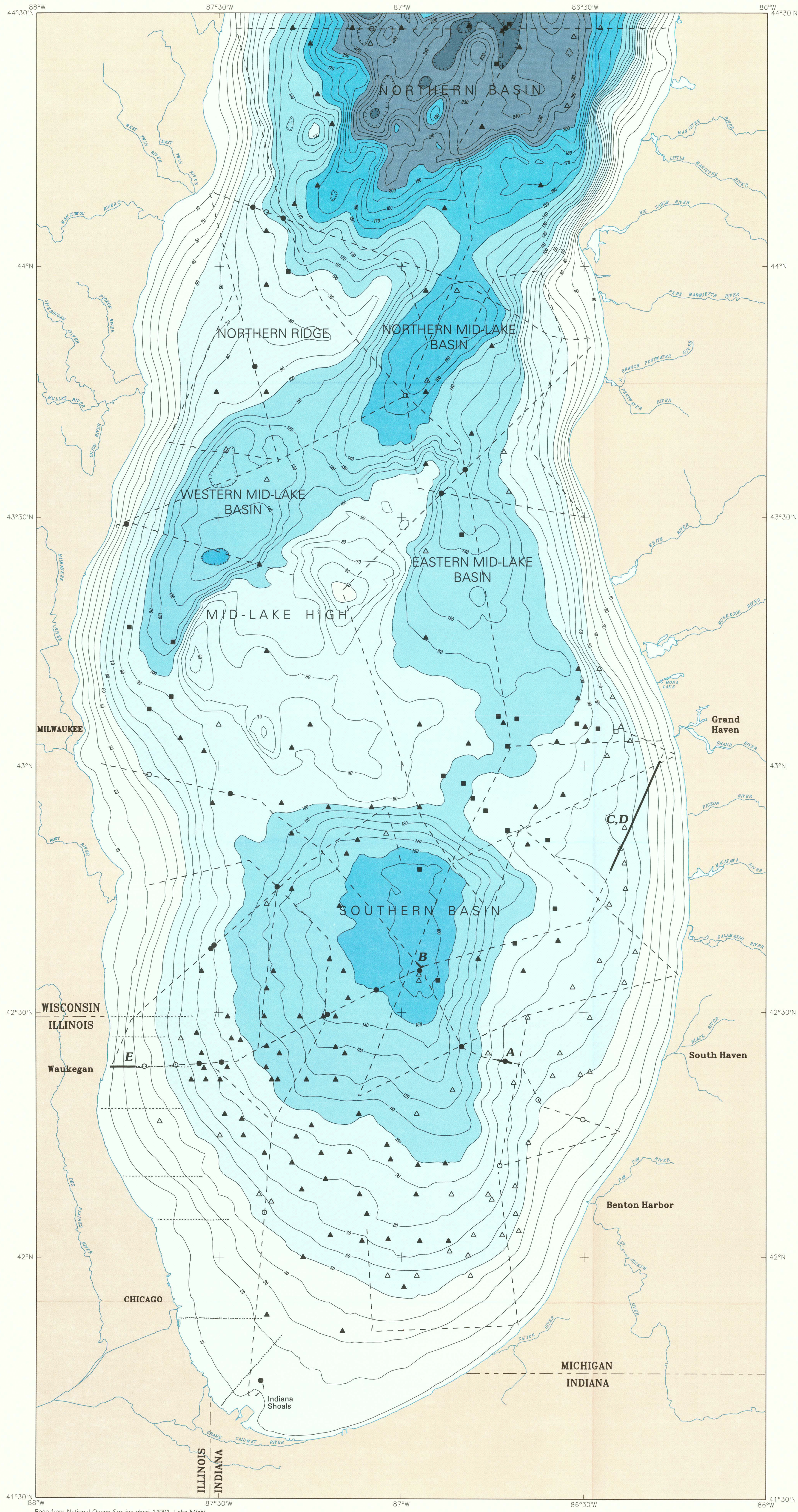

Base from National Ocean Service chart 14901, Lake Michigan, 1986
Coastline digitized from National Ocean Service charts 14903, 14904, 14905, 14906, and 14907, scale 1:120,000
Mercator projection. Latitude of true scale 44° N.
Not to be used in navigation

Figure 1.—Bathymetric map showing core sampling locations and the tracklines along which seismic profiles *A–E* were collected (see figure 4).

