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SUBSURFACE BELT SANDSTONES IN THE HARDINSBURG FORMATION (LATE MISSISSIPPIAN) OF INDIANA

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INTRODUCTION

The purpose of this report is to present the general stratigraphy of the Hardinsburg Formation, Stephensport Group (Figure 1), in the subsurface of Indiana and to consider factors that have combined to create a belt of massive sandstones in the Hardinsburg in southwestern Indiana. These Mississippian rocks lie near the Lower Carboniferous Visean-Namurian series boundary of international terminology. The study area (Figure 2) is south of the northern boundaries of Sullivan and Greene Counties and west of the eastern boundaries of Greene, Martin, and Dubois Counties.

The data for this report were taken from well information on file with the Indiana Geological Survey, Bloomington (Table 1). Initially, the records of approximately 12,000 wells were inspected. A single well per section was selected for construction of the thickness maps, and no more than three wells per section were chosen to construct the cross sections. Intensive drilling for petroleum throughout much of the study area provides at least one well per section for which both well samples and a geophysical log are available. In areas of less dense drilling, we necessarily used wells for which either samples or wire-line logs existed.

PREVIOUS WORK

Reviews of Late Mississippian surface and subsurface stratigraphy and depositional systems in the Illinois Basin area can be found in Swann (1963,1964), Potter (1962,1963), Willman, *et al.* (1975), Sable (1979), and Shaver, *et al.* (1986). For treatment of the underlying West Baden Group in Indiana, see Sullivan (1972) and for the overlying Buffalo Wallow Group, see Droste and Keller (in press). Typical reconstructions of paleogeography during Mississippian time, based on paleomagnetic data, place Indiana between 5 and 10 degrees south latitude (Sable, 1983; Gutschick and Sandberg, 1979).

In his comprehensive classification of Late Mississippian rocks of the Illinois Basin, Swann (1963) enlarged on an earlier statement by Stuart Weller (1922) that a river (named the Michigan River by Swann) was the fluvial transport system for terrigenous sand and mud to sites of deposition in the Illinois Basin. The headwaters of the Michigan River were far to the northeast in the eastern part of the present Canadian Shield, and the Michigan River terminated in a birdsfoot delta situated in Indiana and Illinois. Swann (1964) subsequently proposed that elongate sand bodies in the Late Mississippian rocks were products of deposition as distributary mouth bars or finger bars resulting from the south-

MISSISSIPPIAN SYSTEM	BUFFALO WALLOW GROUP	GROVE CHURCH SHALE
		KINKAID LIMESTONE
		DEGONIA FORMATION
		CLORE FORMATION
		PALESTINE FORMATION
		MENARD LIMESTONE
		WALTERSBURG FORMATION
		VIENNA LIMESTONE
		TAR SPRINGS FORMATION
	STEPHENSPORT GROUP	GLEN DEAN LIMESTONE
		HARDINSBURG FORMATION
		HANEY LIMESTONE
		BIG CLIFTY FORMATION
		BEECH CREEK LIMESTONE
	WEST BADEN GROUP	CYPRESS FORMATION
		REELSVILLE LIMESTONE
		SAMPLE FORMATION
		BEAVER BEND LIMESTONE
		BETHEL FORMATION

FIGURE 1. Chart of stratigraphic nomenclature of a part of the Mississippian System.

westward progradation of the Michigan River birdsfoot delta. During regressions, the shoreline moved as far south as northern Arkansas, and during transgressions, the shoreline lay as far northeast as southern Ontario. The interpretation of extensive shoreline migration (Treworgy, 1988) continues to be a favored interpretation, but this model is currently being challenged. Droste and Keller (1989, in press) argue that not just one (the Michigan River) but at least three river systems (Figure 3) were necessary to explain the distribution of sandstone bodies in the post-Hardinsburg Buffalo Wallow Group and of the river systems that flowed on the pre-Pennsylvanian surface. They further indicated that almost all the middle and late Chesterian rocks were deposited in tidally dominated marine rather than fluvial dominated environments.

Potter (1962,1963) described and classified sheet and elongate sand bodies in Mississippian and Pennsylvanian rocks in the Illinois Basin. In this report, we use his classification of elongate sand bodies. Pods are isolated sand bodies whose lengths are less than twice their width. Ribbons commonly exhibit lengths much greater than twice their width, and belt sand bodies are measured in widths of miles and lengths of 10's to 100's of miles. Potter (1962,1963) illustrated the distribution of belt sandstones in the Hardinsburg and concluded that, although

