Subsurface Analysis Of The Depositional Environments Of The Bedford And Berea Formations In Northern Central Ohio

A Senior Thesis

Presented in Partial Fulfillment of the Requirements for
the degree Bachelor of Science
of the Ohio State University

by

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The Ohio State University

1990

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ACKNOWLEDGEMENTS

I wish to express my utmost gratitude to Dr. Lawrence A. Krissek for his guidance, expertise, and patience that he selflessly provided me throughout this project. Special thanks to Daniel Balcer and Tim Horner, for their advice and assistance during the processing of data.

Finally, I wish to express my sincerest gratitude to my parents for the love and support that they continually provided throughout my undergraduate years and throughout my life.

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ABSTRACT

The Bedford and Berea formations of eastern Ohio, western Pennsylvania and West Virginia, and eastern Kentucky have been studied by generations of geologists because of their economic and educational value. The Bedford and Berea are clastic units which display a distinct coarsening-upward trend. Past studies have proposed a prograding deltaic complex as the depositional origin of these formations, but much debate still surrounds the interpretation of specific depositional environments within the Bedford/Berea complex.

This study utilized 130 geophysical well logs from Morrow, Knox, and Richland counties to determine the distribution and depositional setting of the Bedford/Berea in north central Ohio. Data collected from these wells were used to construct isopach maps of the Bedford and Berea and surface structure contour maps on the tops of the Ohio Shale and Berea Sandstone. These maps support the general interpretation of clastics prograding to the south and southeast into the Appalachian Basin in late Devonian and early Mississippian time. Some of the isopach patterns strongly suggest influence by pre-existing structures in the Ohio Shale on the deposition of the overlying Bedford Shale and Berea Sandstone. Other patterns indicate the importance of gravity driven flows in depositing these sediments.

INTRODUCTION

The Bedford and Berea formations have been the subject of many geologic studies. The fact that the Devonian-Mississippian contact is typically placed at the base of the Bedford Shale, and that the Bedford-Berea complex is an excellent example of a coarsening-upward sequence, has piqued the interest of many sedimentologists. The Berea has also been shown to be of economic interest as a very good source of water, natural gas, and oil, providing an additional incentive for research by industry. In northern Ohio, the Berea has been quarried as a building stone for its excellent aesthetic and physical properties. Properties such as uniform grainsize and porosity have also made the Berea a type reservoir sandstone in petroleum engineering research. The continued study of the Bedford/Berea complex can provide important information to these various industries, along with providing another example to compare with shoaling- or coarsening-upward sequences found elsewhere in the world.

This study mainly utilized data from subsurface geophysical logs, both gamma-ray and neutron logs, to pick tops and bases of units. This provided thickness data used to construct isopach and subsurface structure contour maps of the study region. These maps were then used to support the hypothesis that the coarsening-upward sequence of the Bedford and Berea is the result of a prograding shallow marine system. The geometry of the sands and silts provides evidence of a storm-dominated deltaic system that prograded south-southeast.

STRATIGRAPHY

The Bedford and Berea formations are underlain by the Ohio Shale of late Devonian age and overlain by the Sunbury Shale of middle Mississippian age. In Ohio, the Ohio Shale has been further divided into three members: the Huron Shale, which is the basal member, overlain by the Chagrin Shale member, and capped by the Cleveland Shale member (Coats, 1988). The Bedford also contains three members: the Euclid and Sagamore shale members and the Second Berea Sand member. However, these members are very restricted in areal extent and are not recognized statewide (Collins, 1979; Fig. 1).

In central Ohio the Ohio Shale averages 650 feet thick. It thins southward to the Ohio River and thickens to the east. The majority of the Ohio Shale is considered a black bituminous shale (Pepper et al., 1954), which is organic rich, fissile, unfossiliferous, and radioactive (Coats, 1988). Its radioactive property provides an excellent marker on gamma-ray logs, allowing easy determination of the Bedford Shale/Ohio Shale contact.

The contact betwen the Ohio Shale and the Bedford Shale is generally conformable, and is generally used to define the Devonian-Mississippian boundary. The exact placement of the Devonian-Mississippian boundary has been argued for years, as expressed by Pepper et al,(1954): "The placement of the plane dividing the Devonian system from the Mississippian

OHIO

SYSTEM	GROUP	FORMATION OR BED	MEMBER
PERMIAN	Dunkard	Washington (No. 12) coal	
PERMIAN—PENNSYLVANIAN			
PENNSYLVANIAN	Monongahela	Waynesburg (No. 11) coal Pittsburgh (No. 8) coal	
	Conemaugh	Ames Limestone	
	Allegheny	Upper Freeport (No. 7) coal Brookville (No. 4) coal	
	Pottsville	Sharon Conglomerate	
MISSISSIPPIAN	Waverly	Maxville Limestone	
		Logan Formation	Vinton Sandstone Allensville Conglomerate Byer Sandstone
		Cuyahoga Formation	Berne Conglomerate Black Hand Sandstone Portsmouth Shale Buena Vista Sandstone Henley Shale
		Sunbury Shale	
		Berea Sandstone	
		Bedford Shale	Sagamore Shale Euclid Shale
DEVONIAN		Ohio Shale	Cleveland Shale Chagrin Shale Huron Shale

FIGURE 1 - Generalized stratigraphic column of formations in Ohio. Note placement of the Devonian-Mississippian boundary between the Ohio Shale and the Bedford Shale formations (Collins H.R.,1979).

series in the sequence of rocks between the base of the Ohio Shale and the top of the Sunbury Shale has become a time honored controversy." However, geologists today generally agree to place this boundary at the Ohio Shale-Bedford Shale contact.

In a general sense, the Bedford Shale is composed of three lithofacies: gray shale, siltstone, and very fine-grained sandy siltstone. The superposition of these facies forms a coarsening-upward sequence. A red shale lithofacies overlies the sandy siltstones, but this change in color is interpreted to reflect postdepositional diagenetic changes rather than changes in source or depositional environment (Coats, 1988).

The Bedford is areally extensive, extending from Lorain and Cuyahoga counties in northern Ohio south to the region of Vanceburg, Kentucky, and eastward into Pennsylvania and West Virginia. The three Bedford members mentioned earlier are identifiable in the eastern sections of the Bedford. The Euclid and Sagamore members are restricted to the northeast, whereas the Second Berea Sand member has been identified in southeastern Ohio (Pepper et al., 1954).

The contact between the Bedford Shale and Berea Sandstone is considered to be gradational in central to southern Ohio, but much debate surrounds the presence of an erosional unconformity between these formations further to the north. Nonetheless, the overlying Berea Sandstone continues the coarsening-upward sequence developed in the Bedford. The

Berea Sandstone in northern Ohio, is dominated by fine- to medium-grained moderately sorted sandstone, which is often calcareous (Lewis, 1988). Along the outcrop belt between Berea and Columbus, Ohio, the Berea Sandstone is fine- to medium-grained but becomes a clay-bonded quartz sandstone (Pepper et al., 1954). The Berea in northern Ohio consists of three parts: a thin blanket sand, overlain by a thick layer that contains channel-form features, and capped by sands of a blanket-like geometry (Lewis, 1988). To the south the Berea becomes increasingly thin bedded, and the large channel-like features are no longer present. Overall thickness and grainsize of the Berea decrease southward, so that it becomes increasingly difficult to differentiate the Berea from the underlying Bedford Shale (Pepper et al., 1954).

The Sunbury Shale conformably overlies the Berea Sandstone. The Sunbury Shale consists of thin-bedded carbonaceous black shale, very similar to the Cleveland member of the Ohio Shale. The unit is relatively thin (approximately 20 feet thick), but is very extensive. The basal three inches are characterized by a pyrite layer and a fossiliferous layer containing conodonts, which suggests its origin as a marine shale (Pepper et al., 1954).

PREVIOUS STUDIES OF DEPOSITIONAL ENVIRONMENTS

The present-day extent of the Bedford and Berea formations is limited due to erosional processes. The western edge of these formations is presently identified by a series of outcrops that extend from Berlin Heights southward through central Ohio and continue into Kentucky. Eastward the formations exhibit a shallow dip to the east and continue in the subsurface into western Pennsylvania and western West Virginia (Forman et al., 1940; Fig 2).

The pre-erosional western extent of these formations has been interpreted as the eastern limb of the Cincinnati Arch by Pepper et al.(1954). During the latest Devonian, a shallow epeiric sea covered much of the eastern two-thirds of Ohio and has been named the Ohio Bay by Pepper et al.(1954). This large body of water received clastic sediment from a paleoriver system known as the Ontario River. This river entered the Ohio Bay from the north, paralleling the trend of the Cincinnati Arch. As a result of this sediment supply, a large deltaic complex prograded southward into the Appalachian Basin. This prograding deltaic system transported increasingly coarser grained material southward, covering the finer clastics of the Ohio Shale with the Bedford Formation and finally capping the Bedford with the Berea Sandstone (Fig. 3). Pepper et al.(1954) termed this system the Red Bedford Delta, and further suggested that this delta was elongate, peninsular and formed a subaerially exposed land mass with a flanking lagoon and barrier bar to

