Effects of bottom currents and fish on sedimentation in a deep-water, lacustrine environment

THOMAS C. JOHNSON, JOHN D. HALFMAN } *Duke University Marine Laboratory, Beaufort, North Carolina 28516*
WILLIAM H. BUSCH *Department of Earth Sciences, University of New Orleans, New Orleans, Louisiana 70148*
ROGER D. FLOOD *Lamont-Doherty Geological Observatory, Columbia University, Palisades, New York 10964*

ABSTRACT

Sands and muds accumulating under the influence of apparently strong bottom currents in a deep-water environment of Lake Superior were studied in detail using 3.5-kHz echo sounding; side-scan SONAR; piston, gravity, and box coring; and lake-floor photography. The study area includes a well-defined slope and basin environment. Bottom currents maintain a scoured trough, 20 m deep and 2 km wide, at the base of the slope and modify the shapes of large ringlike depressions that are common in many regions of Lake Superior. Side-scan SONAR records reveal lineations subparallel to the direction of bottom-current flow that are interpreted in different areas to be sand ribbons, slight depressions, or depositional furrows.

The sediments range from silty sand in the scoured trough to sandy clays farther offshore. Radiocarbon dating and ^{210}Pb dating show the sediments to be postglacial rather than relic glacial-lacustrine sediments. Grain size distributions are affected by bottom currents and a nearby source of sand. Some sedimentary structures, including plane laminations and interbedded sands and muds, are due to bottom currents. Fish create dish laminations, however, that often obscure the effects of the bottom currents. Fish and fish-scour depressions are common in lake-floor photographs, whereas evidence for bottom currents is not. Biological activity therefore appears to erase traces of intermittent currents.

INTRODUCTION

Numerous studies have been made upon the interbedded sands and muds that accumulate on continental slopes and rises of the world ocean. Many of these deposits are unmistakably turbidites, whereas others are contourites, sediments with textural and other properties that are influenced chiefly by bottom currents that generally flow parallel to bathymetric contours. Several attempts at distinguishing sedimentological differences between modern contourites and turbidites (for example, Hubert, 1964; Hollister and Heezen, 1972; Bouma and Hollister, 1973; Stow and Lovell, 1979) have been plagued by two major complications. First, most marine environments that contain contourites also contain interbedded turbidites, and unequivocal distinction between them in sediment cores is difficult. Second, modern sediments in most marine settings are greatly disturbed biologically, which smears the initial imprint of bottom currents upon sediment texture and fabric.

In August 1981, we conducted a detailed study of sands and muds accumulating under the influence of what must be strong bottom currents in a deep-water environment of Lake Superior (Fig. 1). This region was described previously by Johnson and others (1980) as a site of deposition of lacustrine contourites. Our 1981 study was to investigate in more detail the lake-floor morphology and sedimentary textures and structures of this dynamic "hemipelagic" environment. There is no indication of turbidity currents in the study area (Johnson, 1980; Johnson and others, 1980), and biological mixing throughout Lake Superior is usually limited to the upper 1–2 cm of sediment (Evans and others, 1981). Factors that complicate the examination of contourites in the marine environment thus are greatly diminished in this investigation.

This paper describes the lake-floor morphology and sediments of the study area. Both features clearly reveal the influence of strong bottom currents, and the sediment descriptions provide criteria for comparison in future studies of contourites, both modern and ancient, lacustrine and marine. Companion papers describe in greater detail than here the results of side-scan SONAR surveys (Flood and Johnson, in press) and grain-size analyses (Halfman and Johnson, in press) in the study area.

The region investigated lies just north of the Keweenaw Peninsula in south-central Lake Superior (Fig. 1). It is approximately 45 km long by 20 km wide and underlies the northeastward-flowing Keweenaw Current (Ragotzkie, 1966; Terrell and Green, 1978). The offshore region of the study area is ~250 m deep, with generally low relief interrupted by 3 north-northwest–trending end moraines (Landmesser and others, 1982) (Fig. 2). The lake floor shoals rapidly along the south-central margin, creating a steep (~6°), well-defined "continental slope" with a shelf less than 0.5 km wide. The slope to the northeast and southwest of this area is more gradual (<1°), and the shelf is >2 km wide in the southwest sector of the study area (Fig. 1). Late Precambrian conglomerates and sandstones are exposed in places along the shoreline and along the shelf and slope offshore. Johnson and others (1980) reported preliminary evidence from 3.5-kHz echo soundings and sediment cores that indicates lake-floor sediments at the base of the slope and immediately offshore are strongly affected by contour currents. They speculated that this occurs during major storms in the spring or fall, when the water column is isothermal and the wind-driven Keweenaw Current could extend to depths exceeding 200 m. (The Keweenaw Current has been studied only during summer months, when the lake is stratified and the current is restricted to the epilimnion; for example, Ragotzkie, 1966.)

METHODS

A five-day survey of the study area was conducted in August 1981 aboard the R/V *Laurentian*. Subbottom reflection profiles (3.5 kHz) and side-scan SONAR records (100 kHz) were obtained along the ship track illustrated in Fig-

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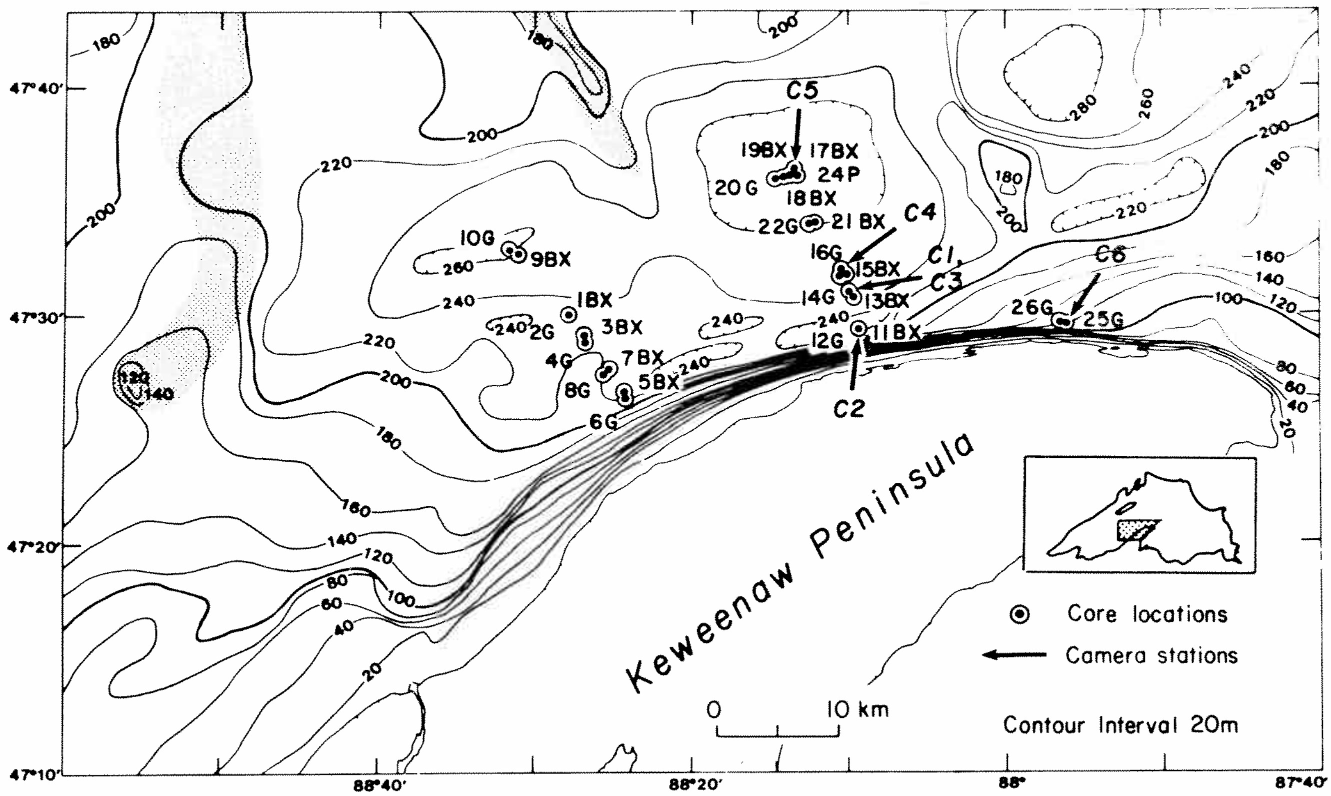


Figure 1. Location of the study area (inset) and locations of gravity (G), piston (P), and box (BX) cores (circles) and camera stations (arrows). Stippled areas show outcrops of two end moraines. The third moraine at 88°W is covered by postglacial sediment.

