area of discussion. In southern Illinois the top of the Abbott is the first sandstone below the lowest coal in the Spoon Formation identified by floral population.

Sandstone members. Sandstones, sandy shales, and siltstones constitute more than 90 percent of the Abbott Formation. The sandstones occur in narrow elongate bodies as much as 150 feet (46 m) thick and in thin sheets that average less than 30 feet (9 m) thick. The most common structures in the elongate sandstones are cross-bedding and small erosional channels; in the sheets, ripple marks are the most common. Individual sandstone members can be identified and correlated in areas where the associated coals occur, but where coals are lacking these strata are indistinguishable from one another. The sandstones also change facies abruptly from elongate to sheet phases. This obscures lateral trends in that the elongate sandstones are very similar to one another, and the sheet sandstones are very similar to one another, but an elongate phase and a sheet phase in the same member are very dissimilar.

Lithologically the sandstones are quartz arenites (Pettijohn, Potter, and Siever, 1973). The average composition of the detrital components (modified from Potter and Glass, 1958) are as follows: quartz, 83 percent; detrital matrix, 9.7 percent; mica, 2.6 percent; feldspar, 2.5 percent; chert and rock fragments, 1.1 percent; and heavy minerals and miscellaneous constituents, 1.1 percent. The heavy minerals are principally zircon, tourmaline, and rutile. The sandstones are fine grained, moderately well sorted, and commonly have subrounded grains with secondary quartz overgrowths. In elongate phases the sandstones are better sorted than those in sheet phases and generally decrease in grain size upward. Sheet sandstones have no regular size gradation. In general, the percentages of detrital matrix and mica in the sandstones increase from the lower to the upper portion of the formation. Elongate sandstone bodies are prominent east of the Campbell Hill Anticline in northwestern Jackson County (fig. 1) and make up much of the thickness of the formation over large areas. Calcareous sandstone and sandy limestone lenses with abraded marine fossils occur in several elongate bodies in southeastern Jackson and southern Saline Counties. These are the only indications of marine carbonate deposition in this area. Northwest of the Campbell Hill Anticline, the formation is almost entirely silty shale and siltstone and a few minor sandstone lenses. Here the lack of other lithologies precludes division of the formation into members.

The sandy deposits in the Abbott Formation are divided into the Grindstaff Sandstone Member, Finnie Sandstone Member, and Murray Bluff Sandstone Member (fig. 2). The Grindstaff Sandstone occurs in prominent elongate bodies in extreme southeastern Illinois, where it is readily recognized. It is correlated with the Babylon Sandstone of western Illinois, the upper part of the Mansfield Sandstone of Indiana, and the Grindstaff Sandstone of western Kentucky. The Finnie and Murray Bluff Sandstone

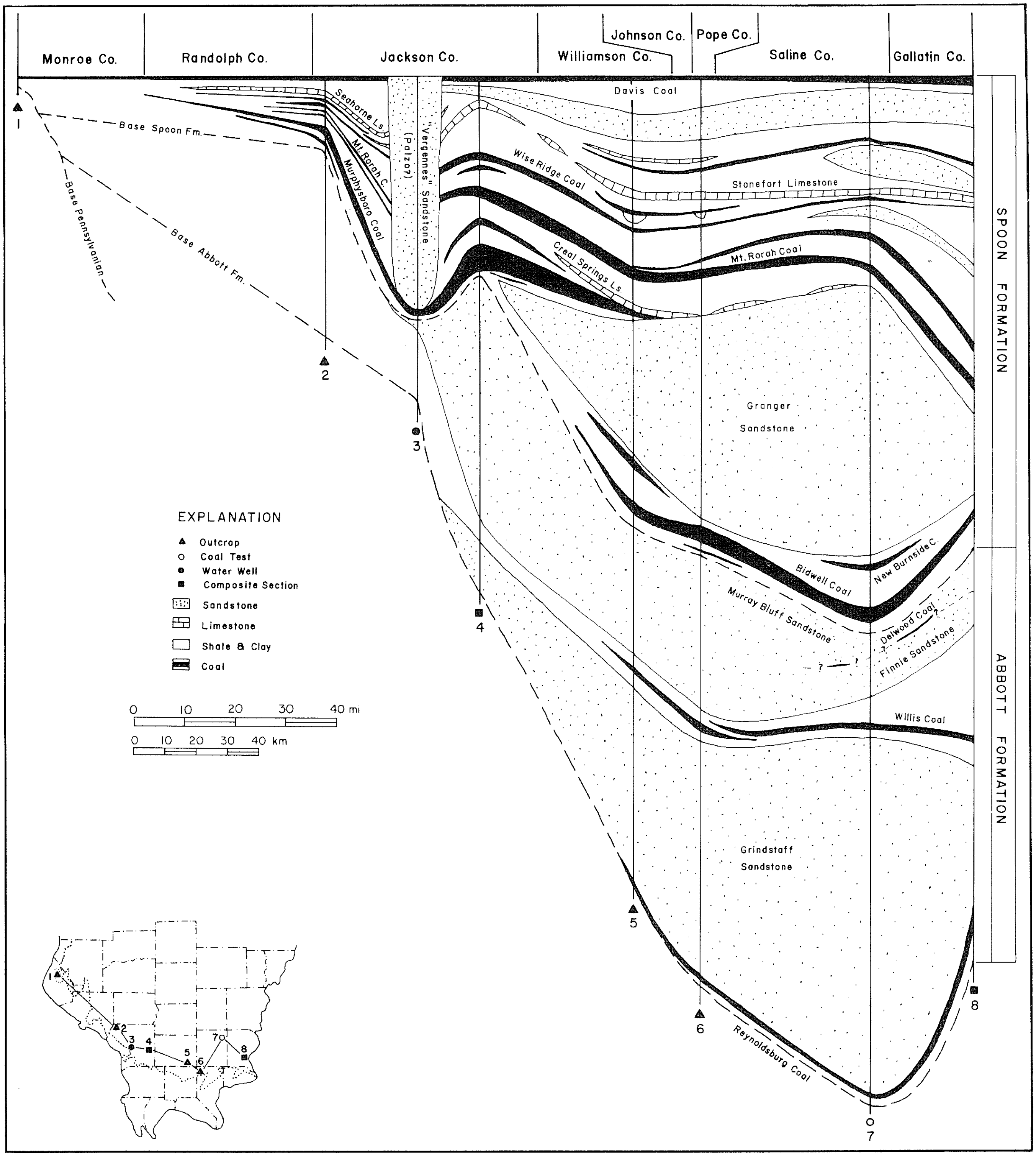

Figure 3. Stratigraphic cross section of key members in the Abbott and lower Spoon Formations in the outcrop belt of southern Illinois.

Members are very similar in occurrence to the Grindstaff. Where no confining strata can be identified, however, it is impossible to distinguish between the two members, and both names must be applied. The Murray Bluff Sandstone is correlated with the Bernadotte Sandstone of western Illinois and the Aberdeen Sandstone of western Kentucky.

Coal members. Three coal members are named in the Abbott Formation: Reynoldsburg Coal Member, Willis Coal Member, and Delwood Coal Member (fig. 2). The Reynoldsburg Coal, at the base of the Abbott Formation, is known only in the vicinity of the type area. The coal is highly variable in thickness, ranging from a maximum of 3.5 feet (1 m) to a few inches of coal and canneloid black shale. The Reynoldsburg Coal has been correlated with the No. 2 coal of western Kentucky. The Willis Coal overlies the Grindstaff Sandstone and underlies the Finnie Sandstone. The Willis Coal is also very local in its occurrence and is restricted to a few localities in extreme southeastern Illinois where it averages 3 to 3.5 feet (about 1 m) thick. West of the type area in southwestern Johnson County, a thin coal crops out in the approximate stratigraphic position of the Willis. The floral population of this coal suggests that it may be slightly older than the Willis, as shown in figure 3. The Willis Coal is correlated with the Tarter Coal of western Illinois and the Lower Block Coal of Indiana. The Delwood Coal may occur in a few scattered localities in southeastern Illinois. Exact areas of development of the coal are difficult to determine, however, because the name has been applied to coals in several areas although no identifiable associated strata are present. Palynological studies strongly suggest that at least some of these coals are equivalent to coals in the lower part of the Spoon Formation. The Delwood Coal is correlated with the Pope Creek Coal of western Illinois, the Upper Block Coal of Indiana, and the Ice House (No. 3) Coal of western Kentucky.

Kewanee Group

The Kewanee Group includes the Spoon (lower) and Carbondale (upper) Formations. In southern Illinois, strata between the top of the Murray Bluff Sandstone Member of the Abbott Formation and the top of the Danville (No. 7) Coal Member are included in the Kewanee Group.

Spoon Formation

The Spoon Formation consists of strata between the top of the Murray Bluff Sandstone Member of the Abbott Formation and the base of the Colchester (No. 2) Coal. Named members of the Spoon Formation in southern Illinois are illustrated in figure 2. Sandstones, gray mudstones, discontinuous coals, and thin limestones are the most important rock types in the Spoon Formation. Although coals thin and thicken abruptly and are laterally restricted in the lower portion of the Spoon, similar to those in the Abbott Formation, they generally cover larger areas, and several are locally more than 5 feet (1.5 m) thick. Like the Abbott Formation, the Spoon Formation is most complete and varied east of the Campbell Hill Anticline (fig. 1). The lower portion of the formation as a whole, but particularly the sandstones, thins from east to west from approximately 250 feet (76 m) in Saline County to 100 feet (30 m) in Jackson County. West of the Campbell Hill Anticline, this portion of the Spoon does not exceed 45 feet (14 m) thick and is largely coal and shale.

Sandstone members. Sandstones and sandy shales are the dominant lithologies in the lower portion of the Spoon Formation. Like the sandstones in the Abbott Formation, those in the Spoon occur in narrow elongate bodies, as much as 110 feet (33 m) thick, and in sheets commonly less than 10 feet (3 m) thick. As in the Abbott, the most common structures in the elongate phases are cross-bedding and minor erosional channels, and, in the sheets, ripple marks. The vertical trend of increasing percentages of detrital matrix and poorer sorting that was noted in the Abbott sandstones is continued in the sandstones in the Spoon Formation. The sandstones are predominantly fine-grained quartz wackes (Pettijohn, Potter, and Siever, 1973). The following composition of the detrital components of the sandstones is modified from Potter and Glass (1958): quartz, 65.3 percent; detrital matrix, 20.1 percent; feldspar, 4.5 percent; micas, 4.1 percent; chert and rock fragments, 3.5 percent; and heavy minerals and miscellaneous constituents, 2.5 percent. Percentages of heavy minerals vary greatly among the sandstones, but zircon, tourmaline, and rutile are the most abundant.

At least five sandstones in the lower portion of the Spoon Formation are extensive enough to be traced over portions of the outcrop belt, but only two have formal names (figs. 2 and 3): the Granger Sandstone Member and the Vergennes Sandstone Member. The Granger Sandstone is widespread in southeastern Illinois east of the Campbell Hill Anticline (fig. 1). It is more than 100 feet (30 m) thick in an elongate deposit in southeastern Williamson and northeastern Johnson Counties. The Granger thins abruptly on the margins of the elongate deposit and is generally less than 15 feet (5 m) thick in other areas. West of the Campbell Hill Anticline, the Granger is absent. The Granger Sandstone is correlated with the Curlew Sandstone of western Kentucky. The Vergennes Sandstone occurs in a single elongate body on the Campbell Hill Anticline in northwestern Jackson County, where it is approximately 110 feet (33 m) thick. Here it rests on the Caseyville Formation. Erosion has removed all overlying strata, so the stratigraphic position of the Vergennes is unknown; however, lithologically the Vergennes Sandstone is very similar to the Palzo Sandstone of the Spoon Formation (fig. 2), and the two may be equivalent.

Coal members. The coals in the lower portion of the Spoon Formation are much more widespread than are those in the Abbott Formation. Palynologic studies have indicated that several of the coals occur in areas as large as several counties. Generally the coals are best developed east of the Campbell Hill Anticline; west of this structure they are either very thin or absent. The named coal members are Bidwell Coal Member, New Burnside Coal Member, Murphysboro Coal Member, Mt. Rorah Coal Member, Wise Ridge Coal Member, and Davis Coal Member. Several other thin discontinuous unnamed coals occur within the lower portion of the Spoon Formation (fig. 3).

The Bidwell Coal, although discontinuous, occurs from eastern Jackson County eastward to the Ohio River and is the basal member of the Spoon Formation in this area (fig. 3). The coal is generally thin, but locally is as much as 4 feet (1.2 m) thick.

The New Burnside Coal occurs 15 to 25 feet (5 to 8 m) above the Bidwell Coal, but is more scattered in its distribution. Although generally only a few inches thick, locally it is as much as 5 feet (1.5 m) thick. The New Burnside Coal is correlated with the Brush Coal of western Illinois.

The Murphysboro Coal is best developed in Jackson and western Williamson Counties, northwest of the area in which the Bidwell and New Burnside Coals are developed. In this area the coal is in several benches separated by gray mudstone and clay and averages an aggregate 3 to 4 feet (about 1 m) thick. Outside the area of thickest development, the Murphysboro Coal is thin and discontinuous. Where these coals and the overlying Granger Sandstone pinch out, the Murphysboro Coal is the lowest member of the Spoon Formation (fig. 3).

The Mt. Rorah Coal is more widespread than any of the coals below it, but is generally thin and rarely is as much as 2 feet (60 cm) thick. In southeastern Williamson County, it occurs in two benches with a thin clay parting between them. Eastward, the parting thickens to 10 or 15 feet (3 to 5 m) of gray mudstone and clay, and the two benches are considered to be separate coals.

The Wise Ridge Coal thickens and thins abruptly, but is widespread in southern Illinois. It is 2 to 55 feet (< 1 m to 17 m) above the Mt. Rorah Coal and is coextensive with it.

The Davis Coal is the first widespread blanket coal in southern Illinois, is present throughout the outcrop belt, and averages approximately 4 feet (1.2 m) in thickness. The Davis Coal is correlated with the Wiley Coal of western Illinois and the Davis (No. 6) Coal of western Kentucky.

Limestone members. Several thin limestones, which vary from scattered nodules in shale to beds up to 4 feet (1.2 m) thick, are widespread in the lower portion of the Spoon Formation and are named Creal Springs Limestone Member, Stonefort Limestone Member, and Seahorne Limestone Member (fig. 2). The Creal Springs Limestone is a thin, light-gray, dense cherty biomicrite that is persistent from southeastern Williamson County eastward to Gallatin County. The fauna is made up of varied shallow marine forms typified by brachiopods and fusulinids. In many localities the limestone has been totally altered to chert. The Creal Springs Limestone is correlated with the Holland Limestone of Indiana.

The Stonefort Limestone is dense, light bluish gray, marine biomicrite and averages 1 to 2 feet (30 to 60 cm) thick. It is approximately 50 feet (15 m) above the Creal Springs Limestone and is nearly continuous from Williamson County eastward. West of Williamson County, the Stonefort is developed in only a few isolated areas.

The Seahorne Limestone is an intramicrudite described by Simon and Hopkins (1975) as "conglomeratic and brecciated and consists of dark gray fragments that contain abundant brachiopods embedded in a light gray matrix that is dominated by a diverse gastropod fauna. Another fauna, Spirorbis and ostracods, is found at places and is generally considered nonmarine." The limestone is thin, rarely exceeding 2 feet (60 cm) thick, and is discontinuous from western Saline County into northwestern Randolph County.

SEDIMENTARY PATTERNS

The sedimentation during deposition of the Abbott and Spoon Formations is summarized in table 1, which has been

TABLE 1. Summary of sedimentation during deposition of the Abbott and Spoon Formations.

Parameter	Abbott Formation	Spoon Formation
Basin configuration	Broad, shallow depression gently sloping to the southwest into basin. Asymmetrical transverse cross section with hinge at the Campbell Hill Anticline. Beyond the hinge, relatively flat shelf. Total section thickens to southwest.	Broad, shallow depression gently sloping to the southwest into a basin. Asymmetrical transverse cross section with hinge at the Campbell Hill Anticline. Beyond the hinge, relatively flat shelf. Total section thickens to southwest.
Lithologies	Quartz arenites, sandy shales, and siltstones predominate. Several thin discontinuous coals. Carbonates restricted to calcareous zones in sandstones. Vertical and horizontal facies changes are rapid in coarser clastics.	Quartz wackes, sandy shales, and siltstones predominate. Coals more numerous and widespread than in Abbott. Several thin widespread marine limestones. Vertical and horizontal facies changes are rapid in coarser clastics.
Sedimentary structures	Cross-bedding, cut-and-fill structures, and ripple marks in sandstones most important in sedimentary analysis.	Cross-bedding, cut-and-fill structures, and ripple marks in sandstones most important in sedimentary analysis.
Paleocurrent patterns	Elongate sandstone bodies generally oriented in northeast-southwest direction. Cross-bedding indicates paleoslope to southwest.	Elongate sandstone bodies generally oriented in northeast-southwest direction. Cross-bedding indicates paleoslope to southwest.
Fossils	Abraded marine forms in calcareous zones in sandstones; only fossils other than plant remains in coals.	Shallow marine, open-circulation planktonic and benthonic types in limestones; plant remains in coals.
Cyclic deposition	Fluctuations of strand line indicated by sandstone-shale-coal; sandstone-shale-coal.	Fluctuations of strand line indicated by sandstone-shale-coal; sandstone-shale-coal-shale-limestone.
Provinence	Relatively mature source to the northeast.	Relatively immature source to the northeast.

SOURCE: Modified from Potter and Glass (1958) and Potter (1963).

modified from Potter and Glass (1958) and Potter (1963).

Potter and Glass (1958, p. 54) summarized the sedimentary environment during deposition of the Abbott and Spoon Formations as follows:

The Pennsylvanian sediments along this southern portion of the Eastern Interior coal basin accumulated on a southwestward-dipping, low lying coastal plain-shallow marginal shelf that became progressively more negative and probably more gently dipping with passage of time. This physiographic couple received more immature detritus as source-area erosion progressively unroofed metamorphic and/or igneous rocks and earlier sediment sources were overlapped.

REFERENCES

HOPKINS, M. E., and J. A. SIMON, 1975, Pennsylvanian System, *in* H. B. Willman, Elwood Atherton, T. C. Buschbach, Charles Collinson, John C. Frye, M. E. Hopkins, Jerry A. Lineback, and Jack A. Simon, Handbook of Illinois stratigraphy: Illinois State Geological Survey Bulletin 95, p. 177-187.

KOSANKE, R. M., J. A. SIMON, H. R. WANLESS, and H. B. WILLMAN, 1960, Classification of the Pennsylvanian strata of Illinois: Illinois State Geological Survey Report of Investigations 214, 84 p.

PETTIJOHN, F. J., P. E. POTTER, and R. SIEVER, 1973, Sand and sandstone: Springer-Verlag, New York, p. 149-172.

POTTER, P. E., 1963, Late Paleozoic sandstones of the Illinois Basin: Illinois State Geological Survey Report of Investigations 217, 92 p.

POTTER, P. E., and H. D. GLASS, 1958, Petrology and sedimentation of the Pennsylvanian sediments in southern Illinois: A vertical profile: Illinois State Geological Survey Report of Investigations 204, 60 p.

Paleoecology and depositional history of rock strata associated with the Herrin (No. 6) Coal Member, Delta Mine, southern Illinois

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INTRODUCTION

Mining operations at the Delta Mine, Williamson County, Illinois, expose Middle Pennsylvanian rocks ranging from the underclay beneath the Herrin (No. 6) Coal Member to the Bankston Fork Limestone Member of the Carbondale Formation, Kewanee Group, and the overlying glacial deposits and loess (fig. 1). These members of the Carbondale Formation classically have been included in three cyclothems: in ascending order, the Brereton Cyclothem, the Jamestown Cyclothem, and the Bankston Cyclothem (Kosanke et al., 1960). At the Delta Mine, the units in the Jamestown Cyclothem lie within the Brereton Cyclothem (fig. 1).

Much work has been done on Middle Pennsylvanian environments of deposition by Harold Wanless and his students. Johnson (1962) delineated some fossil communities in Pennsylvanian rocks of Illinois. The descriptions and interpretations presented here are based largely on the work of Givens (1968), Utgaard and Givens (1973), Wetendorf (1967), Fraunfelter and Utgaard (1970) and Hopkins (1958). The interpretation of the general depositional setting here involves interlayering and intertonguing of thin marine and thin, broad deltaic deposits rather than classical cyclothemic sequences.

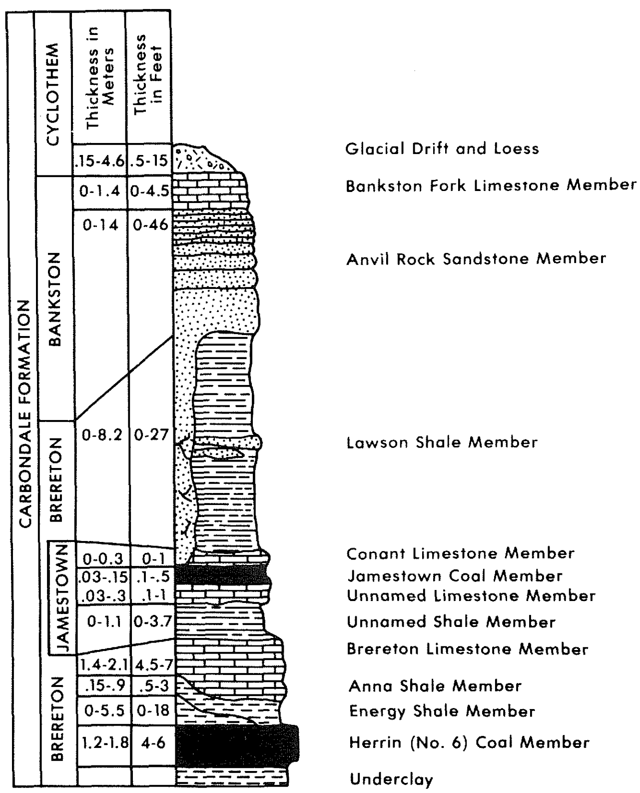

Figure 1. Generalized columnar section showing cyclothems and members of the Carbondale Formation exposed at the Delta Mine. (Modified from Utgaard and Givens, 1973.)

LITHOLOGY, PALEOECOLOGY, AND ENVIRONMENT OF DEPOSITION

Underclay

An underclay, containing roots, underlies the Herrin (No. 6) Coal Member and is exposed in several places in the mine.

Herrin (No. 6) Coal

The Herrin (No. 6) Coal Member ranges from 4 to 6 feet (1.2 to 1.8 m) thick in the Delta Mine. It can contain several clay or shale partings and here contains a considerable amount of pyrite. Elsewhere, where the gray shale (the Energy Shale Member) intervenes between the Herrin (No. 6) Coal Member and the Anna Shale Member, in thicknesses of 20 feet (6.1 m) or more, the Herrin Coal Member has a lower sulfur content (Gluskoter and Hopkins, 1970, p. 91, 92).

Cordaites stems and coal balls have been found in the Herrin Coal Member at the Delta Mine. Eggert and Cohen (1973) found many similarities between these coal balls and modern peat from the Everglades and Okefenokee. The coal probably represents a widespread system of peat swamps developed on a low, broad deltaic plain.

Energy Shale Member

Locally within the Delta Mine, a soft, gray shale, the Energy Shale Member, intervenes between the Herrin (No. 6) Coal Member and the Anna Shale Member. Drill records indicate that the gray shale reaches a maximum thickness of 18 feet (5.5 m) in the vicinity of the mine. This unit apparently occurs in lenses. Elsewhere, the gray shale can be up to 75 feet (22.8 m) thick. At the Delta Mine, the gray shale contains macerated plant fragments and a few recognizable stems of *Calamites.* The fauna includes *Dunbarella rectilaterarius* (Cox), other bivalves, cephalopods, and brachiopods.

The environment of deposition of the gray shale is problematical. The low-diversity fauna suggests slightly brackish water or near-shore aerated water of normal marine salinity. The fauna is more diverse and indicates marine conditions that are more nearly normal than the fauna of the Anna Shale Member. The elongate lens shape and intermittent nature of the gray shale suggests local sites of deposition, possibly in inlet channels where aerated marine waters invaded the coal swamps. The continuous extent of the Anna Shale Member over the gray shale lenses, with no appreciable thinning, and the thinning of the Brereton Limestone Member over the gray shale lenses suggests possible topographic inversion during compaction.

Elsewhere, where channel sandstone deposits such as the Walshville Channel are near, the Energy Shale Member is thicker, contains mostly plant debris (Dutcher, Dutcher, and Hopkins, 1977, p. 26), and has been interpreted as an overbank deposit associated with the Walshville Channel Sandstone (Edwards et al., 1978, p. 252). More detailed studies of the fauna and environments of deposition of the gray shale are in progress.

Anna Shale Member

Throughout most of the Delta Mine, the Herrin (No. 6) Coal Member is overlain by the Anna Shale Member, a dark-gray to grayish-black shale with sheety fissility. It contains abundant organic matter and pyrite and averages 20 inches (51 cm) thick.

Fossils in the Anna Shale Member include the inarticulate brachiopod *Orbiculoidea missouriensis* (Shumard), the bivalve *Dunbarella* cf. *D. rectilaterarius,* relatively large placoid denticles of an elasmobranch shark (*Petrodus*), conodonts (mostly *Hindeodella*), spines of fish (*Listracanthus*), and driftwood fragments. Sporadic distribution of shark denticles and fish spines suggests that they were released during decay of the fish and fell to the bottom. The spines are generally intact and are pyritized. Specimens of *Orbiculoidea* usually are complete. Disarticulated but unbroken valves of the pectinoid bivalve *Dunbarella* are preserved as molds or are pyritized. The laminae of the sheety shale are not disturbed, and there are no traces of vagrant infauna or epifauna in the sediments or on the bottom. *Petrodus, Listracanthus,* and possibly the conodont-bearing animal, represent pelagic organisms. *Orbiculoidea* and *Dunbarella* were sessile epifauna and could have lived attached to algae floating above the bottom. The bottom was probably little agitated and stagnant. *Dunbarella* is the only member of this low-diversity fauna that has been interpreted as being stenohaline, and it increases in relative abundance upward in the Anna Shale Member (fig. 2).

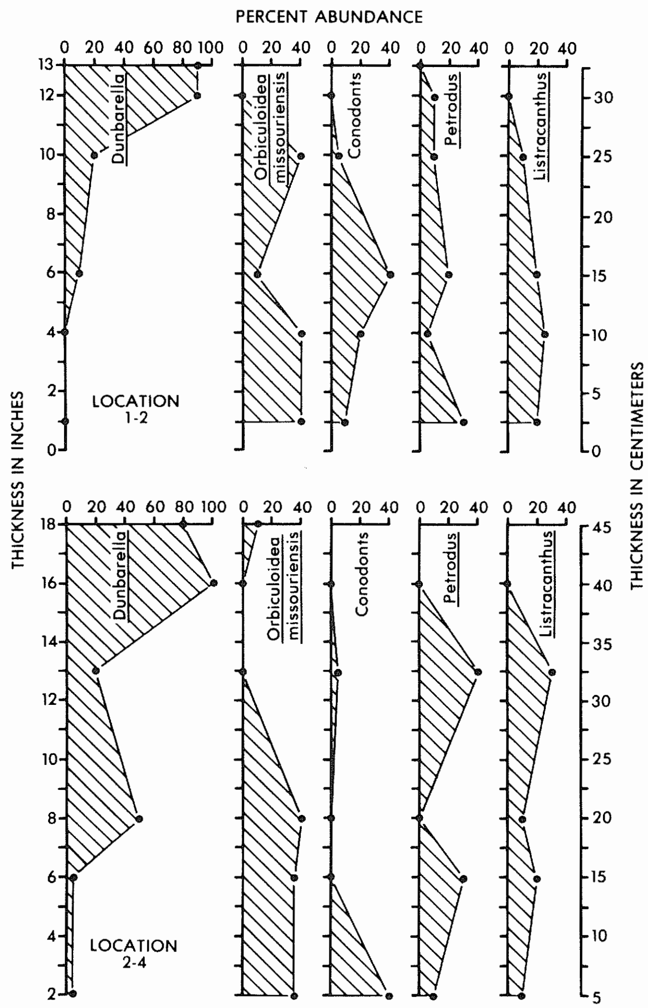

Figure 2. Graphs showing relative abundance and vertical distribution of the fauna of the Anna Shale Member at two collecting localities in the Delta Mine. (Modified from Utgaard and Givens, 1973.)

The gray shale probably represents local incursions of the aerated marine water onto the peat swamps, initiating the destructional phase of this delta. The Anna Shale Member probably represents a general incursion of marine waters, from the west and southwest, over the peat swamps on the deltaic plain. A highly carbonaceous black mud was deposited over the peat and over the gray shale lenses. With time, waters of this marine incursion became more saline and probably approached normal marine salinity near the end of Anna Shale deposition. Apparently the bottom was euxinic, was not stirred by currents or waves, and did not support a bottom fauna. Possibly a floating mat of vegetation kept the bottom waters from being agitated and contributed to the high organic content of the shale.

Brereton Limestone Member

The Brereton Limestone Member is 4½ to 7 feet (1.4 to 2.1 m) thick in the Delta Mine. It is generally a hard, dense, fine-grained fossiliferous micrite but contains layers of fossiliferous, argillaceous, fine-grained limestone. Fossils generally constitute 25 percent of the rock and locally make up 50 percent of the components. Clay content and other insoluble residues increase toward the south and range from 5 to 30 percent of the constituents. This increase in clay content is accompanied by a decrease in thickness from 7 feet (2.1 m) to 5½ feet (1.7 m). Clay content generally increases upward in the Brereton Limestone Member, but layers of argillaceous limestone can be found interbedded with the fossiliferous micrite.

The fauna of the Brereton Limestone Member is diverse and indicates offshore shallow-water marine deposition. The fauna grossly resembles middle to offshore shelf faunas reported in other Pennsylvanian communities (Bretsky, 1969).

The fossiliferous micrite contains fusulinid and textulariid foraminifera, the brachiopod *Kozlowskia* cf. *K. splendens* (Norwood and Pratten), fragments of other brachiopods, bryozoans, corals, the sponge *Wewokella,* and crinoids. The more argillaceous parts of the Brereton Limestone Member contain the large spiny productid brachiopods *Antiquatonia portlockianus* (Norwood and Pratten), *Linoproductus* sp., and *Juresania nebrascensis* (Owen). Additional brachiopods include *Composita subtilita* (Hall), *Meekella striatocosta* (Cox), *Derbyia crassa* (Meek and Hayden), *Neospirifer triplicatus* (Hall), *Punctospirifer kentuckyensis* (Shumard), and *Mesolobus mesolobus* (Norwood and Pratten). Additional fossils include the sponge *Wewokella,* the bryozoans *Polypora* and *Prismopora,* crinoids, lophophyllid corals, and *Stigmaria* roots and rootlets.

Variations in the lithology and fauna within the Brereton Limestone Member at the Delta Mine probably reflect local or short-term variations in water agitation and deposition of detrital clay, which resulted in local or short-term colonization of the bottom by populations of benthos that were better adapted to a softer substrate. The variations probably do not represent major changes in the generally offshore, shallow shelf environment of deposition or the migration of major level-bottom communities.

In the Illinois Basin, to the northwest, the Brereton Limestone Member is overlain by the Lawson Shale Member of the Brereton Cyclothem, but at the Delta Mine, the thin units of the Jamestown Delta (or Jamestown Cyclothem) intervene between the Brereton Limestone Member and the Lawson Shale Member.

Unnamed Shale Member of the Jamestown Cyclothem

This unnamed unit is generally a dark-gray calcareous, fossiliferous, silty shale in the Delta Mine. The shale is slightly carbonaceous; fossils can constitute 3 to 25 percent of the rock volume. The unit is generally 6 inches (15 cm) to 3 feet (90 cm)thick in the Delta Mine and is thickest toward the south.

The lower part contains a fauna that is similar to that in the upper, shaly parts of the Brereton Limestone Member. The middle part of the unnamed shale member is poorly fossiliferous and may reflect fairly rapid deposition of detrital clay in turbid water, possibly representing prodelta muds from the Jamestown Delta. A diverse, level-bottom community was established during deposition of the upper few inches (upper few centimeters) of the unnamed shale member, possibly as a result of slowing of the influx of detrital mud and a reduction in the turbidity. This marine community is characterized by clumpy distribution of four localized fossil assemblages and one widespread assemblage.

Givens (1968) and Utgaard and Givens (1973) discussed the components of these assemblages. The dominant species of each assemblage are listed in table 1. These five fossil assemblages probably do not represent five separate or distinct offshore marine communities but rather represent one level-bottom marine community that had high diversity and low dominance, was inhomogenous (with a patchy or clumpy distribution), and had undergone little or no post-mortem mixing or transportation. Most of the brachiopods, particularly the thin-shelled productids, are badly broken, but most of the breakage can be attributed to postburial compaction rather than to preburial transportation, as evidenced by the close association of many angular fragments of one brachiopod. Other than the angular fragmentation, the fossils show no signs of abrasion and sorting is poor; this further suggests little or no preburial transport.

Many of the brachiopods, particularly the productids and debryids, could have lived on a relatively soft, fine-grained substrate. Others, such as *Composita* and *Punctospirifer,* had a pedicle for attachment and their distribution is clumpy (they are generally found in assemblage III and assemblage V), suggesting local areas of firmer substrate. The relatively rare incrusting bryozoans and *Crania* used shell material as an attachment site. The bryozoan growth forms that are common in this community (delicate branching, delicate trifoliate branching, and fenestrate) suggest moderately quiet water.

The preserved part of the community is dominated by sessile epifaunal suspension feeders, suggesting relatively slow deposition of detrital muds and low to moderate turbidity. The community resembles other middle-shelf, level-bottom communities reported from Pennsylvanian rocks (Bretsky, 1969).

Unnamed Limestone Member of the Jamestown Cyclothem

The unnamed limestone member of the Jamestown Cyclothem is not everywhere present below the Jamestown Coal in the mine area; but in the area sampled in detail, it is 5 to 13 inches (13 to 33 cm) thick. The amount of detrital clay increases northward in the mine area from 15 percent to 45 percent. The lower contact is gradational in the northern part of the mine and this unit appears to be a facies of the upper part of the underlying unnamed shale member. The fauna of this unit is similar to that of the unnamed shale member but is more diverse and contains the sponge *Wewokella,* the brachiopods *Kozlowskia* cf. *K. splendens* and *Echinaria semipunctata,* large bivalves (possibly *Edmondia*), a chaetetid coral, low- and high-spired eotomarid gastropods and *Stigmaria.*

The fauna of this limestone unit, like that of the unnamed shale member, has a patchy distribution. Givens (1968) and Utgaard and Givens (1973) have described five fossil assemblages from this unit (table 1). The assemblages probably represent one level-bottom fossil community with high diversity, low dominance, and inhomogeneity (patchyness) in spatial distribution of fauna. Additional evidence that these assemblages represent one fossil community include the wide variation in size in many species (no sorting) and general lack of features of abrasion. This community is similar to the fossil community in the unnamed shale member of the Jamestown Cyclothem, particularly when assemblages I, II and IV from the unnamed limestone member are compared to assemblages IV, I, and V and III of the unnamed shale member (table 1). All of these assemblages are found in areas of high clay content and probably reflect somewhat soft bottom conditions.

Assemblages III and V of the unnamed limestone member apparently reflect areas of lower clay content and a firmer bottom and have no counterparts in the unnamed shale member (table 1). Some episodes of stronger current or wave action are probably recorded in the local patches of better-sorted crinoid debris in assemblage V. Variations in detrital clay influx and substrate softness are considered to be among the prime causes of the patchyness of the assemblages within this community. Substrate, turbidity, and other environmental conditions evidently were not uniform over this rather small area (detailed collecting was undertaken over an area of 1 by 1½ miles [1.6 by 2.4 km]) of an offshore, level-bottom site of deposition, probably near the margin of the Jamestown Delta.

At many localities, the unnamed limestone member contains in situ *Stigmaria* roots with attached rootlets; this indicates that this argillaceous marine carbonate served as the growth surface for the plants that produced the Jamestown Coal. Thus, the subaerial platform upon which the Jamestown coal swamp plants grew evidently was produced by emergence (sea level lowering or uplift) and was not a deltaic subaerial plain constructed by delta progradation.

Jamestown Coal Member

The Jamestown Coal Member is 2 to 6 inches (5 to 15 cm) thick at the Delta Mine and is interpreted to have accumulated in situ in a swamp developed on top of the unnamed limestone member.

Conant Limestone Member

The Conant Limestone Member of the Jamestown Cyclothem is a medium- to dark-gray argillaceous and fossiliferous limestone. It is a thin unit, generally 4 inches (10.1 cm) to 1 foot (30.5 cm) thick, and detrital clay content ranges from 15 percent in the southeast to 42 percent in the northwest part of the mine.

The Conant Limestone Member contains an offshore marine fauna, similar to the one in the unnamed limestone member of the Jamestown Cyclothem; however, the Conant has fewer *Stigmaria* and contains the bivalves *Schizodus amplus* (Meek and Worthen) and *Acanthopecten carboniferous* (Stevens) and the youngest known edrioasteroid, *Agelacrinites hybolopus* Fraunfelter and Utgaard.

Within the mine area, the fauna displays an inhomogenous distribution; six assemblages have been recognized by Givens (1968) and Utgaard and Givens (1973). The dominant species in each assemblage are listed in table 1.

Clumpy distribution in a relatively small area, lack of abrasion and sorting, and excellent preservation of many of the fossils suggest that these assemblages underwent little transportation and are essentially the remains of one fossil community that lived at the site of deposition. The amount of clay (table 1) is apparently partly related to the patchy distribution of the assemblages in this community; it probably reflects control of their distribution by substrate conditions and, to a lesser extent, by the amount of suspended sediment. To the southwest, the fossils show some evidence of preburial transport, including separation of valves and incrustations before burial, but not significant preburial mixing or alteration.

Striking similarities between the several individual assemblages and the fossil community in the Conant Limestone Member, and between the unnamed limestone member and the unnamed shale member of the Jamestown Cyclothem (table 1) suggest that marine conditions were essentially similar immediately before and after deposition of the Jamestown Coal and permitted reestablishment of essentially the same, recurrent community in the Conant Limestone Member.

Lawson Shale Member

In the Illinois Basin to the northwest, the Lawson Shale Member rests directly on the Brereton Limestone Member. When originally named, the Lawson and the Brereton Limestone Members were included in the Brereton Cyclothem. Here the members of the Jamestown Cyclothem intervene between the Brereton Limestone Member and the Lawson Shale Member.

The Lawson Shale Member is a medium-gray, micaceous, carbonaceous, silty shale. Wetendorf (1967) determined that, in the Delta Mine, the Lawson coarsens upward. In like manner, there is an increase in abundance of mica (from 1 percent to 10 percent), plant debris, and quartz silt. Lenticular silt-shale interlaminations, some approaching flaser bedding in appearance, also increase in abundance upward.

The fauna of the Lawson Shale Member is mostly trace fossils. Horizontal and vertical dwelling burrows are common in the Delta Mine, and vertical, U-shaped dwelling

TABLE 1. Comparison of dominant species, fossil assemblages, insoluble residue (clay)content, and inferred bottom conditions in the fossil marine communities occurring in the three marine members of the Jamestown Cyclothem at the Delta Mine. (Modified from Utgaard and Givens, 1973.)

Unnamed shale member	Unnamed limestone member	Conant limestone member	Inferred bottom conditions
Assemblage I (W)[a] *Antiquatonia portlockianus*[b] *Linoproductus* sp.[b] Fenestrate bryozoans Rhomboporoid bryozoans Crinoids	Assemblage II (W)[a] *Antiquatonia portlockianus*[b] *Linoproductus* sp.[b] *Juresania nebrascensis*[b] Fenestrate bryozoans *Prismopora* INSOLUBLE RESIDUE 25 to 43%, GENERALLY 35%	Assemblage II *Antiquatonia portlockianus*[b] *Linoproductus* sp.[b] Fenestrate bryozoans *Prismopora* INSOLUBLE RESIDUE 36 to 42%	Level bottom with relatively soft, muddy areas and enough shells for attachment of bryozoans.
Assemblage II *Juresania nebrascensis*[b] Fenestrate bryozoans *Prismopora*	None, but assemblage II (above) is somewhat similar	Assemblage IV *Juresania nebrascensis*[b] Fenestrate bryozoans *Antiquatonia portlockianus*[b] *Linoproductus* sp.[b] INSOLUBLE RESIDUE 38 to 40%	Level bottom with relatively soft, muddy areas and enough shells for attachment of bryozoans.
Assemblage IV *Antiquatonia portlockianus*[b] *Linoproductus* sp.[b] Fenestrate bryozoans Rhomboporoid bryozoans Crinoids *Derbyia crassa*[b] *Meekella striatocostata* *Neospirifer* cf. *N. triplicatus* *Mesolobus mesolobus*	Assemblage I (W)[a] *Antiquatonia portlockianus*[b] *Linoproductus* sp.[b] *Echinaria semipunctata*[b] Fenestrate bryozoans *Prismopora* *Derbyia crassa*[b] *Meekella striatocostata* *Neospirifer* cf. *N. triplicatus* INSOLUBLE RESIDUE 27 to 46%, GENERALLY 35%	Assemblage I (W)[a] *Antiquatonia portlockianus*[b] *Linoproductus* sp.[b] Fenestrate bryozoans *Prismopora* *Derbyia crassa*[b] *Meekella striatocostata* *Neospirifer* cf. *N. triplicatus* INSOLUBLE RESIDUE 29 to 42%	Level bottom with relatively soft, muddy areas and enough shells for attachment of bryozoans. Contains firmer areas than localities with the above two sets of assemblages.
Assemblage V *Composita subtilita* *Prismopora* Assemblage III *Punctospirifer kentuckyensis* *Composita subtilita* Rhomboporoid bryozoans	Assemblage IV *Composita subtilita* *Punctospirifer kentuckyensis* *Prismopora* INSOLUBLE RESIDUE 22 to 34%	Assemblage III *Composita subtilita* *Prismopora* Fenestrate bryozoans Crinoids INSOLUBLE RESIDUE 25 to 29%	Level bottom with relatively firm substrate. No large soft, muddy areas, and enough shell material for attachment of bryozoans.

Table 1. *Continued.*

Unnamed shale member	Unnamed limestone member	Conant limestone member	Inferred bottom conditions
	Assemblage III (W)[a] *Mesolobus mesolobus* *Kozlowskia* cf. *K. splendens* *Wewokella* Crinoids Chaetetid corals *Edmondia* (?) *Prismopora* *Antiquatonia portlockianus*[b] *Linoproductus* sp.[b] INSOLUBLE RESIDUE 14 to 32%	Assemblage VI (W)[a] *Mesolobus mesolobus* *Kozlowskia* cf. *K. splendens* *Wewokella* Crinoids Chaetetid corals *Edmondia* (?) *Prismopora* *Antiquatonia portlockianus*[b] *Linoproductus* sp.[b] INSOLUBLE RESIDUE 15 to 30%	Level bottom with firm substrate. Few soft, muddy areas. Abundant shell material.
	Assemblage V Same as assemblage III, but crinoid parts very abundant. INSOLUBLE RESIDUE 16 to 27%.	Assemblage V Same as assemblage III, but crinoid parts very abundant. INSOLUBLE RESIDUE 19 to 23%.	Level bottom with firm substrate. Few soft, muddy areas. Abundant skeletal material, dominated by crinoid parts.

[a]Widespread assemblage.
[b]Species adapted to living on soft bottom.

burrows with upward-migrating (retrusive) spreiten are locally common in the Lawson Shale Member southeast of the Delta Mine. Some zones in the Lawson Shale Member are extensively burrowed, and some trails and feeding burrows are abundant in the upper part.

Wetendorf (1967) suggested that the Lawson Shale Member represents rapid deposition in turbid water as a prodelta deposit or a delta front deposit on a lobate delta. Another possible interpretation is that the Lawson Shale Member represents an interdistributary bay deposit.

Anvil Rock Sandstone Member

The Anvil Rock Sandstone Member of the Bankston Cyclothem is a quartz sandstone that is light gray, medium to very fine grained, micaceous, argillaceous, and carbonaceous. Hopkins (1958) recognized a sheet phase and a thicker channel phase in the Anvil Rock Sandstone Member; both are present in the Delta Mine.

The sheet phase consists of beds from less than 4 inches (10 cm) thick (generally near the top) to beds up to 8 feet (2.4 m) thick (generally near the bottom). Shale partings and interbeds are common and range up to 18 inches (46 cm) in thickness. One fossil bivalve (*Aviculopecten*), burrows, and abundant plant fossils, such as *Pecopteris* and *Calamites,* have been found in the shale interbeds. The sandstones contain trough cross-beds and current and oscillation ripple marks.

Several channels, generally less than 150 feet (46 m) across, are found in the Anvil Rock Sandstone Member in the Delta Mine. Sandstones in the channel phase contain some coal fragments and plant fragments. A channel in the abandoned highwall on the south side of Illinois Highway 13 cuts down to just above the Jamestown Coal Member. Here, Wetendorf (1967) has interpreted the channel as displaying point bar accretion; migration of the point bar is from east to west. This channel has a fining upward sequence. The upper, thin-bedded part of the channel phase is continuous laterally with the thin-bedded sheet phase and may represent deposits associated with final channel abandonment or crevasse splays.

Small channel sandstones within the upper part of the Lawson Shale Member are interpreted as being submarine channels in which sand was transported on the delta front or within the interdistributary bay. The channel sandstones are believed to be genetically related to the Anvil Rock Sandstone Member. Wetendorf (1967) has interpreted the Anvil Rock Sandstone Member as being partly time equivalent to the Lawson Shale Member and as representing minor distributary channels, delta front sands in a lobate delta, and interdistributary bay deposits. Together, the Lawson Shale Member and the Anvil Rock Sandstone Member are interpreted as representing the constructional phase of another thin, broad delta building out into the Middle Pennsylvanian sea.

