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LAKE-FLOOR GEOMORPHOLOGY OF LAKE ERIE

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Abstract

Lake floor physiographic features of Lake Erie, many seen in detail for the first time, are described with the aid of new bathymetry. Geomorphology of these features is discussed utilizing the bathymetry, existing data, and previous interpretations. The nearshore zone surrounding the main basins of Lake Erie deepens to 5-15 m within the first 1-3 km of the shore, exposing bedrock, glacial drift, and glaciolacustrine clay. Glacial erosion interacting with bedrock of varying resistance to erosion has accounted, directly or indirectly, for certain Lake Erie escarpments and other features, such as those occurring within the islands area and in the eastern Basin. Long Point Escarpment is apparently the surface expression of a bedrock escarpment formed on the edges of erosion-resistant southward-dipping strata. Clear Creek Ridge resembles an offshore bar built from accumulations of sand moving along the former shore at lower lake levels, though it may have a morainic foundation. The Pelee-Lorain, Long Point-Erie, and Point Pelee Ridges, are interpreted as morainic ridges on which sands were later concentrated by longshore transport at lower than present lake levels. Conneaut Bank, Fairport Ridge, and Point Pelee Fan are interpreted as deltas formed at lower lake levels. Pennsylvania Ridge flanks Pennsylvania Channel and resembles a natural levee extending westward from the southern end of the Long-Point Erie Ridge. Strong westward currents at depth through Pennsylvania Channel have apparently kept the channel open.

INTRODUCTION

Bathymetry at one-meter contour intervals has been completed for all of Lake Erie and Lake Saint Clair. This bathymetry exceeds in detail any previous bathymetry and provides significantly improved resolution of lakefloor topography, revealing lakefloor features never before seen. This bathymetry has resulted from continuing cooperative efforts between researchers and bathymetrists at the NOAA National Geophysical Data Center, the NOAA Great Lakes Environmental Research Laboratory, and the Canadian Hydrographic Service. It also includes the contributions of investigators at cooperating academic laboratories including the NOAA/ University of Colorado Cooperative Institute for Research in Environmental Sciences (CIRES), and the NOAA/ University of Michigan Cooperative Institute for Limnological and Ecosystems Research (CILER).

This paper describes and illustrates lakefloor physiographic features of Lake Erie and Lake Saint Clair, as revealed by the one-meter bathymetry; and reinterprets lakefloor geomorphology based on greatly improved definition of topographic features. Lakefloor geomorphology of western Lake Erie was discussed in a previous paper (Holcombe, et al., 1997), and therefore it will be largely excluded from discussion in this paper. A scale 1: 250,000 color poster depicting the bathymetry of Lake Erie and Lake Saint Clair, as well as an accompanying CD-ROM containing digital bathymetric data sets and imagery, has been published (National Geophysical Data Center, 1998). A smaller version of the bathymetry is included in this report (plate 1A), together with large-scale inset maps illustrating specific features (plate 1D, 1E, 1F, and 1H) and three-dimensional perspective diagrams (plate 1C, 1G).

Bathymetric sounding data employed in compiling the one-meter bathymetry (National Geophysical Data Center, 1998) were collected over a 100-year period for purposes of navigation safety and nautical charting by the U. S. Army Corps of Engineers, the NOAA Coast Survey, and the Canadian Hydrographic Service. These bathymetric data, totaling several hundred thousand soundings, are separated four ways in existing archives: by whether they exist in digital form or reside only on paper sheets; and by whether they were collected by the U. S. or Canada. Final assembly of the new bathymetry has resulted from synthesis of bathymetric data from the four sources.

Bathymetric contours were prepared by geologists using sounding data contained in the paper archives at the scale of the survey sheets (scales ranging from 1: 100,000 to 1: 10, 000); or from sounding data contained in digital data bases at standard scales of either 1: 100,000 or 1: 50,000. Details concerning the methods of compilation are given in the western Lake Erie paper (Holcombe, et al., 1997). Bathymetric contours have been spatially reconciled with the NOAA Coast Survey nominal scale 1:80,000 digital vector shoreline, which by definition coincides with the Lake Erie low water datum, the zero-depth employed for bathymetric surveys and nautical charting. Bathymetric contours were digitally scanned and vectorized so that the entire bathymetric contour data base resides in the digital domain as a single data set.

LAKE ERIE GEOMORPHOLOGY

Overviews of Lake Erie geology and geomorphology appear in the LAKE ERIE AND LAKE SAINT CLAIR HANDBOOK (Bolsenga and Herdendorf, 1993); in the book LIVING WITH THE LAKE ERIE SHORE (Carter, et al., 1987); and in papers by Herdendorf (1989), Sly (1976), and Sly and Lewis (1972). We repeat here only a summary of the main episodes of geological history which have resulted in present-day lakefloor topography.

Geological history of Lake Erie, its three distinct basins – Western, Central, and Eastern, and the surrounding region, began with recurrent long periods of deposition of a variety of shallow marine, coastal, and nonmarine sedimentary rocks throughout most of Paleozoic time (250-500 ma). The lakefloor itself is underlain by about 300m of gently dipping, easily erodible uppermost Silurian and Devonian (350-400 ma) shallow-water marine shales. Devonian carbonates, which are more resistant to erosion, form positive bedrock relief features in the islands area of the Western Lake Erie Basin, and along the north shore of the Eastern Lake Erie Basin. Some silty shales and siltstones, composed of lithified terrigenous sediments brought westward from the upper Devonian Catskill Delta, extend westward beneath the easternmost lake floor.

During all of Mesozoic and Cenozoic time (250 ma to present), the region was probably elevated and relatively exposed, because no post-paleozoic pre-glacial bedrock occurs in the region. The Paleozoic bedrock surface must have been subjected to episodic or long-continued erosion, for there is an elaborate system of post-Paleozoic, preglacial drainage channels which have been incised into the bedrock of the region. Preglacial drainage has been inferred beneath the shallow western end of the lakefloor, but glacial episodes swept away evidence for pre-glacial channels in the central and eastern basins of the Lake.

During the last two million years (2 ma to present), the region was subjected to repeated episodes of glacial erosion and deposition associated with successive advances and retreats of Laurentide ice sheets. Present-day lakefloor topography is the result of the cumulative effect of these repeated episodes of erosion of lakefloor sedimentary deposits and bedrock, and re-deposition of the sedimentary products of this erosion. Present-day topography is essentially that left following the most recent retreat of glacial ice out of the Lake about 13,000 ya, but with some significant modifications occurring in postglacial time.

