LATE PALEOZOIC SANDSTONES OF THE ILLINOIS BASIN

Paul Edwin Potter

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Topographic mapping in cooperation with the United States Geological Survey.

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LATE PALEOZOIC SANDSTONES OF THE ILLINOIS BASIN

Paul Edwin Potter

ABSTRACT

The sandstones of the Pennsylvanian and late Mississippian sediments are one of the distinguishing characteristics of the late Paleozoic fill of the Illinois Basin.

These sandstones are discussed in terms of sand-body shape, petrology, texture, and sedimentary structures. Detailed subsurface maps of local sandstone thickness, detailed outcrop maps, and seven regional maps of sandstone thickness are presented. Maps of Pennsylvanian sandstones were made of three intervals—from the Herrin (No. 6) Coal Member to the Harrisburg (No. 5) Coal Member, from the Harrisburg (No. 5) Coal Member to the Summum (No. 4) Coal Member, and from the Colchester (No. 2) Coal Member to the Davis Coal Member. Maps of Chesterian sandstones include the sandstones in the Degonia, Palestine, Waltersburg, and Hardinsburg Formations.

The local and regional maps contributed to the better understanding and solution of many problems associated with the sandstones. These problems include the origin of multistory sand bodies, the relationship between internal directional properties and direction of elongation of sand bodies, compaction around elongate sand bodies, and the recognition of the complexity of sand deposition.

A recurring dispersal system supplied most of the sand and mud during late Mississippian and Pennsylvanian time. The essential feature of this system was a large river that brought the sediments to a coastal plain and a shallow marine shelf. Depending upon magnitude of sand input and extent of marine transgression or regression, the sand formed 1) dendritic patterns, 2) complex braided patterns, 3) deltas, and 4) isolated, relatively straight, elongate bodies largely of marine origin. The orientation of these sand bodies, both marine and nonmarine, was controlled by a regional slope that usually dipped gently to the southwest. Areas of thick sand deposition were generally localized by persistent weakly negative areas within the basin.

A depositional model for the late Paleozoic Illinois Basin, emphasizing basin geometry, lithic fill, arrangement of the fill, current system, and tectonic setting, summarizes the salient features of late Paleozoic sedimentation and facilitates the application of this information to the exploration of similar basins elsewhere.

INTRODUCTION

The recurrence of patterns of sedimentation throughout the geologic past has led to the concept that the entire sedimentary column can be thought to consist of a relatively small number of sedimentary associations.

The Pennsylvanian and late Mississippian (Chesterian and late Valmeyeran) fill of the Illinois Basin is an example of such a sedimentary association. The Pennsylvanian part of the association is dominantly clastic. The Mississippian part, the Pope Megagroup (Swann and Willman, 1961, p. 481), is an alternating sequence of clastic and carbonate rocks easily differentiated from the underlying dominantly limestone Mammoth Cave Megagroup. Deposition of the Pope Megagroup sediments began in late Valmeyeran time in the northwestern part of the basin but not until Chesterian time in the southeastern part.

These sediments are well suited for study because the Illinois Basin has a minimum of structural complexity, its stratigraphy is well established, and the sequence can be examined in detail in both subsurface and outcrop. The sandstones are one of the distinguishing characteristics of this sequence. The object of this paper is to describe and relate the properties of these sandstones to the other features of late Paleozoic sedimentation in the basin.

The sandstones, especially the thick ones, are the most discontinuous and most irregularly distributed lithology of the Pennsylvanian and late Mississippian sediments. Thick sandstones commonly have elongate, discontinuous distribution patterns that may be either relatively straight or meandering. Unlike the much more continuous limestones, coals, and shales, sandstones can present difficult mapping problems. The sandstones disrupt the "layer cake" continuity of the sequence. Erosion at the base of thick sandstones may have eliminated underlying stratigraphic members. Differential compaction along the flanks of elongate sand bodies accentuates initial thickness contrasts and complicates the identification of minor anticlinal folds of true tectonic origin.

The sandstones are also of economic interest. Late Mississippian sandstones have long made important contributions to the oil production of the Illinois Basin. Pennsylvanian sandstones, although not as productive, were the first to produce oil in the basin. Other Pennsylvanian sandstones are more important in a negative way in their effect upon coal mining operations. Erosion at the base of some thick sandstones has locally removed economically important coal beds, and the presence of a permeable, water-bearing sandstone above the coal may adversely affect mine roof and mining conditions.

The character of the sandstones is described in this report in terms of petrology, texture, and sedimentary structures. Local maps of sand-body shape and regional maps of sand thickness illustrate other aspects of the sandstones.

Acknowledgments

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Members of the University of Illinois faculty also were helpful. Colin R. Blyth gave statistical advice. James H. Bartlett and J. L. Doob assisted the writer in the field on several occasions. Charles Wier of the Indiana Geological Survey, Edward Wilson of the Kentucky Geological Survey, and Allan Mullins of the Tennessee Valley Authority provided assistance. The Humble Oil Company and the Ohio Oil Company permitted use of their electric log records for areas outside of Illinois.

REGIONAL SETTING

The principal structural features and the distribution of Mississippian and Pennsylvanian sediments in the Mississippi Valley and adjacent areas are shown in figure 1.

The Illinois Basin lies on the buried south-central extension of the Canadian Shield. The basin is bounded on the east and northeast by the Cincinnati and Kankakee Arches and separated from the Mid-Continent Basins by the Ozark Dome and Mississippi River Arch. The Illinois and Michigan Basins and the Mid-Continent complex of basins were already well defined by the close of Devonian time. Subsequent mild regional warping has accentuated the contrasts between these basins and the wide, gently rising arches that bound them.

Mature sandstones, carbonates, and some evaporites are characteristic of most of the pre-Mississippian Paleozoic sediments in the area of figure 1, west of the Cincinnati Arch. Beginning in Mississippian and con-

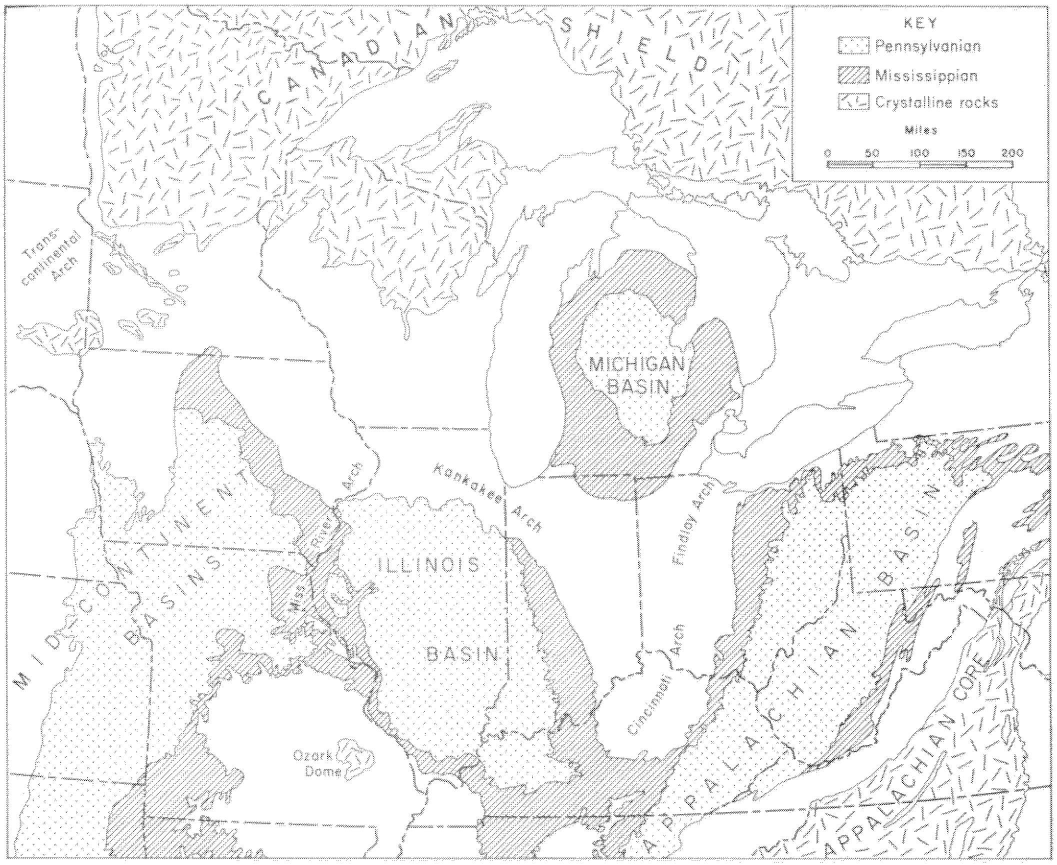


Fig. 1—Principal structural features and distribution of Mississippian and Pennsylvanian sediments in the Mississippi Valley and adjacent areas.

tinuing into Pennsylvanian time, large volumes of mud and sand were introduced into the Illinois Basin across the Cincinnati and Findlay Arches. In the Illinois Basin, early Mississippian clastics of Kinderhookian and early Valmeyeran age were followed by middle Mississippian carbonate deposition. Continuous limestone deposition ceased in late Valmeyeran time in some areas but continued into Chesterian time in others. In late Mississippian (late Valmeyeran and Chesterian) time, sand and mud alternated with carbonate deposition.

Following Mississippian sedimentation, regional erosion cut deeply into underlying rocks to the north and along the broad, gentle arches and domes of the region and beveled the older strata. In the Illinois Basin, sediments of the Pope Megagroup were regionally truncated to the northeast, north, and northwest. The last stage in this erosion was the development of an integrated, entrenched, dendritic pattern of generally southwesterly oriented valleys at the unconformity (Siever, 1951; Wanless, 1955, fig. 2). Subsequent sedimentation, especially later in Pennsylvanian time, covered much of the area connecting the Illinois, Michigan, and Mid-Continent Basins and extended over the Cincinnati Arch.

Figure 2 shows generalized thickness of Pennsylvanian and late Mississippian sediments in the Illinois Basin. The late Mississippian sediments have maximum thickness of approximately 1400 feet in southern Illinois. They thin to the northeast, north, and northwest, in part as the result of original sedimentation but principally as the result

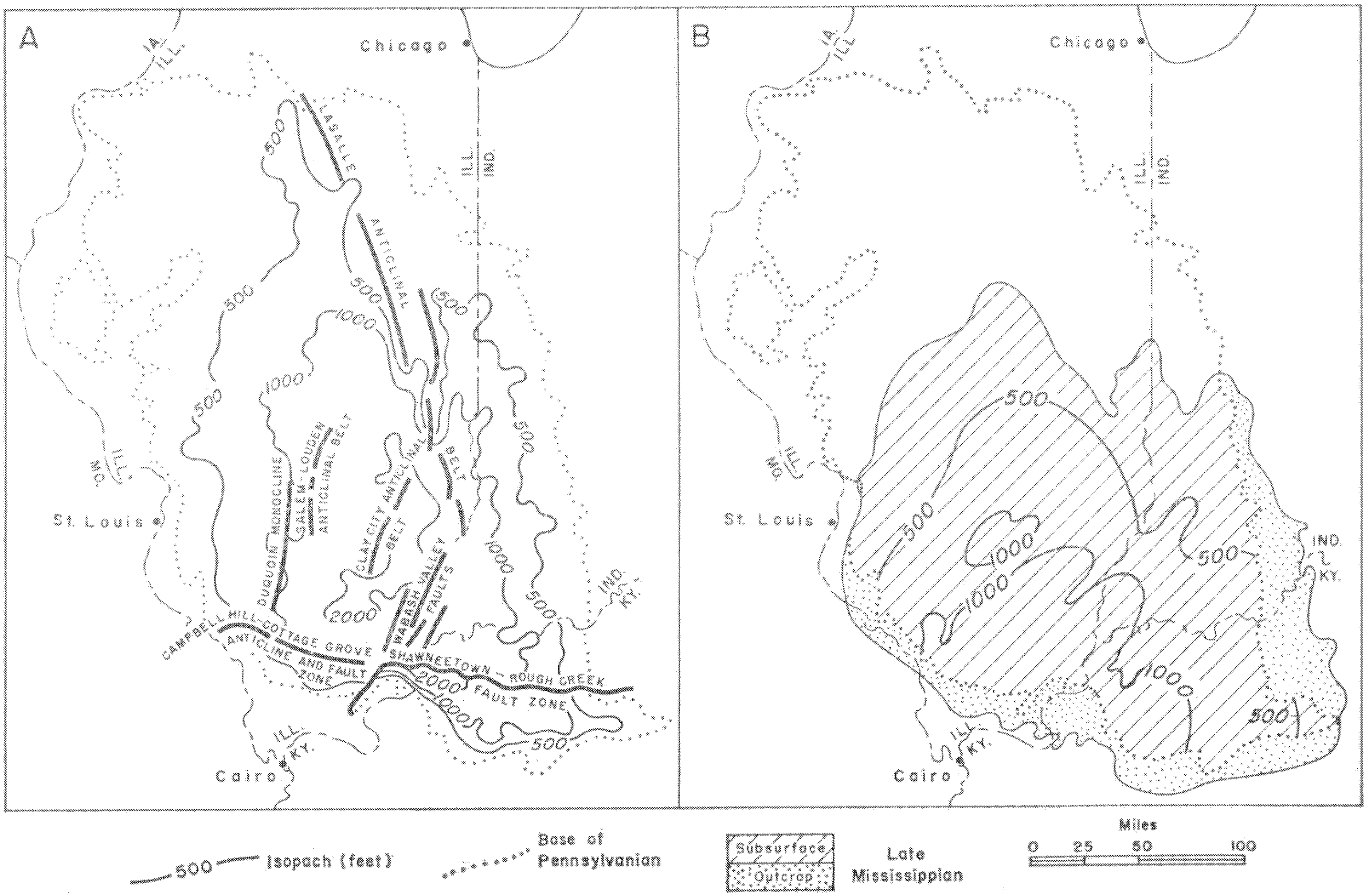


Fig. 2—Thickness of (A) Pennsylvanian sediments and principal structural features, and (B) Mississippian sediments above the base of the Aux Vases Sandstone. (A is modified from Wanless, 1955, figs. 4, 7; B is modified from Swann and Bell, 1958, fig. 5.)

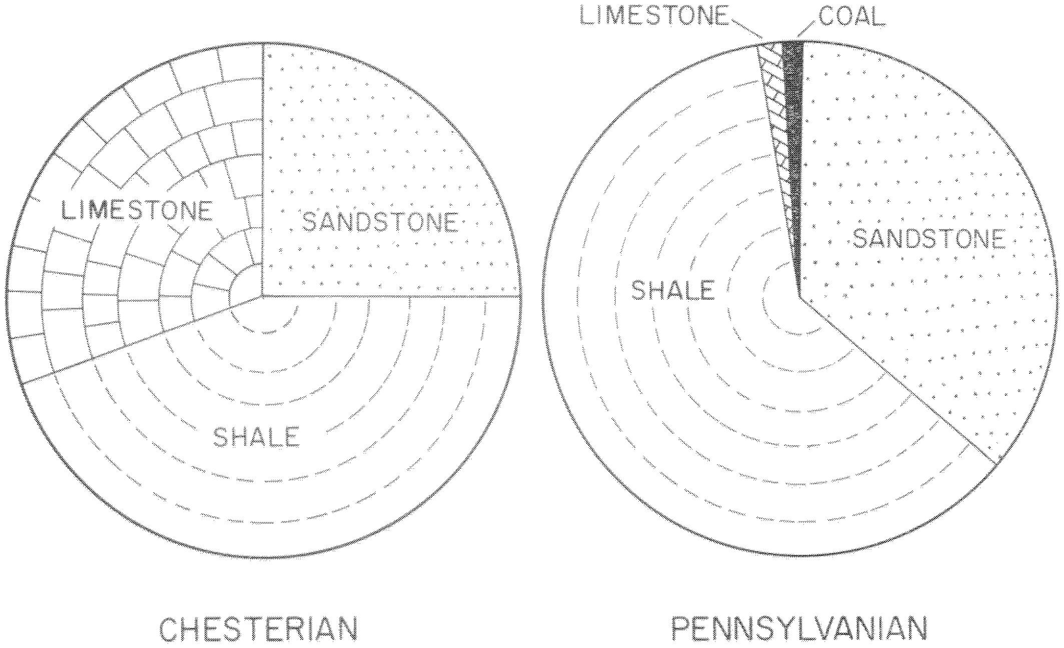


Fig. 3—Proportions of rock types in Chesterian and Pennsylvanian sediments along the southern edge of the Illinois Basin in southeastern Illinois.

of pre-Pennsylvanian erosion. Late Mississippian sediments occur in approximately 35,000 square miles of the basin.

Pennsylvanian sediments have maximum thickness of approximately 3000 feet and occur in approximately 55,000 square miles of the basin. Because of greater differential subsidence, contrasts between the shelf area and the more rapidly subsiding basin are more clearly expressed in Pennsylvanian than in late Mississippian sediments. The Pennsylvanian sediments of the western and northern shelf area are thinner and have a smaller proportion of clastics than the more rapidly subsiding basin (fig. 2). Post-Pennsylvanian uplift and erosion have truncated Pennsylvanian sediments along the edges of the basin.

The proportions of major rock types in the late Mississippian and Pennsylvanian sediments along the south-central border of the basin are shown in figure 3. In this area Chesterian sediments contain roughly 45 percent shale, 30 percent limestone, and 25 percent sandstone. The Pennsylvanian sediments contain approximately 63 percent shale, 33 percent sandstone, and 4 percent limestone and coal.

The cyclical arrangement of the Pennsylvanian and late Mississippian sediments has been commented on by many writers. Pennsylvanian sediments occur in a cyclical arrangement of (from the base upward) sandstone, silty shale, underclay, coal, gray shale, black fissile shale, limestone, and gray shale (Udden, 1912, fig. 2, and p. 47-50; Weller, 1930). A complete sequence of units is not usually present in one locality. Because only a few thin underclays, coals, and black fissile shales occur in late Mississippian sediments, their cyclical arrangement is chiefly an alternation of sandstone, shale, and limestone.

Limestones and coals illustrate other points of contrast in the two systems. Late Mississippian limestones, both calcilutites and calcarenites, are more abundant and thicker and contain less argillaceous material than the typical thin, fine-grained, argillaceous Pennsylvanian limestones. Pennsylvanian coal beds are much more abundant, thicker, and more widespread than those in the Mississippian.

The greater dominance of clastics in Pennsylvanian sediments accounts for most of the differences between the rocks of the two

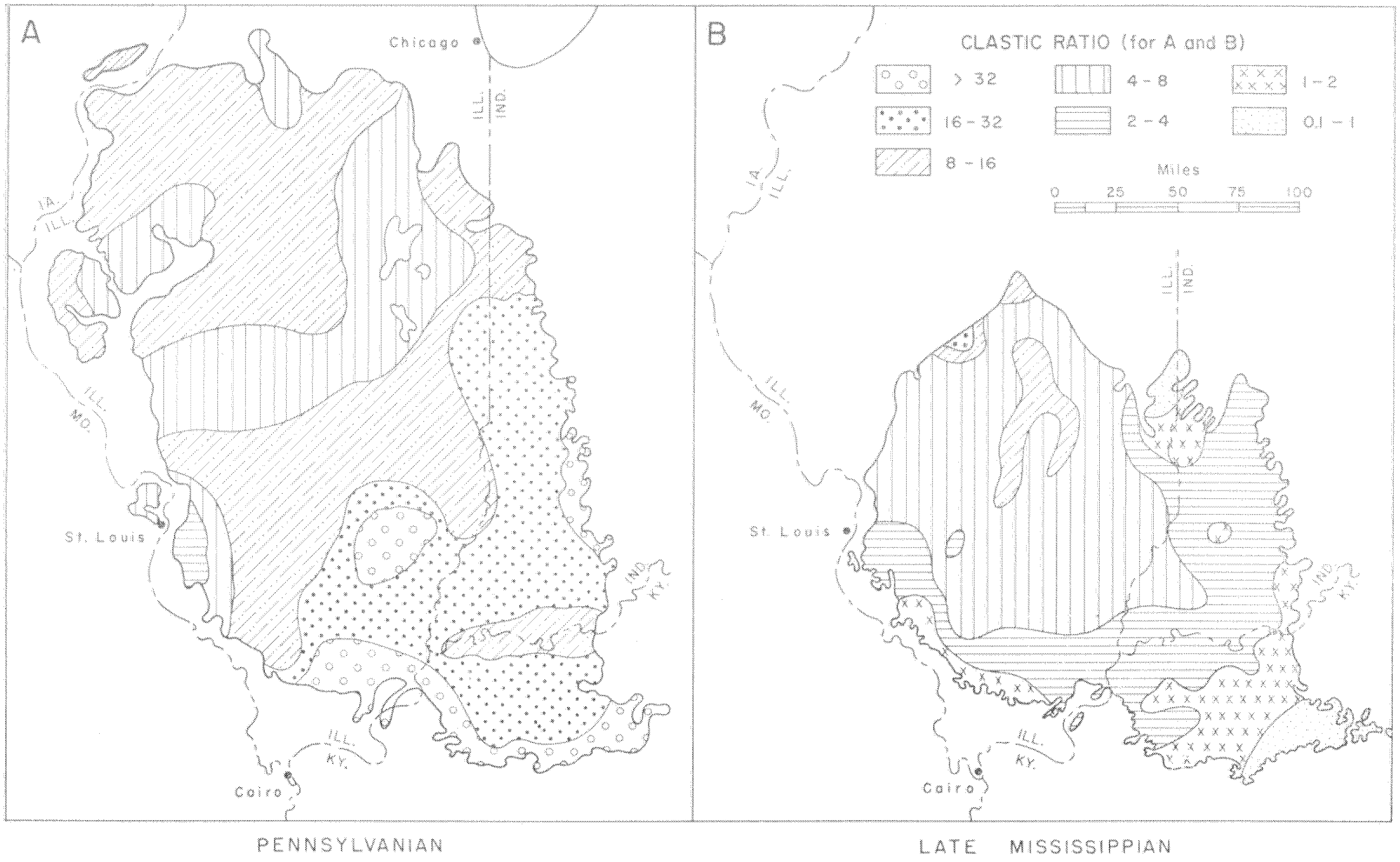


Fig. 4—Clastic ratios of (A) Pennsylvanian sediments and (B) Mississippian sediments above the base of the Aux Vases Sandstone. (A is after Wanless, 1955, fig. 11, and B is adapted from Swann and Bell, 1958, fig. 5.)

systems. Figure 4 compares clastic ratios of the Pennsylvanian and late Mississippian sediments. In the Pennsylvanian System the clastic ratio is usually more than 8 and in some places is greater than 32. In the late Mississippian sediments the clastic ratio is usually less than 8, and in a large area in the southeastern corner of the basin the clastic ratios are less than 2. In late Mississippian time there were 10 major pulses of sand input into the basin, whereas in the Pennsylvanian there were over 20 major pulses. The generally coarser sands and siltier shales are other reflections of the greater clastic input during Pennsylvanian time.

Figures 5 and 6 give the nomenclature of Pennsylvanian and Mississippian sediments referred to in this report.

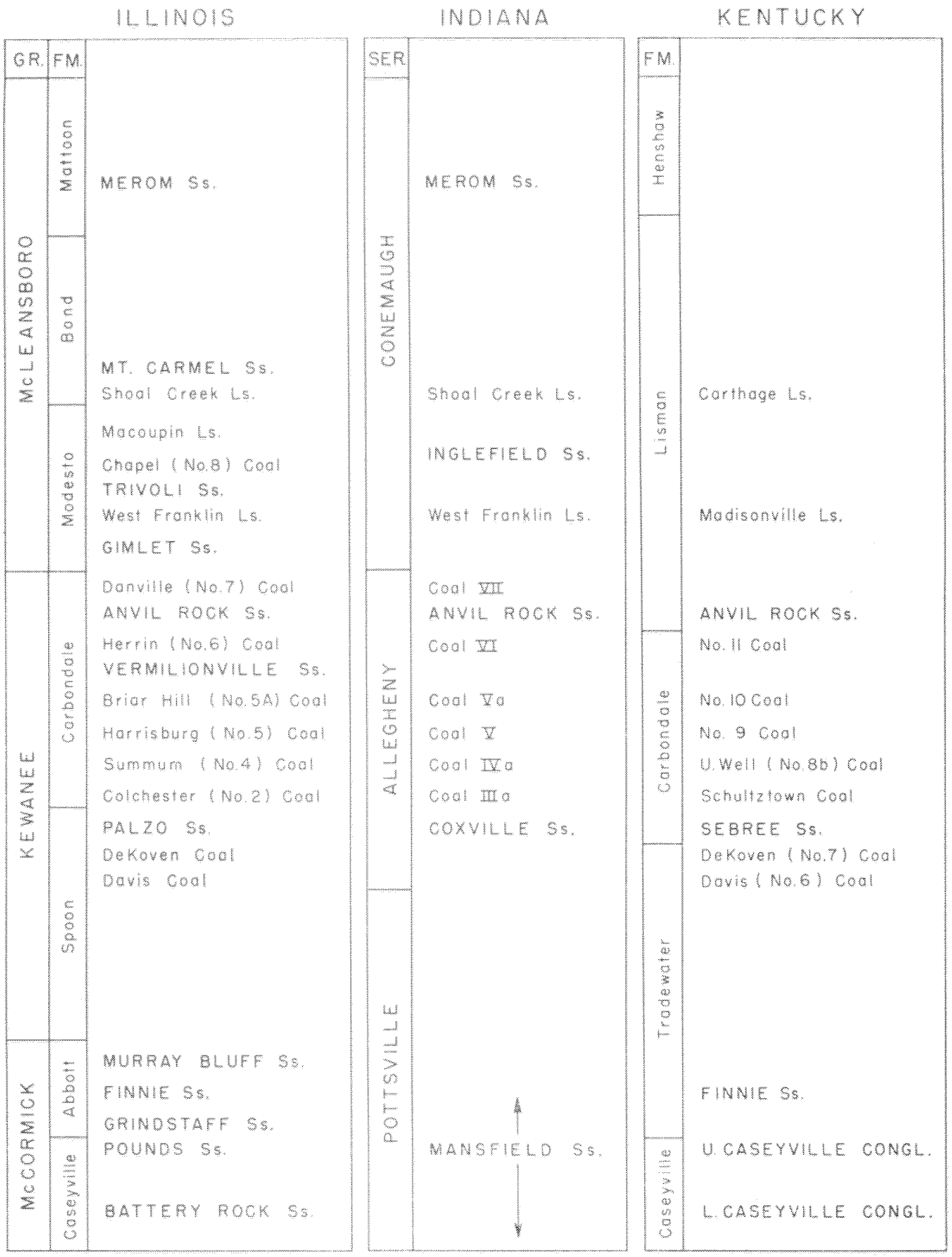
Good descriptions of the late Mississippian and Pennsylvanian sediments of the basin have been given by a number of geologists. Weller and Sutton (1940) provided a regional description of the Mississippian sediments in outcrop around the southern border of the basin. Weller (1940, p. 31-43) described the Chesterian and lower Pennsylvanian in southern Illinois. Perry and Smith (1958) described portions of the Chesterian Series in outcrop in Indiana. Swann (1963) classified the Chesterian and Genevievian rocks of Illinois. Ashley (1899) described the Pennsylvanian strata of Indiana. Wanless (1955, 1962) summarized the literature and regional geology of the Pennsylvanian sediments. Kosanke et al. (1960) presented a revised stratigraphic classification for Pennsylvanian sediments in Illinois that reviewed much literature. Baxter, Potter, and Doyle (1963) described the Chesterian outcrop and much of the Pennsylvanian in Hardin County in southeastern Illinois. Willman and Payne (1942) described the Pennsylvanian of northern Illinois, and Wanless (1957) did the same for western Illinois.

CLASSIFICATION OF SAND BODIES

In 1923 Rich introduced the term "shoestring" for sand bodies whose length greatly exceeds their width. In subsequent years comparatively little has been added to the published literature on the classification and terminology of different types of sand bodies in ancient sediments. That this is so, in spite of the vast increase in subsurface information, probably reflects the difficulty of the task. Genetic classifications are subject to error because establishing the environment of deposition of many ancient sand bodies is difficult. In addition, one type of sand body often grades into another. Still another aspect of the problem is that a classification based on subsurface criteria may not be applicable to outcrop, or vice versa. Criteria based on subsurface distribution pattern, cross section, or orientation of the sand body with respect to depositional strike cannot be used effectively in many outcrop studies. Both published studies of other areas and work in the Illinois Basin indicate, however, that there are only a few types of sand bodies that recur. Both outcrop and subsurface reports emphasize the similarity of the Pennsylvanian and late Mississippian sand bodies in the Illinois Basin. This paper presents a classification of these sand bodies that is applicable to similar facies elsewhere. Friedman (1960, p. 51) presented an earlier classification of the middle Pennsylvanian sand bodies of west-central Indiana.

Late Paleozoic sand bodies in the Illinois Basin belong to two types: thin, relatively widespread sheet sand bodies and thick, lenticular, sometimes discontinuous elongate sand bodies. Table 1 summarizes the properties of the two types. When a sand body is being classified as either sheet or elongate, all the properties in table 1 should be considered rather than any particular one. Both types can be recognized in outcrop and subsurface. In the same stratigraphic unit, sheet sandstones can be lateral to or on top of elongate sand bodies. In the latter case they represent the waning phase of sand deposition in transition to silt and mud above. Plates 2 and 3 show outcrop examples of sheet and thick elongate sand bodies in the Degonia Formation (Mississippian) and in the Battery Rock Sandstone Member (Pennsylvanian).

Subclasses of elongate sand bodies generally can be recognized more easily in subsurface than outcrop. Maps of the subsurface show that elongate sand bodies commonly have



ILLINOIS			INDIANA		KENTUCKY	
GR.	FM.		SER.		FM.	
McLEANSBORO	Mattoon	MEROM Ss.	CONEMAUGH	MEROM Ss.	Henshaw	
	Bond	MT. CARMEL Ss.			Lisman	
		Shoal Creek Ls.		Shoal Creek Ls.		Carthage Ls.
	Modesto	Macoupin Ls.				
				INGLEFIELD Ss.		
		Chapel (No.8) Coal				
		TRIVOLI Ss.				
		West Franklin Ls.		West Franklin Ls.		Madisonville Ls.
		GIMLET Ss.				
KEWANEE	Carbondale	Danville (No.7) Coal	ALLEGHENY	Coal VII		
		ANVIL ROCK Ss.		ANVIL ROCK Ss.		ANVIL ROCK Ss.
		Herrin (No.6) Coal		Coal VI	Carbondale	No. 11 Coal
		VERMILIONVILLE Ss.				
		Briar Hill (No.5A) Coal		Coal Va		No. 10 Coal
		Harrisburg (No.5) Coal		Coal V		No. 9 Coal
		Summum (No.4) Coal		Coal IVa		U. Well (No.8b) Coal
		Colchester (No.2) Coal		Coal IIIa		Schultztown Coal
	Spoon	PALZO Ss.		COXVILLE Ss.		SEBREE Ss.
		DeKoven Coal			Tradewater	DeKoven (No.7) Coal
		Davis Coal				Davis (No.6) Coal
McCORMICK	Abbott	MURRAY BLUFF Ss.	POTTSVILLE			
		FINNIE Ss.				FINNIE Ss.
		GRINDSTAFF Ss.				
	Caseyville	POUNDS Ss.		MANSFIELD Ss.	Caseyville	U. CASEYVILLE CONGL.
		BATTERY ROCK Ss.				L. CASEYVILLE CONGL.

Fig. 5—Nomenclature and correlation chart for Pennsylvanian units of Illinois, Indiana, and Kentucky referred to in this report. Sandstone names are in capitals. (Modified from Kosanke et al., 1960, pl. 1.)

four distinct distribution patterns. These are termed pods, ribbons, dendroids, and belts. The patterns, along with that of the sheet sand body, are shown in figure 7. Pods are isolated, slightly elongate sand bodies whose length is rarely twice as great as their width. Ribbons are relatively straight, usually isolated sand bodies with pronounced elongation. In the petroleum industry the term "bar" is commonly applied to sand bodies having pod and ribbon patterns. Dendroid patterns may extend only a few hundred feet in width and generally less than 2 miles. The wider dendroid patterns grade into belt patterns that may be 25 miles or more wide. Both belt and dendroid patterns exhibit weak-to-strong meanders. Belt patterns commonly contain "islands" where there is no sandstone. Because patterns generally cannot be identified in outcrop, the elongate pods, ribbons, and dendroids may be difficult to identify in the field. Because of their width, however, belt sand bodies are readily identifiable in outcrop, as, of course, are the thin sheet sand bodies.

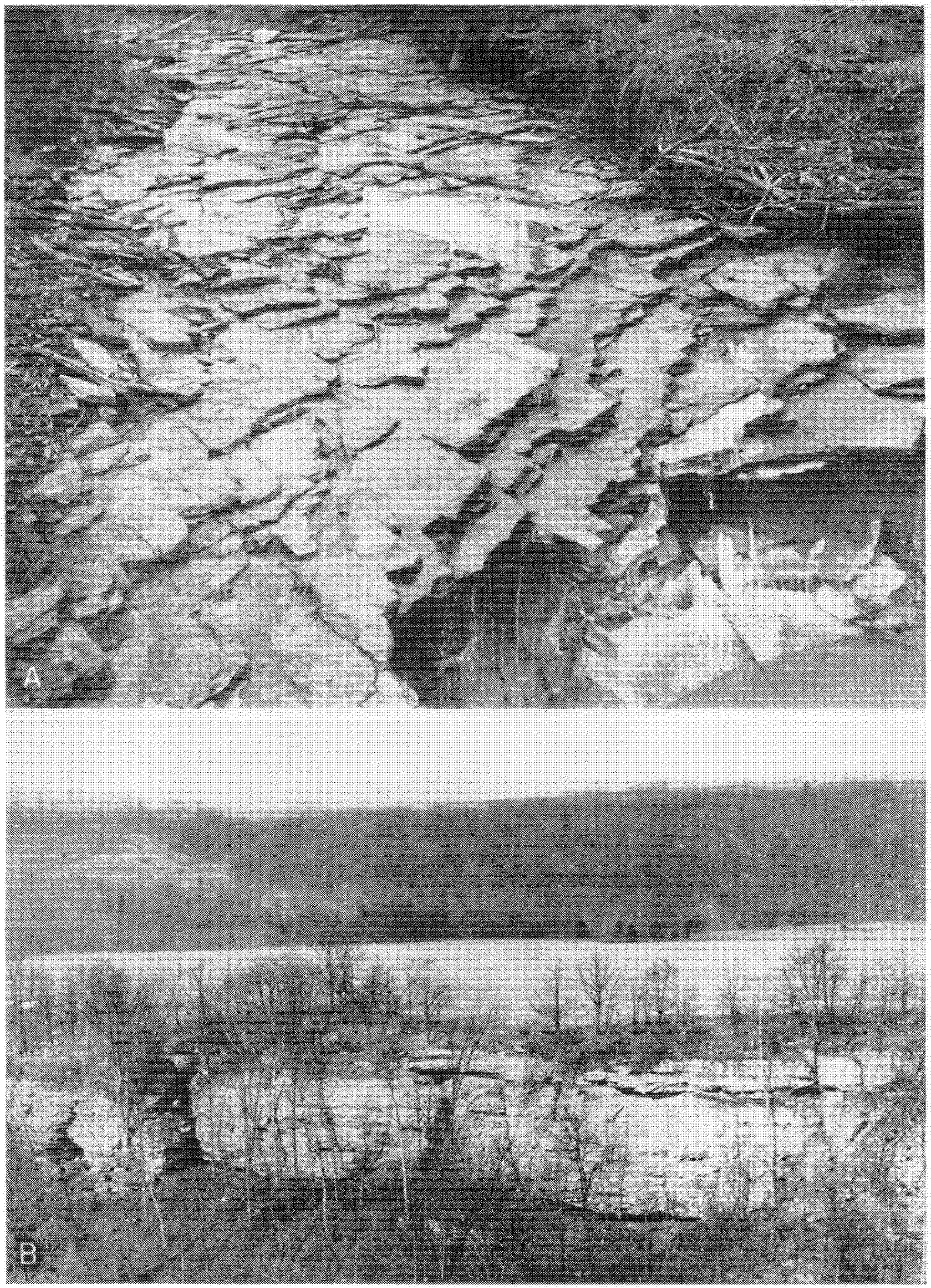
In outcrop, thick elongate sand bodies commonly have a nontransitional, unconformable basal contact indicating erosion at the base of the sand body. In subsurface, the unconformity at the base of thick elongate sand bodies can commonly but not always be recognized in diamond cores. When electric logs are used, the unconformity at the base of an elongate sand body can be recognized only when underlying marker beds are replaced by sandstone. Lack of such underlying marker beds can result in an apparently flat-bottomed sand body that only outcrop observation can convincingly prove to have an unconformable basal contact. Such factors complicate the use of cross sections in identifying the environment of deposition of a sand body.

Every major pulse of sand input into the basin in late Paleozoic time produced elongate and sheet sand bodies. Many major Chesterian sandstones exhibit pod, ribbon, dendroid, and belt patterns. Most major Pennsylvanian sandstones exhibit pod, dendroid, and belt patterns.

CHESTERIAN SERIES	Grove Church Fm.
	Kinkaid Fm.
	DEGONIA Ss.
	Clore Fm. (includes TYGETT Ss. Mbr.)
	PALESTINE Ss.
	Menard Ls.
	WALTERSBURG Fm.
	Vienna Ls.
	TAR SPRINGS Ss.
	Glen Dean Ls.
	HARDINSBURG Ss.
	Haney (U. Golconda) Ls.
	Fraileys Shale (equals BIG CLIFTY "JACKSON" Ss.)
	Beech Cr. (Barlow) Ls.
	CYPRESS Ss.
	Reelsville Ls.
	SAMPLE Ss.
	Beaver Bend Ls.
	BETHEL Ss.
	Downeys Bluff Ls.
VALMEYERAN	YANKEETOWN "BENOIST" Ss.
	Renault Ls.
	AUX VASES Ss.
	Ste. Genevieve Ls. (includes SPAR MOUNTAIN Ss. Mbr.)

Fig. 6—Nomenclature of late Mississippian formations (sandstone names in capitals) of the Illinois Basin (Swann, 1963).

Examples of distribution patterns of Pennsylvanian sandstones in the Illinois Basin are relatively numerous. Ekblaw (1931) outlined the pattern, in outcrop, of a channel system in western Illinois. Wier (1953) outlined a channel in Coal V of Pike County, Indiana. Friedman (1956, 1960) mapped in subsurface a series of middle Pennsylvanian sandstones in west-central Indiana. Wanless (1957), using closely spaced outcrops, outlined several channel systems in western Illinois. Mueller and Wanless (1957) showed patterns of sandstones in Jefferson County, Illinois. Hopkins (1958, fig. 4) and Potter and Simon (1961, fig. 4) mapped the Anvil Rock Sandstone Member in the southern



(A) Thin sheet sand body in the Degonia Formation in NE¼ SW¼ NE¼ sec. 30, T. 11 S., R. 1 W., Union County, Illinois. Sheet sandstone east of the main belt sand body is 6 feet thick. (B) Oblique aerial photograph of 60-foot bluff of belt sand body in the Degonia Formation in SW¼ sec. 23, T. 11 S., R. 1 W., Union County, Illinois.