Bankston Fork Limestone Member

The Bankston Fork Limestone Member of the Bankston Cyclothem is a light- to medium-gray limestone that is finely crystalline, argillaceous, and fossiliferous. It is only locally preserved beneath loess and other Pleistocene deposits in the Delta Mine. A study of its fauna and petrology has not been undertaken.

REFERENCES

BRETSKY, Peter W., Jr., 1969, Evolution of Paleozoic benthic marine invertebrate communities: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 6, p. 45-59.

DUTCHER, Linda A., Russell R. DUTCHER, and M. E. HOPKINS, 1977, Geology of southern Illinois coal deposits, *in* Charles O. Frank [ed.], Guidebook for Field Trips, Carbondale 1977: Postmeeting Field Trips, 11th Annual Meeting of the North-Central Section of the Geological Society of America, Department of Geology, Southern Illinois University at Carbondale, v. 2, p. 1-33.

EDWARDS, Martin J., Ralph L. LANGENHEIM, Jr., W. John NELSON, and Chris LEDVINA, 1978, Petrology of the Energy Shale and the origin of "rolls" in the Herrin (No. 6) Coal, Pennsylvanian, in the Orient No. 6 Mine, Jefferson County, Illinois (abstract): Geological Society of America, Abstracts with Programs, v. 10, no. 6, p. 252.

EGGERT, Donald L., and A. D. COHEN, 1973, Petrology of coal balls from the Herrin, Number Six Coal (Carbondale Formation), Williamson County, Illinois (abstract): Geological Society of America, Abstracts with Programs, v. 5, no. 4, p. 312-313.

FRAUNFELTER, G. H., and John UTGAARD, 1970, Middle Pennsylvanian edrioasteroid from southern Illinois: Journal of Paleontology, v. 44, no. 2, p. 297-303.

GIVENS, Terry J., 1968, Paleoecology and environment of deposition of part of the Brereton and Jamestown Cyclothems (Middle Pennsylvanian) of Williamson County, Illinois: Unpublished M.S. thesis, Southern Illinois University, 182 p.

GLUSKOTER, Harold J., and M. E. HOPKINS, 1970, Distribution of sulfur in Illinois coals, *in* W. H. Smith, Roger B. Nance, and M. E. Hopkins, Depositional environments in parts of the Carbondale Formation—western and northern Illinois: Illinois State Geological Survey Guidebook Series No. 8, p. 89-95.

HOPKINS, M. E., 1958, Geology and petrology of the Anvil Rock Sandstone of southern Illinois: Illinois State Geological Survey Circular 256, 49 p.

JOHNSON, R. G., 1962, Interspecific associations in Pennsylvanian fossil assemblages: Journal of Geology, v. 70, p. 32-55.

KOSANKE, R. M., J. A. SIMON, H. R. WANLESS, and H. B. WILLMAN, 1960, Classification of the Pennsylvanian strata of Illinois: Illinois State Geological Survey Report of Investigations 214, 84 p.

UTGAARD, John, and Terry GIVENS, 1973, Middle Pennsylvanian depositional environments: Delta Mine, Williamson County, Illinois, *in* Frank G. Ethridge, George Fraunfelter, and John Utgaard [eds.], Depositional environments of selected Lower Pennsylvanian and Upper Mississippian sequences of southern Illinois: 37th Annual Tri-State Field Conference, Department of Geology, Southern Illinois University, Carbondale, p. 90-106.

WETENDORF, Fred H., Jr., 1967, Environment of deposition of parts of the Brereton, Jamestown and Bankston cyclothems (Middle Pennsylvanian) of Williamson County, Illinois: Unpublished M.S. thesis, Southern Illinois University, 87 p.

Depositional environments of strata of late Desmoinesian age overlying the Herrin (No. 6) Coal Member in southwestern Illinois

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INTRODUCTION

The Herrin (No. 6) Coal Member of the Carbondale Formation (Pennsylvanian) contains more than 40 percent of the total mapped reserves in Illinois and is the state's most productive coal seam. The Herrin Coal commonly exceeds 6 feet (2 m) in thickness in southwestern Illinois. Underground mining in southwestern Illinois has been restricted mainly to mines near the outcrop of the Herrin Coal and to several small mines where the coal is at greater depths in Marion and Clinton Counties. A substantial expansion of underground mining in this area seems likely in the future.

The depositional history of the Herrin Coal and associated strata in the area have affected both the quality and minability of the coal. Depositional facies of strata associated with the Herrin Coal in southwestern Illinois are identified and mapped in this report.

GEOLOGIC SETTING

Areas of occurrence of the Herrin Coal in southwestern Illinois in all or parts of the following six counties—Clinton, Jackson, Perry, Randolph, St. Clair, and Washington (fig. 1)—constitute the area of study for this report. Detailed stratigraphic analysis was limited to nine townships in Washington County.

The Herrin Coal Member crops out and has been surface-mined extensively along the southwestern margin of the report area. The coal dips at a low angle toward the north and northeast. At Nashville in central Washington County, the coal is about 400 feet deep (120 m) and is nearly 600 feet (180 m) underground at the northeastern margin of the report area (fig. 1).

The area is structurally separated from the deeper part of the Illinois Basin to the east by the Du Quoin Monocline, which has local structural relief of about 500 feet (150 m) at the horizon of the Herrin Coal. At the axis of the monocline, the dip of the Herrin Coal increases eastward toward the deep part of the Illinois Basin. In the report area, dips to the north and northeast are much lower and are interrupted by numerous local flexures.

The stratigraphic interval considered in this report extends from the Herrin Coal Member of the Carbondale Formation to the Piasa Limestone Member of the Modesto Formation (fig. 2). Data are based on examination of outcrops, diamond drill cores, and geophysical logs. Data processing by computer was utilized to generate maps of lithofacies and isopachs. Possible cut-and-fill structures are recognized above the Herrin Coal; they may have resulted from tidal scouring in very shallow water. Cut-and-fill, point-bar, and slump structures and other specific characteristics of sedimentation were not mapped during this study, mainly because of difficulty in reliably identifying such features from drill-hole data. Future detailed study and mapping may permit the identification of such features; this would supplement the major facies variations recognized in this report.

GENERAL DEPOSITIONAL FRAMEWORK

Sediments forming rock strata of the study area were deposited during the Desmoinesian Epoch when a "virtually uninterrupted depositional surface extended from the Nemaha Anticline of eastern Kansas and Nebraska across Missouri and Iowa to Illinois" (Wanless, 1975, p. 72). The Ozark Uplift, a pronounced positive area during much of geologic history, was at or below depositional base in Desmoinesian time as indicated by preserved Desmoinesian strata in several caves in central Missouri (Wanless, 1975, p. 105). Depositional conditions were generally uniform to the north, south, and west of the report area. The Du Quoin Monocline along the eastern boundary of the study area was structurally active late in Desmoinesian time; this action resulted generally in a thicker sequence of clastic sediments to the east. Within the report area and in the interval studied, rock strata are 40 percent limestone, in contrast to a correlative interval east of the monocline that is only about 17 percent limestone, is considerably thicker, and contains thick clastic deposits.

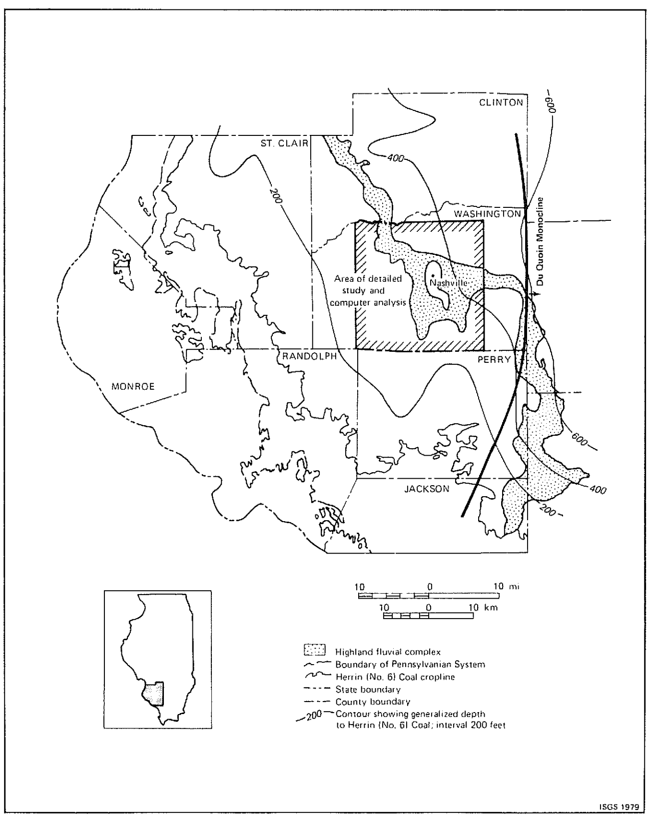

Figure 1. Highland fluvial complex and area of detailed study in southwestern Illinois.

SUMMARY OF DEPOSITIONAL HISTORY

Most of the rock strata above the Herrin Coal consist of limestones, argillaceous limestones, and some calcareous shales and siltstones, all of which were deposited in a shallow marine-shelf environment. A small portion is made up of coals, nodular limestones, claystones, shaly claystones, shales, siltstones, and sandstones. These strata were deposited in fresh to brackish water and in transitional environments that periodically succeeded the marine environment (fig. 3).

The Herrin Coal developed from a swamp that originated on deltaic deposits to the north and east and spread over a broad coastal plain underlain by marine carbonates and transitional clastic sediment. The coal is overlain by the black Anna Shale Member, which formed in shallow, brackish to marginal-marine lagoonal and estuarine bodies of water that had anaerobic bottoms. These water bodies are believed (Wetendorf, 1967; Givens, 1968) to have been covered by algal mats that baffled wind currents. The mats provided a source for most of the black organic matter in the mud and a place of attachment for epiplanktonic organisms, in a similar manner to that described by Zangerl and Richardson (1963) for the Mecca Quarry Shale Member. The coal is overlain locally by gray shale of the Energy Shale Member or by the Brereton Limestone Member.

A moderate increase in water depth or the development of more open marine conditions caused the deposition of carbonate mud of the Brereton Limestone Member. The Brereton fauna—crinoids, brachiopods, some ostracods, bivalves, fusulinids, and other foraminifera—indicate that deposition was in a warm, shallow carbonate shelf environment. Work by Ross (1969) on a similar Pennsylvanian limestone in Texas indicated depth of water of 15 to 30 feet (5 to 10 m).

The introduction of silt and clay, particularly in the vicinity of splay deposits of the Energy Shale Member, interrupted the deposition of lime mud. The fauna of this unnamed calcareous silty shale is marine, but was dominated by forms that could tolerate a very muddy, soft bottom (Givens, 1968).

The Jamestown Coal Member is thin and locally discontinuous in the study area. The coal and associated strata were deposited during a relatively brief regression in southwestern Illinois. In southeastern Illinois, southern Indiana, and western Kentucky, the deposited peat formed a thick Jamestown Coal Member; this suggests a regression of longer duration.

A restricted marine environment subsequently was reestablished in the area with deposition of the Conant Limestone Member; however, substantial clay deposited with the lime muds created a muddier bottom on which productid brachiopods thrived (Wetendorf, 1967; Givens, 1968).

A major influx of clastics into the Illinois Basin after deposition of the Conant Limestone resulted in a lithic unit named Anvil Rock Sandstone by Owen (1856). This unit, studied in detail by Hopkins (1958) and others, may be correlative with fine clastics of the Lawson Shale Member west of the Du Quoin Monocline. Channel-fill deposits of the Anvil Rock Sandstone Member have been identified tentatively at a few localities in the study area. The lower

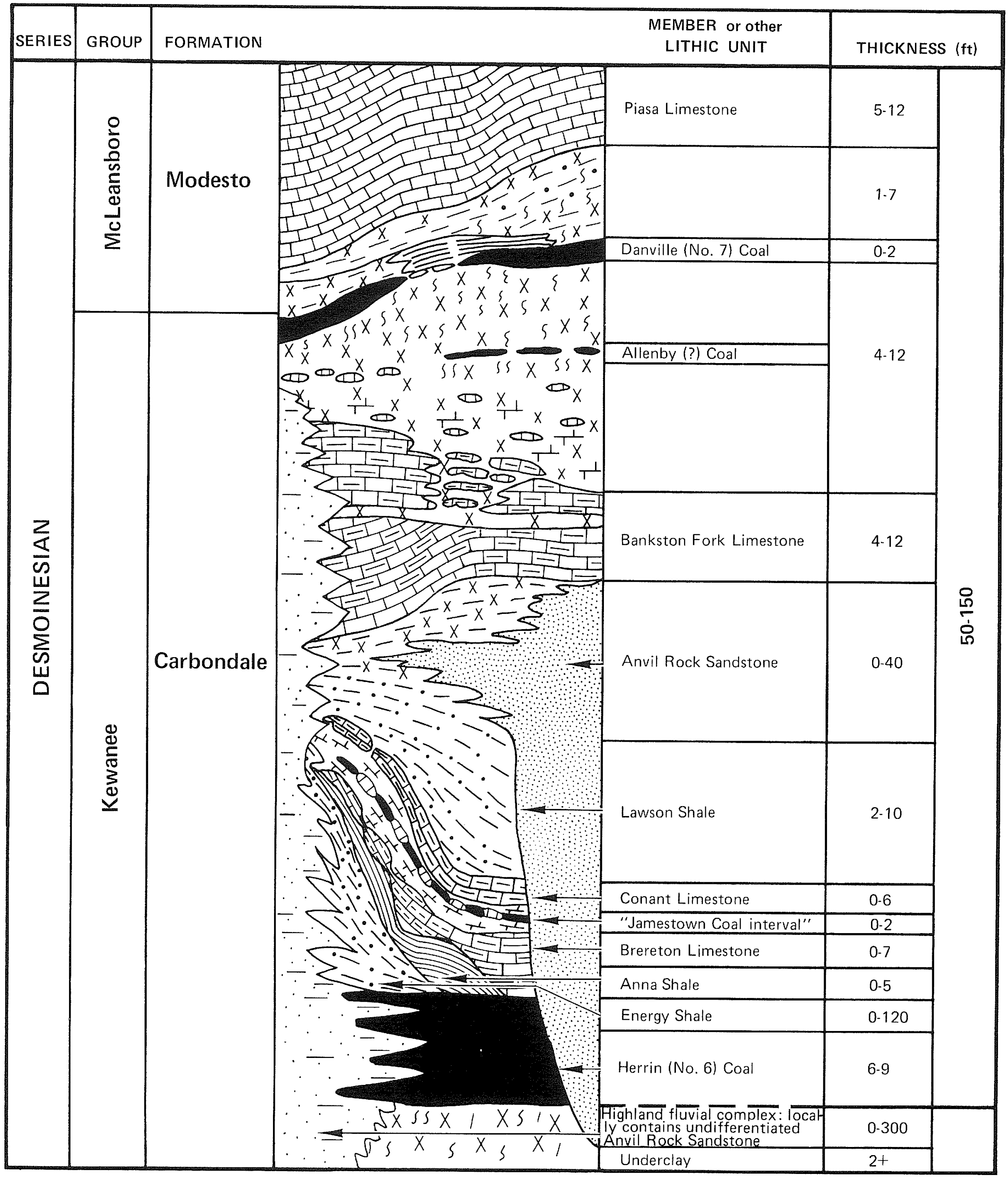

Figure 2. Generalized columnar section of strata in the study area.

Figure 3. Lithology, faunal and floral assemblages, and inferred depositional history of upper Desmoinesian strata in southwestern Illinois.

Member or other lithologic unit	Lithology	Thickness and distribution	Faunal or floral assemblage	Summary of depositional conditions	Depositional environments: Freshwater Brackish Marine
Piasa Limestone	Limestone; white to light gray, massive, hard, dense, bioclastic to micritic, fossiliferous. Basal clayshale zone transitional, calcareous, mottled green-gray, fossil debris and limestone nodules abundant.	Present over entire area. Ranges in thickness from 5 to 12 feet.	Crinoids, brachiopods, some ostracods, and fusulinids. Basal zone contains in addition conodonts, bryozoans, and fish.	Deposition of fine carbonate mud and bioclastic debris on very shallow, open-marine, carbonate shelf that covered entire area.	
Unnamed shales	Silty shale to shaly claystone; medium gray, massive	Variable in thickness, 1 to 7 feet throughout area.	*Stigmaria* rootlets.	Deposition of mud and silt from thick delta forming in eastern Illinois Basin. Development of shallow-water platform on which localized swamps developed. Influx of fresher water from east produced fresh to brackish water.	
	Shale; black, brittle, carbonaceous. Shaly claystone; calcareous, well-laminated, dark-gray to green, mottled. Both fossiliferous.	Thin, discontinuous, 0 to 2 feet throughout area.	Abundant brachiopods.	Short-term, marginal-marine to brackish lagoons and estuaries with anaerobic bottoms. May have developed algal mat similar to Anna Shale.	
Danville (No. 7) Coal	Coal, normal bright-banded.	Widespread, persistent, locally discontinuous. Thickness ranges from 0 to 2 feet.	Predominantly lycopods such as *Lepidodendron* and *Sigillaria* sp. Seed ferns and tree ferns common. Scattered Sphenopsids and Cordaites also present.	Brackish- to freshwater swamps. Developed on thin, widespread lower delta plain muds.	
Unnamed shaly claystone succession	Shaly claystone; calcareous, gray to greenish gray; small limestone nodules. Grades upward into gray to greenish-gray claystone containing *Stigmaria.* Thin, shaly coal (Allenby?) near middle in northeastern part of area. Thin nodular limestone near middle in south.	Present over entire area. Ranges from 4 to 12 feet in thickness.	*Stigmaria* rootlets in upper half and below shaly coal zone. Algal limestone nodules in lower half. Ostracods and *Spirorbis* in algal limestone nodules near middle.	Deposition of mud in shallow, widespread interdistributary bays. Weathering of shales in upper part by acidic swamp conditions and intensive rooting of the overlying Danville Coal Swamp. Local, sporadic invasions of swamp plants throughout. Deposition of algal carbonates in scattered lakes and ponds of lower half.	

Figure 3. *Continued.*

Member or other lithologic unit	Lithology	Thickness and distribution	Faunal or floral assemblage	Summary of depositional conditions	Depositional environments Freshwater Brackish Marine
Bankston Fork Limestone	Limestone, light-gray to light greenish-gray micrite, fossiliferous; generally 2 but occasionally 3 benches separated by greenish-gray, mottled shaly claystone containing thin, discontinuous limestone horizons. Upper bench often nodular, grading into shaly claystone sequence above.	Member present in entire area. Lower bench 1 to 3 feet thick. Parting 0.5 to 6 feet thick. Upper bench 3 to 7 feet thick.	Upper bench—Marginal marine ostracods, calcareous algae, fish, amphibians, *Spirorbis* sp., *Stigmaria* rootlets; crinoids and few brachiopods. Parting—abundant ostracods, crinoids, brachiopods, marginal-marine calcareous algae, scattered *Stigmaria* rootlets, fish and amphibians. Lower bench—calcareous foraminifera, crinoids, brachiopods, ostracods, calcareous algae—*Archaeolithophyllum* sp.	Upper bench—shallow, marginal marine, shelf, bay, to tidal flat carbonate deposition. Occasionally subject to subareal weathering. Parting—tidal flat; burrowing and weathered muds. Calcareous algae in scattered tidal ponds. Lower bench—shallow marine carbonate shelf; algal bank development.	
Upper part of Lawson Shale	Claystone and shale; greenish to dark gray, mottled.	From 0 to 3 feet thick throughout area.	Barren except for a shell-hash of brachiopods, ostracods, crinoids, corals, and bryozoans in a zone at top.	Tidal flat, mud may have come from Anvil Rock distributary system.	
Anvil Rock Sandstone	Sheet sandstone; fine-grained, argillaceous, gray, ripple-bedded. Channel-fill sandstone; medium-grained, clean, planar and trough cross-bedded.	Facies of upper Lawson Shale. Sheet sandstone 0 to 20 feet thick. Minor channels 21 to 40 feet thick. Major channels more than 40 feet thick.	Plant stems, branches, and trunks in channel lag deposits.	Sands deposited in distributary or coastal-plain stream channels, on tidal flats and in shallow-marine sheet deposits along margins of distributaries.	
Lower part of Lawson Shale	Shale; silty, medium gray, well laminated, bioturbated. Grades into shale above.	Ranges from 2 to 7 feet thick in area.	Sponges, burrowing bivalves, small gastropods, bryozoans, scattered brachiopods (*Lingula carbonarta* and *Orbiculoidea missouriensis*).	Fine clay and silt deposited on shallow marine shelf. Distal prodelta muds of advancing Anvil Rock distributary system to the north and east.	
Conant Limestone	Limestone; dark-gray, argillaceous, fossiliferous micritic; to shale, medium gray, hard, silty, calcareous. Both contain same fossil assemblage.	Micrite facies average from 1 to 2 feet in most of area, from 2 to 6 feet in some southern parts of study area. Calcareous shale facies present along some of Energy crevasse splays 2 to 6 feet thick.	Abundant, calcareous foraminifera *Ammodiscus* sp. and *Serpulopsis* sp. Large productid brachiopods, crinoids, scattered ostracods, bivalves, gastropods, and bryozoans.	Lessening of mud and silt deposition over most of shallow, warm carbonate shelf environment, except at splay margins where mixture of carbonate muds and reworked splay deposits accumulated as calcareous mud.	

Figure 3. *Continued.*

Member or other lithologic unit	Lithology	Thickness and distribution	Faunal or floral assemblage	Summary of depositional conditions	Depositional environments Freshwater	Brackish	Marine
				Fine-grained carbonates accumulated over majority of shelf area away from splays.			
Unnamed calcareous shale	Shale; medium gray, moderately hard, silty, calcareous. Grades upward into Conant Limestone Member.	From 0 to 2 feet thick; occurs as widespread lenses in most of area. Where Jamestown is absent, this unit continuous with calcareous shale below.	Large productid brachiopods, few small brachiopods, crinoids; few ostracods, scattered gastropods, and bivalves. Abundant calcareous foraminifera.	Reestablishment of shallow, marine-shelf conditions. Deposition of muds and silts (possibly reworked Energy crevasse splay sediments) and carbonate muds over shelf area.			
"Jamestown Coal interval"	Shale; brownish gray, hard, silty, calcareous.	From .2 to .5 foot thick, lenticular, discontinuous.	Predominantly a nonmarine bivalve resembling *Anthracosia* sp. Few specimens of *Solemya radiata*.	Deposition of silt in fresh to brackish lagoons, estuaries, and lakes. Coal swamp dies out.			
	Coal; thin, shaly, sometimes split. Grades laterally to limestone; thinly interlaminated, ostracod and *Spirorbis* biomicrite and biosparite.	From .4 to 1 foot thick, lenticular and discontinuous.	Ostracods (*Geisina, Hatisfabia;* and *Macrocypris* sp.), *Spirorbis* sp., fish remains, in limestone and strata interfingering with coal.	Brackish to freshwater, coal swamp. Contained quiet, shallow lagoons, lakes, estuaries having prolific ostracods and *Spirorbis* on algal mats.			
	Shale; hard, dark, gray to black, carbonaceous, brittle, fossiliferous.	From .5 to 1 foot thick, lenticular, and discontinuous.	*Lingula carbonaria,* herbaceous gastropods, *Myalina wyomingensis.*	Marginal-marine to brackish, anaerobic-bottomed lagoons forming on regressive marine-shelf muds.			
Unnamed calcareous shale	Shale and siltstone; medium gray, calcareous.	From 2 to 3 feet thick in most of area, 7 feet or greater at edges of crevasse splays.	Large productid brachiopods (*Antiquatonia, Linoproductus* and *Juresania* sp.) Crinoids, scattered small brachiopods, bryozoans	Silt and mud possibly derived from reworked Energy Shale crevasse splays along the Highland fluvial complex. Redeposited over widespread area of shallow marine shelf.			
Brereton Limestone	Limestone; massive, dark gray, irregularly laminated, argillaceous, fossiliferous micrite, interbedded light-gray to white neomorphic microspar bands. Thin calcareous gray-shale partings in upper portion. Grades laterally	Occurs in irregular, elongate lenses and pods, 0 to 7 feet thick. Overlies coal or thin Anna between adjacent thick Anna lenses. Calcareous-shale facies occurs in thick areas along Energy Shale wedges.	Limestone—Crinoids, brachiopods, ostracods, bivalves, abundant *Fusulina* sp., other calcareous foraminifera. Calcareous shale—Large productid brachiopods, crinoids, some small brachiopods, bryozoans.	Limestone formed in shallow (5 to 10 m), warm, marine, carbonate shelves. Calcareous shale facies formed from silt and mud deposited on marine shelf by crevasse splays of the Highland fluvial complex.			

Figure 3. *Continued.*

Member or other lithologic unit	Lithology	Thickness and distribution	Faunal or floral assemblage	Summary of depositional conditions
	to medium-gray calcareous shale and siltstone.			
Anna Shale	Shale; black, brittle, carbonaceous, extensively bioturbated at top. Contains basal transgression shell breccia.	Occurs in irregular winding lenses. Range from 200 to 1000 feet wide, 0 to 5 feet thick.	Necktonic forms—Sharks, other fish, cephalopods, conodonts, Epiplanktonic forms (attached to algal mat)—*Dunbarella rectalaterea, Pteria* sp., *Lingula carbonaria, Orbiculoidea missouriensis.*	Brackish to near marine lagoonal and estuarine water bodies; anaerobic bottoms, probably covered by floating algal mat that baffled wind currents and was source for most of black organic material in mud.
Energy Shale	Shale to shaly claystone; medium gray, thinly laminated, soft (terrestrial facies).	Thick wedge (0 to 120 feet) along the Highland fluvial complex in northern St. Clair, northwestern Washington Counties. Locally extends to Lawson Shale Member. Overlying marine limestone and transitional shales rise over Energy wedges. Where thickness exceeds 30 feet, Anna Shale and Brereton Limestone are often absent.	Contains well-preserved plant remains and the clam-shrimp *Leaia tricarinata.*	Deposited as a large fine-grained crevasse splay into a large, shallow, fresh to brackish lake along a river in the Highland fluvial complex.
	Shale; carbonaceous, dark gray; coal stringers. Silty shales and siltstones, and fine, silty sandstones; medium gray. (Marginal marine to terrestrial facies.)	Occur as thick lobate wedges along Highland fluvial complex; 0 to 120 feet thick. Grades laterally into 0 to 10 feet thick pods of shale in the eastern two-thirds of Washington and Perry and northeastern Jackson Counties.	Contains fragmental, well-preserved plant remains. Parts of wedges and all of thin pods contain marginal marine fauna—*Dunbarella* sp., other bivalves, some cephalopods, and the inarticulate brachiopod, *Lingula carbonaria.*	Deposited in large crevasse splays along a river in Highland fluvial complex into brackish, marginal-marine water.
Herrin (No. 6) Coal	Coal, normal bright-banded.	From 6 to 9 feet thick. Occurs persistently in study area. Split by persistent 1- to 2-inch claystone parting called "blue band." Coal split into multiple benches by gray shale in vicinity of Highland fluvial complex.	Flora similar to that of Danville Coal.	Brackish to freshwater swamps originating on deltaic deposits to north and east, rapidly spreading and coalescing over a broad coastal plain consisting of marine carbonates and shales following a regression of marine waters.

Depositional environments: Freshwater, Brackish, Marine

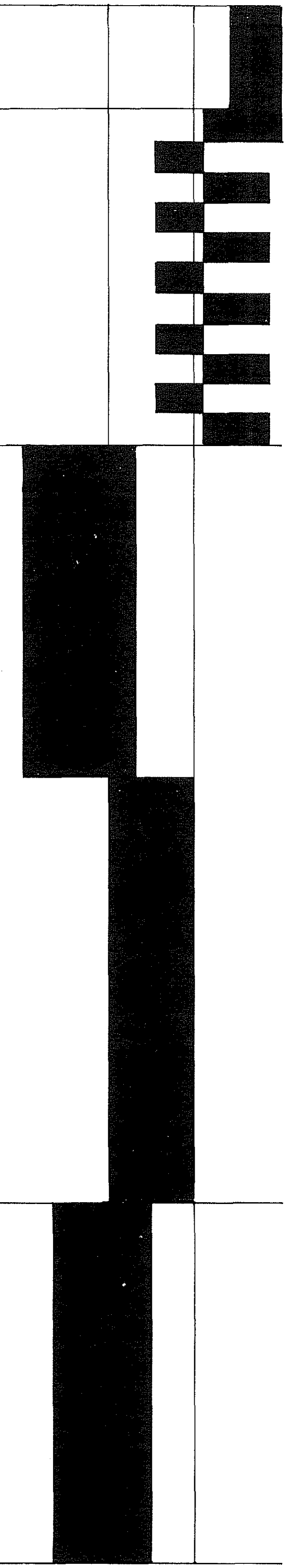

Figure 3. *Continued.*

Member or other lithologic unit	Lithology	Thickness and distribution	Faunal or floral assemblage	Summary of depositional conditions	Depositional environments: Freshwater	Brackish	Marine
Sediments in the Highland fluvial complex	Sandy shale; siltstone, silty to clean; sandstone fine to coarse grained.	Occurs in a winding one- to three-mile-wide bank crossing study area in Clinton and Washington Counties. Extends from about 250 feet below Herrin Coal up to Piasa Limestone horizon. Consists of multiple sandstone, siltstone, and shale bodies.	Large and small plant debris, mostly stems and logs in channel lag.	Sequence of stacked channel-fill, point-bar, and overbank deposits. Deposited in an adjacent to major river that repeatedly occupied nearly the same course through several transgressive-regressive periods.			

part of the Lawson Shale Member contains a fauna of sponges, burrowing bivalves, small gastropods, bryozoans, and scattered brachiopods. The upper part of the shale is nonfossiliferous except in a narrow zone that is transitional with the overlying Bankston Fork Limestone Member where a "hash" of brachiopods, ostracods, corals, bryozoans, and fish accumulated during the initial stages of the Bankston Fork marine transgression.

A return to the shallow marine carbonate shelf environment is indicated by the lower bench of the Bankston Fork Limestone. The shaly claystone parting between the lower and upper benches probably was deposited in a marine tidal flat, whereas the upper bench was deposited in a very shallow marginal marine, carbonate tidal flat or shelf and bay environment. A gradual regression is reflected by the deposition of shale partings and fossils of the marginally marine upper bench.

The return to a predominantly nonmarine environment in which muds forming shaly claystones were deposited is indicated by strata above the Bankston Fork Limestone. These shaly claystones appear to have been deposited in shallow interdistributary bays and were locally intensively rooted by plants growing in swamps associated with the bays. The Allenby Coal Member is tentatively identified in the study area as a thin shaly coal that locally occurs near the middle of the claystone interval. The Danville (No. 7) Coal Member is commonly present in the report area and represents development of a peat swamp that was widespread, but locally poorly developed or absent.

The initial deposit above the Danville Coal is a black shale containing a fauna similar to that of the Anna Shale overlying the Herrin Coal. The deposit is considered likewise to represent the initial marine transgression in which the peat swamp was drowned. A silty shale and shaly claystone containing *Stigmaria* overlie the black shale and indicate a temporary influx of terrestrial sediments into the area. The source of the sediments may have been the thick delta that accumulated in the eastern part of the Illinois Basin and that formed a shallow water platform in the report area on which scattered swamps developed (Manos, 1963).

Subsequently, a broad marine transgression occurred in which the relatively thick and regionally extensive Piasa Limestone Member was deposited. Fine carbonate mud and bioclastic debris accumulated in very shallow water on an open marine carbonate shelf that extended over the entire report area.

HIGHLAND FLUVIAL COMPLEX

A major stratigraphic feature of the study area is a multistory body of sandstone, sandy siltstone, and shale in the Carbondale and Spoon Formations. These deposits extend across the central and eastern part of the report area and southeastward to the cropline of the Herrin Coal. This feature was first recognized by Kay (1915) as a linear zone where the Herrin Coal is absent. Payne and Cady (1944) later mapped an area, including part of the report area, more than 50 miles (80 km) long and as much as 10 miles (16 km) wide where sandstone is commonly present at the horizon of the Herrin Coal. It was evident by 1950 that the mapped segments were part of a large sandstone complex that was deposited in Illinois by fluvial processes during the middle part of Pennsylvanian time. Additional work by Siever (1950), Du Bois (1951), Hopkins (1958), Clegg (1961), and Potter and Simon (1961) provided additional information on the sandstone complex.

Earlier workers (Potter and Simon, 1961) believed the sandstone complex was formed when an erosional channel was filled with stream-transported sand. In a concept supported by evidence presented by Johnson (1972), part of the fluvial complex was considered contemporaneous with the coal-forming swamp of the Herrin Coal; Johnson cited evidence of intertonguing between sediments in the fluvial complex and the Herrin Coal. He proposed the name Walshville channel to differentiate the peat-contemporaneous channel from the previously named channel-fill deposits of the Anvil Rock Sandstone Member, which are clearly younger than the Herrin Coal.

Deposits in the Walshville channel are part of a winding, elongate body of sandstone, siltstone, and shale that is 1 to 3 miles (1.6 to 4.8 km) wide and as much as 300 feet

(90 m) thick. The deposits extend from Shelby County in central Illinois southward to Jackson County in southern Illinois. They contain a succession of multistory sandstones (as described by Potter, 1963), located in the stratigraphic interval between the Seahorne Limestone Member of the Spoon Formation and the Piasa Limestone Member of the Modesto Formation, and include the Anvil Rock Sandstone in southeastern Illinois as mapped by Siever (1950), Hopkins (1958), and others. This multistory unit is herein informally termed the Highland fluvial complex, named after the town of Highland (Madison County), which is centrally located in relation to the sandstone body. The Highland area was one of the first recognized areas where sandstone is present at the horizon of the Herrin Coal. Presently available evidence suggests the Highland fluvial complex comprises lithic units of several named but undifferentiated members. In some areas, the complex may consist only of units of the Anvil Rock Sandstone Member. The term Walshville channel will be retained as an informal term in this report to refer to the channel in the upper part of the fluvial complex contemporaneous with Herrin peat formation.

The Highland fluvial complex contains two recognized disconformities and possibly several others locally. These disconformities suggest repeated disruption of the river course; marine transgressions occurred and subsequent reestablishment of the river course followed in nearly the same position. A similar occurrence of river channels in the same geographic position, but at higher stratigraphic levels, in a coal basin was previously described by Hoover et al. (1969) for the Monongahela Group in the central Appalachians. They attributed these "vertically stacked," or multistory, sandstones to tectonic subsidence that was more rapid in the area of the river than elsewhere. The Highland fluvial complex similarly is believed by us to have been localized by minor subsidence in the shelf area west of the Du Quoin Monocline.

At some places in the report area, the location of the river shifted somewhat with time. Hoover et al. (1969) considered the "offset stacking" to be a result of "differential sedimentation" (e.g., location of natural levees) and differential compaction. The lateral shifting of the Highland fluvial complex probably resulted from similar causes and also from the meandering of the river channel.

Immediately following deposition of the Herrin Coal, the river in the Walshville channel periodically overflowed its banks and deposited crevasse splay and overbank sediments consisting of sandstone, siltstone, and shale—collectively termed the Energy Shale Member. These deposits locally prevented the entry of marine waters that normally increased the postdepositional sulfur content of the coal (Gluskoter and Simon, 1968).

COMPUTER ANALYSIS OF DEPOSITIONAL FACIES

The interval from the Herrin Coal to the Piasa Limestone was studied in detail in central Washington County (T. 1 to 3 S., R. 2 to 4 W.) in southwestern Illinois (fig. 1). The computer-generated maps (fig. 4) are based on data taken from geophysical logs of oil test holes. Much interpretation is based on known successions of lithologic units and on expected response of electric logs to these rocks. In addition, drillers' logs of coal test holes in the northwestern part of the area and a description of rocks exposed in a mine shaft at Nashville were used.

Depth, thickness, and inferred rock type for each member of the Carbondale and Modesto Formations, from the Herrin Coal to the Piasa Limestone, were interpreted from electric logs and stored in a computer file for later manipulation. Where possible, data from two test holes per section were used. Holes were chosen to be as evenly spaced as possible except in critical areas along the boundaries of the Highland fluvial complex, where more closely spaced datum points were used if available. Because drilling in some oil fields is extensive, but not in intervening areas, the number of drill-hole datum points ranges from none in some sections to three or four in others.

The Highland fluvial complex crosses the study area from northwest to southeast and includes a large meander in the southeastern part of the area (fig. 4A). It ranges in thickness from 0 to more than 300 feet (0 to 90 m). The meander in the southeastern part of the study area developed an extremely narrow neck or a cutoff that resulted in the formation of an island where normal peat deposition continued. Protrusions along the southern margin of the meander may be minor distributaries that were active during or prior to deposition of Herrin Coal or may represent remnants of earlier routes in the channel complex.

The river that carried terrigenous material through the swamp in the Walshville channel of the Highland fluvial complex was exceptionally well developed and active during deposition of the Herrin Coal (fig. 4B). The influence of the river on the swamp is reflected by seven areas of thin or split coal (fig. 4B).

This river may have continued to be active throughout deposition of the Anna Shale and Brereton Limestone (fig. 4C and 4D). The absence of these units may be the result of nondeposition over a ridge formed by differential compaction of sediments in the channel complex or by cut-and-fill at a later (possibly Anvil Rock) stage. Several areas where the Anna Shale is missing and overlain by thick Brereton Limestone may reflect initial development of the Brereton Limestone as a series of lime-mud banks during deposition of the Anna or the removal of Anna Shale by scour in tidal channels prior to deposition of Brereton Limestone.

The river in the Walshville channel apparently became completely inactive during deposition of the upper part of the Lawson Shale or the lower part of the Bankston Fork Limestone. During deposition of the Bankston Fork Limestone, sediments in the complex were present only as a series of remnant sand islands and mud banks where limestone was not deposited (fig. 4E). Waves washing these positive areas formed calcareous shale and shaly limestone zones in the Bankston Fork Limestone. Similar breakup of the channel complex for an area to the north was noted by Johnson (1972).

The Piasa Limestone resulted from marine invasion that deposited sediments that covered most of the prior deposits in this nine-township area (fig. 4F). The Piasa Limestone is missing only in a few small areas where the interval consists of sandstone and shale. Its absence in these areas may be due to erosion or nondeposition at or near the

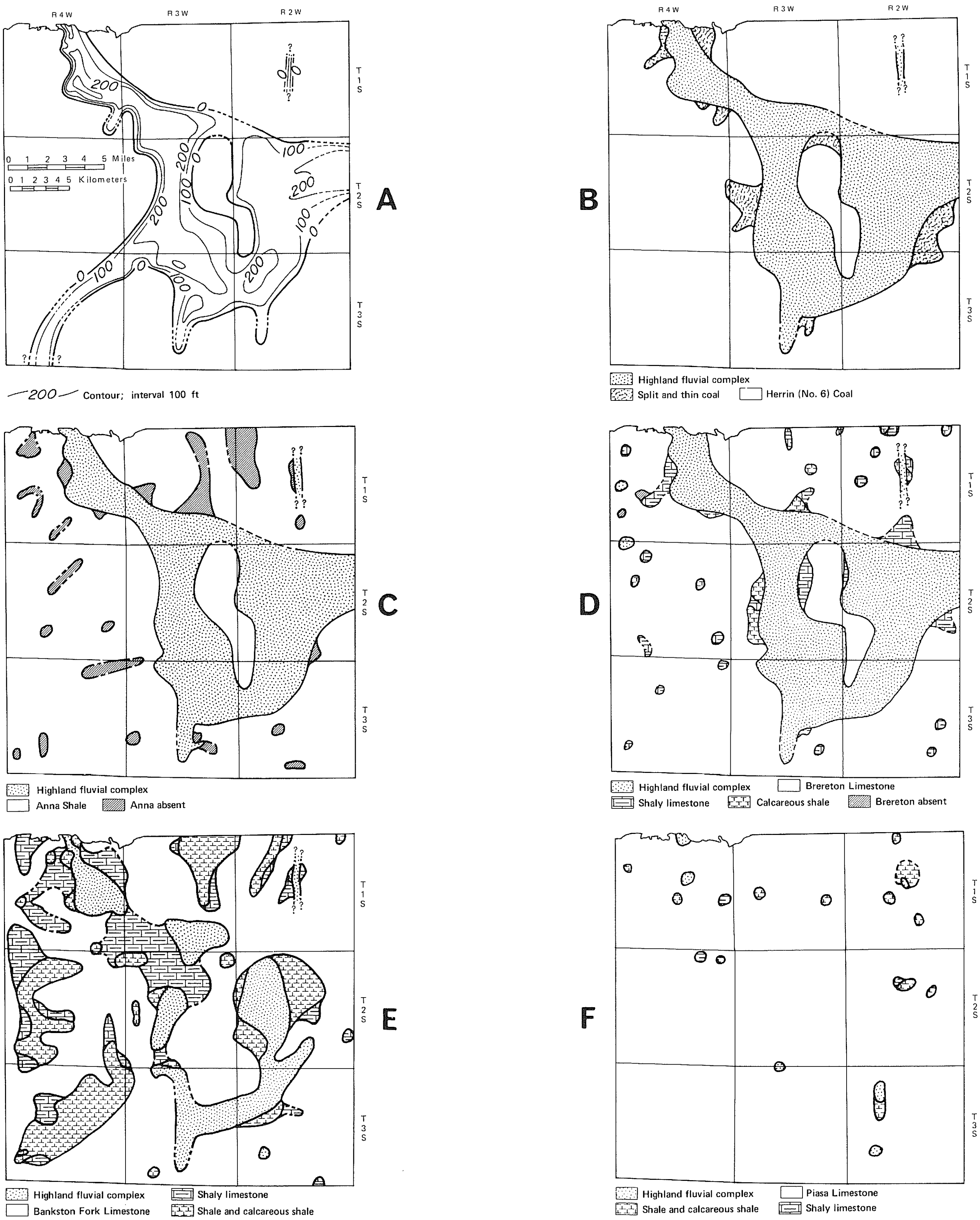

Figure 4. Sequential development of strata overlying the Herrin (No. 6) Coal Member. (A) Thickness of strata in the Highland fluvial complex, (B) Lithofacies of Herrin (No. 6) Coal Member, (C) Lithofacies of Anna Shale Member, (D) Lithofacies of Brereton Limestone Member, (E) Lithofacies of Bankston Fork Limestone, and (F) Lithofacies of Piasa Limestone Member.

crest of the compactional ridge that formed above clastic sediments in the Highland fluvial complex. The Piasa apparently represents the end of terrigenous input and a return to open marine conditions.

SUMMARY AND CONCLUSIONS

Late Desmoinesian-age strata overlying the Herrin Coal in southwestern Illinois were deposited on a relatively stable shelf that was separated from the more rapidly subsiding central part of the Illinois Basin by the Du Quoin Monocline. The report area contained an otherwise open and unrestricted depositional surface. Thicker clastic sediments were deposited in the more rapidly subsiding portion of the basin to the east.

Deposition of sediments forming strata in the interval from the Herrin Coal to the Piasa Limestone occurred largely in a shallow marine-shelf environment. Coal swamps and associated terrestrial sediments were deposited during at least four periods in this interval.

The river in the Walshville channel, which existed contemporaneously with the Herrin Coal swamp, flowed through the southwestern Illinois area; the river persisted along approximately the same course until its disappearance sometime prior to deposition of Bankston Fork Limestone. The river periodically overflowed its banks, to form crevasse splays and overbank deposits (Energy Shale), producing splits in the Herrin Coal. Locally, where these deposits overlie the Herrin Coal, they may have sealed the coal from the marine environment and thus maintained its originally rather low sulfur content.

Deposits in the Highland fluvial complex, including the Walshville channel, occur in a 300-foot (90-m) stratigraphic interval, beginning above the horizon of the Seahorne Limestone and extending up to the horizon of the Piasa Limestone. The strata consist of clastics that were deposited contemporaneously with adjacent shelf strata, and also include channel cut-and-fill deposits. The river course was repeatedly interrupted by shallow marine transgressions. In each case, a river subsequently reoccupied the same general area, producing a sequence of "stacked sandstone" deposits locally as much as 300 feet (90 m) thick.

REFERENCES

CLEGG, K. E., 1961, Subsurface geology and coal resources of the Pennsylvanian System—Sangamon, Macon, Menard, and parts of Christian and Logan Counties, Illinois: Illinois State Geological Survey Circular 312, 28 p.

Du BOIS, E. P., 1951, Geology and coal resources of a part of the Pennsylvanian System in Shelby, Moultrie, and portions of Effingham and Fayette Counties: Illinois State Geological Survey Report of Investigations 156, 32 p.

GIVENS, T. J., 1968, Paleoecology and environment of deposition of part of the Brereton and Jamestown cyclothems (Middle Pennsylvanian), Williamson County, Illinois: Unpublished M.S. thesis, Southern Illinois University, Carbondale, 184 p.

GLUSKOTER, H. J., and J. A. SIMON, 1968, Sulfur in Illinois coals: Illinois State Geological Survey Circular 432, 28 p.

HOOVER, J. R., R. MALONE, G. EDDY, and A. DONALDSON, 1969, Regional position, trend, and geometry of coals and sandstones of the Monongahela Group and Waynesburg Formation in the central Appalachians, *in* Some Appalachian coals and carbonates: Models of ancient shallow-water deposition: West Virginia Geological and Economic Survey, Guidebook for 1969 Geological Society of America Field Trip, 384 p.

HOPKINS, M. E., 1958, Geology and petrology of the Anvil Rock Sandstone of southern Illinois: Illinois State Geological Survey Circular 256, 49 p.

JOHNSON, D. O., 1972, Stratigraphic analysis of the interval between the Herrin (No. 6) Coal and the Piasa Limestone in southwestern Illinois: Unpublished Ph.D. thesis, University of Illinois at Urbana-Champaign, 105 p.