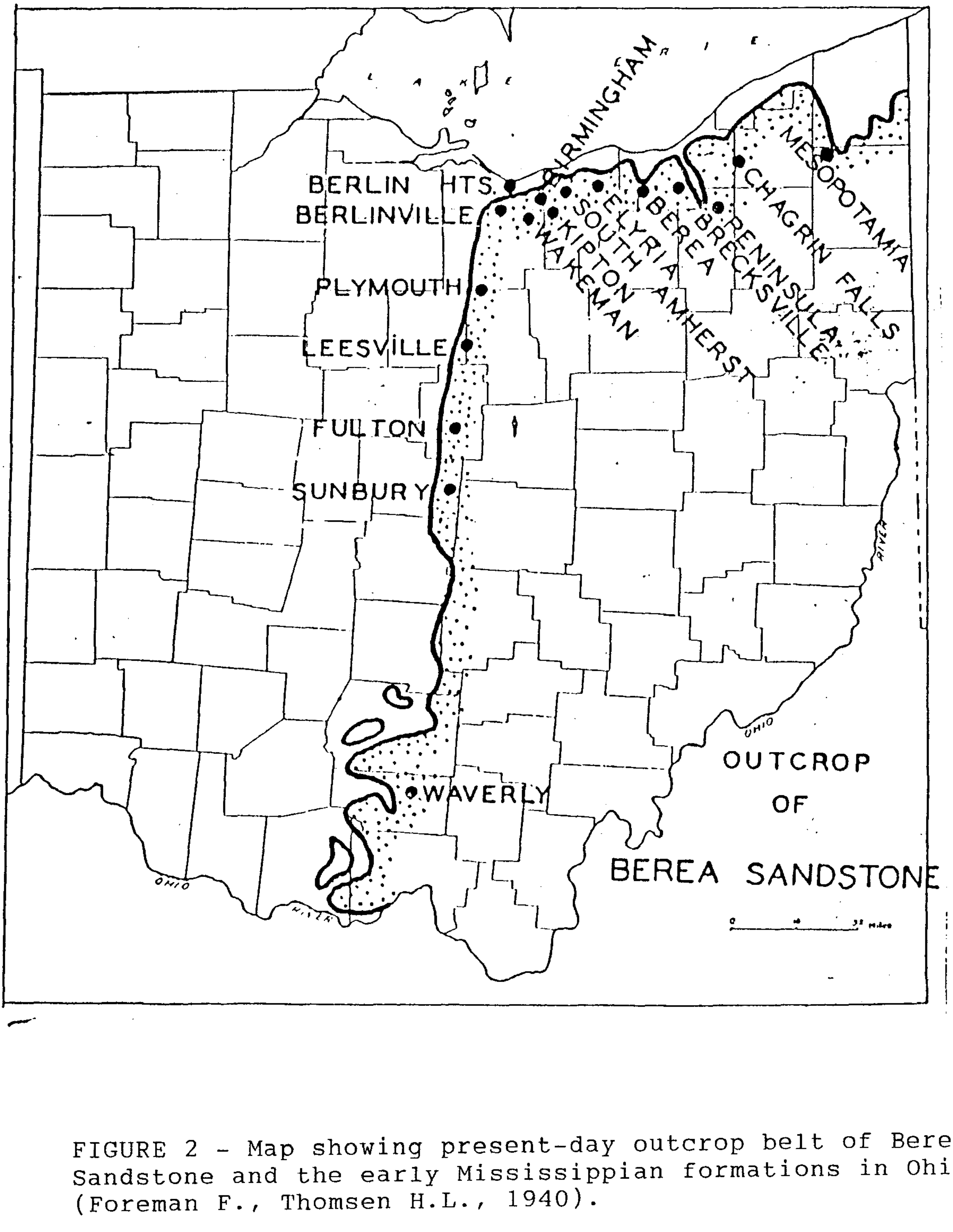

FIGURE 2 - Map showing present-day outcrop belt of Berea Sandstone and the early Mississippian formations in Ohio (Foreman F., Thomsen H.L., 1940).

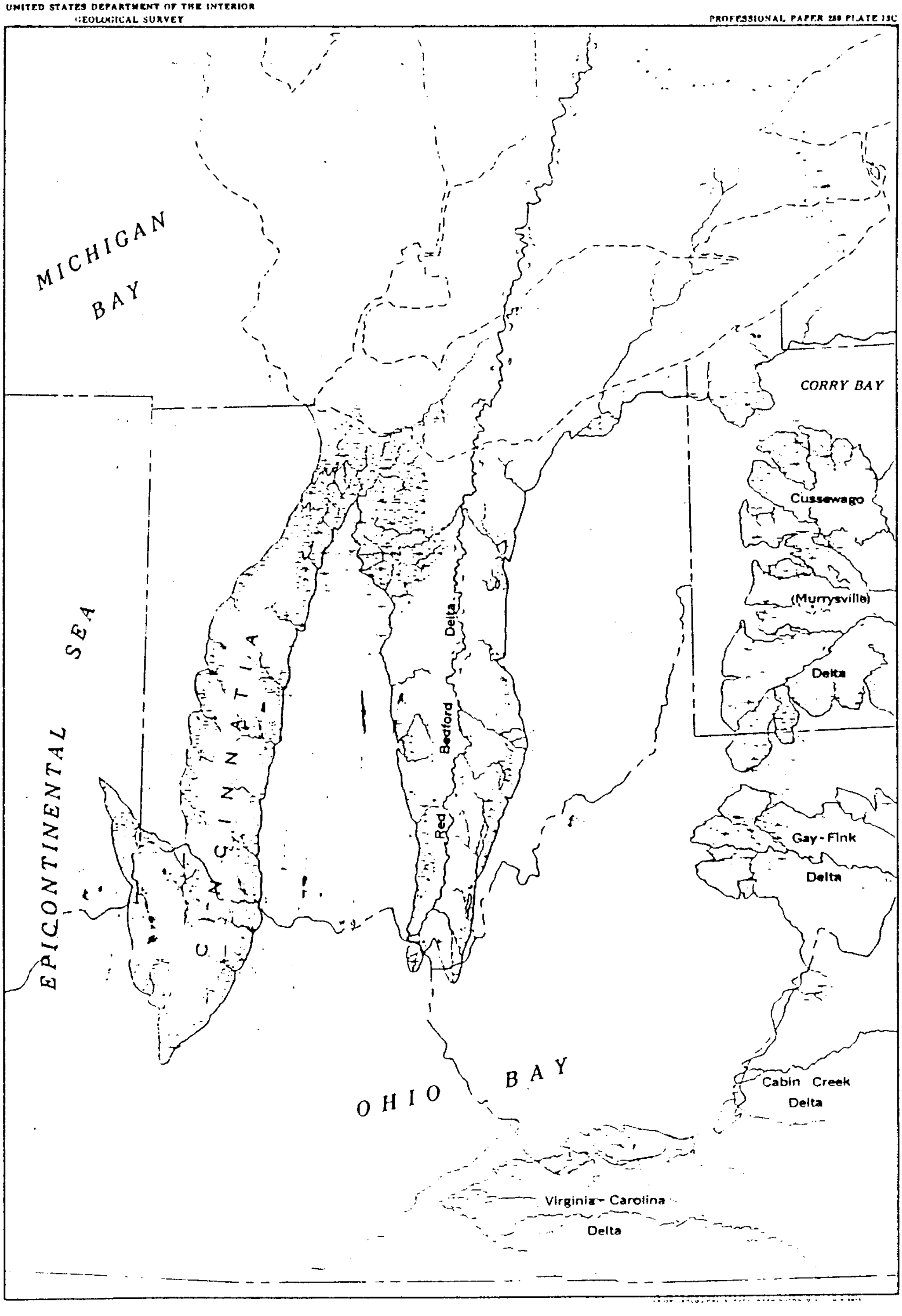

FIGURE 3 - Paleogeographic map showing extent and elongate, peninsular shape of the Red Bedford Delta and basin areas according to Pepper et al. (1954).

the east. Coats (1988) provides a different interpretation for the shape of this delta (Fig. 4). In addition, he contends that deposition was marine and not subaerial in nature.

Potter et al.(1983) produced a work which is in general agreement with the deltaic interpretation of the Bedford/Berea complex by Pepper et al.(1954). Of the major types of deltas (river-, wave-, and tide-dominated) the river-dominated delta is most strongly supported due to their assumption of an elongate shape and a small inshore wave energy within the Ohio Bay (Potter et al., 1983)

Potter et al.(1983) list the subenvironments of a river-dominated delta to include distributary channels, lunate bars at distributary mouths, natural levees, interdistributary marshes and bays, delta front, coastal barriers, and prodelta environments. The prodelta deposits can exhibit structures such as ripple marks, bioturbation, and hummocky cross-stratification. Sediments representing all of these environments are probably present in the Berea (Potter et al., 1983; Fig 5).

Pepper et al.(1954) pointed out that the upper twenty feet of the Berea Sandstone from Berea to Columbus, Ohio, are thickly bedded, with the upper surfaces of the beds showing well-formed oscillation ripples. They also noted that in the northern half of Ohio, the Berea Sandstone generally occurs in isolated thick deposits with sharp convex boundaries which often "cut" into the underlying Bedford Formation. These sharp convex boundaries have been described by Pepper et al.(1954) as

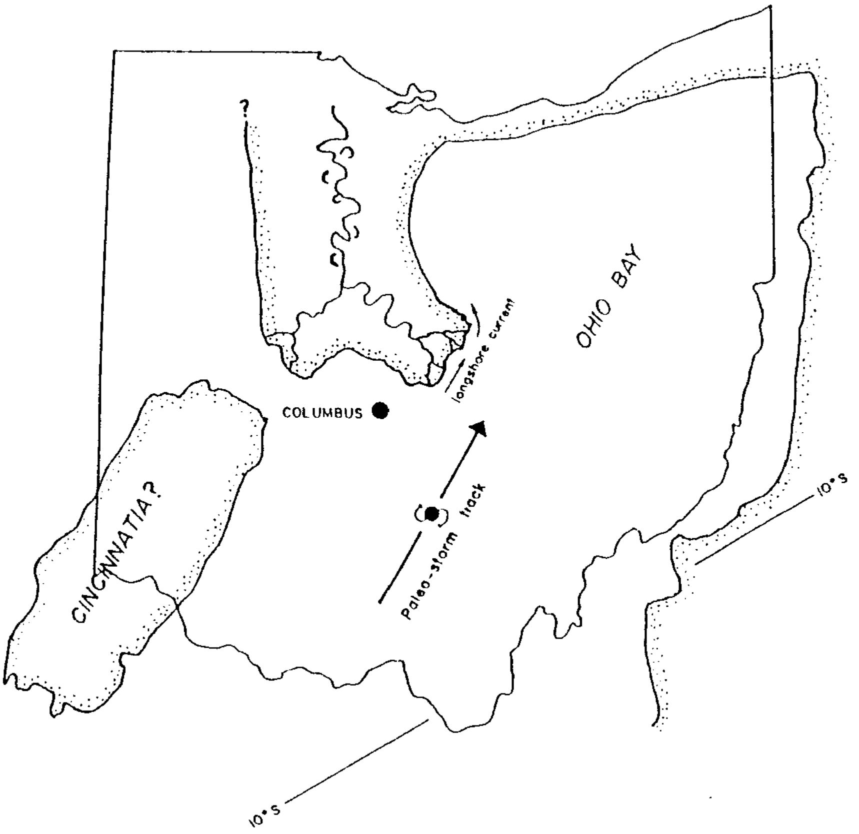

FIGURE 4 - Contrasting paleogeographic construction of the early-Mississippian deltaic complex according to Coats (1988). Note the north-easterly paleo-storm track.