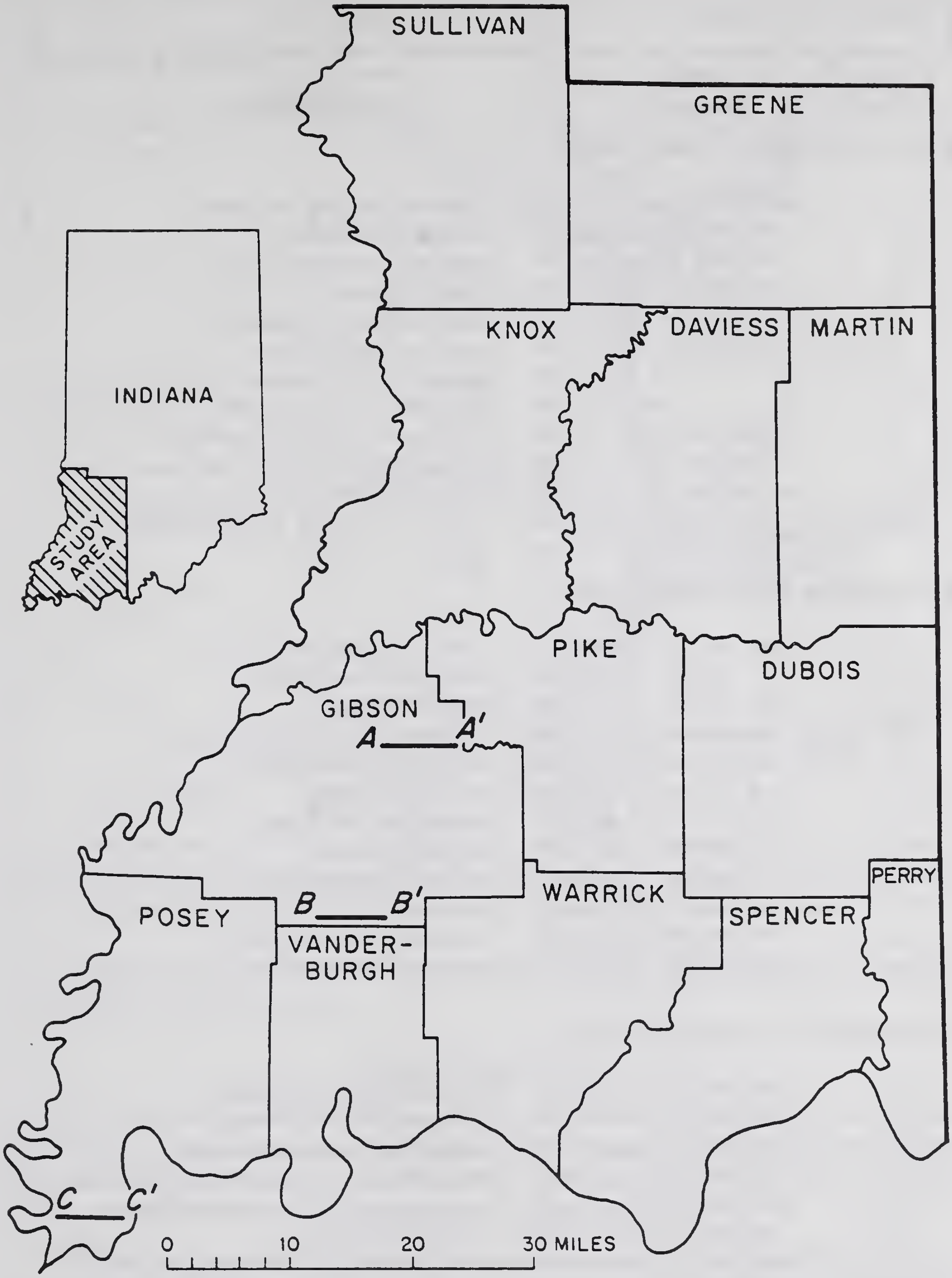

FIGURE 2. Map of study area and general location of the three cross sections (Figures 7-9).

the pattern of belt sand bodies was the principal feature of the system, the overall pattern resulted from a large distribution system in a delta.

Swann (1964) further suggested that cyclical surges of siliciclastic sediment resulted from climatically controlled rhythmic variation in rainfall. A shift to wetter climate with increased rainfall resulted in an increase of terrigenous load delivered to the basin. A shift to a drier climate resulted in a reduction of terrigenous sediment and permitted carbonate sedimentation to dominate across the

TABLE 1. Well locations.

Well No.	Well Location	Operator, Farm
Cross section AA′ (Gibson County)		
1.	NE NE SE 33-15-1S-10W	Cherokee Drilling #6 Kerzan
2.	NW NW SW 34-1S-10W	Collison #1 Kendle
3.	NE NE SE 34-1S-10W	Ecus Corp. #1 Dyer, *et al.*
4.	SW SW NE 35-1S-10W	Kidd #1 Shafer
5.	SE NW 36-1S-10W	George Trust #1 Clem, *et al.*
6.	NW NE SE 36-1S-10W	Ecus Corp. #2 Wilder
7.	SW 31-1S-9W	George Trust #1 Mahon
8.	SW 31-1S-9W	Paco Petroleum #1 Mahan
9.	SW SE SE 31-1S-9W	Mid-Central Prod. #1 Coleman
10.	SW NE SW 32-1S-9W	Jackson Wrather Oil #1 McConnell comm.
11.	SE NE SE 32-1S-9W	Kuzmich #4 McGill, *et al.,* comm.
12.	NW NW SW 33-1S-9W	Kuzmich #1 Smith & Clem. comm.
Cross section BB′ (Gibson County)		
13.	SE NW NW 10-4S-11W	Cherry #1 Epperson
14.	SE SE 10-4S-11W	H & H #1 Ziliak Farms
15.	SW NW SW 11-4S-11W	H & H #6 Spindler
16.	NE NE SW 11-4S-11W	So. Triangle #1 Spindler
17.	NE NE SE 12-4S-11W	Reliance #4 Goldsmith
18.	NW NE SW 12-4S-11W	Aurora #1 Lamey
19.	NE NE SE 12-4S-11W	Sandy Ridge #1 Knapp
20.	NE NW SW 7-4S-10W	Cleff #2A Knapp
21.	SE NE 7-4S-10W	Turner #1 Hirsch comm.
22.	SE NW SE 8-4S-10W	George #1 Keil
23.	NW NW SW 9-4S-10W	Universal Res. #1 Rhinhart
24.	SE SW SW 9-4S-10W	Desloge #1 Bittner Unit
Cross section CC′ (Posey County)		
25.	NE NW SW 17-8S-14W	Mid South Oil #1 Goldman
26.	SE SW NE 17-8S-14W	Gallagher #2 Gray Estate
27.	NW SW NW 16-8S-14W	Buttes #29 Oakland City Col.
28,	SE NW NE 16-8S-14W	Schoonmaker #1 Oakland City Col.
29.	NW NW NW 15-8S-14W	Schoonmaker #D-1 Oakland City Col.
30.	NE SE NW 15-8S-14W	Jarvis #1 Cronbach
31.	SW NW NW 14-8S-14W	Skiles #2 Vogel Althea Spencer, *et al.*
32.	SW NE NW 14-8S-14W	Rush Creek #4 Spencer
33.	SE NW NE 14-8S-14W	Rush Creek #1 Spencer Vogel
34.	NE NW SW 13-8S-14W	Rush Creek #1 East Klein St. of Ind.
35.	NW SW SW 18-8S-13W	Heath #3 Rosenbaum
36.	NW SE SW 18-8S-13W	Heath #3 Highman Hardwick
37.	NW SW SE 18-8S-13W	Fleming #1 Hardwick