KAY, F. H., 1915, Coal resources of district VII (southwestern Illinois) (Coal No. 6 west of Duquoin anticline): Illinois Coal Mining Investigations Bulletin 11, 233 p.

MANOS, C. T., 1963, Petrography and depositional environment of the Sparland cyclothem (Pennsylvanian): Unpublished Ph.D. thesis, University of Illinois at Urbana-Champaign, 110 p.

OWEN, D. D., 1856, Report on the Geological Survey in Kentucky made during the years 1854 and 1855: Kentucky Geological Survey Bulletin Series 1, v. 1, 416 p.

PAYNE, J. N., and G. H. CADY, 1944, Structure of Herrin (No. 6) Coal Bed in Christian and Montgomery Counties and adjacent parts of Fayette, Macon, Sangamon, and Shelby Counties: Illinois State Geological Survey Circular 105, 57 p.

POTTER, P. E., 1963, Late Paleozoic sandstones of the Illinois Basin: Illinois State Geological Survey Report of Investigations 217, 92 p.

POTTER, P. E., and J. A. SIMON, 1961, Anvil Rock Sandstone and channel cutouts of Herrin (No. 6) Coal in west-central Illinois: Illinois State Geological Survey Circular 314, 12 p.

ROSS, C. A., 1969, Paleoecology of *Triticites* and *Dunbarinella* in Upper Pennsylvanian strata of Texas: Journal of Paleontology, v. 43, p. 298-311.

SIEVER, Raymond, 1950, Structure of the Herrin (No. 6) Coal bed in Marion and Fayette Counties and adjacent parts of Bond, Clinton, Montgomery, Clay, Effingham, Washington, Jefferson, and Wayne Counties: Illinois State Geological Survey Circular 164, 100 p.

WANLESS, H. R., 1975, Illinois Basin region, paleotectonic investigations of the Pennsylvanian System in the United States, Part I: Introduction and regional analysis of the Pennsylvanian System: U.S. Geological Survey Professional Paper 853-E, p. 71-95, p. 97-114.

WETENDORF, F. H., 1967, Environment of deposition of parts of the Brereton, Jamestown, and Bankston cyclothems (Middle Pennsylvanian) of Williamson County, Illinois: Unpublished M.S. thesis, Southern Illinois University, Carbondale, 89 p.

ZANGERL, R., and E. S. RICHARDSON, 1963, The paleoecological history of two Pennsylvanian black shales: Chicago Natural History Museum, Fieldiana: Geological Memoir, v. 4, 352 p.

Pennsylvanian correlations between the Eastern Interior and Appalachian Basins

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Correlation of coal beds and other stratigraphic units of Pennsylvanian age between the Eastern Interior (Illinois) and Appalachian Basins has been a matter of conjecture since the earliest geological investigations of the areas. The question of whether the two basins were joined during Pennsylvanian time (Ashley, 1907) has been resolved in part by regional studies of the petrology and cross-bedding directions that show a common source for the basal Pennsylvanian sediments of the two basins from the middle and northern Appalachians and from the southeastern Canadian Shield (Potter and Siever, 1956a, 1956b; Siever and Potter, 1956). However, the character of the Pennsylvanian sediments, the variability of lithology and thickness of beds, and particularly the lack of key beds common to both areas, has hampered detailed correlation between the basins. Coal beds, limestone, or marine-shale beds, whose contacts have commonly been used as either formal or informal stratigraphic boundaries, are limited in their extent and generally have been projected far beyond the areas in which the beds were named and beyond where they can be easily identified. Consequently, Pennsylvanian units are poorly and incorrectly defined in many areas, and the subdivision and nomenclature of Pennsylvanian rocks commonly differ in different parts of the basins as well as in the states that make up the basins.

Harold R. Wanless (1898-1970) had a lifelong interest in Pennsylvanian stratigraphy and was one of the few men with a broad knowledge of the stratigraphy of both the Eastern Interior and Appalachian Basins. His publication on Pennsylvanian correlations of the two basins (Wanless, 1939) is the most comprehensive work on this subject and contains a catalog of virtually every coal bed and important stratigraphic unit recognized in the basins. Those correlations relied almost entirely on physical stratigraphy, the physical character of coal beds and their shale partings, and the nature of and environmental conditions of deposition of the foot and roof strata of coal beds. Although Wanless did not address directly the subject of interbasinal correlations in later publications (1975a, 1975b), he used both fossil floras and faunas for general correlation of intervals and suggested the correspondence of certain limestones of Ohio and Illinois on the basis of their fusulinid content.

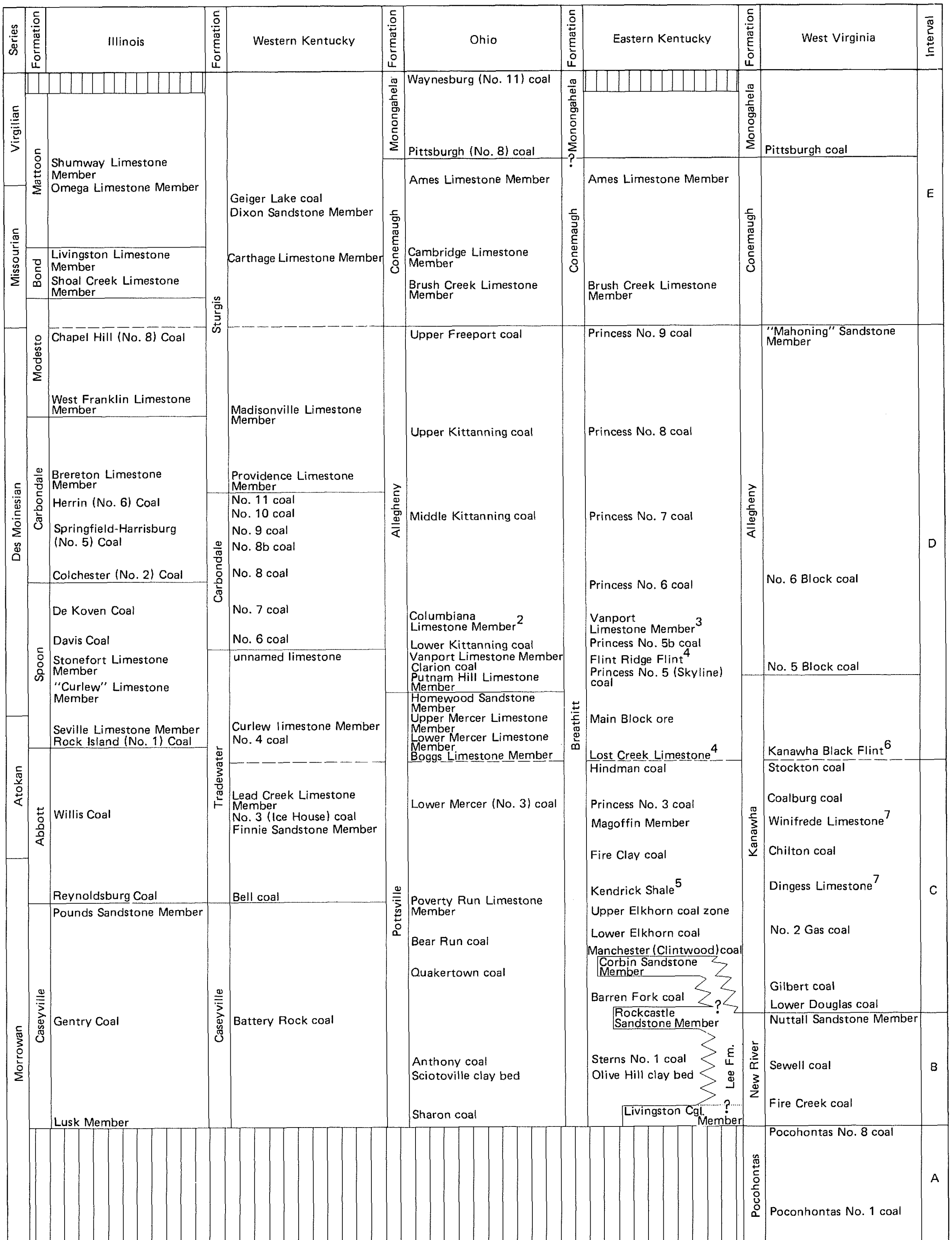
Our correlation chart (fig. 1) is based largely on a reexamination of fusulinids from Pennsylvanian limestones in Ohio, Kentucky, and Illinois (Douglass, 1979) and on the physical stratigraphy established in the cooperative geological mapping program of the U.S. Geological Survey and the Kentucky Geological Survey. We have also been aided by Robert Kosanke (U.S. Geological Survey), who studied the spore assemblages of Pennsylvanian coals in both the Eastern Interior Basin and eastern Kentucky, the latter as a part of the cooperative mapping program noted above. Kosanke (oral communication, 1978) has demonstrated that the top of the range zone of the spore *Schulzopora rara* occurs slightly above interval B (fig. 1) in the upper part of the Caseyville Formation in Illinois and western Kentucky and above the Barren Fork coal bed in eastern Kentucky. Comparison of spores from the coals of the Princess district in northeastern Kentucky with coals of the Eastern Interior Basin (Kosanke, 1973) corroborates our correlations of fusulinid-bearing limestones from Ohio to Illinois.

Identification of fusulinids in the Lost Creek Limestone of Morse (1931) in southeastern Kentucky (Ping, 1978) significantly changes Pennsylvanian correlations of Pennsylvanian beds of eastern Kentucky with beds in Ohio and the Illinois Basin. These fusulinids have attributes intermediate between *Profusulinella* and *Fusulinella* and thus indicate that the Lost Creek Limestone is older than both the "Upper" and the "Lower Mercer Limestone Members" of the Pottsville Formation in Ohio and the Curlew Limestone Member of the Tradewater Formation in western Kentucky. Wanless equated the Mercer Members with the Kendrick Shale of Jillson (1919) and the Magoffin Member of the Breathitt Formation in eastern Kentucky, but this fusulinid discovery clearly indicates that the Mercer limestones are much younger than either of the two marine horizons in eastern Kentucky.

It has been suggested that the Early Pennsylvanian deltas prograded northwestward across West Virginia and Kentucky into an extensive sea (Donaldson, 1974, p. 48); however, no widespread marine units of Morrowan or early Atokan age are present in the Illinois Basin (fig. 1), but at least five named marine units (as well as several unnamed ones) were deposited in eastern Kentucky during the same period (Rice and others, 1979, fig. 13). Their distribution suggests that open-marine water reached eastern Kentucky from the south and southwest along the axis of the subsiding Appalachian geosyncline.

Figure 2 shows the generalized relations between the proposed Pennsylvanian stratotype section 4 in West Virginia (Englund and others, 1977) and sections in other parts of the Appalachian Basin and in the Illinois Basin. It illustrates in particular the great thickening of intervals B and C toward the southeast. Only remnants of interval D are found in southeastern Kentucky—none are found in Tennessee.

The nomenclature used in this report is not necessarily that of the U.S. Geological Survey.



[1]of Glenn (1922); [2]of Sturgeon and DeLong (1964); [3]as used by Phalen (1912); [4]of Morse (1931); [5]of Jillson (1919); [6]of White (1891); [7]of Hennen and Reger (1914).

Figure 1. Correlation chart showing the relation of key beds in parts of the Eastern Interior and Appalachian Basins. Intervals A through E are arbitrary units; only the boundaries between intervals C, D, and E are time-stratigraphic. The boundaries between intervals A, B, and C are rock-stratigraphic, although they commonly have been treated as time-stratigraphic; the upper boundary of B is not projected into Ohio and the Eastern Interior Basin because of insufficient data. (The nomenclature used above is not necessarily that of the U.S. Geological Survey).

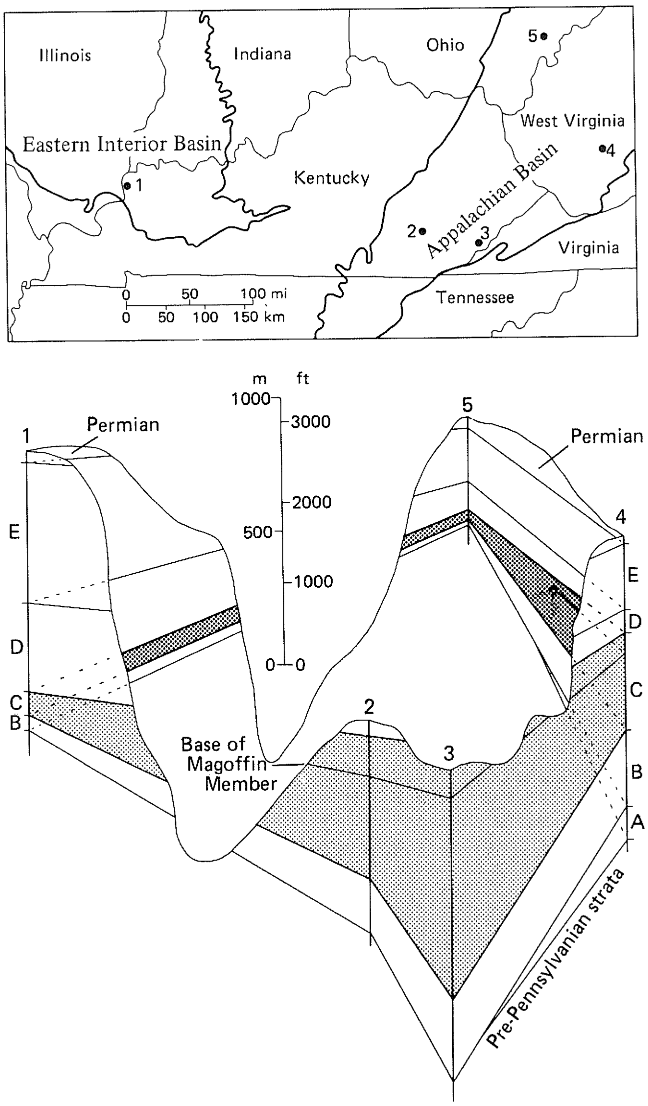


Figure 2. Generalized fence diagram showing correlation and thickness of Pennsylvanian units. Sections 1, 2, and 3 are generalized from drill-hole data; section 4 is generalized from Englund and others (1977); section 5 is from Stout (1939). For purposes of this diagram, interval B includes units in the lower part of the Pennsylvanian System that are characterized by orthoquartzite: the New River, Lee, and Caseyville Formations, and the Sharon Conglomerate Member of the Pottsville Formation in Ohio. Datum is top of interval C.

REFERENCES

ASHLEY, G. H., 1907, Were the Appalachian and Eastern Interior coal fields ever connected?: Economic Geology, v. 2, p. 659-666.

DONALDSON, A. C., 1974, Pennsylvanian sedimentation of central Appalachians, *in* Carboniferous of the southeastern United States: Geological Society of America Special Paper 148, p. 47-48.

DOUGLASS, R. C., 1979, The distribution of fusulinids and their correlation between the Illinois Basin and the Appalachian Basin, *in* James E. Palmer and Russell R. Dutcher [eds.], Depositional and structural history of the Pennsylvanian System of the Illinois Basin: Guidebook for field trip no. 9, part 2, Ninth International Congress of Carboniferous Stratigraphy and Geology, Urbana, IL, p. 15-20.

ENGLUND, K. J., H. H. ARNDT, W. H. GILLESPIE, T. W. HENRY, and H. W. PFEFFERKORN, 1977, A field guide to proposed Pennsylvanian System stratotype, West Virginia: Annual American Association of Petroleum Geologists and Society of Economic Paleontologists and Mineralogists convention, Washington, DC, June 1977.

GLENN, L. C., 1922, Geology and coals of Webster County: Kentucky Geological Survey Series 6, v. 5, 249 p.

HENNEN, R. V., and D. B. REGER, 1914, Logan and Mingo Counties: West Virginia Geological Survey [county report], 776 p.

JILLSON, W. R., 1919, The Kendrick Shale—A new calcareous fossil horizon in the coal measures of eastern Kentucky: Kentucky Department of Geology and Forestry, Mineral and Forest Resources of Kentucky Series 6, v. 36, p. 293-348.

KOSANKE, R. M., 1973, Palynological studies of the coals of the Princess reserve district in northeastern Kentucky: U.S. Geological Survey Professional Paper 839, 25 p.

MORSE, W. C., 1931, The Pennsylvanian invertebrate fauna of Kentucky, in the paleontology of Kentucky: Kentucky Geological Survey Series 6, v. 36, p. 293-348.

PHALEN, W. C., 1912, Description of the Kenova quadrangle [Kentucky-West Virginia-Ohio]: U.S. Geological Survey Geological Atlas, Folio 184.

PING, R. G., 1978, Geologic map of the Cutshin quadrangle, Leslie County, Kentucky: U.S. Geological Survey Geological Quadrangle Map GQ-1424.

POTTER, P. E., and Raymond SIEVER, 1956a, Cross-bedding, Sources of basal Pennsylvanian sediments in the Eastern Interior basin, part 1: Journal of Geology, v. 64, no. 3, p. 225-244.

POTTER, P. E., and Raymond SIEVER, 1956b, Some methodological implications, Sources of basal Pennsylvanian sediments in the Eastern Interior basin, part 3: Journal of Geology, v. 64, no. 5, p. 447-455.

RICE, C. L., E. G. SABLE, G. R. DEVER, Jr., and T. M. KEHN, 1979. The Mississippian and Pennsylvanian (Carboniferous) systems in the United States—Kentucky: U.S. Geological Survey Professional Paper 1110-F.

SIEVER, Raymond, and P. E. POTTER, 1956, Sedimentary petrology, Sources of basal Pennsylvanian sediments in the Eastern Interior basin, part 2: Journal of Geology, v. 64, no. 4, p. 317-335.

STOUT, Wilber, 1939, Generalized section of coal bearing rocks of Ohio: Ohio Geological Survey Series 4, Information Circular 2.

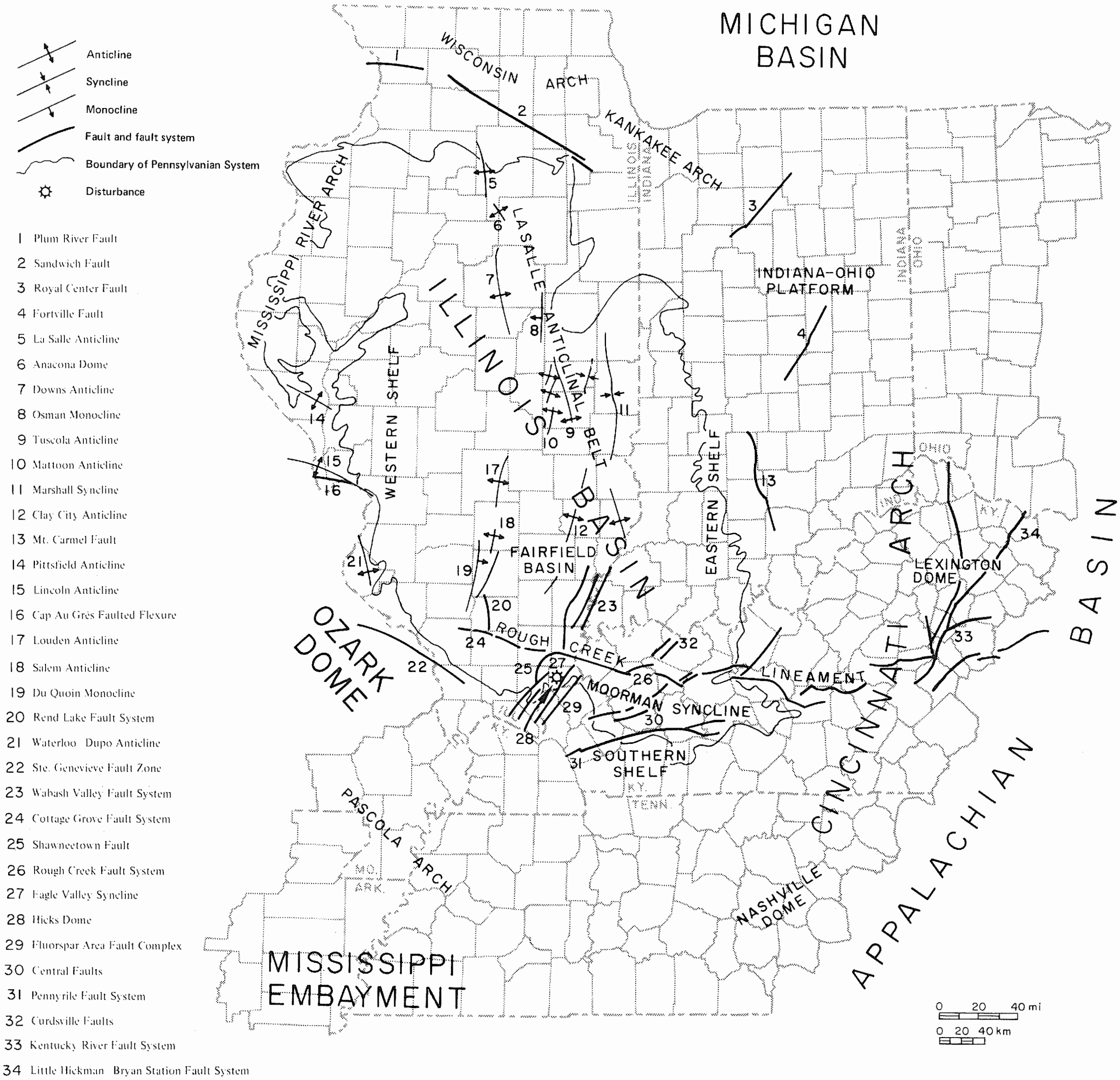
STURGEON, M. T., and S. E. DeLONG, 1964, Revision of some stratigraphic names between the Lower and Middle Kittanning coals in eastern Ohio: Ohio Journal of Science, v. 64, no. 1, p. 31-43.

WANLESS, H. R., 1939, Pennsylvanian correlations in the Eastern Interior and Appalachian coal fields: Geological Society of America Special Paper 17, 130 p.

WANLESS, H. R., 1975a, Appalachian region, *in* Paleotectonic investigations of the Pennsylvanian System in the United States, Pt. 1, Introduction and regional analyses of the Pennsylvanian System: U.S. Geological Survey Professional Paper 853, p. 17-62.

WANLESS, H. R., 1975b, Illinois Basin region, *in* Paleotectonic investigations of the Pennsylvanian System in the United States, Pt. 1, Introduction and regional analyses of the Pennsylvanian System: U.S. Geological Survey Professional paper 853, p. 71-95.

WHITE, I. C., 1891, Stratigraphy of the bituminous coal field of Pennsylvania, Ohio, and West Virginia: U.S. Geological Survey Bulletin 65, 212 p.



Structural features of the Illinois Basin. (Compiled from Clegg, 1970; Bristol and Buschbach, 1971; Sutton, 1971; and Willman and others, 1975. Full references given on p. 119-120.)

STRUCTURAL GEOLOGY AND GEOMORPHOLOGY

Plate-tectonic implications of the Pennsylvanian System in the Illinois Basin

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INTRODUCTION

Perhaps the most widely accepted theory relating continental-interior events to global tectonics is that introduced by Hallam (1963) and played with variations by many others, including Hays and Pitman (1973). The scenario includes these elements of stagecraft: (1) acceleration of plate motions at divergent boundaries creates thermally inflated midocean ridge systems; (2) inflated ridges displace oceanic water, elevating global sea levels and decreasing the freeboard of continents; (3) marine transgressions occupy topographically low continental margins, eventually extending to depressed regions of continental interiors; (4) excess mass (water replacing atmosphere) finds isostatic adjustment by subsidence of depressed areas; (5) further subsidence is a response to sedimentation and the accompanying accumulation of still greater excess mass, which is concentrated on continental shelves and interior basins. Thus, areas of long-continuing topographic depression, such as the Illinois Basin, become the sites of thick sedimentary accumulation; adjoining, rarely depressed elements, such as the Cincinnati Arch and the Ozark Dome, escape sedimentary loading and receive relatively thin, frequently interrupted, sedimentary covers.

The above is perhaps my favorite among sedimentary-tectonic concepts—it satisfies the majority of observational data, it is susceptible to elegant quantitative modeling, and it brings continental-interior regions and their investigators into the modern scene of global tectonics. It is therefore most unfortunate that the hypothesis must be discarded as an explanation of first-order tectonic states on cratons. Thoughtful stratigraphers have had nagging doubts for some time: Why do basins and arches remain fixed in place for hundreds of millions of years? How do we account for the rapid subsidence of sediment-starved basins? By what magic is high-density mantle displaced by an equivalent volume of low-density water and sediment? The latter issue has been addressed rigorously in recent years (Watts and Ryan, 1976); it has been determined that there is an inevitable excess of subsidence (about 35 percent) over what can be accounted for by water-and-sediment loading. Other "driving forces," beyond those imposed by surficial loading, must be invoked in order to explain the differential rates of subsidence exhibited by basins and arches of the continental interior.

The topic "driving forces" brings forth yet another set of varied responses. Among these, thermal contraction models appear to be the most popular (Sleep, 1971; Haxby, Turcotte, and Bird, 1976); here, a heating event is followed by cooling, cooling leads to contraction and the subsidence of basins. A major flaw in the hypothesis rests in repetitive and episodic basin behavior; it seems to assume repeated heating (and thus uplifting) events for which no substantiation exists. Sleep (1976) skillfully steps around the problem of episodic basin subsidence by calling upon recognized episodes of eustatic marine highs to accelerate sedimentation rates. Phanerozoic heating events (and concomitant basinal uplift) to initiate subsidence have not been identified, however, nor can the effects of any single event be prolonged for the active time spans of many cratonic basins.

Where, then, does this leave us as we attempt to understand Pennsylvanian tectonics and sedimentation in the Illinois Basin? It would appear reasonable to postpone further speculation until consideration has been given to the history of the basin in relation to the North American craton as a whole and to what is known of global history.

ILLINOIS BASIN: ENCAPSULATED COMPARATIVE HISTORY

We really know very little about the Precambrian basement of the Illinois Basin from direct observation; the only pertinent exposures are those in the adjacent Ozark uplift, and very few drill holes penetrate the basement. Reliance must be placed on interpretation of the regional magnetic and gravity fields, therefore, and such interpretations are more variable than the fields themselves. McGinnis (1970) has produced the most intensive study of regional gravity; his maps show that the northern half of the basin, with local high-frequency variation suppressed, looks like many other cratonic areas that have no particular tectonic tendencies. The southern half of the basin is dominated by a prominent, positive anomaly that extends from well south of the present basin, includes the area of thickest preserved sediment, and diverges from basin configuration northeastward into Indiana. Part of the anomalous mass is attributed by McGinnis to Cretaceous plutonics of the type that is widespread on the margins of the Mississippi Embayment, and part, to Cambrian rifting and accompanying igneous activity. No evidence exists for pre-Keeweenawan (about 1,000 million years) rocks or structures that would predispose the region toward basinal subsidence.

Figure 1 is a generalized isopach representation of Cambro-Ordovician (Sauk Sequence) strata. The "basin" appears as a southward-plunging trough, unconfined by later features (Cincinnati Arch, Kankakee Arch, Ozark-Mississippi River Arch) and seemingly open to the south as an extension of the Mississippi Embayment. The form is not unlike that exhibited by equivalent strata of the Anadarko Basin area, but, except in extreme southern Illinois, there is little correspondence to the configuration of the gravity field. The Anadarko Basin has been called an aulacogen (Hoffman, Dewey, and Burke, 1974), and there is a clear igneous component to the early history of the basin.

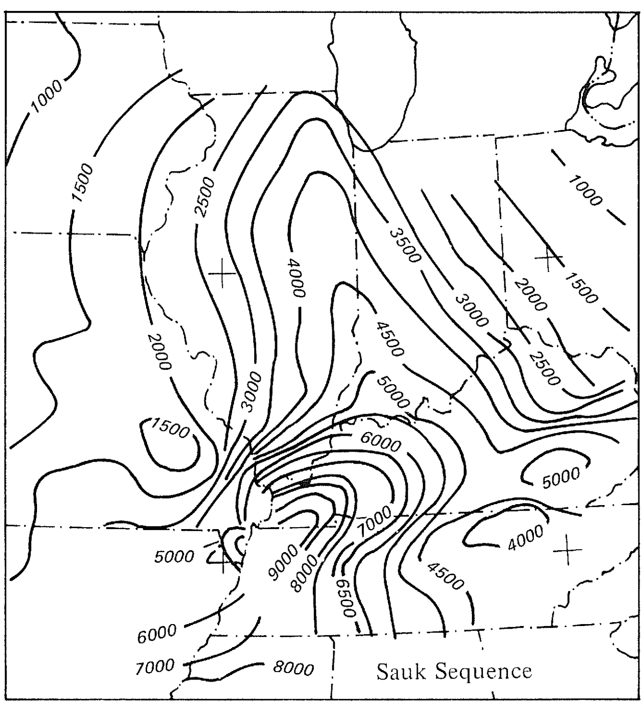

Figure 1. Generalized isopach map of the Sauk Sequence (Cambrian-Lower Ordovician) of the Illinois Basin area. (Modified from Bond and others, 1971, figs. 17 and 18.)

Perhaps the Cambro-Ordovician precursor of the Mississippi Embayment and Illinois Basin should also be considered an aulacogen; if so, conventional explanation would suppose a triple junction at the point of divergence of Anadarko and Embayment trends. I do not think, however, that claiming the existence of such a junction would add significantly to our considerations.

The early Paleozoic history of the Illinois Basin indicates a geometry of high-relief subsidence that is different from that adopted later. The geometric form is equally distinct from the very gentle subsidence during the same time in areas (e.g., Michigan, Williston, Hudson Bay) that later became typical craton-interior basins.

From Middle Ordovician through Early Carboniferous (Tippecanoe and Kaskaskia Sequences), much of the present western, northern, and eastern confining elements that bound the Illinois Basin evolved. No effective closure to the south existed (fig. 2). As a consequence, and in continued contrast to the more typical interior basins, no basin-center salt accumulated. Other evidences of restricted circulation are scarce and generally limited to lagoonal environments. Carbonate and basin-margin sulfate deposition in facies belts roughly concentric with the northern and eastern boundaries of the basin dominated, interrupted only by relatively thin transgressive quartz arenites covering unconformities, by minor incursions of mud from Appalachian clastic wedges, and by ubiquitous Late Devonian—earliest Carboniferous black shales. An important exception is found in a mid-Viséan distal-deltaic silt tongue that crossed the basin from the northeast.

Evidence of significant change appears in Late Viséan-Early Namurian (Chester) rocks; repeated minicyclothems, typically grading from fluvial to marine, and separated by erosional surfaces, mark the end of long-continued and stable, or slowly advancing and retreating shorelines, and the introduction of coarse detrital materials from northeastern sources.

In the Illinois Basin area, pre-Pennsylvanian facies and environments were not unlike those encountered on passive continental margins; open circulation was the rule and depositional and diagenetic facies aligned with tectonically defined bathymetric zones. In tectonic terms, the basin obviously did not evolve on a simple passive margin; rather, it appears as an open cratonic embayment, possibly (but far from certainly) initiated by early Paleozoic rifting. Until late in Kaskaskia deposition, such detritals that entered the basin were derived locally in very small volume or were in continuity with very widespread sand sheets overstepping regional unconformities. Differential subsidence was slow and was controlled largely by flexure.

Profound changes, foreshadowed by Chesterian oscillations of relative sea levels, characterize Pennsylvanian sedimentary and tectonic states in the Illinois Basin and its detrital-source regions. The sub-Pennsylvanian unconformity is basin-wide; the accompanying erosion stripped thousands of cubic kilometers of older strata and cut at least as deep as Middle Ordovician. During the hiatus represented by the unconformity, sharply defined intrabasin anticlines emerged, probably controlled by high-angle faulting in the basement. The major elements, such as the La Salle Anticline, persisted throughout much of Pennsyl-

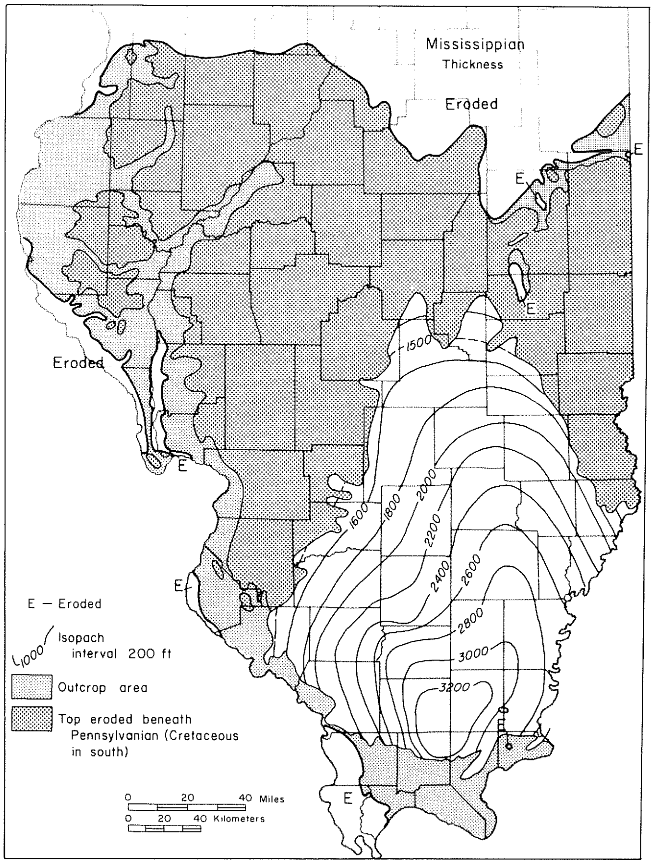

Figure 2. Isopach map of the Mississippian System in Illinois. (From Atherton and others, 1975.)

vanian time and influenced thickness of accumulation and depositional facies.

Details of Pennsylvanian stratigraphy and sedimentation require no review here. It is sufficient to note the documentation of 50-odd oscillations from supra- to sub-baselevel states, commonly involving transitions from subaerial erosion to marine inundation. Further, the largely quartzose sands of earlier detrital episodes are replaced by arenites and wackes that bear an appreciable feldspar content and suggest a source in spasmodically uplifted highlands in the Canadian Shield. Finally, the paleoslopes described by the stream systems feeding Pennsylvanian deltas are in reasonable conformity with basin geometry. This evidence, in conjunction with isopach patterns of the Pennsylvanian System (fig. 3) and of vertically successive Pennsylvanian units, indicates the continued subsidence of a broad depression that is open to the south and southwest.

Effective subsidence apparently ceased at some point in Late Virgillian (Stephanian) or Early Permian (Sakmarian) time. Indeed, there is no evidence of significant further subsidence until Cretaceous time when the southern reaches of the Illinois Basin area marked the northern extension of the modern Mississippi Embayment. The absence of Permo-Triassic subsidence of sufficient magnitude to carry deposits below the levels of subsequent erosion sets the Illinois Basin apart from the major basins west of the Mississippi River.

The timing of uplift of the Pascola Arch and the age of initiation of fault systems that now close the basin on the south remain obscure, at least to me. Latest Pennsylvanian and Early Permian were times of fairly violent movement along high-angle faults in the area of the Anadarko Basin (and from there westward to New Mexico and Colorado); it would not be surprising if what is now the southern margin of the related (?) Illinois Basin was similarly affected. Whenever faulting may have started, igneous activity in the Cretaceous and current seismicity along the bounding fault trends indicate long-continuing movement.

GLOBAL CRATONIC HISTORY

In recent decades, widespread exploratory drilling on all continents and the development of modern technology for seismic profiling have led to the accumulation and integration of useful amounts of subsurface data on a global scale.

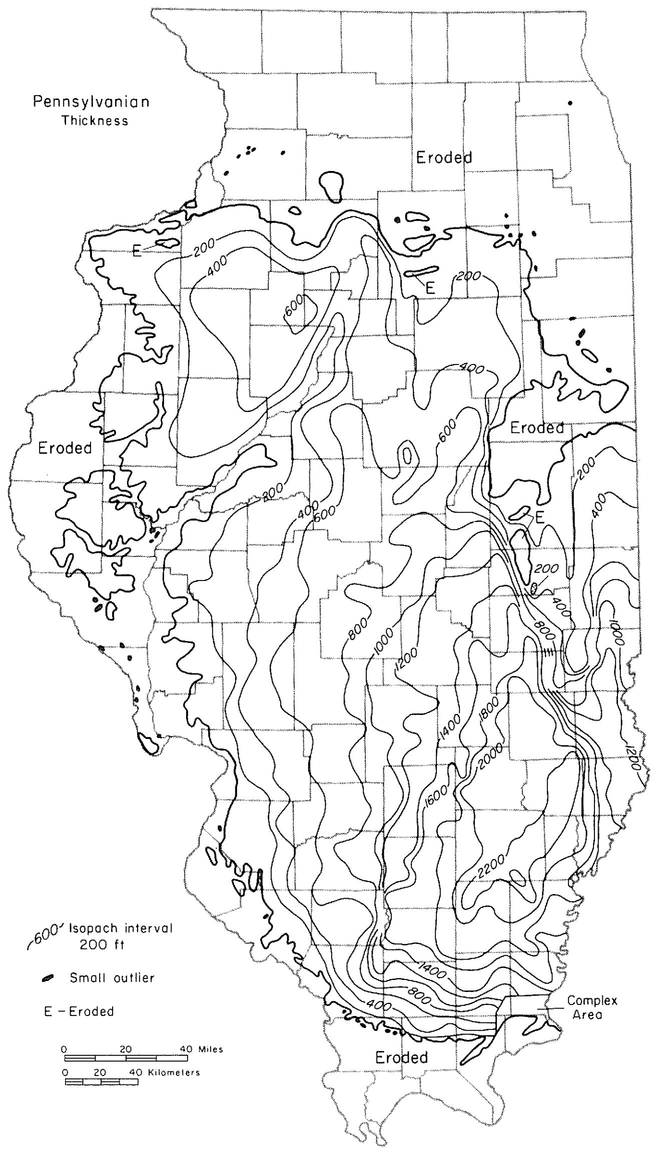

Figure 3. Isopach map of the Pennsylvanian System in Illinois. (From Hopkins and Simon, 1975.)

These data now clearly demonstrate that all cratons participate in a common history of roughly synchronous emergences and submergences, regressions and transgressions (Vail, Mitchum, and Thompson, 1977), much of which can be ascribed to eustatics controlled by changes in the volumes of midocean ridge systems. What cannot be so explained, however, is the existence of pan-cratonic tectonic episodes that are almost equally synchronous (Sloss, 1976, 1978) and are characterized by (1) broad flexural deformation represented by the subsidence of cratonic basins; (2) times of general cratonic stability lacking significant differentiation of basins and arches, or (3) sharply defined subsident and emergent blocks, commonly bounded by high-angle faults.

Early Phanerozoic time (Cambrian through much of Early Carboniferous) is occupied by episodes of the first and second types enumerated above. The flexural episodes are represented in North America by the Sauk, Tippecanoe, and Kaskaskia sequences and by their remarkably similar equivalents on other cratonic interiors; the intersequence unconformities mark the intervention of undifferentiated stable cratons. From latest Mississippian to Early Jurassic, cratons behaved in the manner of episodes of the third kind. In an earlier paper (Sloss and Speed, 1974), these three modes of cratonic tectonism were labeled *submergent, emergent,* and *oscillatory,* respectively, the appellations deriving from the gross relationships of cratons with respect to sea level. It was further noted that (1) submergent episodes were times of continental-margin orogenesis, presumably in response to plate convergence at such margins; (2) emergent episodes appear to lack evidence of large-scale plate interaction; and, (3) oscillatory episodes were characterized by convergence at island arcs at a distance from continental margins while continental interiors were subject to high-relief vertical dislocations, in some places and times accompanied by Hercynian-type manifestations of heat flow, including alkalic and subalkalic plutonism, and by volcanism.

Thus, if there is merit in this analysis, the Pennsylvanian of the Illinois Basin accumulated during the early stages of an oscillatory episode shared by all cratons. Explanation is now required for the oscillatory behavior responsible for the deposition, maturation, and preservation of Pennsylvanian coal and for the change in tectonic style of the basin itself and of its sediment-source areas. The questions lead to the largely unsupported speculations that follow.

A PLATE-TECTONIC MODEL FOR PENNSYLVANIAN SEDIMENTATION

Constraints on the model

The multiple transgressions and regressions characteristic of Late Carboniferous sedimentation of many areas may be explained by (1) eustatic shifts of sea level, (2) variation in the rate of sediment supply, or (3) tectonic oscillation of the depositional area with respect to sea level. The Pitman model of sea-level change as a function of ridge-system volume is inapplicable because of the high frequency of the oscillations. If we assign 20 million years to the 50+ oscillations recorded in Illinois, then each regressive/transgressive event occupied approximately 400 thousand years. The response rate of thermal contraction of the crust is at least an order of magnitude too slow.

Many have noted the coincidence of continental glaciation of Gondwana continents and the development of late Paleozoic coal cycles; sea-level controls of cyclicity by glacial eustacy have been intermittently popular and difficult to suppress. There is no evidence for the large number of discrete glacial episodes that would be required, however, nor is there evidence for significant glaciation extending from Early Carboniferous to at least Middle Permian, as would be demanded to produce the cyclicity observed in one part of the world or another. There are many regions characterized by late Paleozoic shallow-water marine or deltaic sedimentation that should have been sensitive to eustatic changes but which lack manifestations of cyclicity at anything approaching the frequency recorded in the coal basins. Therefore, eustatics, whether controlled by ocean-ridge tectonics or by glaciation, cannot be accepted as a rational explanation of cyclothems.

Variation in the rate of sediment supply may reflect changes in drainage patterns. Heavy detrital loads may have been alternately directed to the Illinois Basin, causing delta progradation, or they may have been diverted elsewhere, leading to marine inundation of the basin. If such were the case, other midcontinent basins or the Appalachian Basin should bear complementary relationships to the Illinois area; they would become sites of delta progradation while the Illinois Basin suffered marine transgression, and conversely. Instead of this complementary relationship, major episodes of transgression are traceable from the Cumberland Plateau to the Texas panhandle and certain coals are believed to extend, as subsynchronous delta-platform deposits, across several basins. The conclusion must be that major river systems and their terminal deltas remained relatively fixed in position by tectonically controlled topography.

The above argumentation leaves tectonics as the root cause of Pennsylvanian cyclicity, but it does not distinguish between vertical movements of source and sink regions. The pattern of sedimentation and the degree of cyclicity would be the same whether the areas of detrital provenance were spasmodically uplifted while the basin subsided at a constant rate, or if the reverse were the case. In Oklahoma and the Rocky Mountain states, where sources and sinks were closely adjacent, it is clear that positive and negative vertical movements were concomitant during late Paleozoic time; I am impelled to believe, intuitively, that the same synchroneity of source elevation and basin downwarp existed in the Pennsylvanian of the Illinois Basin.

What source area? It has been customary to appeal to Appalachian highlands; thus, the Pennsylvanian of the Illinois Basin becomes a kind of "post-orogenic molasse." Conventional folk wisdom proceeds from there to involve convergence, collision, and a paradigm of Atlantic and continental-margin events to explain Eastern Interior sedimentary tectonics. A number of facts and well-founded interpretations are ignored in this intellectual exercise: (1) the Pennsylvanian of the Appalachian Basin was strongly deformed by Appalachian movements; it cannot be simultaneously pre- and post-orogenic; (2) during long intervals of Pennsylvanian time, clastics deposited in the same area coarsen to the north, northwest, and northeast in harmony with their paleoslopes; relatively little sediment is clearly derivable from a southeastern source; (3) similarly, there is no significant gradient in textural or mineralogic maturity from the Appalachians westward to Illinois (or Kansas); (4) the intensity of vertical movement increases from the Illinois Basin to the west and southwest, not in the direction of the Atlantic border. One could go on, but the measure of evidence weighs heavily against reliance on an Appalachian source tied to ocean-continent or continent-continent convergence. The totality of cratonic Pennsylvanian structure and sedimentation forces us to look to the Canadian Shield as a source; spasmodic uplift along high-angle faults in central Quebec would do very nicely in satisfying Pennsylvanian sedimentary petrology and the available data on paleoslopes of the Illinois area.

The North American craton is not unique and does not require a unique explanation for its late Paleozoic behavior; indeed, any such explanation must be global in scope and not restricted to happenings in one ocean basin or one continental margin. Beginning near the end of Early Carboniferous time, the tectonic style and geography of all cratons changed markedly from those prevailing during the preceding 200 to 300 million years. Old basins were strongly modified and new basins were created; old epeirogenic uplifts became violently positive, some becoming mountain blocks as new, typically fault-bounded, blocks emerged; detrital deposition, commonly deltaic, replaced carbonates; and oscillation with respect to sea level and base level increased tenfold in frequency.

These, then, are some of the limiting fences within which the game of controlled speculation is to be played.

The model

In Sloss and Speed (1974), attention was drawn to the fact that conditions during much of Cenozoic time (elevated continental interiors, oscillatory sea levels, dominance of detrital sedimentation on cratons, active vertical uplift and downwarp) closely resemble conditions that must have prevailed in the late Paleozoic. Cenozoic spreading rates are demonstrably slower than those from Late Jurassic through Cretaceous, ocean-continent plate convergences are largely confined to island-arc sites at a distance from cratons, and Cenozoic continental volcanism is commonplace. Spreading rates are slow because lesser volumes of material are delivered to ridge systems; instead, melt is diverted to marginal back-arc basins where it serves to drive arc/trench couples ever farther from cratons; other melt is diverted to cratonic fractures, leading to plateau basalts, explosive volcanism, and the emplacement of numerous small plutons. The short paths for melt extrusion and intrusion (as contrasted with the distance from continents to midocean ridges) makes for rapid evacuation of subcontinental (asthenospheric?) melt and concomitant rapid continental collapse along fractures. Such conditions, intermittently interrupted by the plugging of melt-discharge routes and the accompanying continental swelling, explain the high-frequency oscillations of cratons, the development and repeated activation of cratonic and pericratonic fractures, and the evolution of radical change in tectonic geography.