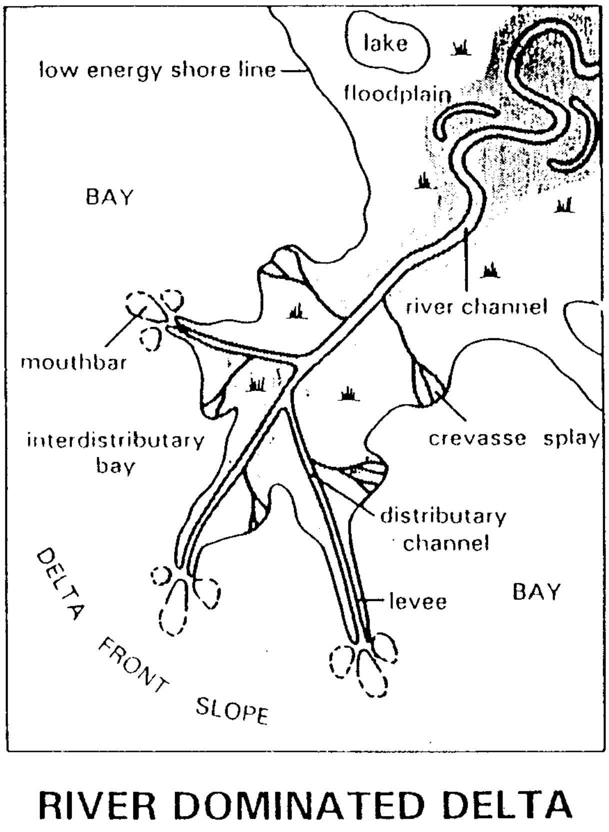

FIGURE 5 - River-dominated delta displaying subenvironments of the complex (Potter et al., 1983).

"channels", and suggest, at least locally, an erosional unconformity at the base of the Berea. However, Lewis (1988) proposed that these "channels" are the result of loading which caused soft sediment deformation and faulting of the underlying mudshales. Lewis (1988) supports this interpretation by observing that multiple normal faults that parallel the "channel" margin can be seen in many of these "channel" deposits.

The Berea thins from north to south, where separation of the Bedford from the Berea becomes difficult. (Fig. 6) Thickness of the Berea is extremely variable in northern Ohio due to the "channel-like" forms that cut into and sometimes through the Bedford Shale. (Fig. 7) The size and depth of the "channels" decrease south of Norwalk to Columbus where Pepper et al.(1954) consider the contact to be a "gently undulatory unconformity which dies out to the south." However, the existence of an unconformity between the Bedford and Berea formations is controversial.

Potter et al.(1983) also support the existence of coastal barrier island or bar deposits in the Berea. Coastal barriers have a distinctive coarsening-upward sequence along with sedimentary structures that change upward from ripples interlaminated with shale into sandier and thicker beds with cross-bedding and planar bedding. This progression of sedimentary structures is common in the Berea Formation and is also present in isolated elongate sand bodies in the Bedford. These bodies in the Bedford are the Sagamore, Euclid, and Second Berea Sand Members. Pepper et al.(1954) and Lewis (1988) both interpret

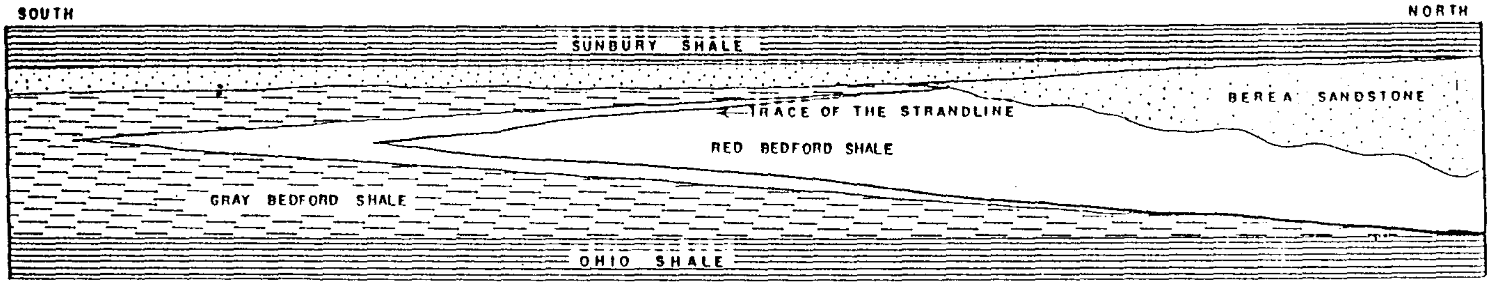

FIGURE 6 - Block diagram which shows the general thinning/thickening changes within the Bedford and Berea formations from southern to northern Ohio. Note the unconformity between the Bedford Shale and the Berea Sandstone in northern Ohio, from Pepper et al., 1954.

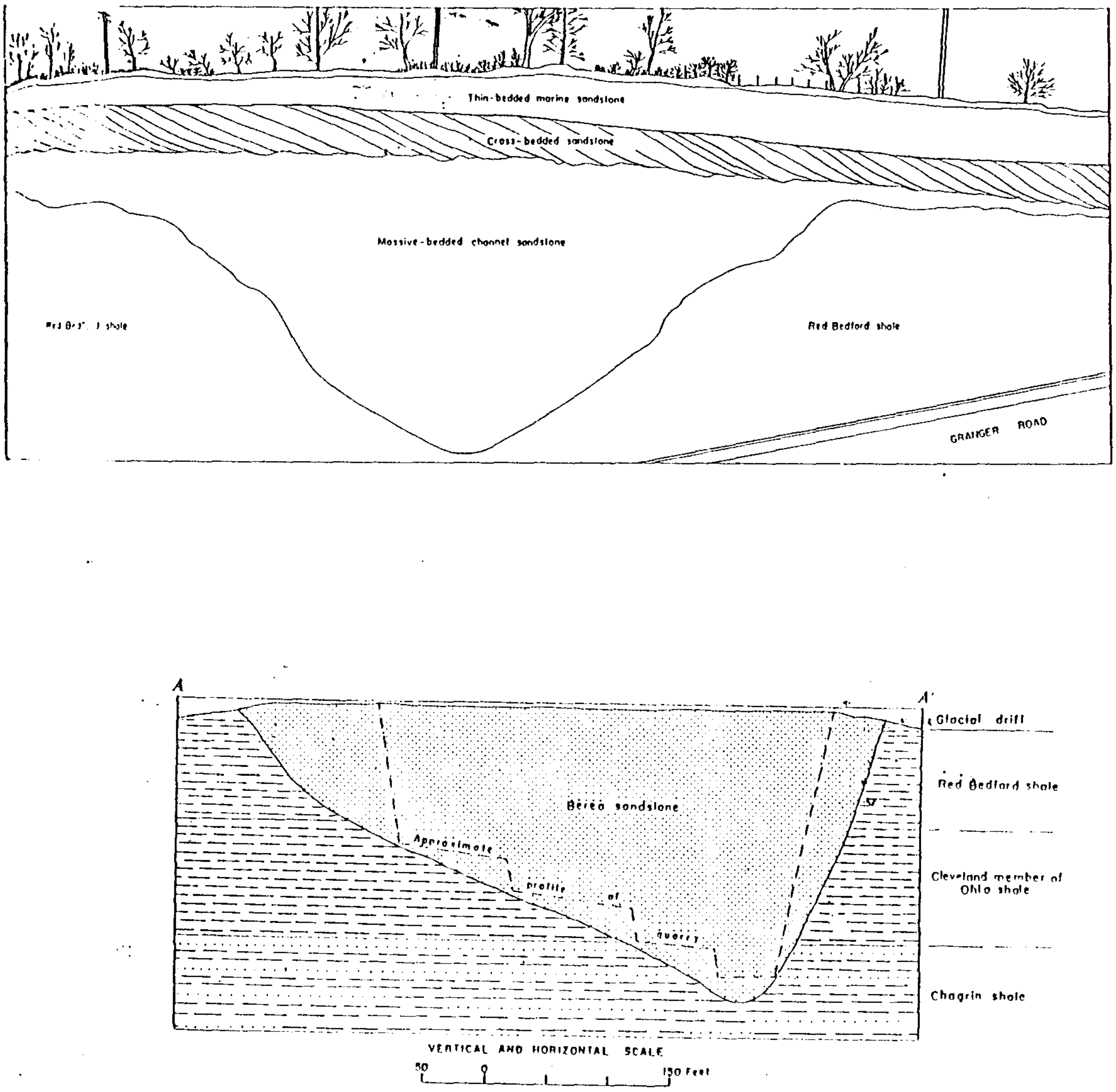

FIGURE 7 - "Channel" sandstone deposits in the Berea Sandstone of northern Ohio. These illustrations show the extent of the "down-cutting" into the underlying formations (Pepper et al., 1954). Lewis (1988) proposed that these "channels" formed by soft-sediment deformation and faulting.

these members as barrier bar sands. Lewis (1988) further suggests that these sand bodies may also represent tempestites.

Marine shelf sandstones have been interpreted to form a major part of the Berea. These sandstones include sediments deposited above fairweather wave base, and sediments deposited between fairweather and storm wavebase; processes in both settings produce elongate bodies of variable lateral extent and thickness. Fairweather deposits commonly are bioturbated and display wave ripples, whereas storm deposits display hummocky cross-stratification. Both of these environments produce coarsening-upward sequences if the sediment source progrades (Potter et al., 1983).

Work by Kohout and Malcuit (1969) suggests an environmental interpretation of the Berea and Bedford that is summarized in Figure 8.

Lithofacies	Interpreted environments
cross-bedded medium-grained sandstone (Berea Formation)	fluvial
red shale (Bedford Formation)	wind tidal flat
gray ripple-marked siltstone and shale (Bedford Formation)	lagoon
siltstone and fine-grained sandstone (Bedford Formation)	submarine bar or beach
gray shale (Bedford Formation)	shoreface
black shale (Ohio Shale)	offshore marine, oxygen poor bottom

FIGURE 8 - Depositional environments of the Bedford Shale and Berea Sandstone as interpreted by Kohout and Malcuit (1969).

Kohout and Malcuit (1969) propose a subaerial, wind-influenced tidal flat as the depositional environment of the red shale of the Bedford Formation. In contrast, Coats (1988) argues that the change in color of the Bedford Shale from gray to red is a result of post-depositional oxidation, possibly due to diagenetic controls and or groundwater movement. Coats (1988) contends that the Bedford was deposited in the deeper water away from the sediment supply. The continued shoaling caused by the prograding delta allowed the deposition of coarser clastics upon finer clastics. This prograding delta formed a depositional wedge of Bedford Shale that increases in thickness southward, whereas the Berea Sandstone thickens to the north

Throughout the Berea Sandstone, sedimentary structures reflect continued shoaling. Coats (1988) cites the gradual coarsening-upward sequence, along with bedding changes from hummocky-dominated to swaley-dominated upsection, as representing deposition in shallower waters. Hummocky cross-stratification reflects deposition slightly above storm wave base, whereas swaley cross-stratification occurs just below fair-weather wave base. This sequence of sedimentary structures would be expected in a prograding delta complex as infilling of the basin occurred.

METHODS

Field Data

Three stratigraphic sections of the Bedford and/or Berea formations were investigated briefly to become familiar with features such as sedimentary structures, nature of contacts between units, vertical lithologic successions, color, and lateral lithologic continuity. These three outcrops lie along the north-south trend of exposures shown in Figure 2. These exposures were located in Sunbury along Big Walnut Creek, at the Galena Clay Pits, and in Gahanna at Rocky Fork. Each exposure was described in detail by Coats (1988).