SCALE 1: 500 000

10 0 10 20 30 NAUTICAL MILES

10 0 10 20 30 KILOMETERS

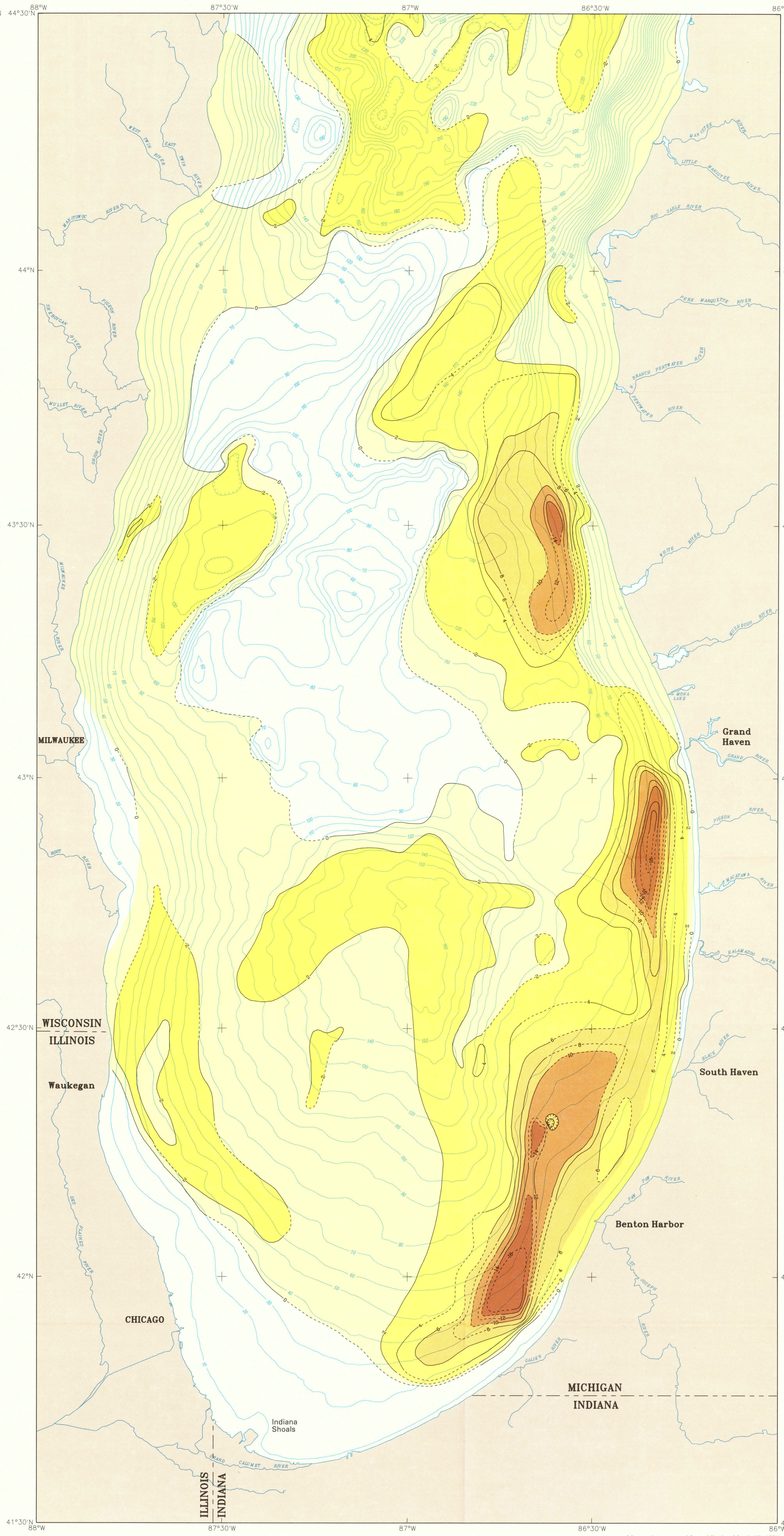

Figure 2.—Postglacial-sediment isopach map.

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EXPLANATION FOR FIGURE 1

Trackline from RV *Roger Simons* and RV *Laurentian* cruises—Heavy line-segment with letter label refers to seismic profile in figure 4

Trackline from RV *Neptune* cruise—Heavy line-segment with letter label refers to seismic profile in figure 4

Locality of core sample showing maximum postglacial sediment thickness:

- Hough (1955, 1958)
- Lineback (1970, 1971, 1974); Lineback and Gross (1972); Wickham and others (1978); ISGS, unpub. data, 1975
- This study

Locality of core sample showing minimum postglacial sediment thickness:

- Hough (1955, 1958)
- Lineback (1970, 1971, 1974); Lineback and Gross (1972); Wickham and others (1978); ISGS, unpub. data, 1975
- This study

Bathymetric contour—Interval 10 m. Where not marked with depth value, closed contour indicating depression is hachured

Bathymetric 50-m intervals—Shoreline represents International Great Lakes Datum of 1955 (576.8 ft [175.8 m] above sea level)

50
100
150
200
250

EXPLANATION FOR FIGURE 2

Postglacial sediment isopach—Interval 2 m. Hachures indicate thinning; isopachs dashed where inferred or uncertain. Thickness was measured from seismic-reflection profiles, assuming a sound velocity of 1500 m/s in water and sediment, and from cores whose localities are shown in figure 1

Sediment-thickness intervals, in meters

0–2
2–6
6–10
10–14
>14

Bathymetric contour—Interval 10 m. Where not marked with depth value, closed contour indicating depression is hachured

DISCUSSION

INTRODUCTION

Postglacial lacustrine sediments record much of the history of Lake Michigan, including the history of lake-level changes and the response of the lake to those changes. Lake-level fluctuations directly influence erosion rates along the Lake Michigan coast, and the history of lake-level changes during the past several thousand years is a key to understanding likely future trends. This report describes the thickness and distribution of the postglacial lacustrine deposits of Holocene age beneath the southern two-thirds of Lake Michigan.

Thickness estimates for postglacial sediment were derived primarily from a combination of high-resolution seismic-reflection profiles and cores that were collected in Lake Michigan south of lat 44°30′ N. Three research vessels were contracted by the U.S. Geological Survey for the field program. Data were collected aboard the RV *Roger Simons* (U.S. Environmental Protection Agency) in September 1988, along 950 km of tracklines, and aboard the RV *Laurentian* (University of Michigan) in June 1989, along 1250 km of tracklines (fig. 1). An additional 160 km of 3.5-kHz seismic profiles were collected along the Illinois coast in May 1989, aboard the RV *Neptune* (Hydrographic Survey Co.) (fig. 1). Positioning was determined with a Megapulse Accufix 500 Loran-C receiver. Two types of seismic profiling systems were employed: (1) an ORE 3.5-kHz system used along seismic lines and during coring operations, and (2) a boomer-type system that used a Huntec source (500 joules) in 1988 and an ORE Geopulse source (280 joules) in June 1989. The boomers were triggered every 0.5 s, and the seismic signals were filtered between 300 and 5000 Hz. The 3.5-kHz and boomer seismic profiles were usually recorded at a 0.25-s sweep rate. The 3.5-kHz system penetrated the lacustrine deposits with resolution superior to that of the boomer-type systems; therefore, most of the interpretations in this report are derived from the 3.5-kHz profiles. Seismic interpretations were verified with stratigraphy from cores (Colman and Foster, 1990) collected at 29 sites (fig. 1) during the cruises in September 1988 and June 1989.