Application of the model to Pennsylvanian time is difficult to test in the absence of data on spreading rates. Classic orogenic trends of late Paleozoic-early Mesozoic age, such as can be ascribed to convergence and subduction at continental margins, have not been clearly identified; there is growing evidence of the existence of magmatic and accretionary arcs of the appropriate age on the Pacific border of North America. Cratonic heat flow comparable to that of the Cenozoic was not common in the late Paleozoic and early Mesozoic of North America but elsewhere, notably in Europe and the Gondwana continents, volcanism and plutonism were widespread.

Whatever hypothesis eventually emerges to satisfy all available information and to explain the behavior of the North American craton, and of the Illinois Basin in particular, such an ultimate hypothesis will surely involve a close relationship between the Pennsylvanian of the basin and global events and conditions of earth's crust and mantle.

ACKNOWLEDGMENTS

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REFERENCES

ATHERTON, Elwood, Charles COLLINSON, and J. A. Lineback, 1975, The Mississippian System, *in* H. B. Willman, Elwood Atherton, T. C. Buschbach, Charles Collinson, John C. Frye, M. E. Hopkins, Jerry A. Lineback, and Jack A. Simon, Handbook of Illinois stratigraphy: Illinois State Geological Survey, Bulletin 95, p. 123-163.

BOND, D. C., Elwood ATHERTON, H. M. BRISTOL, T. C. BUSCHBACH, D. L. STEVENSON, L. E. BACKER, T. A. DAWSON, E. C. FERNALLD, Howard SCHWALB, E. N. WILSON, A. T. STATLER, R. G. STEARNS, and J. H. BUEHNER, 1971, Possible future petroleum potential of region 9—Illinois Basin, Cincinnati Arch, and northern Mississippi Embayment, *in* Ira H. Cram [ed.], Future petroleum provinces of the United States—Their geology and potential: American Association of Petroleum Geologists Memoir 15, v. 2, p. 1165-1218.

HALLAM, A., 1963, Major epeirogenic and eustatic changes since the Cretaceous and their possible relationship to crustal structure: American Journal of Science, v. 261, p. 397-423.

HAXBY, W. F., D. L. TURCOTTE, and J. M. BIRD, 1976, Thermal and mechanical evolution of the Michigan basin: Tectonophysics, v. 36, p. 57-75.

HAYS, J. D., and W. C. PITMAN III, 1973, Lithospheric plate motion, sea level changes and climatic and ecological consequences: nature, v. 246, p. 18-21.

HOFFMAN, Paul, J. F. DEWEY, and K. BURKE, 1974, Aulacogens and their genetic relation to geosynclines, with a proterozoic example from Great Slave Lake, Canada, *in* R. H. Dott, Jr., and R. H. Shaver [eds.], Modern and ancient geosynclinal sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication 19, p. 38-55.

HOPKINS, M. E., and J. A. SIMON, 1975, Pennsylvanian System, *in* H. B. Willman, Elwood Atherton, T. C. Buschbach, Charles Collinson, John C. Frye, M. E. Hopkins, Jerry A. Lineback, and Jack A. Simon, Handbook of Illinois stratigraphy: Illinois State Geological Survey Bulletin 95, p. 163-201.

McGINNIS, L. D., 1970, Tectonics and the gravity field in the continental interior: Journal of Geophysical Research, v. 75, no. 2, p. 317-331.

SLEEP, N. H., 1971, Thermal effects of the formation of Atlantic continental margins by continental break-up: Geophysical

Journal of the Royal Astronomical Society, v. 24, p. 325-350.
SLEEP, N. H., 1976, Platform subsidence mechanisms and "eustatic" sea-level changes: Tectonophysics, v. 36, p. 45-56.
SLOSS, L. L., 1976, Areas and volumes of cratonic sediments, western North America and eastern Europe: Geology, v. 4, p. 272-276.
SLOSS, L. L., in press, Global sea level change: The view from the craton, *in* J. S. Watkins and L. Montadert [eds.], Geophysical investigations of continental slopes and rises: American Association of Petroleum Geologists Bulletin.
SLOSS, L. L., and R. C. SPEED, 1974, Relationships of cratonic and continental margin tectonic episodes, *in* W. R. Dickinson [ed.], Tectonics and sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication 22, p. 98-119.
VAIL, P. R., R. M. MITCHUM, Jr., and S. THOMPSON III, 1977, Global cycles of relative changes of sea level, *in* C. E. Payton [ed.], Seismic stratigraphy—Applications to hydrocarbon exploration: American Association of Petroleum Geologists Memoir 26, p. 83-97.
WATTS, A. B., and W.B.F. RYAN, 1976, Flexure of lithosphere and continental margin basins: Tectonophysics, v. 26, p. 25-44.

History of the structural uplift of the southern margin of the Illinois Basin

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INTRODUCTION

The Illinois Basin was a predominantly negative area in Illinois, southwestern Indiana, and western Kentucky throughout most of Paleozoic time. Structural closing of the southern margin near the end of the Paleozoic Era ultimately established the spoon-shaped structure of the gently dipping strata.

ILLINOIS BASIN AREA AT CLOSE OF PRECAMBRIAN

Two major linear zones of weakness intersect at the southern tip of Illinois; probably they have persisted since late in Precambrian or early in Cambrian time. The zones are: (1) the Rough Creek Lineament that trends east-west through southern Illinois and western Kentucky (see p. 106); and (2) a north-northeast trending feature that influences the axis of the Mississippi Embayment and the Wabash Valley Fault System. North of the Rough Creek Lineament, the geology appears to be simple and easy to interpret from the data available. Precambrian basement rocks consist chiefly of granites and some rhyolites; they are dated between 1.2 and 1.5 billion years old. When Cambrian seas encroached on the region, the Precambrian surface formed a hilly terrain having up to several hundred meters of local relief. To the south of the Rough Creek Lineament, the deeper rocks are not as well understood because subsurface information is scarce. We do, however, expect the unexpected. Cambrian sediments exhibit marked facies changes and thicken abruptly south of the lineament, where two depressions, the Rough Creek Graben, a westward extension of the Rome Trough (Buschbach, 1977), and the Reelfoot Rift, a predecessor to the Mississippi Embayment (Ervin and McGinnis, 1975), received several hundred to several thousand meters of middle and possibly early Cambrian sediments (fig. 1). These ancient features were bordered by hinge lines or faults that subsequently have been reactivated.

PALEOZOIC HISTORY OF ILLINOIS BASIN

Although centers of maximum deposition shifted several hundreds of kilometers from Croixan (late Cambrian) to Pennsylvanian time, basinal features were present during most of the Paleozoic Era in a broad trough that extended north-northeast from western Tennessee, along the Illinois-Indiana border, and into Michigan. This Paleozoic basin was usually open only to the south, as demonstrated by the strata that generally thicken to the south, contain fewer and finer clastics, and appear to have been deposited in deeper water in that direction.

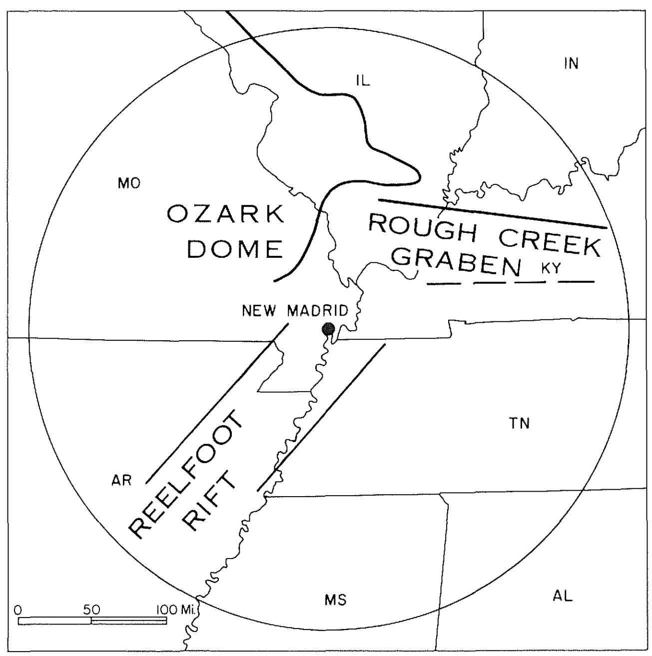

Figure 1. Tectonic elements present in the southern Illinois Basin area late in Precambrian and in Cambrian time. (Modified from Buschbach, 1977.)

ERATHEM	SYSTEM	SERIES	Rock units discussed in text	Comments	
MESOZOIC	CRETACEOUS	GULFIAN	Tuscaloosa Fm.		
		LOWER		Absent	
	JURASSIC			Absent	
	TRIASSIC			Absent	
PALEOZOIC	PERMIAN			Absent	
	PENNSYLVANIAN	VIRGILIAN			CARBONIFEROUS
		MISSOURIAN			
		DESMOINESIAN			
		ATOKAN			
		MORROWAN			
	MISSISSIPPIAN	CHESTERIAN			
		VALMEYERAN		Includes Meramecan and Osagian of some classifications	
		KINDERHOOKIAN			
	DEVONIAN	UPPER			
		MIDDLE			
		LOWER			
	SILURIAN	CAYUGAN			
		NIAGARAN			
		ALEXANDRIAN			
	ORDOVICIAN	CINCINNATIAN			
		CHAMPLAINIAN			
		CANADIAN	Knox Dolomite Megagroup		
	CAMBRIAN	CROIXAN			
		MIDDLE		Currently undifferentiated	
		LOWER			
PRECAMBRIAN					

ISGS 1979

Figure 2. Stratigraphic column for the southern part of the Illinois Basin showing Paleozoic and Mesozoic systems, series, and rock units discussed in text.

North of the basin, most stratigraphic units thin toward the Canadian Shield and Wisconsin Arch, areas that furnished much of the early clastics present in the basin. Eastward. most of the units thin onto the Cincinnati Arch (see p. 106) or its predecessor, the Waverly Arch. The Cincinnati Arch furnished little sediment to the basin area, but during some periods it acted as a barrier that prevented coarser sediments off the Appalachian highlands from reaching the Illinois Basin area. Late in Ordovician time and late in Devonian time, the arch served principally as a hinge line between a thickening wedge of sediments to the east and a thinning wedge of fine clastics to the west.

To the west and northwest, the older Paleozoic units thin regularly toward the Nemaha and Sioux Arches, located along the eastern edges of Kansas, Nebraska, and South Dakota. Chesterian (late Mississippian) and Pennsylvanian rocks thin toward the Mississippi River Arch, indicating a tighter structural confinement at that time.

At the close of Canadian (early Ordovician) time, a broad arch rose between the Michigan and Illinois Basins (Atherton, 1971, p. 37). This early appearance of the Kankakee Arch was accompanied by tilting of the strata down to the south and widespread truncation of the Knox Megagroup, carbonates of Croixan-Canadian age. A period of solution and erosion after Knox deposition produced an irregular karstic surface with more than 100 meters of local relief from Indiana, across northern Illinois, and into eastern Iowa. At that time also, uplift on two major structures, the Ozark Dome to the southwest and the Nashville Dome to the southeast, further restricted the southern opening of the Illinois Basin.

Although the Ozark Dome stood as a positive feature when Croixan sediments were first deposited in the area, it had subsided and was covered by Cambrian and Canadian sediments. By the beginning of Champlainian (middle Ordovician) time, the Ozarks became a positive feature again; the central part of the dome probably did not subside enough to be covered by significant deposits until Valmeyeran (middle Mississippian) time and again in Pennsylvanian time. Throughout its long history, the Ozark Dome provided the source for only minor amounts of the sandstones and red shales that are present in the Illinois Basin.

The Nashville Dome is a southwesterly extension of the Cincinnati Arch that began to swell after Knox deposition. The dome furnished practically no sediments to the Illinois Basin area, and, in fact, it was commonly covered by shallow seas throughout most of the Paleozoic Era. The dome continued its differential swelling after Ordovician time, nevertheless, and effectively formed the southeastern boundary of the Illinois Basin.

At the close of the Mississippian Period, uplift and minor warping, especially along the La Salle Anticlinal Belt and Du Quoin Monocline, and downtilting to the south were followed by erosion that cut valleys as much as 100 meters deep across southern Illinois. The central part of southern Illinois sank more than the shelf areas to the west and east to form the Fairfield Basin. This basin is separated from the Western Shelf by the Du Quoin Monocline and from the Eastern Shelf by the La Salle Anticlinal Belt, an en echelon set of anticlines active before, during, and after deposition of the Pennsylvanian strata now present in the basin. Pennsylvanian sedimentation was followed by further downwarping in the Illinois Basin area and then a long interval of erosion. Sedimentation may have continued from Pennsylvanian into Permian time, but any Permian strata that may have been present have been removed by erosion. Coalification studies of Pennsylvanian-age coals indicate that this upper part of the Paleozoic column, which was lost to erosion, may have been 1,500 to 2,000 meters thick (Damberger, 1971, fig. 4).

A hiatus that represents more than 150 million years followed Pennsylvanian deposition in southernmost Illinois, so precise times of structural movements are difficult to establish; however, fragments of information can be assembled to reconstruct the tectonic history of the region during that interval. There is no evidence of restricted communication between the Illinois Basin and areas to the south until near the end of the Paleozoic Era. Active pressure from the south in the Ouachita belt heralded new forces in the area, forces that continued at least until early in Permian time and resulted in the structural closing of the Illinois Basin. Post-Pennsylvanian tectonism resulted in uplift of Hicks Dome and in complicated faulting that took place from Ste. Genevieve County, Missouri, to Grayson County, Kentucky. Faulting at that time represents renewed movement along a major zone of weakness that was established as a scarp or hinge line in Cambrian time.

Rocks of Pennsylvanian age are faulted along the Rough Creek Lineament, and clearly the major movements, including those resulting from compressional forces along the Shawneetown Fault portion, took place after the youngest Pennsylvanian rocks now present in the area were deposited. Igneous dikes and sills are present on both sides of the Rough Creek Lineament. These have been dated from Permian to mid-Cretaceous. Considering the tectonic activity of the Appalachian Revolution in the Appalachian and Ouachita belts during Pennsylvanian and Permian time, it seems reasonable to assume the time of major movements at the southern end of the Illinois Basin to have been near the end of the Paleozoic Era.

PASCOLA ARCH

The rise of the Pascola Arch, an uplift of about 4,000 meters, created the southern margin of the Illinois Basin. The arch effectively connected two older positive areas, the Ozark and Nashville Domes. Wilson (1939, p. 591-592) first postulated the presence of this structure on the basis of tectonic patterns in eastern United States. He proposed that the Cincinnati Arch (including the Nashville Dome) and the Ozark Dome formed a belt of "complementary arches" that was located on the foreland side of, and genetically related to, the Appalachian and Ouachita belts. He accepted a postulated connection between the Appalachians and the Ouachitas beneath the Mississippi Embayment sediments; he simply speculated that the Ozark Dome and Cincinnati Arch portions of his belt of complementary arches had also been connected by an unknown high "before it sagged and was covered with sediments of the Mississippi embayment."

Using subsurface records, Freeman (1953, pl. 5) showed that the sub-Cretaceous areal geology defined the general shape of the uplift. Grohskopf (1955, p. 25-26) recognized the structural high in the vicinity of Caruthersville and Pascola, Missouri, and applied the name Pascola Arch. Structure maps by McCracken and McCracken (1965) and McCracken (1971) show the arch to be separated from the Ozarks by a distinct saddle.

Earliest uplift along the arch may have taken place in Pennsylvanian time. H. R. Schwalb (personal communication, 1978) has observed that individual stratigraphic units in the Missourian Series (upper Pennsylvanian) thin southward into the Moorman Syncline. In addition, he noted more abundant red shales in Missourian strata of that area compared to farther north, and he suggested that the red color could indicate a climatic change brought about by elevation of the Pascola Arch (Schwalb, 1969, p. 16).

During the interval between Pennsylvanian and Gulfian (late Cretaceous) time, the arch was uplifted and beveled enough by erosion to expose Cambrian rocks at its crest. Broad, concentric belts of Ordovician, Silurian, and Devonian rocks were exposed around the Cambrian inlier. Apparently the Pascola Arch was a positive structural and topographic feature as late as early in Gulfian time when its uplifted Paleozoic rocks provided the source for coarse chert pebbles deposited in the Tuscaloosa Formation at that time (Marcher and Stearns, 1962, p. 1381). Shortly thereafter, the arch was eroded to a broad base level and subsided into the Mississippi Embayment where it was covered by a southward-thickening wedge of Cretaceous and younger sediments at least 900 meters thick over the crest.

The structural configuration of the Gulfian strata indicates that no significant differential movements have taken place along the axis of the arch since it was covered by those sediments. Currently, however, there is considerable seismic activity in the area of the intersection of the Pascola Arch with the axis of the Mississippi Embayment.

REFERENCES

ATHERTON, Elwood, 1971, Tectonic development of the Eastern Interior Region of the United States: Illinois State Geological Survey Illinois Petroleum 96, p. 29-43.

BOND, D. C., Elwood ATHERTON, H. M. BRISTOL, T. C. BUSCHBACH, D. L. STEVENSON, L. E. BACKER, T. A. DAWSON, E. C. FERNALLD, Howard SCHWALB, E. N. WILSON, A. T. STATLER, R. G. STEARNS, and J. H. BUEHNER, 1971, Possible future petroleum potential of region 9—Illinois Basin, Cincinnati Arch, and northern Mississippi Embayment, *in* Ira H. Cram [ed.], Future petroleum provinces of the United

States—Their geology and potential: American Association of Petroleum Geologists Memoir 15, v. 2, p. 1165-1218.
BUSCHBACH, T. C., 1977, Tectonic patterns and earthquakes in the central Mississippi Valley [summary]: American Nuclear Society Transactions, v. 27, p. 157-158.
DAMBERGER, H. H., 1971, Coalification pattern of the Illinois Basin: Economic Geology, v. 66, no. 3, p. 488-494.
ERVIN, C. P., and L. D. McGINNIS, 1975, Reelfoot Rift, reactivated precursor to the Mississippi Embayment: Geological Society of America Bulletin, v. 86, p. 1287-1295.
FREEMAN, L. B., 1953, Regional subsurface stratigraphy of the Cambrian and Ordovician in Kentucky and vicinity: Kentucky Geological Survey Bulletin 12, Series IX, 352 p.
GROHSKOPF, J. G., 1955, Subsurface geology of the Mississippi Embayment of southeast Missouri: Missouri Geological Survey and Water Resources, 2nd series, v. 37, 133 p.
KRAUSSE, Hans-Friedrich, and TREWORGY, Colin G., 1979, Major structures of the southern part of the Illinois Basin, *in* James E. Palmer and Russell R. Dutcher [eds.], Depositional and structural history of the Pennsylvanian System of the Illinois Basin: Ninth International Congress of Carboniferous Stratigraphy and Geology, Guidebook for field trip no. 9, part 2, p. 115-120.
MARCHER, M. V., and R. G. STEARNS, 1962, Tuscaloosa Formation in Tennessee: Geological Society of America Bulletin, v. 73, p. 1365-1386.
McCRACKEN, E., and M. H. McCRACKEN, 1965, Subsurface maps of the lower Ordovician (Canadian Series) of Missouri: Missouri Geological Survey and Water Resources, 6 sheets.
McCRACKEN, M. H., 1971, Structural features of Missouri: Missouri Geological Survey and Water Resources Report of Investigations 49, 99 p.
SCHWALB, H. R., 1969, Paleozoic geology of the Jackson Purchase Region, Kentucky: Kentucky Geological Survey Report of Investigations 10, Series X, 40 p.
WILSON, C. W., Jr., 1939, Probable connection of the Nashville and Ozark Domes by a complementary arch: Journal of Geology, v. 47, p. 583-597.

Major structures of the southern part of the Illinois Basin

Hans-Friedrich Krausse and Colin G. Treworgy

INTRODUCTION

The Illinois Basin is a gently downwarped structural basin, bounded by a series of uplifts, arches, and domes (see p. 106). Except for the La Salle Anticlinal Belt, the northern two-thirds of the basin is structurally simple. The southern part of the Illinois Basin, in contrast, has a variety of structural features.

GEOLOGIC SETTING

The strata of the Illinois Basin dip gently toward two major depressions, the Fairfield Basin in southeastern Illinois and the Moorman Syncline in western Kentucky. These two structures are separated by the uplifted zone of the Rough Creek Lineament and are surrounded on all sides by broad, shallow shelf areas (see p. 106). Within the Illinois Basin, Paleozoic sediments that are more than 4 kilometers thick have accumulated over the Precambrian basement (Buschbach and Atherton, 1979). Although locally within a downthrown faultblock Permian strata have been found (Douglass, 1979), most of the youngest bedrock strata within the basin are of Pennsylvanian age. Sediments of the Mississippi Embayment, Upper Cretaceous and Tertiary in age, cover the southernmost part of the basin. Glacial deposits that locally exceed 120 meters in thickness overlie the Paleozoic strata in most areas.

The prominent structural belts and zones of the Illinois Basin can be classified as trending in four main directions: east to west; north to south; northeast to southwest; and northwest to southeast (see p. 106). Locally, individual folds and faults may diverge or curve away slightly from the four main directions; they may occur elsewhere in a pinnate or en echelon pattern at an oblique angle to the general trend of the structural belts (fig. 1).

The major upwarping structures within the basin—the La Salle Anticlinal Belt; the Clay City, Louden, and Salem Anticlines; and the Du Quoin Monocline—trend north to south. The most prominent rupturing structures—the Shawneetown-Rough Creek and Cottage Grove Fault Systems—strike east to west (see p. 106). Other fault systems trend northeast to southwest or northwest to southeast.

A number of these structures appear to converge on the deepest part of the Illinois Basin (Precambrian basement, more than 4,000 meters below sea level), located in southeastern Illinois: from the east, the Shawneetown-Rough Creek Fault System and the Moorman-Eagle Valley Syncline; from the north and northeast, the Wabash Valley Fault System; from the west, the Cottage Grove Fault System; from the southwest, the faults of the Fluorspar Area Fault Complex; and from the southeast, the Kuttawa Arch. Further research is needed to determine the significance of structural convergence to regional tectonics and genetics and whether these structures intersect.

STRUCTURES AND FAULT SYSTEMS

The following brief descriptions of the major structural features in the southern part of the Illinois Basin are drawn mostly from previous publications. Although most of these structures have been known and mapped for many years, controversy remains concerning their origin, significance and interrelationships. Much of the structural development is younger than the Pennsylvanian Period but predates the Cretaceous Period, although some structuring, particularly downwarping of the Moorman Syncline and upwarping of anticlines, occurred earlier during the Paleozoic Era.

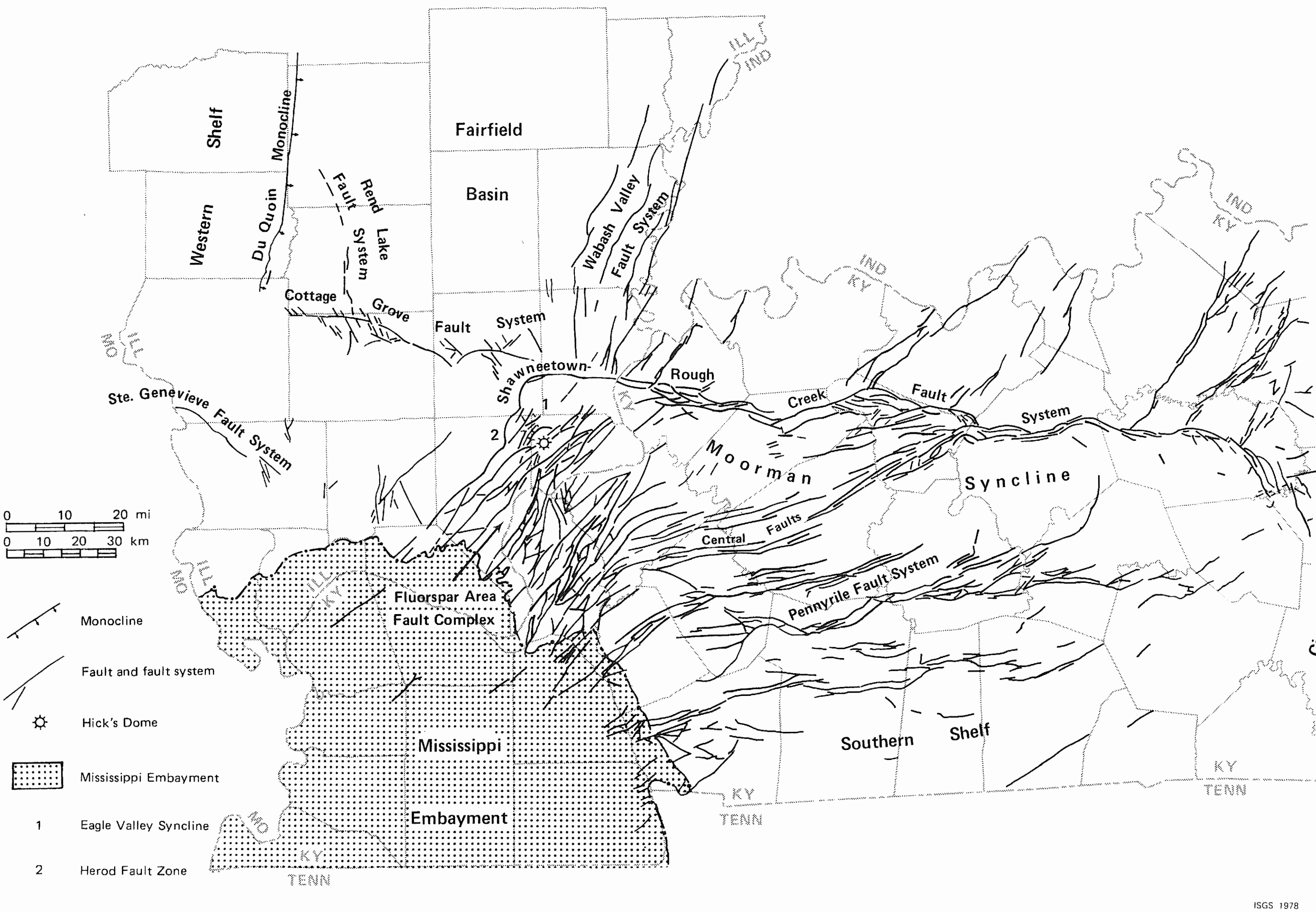

Figure 1. Structural features of the southern part of the Illinois Basin. (Compiled from Root, 1928; Stonehouse and Wilson, 1955; Heyl and Brock, 1961; Baxter et al., 1963, 1965, 1967; Willman and others, 1967; Sutton, 1971; Keys, 1978; Schwalb and Potter, 1978; Bristol and Treworgy, in preparation; and W. John Nelson, personal communication.)

East-to-west-trending structures

The most significant strike of structural features in the southern part of the basin is east to west, which is the trend of the Rough Creek Lineament. The Rough Creek Lineament includes the Rough Creek Fault System in Kentucky and the Shawneetown Fault Zone and the Cottage Grove Fault System in Illinois (fig. 1). Heyl (1972) has mapped the Rough Creek Lineament as part of the 38th Parallel Lineament, which is defined by the apparent alignment of major tectonic structures that extend from Virginia to the Rocky Mountains in Colorado.

Shawneetown-Rough Creek Fault System. The Shawneetown-Rough Creek Fault System is an east-to-west-trending zone of numerous, mostly high-angle faults that display normal, reverse, and strike-slip displacement. The Rough Creek Fault System extends for more than 200 kilometers from the west flank of the Cincinnati Arch in Kentucky to Shawneetown, Illinois, where it is known as the Shawneetown Fault Zone. The Shawneetown Fault Zone continues westward from the state line about 25 kilometers and then appears to swing southward and join the Fluorspar Area Fault Complex.

In some areas the fault system is represented by a single high-angle reverse fault and, in other areas, by a complex zone of block faulting. Dips range from 25 degrees to near vertical, but are predominantly at high angles. Local structural relief of as much as 1,200 meters has been reported (Smith and Palmer, 1974). Pennsylvanian strata at the Shawneetown Fault Zone are downthrown to the north; strata along the Rough Creek Fault System, however, do not appear to have any consistent direction of throw. Numerous scissor faults and small sliver-shaped grabens have been recognized. These characteristics, combined with the lack of wide regional displacement on either side of the fault, have led to the suggestion that the system is a result of strike-slip movement over a fracture zone in the Precambrian basement (Clark and Royds, 1948; Heyl, 1972). Others have discounted the possibility of extensive strike-slip movement and suggest that the faulting and thrusting is the result of major compressional forces from the south (Rehn, 1968; Sutton, 1971; Smith and Palmer, 1974). Movements along the fault system occurred as early as Middle Cambrian (Schwalb, 1978, 1979; Krausse, Nelson, and Schwalb, 1979) and during the Devonian (Sutton, 1971), and had an overall trend down to the south; however, the major throw along the faults happened after Pennsylvanian, probably after early Permian time, and had an inverse overall displacement down to the north.

The Cottage Grove Fault System. The Cottage Grove Fault System is a complex system of normal, reverse, strike-slip, and bedding-plane faults. The fault system has been mapped from numerous drill holes and from exposures in many underground coal mines. The zone of faulting is locally more than 15 kilometers wide and trends roughly east to west. The maximum vertical displacement inferred from drill-hole data is 73 meters; the largest vertical throw observed in an underground mine is 28 meters. The eastern end of the Cottage Grove Fault System is not well recognized; it appears to die out as it approaches the Shawneetown Fault Zone near Equality, Gallatin County. The Cottage Grove Fault System extends westward for more than 75 kilometers to an area 8 kilometers south of Du Quoin. Although there is little direct evidence, Heyl and Brock (1961) stated that it may continue westward and intersect the Ste. Genevieve Fault near Chester, Illinois.

The Cottage Grove Fault System consists of four major structural elements (fig. 1): (1) An east-to-west-trending master fault, which may divide into two or more major faults that split and rejoin along strike. The master fault curves slightly toward west-northwest and appears to be discontinuous in eastern Williamson County. The existence of this fault in Jackson County, west of the Du Quoin Monocline, has not been proven, although locally some faults have been mapped in its westerly projection (fig. 1). (2) Subsidiary faults, which branch off both sides of the master fault. These are arranged in an en echelon or pinnate pattern to the master fault and most commonly strike southeast to northwest. Both normal and reverse faults and, in some cases, scissoring of faults have been recognized. Some faults show a component of strike-slip movement. The subsidiary faults are the most complex. Most faults are steeply inclined, but small low-angle thrust and bedding plane faults also have been mapped. (3) Prominent anticlines and synclines, which accompany the fault system within the zone of faulting. The folds are asymmetrical, and some have more than 30 meters of closure in Pennsylvanian-age strata. Dips of the limbs seldom exceed 20 degrees; dips of 10 to 15 degrees are quite common. The fold patterns are not very consistent; however, they generally trend at an oblique angle to the fault system, in many places east-northeast to west-southwest. (4) Igneous dikes, which have been found at the eastern part of the fault system. They apparently are associated with the northwest-to-southeast-trending subsidiary faults, or may be associated with the dikes in the Fluorspar Area Fault Complex to the southeast. Some dikes are several kilometers long and, in a few places, as much as 20 meters thick (Cady, 1919; Clegg, 1955, 1956).

From the distribution, orientation, and relative movements of the various structural elements along and within the Cottage Grove Fault System, it is inferred that the fault system is due to right-lateral wrench faulting. There are indications that the Cottage Grove Fault System was active from Devonian time throughout the remainder of the Paleozoic.

Moorman-Eagle Valley Syncline. The Moorman-Eagle Valley Syncline is an elongate depression that lies south of and extends parallel to the Rough Creek Lineament. On the south the syncline is bordered by the Pennyrile Fault System in Kentucky and by the Fluorspar Area Fault Complex in Illinois. The Pennyrile Fault System (Schwalb, 1974; Schwalb and Potter, 1978), formerly called the Southern Faults (Mullins, 1968), is a complex series of east-to-west-trending block faults (fig. 1). The Fluorspar Area Fault Complex is a district of northeast-to-southwest striking horst and graben structures, which are described later.

The Moorman-Eagle Valley Syncline trends east to west, plunges from the Cincinnati Arch westward, and plunges and broadens from the Eagle Valley eastward to its deepest part in Kentucky, where it is filled with more than 1,000 meters of Pennsylvanian-age sediments. The syncline is an asymmetrical structure with a gently inclined south flank (dips about 5 degrees) and a more steeply dipping north flank (dips locally as much as 30 to 40 degrees) along the Rough Creek Lineament. The major part of the structure is in Kentucky and is called the Moorman Syncline. The westernmost part in southern Illinois is known as the Eagle Valley Syncline; there, toward the west, the syncline parallels the Shawneetown Fault Zone and curves southwestward until it merges with complexly faulted blocks of the Herod Fault Zone of the Fluorspar Area Fault Complex (fig. 1).

North-to-south-trending structures and faults.

North-to-south-trending structures and faults in the southern part of the Illinois Basin are fewer than east-to-west-trending structures. The Du Quoin Monocline and the Rend Lake Fault System are the two major structural features with north-to-south orientation (fig. 1). The major north-to-south-trending anticlines of the Illinois Basin are located farther to the north (see p. 106) and are not discussed in this paper.

The Rend Lake Fault System. The Rend Lake Fault System is a set of parallel faults in southern Illinois (Krausse and Keys, 1977). It is chiefly known from exposures in underground mines in the Herrin (No. 6) Coal. The Rend Lake Fault System apparently branches from the east-to-west-trending Cottage Grove Fault System near West Frankfort and extends northward for at least 40 kilometers. Along strike, the fault system varies in width, in number of faults, and in magnitude of displacement along individual faults. Generally the faults are normal and dip 45 to 90 degrees either to the west or to the east. The vertical displacement of individual faults varies to a known maximum of 18 meters. It has been observed in coal mines that faults diminish in throw along strike and dip until they become minor faults producing little vertical displacement at the top of the coal seam; they branch downward into a cluster of densely spaced extension fractures in an en echelon or pinnate pattern yielding little or no displacement. Major faults commonly occur in an en echelon pattern. Where one fault decreases and dies out, another appears. Large faults are accompanied by minor synthetic and antithetic faults that contribute to the increase of lateral extension rather than to a vertical displacement. Few reverse faults have been recognized among the subsidiary minor faults.

The Rend Lake Fault System is the expression of a localized zone of east-to-west extension. It is extremely long and linear in contrast to its slight vertical displacement. Because of the lack of post-Pennsylvanian strata, its age cannot be determined accurately. The youngest stratum observed to be penetrated by the faults is the Lawson Shale Member. The location of a pre-Pleistocene river valley follows the trend of the Rend Lake Fault System, suggesting that faulting affected all existing bedrock of the Pennsylvanian System (Keys, 1978).

The Du Quoin Monocline. One of the major intrabasin structures of the Illinois Basin is the Du Quoin Monocline, which trends roughly north to south and faces eastward. It is a true hinge line and separates the Fairfield Basin from the Western Shelf area (fig. 1).

Pennsylvanian strata west of the monocline on the Western Shelf are relatively thin and almost horizontal (dip 1 to 5 meters per kilometer) and much thicker east of the monocline, where they dip gently (3 to 10 meters per kilometer) toward the center of the Fairfield Basin. On the monocline the inclination is considerably greater and averages 50 to 60 meters per kilometer.

The eastern flank of the Du Quoin Monocline is locally accompanied by minor faults of late Pennsylvanian age or younger. Most are high-angle normal faults with known displacement as much as 13 meters.

The major structural movements forming the monocline occurred after the Chesterian Epoch. Significant movement took place during the Pennsylvanian Period.

Northwest-to-southeast-trending structures

Only one major fault within the southern part of the Illinois Basin, the Ste. Genevieve Fault Zone, strikes northwest to southeast. All other northwest-to-southeast-trending faults are either subsidiary faults that branch off the Rough Creek Lineament (as in the Cottage Grove Fault System of Illinois, for example) or secondary tension faults that occur as cross faults within the northeast-to-southwest-trending fault systems of the graben structures in the Fluorspar Area Fault Complex.

Ste. Genevieve Fault Zone. The Ste. Genevieve Fault Zone is a northwest-to-southeast-trending structure separating the southwestern edge of the Illinois Basin from the Ozark Dome. The fault zone has been mapped in Illinois for a distance of only 25 kilometers; however, it extends northwestward into Missouri for more than 120 kilometers. Heyl et al. (1965) suggested that a concealed extension of the fault continues southwestward through Illinois as far as northern Tennessee. The Ste. Genevieve Fault Zone consists of high-angle normal and reverse faults; the southwestern block is upthrown. Maximum relative displacement is 900 meters. Two periods of faulting are recognized—post-Devonian and post-Mississippian or post-Pennsylvanian (McCracken, 1971).

Hicks Dome and the Kuttawa Arch. Structural events that created a broad arch in the complexly faulted area of Hicks Dome and the Kuttawa Arch (Baxter, Desborough, and Shaw, 1967) are believed to have begun late in Pennsylvanian or in Permian time with the upwelling of magma (Heyl and Brock, 1961; Heyl et al., 1965; Baxter, Bradbury, and Hester, 1973). This north-northwest- to south-southeast-trending arch plunges gently southward from Hicks Dome in southeastern Illinois into southwestern Kentucky. The arch has an average structural relief of 600 meters and a maximum structural relief of 1,200 meters at Hicks Dome (Hook, 1974). Formation of the arch created a series of northwest-to-southeast-trending faults and fractures, many of which contain igneous dikes. Zartman et al.

(1967) have dated these igneous dikes as early Permian in age.

Hicks Dome, located at the northern end of the arch, is believed to be a collapsed explosion structure (Brown, Emery, and Meyr, 1954) in which Devonian strata have been lifted more than 1,200 meters and are exposed at the surface. The dome, about 4 kilometers in diameter, is complexly faulted and is intruded with numerous igneous dikes. It contains intrusive breccias (Baxter, Bradbury, and Hester, 1973). Tension associated with the uplift of the dome before collapse created a pattern of radial and arcuate faults around the dome.

Northeast-to-southwest-trending structures

Probably less extensive along strike than the major east-to-west-trending faults are the densely spaced faults that strike northeast to southwest. The most prominent set is the Fluorspar Area Fault Complex in southeastern Illinois and western Kentucky, which is restricted to the area south of the Rough Creek Lineament. Adjacent to but north of the Rough Creek Lineament, the Wabash Valley Fault System runs north-northeast to south-southwest, roughly parallel to the Wabash River. Both systems die out as they approach the Rough Creek Lineament and are not known to intersect it.

Fluorspar Area Fault Complex. Subsequent to arching, the fluorspar area was heavily faulted by northeast-to-southwest-trending faults, which created a complex zone of horsts and grabens. Heyl (1961) suggested that these faults formed in response to movement along the Shawneetown Fault. The faults extend southwestward from the southern edge of the Moorman-Eagle Valley Syncline and are covered by Cretaceous and Tertiary deposits of the Mississippi Embayment in extreme southern Illinois and western Kentucky (fig. 1). No evidence has been established to consider the faults of the Fluorspar Area Fault Complex and the Wabash Valley Fault System as a northeastward extension of the New Madrid Fault Zone, as Heyl and Brock (1961) and Heyl (1972) have suggested.

Faulting is mostly normal; a few faults indicate strike-slip movement. Dips average 65 to 75 degrees, but vary from 45 to 90 degrees. There is no systematic direction of throw. Displacement along individual faults varies from a few meters to a maximum of 450 meters. Total structural relief between horsts and grabens reaches a maximum of 900 meters.

Mineralization occurred after all the major faulting, probably some time during the Mesozoic (Baxter, Bradbury, and Hester, 1973). Important vein deposits of fluorite, sphalerite, and other minerals are found along the fault planes; more than 75 percent of the fluorspar produced in the United States has come from this area.

Wabash Valley Fault System. The Wabash Valley Fault System also is a north-northeast to south-southwest-trending system of faults in Illinois and Indiana that extends from just north of the Shawneetown Fault Zone northeastward for more than 100 kilometers (fig. 1). Electric logs from the many oil tests in the area have permitted fairly detailed mapping of the fault system. There are no known surface exposures of faulting; however, faults have been observed in underground coal mines.

The fault system is characterized by parallel, high-angle normal faults that bound horsts and grabens. Dips of the faults range from 50 to 85 degrees. Maximum known displacement in the fault system is about 135 meters. Faulting in the Wabash Valley can only be dated as post-Pennsylvanian, pre-Pleistocene. The faults of the Wabash Valley Fault System do not appear to intersect or cross the Shawneetown Fault Zone, and they differ in nature from the faults of the Fluorspar Area Fault Complex in the south (Bristol and Treworgy, in preparation).

CONCLUSIONS

The Illinois Basin has been a subsiding basinal feature; sediments were deposited during most of the Paleozoic time. The basin was generally open to the south and otherwise restricted by its bordering uplifts and arches. The basin as it is today, however, was finally formed by a structural evolution, by faulting and uplifting of its southern rim.

Deformational features show preferred orientation in four principal directions. Anticlinal belts dominantly trend north to south. The most prominent fault systems strike east to west, whereas two less extensive, yet major, fault systems are directed northeast to southwest. Accessory, mainly subsidiary, faults to major systems penetrate the deformed strata northwest-to-southeast. Much of the deformation occurred probably during the late Paleozoic Era, possibly along preestablished zones of weakness in the basement.

REFERENCES

BAXTER, J. W., J. C. BRADBURY, and N. C. HESTER, 1973, A geologic excursion to fluorspar mines in Hardin and Pope Counties, Illinois: Illinois State Geological Survey Guidebook Series 11, 30 p.

BAXTER, J. W., and G. A. DESBOROUGH, 1965, Areal geology of the Illinois fluorspar district, part 2: Illinois State Geological Survey Circular 385, 40 p.

BAXTER, J. W., G. A. DESBOROUGH, and C. W. SHAW, 1967, Areal geology of the Illinois fluorspar district, part 3: Illinois State Geological Survey Circular 413, 41 p.

BAXTER, J. W., P. E. POTTER, and F. L. DOYLE, 1963, Areal geology of the Illinois fluorspar district, part 1: Illinois State Geological Survey Circular 342, 44 p.

BRISTOL, H. M., and T. C. BUSCHBACH, 1971, Structural features of the Eastern Interior Region of the United States, *in* D. C. Bond [chr.], Background materials for symposium on future petroleum potential of NPC region 9: Illinois State Geological Survey Illinois Petroleum 96, p. 21-28.

BRISTOL, H. M., and J. D. TREWORGY, in preparation, The Wabash Valley fault system in Illinois: Illinois State Geological Survey Circular 509.

BROWN, J. S., J. A. EMERY, and P. A. MEYR, Jr., 1954, Explosion pipe test well on Hicks Dome, Hardin County, Illinois: Economic Geology, v. 49, no. 8, p. 891-902.

BUSCHBACH, T. C., and Elwood ATHERTON, 1979, History of the structural uplift of the southern margin of the Illinois Basin, *in* James E. Palmer and Russell R. Dutcher [eds.], Depositional and structural history of the Pennsylvanian System of the Illinois Basin: Ninth International Congress of Carboniferous Stratigraphy and Geology, Guidebook for field trip no. 9, part 2, p. 112-115.

BUTTS, C., 1925, Geology and mineral resources of the Equality-

Shawneetown area: Illinois State Geological Survey Bulletin 47, 76 p.

CADY, G. H., 1919, Coal resources of district V: Illinois State Geological Survey Cooperative Mining Series Bulletin 19, 135 p.

CLARK, S. K., and J. S. ROYDS, 1948, Structural trends and fault systems in Eastern Interior Basin: Association of American Petroleum Geologists Bulletin, v. 32, no. 9, p. 1728-1749.

CLEGG, K. E., 1955, Metamorphism of coal by peridotite dikes in southern Illinois, Illinois State Geological Survey Report of Investigations 178, 18 p.

CLEGG, K. E., 1956, Igneous intrusive rocks in Illinois and their economic significance: Illinois State Geological Survey Report of Investigations 197, 19 p.

CLEGG, K. E., 1970, The La Salle Anticlinal Belt in Illinois: Illinois State Geological Survey Guidebook Series 8, p. 106-110.

DOUGLASS, R. C., The distribution of fusulinids and their correlation between the Illinois Basin and the Appalachian Basin, *in* James E. Palmer and Russell R. Dutcher [eds.], Depositional and structural history of the Pennsylvanian System of the Illinois Basin: Ninth International Congress of Carboniferous Stratigraphy and Geology, Guidebook for field trip no. 9, part 2, p. 15-20.

HEYL, A. V., 1972, The 38th Parallel Lineament and its relationship to ore deposits: Economic Geology, v. 67, p. 879-894.

HEYL, A. V., and M. R. BROCK, 1961, Structural framework of the Illinois-Kentucky mining district and its relation to mineral deposits: United States Geological Survey Professional Paper 424-D, p. 3-6.

HEYL, A. V., M. R. BROCK, J. L. JOLLY, and C. E. WELLS, 1965, Regional structure of the southeast Missouri and Illinois-Kentucky mineral districts: United States Geological Survey Bulletin 1202-B, 20 p.

HOOK, J. W., 1974, Structure of the fault systems of the Illinois-Kentucky fluorspar district, *in* A symposium on the geology of fluorspar: Kentucky Geological Survey Special Publication 22, p. 77-86.

KEYS, J. N., 1978, An analysis of the Rend Lake Fault System in southern Illinois. Unpublished master's thesis, University of Illinois, Urbana, Illinois, 59 p.

KRAUSSE, H.-F., and J. N. KEYS, 1977, The Rend Lake fault system and accompanying deformational features observed in the Herrin (No. 6) Coal Member [abstract]: Geological Society of America North-Central Section, April 1977, p. 617.