Subsurface Data

Subsurface data were collected using gamma-ray and neutron density logs from oil, gas, and water wells. These well logs were gathered from an area approximately 34 miles wide by 25 miles long, covering approximately 850 square miles.

The well logs were obtained from the well log files at the Subsurface Section of the Ohio Geologic Survey, located at the Ohio Department of Natural Resources in Columbus, Ohio. Township maps were used to choose wells that were potentially suitable for the study of geophysical logs. For each well selected that contained geophysical logs through the desired interval, the following data were recorded: x-y coordinates, log reference datum, and the depths to the top of the Berea, top of the Bedford, and top of the Ohio Shale.

Picking the tops of the Berea Sandstone and the Ohio Shale was generally straightforward, due to the obvious lithologic and radioactivity differences between the Ohio Shale and the Bedford Shale and between the Berea Sandstone and the Sunbury Shale. The boundary between the Berea Sandstone and the Bedford Shale, however, was not always obvious, due to the gradational nature of the Bedford/Berea contact in the study area. Table 1 lists the counties and townships from which wells were obtained. Appendix 1 lists the wells used for this study and all relevant data collected from each well.

Isopach maps of the Bedford Shale and the Berea Sandstone, and structure contour maps of the tops of the Berea Sandstone and the Ohio Shale were constructed using the subsurface data. A spreadsheet of the data was generated using Lotus 1.2.3., and was then imported into Golden Graphics, a three dimensional contouring program by Golden and Associates. Within the program, variables such as gridding surface techniques, x-y maxima and minima, contour line smoothing, and grid size could be changed to produce the most desirable maps. Test maps were generated by changing these variables, and the most suitable maps were used for this study.

Standard limits of x-y maxima and minima values were chosen for all maps to aid in comparing the maps generated. These standard values also helped to eliminate problems of "edge effects" caused by the gridding program.

TABLE 1
Counties and townships from which well data were collected.

COUNTY	TOWNSHIP
Morrow	Harmony
	Chester
	Franklin
	Perry
	North Bloomfield
	Troy
	Congress
Knox	Wayne
	Morris
	Monroe
	Howard
	Union
	Middlebury
	Pike
	Brown
	Jefferson
Richland	Perry
	Jefferson
	Worthington
	Troy
	Washington
	Monroe

SEDIMENTOLOGY

Field observations were the primary source of data for this section of the report. Three sections of Ohio Shale, Bedford Shale, Berea Sandstone, and Sunbury Shale were investigated. None of these exposures provided a complete section through all four units.

Sunbury

The exposures at Sunbury occur northeast of the town of Sunbury on the property of R. Mohler, 12032 Hartford Road. The outcrops form cliffs along the sides of Big Walnut Creek and exhibit the gradational contact between the Bedford Shale and the Berea Sandstone. The contact between the Bedford and the Berea is placed at the lowest continuous sandstone layer. This layer is only 1-2 inches thick and lies within an interval of interbedded thin sands and muds. The thin sands may represent rapid deposition during storms through small-scale turbidity flows. Many small-scale loading features can be observed on the soles of the sand layers.

Directly above the interbedded sands and muds is a "disturbed" zone of fine grained sand approximately 13 feet thick. This zone contains fluid escape structures or pipes, along with flow rolls and ball and pillow structures. The next observable zone of the Berea Sandstone displays thinly bedded sands which are roughly parallel and relatively undisturbed. Swaley bedding is also evident. This swaley bedding supports the presence of a shoaling upward sequence, since swaley bedding is commonly interpreted to form at depths just below fairweather wave base (Coats, 1988; Walker, 1982).

Galena

The clay pits at Galena contain excellent exposures of the Bedford Shale and the upper portion of the Ohio Shale. The Ohio Shale is a fissile, parallel laminated, black to dark gray shale. Its dark color is due to high organic carbon content. The Ohio shale is more resistant than the overlying Bedford Shale, which is much more easily eroded and forms steep slopes of loose shale fragments. The Bedford is lighter gray in color at the contact, probably due to a decrease in organic carbon (Coats, 1988). The Bedford displays parallel laminations and lenticular bedding. Toward the top of the pits, the Bedford changes to a chocolate brown or reddish brown shale. Coats (1988) has proposed that this color change is due to diagenetic controls, and not a result of changes in depositional environment or sediment source area.

Rocky Fork

Rocky Fork contains three outstanding outcrops, which together show the upper Bedford Shale, the entire Berea Sandstone, and the lower Sunbury Shale. These outcrops occur along Rocky Fork of Big Walnut Creek on the property of Wilbur

Smith and John Vorys.

The outcrop of interest that lies furthest downstream (Outcrop A of Coats, 1988) exposes the upper Bedford Shale, which here is grayish-green and thinly bedded, with some lenticular bedding. Approximately 3 feet upsection the Bedford is still thinly bedded but interbedded layers of slightly coarser material are present. These layers are commonly discontinuous muds and silts, which are slightly more resistant. The Bedford gradually coarsens upsection with the addition of more laterally continuous thin sand layers, until a laterally continuous layer of sandstone 1 to 2 inches thick can be traced across the outcrop. This layer marks the base of the Berea Sandstone. Small-scale loading structures are present on the base of this sandstone layer. Three to seven feet upsection, a deformed layer similar to the one seen at Sunbury is present.

The middle outcrop of interest (Outcrop B of Coats, 1988) is located only a few hundred meters upstream from the first exposure. This outcrop is a continuous wall about 250 yards long. This outcrop is the largest of the three at Rocky Fork and displays the lateral continuity of various layers of Berea Sandstone. This outcrop is easily correlated to the lower outcrop by tracing continuous beds. The deformed layer common to the Berea in this area has well-developed fluid escape structures, flow rolls, and ball and pillow features. Some of the flow rolls are so drastically deformed that they appear to have folded over upon themselves. Approximately halfway up this section swaley bedforms, indicating a shoaling upward of the depositional environment, are present.

The outcrop that is furthest upstream (Outcrop C of Coats, 1988) exposes the middle and upper Berea Sandstone and the contact with the overlying Sunbury Shale. The middle Berea contains swaley cross-stratification, with symmetrical ripples on many of the bedding surfaces. The uppermost Berea is composed of two intervals of massive sandstone that display no definite sedimentary structures. These massive intervals also contain the coarsest sands of the Berea in central Ohio. The cause of the massive nature of these beds is presently unknown, but may be diagenetic. If so, then the primary sedimentary structures were obscured by ground water movements that cemented these beds with pyrite. Pyrite concretions and small nodules are also present in these beds, supporting this hypothesis.

The contact between the Berea Sandstone and the Sunbury Shale appears to be conformable and marks the reduction of coarse clastic influx to the basin.

SUBSURFACE GEOLOGY

Information obtained solely by outcrop study cannot present a clear picture of Bedford and Berea deposition on a regional basis. Instead, study of the Bedford Shale and the Berea Sandstone on a regional scale must utilize subsurface data, because these formations continue into the subsurface along a gentle eastward dip east of the north-south trending Bedford-Berea outcrop belt. For this reason, 130 gamma-ray and neutron density logs from oil, gas, and water wells were collected and studied. The data from the logs were used to construct isopach and surface structure maps to aid in interpreting the depositional geometries and environments of these units. The locations of the wells used for all maps (both structural and isopach) can be seen in Figure 9.

Isopach and Structure Contour Maps

Isopach maps of the Bedford and Berea formations and structure contour maps on the surfaces of the Ohio Shale and the Berea Sandstone were generated by a contouring program called Golden Graphics, by Golden and Associates. This program plots and contours three-dimensional data sets according to parameters that can be specified within the program. These parameters were discussed in general in the Methods section of this paper, and the parameter values chosen for each plot will be presented in the discussion of each map.

Ohio Shale

The thickness of the Ohio Shale was not a primary concern of this study and for this reason only a structure contour map of the top of the Ohio Shale was constructed. A data set containing 130 points was used to generate the Ohio Shale structure contour map (Fig. 10). Program variables used in creating this map included the "Kriging" option to generate a gridding surface, a 25 line grid size, a smoothing factor of 2, and the program's default search method.

The surface of the Ohio Shale (Fig. 10) shows a general increase in depth to the east. This reflects an approximate dip of 0.24 degrees east or about 22 feet per mile. The Ohio Shale has a fairly smooth surface, except for an elongated structural high that trends SSW-NNE in the western third of this map, and a structural depression in the south-central portion centered on x-y coords of (2,018,750, 290,000). Both of these structures will be important in explaining Bedford deposition and thickness patterns.

Bedford Shale

The Bedford Shale isopach map was generated using 115 of the 130 data points. Program variables chosen for this map were identical to those used for the Ohio Shale structure contour map.