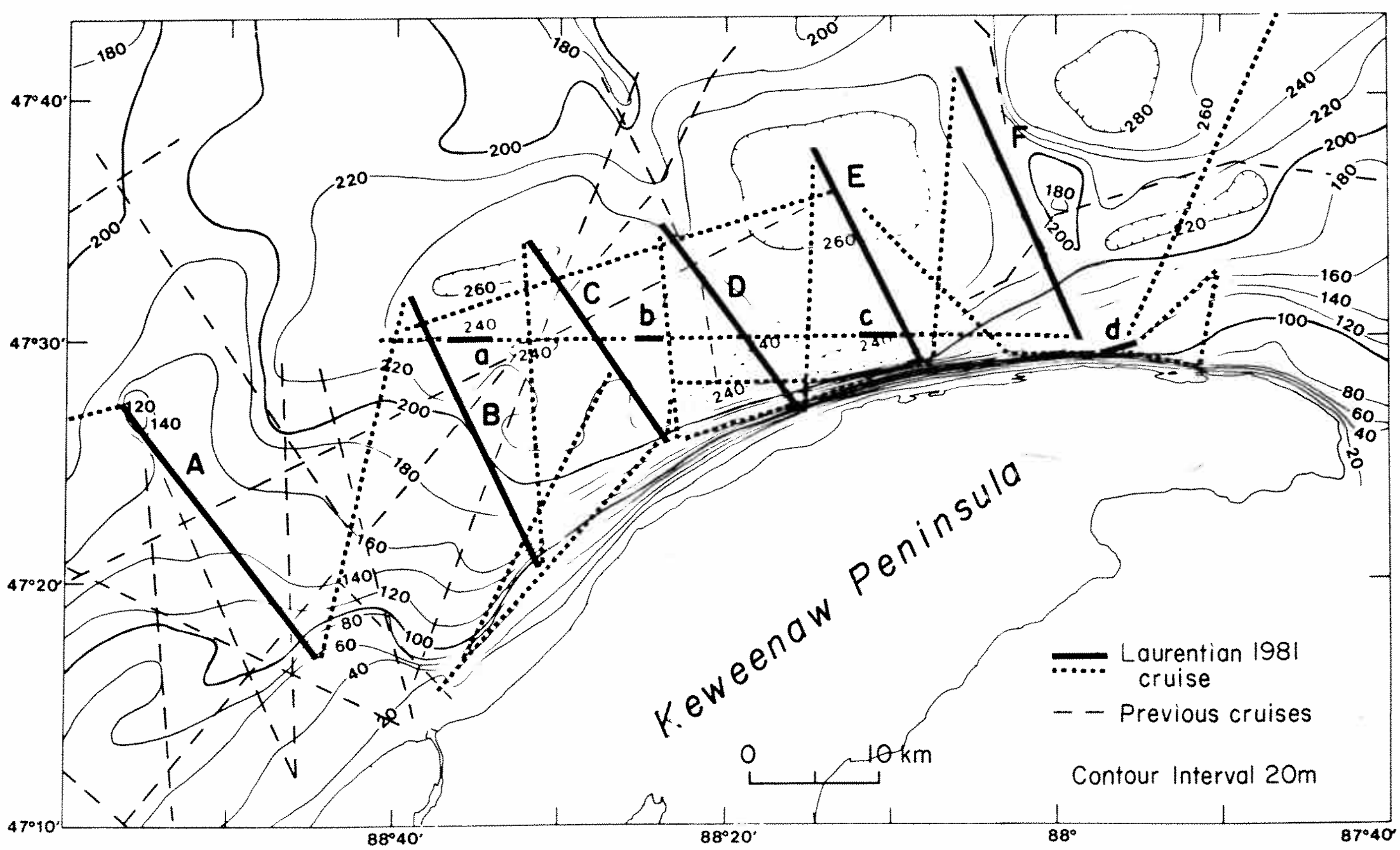


Figure 2. Ship tracks of 3.5-kHz reflection profiles obtained on cruise LRTN 81 and previous cruises. Profiles A, B, C, D, E, and F are illustrated in Figure 4. Side-scan SONAR records at locations a, b, c, and d are illustrated in Figure 6.

ure 2. Normally, the profiles were taken at a ship speed of 8.5 knots, but the long east-west transect (fig. 2) was made at a speed of about 3.6 knots, allowing the side-scan transducers to track at ~30 m above the lake floor. Navigational fixes were made by LORAN C every five minutes while the ship was underway. Accuracy of the fixes is estimated at ±0.2 km.

Along two transects trending perpendicular to the shoreline from the base of the slope lakeward, 12 box cores, 10 gravity cores, and 2 piston cores were taken (Fig. 1). On the gentle slope in the eastern end of the survey area, two additional gravity cores were obtained.

The box corer recovers sediment samples 50 cm^2 by ~50 cm deep. Box cores were subsampled on board ship immediately after recovery. Subsampling included detailed scraping of 0.5-cm intervals of sediment for ^{210}Pb analysis, collection of vertical slabs of sediment for X-ray analysis of sedimentary structures, and collection of ~1 liter of bulk sediment from 10-cm intervals at the top, middle, and bottom of the core for radiocarbon dates. The vertical slabs were obtained by cutting 2 vertical faces at right angles to each other in the sediment, inserting Plexiglas trays that are 20 cm × 40 cm × 1 cm deep into the faces, and then carefully removing the trays of sediment from the core with the sedimentary structures intact. The sediment slabs were X-rayed ashore at 50 kv, 200 ma.

Radiocarbon samples were frozen immediately on board ship and freeze-dried in the laboratory ashore. Samples from L81-13BX and 21BX were sent to the Geochronology Laboratory at the University of Miami, and samples from L81-11BX, 15BX, and 17BX were sent to the Radiocarbon Dating Laboratory at Washington State University.

The piston and gravity cores were split longitudinally onshore for subsequent visual description and grain-size analysis. Samples for ^{210}Pb analyses were stored for several months in airtight glass containers at 4 °C and later transferred to airtight plastic vials and stored at room temperature for as much as 4 weeks prior to analysis. Samples of ~3 g dry weight were treated and analyzed by counting ^{210}Po activity, using methods of Evans and others (1981). No correction was made for ^{210}Po ingrowth, because sedimentation rates were based upon sediments dating older than 10 yr.

Surface samples from the gravity cores were analyzed for grain size by sieving the sand fraction at 0.5-phi intervals and pipetting the silt and clay at 1-phi intervals to 11 phi. Surface samples from the other cores and subsurface samples from the two piston cores and one gravity core (L81-14G) were sieved and pipetted only for percentages of sand, silt, and clay.

The silt fraction of all subsamples was analyzed further for a detailed grain-size distribution using an Elzone electronic particle analyzer, model 80XY, manufactured by Particle Data, Inc. The particle analyzer utilizes the same principle as does a Coulter Counter and determines the relative abundance of particles in 126 discrete size intervals in the range of analysis, in this case, 5.85 to 71.44 μ. The count versus size data were converted to mass versus size assuming spherical particles with a density of 2.6 g/cm^3. All samples were analyzed in duplicate by this method. If the mean size determined in the first 2 analyses did not agree to within 0.09 phi units, a third analysis was performed, and the reported value was the average of the 3 analyses.

Bottom photographs were obtained at six camera stations (Fig. 3). Black and white and color 35-mm photographs were taken with an Olympus OM-1 camera equipped with a 28-mm lens and an automatic film advance mechanism and mounted in an underwater housing. The camera and strobe were mounted on a tubular steel frame, lowered by cable to the lake floor, and activated by a bottom-contact switch.

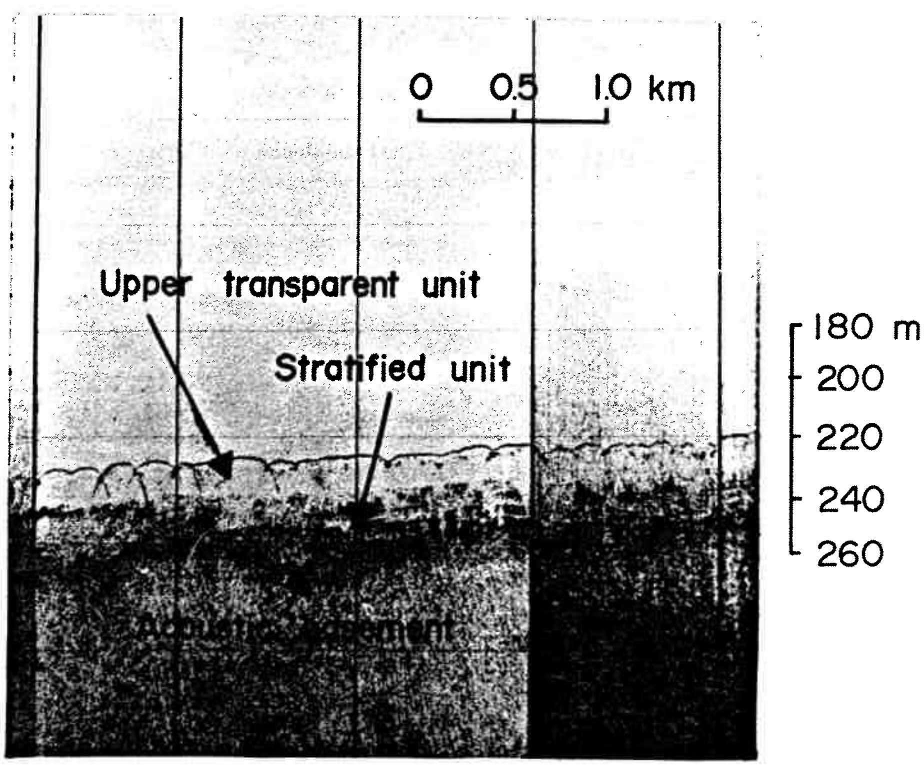


Figure 3. A representative 3.5-kHz profile from the study area, illustrating the three main acoustic units. The depth scale is based upon a speed of sound of 1,500 m/sec.

