CHAPTER 53

PROPERTIES OF LONGSHORE BARS IN THE GREAT LAKES

by

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Longshore bars are permanent features of nearshore bathymetry along the windward coasts of the Great Lakes The stability and permanency of these features have been noted by numerous investigators, but movements of the bars and troughs in relation to varying lake levels and incident wave energies are not fully understood Studies of nearshore bathymetry and sediment properties were conducted during 1967 and 1969 along a forty-five kilometer reach of the eastern coast of Lake Michigan

Results show that the offshore bars migrate significantly due to changes in lake level, a rise of one-half meter in the surface of Lake Michigan between 1967 and 1969 was accompanied by a shoreward movement of bar crests and troughs over a distance averaging 30 meters Elevations of the crests and troughs are also built upward toward new equilibrium levels during rising water levels, but elevating of the crests lags the increase in stage Extensive shore erosion occurs because of the reduced effectiveness of longshore bars in dissipating incident wave energy The average crest depth was found to increase linearly in the offshore direction Average distances between crests increase exponentially These relationships are preserved during the bar growth and shifting that accompanies long term changes in lake level

Bar troughs are characteristically crescent shaped, with no abrupt changes in slope Fathograms from several ranges show atypical trough configurations consisting of flat bottoms with discontinuities in slope on ascent to adjacent crests This unusual trough shape is indicative of an immobile stratum exposed along the bottom of the trough

INTRODUCTION

Longshore bars are permanent features of nearshore bathymetry along the windward coasts of the Great Lakes where an abundant supply of sand-size sediment is present The bars and intervening troughs are oriented essentially parallel to the shoreline Along the eastern coast of Lake Michigan the longshore bars are continuous in coastal reaches exceeding many tens of kilometers, and the structure of these remarkable features has been described by numerous investigators The continuous bars are usually three or four in number in Lake Michigan, although as many as five or six have been observed As a rule, the

spacing between bars increases in the offshore direction, so that the distance between the first and second bars is less than the distance between the second and third bars as one proceeds toward deep water The trough associated with each bar occurs inshore of the crest, and the height of the crest above the trough also increases going offshore, with the exception that the bar farthest offshore is often of small height and configured as a long, gently-sloping swell of the lake bottom lying just lakeward of the more typical longshore bar structures

The longshore bars of Lake Michigan were first described by Desor (1851), and more comprehensively investigated by Evans (1940, 1942) The observations of bar structure made by Evans have been widely reported (e g , Shepard (1950) and Zenkovitch (1967)), and constitute the framework of present knowledge There have been relatively few studies concerning movements of the bar structures due to varying incident waves and currents, or due to long-duration variations in water surface elevation Evans (1940) concluded that minor readjustments in the positions of bars and troughs may occur with changes in intensity or direction of incident waves, but that the bars do not migrate in response to significant increases in water surface elevation He believed that an increase in water level would strand the deeper bars as relicts, and that a new set of crests and troughs would be built inside them The only shoreward migration of bars would be associated with a lowering of lake level, which would decrease the water depth over the innermost bar and cause currents or waves of translation across it With these conditions, Evans felt that the innermost bar would move shoreward as a subaqueous dune Davis and McGeary (1965) studied the stability of nearshore topography in southeastern Lake Michigan during the summer months of 1963 Their results agreed with Evans' findings that the offshore bars do not move appreciably Bajorunas and Duane (1967) studied nearshore topography in a similar environment in southeastern Lake Superior and contrary to previous findings, they showed that considerable movement of bars can occur during just a few months In southeastern Lake Michigan, Hawley and Judge (1968) indicated that the bars and troughs do migrate from year to year, but they did not identify a regular and consistent pattern of movement

This paper describes the results of an investigation of bar stability conducted during 1967 and 1969 on the eastern coast of Lake Michigan The reach of coast studied extends about 45 km, centered about Little Sable Point (Figure 1) Twenty-nine range lines were established perpendicular to the shoreline at nearly equally-spaced intervals throughout the study area Topography was monitored along each range line from the back beach to an offshore water depth of about 9 m, which is a depth in excess of that in which the bar structures occur Sediment samples were collected along each range and grain-size distributions determined in the laboratory Wave height and period and wind speed and direction were recorded continuously from an offshore platform The platform was erected at a site where the water depth was 6 m, and it was located about 500 m north of the Pentwater jetties, near the northerly end of the study area, and 400 m from the strandline Water surface elevation and current speed and direction were also monitored from the platform during the investigations