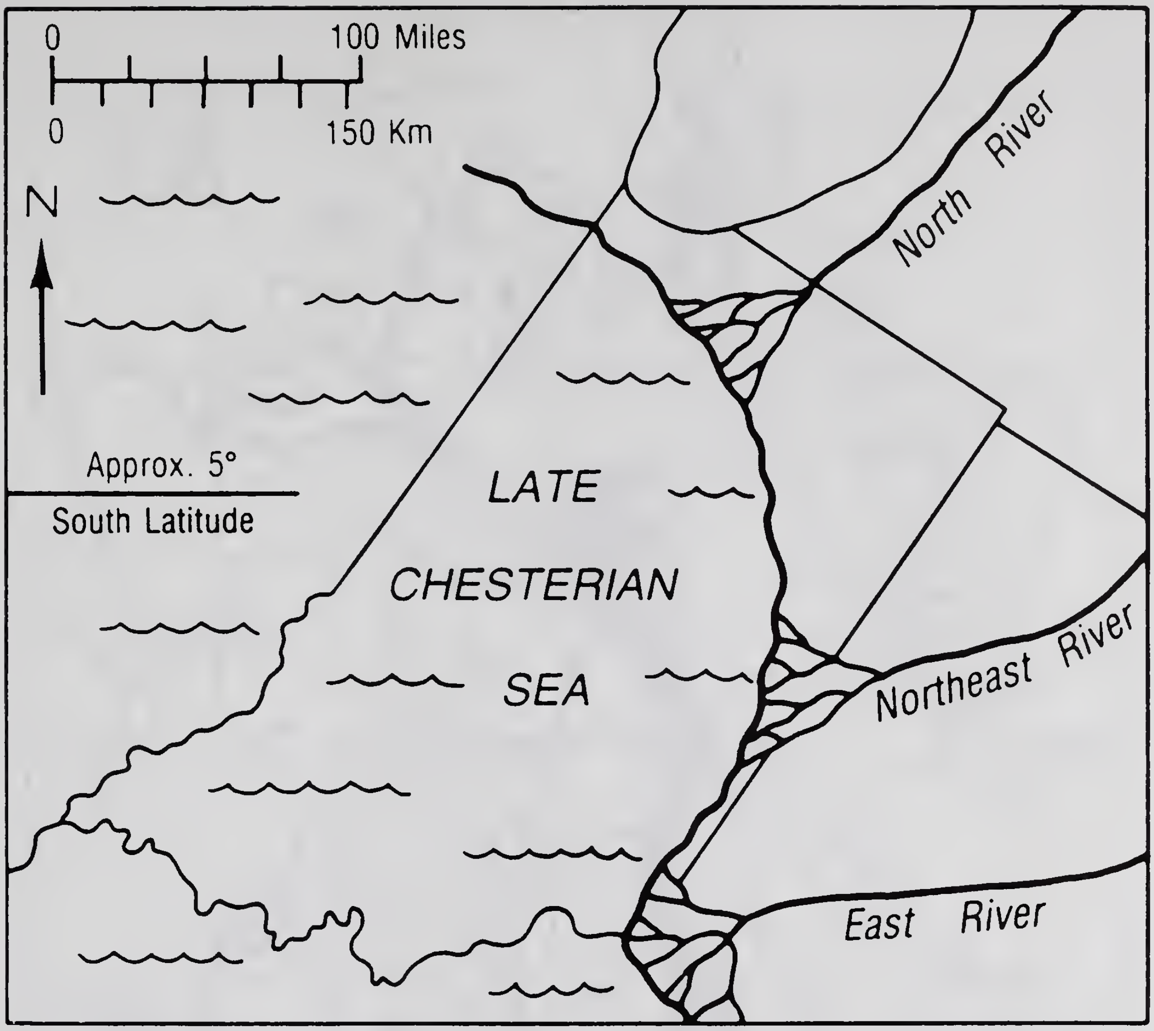

FIGURE 3. Map showing generalized paleogeographic reconstruction during a high level sea stand in Late Mississippian time (Droste and Keller, in press).

basin. With slight modifications, this general interpretation of sequential changes in lithology is followed herein.

STRATIGRAPHY

The Stephensport Group (Figure 1) is composed of, in ascending order, the Beech Creek Limestone, the Big Clifty Formation, the Haney Limestone, the Hardinsburg Formation, and the Glen Dean Limestone. See Shaver, *et al.* (1986) for the history and current usage of these terms in Indiana.

Haney Limestone. The Haney Limestone in Indiana increases in thickness from less than 20 feet near its northern outcrop and subcrop limit to almost 70 feet in southern Posey County (Figure 4). In the north, the Haney consists of a single interval of limestone containing thin interbedded layers of shale. Where the Haney is 40 or more feet thick, 2 to 5 massive beds of packstone, wackestone, and grainstone are interlayered with thin gray and green fossiliferous shale beds.

In an area from Knox County southwestward to Posey County, the Haney is thin and in a few places is absent. In this zone of thin Haney, the overlying Hardinsburg Formation is thickest (Figure 5), the amount of sandstone in the Hardinsburg (Figure 6) is greatest, and a high percent of massive packstone and some grainstone in the Haney is associated with the area of thick sandstone. For