The Bedford map (Figs. 11a & 11b) does not show any

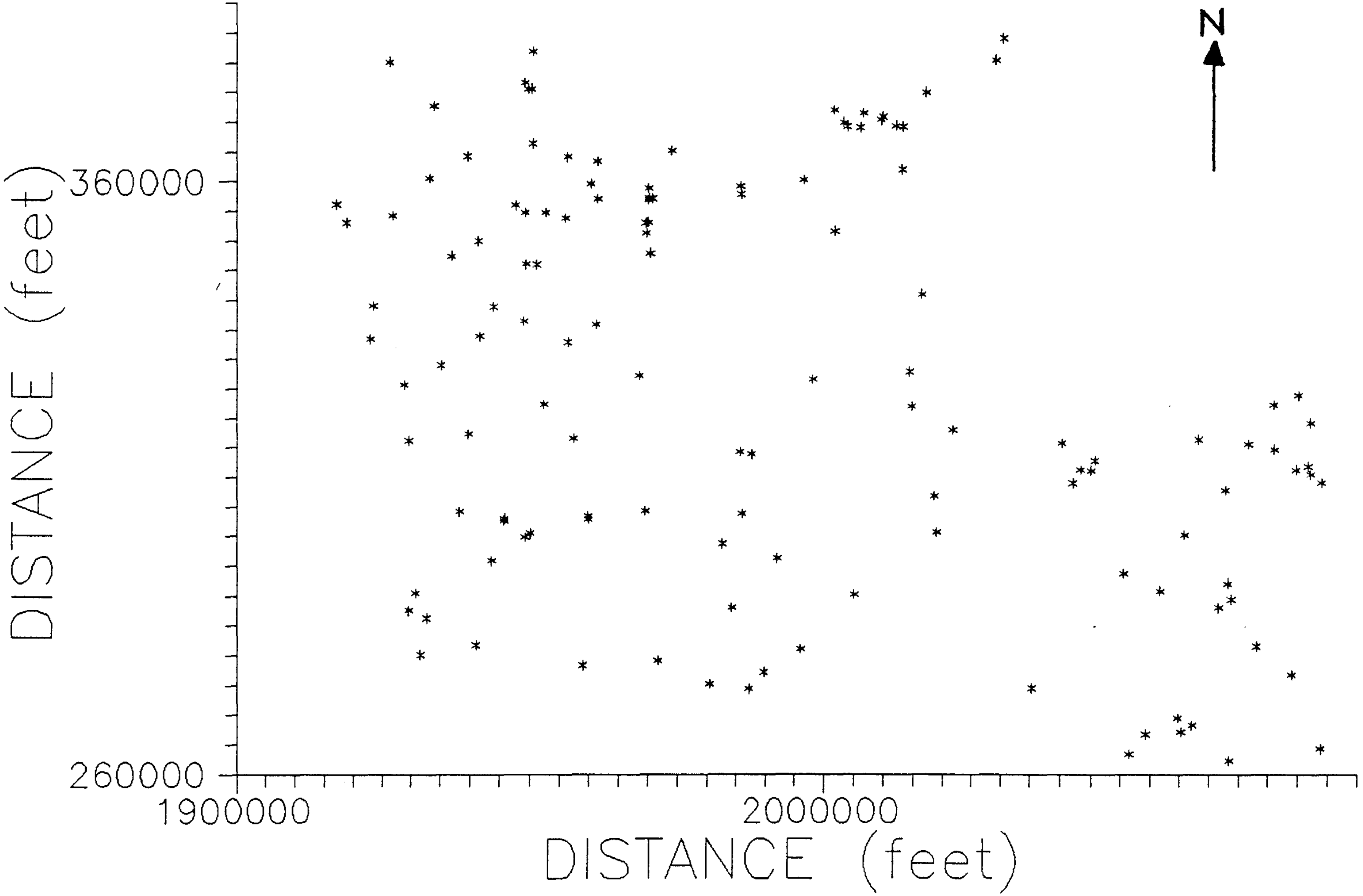

FIGURE 9 - Location of wells used to comprise the data set and to generate the isopach and surface structure contour maps. X-Y values are from the coordinate system used by the Ohio Geologic Survey.

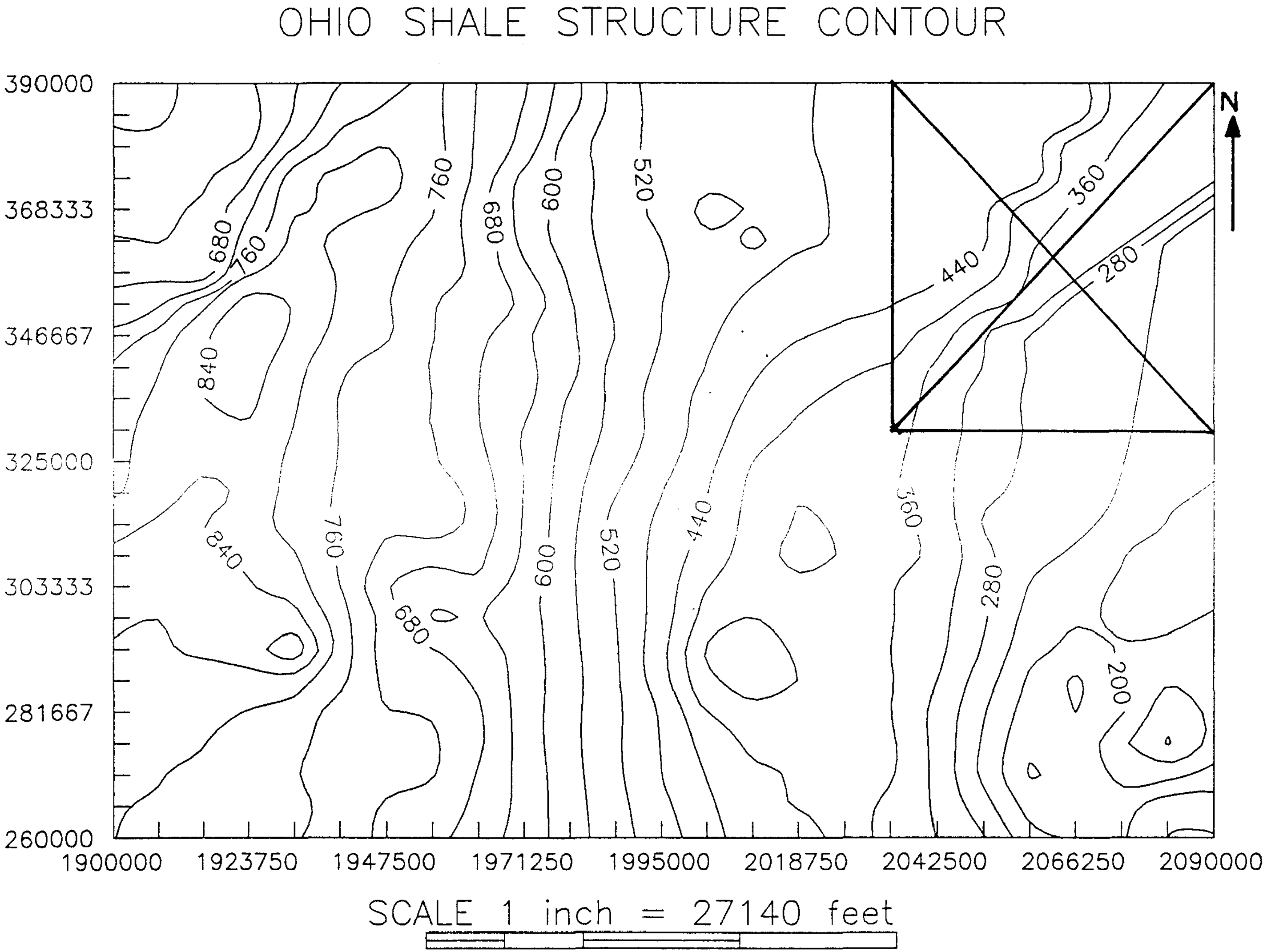

FIGURE 10 - Ohio Shale structure contour map. Contour interval is 40 feet. Area in the northeast corner has been discredited due to the absence of data points in this area.

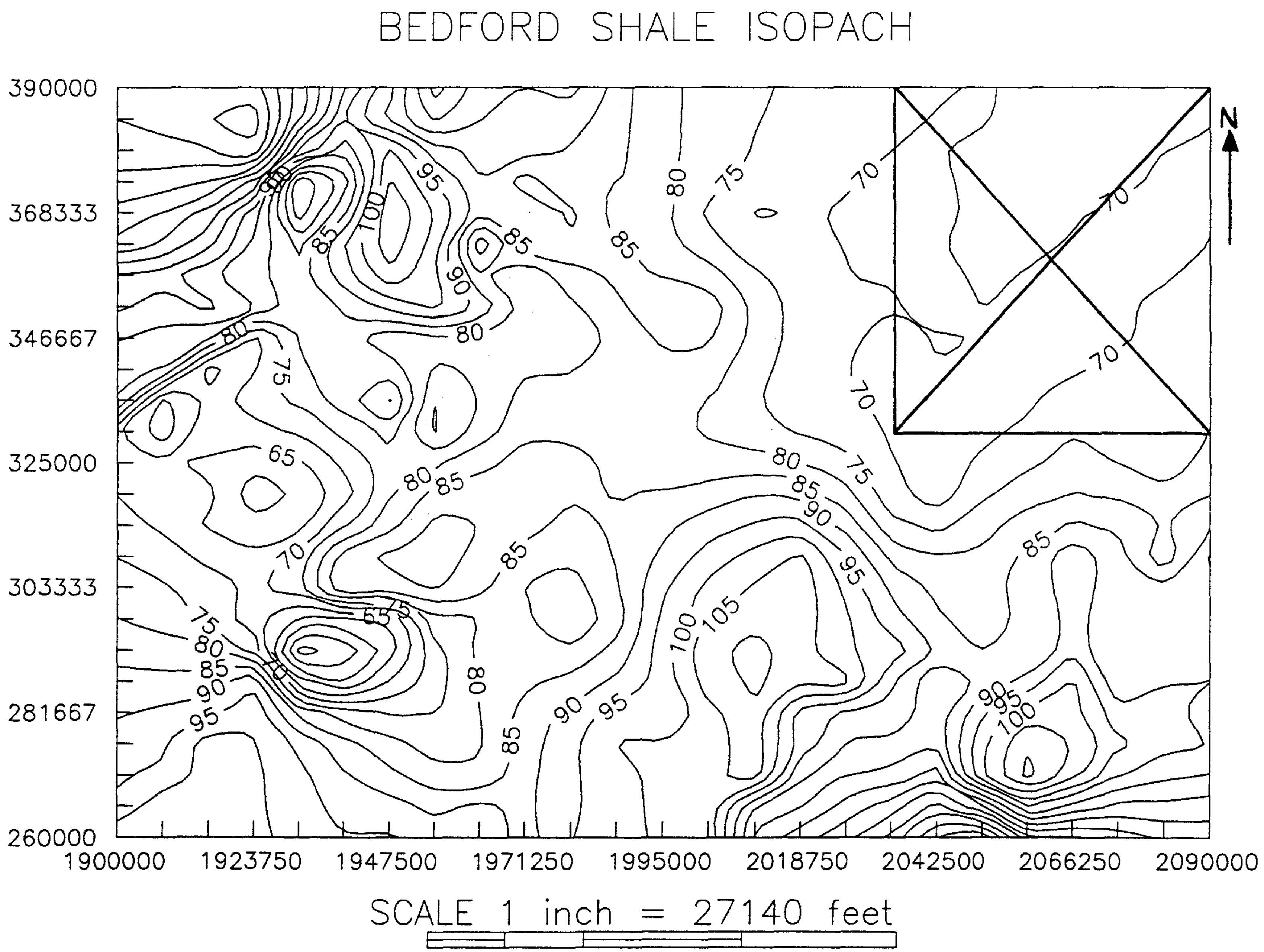

FIGURE 11a - Bedford Shale isopach map. Contour interval is 5 feet. Area in the northeast corner has been