Postglacial (12,500 ya to present) modifications to lakefloor topography consist of those occurring within a large, shallow lake. These modifications include:

1) Shoreline erosion, and deposition of the sand and gravel components of this erosion, along the shoreline as beaches, bars, and spits.
2) Preferential deposition of finer-grained sediments (brought into the lake or eroded from the lakeshore) in the deeper parts of the lake basins.
3) Secondary sculpting of lakefloor sediments by lake water currents.
4) Anthropogenic disturbances such as channel dredging and dumping of dredge spoils; and recovery of lakefloor sand and gravel deposits.

NAMES OF LAKE FLOOR FEATURES

Detailed bathymetry has improved the definition and clarity with which known lake floor features are seen. As noted, several features are revealed for the first time. Names for lake floor features are needed to facilitate discussion and give each feature its own identity. Up until the advent of this bathymetry, there were no official geographic names for any Lake Erie lake floor feature. Consequently, a complete set of new geographic names was proposed to the U. S. Board on Geographic Names (BGN). Most of the names were names of precedence (that is, already unofficially in use), and where known, these names were proposed to BGN. A small number of features had no name, and for these features, new names were proposed. The BGN cleared each name with U. S. state naming authorities (NY, PA, OH, MI), depending on location of each feature, and then signified their approval of most of the names proposed. It is an item of international business for BGN to discuss the proposed names of features which extend into the Canadian portion of Lake Erie with the Geographical Names Board of Canada (GNBC).

Names of lake floor features which are mentioned in the text of this report are shown in figure 1a and 1b. Those feature names, which have been approved by the U. S. Board on Geographic Names, have been highlighted.

FEATURES FORMED BY EROSION OF BEDROCK

Physiographic features formed by glacial erosion of the Lake Erie bedrock are highlighted in the detailed bathymetry. Bedrock geology has been mapped around the perimeter of Lake Erie and on the western Lake Erie Islands, but mapping of inferred bedrock units beneath the lake has, and must remain, tentative. The only basis for extending bedrock boundaries beneath the Lake is the bedrock topography, as formed by glacial erosion acting on rock strata which vary in their resistance to erosion. Generalized mapping of bedrock geological boundaries beneath Lake Erie has been attempted (Sanford and Baer, 1981). More recently, inferred geological boundaries of rock strata underlying Lake Erie have been mapped by one of the co-authors, C. E. Herdendorf. We have included a sketch of the Sanford and Baer 1981 map, registered to the bathymetry (figure 2).

Bedrock Features of the North Shore

East of Long Point the indented Canadian shore is formed in thin glacial drift and intermittent dune and beach sand overlying bedrock of relatively resistant Devonian limestone (Dundee Limestone in Ontario, Onondaga Limestone continuing eastward in Ontario and in New York State). The Devonian limestone crops out intermittently on shore and dips gently southward (Carter, et al., 1987; Rickard and Fisher, 1970; Freeman, 1978; Sanford and Baer, 1981; Bolsenga and Herdendorf, 1993). Small abruptly-rising bedrock ridges extend 2-4 km offshore to depths of 5-10 m, have a spacing of 2.5 to 5 km, and mirror the alignment of shoreline alcoves and promontories (plate 1H). Small banks which extend farther offshore are typically 2-4 km in width, have a relief of a few meters to 15 m or more, and, like the topography nearer shore, are capped by rough microtopography which has been mapped as exposed bedrock (Rukavina and Saint Jacques, 1971). Many of these bedrock ridges extend in a NE- SW direction away from the shore. The preferred orientation of these ridges confers favorably with those forming small ridges on the Port Maitland Bank, and with several smaller ridges occurring farther offshore in deeper water (plate 1H).

Escarpment in the Eastern Basin

A north-facing escarpment having a relief of 15-20 m extends longitudinally about 50 km E-W along the floor of the central part of the Eastern Basin (plate 1A). The escarpment is surrounded by topography of 1-5 m relief which is hummocky and not strongly lineated. The deepest part of the Eastern Basin occurs near the base of the escarpment. The hummocky topography is surrounded by smoother topography which occurs upslope at depths of 15 to 35 m. Evidently this region, though covered with glaciolacustrine clays and postglacial muds of variable thickness up to 70-80 m or more, still bears some residual imprint of the underlying glaciated surface. Seismic reflection records show that the escarpment in the deepest part of the Eastern Basin mimics the bedrock topography through differential compaction of overlying sediments (Cameron, 1991). The underlying bedrock escarpment has a relief of some 30-40 m and it lies 50-100 m below the present lakefloor.

The bedrock escarpment probably lies along a boundary separating gently southward dipping, more resistant upper Devonian strata, probably a limestone bed within the Hamilton Group (figure 2), from underlying less resistant marine shales to the north. Alternately, the escarpment may coincide with an old fault scarp or fault-line scarp along which rock units of differing resistance to erosion were juxtaposed. The escarpment is linear when viewed as a whole, but at the smallest scales it displays topographic irregularities. Paralleling the inferred direction of ice flow down the axis of the lakefloor, the bedrock escarpment probably resulted from direct, intense, under-ice glacial or meltwater erosion. Lack of large-scale irregularity along the trace of the escarpment suggests that in the subglacial regime of erosion, any prominences in the resistant strata which extended northward would have been sheared off due to the eroding power of the ice or meltwater.

Bedrock Features of the South Shore

The southern shore of Lake Erie Basin is straight and relatively free of coves and inlets (plate 1A). Middle and upper Devonian marine shales and terrigenous siltstones of the Hamilton, Genesee, Sonyea, West Falls, Java, and Canadaway Groups, in ascending order, crop out along the shore (figure 2). These Devonian strata intersect the shore at a low angle and extend westward beneath the Lake. Progressively younger strata intersect with and crop out along the shore proceeding from east to west (Rickard and Fisher, 1970; Buehler and Tesmer, 1963). Irregularities in the otherwise straight shoreline between Sturgeon Point and Dunkirk appear to be the result of differential resistance to erosion within successive groups of Devonian strata, and structural features such as localized faults and folds (Hartley, 1962).

Upper Devonian sediments grade westward from thousands of meters of terrigenous siltstones and sandstones in western New York state to about 300 m of relatively soft Devonian marine-platform shales underlying most of Lake Erie. Less resistant shales of the marine-platform facies of the Hamilton Group extend farther east than in most of the younger Devonian strata. The deep axis of easternmost Lake Erie was apparently eroded into Hamilton Group strata, which forms part of the bedrock at Buffalo.

Younger upper Devonian and Carboniferous terrigenous and non-marine siltstones and sandstones underlie the Allegheny Plateau of western New York, Pennsylvania, and eastern Ohio (Bolsenga and Herdendorf, 1993). These massive plateau-forming rocks do not extend north as far as the Lake shore, but they undoubtedly formed a barrier and a westward deflector for advancing glacial ice.