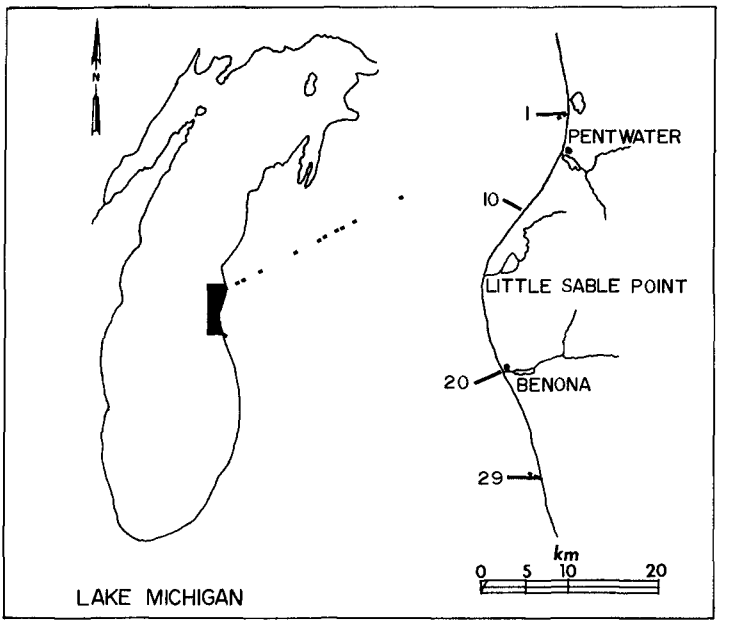

Fig 1 Location of study area and selected ranges

CHARACTERISTICS OF OFFSHORE BARS

From casual observation of the eastern Lake Michigan coast by either personal visits or inspection of aerial photographs, the continuity and regular spacing of the offshore bars and troughs are striking features However, if the nearshore topography is studied in more detail over a lengthy reach of the coast, the regularities of bar structure become more obscure The spacing and number of bars vary from range to range, as does the depth of water over the crests and the distance of the bars from shore The most pronounced variations occur in shallow water near shore The shallow-water bar, or bars, may not conform to the trend of the shore, as do deeper bars, but will sometimes merge at an angle with the beach face In other reaches, the coastal ridge may appear as an alignment of discontinuous shoals, a crescentric bar (horns and cusps directed toward shore), or simply a perturbance on the outer edge of a bench lying below the swash zone Such coastal bar forms are also more variable in time than the deeper longshore bars They are continually subject to changes in size and position, and may disappear and reform in the course of a few days Just south of the Pentwater jetties the entire sequence of longshore bars is virtually absent The jetties, which extend about 150 m into the lake, disrupt littoral drift and as a consequence the fully-developed sequence of bars is not observed again until one proceeds abouts 1 km south From this location southward to the vicinity of Little Sable Point, a quartet of well-developed bars persists with

little variation in geometry At Little Sable Point, the inflection point between a northeasterly and southwesterly trending coast, the regularity of bar-trough configuration is again broken The smooth, regular bar pattern is replaced by an irregular profile which more closely resembles that found on ocean coasts exposed to a wide variety of wave trains A regular sequence of bars is reestablished south of the point and persists throughout the southerly 20 km of the study area The crests are deeper and more widely spaced in this reach, however

In spite of the variations in bar structure from range to range, the entire reach of Lake Michigan coast studied is typified by the presence of three, and in several subreaches four, essentially-continuous longshore bars The spacing and depth of these bars, while not constant, do fit remarkably simple patterns These bars conform with the classical descriptions, in that the elevation of crest above trough (height) increases going offshore, as does the spacing between crests The depth of water over successive crests increases linearly in the offshore direction, as illustrated in Figure 2, which shows the average values observed during 1969 for ranges 1 through 15, and ranges 18 through 29 The continuous bar nearest shore is labeled in the figure as crest 2 because of the frequent presence of one or more low amplitude bar-like structures between it and the strandline In all reaches studied, the crest elevations of the three continuous bars exhibit a nearly linear distribution, although the slope of the line connecting crest elevations does vary along the coast as illustrated in the figure, and the bars are deeper south of Little Sable Point than they are to the north