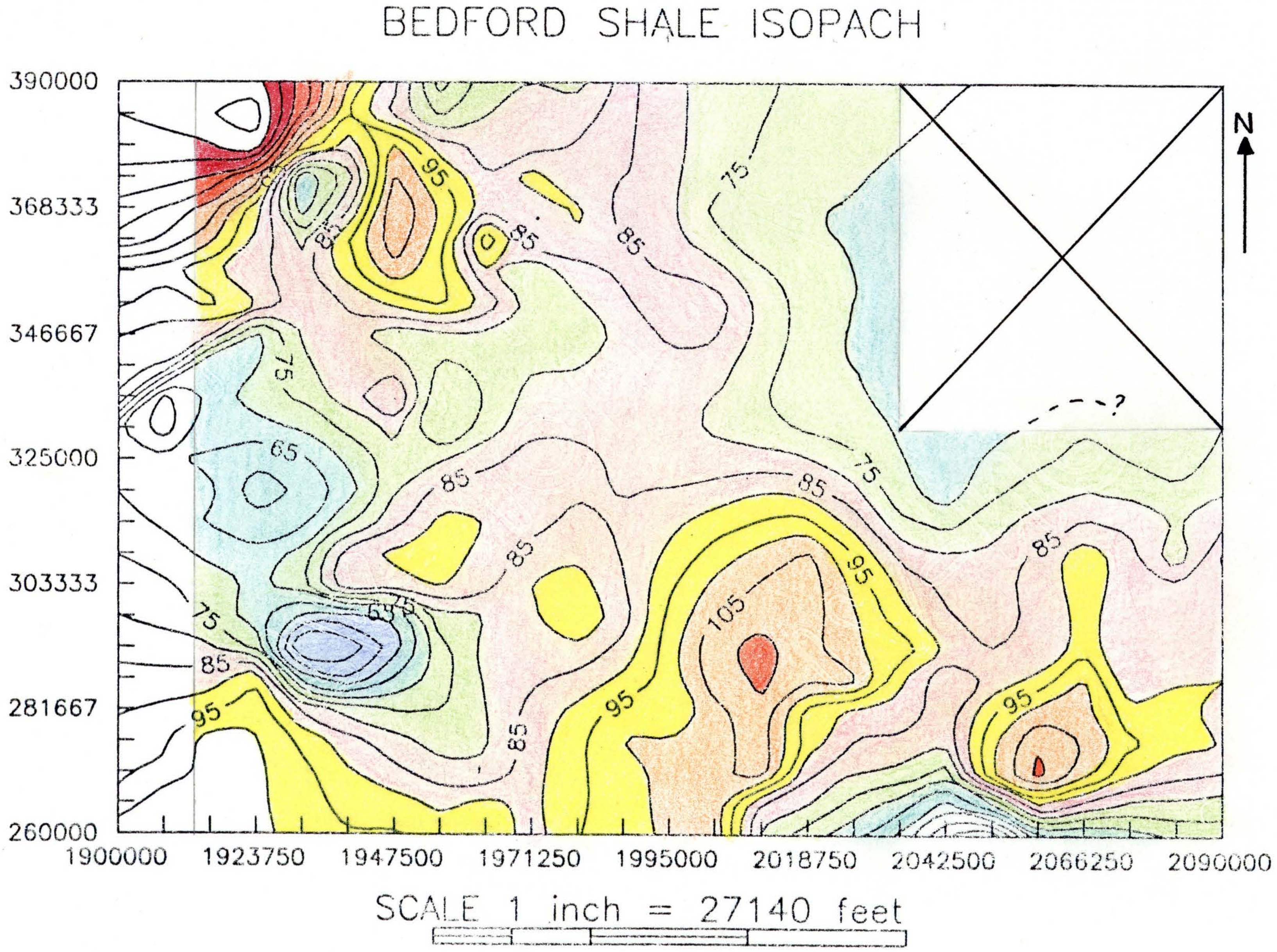

FIGURE 11b - Color Bedford Shale isopach map. Contour interval is 5 feet. Area in north-eastern corner has been discredited due to absence of data points in this area.

distinctive trend of thickness changes in any direction. This isopach instead shows numerous lobes of sediment oriented in a range of directions from north to east to southeast. Some areas of localized thinning are also seen, and are oriented within approximately the same range. This irregular distribution of thicknesses is unlike the pattern expected for a marine shale deposited by relatively uniform pelagic processes in a deep, relatively quiet environment. The western one-third of this map shows several areas where the Bedford Shale thickness is obviously reduced. These areas could be the result of several processes: 1) control on deposition by pre-existing topography (i.e., structural control), 2) early onset of Berea deposition, thereby excluding the fine-grained Bedford Shale, and 3) action of storm events and/or basinal currents, which preferentially deposited sediments in topographic lows. Similar controls may have influenced the development of the thick Bedford lobes, although the effect was the opposite.

The origin of the relatively thick Bedford Shale lobes can be adequately explained by the structural control influence of the Ohio Shale surface. The lobe seen in the northwest corner of the study area is elongated to the south-southeast, possibly following a steepening of the Ohio Shale surface around the north end of the elongate Ohio Shale high (compare Figs. 10 and 11b). The large lobe of thick Bedford sediment in the southcentral portion of this map also seems to reflect the surface of the Ohio Shale, since it lies directly over a structural low in the Ohio Shale. The orientations of most of the remaining lobes and thinning areas also seem to mirror variations in the surface of the Ohio Shale. The large area of reduced thickness in the western-central portion of the map lies upon the elongated structural high of the underlying shale unit. A final example of structural influence is easily seen in the southeast corner, where a thick layer of Bedford Shale lies within an Ohio Shale depression.

Encroachment of Berea sand could also explain some of these thickness changes. Prograding coarse sands from the west, northwest, and northeast may have overridden the Bedford and locally eliminated the deposition of fines. If this process is important, then thin Bedford Shale should be overlain by thick Berea Sandstone; this pattern is observed in the northwestern corner and along the west-central edge of the study area (compare Figs. 11b and 12b). A similar pattern of encroachment may also be expressed by the thicker lobe of Berea that extends from the northeastern corner of the Berea isopach map.

Berea Sandstone

Maps generated for the Berea Sandstone used the same grid program parameters used for the Bedford and Ohio Shale maps. One hundred fourteen data points were used to generate the Berea isopach map, whereas 130 data points were used for the Berea structure contour map.

The Berea isopach (Figs. 12a & 12b) shows a general trend of thinning to the east and southeast. The presence of the

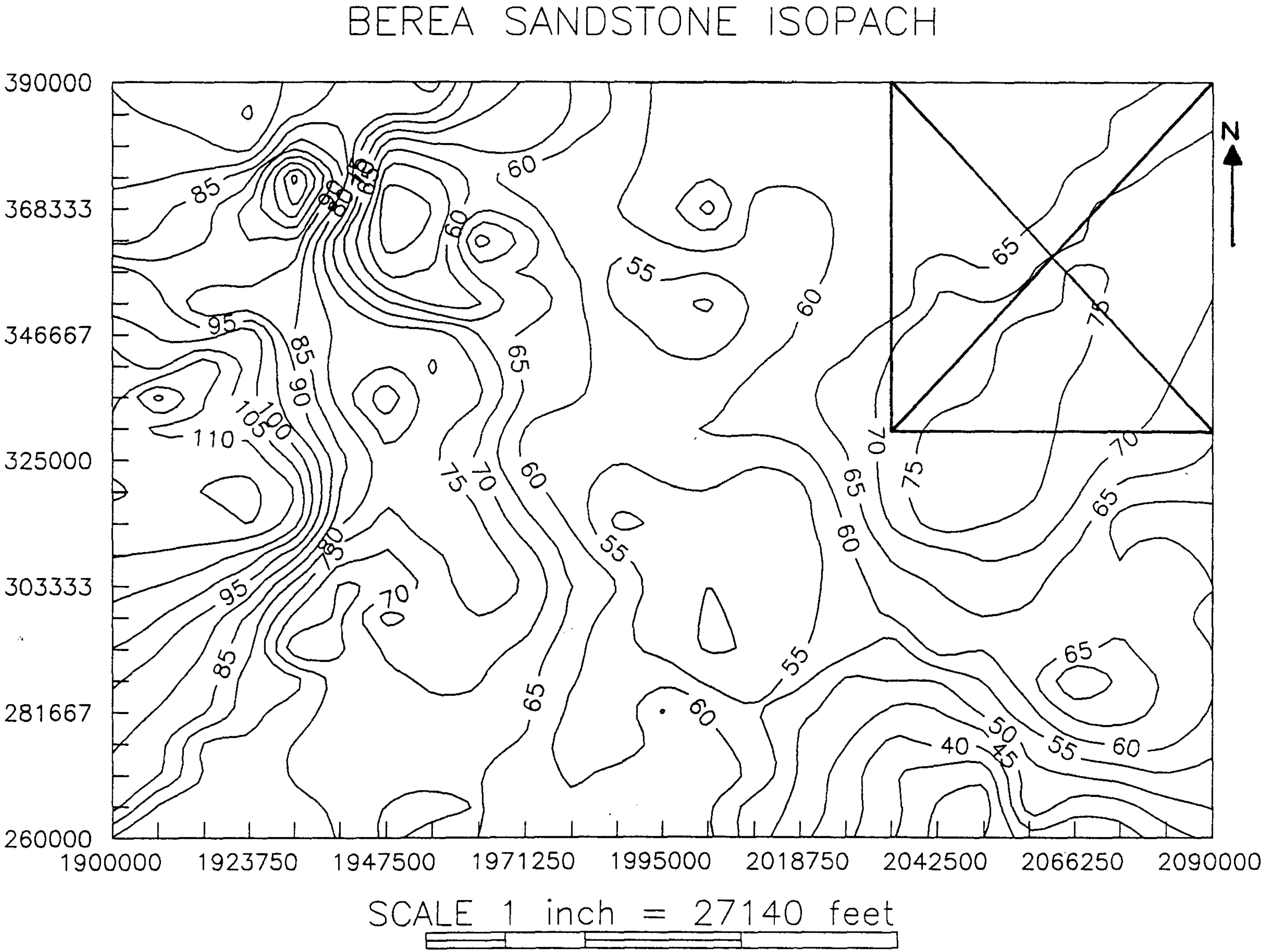

FIGURE 12a - Berea Sandstone isopach map. Contour interval is 5 feet. Area in the northeast corner has been discredited due to the absence of data points in this area.