KRAUSSE, H.-F., W. J. NELSON, and H. R. SCHWALB, 1979, Rough Creek Fault exposure—Green River Parkway—Mile Post 53, *in* James E. Palmer and Russell R. Dutcher [eds.], Depositional and structural history of the Pennsylvanian System of the Illinois Basin: Ninth International Congress of Carboniferous Stratigraphy and Geology, Guidebook for field trip no. 9, part 1, p. 15-20.

McCRACKEN, M. H., 1971, Structural features of Missouri: Missouri Geological Survey and Water Resources Report of Investigations 49, 99 p.

MULLINS, A. T., 1968, Pennsylvanian structure of western Kentucky, *in* Proceedings of the technical sessions: Kentucky Oil and Gas Association thirtieth and thirty-first annual meetings, 1966 and 1967: Kentucky Geological Survey Special Publication 15, p. 81-86.

PALMER, James E., 1969, Fault scarp exposures in the Saint Charles and Nortonville quadrangles, western Kentucky: United States Geological Survey Professional Paper 650-C, p. 75-78.

REHN, E. E., 1968, Petroleum potential of the Rough Creek tectonic element in Kentucky, *in* Proceedings of the technical sessions: Kentucky Oil and Gas Association thirtieth and thirty-first annual meetings, 1966 and 1967: Kentucky Geological Survey Special Publication 15, p. 12-25.

ROOT, T. B., 1928, The oil and gas resources of the Ava-Campbell Hill area: Illinois State Geological Survey Report of Investigations 16, 27 p.

SCHWALB, H. R., 1974, Pennyrile fault system, *in* R. W. Davis, R. O. Plebuch, and H. M. Whiteman, Hydrology and geology of deep sandstone aquifers of Pennsylvanian age in part of the western coal field region, Kentucky: Kentucky Geological Survey Series X, Report of Investigations 15, 26 p.

SCHWALB, H. R., 1978, Paleozoic geology of the New Madrid area, Annual progress report—fiscal year 1978, contract no. NRC-04-76-321, *in* T. C. Buschbach, New Madrid seismotectonic study—Activities during fiscal year 1978: Illinois State Geological Survey, prepared for the Division of Reactor Safety Research Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, contract no. NRC 04-76-204.

SCHWALB, H. R., 1979, Stratigraphy and structural history of the Moorman Syncline (Rough Creek Graben) in western Kentucky [abstract]: Geological Society of America, South-Central Section.

SCHWALB, H. R., and POTTER, P. E., 1978, Structure and isopach map of the New Albany-Chattanooga-Ohio Shale (Devonian and Mississippian) in Kentucky: Western sheet: Kentucky Geological Survey Series X.

SMITH, A. E., and J. E. PALMER, 1974, More testing needed in thrust faults of western Kentucky's Rough Creek Fault System: Oil and Gas Journal, July 8, p. 133-138.

STONEHOUSE, H. B., and G. M. WILSON, 1955, Faults and other structures in southern Illinois—A compilation: Illinois State Geological Survey Circular 195, 4 p.

SUTTON, D. G., 1971, Exploration potential of the Rough Creek Fault System, *in* Proceedings of symposium on future petroleum potential of NPC region 9: Illinois State Geological Survey Illinois Petroleum 95, p. 69-78.

SWANN, D. H., 1968, A summary of geologic history of the Illinois Basin, *in* Geology and petroleum production of the Illinois Basin, A symposium: Cooperative publication of the Illinois, Indiana, and Kentucky Geological Societies, p. 3-21.

TRACE, R. D., 1974, Illinois-Kentucky fluorspar district, *in* A symposium on the geology of fluorspar: Kentucky Geological Survey Special Publication 22, p. 58-76.

WILLMAN, H. B., and others, 1967, Geologic map of Illinois: Illinois State Geological Survey, 1:500,000.

WILLMAN, H. B., Elwood ATHERTON, T. C. BUSCHBACH, Charles COLLINSON, John C. FRYE, M. E. HOPKINS, Jerry A. LINEBACK, and Jack A. SIMON, 1975, Handbook of Illinois stratigraphy: Illinois State Geological Survey Bulletin 95, 261 p.

ZARTMAN, R. E., M. R. BROCK, A. V. HEYL, and H. H. THOMAS, 1967, K-Ar and Rb-Sr ages of some alkalic intrusives from central and eastern United States: American Journal of Science, v. 265, p. 848-870.

The influence of the Carboniferous rocks on the topography of the Illinois Basin

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INTRODUCTION

The field conference of the Ninth International Congress of Carboniferous Stratigraphy and Geology will traverse the Illinois Basin and will focus especially on Carboniferous features. This paper elucidates the nature of the modern topography along the route of the field trip, especially as it is influenced by the Carboniferous bedrock. The Pennsylvanian outcrop in the southern part of the basin is particularly emphasized.

The topography of the Illinois Basin is clearly divisible into a northern plains area of low relief and a southern and southeastern, more hilly area (fig. 1). The plains area, a part of the Central Lowlands Physiographic Province (Fenneman, 1938), is characterized by glacially derived deposits that cover a relatively uniform bedrock dominated by shales. The hilly area, part of the Low Interior Plateaus, is characterized by a topography controlled by differential erosion of the bedrock. The prominent upland ridges are underlain by massive sandstones, whereas the intervening lowlands are dominated by shales. Many of the lowlands, especially along the major rivers, are nearly flat and were formed by Pleistocene deposition of valley trains and backwater alluvium.

GEOLOGIC SETTING

The Illinois Basin is a structural feature that is topographically distinctive only in its southern part. This basin of Paleozoic sedimentary rocks developed at the southern margin of the covered North American Craton. It lies east of the Mississippi River, south of Lake Michigan, north of the Mississippi Embayment, and north and west of the Nashville-Cincinnati positive trend.

The bedrock throughout the central part of the basin is of Pennsylvanian age and, in common usage, marks the Illinois "coal" basin. The Mississippian outcrop surrounds the Pennsylvanian except at the north. In that area, Mississippian rocks were eroded during Caseyville (Pottsville) time. Subsequently, Pennsylvanian sedimentation transgressed this erosional surface (fig. 2). Older Paleozoic rocks crop out along the bounding structural axes.

From the viewpoint of geomorphology, the Carboniferous rocks might be divided stratigraphically into five parts (fig. 2):

1. Lower Mississippian on the eastern side of the basin are largely fine-grained clastics.
2. Mid-Mississippian limestones occur in an arc from south-central Indiana southward around the Kentucky Pennyroyal region, across southern Illinois, and northward along the Mississippi Valley to Burlington, Iowa.
3. Upper Mississippian (Chesterian) alternating cycles of sandstone, shale, and limestone extend along the same arc but terminate in the St. Louis area.
4. Lower Pennsylvanian clastics containing massive sandstone units extend from the Mansfield area in Indiana, around the western Kentucky coal fields, and across southern Illinois to the Mississippi Valley at Chester, Illinois.
5. Mid- and upper-Pennsylvanian cyclothemic section, which contains the commercial coal beds and is dominated by shale, forms the bedrock throughout the central basin.

Note especially the absence of resistant clastic rocks of upper Mississippian (Chesterian) and lower Pennsylvanian (Caseyville or Pottsville) age across the northern part of the basin. This absence has had a profound effect on the erosional history of the region and ultimately has resulted in a plains topography uninterrupted by a hilly region such as that which marks the southern rim of the basin.

PHYSIOGRAPHIC DIVISIONS

Central Lowlands

The Central Lowlands Province extending across northern Illinois and Indiana has a glacial depositional topography (fig. 1). When first settled, it was a vast grassland prairie. Glaciers from three or more epochs contributed to the deposits over the bedrock, but the surficial deposits are of Wisconsinan age. The plain is marked by a series of morainal ridges separated by ground moraine, old lake beds, and outwash plains and sluiceways. Champaign-Urbana is built on one of the morainal ridges some 40 miles north of the terminal Shelbyville moraine. The Shelbyville moraine overlooks the considerably more dissected surface of the Southern Till Plains Section, which originally was formed by deposition from the Illinoian glacier (Leighton, Ekblaw, and Horberg, 1948). This latter till sheet extends to the boundary of the Interior Low Plateaus Province.

The plains slope southward from the Great Lakes area, where the elevation is on the order of 240 meters above sea level, to the junction with the Low Plateaus, where the elevation is more than 120 meters above sea level. The bedrock generally slopes southward and is buried to a greater depth beneath the Wisconsinan till than beneath the Illinoian till surface. In some areas, bedrock hills control the modern topography, especially in the southeastern Mt. Vernon Hill Country where the till is only a thin veneer.

Figure 1. Physiographic diagram of midwestern United States showing major topographic features. The boundary of the Pennsylvanian outcrop and margin of glaciation are also shown. (After Raisz, 1954.)

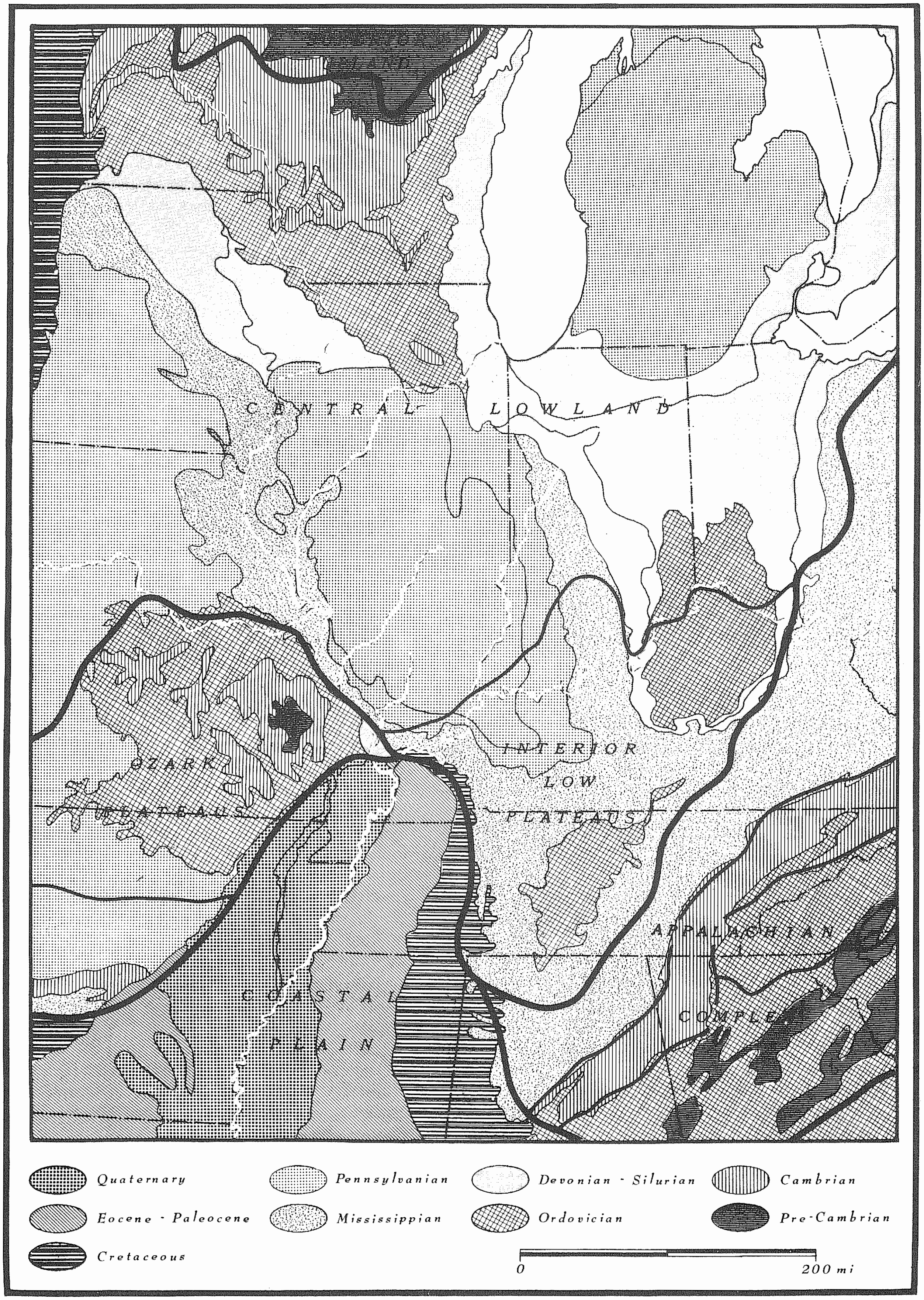

Figure 2. Geology of the midwest.

The absence of Chesterian and lower Pennsylvanian massive sandstones means that no resistant rock interrupts that slope across the north. Therefore, the Pleistocene continental glaciers flowed downhill. They encountered the massive Caseyville ridge in south-central Indiana. The Illinoian glaciers reached the southernmost limit of continental glaciation in North America along the axis of the Illinois Basin, a few miles south of Carbondale and Marion, Illinois. Here they encountered the Shawnee Hills.

The plains section in the Wabash Valley is characterized by extensive outwash terraces of sand and gravel derived from Wisconsinan meltwaters. These deposits are more than 30 meters thick along the thalweg. Toward the Ohio River junction, the lowlands are very broad because of backwater fill along the tributaries.

Island hills of bedrock (Fidlar, 1948) stand above the Pleistocene fill in many places; this indicates that the bedrock topography is considerably rougher than the present surface. The outcrops are especially prominent along the lower course of the White River in Indiana and near Harrisburg, Illinois.

No prominent bluffs mark the valley margins of the Wabash. In many places the overlapping contact of the alluvium with the gentle slope of the upland is veneered by a cover of loess. In contrast, the valleys in the low plateaus are commonly trenchlike, and the uplands are sharply set off from the valleys. We will observe this especially at Cannelton on the Ohio and west of Carbondale on the Mississippi.

The principal commercial coal seams lie beneath the plains. Thus, the ground surface is relatively level. There may be greater relief on the buried bedrock topography than on the surface topography. Strip mines of the No. 5 and No. 6 coals are within sight of the plateau province across the south end of the basin.

Interior Low Plateaus

The Interior Low Plateaus are marked by long parallel cuestas separated by lowlands (fig. 1). Erosional beveling of the structure resulted in alternating outcropping of rocks of differing resistance. Around the southern arc of the basin, the lower Pennsylvanian and Chesterian stratigraphic section is thicker and coarser than to the north and west. Thus, from the center of the basin, the elevation increases gradually, up the backslope of the Mansfield-Caseyville cuesta to the crest of a bold escarpment facing outward. The escarpment is commonly compound; erosion is controlled locally by the particular succession of resistant and weak rocks.

The lower Pennsylvanian-Chesterian outcrop forms a hill land called the Crawford Upland in Indiana and Shawnee Hills in Illinois. These are scenic areas with interesting geologic and vegetative features, including natural forestation, but are not favorable to agriculture. Most of the second day of the field trip will be spent studying the coarse-grained rocks of this province in Indiana and Kentucky.

The famous Dripping Springs Escarpment near Mammoth Cave, Kentucky, is formed by massive lower Chesterian sandstones. It overlooks the karst plain of massive mid-Mississippian limestones. The prominent ridges, reflecting the resistance of the lower Pennsylvanian and the Chesterian (upper Mississippian) sandstones, extend unbroken for many miles across country; however, major streams on the east and southeast transect the cuestas. The White River in Indiana, the Ohio River, and the Nolin, Green, and Barren Rivers in Kentucky all form prominent narrow water gaps marked by high cliffs.

The Wabash and Mississippi Rivers do not cross the cuestas. The Wabash enters the basin from the northeast across glacial sediments, in the region where the Carboniferous sandstones are minor stratigraphic elements. The Mississippi River on the western side of the basin follows the Mississippi River Arch and the margin of the Ozarks, without crossing the outcrop of the resistant sandstones.

All of this drainage is centripetal toward the southwestern corner of the Illinois Basin and the northern extremity of the Mississippi Embayment of the Coastal Plain (fig. 1). In addition to the rivers already mentioned, the Cumberland and Tennessee Rivers draining the western side of the southern Appalachians also turn northward to join the Ohio-Mississippi drainage near their junction at the head of the embayment. Physiographers have speculated about the drainage history that produced this focus 600 miles north of the Gulf of Mexico, but no acceptable explanation has been proposed. Certainly there was a long succession of structural warpings and superpositions, as indicated from covering deposits, but the story is sketchy indeed.

Concentrically around the resistant cuestas, a thick mid-Mississippian limestone sequence forms broad karsted lowlands in Indiana and Kentucky. The surface is marked by sinkholes and the absence of large streams. The outcrop belt contains many cavern systems and sinking rivers. In southern Illinois a few small segments of karst occur in Hardin County and Union-Pulaski Counties. The St. Louis area is also noted for its karstic features.

In Indiana, thick Borden siltstones and shales underlie the limestone and form another hill land called the Norman Upland (Malott, 1922), a prominent escarpment overlooking the Scottsburg Lowland. The lowland is underlain by the weak Kinderhook shales. In Kentucky, the Borden equivalent is a cherty limestone that also forms a cuesta. On the southwest, the cuesta is somewhat obscured by overlap of Coastal Plain sediments and the faulted zone separating the Illinois Basin from the Ozarks. The cuesta is well developed in the St. Louis region, but is obscured northward by the Mississippi River arch structures and the mantle of glacial till.

Mid-Mississippian rocks are exposed northward along the valleys of the Mississippi and Illinois Rivers. They form prominent bluffs and cliffs, but their upland surface is veneered with unconsolidated material that masks a Tertiary landscape

TOPOGRAPHIC FEATURES OF THE MASSIVE SANDSTONES

The landscape formed on the massive Pottsville-Chesterian sandstone units has the greatest relief (fig. 3). Unbroken

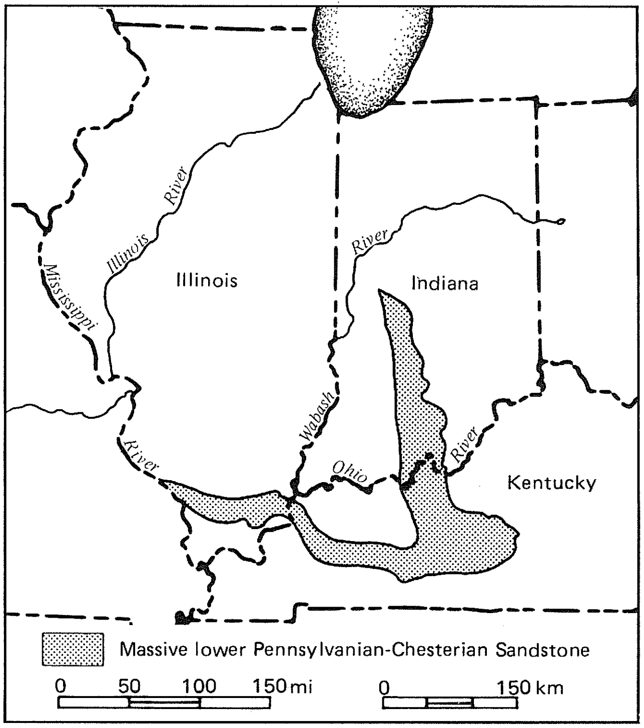

Figure 3. Distribution of massive lower Pennsylvanian-Chesterian sandstones.

escarpments extend for many miles. The scarp overlooks broad lowlands in places or the backslope of the next cuesta. Great cliffs punctuate the scarp as at Garden of the Gods in southeastern Illinois. The massive sandstone has widely spaced joints, some of which have been separated by mass wasting or erosion. Large blocks have slid outward and some blocks are seen far downslope. In many areas, the blocks have separated to form "streets" (Harris, Harrell, and Irwin, 1977).

Iron-oxide cementing is responsible for many peculiar and fascinating features. Joint surfaces are commonly coated with a resistant veneer. Pockets result where the cement was thin or has been removed. Concentrations commonly occur along bedding planes, and, thus, may emphasize cross-bedding. In other places, curious involutions and scrolls caused by ground-water solution and precipitation produce scenic attractions that are enhanced by the removal of sand grains from less well cemented areas.

Overhanging shelters are characteristic of many bluffs. Usually at the base of massive units, these arches in the rock were formed perhaps by removal of the weaker underlying material. Roof collapse gradually expands the shelter. Some overhangs extend for 100 meters and into the bluff for 10 to 15 meters. The roof arches upward from the back to a height partly determined by the thickness of the unit. Most shelter bluffs are on the scarp or valley side and are high above any stream, although streams do undercut some cliffs.

At right angles to the trend of the cuestas, long and parallel consequent valleys are incised into the backslopes. Here, too, the massive sandstone cliffs exhibit features similar to those on the upland. Waterfalls occur where the streams cross the sandstone. Most such streams are ephemeral, however, so waterfalls are active only during the wet season.

Several spectacular natural bridges have been formed from these massive sandstones. Near cliffs, where the joints are widely spaced, water has found its way down a joint and has scoured a path along a bedding plane and into the adjacent valley. Eventually, the block has become separated from the cliff, but the supporting buttresses remain.

Numerous state parks, recreation areas, and nature preserves have been established within this scenic province.

EFFECT OF GLACIATION

The topographic effect of Pleistocene glaciation has been considerable (see fig. 4). In preglacial times, the Kanawha River of West Virginia probably extended northwestward from where it now enters the Ohio River. The river was the main drainage line from the Appalachians and crossed central Ohio, Indiana, and Illinois in a broad valley, sometimes called the Teays Valley, now filled by glacial outwash, backwater sediments, and glacial till. Where the valley passes north and west of Champaign-Urbana, Illinois, the sand and gravel fill is an excellent aquifer and supplies these cities with water. The Teays joined the ancient Mississippi northwest of Springfield, Illinois, and proceeded southward along what is now the Illinois River Valley (Horberg, 1950).

This ancient course crossed the northern flanks of the Cincinnati Arch and advanced into the Illinois Basin north of the resistant sandstones. It left the Illinois Basin on the western margin, northwest of the farthest reach of the massive lower Pennsylvanian sandstones and also beyond the boundary of Chesterian sandstones.

Apparently no valley existed where the Ohio now extends between Huntington, West Virginia, and Louisville, Kentucky. The modern northward-flowing tributaries along this segment formerly continued their northerly course to the now-buried Teays.

The lower course of the Ohio probably had its headwaters on the backslope of one of the cuestas, as did the White River of Indiana. It may have transected the massive Pennsylvanian cuesta. A small remnant of unconsolidated sediments suggests possible superposition (Wayne, 1960).

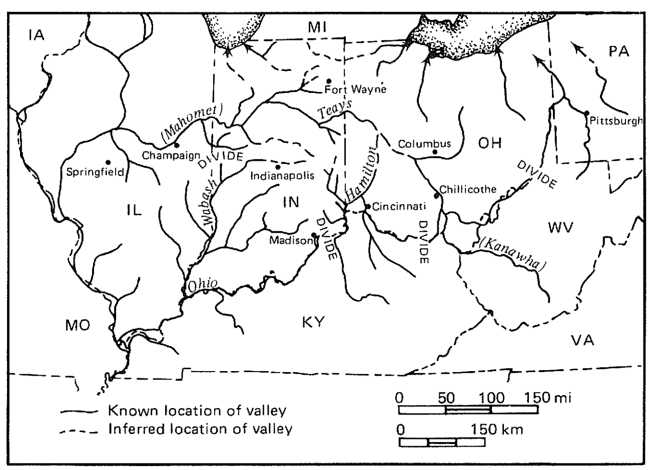

Figure 4. Preglacial drainage systems in central United States.

The upper Wabash probably was tributary to the Teays and the lower segment joined the ancient Ohio (Wayne, 1960).

The present course of the Ohio River was assumed as a result of successive glacial advances that overrode the Teays and dammed the northward-flowing tributaries. The ponded waters overflowed westward, tributary by tributary, eventually reaching the headwaters of the ancient "Ohio" near Louisville. Eventually the modern course was established.

The Pleistocene Epoch was a time of relatively rapid episodic changes in climate and geomorphic processes that drastically affected the river regimes. Today, all the major valleys and most tributaries have a legacy of sediment fill—up to 65 meters thick (thicker where covered by glacial till). Isostatic adjustment to the weight of ice and eustatic sea-level fluctuations were two factors. More important have been the alternations of regimes: (1) when streams were fed only by rainfall and (2) when glacial meltwaters annually surged down the valleys carrying vast loads of sediment. Thus, repeated intervals of deepening and scouring were followed by filling and aggradation.

Wisconsin glaciation brought great quantities of outwash which raised the floodplain levels of the major valleys. The tributaries that did not directly receive meltwaters were flooded by backwaters and so aggraded their valleys, too. Deepening of the valleys has incised the aggraded surfaces during the Holocene. These features will be seen repeatedly along the route of the field trip.

The flat, sometimes swampy, backwater lake surfaces are prominent features of the southern part of the Illinois Basin. During the depositional regime, aggradation of the valley floor surrounded the lowland hills and left bedrock islands standing above the terrace surface. Such island hills are numerous in Indiana along the Wabash and White Rivers, in western Kentucky south of Henderson and Owensboro, and in Illinois, near Shawneetown and Harrisburg. The island hills are mostly in the plains province because the general altitude is lower than in the province dominated by the massive sandstones.

SUMMARY

The distribution of sedimentary rock types in the Illinois Basin has profoundly affected the topography of the region. The hill lands on the east and south are an inheritance of the deposition of massive Carboniferous sandstones. Plains of low relief on the north and west reflect the Carboniferous history of erosion and the subsequent deposition of only fine-grained deposits. The parallel cuesta ridges are transected by a few major streams. Some local topographic offsets are caused by faults of the Cottage Grove-Rough Creek system.

During the Pleistocene, glacial deposits veneered the northern part of the basin. Related alluvial aggradation caused extensive burial of lowland areas at the south. The resulting flat, depositional surfaces contain numerous swamps. Bedrock hills rise above these surfaces like islands.

REFERENCES

FENNEMAN, N. M., 1938, Physiography of the Eastern United States; McGraw-Hill Book Co., New York, 714 p.

FIDLAR, M. M., 1948, Physiography of the lower Wabash Valley: Indiana Department of Conservation, Division of Geology, Bulletin 2, 212 p.

HARRIS, S. E., Jr., C. W. HORRELL, D. IRWIN, 1977, Exploring the land and rocks of southern Illinois: A geological guide: Southern Illinois University Press, Carbondale, IL, 240 p.

HORBERG, C. L., 1950, Bedrock topography of Illinois: Illinois State Geological Survey Bulletin 73, 111 p.

LEIGHTON, M. M., G. C. EKBLAW, and C. L. HORBERG, 1948, Physiographic divisions of Illinois: Journal of Geology, v. 56, p. 16-33.

MALOTT, C. A., 1922, The physiography of Indiana, *in* Handbook of Indiana Geology, Publication No. 21, Department of Conservation, Indiana, p. 59-255.

WAYNE, W. J., 1960, Stratigraphy of the Ohio River Formation: Bulletin 21, Indiana Department of Conservation, Geological Survey, p. 44.

RAISZ, Erwin, 1954, Landforms of the United States: 6th revised edition, private distribution, also *in* W. W. Atwood, Physiographic provinces of North America: Blaisdell, Indianapolis, IN, and Waltham, MA, 1940.

ECONOMIC GEOLOGY

Petrology and related chemistry of coals in the Illinois Basin

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INTRODUCTION

The pioneering research during the early 1900s by S. W. Parr of the University of Illinois on chemistry and classification of coals and by Reinhardt Thiessen of the U.S. Bureau of Mines on the botanical constituents in coals forms the foundation of modern petrologic studies of Illinois Basin coals. Petrologic and petrographic work on coals of the Illinois portion of the Illinois Basin Coal Field has been conducted by former members of the Illinois State Geological Survey under the direction of G. H. Cady, namely, J. A. Harrison, L. C. McCabe, C. E. Marshall, B. C. Parks, and J. M. Schopf. R. C. Neavel of the Indiana Geological Survey directed further research in petrography of coals in Indiana in the late 1950s. Some data on the petrology of the coals in the Kentucky part of the Illinois Basin Coal Field were published by Parks and O'Donnell (1956). Extensive petrographic data on coals from throughout the coal field have been gathered by workers at Pennsylvania State University, under the direction of Professor William Spackman.

Research has shown that coals of the Illinois Basin are different from similar-age coals in the Appalachian Basin. The important petrographic differences are discussed later.

Utilization of Illinois Basin coal began in 1810 with the opening of a mine near Murphysboro in southern Illinois. Since that time, Illinois Basin coals have gained in importance as a resource of fossil fuel. Because of diminishing sources of low-cost energy, these coals will continue to be economically important. Future developments of gasification and liquefaction of coals from the Illinois Basin appear likely because of the relatively high volatility and other desirable qualities of the coals and the closeness of sizable deposits to major urban centers.

DISTRIBUTION OF PENNSYLVANIAN COAL SEAMS IN THE ILLINOIS BASIN COAL FIELD

Except for very rare, thin, and local occurrences, all coals in the Illinois Basin Coal Field occur in the Pennsylvanian (Upper Carboniferous) rocks. The extent of these rocks in the field is shown in figure 1. The stratigraphic positions of most of the named coals (and two unnamed) in the coal field are shown in figure 2. Most of the principal commercial coals are geologically classified as members of the Carbondale Formation (fig. 2). The areal distribution of many of the coals is not known in sufficient detail throughout the field to show their extent on a map. Several of the commercially important coals, however, do occur over wide areas in the Illinois Basin Coal Field. Two seams can be traced for about 300 miles (480 km) from the northwestern to the southeastern parts of the field. These two seams include the Herrin (No. 6) and the Springfield-Harrisburg (No. 5) Coal Members in Illinois, the Herrin Coal Member and the Springfield Coal Member (V) in Indiana, and the No. 11 and No. 9 Coals in Kentucky, respectively. The distribution of these two coal seams in Illinois is shown by Hopkins and others (1979, figs. 4 and 6. See pages 145 and 147.). The Herrin extends from Illinois into Indiana only a short distance, but it does extend a considerable distance into Kentucky (No. 11).

Other coals are widespread in Illinois, particularly the Colchester (No. 2), Summum (No. 4), and Danville (No. 7) Coal Members. These coals vary considerably in thickness, however, and are less than 18 inches (<45 cm) thick in many places.

In Indiana the Seelyville Coal Member (III) is present in all but the eastern fringe of the area underlain by Pennsylvanian rocks (southwestern Indiana, fig. 1), and this

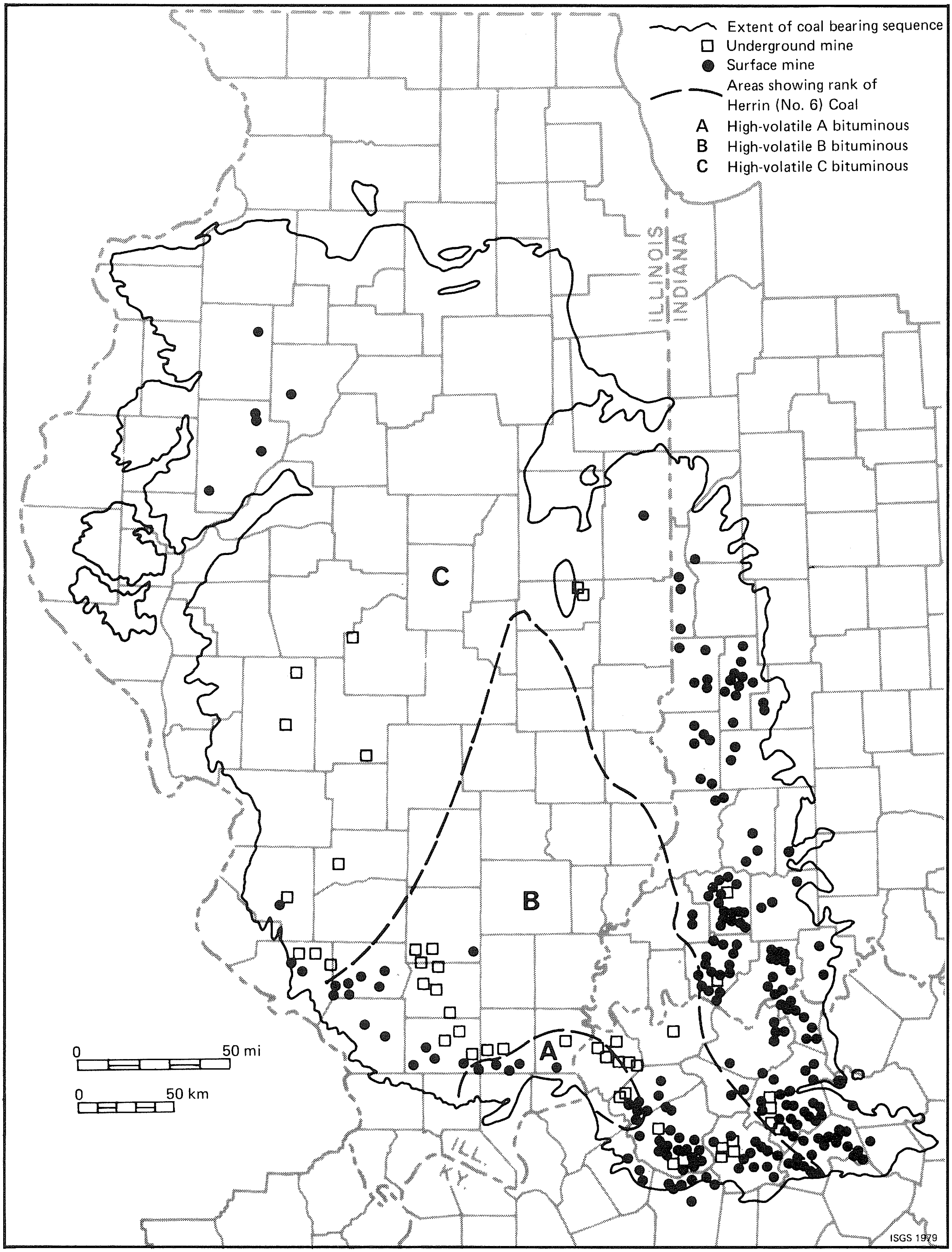


Figure 1. Location of mines in the Illinois Basin Coal Field, 1977.

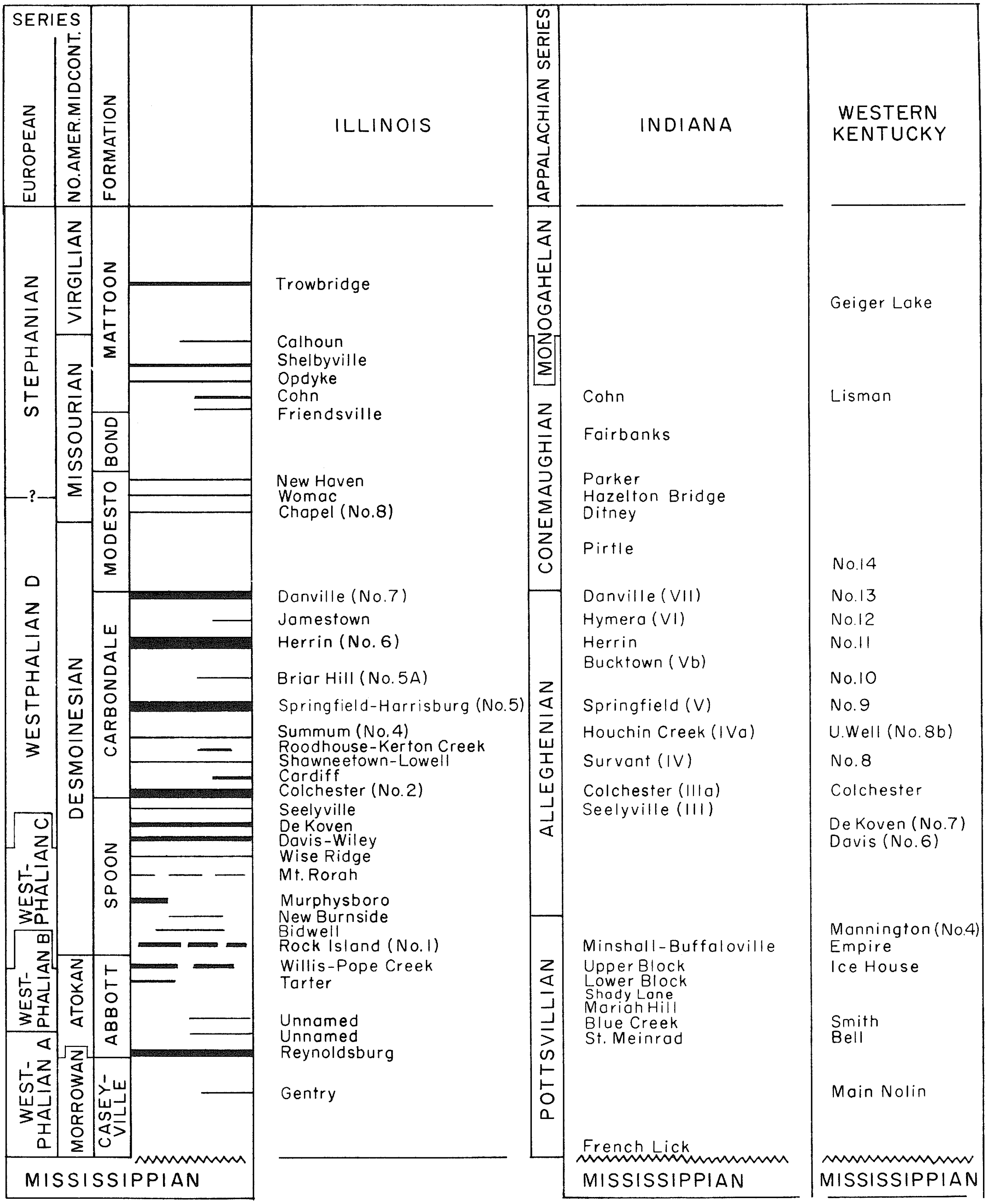


Figure 2. Generalized section of the Pennsylvanian in Illinois showing approximate vertical relations of the principal coals (after Willman et al., 1975) and approximate correlation of coals in Indiana (after Shaver et al., 1970) and in western Kentucky (Peppers and Williamson, personal communication).

seam has been mined in most of the area of its occurrence (Wier, 1973). The Survant Coal Member (IV) also is widespread in Indiana, but thick areas have been found mainly in the northern part of the field in Indiana (Wier, 1973). The Hymera Coal Member (VI) is commonly about 5 feet (1.5 m) thick and occurs extensively in the Indiana portion of the field, but apparently it does not extend beyond this area as a minable coal seam (Wier, 1973).

The No. 9 Coal is widespread in western Kentucky. It occurs in outcrops and in the subsurface in varying thicknesses in most of the Kentucky counties within the field. The No. 14 Coal is mainly exposed in the southern tier of counties within the Pennsylvanian outcrop belt (fig. 1). Many other coals are economically and geologically important in western Kentucky. The areas where significant coal seams are thickest can be observed by noting the distribution of the mines in the various coals (table 1). Many coals in all parts of the field are lenticular in distribution and occur in an area of a few square miles or less.

CHEMICAL CHARACTERISTICS

Some of the results of chemical analyses shown in table 2 may not be entirely typical of the seam, because for a few seams only one sample has been analyzed. Most of the seams that have been analyzed have been sampled from more than eight locations; the samples for these seams are as typical of the sample set as could be chosen, although no two samples are alike in all respects. An informative description of the methods and limitations of these analyses was given by Rees (1966).

For several of the seams, results are given by regions within Illinois. The regions are indicated by abbreviations of the eastern and western halves of the northern, central, and southern thirds of the state (for example, NE, WC, and SE). (See the map in figure 3 for boundaries of these regions.) The coal seams are listed with the youngest seam at the top and progressively older down the table.

The moisture data shown in table 2 are fair to good approximations of the inherent moisture in the coals that on a mineral- or ash-free basis correlated well with the rank (Damberger, 1971) and with the internal surface area of the coal (Thomas and Damberger, 1976). The moisture is generally between 12 and 17 percent for all seams in the northern and central regions. Some samples from the northwestern region and some from the uppermost seams in the central part of Illinois contain as much moisture (mineral-matter free) as 20 percent. Moisture values decrease toward the center and deepest part of the basin (SE Illinois) to a low near 4 percent (mineral-matter free). The as-received ash content of samples (table 2, excluding mineral partings of 3/8 inch [1 cm] or more) varies considerably between 5 and 20 percent, but typically the value is between 7 and 15 percent for Illinois coal. The volatile matter on a dry mineral-matter-free basis decreases from 45 to 50 percent in the northern and central regions to a low of about 30 percent and does not vary significantly from one seam to another.

On a dry ash-free basis the carbon content of Illinois coals averages 80 percent, and the value typically ranges between 78 and 82 percent, depending in part on the location (rank) of the sample. Coals of Illinois have an H/C (atomic basis) value that typically ranges between 0.8 to 0.9.

As shown in table 3, typical results of proximate analyses of coals from western Kentucky are generally lower in moisture and volatile matter than most Illinois and Indiana coals. The data on western Kentucky coals typically show moisture content of less than 10 percent and volatile matter content between 37 and 41 percent. The Indiana coals are similar to those of Illinois in many respects. In comparison, the coals of western Kentucky are lower in moisture and volatile matter contents. A summary of the chemical composition of Indiana coals is given by Neavel (1961) and Wier (1973).

Sulfur in coals of the Illinois Basin Coal Field has been a serious problem for many years, and recently it has received increased attention. From their study of sulfur in coals of Illinois, Gluskoter and Simon (1968) reported the following findings. Sulfate sulfur content in freshly mined coal is usually less than 0.1 percent of the coal. Pyritic sulfur content varies greatly, both laterally and vertically in the seam, but in face channel samples it ranges mostly from 1 to 3 percent (average 1.5 percent of the dry coal); this sulfur is usually more concentrated in fusain bands than in other bands, but it is common in clarain bands and on cleat surfaces too. The organic sulfur generally ranges from 0.4 to 2.5 percent of the dry coal; this sulfur tends to be more uniformly distributed throughout the seam than does pyritic sulfur. The organic sulfur contents in various lithotypes average about 1 percent in vitrain, 1.8 percent in clarain, and 0.5 percent in fusain. The total sulfur in the various coals is generally between 2 and 5 percent (tables 2 and 3); it tends to be highest at the top or bottom of the seam and lower in seams that are overlain by thick gray (nonmarine) shale, as opposed to black and fissile (marine) shale. Relatively low-sulfur coals (less than 2.5 percent S) are known mainly in southern Illinois in parts of Franklin, Williamson, and Saline Counties and in a few local areas in other parts of the state. In studies of the washability of coals by float-sink methods (Helfinstine et al., 1971 and 1974), data from tests of a large number of samples at 80-percent recovery of coal show reduction from 4.11 to 2.52 percent in the average total sulfur.

Sulfur in Indiana coals, reported by Neavel (1961), ranges from 0.1 to 7.9 percent, with a mean of 2.7 percent (as-received basis). About 10 percent of the samples studied contained more than 4.5 percent sulfur. The lower coal seams in Indiana tend to have lower sulfur values (Neavel, 1961, and Wier, 1973). Average washability results, at the 80-percent recovery level, indicate that final sulfur values between 1.6 and 3.7 percent are attainable for various coal seams (Wier and Hutchison, 1977).

The chlorine content of the Illinois coals, as given in table 2, is generally less than 0.2 percent; however, these samples are mainly from shallow depths. The chlorine content in numerous samples collected from a wide areal extent in the Herrin (No. 6) Coal ranged to 0.65 percent (Gluskoter and Rees, 1964; and Gluskoter and Ruch, 1971); they found the chlorine to increase with depth in the basin, especially with increasing salinity of the ground water associated with the coal. Chlorine was found in excess of sodium in many samples; this excess is interpreted

TABLE I. Distribution of principal mining areas, by counties, of the main coals in the Illinois Basin

Illinois		Southwestern Indiana[a]		Western Kentucky[b]	
Seam	Counties (region in state)	Seam	Counties (region in state)	Seam	Counties (region in state)
Opdyke	Jefferson (south central)			No. 14	Hopkins, Muhlenberg, Ohio
Danville (No. 7)	Vermilion (east central)	Danville (VII)	(Western area except southwest corner)		
		Hymera (VI)	Sullivan, Greene, Knox, Gibson, Pike, Warrick	No. 13	Webster, Muhlenberg, Ohio
Herrin (No. 6)	Most counties underlain by Pennsylvanian			No. 11	Union, Webster, Hopkins, Muhlenberg, Ohio (Southern tier of counties within Pennsylvanian outcrop line)
		Bucktown (Vb)	Vermillion, Daviess		
(Springfield-Harrisburg (No. 5)	Most counties underlain by Pennsylvanian	Springfield (V)	(Most of area except eastern fringe and southwest corner)	No. 9	All counties within Pennsylvanian outcrop line
		Houchin Creek (IVa)	Greene		
		Survant (IV)	Vermillion, Vigo, Sullivan, Greene, Daviess, Pike	No. 8	Scattered localities in Hopkins, Muhlenberg, Ohio
Colchester (No. 2)	Kankakee, Grundy, La Salle (northern); Fulton (western)	Colchester (IIIa)	Parke, Vigo, Warrick		
		Seelyville (III)	(Most of area except eastern fringe and southwest corner)		
Davis and De Koven	Williamson, Saline, Jackson (southern)			No. 6	Union, Webster, Hopkins
Murphysboro				Mannington (No. 4)	Hopkins, Christian, Butler, Ohio
Rock Island (No. 1)	Rock Island, Mercer (northwestern)	Minshall-Buffaloville	Fountain, Parke, Clay, Daviess, Spencer		
		Upper-Lower Block	Parke, Clay, Owen, Greene		
		Mariah Hill	Daviess, Dubois, Spencer		
		Blue Creek	Daviess		
		St. Meinrad	Perry, Spencer		

[a]Wier, 1973; Hutchison, 1977; Paul Weir Co., 1969; D. C. Carr (Indiana Geological Survey), personal communication.
[b]Kirkpatrick, 1971; Paul Weir Co., 1969; A. Williamson (Kentucky Geological Survey), personal communication.