RESULTS

3.5-kHz Profiles

The high-resolution reflection profiles reveal three major stratigraphic units throughout much of the study area: an upper transparent unit that ranges from 0 to 15 m thick (and is usually ~10 m thick); a middle stratified unit that is often 10 to 30 m thick; and acoustic basement that is capped by an irregular, relatively strong reflector (Fig. 3). Previous work by Johnson (1980) and Landmesser and others (1982) indicated that the upper unit consists of relatively uniform postglacial sandy clay overlying laminated (varved?) glacial-lacustrine clay, the middle unit is probably glacial outwash material, and the lower unit is glacial till.

The profiles provide evidence for bottom-current impact upon sedimentation in the study area. A series of six profiles oriented perpendicular to the shoreline delineate a current-scored trough at the base of the slope in the central region of the study area (Fig. 4).

The echo patterns can be classified according to their acoustic properties into (1) normal; (2a) long-wavelength and (2b) short-wavelength overlapping; (3) wavy; and (4) strong, irregular echo patterns (Fig. 5). The overlapping and wavy echo patterns are unique to this region of Lake Superior and are the result of bottom-current activity (Johnson and others, 1980).

Normal profiles that are typical for much of Lake Superior are restricted to areas >13 km from the base of the slope. These profiles typically have an upper transparent unit that is thicker than 10 m. The lake floor in these re-

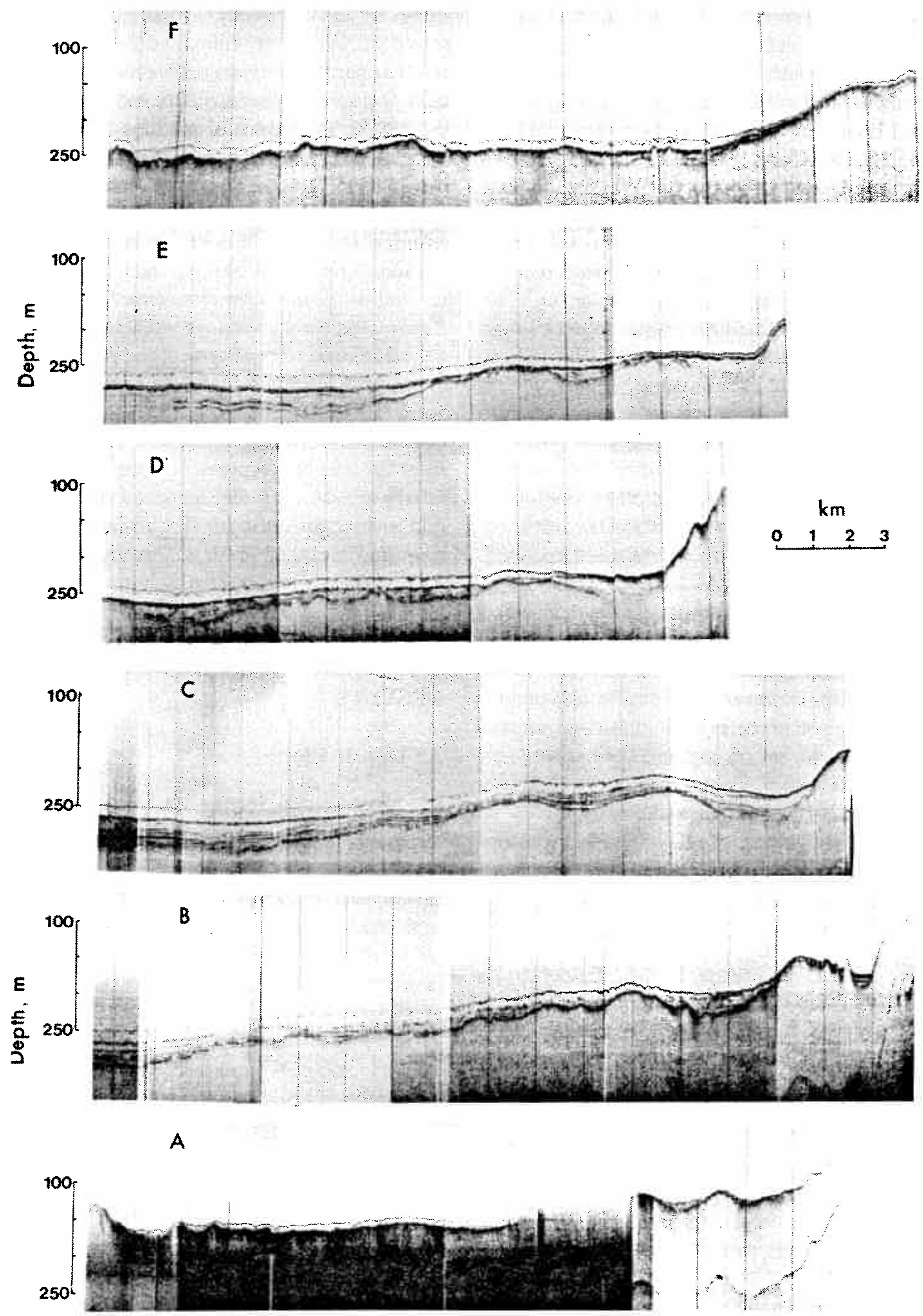


Figure 4. 3.5-kHz reflection profiles trending from northwest (left) to southeast (right) in the study area. Note the truncation of the upper transparent unit in the erosional trough at the base of the slope in profiles C and D. Profile locations are illustrated in Figure 2.

gions is relatively smooth, except where incised by depressions that are ~2 m deep and as much as 100 m wide (Fig. 5A). The base of the depression often is accentuated by a strong point reflector. The spacing of the depressions usually ranges between 200 and 1,000 m.

Profiles with overlapping echoes are restricted to a band that is ~10 km wide, oriented parallel to the bathymetry, just lakeward of the scoured trough. These profiles show an irregular lake floor with nonparallel, irregular subbottom reflectors within 1–2 m below the lake floor. Johnson and others (1980) interpreted these profiles to indicate bed forms that migrate across the lake floor in response to bottom currents. The overlap profiles are subdivided into long-wavelength (Fig. 5B) and short-wavelength (Fig. 5C) categories. The long-wavelength overlapping profiles show depressions 1–2 m deep that typically are spaced >100 m apart (Fig. 5B), whereas the short-wavelength overlapping profiles show depressions of about the same depth spaced ~50–75 m apart (Fig. 5C). The latter profiles are situated landward of the former, and the boundary between the two profile types is gradational. The reflectivity of the lake floor gradually increases landward in the region of overlapping echoes.

Wavy echo returns are restricted to the trough floor at the base of the slope. These profiles have a hard surface reflector that is wavy with a vertical relief of ~1 m and a mean wavelength of ~70–80 m (Fig. 5D), and they characteristically have 1 to 2 subbottom reflectors that are subparallel to the surface reflector.

Profiles with strong, irregular echo returns are common in the western and eastern regions of the study area, from the lower slope lakeward to regions of normal profiles. Johnson and others (1980) categorized these profiles as hyperbolic, but our new data indicate that this is misleading. They characteristically have a hard surface reflector that is irregular and no subbottom reflectors above acoustic basement (Fig. 5E). In some areas, the lake-floor irregularities are hyperbolic, but in many places they are not.

Acoustic basement crops out on many regions of the slope and on end moraines offshore. In most places, it represents clayey or sandy till, but in some areas on the slope, it coincides with exposures of late Precambrian clastic sedimentary rocks.

Side-Scan SONAR

Flood and Johnson (in press) described the details of side-scan SONAR records from the study area. A brief description is provided here to integrate the side-scan results with the other data from the study.

Side-scan SONAR records from the lakeward region of the study area, where "normal" 3.5-kHz profiles are obtained, show large, nearly circular ring depressions (Fig. 6A). These are the same depressions observed on the 3.5-kHz profiles. The rings have diameters of 100–300 m and widths of 20–50 m. The rings are never complete; sediment appears to cover parts of them wherever they are found. The eastern portions of the rings tend to be filled in the offshore regions, and the western portions tend to be filled in the nearshore areas. The floors of ring depressions are more reflective than are surrounding regions, suggesting that surface sediments within the depressions are relatively coarse-grained, perhaps due to local acceleration of bottom currents. A faint east-west–trending lineation pattern with a spacing of ~50 m is superimposed upon the rings (Fig. 6A).