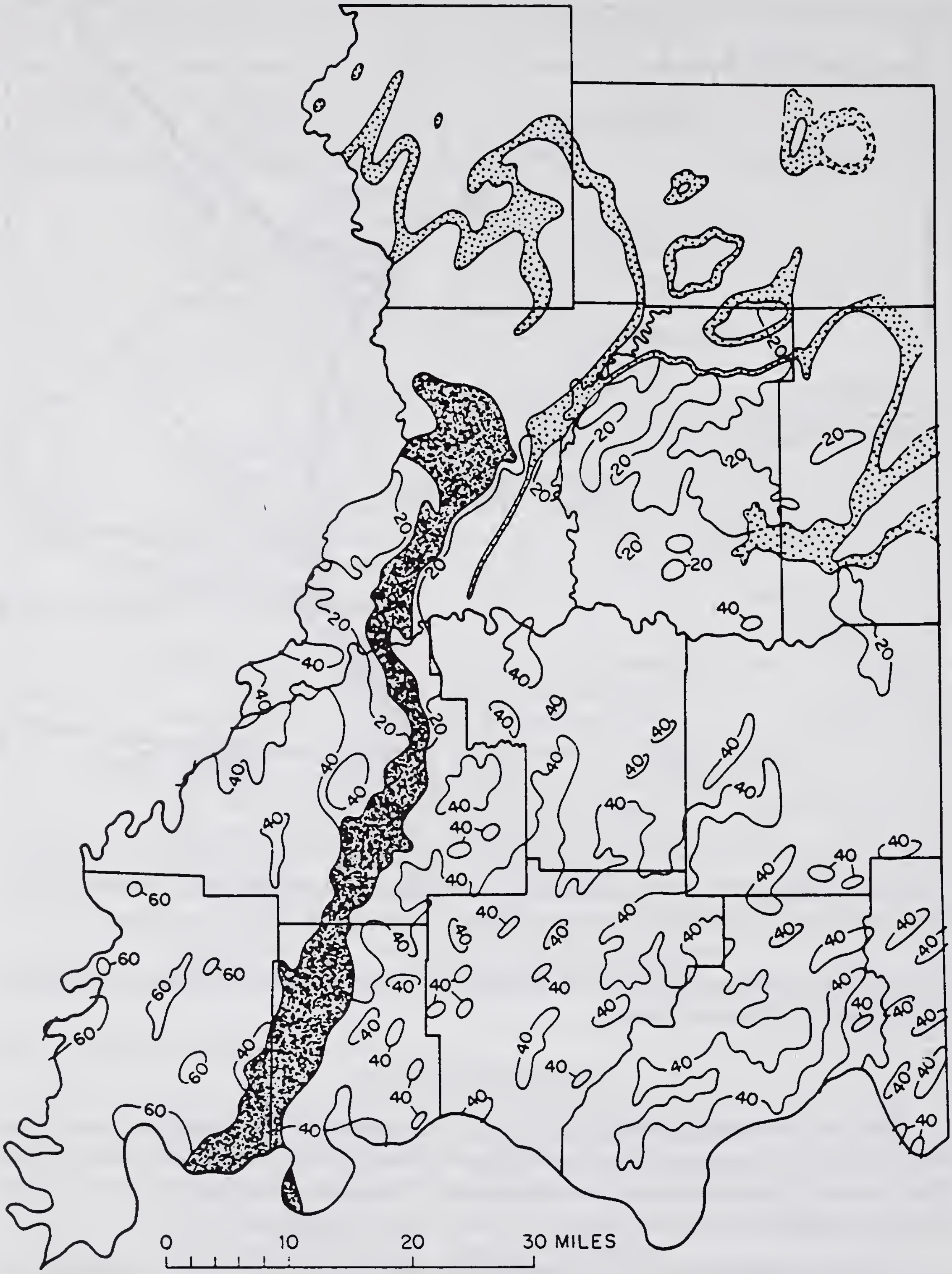

FIGURE 4. Map of thickness of Haney Limestone. The subcrop of the Haney is dotted. Area of thinned Haney (see text) is stippled. Countour interval is 20 feet.

a more detailed regional study of the Haney Limestone, see the recent report by Treworgy (1985). The contact of the Haney with the Big Clifty Formation below is conformable and sharp. The upper contact of the Haney with the Hardinsburg Formation is generally conformable and sharp. No cores are available for confirmation, but where the thick sandstone in the Hardinsburg lies directly on limestone of the Haney, the contact is probably a scoured disconformable surface. In

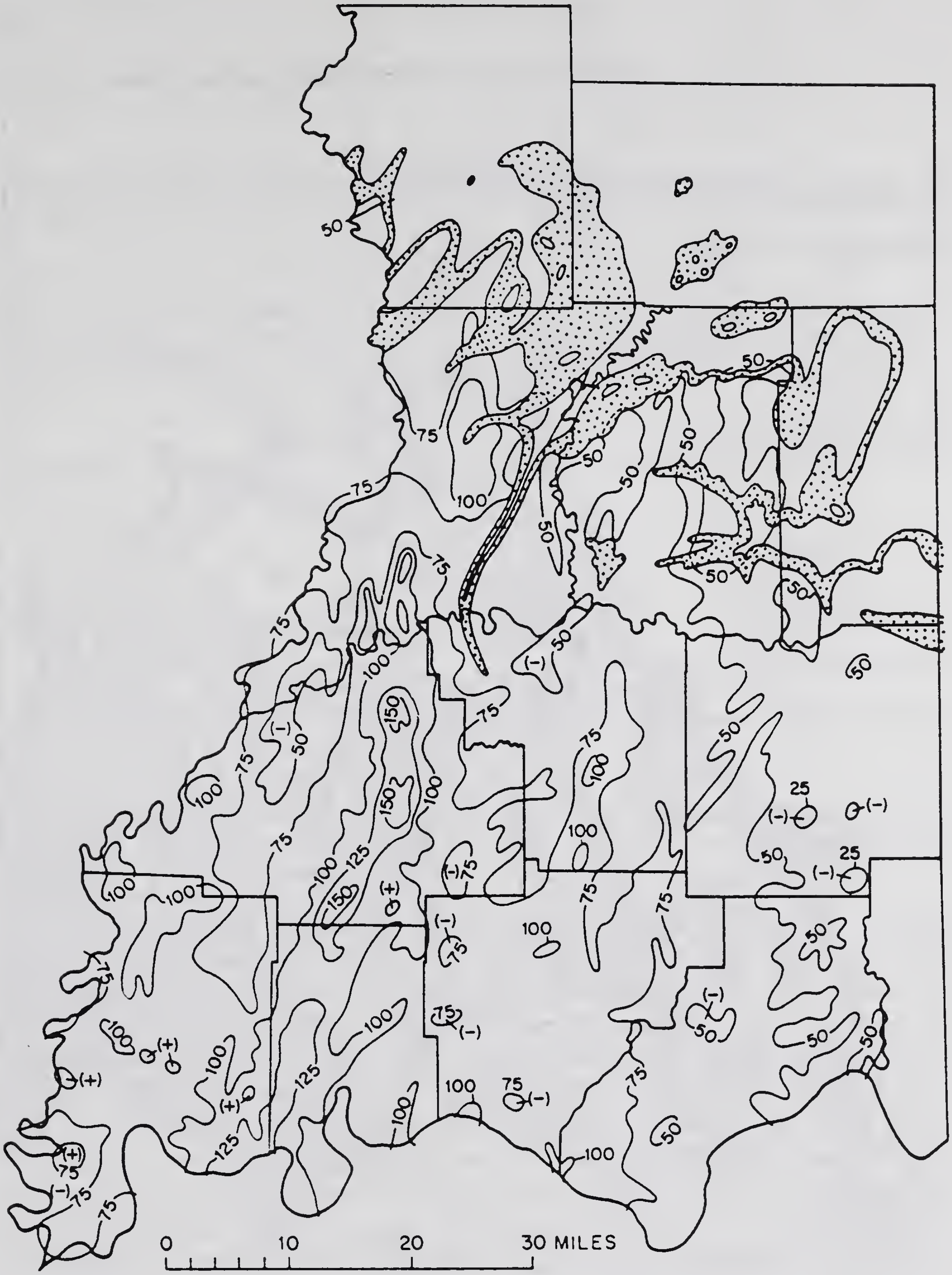

FIGURE 5. Map of thickness of Hardinsburg Formation. The subcrop of the Hardinsburg is dotted. Contour interval is 25 feet.

the area of subcrop (Figure 4) and in places along the outcrop, the Haney is unconformably overlain by rocks of the Pennsylvanian System.