TABLE 1—PROPERTIES OF ELONGATE AND SHEET SAND BODIES

Property	Elongate	Sheet
Basal contact	Erosional and disconformable	Conformable and transitional
Thickness	Sand bodies commonly 20 to 125 feet. Beds thicker than 1 foot common.	Sand bodies rarely exceed 20 feet. Beds generally less than 1 foot.
Texture	Fine to occasionally fine-to-medium size in late Mississippian. Fine-to-medium and occasionally coarse sand in Pennsylvanian.	Fine to very fine
Conglomerates	Shale pebbles plus occasional fragments of limestone and chert in Chesterian sandstones. Pebbles and cobbles of shale, coal, limestone, and clay ironstone in Pennsylvanian sandstones. Quartz pebbles in Caseyville sandstones.	Small pebbles and pellets of shale
Mineralogy	High-tourmaline-zircon ratio	Low tourmaline-zircon ratio
Sedimentary structures	Cross-bedding and cut-and-fill structures predominate.	Ripple marks predominate.
Lithology	Principally sandstone with some interbedded conglomerates, shaly siltstone, and minor siltstone and shale. Usually good self potential on electric logs.	Sandstone plus siltstone and some shale. Poor self potential on electric logs.
Fossils	Marine invertebrate fossils, generally reworked, may be present but are not common. Some plant material in late Mississippian sandstones; usually appreciable plant material in Pennsylvanian sandstones.	Marine fossils may be present but are only rarely abundant. More plant material in Pennsylvanian than late Missisipian sandstones.

part of the Illinois Basin. Andresen (1961) mapped the Trivoli and Inglefield Sandstone Members in the southern part of the basin. Potter (1962a,c) showed the patterns of several sandstones in the Kewanee and McLeansboro Groups in Illinois.

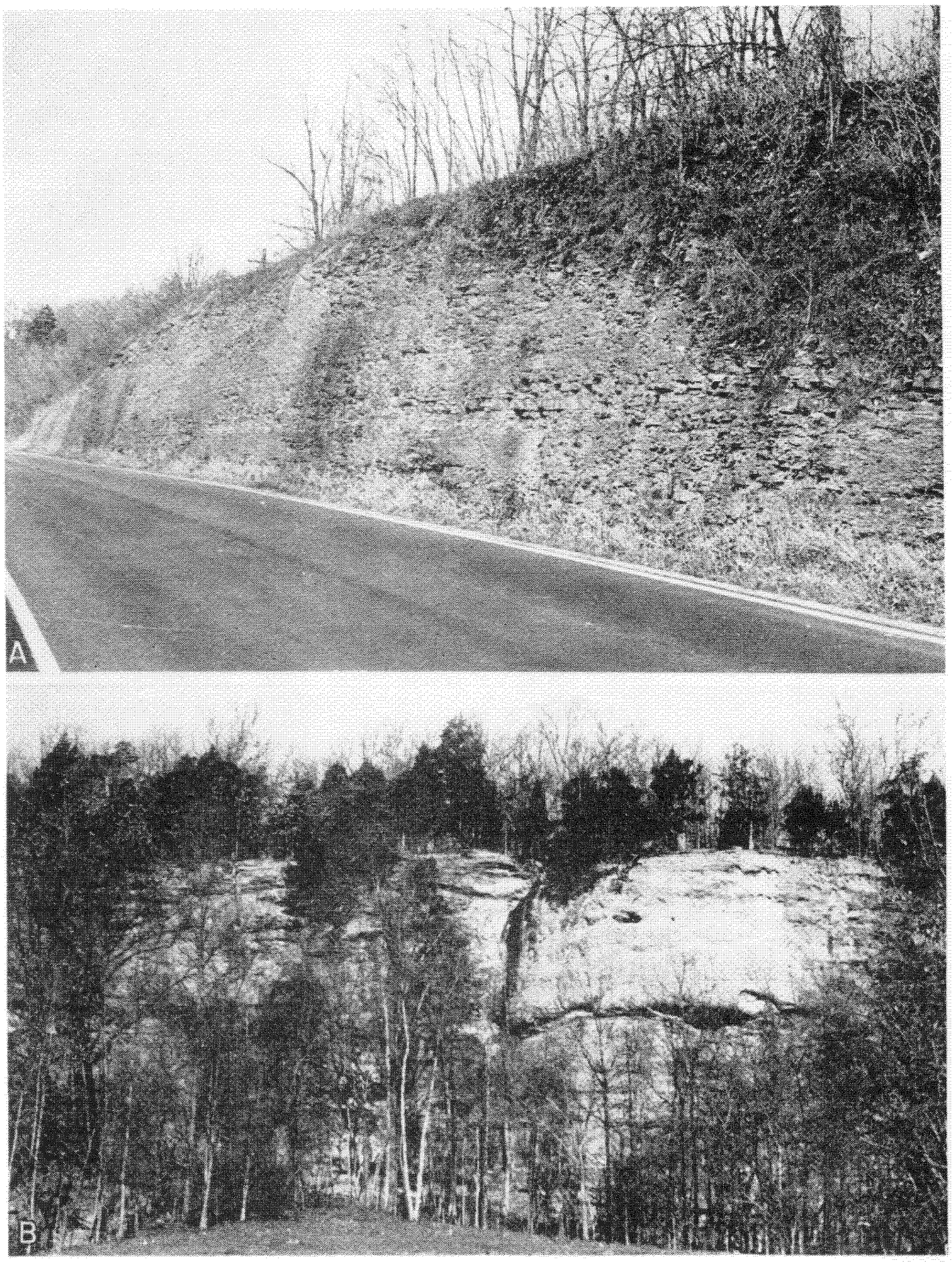
Except for a number of oil pool studies of Chesterian sandstones in western Kentucky, published maps of Chesterian sandstones are less numerous. Swann (1951) mapped sand bodies in the Waltersburg Formation in parts of Illinois, Indiana, and Kentucky. Walker, Puryear, and Cathey (1951, pl. 5) showed a map of sandstone in the Waltersburg Formation in Henderson County, Kentucky. Potter et al. (1958) presented maps of sandstone in the Degonia, Palestine, Tar Springs, and Waltersburg Formations along the southern edge of the basin in Illinois. Whiting (1959) mapped the Spar Mountain Sandstone Member of the Ste. Genevieve Formation in part of central Illinois. Potter included (1962b) statewide maps of sandstone in the Degonia, Palestine, Waltersburg, and Hardinsburg Formations in Illinois.

PETROLOGY AND TEXTURE

Previous Work

The petrographic and textural properties of late Paleozoic sandstones have been studied by many workers, especially during the last decade. This report summarizes petrologic information and supplements previous textural studies with some new data.

Hopkins (1896, p. 199-206), in his study of the Mansfield Sandstone of west-central Indiana, published the first results of thin-section observation in the Illinois Basin. Gault (1938) studied heavy minerals in the same sandstone. Siever (1949, 1953) emphasized thin sections in his study of the Trivoli Sandstone Member (Pennsylvanian)



(A) Sheet sand body, thin bedded and fine grained, that conformably overlies Battery Rock Sandstone Member shown in B. Thickness is 22 feet. NE¼ NE¼ NE¼ sec. 10, T. 11 S., R. 9 E., Hardin County, Illinois. (B) Belt sand body exposed in 55-foot bluff in the Battery Rock Sandstone in E½ NW¼ sec. 10, T. 11 S., R. 9 E., Hardin County, Illinois.

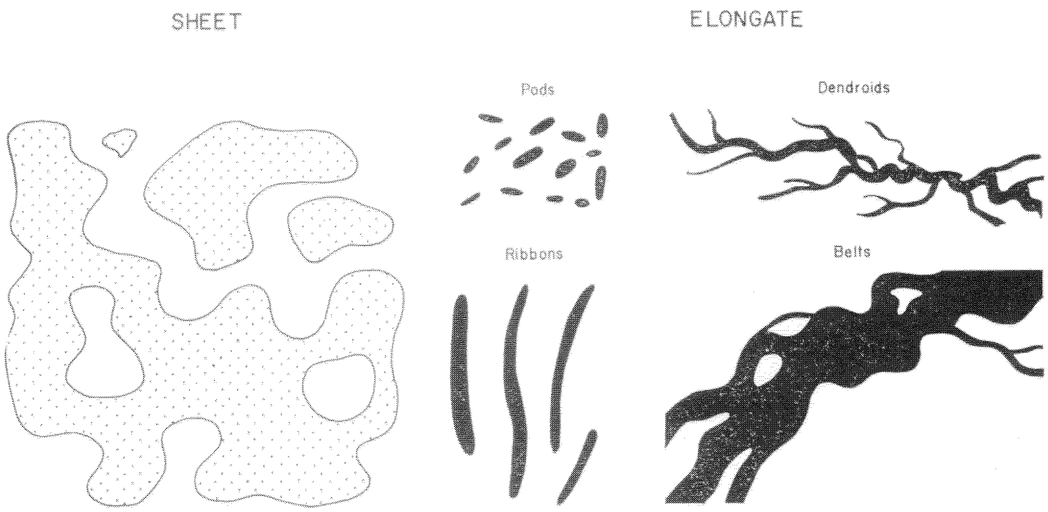


Fig. 7—Patterns of sheet sand bodies and the four types of elongate sand bodies—pods, ribbons, dendroids, and belts.

and late Chesterian sandstones. Grain size and information on heavy minerals were given by Biggs and Lamar (1955) for Chesterian sandstones and sandstones of the McCormick Group in southern Illinois. Siever and Potter (1956) used thin sections and heavy minerals in an examination of sandstone from the Caseyville Formation of the basin. Rusnak (1957), Siever (1957), Hopkins (1958), Potter and Glass (1958), and Andresen (1961) provided data on thin-section composition, heavy minerals, and texture of Pennsylvanian sandstones of the Kewanee and McLeansboro Groups. Siever (1959) reported on cementation of Pennsylvanian sandstones. Greenberg (1960) presented detailed grain size and mineralogical data for the Chesterian and Pennsylvanian sandstones of Indiana. Atherton et al. (1960) emphasized the petrologic contrasts of Caseyville and Chesterian sandstones in the basin. Potter and Pryor (1961, app. 2) provided additional data on thin sections and heavy minerals for Pennsylvanian and Mississippian sandstones. Bradbury, Ostrom, and Lamar (1962) presented detailed chemical and petrologic data on Pennsylvanian sandstones in central Illinois.

Petrographic Composition

In terms of petrographic composition, sandstones of the late Mississippian and the early Pennsylvanian (Caseyville and Mansfield Formations) are quite similar (fig. 8). Generally there is less than 1 percent feldspar and mica. Both rock fragments and matrix average slightly more than 1 percent. These sandstones are borderline protoquartzites or orthoquartzites (Pettijohn, 1957, p. 283-339), depending on clay content. Both well rounded and angular grains are present. More angular grains are present in the sandstones of the Caseyville and Mansfield Formations than in late Mississippian sandstones (Atherton et al., 1960, fig. 4). Petrologically, the late Mississippian sandstones show no major variation in detrital components in the basin. However, Pennsylvanian sandstones do show some differences. The Babylon Sandstone, the basal member of the Abbott Formation in western Illinois, is more mature, contains better rounded grains, and has more stable minerals than the basal sandstones of the Mansfield and Caseyville Formations in the southern and eastern portions of the basin. Quartz pebbles and granules are abundant in sandstones of the Caseyville and Mansfield Formations. Higher in the section the sandstones of the Abbott Formation have more feldspar, mica, matrix, detrital grains, and angular grains than those of the Caseyville Formation. These sandstones are protoquartzites.

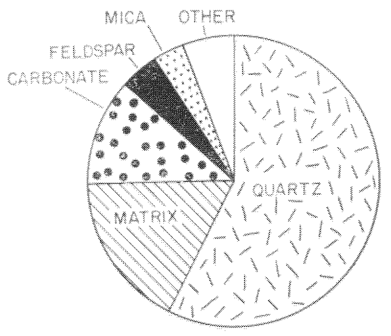
Above the Abbott Formation in the Kewanee and McLeansboro Groups, the sandstones are subgraywackes and contain 3 to 4 percent of both feldspar and mica, appreciable rock fragments, and commonly 10 to 18 percent matrix. Angular grains are common. Some variation in detrital minerals of these sandstones may exist between the eastern and western portions of the basin, but it is much less pronounced in the sandstones of the Caseyville Formation and its equivalents. Petrographic homogeneity is their most impressive feature.

Because the Abbott Formation thins to the north, transitions from relatively mature basal sandstones to less mature sandstones above the McCormick Group can be relatively abrupt in the northern and western shelf areas.

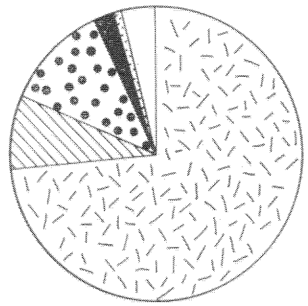
The heavy minerals of both the Pennsylvanian and late Mississippian sandstones compose a restricted suite, especially if only the more abundant minerals are considered. Zircon and tourmaline are the chief heavy minerals, usually forming over 90 percent of the nonopaque count. A small percentage of apatite and garnet also is present in some samples. Rutile and anatase commonly form 1 percent or less of the count. Other heavy minerals, including brookite, corundum, hornblende, hypersthene, epidote, fluorite, topaz, and zoisite, occur but are very rare. Opaque heavy minerals present include magnetite, pyrite, ilmenite, and leucoxene. The weight of heavy minerals is almost always less than 1 percent of the sandstone.

Information on the clay mineral content of the Illinois Basin sandstones (Glass, Potter, and Siever, 1956; Hopkins, 1958, p. 13; Smoot, 1960) indicates that all the major clay minerals are present. Kaolinite appears to be more abundant in the sandstones than in interbedded shales. Kaolinite books and worms observed in thin section suggest a post-depositional origin for much of the kaolinite. Other clay minerals in the sandstones—illite, chlorite, and possibly montmorillonite—also commonly show some post-depositional alteration effects. The greater permeability of the sandstones to circulating fluids after deposition, compared to that of the interbedded shales, is believed responsible.

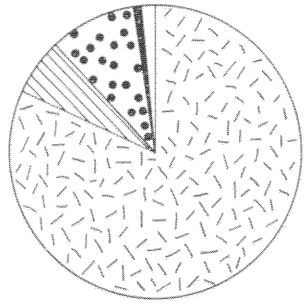
Polycrystalline quartz (approximately 3 percent in late Mississippian and 7 percent in



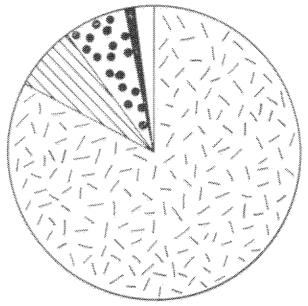
Kewanee and Mc Leansboro Groups



Abbott Formation



Caseyville Formation



Late Mississippian

Fig. 8—Petrographic composition of Pennsylvanian sandstones and late Mississippian sandstones.

Pennsylvanian sandstones) and rounded tourmaline overgrowths on abraded tourmaline cores can be found in most late Paleozoic sandstones. Except in sandstones of early Mississippian age, neither polycrystalline quartz nor rounded overgrowths on abraded tourmaline cores are abundant in the older Paleozoic sandstones of the Mississippi Valley area (Potter and Pryor, 1961, p. 1209-1210).

Grain Size

The sheet and elongate sand bodies generally cannot be distinguished by mineralogical or petrographic means, except for minor distinctions that are linked to contrasts in grain size.

Contrasts in grain size for some late Paleozoic sheet and elongate sandstones are depicted in figure 9. Elongate Pennsylvanian sand bodies are generally markedly coarser grained than their associated sheet sand bodies. Size contrasts between late Mississippian sheet and elongate sand bodies are less sharp and are generally less than 1 phi unit.

Elongate sand bodies of Pennsylvanian age generally are coarser grained than those of late Mississippian age. Median sizes of Pennsylvanian sandstones commonly range from 0.125 to 0.40 mm; those of late Mississippian sandstones from 0.088 to 0.250 mm. Most of the Mississippian sandstones are thus very fine to fine grained, whereas Pennsylvanian sandstones vary from very fine grained to medium grained, with a very few coarse grained—especially those of the Caseyville and Mansfield Formations that contain quartz granules and pebbles.

Sorting in the sandstone was compared by using the measure $\log_{10} S_0$, the logarithm to the base 10 of Trask's sorting coefficient (Pettijohn, 1957, p. 36-37). This permits a linear comparison of the sorting coefficients. Data from Biggs and Lamar (1955, table 4), Hopkins (1958, table 4), Potter and Glass (1958, table 7), and Greenberg (1960, table 3) were supplemented by additional analyses.

In Illinois and Indiana 65 samples from late Mississippian elongate sand bodies had an average sorting value of 0.13, indicating they are well sorted. Individual sorting values as low as 0.06 are not uncommon, but values as high as 0.20 occur. In Illinois, seven samples from late Mississippian sheet sand bodies also had an average sorting value of 0.13. In Indiana, sandstone samples of the Mansfield Formation, principally from elongate sand bodies, had the same average, as did the Caseyville sandstones in southern Illinois. With more matrix present in the younger Pennsylvanian sandstones, sorting is poorer. Seventy-six samples from elongate subgraywacke sand bodies in Illinois, Indiana, and Kentucky averaged 0.17. Nineteen samples of Pennsylvanian sheet sand bodies were even less well sorted, averaging 0.24. Principally because of increase of clay and silt, the Pennsylvanian subgraywacke sandstones are approximately only half as well sorted as the late Mississippian and lower Pennsylvanian sandstones.

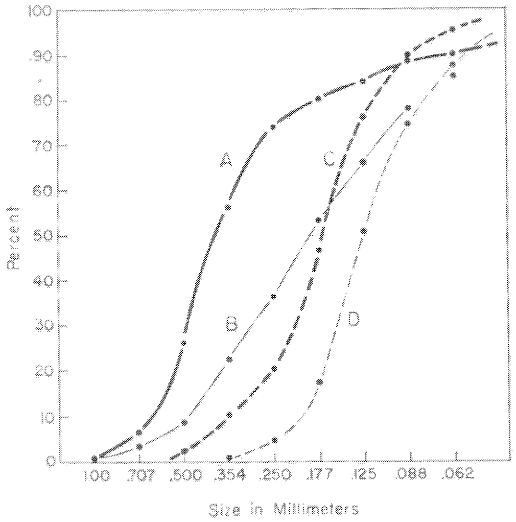


Fig. 9—Cumulative curves of grain size in elongate (heavy lines) and sheet (light lines) sand bodies. (A) 30 samples and (B) 14 samples of the Pennsylvanian Anvil Rock Sandstone Member (Hopkins, 1958, table 4); (C) 9 samples and (D) 7 samples from late Mississippian sandstones.

An important aspect of grain size is its vertical variation in a sand body. Hopkins (1958, fig. 12) showed vertical variation of grain size in the channel and sheet sandstones of the Anvil Rock Sandstone. Swann, Fisher, and Walters (1959, fig. 5) gave some data for late Mississippian sandstones based on rotary sample cuttings. In both studies,

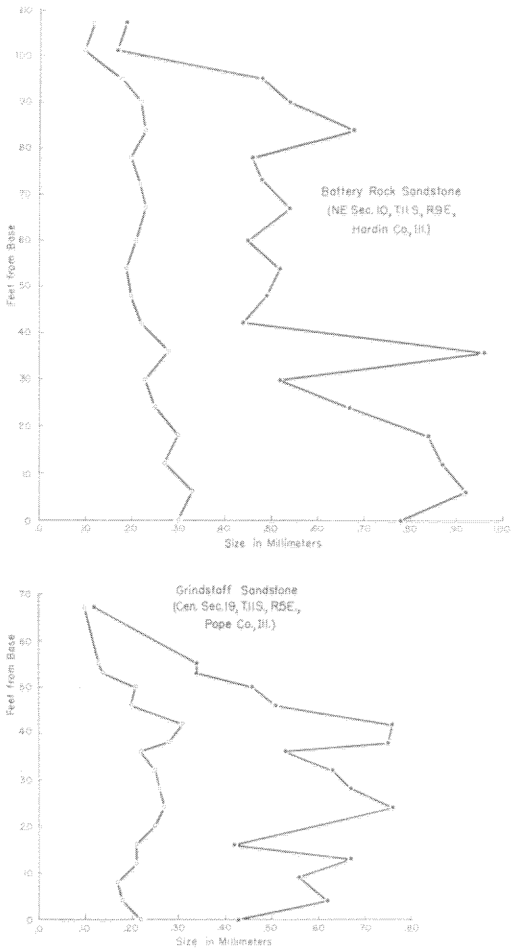


Fig. 10—Vertical profile of estimated median (open circle) and maximum (solid circle) grain size in thick, elongate Grindstaff and Battery Rock Sandstone Members in southern Illinois.

thick elongate sand bodies were found to become finer upward. In the sheet sand bodies in the Anvil Rock Sandstone, vertical variation of grain size was more irregular. The above data were supplemented by additional vertical profiles obtained from outcrops and core materials. Median and maximum grain size were estimated from small chips of sandstone, the identity and order of which were unknown to the operator.

Figure 10 shows estimated median and maximum grain size variation in thick elongate belt sand bodies of the Grindstaff and Battery Rock Sandstones in southern Illinois. Although reversals do occur, especially in the Grindstaff Sandstone profile, both show a general upward decrease in median and maximum grain size. Because they are based on the average of many grains, estimates of median size exhibit less sample-to-sample variation than do estimates of maximum size.

Additional profiles of grain size variation of elongate and sheet sand bodies in Kentucky and Indiana appear in figures 11 and 12.

The grain size profile of an elongate sand body of the Sample Sandstone (fig. 11A) shows a slight decrease in grain size upward. The grain size profile of an unnamed sheet sand body from the Henshaw (?) Formation (Pennsylvanian) in Kentucky (fig. 11B) exhibits similar slight upward decrease. This interval is composed chiefly of siltstone and shale with some sandstone at the base. An elongate sand body between No. 9 Coal and No. 10 Coal in Kentucky (fig. 11C) has a similar slight upward decrease in grain size. In Indiana a vertical profile near the border of a dendroid sand body between Coals V and Vb has a clearly defined (fig. 11D) upward decrease in grain size, especially maximum size. Two profiles were made of grain size in the Big Clifty Sandstone in Indiana. The one (fig. 11E) in sec. 31, T. 3 S., R. 1 E., Crawford County, shows a very small upward decrease. The other (fig. 11F) in sec. 13, T. 2 S., R. 1 W., of the same county shows little upward decrease in median size and an actual increase in maximum size. The original top of this sand body could not be sampled. Figure 12 shows an irregular pattern of vertical grain size variation in a thin sheet sand body of the Cypress Formation.

Vertical grain size variation also was investigated in two thick, megascopically massive beds of sandstone (fig. 13). Their profiles show no clearly defined upward changes comparable to those found in most of the sand bodies or in thick, graded sandstone beds of turbidite origin (Nederlof, 1959, fig. 6).

The above data and those of Hopkins (1958, fig. 12) were combined for a statistical test of size variation in all the elongate and

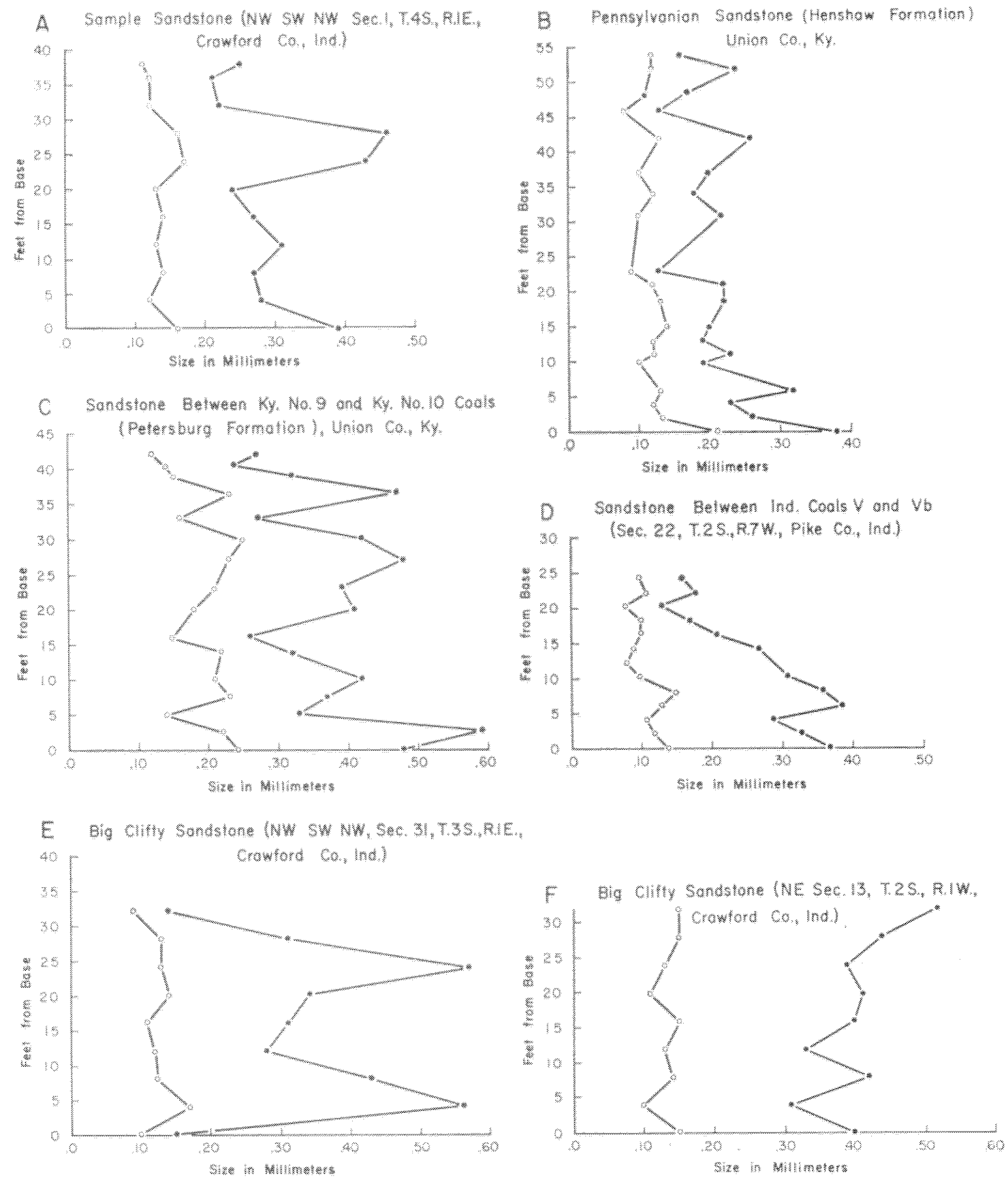


Fig. 11—Vertical profile of estimated median (open circle) and maximum (solid circle) grain size in late Paleozoic elongate (A, B, and C) and sheet (D) sand bodies.

sheet sand bodies studied and for the two homogeneous beds. A nonparametric test, the median test (Mood, 1950, p. 394-395; Siegel, 1956, p. 111), was used. The data and results are given in table 2.

The combined data indicate that elongate sand bodies become finer grained upward. A waning transport competence is implied. Elongate sand bodies that become coarser upward appear to be the exception in the basin. Nanz (1954, p. 110) noted a similar upward decrease in grain size in recent point bars on the Texas Gulf Coast. Neither the sheet sand bodies nor the two samples of massive sandstone beds showed a significant upward decrease in median size, although less information is available for these types of sand bodies.

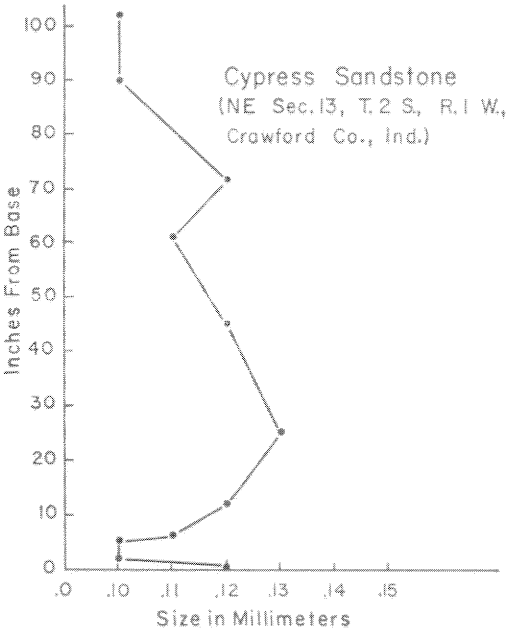


Fig. 12—Vertical profile of estimated median grain size in a sheet sand body in the Cypress Sandstone.

Bedding Thickness

Bedding thickness, although imperfectly understood, has been measured and tabulated by several sedimentologists. Nederlof (1959, p. 638-645) summarized bedding thickness data for graded beds. Schwarzacker (1953, fig. 4) and Pryor (1960, fig. 15) gave data on cross-bedding thickness.

The thickness of 306 late Mississippian and 326 Pennsylvanian individual cross-bedded sedimentation units was measured and is shown in figure 14. The distribution of cross-bedding thickness obtained from an intensive sampling of a belt sand body in the Aux Vases Formation in portions of Randolph County, Illinois, also is shown, data for which (79 measurements) are not included in the compilation of late Mississippian thicknesses. The data, as are nearly all distributions of bedding thickness, are skewed. Median thickness is 8.7 inches for late Mississippian sandstones and 9.6 for Pennsylvanian sandstones. In both the late Mississippian and Aux Vases compilations, the mode is the 4- to 8-inch interval, and in Pennsylvanian sandstones it is the 8- to 12-inch interval. Maximum measured thickness of a Mississippian cross-bedded unit was 67 inches, and that of a Pennsylvanian unit was 97 inches. Thicker Pennsylvanian cross-beds reflect, along with coarser grain, the greater competence of the currents that transported sand into and across the basin in Pennsylvanian time.

It has been suggested that the skewness of bedding thickness distributions tends to be normalized after logarithmic transformation (Pettijohn, 1957, p. 160-161). Figure 15 shows three straight lines fitted by eye to the cumulative curves of figure 14. Because of the large number of observations and the departures from a straight line fit, the Penn-

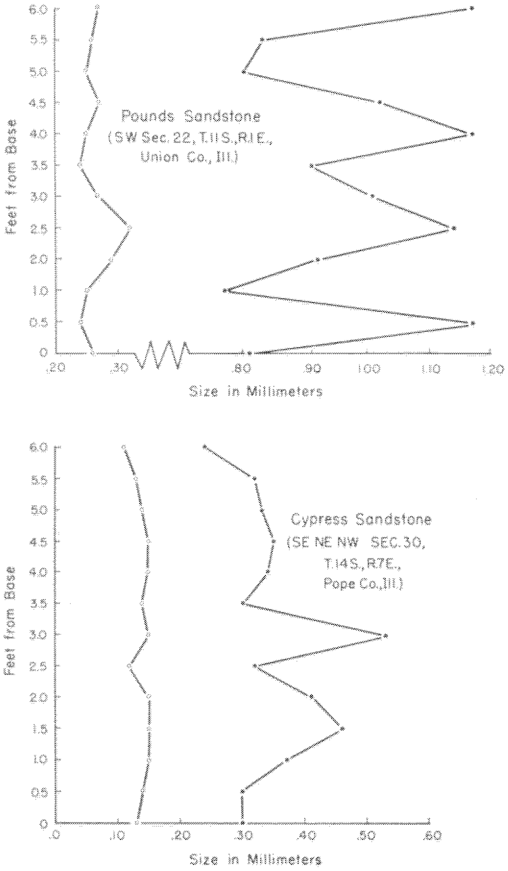


Fig. 13—Vertical profile of estimated median (open circle) and maximum (solid circle) grain size in thick, megascopically massive beds of the Pounds and Cypress Sandstones in southern Illinois.

TABLE 2—COMPOSITE TEST OF VERTICAL GRAIN SIZE VARIATION IN SANDSTONES

Type of sand body	Above combined median sample		Below combined median sample		Observed value of X^2
	<Median size	>Median size	<Median size	>Median size	
11 elongate sand bodies	43	24	19	45	15.90
4 sheet sand bodies	9	11	9	8	0.51
2 massive sand bodies	6	7	5	7	0.84

$X^2_{0.01}(1) = 6.63$

sylvanian and late Mississippian data of figure 15 probably would fail an exact statistical test of logarithmic normality and can be considered only as a very imperfect approximation to a log-normal distribution. The thickness data from the sand body in the Aux Vases appear to approach a logarithmic normal distribution more closely.

SEDIMENTARY STRUCTURES

The primary directional structures of the late Paleozoic sandstones of the Illinois Basin are classified into two types—directional and nondirectional (table 3).

Directional structures are further subdivided into two major kinds—those that indicate a specific direction (one-way) and those that indicate only a line of transport (two-way). Cross-bedding is an example of the former and parting lineation an example of the latter. Nondirectional structures comprise two groups—those that result from animal activities and those that result from deformation of soft sediments by physical processes.

Types of Sedimentary Structures

The sedimentary structures in Pennsylvanian and late Mississippian sandstones are essentially identical.

Potter and Glass (1958, p. 18-23) described the sedimentary structures of the Pennsylvanian sequence in southern Illinois. Photographs of sedimentary structures that are virtually identical to those in the Illinois Basin appear in an atlas of lithologic types of the Donets Basin (Botvinkina et al., 1956).

Animal Borings

Borings of benthonic animals occur in a few fine-grained, thin-bedded sandstones.

TABLE 3—CLASSIFICATION OF SEDIMENTARY STRUCTURES IN LATE PALEOZOIC SANDSTONES

Directional structures		Nondirectional structures
One-way structures	Two-way structures	
Asymmetrical ripple marks	Symmetrical ripple marks	Animal borings
Cross-bedding	Parting lineation	Animal trails
Drag marks (unlike ends)	Drag marks (like ends)	Deformational structures
Flute marks	Plant debris	Load casts
	Small erosional channels	Shrinkage structures
		Syneresis casts

Never abundant, they are best observed in diamond drill cores of thin siltstone beds interlaminated with shale. Borings are rarely more than 2 to 3 inches long. Greensmith (1956, pl. 3) showed examples of borings in the Upper Carboniferous of England that are duplicated in the Illinois Basin. Botvinkina et al. (1956, pl. 41, fig. 2; pl. 43, fig. 1) pictured good examples from the Middle Carboniferous sediments of the Donets Basin that are comparable to those in the Illinois Basin. Some thin zones of irregularly bedded or structureless, argillaceous, fine-grained sandstones and siltstones may have resulted from the activity of benthonic organisms, as diagrammed by Moore and Scruton (1957, fig. 12). Worm borings, which are not abundant in the basin, occur in the Renault Formation in southwestern Illinois (Weller and Sutton, 1940, p. 824).

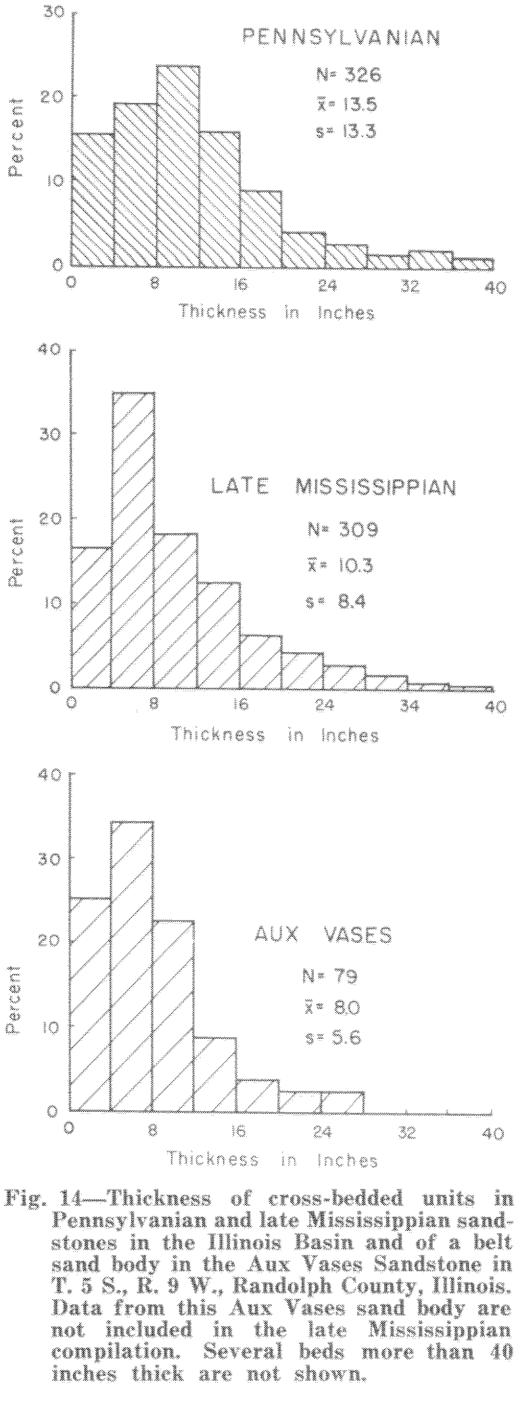


Fig. 14—Thickness of cross-bedded units in Pennsylvanian and late Mississippian sandstones in the Illinois Basin and of a belt sand body in the Aux Vases Sandstone in T. 5 S., R. 9 W., Randolph County, Illinois. Data from this Aux Vases sand body are not included in the late Mississippian compilation. Several beds more than 40 inches thick are not shown.

Conglomerates

Pebbles and occasional cobbles of shale are the most common lithology of conglomerates in the sandstones. A typical example of the casts of a shale-pebble conglomerate is shown in figure 16. Shale-pebble conglomerates occur in both sheet and elongate sand bodies. Pebbles and cobbles of limestone and clay ironstones are present in some elongate sand bodies, especially at their bases. Pebbles and cobbles of coal and rafted coaly materials are common conglomeratic elements in

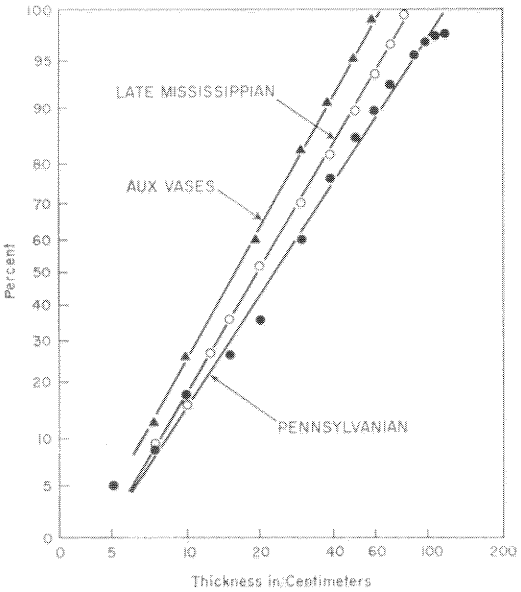


Fig. 15—Cumulative plots of cross-bedding thickness on log probability scale. Based on same data as figure 14.