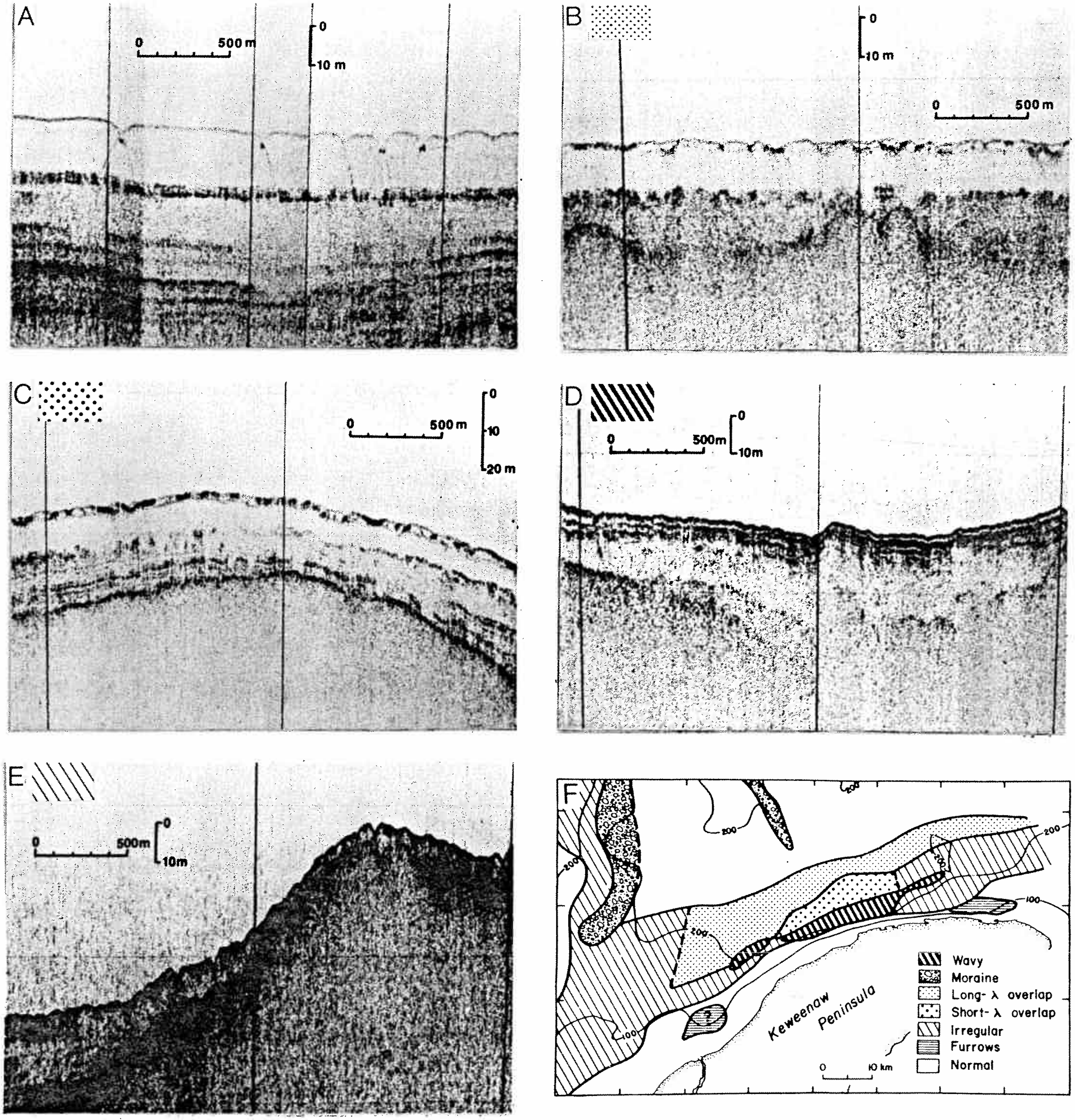


Figure 5. Examples of different classes of 3.5-kHz profiles. A. Normal. B. Long-wavelength overlap. C. Short-wavelength overlap. D. Wavy. E. Irregular with some hyperbolae. F. Distribution of profile types in the study area.

The ring-like targets are modified, presumably by bottom currents, in the region of overlapping 3.5-kHz profiles. Ring walls are distinctly scalloped; only small segments of large rings have not been filled in; and, in regions of short-wavelength overlapping 3.5-kHz records, rings are elongated in an east-west direction (Fig. 6B). Ring-wall heights are asymmetric, with higher walls on the west side of the depression. Background lineations are more pronounced than farther offshore, and their spacing decreases to 10–20 m.

The nature of the lake floor changes abruptly in the region of wavy 3.5-kHz profiles. Ring structures disappear, and acoustic reflectivity of the lake floor increases, due to a high sand concentration. Lineations parallel to the shoreline are common, and they appear to be slight de-

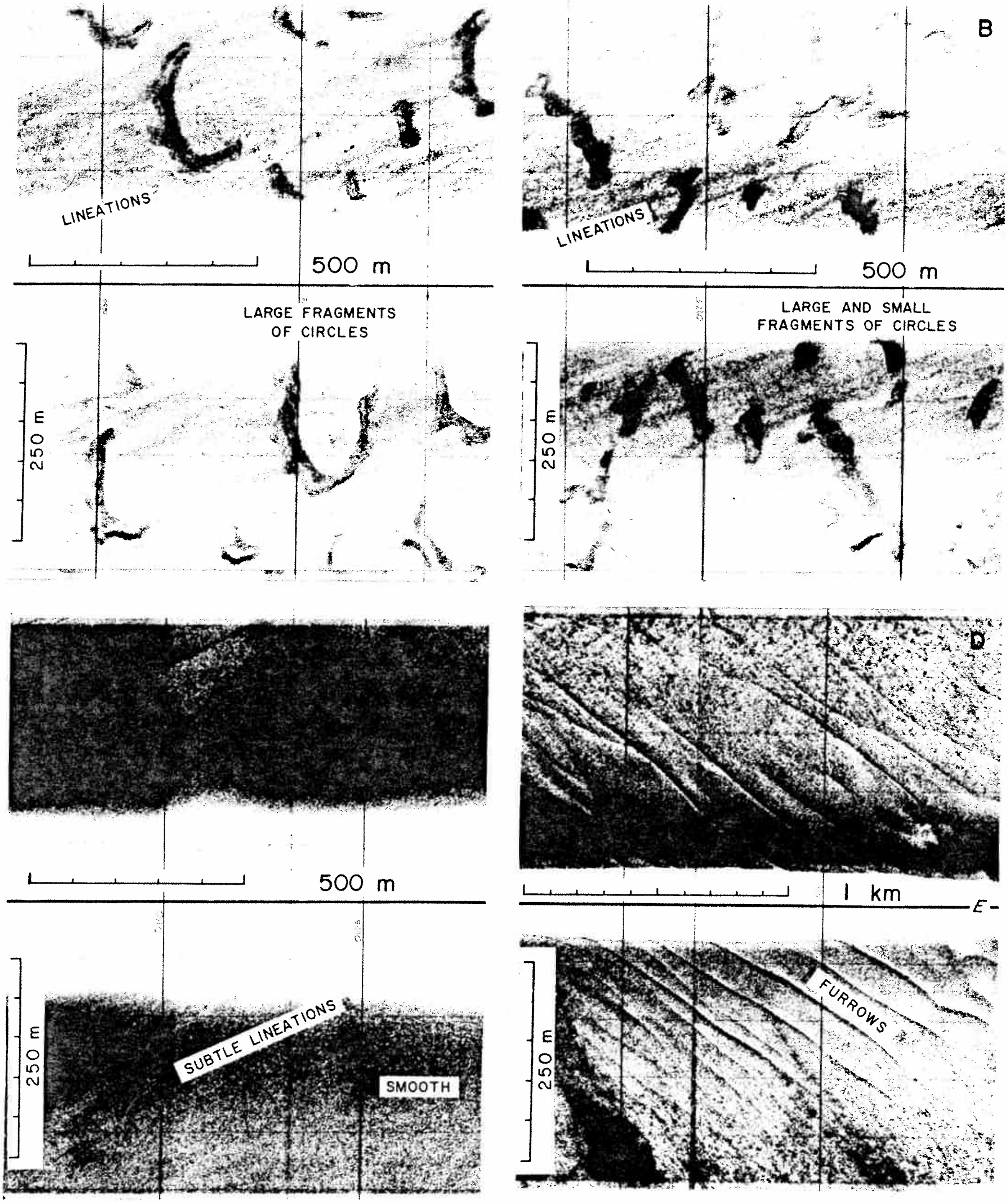


Figure 6. Side-scan SONAR records from locations indicated in Figure 2. Modified from Flood and Johnson (in press).

pressions containing sediment inferred from reflectivity contrast to be relatively coarser than that of the adjacent lake floor (Fig. 6C).

A field of furrows is observed at depths of 40 to 140 m at the eastern end of the survey area, where the slope is not very steep and the sediment cover is unusually thick (10 m) for the slope region. The furrows are ~5 m wide and as much as 2 m deep and have spacings of 20 to 50 m (Fig. 6D). They are aligned parallel to the contours, and adjacent furrows often merge from west to east.