The isopach map (fig. 2) was generated from the data described above, supplemented by additional previously published information. Cores described by Hough (1955, 1958) and the Illinois State Geological Survey (ISGS) (Lineback and others, 1970, 1971, 1974; Lineback and Gross, 1972; Wickham and others, 1978; ISGS, unpub. data, 1975) provided additional values of sediment thickness (fig. 1). Where our data were sparse, isopachs were dashed and were positioned parallel to isopachs derived by Wickham and others (1978). Bathymetric features, such as basins and local highs, were also used as an aid in contouring areas having sparse data.

BASIN MORPHOLOGY

The bathymetric map (fig. 1) was created by gridding and contouring digital depth soundings (National Geophysical Data Center, 1987) using Interactive Surface Modeling (ISM) software developed by Dynamic Graphics, Inc. The bathymetry reveals several major basins that affect postglacial lacustrine sedimentation. Glacial scouring of eastward dipping Paleozoic bedrock formed the overall basin morphology (Thwaites, 1949; Emery, 1951; Hough, 1958; Wickham and others, 1978). Soft shale underlies the deep basins, and cuestas of resistant dolomite, limestone, and sandstone form ridges between the basins. Till deposited by the retreating late Wisconsinan glacier partly fills bedrock depressions, smoothing the form of the basins. Minor readvancements of the glacier deposited moraines and till wedges that in places have formed basin slopes and sills between basins.

The major southern and northern basins of the lake are separated by the mid-lake high, three smaller mid-lake basins, and a ridge that trends northeast (fig. 1). The three small mid-lake basins flank the mid-lake high to the east, west, and north. A bedrock ridge, hereafter referred to as the northern ridge, extends northeastward from the west side of the lake, separating the western and northern mid-lake basins from the major northern basin.

BOUNDARY BETWEEN GLACIAL AND POSTGLACIAL DEPOSITS

Mapping the thickness and distribution of the postglacial sediments requires clear definition of the contact between glacial and postglacial lacustrine deposits. In his early work on core stratigraphy (fig. 3*A*), Hough (1955) suggested that deglaciation was immediately followed by a low-level lake, Lake Chippewa, which had a level of 107 m below present lake-level. The formation of Lake Chippewa was attributed to deglaciation of the isostatically depressed northern outlets near North Bay, Ontario (Hough, 1955; also see location map) about 10.3 ka (Larsen, 1987). Hough (1955) showed that cores from water depths greater than 107 m in Lake Michigan contain a complete "deepwater sequence" consisting of gray clay that grades downward into red clay (fig. 3*A*). Cores from water depths less than 107 m contain a sand and shell zone that replaces part of the "deepwater sequence". This sand and shell zone marks the unconformity associated with the transgression that followed the low Chippewa level.

In the seismic and core stratigraphy of the Lake Michigan Formation (figs. 3*B, C*) determined by the ISGS (Lineback and others, 1970, 1971, 1974; Wickham and others, 1978), the sand and shell layer separates the overlying Waukegan (dark-gray silty clay), Lake Forest (gray silty clay), and Winnetka (brown silty clay) Members from the underlying Sheboygan (reddish-brown clay) and South Haven (reddish-gray clay) Members. Previous publications by the ISGS have simplified the color scheme by referring to the Waukegan, Lake Forest, and Winnetka Members as gray clay and the Sheboygan and South Haven Members as red clay. Wickham and others (1978) and Lineback and others (1979) suggested that the upper Sheboygan Member contains reworked red clay that was deposited over the Wilmette Bed (part of the Sheboygan Member) during the regression of the lake to the low Chippewa level. Another possibility is that the red clay of the upper Sheboygan Member may have come from meltwater that flowed across the Upper Peninsula of Michigan into the Lake Michigan basin during the Marquette advance (9.9 ka) in the Superior basin (Drexler and others, 1983). The red color of the clay originates from the iron-rich bedrock in the Lake Superior basin (Dell, 1975; Lineback and others, 1979). This potential source of red glacial clay was cut off from the Lake Michigan basin with the retreat of the Marquette ice shortly after about 9.8 ka (Drexler and others, 1983; Teller, 1985; Larsen, 1987). Wickham and others (1978) and Lineback and others (1979) suggested that a shift from glaciolacustrine sedimentation to deposition of local reworked sediment and sediment from river input resulted in a gradual change in deposition, from the red Sheboygan Member to the brown Winnetka Member in the deep basins. Following the Chippewa low stage, the lake transgressed to the Nipissing high lake-level and has remained relatively high since. During this time, the gray Lake Forest and Waukegan Members of Lineback and others (1970) were deposited.

In accord with previous core stratigraphy (figs. 3*A–C*), we define the contact between glacial and postglacial lacustrine sediments as the unconformity between the sand and shell layer (at the base of the gray clay) and the red clay (fig. 3*D*). This sharp stratigraphic break marks the transgression of lake level from the low Chippewa level to the high Nipissing level, the Chippewa unconformity. The equivalent stratigraphic break in the deep basin cores is less clear, because the transition from red to gray clay is gradational. Furthermore, deposition of reworked red clay or red glacial clay derived from the Marquette advance in Lake Superior may slightly postdate the opening of the North Bay outlet. In the deep basins we recognize the glacial-postglacial boundary within the transition zone of red to gray clay.