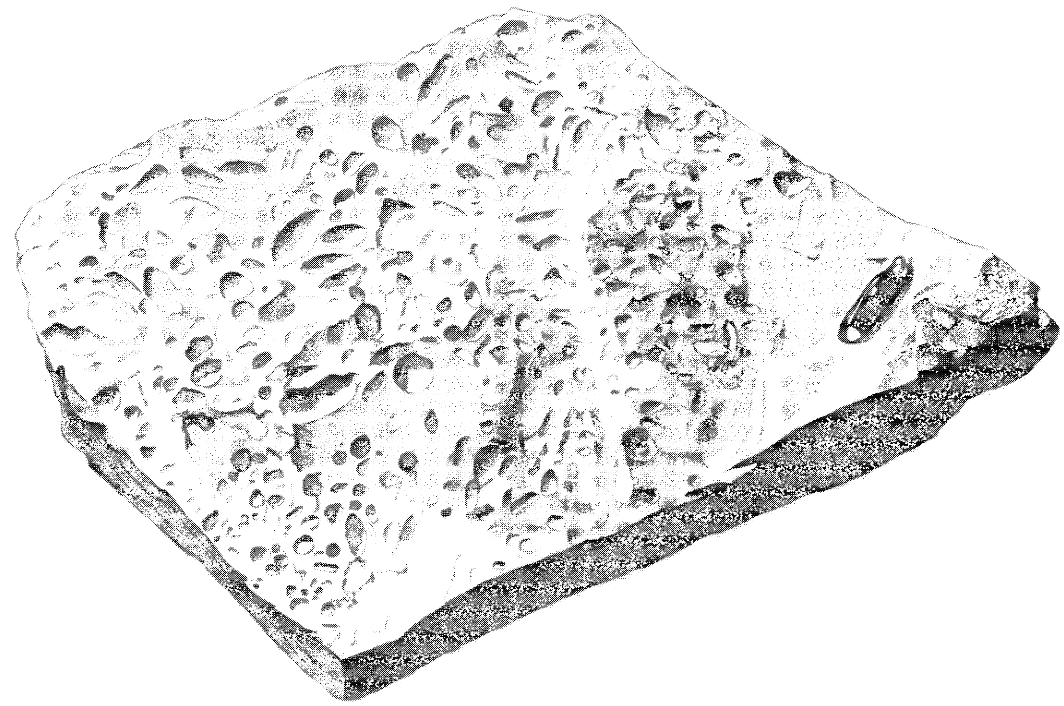


Fig. 16—Casts of shale pebbles in Hardinsburg Sandstone in SW¼ NE¼ NE¼ sec. 32, T. 13 S., R. 4 E., Johnson County, Illinois.

Pennsylvanian sandstones. Quartz granules and pebbles are commonly present in the Caseyville and Mansfield Formations. The fabric of conglomerates can be used for determining current direction, but in the Illinois Basin, where cross-bedding is abundant, it is rarely so used.

Deformational Structures

Zones of deformed bedding occur in both Pennsylvanian and late Mississippian sandstones. The zones vary in intensity from gentle internal plications within one bed to complex folds and deformations that include several beds and may be 2 or 3 feet thick. They are nondirectional structures. The smaller deformed beds are easily seen in diamond drill cores. Their penecontemporaneous origin is demonstrated by undisturbed overlying beds. Figure 17 is a drawing of a penecontemporaneous zone of disturbed bedding, called ball-and-pillow structure (Potter and Pettijohn, 1963, p. 148), in the Lusk Shale Member (Pennsylvanian). Horizontal movement on a small scale may have occurred but usually cannot be demonstrated. The origin of such zones appears to be dependent on the original thixotropic state and the water content of the bed. Unusual conditions of water saturation or salinity content within the bed, rapid deposition of overlying beds, or possibly even seismic tremors are possible causes for this type of contorted bedding.

Other deformational structures include the internal structure of load casts, pull-a-parts, and sandstone balls. Sandstone balls are usually 6 inches or less in diameter and contain an internal spiral structure. They probably were developed by the rolling of the mass down a sloping surface. Figure 18 shows an unusually large sandstone ball in the Lusk Shale. Development of sandstone balls is favored by an interlaminated sand and mud sequence with a sloping surface.

Some outcrops display deformational structures that are related to compactional adjustment along irregular contacts such as an uneven erosional channel-cut surface. In some Pennsylvanian sandstones, deformed laminations and lenses of coal reflect post-depositional compaction (Wanless, 1954, p. 155-163). Other small compactional struc-

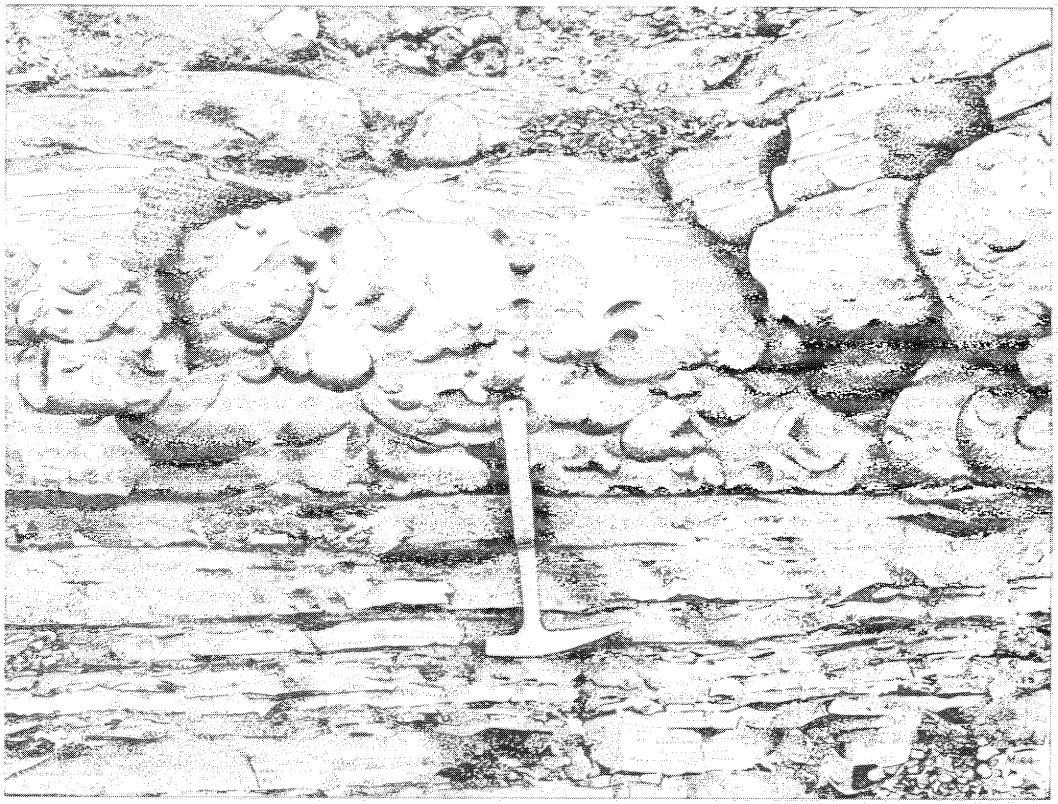


Fig. 17—Ball-and-pillow structure in sandstone in the Lusk Shale Member (Pennsylvanian) in SE¼ NE¼ sec. 27, T. 11 S., R. 1 E., Union County, Illinois.

tures may develop locally as a response to unequal loading in shales and siltstones underneath a thick, overlying elongate sand body. Hutchison (1960, p. 28-30) described contorted Pennsylvanian sediments in west-central Indiana.

Deformational structures and small gravity faults have been observed along the margins of the Pleasantview Sandstone Member (Rusnak, 1957, fig. 5). Some deformed sediments and slides are believed to have developed in response to penecontemporaneous movement along fault lines and flexures active in Pennsylvanian time (Potter, 1957; Potter and Glass, 1958, p. 21; Desborough, 1962).

The foresets of cross-bedding also can be deformed prior to deposition of the overlying sedimentation unit.

Cross-Bedding

Cross-bedding is probably the most conspicuous and one of the most abundant of all the primary structures of the late Paleozoic sandstones in the Illinois Basin. It is a one-way directional structure.

Cross-bedding varies widely in size from less than 1 inch thick, where it may appear in cross section as a ripple mark, to units that exceed 10 feet thick. In width it varies from several inches (micro-cross-bedding or rib-and-furrow) to more than 50 feet. Length may vary from a few to more than 50 feet. The basal contact of a cross-bedded unit may be either planar (for wide units) or concave (for narrow ones), and the corresponding bedding is called planar cross-bedding or trough cross-bedding. Gradations between planar and trough cross-bedding exist and both may occur in the same outcrop. The large cross-beds are nearly always found in thick elongate sand bodies. Micro-cross-bedding is usually less than 1 inch thick, 3 to 4 inches wide, and rarely more than 2 feet long. It may be present in thick elongate sand bodies but generally is best developed in thin sheet sand bodies. Regardless of scale, the foreset beds within a cross-bedded sedimentation unit are virtually always concave in the down-current direction.

Plate 4A shows micro-cross-bedding in a series of thin, fine-grained sandstone beds in the Hardinsburg Formation in southern Illinois. Each cross-bedded unit is 3 to 4 inches wide and approximately half an inch thick. Orientation generally is very constant from bed to bed. Parting lineation is a commonly associated sedimentary structure.

Cross-bedding of slightly larger scale is shown in the drawing of a cross-bedded siltstone overlying evenly laminated siltstone (fig. 19). The cross-bedded unit is approximately half an inch thick and slightly more than 8 inches wide. The foresets dip down-current at a low angle and are concave in the down-current direction.

Another example of the down-current concave curvature of foresets is shown in figure 20, which depicts cross-bedding in the Tar Springs Sandstone where it is exposed in a small stream in Breckinridge County, Kentucky. The foresets dip away from the viewer at a relatively low angle. Although not exposed for its entire width, the cross-bedded unit is probably 10 to 12 feet wide.

Plate 4B shows a portion of the topset and the underlying foresets of a cross-bed in a belt sand body in the Degonia Formation. The foresets dip away from the viewer. Because of the width of the foresets, their radius of curvature is very large. This cross-bed could be 50 feet wide. Direction of maximum dip of the cross-bed parallels the long axis of the belt sand body in which it occurs.

A typical longitudinal cross section of cross-bedding is shown on plate 5A, a Pennsylvanian sandstone of the Spoon Formation

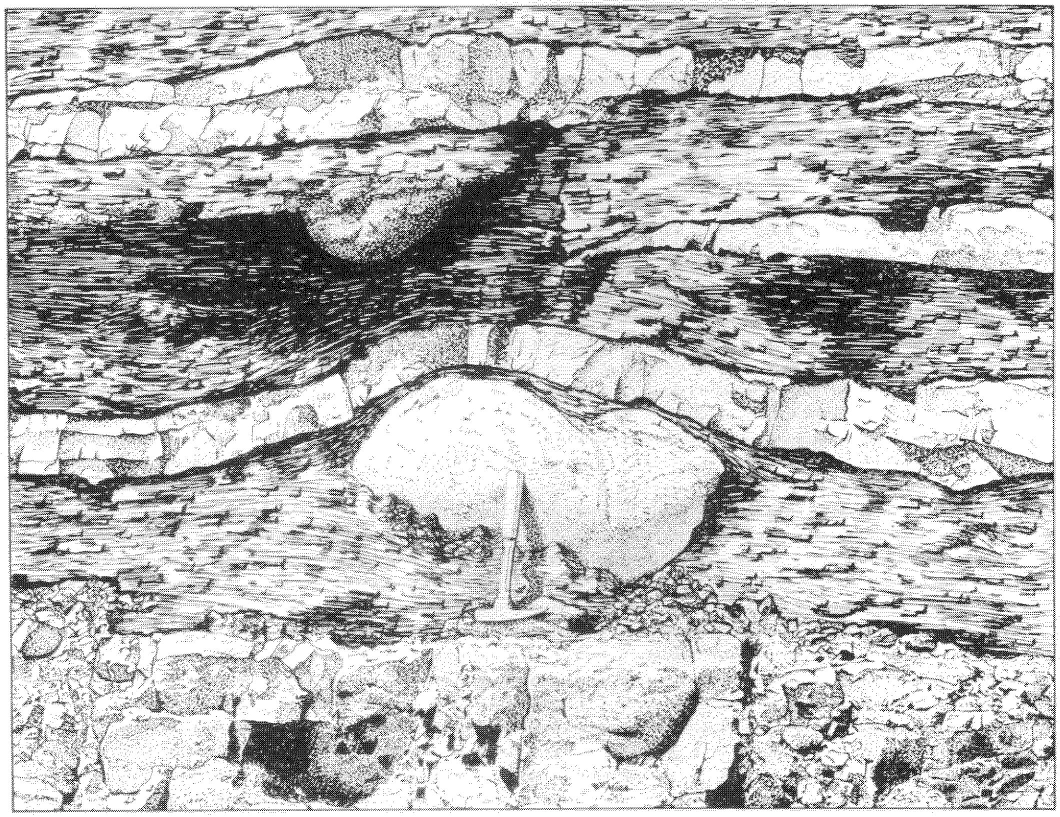
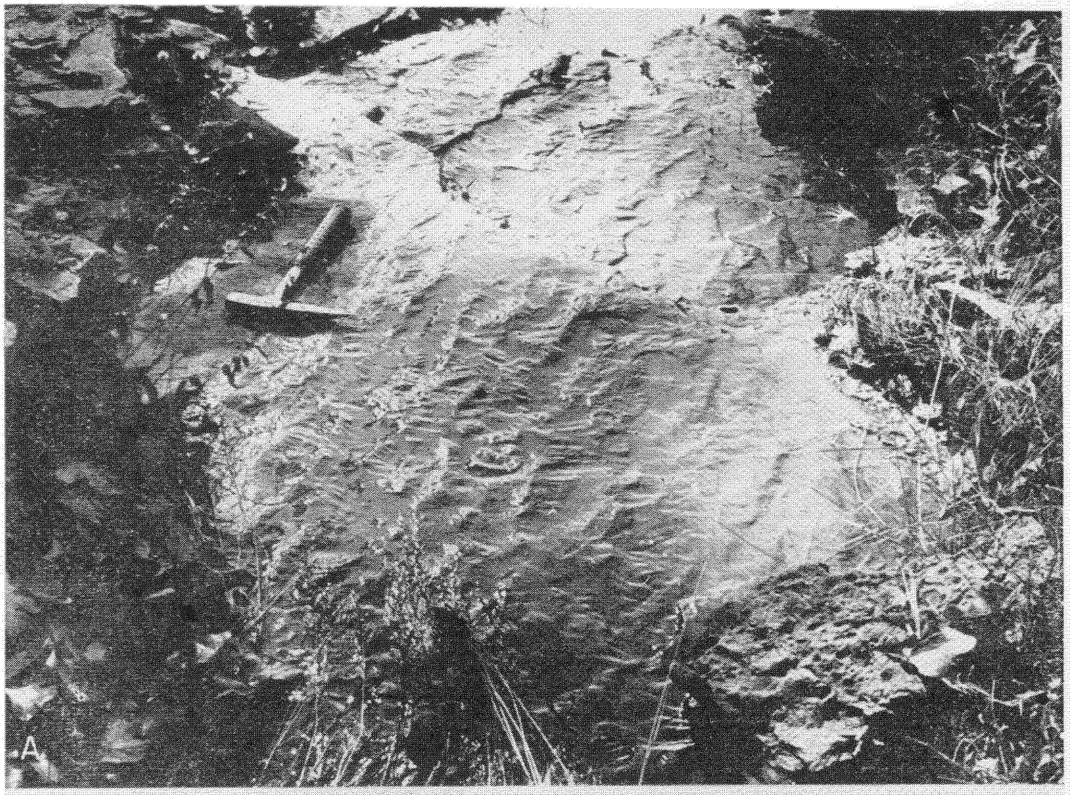
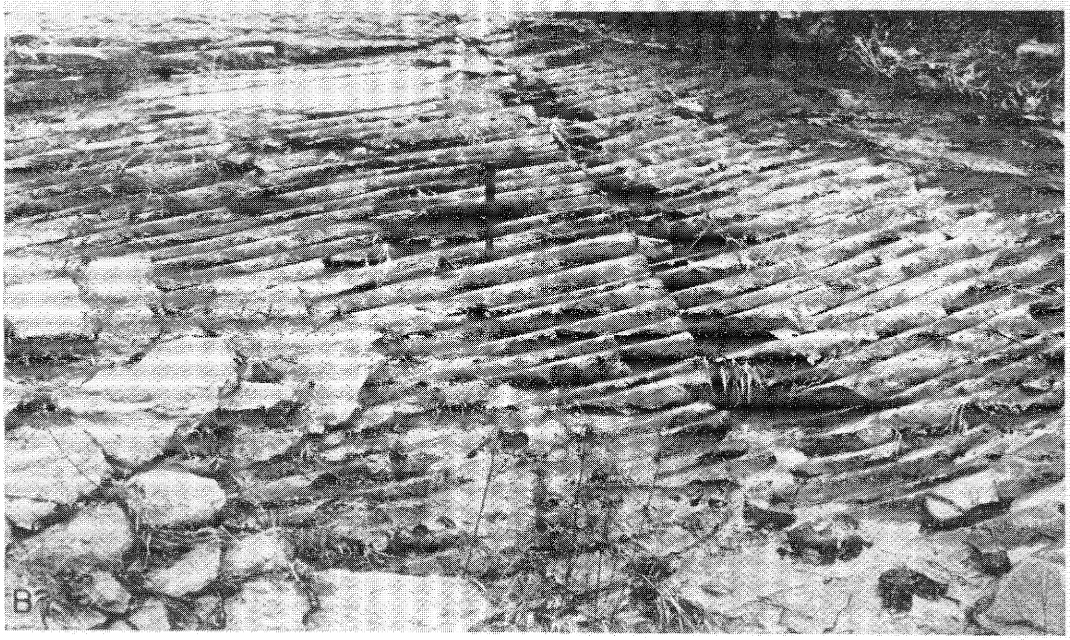


Fig. 18—Deformed beds and probable large sandstone ball in Lusk Shale Member (Pennsylvanian) in SE¼ NE¼ sec. 27, T. 11 S., R. 1 E., Union County, Illinois.





(A) Micro-cross-bedding in fine-grained, thin-bedded sandstone of the Hardinsburg Formation in SW¼ NE¼ NE¼ sec. 32, T. 13 S., R. 4 E., Johnson County, Illinois.

(B) Cross-bedding and overlying level beds in thick belt sand body in the Degonia Formation in NE¼ NE¼ NE¼ sec. 23, T. 11 S., R. 1 W., Union County, Illinois.

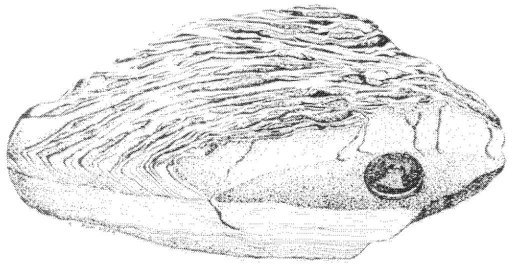


Fig. 19—Cross-bedding in siltstone of Desmoinesian Series (Pennsylvanian) in NW¼ NE¼ NE¼ sec. 34, T. 77 N., R. 1 W., Muscatine County, Iowa.

in Rock Island County, Illinois. If they could be seen in plan view, the cross-beds of plate 5A would have an appearance similar to those shown in figure 19 and plate 4B.

In some cross-beds, foresets were overturned in the down-current direction prior to deposition of the overlying bed (Potter and Glass, 1958, fig. 9). A few foresets are ripple marked by secondary currents. Generally the ripples strike parallel to maximum dip direction. If sufficiently coarse grained, as are some in the Caseyville Formation, foreset beds may be graded.

Parting Lineation

Parting lineation, a series of even, thin laminations, develops from a smooth, water-sediment interface and is a two-way directional structure. Subsequent breakage of the laminations gives a lineated parting that probably reflects internal grain fabric. Plate 5B shows parting lineation directly underlying asymmetrical ripple marks. Parting lineation is present in both elongate and sheet sand bodies, but, because it develops

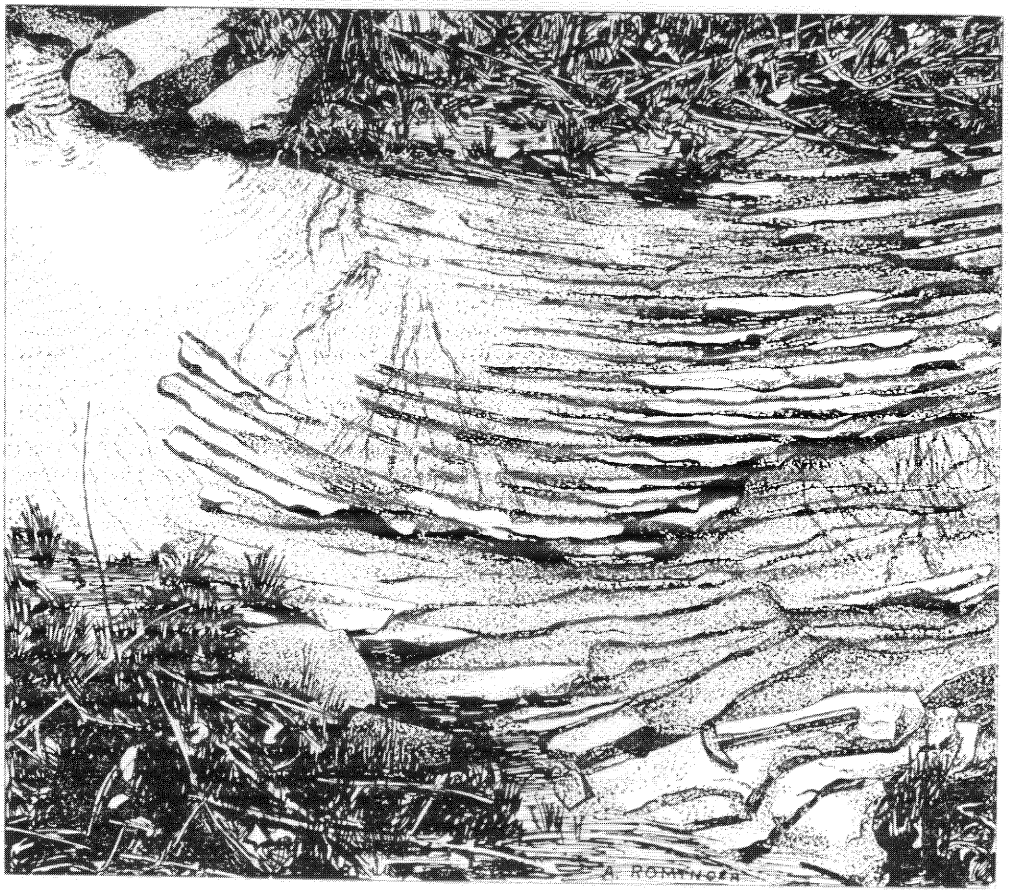
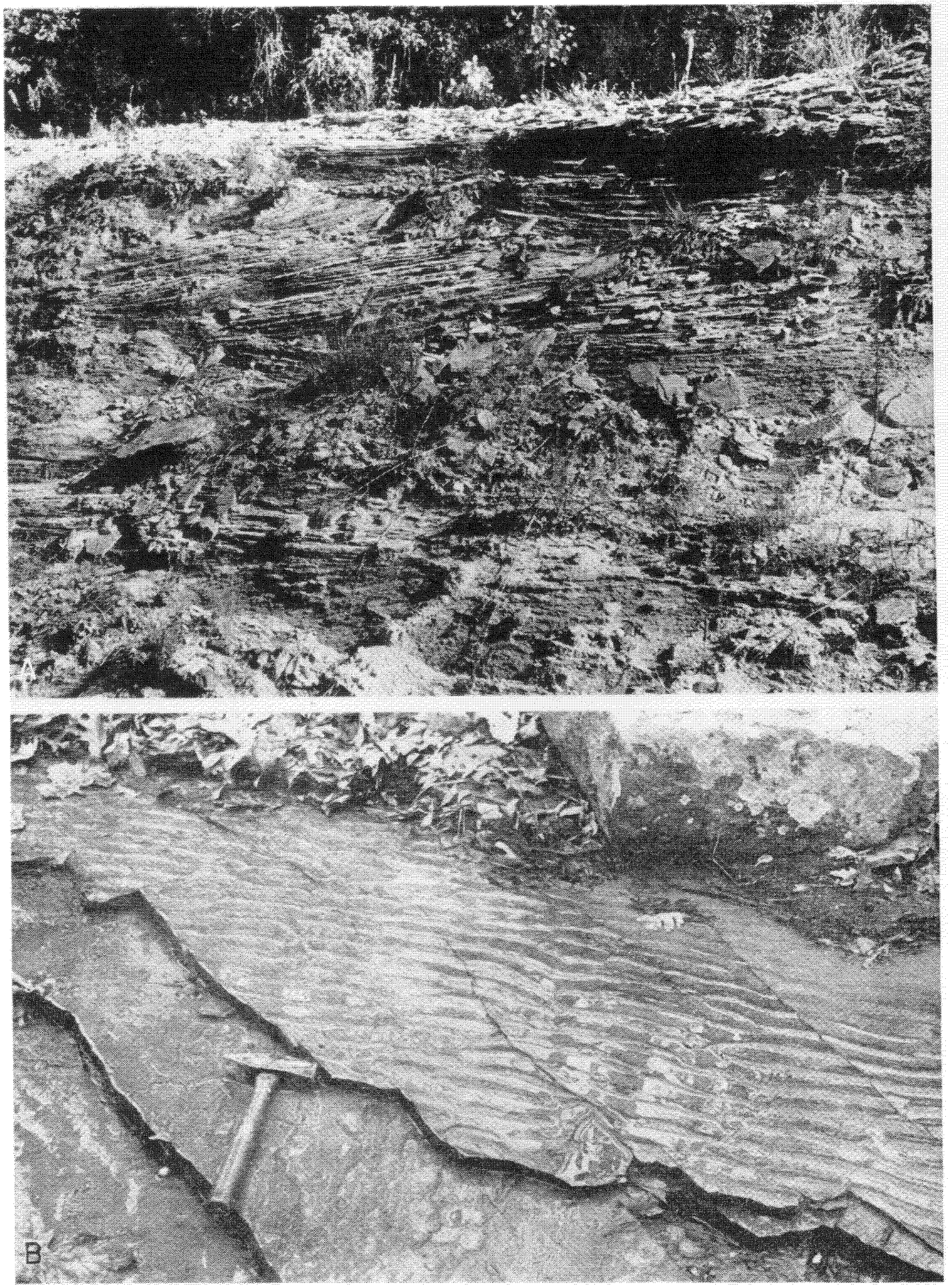


Fig. 20—Cross-bedding in Tar Springs Sandstone, 5500 F.W.L., 11,300 F.N.L., Carter grid rectangle 0-36, Breckinridge County, Kentucky.



(A) Cross-bedding of a sandstone in the Spoon Formation in SW¼ SW¼ SE¼ sec. 6, T. 16 N., R. 5 W., Rock Island County, Illinois. (B) Asymmetrical ripple marks and parting lineation on the underlying bed. Ripple marks strike at right angles to parting lineation. Caseyville Formation in SW¼ SE¼ NE¼ sec. 28, T. 10 S., R. 2 W., Union County, Illinois.

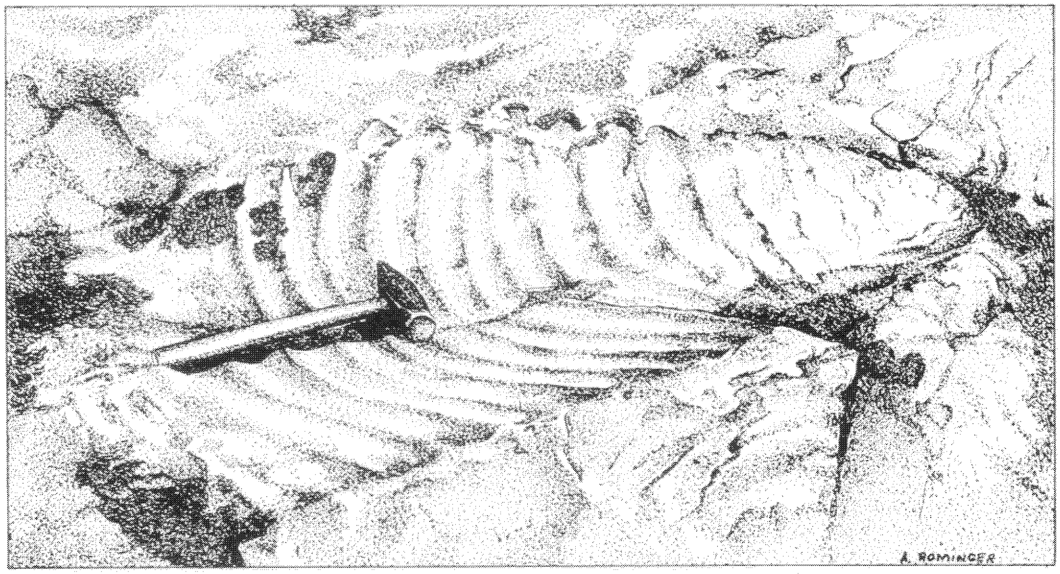


Fig. 21—Shallow ripple scour in Degonia Sandstone in SW¼ SW¼ SE¼ sec. 22, T. 11 S., R. 1 W., Union County, Illinois. Hammer handle indicates axis of scour.

in less turbulent water, it is a relatively common structure in sheet sand bodies.

Small Erosional Channels

Small erosional channels, from a few feet wide and a few inches deep to more than 30 feet wide and 5 feet deep, occur in late Paleozoic sand bodies in the basin. They are two-way directional structures.

Small shallow channels, called ripple scours by Potter and Glass (1958, pl. 5), that are usually ripple marked (fig. 21) are relatively common. Their long axes generally subparallel nearby cross-bedding direction.

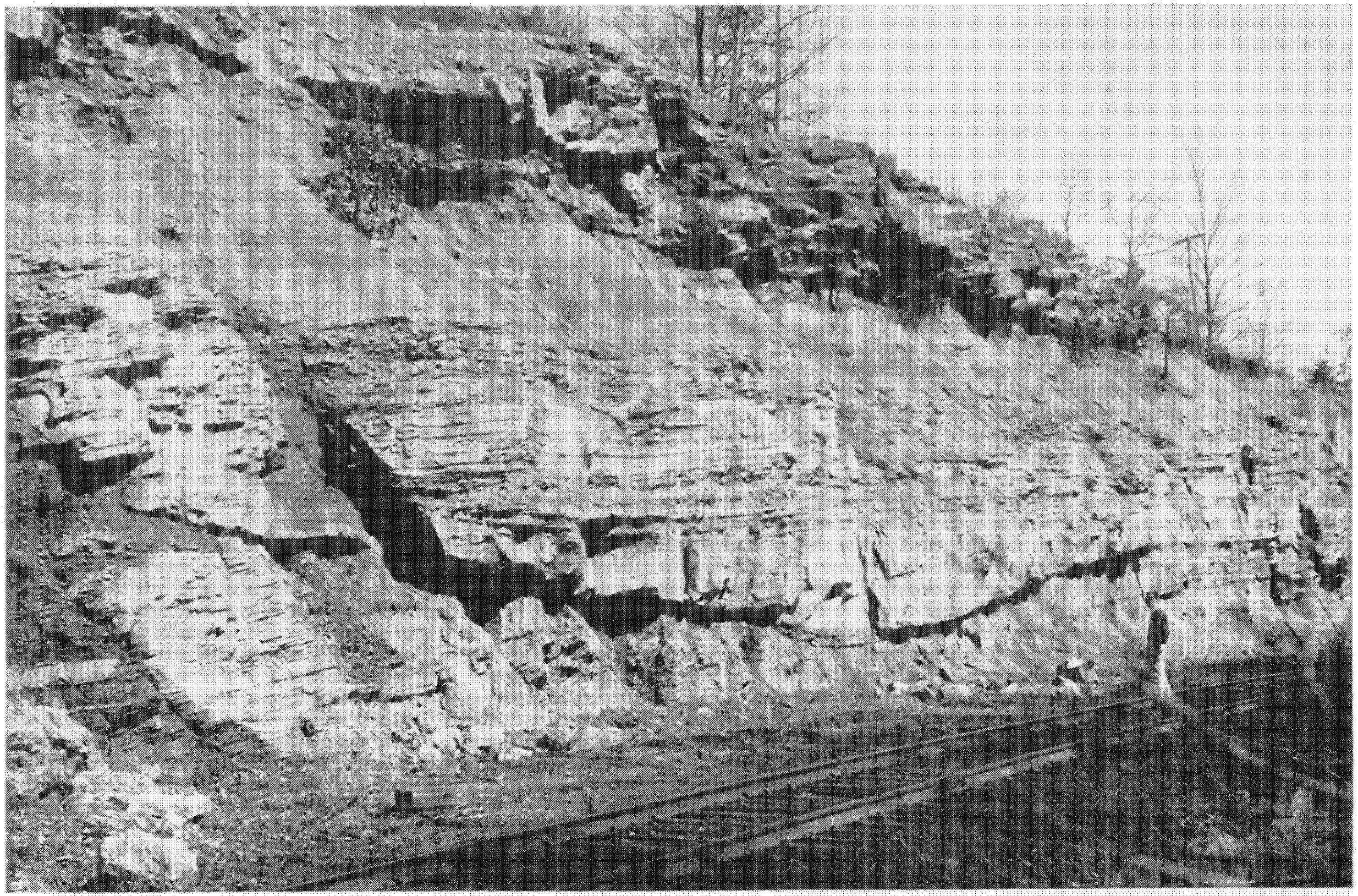
Bottom erosion is greater when the turbulence and velocity of the current is high. Figure 22 shows a small channel filled with evenly laminated, fine-grained Pennsylvanian sandstone in Pike County, Indiana. Bedding laminations near the contact are subparallel to it. Small channels such as these are relatively common in elongate sand bodies. Channel erosion on a larger scale is shown in the Tar Springs Sandstone in Pope County, Illinois (fig. 23), where erosion removed approximately 3 feet of previously deposited sand. Bedding within the channel fill subparallels the basal erosional contact.

Small channels occur not only within sand bodies but also at their bases, as shown in the drawing (fig. 24) of a small channel at the base of the Cypress in Martin County, Indiana. The fill of this small channel is largely fine-grained, massively bedded sandstone.

Channels, although most common in elongate sand bodies, can also be found in sheet sand bodies. A broad, gently sloping, erosional channel in an evenly bedded sequence of siltstone and fine sandstone in the Tradewater Formation in Muhlenberg County, Kentucky, is shown on plate 6. Probably because of its width, the bedding of the subsequent channel fill is not parallel to the basal contact.

Plant Debris

Water-transported plant material (fragments of leaves, branches, and trunks) occurs in many Pennsylvanian sandstones but generally is less abundant in late Mississippian sandstones. This material, principally remains of the Lycopsida and Sphenopsida, occurs as both compressions and casts, which are two-way directional structures. Macerated plant debris, from less than a millimeter to more



Broad, gently sloping channel in sheet sand body in the Tradewater Formation in cut of Louisville and Nashville Railroad, 5200 F.E.L., 10,800 F.N.L., Carter grid rectangle H-30, Drakesboro Quadrangle, Muhlenberg County, Kentucky.

than 4 millimeters long, also is present and is in part fusainized. Sandstones may also contain small spores and megaspores. In contrast to those in shales and coals, spores found in sandstones generally are abraded and poorly preserved.

Some sandstone, especially sheet sand bodies, contains in situ stigmarian axes and rootlets. Stigmarian axes may be as much as 3 to 6 inches thick and, where well exposed in creek beds, may be traced for 12 feet without appreciable thinning. Stigmarian rootlets similar to those of underclays also occur in some sheet sand bodies, especially toward the top. Vertical in situ trunk remains in sandstone have been reported in the Illinois Basin but are very rare.

Ripple Marks

Ripple marks, both symmetrical and asymmetrical, are present in Illinois Basin sand bodies. They are best observed in creek beds in the finer grained, thinner bedded, and better indurated sheet sand bodies. A typical example of asymmetrical, cuspate ripple marks occurs in the Palestine Formation in Union County, Illinois (pl. 7A). Regular asymmetrical ripple marks such as those shown on plate 5B are somewhat less common. Wave lengths of symmetrical ripple patterns rarely exceed 4 inches. Wanless (1957, fig. 38) and Potter and Glass (1958, pls. 1A, 2) illustrated other examples of ripple marks in Pennsylvanian sandstones. Asymmetrical ripple marks are one-way directional structures, whereas symmetrical ripple marks are two-way structures.

Sole Marks

Bottom or sole marks of various types, such as flute marks, load casts, and drag marks, are found in both late Mississippian and Pennsylvanian sandstones. Sole marks can be observed best on undersurfaces of rocks exposed in creek beds.

Flute marks represent the erosion of the sediment interface by currents scouring the bottom. Flute marks are asymmetrical, with

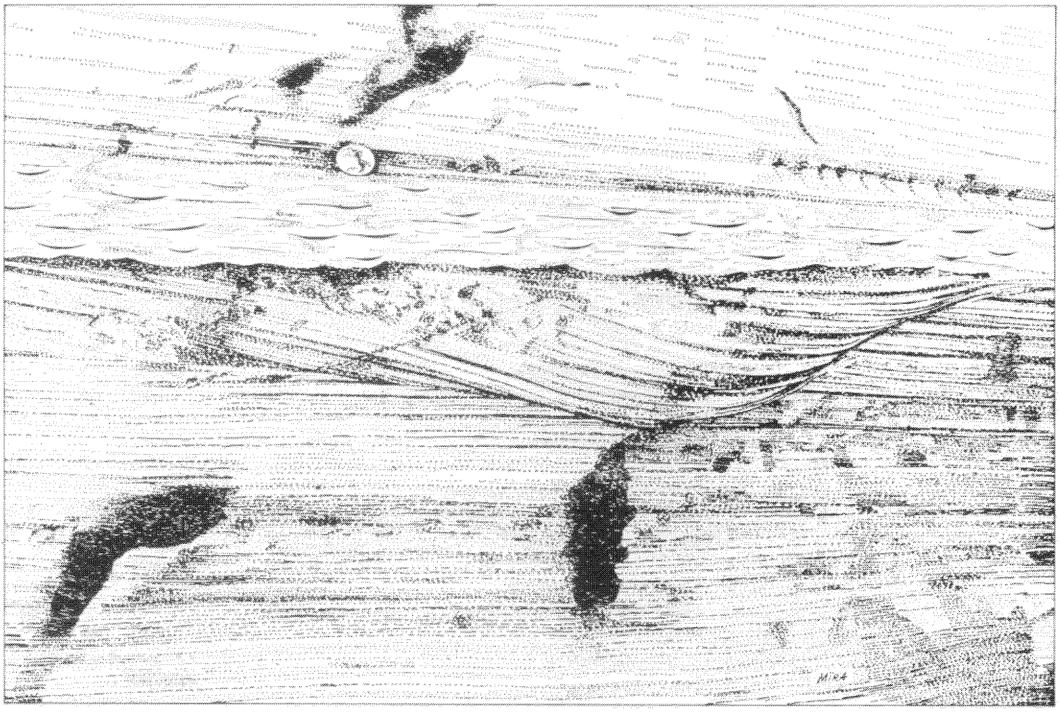


Fig. 22—Small channel in evenly laminated, fine-grained sandstone above Coal V in NE¼ SE¼ NE¼ sec. 17, T. 2 S., R. 7 W., Pike County, Indiana.