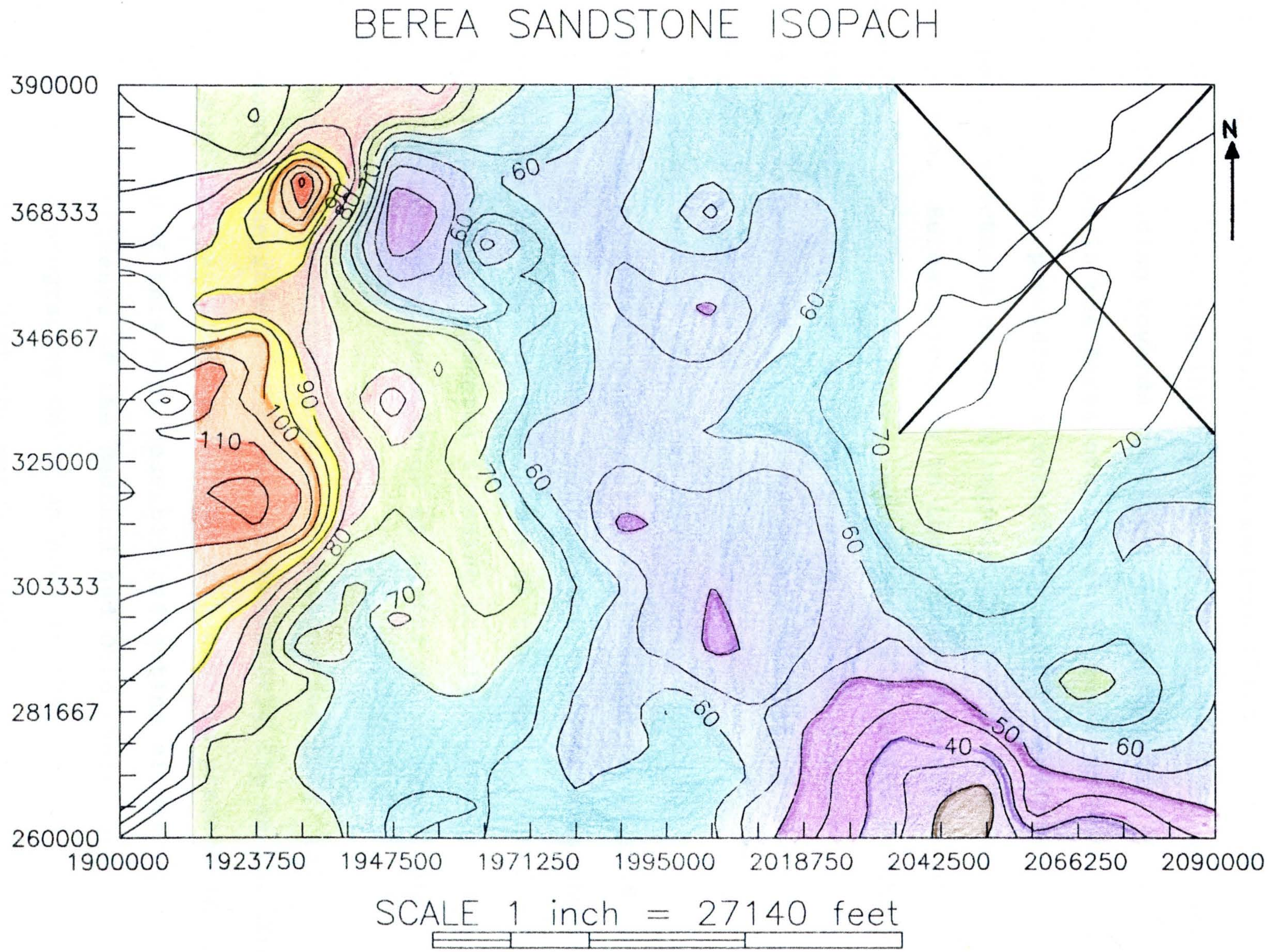

FIGURE 12b - Color Berea Sandstone isopach map. Contour interval is 5 feet. Color bands are 10 foot intervals. Northeast corner and west edge are omitted due to lack of data.

thick lobes of Berea sand in the western third of the study area is consistent with the interpretation of deposition in a delta complex prograding towards the south and southeast. Many of the thin areas in the Berea overlie thick zones of Bedford Shale, and vice versa, providing a relatively uniform Bedford/Berea composite thickness of approximately 150-160 feet across the study area. Berea thickness in the eastern two-thirds of the study area is fairly uniform, except for a decrease in the southeastern corner of the study area. Berea deposition may have been affected by structures in the underlying Bedford, but these effects seem to have been minor.

Past studies of the Berea have proposed that a southwest-to-northeast storm track distributed Berea sand in this shallowing environment. The distribution of even sheet-like sands across the eastern two-thirds of the map is consistent with this theory. A general thinning trend to the east can also be explained by deposition of distal delta front sands from a western source.

The Berea Sandstone structure contour map (Fig. 13) illustrates the same gentle east-southeasterly dip as the Ohio Shale surface. An elongated structural high is present in the western third of this map, possibly reflecting either the structural influence of the Bedford and Ohio shales or the effect of the prograding delta as seen in the Berea isopach map. Eastward from this high the Berea surface is fairly even and slopes steadily to the east or southeast.

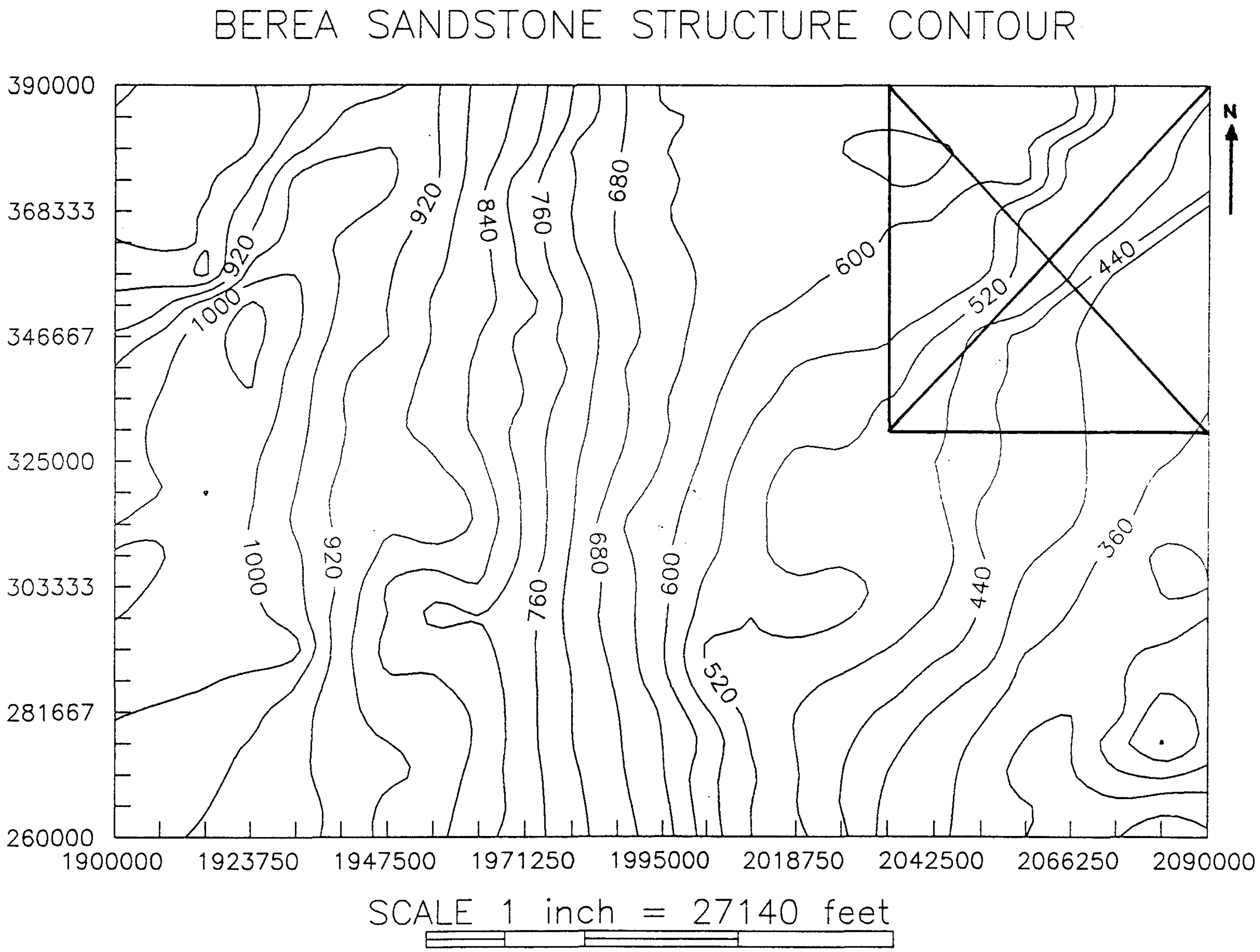

FIGURE 13 - Berea Sandstone structure contour. Contour interval is 40 feet. Area in northeast corner has been discredited due to absence of data in this area.

DISCUSSION AND SUMMARY

The most obvious changes in the thickness of the Bedford Shale are located near irregularities on the top of the Ohio Shale, suggesting depositional influence of structural elements in the Ohio Shale. The infilling of depressions or more rapidly subsiding zones of the Ohio Shale by the Bedford sediments and the thinning of the Bedford Shale across Ohio Shale structural highs suggest that sediment was transported downslope by bottom-seeking, gravity-driven flows, perhaps generated during storm events. A gradually shoaling environment, as has been suggested for deposition of the Bedford/Berea sequence, would be favorable for the development of storm-induced turbidity flows, which then flowed towards the east and southeast into the deeper waters of the Ohio Bay. The lobes of sediment in the Bedford isopach nicely illustrate this orientation. The zones of thin Bedford in the west may have been caused by diversion of bottom-seeking flows around and off of the "topographic high" present at that time. This thin zone may also have been affected by prograding Berea sands, which covered the Bedford Shale and prevented further deposition in this area. In this case, structural influence, action of storm events, and Berea progradation were probably all important in determining the present-day distribution of the Bedford Formation.

The Berea is interpreted as the coarser sediments of a delta complex that prograded to the south and southeast. Some areas of the Berea even suggest progradation to the east. The north-northeast trending delta front may reflect influence of a southwest-northeast trending storm track. This storm track moved sand parallel to the delta front by the influence of longshore currents. Berea sands were moved into deeper waters by turbidity flows which helped to maintain the generally uniform thickness of the sands to the east. The Berea isopach also suggests the presence of a lobe of sediment derived from the northeast; due to the absence of data points in the northeastern corner of the study area, however, further work will be needed to investigate this pattern.

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APPENDIX A

Listing of well data which was collected from gamma-ray and neutron lithology/porosity logs. All data were collected from well logs stored at the Ohio Geologic Survey - Subsurface Section. All numeric data are recorded in feet. Symbols used are as follows: X, Y - Geographic coordinates of well, BE - Berea Sandstone, BD - Bedford Shale, OH - Ohio Shale, Thick - thickness of unit, Elv - elevation of surface of unit above sea level.