The nearshore zone extends to depths of 10-15 m off the southern shore of eastern Lake Erie (figure 1). This zone is floored by bedrock which is exposed all along the south shore (Carter, et al., 1987; Lewis in Sly and Lewis, 1972; Thomas, et al., 1976); Fuller and Foster, 1998). Ledges are evident in the small-scale topography (figure 1), such as one would expect in a succession of stratified rocks.

Southwest of Buffalo a nearly-level platform adjoins the steep shoreline topography and extends SW to Sturgeon Point. This platform is bordered along its northwestern edge by small topographic highs which are aligned NE-SW and includes Buffalo Knoll, a small bank extending upward to a depth of 4 m and having steep sides down to a depth of 9 m. These NE-SW aligned topographic highs might be erosional remnants of more resistant stratigraphic zones within upper Devonian bedrock as described by Rickard and Fisher (1970); Buehler and Tesmer (1963); and Sanford and Baer (1981).

West of Sturgeon Point, the shoreline offsets to the south, and another, narrower platform extends west as far as Dunkirk. This platform occurs at a depth of 16 to 19 m. It also has some small 1-3 m topographic highs along its outer margin.

Dunkirk Bank occupies a zone of rough topography extending 7-8 km offshore just west of Dunkirk (plate 1A; figure 1b). Topography of the Bank consists of a number of knolls of 3-6 m relief which crest at 13-15 m depth along its northern rim, enclosing several small basins of a few meters relief inshore. This zone of rough topography and the narrow platform to the northeast are bounded on the northwest by a relatively short NE-SW trending escarpment. This escarpment increases in relief from 7 to 20 m from NE to SW, and the escarpment steepens concomitant with increasing scarp relief, as well as with increasing depth of the Eastern Lake Erie Basin. Several stratiform ledges are present along the side slopes of this escarpment.

Dunkirk Bank could have been sculpted by glacial erosion, or it could be partly an anthropogenic feature dating from the time when Dunkirk was a major port at the Lake Erie terminus of the Erie Railroad.

West of the zone of rough topography and its bounding escarpment northwest of Van Buren Point, the deep part of the Eastern Lake Erie Basin is offset southward as if former glacial erosion has here eroded southward and stratigraphically upward through the upper Devonian (plate 1A). From this point the Dunkirk Escarpment extends westward, a 10-20 m arcuate escarpment which forms the northern boundary of a narrow platform at 15-20 m depth. A line of small ridges occurs on the outer edge of this narrow platform, suggesting the presence of a resistant upper Devonian rock stratum. The escarpment diminishes in relief approaching Presque Isle, and here merges with the south slope of the Pennsylvania Channel.

Bedrock is exposed almost continuously near the shore from Pennsylvania to the Grand River, intermittently from the Grand River west to Cleveland, and west of Cleveland to Vermilion except off the Black River at Lorain (Hartley, 1961; Fuller and Foster, 1998; figure 2). Uppermost Devonian shale (Antrim and Kettle Point Formations or Ohio Shale) forms the bedrock, which thins westward and become less silty. Proceeding westward, progressively younger rocks are exposed along the Lake shore as far as Cleveland, topping out in the uppermost Devonian Cleveland Shale member and Huron Shale member of the Ohio Shale. West of Cleveland, age of bedrock strata reverses, becoming progressively older toward the west as bedrock levels rise approaching the Findlay Arch.

Nearshore Zone

The bathymetry provides for the first time a more detailed and integrated view of near shore topography around the entirety of Lake Erie and Lake St. Clair. The nearshore zone is characterized by fine-scale irregular topography which steeply deepens (slope 0.25-0.55 degrees) within the first ½-3 km of the shore (plates 1A, 1E, figure 3). Depth of the outer limit of this nearshore "steep" topography ranges from 2 to 27 m, but varies between 5-15 m off most of the shoreline facing the open Lake (figure 1). The steep zone is characterized by exposed bedrock, exposed glacial drift or glaciolacustrine clay, and little or no postglacial deposition except for intermittent shoreline or lag-concentrate deposits of sand and gravel (Carter, et al., 1987; Lewis, et al., 1966; Rukavina, 1976). Along the southern shore of the lake occur the aforementioned extensive outcrops of exposed bedrock (Carter, et al., 1987; Fuller and Foster, 1998; Thomas, et al., 1976; Sly and Lewis, 1972).

Depth of the outer limit of the steep nearshore zone varies around the Lake (figure 3). A positive correlation exists between the depth of this outer limit and the amount of wave energy impinging on the shore. This outer limit is deeper off headlands, along shore facing the full fetch of the open Lake, and where deeper basins approach the shore. The outer limit is less deep in the shallow western Basin of Lake Erie, in Lake Saint Clair, and in sheltered embayments.

The steep nearshore zone, the onshore wave-cut cliffs, and the gently sloping zone farther offshore, together coincide with the zone of high wave energy impinging on the shoreline in a shallow lake. Shore erosion has resulted in deepening and steepening of the inner shore profile and leveling of the areas farther from shore. The fine-grained sedimentary products of shore erosion have been transported out of the high energy shore zone and into the main Lake basins. Some sand-and-gravel sized sediment eroded from the shore has remained in the shore zone, usually having been transported in one direction or the other along the shore.

It is apparent that shore erosion in the zone of high wave energy has been effective in altering and shaping the unconsolidated glacial drift and soft shales which characterize the Lake Erie shoreline. As is characteristic of a shallow lake, steepening, deepening, and straightening has occurred in the nearshore zone, and the erosion products of this erosion have been deposited farther offshore in deeper water. The rate at which the shore profile adjusts to a given lake level, and whether the shore profile of today is in fact the result mainly of erosion at today's lake level, or whether it formed at a slightly lower lake level, are matters for speculation.

FEATURES FORMED BY GLACIATION

The Lake Erie bathymetry better defines the morphology of features which have been sculpted by glaciation. Features previously identified as moraines include the Pelee, Erieau, Norfolk, and Port Maitland moraines (Lewis, et al., 1966; Sly and Lewis, 1972). These features are highlighted and labeled in figure 4. The new bathymetry has uncovered ridges not previously known, bordering the Central Basin and lying west of the Norfolk moraine, which are designated as moraines and also highlighted in figure 4. For comparison with known and inferred lake floor moraines, the moraines of southern Ontario as outlined by Chapman and Putnam (1951) and Barnett (1998) are also shown in figure 4. These features will be discussed in more detail below.