Between the continuous bar nearest shore and the strandline, one or more bar-like structures are occasionally observed If more than one are present, the depth of water over the crests is nearly the same and averages about 0 5 m These shallow-water features show much variability from range to range and they are not continuous along the coast for lengthy distances The 1967 investigations were conducted in the northern third of the coastal reach and during the summer months of June through August During this period the shallow-water crests were always present, but they were not as prevalent on the same ranges during the 1969 studies made during the spring and fall months The summer months on Lake Michigan are characterized by moderate winds and waves, with storms occurring infrequently, while during spring and fall the coast is subjected to frequent intervals of high wave stress Thus, the shallow-water features are prominent in summer when the deeper and permanent bars are inactive and lie below the depth of the normal wave forces They represent the reworking of the nearshore sediment due to moderate waves which pass unaltered across the deeper bars Intense storm waves effect the entire bottom structure and disrupt the shallow-water structures built under moderate wave conditions

Much variability in bar structure also occurs offshore from the three continuous crests In the northern parts of the study area, a forth continuous bar is present and the depth of water over its crest is linearly related to the depth of water over the three shallower continuous crests In this region, the fourth continuous bar conforms with the characteristics of the inner three, as the amplitude and bar

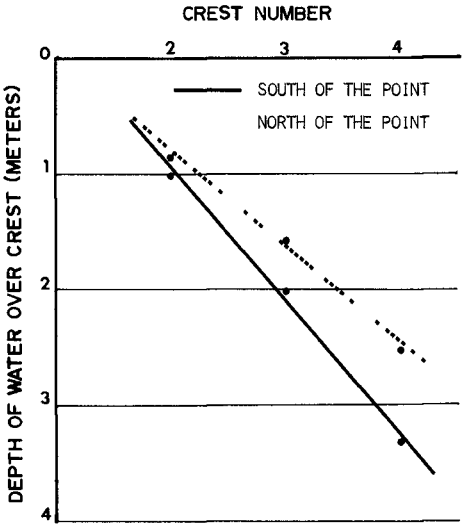

Fig 2 Average depth of water over successive bar crests

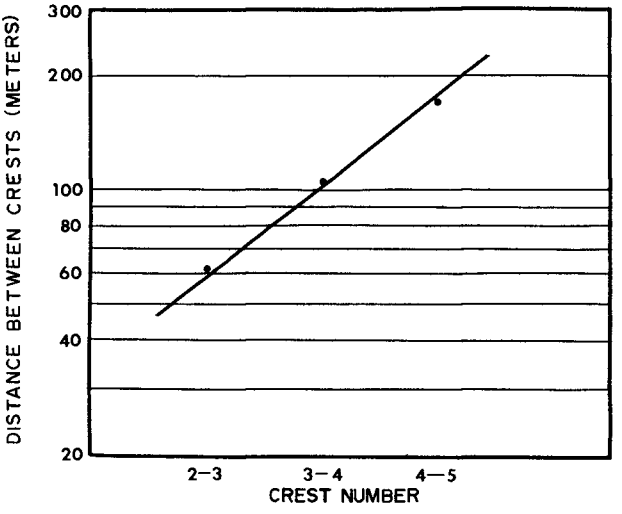

Fig 3 Average distance between bar crests based on measurements at 29 sites over approximately 45 km

spacing increase in a regular fashion going offshore Outside of the quartet of continuous crests, a long-crested, low-amplitude swell of the lake bottom is sporadically present on various ranges The northern half of the reach south of Little Sable Point is also characterized by four continuous crests, while near the southerly end of the coastal reach only the three continuous crests are present Again, the low-amplitude swell occurs lakeward of the continuous features on only several of the range lines

The depth of water over the crests of shallow-water bars and of the deep lake bottom swells does not fit the linear distribution observed for the continuous crests At both ends, the observed water depths are greater than those which would be obtained from interpolation of the linear trend for the persistent triplet If the linear distribution of crest elevations is truely representative of an equilibrium longshore bar structure, as is certainly suggested by the consistent observations, the deep swells of the lake bottom must be representative of bar formation at a depth where there is insufficient energy expended by breaking waves for full bar development This is perhaps to be expected, since the deep crests would cause wave breaking only for the most intense and infrequent Lake Michigan storms The sporadic occurrence of the deep swells, and the development of four continuous bars in two subreaches, would be the result of the variations in wave intensity along the coast due to wave refraction and differences in exposure