Using seismic stratigraphy, we separate the Lake Michigan Formation into a lower unit (Qll) and an upper unit (Qlu) (fig. 3*D*), which cores show are composed of glaciolacustrine red silty clay and postglacial lacustrine gray silty clay, respectively (Colman and Foster, 1990). The color and grain-size scheme of the Lake Michigan Formation is simplified as red and gray clay (fig. 3*D*) to be consistent with previous work. A continuous, planar reflection (R2) in part represents an unconformity at the base of the unit Qlu; this unconformity truncates underlying seismic units in the nearshore and basin slopes to depths between 80 and 100 m below present lake level. The planar, smooth reflection and absence of erosional channeling of the reflector suggest that the unconformity was formed subaqueously by wave erosion. We infer that the time-transgressive Chippewa unconformity formed during the transition from the low Chippewa level at about 10.3 ka (Larsen, 1987) to the high Nipissing level at about 4.8 ka (Larsen, 1985a,b). The sand and shell layer in cores is the basal transgressive sand that was deposited as lake level rose. The maximum depth of the Chippewa low level is questionable because the deepest extent of the unconformity formed at wave base, and the transition from an erosional surface to a conformable surface in the deep basin is gradational. There is no evidence in seismic profiles of a regressive unconformity that may have formed with the fall of lake level to the low Chippewa level. The transgression that followed the low Chippewa level most likely eroded any regressive deposits and paleochannels that formed as lake level fell.

A second reflection (R1) locally occurs between 42 and 94 m below present lake level, usually less than 1 m above the basal reflection (R2) of the postglacial unit (Qlu). In some places, specifically on the western slope of the southern basin, the upper reflection (R1) converges basinward with the lower reflection (R2); in other areas, particularly on the eastern slope of the southern basin, the lower reflection (R2) fades out basinward before converging with reflection R1 (fig. 4*A*). In either case, reflection R2 represents a conformable contact between the glacial and postglacial lacustrine deposits that can be traced to the deep basins (fig. 4*B*), where reflection R2 closely correlates with the transition from red to gray clay observed in cores. Landward, the upper of the two reflections (R1) converges with and onlaps the lower reflection (R2) (fig. 4*D*). The lens of sediment locally preserved between reflectors R1 and R2 is primarily a transgressive lacustrine deposit. The upper reflection (R1) may occur at a facies change within the postglacial unit, suggesting that a change from relatively high-energy to low-energy deposition resulted as lake level transgressed.

POSTGLACIAL SEDIMENT THICKNESS AND DISTRIBUTION

For mapping purposes, we define the postglacial lacustrine deposit of the upper Lake Michigan Formation (Qlu) as a seismic sequence (fig. 3*D*) that is equivalent to the gray clay revealed in cores. The upper boundary of the seismic sequence forms the lake floor except where no postglacial sediment occurs in areas of erosion or nondeposition (fig. 2). The lower boundary is the reflection (R2) that marks the Chippewa unconformity, and, in the deep basin, the conformable contact between glacial and postglacial sediment. The isopach map (fig. 2) reveals an asymmetric distribution of postglacial sediment beneath the deep basins, marginal slopes, and nearshore zone of Lake Michigan.

The most prominent feature of the isopach map is the thick wedge of postglacial sediment that forms three distinct lobes along the eastern slope of the southern basin and along the eastern mid-lake basin (fig. 2). The maximum thickness (almost 20 m) occurs along the basin slope, so that the postglacial deposits thin both shoreward and basinward. In cross section (figs. 4*C, D*), the lobes contain parallel, weak-to-moderate-strength-, continuous reflections that converge toward the nearshore zone and deep basins. Penetration in the 3.5-kHz profiles was locally hindered by biogenic gas trapped in the thickest part of the wedges (fig. 4*C*). However, the broader frequency band of the boomer-type systems was able to penetrate the postglacial unit (Qlu) where gas occurs (fig. 4*D*).

The thickest postglacial deposits on the western slope of the lake occur in a belt of sediment, 2–4 m thick, in the southern basin. Elsewhere on the western side of the lake, the postglacial sediment forms a thin sheet that is less than 2 m thick. A large area in the southwestern corner of the lake is virtually free of postglacial sediment.

In the deep part of the southern basin, the postglacial seismic unit Qlu forms a sheet that drapes deeper seismic units (fig. 4*B*). Internally, the unit is acoustically transparent or contains weak, parallel, continuous reflections. Postglacial deposits are generally 2–3 m thick in a band that curves around the eastern and northern side of the southern basin (fig. 2). Elsewhere in the southern basin, postglacial deposits are generally less than 2 m thick. The western mid-lake basin has an evenly distributed thickness of slightly more than 2 m. A thick (as much as 14 m) lobe thins from the eastern side of the eastern mid-lake basin to the western side, where there is 2 m or less of sediment. The northern mid-lake basin has a relatively even thickness distribution of postglacial deposits, which are 4–6 m thick in the center of the basin. The deeper parts of the northern basin generally have 2–4 m of postglacial sediment deposited in depressions that lie between bedrock (Pz) pinnacles and ridges, whereas less than 2 m of postglacial sediment has been deposited over the pinnacles and ridges.