Permit Number	County	Township	Log Datum	X	Y	Top BE	Top BD	Top OH	BE Thick	BD Thick	BE Elv	OH Elv
2500	Morrow	Harmony	1247	1931600	280100	310	380	470	70	90	937	777
2763	Morrow	Harmony	1217	1932750	286250	270	345	405	75	50	947	812
3335	Morrow	Harmony	1206	1930775	290525	168	230	270	62	40	1038	936
2508	Morrow	Harmony	1218	1929600	287550	245	330	425	85	95	973	793
2672	Morrow	Chester	1139	1943700	295850	315	380	425	65	45	824	714
2130	Morrow	Chester	1215	1941075	281725	333	400	480	67	80	882	735
3464	Morrow	Chester	1192	1949275	299925	320	408	474	88	66	872	718
2495	Morrow	Chester	1242	1958990	278310	372	440	515	68	75	870	727
2737	Morrow	Franklin	1248	1929550	316250	278	400	458	122	58	970	790
3777	Morrow	Franklin	1375	1939700	317350	472	554	621	82	67	903	754
1435	Morrow	Franklin	1209	1938300	304175	285	350	444	65	94	924	765
3510	Morrow	Franklin	1212	1945750	303000	346	410	502	64	92	866	710
1838	Morrow	Franklin	1333	1957400	316700	395	475	568	80	93	938	765
3434	Morrow	Franklin	1212	1945670	302650	346	412	493	66	81	866	719
2657	Morrow	Franklin	1310	1959850	303450	455	536	620	81	84	855	690
1780	Morrow	Franklin	1298	1959900	302950	438	515	610	77	95	860	688
2704	Morrow	Perry	1264	1952400	322450	368		534			896	730
3686	Morrow	Perry	1381	1961150	336000	536	616	690	80	74	845	691
2517	Morrow	Perry	1410	1956500	333050	550	630	692	80	62	860	718
2621	Morrow	Perry	1426	1948990	336590	532	597	690	65	93	894	736
2315	Morrow	Perry	1373	1949310	346110	455	540	610	85	70	918	763
2368	Morrow	Perry	1358	1951150	346050	460	552	620	92	68	898	738
3573	Morrow	N.Bloomfield	1296	1933900	372750	292	422	468	130	46	1004	828
3423	Morrow	N.Bloomfield	1362	1933150	360600	368	456	538	88	82	994	824
3432	Morrow	N.Bloomfield	1204	1917050	356200	372		555			832	649
2772	Morrow	N.Bloomfield	1202	1926275	380180	362	430	570	68	140	840	632
2225	Morrow	N.Bloomfield	1372	1939650	364300	419	485	580	66	95	953	792
3537	Morrow	Troy	1304	1949775	375617	345	399	498	54	99	959	806
3656	Morrow	Troy	1263	1949150	376700	287	328	448	41	120	976	815
3666	Morrow	Troy	1345	1950300	375650	380	421	532	41	111	965	813
3616	Morrow	Troy	1424	1950500	366475	484	520	637	36	117	940	787
3802	Morrow	Troy	1389	1956400	364150	502	552	650	50	98	887	739
2399	Morrow	Troy	1302	1947625	356050	380	435	537	55	102	922	765
2919	Morrow	Troy	1294	1952650	354850	406		556			888	738
3164	Morrow	Troy	1304	1949250	354850	394	450	552	56	102	910	752
3743	Morrow	Troy	1282	1956050	353920	412	464	565	52	101	870	717

Permit Number	County	Township	Log Datum	X	Y	Top BE	Top BD	Top OH	BE Thick	BD Thick	BE Elv	OH Elv
2905	Morrow	Congress	1405	1941400	350050	463	533	618	70	85	942	787
3470	Morrow	Congress	1270	1926750	354300	240	330	420	90	90	1030	850
3615	Morrow	Congress	1218	1918850	353100	150	225	347	75	122	1068	871
1915	Morrow	Congress	1378	1936950	347450	419	495	581	76	86	959	797
3768	Morrow	Congress	1386	1943900	339000	497	559	657	62	98	889	729
3887	Morrow	Congress	1270	1923400	339100	226	287	411	61	124	1044	859
3832	Morrow	Congress	1252	1922900	333450	214	288	405	74	117	1038	847
3837	Morrow	Congress	1415	1941700	334000	517		677			898	738
3781	Morrow	Congress	1369	1935122	329057	420	492	574	72	82	949	795
3472	Morrow	Congress	1287	1928750	325750	314	388	486	74	98	973	801
3702	Knox	Wayne	1061	1984300	288100	370		515			691	546
1600	Knox	Wayne	1097	1982650	298900	420	480	553	60	73	677	544
1662	Knox	Wayne	1188	1971720	279080	418	484	572	66	88	770	616
1499	Knox	Wayne	1152	1980550	275100	440	495	590	55	95	712	562
2886	Knox	Wayne	1092	1987300	274350	408	470	568	62	98	684	524
2466	Knox	Morris	1084	1992100	296400	450	502	595	52	93	634	489
3471	Knox	Morris	1042	1989800	277200	374	426	532	52	106	668	510
3282	Knox	Morris	1031	1996075	281100	400	468	562	68	94	631	469
2584	Knox	Morris	1070	2005080	290300	590	638	751	48	113	480	319
3287	Knox	Monroe	986	2035370	274480	584		616			402	370
1712	Knox	Monroe	1127	2079100	276775	650	713	808	63	95	477	319
3799	Knox	Howard	1015	2051600	263350	668	698	742	30	44	347	273
1888	Knox	Howard	926	2054300	266750	604	625	750	21	125	322	176
2738	Knox	Howard	915	2060275	267150	590	656	742	66	86	325	173
3821	Knox	Howard	1032	2059650	269550	736		878			296	154
2994	Knox	Union	954	2062125	268300	646	694	802	48	108	308	152
2138	Knox	Union	1183	2083950	264220	922		1082			261	101
3558	Knox	Union	1082	2068240	292180	732	794	886	62	92	350	196
3639	Knox	Union	1083	2068800	289500	746	821	896	75	75	337	187
3581	Knox	Union	982	2068450	262290	692	725	792	33	67	290	190
2986	Knox	Union	1088	2066630	288090	758	834	936	76	102	330	152
3575	Knox	Union	1182	2073110	281540	854		1004			328	178
1614	Knox	Middlebury	1192	1985600	314500	522		672			670	520
2805	Knox	Middlebury	1162	1987590	314100	526	574	660	48	86	636	502
1594	Knox	Middlebury	1149	1950100	300550	455	512	600	57	88	694	549
1676	Knox	Middlebury	1288	1969400	304400	497	574	655	77	81	791	633
1645	Knox	Middlebury	1088	1985950	304000	416	478	562	62	84	672	526
2040	Knox	Pike	1323	2021900	318150	821		961			502	362
1418	Knox	Pike	1324	2014800	322100	820	870	957	50	87	504	367
2817	Knox	Pike	1200	2018730	306900	697	748	857	51	109	503	343
1589	Knox	Pike	1206	2019050	300800	654	708	815	54	107	552	391
3515	Knox	Brown	1221	2045750	312820	787		943			434	278
3522	Knox	Brown	1155	2045140	311140	656	730	809	74	79	499	346
3686	Knox	Brown	1223	2043400	311280	700	774	858	74	84	523	365
3519	Knox	Brown	1285	2040330	315770	770	850	916	80	66	515	369
3517	Knox	Brown	1335	2042090	309010	830	898	978	68	80	505	357
2205	Knox	Brown	1008	2060890	300220	642		790			366	212
2995	Knox	Brown	990	2056700	290900	630	694	776	64	82	360	214
2236	Knox	Brown	1164	2050600	293750	732		882			432	282

Permit Number	County	Township	Log Datum	X	Y	Top BE	Top BD	Top OH	BE Thick	BD Thick	BE Elv	OH Elv
3233	Knox	Jefferson	1120	2071670	315630	735		880			385	240
3178	Knox	Jefferson	1102	2063250	316450	684	758	840	74	82	418	262
826	Knox	Jefferson	965	2082230	310560	656	727	787	71	60	309	178
2802	Knox	Jefferson	1060	2079800	311310	755	814	892	59	78	305	168
3022	Knox	Jefferson	1171	2081840	311890	840	896	974	56	78	331	197
3024	Knox	Jefferson	982	2076050	314750	618	673	756	55	83	364	226
2569	Knox	Jefferson	1098	2067800	307800	722	774	869	62	95	376	229
2950	Knox	Jefferson	892	2084100	309125	573	630	722	57	92	319	170
3114	Knox	Jefferson	1170	2076100	322300	794	860	936	66	76	376	234
3175	Knox	Jefferson	1212	2080150	323850	846	914	986	68	72	366	226
3136	Knox	Jefferson	912	2082240	319290	568		706			344	206
601	Richland	Perry	1249	1970000	353250	426	493	576	67	83	823	673
602	Richland	Perry	1198	1969700	351350	380	459	523	79	64	818	675
617	Richland	Perry	1282	1969517	353084	398	457	552	59	95	884	730
603	Richland	Perry	1207	1970300	348000	422	484	560	62	76	785	647
330	Richland	Perry	1224	1968450	327350	424	483	570	59	87	800	654
401	Richland	Jefferson	1365	2001775	351800	730	778	867	48	89	635	498
594	Richland	Jefferson	1292	1998050	326850	664	725	806	61	81	628	486
502	Richland	Worthington	1083	2016500	341150	521	584	656	63	72	562	427
599	Richland	Worthington	1145	2014350	328000	612	674	750	62	76	533	395
583	Richland	Troy	1358	1950500	381925	422	502	578	80	76	936	780
618	Richland	Troy	1300	1974000	365300	555	610	702	55	92	745	598
624	Richland	Troy	1316	1970000	358950	504	585	670	81	85	812	646
616	Richland	Troy	1348	1960300	359700	462	545	608	83	63	886	740
642	Richland	Troy	1343	1961350	363520	474	550	621	76	71	869	722
308	Richland	Troy	1352	1961500	357200	485	549	632	64	83	867	720
299	Richland	Troy	1298	1969950	356950	494	555	632	61	77	804	666
598	Richland	Troy	1295	1970100	357325	492	551	630	59	79	803	665
296	Richland	Troy	1307	1970675	357250	510	578	655	68	77	797	652
342	Richland	Washington	1306	2009550	370490	700	753	825	53	72	606	481
353	Richland	Washington	1258	2009850	371000	630	695	765	65	70	628	493
361	Richland	Washington	1457	2003275	370050	835	907	980	72	73	622	477
386	Richland	Washington	1378	2006525	371600	738	806	882	68	76	640	496
390	Richland	Washington	1386	2001650	372200	760	823	900	63	77	626	486
385	Richland	Washington	1391	2006075	369175	794	862	928	68	66	597	463
424	Richland	Washington	1409	2003900	369400	800	875	949	75	74	609	460
409	Richland	Washington	1240	2012050	369500	610	686	749	76	63	630	491
408	Richland	Washington	1437	1996525	360450	784	838	915	54	77	653	522
527	Richland	Washington	1152	1985700	359375	470	534	605	64	71	682	547
528	Richland	Washington	1157	1985800	357950	464	530	609	66	79	693	548
578	Richland	Monroe	1296	2030450	384200	691	747	829	56	82	605	467
576	Richland	Monroe	1266	2029180	380515	676	746	807	70	61	590	459
415	Richland	Monroe	1253	2017250	375100	625	697	760	72	63	628	493
421	Richland	Monroe	1230	2013275	369400	600	678	743	78	65	630	487
419	Richland	Monroe	1401	2013050	362150	775	852	918	77	66	626	483