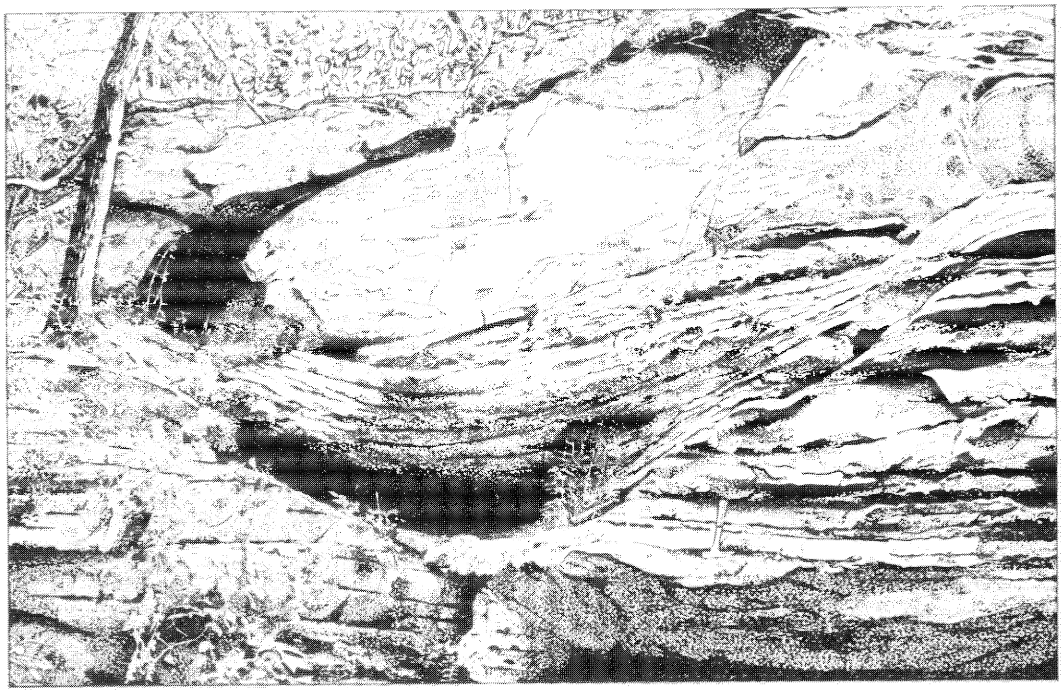


Fig. 23—Erosional channel in Tar Springs Sandstone in NE¼ NE¼ NW¼ sec. 18, T. 15 S., R. 7 E., Pope County, Illinois.

the blunt end indicating the up-current direction. A good example from the Caseyville Formation is shown on plate 7B.

Other sole markings of current origin may have resulted from the dragging of fine debris along the bottom. Fine, linear, sometimes intermittent markings were left in the wake of debris (fig. 25).

Sole markings of other post-depositional origins also are present. They represent intrusion of sand from an overlying bed into an underlying sand or mud bed. Figure 26 shows load casts in fine-grained, calcareous sandstone of the Ste. Genevieve Formation. Load casts are nondirectional structures. These protrusions occur in a variety of coarse and fine textures. Plate 8A shows load casts with both smooth and crenulated surfaces.

On plate 8B, what may be much smaller load casts have a weak preferred orientation (parallel to the longer pencil). Weak, regularly spaced ridges (parallel to the shorter pencil) reflect ripple marks on the surface of the underlying bed. The small size, density, and weak orientation of the sole markings could possibly be the result of flute markings. This illustrates the difficulties of distinguishing between flute marks and load casts. Flute marks can occur in conjunction with load casts, and through subsequent soft-sediment deformation may be transformed into load casts.

Animal tracks and trails are other types of sole markings. They occur on a few beds in the late Paleozoic sandstones and usually show little preferred orientation.

Syneresis casts, sand from an overlying bed that filled a syneresis crack in an underlying shale lamination, occur (White, 1962) but are not common.

Field Mapping of Directional Structures

The directional structures in late Paleozoic sandstones were investigated by detailed field observation and mapping. The foremost directional structure of these sandstones is cross-bedding. Although other directional structures were noted and measured during field work, only cross-bedding lent itself to systematic mapping. The ease and objectivity with which it can be measured in the field (Potter et al., 1958, app. I) facilitates its study.

Vertical Profiles of Cross-Bedding

The vertical consistency of direction or cross-bedding in elongate sand bodies was investigated by means of three vertical profiles (fig. 27). These profiles, measured in outcrop from bluffs and cliffs, approximated vertical profiles that could be obtained from oriented drill cores. One measurement was obtained from each successive exposed cross-bed in the outcrop.

The Caseyville Formation in Kentucky provides the thickest of these profiles. The sand body there is almost 150 feet thick, and 66 measurements were made (fig. 27A). Consistency of direction of cross-bedding is pronounced along the profile. The two shorter profiles in the Degonia (fig. 27B) and Hardinsburg (fig. 27C) Formations contain 42 and 28 observations, respectively, and show generally comparable homogeneity in direction. The standard deviations of the Caseyville, Hardinsburg, and Degonia profiles, computed around the vector mean, are 37°, 57°, and 40° and are of the same order of magnitude. A standard deviation of 31° was obtained from 27 observations from the Aux Vases Formation in a 72-foot section in Randolph County, Illinois (Mast and Potter, 1963, fig. 12). These data suggest that the typical Pennsylvanian and late Mississippian elongate sand body in the Illinois Basin had, at any one point, a preferred direction of sediment transport that changed but little throughout its history. As shown by the four standard deviations, approximately two-thirds of the observations occur between ±30° and ±50° of the vector mean.

These vertical profiles make it possible to determine whether or not cross-bedding direction is serially correlated (Wallis and Roberts, 1956, p. 560-565)—that is, to investigate the dip direction of cross-bedding in subsequent pulses of deposition.

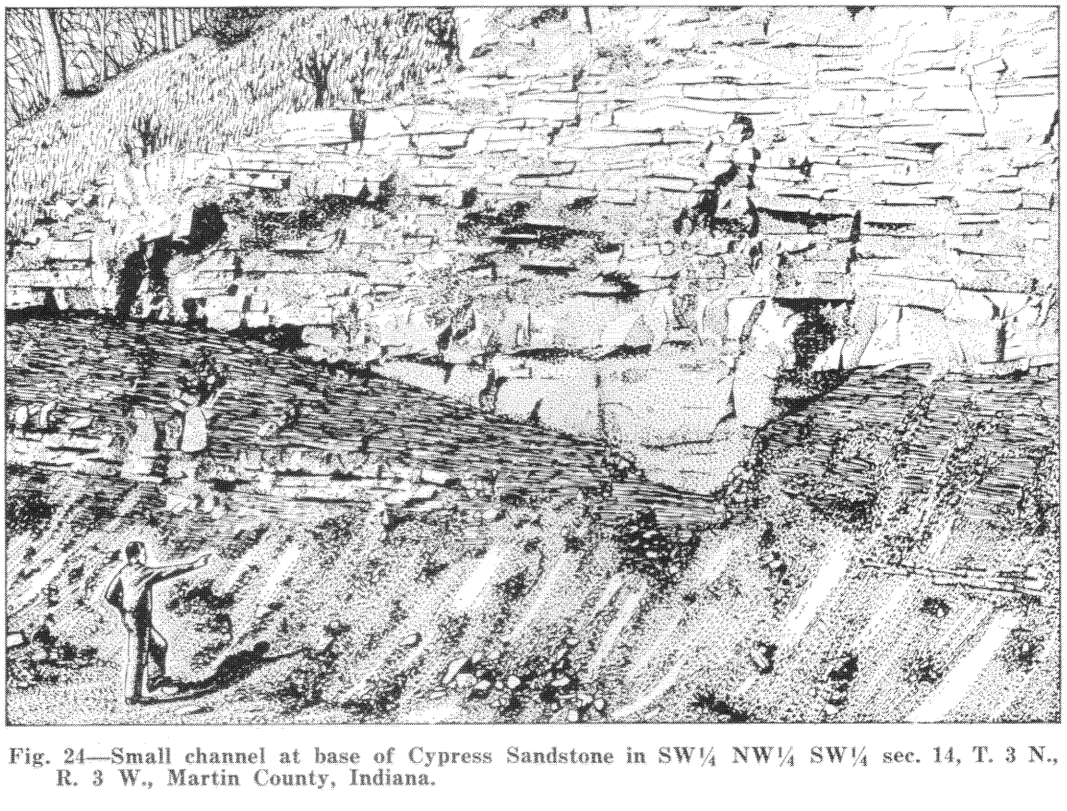
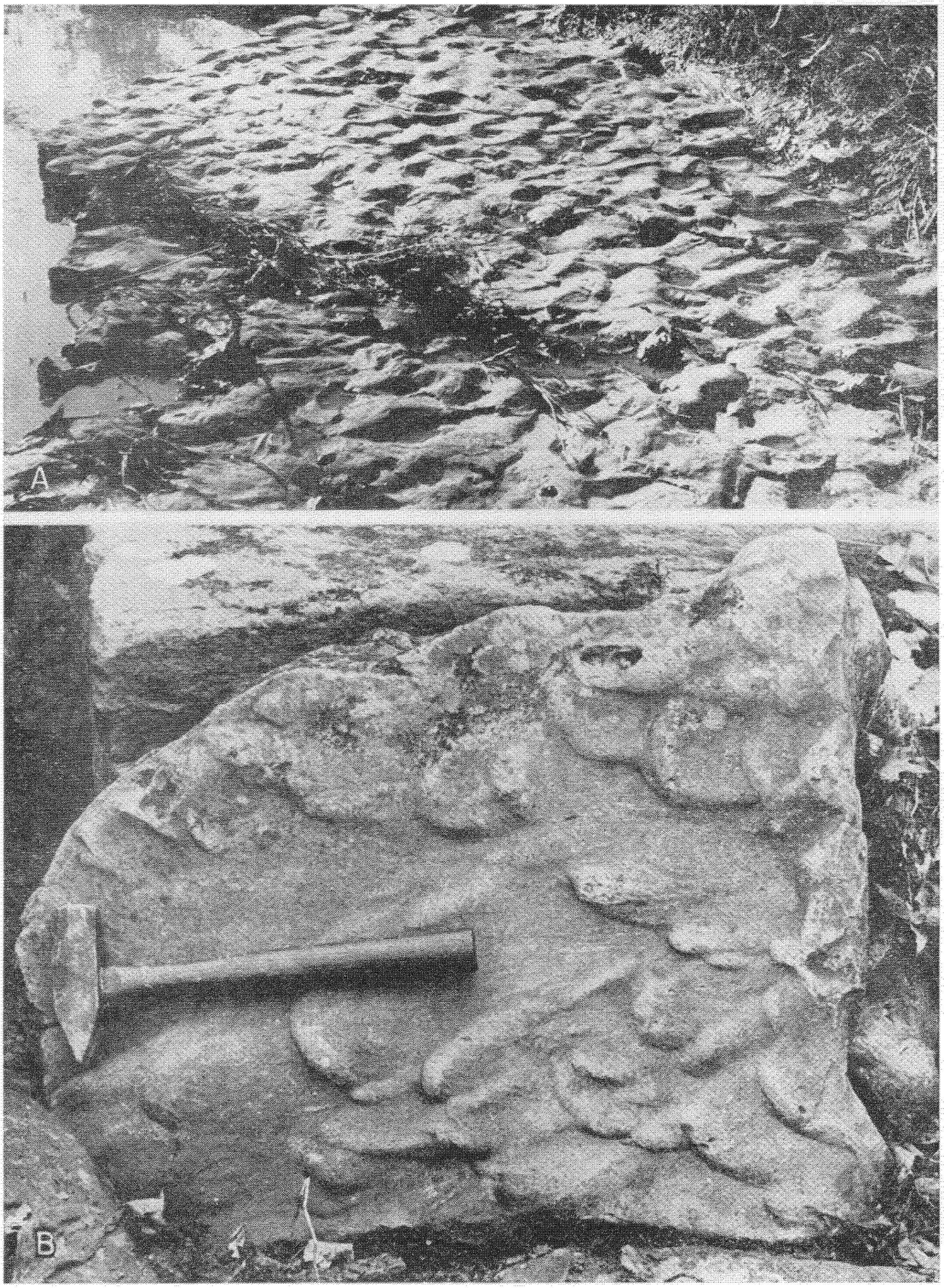


Fig. 24—Small channel at base of Cypress Sandstone in SW¼ NW¼ SW¼ sec. 14, T. 3 N., R. 3 W., Martin County, Indiana.



(A) Cuspate ripple marks in a sheet sand body in the Palestine Formation in NE¼ SE¼ SE¼ sec. 25, T. 11 S., R. 1 W., Union County, Illinois.

(B) Flute marks on the underside of a sandstone bed in the Caseyville Formation in SW¼ SE¼ NE¼ sec. 28, T. 10 S., R. 2 W., Union County, Illinois.

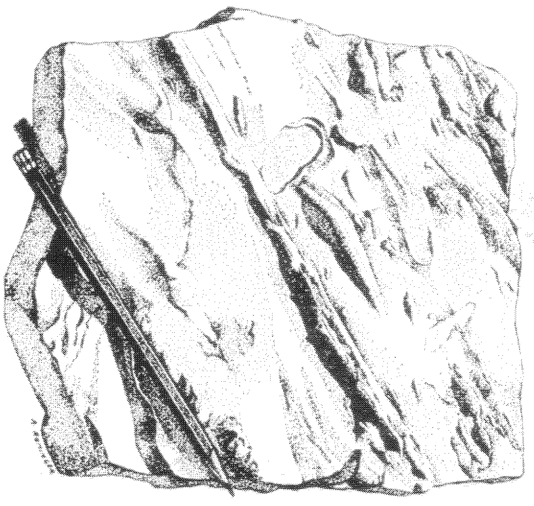


Fig. 25—Drag grooves and other sole markings on lower side of slab of Tar Springs Sandstone at west side of U. S. Highway 41, 1.2 miles south of Crofton, Christian County, Kentucky.

Using the circular formula (Bennett and Franklin, 1954, p. 685),

$$R_h = \frac{\sum\limits_{i=1}^{n} x_i \, x_{i+h} - \frac{\left(\sum\limits_{i=1}^{n} x_i\right)^2}{n}}{\sum\limits_{i=1}^{n} x_i^2 - \frac{\left(\sum\limits_{i=1}^{n} x_i\right)^2}{n}}$$

$$= \frac{1}{ns^2} \sum_{i=1}^{n} (x_i - \bar{x})(x_{i+h} - \bar{x})$$

where

R_h = serial correlation of order h

n = number of observations

x_i = direction of the i-th cross-bed

$\bar{x}$ = arithmetic average of cross-bed directions

$$s^2 = \frac{\sum\limits_{i=1}^{n} (x_i - \bar{x})^2}{n}$$

the sample variance

serial correlations to the eighth order were computed with the Illiac computer for the Caseyville, Degonia, Hardinsburg, and Aux Vases (Mast and Potter, 1963, fig. 12) profiles. The first order gives the correlation of adjacent pairs, the second order the correlation between pairs separated by one observation, the third order between pairs separated by two observations, and so on. Table 4 shows the correlations.

TABLE 4—SERIAL CORRELATION OF CROSS-BEDDING ORIENTATION IN VERTICAL PROFILES

Order	Caseyville Formation	Degonia Formation	Hardinsburg Formation	Aux Vases Formation
1	0.416*	0.374*	0.264	0.190
2	0.276*	0.375*	0.035	−0.386*
3	0.246*	0.110	−0.247	0.259
4	0.069	0.133	−0.113	0.207
5	0.140	0.239	−0.180	−0.298
6	0.023	−0.021	−0.021	−0.124
7	−0.080	0.183	−0.036	0.189
8	−0.300*	−0.044	−0.100	−0.106
n	66	42	29	27

*Significant at 0.05 level

The statistical significance of these correlations was tested, following the techniques suggested by Bennett and Franklin (1954, p. 285-287). Values in table 4 marked with an asterisk indicate statistical significance at the 0.05 level.

Correlations for low orders (closely spaced measurements) are significant only for the Caseyville and Degonia profiles. Over all, however, there is no strong pattern of statistically significant correlation between cross-bedding direction in proximal beds. These results show that while there is a strong preferred orientation throughout the vertical profiles there were no pronounced systematic shifts in current direction from bed to bed.

Detailed Maps of Cross-Bedding

The vertical homogeneity of cross-bedding orientation shown in figure 27 is also demonstrated by local detailed maps.

TABLE 5—LATE PALEOZOIC CROSS-BEDDING IN THE ILLINOIS BASIN

Unit	Class interval (azimuth)									Total observations	Vector mean
	1-40	41-80	81-120	121-160	161-200	201-240	241-280	281-320	321-360		
*Pennsylvanian**											
Above Shoal Creek Ls.*	5	4	1	2	10	14	13	16	6	71	252
Shoal Creek Ls. to Colchester (No. 2) Coal*	38	28	45	87	102	92	98	82	70	642	227
Colchester (No. 2) Coal to base of Pennsylvanian System*	47	45	39	129	227	311	210	114	52	1174	219
All Pennsylvanian	90	77	85	218	339	47	321	212	128	1887	222
Chesterian‡	81	98	94	155	199	298	202	127	93	1347	215

*From Potter (1962c, table 1). ‡From Potter et al. (1958, table II).

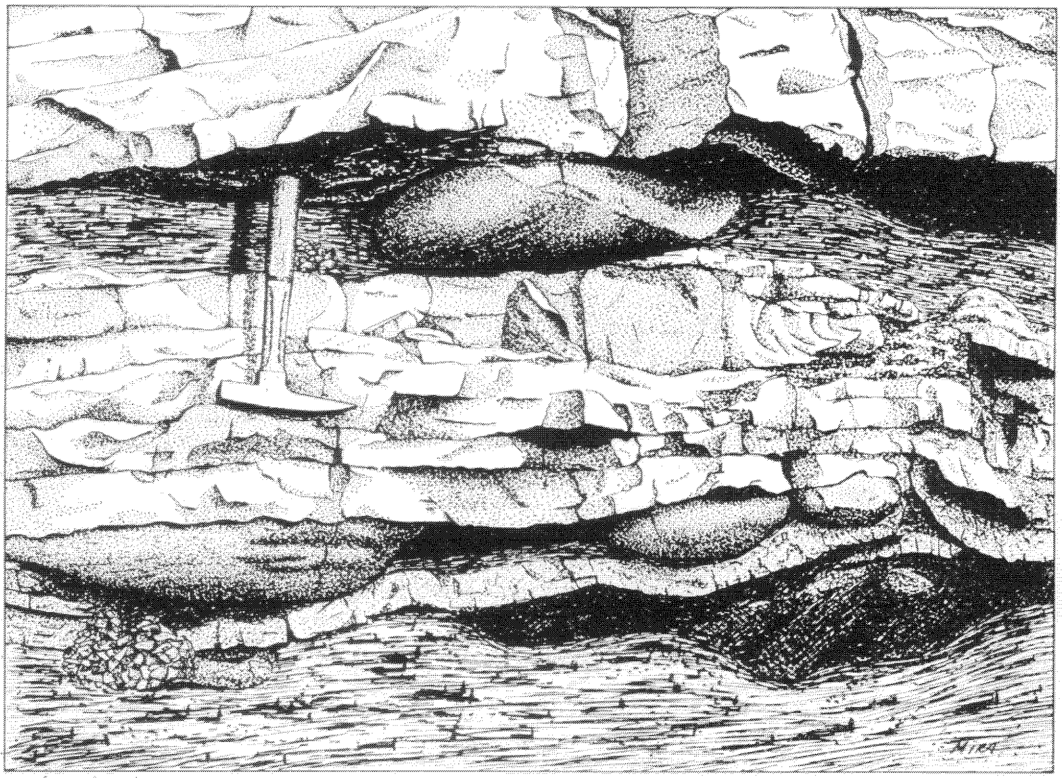


Fig. 26—Load casts in sandstone in the Ste. Genevieve Formation in a roadcut on Interstate Highway 57, SW¼ NW¼ SW¼ sec. 6, T. 13 S., R. 1 E., Union County, Illinois.

Figure 28 is a plane table map of part of an elongate sand body of the Spoon Formation exposed in the spillway of Crab Orchard Lake in Jackson County, Illinois. This map shows the similarity of cross-bedding orientation throughout a small area. It also shows the widely varying size of the cross-beds that range from more than 45 feet wide and 50 feet long to narrow elongate units approximately 4 feet wide and 16 feet long. Most units are a foot or less thick. Outcrop observations show that cross-bedding with comparable similarity of orientation and variation in size is characteristc of the majority of elongate late Paleozoic sand bodies.

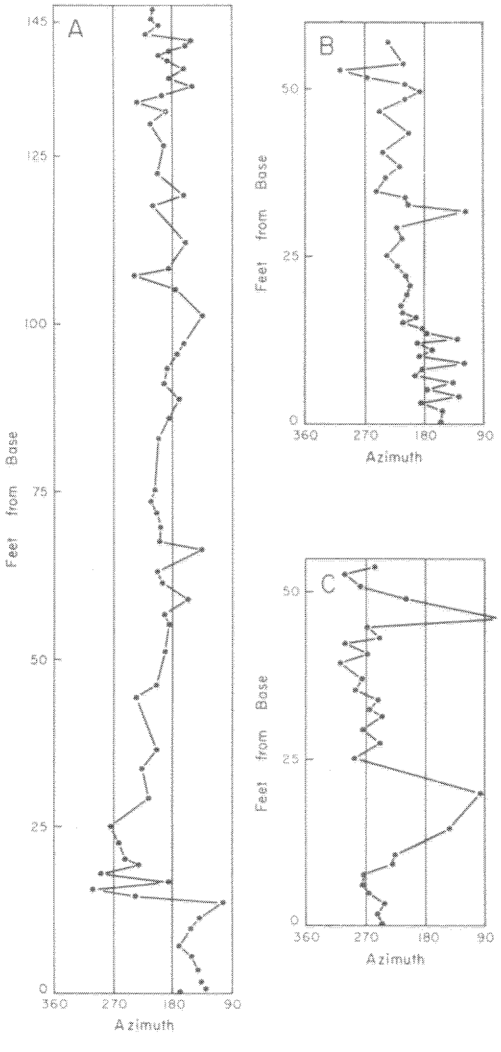


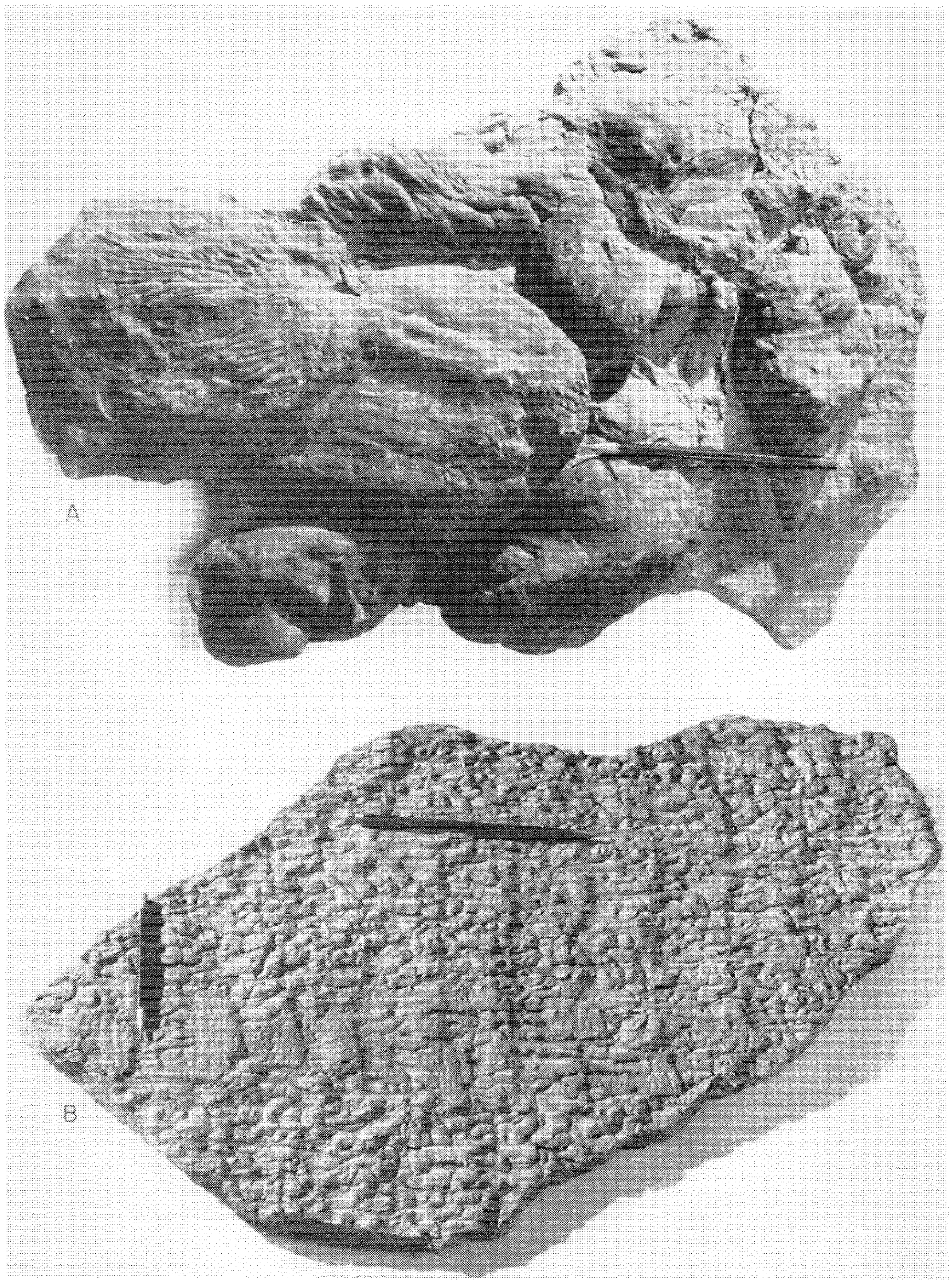
Fig. 27—Vertical profiles of cross-bedding orientation of three elongate sand bodies. (A) Caseyville Sandstone at Pine Knob Bluff near Tribune, Crittenden County, Kentucky, 7700 F.W.L., 6950 F.N.L., Carter grid rectangle J-16. (B) Degonia Sandstone in SW¼ SE¼ sec. 22, T. 11 S., R. 1 W., Union County, Illinois. (C) Hardinsburg Sandstone at Weston, Crittenden County, Kentucky.

Maps of individual elongate sand bodies also show a preferred transport direction. The orientation of cross-bedding in the Finnie Sandstone Member in Johnson and Pope Counties, Illinois, is shown in figure 29. This map represents a less dense sampling of an elongate—probably a belt—sand body that, in detail, has a pattern of cross-bedding orientation similar to that shown in figure 28. The average direction is to the southwest with relatively little dispersion, even though the occasional reversals that are present in most sandstones do occur. In the map area of figure 29 the Finnie Sandstone has a maximum thickness of approximately 60 feet and an erosional basal contact. The homogeneity of cross-bedding orientation shown by the Finnie Sandstone is typical of most elongate sand bodies in the Illinois Basin.

Late Paleozoic Cross-Bedding

Cross-bedding in late Paleozoic sandstones in the basin has been measured and reported in a number of studies (Potter and Olson, 1954; Potter and Siever, 1956; Rusnak, 1957; Hopkins, 1958; Potter et al., 1958; Desborough, 1961; Andresen, 1961; Potter, 1962c). In most, an effort was made to distribute sampling along the outcrop. One outcrop per stratigraphic unit per square mile or per township generally was designated. Along the basin margins, this procedure usually yielded a relatively uniform density of outcrops. One to ten measurements per outcrop were obtained.

Figure 30 shows measurements of cross-bedding in Pennsylvanian sandstones along the present northeastern limit of the Pennsylvanian sediments. The interval from the Gimlet Sandstone Member to the base of the Pennsylvanian System is about 500 feet. Regional sampling around the basin margin usually indicated comparable variability of



(A) Load casts on the underside of a sandstone bed in the Aux Vases Formation in SW¼ NW¼ NW¼ sec. 3, T. 5 S., R. 9 W., Monroe County, Illinois.

(B) Weakly oriented, fine-textured sole markings (parallel to long pencil). Short pencil is parallel to ripple marks on underlying bed. Tar Springs Formation in NE¼ SW¼ SW¼ sec. 25, T. 3 S., R. 1 W., Crawford County, Indiana.

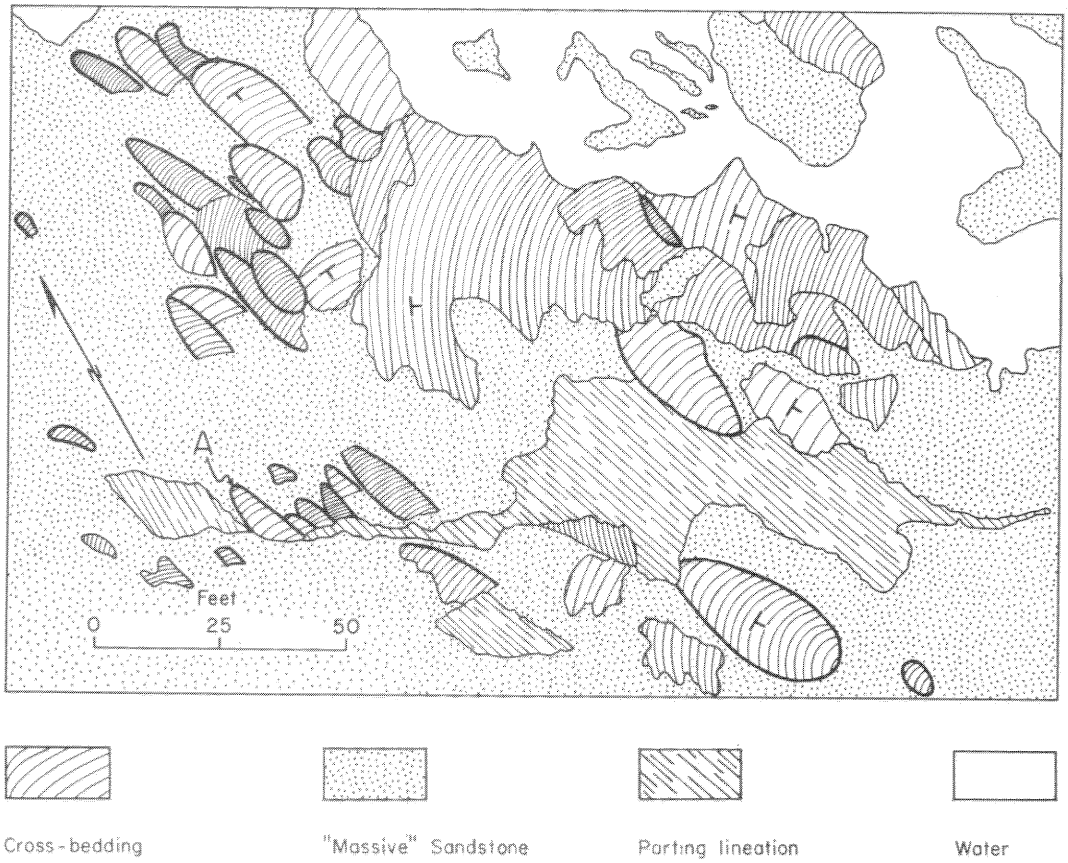


Fig. 28—Plane table map of cross-bedding and parting lineation in a sand body of the Spoon Formation exposed on the surface of the spillway of Crab Orchard Lake, SE¼ NW¼ NW¼ sec. 30, T. 9 S., R. 1 W., Jackson County, Illinois. Edges of cross-beds are concave in down-current direction. Dip-and-strike symbol shows inclination of cross-bedding. Heavy lines represent natural boundaries of cross-beds; light lines represent eroded or overlapped units. Plate 1A of Potter and Glass (1958) depicts cross-bed A.

both cross-bedding orientation and distribution of outcrops. In the center of the basin, however, low regional dip and glacial drift reduce the number of outcrops to a minimum.

Table 5 summarizes cross-bedding directions from regional sampling. Altogether 3,834 measurements were obtained. Approximately 600 measurements from detailed local studies are omitted from the table.

The vector means of all the Chesterian and Pennsylvanian cross-bedding measurements differ only a few degrees, 215° to 222°. Within the Pennsylvanian sequence below the Shoal Creek Limestone Member there is little variation. Above the Shoal Creek Limestone, the available data indicate a more westerly direction of 252°.

Relationships Between Directional Structures

Mapping of directional structures in the sandstones shows that the various directional structures are the integrated response to a common current direction.

In figure 28 parting lineation and cross-bedding direction indicate the same transport direction. Figure 31A is a scatter diagram constructed by plotting the average cross-bedding direction at an outcrop against aver-

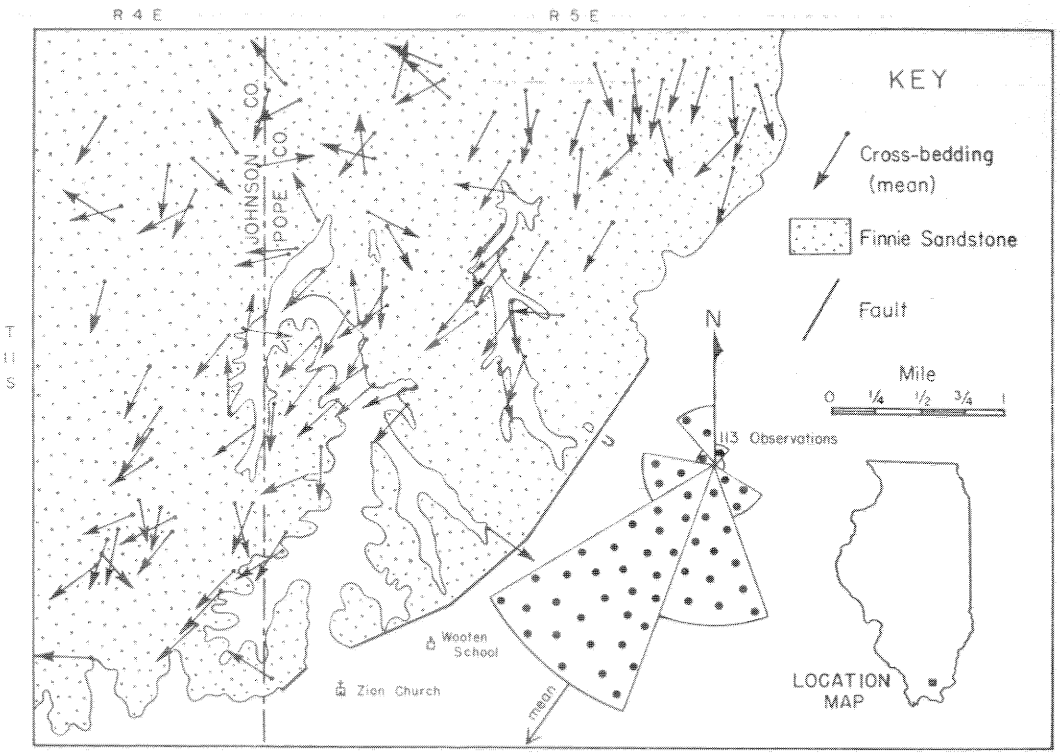


Fig. 29—Cross-bedding in the Finnie Sandstone Member in parts of Pope and Johnson Counties, Illinois. Current rose shows distribution and mean of 113 observations.

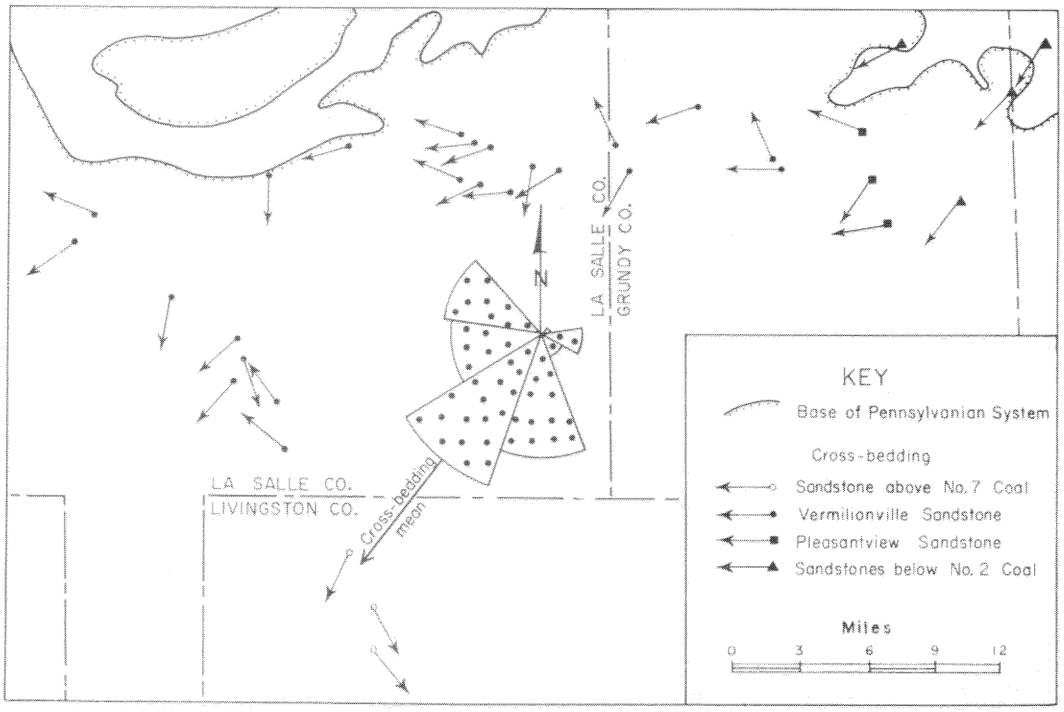


Fig. 30—Cross-bedding direction in parts of LaSalle, Livingston, and Grundy Counties, Illinois. Current rose shows distribution and mean of 94 observations.

age direction of parting lineation at the same outcrop. The direction of parting lineation that gave the smaller angle with the cross-bedding direction was used. Although a few points are far from the line of perfect correlation, most lie relatively close to it.

Micro-cross-bedding and cross-bedding demonstrate an even better correlation (fig. 31B) with relatively few points lying far from the line of perfect correlation.

Poorest correlation exists between cross-bedding direction and orientation of plant casts (fig. 31C). The orientation of the plant cast that gave the smaller angle with cross-bedding direction was plotted. Several factors probably are responsible for the relatively poor correlation. First, cross-bedding, parting lineation, and micro-cross-bedding are structures that develop concurrently with sand transport at the sediment interface. In contrast, plant debris may have moved along the interface slightly later and hence may not have been influenced by exactly the same currents. A second and probably more important factor explaining poorer correlation is that plant stems can lie on the sediment interface at relatively large angles to current direction.

Because of problems of measurement, it was not possible to investigate the correlation of ripple marks and cross-bedding orientation. However, as plate 5B shows, ripple marks can have a simple orthogonal relation to other directional structures. Because ripple marks can be formed by even weak, variable currents, however, their orientation can differ markedly from that inferred from other directional structures.

Fabric studies (Potter and Mast, 1963) of sand-grain orientation show that sand grains in the foresets of cross-beds tend to lie with their long axes parallel to maximum dip direction of the foreset beds and that their

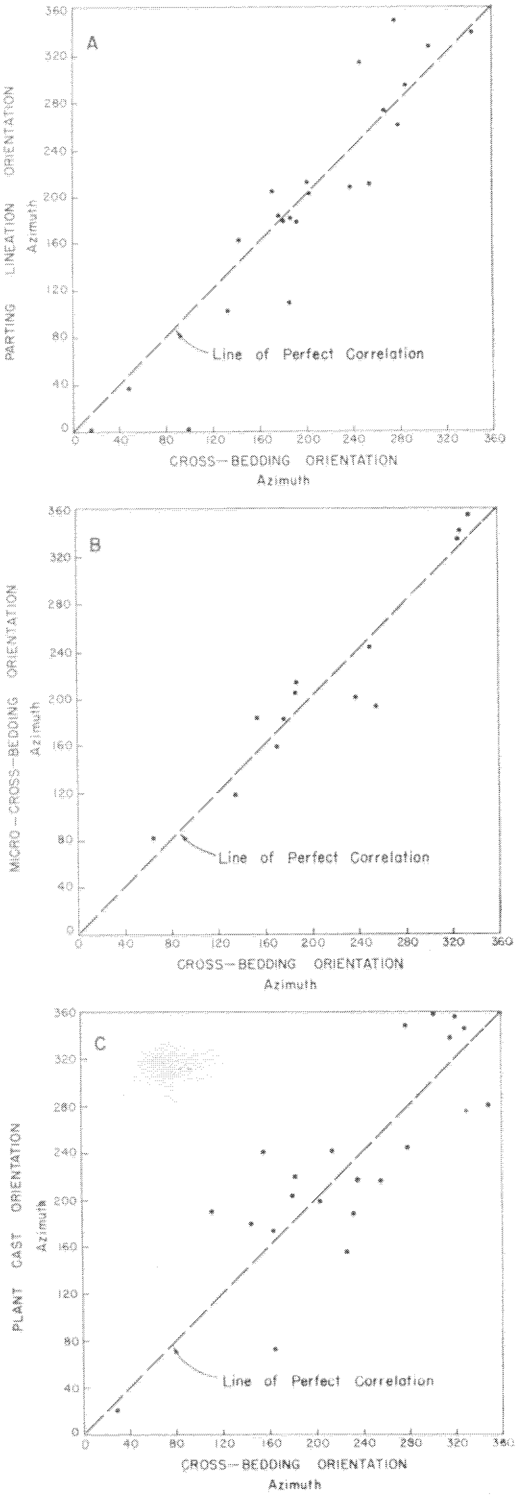


Fig. 31—Scatter diagrams showing orientation of (A) cross-bedding and parting lineation; (B) cross-bedding and micro-cross-bedding (rib-and-furrow); and (C) cross-bedding and plant casts. Each point represents the average direction for each of the two properties at a single outcrop.