Hardinsburg Formation. The Hardinsburg Formation consists of shale and sandstone and increases in thickness from less than 50 feet along the northern subcrop and eastern outcrop to nearly 175 feet in Gibson County (Figure 5). In

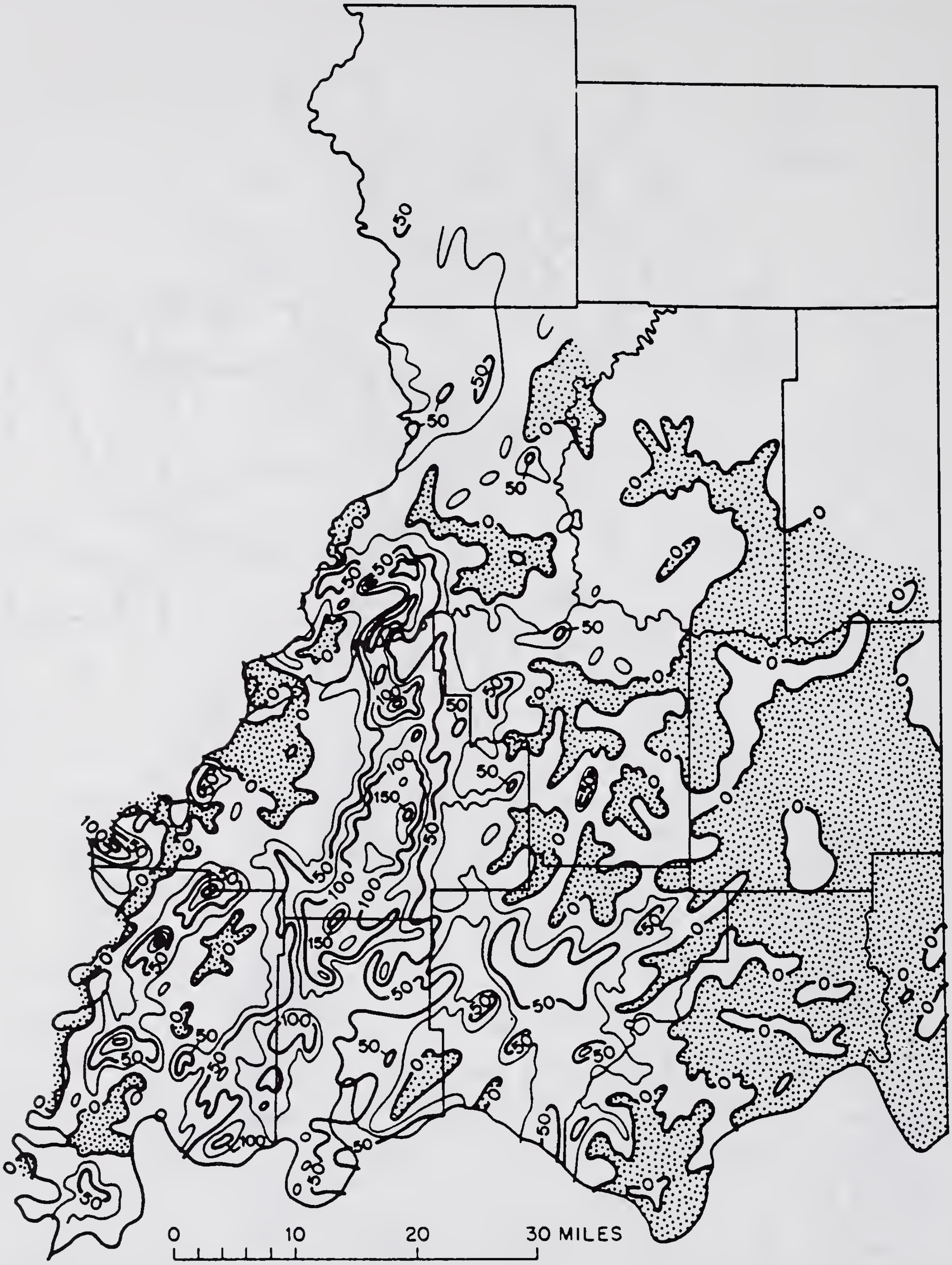

Figure 6. Map of net thickness of sandstone in Hardinsburg Formation. Areas where sandstone is absent in the Hardinsburg are dotted for emphasis. Contour interval is 25 feet.

several areas at the surface and in the shallow subsurface, particularly in Dubois County, the Hardinsburg Formation is less than 25 feet thick.

The Hardinsburg Formation is predominantly green and gray shale throughout much of the study area. A zone of red and maroon shale 5 to 10 feet thick in the upper part of the Hardinsburg is observed in many sample sets, and many