Postglacial unit Qll generally thins toward basin slopes except where thickening occurs along the eastern slopes of the southern basin and eastern mid-lake basin. Unit Qlu overlaps the pinchout of the older glacial unit Qll on most of the basin slopes (fig. 4*A*). In some areas, however, unit Qlu thins and pinches out at a greater depth than the pinchout of the underlying unit Qll, especially on the erosional or nondepositional slopes on the northern part of the mid-lake high and northern ridge. Generally pinching out in the nearshore zone, the postglacial deposits extend close to shore between Benton Harbor and South Haven, Mich., and near Waukegan, Ill. Internal reflections within unit Qlu in the nearshore zone are generally parallel to the lake floor, but they are stronger and more discontinuous than internal reflections beneath the slopes and deep basins.

Where seismic coverage permitted, and where unit Qlu feathers out, we drew a zero-thickness contour. However, beyond the zero-thickness contour there may be a veneer of as much as 10 cm of postglacial sediment; 10 cm is the approximate vertical resolution of the 3.5-kHz seismic system. Coarse-grained deposits consisting of sand and gravel up to several meters thick underlie nearshore shoals between Indiana Shoals and offshore of Chicago. Within 1 km of the shoreline, particularly near Waukegan, Ill., a wedge of sand extends lakeward from the coast. These coarse-grained nearshore deposits are not mapped in figure 2.

Two large regions of the lake floor appear to be erosional or are lacking postglacial sediment cover. The first is a broad shelf off the Illinois and western Indiana shore that locally has a veneer of postglacial sediments, some of which may be lag deposits. The second area is the mid-lake high and the northern ridge. The sill between the eastern mid-lake basin and the southern basin, as well as the sill between the western and northern mid-lake basins, also may be erosional or may lack postglacial deposits.

ANALYSIS

The geometry of the postglacial deposits shown on our map is similar to that mapped by Wickham and others (1978), but our thickness values in the deep basins are different from theirs. Wickham and others (1978) divided the Lake Michigan Formation into two units, primarily on the basis of acoustic stratigraphy derived from 14.25-kHz echosounder profiles (fig. 3*C*). Their upper unit contains closely spaced reflections interpreted to be gray clay of the Waukegan, Lake Forest, and Winnetka Members. Their lower unit is acoustically transparent in the southern basin, but internal reflections become more common to the north. The lower unit was interpreted as red clay of the Sheboygan and South Haven Members. Wickham and others (1978) showed more than 5 m of gray clay in the deep basins, whereas our data indicate only 2–4 m in most of those basins. Available core descriptions (Hough, 1955, 1958; Lineback and others, 1970, 1971, 1974; Lineback and Gross, 1972; Colman and Foster, 1990; ISGS, unpub. data, 1975) clearly indicate only 2–4 m of gray clay in the deep basins and conflict with the interpretation of Wickham and others (1978). However, our deep basin thicknesses are compatible with an earlier isopach map of the southern basin (Lineback and others, 1971) based primarily on core data. In the deep basins, our seismic profiles show a strong reflection (R3), which commonly occurs beneath the weaker reflection (R2) that coincides with the base of the postglacial gray clay in all of the available core data (fig. 4*B*). Wickham and others (1978, fig. 4) appear to have used the stronger, deeper reflection (R3), within what we interpret as the glaciolacustrine red clay (Qll), as the base of the gray clay (Qlu).

The asymmetric distribution of postglacial sediment on the eastern slope and deep basins is extreme: deposits are almost 20 m thick on the eastern slope, southwest of the Grand River, compared to 2–4 m thick in the deeper part of the southern basin (fig. 2). Our isopachs of the thick postglacial deposit on the eastern slope show thicknesses similar to those mapped by Wickham and others (1978). However, our map shows more detail of the distribution of slope deposits, partly because we used a 2-m contour interval. We agree with Lineback and Gross (1972) that the thick sediment on the eastern slope probably has resulted from deposition from rivers along the Michigan coast as well as from coastal erosion, and that lake circulation probably has redistributed this sediment along the eastern slope. Lineback and others (1971), Lineback and Gross (1972), and Wickham and others (1978) suggested that the gray clay was deposited on the eastern slope as a continuous belt on the steepest part of the former lake-floor slope, the steep slope being analogous to the foreset slope of a prograding delta. We recognize three distinct lobes, rather than a continuous belt, that in cross section form wedges that thin both shoreward and basinward. We did not observe prograding reflections within the wedges, rather internal reflections that generally are parallel to the lake floor but which converge slightly toward the nearshore zone and deep basin. The thickest part of the lobes, the zone of maximum deposition, fills the negative relief of the pre-Nipissing transgressive surface (R2, Chippewa unconformity) where there is an inflection in slope, not on the steepest part of the slope as Lineback and Gross (1972) suggested. Therefore, we interpret the thick sediment wedges as slope-front fill deposits; that is, the thickest part of the wedges fills the concave-upward inflection in slope at the base of the postglacial deposit, the Chippewa unconformity. The thickest parts of the lobes are located southwest of the St. Joseph River, south of the Grand River, and northwest of the Muskegon and White Rivers.

Our zero-thickness contour (fig. 2) is consistently closer to shore than the zero-thickness contour generated by Wickham and others (1978). A possible explanation is that the 14.25-kHz echosounder used by Wickham and others (1978) did not penetrate the sandy equivalent of the gray clay in the nearshore areas of the lake. The 3.5-kHz system that we used usually was able to penetrate the sandy nearshore facies (fig. 4*E*); therefore, we have extended the limit of the postglacial deposit closer to shore. The limit of the area of erosion or nondeposition on the mid-lake high (fig. 2) is practically the same as that mapped by Wickham and others (1978). We have interpreted a larger area of the northern ridge and of the sill between the western and northern mid-lake basins to be essentially free of postglacial sediment. This difference in interpretation stems from Wickham and others' (1978) apparent use of reflection R3 (within what we consider is the red glaciolacustrine unit, Qll) as the base of the gray clay. Therefore, we have shown the gray postglacial unit (Qlu) to pinch out at a lower altitude than the red glaciolacustrine deposits (Qll) north of the mid-lake high.