TABLE 2. Typical results of chemical analyses of face channel samples of Illinois coals[a]

Coal seam	Region (fig. 3)	County	As received (%)		Dry, mineral-matter free (%)		Dry (%)			Dry, ash free (%)				Heating value[b]		Rank[c] HVB
			Moist-ure	Ash	Volatile matter	Fixed carbon	Pyritic S	S	Cl	H	C	N	O	(Btu/lb)	(cal/gm)	
Trowbridge	EC	Shelby	17.2	17.5	43.1	56.9	—	2.5	—	5.2	79.2	2.0	10.5	11,414	6,335	C
Shelbyville	EC	Shelby	14.3	7.2	46.9	53.1	3.0	4.5	0.07	6.0	78.3	1.3	9.6	12,104	6,718	C
Opdyke	SE	Jefferson	10.6	13.6	49.9	50.1	2.7	4.2	0.03	5.9	77.1	1.9	10.2	12,571	6,977	C
Friendsville	SE	Wabash	14.7	8.7	46.6	53.4	0.5	2.4	—	—	—	—	—	12,061	6,694	C
Danville (No. 7)	NW	Knox	15.6	12.1	45.2	54.8	2.0	4.2	—	5.7	78.0	1.5	9.9	11,826	6,563	C
	NE	Grundy	13.1	9.6	49.7	50.3	—	4.0	0.05	6.1	79.4	1.3	8.8	12,276	6,813	C
	WC	Madison	8.9	14.2	47.2	52.8	—	5.4	0.03	—	—	—	—	12,847	7,130	C
	EC	Vermilion	12.8	9.7	51.2	48.8	2.0	3.8	0.19	5.7	79.9	1.5	8.7	12,584	6,984	C
	SE	Wabash	11.2	10.4	45.3	54.7	1.5	2.8	0.05	—	—	—	—	12,485	6,929	C
Jamestown	EC	Crawford	8.9	17.4	46.7	53.3	1.5	2.8	0.22	—	—	—	—	13,170	7,309	B
	SE	Richland	7.1	13.2	43.5	56.5	—	2.9	—	—	—	—	—	13,617	7,557	B
Herrin (No. 6)	NW	Knox	17.0	9.9	47.7	52.3	1.2	3.2	0.04	5.8	78.0	1.3	11.4	11,550	6,410	C
	NE	La Salle	12.8	9.5	48.0	52.0	2.6	4.2	—	5.6	78.7	1.3	9.8	12,500	6,938	C
	WC	Macoupin	13.3	10.4	48.2	51.8	2.0	5.2	0.10	5.6	77.3	1.5	9.7	12,052	6,689	C
	EC	Douglas	13.5	6.4	46.4	53.6	0.9	2.2	0.11	6.1	80.6	1.5	9.4	12,564	6,973	C
	SW	Randolph	10.9	11.3	45.1	54.9	1.6	3.7	0.05	5.6	78.5	1.3	10.3	12,510	6,943	C
	SE	Saline	6.8	10.6	42.0	58.0	2.1	3.4	0.05	5.5	80.1	1.4	9.2	13,647	7,574	B
Spring Lake	NE	La Salle	—	19.5	48.2	51.8	—	—	0.09	—	—	—	—	—	—	—
Briar Hill (No. 5A)	SE	Gallatin	2.1	15.5	43.4	55.6	—	4.2	0.20	—	—	—	—	14,886	8,262	A
Springfield-Harrisburg (No. 5)	NW	Fulton	15.8	10.4	48.2	51.8	2.3	4.5	0.01	5.6	78.9	1.3	9.1	11,910	6,610	C
	WC	Logan	14.7	12.6	47.7	52.3	2.0	4.1	0.14	5.9	78.8	1.7	8.9	11,867	6,586	C
	EC	Edgar	9.6	10.6	48.5	51.5	3.2	4.6	0.24	—	—	—	—	13,061	7,249	B
	SW	Randolph	8.7	11.6	44.5	55.5	2.6	5.0	0.01	5.8	78.9	1.6	8.1	13,044	7,239	B
	SE	Gallatin	5.9	11.1	43.4	56.6	2.6	4.1	0.26	5.7	81.1	1.7	6.8	13,966	7,751	B
Summum (No. 4)	NW	Fulton	11.6	6.5	50.0	50.0	1.3	3.7	—	—	—	—	—	12,830	7,121	C
	NE	Grundy	12.5	8.8	49.9	50.1	1.7	3.8	0.04	5.8	78.5	1.3	10.2	12,570	6,976	C
	SE	Saline	4.1	13.7	43.0	57.0	3.8	5.6	0.14	5.9	79.6	1.7	6.4	14,115	7,834	A
Kerton Creek	NW	Fulton	13.9	8.7	47.8	52.2	6.3	7.8	—	—	—	—	—	12,464	6,918	C
Shawneetown-Lowell	NE	Livingston	—	19.6	47.6	52.4	1.7	2.7	0.09	6.1	80.3	1.6	8.6	—	—	—
	WC	Edgar	12.1	8.9	43.6	56.4	0.4	1.0	0.38	—	—	—	—	12,657	7,025	C
	SW	Jackson	6.8	6.8	44.5	55.5	2.4	3.5	0.27	—	—	—	—	13,688	7,597	B
	SE	Gallatin	2.5	14.7	44.2	55.8	2.3	3.4	0.23	6.1	82.2	1.6	6.2	14,687	8,151	A
Cardiff	NE	Kankakee	12.4	15.1	48.6	51.4	—	4.1	0.05	5.8	77.5	1.4	10.3	12,286	6,819	C
Colchester (No. 2)	NW	Fulton	14.5	8.1	46.2	53.8	3.4	4.8	0.04	6.0	80.3	1.4	6.9	12,215	6,779	C
	NE	Will	13.9	6.9	43.6	56.4	2.3	3.2	0.02	5.8	79.5	1.5	9.7	12,160	6,749	C
	WC	Adams	11.2	9.0	47.2	52.8	3.4	4.9	0.03	5.4	80.5	1.6	7.1	12,929	7,176	C
	EC	Edgar	11.3	7.1	48.0	52.0	3.2	4.4	—	—	—	—	—	12,873	7,145	C
Seelyville	EC	Crawford	4.9	14.8	45.1	54.9	5.4	6.9	0.30	—	—	—	—	13,981	7,759	B
De Koven	SE	Gallatin	2.4	9.6	31.4	68.6	1.4	2.4	0.28	5.3	82.7	1.8	7.5	14,754	8,188	A

Table 2. *Continued*

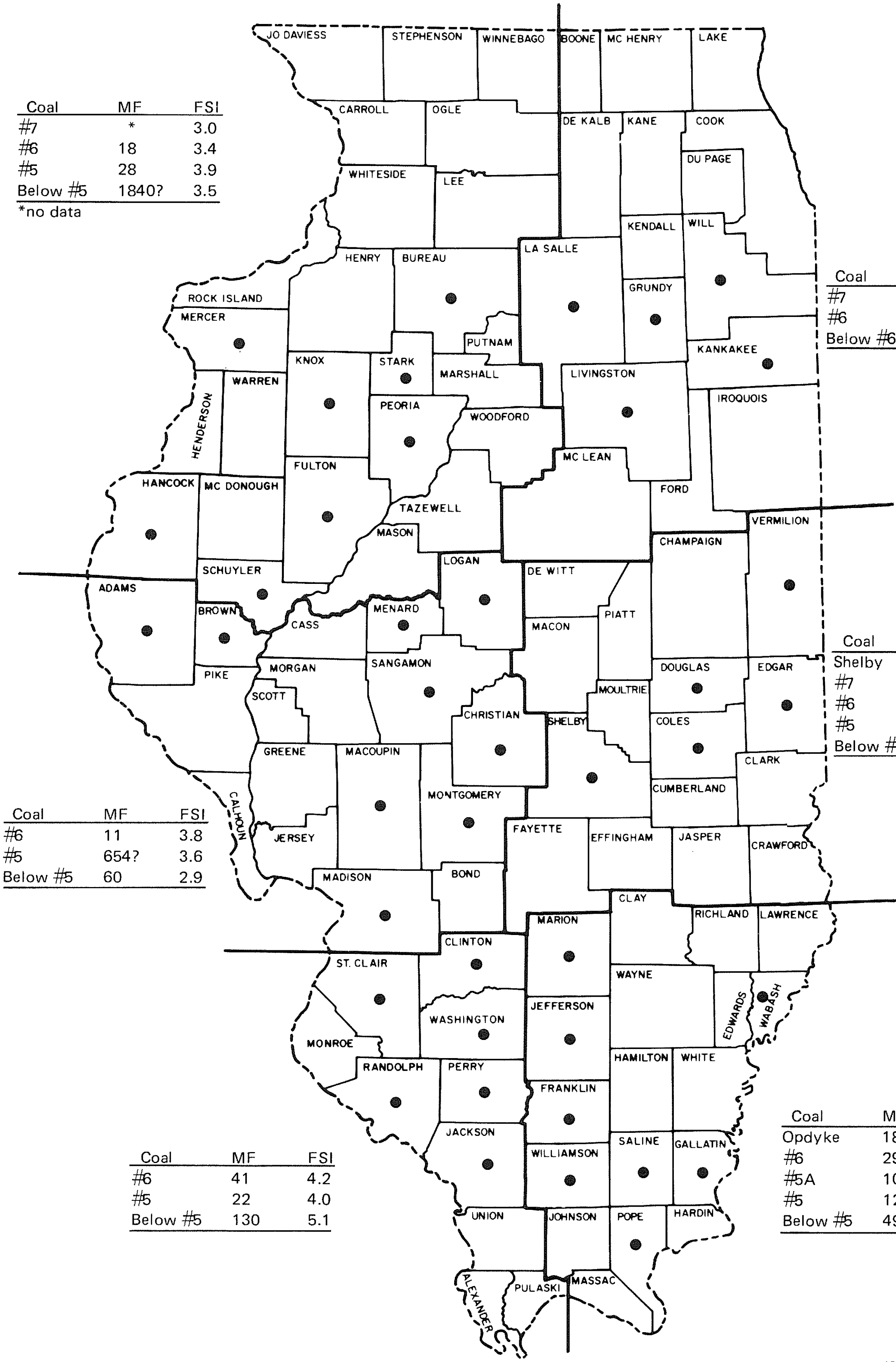
Coal seam	Region (fig. 3)	County	As received (%)		Dry, mineral-matter free (%)		Dry (%)			Dry, ash free (%)				Heating value[b]		Rank[c] HVB
			Moisture	Ash	Volatile matter	Fixed carbon	Pyritic S	S	Cl	H	C	N	O	(Btu/lb)	(cal/gm)	
Davis-Wiley	NW	Peoria	—	18.8	45.6	54.4	—	7.3	0.04	—	—	—	—	—	—	—
	SE	Williamson	4.1	15.4	43.3	56.7	2.9	4.2	0.07	5.3	81.7	1.7	6.3	14,321	7,948	A
Murphysboro	SW	Jackson	5.3	10.6	40.1	59.9	3.8	4.9	0.09	5.5	80.2	1.5	7.2	14,030	7,787	A
New Burnside	SE	Johnson	8.4	5.3	41.9	58.1	—	2.2	—	5.6	82.4	1.5	8.2	13,716	7,612	B
Bidwell	SE	Pope	9.1	7.5	37.5	62.5	0.8	1.2	0.11	5.4	82.2	1.6	9.5	13,167	7,308	B
Rock Island (No. 1)	NW	Knox	14.8	7.3	46.6	53.4	3.2	4.9	—	5.5	78.6	1.3	9.3	12,243	6,795	C
	EC	Edgar	11.9	15.3	41.4	58.6	2.1	2.8	0.50	—	—	—	—	12,518	6,947	C
Willis	SE	Gallatin	3.4	10.3	36.7	63.3	3.8	4.7	—	5.2	83.4	1.5	4.7	14,870	8,253	A
Tarter	NW	Fulton	14.8	7.7	44.0	56.0	—	4.3	0.09	—	—	—	—	12,381	6,871	C
Reynoldsburg	SE	Pope	6.7	6.6	33.6	66.4	1.1	1.7	0.12	5.2	83.6	1.5	7.9	13,903	7,716	B

[a]Analyses of entire seams, exclusive of mineral partings 3/8 inch or more, in mines and of drill cores by Analytical Chemistry Section, Illinois State Geological Survey.
[b]Mineral-matter free and moist basis. To convert to kilojoules per gram, multiply the Btu/lb values by 2.326, or the cal/gm values by 0.004186.
[c]ASTM (1977, D388), mineral-matter free and moist basis. All samples have a rank of high-volatile bituminous (HVB)—A, B, or C.

Coal	MF	FSI
#7	*	3.0
#6	18	3.4
#5	28	3.9
Below #5	1840?	3.5

*no data

Coal	MF	FSI
#7	790	4.7
#6	4	2.5
Below #6	3035	4.1



Coal	MF	FSI
Shelby	20	2.8
#7	1340	4.6
#6	435	4.1
#5	4500	3.5
Below #5	1794	3.5

Coal	MF	FSI
#6	11	3.8
#5	654?	3.6
Below #5	60	2.9

Coal	MF	FSI
#6	41	4.2
#5	22	4.0
Below #5	130	5.1

Coal	MF	FSI
Opdyke	18	4.0
#6	2920	5.1
#5A	10000	7.5
#5	1285	5.5
Below #5	4970	7.1

ISGS 1979

Figure 3. Average maximum fluidity (MF) in dial divisions per minute and free swelling index (FSI) for various coal seams in six regions of Illinois. Data included in the averages are from counties indicated by a dot (.).

TABLE 3. Typical chemical analyses of some western Kentucky and Indiana coals

Coal seam	County	As received (%) Moisture	As received (%) Ash	Dry, mineral-matter free (%) Volatile matter	Dry, mineral-matter free (%) Fixed carbon	Dry (%) S	Heating value, moist, mineral-matter free (Btu/lb)	Rank[a] HVB	FSI[b]
WESTERN KENTUCKY (Tipple or mine run or delivered samples; from Fieldner et al. (1942); adjusted to the above bases)									
No. 14	Henderson	11.6	9.4	40.5	59.5	2.3	12,620	C	
	Hopkins	8.6	7.6	42.0	58.0	2.6	13,290	B	
	Ohio	9.1	9.8	44.6	55.4	5.0	13,100	B	
	Webster[c]	6.1	8.5	40.2	59.8	2.9	13,890	B	5.5
No. 12	Hopkins[c]	9.0	13.3	48.7	51.3	3.4	13,140	B	4.0
	Muhlenberg[d]	9.4	10.1	44.9	55.1	3.2	12,980	C	4.0
	Webster	5.6	9.4	39.3	60.7	1.5	14,070	A	
No. 11	Hopkins	6.0	10.3	43.4	56.6	4.0	13,820	B	(5.0)[c]
	Muhlenberg	6.4	8.7	46.2	53.8	4.1	13,750	B	(3.5)[d]
	Union	8.9	9.4	44.9	55.1	3.8	13,184	B	
	Webster	5.2	10.8	42.3	57.7	4.6	13,960	B	
No. 10	Union	5.4	11.9	40.8	59.2	4.2	14,170	A	
No. 9	Daviess	11.2	12.8	43.8	56.2	4.6	12,660	C	(3.5)[c]
	Henderson	10.5	12.2	44.3	55.7	4.4	12,860	C	
	Hopkins	7.0	10.5	43.2	56.8	4.0	13,650	B	(5.0)[c]
	Muhlenberg	8.0	10.1	43.0	57.0	3.8	13,500	B	
	Ohio	9.0	9.4	43.2	56.8	3.7	13,250	B	(5.5)[c]
	Union	4.3	10.6	42.7	57.3	3.9	14,310	A	(7.0)[c]
	Webster	4.5	10.6	42.0	58.0	3.8	14,280	A	
No. 6	Butler[e]	8.6	6.7	45.8	54.2	2.2	13,430	B	4.0
	Christian	10.6	5.6	41.6	58.4	2.5	13,060	B	
	Hopkins	9.5	7.8	41.6	58.4	3.4	13,300	B	
	Muhlenberg	8.1	5.5	44.2	55.8	4.4	13,630	B	
	Ohio[f]	10.6	5.5	43.5	56.5	2.2	13,100	B	3.5
No. 1	Crittenden	8.7	6.6	36.0	64.0	1.1	13,790	B	
INDIANA (Channel samples of raw coals; from Wier (1973); adjusted to the above bases)									
Danville (VII)		12.6	12.2	46.0	54.0	2.3	12,600	C	
		10.9	11.4	44.4	55.6	1.9	11,790	C	
Hymera (VI)		13.4	9.9	45.2	54.8	3.0	12,430	C	(4.0)[c]
		8.6	17.9	42.3	57.7	4.0	13,030	B	
Springfield (V)		10.0	9.3	50.2	49.8	3.7	12,960	C	(4.0)[c]
		7.7	10.5	48.1	51.9	6.6	13,300	B	
Survant (IV)		14.4	8.4	43.4	56.6	1.3	12,300	C	(4.0)[e]
		12.7	7.9	41.9	58.1	2.0	12,270	C	
Seelyville (III)		11.3	11.2	50.3	49.7	3.4	12,670	C	
		11.1	14.9	46.0	54.0	6.4	12,650	C	
Minshall		11.2	11.1	51.1	48.9	3.5	12,720	C	
Upper Block		15.5	6.3	40.6	59.4	3.2	12,390	C	
		10.2	8.4	44.5	55.5	2.3	12,270	C	
Lower Block		13.3	7.5	45.1	54.9	1.9	12,610	C	

[a]As per ASTM (1977, D388); mineral-matter, free and moist basis. All samples have a rank of high-volatile bituminous (HVB)—A, B, or C.
[b]Free swelling index; data in parentheses are from samples from the county other than the chemical sample.
[c]Aresco et al. (1960).
[d]Janus (1976).
[e]Janus (1977).
[f]Janus (1975).

to be most likely in organic combination (Gluskoter and Ruch, 1971). Most mining in Illinois has been at depths less than 600 feet (∿180 m), where the chlorine is less than about 0.35 percent. Future mining at greater depths is likely to encounter higher chlorine values.

PHYSICAL CHARACTERISTICS

Two physical properties of coal of interest here are the free swelling index (FSI), as tested according to ASTM, (1977, D720), and the fluidity, as tested according to ASTM, (1977, D2639). For many years Illinois State Geological Survey has conducted these tests on samples collected from coals in Illinois. Results of these tests were tabulated by seam, and the average values were determined on a county-wide basis. These are summarized, by further averaging by region, in figure 3. The FSI values are relatively consistent on a regional basis, and thus the averages are fairly meaningful. The data show the FSI to be 4 or higher in the southeastern region, and in the other regions the values generally range from 3 to 4. In the northeast and east-central regions, the Danville (No. 7) Coal averages a higher FSI than the underlying Herrin (No. 6) Coal, for reasons yet to be determined. The fluidity values show a wide range from sample to sample within a region and within a county. The significance of the fluidity values is questionable because of the possibility of the sample's spinning in the crucible during the test, which would cause errors in the results. The most noteworthy significance of these data (fig. 3) are the abundance of relatively high values for samples from the southeastern region, the region of higher rank coals in Illinois. Table 3 lists a few FSI values for Kentucky coals. A high of 7 is indicated for a sample of high-volatile *A* bituminous (No. 9 Coal, Union County, Kentucky). None of the samples reported have values less than 3.5; these values reflect the abundance of coals of rank *B* and *A* in the Kentucky part of the Coal Field.

PETROGRAPHIC COMPOSITION

Megascopic features

The outstanding megascopic feature of most coals of the Illinois Basin is that they are bright—rich in vitrain and clarain. For example, in a megascopic study of 21 complete column samples of the Herrin (No. 6) Coal, McCabe (1934) found the bright bands of vitrain and clarain to average 90 percent of the coal. Parks (1949) reported these bands to total 96 percent in a sample of the No. 2 from Fulton County; the same percentage in a sample of the No. 5 from Saline County; and in samples from widely scattered locations in the No. 6, these bands ranged from 82 to 97 percent of the coal. Some of the duller bands of clarain present in these samples were included in the percentages. In a recent study, Cameron (1978) found that the No. 6, No. 5, Davis, and the De Koven seams in Illinois contain from 86 to 95 percent vitrain and clarain; however, when he divided the clarain into bright and less bright units, he found that the No. 6 and Davis seams were the brightest, having 75 percent or greater vitrain, plus bright clarain, and the De Koven seam to be the dullest, having only 54 percent bright bands. The No. 5 seam was intermediate with 59 percent. In Indiana, Neavel (1961) found all but the lowest seam tested to have a brightness index more than 70 (table 4).

Dull coals, those consisting of bands of durain or splint coal, are rare in the seams of the Illinois Basin; occurrences of dull boghead and cannel coals are also rare and tend to be localized (Ashley, 1918; Kosanke, 1951; and Neavel, 1961). In addition, a dull "paper coal" with 23.5 percent sporinite and cutinite occurs in Indiana (Neavel and Guennel, 1960).

Maceral composition

As could be expected from the megascopic features, the outstanding microscopic characteristics of the coals of the basin are a very high vitrinite content, typically 65 to 85 percent, and a paucity of inertinite macerals, whose content typically ranges from 4 to 12 percent (tables 5 and 6). For many of the samples in table 5, the vitrinite value is a sum of the percentage of macerals identified as vitrinite A and vitrinite B, the latter having the lower reflectance of the two. The ratio of vitrinite A to vitrinite B varies from 0.6 to 3. According to Benedict and Thompson (1973), some vitrinite particles in these coals have optical characteristics of pseudovitrinite as described in Appalachian coals by Benedict et al. (1968); this type of vitrinite is routinely counted during maceral analyses in laboratories of Southern Illinois University, Pennsylvania State University, and Homer Research Laboratory of Bethlehem Steel Corporation.

Table 4. Megascopic brightness indices and anthraxylon/attritus brightness ratio[a] of Indiana coals
(From Neavel, 1961)

	Coal seam						
	Lower Block	Upper Block	Coal (III)	Coal (IV)	Coal (V)	Coal (VI)	Coal (VII)
Number of columns analyzed	2	1	2	1	5	2	1
Brightness index	50.9	85.4	86.8	72.5	89.8	80.0	87.1
Anthraxylon/attritus brightness ratio	1.7	1.1	0.9	1.2	1.0	1.1	0.9

[a]The brightness index is the total of the weighted averages of the anthraxylon and attritus brightness of the various benches of coal in the column. Both sets of averages are based on the percentage of abundance and brightness assigned and tabulated during detailed visual study of the polished column of coal.

TABLE 5. Typical maceral and reflectance analyses of Illinois coals[a]

FORMATION Coal seam	Region (fig. 3)	County	Volume (%) Vitrinite	Resinite	Exinite	Semi-fusinite	Fusinite	Micrinite and macrinite	Minerals Pyrite	Other[b]	Mean reflectance[c]
MATTOON											
Trowbridge	EC	Shelby	66	1	10	2	6	4	tr	11	.56
Calhoun	SE	Clay	78	1	8	1	2	2	1	8	.47
CARBONDALE											
Danville (No. 7)	NE	Grundy	82	2	3	3	1	4	2	4	.59
	EC	Vermilion	74	2	7	3	3	4	1	6	.57
	SE	Hamilton	78	tr	5	2	2	5	7	2	.64
Jamestown	EC	Crawford	—	—	—	—	—	—	—	—	.54
Herrin (No. 6)	NW	Fulton	85	2	5	tr	tr	2	3	3	.51
	NE	Bureau	75	1	8	1	1	7	tr	7	.55
	WC	Macoupin	79	1	6	2	2	4	2	5	.56
	EC	Vermilion	81	1	5	2	2	4	1	5	.56
	SW	Washington	68	4	9	2	4	5	1	7	.60
	SE	Saline	89	1	2	3	2	3	1	tr	.72
Briar Hill (No. 5A)	SE	Gallatin	79	1	6	2	1	4	1	7	.73
Springfield-Harrisburg (No. 5)	NW	Fulton	79	1	5	2	1	3	1	8[d]	.53
	NE	Kankakee	77	1	6	5	3	3	2	4	.45
	WC	Macoupin	66	4	7	2	3	5	3	10	.59
	EC	Crawford	—	—	—	—	—	—	—	—	.53
	SW	Perry	78	2	6	2	1	3	1	6	.60
	SE	Gallatin	77	tr	9	2	5	4	3	tr[d]	.88
Summum (No. 4)	SE	Gallatin	75	1	7	1	4	5	1	6	.69
Kerton Creek	NW	Fulton	79	1	6	1	1	2	3	7	.51
Shawneetown	SE	Gallatin	73	1	6	4	2	5	1	8	.71
Cardiff	NE	Will	77	1	6	5	1	4	3	3	.58
Colchester (No. 2)	NW	Fulton	84	1	7	1	tr	2	2	3	.51
	NE	Will	88	tr	5	1	1	2	—[e]	3	.54
	WC	Adams	83	tr	7	1	1	1	2	5	.48
	EC	Crawford	—	—	—	—	—	—	—	—	.52
	SE	Gallatin	86	1	6	1	2	1	3	1[d]	.55
SPOON											
Davis-De Koven	SE	Gallatin	80	tr	6	1	2	3	6	2	.74
Murphysboro	SE	Williamson	76	1	8	1	4	3	4	3	.68
New Burnside	SE	Johnson	81	2	5	1	3	3	4	tr	.72
Rock Island (No. 1)	NW	Knox	77	2	7	2	1	5	—[d]	6	.51
ABBOTT											
Willis	SE	Gallatin	—	—	—	—	—	—	—	—	.86
Unnamed	SE	Pope	—	—	—	—	—	—	—	—	1.10
Unnamed	SE	Pope	62	tr	8	3	9	10	tr	9	.92
Reynoldsburg	SE	Johnson	92	tr	5	tr	tr	tr	tr	3	.81

[a]Channel and face channel samples from mines and drill cores. Data largely determined from 1962 to 1966 under supervision of John A. Harrison of the Illinois State Geological Survey.

[b]Mainly various types of clay minerals, determined by difference of measured pyrite and the total mineral matter as calculated from the ash and sulfur contents (ASTM, 1977, D2799).

[c]Mean of the maximum reflectance in oil of vitrinite A (or telocollinite).

[d]Microscopically measured.

[e]This sample not analyzed for pyrite; the total may include some percentage of pyrite.

TABLE 6. Typical maceral and reflectance analyses of Indiana and Western Kentucky coals[a]
(Whole seams from mines active at time of sampling)

FORMATION Coal seam	County	Volume (%) Vitrinite	Resinite	Exinite	Semi-fusinite	Fusinite	Micrinite and Macronite	Minerals	Mean R_o
	INDIANA								
DUGGER	Sullivan	78	tr	1	4	8	2	6	0.50
Danville (VII)	Warrick	82	0	1	2	3	tr	12	0.44
Hymera (VI)	Sullivan	83	1	2	1	1	2	10	0.50
	Warrick	82	0	1	3	3	1	11	0.45
PETERSBURG	Gibson	81	0	1	4	4	1	10	0.41
Springfield (V)	Gibson	83	0	1	3	4	1	9	0.42
STAUNTON Seelyville (III)	Greene	61	1	3	14	4	5	13	0.45
BRAZIL	Clay (top vein)	60	1	21	2	4	8	3	0.78
Coal (I)[b]	Owen	57	1	20	3	6	7	7	0.56
	WESTERN KENTUCKY								
CARBONDALE No. 12	Muhlenberg	80	0	1	3	4	tr	12	0.55
	Muhlenberg	76	tr	3	2	5	4	11	0.62
No. 11	Muhlenberg	79	1	2	1	3	4	10	0.53
	Muhlenberg	80	tr	2	2	3	4	10	0.59
No. 9	Muhlenberg	78	tr	3	2	6	5	6	0.63

[a]Data from Pennsylvania State University Coal Data Base, courtesy of Professor William Spackman.
[b]Probably Upper or Lower Block Coal Member.

Comparison of the maceral compositions of the Illinois No. 5 and 6 seams on a mineral-free basis and the compositions of four Appalachian coal seams (table 7) shows that the vitrinite content of the Illinois coals, on this relative basis, is about 8 to 30 percent greater than the Appalachian seams; the inertinite content is respectively about 10 to 30 percent lower.

Photomicrographs of typical maceral occurrences, including some fluorescent macerals, are shown in figure 4. The newly defined fluorescent macerals—fluorinite, bituminite, and exsudatinite, as well as a type of fluorescing vitrinite—were reported to occur in Illinois Basin coals by Teichmüller (1974a, 1974b) and Spackman et al. (1976). We are currently investigating these fluorescent macerals.

Another group of liptinite macerals that have been reported in Illinois Basin coals are resin rodlets. Kosanke and Harrison (1957) describe a variety of these macerals, including some that are fusinized to such a high degree that they are often confused with sclerotia because of their high reflectance. Kosanke and Harrison have stated that no true sclerotia have been found in Illinois coals.

Mineral matter

Four groups of minerals commonly occur in the coals of the Illinois Basin: clay minerals, quartz, carbonates, and sulfides. Only the latter group have properties that enable them to be studied microscopically in reflected light. Pyrite is the common sulfide, and it varies considerably in abundance both laterally and vertically in the coals. In over 60 face channel samples (exclusive of mineral partings of 3/8 inch [1 cm] and thicker) of various seams in Illinois, the pyrite content of the mineral-matter fraction of the coal varied from 7 to 48 percent by weight (Rao and Gluskoter, 1973). In only a few samples have the grain size of the pyrite been determined. These results show more than half the grains (on a grain number basis) were less than 2 μm across. The mean grain size, on weight basis, would be much larger, because pyrite is much more dense than is the organic matter. Framboids, 5 to 10 μm in diameter, occur in trace amounts in most samples. Many nodules of pyrite are quite large; some are more than 10 cm across. Pyrite is most abundant in fusain, but it is also common in clarain and less common in vitrain bands (Gluskoter and Simon, 1968). Pyrite is common along cleat types of fractures. Marcasite is rare, as are other sulfides in comparison to pyrite. Sphalerite is a common trace mineral in coals throughout the coal field, notably in northwestern Illinois, where samples contain up to 1 percent sphalerite (Hatch, Gluskoter, and Lindahl, 1976). There the sphalerite occurs as epigenetic fillings in fractures, cleat surfaces, and other formerly open spaces in the coal (Cobb et al., 1978).

The following summarizes the research reported by Rao and Gluskoter (1973) on the occurrence and distribution of minerals in Illinois coals. The minerals were separated from coal material by use of a low-temperature ashing apparatus and the mineral composition of the residue was determined mainly by x-ray diffraction methods. Their samples were face channel samples representing the entire seam exclusive of mineral partings 3/8 inch (1 cm) or more thick. The mineral composition (average) of the samples was 52 percent clay (illite $>$ expandable clays $>$ kaolinite), 23 percent pyrite, 15 percent quartz, and 9 percent carbonates (mainly calcite). Other minerals commonly observed in trace amounts are siderite, dolomite, feldspar, gypsum, marcasite, and sphalerite. Illite is the predominant clay

TABLE 7. Comparison of maceral contents of Illinois and Appalachian coal seams[a]

Coal seam	Location	Volume (%), mineral-matter free basis		
		Vitrinite	Liptinite[b]	Inertinite[c]
Herrin (No. 6)	NW Illinois	90	7	2
	NE Illinois	81	10	10
	WC Illinois	85	7	9
	EC Illinois	86	6	9
	SW Illinois	74	14	12
	SE Illinois	90 (84)[d]	3 (8)[d]	8 (8)[d]
Springfield-Harrisburg (No. 5)	NW Illinois	87	7	7
	NE Illinois	82	7	12
	WC Illinois	76	13	12
	SW Illinois	84	9	7
	SE Illinois	79 (82)[d]	9 (9)[d]	11 (10)[d]
Pittsburgh	Pennsylvania	75	7	19
		77	6	17
		73	6	21
		78	6	16
		75	7	18
		74	6	20
		73	6	21
		77 (75)[d]	6 (6)[d]	17 (19)[d]
C-Seam	E. Kentucky	66	10	24
		68	9	24
		66	9	26
		65 (66)[d]	9 (9)[d]	26 (25)[d]
High Splint	E. Kentucky	52	9	39
		54	10	36
		46	13	41
		55 (52)[d]	10 (11)[d]	36 (38)[d]
Winefrede	E. Kentucky	61	9	29
		56	10	34
		61	8	31
		56 (59)[d]	10 (9)[d]	34 (32)[d]

[a]Data for Illinois Coals from Table 5, for seams in Pennsylvania and Eastern Kentucky from Leonard (1964).
[b]Exinite and resinite.
[c]Semifusinite, fusinite, macrinite, and micrinite.
[d]Average.

mineral in coals of the Illinois Basin. Kaolinite is rather uniform in most samples and much of it is thought to have formed in place (authigenic), but relatively large amounts of kaolinite are reported to occur along alluvial channels in the coal seams, where the coal is overlain by transitional or nonmarine rocks. Pyrite is variable in the coals, as described above. Quartz was present in all samples studied and ranged from 2 to 28 percent of the mineral matter; samples containing less than 5 percent quartz were rare. The mineralogy of the mineral matter in samples of the Herrin (No. 6) Coal from a large number of locations was studied and trends were observed. The most notable trend was the increase of calcite and the decrease of clay across the basin from the northeast to the southwest.

A delta distributary system was judged by Rao and Gluskoter (1973) to be the best model to explain the differences and trends of the mineral data in the Herrin Coal. Their model consists of three zones: (1) a landward area to the northeast and east of the coal field, (2) a river that meandered southward through a peat swamp and deposited alluvial sediments along a channel (Palmer, Jacobson, and Trask, 1979; see pages 92-102), and (3) an open marine environment some distance toward the west and southwest.

A detailed study of the minerals in the Springfield-Harrisburg (No. 5) Coal (Ward, 1977), based on face channel samples taken from numerous exposures of this seam through the coal field, provides a large data base for useful geologic considerations. Ward found the average mineral composition of the mineral matter within this coal to be similar to that in the Herrin Coal reported by Rao and Gluskoter (1973). Ward interpreted the ratio of the kaolinite/mixed-layer clays to be indicative of the amount of sediment that was supplied to the peat swamp. Mixed-layer (expandable) clays were found to be most abundant in shelf and channel areas where the supply of sediment was abundant. Kaolinite is more abundant in the more basinward areas and in sediment-starved areas (in contrast to that observed in the Herrin Coal discussed above). Ward also concluded that much of the kaolinite formed in place and that it formed by precipitation of dissolved ions or gels of silica and alumina that were present in the waters of the swamp. He considers this precipitation to have been catalyzed by organic acids in the peat.

Rank

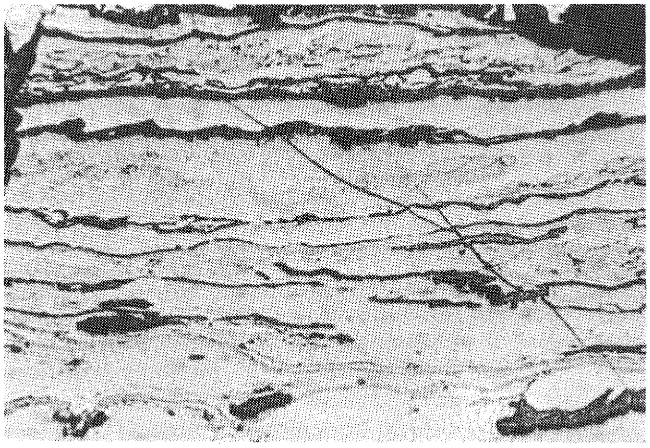
As shown in figure 1 and tables 2 and 3, the rank of the coals in the Illinois Basin generally increases from high volatile *C* bituminous (ASTM classification, D388) in the northwest to high volatile *A* bituminous in the southeastern part of Illinois, first reported by Cady (1935). The coals belong to class numbers 5 through 9 of the United Nations classification (UN, 1956). Damberger (1971) reported that the increase in rank corresponds to increases in structural depth contours in all but the southern part of the basin. In southern Illinois lines of equal rank cross the structural contours; there, the rank of the coal increases, whereas the seams now occur at shallower depths. Damberger (1971) suggested two possible explanations for this: (1) that the coal seams were originally deeper and hence more coalified before a tectonic uplift and closure of the southern part of the basin, and (2) that the southeastern part of the basin was subjected to increased coalification caused by a plutonic intrusion.

Although data for reflectance (tables 5 and 6) range from .47 to .60 percent in the central part of Illinois, they systematically increase to more than 1.0 percent in the southeastern part of Illinois. The percentage generally increases with increasing calorific value and with decreasing volatile matter of the coals, but not to a high degree of correlation. In a study of drill cuttings of coals from seven wells in east-central and southeastern regions of Illinois, Kaegi (1976) found the mean reflectance to increase at an average rate of 0.022 to 0.099 percent for each 100 meters of depth (about 0.07 to 0.30 percent R per 1000 ft).

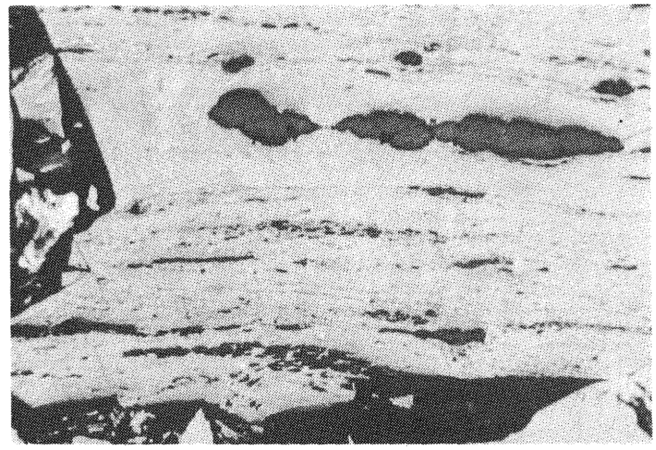
It also should be noted that the rank change across the Illinois Basin spans the "first coalification jump" of Teichmüller (1975) and the "first discontinuity in the coal metamorphic series" of Thompson and Benedict (1974). Thus, in the single coal seams that span the basin, significant fundamental changes in the nature of the coal must occur.

Coking properties

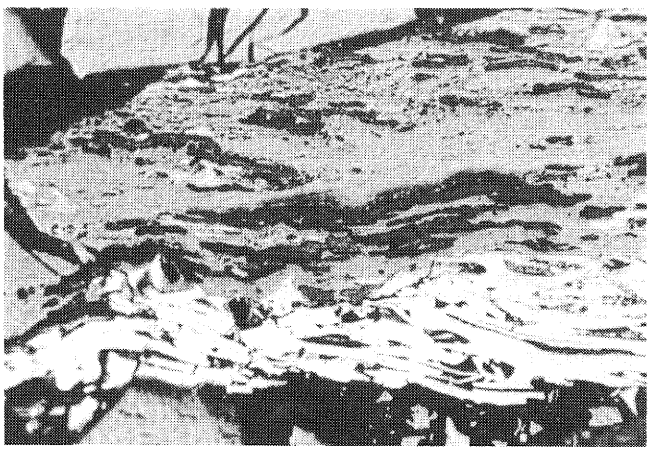
Although most of the coal mined in the Illinois Basin is used to generate steam at electric power plants, some pro-



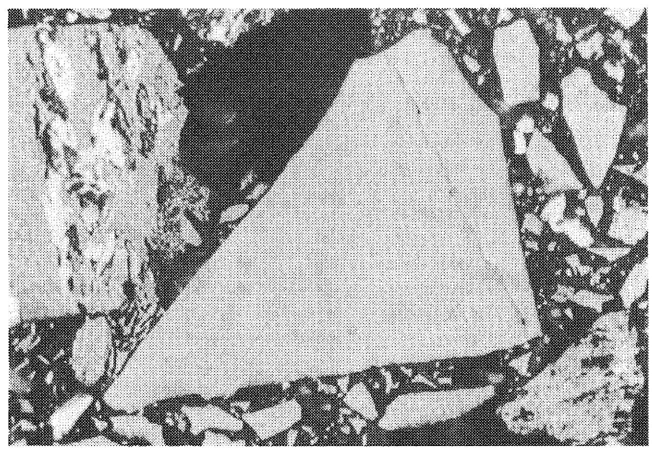
A. No. 6 Coal, Burning Star No. 5 mine, showing long stringers of cutinite (dark) interlayered with vitrinite (gray) and scattered inclusions of ovoid-shaped sporinite (dark, lower half).



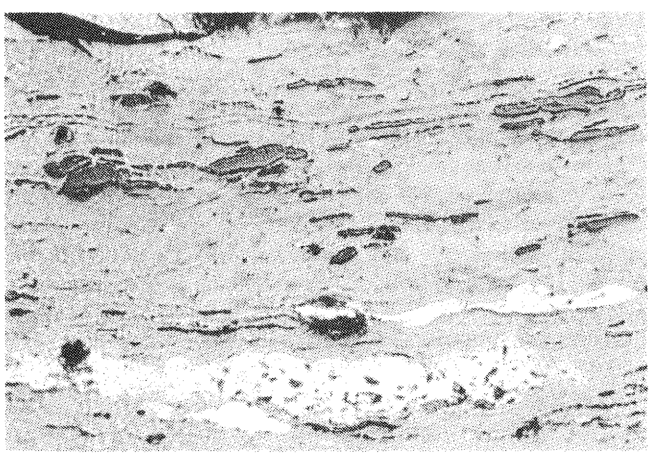
B. No. 6 Coal, Burning Star No. 5 mine, showing typical occurrence of resinite (large dark masses) and scattered sporinite (dark) and fluorinite (dark, small, elliptical masses in lower center) in vitrinite (gray).



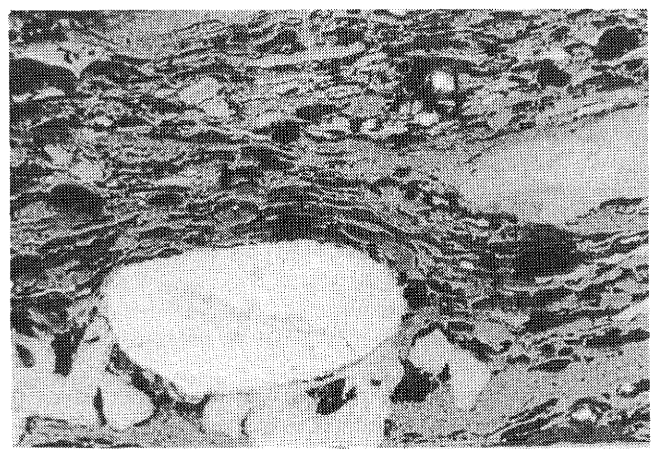
C. No. 6 Coal, Burning Star No. 5 mine, showing typical assemblage of vitrinite (gray), sporinite (dark gray), and fusinite (white). The latter displays collapse structure.



D. No. 6 Coal, Burning Star No. 4 mine, showing large particle of vitrinite. This particle shows two of the important properties of "pseudovitrinite," uniformly high reflectance and serrated edges.



E. No. 5 Coal, Captain mine, showing vitrinite (gray) and inclusions of dark exinites (mainly sporinite) and fusinite (white).



F. No. 5 Coal, Burning Star No. 4 mine, showing large macrinite particle (white), semifusinite (light gray), sporinite, and possibly other exinites (dark), all interlayered in vitrinite (gray). Differential compaction structures are shown around the macrinite particle.

100 μm

Figure 4. Photomicrographs showing assemblages of macerals in Illinois coals, in reflected light with oil immersion, all at the same magnification.

duction in southern Illinois, from the No. 6 seam in Franklin and Jefferson Counties and from the No. 5 seam in Saline County, is used in blends for use in the manufacture of coke. Numerous studies—particularly Jackman and others (1956); Jackman, Eissler, and Reed (1959); and Jackman and Helfinstine (1967)—have shown that these coals can be used in blends with higher-ranked coals to produce a coke of high strength and metallurgical quality. The main disadvantage of using Illinois Basin coals in the manufacturing of coke is their generally higher sulfur content and lower yields of coke caused by higher content of moisture and volatile matter in comparison with the coking coals from other fields. Thompson and Benedict (1976) have shown that coals from the Illinois Basin tend to produce low-reflectance cokes that lack mosaic structure and have a high reactivity with carbon dioxide.

The effects of the petrographic composition of the Illinois Basin coals on coking characteristics were studied by Marshall and others (1958). Harrison, Jackman, and Simon (1964) were able to modify the Schapiro-Gray system to use petrographic characteristics to predict the coking properties of Illinois coals and various coal blends.

Recent work by Jackman and Helfinstine (1970) and Helfinstine (1976) has shown that the strength of cokes made from Illinois coal can be greatly improved by preheating the coal before it is charged into the coke oven.

REFERENCES

AMERICAN SOCIETY FOR TESTING AND MATERIALS, 1977, Annual book of ASTM standards, part 26, Gaseous fuels; coal and coke; atmospheric analysis: American Society for Testing and Materials, Philadelphia, PA, 837 p.

ARESCO, S. J., C. P. HALLER, and R. F. ABERNETHY, 1960, Analyses of tipple and delivered samples of coal collected during fiscal year 1959: U.S. Bureau of Mines Report of Investigation 5615, 20 p.

ASHLEY, G. H., 1918, Cannel coal in the United States: U.S. Geological Survey Bulletin 659, 127 p.

BENEDICT, L. G., and R. R. THOMPSON, 1973, Coal and coke petrography and coke reactivity [preprint]: Geological Society of America, Northeast Section, Allentown, PA, p. 1-13.

BENEDICT, L. G., R. R. THOMPSON, J. J. SHIGO III, and R. P. AIKMAN, 1968, Pseudovitrinite in Appalachian coking coals: Fuel, v. 47, p. 125-143.

CADY, G. H., 1935, Classification and selection of Illinois coals: Illinois State Geological Survey Bulletin 62, 354 p.

CAMERON, A. R., 1978, Megascopic description of coal with particular reference to seams in southern Illinois, *in* R. R. Dutcher, [ed.], Field description of coal, ASTM STP 661, American Society for Testing and Materials, Philadelphia, PA, p. 9-32.