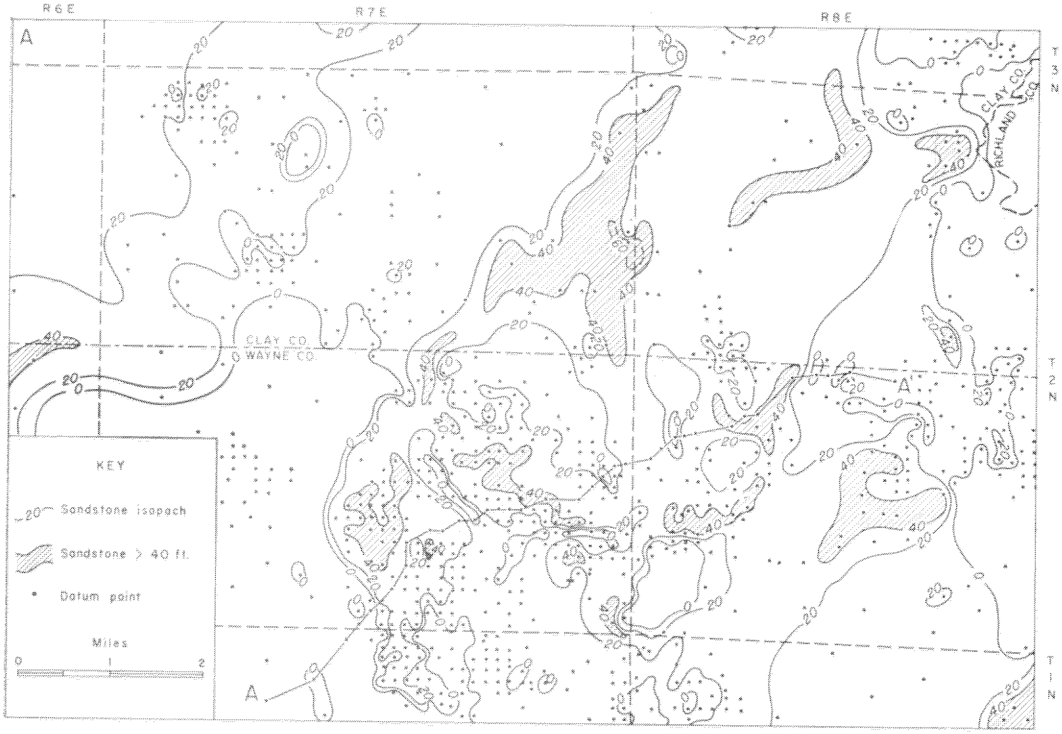


Fig. 32A—Thickness of sandstone in the Mt. Carmel Sandstone Member in parts of Wayne and Clay Counties, Illinois. Map contains 785 control points.

orientation also tends to parallel the trend of parting lineation. Although the correlation is far from perfect, this evidence indicates that there are systematic, regular relationships between the form of constructional sedimentary structures and their constituent sand grains.

Interpretation of Sedimentary Structures

Most of the primary sedimentary structures result from traction transport of sand at the sediment interface. The differences in the various structures are determined by hydrodynamic conditions of velocity and turbulence and upon sand supply. Some structures, such as cross-bedding and channels within a sand body, vary widely in size and thus can develop under a wide range of conditions. Others, such as parting lineation and micro-cross-bedding, appear to have relatively restricted dimensions and grain-size distributions that suggest more restrictive hydrodynamic conditions of origin (Hamblin, 1961, p. 399).

Observations of late Paleozoic sandstones show some of the relationships between these conditions. Thick cross-beds are associated with coarse sand, implying high current velocities. The thickest cross-beds are found in the most conglomeratic and coarsest Pennsylvanian sandstones and show better developed scouring and channeling. In contrast, cross-bedding in siltstones and very fine-grained sandstones usually is not more than a few inches thick and implies weaker currents.

The same currents that produced cross-bedding dragged debris along the surface, scored the surface producing oriented flute marks, and generally eroded a variety of elongate channels within the sand body. Weaker currents produced parting lineation, micro-cross-bedding, delicate drag marks, and a variety of ripple marks. Ripple marks are commonly present at the sediment interface and may occur on the tops of beds, on fore-

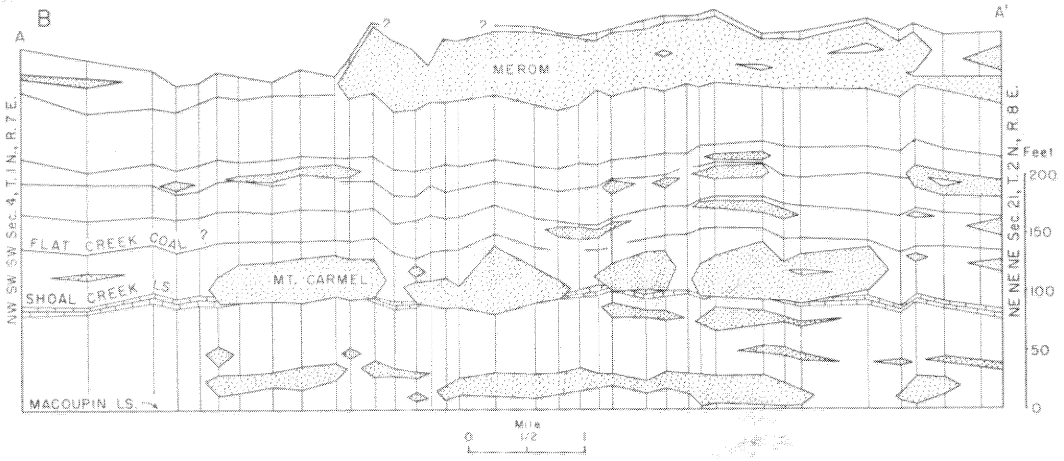


Fig. 32B—Cross section of the sandstone in figure 32A.

sets, or on the surfaces of channels within the sand body. Graded bedding is virtually absent in the sandstones of the basin, except for rare occurrences on coarse-grained foresets.

Most of the directional structures in a sand body are responses to similarly oriented currents and thus have related orientations. Directional structures that were the response to high velocity currents may correlate better than those that developed from weak and possibly more variable currents.

During or shortly after deposition, sedimentary structures such as load casts, deformational structures, and animal borings that resulted from soft-sediment deformation developed. Both oriented and nonoriented sole marks are present in the late Paleozoic sandstones of the basin, demonstrating that they are not an exclusive feature of turbidite sandstones.

The kind of primary structures most abundant in sand bodies is closely related to the sand body type. Sheet sand bodies are distinguished by ripple marks, parting lineation, small shale-pebble conglomerates, and micro-cross-bedding. Thin cross-beds are present but not abundant. The presence of these structures, in conjunction with thin beds and small grain size, implies deposition by relatively weak currents. The general absence of unconformity at the base of sheet sandstones is consistent with deposition by such currents.

In the thick elongate sand bodies, cross-bedding is usually very abundant, and some contain cross-beds more than 6 feet thick. Erosional channels within the sand body also may be present. Although ripple marks, parting lineation, and shale-pebble conglomerates are all present, cross-bedding, coarser conglomerates, and ripple scours are the distinguishing features of these sand bodies, and, in conjunction with thicker beds and coarser grain, imply deposition by relatively strong currents. The unconformity at the base of elongate sand bodies also implies deposition from such currents.

Comparatively little contrast is exhibited between structures of soft-sediment origin that developed shortly after deposition in sheet sand bodies and those developed in elongate sand bodies.

LOCAL MAPS OF SAND BODIES

Local maps and cross sections of sand bodies in subsurface, supplemented by local maps of elongate sand bodies in outcrop, provided much information on the shape, distribution pattern, and origin of elongate sand bodies in the basin.

Subsurface Maps and Cross-Sections

Local detailed subsurface maps of sand bodies in the basin have been published by

Swann (1951, fig. 5), Wier (1953), Friedman (1956, 1960), Mueller and Wanless (1957), Andresen (1961, fig. 6), and Potter (1962a, b, and c).

Most of the subsurface maps and all of the cross sections of this report were based on electric logs. Sandstone was defined as the footage of self potential 10 millivolts to the left of the shale base line of the electric logs. All the cross sections were made by using as a datum line a marker bed that was under and as close as possible to the sand body.

Pennsylvanian Sand Bodies

The map of the thickness of sandstone in the Mt. Carmel Sandstone Member (fig. 32A) shows two sand bodies trending southwest. The one in the northwest corner of the map is outlined by the 20-foot isopachs and has a meandering pattern. The other is locally more than 40 feet thick and encloses areas without sandstone. Most Pennsylvanian sandstone units do not have such complex distribution patterns.

Cross Section A-A′ (fig. 32B) indicates that the Shoal Creek Limestone is absent under some thick portions of the Mt. Carmel sand body. However, in no case does the sandstone extend far below the position of the Shoal Creek Limestone. Differential compaction of the shales surrounding the thicker elongate sand bodies was slight.

A much less complex pattern is displayed by figure 33, which shows a southwest-trending dendroid of Anvil Rock Sandstone 2 to 3 miles wide. Locally, sandstone thickness

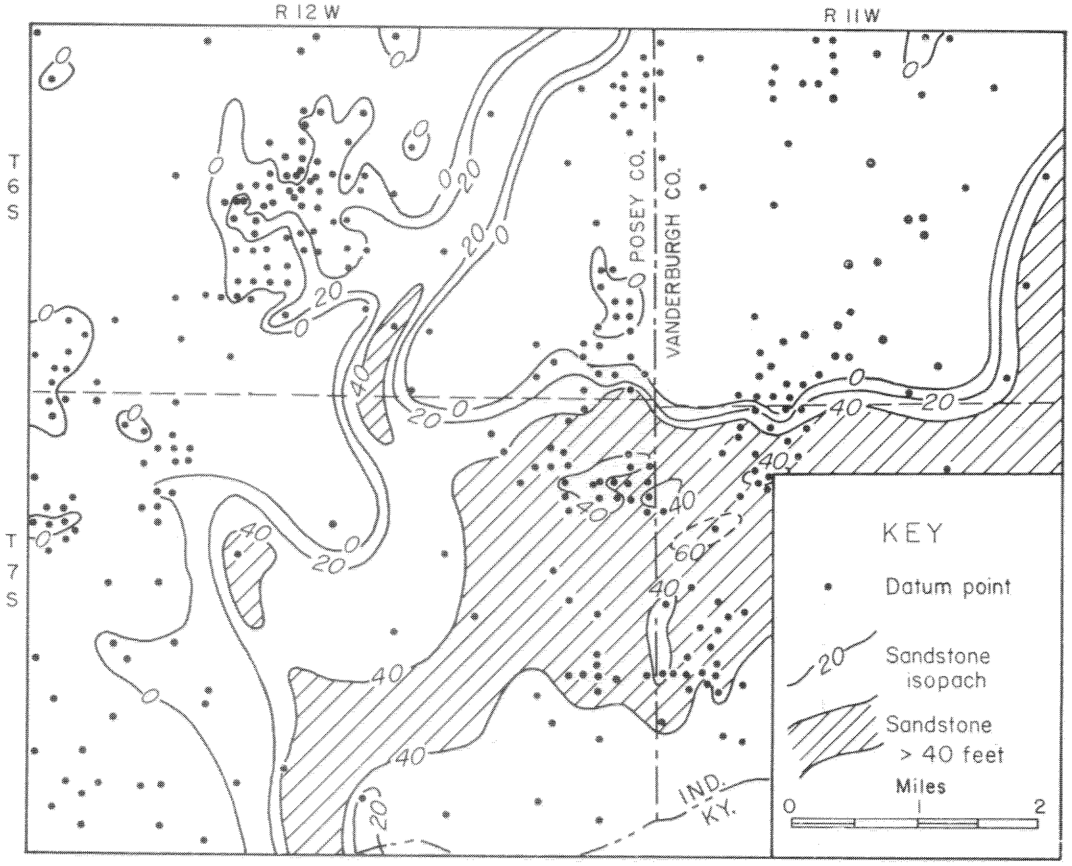


Fig. 33—Thickness of sandstone in the Anvil Rock Sandstone Member in parts of Posey and Vanderburgh Counties, Indiana. Map contains 288 control points.

exceeds 60 feet. A smaller sand body approximately half a mile wide joins the larger sand body with acute "down-stream" angle in T. 7 S., R. 12 W. In T. 6 S., R. 12 W., the small sand body has what may be either small tributary or distributary extensions. Similar features appear on other detailed maps.

A small elongate sand body of the Vermilionville Sandstone (fig. 34A) has abrupt boundaries, local thickness in excess of 40 feet, and a general south-southeast trend. The striking feature of the map is the absence of sandstone thicker than 20 feet in the east-central portion of T. 6 S., R. 5 E., which illustrates that permeable sandstone may be unequally developed along elongate sand bodies. The cross sections of the sand body (fig. 34B and C) show an underlying member replaced by the sandstone. Channel erosion is inferred. The increased elevations of the Herrin (No. 6) and Danville (No. 7) Coals above the Vermilionville reflect the presence of the elongate sand bodies.

The Coxville Sandstone in portions of Posey and Vanderburgh Counties, Indiana (fig. 35A), is an example of a well defined elongate sand body containing a large "island" with no sandstone. In the map area, maximum sandstone thickness exceeds 60 feet. This sand body has abrupt boundaries. In the northwestern corner of the map, in portions of Ts. 5 and 6 S., R. 13 W., is a small tributary or distributary similar to that in figure 33.

The cross section of the Coxville sand body (fig. 35B) shows the sand body lying close to or directly on Coal III of Indiana. The absence of coals between Coal III and Coal IIIa does not permit subsurface demonstration of a channel origin. However, outcrop observation indicates that thick Pennsylvanian elongate sand bodies have erosional and unconformable basal contacts. Because of the open spacing of even the most dense subsurface control, however, unconformable basal contacts may be inferred in the subsurface only if underlying marker beds are progressively replaced by sandstone. Thus the flat base of a sand body, determined in subsurface by electric logs, does not necessarily have environmental significance. A factor contributing to the flat base of Pennsylvanian sandstones where they directly overlie coal beds may have been the cohesiveness of peat prior to lithification (Wanless, 1954, p. 158-161).

A map of the Coxville Sandstone equivalent in Illinois, the Palzo Sandstone, is shown in figure 36A. This is a good example of a belt sand body. Width varies from 4 to 6 miles, and locally the sand body is more than 80 feet thick. Boundaries generally are abrupt and have weakly meandering outlines.

The cross section of the Palzo sand body (fig. 36B) shows the variable distance between the Davis Coal and the base of the Palzo Sandstone. It also illustrates the compactional "bump" of the overlying coal beds above the sand body. Where thick sections of the Palzo Sandstone can be seen in outcrop, the basal contact is erosional and unconformable even though the cross section would be comparable to that of figure 35.

Figure 37A shows a valley or channel developed during the pre-Pennsylvanian erosional period. This channel, in the area of the Inman East oil pool in T. 8 S., R. 10 E., Gallatin County, Illinois, was eroded more than 150 feet deep into the underlying Chesterian formations. Subsequently, it was partially filled with a sandstone of the Caseyville Formation. A belt sand body overlies this channel. Channels 150 or more feet deep generally occur only at the Mississippian-Pennsylvanian unconformity, although others as deep as 100 feet have been reported by Wanless (1954, p. 153). Hopkins (1958, pl. 1) reported the Anvil Rock Sandstone was more than 180 feet thick, but the possibility that a sandstone of one cycle is superimposed on an underlying one complicates estimates of the depth of erosion.

In figure 37B an erosional channel filled with Anvil Rock Sandstone is shown. The underlying Herrin (No. 6) Coal and the Briar Hill (No. 5A) Coal have been eroded. The Danville (No. 7) Coal has a structural high over the underlying sand body.

Figure 37C is a cross section at right angles to a prominent southwest-trending belt sand body of the Mt. Carmel Sandstone in White

County, Illinois. The sand body is over 150 feet thick and about 12 miles wide. Several minor coal beds and the Shoal Creek Limestone have been replaced by sandstone. Overlying coal beds reflect structurally the presence of this unusually thick belt sand body. Although it has not been definitely established, the sandstones of two or more cycles may be superimposed to form such an unusually thick belt sand body.

Late Mississippian Sand Bodies

Late Mississippian sand bodies exhibit most of the patterns shown by Pennsylvanian sand bodies and have one additional type.

Figure 38A shows the thickness of sandstone in the Palestine Formation in part of Hamilton County, Illinois. The principal sand body trends southwestward across the area and has a maximum thickness of 118 feet. Boundaries of the thick sand body are very abrupt and in outline are weakly meandering.

The cross section of the Palestine sand body (fig. 38B) shows that the thick sand bodies of the Palestine Formation generally lie close to the top of the Menard Limestone and in a few places lie directly on it. Where thick sections of sandstone in the Palestine can be observed in outcrop, they have unconformable basal contacts. The overlying Clore Formation is structurally high over the thick elongate sand body.

A good example of a relatively straight and apparently isolated sand body is provided by figure 40A, a map of the thickness of sandstone in the Waltersburg Formation in part of Saline County, Illinois. In the figure, the sandstone is contoured as a series of relatively straight, parallel, en echelon, disconnected pod and ribbon sand bodies. Available evidence suggests that isolated pod and ribbon sand bodies are more common in late Missis-

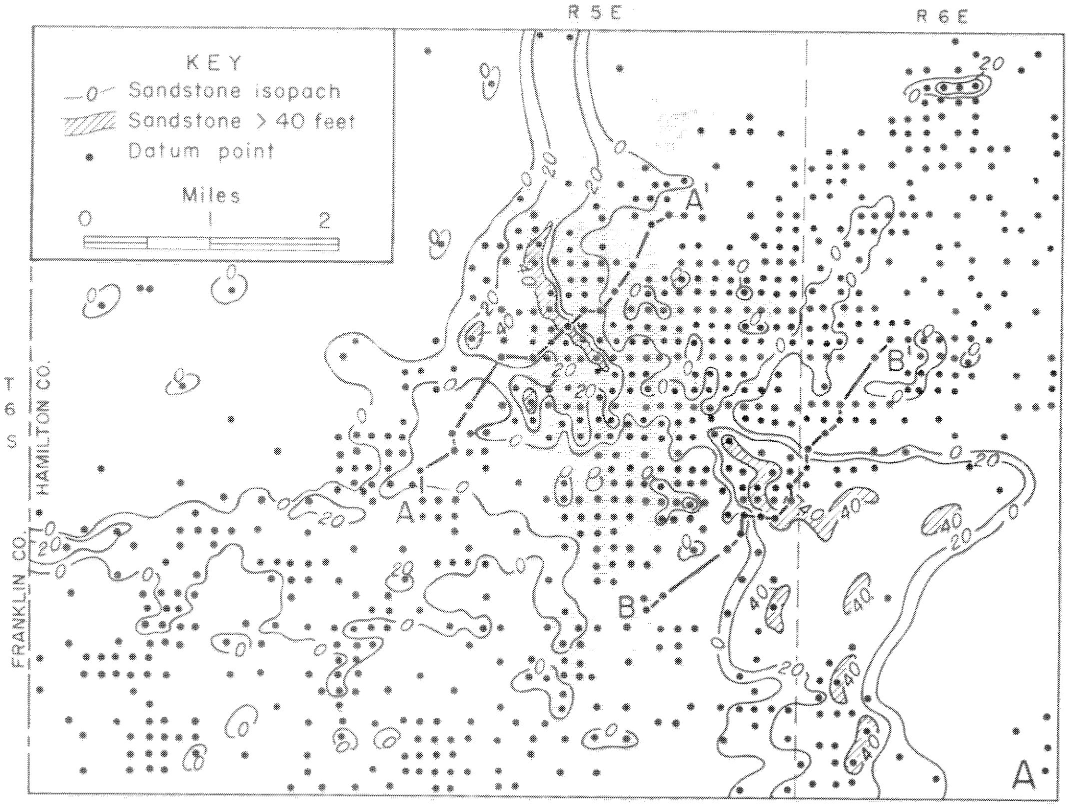


Fig. 34A—Thickness of sandstone, based on 804 control points, in the Vermilionville Sandstone Member in part of Hamilton County, Illinois.

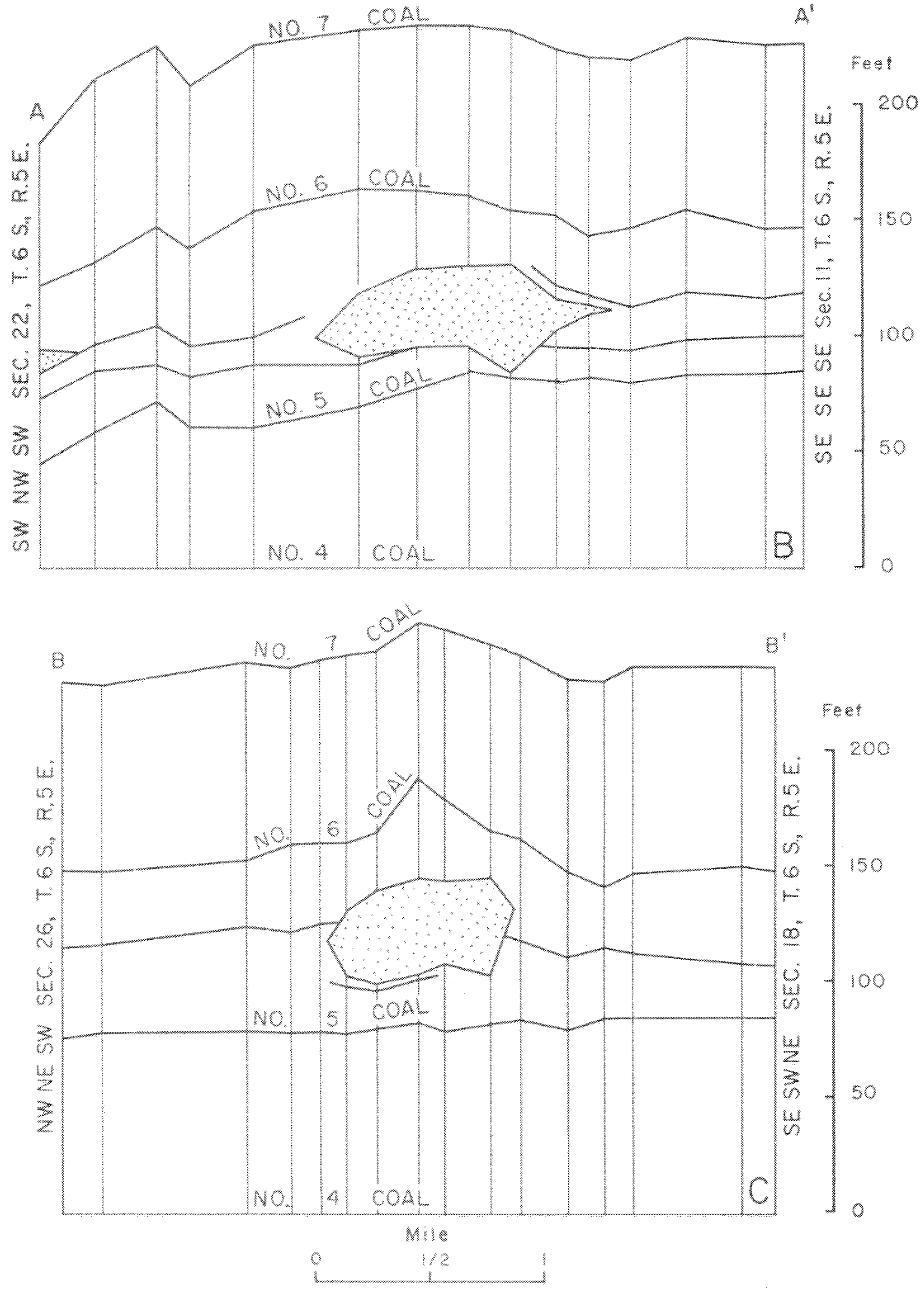


Fig. 34B and C—Cross sections of the sandstone in figure 34A.

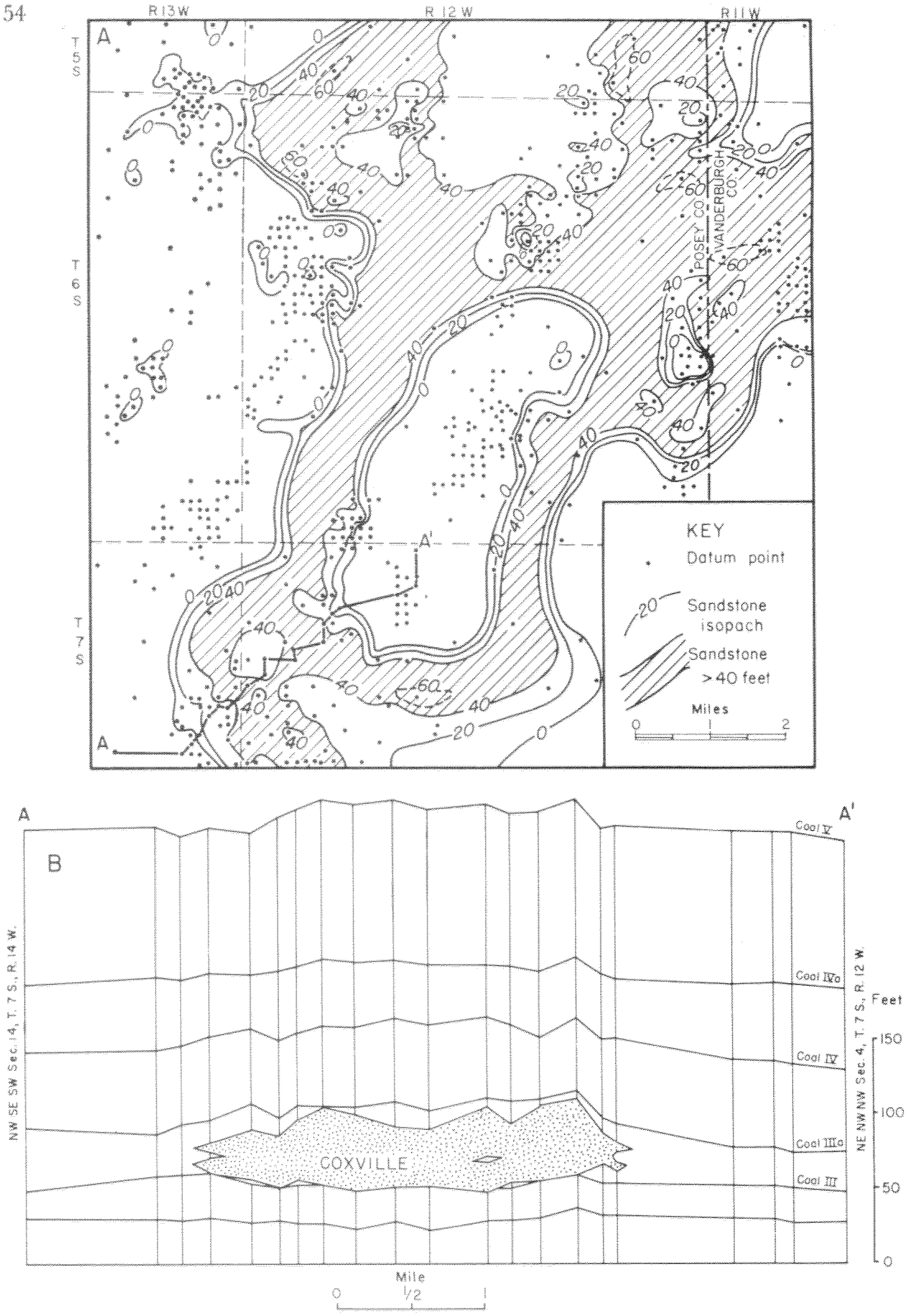


Fig. 35—(A) Thickness based on 617 control points of sandstone in the Coxville Sandstone Member in parts of Posey and Vanderburgh Counties, Indiana. (B) Cross section of sandstone above.

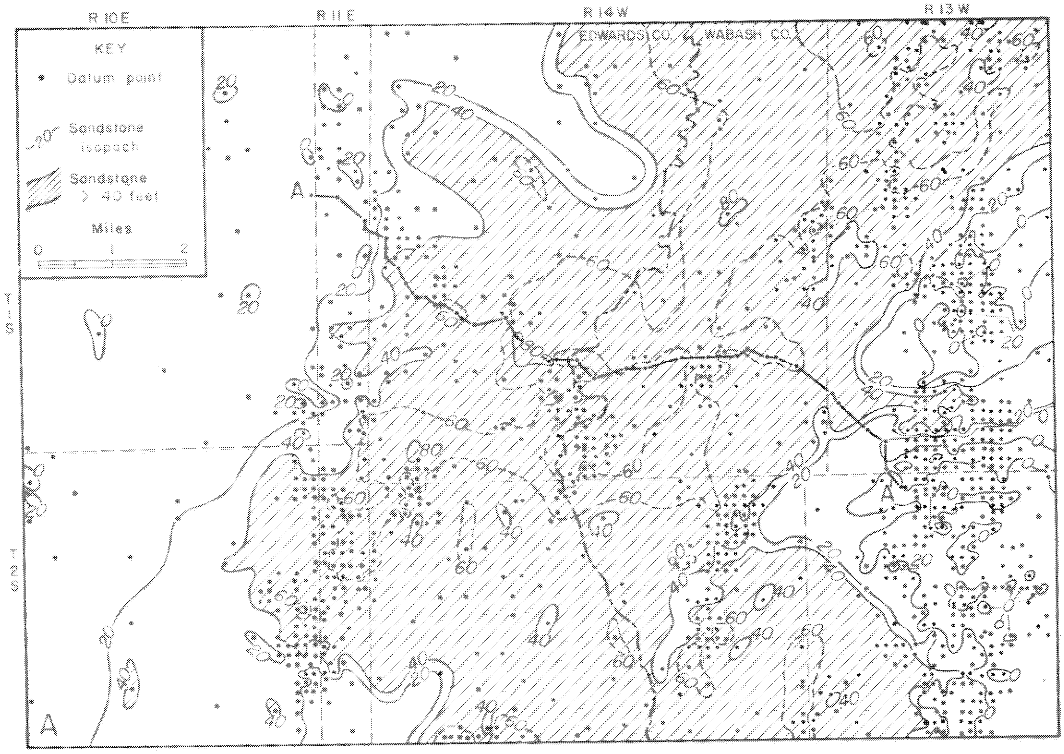


Fig. 36A—Thickness of sandstone in the Palzo Sandstone Member in parts of Edwards and Wabash Counties, Illinois, based on 1182 control points.

sippian than in Pennsylvanian sandstones. Potter (1962b) discussed criteria that may be useful in deciding whether or not two nearby sand bodies may be connected.

A good example of a small but thick pod sand body in the Waltersburg is shown in figure 39. Maximum thickness is 84 feet. Contacts are relatively abrupt, and the long axis of the sand body is oriented south-southwest. The structure of the overlying Menard Limestone reflects the presence of this sand body.

The cross section in figure 40B differs relatively little from that of many elongate sand bodies with meandering patterns. Thick outcrop sections of sandstone in the Waltersburg Formation have unconformable basal contacts.

Sandstone bodies in the Hardinsburg Formation were mapped in detail in two areas. The area in portions of Gallatin County, Illinois, Posey County, Indiana, and Union County, Kentucky, has a relatively complex pattern (fig. 41). In the northern and cen-

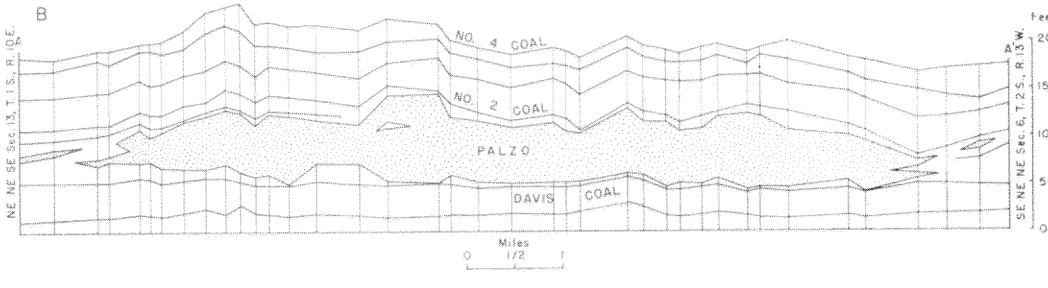


Fig. 36B—Cross section of sandstone in figure 36A.

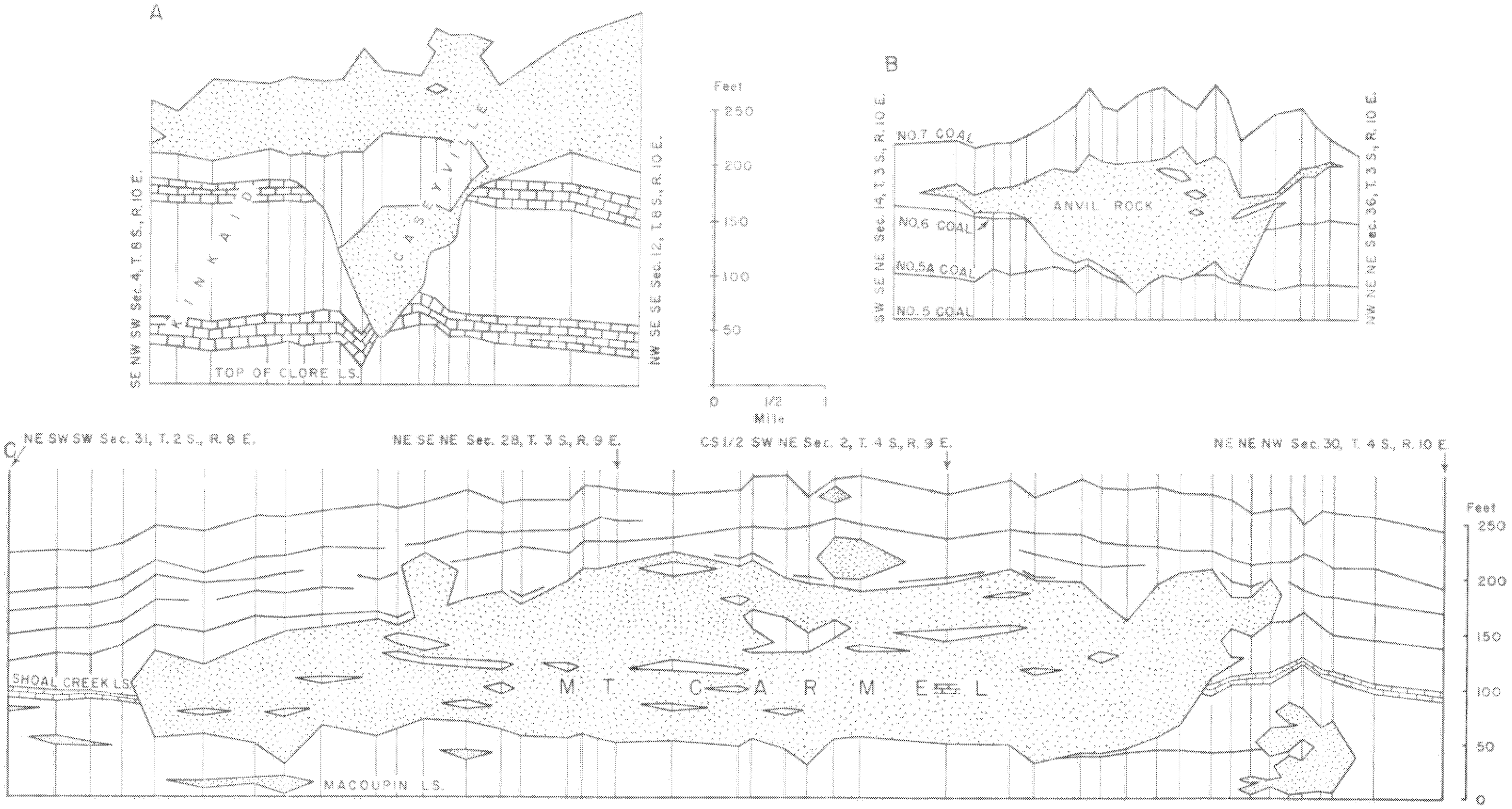


Fig. 37—Cross sections showing (A) pre-Pennsylvanian valley filled with Caseyville Sandstone in Gallatin County, Illinois; (B) channel filled with Anvil Rock Sandstone in Edwards County, Illinois (from Potter, 1962a, fig. 7); and (C) Mt. Carmel Sandstone in White County, Illinois.

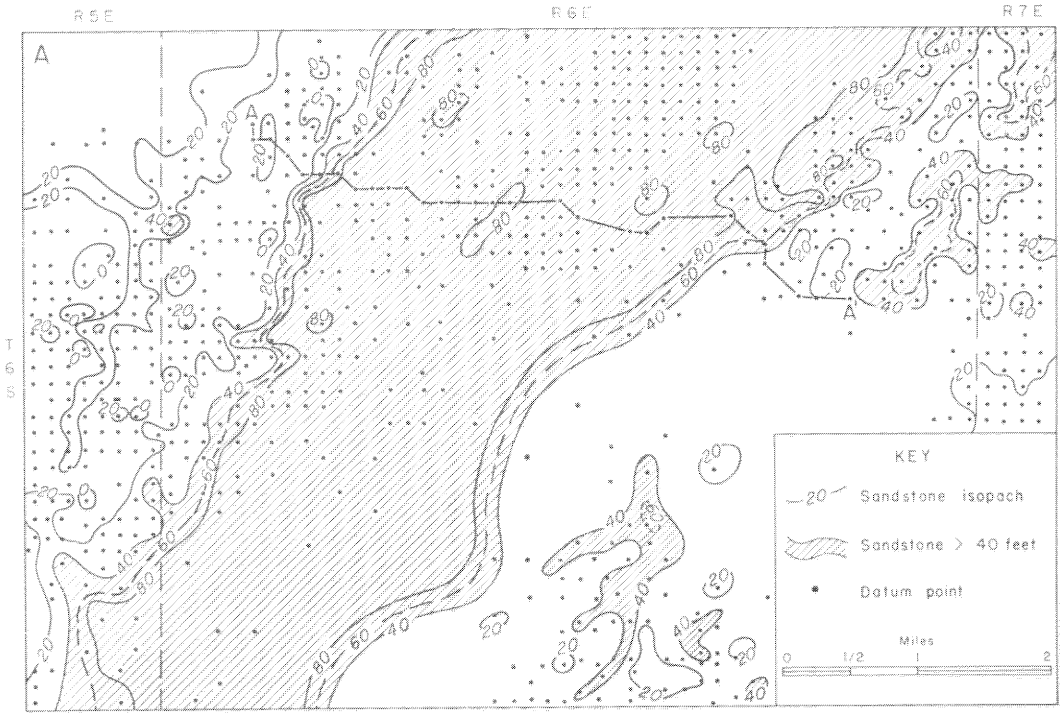


Fig. 38A—Thickness, based on 804 control points, of sandstone in the Palestine Formation in part of Hamilton County, Illinois.