Sediment Grain Size

Details of the grain-size analyses are reported in Halfman and Johnson (in press). Briefly, grain size generally decreases from the trough at the base of the slope, where sediment consists of 70% to 80% sand and has a mean size of ~3 phi (125 μm), lakeward to the core sites farthest offshore, where the sediment typically contains < 10% sand and has a mean grain size of ~10 phi (1 μm). Superimposed upon this general trend, however, is an occasional core from an offshore site that contains a relatively well-sorted sandy cap yielding an anomalously coarse mean grain size for its geographic location. Halfman and Johnson (in press) interpreted these cores to be from ring depressions that the side-scan SONAR and 3.5-kHz records suggest have relatively coarse sediment. Alternatively, the samples may come from the faint lineations observed on the side-scan records.

The sieve and pipette results show the sediments possess a bimodal size distribution consisting of a well-defined sand mode at 2 phi (0.25 μm) and a diffuse clay mode at 11 phi (0.5 μm). The relative proportions of the two modes change predictably in a lakeward direction (Fig. 7), except for the textural anomalies associated with the ring depressions or lineations. This change results in a decrease in skewness values from about +0.67 in the trough to about −0.45 at core sites farthest offshore.

Detailed analyses of the silt size fraction by the electronic particle analyzer show a decrease in mean grain size lakeward from the trough and a significant change in the shape of the cumulative frequency curve (Fig. 8). Trough sediments have a mean silt size of 5.0 to 5.3 phi (29–31 μm) and positively skewed curves (0.20 to 0.40) that are convex upward in the 65–20 μm range and concave upward in the 20–5 μm range (Fig. 8). Open-lake sediments possess mean silt sizes of ~5.7 to 6.0 phi (16–22.4 μm) and negatively skewed curves (0 to −0.10) that are slightly concave upward over the entire silt size range (Fig. 8). There is a direct correlation between the degree of upward convexity in the coarse silt range and proximity to the scoured trough (that is, presumably to the strength of the bottom currents at the depositional site).

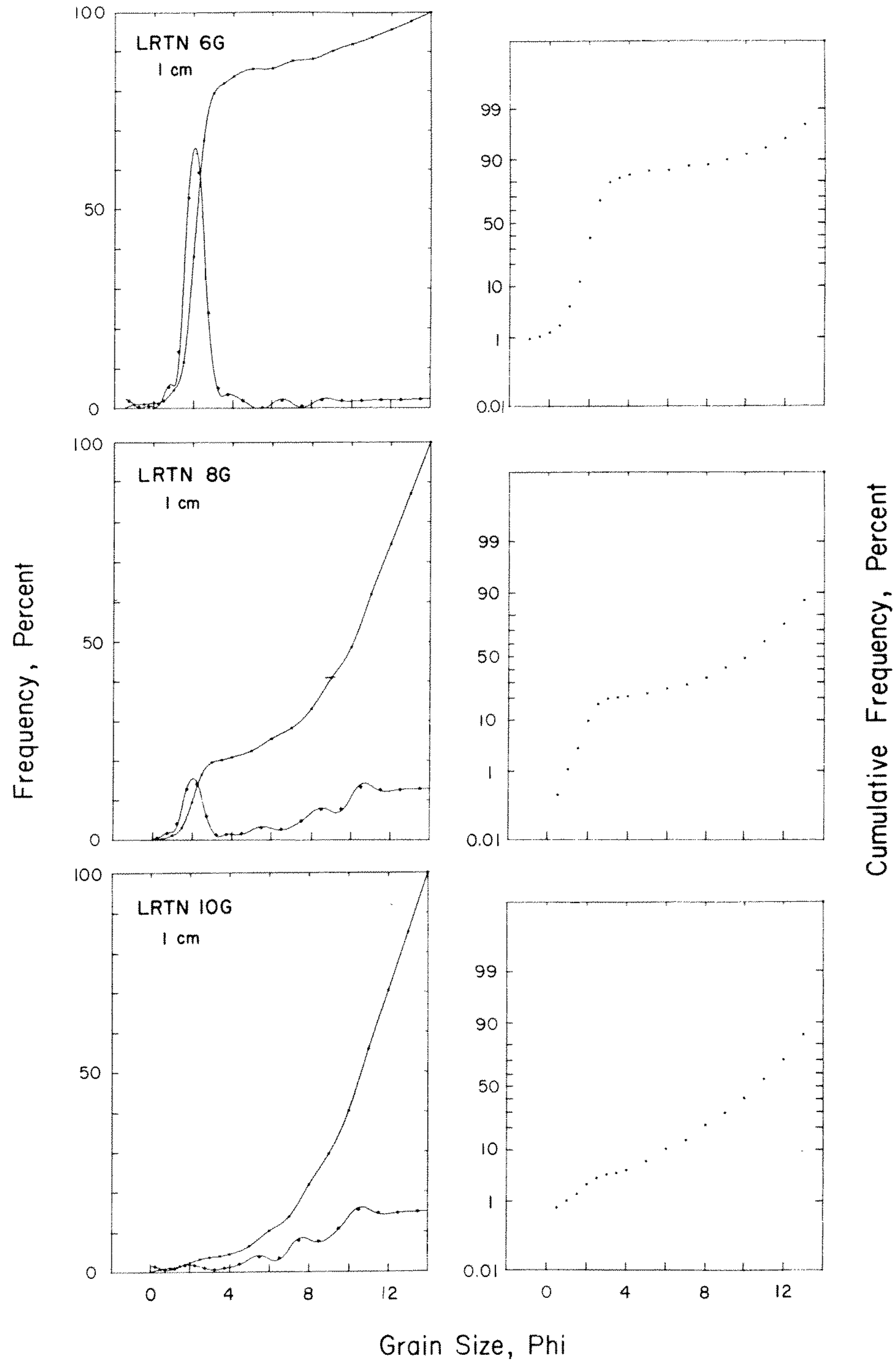


Figure 7. Grain-size distributions from three cores representing trough sands (6G) and sandy clays from farther lakeward (8G and 10G). Core locations are indicated in Figure 1.

Mean grain size increases downcore in two of the three cores examined. The third core shows the opposite trend. Halfman and Johnson (in press) tentatively interpreted the downcore increase in grain size to indicate that bottom-current intensity has decreased gradually throughout the region during the past 9,500 yr. The anomalous results from the third core may be the result of a localized intensification of bottom currents in the vicinity of a ring depression or lineation.

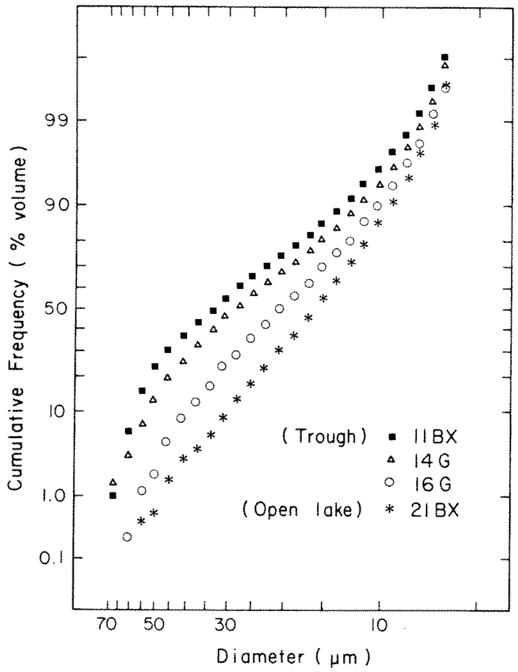


Figure 8. Cumulative-frequency curves for the silt-size fractions of surface sediments, determined by particle analyzer. There is a progressive shift in the size distribution from the trough (core 11BX) lakeward to the open lake (core 21BX). Core locations are indicated in Figure 1.

A few sediment slabs were taken from horizontal planes in three of the box cores to see if bedding-plane lineations could be observed. Lineations were observed in trough sand in core L81-11BX (Fig. 10A). Spacing of the lineations is 1–2 cm. Lineations were not observed in trough sand in core L81-13BX (Fig. 10B) or in sandy clay in core L81-21BX.

Sedimentary Structures

Sedimentary structures are faintly visible in cores of sandy trough sediments and in cores with sand layers interbedded with sandy clays farther offshore. Sedimentary structures are not visible to the eye in most of the sandy clay units, but X-radiographs show that the structures are abundant. The sands typically are yellowish to reddish brown (10 YR, 3/2) and the sandy clays range from yellowish brown (10 YR, 4/4) in the top 5–10 cm of cores to olive gray (5 Y, 4/2) below. Well-defined laminae, 1–2 mm thick, of black manganese oxides overlying orange iron oxides are found at depths of 5 to 12 cm in many of the box cores, forming the boundary between the oxygenated brown sediment above the presumably anoxic gray sediment below. Some box cores contain more oxide layers at greater depths that are not as sharply defined as the top one and may be as thick as 1–2 mm. These are interpreted to be relic boundaries between oxic and anoxic layers that are in the process of dissolving under present reducing conditions. At present, we have no chemical data on the interstitial waters to support this interpretation.