The distribution and thickness of postglacial deposits (fig. 2) can be used to interpret the overall rate of sedimentation during the past 10,000 years. Lineback and Gross (1972) pointed out that present sedimentation rates are higher on the eastern side of the southern basin, where thick postglacial deposits occur, than on the western side. Present sedimentation rates are inferred to be higher on the eastern side of the southern basin also on the basis of concentrations of anthropogenic trace elements (Lineback and Gross, 1972) and organic compounds in the surface sediment (Eadie and Robbins, 1987). The pattern of concentration of these materials in the surface sediment is similar to the pattern of postglacial sediment thickness (fig. 2). In general, higher concentrations coincide with thicker postglacial sediments. Rates of postglacial deposition probably have not been linear, but the spatial association of high modern sedimentation rates with thick postglacial deposits suggests a relatively uniform pattern of deposition over the past 10,000 years.

Rates of modern erosion, transport, deposition, and reworking of sediments in the lake are not well known, especially in the deep basins. Evidence for sediment movement by bottom currents exists in water depths of 240 m in Lake Superior (Flood and Johnson, 1984; Johnson and others, 1984; Flood, 1989); deposition patterns are probably influenced by bottom currents in Lake Michigan as well. The curved belt of deposits 2–4 m thick in the southern basin (fig. 2) may reflect counterclockwise circulation in the basin. The large nondepositional area in water depths of 50–100 m on the mid-lake high and as deep as 170 m at the northeastern end of the northern ridge may also result from bottom-current circulation.

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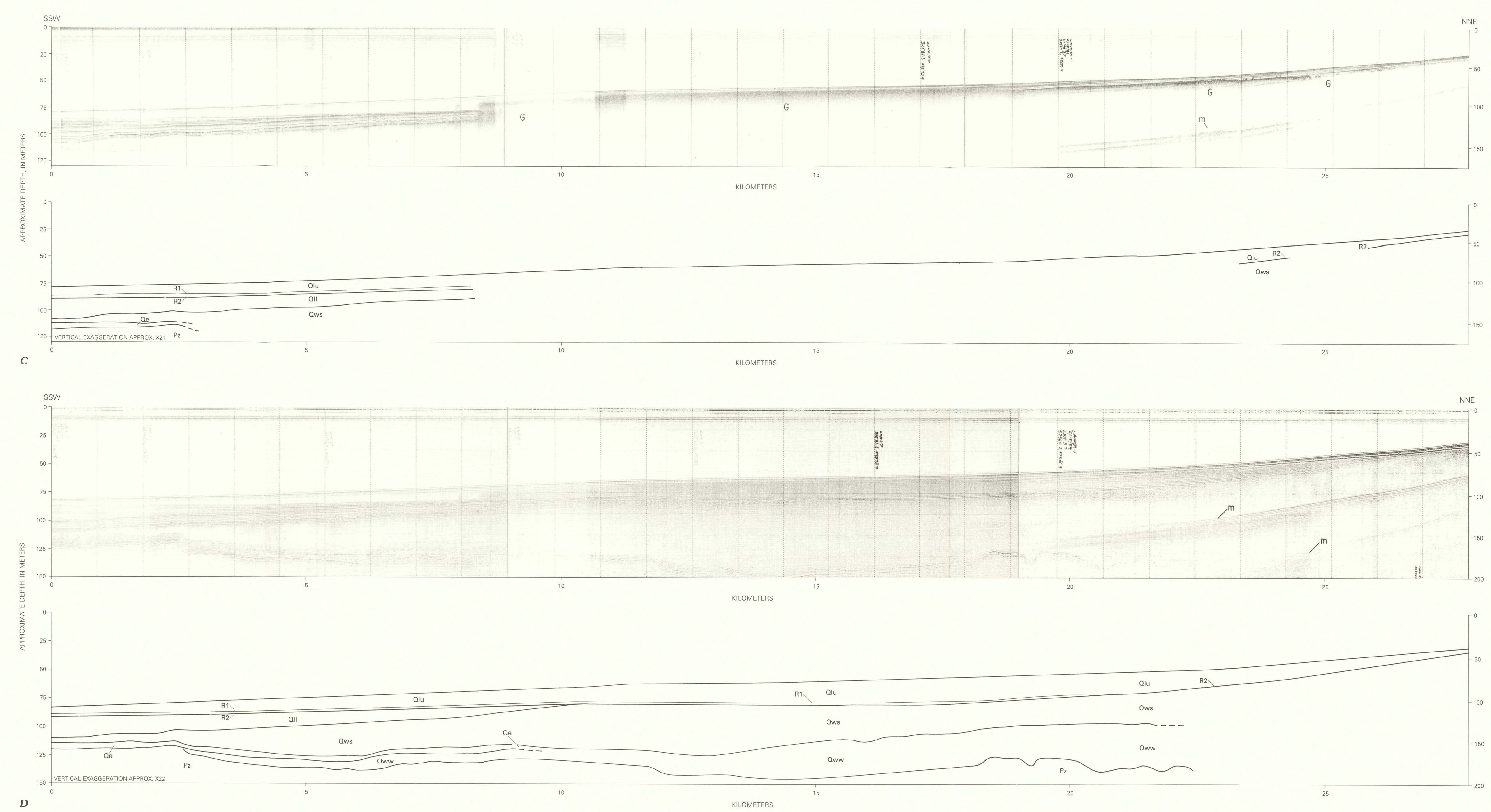