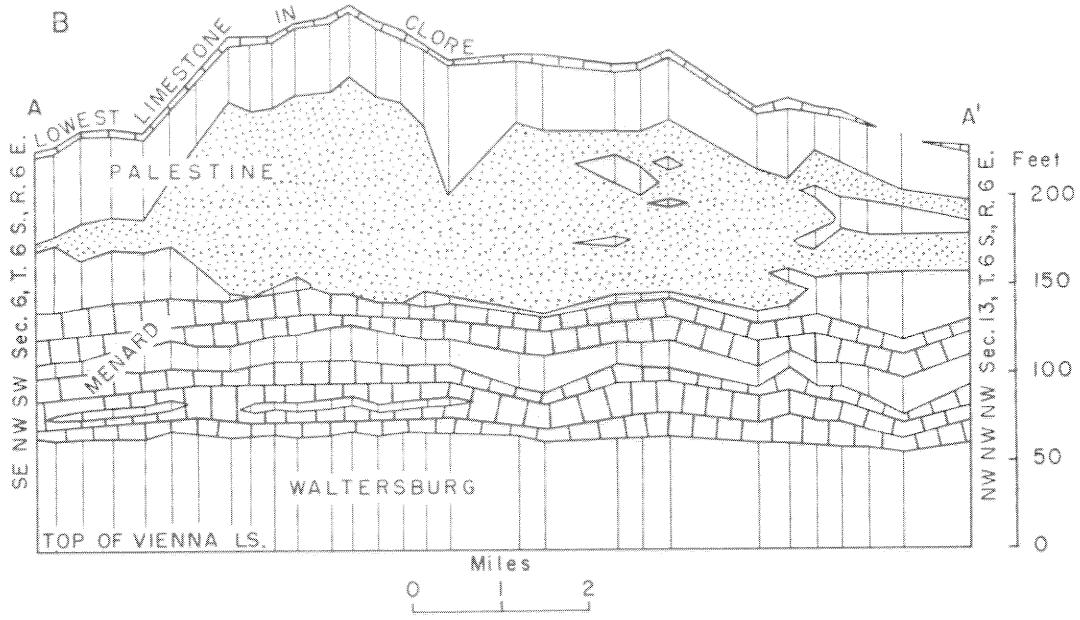


Fig. 38B—Cross section of sand body in figure 38A.

tral portions of the map are three elongate sand bodies, each generally less than a mile wide, with meandering and complex pattern. In the southern part of the area these join to form a well defined southwest-trending belt sand body over 6 miles wide. Maximum thickness is 85 feet. This pattern shows some similarity to that of the Mt. Carmel Sandstone (fig. 32).

The sandstone thickness in the Hardinsburg Formation in Hamilton County, Illinois, is shown in figure 42A. It is locally as much as 198 feet thick. Two principal sand bodies are present, one along the western portion of the map and the other in the eastern half. Both have south-southwest trends. The eastern sand body exhibits a well defined bifurcation in the southeastern corner of the map.

The cross section (fig. 42B) displays a striking erosional channel cut into the Haney Limestone and subsequently filled with sandstone of the Hardinsburg. The overlying Glen

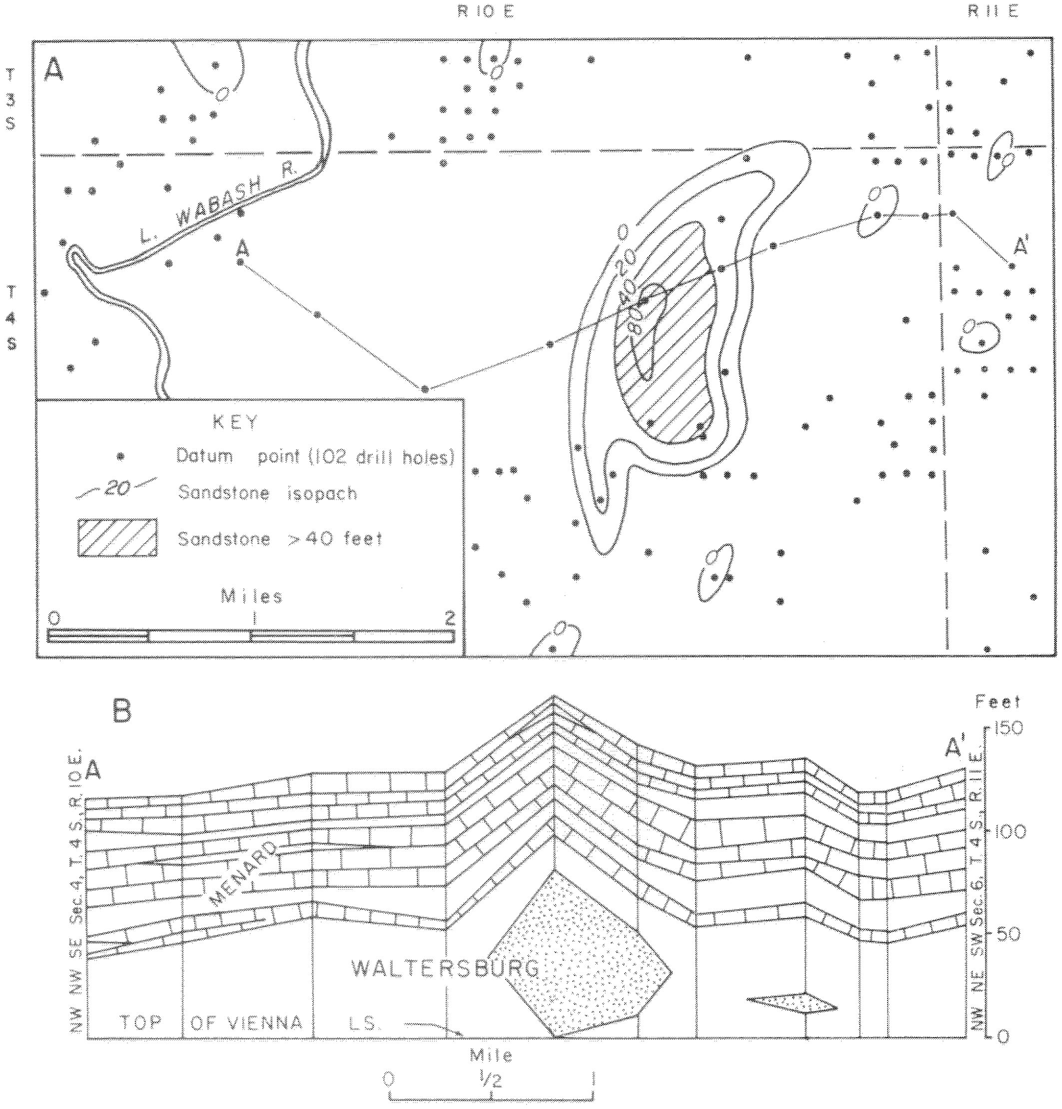


Fig. 39—(A) Thickness of sandstone, based on 102 control points, in the Waltersburg Formation in part of White County, Illinois. (B) Cross section of sand body above.

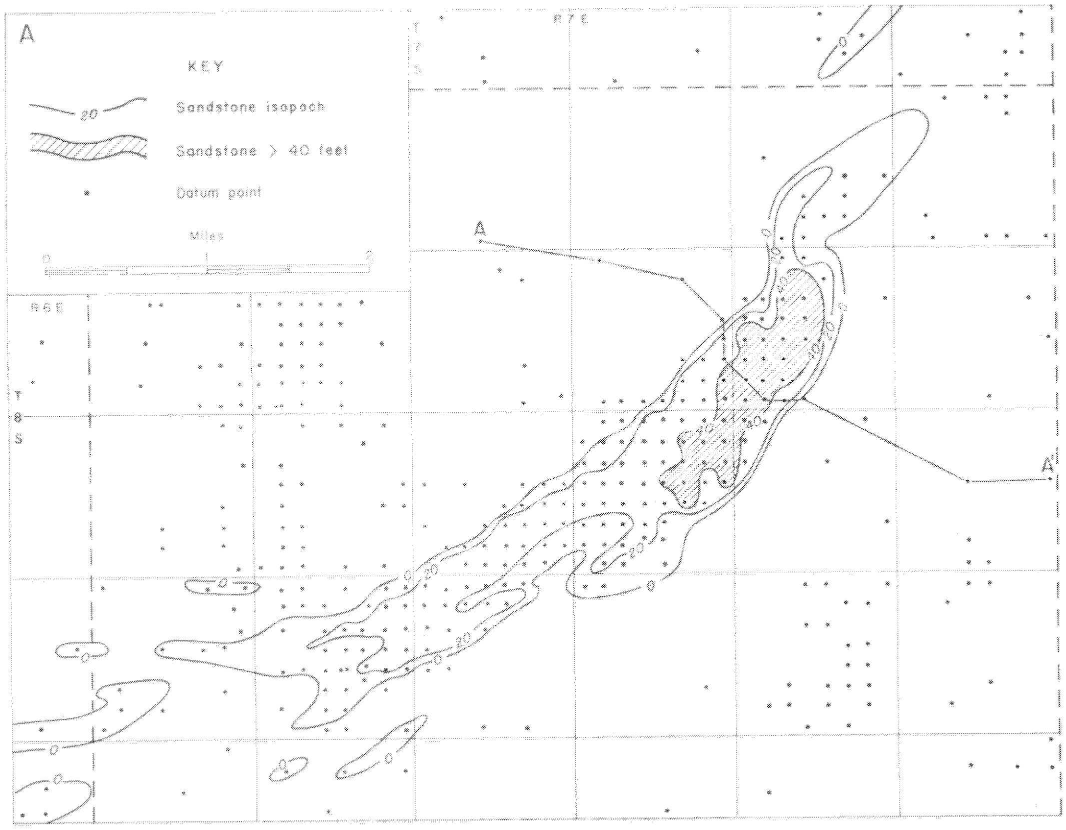


Fig. 40A—Thickness of sandstone, based on 375 control points, in the Waltersburg Formation in part of Saline County, Illinois (from Potter, 1962b, fig. 9).

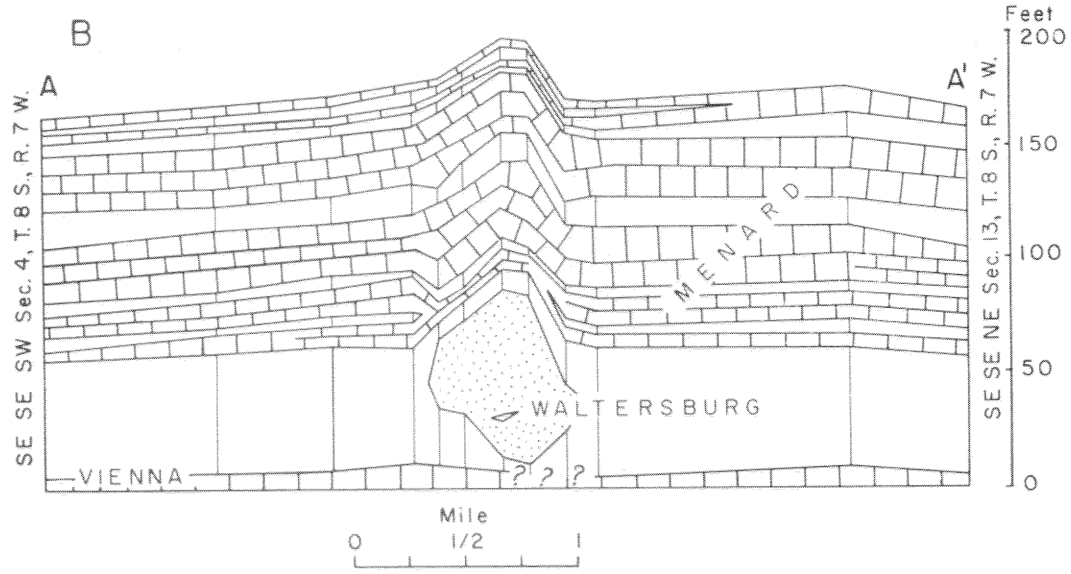


Fig. 40B—Cross section of sand body in figure 40A.

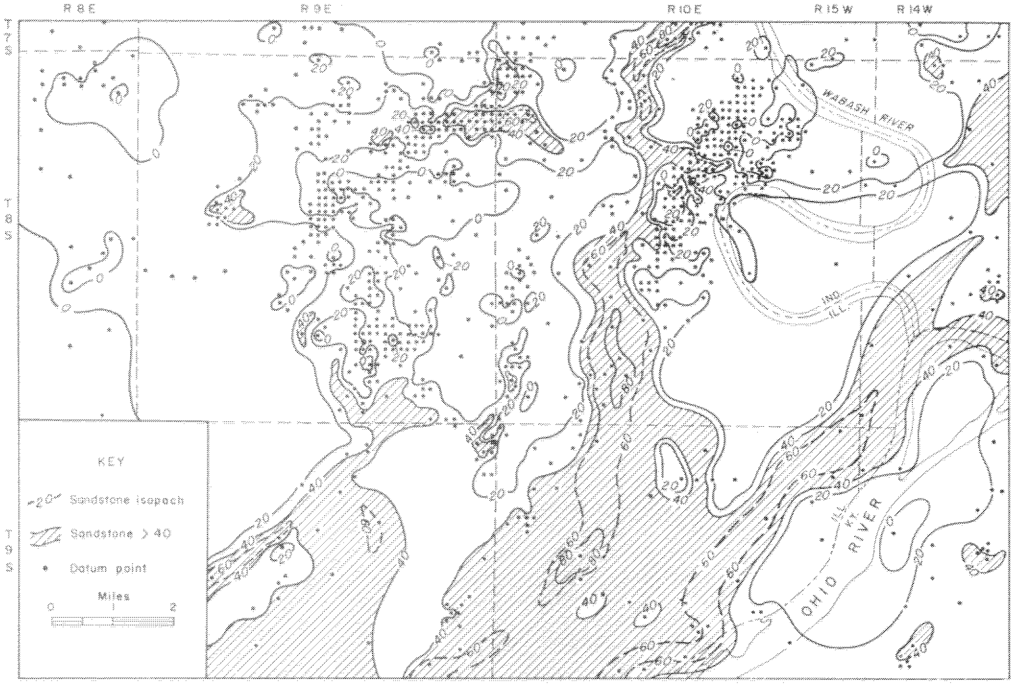


Fig. 41—Thickness of sandstone in the Hardinsburg Formation in parts of Gallatin County, Illinois, Posey County, Indiana, and Union County, Kentucky; based on 833 control points.

Dean Limestone has a pronounced structural high over the thickest section of the sandstone.

Three selected cross sections of Chesterian sand bodies are shown in figure 43.

Cross section A is drawn at right angles to a small elongate sand body in the Degonia Formation in Saline County, Illinois. This cross section shows that the upper limestones of the Clore Formation were removed locally before deposition of the sandstone. The structure of the overlying Kinkaid Limestone is influenced by the presence of this sand body.

Cross section B is of the Degonia in Wayne County, Illinois. This elongate sand body truncates units in the underlying Clore Formation, defining a good channel cross section. Its precise lower contact is in part uncertain because the sand body is superimposed on an underlying sandstone of the Clore Formation.

Cross section C is of the interval from the Glen Dean Limestone to the base of the Downeys Bluff Limestone in Vanderburgh and Warrick Counties, Indiana. It shows the sandstone in the Cypress Formation superimposed on the sandstone in the Bethel Formation. The greatest thickness of the combined sandstones is over 200 feet. The Reelsville and probably the Sample were eroded before deposition of the Cypress Sandstone along the entire cross section area. The sandstone in the Bethel thickens in the area where the Beaver Bend Limestone is absent. This suggests that a common control localized good development of both sandstones. Similar controls also may have been responsible for the possible superposition of sandstones in the thick section of figure 37C.

An additional feature of cross section C is the erosion of the Haney Limestone under the sandstone in the Hardinsburg.

Conclusions

The detailed maps of sandstone thickness and the related cross sections (figs. 32 to 43) reveal the following points:

1. Elongate sand bodies generally have very clearly defined trends.

2. Elongate sand bodies commonly have abrupt boundaries. Transitions from zero to more than 80 feet can occur between 40-acre and even 10-acre well spacings.
3. Elongate sand bodies with dendroid and belt distribution patterns display
    a) both small and large tributaries and distributaries
    b) weakly to strongly meandering boundaries
    c) some truncation of underlying strata (indicated by subsurface cross sections that are generally biconvex)
    d) "islands" with no permeable sandstone
4. Elongate ribbon sand bodies have relatively straight or gently curved distribution patterns.
5. Elongate ribbon and pod sand bodies may, but usually do not, truncate underlying beds.
6. Ribbon and pod sand bodies generally have a biconcave cross section.
7. Overlying marker members or beds usually are structurally high over thick elongate sand bodies. The greater the ratio of thickness to width of the sand body, the sharper the compactional bump on the overlying marker bed.
8. Unusually thick sand bodies may result from superimposition of two or more cycles of sand deposition.

Surface Maps

Detailed maps were made of outcrops of one Pennsylvanian and three late Mississippian sand bodies (figs. 45 to 48). The sand bodies were examined for kinds and amounts of various sedimentary structures, thickness, fossil content, grain size, and character of basal contact if exposed. Primary directional properties were measured wherever possible.

Anvil Rock Sandstone Member

Figure 44 shows the edge of a channel filled with Anvil Rock Sandstone that is exposed in the Gilbraltar strip mine near Central City, Kentucky. A thin coal above No. 11 Coal lies directly beneath 20 feet of Anvil Rock Sandstone along the margin of the channel. Both the coal and the shale underlying it have been eroded and the erosional channel filled with Anvil Rock Sandstone. This exposure demonstrates how abrupt the margins of elongate sand bodies can be.

Sandstone Above Coal V (Indiana)

The cutout, or washout, in Coal V in T. 2 S., Rs. 7 and 8 W., Pike County, Indiana, was illustrated by Wier (1953). Low structural dip into the basin and extensive strip and underground mining together provide an unusual opportunity to combine good subsurface information with excellent outcrops.

Figure 45, modified from Wier (1953), shows the mapped area and a simplified stratigraphic section. Outcrop observation indicates that away from the cutout of Coal V, south and west of Augusta, Indiana, only a thin sheet sand body is present. This sand body is thin bedded and has little cross-bedding. As the cutout is approached, the sandstone becomes thicker, coarser grained, and develops prolific cross-bedding and an unconformable lower contact. Erosion beneath the sandstone has progressively removed two thin overlying coals before Coal V is cut out. Plate 9 shows the unconformity at the base of the sandstone and the erosion of the upper of the two coals near the cutout. Generally within 500 to 2000 feet of the margin of the cutout, the sandstone lies directly on Coal V and contains large amounts of transported coal debris in thin layers. Coal V is thinned by erosion near the cutout. Along the margins of the cutout there are several penecontemporaneous slide structures in the sediments above Coal V.

Both the pattern of the cutout and the distribution of sandstone thickness associated with it indicate that this elongate sand body is very similar to other Pennsylvanian sandstones mapped in subsurface. Field relations indicate that the elongate sand body developed after the deposition of as much as 30 or more feet of sediment above Coal V. The elongate sand body in and proximal to the cutout area fills an eroded channel and, in reality, consists of three sand bodies superimposed (fig. 45). The three sand bodies are separated by unconformities and have some bedding contrasts. Sandstones B and C can be distinguished only in and near the cutout.

Sandstone A has prolific cross-bedding and appears to fill most of the cutout. The cross-bedding of sandstone A in general parallels the cutout area of Coal V as determined by bore holes and mining operations. The cross-bedding of sandstones B and C also shows a general correspondence to the trend of the cutout but has somewhat greater variability in direction. There is good correspondence between the trend of the whole elongate

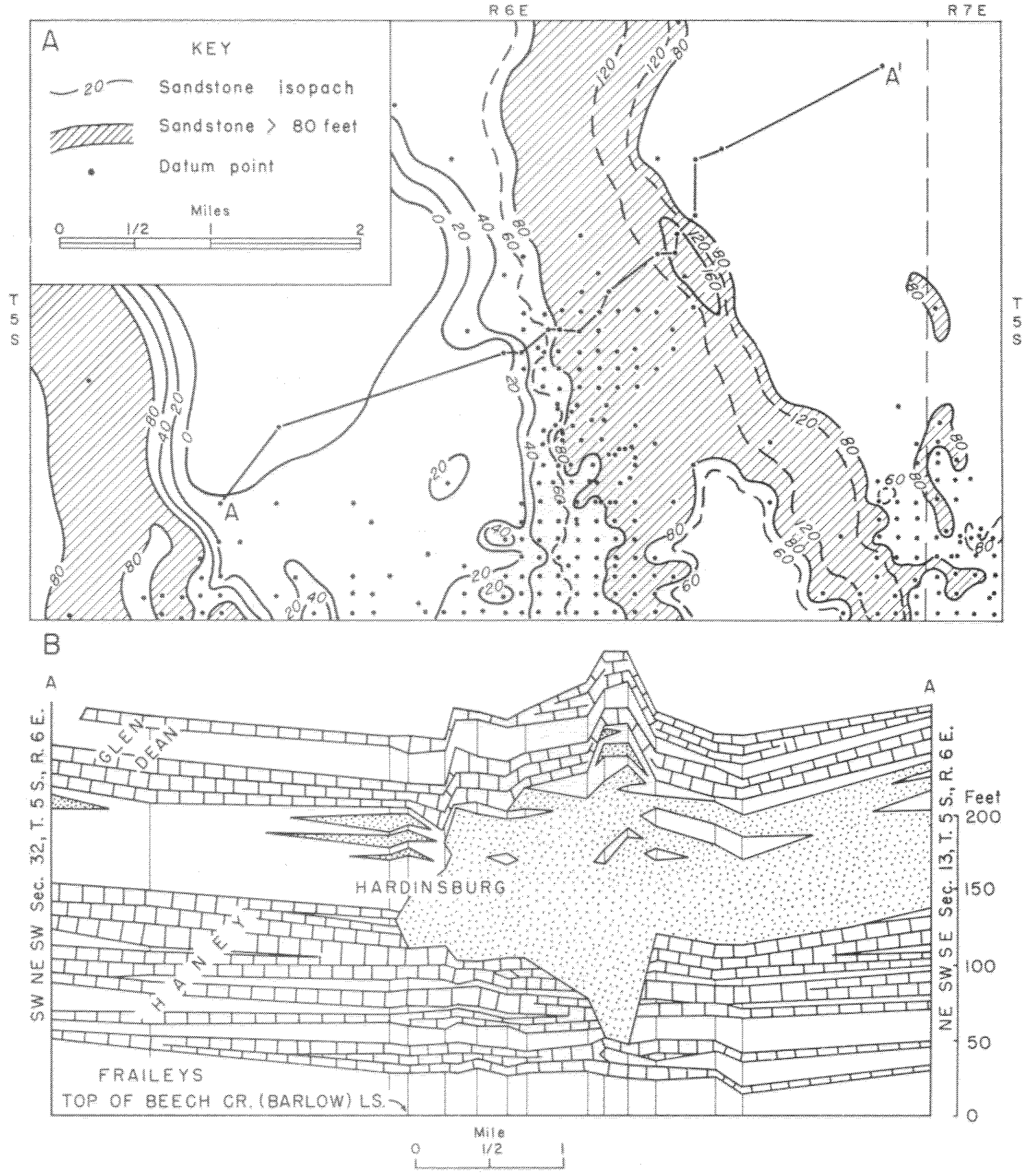


Fig. 42—(A) Thickness of sandstone, based on 225 control points, in the Hardinsburg Formation in part of Hamilton County, Illinois. (B) Cross section of sand bodies above.

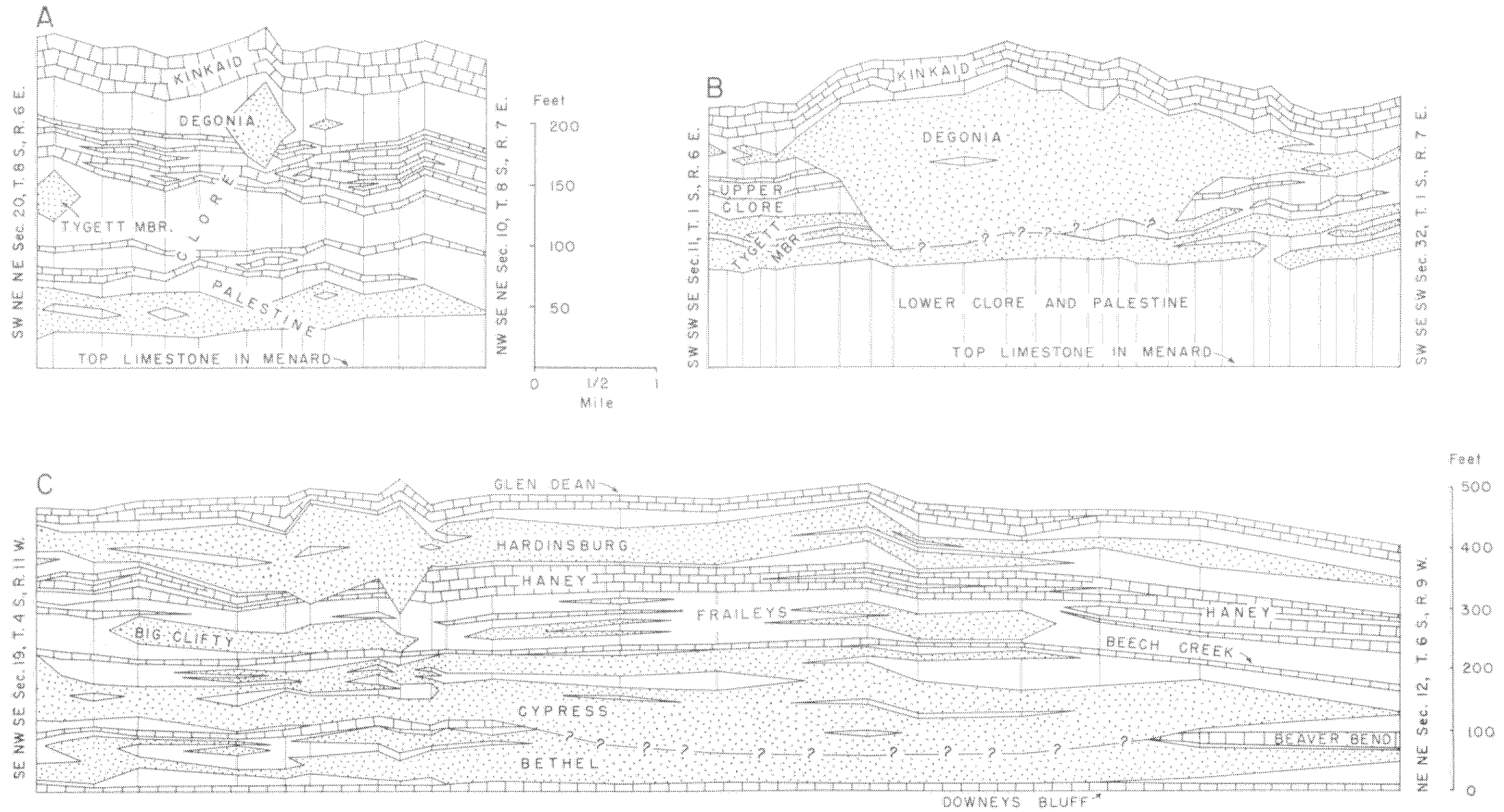
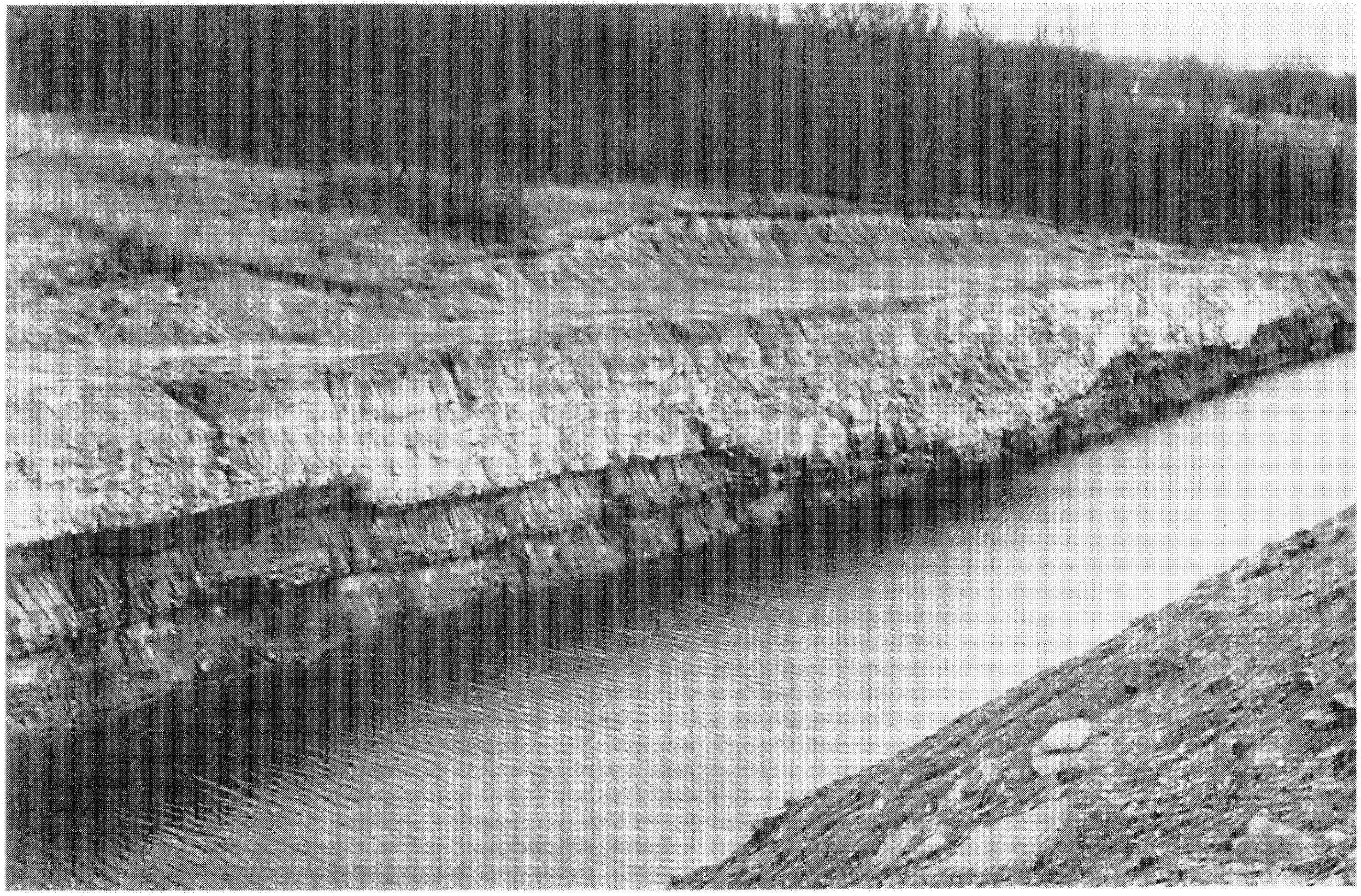


Fig. 43—Cross sections of Chesterian sandstones. (A) Degonia Sandstone in Saline County, Illinois; (B) Degonia Sandstone in Wayne County, Illinois; and (C) Cypress Sandstone in Vanderburgh andWarrick Counties, Indiana.



Channel filled with sandstone above Coal V (Indiana). The two rider coals are approximately 7 feet apart. Exposure in NW¼ NW¼ sec. 7, T. 2 S., R. 7 W., Pike County, Indiana.

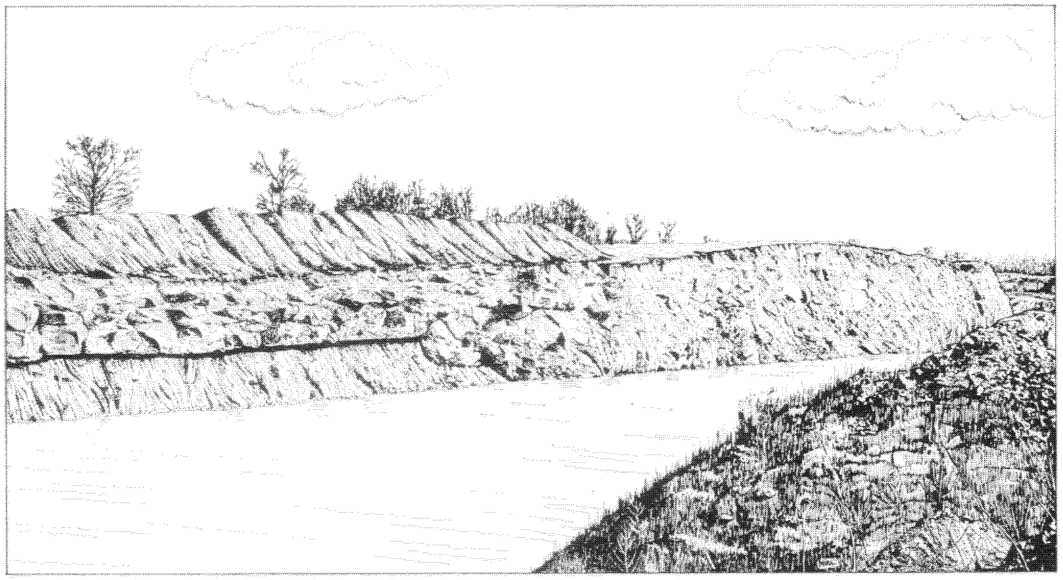


Fig. 44—Edge of deep channel at base of Anvil Rock Sandstone in Gibraltar strip mine (Carter grid rectangle 10-J-29) near Central City, Muhlenberg County, Kentucky. Note sandstone at top of thin coal to left of channel. Highwall has maximum height of approximately 55 feet above water level.

sand body and cross-bedding direction, which should be helpful in predicting the direction of the coal cutouts.

Field mapping also demonstrated that the elongate sand bodies of a single stratigraphic unit, for example the Vermilionville Sandstone, may consist of several pulses of sand deposition. The various pulses generally can be recognized only with difficulty in the subsurface. Nevertheless, the possibility of such a complex history should be kept in mind when interpreting the distribution patterns of sandstone in subsurface.

In spite of the good exposures in this area, the relative ages of the sheet and elongate sand bodies could not be unequivocally determined.

Degonia Sandstone

Thick elongate and thin sheet sand bodies in the Degonia Formation were mapped in part of Union County, Illinois (fig. 46). The sheet phase of the Degonia Sandstone as mapped in figure 46 includes (following Lamar, 1925, pl. 1) some thin sandstone beds in the upper part of the Clore Formation.

The area of figure 46 includes the eastern edge of a large southwest-trending belt sand body in T. 11 S., R. 1 W., and a smaller elongate sand body in T. 11 S., R. 1 E. Plate 2B is an oblique aerial photograph of a portion of the belt sand body and plate 2A is a photograph of a thin sheet sand body in the Degonia nearby.

Figure 46A shows the distribution of sandstone thickness, grain size, and bedding thickness at each outcrop. There is good correlation between thick sandstone sections and both coarser grain and thicker beds. Maximum measured thickness of the belt sand body was 78 feet. Typical exposed thicknesses of the sheet sand bodies were 10 to 15 feet.

The directional properties of the sand bodies are shown in figure 46B. Cross-bedding is abundant in the elongate sand bodies and parallels the trend of the belt sand body as it has been mapped in subsurface to the north (Potter et al., 1958, fig. 14; Potter, 1962b, pl. 1). The vertical profile of cross-bedding in the Degonia, shown in figure 27B, was obtained from this belt sand body (see VP on fig. 46B). Plate 4B shows some of the cross-bedding. Cross-bedding is more variable in the smaller elongate sand body in T. 11 S., R. 1 E., where there are three distinct superimposed sand bodies, each with different cross-bedding directions.

Some cross-bedding was also noted in the sheet sand bodies. Its orientation is broadly similar to that of cross-bedding in the elongate sand bodies. Strike of asymmetrical and symmetrical ripple marks is approximately at right angles to the dominant southwest orientation of the cross-bedding and of the elongate sand bodies.

Although the sheet sand body was found close to the principal elongate sand bodies in the Degonia, relative age relations could not be established in the field.

Waltersburg Sandstone

Outcrops of elongate and sheet sand bodies in the Waltersburg Formation occur in parts of Johnson and Pope Counties, Illinois (fig. 47), one of the very few areas in the basin where thick sandstone of the Waltersburg is exposed. Maximum observed thickness of the elongate sand body was 74 feet. The basal contact is unconformable. Typical thickness of sheet sand body exposures were 6 to 10 feet. The basal contact of the sheet sand bodies is conformable. The transition zone

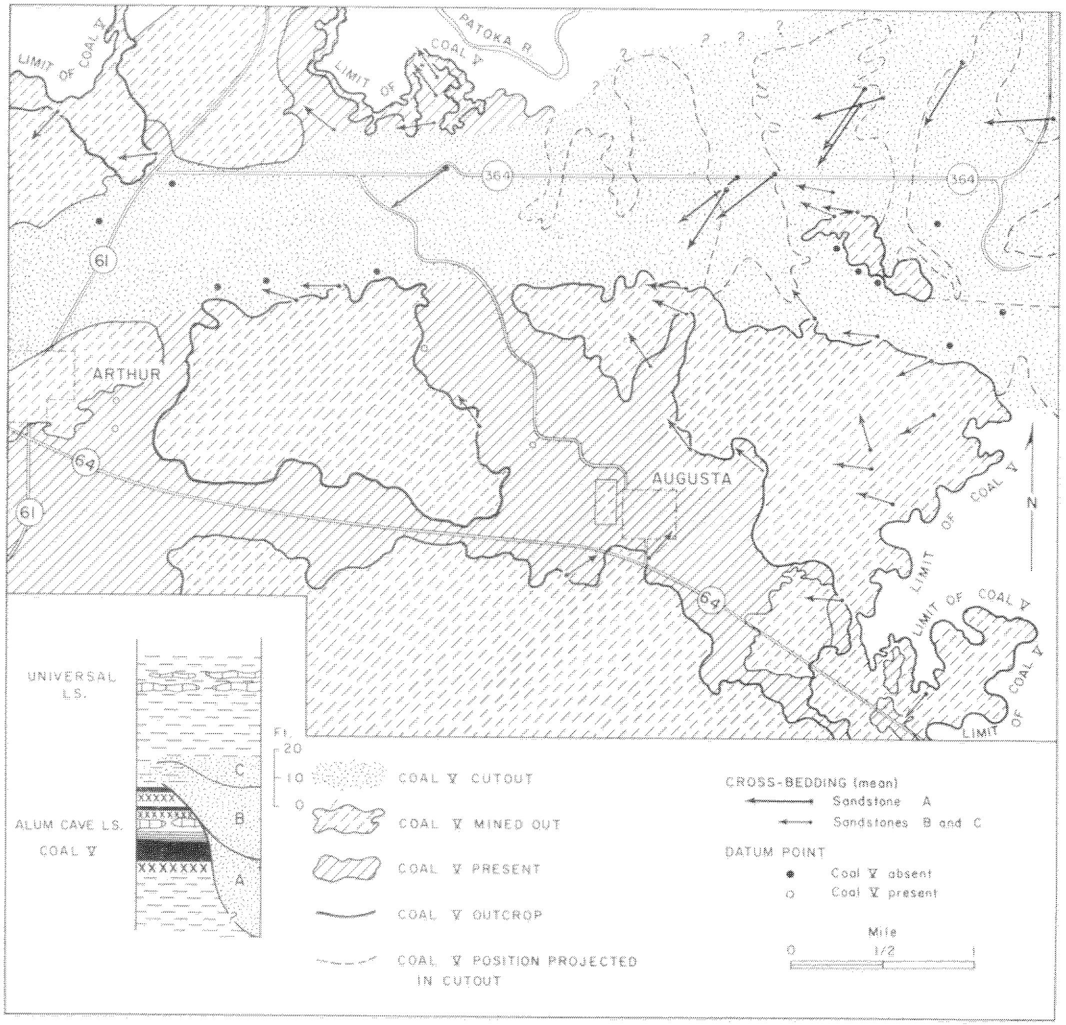


Fig. 45—Sandstone cutout in Coal V (modified from Wier, 1953) in part of Pike County, Indiana.