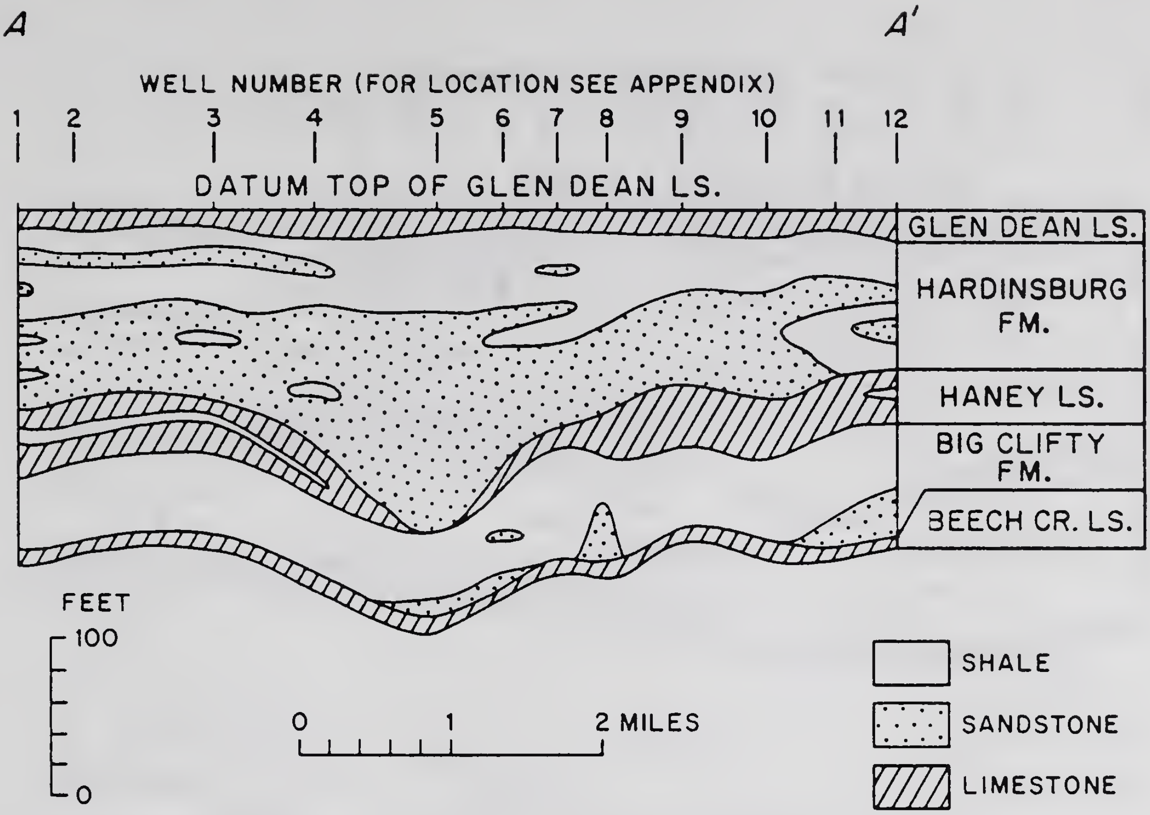

FIGURE 7. Cross section AA′. Location and other well information is given in Table 1.

driller's logs note the footage of this "red zone". The shales are very sparingly to moderately fossiliferous based on the observed abundance of fossil fragments in samples.

The net sandstone thickness in the Hardinsburg is less than 25 feet throughout most of the study area (Figure 6). A significant increase in sandstone thickness in very short distances in Knox, Gibson, Vanderburgh, and Posey Counties marks the location of belt sandstone bodies. In a detailed study of the sandstone bodies in several townships in Gibson County, Laurin (1988) documented the complexity of the belt sandstone and sandstone pods and ribbons in the Hardinsburg. The pod and ribbon quartz sandstone bodies are characteristically very fine grained, moderately sorted, and light brown, pale yellow-brown, or less commonly white. The quartz sand in the light colored belt sand bodies is fine grained and well sorted in the lower 1/2 to 2/3 of their thickness, and the sand is very fine grained and moderately sorted in the upper part of the body. Geophysical logs indicate that the belt sandstones are totally massive. In numerous places where the Haney Limestone is thin or absent (Figure 4), the lowest 10 to 20 feet of the belt sandstone is very limy and is almost a sandy limestone.

As seen in cross section, the generally massive belt sandstone bodies (Figures 7, 8) that lie directly on the Haney Limestone have irregular upper and lower contacts and, in some places, contain interbedded shale. In other areas (Figure 9), a significant shale interval in the Hardinsburg separates the belt sandstone body from a moderately thinned Haney Limestone. Of the smaller elongate sand bodies in the Hardinsburg, the pods are more abundant than are ribbons, particularly in association with belt sand bodies.

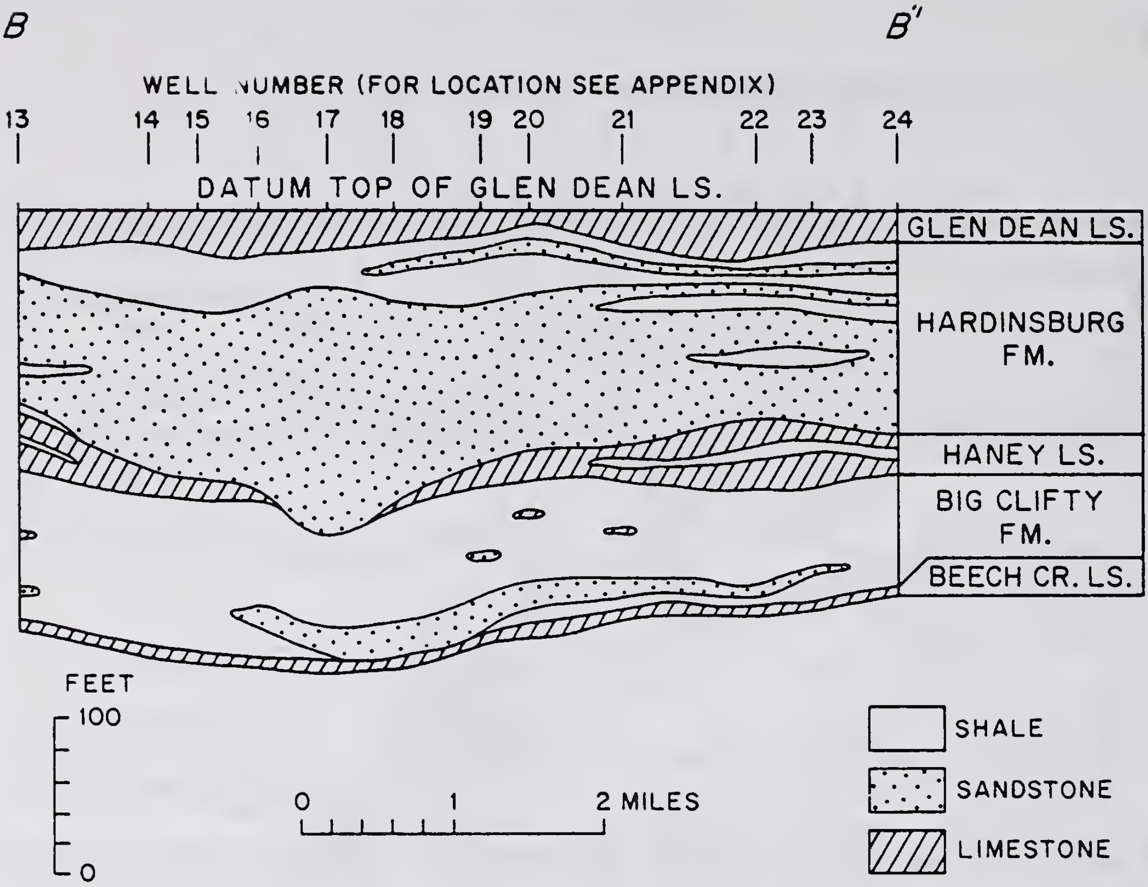

FIGURE 8. Cross section BB′. Location and other well information is given in Table 1.