COBB, J. C., J. D. STEELE, C. G. TREWORGY, J. F. ASHBY, and S. J. RUSSELL, 1978, The geology of zinc in coals of the Illinois Basin: Final report to U.S.G.S. contract 14-08-0001-G-249, 69 p.

DAMBERGER, H. H., 1971, Coalification pattern of the Illinois Basin: Economic Geology, v. 66, no. 3, p. 488-494.

FIELDNER, A. C., W. E. RICE, and H. E. MORAN, 1942, Typical analyses of coals of the United States: U.S. Bureau of Mines Bulletin 446, p. 22-25.

GLUSKOTER, H. J., and O. W. REES, 1964, Chlorine in Illinois coal: Illinois State Geological Survey Circular 372, 23 p.

GLUSKOTER, H. J., and R. R. RUCH, 1971, Chlorine and sodium in Illinois coals as determined by neutron activation analyses: Fuel, v. 50, no. 1, p. 65-76.

GLUSKOTER, H. J., and J. A. SIMON, 1968, Sulfur in Illinois coals: Illinois State Geological Survey Circular 432, 28 p.

HARRISON, J. A., H. W. JACKMAN, and J. A. SIMON, 1964, Predicting coke stability from petrographic analyses of Illinois coals: Illinois State Geological Survey Circular 366, 20 p.

HATCH, J. R., H. J. GLUSKOTER, and D. C. LINDAHL, 1976, Sphalerite in coals from the Illinois Basin: Economic Geology, v. 71, no. 3, p. 613-624.

HELFINSTINE, R. J., 1976, Charging preheated coals into a pilot coke oven: Ironmaking Proceedings Association of Industrial Mining Engineers, v. 35, p. 440-449.

HELFINSTINE, R. J., N. F. SHIMP, M. E. HOPKINS, and J. A. SIMON, 1971, Sulfur reduction of Illinois coals—washability studies. Part 1: Illinois State Geological Survey Circular 462, 44 p.

HELFINSTINE, R. J., N. F. SHIMP, M. E. HOPKINS, and J. A. SIMON, 1974, Sulfur reduction of Illinois coals—washability studies. Part 2: Illinois State Geological Survey Circular 484, 32 p.

HOPKINS, M. E., R. B. NANCE, and C. G. TREWORGY, 1979, Mining geology of Illinois coal deposits, *in* J. E. Palmer and Russell R. Dutcher [eds.], Depositional and structural history of the Pennsylvanian System of the Illinois Basin: Guidebook for field trip no. 9, part 2, Ninth International Congress of Carboniferous Stratigraphy and Geology, p. 142-151.

HUTCHISON, H. C., 1977, Map of southwestern Indiana showing locations of active coal mines: Indiana Geological Survey.

JACKMAN, H. W., R. L. EISSLER, and R. J. HELFINSTINE, 1956, Coke from medium-volatile and Illinois coals: Illinois State Geological Survey Circular 278, 24 p.

JACKMAN, H. W., R. L. EISSLER, and F. H. REED, 1959, Coking coals of Illinois—their use in blends for metallurgical coke: Illinois State Geological Survey Circular 219, 30 p.

JACKMAN, H. W., and R. J. HELFINSTINE, 1967, A survey of the coking properties of Illinois coals: Illinois State Geological Survey Circular 412, 27 p.

JACKMAN, H. W., and R. J. HELFINSTINE, 1970, Preheating coal blends as a means of increasing coke strength: Illinois State Geological Survey Circular 453, 15 p.

JANUS, J. B., 1975, Analyses of tipple and delivered samples of coal collected during fiscal year 1974: U.S. Bureau of Mines Report of Investigations 7997, 6 p.

JANUS, J. B., 1976, Analyses of tipple and delivered samples of coal collected during fiscal year 1975: U.S. Bureau of Mines Report of Investigations 8115, 5 p.

JANUS, J. B., 1977, Analyses of tipple and delivered samples of coal collected during the period July 1975 through September 1976: U.S. Bureau of Mines Report of Investigations 8213, 7 p.

KAEGI, D. D., 1976, A coal rank profile of southeastern Illinois as determined by vitrinite reflectance: M.S. thesis, Southern Illinois University, Carbondale, 98 p.

KIRKPATRICK, H. N., 1971, Annual Report, Kentucky Department of Mines and Minerals: Kentucky Department of Mines and Minerals, 173 p.

KOSANKE, R. M., 1951, A type of boghead coal from Illinois: American Journal of Science, v. 249, p. 444-450.

KOSANKE, R. M., and J. A. HARRISON, 1957, Microscopy of the resin rodlets of Illinois coal: Illinois State Geological Survey Circular 234, 14 p.

LEONARD, J. W., 1964, Grindability tests—short cut to blending coals for strong coke: Mining Engineering, v. 16, no. 3, p. 45-47.

McCABE, L. C., 1934, The lithology of coal No. 6: Transactions of the Illinois State Academy of Science, v. 25, no. 4, p. 149-150.

MARSHALL, C. E., J. A. HARRISON, J. A. SIMON, and M. A. PARKER, 1958, Petrographic and coking characteristics of coal: Illinois State Geological Survey Bulletin 84, 120 p.

NEAVEL, R. C., 1961, Petrographic and chemical composition of Indiana coals: Indiana Geological Survey Bulletin 22, 81 p.

NEAVEL, R. C., and G. K. GUENNEL, 1960, Indiana paper coal: Journal of Sedimentary Petrology, v. 30, p. 241-248.

PALMER, J. E., R. J. JACOBSON, and C. B. TRASK, 1979, Depositional environments of strata of Late Desmoinesian age overlying the Herrin (No. 6) Coal Member in southwestern Illinois, *in* J. E. Palmer and Russell R. Dutcher [eds.], Depositional and

structural history of the Pennsylvanian System of the Illinois Basin: Guidebook for field trip no. 9, part 2, Ninth International Congress of Carboniferous Stratigraphy and Geology, p. 92-102.
PARKS, B. C., 1949, Petrographic analysis of coal by the particle count method: Economic Geology, v. 44, no. 5, p. 376-424.
PARKS, B. C., and H. J. O'DONNELL, 1956, Petrography of American coals: U.S. Bureau of Mines Bulletin 550, 193 p.
PAUL WEIR COMPANY, 1969, Shipping coal mines: Paul Weir Co., Chicago.
RAO, C. P., and H. J. GLUSKOTER, 1973: Occurrence and distribution of minerals in Illinois coals: Illinois State Geological Survey Circular 476, 56 p.
REES, O. W., 1966, Chemistry, uses, and limitations of coal analyses: Illinois State Geological Survey Report of Investigations 220, 56 p.
SHAVER, R. H., A. M. BURGER, G. R. GATES, H. H. GRAY, H. C. HUTCHISON, S. J. TELLER, J. B. PATTON, C. B. REXROAD, N. M. SMITH, W. J. WAYNE, and C. E. WIER, 1970, Compendium of rock-unit stratigraphy in Indiana: Indiana Geological Survey Bulletin 43, 229 p.
SPACKMAN, W., A. DAVIS, and G. D. MITCHELL, 1976, The fluorescence of liptinite macerals: Brigham Young University of Geological Studies, V. 22, part 3, p. 59-75.
TEICHMÜLLER, M., 1974a, Über neue Macerole der Liptinite-Gruppe und die Entstehung von Micrinite: Fortschritte in der Geologie von Rheinland und Westfalen, v. 24, p. 37-64.
TEICHMULLER, M., 1974b, Generation of petroleum-like substances in coal seams as seen under the microscope, *in* Advances in Organic Geochemistry, 1973, Technip, Paris, (Proceedings 6th International Meeting on Organic Geochemistry, Rueil-Malmaison France, September 18-21, 1973), p. 321-349.
TEICHMÜLLER, M., 1975, Origin of the petrographic constituents of coal, *in* Stack's Textbooks of Coal Petrology, 2nd ed., Gebrüder Bomtraege, Stuttgart, p. 176-238.
THOMAS, J., Jr., and H. H. DAMBERGER, 1976, Internal surface area, moisture content, and porosity of Illinois coals: variations with rank: Illinois State Geological Survey Circular 493, 38 p.
THOMPSON, R. R., and L. G. BENEDICT, 1974, Vitrinite and reflectance as an indication of coal metamorphism for cokemaking, *in* Carboniferous materials as indicators of metamorphism, GSA Special Paper 153, p. 94-108.
THOMPSON, R. R., and L. G. BENEDICT, 1976, Coal composition and its influence on cokemaking: Iron and Steel Maker, v. 3, no. 2, p. 21-31.
UNITED NATIONS, 1956, International classification of hard coals by type: Secretariat of the Economic Commission for Europe, Geneva, 52 p.
WARD, C. R., 1977, Mineral matter in the Springfield-Harrisburg (No. 5) Coal Member in the Illinois Basin: Illinois State Geological Survey Circular 498, 35 p.
WIER, C. E., 1973, Coal resources of Indiana: Indiana Geological Survey Bulletin 42-I, 40 p.
WIER, C. E., and H. C. HUTCHISON, 1977, Reduction of sulfur in Indiana coal by washability techniques: Indiana Geological Survey Bulletin 55, 61 p.
WILLMAN, H. B., Elwood ATHERTON, T. C. BUSCHBACH, Charles COLLINSON, John C. FRYE, M. E. HOPKINS, Jerry A. LINEBACK, and Jack A. SIMON, 1975, Handbook of Illinois stratigraphy, Illinois State Geological Survey Bulletin 95, 261 p.

Mining geology of Illinois coal deposits

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INTRODUCTION

Large coal resources and geologic conditions that are generally favorable for mining are key factors in Illinois' leading role in the United States coal industry. Illinois currently ranks fourth in total production among coal-producing states. Although the number of coal mines operating in Illinois has been declining since the early 1950s (when there were more than 150 mines), coal production has increased. Of the 100 largest mines in the country, 20 are in Illinois, including the largest underground mine (Keystone, 1978). In 1977, 70 mines in Illinois—25 underground and 45 strip—produced 54 million tons of coal (fig. 1). Underground coal production accounted for 56 percent of the total. Annual production is forecasted to increase to 93 million tons by 1985 (Malhotra and Simon, 1976).

In this report, *resources* include all coal that is 18 inches (0.5 m) or more thick and is less than 150 feet (45 m) deep (strippable coal) and all coal that is 28 inches (0.7 m) or more thick and is 150 feet (45 m) or more deep. *Demonstrated reserves* include only coal whose presence has been reliably substantiated by drilling, mines, or surface exposures.

Illinois has 161 billion (10^9) tons of bituminous coal resources, of which 20 billion (10^9) tons are strippable (Smith and Stall, 1975). Illinois ranks third in total coal resources, first in bituminous coal resources, and is second only to Montana in demonstrated reserves (U.S. Bureau of Mines, 1974). Table 1 shows the demonstrated coal reserves for the Illinois Basin Coal Field.

GEOLOGY OF THE COAL FIELD

About 65 percent of the surface area of Illinois (37,000 square miles [96,000 km^2]) is underlain by coal-bearing

TABLE 1. Demonstrated reserve base of the Illinois Basin Coal Field

	Deep reserves (millions of tons)	Strippable reserves (millions of tons)	Total reserves (millions of tons)
Illinois	53,442	12,223	65,665
Indiana	8,948	1,674	10,622
Western Kentucky	8,720	3,904	12,624
Total	71,110	17,801	88,911

SOURCE: U.S. Bureau of Mines, 1974.

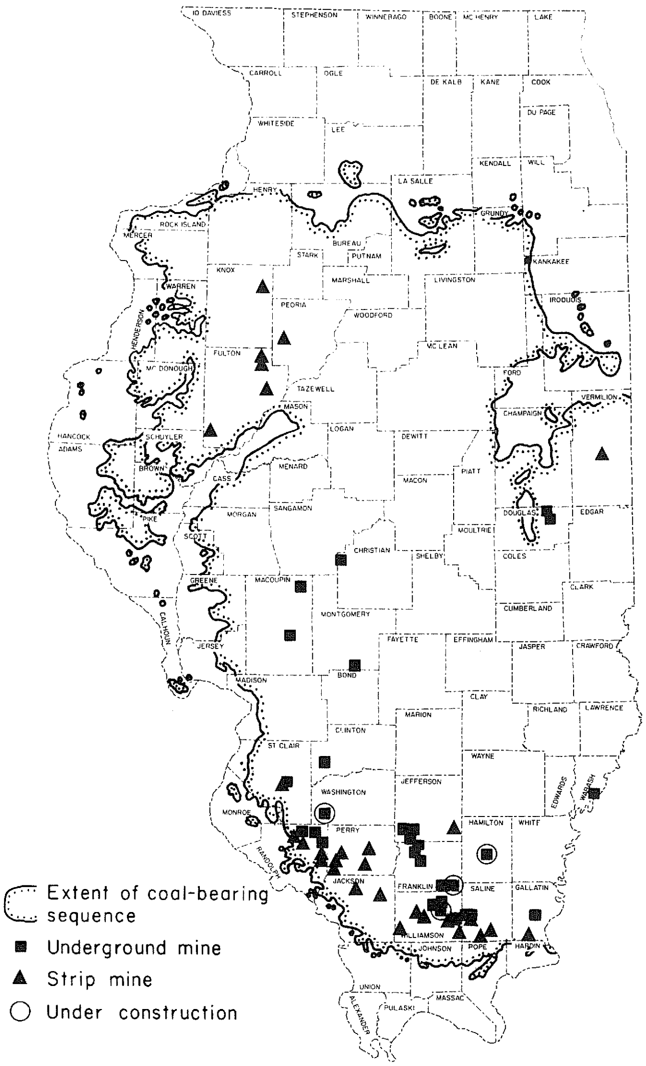

Figure 1. Operating coal mines, January 1978. (From Treworgy, Bengal, and Dingwell, 1978.)

strata of the Illinois Basin Coal Field. The coal basin extends eastward into Indiana and southeastward into Kentucky. Rock strata dip gently from the margins of the basin towards its center, in south-central Illinois, where the Pennsylvanian strata attain their maximum thickness in Illinois of about 2,500 feet (760 m). The major seams outcrop along the margins of the basin and are at depths of more than 1,000 feet (300 m) at the basin's center. Surficial deposits of glacial drift, loess, and alluvium, sometimes more than 400 feet (120 m) thick, cover most of the state.

More than 75 known coal seams occupy strata of Pennsylvanian age (Upper Carboniferous) in Illinois. The majority of these seams, however, are too thin or discontinuous to be minable. Coals within the lower Pennsylvanian, McCormick Group (fig. 2), are normally thin (less than 3 feet [< 1 m]), are of only local occurrence, and are relatively unimportant as minable resources. Most of the economic coal deposits are in the middle Pennsylvanian, Kewanee Group, particularly in the Carbondale Formation (fig. 2). Of the 161 billion (10^9) tons of identified resources in Illinois, 93 percent are in the Carbondale Formation; 74 percent are in two seams, the Herrin (No. 6) and the Springfield-Harrisburg (No. 5) Coals (fig. 3). Other coals in the Kewanee Group that have not been as intensively mapped as the Herrin and Springfield-Harrisburg Coals, but contain significant resources, are the Danville (No. 7), Colchester (No. 2), Seelyville, De Koven, and Davis Coals. Several coals within the upper Pennsylvanian, McLeansboro Group (fig. 2), are fairly widespread throughout much of the central part of the Illinois Basin; however, they are normally 2 feet or less (< 60 cm) thick and constitute only a minor surface-minable resource.

Correlations of major minable coals and associated strata of the Kewanee Group are, for the most part, well established because of the persistence of coal beds and other key stratigraphic units (mostly black shale, limestone, and underclays). Though many Illinois coals have been extensively mapped and studied, significant areas remain to be tested, particularly in the northern, eastern, and the deep central parts of the coal field.

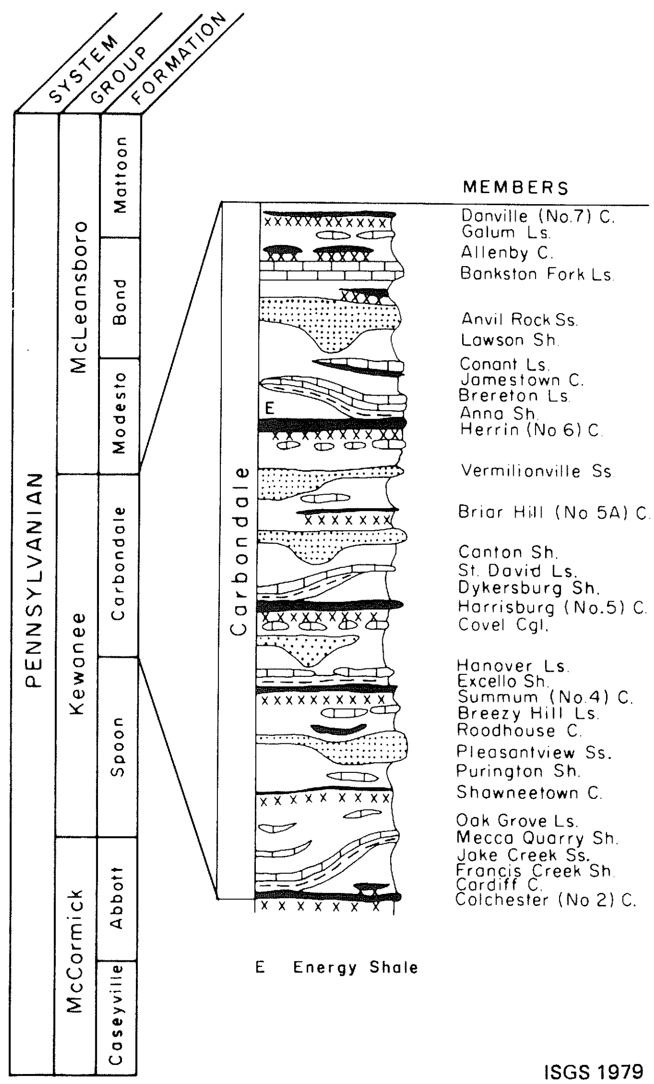

Figure 2. Generalized stratigraphic section of selected coals in Illinois (after Hopkins and Simon *in* Willman, 1975). See also Harvey et al., 1979, p. 129.

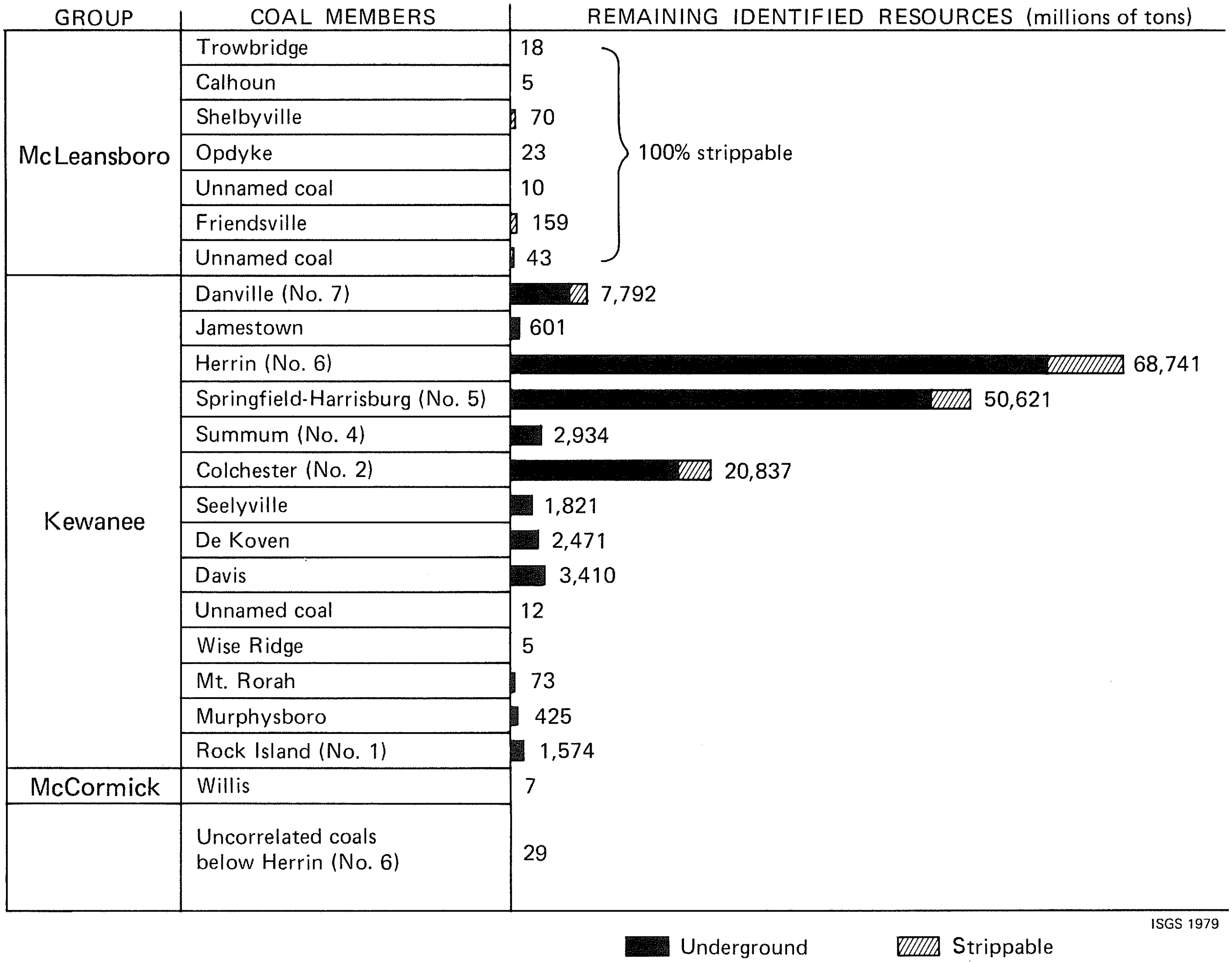

Figure 3. Remaining identified resources of coal in Illinois by coal seam, January 1976. (Modified from Smith and Stall, 1975.)

Danville (No. 7) Coal Member

The Danville (No. 7) Coal is thickest in eastern and northern Illinois. It has been extensively mined by both underground and surface methods in Vermilion County, east-central Illinois, where the coal sometimes is more than 6 feet (2 m) thick. The coal has been mined locally in northern Illinois, particularly in Livingston, La Salle, and Marshall counties. The Danville Coal has not been systematically mapped throughout the central and southern part of the coal field, but is believed to be generally less than 3 feet (1 m) thick. Only one mine, a small surface mine, currently is producing from the Danville Coal Member. In western and southern Illinois, several large surface mines that mine the Herrin Coal have Danville Coal in their highwall, but do not systematically attempt to recover it.

The sulfur content of the Danville Coal usually is more than 3 percent. An area of relatively low-sulfur coal in eastern Illinois has recently been explored; similar conditions may exist in adjacent areas.

Herrin (No. 6) Coal Member

The Herrin (No. 6) Coal Member (Carbondale Formation), the most widespread coal of minable thickness in Illinois, is present in most areas of the Illinois Basin Coal Field. It is 42 inches or more thick in an area of about 9,200 square miles (23,500 km^2) (Smith and Stall, 1975). The Herrin Coal also is widespread in western Kentucky (No. 11 Coal) and is present in southern Indiana (Herrin Coal). Equivalents also are mined in southern Iowa (Mystic Coal) and in northern Missouri (Lexington Coal).

The Herrin Coal in Illinois usually is thickest in a wide area adjacent to the Walshville channel, the course of an ancient stream that existed during and shortly after the formation of the extensive peat deposit (fig. 4). The Walshville channel can be traced for more than 190 miles (300 km) in Illinois and varies in width from about 1 to 4 miles (1.5 to 6.5 km) (Smith and Stall, 1975). Within the channel area, coal is absent; this may be due to either nondeposition or erosion. Immediately adjacent to the channel,

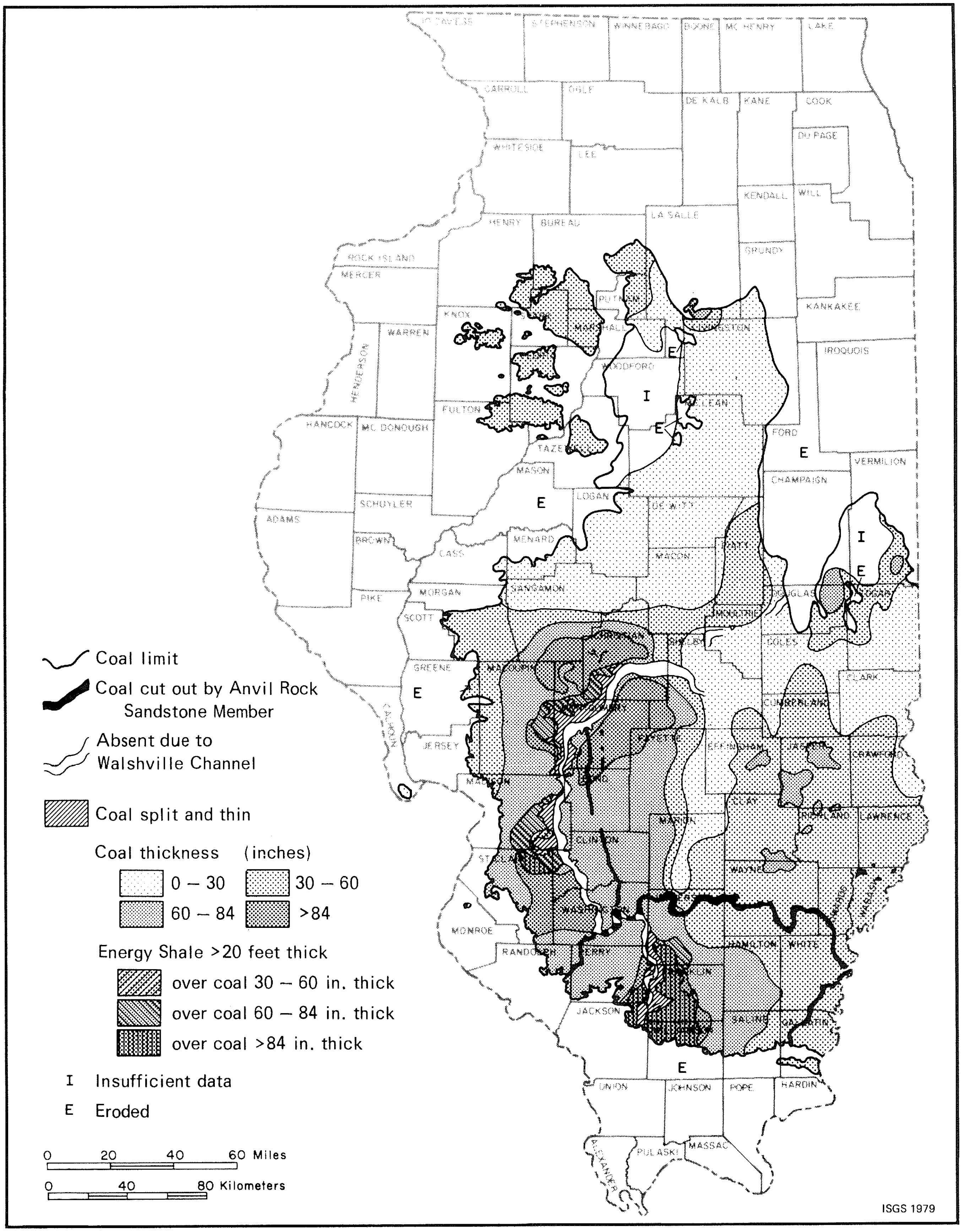

Figure 4. Generalized thickness of Herrin Coal. (From Smith and Stall, 1975.)

the coal is often thin or split by shale partings. The thick areas of coal, 7.5 feet (2.3 m) and greater, probably represent lower lying areas where thicker peat accumulated—areas more favorable for swamp development than surrounding higher areas. In southeastern and northwestern Illinois, areas away from the Walshville channel, the Herrin Coal is normally 3 to 6 feet (1 to 2 m) thick.

Closely associated with the channel, the Energy Shale Member, a crevasse splay deposit of gray shale, siltstone, and sandstone, directly overlies the Herrin Coal. At several localities adjacent to the channel, the Herrin Coal is immediately overlain by more than 100 feet (> 30 m) of Energy Shale. In areas where the shale is 20 feet (6 m) or more thick, the Herrin Coal has a relatively low sulfur content of 0.5 to 2.5 percent (Gluskoter and Simon, 1968).

Roof characteristics of the Herrin Coal. Where present, the Energy Shale immediately overlies the Herrin Coal (fig. 5). In other areas, the coal is overlain by the Anna Shale Member (marine black shale) or the Brereton Limestone Member; in some places both members are absent and higher stratigraphic units rest directly on the coal. The variability of the marine Brereton Limestone and of the transitional to nonmarine Energy Shale produces the principal differences in roof character. The Brereton Limestone is the preferred horizon for anchoring roof bolts. Where the Energy Shale is thin or absent, the Brereton commonly lies within 6 feet (3 m) of the top of the coal. Although geologic mapping of underground mines has indicated that the continuity of the Brereton Limestone may change considerably within small areas, the following generalizations can be made.

In southeastern Illinois the Brereton Limestone is well developed, normally more than 4 feet (> 1 m) thick, and very persistent, even where it overlies as much as 20 feet (6 m) of Energy Shale (fig. 4). Where thin deposits of Energy Shale immediately overlie the coal, the roof is generally less stable. Where thick deposits of Energy Shale, more than 20 feet (> 6 m), overlie the coal, roof conditions range from good to poor (fig. 4). Roof conditions are good where the Energy Shale is relatively homogeneous siltstone or shale. In other areas the shale has abundant sandy, silty, carbonaceous, and micaceous partings and forms a less competent roof, especially when wet. Some mines operating near the Walshville channel have encountered a sandy facies of the Energy Shale that contains abundant water and produces very wet mining conditions. Thin coal riders are a common local occurrence in Energy Shale roof and frequently produce small roof falls. Additional description of mining conditions in gray shale roof areas can be found in Nelson, 1979.

In southwestern Illinois, the Brereton Limestone is also well developed and generally persistent; however, studies have demonstrated much local variation. The Bankston Fork Limestone Member is also well developed within this area (fig. 2). Since the major intervening clastic units (Lawson Shale and Anvil Rock Sandstone, fig. 2) between these limestones are relatively thin or absent in southwestern Illinois, the percentage of competent limestone within 50 to 60 feet (15 to 18 m) above the coal is greater than in any other area of the state. This allows for fairly stable roof even at relatively shallow mining depths, 100 feet (30 m) or less.

In west-central Illinois the Brereton Limestone is locally lenticular and discontinuous and may be thin to absent over thick, 4 to 6 feet (1 to 2 m), Anna Shale or over thin, 2 to 6 feet (0.5 to 2 m), Energy Shale. Detailed mapping in underground mines within this part of the state has shown local variability of the immediate roof strata and no discernible trends of continuity (Krausse et al., 1979).

It is generally impossible to map areas of specific mine roof conditions from drill-hole data. Experience has shown that exploratory drill-hole data may indicate only the type of stratigraphic variability to be expected in the area. Experience has shown also that wet conditions may be encountered in areas of mining where no Brereton Limestone underlies thin deposits, 3 to 8 feet (1 to 2.5 m), of the Anvil Rock Sandstone Member.

In northern Illinois and parts of eastern Illinois, the Brereton Limestone is normally thin, less than 2 feet (0.5 m), or only locally developed. In northwestern Illinois, the Herrin Coal is often overlain by a discontinuous claystone as much as 2 feet (0.5 m) thick called "white top" (Damberger, 1970); associated with it are irregular claystone dikes of variable thickness in the coal vein that have severely affected the roof stability. These dikes increase the ash content of the mined coal in both underground and strip operations.

Springfield-Harrisburg (No. 5) Coal Member

The Springfield-Harrisburg (No. 5) Coal Member (Carbondale Formation) is also widespread in Illinois (fig. 6). The coal is 42 inches (1 m) or more thick over an area of 7,630 square miles (19,760 km^2) (Smith and Stall, 1975). It is currently deep mined in only five mines. The Springfield-

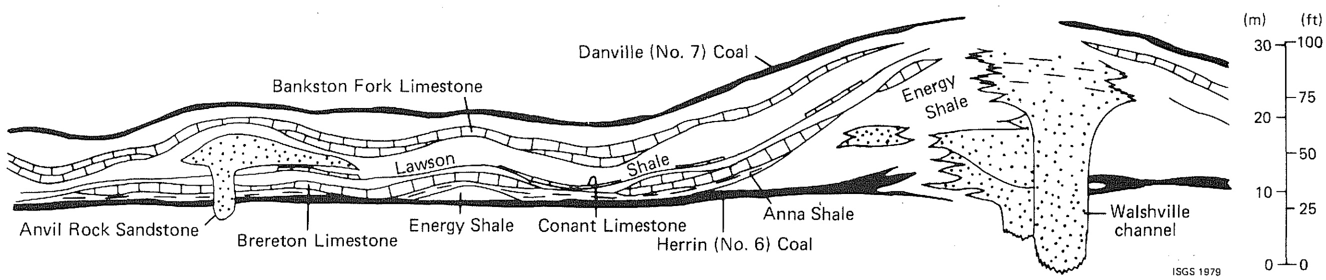

Figure 5. Diagrammatic cross section showing stratigraphic relations of Walshville and Anvil Rock channels and roof strata of the Herrin (No. 6) Coal.

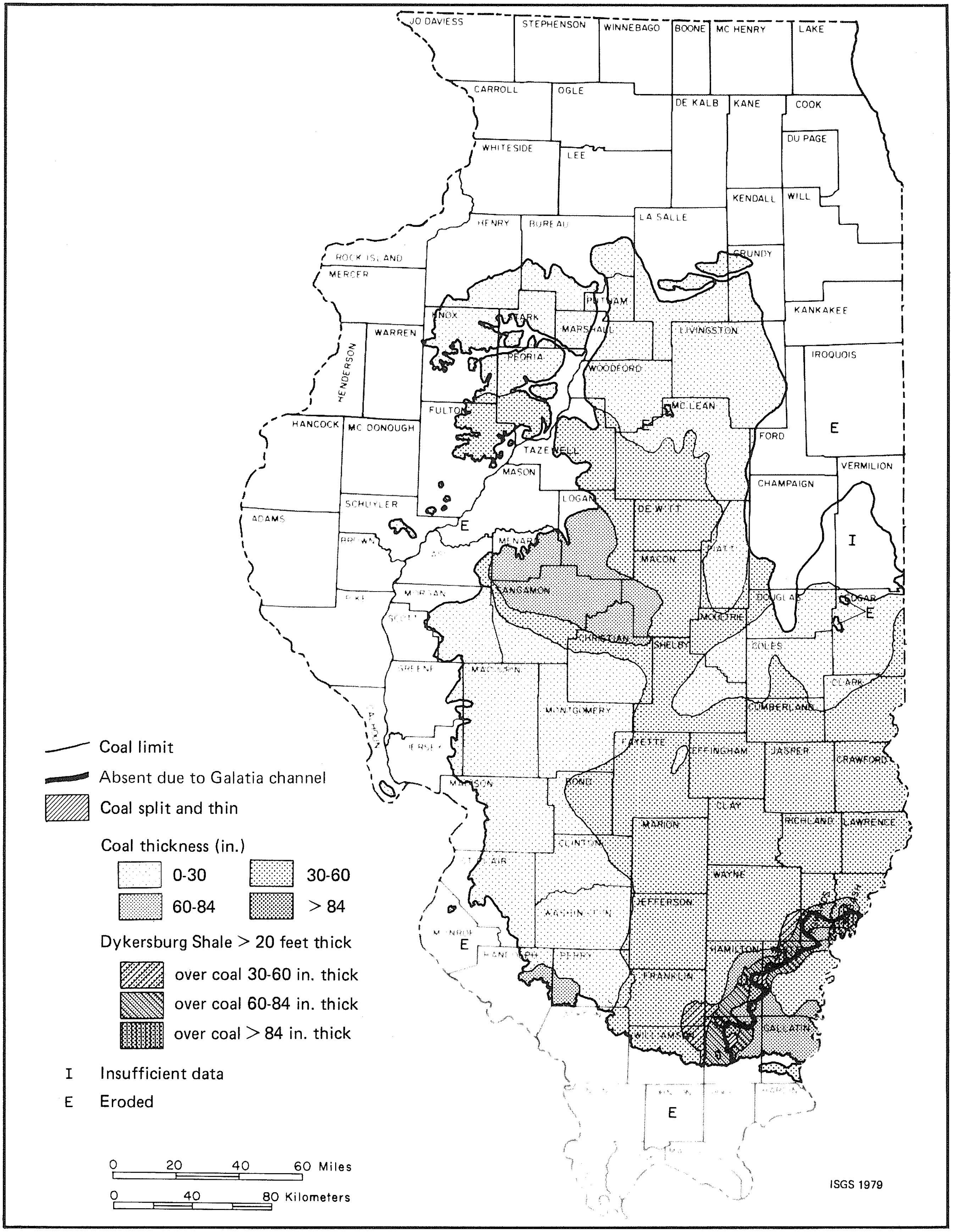

Figure 6. Generalized thickness of the Springfield-Harrisburg Coal. (Modified from Smith and Stall, 1975.)

Harrisburg Coal is the principal coal mined in Indiana (Springfield V Coal) and western Kentucky (No. 9 Coal). It is correlated with the Summit Coal of Missouri.

The Springfield-Harrisburg Coal is consistently thick over two large areas in the southeastern and northwest-central parts of Illinois (fig. 6). In southeastern Illinois, where it is known as the Harrisburg Coal, the thickness and quality of the coal are related to the prominent, southwesterly trending channel system, which is here named the Galatia channel after the town of Galatia in northwestern Saline County. It represents an ancient stream that existed during or close to the time of the deposition of the Harrisburg Coal. The stream eroded or prevented development of coal within its course. A sandstone and siltstone deposit occupies the position of the Harrisburg Coal in the Galatia channel. The pattern of coal development suggests that the stream was in part contemporaneous with the peat swamp. The areas of thickest peat accumulation parallel the trend of the channel; immediately adjacent to the channel, the coal is split by shale partings. The Galatia channel deposits are generally from ½ to ¾ mile (0.8 to 1.2 km) wide and have been mapped for more than 150 miles (240 km) in Illinois (Hopkins, 1968) and Indiana (Donald Eggert, personal communication).

The stratigraphic relations of rocks overlying the Harrisburg Coal are similar to those described for the Herrin (No. 6) Coal. Adjacent to the channel, the Harrisburg Coal is overlain by the Dykersburg Shale Member, which is composed of crevasse splay deposits of gray sandy shale. Away from the channel, the coal is overlain by a marine sequence of black shale and limestone. The sulfur content of the coal underlying the Dykersburg Shale (mainly nonmarine) generally is lower ($<$ 2.5 percent) than that of the coal underlying rocks of marine origin (3 to 5 percent) (Hopkins, 1968).

The second area of thick No. 5 Coal development is in central and western Illinois, where the coal is known as the Springfield Coal. The coal shows no significant variations in quality throughout the area and probably is everywhere overlain by a thin, black, fissile shale. Only surface-mining operations are now active in this area, although formerly underground mining near Springfield in Sangamon County and in the Canton-Peoria district in Fulton and Peoria Counties was extensive.

Roof characteristics of the Springfield-Harrisburg Coal. The variation in characteristics of the roof strata as it affects mining conditions is similar to conditions associated with the Herrin Coal, particularly in regard to black fissile shale and gray sandy shale. The Dykersburg Shale has the same range of thickness, as much as 100 feet (30 m), as the Energy Shale and is similar in general characteristics. Depending on the thickness, the relative amount of sand or silt, and the nature of bedding or interbedding (with the coal), variable roof conditions are to be expected in areas of Dykersburg Shale. Where it is thin, the Dykersburg Shale tends to be finer grained and softer and is not as competent a roof as the thicker, more sandy facies.

In most of the area where the Springfield-Harrisburg Coal occurs, the coal is overlain by a black fissile shale similar to the Anna Shale that overlies the Herrin Coal. The black shale averages about 2 feet (0.5 m) thick and is regionally persistent. In general, it forms a fairly competent roof unless extensively disturbed by clay dikes, which are common in the northwestern part of the coal field (Damberger, 1970).

The thickness and quality of the St. David Limestone (fig. 2) overlying the Springfield-Harrisburg Coal may be important in determining the quality of the roof strata, although no studies on this subject have been made. The St. David Limestone is normally much thinner than the Brereton Limestone that overlies the black Anna Shale; consequently, it does not constitute as competent an anchor rock for roof bolting. The St. David Limestone is thin or absent over much of southeastern Illinois.

Colchester (No. 2) Coal Member

The Colchester (No. 2) Coal is the most widespread coal in Illinois and possibly in the United States (Wanless, 1957). The coal is correlated with the Whitebreast Coal in Iowa; the Indiana IIIa Coal; The Croweburg Coal of Kansas, Nebraska, Oklahoma, and Missouri (Wright, 1965); and the Colchester Coal of Kentucky (Williamson, personal communication, 1978). The Colchester Coal is thickest in northern Illinois, where it ranges from 30 to 40 inches (0.8 to 1 m) thick. The coal is 18 to 30 inches (0.5 to 0.8 m) thick in western Illinois and less than 24 inches (0.5 m) thick throughout most of central and southern Illinois.

The Colchester Coal was extensively mined in northern Illinois during the early 1900s. Most of the mapped resources of this coal are too thin to be mined underground at the present time. In recent years the only production from this seam has come from surface mines in the northwestern part of the coal field; one mine currently is producing this coal. Large areas of the coal in western Illinois are at depths of less than 100 feet (30 m) and have relatively soft overburden that requires little blasting.

Seelyville, De Koven, and Davis Coal Members

The Seelyville Coal of eastern Illinois and the De Koven and Davis Coals of southern Illinois are found at about the same stratigraphic horizon and may be in part correlative. The Seelyville is exposed and has been extensively mined in Indiana where it is known as Coal III, but has no known exposures in Illinois. The coal is believed to be 5 to 7 feet (1.5 to 2 m) thick within several counties in eastern Illinois, but because it is 500 to 1,400 feet (150 to 425 m) deep, there has been little testing. Indications are that the Seelyville Coal in some areas may contain thick shale partings that would reduce its quality and minability. One mine produced this coal for a short time during the 1960s.

The De Koven and Davis Coals have been extensively mined along their outcrop in southern Illinois, where they commonly occur stratigraphically within 10 to 40 feet (3 to 12 m) of one another. In the deeper parts of the basin, north of this outcrop, the coals are relatively untested because minable thicknesses of the Herrin and Springfield-Harrisburg Coals are present at shallower depths. The only production of De Koven and Davis Coals currently is from surface mines.

MINING CONDITIONS

Underground mining

In comparison to mining conditions in other coal fields, conditions in Illinois mines are relatively good. Coals are generally persistent over broad areas, are nearly flat lying, contain relatively few partings, and ordinarily have little associated gas. Although some water problems have been encountered, mines are generally dry. Roof strata normally contain competent beds that are within reach of roof bolts of ordinary length, usually 6 feet (1.8 m) or less. Limestones are the most desirable strata in which to anchor roof bolts. In areas where the "cap-rock" limestone is not present or not of sufficient thickness, roof conditions are less stable.

Several major tectonic structures within the Illinois Coal Basin, such as the La Salle Anticlinal Belt, Louden and Salem Anticlines, and Du Quoin Monocline (Krausse and Treworgy, 1979; see also page 106) affect the distribution, depth, and thickness of minable coals. Of primary importance are four systems of faults, located in the southern portion of the basin, which directly affect coal mines: The Shawneetown-Rough Creek Fault System, Cottage Grove Fault System, Wabash Valley Fault System, and the Rend Lake Fault System (Krausse and Treworgy, 1979).

All of the mines throughout the Illinois Coal Basin have small faults, usually of less than 4 feet (< 1 m) displacement. These faults cause local mining problems, where they affect the competency of the roof strata. Most of the faults are related to differential compaction and gravity movements during or shortly after deposition of the coal.

Coals as thin as 28 inches (0.7 m) have been mined underground in Illinois, but the thinnest coal currently mined is about 4½ feet (1.4 m) and most coals average 6 feet (1.8 m) or more thick. Only the Herrin (No. 6) and Springfield-Harrisburg (No. 5) Coals are currently mined in Illinois by underground methods.

At present the depth of underground coal mining in Illinois varies from slightly less than 100 feet to almost 1,000 feet (30 to 300 m). In areas that have shallow underground mines, normally more than one competent limestone is within the overlying bedrock, and unconsolidated surficial deposits (glacial drift) are usually less than 30 feet (9 m) thick. Where the unconsolidated sediments are in excess of 100 feet (30 m) thick and the thickness of glacial drift to bedrock overburden approaches a ratio of 1:1 or more, unstable roof conditions may develop (Hunt, personal communication, 1978). In addition, fractures in the roof strata may permit water to enter the mine from unconsolidated material lying relatively close to the coal.

Most coals in Illinois are underlain by a relatively soft underclay that commonly is about 3 feet (1 m) thick and makes a fairly soft floor, especially when wet. Floor heaving can occur when the floor has a high moisture content and is overstressed (Hunt, personal communication, 1978). Severe floor heaving of the underclay or a deeper lying shale or claystone may develop in areas where the thickness of glacial drift sediments is nearly equal to the thickness of the bedrock overburden sediments (White, personal communication, 1978).

Generally favorable mining conditions, which extend over large areas of the coal field, allow development of large underground mines. Most underground mines in Illinois produce more than 1 million tons of clean coal per year; several mines that are planned will produce more than 3 million tons per year. The largest underground mine in the United States (Peabody No. 10 Mine) is located in Illinois; it has at times produced more than 4 million tons per year.

Continuous miners and room-and-pillar methods are used in most Illinois mines. In southern Illinois, pillars in some mines are removed during retreat out of a panel. Longwall equipment has been experimented with for many years, but only recently has it been successfully adapted for mining in Illinois; two longwall panels currently are operating and several more are expected to be installed.