In the trough sands, two sedimentary structures prevail: plane laminations and dish laminations (Fig. 9A). The plane laminations are composed of interbedded clay and sand layers 2–8 mm thick. The clay layers are discontinuous, usually no more than 7–8 cm long, whereas the sand layers tend to be slightly longer and thicker. The dish laminations are concave upward, quite symmetrical, and usually 5–10 cm across and ~3–8 mm deep. The dish laminations are lined with a concentration of sand grains at their bases and are filled in with clay. A few granules and pebbles are dispersed through the sands and are interpreted to be ice rafted from the shoreline to the south.

The sandy clays lakeward of the trough frequently contain dish laminations, but plane laminations are rare (Figs. 9B, 9C). The size of the laminae is about the same as in the trough. The dish laminae again are lined with sand and filled with sediment that is finer than the surrounding sandy clay. The abundance of dish laminations drops off significantly from the trough in a lakeward direction, but they are still present in the northernmost cores of the sandy area. Dish laminations have been found in only one box core that we have taken in other regions of Lake Superior, and they are very faint in this core.

Sand layers are in sharp contact with sandy clays in offshore regions (Figs. 9D, 9E, 9F). The contacts can be either planar or irregular. In core L81-18BX, the contact is very distorted by loading deformation (Fig. 9F). Sand layers buried by sandy clays in other cores from the study area have sharp upper as well as lower contacts. All three box cores that contain sand caps exhibit planar laminations in the sandy clays just below the sand-clay contact. The planar laminations gradually disappear within 10–15 cm downcore. None of the other box cores of sandy clays from this study area contains plane laminations.

The sandy clays exhibit a faint horizontal bedding in addition to the more obvious laminations already described. The bedding is ~1–3 cm thick and is caused by subtle variations in the abundance of sand observable on the X-radiographs. There are no sharp contacts or graded bedding associated with this structure.

Sediment Geochronology

Results from the radiocarbon analyses (Table 1) are impossible to use for determination of sedimentation rates, because the ages of surface-sediment samples are older than those of deeper samples in two cores (13BX and 17BX) and are very old compared to the total age range in all cores. Postglacial sediment in Lake Superior has no carbonate minerals (there is practically no limestone or dolomite in the drainage basin), and radiocarbon dating must be performed on the particulate organic carbon. Lake Superior sediment typically contains just 2% to 3% total organic carbon (Johnson and others, 1982). The results indicate that there is too much old, detrital carbon mixed in with new carbon in this high-energy environment, making the dates much older than the actual sediment ages.

The radiocarbon dates, although not usable for determination of sedimentation rates, are at least useful in indicating that the sediments and sedimentary structures throughout the study area are the result of postglacial processes.

Preliminary results from ^{210}Pb analysis yielded sedimentation rates for the past 100 yr of 0.2 mm/yr in both cores L81-1BX and L81-3BX. Background ^{210}Pb activity is found within 6-cm burial depth in the cores. Core 3BX has nearly uniform ^{210}Pb activity in the upper 2 cm of the core, whereas core 1BX shows much less evidence of sediment mixing. These results are typical of much of Lake Superior (see Evans and others, 1981) and show no significant effects of bottom currents (for example, increased mixing).

Lake-Floor Photographs

Photographs of the lake floor show little or no evidence of bottom-current impact upon sedimentation. The most common features are round to circular depressions that are estimated to be as much as 10 cm in diameter and no more than 1–2 cm deep (Fig. 11A). Smaller, irregular gouge marks are also common (Fig. 11B). Both of these microtopographic features are attributed to biological activity. Many of the photographs show small fish, probably sculpins, that could make the circular depressions. The fish are about the right size to have made the depressions, a few photographs show fish within depressions (for example, Fig. 11C), and one photograph illustrates the effectiveness of the fish as sedi-

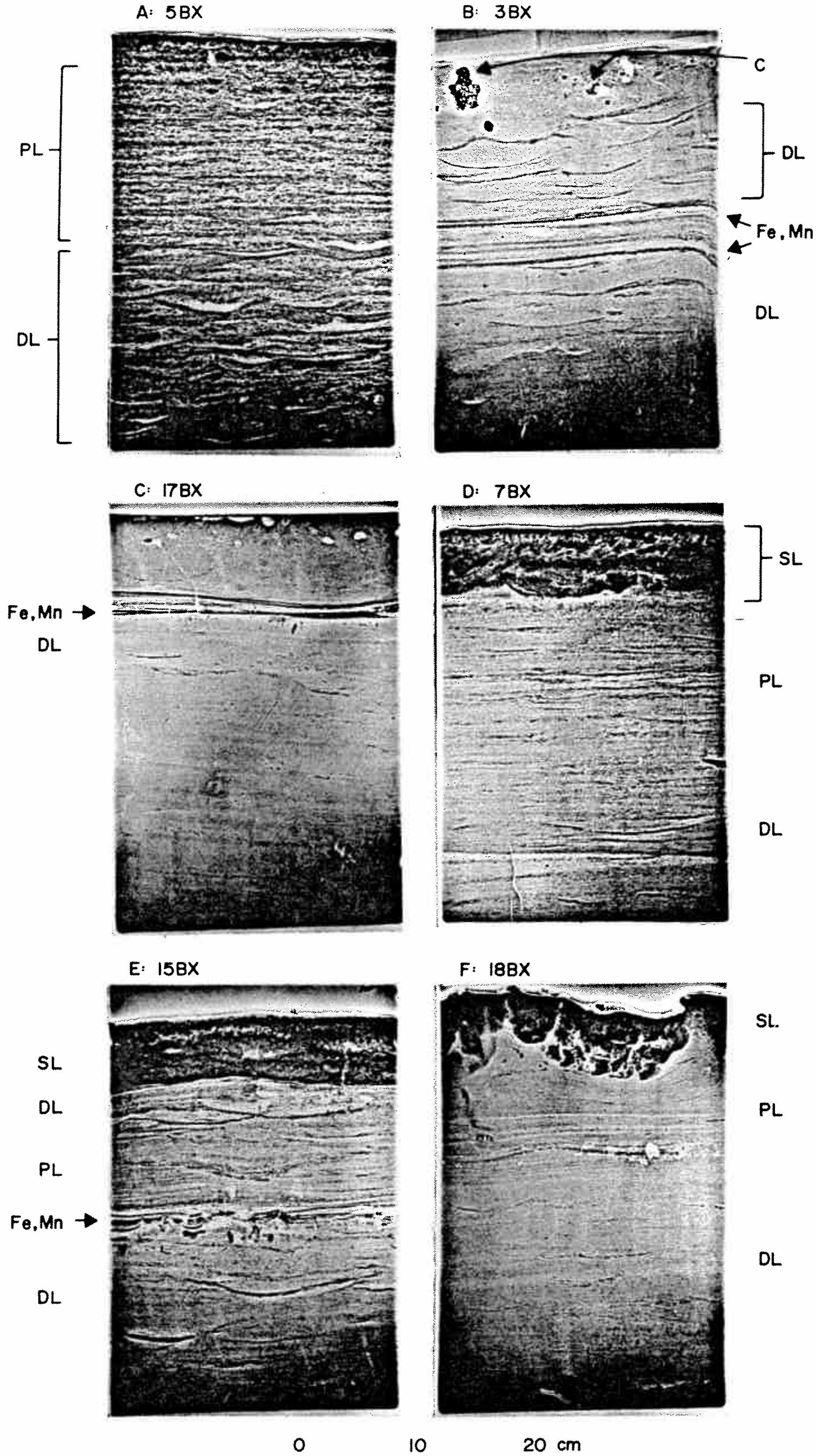


Figure 9. X-radiographs of vertically oriented slabs from box cores, illustrating plane laminations (PL), dish laminations (DL), sand layers (SL), iron and manganese oxide crusts (Fe, Mn). Clinkers from coal-fired freighters designated by "C." Core locations are indicated in Figure 1.

TABLE 1. RADIOCARBON AGES OF BOX CORES FROM THE EASTERN CORE TRANSECT

Core	Sample depth (cm)	Sample number*	Age (yr B.P.)
11BX	0–10	WSU–2707	665 ± 100
	10–20	WSU–2710	790 ± 90
13BX	0–10	UM –2597	2,819 ± 70
	10–20	UM –2598	2,048 ± 90
	26–36	UM –2599	3,622 ± 100
15BX	6–16	WSU–2708	3,165 ± 60
	31–41	WSU–2712	4,420 ± 115
17BX	0–7	WSU–2706	1,865 ± 90
	7–17	WSU–2709	1,090 ± 100
	31–42	WSU–2713	2,540 ± 40
21BX	0–10	UM –2600	2,026 ± 80
	35–45	UM –2601	2,103 ± 70

*WSU = Washington State University; UM = University of Miami.

ment scourers (Fig. 11D). The irregular gouge marks also may be formed by fish, or by some other benthic organism. The invertebrates of Lake Superior (Heuschele, 1982) are usually shorter than 1 cm, so it is unlikely that they are responsible for the gouge marks.

One feature photographed on the lake floor is clearly of biological origin. This is a set of V-shaped depressions spaced evenly across a photograph (Fig. 11E) that may have resulted from a fish hopping along the lake floor on its pectoral fins (M. Auer, 1983, personal commun.). The V-shaped depressions are estimated to be ~23 cm long and spaced ~25 cm apart. This feature was observed in only one of the 85 exposures in the study area.