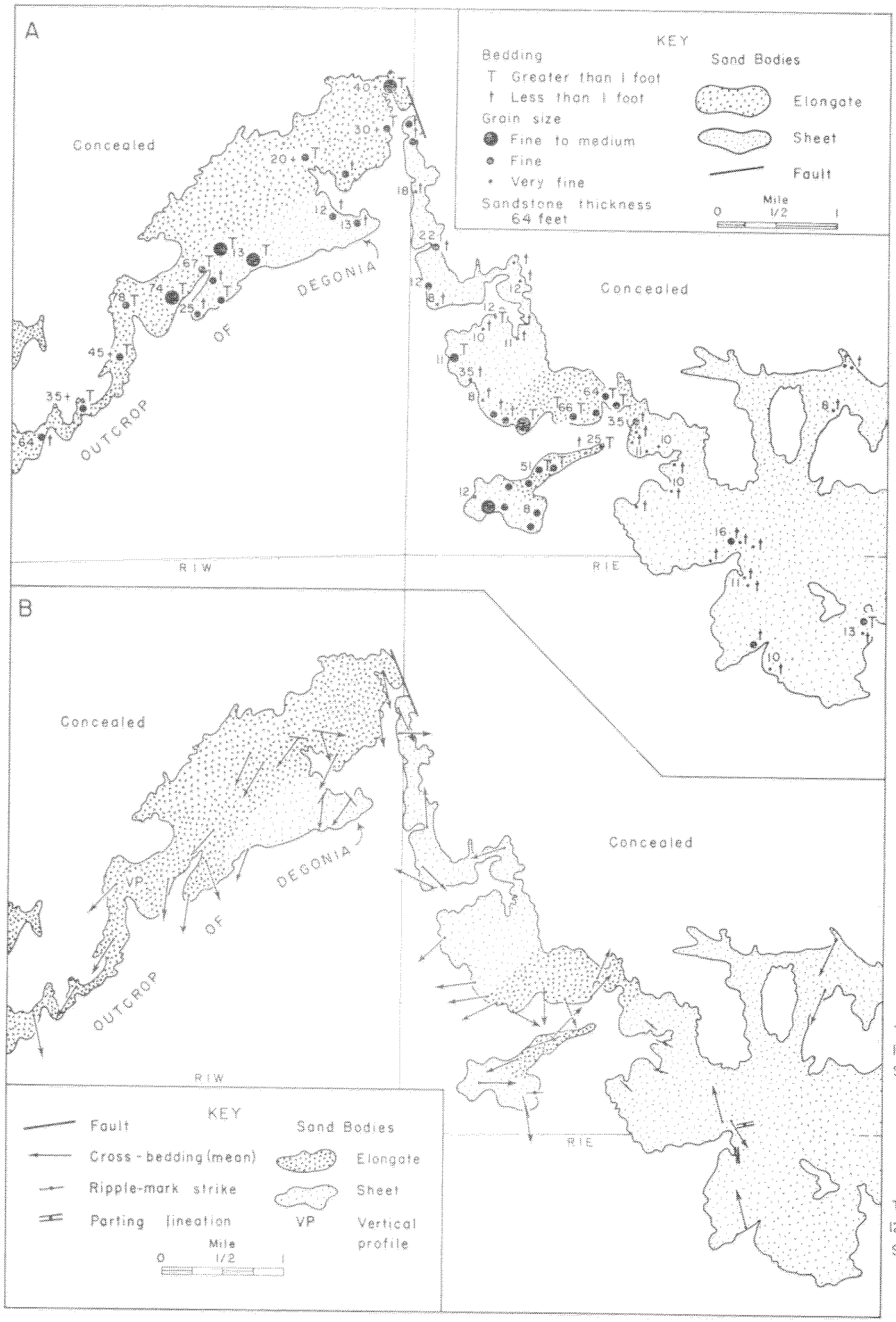


Fig. 46—Generalized geologic map of the Degonia Formation in part of Union County, Illinois, showing (A) sandstone thickness, bedding, and texture, and (B) directional structures of sandstone. The sheet phase includes sandstone of the underlying Clore Formation.

between the two extends laterally about 1000 feet. In this zone the elongate sand body thins rapidly. Outcrop observations did not permit determination of the relative age of the sheet sand body.

There is good correlation between thick sections, thick beds, and coarser grain (fig. 47A). Cross-bedding (fig. 47B) is almost entirely confined to the elongate sand body, where it is usually abundant. Variability of cross-bedding direction is comparable to that of most of the other sandstones mapped in detail.

Field observation of sedimentary structures, grain size, thickness, and contact relations indicate that these exposures of thick sandstone in the Waltersburg do not differ in any significant way from other late Mississippian sandstones.

Aux Vases Sandstone

Exposures of the Aux Vases Formation in portions of Randolph and Monroe Counties, Illinois, exhibit sheet and elongate sand bodies. Although subsurface data are limited, a thick belt sand body can be identified.

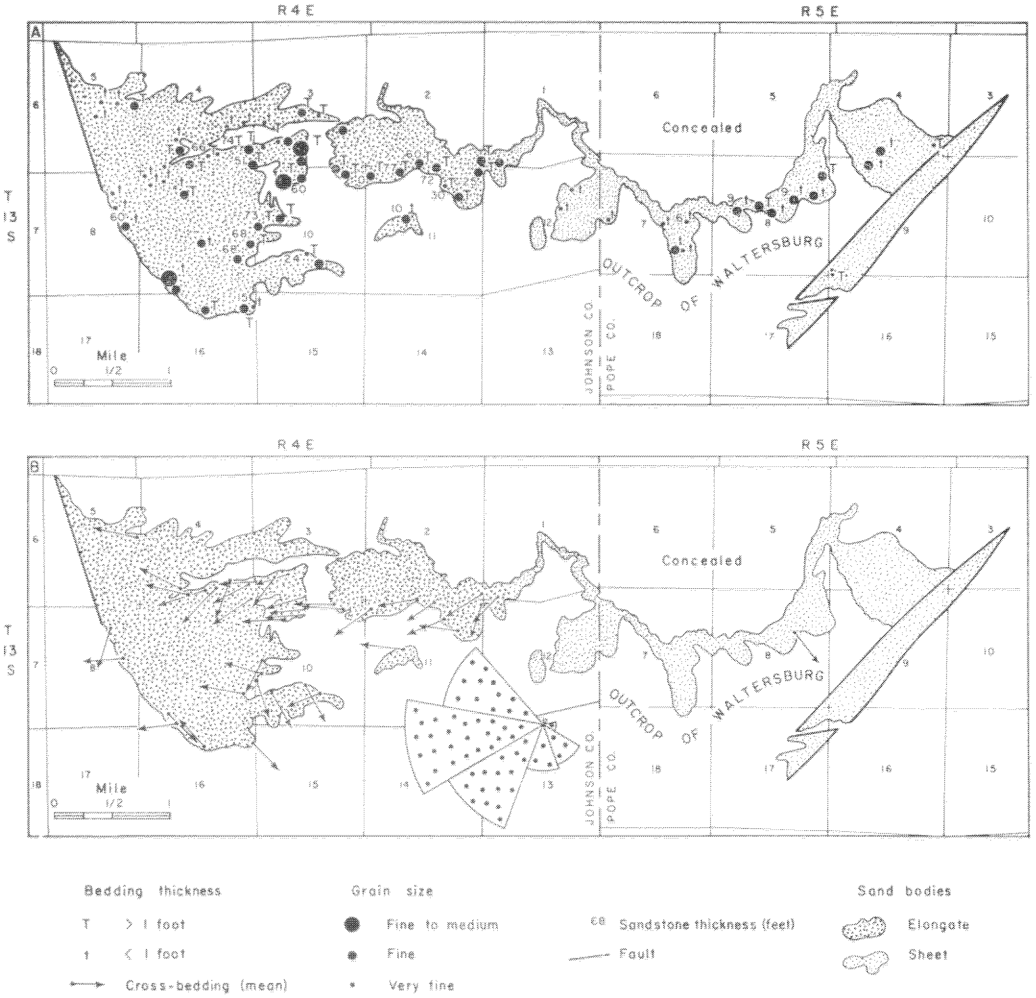


Fig. 47—Generalized geologic map of the Waltersburg Formation in parts of Johnson and Pope Counties, Illinois, showing (A) sandstone thickness, bedding, and texture, and (B) cross-bedding of sandstone.

Figure 48A shows the belt sand body in outcrop and subsurface. The western border of the belt generally strikes north-south and appears to meander. Sandstone thickness exceeds 80 feet in the subsurface, and one outcrop section has approximately 90 feet of sandstone. The belt sand body has pronounced unconformity with the underlying Ste. Genevieve Limestone. The transition from belt to sheet sand body occurs within approximately 2000 feet in the north-central portion of T. 5 S., R. 9 W. The sheet sand body is 8 to 10 feet thick or may be locally absent. Unlike the belt sand body, it has a conformable lower contact. Figure 48A also shows that the cross-bedding in the area has

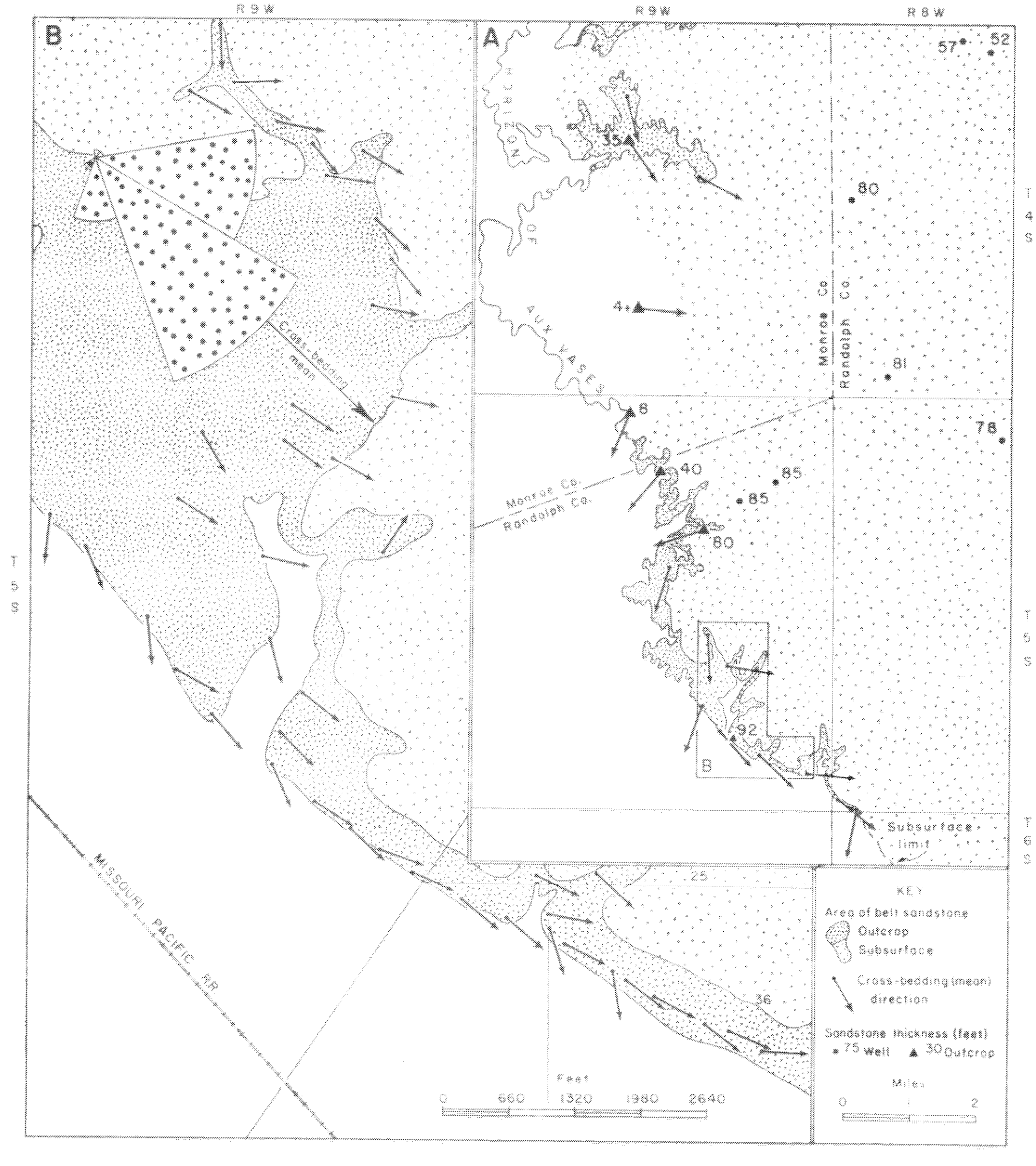


Fig. 48—(A) Thickness and cross-bedding of sandstone in Aux Vases Formation in parts of Monroe and Randolph Counties, Illinois. (B) Detailed cross-bedding map in parts of T. 5 S., R. 9 W., Randolph County, Illinois.

a south-southeast orientation, generally parallel to the trend of the sand body.

Figure 48B shows the striking homogeneity of 83 cross-bedding measurements of a small area of the belt sand body.

Conclusions

The detailed maps (figs. 45 to 48) of the sand bodies, based on outcrops, support the following conclusions:

1. Transitions from elongate to sheet sand bodies are as abrupt laterally in outcrop as in the subsurface.
2. Elongate sand bodies of any single stratigraphic unit may consist of two or three pulses of sand deposition and thus have had a relatively complex history.
3. Wherever mapped in detail, cross-bedding nearly always showed a strong preferred orientation, and its average direction paralleled direction of elongation of sand bodies.
4. Although measurable directional structures are less abundant in sheet sand bodies, they suggest that current direction in those sand bodies was similar to that of adjacent elongate sand bodies.

Internal Directional Structures and Elongate Sand Bodies

Substantial information, usually obtained incidental to other studies in the basin, is available on the relationships of internal directional structure and elongate sand bodies, especially those of Pennsylvanian age. Potter and Olson (1954, fig. 6) and Potter and Siever (1956, fig. 6) showed good correlation between orientation of two pre-Pennsylvanian channels and cross-bedding directions of their subsequent sand fill. Rusnak (1957) made a study of internal directional properties and sand body shape. He measured cross-bedding and sand fabrics of the Pleasantview Sandstone in western Illinois and related the results to channel outline, as determined in outcrop by Ekblaw (1931). Rusnak found (1957, table 3) that cross-bedding, sand fabrics, and some ripple marks indicated a transport direction to the northwest, roughly parallel to a part of the channel system mapped by Ekblaw. Rusnak (1957, p. 52) concluded that, because channel gradient was to the southeast and internal directional properties indicated transport to the northwest, the processes that cut the channel were unrelated to those that subsequently filled it.

Potter et al. (1958, figs. 11 to 14) found that average cross-bedding direction and isopach trends of sandstone in the Degonia, Palestine, Waltersburg, and Tar Springs Formations in southern Illinois had good general agreement. Friedman (1960, p. 34) qualitatively observed the correspondence between cross-bedding direction and trend of middle Pennsylvanian channel-filled sandstones in west-central Indiana. Moore (1959, p. 533) commented on the good qualitative agreement between orientation of elongate sandstones and cross-bedding direction in Lower Carboniferous sediments in Great Britain. Doty and Hubert (1962, fig. 1) showed excellent agreement between cross-bedding direction and sand body orientation in the Warrensburg Sandstone of Missouri. These data suggest good agreement between internal directional properties and direction of elongate sand bodies that fill many Carboniferous basins. The present study confirms the conclusion that the cross-bedding direction parallels direction of elongation, as shown by the Aux Vases (fig. 48), the Degonia (fig. 46), and the sandstone above Coal V of Indiana (fig. 45).

A small sand body in the Anvil Rock Sandstone Member that has been mapped underground in a mine (Potter and Mast, 1963, fig. 10) in west-central Illinois provides additional information on the relationships between internal directional properties and direction of elongation. Sand fabrics of elongate quartz grains from 10 samples were studied and the orientation of four cross-beds was measured (Mast and Potter, 1963, fig. 11). Figure 49 shows the outline of the sand body as determined in the main haulage entry of the mine and as reconstructed in mined-out areas, now sealed off, away from the haulage entry. The sandstone has an unconformable basal contact and a well defined elongate pattern in the mine roof. Undoubtedly, however, it has more irregular boun-

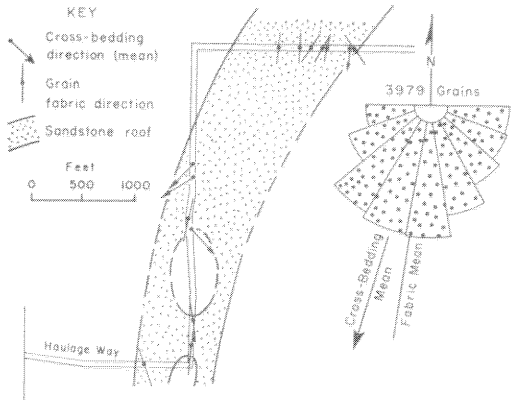


Fig. 49—Distribution of Anvil Rock Sandstone in roof of underground mine at Virden, Macoupin County, Illinois, and internal directional structure—current rose of grain orientation, mean fabric direction, and average of all cross-bedding measurements (from Potter and Mast, 1963, fig. 10).

daries than those shown and probably contains more "islands" of uneroded material such as the island of Brereton Limestone that forms the roof in the north-south haulage way. Both sand fabric and cross-bedding show good agreement with the trend of the sand body. The thickness of this sandstone is unknown.

Collectively, the above results imply that internal directional structure of the typical elongate late Mississippian or Pennsylvanian sand body can be effectively used to predict the direction of elongation of belt and dendroid sand bodies and probably of most ribbon and pod sand bodies. Although not many data are available, the directional structures of the sheet sand bodies generally indicate a transport direction similar to that of nearby elongate sand bodies.

Multistory Sand Bodies

Detailed mapping of sandstone thickness in the subsurface revealed the existence of unusually thick sections of sandstone. These thick sections can result from the superimposition of an elongate sand body of one cycle on an elongate sand body of an underlying cycle. The name "multistory" has been given to sand bodies of this origin (Feofilova, 1954, p. 255). Feofilova and Yablokov (1954) gave many examples of two- and three-story sand bodies in the Middle Carboniferous deposits of the Donets Basin. Although they did not use this term, Lee et al. (1938, p. 2) described multistory sandstones in the Pennsylvanian sediments in Texas. Andresen (1961, fig. 4) illustrated a multistory sand body in Illinois.

Figure 50 shows diagrammatically the origin of multistory sand bodies. Three sandstones of adjacent cycles have distribution patterns that almost coincide. The points A, B, and C in figure 50 represent three wells drilled through the sand bodies. In well A the youngest sandstone (1) is separated from the oldest (3). No mapping problems arise. In well C the intermediate sandstone (2) is superimposed on the oldest (3). In well B all three sandstones are well developed and

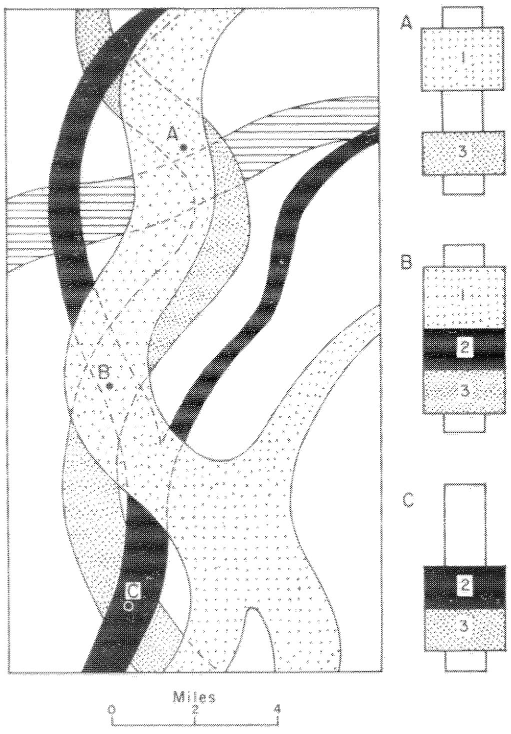


Fig. 50—The origin of multistory sand bodies —(A) separate sand bodies, (B) a three-story sand body, and (C) a two-story sand body. The position of an underlying sand body (horizontal ruling) was not controlled by the same factors that localized sand bodies 1, 2, and 3.

an unusually thick section results. The possibility of distinguishing the different sandstones in well C depends on the abundance and kind of well data available.

Multistory sand bodies also may develop from the superposition of belt and ribbon as well as dendroid sand bodies.

The cross sections of the Mt. Carmel (fig. 37C), the Degonia (fig. 43B), and the Cypress Sandstones (fig. 43C) illustrate multistory sand bodies in subsurface in the basin. Multistory sand bodies are relatively common in the McCormick Group, as sandstone is abundant and intervening marker beds are poorly developed. Probably the best example of multistory sandstone development in outcrop, however, is in the Chesterian Series in portions of Hardin County, Illinois, and Crittenden and Livingston Counties, Kentucky, where locally there is essentially continuous sandstone from the top of the Cypress to the base of the Bethel (Sutton, 1950, and Baxter et al., 1963, pl. 1). Swann and Atherton (1948, fig. 5) showed cross sections of these thick elongate sand bodies in subsurface to the north.

Commonly multistory sand bodies result from relatively persistent localization of elongate sand bodies by a common controlling factor. Areas of weak differential subsidence within the basin are the most likely cause. The persistence of a weakly negative area, localizing the position of elongate sand bodies through 2 to 4 adjacent cycles of sedimentation, would produce the results illustrated in figure 50. Less commonly, multistory sand bodies can develop from random superposition, which could be the case in the area mapped by Mueller and Wanless (1957, fig. 5).

The association of coal cutouts with splits in coal beds in the Pennsylvanian System probably also is a reflection of control of clastics by persistent localized subsidence. In west-central Illinois a split coal area in the Herrin (No. 6) Coal is locally associated with subsequent channel erosion at the base of the overlying Anvil Rock Sandstone (Potter and Simon, 1961, p. 9-10). It is inferred that local subsidence determined the position of a small stream carrying silt and mud in the coal swamp and that later similar local subsidence determined the position of the principal Anvil Rock dendroid sand body.

Compaction

The cross sections of many of the elongate sand bodies described previously indicate structural highs on overlying marker beds. Zhemchuzhnikov (1954, p. 9-10) showed similar compactional highs on a coal bed above a narrow sandstone channel in the Donets Basin. Such compactional highs complicate the identification of small anticlinal flexures of true tectonic origin. Brownfield (1954, p. 17) commented on the differential compaction over lenticular sand bodies. Mueller and Wanless (1957) computed the percentage of differential compaction in non-channel areas compared to areas of channel sandstones. They estimated that compaction in the shales and siltstones of non-channel areas was 21 to 54 percent greater than in areas of thick channel sandstones. Their calculations assumed that the overlying marker bed was horizontal at the time of its deposition. Their data also suggested that percentage of compaction increased with depth of burial.

Differential compaction complicates the study of sand body shape. Obviously, cross sections of lenticular elongate sand bodies that use an overlying marker bed as a level line can produce misleading results. Cross sections based on a level line below the sand body generally provide a better representation of sand body shape. Ideally, however, the best reconstruction of sand body shape would be obtained by having independent estimates of the percentage of compaction in shale and sandstone that could be used to restore original dimensions.

Age of Sheet and Elongate Sand Bodies

Where a sheet sand body conformably overlies an elongate sand body, as on plate 3A, it is, of course, younger. Commonly, however, if only a sheet sand body is present, it is difficult or impossible to establish by field mapping its age relative to a nearby elongate sand body in the same stratigraphic position.

The apparent conformable and transitional basal contact of the sheet sand bodies with the underlying sediments, which are commonly at least partly of marine origin, points to an age older than that of the elongate sand body. By this interpretation the sheet sand body could be a regressive marine sand. Later, elongate sands may have developed that cut into the more widespread sheet sand bodies. Hopkins (1958, p. 38-40) believed this interpretation applied to the Anvil Rock Sandstone. On the Mississippi delta, Fisk (1955, p. 388) found that, as the delta builds seaward, distributaries scour channels into the underlying sheet sands. Subsequently, these scour channels are filled with thick sand deposits. This interpretation appears to be satisfactory for most late Paleozoic sheet sand bodies in the Illinois Basin, except for those that directly overlie thick elongate sand bodies. Unfortunately, no example of an elongate sand body that definitely truncates a sheet sand body of the same stratigraphic interval has been found in outcrop in the basin.

The alternative interpretation, that the sheet sand bodies are everywhere younger than the elongate sand bodies, implies that most elongate sand bodies represent the fill of erosional channels and that, as sedimentation proceeded, first the channel and finally interchannel areas were alluviated. The sheet sand bodies would have been produced by the final alluviation, and thus there should be an unconformity beneath the sheet sand bodies. The generally conformable and transitional basal contact of the sheet sandstone contradicts this interpretation. The presence of sheet sand bodies that are far removed from elongate sand bodies also makes their origin as fluvial, alluvial deposits unlikely.

Another possibility is that sheet sand bodies are not exclusively either younger or older than neighboring elongate sand bodies but, depending upon the type of elongate sand body, may vary in age or even be contemporaneous.

Contouring

Because they have great variability in thickness, elongate sand bodies present most difficult problems in contouring.

Drill holes, as a rule, are unevenly distributed. Contouring sandstone thickness by arithmetic spacing generally yields poor estimates of both width and location of elongate sand bodies. More effective contouring is possible if both sand body width and marginal change in sandstone thickness are determined in areas of dense control and used as guides in areas of sparse control. Elongate sand bodies may have either relatively straight or weakly to strongly meandering lateral boundaries.

Over any small area, from a few square miles to several townships, detailed subsurface mapping of sandstone thickness will nearly always define a trend and pattern of sand bodies. This pattern is the basis for prediction of sandstone occurrence and thickness. Because elongate sand bodies in the basin appear to be elongate parallel to cross-bedding direction, knowledge of cross-bedding orientation can be a guide to more effective contouring.

REGIONAL MAPS OF SANDSTONE THICKNESS

Regional maps of three Pennsylvanian and four Chesterian sandstones were made for the southern and south-central portions of the basin where subsurface control is good. In much of Illinois and portions of Indiana, two to four drill hole logs per section, if available, were used to construct the regional maps. Elsewhere one log per section was used. Figure 51 shows the resultant pattern of drill hole control for the sandstone in the St. David Cyclothem in the south-central portions of the basin. The largest of the regional maps is based on approximately 11,500 drill hole logs. Electric logs of oil test holes were the chief source of information.

Pennsylvanian Sandstones

The three maps of Pennsylvanian sandstones (pl. 1A, B, C), along with those of Hopkins (1958) and Andresen (1961), show most, if not all, of the regional distribution patterns of Pennsylvanian sandstones in the basin. Although Pennsylvanian sandstones be-

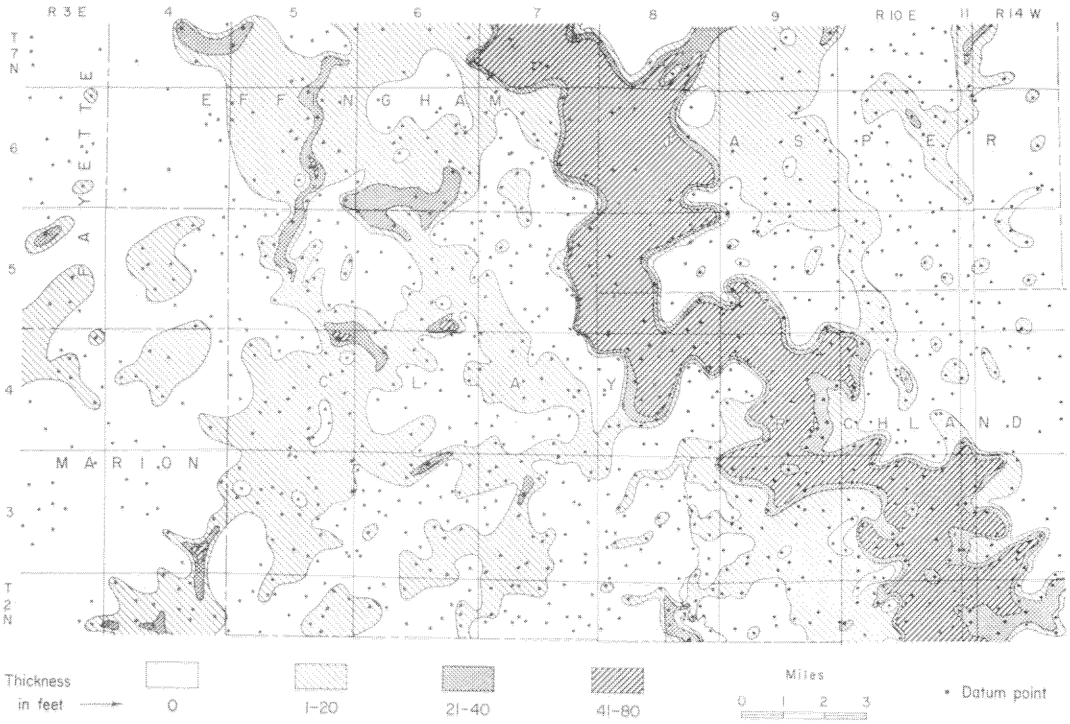


Fig. 51—Thickness of sandstone of St. David Cyclothem in south-central Illinois. Note meandering pattern of principal sand trend (dark pattern).

low the Spoon Formation cannot be regionally mapped in subsurface because of the absence of related traceable coal beds and limestones, outcrop observation suggests that their distribution patterns differ little, if any, from those of the higher sandstones.

Interval Between Herrin (No. 6) and Harrisburg (No. 5) Coals

The interval between the Herrin (No. 6) and the Harrisburg (No. 5) Coals contains two sandstones (pl. 1A). The sandstone below the Herrin (No. 6) Coal, the Vermilionville Sandstone, is the principal sandstone in this interval. The other, an unnamed sandstone of the Briar Hill Cyclothem, occurs between the No. 5 Coal and the overlying Briar Hill (No. 5A) Coal. The Briar Hill Cyclothem is largely confined to the more rapidly subsiding portion of the basin, where an additional coal is present locally, possibly representing a higher unnamed cycle. Because of these complications, it was not feasible to measure the thickness of the Vermilionville Sandstone alone. Locally, the strata in this interval have been eroded and subsequently filled, at least in part, by the overlying Anvil Rock Sandstone. These factors result in a relatively complicated map pattern.

Asymmetry of sand development—little sandstone along the western and northern parts of the area and relatively abundant dendroid sand bodies along the eastern side—is shown on plate 1A. The principal feature of the map is a system of belt and dendroid sand bodies that extends from Knox County, Indiana, westward and southwestward into Illinois. This system has a series of delta-like distributaries in portions of Hamilton, Jefferson, Franklin, White, and Marion Counties, Illinois, and also extends to the south into Saline County, where it divides into several distributary dendroid sand bodies. Where the Vermilionville Sandstone (in the map area) is thick, the No. 5A Coal is usually absent. To the west and north of the principal distributary system, there is little sandstone in the interval. Beyond the map area in northern and western Illinois, the occurrence of several dendroid sand bodies (Willman and Payne, 1942, p. 127-128; Wanless, 1957, p. 107-108) suggests the presence of another distributary system.

In contrast to poor sand development in the western part of the mapped area, a series of elongate sand bodies is found along the eastern side of the basin in Indiana and Kentucky. A well defined dendroid sand body trends southwestward in Gibson and Vanderburgh Counties, Indiana, extends southward into Henderson County, Kentucky, and turns westward in Union County, Kentucky. In northern Webster County, Kentucky, the same dendroid sand body joins two east-west channels in Daviess and Hopkins Counties, Kentucky. Along the Wabash River Valley in White and Gallatin Counties, Illinois, and Posey and Gibson Counties, Indiana, is a series of small, apparently isolated, elongate sand bodies with relatively complex pattern. These may, in fact, be part of a complex dendroid system.

Interval Between Harrisburg (No. 5) and Summum (No. 4) Coals

In Illinois the interval between the Harrisburg (No. 5) and Summum (No. 4) Coals contains the sandstone of the St. David Cyclothem. Because the bounding markers are well defined, the sandstone in this interval can be mapped with confidence over a wide area of the basin (pl. 1B). The interval contains relatively little sandstone and also is little affected by erosion. The sandstone has a simple basin-wide pattern of well defined meandering dendroid and belt sand bodies. Neither tributaries nor distributaries are numerous.

Two dendroid systems combine in Shelby County to form a meandering dendroid and belt sand body that extends southeastward into Knox and Gibson Counties, Indiana. In Gibson County this dendroid-belt sand body joins an east-west belt sand body that extends into Wabash County, Illinois. In northern Knox County, Indiana, there is a well defined belt sand body that is probably connected with the east-west belt sand body in Gibson County. From Wabash County a relatively narrow dendroid extends southwestward toward the outcrop. Westward in Clinton and Washington Counties, Illinois, there is some local sandstone. In Posey County, Indiana, there is an irregular band of sandstone locally more than 20 feet thick. In Kentucky a few irregular elongate sand bodies are in this interval.

Interval Between Colchester (No. 2) and Davis Coals

The Palzo Sandstone Member in Illinois, which is called Coxville in Indiana and Sebree in Kentucky, is the principal sandstone of the interval between the Colchester (No. 2) and Davis Coals. Because the underlying DeKoven Coal Member is not consistently well developed, it was not possible to map the Palzo Sandstone separately from a lower, usually thin, sandstone beneath the DeKoven.

Dendroid and belt sand bodies of the Palzo, Coxville, and Sebree Sandstones commonly have a preferred orientation to the southwest. A few are oriented to the south and southwest (pl. 1C).

A major belt sand body, 6 to 10 miles wide, extends southwestward in Illinois from Wabash and Edwards Counties into White County. From this point a combination of belt and dendroid sand bodies extends across Wayne County into Jefferson, Franklin, and Williamson Counties. From northern White County two other complex dendroids extend southwestward. Both are extensions of the large belt sand body of Wabash and Edwards Counties. In Washington and Perry Counties, Illinois, a well defined dendroid is oriented to the southwest.

In Wabash County, Illinois, the large belt sand body is joined by a smaller channel from the east that can be traced into Gibson and Pike Counties, Indiana. A combination belt and dendroid sandstone extends westward from the Indiana outcrop in Warrick County across Vanderburgh and Posey Counties into Kentucky, back into Posey County, and joins a channel sandstone in the area of the Wabash River in Gallatin County, Illinois.

In Kentucky, the over-all distribution pattern is complex. Several dendroid systems are present, and both tributaries and possible distributaries occur. In southern Hopkins County, Kentucky, the correlation of the Davis Coal is uncertain on electric logs.

Chesterian Sandstones

The entire extent of the sandstones in the Degonia, Palestine, Waltersburg, and Hardinsburg Formations was mapped. The maps show most of the typical patterns of Chesterian sandstones in the Illinois Basin and the thickness of the major sand bodies.

Sandstone in the Degonia Formation

The principal feature of the sandstone in the Degonia Formation is the north-south belt sand body with its southwest-trending channel tributaries that join it from the east (pl. 1D). Broad areas in Indiana and Kentucky have little or no sandstone. The map also shows pre-Pennsylvanian channels, the largest of which is the Evansville channel (Wanless, 1955, p. 1765).

The north-south belt sand body is locally more than 15 miles wide. Three southwest-trending dendroids join it with acute "downstream" angle, two of them in Wayne and Hamilton Counties, Illinois. The third begins in Gibson and Posey Counties, Indiana, crosses White and Hamilton Counties, Illinois, and joins the main belt sandstone in Franklin County, Illinois. What may be a distributary complex occurs in Williamson and Saline Counties, Illinois. Comparatively little sandstone is present in the Degonia Formation in either Indiana or Kentucky.

Sandstone in the Palestine Formation

The distribution of sandstone in the Palestine Formation is shown on plate 1E. The principal feature of the map is the distributary system that extends southwestward from Edwards County, Illinois. This combination belt and dendroid system bifurcates in White County. The eastern arm bifurcates in southwestern Hamilton County and again in Williamson County. What may be a small tributary dendroid sand body extends from eastern Wayne County southward to northern White County. Elsewhere in Illinois, sheet sand bodies are commonly present in the Palestine Formation, but there are some areas where no permeable sandstone occurs. In most of Indiana and Kentucky only sheet sand bodies are present and there is a substantial area in Kentucky where electric logs indicate that no sandstone is present.

The secondary feature of the map is a narrow elongate sand body that extends from the outcrop in Spencer County, Indiana, southwestward through Daviess County into Webster County, Kentucky. Although shown on plate 1E with a high degree of continuity, this sand body may in fact consist of a series of en echelon ribbon sand bodies. It may lie in the upper part of the Menard Limestone.

Because the Palestine lies stratigraphically lower than the Degonia, pre-Pennsylvanian valleys are less prominent.

Sandstone in the Waltersburg Formation

The distribution of sandstone in the Waltersburg Formation (pl. 1F) is more complex than in the Degonia. Despite this complexity, the map shows a strong southwest trend defined by pods, ribbons, dendroids, and belts.

One of the principal areas of sandstone is along the Wabash Valley in Gibson, Vanderburgh, and Posey Counties, Indiana; it extends into Henderson and Union Counties, Kentucky, and Gallatin County, Illinois. This complex of dendroid and belt sand bodies has an over-all strong southwest trend. The eastern margin of this complex is relatively straight and abrupt throughout most of its length, but in Henderson County are what may be two elongate deltaic distributaries. The one appears to terminate along the Ohio River and the other extends southwestward toward the outcrop. The latter may be a series of en echelon ribbon sand bodies.

Sand accumulation to the southwest in Jasper, Edwards, Wayne, Richland, White, and Hamilton Counties, Illinois, also is shown on the map. Southwest-trending sand bodies predominate. A sand body also extends northwestward from Richland County into Effingham County. Two narrow elongate sand bodies in Richland and in Lawrence, Wabash, and Edwards Counties appear to have supplied most of the sand to the southeastern Illinois area north of White County.

Other features of the Waltersburg are its isolated pod and ribbon sand bodies. These generally are oriented to the southwest, south, or southeast. In southern Illinois the ribbon sand bodies have weak en echelon arrangement.

Most of the area in which the sandstone of the Waltersburg is thick lies within about 30 miles of the Wabash River. Sandstone is largely absent to the west and north of this area and in most of Kentucky, except as noted previously.

Pre-Pennsylvanian channels are largely restricted to the margins of the mapped area, except in Indiana where the Evansville channel (Wanless, 1955, p. 1763) is well developed.

Sandstone in the Hardinsburg Formation

The sandstone in the Hardinsburg has a pattern of moderate complexity. Its principal feature is a large distributary system, which can be traced from the subcrop in Knox County, Indiana, southward to the southern outcrop (pl. 1G).