Where very thick belt sandstones lie at its base, the lower contact of the Hardinsburg is a scoured surface of discontinuity. In the area of thinned Haney (Figure 4), the Hardinsburg belt sandstones lie in some places on the Big Clifty Formation. Away from the thick belt sandstones the contact between the Hardinsburg and Haney is conformable. The Hardinsburg is conformably overlain by the Glen Dean Limestone or unconformablly overlain by rocks of the Pennsylvanian System.

DISCUSSION

The belt sandstone bodies in the Hardinsburg have been variously interpreted as fluvial deposits filling channels previously cut by subaerial erosion, as fillings in channels eroded by marine processes, and as distributary sandstones associated with deltaic sedimentation (Swann, 1964). Whether deposited by fluvial or deltaic processes, favored interpretations commonly invoke regression of the sea and movement of the shoreline, frequently beyond the limits of the present Illinois Basin.

Not all geologists are satisfied with a model invoking extensive transgression and regression as the dominant influence on the alternation of siliciclastic and carbonate rocks of the Chesterian Series in the Illinois Basin. For example, Sullivan (1972) concluded that the massive sandstones that occupy much of the entire West Baden interval, in what he called the West Baden clastic belt, were deposited at the same time as the normal sandstone, shale, and limestone succession that

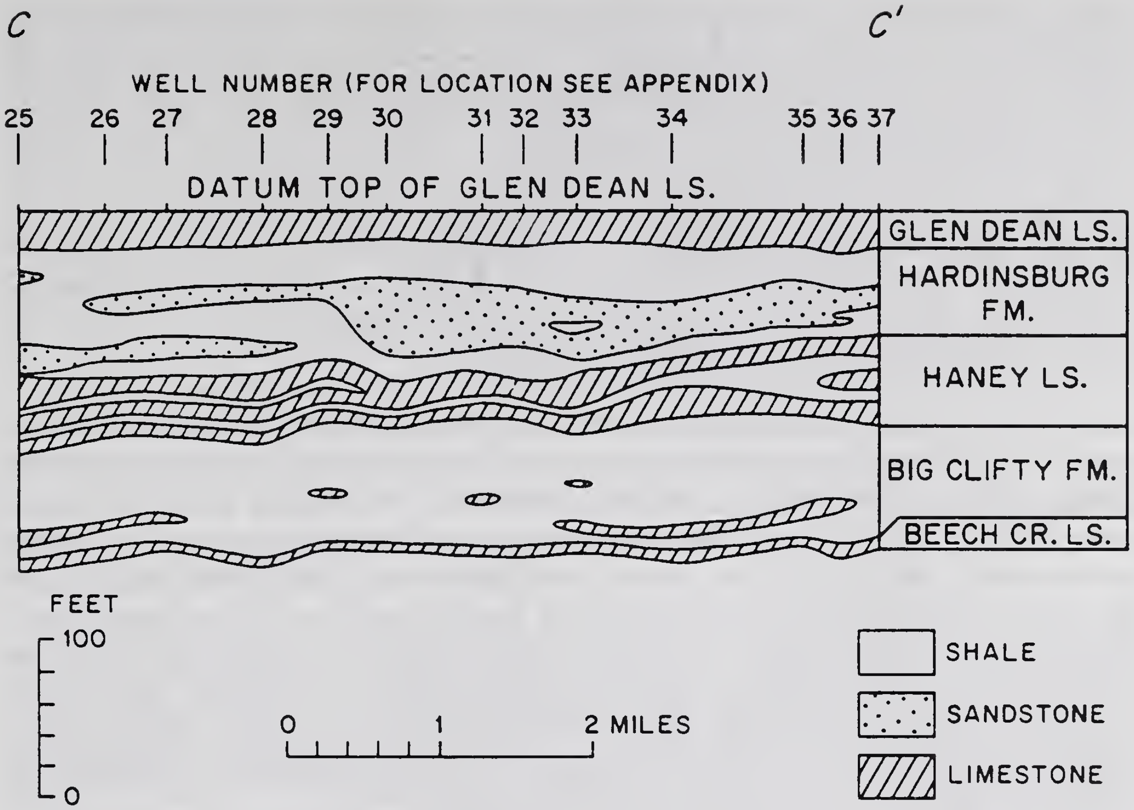

FIGURE 9. Cross section CC′. Location and other well information is given in Table 1.

accumulated outside of the clastic belt. In several places within the West Baden clastic belt, the contact of the basal sandstones with the underlying Paoli Limestone is a scoured surface of discontinuity (Droste and Carpenter, 1990). The western branch of the West Baden clastic belt has an orientation and location very similar to the belt sands in the overlying Hardinsburg Formation. Gray (1978) reported that he saw no convincing evidence that the rocks of the Buffalo Wallow Group, overlying the Hardinsburg, were deposited in non-marine environments. Droste and Keller (1989) agreed with Gray, and they suggested that the belt sandstones in the Tar Springs and Waltersburg Formations of the lower Buffalo Wallow Group were deposited in peritidal and shallow subtidal environments. The Tar Springs and Waltersburg belts of elongate sand bodies also have locations and orientations very similar to those of the Hardinsburg. Treworgy (1988) has reviewed those studies that interpret the Big Clifty Sandstone as tidally influenced. The ultimate test of the lateral equivalence of clastics and carbonates awaits a more finely divided biochronologic time scale than currently exists.