Strongly lineated features associated with bedrock occurring mainly along the north lake shore east of Long Point, and with Port Maitland Bank, are highlighted in figure 4. These features form a group of NE-SW lineations which are drumlin-like and are probably glacial in origin. Their trend confers favorably with that of the moraines of southern Ontario. Trends of the Gasline Ridge, the Long Point Escarpment, and the Dunkirk Escarpment, are also shown in figure 4.

At depths greater than 40m in the Eastern Basin, topography remains which probably mimics that left by glaciation, though relatively thickly sedimented. In the Eastern Basin, glacial ice advanced first, remained longer, and retreated last. The last readvance of ice into Lake Erie occurred about 13 ka and only occupied the northeastern part of the

Eastern Basin (Bolsenga and Herdendorf, 1993; Leverett and Taylor, 1915; Barnett, 1985; Calkin and Feenstra, 1985).

Lakeward of the nearshore zone, along the northern edge of the gently sloping Central Basin, there are areas where glacial drift is exposed at the lake surface (figure 4). Smaller extensions of this zone occur west of Pointe aux Pins and in irregular-shaped pockets bordering the eastern Basin between Long Point and Buffalo. This zone extends lakeward to the northern limit of postglacial sediment accumulation (figure 4; Thomas, et al., 1976). The region is relatively smooth and gently sloping, with locally occurring fine-scale topography characterized by small hills and irregularities, having one to several meters relief (plate 1A; figure 1; figure 4). Some of the hills are elongated, some have a complex shape, and some are aligned to form larger composite ridge segments. This region is 5-10 km wide along most of its extent, but it widens considerable at the western approaches to Clear Creek Ridge and Long Point- Erie Ridge.

In these areas, till, glaciolacustrine clay, and associated lag sand and gravel deposits are exposed at the lake floor (Rukavina and Saint Jacques, 1978; Rukavina and Saint Jacques, 1971; Saint Jacques and Rukavina, 1973). This shallow, high-energy subaqueous area has been actively eroded, or at least deposition of postglacial muds has been prevented; no postglacial mud has accumulated. Some of the aforementioned small-scale features may have been formed or severely modified due to the erosive and sculpting action of postglacial currents.

Six ridge segments which have evidently survived postglacial erosion, and which extend directly across this zone, normal to the shoreline, may be offshore extensions of morainic ridges (Galt, Paris, Lakeview, Mabee, Courtland, and Blenheim moraines) which occur onshore in Ontario (Barnett, 1998; Chapman and Putnam, 1951; figure 4). The Long Point- Erie Ridge has been correlated with the onshore Paris and Galt Moraines (Barnett, 1998). Following this same path of correlation, the Erieau Ridge could be an offshore extension of the Blenheim Moraine, described by Chapman and Putnam (1951). Another small ridge segment occurs a few km west of the main Erieau Ridge. There exists a substantial westward offset of the onshore moraines, with respect to their inferred offshore extensions. This offset is on the order of tens of kilometers.

The Erieau Ridge aligns with, but is not topographically continuous with, a very low (less than 1 m relief) almost buried ridge extending northward from Cleveland to a point about half way across the Lake (plate 1A). Cores penetrating the overlying postglacial mud on these two aligning ridge segments, which were given the name Erieau-Cleveland Ridge by Lewis, et al. (1966), encountered sorted sand. This Ridge has been interpreted as the remaining trace of an end moraine extending across the Lake (Sly and Lewis, 1972; Coakley, 1992).

Pointe aux Pins has the shape and morphology of a cuspate foreland (plate 1A), and is interpreted as a sediment constructional feature formed in a zone of net longshore convergence (Carter, et al., 1987; Coakley, 1992). A succession of beach ridges extends southward, parallel to the eastern face of this foreland, and these same beach ridges intersect with the southwest face of the feature (see Carter, et al., 1987, p. 156), demonstrating that the foreland has accreted sediment on its eastward face and undergone erosion along its southwestern face. Pointe aux Pins may have initially formed opposite the moraines of Erieau Ridge and slowly migrated northeastward along the shore.

The bedrock banks of the northern shore, east of Long Point, rise abruptly from the surrounding smooth topography, which forms valleys between the banks (plate 1H). These valleys merge around the end of the bedrock ridges and form an apron which slopes gently toward the center of the Eastern Lake Erie Basin. The valleys are underlain mostly by glacial drift west of Port Colbourne, with sand near shore, and mostly by sands east of Port Colbourne, with some silty sand and glacial drift farther offshore (Rukavina and Saint Jacques, 1971). Off the western part of this shoreline near Port Dover, several of the banks form isolated outliers surrounded by sediment-smoothed topography. Overall the zone of shore topography extends through a width of 4-8 km and is confined to depths less than 20 m (plate 1H). Postglacial sediment deposition has been limited to sands/silts in sheltered areas near shore, or farther offshore. Otherwise, no postglacial sediments have been deposited. Some erosion and modification of the surface of glacial drift may have occurred, as evidenced by the continuous apron-like nature of the non-bedrock topography.

Port Maitland Bank occurs farther (8-14 km) offshore (plate 1H). This bank has an overall relief of 10-12 m, is 5-8 km wide, extends NE-SW, and is capped by a succession of small ridges having a few meters relief. The outer edge of this bank is arcuate, convex southward. A veneer of sand, probably lag sand deposits, occurs over the bank (Rukavina and Saint Jacques, 1971), and glacial till and laminated glacio-lacustrine clay were sampled by sediment cores which penetrated the sand veneer (Lewis, et al., 1966). This feature is therefore regarded as a remnant of glacial moraine (Rukavina and Saint Jacques, 1971), with its surface topography being the product of glacial erosion and deposition. To the west, several small NE-SW trending ridges occurring in depths of 20-25 m could also be remnants of glacial moraines. If the Bank is a moraine it could have formed during an ice re-advance correlating with the 13,000 ya Port Huron Stade (Barnett, 1998).

Small-scale hummocky topography occurs offshore of the mouth of the Grand River (Ontario) and off the entrance to the Welland Canal. This topography may be anthropogenic, resulting from dumping of dredge spoils. A significant delta has not formed off the Grand River, even though it is one of the larger rivers entering Lake Erie.

In the northeast corner of Lake Erie, just off Buffalo, features resembling offshore bars and spits occur at depths of 10-12 m (plate 1D). These features connect the offshore ends of three ridges extending southward from the Niagara River outlet at Fort Erie, and they form a barrier across the valleys between the headlands formed by these ridges. A similar bar or spit, also at 10-12 m depth, is on trend with the Buffalo Knoll, and extends northeastward away from it. These features have important implications for the Holocene history of Lake Erie, because they are apparently drowned shoreline features documenting lower Lake levels near the outlet sill at Buffalo. Further investigation is needed, because an alternate possibility is that these features were formed by deposition along the margins of stagnant and wasting ice of the Port Huron Stade. West of Buffalo along the northern shore, other features which suggest former lower lake levels include the steep sides of the bedrock ridges which abruptly terminate at their base as if they are former wave-cut cliffs; and several additional features occurring at depths of 10-20 m which resemble spits and offshore bars.