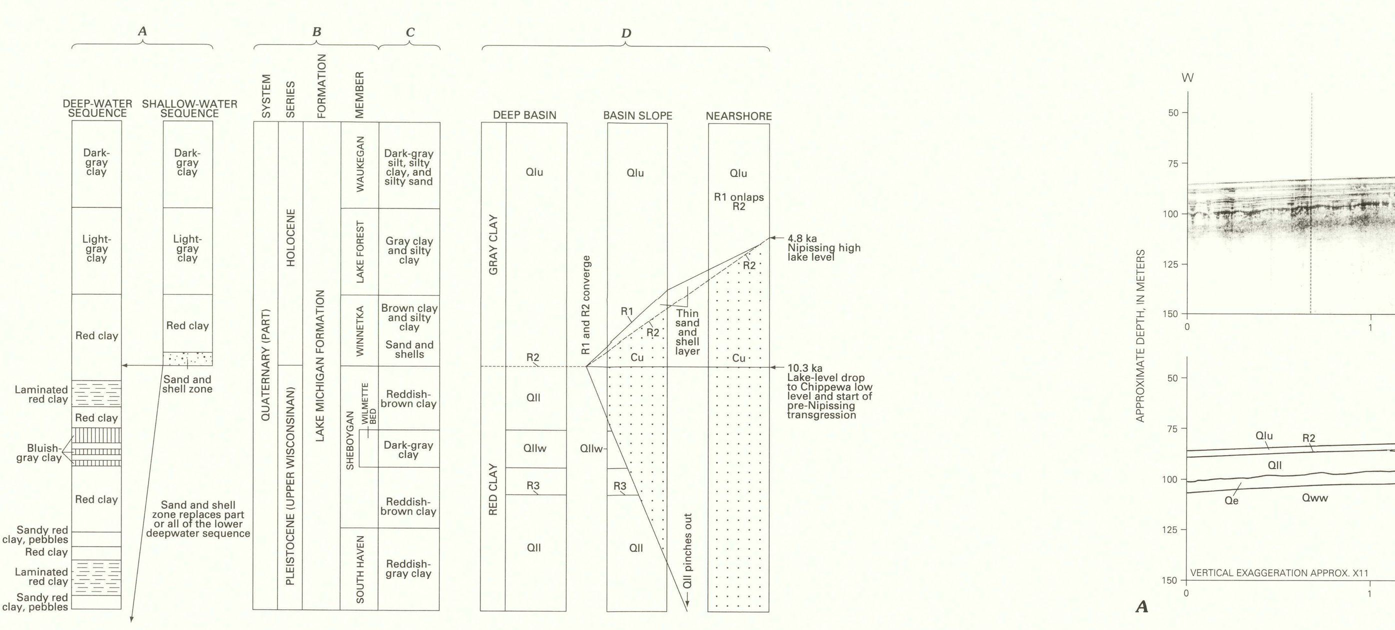
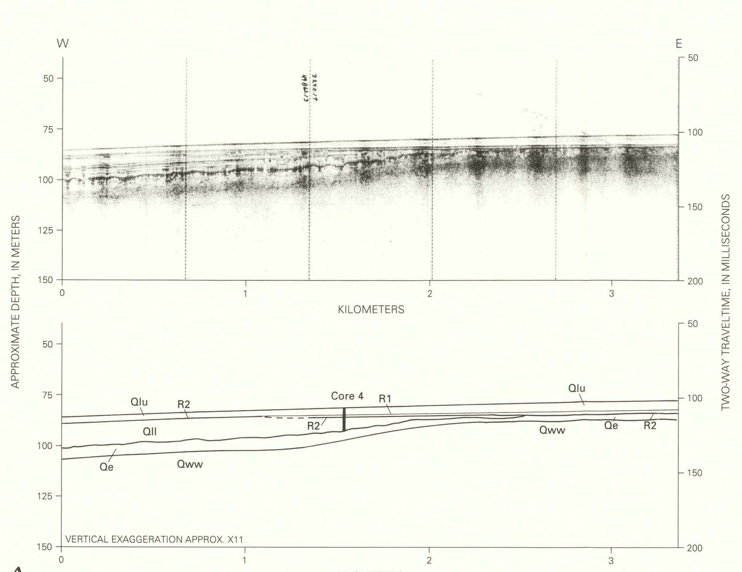


Figure 3.—Lithostratigraphic and seismic stratigraphic columns. *A*, Lithostratigraphy after Hough (1958); *B*, Stratigraphic units after Lineback and others (1970); *C*, Lithostratigraphy after Lineback and others (1970, 1971, 1974) and Wickham and others (1978); *D*, Seismic and lithostratigraphic units (this study). Qlu, upper Lake Michigan Formation; Qll, lower Lake Michigan Formation; Qllw, Wilmette Bed. Stipple pattern indicates deposits are absent. Seismic reflections: R1, facies change within the upper Lake Michigan Formation; R2, Chippewa unconformity (long-dashed line) and equivalent glacial-postglacial conformity (short-dashed line) in the deep basins; Cu, inferred regressive Chippewa unconformity which is not observed in seismic profiles; R3, reflection within the lower Lake Michigan Formation, interpreted by Wickham and others (1978) as the red-to-gray clay contact.