Surface mining (strip mining)

Most surface mines in Illinois are located near the margins of the coal field where the major seams lie near the surface (fig. 1). The prevailing gentle topographic relief and very flat lying strata are ideally suited for using large-scale mining equipment in area surface mining. The largest shovel in the world, a 180-cubic yard (138 m^3) bucket, is operating at the Southwestern Illinois Coal Co. Captain Mine. Ratios of overburden to coal thickness vary, but ratios up to 30:1 are considered practical. At present, the maximum depth of stripping is about 150 feet (40 m).

Coals as thin as 18 inches (0.5 m) are surface mined in Illinois; however, most coal is 4 feet (> 1 m) thick or greater. Most of the production is currently from the Herrin (No. 6) and the Springfield-Harrisburg (No. 5) Coals, but other seams are being actively mined including the Opdyke, Danville (No. 7), Colchester (No. 2), De Koven, Davis, and Murphysboro Coals.

The thickness and other characteristics of the glacial sediments that overlie the Pennsylvanian bedrock influence surface mining. Where the glacial material is very thick, the highwall may be unstable and incapable of standing at a high angle. Frequently the unconsolidated material and bedrock are handled separately. Bucket wheel excavators are used in several mines to remove unconsolidated material. Although many of the older mines use shovels to remove overburden, most new mines use draglines, which are generally capable of excavating to greater depths and better able to segregate overburden materials for reclamation.

Where limestones and sandstones are well developed, extensive blasting of the overburden is required. Where the overburden is mostly shale and glacial material, blasting costs are significantly lower.

With the development of large stripping equipment in recent years, several mines have begun mining the Herrin and Springfield-Harrisburg Coals by multiseam mining methods, that is, mining both coals in a single pit. The interval between these two coals varies throughout the state from 20 to 120 feet (6 to 36 m) (fig. 7). Most multiseam operations are in southwestern Illinois, where the interval between the two coals is less than 30 feet (9 m); however, at least one operation in western Illinois has mined both seams, even though the interval is more than 50 feet (15 m). In southern Illinois, the De Koven and Davis Coals

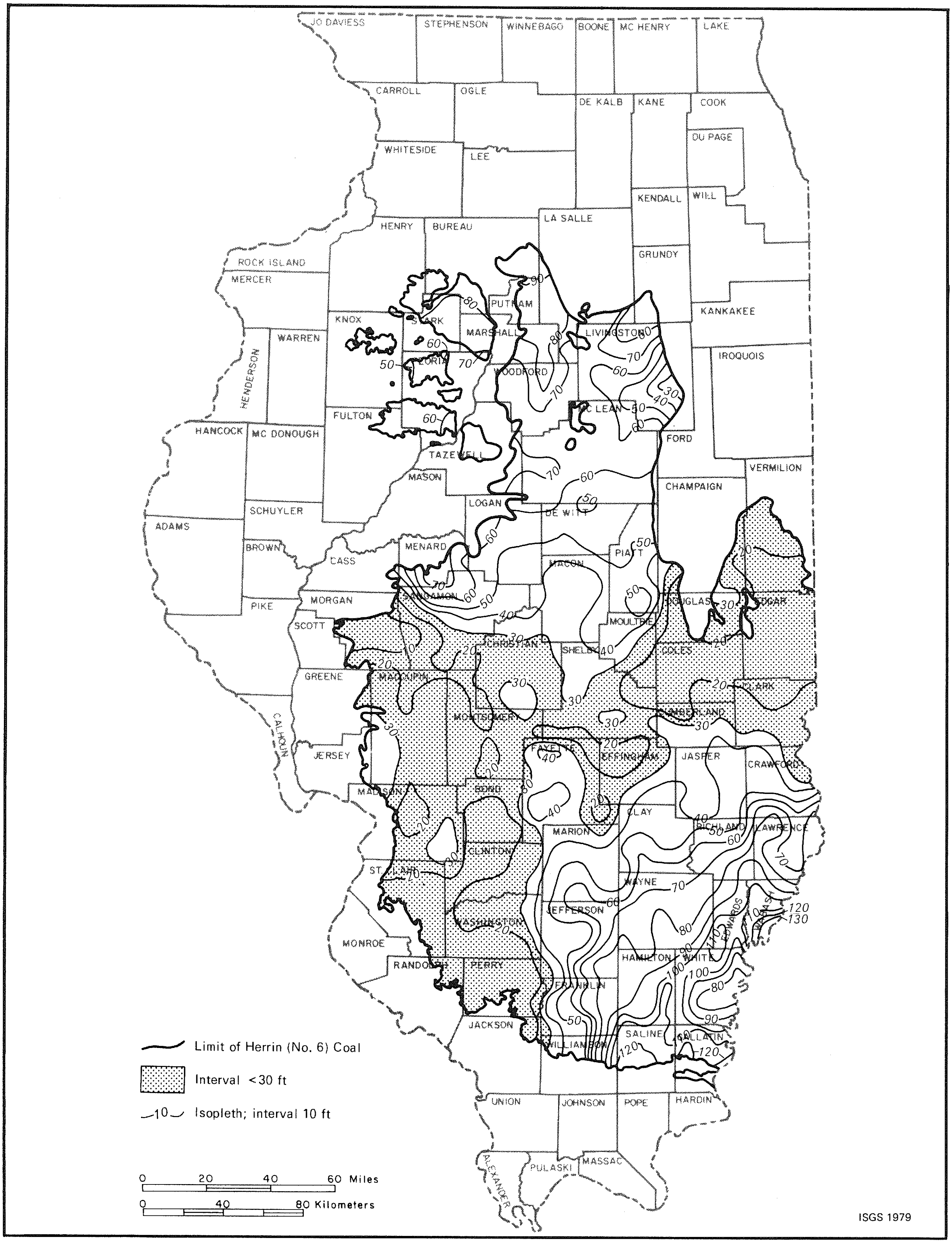

Figure 7. Generalized thickness of the interval between the Herrin and Springfield-Harrisburg Coals. (From Smith and Stall, 1975.)

commonly lie stratigraphically within 10 to 40 feet (3 to 12 m) of each other and often are mined together.

Reclamation is an important aspect of surface mining and is a significant factor in cost. Operators are required to remove top soil separately and to replace it after they regrade the spoils to the approximate original contours. The upper 4 feet (1 m) of reclaimed land must be free of large rocks and the land must be returned to its former use. Acid mine drainage is usually not a serious problem in Illinois because the low topographic relief reduces runoff and the high percentage of calcareous material in the overburden neutralizes acidic (pyritic) material.

REFERENCES

DAMBERGER, H. H., 1970, Clastic dikes and related impurities in Herrin (No. 6) and Springfield (No. 5) Coals of the Illinois Basin, *in* Depositional environments in parts of the Carbondale Formation—western and northern Illinois: Illinois State Geological Survey Guidebook Series No. 8, 119 p.

GLUSKOTER, H. J., and J. A. SIMON, 1968, Sulfur in Illinois coals: Illinois State Geological Survey Circular 432, 28 p.

HARVEY, R. D., J. C. CRELLING, R. R. DUTCHER, and J. A. SCHLEICHER, 1979, Petrology and related chemistry of coals Illinois Basin, *in* James E. Palmer and Russell R. Dutcher [eds.], Depositional and structural history of the Pennsylvanian System of the Illinois Basin: Guidebook for field trip no. 9, part 2, Ninth International Congress of Carboniferous Stratigraphy and Geology, p. 127-142.

HOPKINS, M. E., 1968, Harrisburg (No. 5) Coal reserves of southeastern Illinois: Illinois State Geological Survey Circular 431, 25 p.

KEYSTONE COAL INDUSTRY MANUAL, 1978, McGraw-Hill Mining Publications, New York, 1265 p.

KRAUSSE, H.-F., and C. G. TREWORGY, 1979, Major structures of the southern part of the Illinois Basin, *in* James E. Palmer and Russell R. Dutcher [eds.], Depositional and structural history of the Pennsylvanian System of the Illinois Basin: Guidebook for field trip no. 9, part 2, Ninth International Congress of Carboniferous Stratigraphy and Geology, p. 115-120.

KRAUSSE, H.-F., H. H. DAMBERGER, W. J. NELSON, S. R. HUNT, C. T. LEDVINA, C. G. TREWORGY, and W. A. WHITE, 1979. Engineering study of structural geologic features of the Herrin (No. 6) Coal and associated rock in Illinois: Final Report, contract H0242017, U.S. Bureau of Mines, Illinois State Geological Survey open file, 2 vols.

MALHOTRA, Ramesh, and J. A. SIMON, 1976, Illinois coal—development potential: Illinois State Geological Survey, Illinois Minerals Note 65, 20 p.

NELSON, John, 1979, Geologic effects of the Walshville channel on coal mining conditions in southern Illinois, *in* James E. Palmer and Russell R. Dutcher [eds.], Depositional and structural history of the Pennsylvanian System of the Illinois Basin: Guidebook for field trip no. 9, part 2, Ninth International Congress of Carboniferous Stratigraphy and Geology, p. 151-158.

SMITH, W. H., and J. B. STALL, 1975, Coal and water resources for coal conversion in Illinois: Illinois State Geological Survey Cooperative Resources Report 4, 79 p.

TREWORGY, C. G., Lawrence E. BENGAL, and Amy G. DINGWELL, 1978. Reserves and resources of surface-minable coal in Illinois: Illinois State Geological Survey Circular 504, p. 4.

U.S. BUREAU OF MINES, June 1974, Demonstrated coal reserve base of the United States on January 1, 1974: U.S. Bureau of Mines Mineral Industry Surveys, 6 p.

WANLESS, H. R., 1957, Geology and mineral resources of the Beardstown, Glasford, Havana, and Vermont quadrangles: Illinois State Geological Survey Bulletin 82, 233 p.

WILLMAN, H. B., Elwood ATHERTON, T. C. BUSCHBACH, Charles COLLINSON, John C. FRYE, M. E. HOPKINS, Jerry A. LINEBACK, and Jack A. SIMON, 1975, Handbook of Illinois stratigraphy: Illinois State Geological Survey Bulletin 95, 261 p.

WRIGHT, Cynthia W., 1965, Environmental mapping of the beds of the Liverpool Cyclothem in the Illinois Basin and equivalent strata in the northern Mid-continent Region: University of Illinois, unpublished Ph.D. thesis, 100 p.

Geologic effects of the Walshville channel on coal mining conditions in southern Illinois

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INTRODUCTION

The Walshville channel is an important geologic feature affecting mining of the Herrin (No. 6) Coal Member in southern Illinois. The channel is the course of an ancient river that flowed through the coal swamp during and following formation of the Herrin Coal, and it is indicated by channel fillings, mainly of sandstone. The channel was, at least in part, contemporaneous with peat formation along its margins during deposition of the Herrin (No. 6) Coal; its effect on the adjacent peat was widespread and varied. The deposits of the Herrin (No. 6) Coal that are thickest and lowest in sulfur (1 to 2 percent) are found next to the channel; therefore, mining has been concentrated along the margins of the channel.

Coal mining began in shallow drift and slope mines along the outcrop in Williamson County in the late 1800s. In the early 1900s, deeper shaft mines were sunk in Franklin County and later, farther north in Jefferson County. The area of thick coal along the Walshville channel became known as the "Quality Circle" because of the great thickness and low sulfur content of the coal. At present most of the active mines in the Quality Circle are in northern Franklin and southern Jefferson Counties; shafts range from 500 to 800 feet (152 to 244 m) deep. In Jackson and Williamson Counties, a few strip mines, mostly small local operations, currently are extracting coal left behind by earlier operators. The mined-out areas of Herrin Coal are concentrated near the channel in the area of southern Illinois shown in figure 1.

The value of the coal near the Walshville channel is reduced by a number of channel-related conditions unfavorable to mining. Detrimental effects include occasional absence of the coal and its replacement by channel-fill sedi-

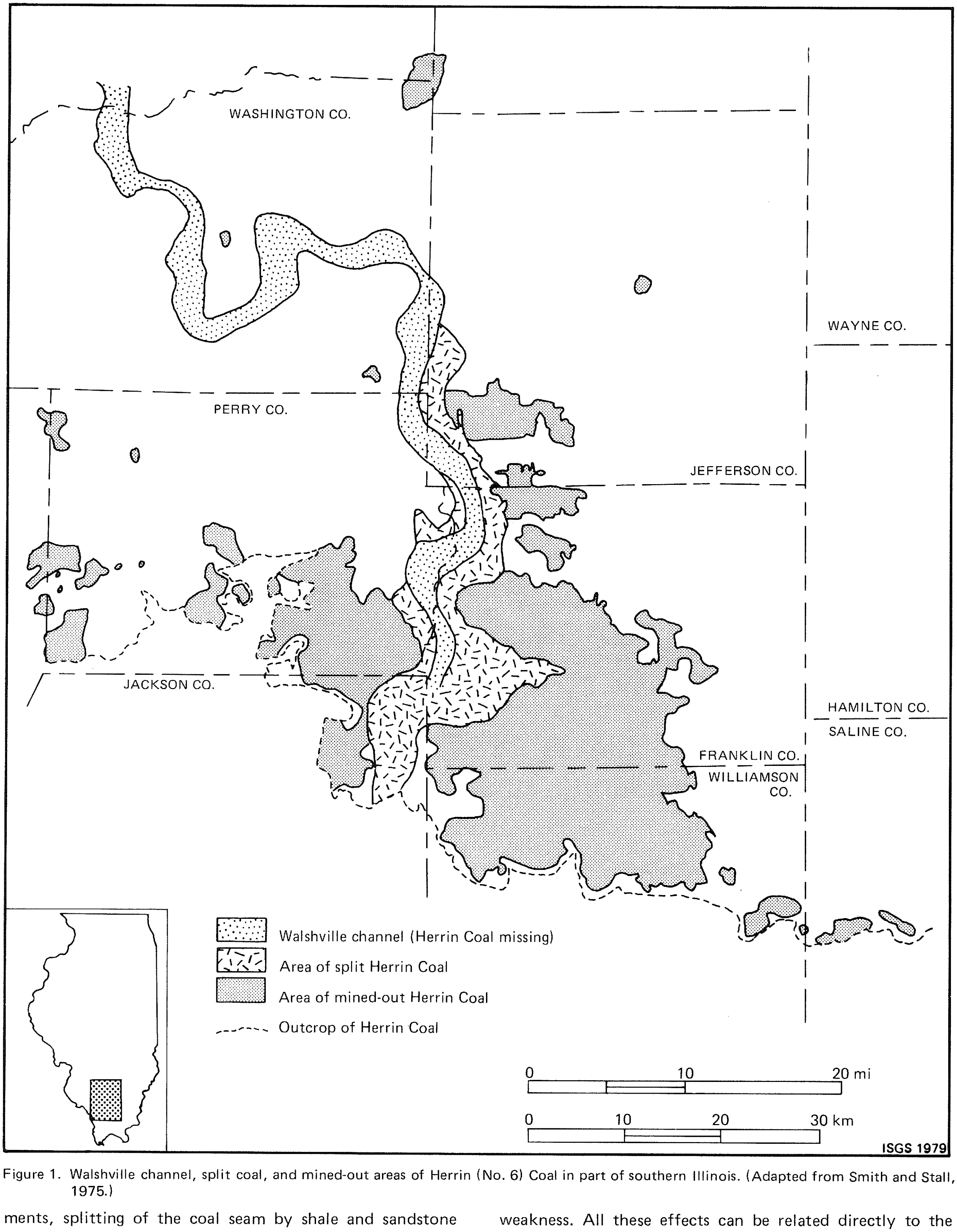


Figure 1. Walshville channel, split coal, and mined-out areas of Herrin (No. 6) Coal in part of southern Illinois. (Adapted from Smith and Stall, 1975.)

ments, splitting of the coal seam by shale and sandstone partings, the presence of "rolls" and steep grades in the coal, water influx from porous channel-fill sandstones, and unstable roof conditions caused by structural and lithologic weakness. All these effects can be related directly to the conditions of deposition in the channel and adjacent peat swamp areas.

The geologic information in this report was collected over the years by many Survey geologists as they conducted studies of the influence of geologic conditions on coal mining. Much of the data are from a recent investigation of geologic factors influencing mine roof stability (Krausse et al., 1979). The geologists whose unpublished observations are presented here include Robert Bauer, Heinz Damberger, Philip DeMaris, M. E. Hopkins, Stephen Hunt, Russell Jacobson, H.-F. Krausse, Christopher Ledvina, Fred Murray, James E. Palmer, John Popp, and Colin Treworgy.

GENERAL GEOLOGY

The Herrin (No. 6) Coal Member is the most widespread of the minable coals in Illinois. It is 30 inches (76 cm) or thicker over most of the Illinois Basin Coal Field, and averages 6 to 7 feet (1.8 to 2.1 m) thick over broad areas. The thickest and most intensively mined deposits of Herrin Coal are in the "Quality Circle," where it generally ranges from 7 to 10 feet (2.1 to 3.0 m) and locally attains a thickness of 14 feet (4.3 m).

The sediments of the Walshville channel are known from extensive drill hole and mine records. The Walshville channel has been traced along a continuous, meandering course 170 miles (274 km) from central Illinois to northeastern Jackson County, Illinois, where the sediments crop out. The width of the channel, as defined by the absence of the Herrin Coal, varies from 2 to 5 miles (3.2 to 8.0 km). In places strata apparently contemporaneous with the channel sediments are as young as the Piasa Limestone Member and as old as the Seahorne Limestone Member of the Spoon Formation (Palmer et al., 1979).

Adjacent to the channel the coal commonly is split by partings of shale, siltstone, and sandstone. The partings vary greatly in number, thickness, and position in the seam, but the intensity of splitting generally increases toward the channel. The width of the zone of split coal varies from 0 to more than 6 miles (9.7 km); in some places the thickness of the Herrin Coal may extend to 30 feet (9.1 m) or more because of the presence of splits. Splits are a detriment to mining because either a thinner layer of coal must be mined or large amounts of rock must be handled. Where split coal is left in the roof, falls may occur because the roof splits easily along the coal partings. Underground mines seldom are extended far into split areas because of these problems.

The split coal is strong evidence that the Walshville channel existed at the time of peat accumulation. The splits probably developed as layers of sediment deposited on the peat during floods along the channel. After a flood, peat growth was reestablished on top of the freshly deposited sediment; the cycle appears to have been repeated several times in certain places.

In Illinois a "roll" is a miners' term for a protrusion of the roof material into the top layers of the coal seam. Under large rolls the entire coal seam may be folded downward into a trough. Serious mining problems may result from the thinning of the coal and the steep grades created on the flanks of rolls. Large rolls may necessitate mining through rock or the abandoning of the heading. The roof in the vicinity of rolls also is commonly unstable; this instability is due to slickensided slips and coal "riders" (thin coal layers branching off the main seam) in the roof, which create planes of weakness.

Water problems commonly arise in mines because of coarse, porous sandstone in the roof. The sandstones and associated deposits in the channel often are water bearing. Water may enter the mine along fractures, roof bolt holes, or in the area where the sandstone is the immediate roof. Some sandstones run dry soon after mining, but others continue to flow water for months or years.

In mines adjacent to the channel, the immediate roof usually consists of gray shales, siltstones, and sandstones, which are collectively named the Energy Shale Member (Allgaier and Hopkins, 1975). The Energy Shale forms wedges or lobes that are up to several miles wide and thicken toward the Walshville channel and interfinger with the channel-fill sediments (figs. 2 and 3). The Energy Shale

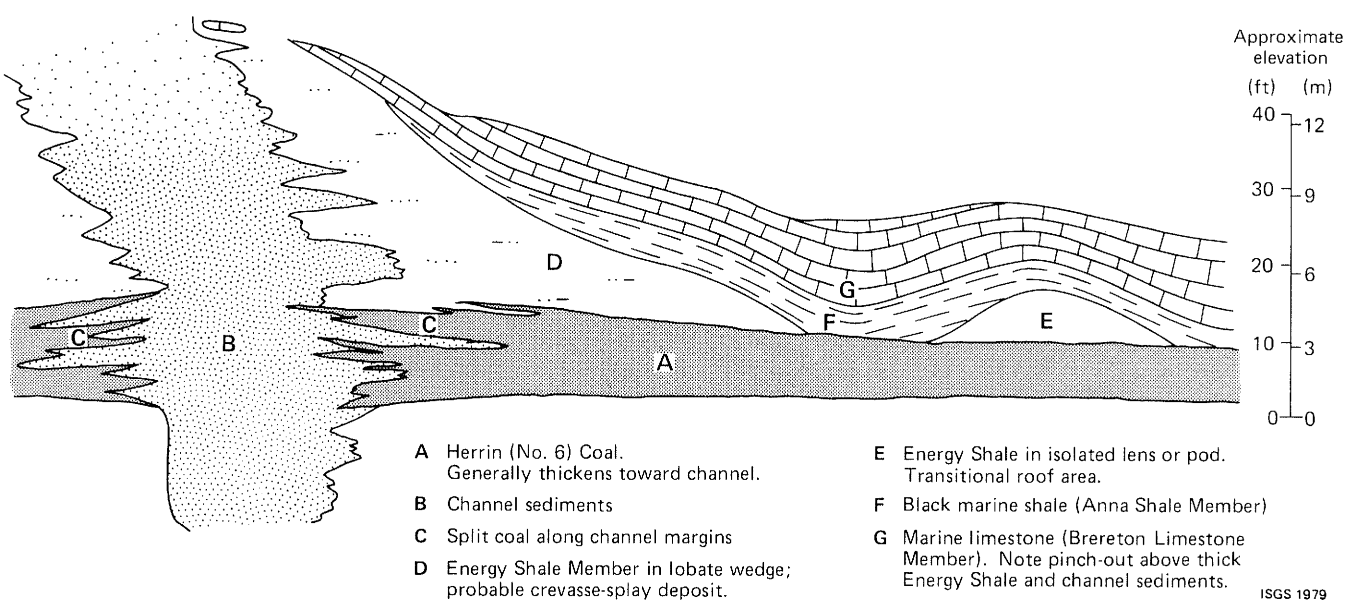


Figure 2. Schematic cross section showing relationship of Walshville channel with Herrin (No. 6) Coal and overlying rock units.

shows abrupt lateral changes of thickness; locally it reaches more than 100 feet (30 m). The marine black shale and limestone, which lie directly on the Herrin Coal away from the channel, overlap the Energy Shale wedges and tend to pinch out as the Energy Shale thickens. In a transitional zone beyond the edges of the lobes, the Energy Shale occurs as isolated pods or lenses that are a few hundred to several thousand feet across, up to 20 feet (6.1 m) thick, and overlain by black shale and limestone.

The thick lobate wedges of Energy Shale probably are crevasse-splay deposits that formed when the river breached its natural levees and flowed out over the peat swamp (fig. 3). The smaller lenses of Energy Shale in the transitional zone may be sediments deposited in depressions on the surface of the swamp.

The most common lithology of Energy Shale is medium-gray, rather soft, weakly bedded shale. It is reactive to moisture in the mine and can be difficult to support with roof bolts. Closer to the channel, the Energy Shale deposits coarsen to siltstone or sandstone. Massive or thick-bedded siltstone and sandstone make strong roof, but thinly laminated sandstone can be very unstable. Partings of shale and carbonaceous material cause separation along bedding planes, and roof falls may result (fig. 4).

Specific examples follow of channel-related problems in four Illinois coal mines operating along the margins of the Walshville channel. The mines include one surface mine and three underground operations.

EXAMPLE *A*

This example is based on unpublished field observation by H.-F. Krausse, John T. Popp, and W. John Nelson, 1977.

The Burning Star No. 5 mine of Consolidation Coal Company is located along the outcrop of the channel-fill sediments. At present (1978) the Herrin (No. 6) Coal is being mined in a large pit east of the channel. Future plans call for mining both the Herrin (No. 6) and the underlying Harrisburg (No. 5) Coals.

In the pit the Herrin Coal is 8 to 9 feet (2.4 to 2.7 m) thick and is not split noticeably. The coal is overlain by gray shale, which is overlain by coarse, friable brownish sandstone. The contact of the sandstone with the shale is sharp and appears to be erosional. The sandstone appears to

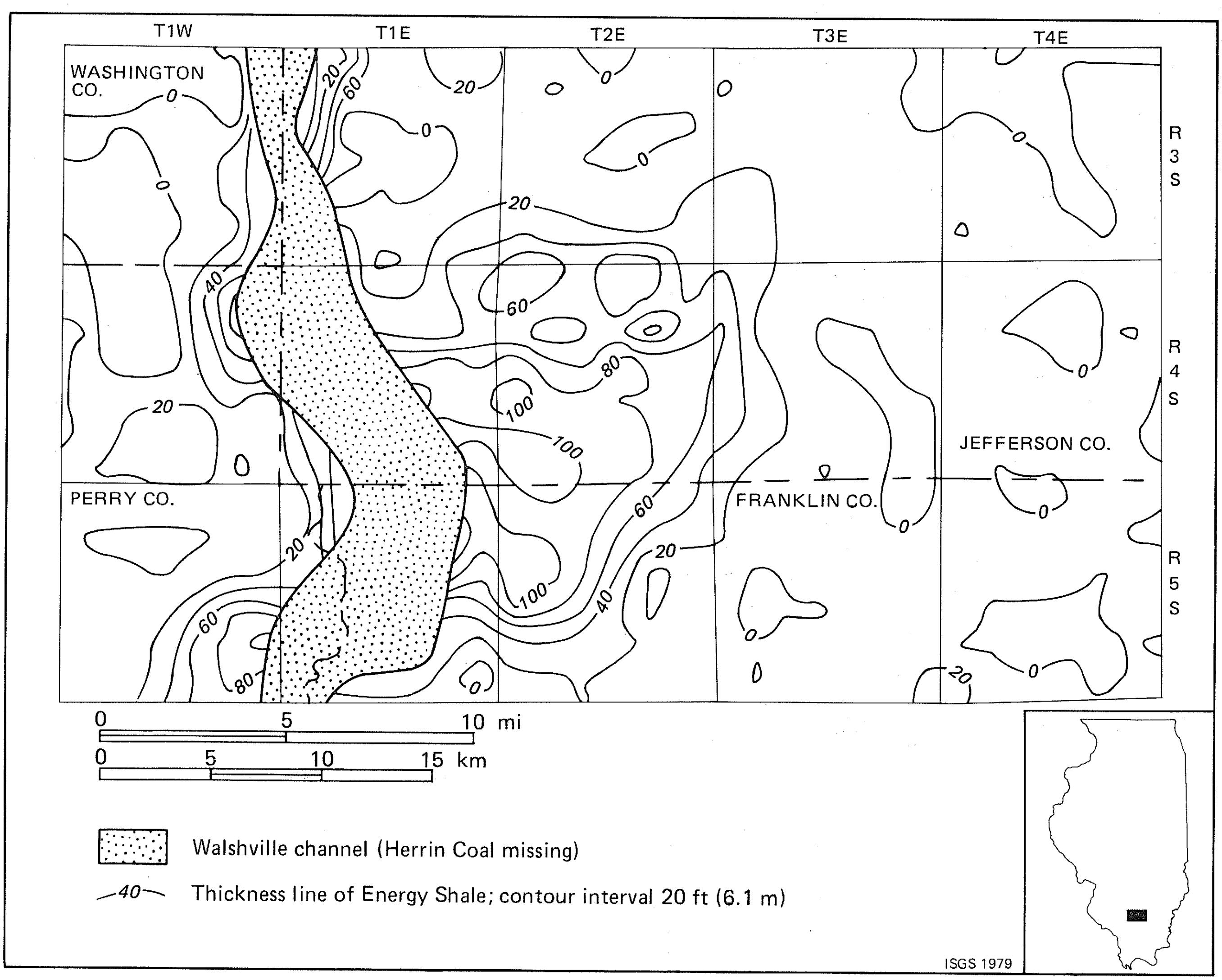


Figure 3. Thickness of Energy Shale Member in part of southern Illinois. (Adapted from Krausse et al., 1979.)

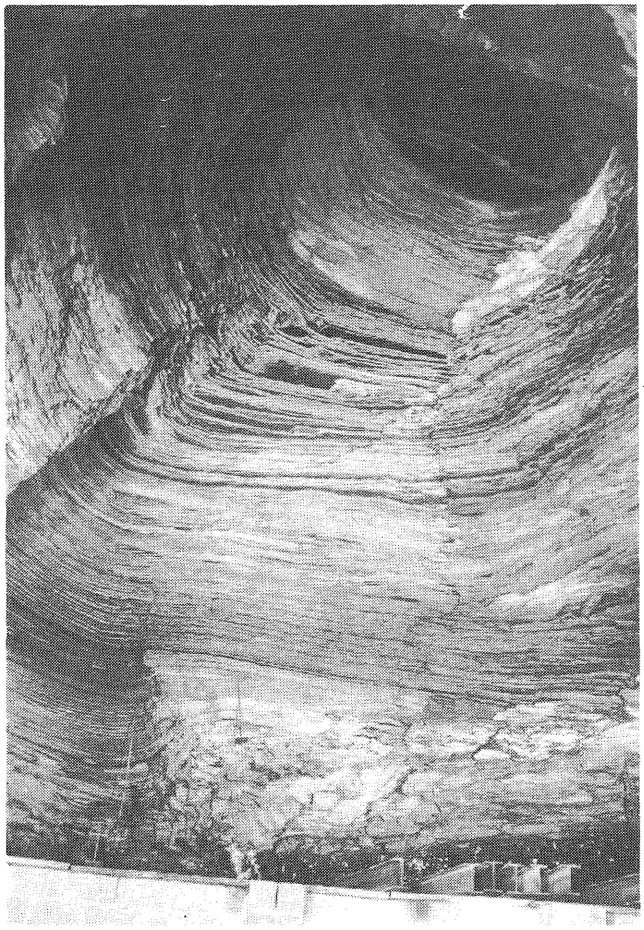


Figure 4. Large roof fall (30 to 40 ft [9 to 12 m] high) in thinly bedded sandstone of the Energy Shale adjacent to the sediments in the Walshville channel. The bedding planes of the sandstone are coated with abundant mica and carbonaceous debris which allow it to break readily into layers. Falls propagate upward with almost vertical walls. In many places the sandstone is porous; the water it contains creates additional mining problems.

be down-cutting to the west, but was not observed directly on the coal. The sandstone is so poorly cemented and so very permeable that the mine has experienced problems with highwall stability and an influx of water to the pit.

West of the active pit is a small abandoned pit that shows a different highwall sequence. Above the coal are interbedded shale and sandstone that locally contain shale-pebble conglomerates. To the east many layers of coal are interbedded with shale and sandstone in the highwall. Whether these are discontinuous or connect with the main seam was not observed. The coarse, friable sandstone observed in the main pit also is present in the west pit; it overlies the mixed lithologies with what appears to be an erosional contact. The stratigraphic relationships are not clear because of incomplete exposures, but both contemporaneous and postcoal channels are indicated. The split coal indicates the contemporaneous relationship of the coal and the river; the upper coarse, friable sandstone may belong to a channel filled by the Anvil Rock Sandstone Member, a postcoal channel. Alternatively, the deposits may represent successive stages of the same river system.

Split coal is known to exist in boreholes elsewhere on the Burning Star No. 5 property. The Herrin Coal is split into as many as five different benches, separated by thick layers of shale and sandstone. The individual coal layers are generally 2 feet (0.6 m) thick or more, and thus can be mined by cutting a series of benches with two draglines. This is an example of greater flexibility permitted in surface mining. If such a split seam were encountered in an underground mine, it would probably halt operations.

EXAMPLE *B*

This example is based on unpublished observations by M. E. Hopkins and F. N. Murray, 1966.

An underground coal mine in Franklin County encountered severe mining difficulties in its west workings adjacent to the Walshville channel. Splits, cutouts, steep dips, and large compactional faults forced major alterations of the mining plan. Areas of thick coal, known to be present from drilling, were not mined because of wide barren areas between the coal and the main workings.

The geologic pattern is complicated and has not been delineated fully. There appear to be several interconnected, curving channels in which the coal is largely or completely cut out. In some places the coal is cut out abruptly. The coal bedding is truncated locally at a 30° angle, and the coal appears to dip beneath the cutout. The filling consists of gray, silty, carbonaceous shale or siltstone, containing abundant fragments and stringers of coal.

These cutouts clearly were formed after the peat was completely accumulated, but before it had coalified. In some places blunt-ended siltstone intrusions split the coal near channel margins (fig. 5); they appear to have formed when sediment squeezed laterally between layers of soft peat. Other indications for soft-sediment deformation are large, low-angle faults; most are roughly parallel to channel margins. They are probably the result of differential com-

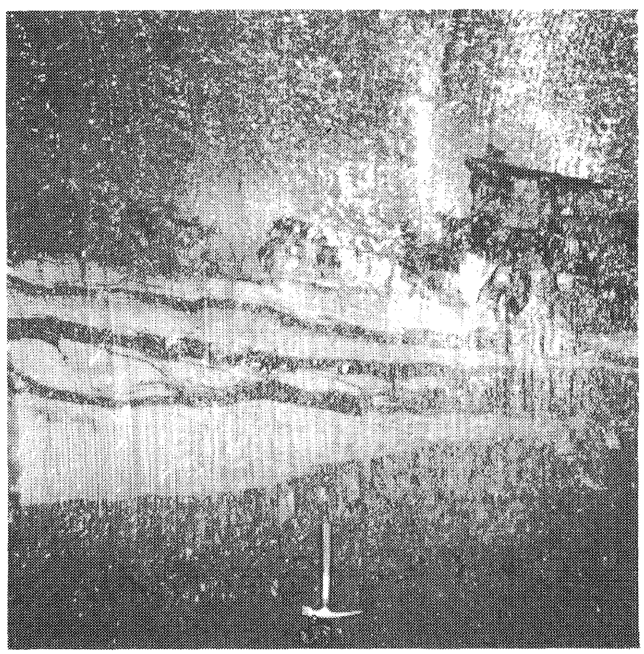


Figure 5. Split coal—Example *B*.

paction of peat and sediment. Some faults have as much as 10 feet (3 m) displacement.

In other areas the coal is not cut out but is severely split and has thick partings of shale and siltstone. Splits occur at all levels in the coal seam and generally are irregular and discontinuous (fig. 5); however, some splits persist laterally for several tens of feet (10 to 20 m). The splits record inundation of the peat swamp at different stages, deposition of sediment, and reestablishment of peat growth. Other splits, as noted, appear to be sediment injected between peat layers by overburden pressure.

The pattern provides good illustration of a dynamic stream system that persisted throughout the time of Herrin peat formation. The split coal documents the presence of rivers that periodically overflowed their banks and deposited sediment on top of peat. Angular cutouts of the coal show that the streams were still active after peat formation was completed. Such a stream system produced intricate patterns of coal interruption, which makes mine planning difficult.

EXAMPLE *C*

This example is based on maps by H.-F. Krausse et al., 1979.

Water influx, unstable roof, large rolls, and split coal have added to mining costs in an underground mine located east of the Walshville channel. These problems also have created safety hazards in the western part of the mine.

In most of the mine the roof consists of firm, silty gray shale or siltstone of the Energy Shale Member, generally dry and stable. Problems are encountered where coarse, planar-bedded sandstone lies within 10 feet of the top of the coal. The sandstone roof lies along a northwest-southeast-trending zone that is parallel with and approximately one mile (1.6 km) east of the channel.

The sandstone is porous and water bearing and is divided into thin planar beds by partings of coarse mica and carbonaceous plant material. The contact of the sandstone with the underlying shale is sharp and locally unconformable, indicating erosion. The sandstone splits easily along the bedding planes to produce large roof falls (fig. 4). Water seepage corrodes equipment, softens the underclay, and creates generally unfavorable working conditions. The seepage also tends to soften the shale beneath the sandstone, further decreasing roof stability.

Where the sandstone lies directly on the coal, additional problems are presented by steeply dipping coal and rolls. The rolls protrude downward into the coal seam or are large lens-shaped bodies of rock partially within the seam (fig. 6). The top layers of coal generally splay upward

Figure 6. An example of large sandstone-filled rolls common in area of example *C*. The coal is complexly split and interfingers with the finely laminated sandstone filling the roll. Sandstone shows much internal deformation caused by slumping or differential compaction. Note that miner has been forced to take a large amount of rock with the coal, resulting in irregular roof. Width of view is about 12 feet (4 m).

into the roof, and the lower layers are bent downward. Large slips further displace the coal in many rolls. The bedding of the sandstone filling the roll generally is folded and contorted. Although many rolls resemble small channel-fill deposits, there is little evidence that coal has been eroded. Rather, most rolls appear to have formed by slumping that possibly resulted from uneven loading of soft peat by sand.

Rolls range in size from structures only a few feet across to large bodies that necessitate changes in mining plans. One large roll encountered in the southwestern part of the mine was several hundred feet (100 m) long and as much as 100 feet (30 m) wide; it depressed the coal 12 feet (3.6 m) or more. The mining company was forced to change the entry layout and grade through rock because continuous miners could not follow the dip of the coal. Near this roll the coal dipped as much as 25° and varied in thickness from 4 to 12 feet (1.2 to 3.6 m).

Beyond the zone of rolls in the westernmost mine workings, the mining company has encountered an area of split coal. The splits consist of partings of carbonaceous shale or claystone, mostly in the upper half of the seam. In the present mining area, less than a foot of shale is in the seam. The splits increase in number and thickness to the west, toward the channel.

EXAMPLE *D*

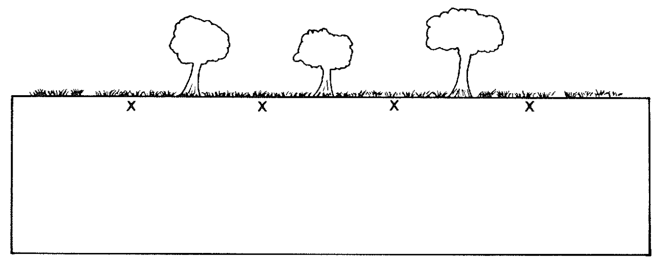
This example is based on unpublished field observations by Robert A. Bauer, Philip J. DeMaris, H.-F. Krausse, John T. Popp, and John Nelson, 1977.

An underground mine east of the Walshville channel encountered numerous mining problems. Drill holes show that the coal is missing about 2 miles (3.2 km) west of the present workings in a zone about 2 miles (3.2 km) wide and in a belt of split coal to the east.

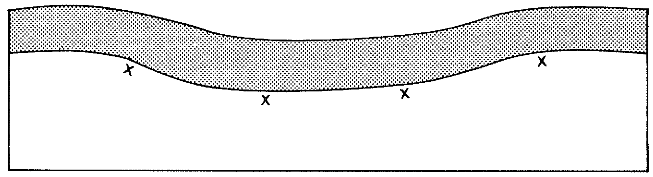
A narrow northeast-southwest-trending zone of severely split coal was encountered in the mine workings. The zone was traced more than two miles (3.2 km) to its termination to the northeast; it is as much as a quarter mile (0.4 km) wide. In most places mining halted at the margins of the split area, but one set of entries needed for ventilation permitted a view of the interior of the split coal area.

The pattern is extremely complicated and, despite extensive mapping, has not been completely deciphered. In essence, the coal is folded into a broad arch with a broken northwest flank and is divided into numerous benches with partings of gray shale, siltstone, and sandstone. The benches and splits are irregular and discontinuous; the difficulty of tracing them laterally is increased because the mine entries do not continuously follow one horizon.

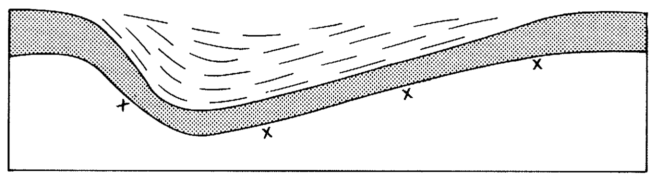
At the southern end of the split area, a fairly simple pattern exists. The coal is split into a main bench about 8 feet (2.4 m) thick and an upper bench 1 to 5 feet (0.3 to 1.5 m) thick. The main bench drops into a broad trough. Dips on the flanks approach 20° and are difficult for continuous mining equipment to follow. Although the trough is as much as 12 feet (3.6 m) deep, the upper bench of coal remains horizontal. The trough and splits may have formed through alternating stages of subsidence and deposition (fig. 7).



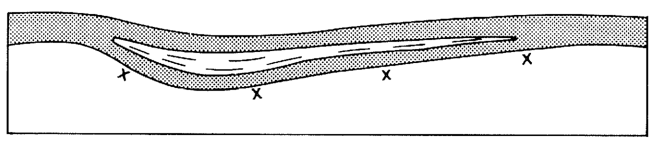
1. The original surface may have been flat, allowing normal peat development.



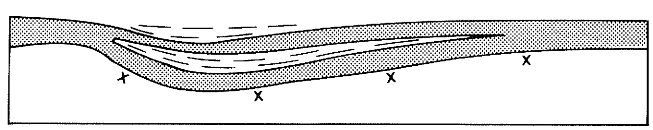
2. During peat accumulation a trough developed due to differential compaction of underlying sediments (possibly channel-fill sands under flanks and more compressible muds under trough).



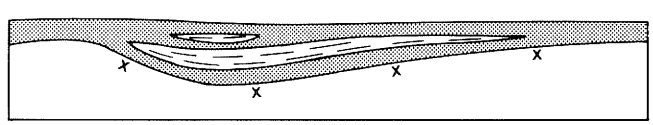
3. Muds were next deposited in the low area overlying the peat, probably in a short-term event such as a flood.



4. Conditions again became favorable for peat formation, and a new layer of peat developed over the trough-fill muds, which began to compact and sag.



5. A second episode of flooding and mud deposition occurred.



6. The original form and topography, although somewhat altered by compaction, are preserved today in the coal and associated strata.

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Figure 7. Schematic interpretation of the origin of trough and split coal in example *D*.

In one place along the air course, the coal appears to interfinger with the sediments that fill the channel. The coal abruptly forms a fishtail into a deposit of massive, fine-grained sandstone containing abundant coal fragments. Lenses of shale and sandstone are found in the coal. Both coal and sandstone are overlain by the marine black shale and limestone. The relationships show that sandstone deposition occurred prior to marine invasion and is essentially contemporaneous with peat formation (fig. 8).

The exposure along the air course at this mine illustrates the great complexity of features associated with the channel. Much future study will be needed to understand the depositional patterns of the sediments that filled the channel.

SUMMARY AND CONCLUSIONS

Coal mining is affected extensively and in various ways by the occurrence of the Walshville channel. Structural and

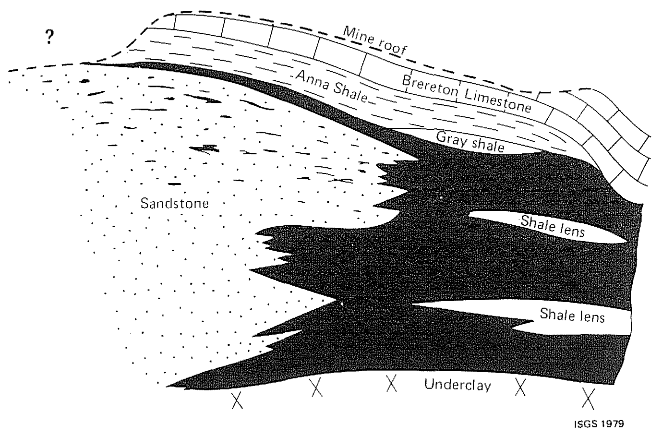

Figure 8. Feature interpreted to be a contemporaneous channel (example *D*). The coal abruptly forms a fishtail against fine-grained, massive sandstone that contains abundant fragments and stringers of coal in the upper part. Splits and lenses of shale are present in the coal away from the sandstone body. The coal, and probably the sandstone, are directly overlain by marine black shale and limestone (compare fig. 2). The sandstone represents lag deposits of a stream channel that existed during peat formation. The area indicated by a question mark was not exposed.

sedimentary features associated with the channel interfere with mining operations, decrease production, increase handling of waste rock, lower roof stability, and introduce water into the mine.

The ability to map and predict channel-related features in advance of mining would be of great benefit to the mining industry. Prediction requires an understanding of the events and processes through which the channel was formed. Apparently the channel area was occupied by a major stream during the time of coal formation. The river probably shifted its course continually, eroding its banks in one place and depositing sediments elsewhere, then cutting back through its own deposits. Therefore, the record in the rocks is complex and not always readily understood.

Intensive geological studies will be needed to outline and predict problem areas near the Walshville channel. Full use should be made of subsurface information from geophysical logs and coal test cores. New techniques, such as seismic studies, could be applied to locate channels and related features. Geologic mapping in surface and underground mines should yield much valuable information.

REFERENCES

ALLGAIER, G. J., and M. E. HOPKINS, 1975, Reserves of the Herrin (No. 6) Coal in the Fairfield Basin in southeastern Illinois: Illinois State Geological Survey Circular 489, 31 p.

KRAUSSE, H.-F., H. H. DAMBERGER, W. J. NELSON, S. R. HUNT, C. T. LEDVINA, C. G. TREWORGY, and W. A. WHITE, 1979, Engineering study of structural geologic features of the Herrin (No. 6) Coal and associated rock in Illinois: Final report, contract H0242017, U.S. Bureau of Mines, Illinois State Geological Survey open file, 2 vols.

PALMER, James E., Russell J. JACOBSON, and C. Brian TRASK, 1979, Depositional environments of late Desmoinesian age overlying the Herrin (No. 6) Coal in southwestern Illinois, *in* James E. Palmer and Russell R. Dutcher [eds.], Depositional and structural history of the Pennsylvanian System of the Illinois Basin: Guidebook for field trip no. 9, pt. 2, Ninth International Congress of Carboniferous Stratigraphy and Geology, p. 92-102.

SMITH, William H., and John B. STALL, 1975, Coal and water resources for coal conversion in Illinois: Illinois State Water Survey and Illinois State Geological Survey Cooperative Resources Report 4, 79 p.