A small narrow ridge having about 3 meters relief extends NW from the shore about halfway between Buffalo and Sturgeon Point (figure 3). This feature could also be a relict spit, or it could be of anthropogenic origin.

POSTGLACIAL DEPOSITIONAL FEATURES

Postglacial sediments have accumulated in the main basins of Lake Erie, as mapped by Sly and Lewis (1972) and Thomas, et al. (1976), and shown in figure 5. These sediments are mostly muds composed of silts and clays, which are presumed to have entered the lake from river input, from shore erosion, and from winnowing of glacial drift already deposited on the lake floor (Lewis, et al., 1966; Thomas, et al., 1976). The muds are siltier beneath the Western Basin; they contain varying amounts of sand near the Long Point - Erie Ridge and adjacent to the southern shore. Postglacial muds accumulated in thicknesses of 10 m in the Western and Sandusky Basins, 20 m in the Central Basin, and 40 m or more in the Eastern Basin (Thomas, et al., 1976); with greatest thicknesses concentrated in the deepest basins of the original postglacial topographic surface (Lewis, et al., 1966).

Most of the first-order topographic features of Lake Erie, and many of the secondary features – ridges, banks, spits, bars, deltas, and forelands - were shaped by postglacial deposition, and became resting places for coarser sediments – gravel, sand, and silt. Included among these features are the moraines, which have been subject to later topographic modifications resulting from postglacial deposition. These features as a group are highlighted in figure 5. Complex changes in lake levels and positions of shorelines have occurred in Holocene time as the shallow lake basin has been modified, not only by erosion and deposition, but also by changes in lake level associated with isostatic rebound and changes in the water-flow regimen. A majority of the postglacial/ depositional features were formed at lake levels lower than those of today. Estimates of lake level associated with each depositional feature are shown in figure 5. Specifically, Pelee-Lorain Ridge, Clear Creek Ridge, and Long Point-Erie Ridge are believed to have been former sites of sand transport and deposition, in the same manner that Long Point Spit and Point Pelee are sites of sand accumulation at present. Holocene lake-level history is treated in more detail in a separate paper (Holcombe, et al, 2003).

Many of the postglacial/ depositional features are better described and explained thanks to the availability of detailed bathymetry, and some of the features, including Clear Creek Ridge, are seen for the first time. More detailed physiographic descriptions of features, with discussion of their geomorphology, are given below.

Postglacial Sediment Accumulation and Bathymetry

Patterns of postglacial mud thickness, shoreline modification, and the overall bowl shape of the main basins, demonstrate sediments having been preferentially deposited in the low-lying areas of the basins, diminishing or obliterating the topography of the glaciated surface, and accounting for the relatively featureless topography of the main basins. The pattern suggests sediment deposition in a current regime bearing some relationship to basinwide gyres in water circulation (Saylor and Miller, 1987). Topographic modifications due to erosion and deposition along former low-level but high-energy shorelines may also have been a factor

Finer-grained sediments are generally not deposited in the high-energy shore zone or offshore areas where little or no postglacial sedimentation has occurred, particularly the north shore zone in the Central and Eastern basins along the Canadian shore (Lewis, et al., 1966; Rukavina, 1976). Sand deposits occur along the shore and in beach deposits, on the Long Point - Erie and Pelee - Lorain Ridges, and around nodal zones of longshore sediment accumulation at Presque Isle, Erieau, and Point Pelee (Thomas, et al., 1976).

Highest rates of present-day sedimentation (5-15 m/ky) of postglacial silty-clay muds are reported to occur in the Western Basin, near the entry points of the Detroit and Maumee Rivers, and in the Eastern Basin near Long Point (Kemp and Thomas, 1976; Kemp, et al., 1977). Even though the Western Basin has high rates of present-day sedimentation, thicknesses of postglacial mud are less than the other two basins because of the relatively short period of time that rising lake water has occupied the Western Basin (Lewis, 1969). Another factor is that the Western Basin is so shallow that sediments are re-suspended and transported out. Elsewhere in the main basins, sedimentation rates are mostly in the range of 1-5 m/ky.

These rates are higher than earlier accumulation rates for most of postglacial time, judging from estimated total thicknesses of postglacial muds (Thomas, et. al., 1976). The possible reasons for this rate change are discussed later. However, in the deepest part of the Eastern Basin, 30 to 40 m of glaciolacustrine clay accumulated, followed by a similar thickness of postglacial mud (Cameron, 1991).

Conneaut Bank and Other Promontories

Along the south shore of central and western Lake Erie, several submerged promontories are present. These include Conneaut Bank off Conneaut Creek, Fairport Ridge off the Grand River, Cleveland Ridge off the Cuyahoga River, Lorain Bank off the Black River; and smaller promontories off the Ashtabula and Chagrin rivers (figure 1; figure 5; plate 1A).

The largest of the south shore depositional features is Conneaut Bank (plate 1A; figure 1), which extends about 12 km out into the Lake, and is about 15 km in length in the longshore direction (plate 1F, 1G). Crestal depths are 12 to 14 m, and the bank extends out into the Central Lake Erie Basin along an axis trending NW-SE to a depth of 20 to 21 m. The bank is asymmetrical, being steeper along its northeasterly facing edge. A series of small 1-2 m relief ridges (current-formed features?) extend E-W across the top of the bank. Fairport Ridge extends from the mouth of the Grand River about 8 km NW to a depth of 20 meters. Fairport Ridge compares with Conneaut Bank in that crestal depths of both banks are in the range of 12-14 meters, and both banks are asymmetrical along a NW-SE axis, with small longshore-aligned ridges of 1-2 m relief. Fairport Ridge is considerably smaller than Conneaut Bank. Other promontories to the west, including Cleveland Ridge and Lorain Bank, are even smaller, but occur at the same depth of 10-15 m. Conneaut Bank occurs to the right of the mouth of Conneaut Creek, and Fairport Ridge occurs to the right of the former mouth of the Grand River (Grand River's mouth was formerly about 10 km west of its present location; Carter, et al., 1987).

The direction of asymmetry, and position of the shallow axes of Conneaut Bank and Fairport Ridge, is opposite that of Presque Isle Spit, and also the Niagara Delta in Lake Ontario. East-to-west longshore drift and/or currents, during early Holocene time when these features formed, are suggested.