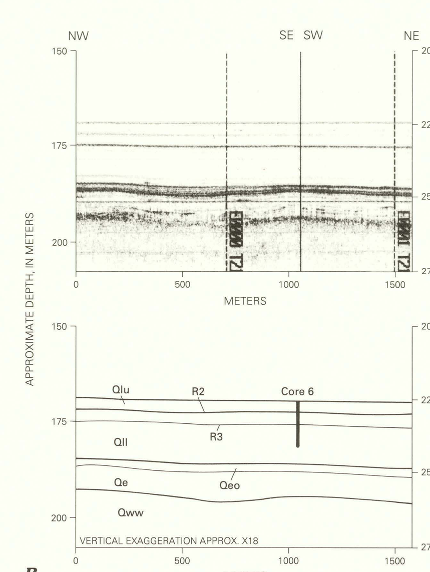
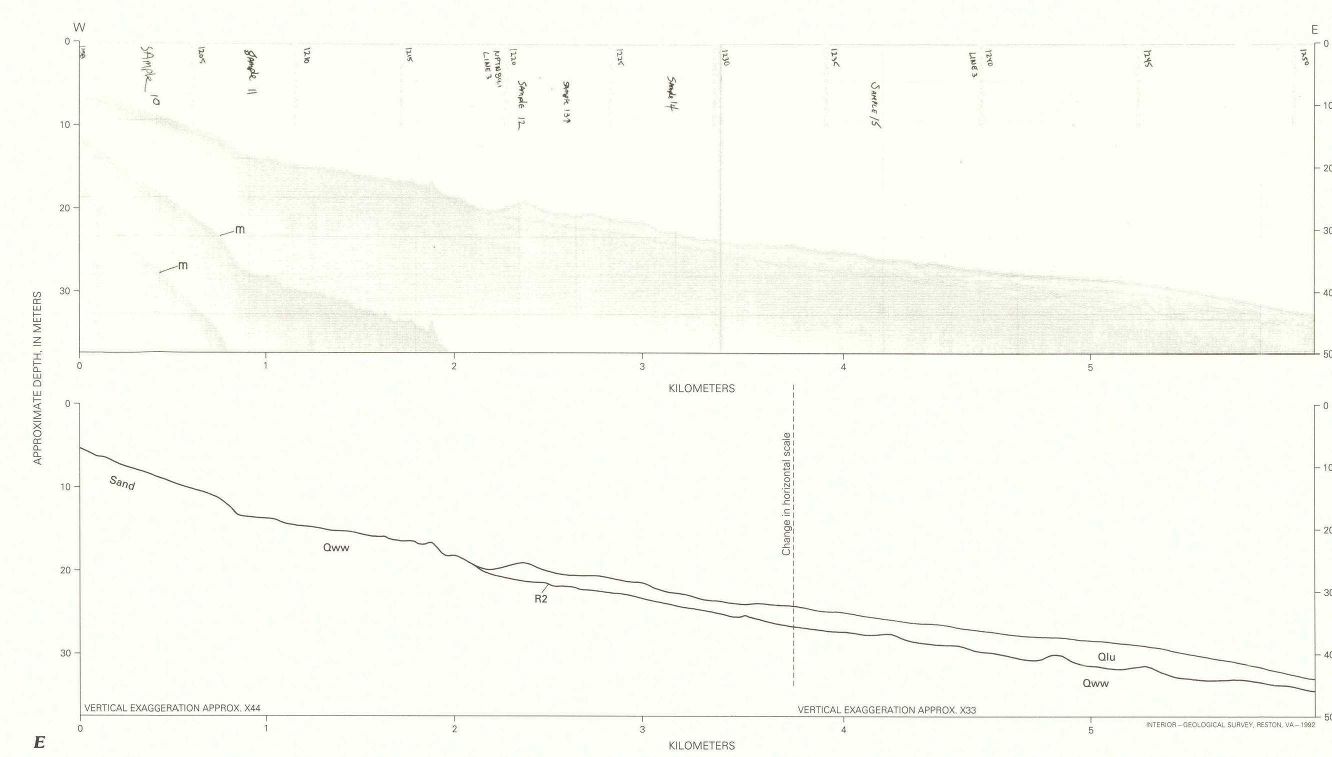


Figure 4A–E.—Selected 3.5-kHz and Geopulse seismic-reflection profiles. See figure 1 for location of profile tracklines. Depth scale on seismic profiles assumes a sound velocity of 1500 m/s in water and sediment. Heavy lines are unit contacts. Light lines represent internal reflections. Contacts are dashed where inferred. Profiles *C* and *D* are of the same area but were obtained by different methods, hence the difference in their appearance. In *C*, a 3.5-kHz seismic profile, penetration beneath the lake floor was locally hindered by biogenic gas trapped in the thickest part of the sediment wedges. In *D*, a boomer seismic profile, the broader frequency band of that system was able to penetrate postglacial unit Qlu where gas occurs. Seismic stratigraphic units: Qlu, upper Lake Michigan Formation; Qll, lower Lake Michigan Formation; Qe, Equality Formation; Qeo, ice-proximal sublacustrine outwash facies of the Equality Formation; Qws, Shorewood Till Member of the Wedron Formation; Qww, Wadsworth Till Member of the Wedron Formation; Pz, Paleozoic bedrock. Seismic reflections: R1, facies change within the upper Lake Michigan Formation; R2, Chippewa unconformity and equivalent glacial-postglacial conformity in the deep basins; R3, reflection within the lower Lake Michigan Formation, interpreted as the red-to-gray clay contact by Wickham and others (1978). M, multiple reflection; G, gas-charged sediment. Cores located in figures 4*A* and *B* are described by Colman and Foster (1990).



LOCATION MAP

MAPS AND SEISMIC PROFILES SHOWING THICKNESS AND DISTRIBUTION OF POSTGLACIAL DEPOSITS BENEATH THE SOUTHERN TWO-THIRDS OF LAKE MICHIGAN

By
David S. Foster and Steven M. Colman
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