Evidence for bottom currents is subtle at best. Figure 11B shows a hint of regularly spaced ripples aligned from upper left to lower right in the photograph. Figure 11E has a series of fish(?) depressions in the lower left corner that appear to have been modified by bottom currents. Figure 11F also has circular depressions and gouge marks that appear to have been modified slightly by bottom currents.

Camera station 6 was in much shallower water, 120 m, in the region of depositional furrows. The water was not as clear as at the other camera stations, and so some lake-floor features may have been obscured. The lake floor here is smoother in microscale than at the deep-water sites. No circular depressions can be seen in the photos, and irregular gouge marks appear to have been smoothed out to some extent, perhaps by bottom currents. Sediment plumes are observed in 36% of the photographs, perhaps due to camera impingement on furrow walls. Fish are rare at this site.

DISCUSSION

Several of the features observed in the study area are the result of bottom-current influence upon sedimentation and are similar to what is observed in many other dynamic sedimentary environments, particularly in the oceans. These

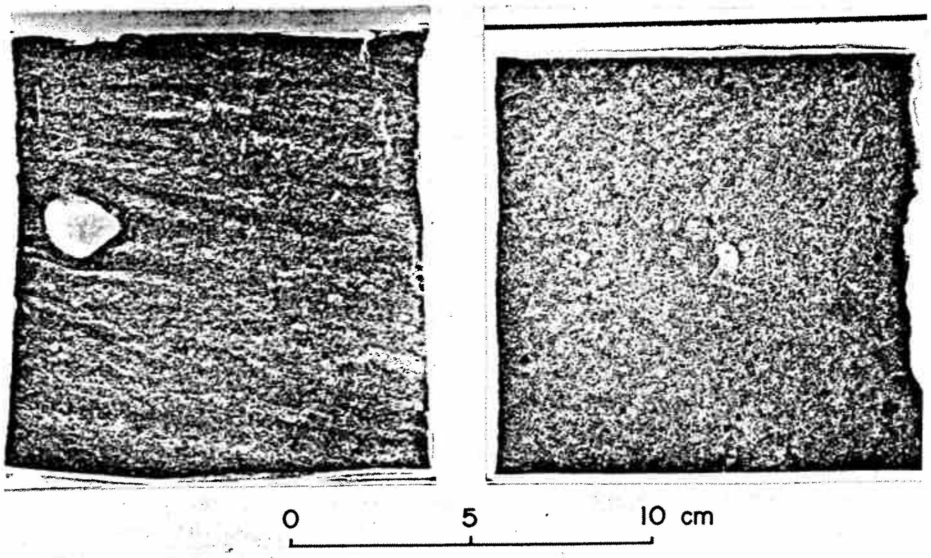
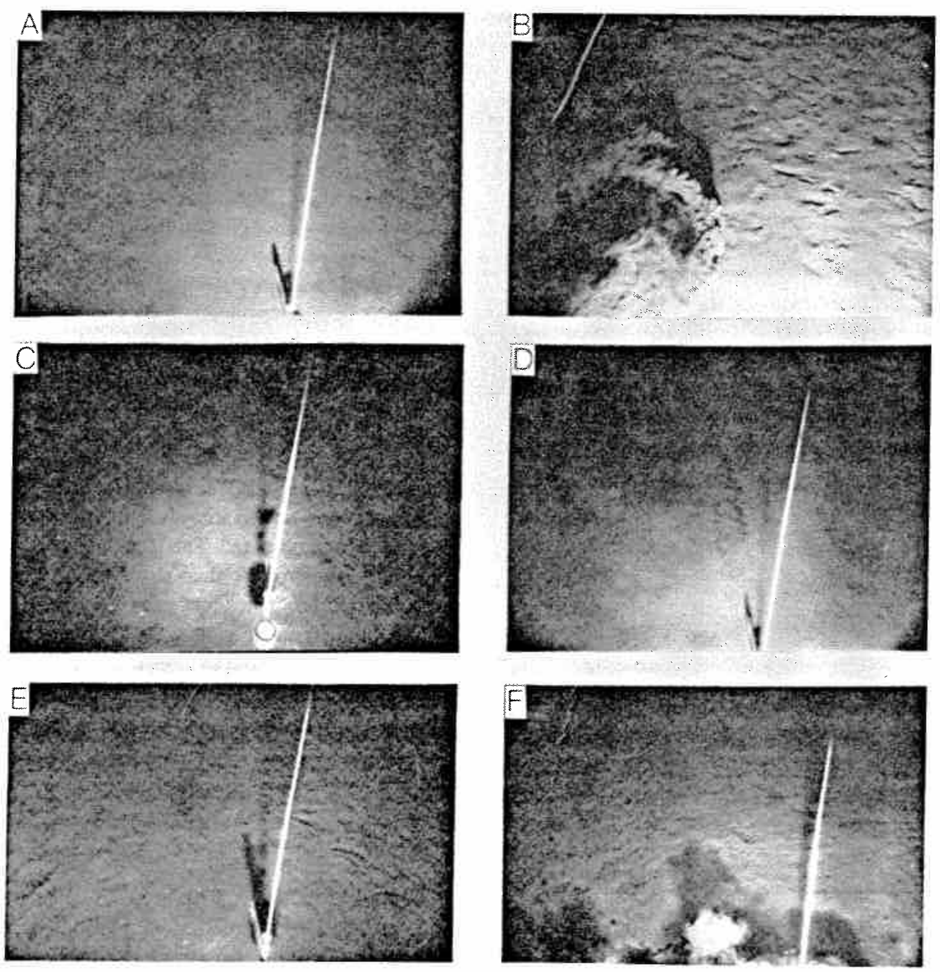


Figure 10. X-radiographs of two horizontally oriented slabs from box cores, illustrating bedding-plane lineations and a pebble in core 11BX and the more commonly observed homogeneous structure in core 13BX.



features include: (1) the presence of the erosional trough at the base of the slope, (2) the change in sediment grain size from the trough lakeward, (3) the presence of furrows on the slope, and (4) the presence of plane laminations in some of the box cores. Radiocarbon dates indicate that the features clearly resulted from Holocene processes and are not relics from a Pleistocene glacial-lacustrine environment.

The 3.5-kHz profiles from the study area somewhat resemble seismic-reflection profiles of contourites obtained in the oceans. The wavy 3.5-kHz profiles are similar in appearance, although not in scale, to profiles of wavy contourites in the western North Atlantic (Bouma and Hollister, 1973). Similar echo-sounding profiles may result, however, from turbidity currents (Damuth, 1975) or slumping (Embley, 1975). The overlapping 3.5-kHz profiles resemble profiles of drift deposits from the western Indian Ocean that were formed by contour currents (Johnson and Damuth, 1979, Fig. 11).

Close agreement exists between maps of lake-floor features determined by 3.5-kHz normal-incidence profiling (Fig. 5) and side-scan SONAR (Flood and Johnson, in press, Fig. 12). Regions of normal 3.5-kHz profiles (Fig. 5A) coincide with regions having large fragments of unmodified circular depressions on side-scan SONAR records (Fig. 6). Regions of overlapping features on 3.5-kHz profiles (Fig. 5B) have current-modified circles (Fig. 6B), and wavy 3.5-kHz profiles (Fig. 5D) are found where side-scan SONAR records reveal a relatively smooth lake floor with faint lineations (Fig. 6C).

The circular or ring depressions are unlike any lake- or sea-floor features reported previously from side-scan SONAR surveys, with the exception of a polygonal system of cracks on the floor of Lake Superior reported by Berkson and Clay (1973). The quality of our side-scan records is better than Berkson and Clay could obtain with equipment available at the time of their survey; our records clearly indicate that the depressions are not linear segments of polygons. The cause of ring depressions is not known.

Figure 11. Lake-floor photographs, illustrating fish depressions (A), more fish depressions and biogenic gouge marks and possible ripples at left (E), and more biogenic structures, perhaps modified by currents (F). Photographs A and D are from camera station (CS) 2, B and E are from CS 4, C is from CS 5, and F is from CS 1. Camera-station locations are indicated in Figure 1. The compass face in the photographs is ~8 cm across.

Berkson and Clay (1973) suggested that the depressions form by syneresis operating on a large scale. Johnson (1980) suggested that they result from dewatering associated with compaction of sublacustrine glacial deposits that, in places, are >400 m thick (Wold and others, 1982). Ring depressions are observed in many regions surveyed in western Lake Superior (Flood and Johnson, in press), but they are best developed in the study area and in a deep-water setting off the Minnesota shoreline. The ring depressions probably are not formed by bottom currents, but they are modified by them.