Surficial deposits of sand and/or gravel have been mapped on the crest of Conneaut Bank as well as intermittently to the north and east, across the Central Lake Erie Basin at the western approaches to the Pennsylvania Channel, Pennsylvania Ridge, and Clear Creek Ridge (Hartley, 1961). Sand and gravel make up the surficial sediments of Fairport Ridge and occur intermittently between Fairport and Cleveland in a 10 km wide zone where small topographic irregularities occur (Hartley, 1961). Sand dredging was carried out in these areas (Hartley, 1961), introducing anthropogenic modifications of the topography which may or may not be seen in the bathymetry, depending on whether bathymetric surveys were conducted before or after episodes of sand dredging. Here, as elsewhere around Lake Erie, it is not always possible to clearly separate naturally occurring topography from anthropogenic modifications.

There appear to be several possibilities for the origin of Conneaut Bank, Fairport Ridge, and the other promontories. Off the submerged river-mouth promontories the sediments are probably deltaic sands. Because of their 10-15 m crestal depths, these presumed deltas were probably formed in the early Holocene when Lake level was 12-20 m below present level. On the other hand, some of the sand and gravel in these offshore areas may have been initially deposited in glacial drift, and later concentrated by current winnowing. Longshore drift, both now and in early postglacial times at lower Lake levels, contributed to the observed distribution of sand and gravel. Some of the sand reaching Conneaut Bank was probably transported from the Canadian shore via Clear Creek and Long Point Ridges, before being transported westward by currents in the Pennsylvania Channel (figure 5). These re-suspended sediments could have finally been deposited on the south bank of Pennsylvania Channel, in and around Conneaut Bank (see section on Pennsylvania Channel and Pennsylvania Ridge).

Conneaut Bank lies offshore near the mouth of Conneaut Creek, and its axial ridge lies NE of the mouth of the Creek. Having a streamflow about 1/3 to 1/4 of that of the

Cuyahoga or Grand Rivers of Ohio (Bolsenga and Herdendorf, 1993), Conneaut Creek today does not seem large enough to form a delta comparable in size with Conneaut Bank. This suggests that early Holocene shifts in drainage patterns accompanying isostatic rebound could have altered drainage patterns, and consequently, stream flows in Conneaut Creek, and possibly Elk Creek nearby to the northeast, could have been significantly larger in the early Holocene. An alternate possibility is that the suggested transport of sand from the north, via Long Point/ Clear Creek Ridges and Pennsylvania Channel, was volumetrically large. Finally, it may be considered that Conneaut Bank was formed on a pre-existing foundation, such as a moraine.

Presque Isle Spit and Presque Isle Bank

In morphology the Presque Isle Spit has the form of a recurved spit or hook, and has been described as a sand spit (plate 1F, 1G). It consists of an offshore bar which follows the arcuate outer shore of the spit facing the Lake, and a succession of en-echelon sand ridges, which project shoreward from the main spit. From the pattern of sand ridges, it is apparent that the spit is eroding from the west and incrementally adding new sand ridges at its eastern extremity (see Bolsenga and Herdendorf, 1993). Therefore it is slowly migrating from west to east, and the inferred main source of sediments is via longshore drift from the west (Carter, et al., 1987). The spit apparently lies in a zone of convergence of net longshore drift; the position of which may be consequent on predominant patterns of wave motion and lake water circulation, set up by overall shape of the Lake basin and predominant wind fields. In this case the null point lies opposite the boundary between Central Basin and Eastern Basin gyres (Saylor and Miller, 1987).

Adjacent to the Presque Isle Spit to the west lies a shallow bank (7-10m depth) which is roughly 5 x 10 km in areal extent, referred to as Presque Isle Bank (plate 1F, 1G). Atop this bank is a 1-2 m relief arc-shaped bar which resembles in size, shape, and orientation, the main recurved portion of the Presque Isle Spit. Its position suggests eastward shift of Presque Isle Spit from a former position about 7-8 km to the west. Such an eastward shift in the inferred convergence zone of net longshore drift may have been gradual, but more likely it was episodic. Incremental outbuilding of Long Point Spit, directly across the Lake, may have altered circulation patterns, which contributed to eastward movement of the longshore convergence zone around Presque Isle Spit. As Long Point Spit continued its outbuilding, a shift eastward in the south shore convergence zone may have resulted. The overall 0-10 m crestal depth of Presque Isle and Presque Isle Bank suggests formation at or near present water levels. Therefore Presque Isle Spit and Presque Isle Bank are post-Nipissing features formed in the last 4,000-5,000 years.

Long Point Spit

This very large spit extends about 35 km east-southeastward from the Ontario shore out into the Eastern Lake Erie Basin (plates 1A, 1F, 1G). It exhibits complex depositional forms including a succession of en-echelon beach ridges diagonal to the main trend of the spit, and smaller, partially submerged small spits extending outward from the north side of the spit. Steep slopes and 55 m of relief, highest lakefloor relief in Lake Erie, separate the spit from the floor of the Eastern Basin of Lake Erie.

The geology of Long Point, as determined from borehole samples and seismic reflection data, was summarized by Coakley (1992). The spit is a late Holocene to recent (the last 5000 years) depositional feature constructed of sands and silts eroded from the Ontario shore bluffs to the west and brought eastward and deposited by longshore drift. Like its companion feature across the Lake, the Presque Isle Spit, the formation of Long Point has occurred at present or near-present lake levels. Outbuilding of the Long Point Spit probably began as a consequence of the Nipissing Rise in Lake level, which overtopped the Long-Point Erie Ridge and changed the lake shoreline and current regime to approximately that of the present.

Sediments exposed along the shore for about 40 km west of Long Point contain a relatively high percentage of sand (in some localities as high as 50 to 100 percent), whereas elsewhere around Lake Erie, sand in the eroding shore bluffs generally consists of a much smaller percentage of the total sediment. The bluffs west of Long Point are very erodible, and rates of shore erosion are among the highest of any place on the Lake Erie shore (Rukavina and Zeman, 1987; Barnett, 1998). The amount of sand per unit time per km of shore line introduced into the shore zone west of Long Point is probably an order of magnitude in excess of that introduced into the shore zone elsewhere around the Lake. This accounts for the uniqueness and overwhelming scale of the Long Point Spit.

Long Point-Erie Ridge

The Long Point- Erie Ridge is a broad (14-22 km) arcuate ridge of 5-10 m overall relief, capped by complex topography, extending upward to minimum depths of 10-15 m, and extending across the lake floor from near the inshore end of the Long Point Spit, almost to the Presque Isle Spit at Erie, PA (plates 1F, 1G). It is separated from the Pennsylvania shore by a channel 23 m deep and 5 km in width. The Ridge is more or less continuous but two channels 15-16 m deep cut through the Ridge near its mid section, and two channels 18 and 20 m deep segment the Ridge near its southern end. The southernmost segment of the Ridge is continuous with the Clear Creek Ridge. Figure 6 shows section lines for longitudinal crestline topographic sections of Clear Creek Ridge, and Long Point-Erie Ridge, displayed in figures 7 and 8, respectively.