BELT SAND DEPOSITION

The interpretation that follows modifies and expands the depositional history presented for belt sandstones in the Tar Springs and Waltersburg Formations (Droste and Keller, in press) and in the Hardinsburg Formation (Laurin, 1988). For comparison with better known and more recent geological rhythms, we assume that the Chesterian Series was approximately 10 million years in duration (for example, see Shaver, *et al.*, 1985) and the interval of time during which the Hardinsburg rocks were deposited was several hundred thousand years. Following

Potter (1963, plate IG), we assume that the two areas of belt sandstone in the Hardinsburg have a common junction in Knox County, Indiana. They were deposited in very similar sedimentary environments during the same time interval and represent sand bodies in the "Hardinsburg delta" as shown by Potter (1963: 82, fig. 54). The factors affecting the preserved record mainly depend on 1) relationships between the tectonic events in the basin of deposition and in the surrounding source lands, 2) variation in climatic patterns, 3) minor variation in processes of sedimentation in the basin of deposition at the time the sediment accumulated permanently, and 4) post-depositional events that may destroy the evidence for and the scope of original deposition.

In Late Mississippian time, the Illinois Basic area was a gently subsiding cratonic embayment of a continental margin that lay several hundred kilometers to the southwest. Treworgy (1988) has described this setting as a tidally and tectonically influenced ramp. The area was a locus of deposition in shallow marine environments (Figure 3). Slow basinal subsidence rates made room both for the terrigenous load provided by slowly rising source lands and for carbonate sediments during times of lower siliciclastic input. Subtle basement movements associated with such features as the Wabash Valley Fault System, the LaSalle Anticlinal Belt, and the Rough Creek Lineament were operational and produced subdued topography on the sea floor. Former sea floor topography is inferred from units that thin over the former topographic highs.

A cyclical or rhythmic variation in the amount of rainfall associated with a changing climatic pattern, controlled at least in part by changes in storm tracking across the basin, produced times of both higher and lower terrigenous input to the basin. During times when storm tracts were either more common or more intense as they crossed the basin from the continental margin to the southwest toward the cratonic sources lands, heavy rainfall resulted and more mud and sand were delivered by streams to sites of deposition within the basin. During times when the storm paths were neither numerous nor intense, periods of lower rainfall in source areas resulted in reduced terrigenous input and carbonate sedimentation prevailed throughout the basin. The north river (Figure 3) clearly was the major supply route for the quartz sand in the belt sandstones of the Hardinsburg. Mud was delivered to the basin by the northeast and east rivers, but neither of these two systems carried a load rich in quartz sand. The north river became the major sand contributor because preferential northward storm tracking produced higher rainfall in northern sources, and northern sources probably contained more exposed quartz-rich sandstone. Inferentially, stream gradients differed little among these rivers because their headwaters were hundreds of kilometers to the north and east. The paleogeographic and tectonic setting as well as the mineralogy would seem to preclude arid conditions along the river courses in contrast to Swann's original proposal of arid-humid cycles.

General water depth was controlled principally by regional tectonics affecting the rate of source uplift and rate of basin subsidence, but shallow water environments prevailed. Sea floor lows, produced by a slightly greater rate of subsidence, became loci of strong current activity produced by storm surges, wind forcing, and tidal action. Based on the thickness of sandstone in the Hardinsburg Formation, the major area of local increased subsidence was a zone trending southward through Knox and Gibson Counties and southwestward from northern Vanderburgh through southeastern Posey County. In addition to the major area of thick belt sandstone, smaller areas of belt sand occur that are not as long or as wide as the major sand belt. For example, a distinct zone of belt sandstone trending southwestward in western Posey County is roughly parellel but separate from the major belt sand zone in northern Vanderburgh and southeastern Posey County. The margins of zones of belt sands are very irregular and range in width from less than 5 miles to more than 15 miles. Quartz sand was funneled into these areas and focused current activity produced much reworking. Where the currents were most concentrated, scouring of the sea floor was common. As long as the focused current activity prevailed and the quartz sand supply was maintained, belt sand bodies accumulated. The fining-upward texture and decrease in sorting in the belt sand bodies resulted when current funneling was reduced. Away from the areas of belt sand accumulation storm currents mobilized sand and local tidal currents produced pods and ribbon deposition above storm wave base. Post-depositional erosion prior to the onset of sedimentation in Pennsylvanian time has forever removed the evidence to document the full extent of the deposition that occurred in Late Mississippian time.

The Hardinsburg belt sandstones in the area between Knox County and southward into Kentucky began forming in Haney time. That is, the deposition of limestones in the Haney had not been completed before the onset on quartz sand deposition of the belt sand bodies in the Hardinsburg. Lows on the sea floor resulted because of an increase in subsidence rate locally. Early-formed Haney limestone beds may have been scoured, and belt sand bodies accumulated in areas where currents were focused. Carbonate deposition continued away from the area of concentrated currents. As the climate in the northern source area changed to produce greater rainfall, more and more terrigenous sand and mud were delivered to the basin, and eventually areas of carbonate deposition were smothered. Belt sand continued to accumulate until a climatic change resulting in less rainfall diminished the supply of terrigenous sediment. Finally, the terrigenous load was so reduced that carbonate deposition in clear, shallow water began in Glen Dean time.

A satisfactory modern analogue of the Illinois Basin, that is, a low latitude basin on a broad cratonic platform, apparently does not exist. The broadest platforms today are in temperate and higher latitudes, and low latitude shelves are in zones of active tectonism (southeast Asia). Perhaps the shelves of northern Australia provide the best modern models, but they are very poorly studied. The recent reports of the 3-dimensional distribution of sand bodies in the Amazon Deep-Sea Fan (Damuth, *et al.*, 1988; Manley and Flood, 1988) suggest that this might be a model for sand deposition as modified by conditions in much shallower water on a cratonic ramp. The modern Amazon Fan exhibits stacking of sand bodies, meanders, sand belts, and cyclicity, all of which are found in the Chesterian clastic intervals in the Illinois Basin. Not surprisingly, carbonates are lacking in this steep-slope, deep-water, modern analogue.

Alternations of transgressive and regressive seas through the late Mississippian (Chesterian) implies either a rhythmic rise and fall of sea level or a comparable tectonic rise and fall. Neither of these alternatives is at present appealing to us. Rhythmic tectonism has been widely postulated in this century, although inadequately explained as a process, and late Mississippian glaciations are too poorly dated and documented (Caputo and Crowell, 1985) to provide convincing evidence for the rhythmic rise and fall of late Mississippian sea levels. Nevertheless, Algeo and Wilkinson's (1988) analysis of Carboniferous sedimentary cycles suggests that these cycles are consistent with, but not proof of, Milankovitch orbital modulations mediated by Carboniferous glaciations. The resolution of Carboniferous chronologies is presently too coarse to independently test this model.

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