There have been no direct measurements of bottom-current velocities in the study area, but they can be estimated from grain size and sedimentary structures. The sand mode of 2 phi (250 μm) in the trough sediment may be the coarsest grain size moved by the fastest bottom currents. If this is true, the empirical equation of Miller and others (1977) suggests that currents at 1 m above the bed achieve a speed as great as 42 cm/sec. This is much faster than any current measured in the deep water of Lake Superior, although few such measurements have been made. Carlson (1982) reported a maximum current speed of 35 cm/sec at mid-depth (150 m) and 15 cm/sec at 10 m above the lake floor in a 2-month period of continuous measurements at a location off the northeastern tip of Isle Royale in September 1979. There were no *major* storms during the measurement period (although the periods of fast currents coincided with periods of relatively high winds), and the water column was stratified. Spectral analysis of the current meter records revealed near-inertial frequencies in both current magnitude and direction. The results can be attributed to the presence of interfering Kelvin and Poincaré waves generated in the lake by passing storms (Mortimer, 1974). If bottom-current speeds as much as 15 cm/sec can be measured during relatively quiet periods at a location that does not have erosional features as spectacular as those in the study area, then current speeds of as much as 42 cm/sec under more dynamic conditions seem plausible.

The bimodal grain-size distribution is strongly influenced by the local sources of sediment. The relatively well-sorted sand with a mode of 2 phi is probably from glacial moraines exposed on the lake floor in the western part of the study area (Halfman and Johnson, in press), and the finer mode in the clay range is from postglacial lake deposits and clayey tills. The clay mode is typical for offshore sediment throughout most of Lake Superior. The percentage of silt and clay in the trough sand is quite high, 15% in 6G and 50% in 12G, indicating that current speeds are not fast enough much of the time to winnow even silt.

The shapes of the cumulative frequency curves generated by pipette and sieve analysis are distinctive, but not like the curves of marine contourites presented in Piper and Brisco (1975). The curves can be divided into straight-line sediments that may represent subpopulations responding to different processes (for example, traction, saltation, suspension) (Visher, 1969; Middleton, 1976). Curves of trough sand typically have a small population of coarse material, illustrated by the population coarser than 1 phi in core 6G (Fig. 7). Both the trough sand and the sandy clay offshore show a significant population in the range between 0.5 and 2.5 phi (Fig. 7). This is the population that would be attributed to traction-load transport by Visher (1969), although here we can say only that this population is characteristic of the nearby source of sand (sublacustrine glacial outwash), and that it has been transported into the area as bed load. The cumulative frequency curves usually have two or more subpopulations defined by straight-line segments in the size range of 2.5 to 14 phi (Fig. 7). The significance, if any, of these subpopulations has not been determined.

The shape of the cumulative frequency curve of the silt fraction, determined by the electronic particle analyzer, varies systematically from high to low velocity regions and may be the best textural criterion to use to identify contourites in Lake Superior. The curves are smooth, and they cannot be subdivided into straight-line segments, as the whole-sediment curves can. The change in curve shape is quantified by skewness, which changes from about +0.30 in the trough to −0.05 offshore. Comparable studies of the silt fraction of marine contourites have been carried out by Allison and Ledbetter (1982) and Blaeser and Ledbetter (1982). Both studies showed skewness values to be higher in areas influenced by strong bottom currents, as is the case for Lake Superior. The values are lower than the Lake Superior values, however, ranging between −0.02 and 0.08. The mean size silt of the marine contourites studied by Ledbetter and his coworkers ranges between 6.2 and 6.7 phi. This is much finer than what is found in Lake Superior and may explain the difference in skewness values.

The sedimentary structures observed in the box cores are not all formed by bottom currents. The dish laminations that are so prevalent in both trough sands and sandy clays offshore are attributed to fish scour. Sediment slabs cut at right angles to one another show the same symmetrical features, indicating that they are nearly circular in plan view. There is no evidence of

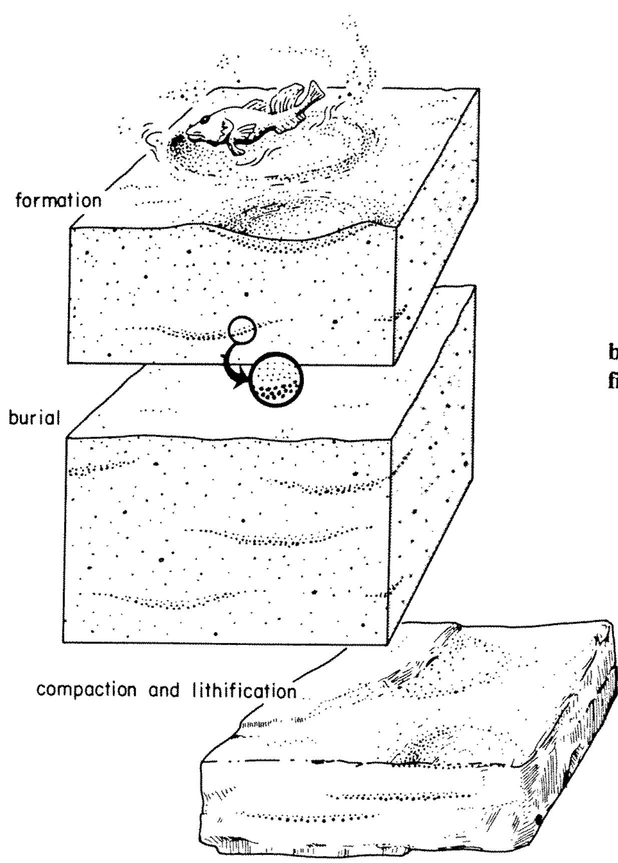


Figure 12. Formation, burial, and compaction of fish-scour structures.

cross-bedding. The width of the lenses is close to the diameter of the circular depressions in the bottom photographs that are believed to be formed by fish scour. The size of the dish laminations does not change systematically with distance offshore from the trough, nor with mean grain size. This suggests that the structures are not formed by bottom currents. Bottom photographs clearly indicate that fish are abundant in the study area, resuspend sediment (Fig. 11D), and occupy the circular depressions on the lake floor (Fig. 11C). A fish presumably creates a circular depression by rapid fin movement that scours away fine sediment, leaving behind a lag deposit of sand that lines the depression. When the depression is abandoned, it may take on the order of 40 yr to fill in with fine-grained sediment, as based upon a mean depth for the depression of 0.8 cm, and a sedimentation rate, from our ^{210}Pb analysis, of 0.2 mm/yr. The time to fill the depression may be much shorter, however, because it probably is a more effective sediment trap than is the adjacent lake floor.

Compaction and lithification of the fish-scour depressions will create sedimentary structures that should be distinguishable from structures formed by bottom currents. Compaction will flatten the concave-upward laminae by ~90% into nearly planar structures. These will be discrete, round sand layers in plan view, 1–2 sand-grain diameters in thickness and 5–10 cm in diameter, embedded in sandy mudstone in the case of the offshore sediments, and similarly sized features, but made of mudstone, embedded in muddy sandstone in the case of the trough sediments (Fig. 12).

The structures formed by bottom currents, on the other hand, will lithify into features that are distinctly different from the fish-scour structures. The plane-laminated mud and sand structures observed in the upper half of core L81-5BX (Fig. 9A) will lithify into a plane-laminated muddy sandstone with discontinuous shaly laminations with occasional bedding-plane lineations. The shaly laminations will not be round in plan view, in contrast to the fish-scour structures. The sand layers interbedded with sandy clays will lithify into sandstone layers embedded in sandy mudstone. The layers will have sharp upper and lower boundaries, sometimes will show loading deformation, and often will be underlain by plane-laminated sandy mudstone.

CONCLUSIONS

This study documents the strong impact that bottom currents have had upon sedimentation in a lacustrine deep-water environment. Lake-floor morphology has been modified, primarily by the formation of a scoured trough as much as 20 m deep and 2 km wide at the base of a slope that channels flow northeastward around the Keweenaw Peninsula. The dominant features in offshore regions of sandy clay are the large fragments of ring depressions of unknown origin. They may contain sediment coarser than the surrounding lake floor, possibly because the depressions funnel and locally accelerate the slower regional flow. The ring depressions are modified by bottom currents, becoming fragmented, scalloped, and elongated in a direction subparallel to the current flow. Superimposed upon these features there are lineations in surface-sediment texture (sand ribbons?), also aligned subparallel to the direction of current flow, that are faint offshore and become more pronounced with proximity to the scoured trough. Depositional furrows are well developed in a slope environment where bottom currents probably decelerate.

Sediment grain size decreases from clayey sand in the scoured trough to sandy clay in offshore regions. The grain-size distributions are of two modes: a relatively well-sorted sand mode centered at 2 phi and a poorly sorted clay mode. Detailed size analyses of the silt fraction by an electronic particle analyzer yield distinctly shaped cumulative-frequency curves that change systematically with bottom-current strength. Downcore analyses of grain size suggest that bottom currents have become progressively weaker in the study area during the past 9,500 yr.

Certain aspects of the study area are unique and limit application of the results to other environments of contourite formation. The ring depressions are unusual features, although they may be present in other large, glaciated lakes. The nearby locations of glacial-outwash sand strongly affect the grain-size distributions. Finally, the abundance of fish and their impact upon sedimentary structures are substantial. Consequently, although the results are not complicated by the presence of turbidites or invertebrate bioturbation, they are indeed affected by other complications. The effects of bottom currents in this lacustrine environment nevertheless are well defined and serve as a basis for comparison in the future study of contourites.

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