The Long Point - Erie Ridge is reported to be underlain by glacial till, and capped by sand deposits which mainly occur at depths less than 18-20 m (Lewis, et al., 1966). The Ridge has been interpreted as an end moraine formed during the last readvance of glacial ice into the Eastern Basin of Lake Erie (Lewis, et al., 1966; Coakley, 1992). The Ridge has been associated with a readvance occurring at about 13,400 ya, just prior to or during the Mackinaw interstade, which also resulted in formation of the onshore Galt and Paris Moraines (Barnett, 1985; Barnett, 1998). Overall morphology of the Long Point - Erie Ridge and the Eastern Basin, as seen in the new bathymetry, is consistent with interpretations that this feature is a moraine.

The Long-Point Erie Ridge would have been a peninsula at water levels more than 16 m below present, or a low, sandy island chain at water levels of 13 to 16 m below present. Sands underlying the crest of the moraine probably had as their source: 1) lag deposits resulting from winnowing of glacial till (Lewis, et al., 1966); and 2) sands eroded from the north shore of the Lake and brought southward via longshore drift (Barnett, 1985; Coakley, 1992). In the latter instance the Ridge crest resembled a large spit, similar to Long Point at present. The sand must have had the same source as that which later formed Long Point Spit, having been eroded from the shoreline to the northwest where the Norfolk Sand Plain and underlying sandy glaciolacustrine and deltaic deposits extend to the Lake edge (Barnett, 1985; Coakley, 1992).

Southward transport and deposition of sand on the Long Point - Erie Ridge probably ceased when the Nipissing rise overtopped the Ridge, and changed the Lake Erie current regime. Sediments, which would have been deposited on the Long Point - Erie Ridge, were now carried eastward down the shore, and construction of the Long Point Spit began. Note has been made of the fact that there seems to have been no transitional features which record this change in the current/sedimentation regime, such as would be expected with a gradual rise in Lake level (Coakley, 1992). The morphological evidence cited above suggests pre-Nipissing water levels 10-20 m below present level. There is uncertainty surrounding the time of occurrence and rise rate of the Nipissing event, but one or more relatively rapid rises of 10 m or more seem likely.

Clear Creek Ridge

A narrow ridge of 4-5 m relief with a crestal depth ranging from 14-17 m extends in a SSE direction, from offshore of Clear Creek on the Ontario shore, almost to the Pennsylvania Channel just offshore Erie PA (plates 1F, 1G; figure 7). This ridge lies 10-30 km west of the Long Point- Erie Ridge, with the distance between the two ridges closing toward the southeast. Both ridges are convex to the west, with the Clear Creek Ridge following a broader arc and having greater linearity. Clear Creek Ridge was not known to exist until the advent of the bathymetry described in this paper.

In its southern half the Clear Creek Ridge becomes broader in profile and more complex in its form. Crestal depths of the southern half of the Ridge are mainly 15-17 m, a few meters deeper than the 14-15 m crestal depths typical of the northern half of the Ridge. Along the southern sector of the Ridge, subsidiary ridges of a few meters relief extend southwest away from the main ridge and one subsidiary ridge extends away to the northeast. Several of these subsidiary ridges are sinuous and complex. One discontinuous set of small ridges forms an arc which extends southwestward from the main ridge.

Depths reach 18-20 m in the inter-ridge low between Clear Creek and Long Point – Erie ridges. Remnants of a low ridge, parallel to the main ridges and cresting at about 16 m, are present just east of the inter-ridge low. At its southern end the main Clear Creek Ridge becomes more sinuous and wraps eastward around the southern end of the Long Point- Erie Ridge. Here the two ridges are separated by a channel extending downslope toward the southeast. The Clear Creek Ridge terminates adjacent to and north of the east-west trending Pennsylvania Ridge.

A model for postglacial formation of Clear Creek Ridge appears in figure 9. The feature probably formed during the early Holocene, when water level was low, but had risen sufficiently (probably about 18 m below present lake level) to fill a large shallow lake in the Central Lake Erie Basin. Once wave energy was focused on the western approaches to Long Point- Erie Ridge, a peninsula, offshore bar, or barrier island formed on the gently sloping lakefloor at the point of breaking storm waves, probably coincident with a low morainic ridge. This presumed offshore bar formed nearer the Long-Point Erie Ridge in its southern sector, where greater water depths are encountered. Once formed, the offshore bar became the conduit for longshore drift of sands eroded from the Ontario shore west of Clear Creek. At this point its formation and growth were analogous to that of present day Long Point. The crestline of Clear Creek Ridge is deeper by about 2 m than Long Point-Erie Ridge (figures 7 and 8). Early Holocene rising water levels probably overtopped Clear Creek Ridge, eventually shifting the focus of longshore movement of sand to the shallower Long Point-Erie Ridge. Finally, the Long Point-Erie Ridge was flooded during the Nipissing Rise in Lake level, which probably raised water level in this part of Lake Erie to about 4-5 m below present Lake level. At this time focus of the longshore movement of sand was shifted, this time to the Long Point Spit.

Pennsylvania Channel and Pennsylvania Ridge

Pennsylvania Channel is 4-5 km wide at its narrowest point, 30 km long, and 22-24 m deep throughout its length (plates 1F, 1G). It connects the Eastern and Central Basins of Lake Erie. Its southern slope coincides with the offshore boundaries of Presque Isle and Conneaut Banks. Bounding the northern slope of the Channel is a ridge (which we refer to as the Pennsylvania Ridge), 25 km long, 2-3 km wide, and having 3-5 m relief, which extends westward from the southern terminus of the Clear Creek and Long Point Ridges (plates 1F, 1G). The top of this ridge deepens westward from 18 m to about 21 m.

Location and morphology of Pennsylvania Ridge suggests that it originated as a “natural levee” built of sandy/ silty sediments transported southward along the Clear Creek Ridge and the Long Point-Erie Ridge and finally carried westward and deposited as overbank deposits. Pennsylvania Channel was and is the location of strong return flow from the Eastern Basin to the Central Basin (Boyce, et al., 1980), during and following periods of strong frontal winds blowing from west to east longitudinally down the length of the lake surface. Such winds transport surface water eastward and raise lake levels in eastern Lake Erie, requiring a compensating westward flow at depth once equilibrium is reached, and also following relaxation of the strong forcing winds.