In Knox County, Indiana, the belt sand body bifurcates, one arm turning westward into Illinois and the other continuing southward across Gibson, Vanderburgh, and Posey Counties, Indiana, into Henderson County, Kentucky. In Posey County there are several distributaries trending westward into Illinois. In much of western Kentucky the sandstone has a more complex pattern with numerous bifurcations and distributaries. Along the eastern margin of this complex, sandstone thickness decreases relatively abruptly in a series of small distributaries of bird-foot outline, commonly oriented northeast and southeast.

The major bifurcation that enters Illinois from Knox County, Indiana, extends southwestward across Wabash, Edwards, White, and Franklin Counties in a relatively complex pattern. Width of thick sandstone increases in a southwesterly direction, especially as successive bifurcations develop. From Jackson County on the west to Gallatin County on the east there are six bifurcations. Although not so well defined, the northwestern side of this distributary system has some small distributaries. To the west, northwest, and north of the distributary system, sandstone thickness decreases progressively until there are broad areas with no permeable sandstone.

Summary

The regional maps show many similar features. A summary of the significant data furnished by the maps, combined with that of previously published regional studies (Hopkins, 1958; Potter et al., 1958; Andresen, 1961; Potter, 1962a, b) and supplemented by information on sandstone distribution obtained from outcrops reveals that

1) Elongate sand bodies commonly are oriented to the southeast, south, and southwest.
2) Pod, ribbon, dendroid, and belt sand bodies are all present in most areas.
3) Both tributaries and distributaries occur.
4) The various patterns of sand distribution are part of an integrated dispersal system.

Complexity of Sand Deposition

In evaluating the regional maps of sandstone thickness, the actual complexity of events that they represent should be kept in mind. To interpret regional sand body patterns as the result of a single episode of sand dispersal could be an oversimplification.

For instance, the complexity of patterns displayed by the Sebree and Coxville Sandstones in Kentucky and Indiana (pl. 1C) suggests that their distribution patterns did not develop simultaneously. The relatively complex regional pattern of the Waltersburg (pl. 1F) also may represent markedly different ages of sand dispersal in the basin. What is commonly thought of as one continuous sequence of sand deposition may, in fact, represent several periods of deposition.

Another feature that complicates the interpretation of the regional maps is the uncertainty that commonly exists concerning direction in which elongate sand bodies developed in the basin (Botvinkina, 1958). Is sand deposition oldest at the southern edge of the basin and youngest at the northern edge or vice versa? Only when sand deposition had a definitely deltaic pattern — like that, for example, found in the Palestine Formation — can a prograding sequence be assumed with some confidence.

A third complicating feature, especially in Chesterian sandstones, stems from the marine transgressions that usually directly followed sand deposition. Superposition of marine on nonmarine enviroments may produce sand bodies of mixed enviromental origins that may be included as one sand thickness on a map and hence complicate interpretation.

Source of Sandstone in Tributaries

The source of sandstone in tributaries is difficult to determine. Hopkins (1958, p. 41), Friedman (1960, p. 33-40) and Andresen (1961, p. 26) all commented on this problem. In part, the sandstone fill of the tributaries may have been derived from the erosion of underlying sediments. Friedman (1960, p. 40-45) thought it possible that small middle Pennsylvanian sand bodies along the eastern edge of the basin were derived from erosion of older Pennsylvanian sandstones east of the present outcrop. This explanation is not generally applicable. Hopkins (1958, p. 11-42) thought the minor channels may have derived their sand from erosion of the underlying sheet sand deposited earlier in the same cycle. Another possibility is that sand may have been introduced from what is now the main elongate sand body, at least near the junction. The good permeability of the fill suggests that this is unlikely, however, because slackwater fill should be principally silt and mud.

Another theory is that some of the tributaries are in fact distributaries. Although this explanation would solve many problems, it cannot be applied to those tributaries with dendritic pattern that join the main sand body with a well defined, acute "downstream" angle. The smaller and commonly irregular, appendage-like sand bodies that sometimes occur near elongate sand bodies (see T. 6 S., R. 12 W., of figure 33 and Ts. 5 and 6 S., R. 13 W., of figure 35) may in fact correspond to crevasse fillings similar to those found along the lower courses of some large rivers.

Elongate Sand Bodies and Local Tectonic Structures

Although major structures such as the LaSalle Anticlinal Belt undoubtedly influenced position and orientation of some elongate sand bodies, the effect of relatively local structures on location of such sand bodies is less clear. Separation of local tectonic structures from those of compactional origin can be difficult. Moreover, once the tectonic character of a structure has been established, it is necessary to determine whether it existed when the sand body was deposited. Friedman (1960, p. 45-47) noted some of the complicating factors. Andresen (1961, p. 26-27) suggested that the principal belt and dendroid sand bodies of the Trivoli Sandstone avoided structures in the basin such as the Clay City Anticlinal Belt. In general, however, relations of ribbon, dendroid, and belt sand bodies to local structures are not clearly established, suggesting that other local factors, perhaps operating more or less randomly on a weakly inclined regional slope, were of comparable importance.

Variable Thickness of Sandstone Along Sand Bodies

Regional maps reveal pronounced local variations in thickness along many well defined elongate sand bodies, especially those with dendroid and belt distribution patterns. The reasons for this lengthwise variation in thickness are not completely understood.

Local development of multistory sandstones is one possible cause of thick sand bodies. In many places, however, such development definitely can be excluded — for instance, where the sandstone lies between marker beds.

Another possibility is that an erosional channel was originally filled partly with sand and partly with silt and mud. If the silt and mud were irregularly deposited at the bottom of the erosional channel, they could not be distinguished from underlying shales and siltstones by electric logs. The logs would indicate an irregular thickness of sandstone.

Another explanation that may apply, especially to some ribbon sand bodies, is that unequal thickness of sandstone simply reflects variable local duration of sand deposition. A facies change to the associated shale is implied rather than the incomplete sand fill of an erosional channel.

Still another possibility, although not a very likely one, is that the elongate sand body might have developed over either an active synclinal structure, in which case the sandstone would be thick, or an anticlinal structure, in which case the sandstone would be thin.

Choice of one of these alternatives requires detailed study, and interpretation is commonly very difficult.

Gradients for Sand Dispersal

Although the direction of sediment transport in sandstone can be established with confidence, it is still difficult to reconstruct the gradients of sand transport. The fact that major sandstones are either transgressive or regressive further complicates estimates of regional gradient.

Friedman (1960, p. 16) has inferred local gradients in Indiana as high as 14 feet per mile for Pennsylvanian sandstones. Andresen (1961, p. 15) suggested approximately 1 foot per mile for the Trivoli Sandstone. Hinds and Greene (1915, p. 91) suggested a gradient of 1.4 to 2 feet per mile for the Warrensburg Sandstone in Missouri. Although gradients undoubtedly varied in the Illinois Basin, gradients less than 1 foot per mile, and probably less than 0.5 foot per mile, may have been typical. A gradient of less than 0.5 foot per mile would compare favorably with that of the Mississippi River from Cairo, Illinois, to the Gulf of Mexico, which, over a distance of 1000 miles, has an average gradient of 0.3 foot per mile.

ORIGIN OF LATE PALEOZOIC SANDSTONES OF THE ILLINOIS BASIN

Dispersal System

The basin-wide patterns of sandstone distribution in the Illinois Basin provides the essential clue to their origin.

The idea that the great bulk of late Paleozoic clastics of the Illinois Basin was transported to and across the basin by an integrated dispersal system was first proposed by Stuart Weller (1927, p. 26), who suggested that an ancient river system, entering the basin from the north, was the principal supplier of late Mississippian clastics. This river system, which has been named the Michigan River by Swann (1963, p. 12), was comparable to, if not a descendant of, the earlier Ontario River (Pepper, deWitt, and Demarest, 1954, p. 95-107), which is believed to have transported clastics from southern Labrador and Quebec to the Berea delta in Ohio. Such river systems carried the detritus from far-removed source regions to the mildly subsiding basins of the craton.

Gilligan (1919, fig. 2) suggested a somewhat similar river system for the dispersal of the clastics of the Millstone Grit in the coal measures of Great Britain. Moore (1959) emphasized the role of deltas in the Lower Carboniferous deposits of Great Britain, as Zhemchuzhnikov et al. (1960, pl. 7, figs. 39, 47, 54; pl. 8, figs. 56, 58) did for the Middle Carboniferous deposits of the Donets Basin.

Individually, the sandstones of the basin show one or two of four basic regional patterns: (1) dendritic tributaries, (2) anastomosing braided belts with some tributaries and distributaries, (3) deltas, and (4) offshore marine ribbons and pods. Figure 52 shows the relationships among these patterns.

Some sandstones, such as the Trivoli (Andresen, 1961, fig. 7) and the Degonia (pl. 1D), display chiefly dendritic tributary patterns. Others, such as the Palzo Sandstone and its equivalents and the Anvil Rock Sandstone, show dendritic tributary patterns combined with relatively complex patterns of braids, tributaries, and distributaries. Sandstones such as the Palestine have simple deltaic patterns. The Hardinsburg has a more complex deltaic pattern that is in part combined with a complex system of braids, tributaries, and distributaries. The sandstone in the interval between No. 6 and No. 5 Coals also appears to represent a combination of deltaic and braided belt patterns. A deltaic

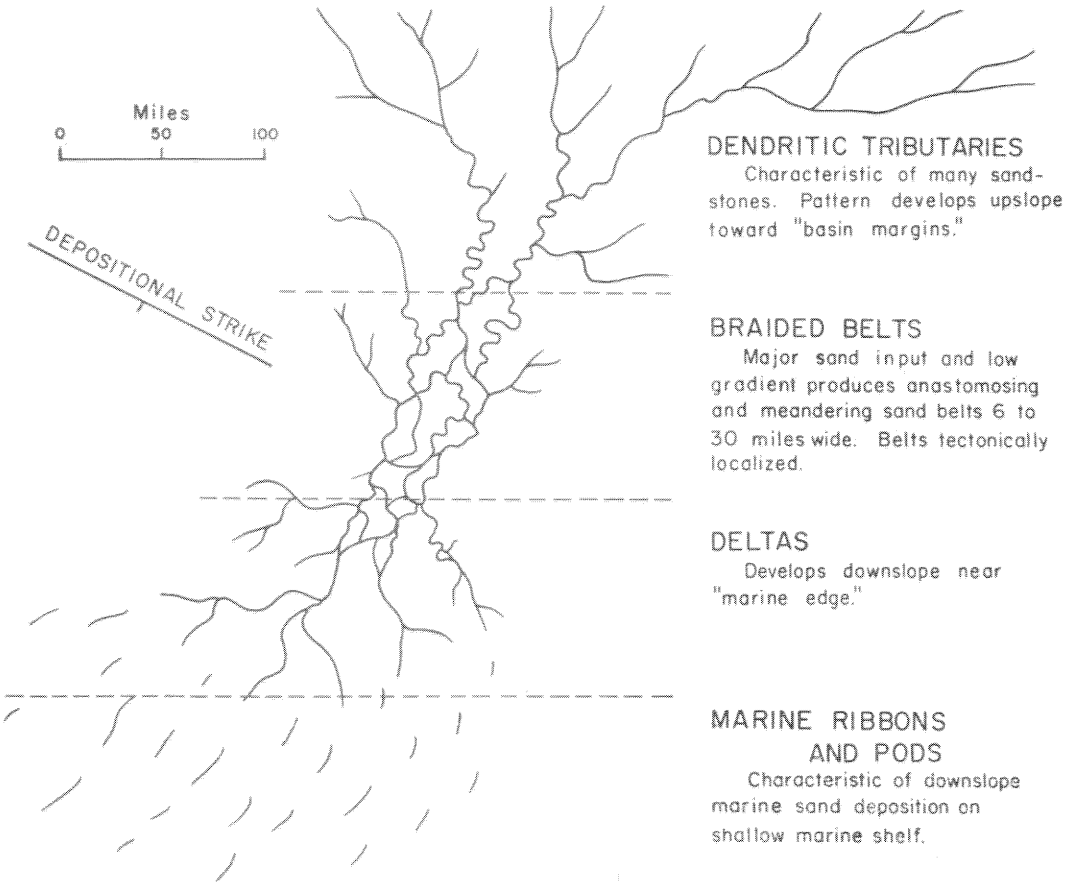


Fig. 52—Dispersal system for Pennsylvanian and late Mississippian sandstones of the Illinois Basin.

origin may also apply to the Pleasantview Sandstone of western Illinois and would explain the apparent anomaly of internal directional properties that indicate a northwestward "up-gradient" direction of sediment transport (Rusnak, 1957, table 3). Throughout much of its southern extent, the sandstone in the Waltersburg Formation contains many pod and ribbon sand bodies. These appear to represent pro-delta marine deposits. Much of the sand deposition in the Big Clifty in Indiana and Kentucky and the Spar Mountain and Aux Vases in southeastern Illinois (Whiting, 1959) may be similar to the Waltersburg.

Within the southern two-thirds of the basin, where subsurface data are sufficient for adequate regional maps, most maps of sand thickness display one main map pattern and one or two subordinate patterns. The sand dispersal system (fig. 52) was extensive, perhaps as much as 400 to 800 miles long, and most maps of sandstone thickness show only part of it. Simplified maps of sandstone thickness in the Palestine and Hardinsburg Formations (figs. 53, 54) show the relation of the dispersal system to the paleoslope.

In figure 53, the outline of the Palestine delta system is shown, together with an isopach of the underlying Menard Limestone and a current rose of all the Palestine cross-bedding. The strike of the isopach lines of the Menard is considered as depositional strike. The delta outline and the cross-bedding are essentially perpendicular to depositional strike.

In figure 54, the delta of the Hardinsburg Sandstone is shown, together with a current rose of all the Hardinsburg cross-bedding and the total thickness of all limestone in the overlying Glen Dean and the underlying Haney and Fraileys Formations. As in figure 53, southwest orientation of the delta and depositional strike defined by total limestone thickness are essentially perpendicular. One difference is the thinness of limestone in the vicinity of the principal eastern distributary that extends southward across Indiana into Kentucky. The thinness of both the underlying and overlying limestones may reflect the inhibition of carbonate deposition during periods of marine transgression by mud deposited "offshore" or down dip of the ancestral river that deposited the sands of the Hardinsburg delta.

Delta orientation, therefore, agrees with other evidence and indicates the paleoslope of the dispersal system of late Mississippian sandstones. Late Mississippian cross-bedding substantiates the orientation of these delta patterns. Gilligan (1919, p. 283-284) early suggested similar agreement in the Millstone

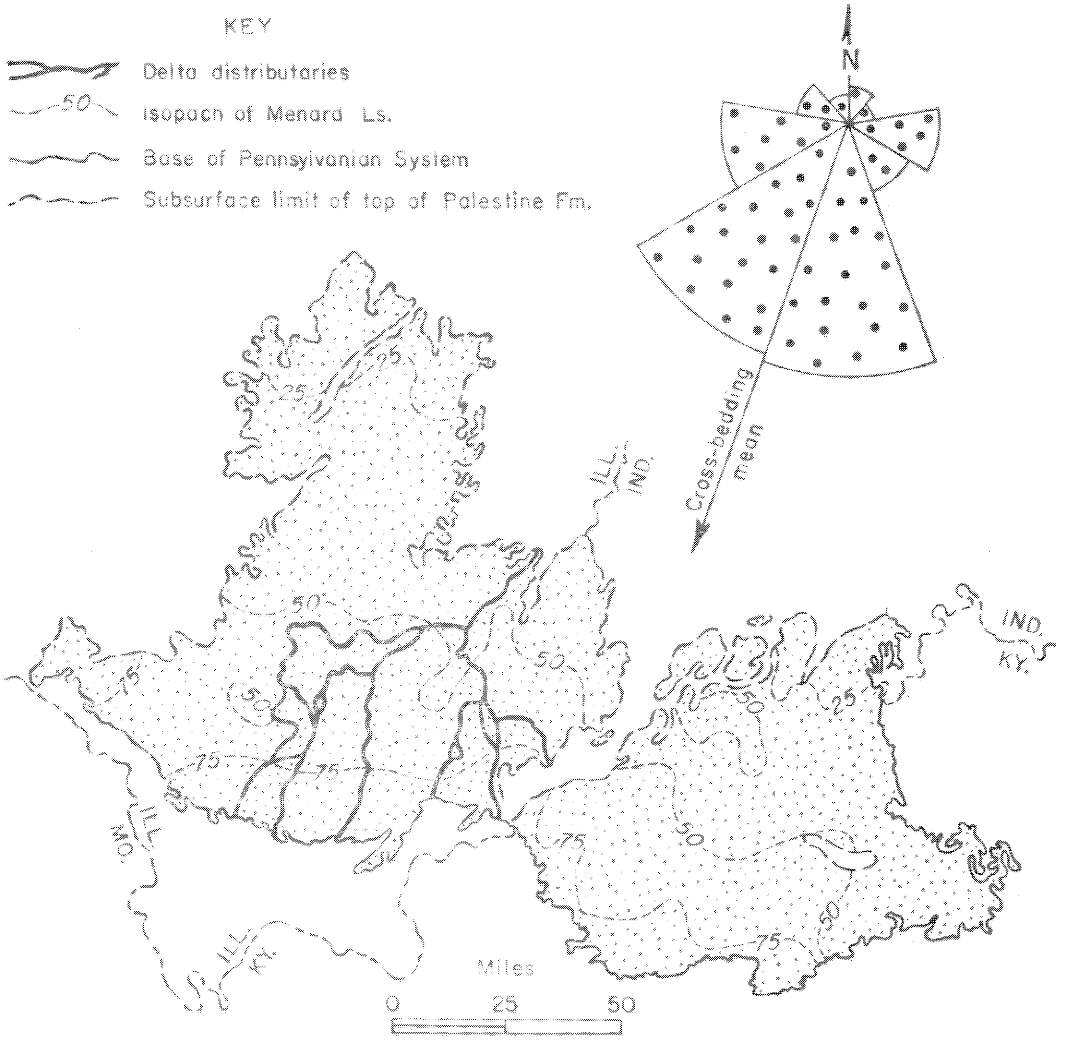


Fig. 53—Delta pattern in Palestine Formation, with isopach of underlying Menard Limestone. Limestone isopachs give depositional strike. Current rose shows distribution and mean of 79 cross-bedding measurements.

Grit. The southwest orientation of the subaerial erosional channels of the Mississippian-Pennsylvanian unconformity (Wanless, 1955, fig. 2) indicates that this slope continued to prevail during a major erosional interval. During Pennsylvanian time, most of the dendritic patterns and complexes of braids, tributaries, and distributaries also were ori-

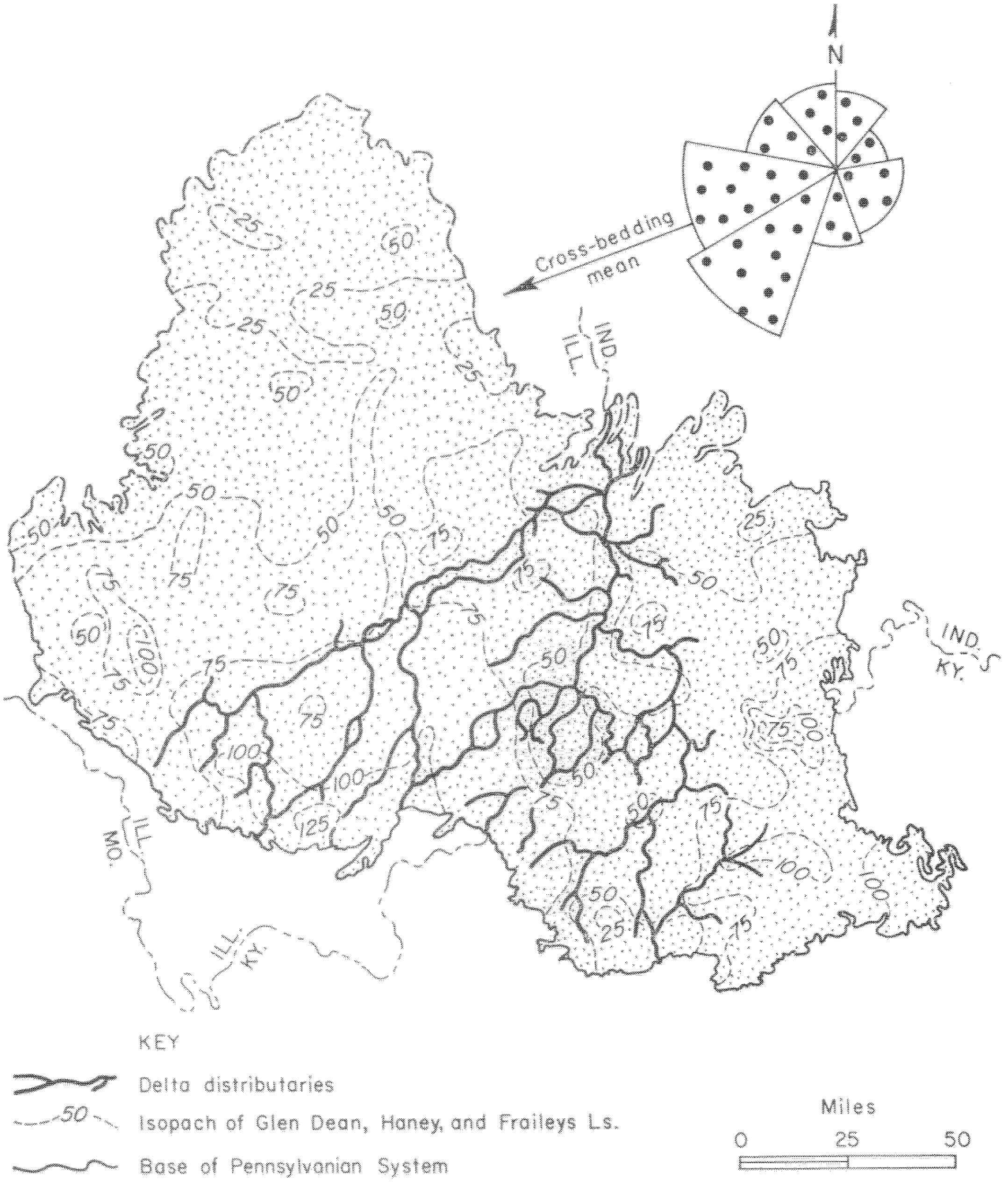


Fig. 54—Delta pattern in Hardinsburg Formation, with isopach of limestone of the overlying Glen Dean and underlying Haney and Fraileys Formations. Limestone isopachs give depositional strike. Current rose shows distribution and mean of 118 cross-bedding measurements.

ented to the southwest. A dispersal system operating essentially perpendicular to depositional strike therefore supplied most of the material for the late Paleozoic sandstones. Depending upon sand input and magnitude of transgression or regression, either delta distributaries developed on a shallow marine shelf or dendritic patterns and complexes of braids, tributaries, and distributaries developed on a low-lying coastal plain. Because of its greater quantity of clastics, dendritic and complex braided patterns are more common in the Pennsylvanian System than in the late Mississippian, in which deltaic, ribbon, and pod patterns predominate.

Late Paleozoic Deltas of Illinois Basin and Mississippi Delta

Several comparisons between coal measures in ancient basins and modern deltas have been made. Moore (1958, p. 127-131; 1959, table 3) compared broadly similar rock types of British Lower Carboniferous cyclothems to Mississippi delta deposits. Gray, Jenkins, and Weidman (1960, p. 58) compared the clastic rock types in late Paleozoic sediments of Indiana to those of the Gulf Coast. Beerbower (1961, table 2) compared lithologies of the Dunkard Group, which closely correspond to those of late Paleozoic clastics, to modern Mississippi delta and alluvial sediments. Although other deltas have rather different characteristics (Scruton, 1960; Van Straaten, 1960), the comparison of the late Paleozoic deltas of the Illinois Basin to the Mississippi delta is instructive (table 6).

Most of the arenaceous and argillaceous clastics of the modern Mississippi delta and the late Paleozoic clastics of the Illinois Basin are essentially identical. Depth of shelf varies and is responsible for most of the contrast between them.

The Mississippi delta has both "shoal-water" distributary channels and deep-water bar fingers at the mouths of the delta distributaries (Fisk, 1955, p. 381-390), but only shoal-water distributary channels appear to be present in late Paleozoic strata. The erosional contact at the base of most thick elongate sand bodies in the Illinois Basin also suggests that sandstones of bar-finger origin with gradational and transitional basal contacts (Fisk, 1955, p. 384) are largely absent.

Proximity to the edge of the continental shelf inhibits forward growth of the Mississippi delta, but during late Paleozoic time a similar shelf may have been 400 to 500 miles wide. A probable wide expanse of shallow water in a broad embayment appears to have inhibited strong longshore currents. A wide, gently sloping and subsiding platform favored far-ranging transgressions and regressions during late Paleozoic time, whereas a similar change in base level would have less effect on most modern strand lines.

Because of the large volume of mud and sand, carbonate development is restricted in the modern Mississippi delta, but carbonate deposition did occur in Pennsylvanian time and was extensive in Chesterian time.

Important as they are for the insight they provide into late Paleozoic sedimentation in the basin, sandstones of deltaic origin are probably less abundant than those with complex braids and tributary patterns.

Absence of Depositional-Strike Sand Bodies

The major missing ingredient in a comparison with the Gulf Coast region is the absence in the Illinois Basin of elongate sand bodies that lie essentially parallel to depositional strike, such as the barriers along the Gulf Coast described by Shepard (1960, p. 111-220) or the cheniers of the Mississippi delta (Byrne, LeRoy, and Riley, 1959, pl. 1). Moreover, sandstones with bedding similar to that described in modern beaches (McKee, 1957, p. 1706-1718) have not been observed in late Paleozoic outcrops. The general absence of elongate sand bodies with orientation perpendicular to regional slope suggests that either there were no major longshore currents perpendicular to depositional strike or that depositional strike barriers, if they did originally exist, were not preserved. Although the northwest-oriented sand body in the Waltersburg (pl. 1F) that extends from Richland

TABLE 6—SEDIMENTS OF THE MODERN MISSISSIPPI DELTA AND THE LATE PALEOZOIC ILLINOIS BASIN

	Property	Modern Mississippi alluvial and deltaic sediments	Late Paleozoic sediments of the Illinois Basin
Similarities	Clastic sediments	"Shoal water" delta channels, sheet sands, silts, silty muds, and silts and muds with plant roots	"Shoal water" delta channels, sheet sandstones, siltstones, silty shales, and underclays with plant roots
	Non-clastic sediments	Peat	Coals
	Orientation with respect to regional slope	Essentially parallel to regional slope	Essentially parallel to regional slope
	Localization of delta	Extension of Mississippi Embayment	Weak-negative tectonic axis between regional positive elements produces embayment-like characteristics.
Differences	Clastic sediments	Relatively deep-water bar-finger sands and beach ridges or cheniers	Bar-finger sands and beach deposits parallel to depositional strike not observed. Pod and ribbon sand bodies oriented down dip.
	Non-clastic sediments	Few carbonates; development inhibited by rapid clastic deposition.	Carbonates developed when clastic input was low. Minor in Pennsylvanian but prominent in Chesterian.
	Depth of shelf	Relatively deep water favors bar-finger sand development and stronger longshore currents that produce beach deposits. Base level change would cause relatively restricted migration of shore line. Continental shelf ends relatively abruptly, retarding forward growth.	Shallow water inhibits development of bar-finger sands and longshore currents that produce depositional strike barriers. Base level change produces far-ranging migration of shore line. Continental shelf extends for several hundred or more miles and forward growth is unhampered.

to Effingham County, Illinois, may in part have been a barrier, the vast majority of ribbon and pod sand bodies tend to orient to the southwest, parallel to regional slope. Such sand bodies do not lie parallel to depositional strike and thus differ from the barriers of the Gulf Coast. Although the evidence is not definitive, because of lack of diamond drill core samples, there appears to be little lithologic contrast on opposite sides of these elongate sand bodies. Lack of lithologic contrast minimizes the possibility of their origin as depositional strike barriers that would have separated marine from nonmarine sediments.

Origin of Marine Pod and Ribbon Sand Bodies

Several possibilities seem likely for the origin of the southwest-oriented marine pod and ribbon sand bodies. One is that they are marine sands formed on shallow shelves by tidal currents generally operating perpendicular to depositional strike. An absence of strong longshore currents would favor such an origin. Such tidal currents may have operated relatively far from shore or have been closely associated with delta distributaries. Oomkens and Terwindt (1960) described such inshore estuarine sand bodies in one of the Rhine-Maas estuaries in the Netherlands. The sands of that estuary are believed to be of marine origin and to have formed in response to tidal currents. Cross-bedding is present and parallels both the direction of elongation of the sand body and the orientation of the estuary. Off (1963) presented numerous examples of "tidal current ridges" that occur on modern marine shelves with strong tidal currents and a plentiful supply of sand. These ridges are from 25 to 100 feet high and from 5 to 40 miles long. Such ridges parallel tidal currents that are perpendicular to depositional strike. Tidal currents on carbonate shelves also may have been responsible for deposition of some of the sandstone of the Ste. Genevieve Formation.

Another possibility is that some of the isolated pods and ribbons in late Mississippian time may have been formed by jet currents off the mouths of delta distributaries (Bates, 1953). Jet currents in a broad, shallow, marine embayment would probably have been more effective than similar currents along many modern coast lines because longshore currents probably were weaker.

The possibility that some of these marine pods and ribbons may have had a turbidite origin, as suggested by Passega (1954) for some elongate sand bodies of marine shelves, seems unlikely, especially in view of the sedimentary structures of the sandstones, which are not those of typical turbidites.

In the Pennsylvanian and in some late Mississippian sandstones of the basin, some pod sand bodies may have originated as channel-fill deposits.

Paleoslope and Differential Subsidence Within the Basin

Comparison of the cross-bedding data of table 5 and the regional maps shows the broad similarity of transport direction in the various parts of the basin. This similarity is a reflection of the stability of the paleoslope in late Paleozoic time. Moreover, the location of areas of differential subsidence remained relatively constant. Thus the thickness, lithologic proportion, and paleoslope of different units usually are more alike in vertical section than the thickness, lithologic proportion, and paleoslope of a single unit compared laterally across the basin. As sedimentation progressed, maintenance of slope orientation and areas of maximum subsidence were responsible for many multistory sand bodies and for the areas of similarly oriented belt sand body development.

Some contrasts between distribution of clastics in late Mississippian and Pennsylvanian time are present, however.

The proportions of shale and limestone in the late Mississippian strata differ on the southeastern and northwestern sides of the principal axis of sandstone deposition located along the Wabash Valley. Although nearly all carbonate units thicken to the south in the basin, the southeastern part of the basin has the highest proportion of carbonates (Swann and Bell, 1958). Some clastic units, such as the Aux Vases, Bethel, and Cypress, are almost completely replaced by carbonates at the southeastern corner of the basin (McFarlan et al., 1955). In contrast, many formations like the Waltersburg and Hardinsburg consist principally of shale northwest of the major sandstone trend. This indicates that muds were more readily deposited to the northwest than to the southeast in Chesterian time. A somewhat similar contrast can be observed along the Gulf Coast. Carbonates and quartz sands are more abundant east of the modern Mississippi delta and muds more abundant to the west (Gould and Stewart, 1955; Van Andel, 1960). The absence of depositional-strike sand bodies and the presence of pod and ribbon sand bodies oriented to the southwest suggest caution, however, in interpreting this contrast as a result of longshore currents' carrying mud more readily to the northwest than to the southeast.

In Pennsylvanian time, sand supply was asymmetrical, with more sand entering the basin from the east and northeast than from the northwest. Sandstones are better developed in the more rapidly subsiding part of the basin than on the more stable western and northern shelf areas.

No evidence exists that major amounts of clastics entered the Illinois Basin from the south in late Paleozoic time.

Causes of Cyclic Deposition

The cyclical arrangement of late Paleozoic strata has been commented on by many authors. Much of the literature is concerned with explanations for the periodic introduction of clastics, especially the sands, into a basin. A number of theories explaining the periodic increased competence required for sand dispersal into a basin have been proposed. Weller (1930, 1956) suggested regional diastrophic or tectonic controls that periodically steepened gradients between basins and source areas. Savage (1930, p. 133) suggested that cyclic deposition resulted from intermittent subsidence in the basin. Wanless and Shepard (1936) related cyclothems to late Paleozoic glaciation. They believed that relatively continuous subsidence in the basin, coupled with glacially induced fluctuations of sea level, may have produced cyclic deposits. Moore (1959, p. 538) related cyclic sedimentation in the Lower Carboniferous Yoredale Series of Great Britain to delta formation in a shallow epicontinental sea. Crevassing caused delta migration and initiated a new sedimentary cycle. Beerbower (1961, p. 1046-1048) favored a climatic, but not necessarily glacially induced, control. Change in climate would vary the competence of the dispersal system introducing variable amounts of clastics to a continuously subsiding basin. Choosing one of these hypotheses for a specific basin is difficult. The widespread occurrence of cyclic deposition in late Paleozoic sediments in widely separated areas points to a worldwide control. Climatic controls seem plausible.

Provenance

The long distance separating the Illinois Basin from major sediment sources such as highlands east of the Appalachian Basin or the Canadian Shield complicates identification of the source of late Paleozoic sandstones. The following discussion summarizes the problem.

Polycrystalline quartz and multicycle tourmaline grains are found in all the late Mississippian and Pennsylvanian sandstones (Potter and Pryor, 1961). These grains were derived from an area of complex tectonic history. Their scarcity in pre-Mississippian sandstones indicates that they were not generally available in the source areas that supplied the pre-Mississippian clastics of the basin.

Pre-existing sandstones with a relatively complex history supplied most of the detritus of Mississippian sandstones. This detritus entered the basin principally from the northeast. The over-all petrographic uniformity of this detritus suggests a common source, but transport undoubtedly enhanced petrographic homogeneity. Available evidence suggests that the northern part of the Appalachian Basin, or highlands to the east of it, and the Canadian Shield were the chief source.

In Pennsylvanian time, highlands to the east of both the middle and northern parts of the Appalachian Basin and portions of the southern Canadian Shield made important contributions. These areas, but probably more especially the highlands to the southeast of the Appalachian Basin, supplied quartz granules, pebbles, and occasional cobbles to the Illinois Basin at the time of deposition of the Caseyville and Mansfield Formations. Clastics were transported to the Illinois Basin by a series of large river systems. Some detritus also may have entered the basin from the northwest and west.

Pre-existing sediments, somewhat less mature than those from which the Chesterian sands were derived, were the chief source of sandstones of the Caseyville Formation. Initially, Chesterian sandstones may have contributed directly to basal Pennsylvanian sandstones. Subsequently, more immature sediments in distal areas and quartzofeldspathic terrains contributed detritus. This was probably the result of both continued erosion in the source regions and subsequent sedimentation and Pennsylvanian overlap of older sediments.

DEPOSITIONAL MODEL FOR THE ILLINOIS BASIN IN LATE PALEOZOIC TIME

Recurring patterns of sedimentation in the geologic past suggests that, instead of a vast complexity of previous sedimentary events that do not permit generalization, there are only a relatively few major types of patterns of sedimentation. The identification and understanding of these types is facilitated by description in terms of a few essential elements of general applicability. Although the idea that there are relatively few major patterns of sedimentation is an old one, a description of these types, in terms of objectively identifiable essential features, is still not generally available (Pettijohn, 1957, p. 611-644). Some aspects of this problem were discussed by Potter (1959). Pryor (1960, table VIII) described the Cretaceous sediments of the Upper Mississippi Embayment in terms of eight elements.

The late Paleozoic sediments of the Illinois Basin can be described in terms of five elements: *geometry,* or basin shape; *lithic fill,* or the principal lithologies that constitute the sedimentary volume; *arrangement,* or the spatial distribution of major lithologies with respect to basin geometry; *current system;* and *tectonic setting,* which relates the basin to distribution and activity of major tectonic elements. The first four of these are entirely descriptive in character, necessitating a minimum of interpretation. The fifth, tectonic setting, is highly interpretative but its inclusion is desirable because it relates the descriptive elements of the model to an important genetic one.

TABLE 7—DEPOSITIONAL MODEL FOR LATE PALEOZOIC SEDIMENTS OF THE ILLINOIS BASIN

Property	Late Mississippian	Pennsylvanian
Basin geometry	Broad, shallow, trough-like depression opening down paleoslope to the southwest. Symmetrical transverse cross section. Total section expands down paleoslope.	Broad, shallow, trough-like depression opening down paleoslope to the southwest. Asymmetrical to symmetrical transverse cross section. Total section expands down paleoslope.
Lithic fill	Marine and some nonmarine shales, approximately 50%. Orthoquartzitic and protoquartzitic, elongate, cross-bedded sandstones, both marine and nonmarine, 25%. Relatively pure calcarenites and calcilutites, approximately 25%. Coals occur but are volumetrically negligible.	Marine and nonmarine shales, approximately 65%. Orthoquartzitic to subgraywacke, elongate, cross-bedded sandstones, dominately nonmarine, 30%. Argillaceous, fine-grained nonreef carbonates, approximately 4%. Coal, approximately 1%.
Arrangement	Sand bodies chiefly parallel to paleoslope and concentrated along basin axis. Carbonates thicken down paleoslope. Relatively rapid and periodic vertical lithologic change. Wide lateral persistence of lithologies, except sandstone.	Sand bodies chiefly parallel to paleoslope. Carbonates and coals have weak, if any, relationship to regional slope. Rapid vertical and periodic lithologic change. Wide lateral persistence of lithologies, except sandstone.
Current system	Mainly cross-bedding and ripple-marks which regionally reflect paleoslope. Chiefly longitudinal clastic filling.	Chiefly cross-bedding and ripple marks, which regionally reflect paleoslope. Longitudinal plus asymmetrical lateral clastic filling.
Tectonic setting	Embayment at time of deposition; at present an intracratonic basin. Principal source was distal orogenic belt undergoing mild uplift and rejuvenation.	Embayment at time of deposition; at present an intracratonic basin. Principal source was distal orogenic belt undergoing mild to moderate uplift and erosion.

Absolute size is not included above. If it were, few, if any, basins would be alike and no generalization would be possible. On the other hand, if two basins were identical in all but size, genetic controls would obviously be the same and, consequently, detailed knowledge of the one basin could be effectively used in the exploration of the other.

Table 7 summarizes the late Paleozoic sediments in terms of basin geometry, lithic fill, arrangement, current system, and tectonic setting. The late Mississippian and Pennsylvanian sediments of the basin are very much alike in all but lithic fill, making a single depositional model applicable, even though some differences do exist. For example, limestones are much more abundant in late Mississippian than in Pennsylvanian sediments. Pennsylvanian sandstones are less mature than those of the late Mississippian. Transverse cross section is symmetrical in the late Mississippian, but less so in the Pennsylvanian. Longitudinal clastic filling prevalent during late Mississippian time was supplemented at the time of Pennsylvanian deposition by important lateral filling from the east.

These differences, however, do not obscure the similarity between the over-all sedimentation patterns of the late Mississippian and Pennsylvanian sediments of the basin. Comparable arrangement of lithic fill and orientation of current systems are the essential features of this similarity. In both late Mississippian and Pennsylvanian time, sandstones extended down a stable paleoslope at right angles to depositional strike. Major sand deposition was localized by weakly negative areas within the basin, much as the present Mississippi River follows the structural axis of the Mississippi Embayment. Vertically, sedimentation was cyclic and directions of regression and transgression were controlled by paleoslope.

Beyond summarizing the significant elements of late Paleozoic sedimentation in the Illinois Basin, the depositional model has greatest potential value for improved exploration in similar basins that are as yet incompletely explored. Correct application of the late Paleozoic Illinois Basin model to a new sedimentary basin requires reasonable similarity of lithic fill, arrangement, basin geometry, and current system. Significant change in any one of these would alter the model and lessen the value of comparison and correct prediction.

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