Pennsylvania Channel, a broad (10-15 km) and shallow (1-2 m) channel, continues westward for about 50 km into the Central Basin, and also for about 15 km eastward into the Eastern Lake Erie Basin to about the 24 m isobath. Morphology of the Pennsylvania Ridge at the point of intersection with the Long Point – Erie Ridge suggests that the sands capping the Ridge may have built out into the Channel, and consequently Pennsylvania Channel width was formerly greater than it is today. Southward movement of sand may therefore have partially choked off the Channel, but a narrower channel was able to maintain itself through the sand-choked area.

CONCLUSIONS

1) Names of Lake Erie lakefloor features are proposed for official use. The detailed bathymetry provides the impetus for naming known features that are subjected to increased definition, and newly revealed features. Names of precedence were used for most previously known features.

2) Areas of bedrock outcrops are mapped in greater detail using a combination of detailed bathymetry and existing information. The new bathymetry provides a base map for improved description and mapping of inferred geological bedrock boundaries beneath the lake floor.

3) Nearshore bedrock ridges of the north shore east of Long Point have a preferred NE-SW lineation, as do ridges atop the Port Maitland Bank. These lineations occurring beneath the eastern Lake Erie Basin form an integrated NE-SW pattern which was imparted by glacial erosion.

4) Long Point Escarpment appears to be the surviving trace of a bedrock escarpment formed in gently south-dipping rock strata, the upper part of which was more resistant to under-ice glacial erosion than the underlying strata.

5) Stratification is observed in the form of ledges occurring in bedrock outcrops along the southern shore of Lake Erie.

6) In shallow Lake Erie, erosion of the shore zone has proceeded at a high rate within glacial drift on the north shore (west of Long Point), and within the soft shales of the south shore. Bathymetry provides an integrated view of the zone of shoreline erosion around the entirety of the Lake. Shore erosion has resulted in a steepened and deepened shore profile within 1-3 km of the shore, with an abrupt transition to a gently sloping, relatively smooth surface of erosion/nondeposition of postglacial muds or glacial sediments farther from shore. Finer-grained products of this shore erosion, silts and clay, have been removed to the main basins of the Lake, beyond the zone of intense wave energy. Sand and gravel have remained in the shore zone, and are transported along the shore by longshore drift.

7) Depth to the base of the steep, wave-cut portion of the shore profile varies around the Lake. This base depth is greatest facing the open Lake in the eastern Basin and less

deep facing the open Lake in shallower and/or more sheltered basins. The base depth is shallowest in Lake St. Clair, in sheltered bays, and in other very shallow areas.

8) Wave erosion is effective in altering the shore profile of Lake Erie. Whether the present shore profile has resulted from erosion at present lake levels, or from erosion at slightly lower lake levels, is a matter for speculation.

9) The new Lake Erie bathymetry better defines the morphology of features which have been sculpted by glaciation. Four ridges which extend across the Lake, and which have been identified as moraines, include the Pelee, Erieau, Norfolk, and Port Maitland moraines, from west to east, respectively. A cross-lake ridge not previously known is the Clear Creek Ridge. This latter ridge may have a foundation of moraine, at least in the northern part of its extent. Several ridge segments seen for the first time in the bathymetry lie perpendicular to the north shore of the Central Basin. These ridge segments align with mapped moraines in southern Ontario, but positive correlation awaits further information.

10) If the Blenheim moraine correlates with Erieau moraine and the Paris and Galt moraines correlate with the Norfolk moraine, as has been proposed, then a significant eastward offset exists in the position of these moraines across the shore zone. This offset suggests that ice within the main lake basin did not extend as far westward as ice at the basin margins.

11) The low ridges aligning with the shore near Buffalo, at a depth of about 10 m, are unexplained. They may be moraine correlating with the Port Huron stade, with kettles behind them, or they may be offshore bars formed at a lower lake level. The latter explanation, if true, would be compelling evidence that Lake Erie fell below the level of its sill in early Holocene time.

12) The bathymetry complements previous mapping of the extent of postglacial sediments which have accumulated in the main basins of Lake Erie. These sediments are predominantly silts and clays, presumed to have entered the lake from river input, from shore erosion, and from winnowing of glacial drift already deposited on the lake floor.

13) Many of the first-order topographic features of Lake Erie – ridges, banks, spits, bars, deltas, and forelands - were shaped by postglacial deposition, and became resting places for coarser sediments – gravel, sand, and silt. Moraines have been subjected to topographic modifications resulting from postglacial deposition. Most of this deposition came in the form of longshore drift of sands and gravels, and such deposition has built or significantly altered the topography of the Point Pelee, Pelee-Lorain, Clear Creek, and Long Point-Erie Ridges, and the Long Point Spit, as well as several smaller banks and ridges. These ridges contain most of the commercial quantities of sand and gravel occurring on the lake floor. The bathymetry has significantly improved the description of these ridges and yielded insight into the conditions of their formation.

14) Most of the features formed or altered by postglacial deposition were formed at lake levels significantly lower than present levels. Several of the features, including Long Point-Erie Ridge which was a peninsula at lower lake levels, were active features being built by longshore drift until the Nipissing Rise flooded the Lake and removed these features from the zone of active shoreline deposition. Active deposition on the Clear Creek Ridge probably ceased earlier than such deposition on the Long Point-Erie Ridge - the crestline depth of Clear Creek Ridge is 2 meters below that of the Long Point-Erie Ridge.

15) Long Point is a late Holocene to recent depositional feature constructed of sands and silts eroded from the Ontario shore to the west and brought eastward by longshore drift. Like its companion feature across the Lake, the Presque Isle Spit, and unlike most of the other features of the Lake Floor, formation of Long Point has occurred at present or near-present lake levels. The outbuilding of the Long Point Spit began when the Nipissing Rise in Lake level flooded the Long-Point Erie Ridge, and changed the lake shoreline and current regime to approximately that of the present.

16) Location and morphology of Pennsylvania Ridge suggests that it originated as a "natural levee" built of sandy/ silty sediments transported southward along the Clear Creek Ridge and the Long Point-Erie Ridge, and finally carried westward and deposited as overbank deposits. Pennsylvania Channel apparently was able to maintain itself through the formerly sand-choked area.

17) Strong westward flow from the Eastern Basin to the Central Basin is known to occur via Pennsylvania Channel during and following periods of strong frontal winds blowing from west to east longitudinally down the length of the lake surface. Such winds transport surface water eastward and raise lake levels in eastern Lake Erie, requiring a compensating westward flow at depth once equilibrium is reached, and also following relaxation of the strong forcing winds.

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