The spacing between crests in the offshore direction does not increase in a linear fashion, but rather increases exponentially The spacing between bars shows more variability than the depth of water over the crests, although there are clearly defined distributions Figure 3 shows the bar spacings observed during the spring of 1969 in the entire coastal reach The numbering scheme for the crests shown on the figure is the same as used previously, i e , crests 2-4 refer to the three bars continuous along the coast The spacing between crests varies considerably as the offshore gradient varies from range to range At Little Sable Point, for example, the slope is greater than it is at the northern end of the study area, so that the bars are compressed together even though an exponential increase in spacing is still observed in the offshore direction

The ratio of water depth over the trough (Dt) to depth over the crest (Dc) falls between 1 1 and 2 1 Keulegan (1948) reported that this parameter remained fixed even as other measures of the bar changed due to varying wave conditions The average value of 1 5 from our data agrees closely with value 1 5 (below llw) given by Shepard (1950) as most typical of Pacific beaches, and with the average of 1 69 determined by Keulegan in wave tank experiments It should be noted, however, that choice of reference level (mlw, llw, etc) and method of calculating the average can significantly alter the results Further, no relationship between the type of bottom material and Dt/Dc could be found even through the bottom material was found to exert a major influence on bar profile configuration, as will be discussed later

In examining bar measurements made on the Pomeranian coast by Otto

and Hartnack (in Keulegan, 1948) and on Lake Michigan by Evans (1940), Keulegan felt that there was field evidence that Dt/Dc increases with increasing distance of the bar from shore No significant difference was found in this ratio for the three persistant bars (2, 3, and 4) in this study A lower value of 1 3 for the outer bar contributes to the evidence that the outer bar, which is out of the reach of frequent wave disturbance, has not yet been able to build to an equilibrium state

The physical significance of the linear increase in depth of water over successive crests and of the exponential increase in bar spacing is not readily apparent The water depth at which incident wind waves break is a constant fraction of the depth, i e , the waves break when the wave height is on the order of 0 8 of the water depth Thus, a linear increase in water depth over the crests going offshore would imply a linear decrease in the height of waves breaking on successive crests in the onshore direction Since wave energy is proportional to the square of the wave height, the energy dissipated on each bar would not decrease in a linear manner, and the energy dissipated on each crest may play an important role in determining bar spacing However, it is probable that the large wave heights are associated with the longer wave lengths incident on the coast so that the process of breaking across successive bars can filter out wave lengths as well as wave heights The wave length may also be a factor in determining bar spacing

BAR STABILITY

After reaching record low levels in 1964, the water surface elevation of Lake Michigan increased steadily through 1969 (Figure 4) According to Evans' (1940) hypothesis, the rise in lake level should have stranded the deeper bars as relicts, with a new set of longshore bars built inside them But the observations do not indicate that this has occurred On the contrary, the bars have built upward toward the water surface and moved inshore Figure 5 shows bottom elevations measured along two ranges in the northern third of the study area which typify the observations in this coastal reach The profiles were measured during the summer of 1967 and the spring and fall of 1969

An onshore movement of bars and troughs is unmistakable, and for the profiles shown in Figure 5 averages about 30 m The direction of movement in relation to long-duration changes in lake level is exactly opposite to the movements hypothesized by Evans (1940), who indicated that onshore movement of the shallower continuous bars would be associated with falling lake levels During the summer months the deeper bars exhibit much stability, in agreement with summer observations made by Davis and McGeary (1965) Comparison of aerial photographs may also give a misleading interpretation of bar stability unless the cyclical changes with respect to water surface elevation are taken into account

The average depths of water observed over successive crests during the summer of 1967 and spring of 1969 are compared in Figure 6 for those ranges studied both years If the bars were static, fossil fea-

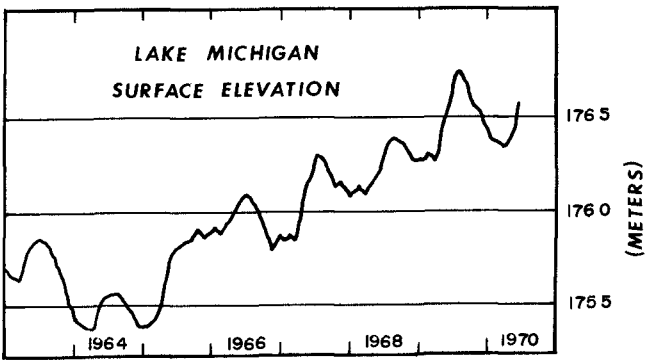

Fig 4 Hydrograph of monthly mean levels of Lake Michigan since the record low of 1964 (IGLD, 1955)

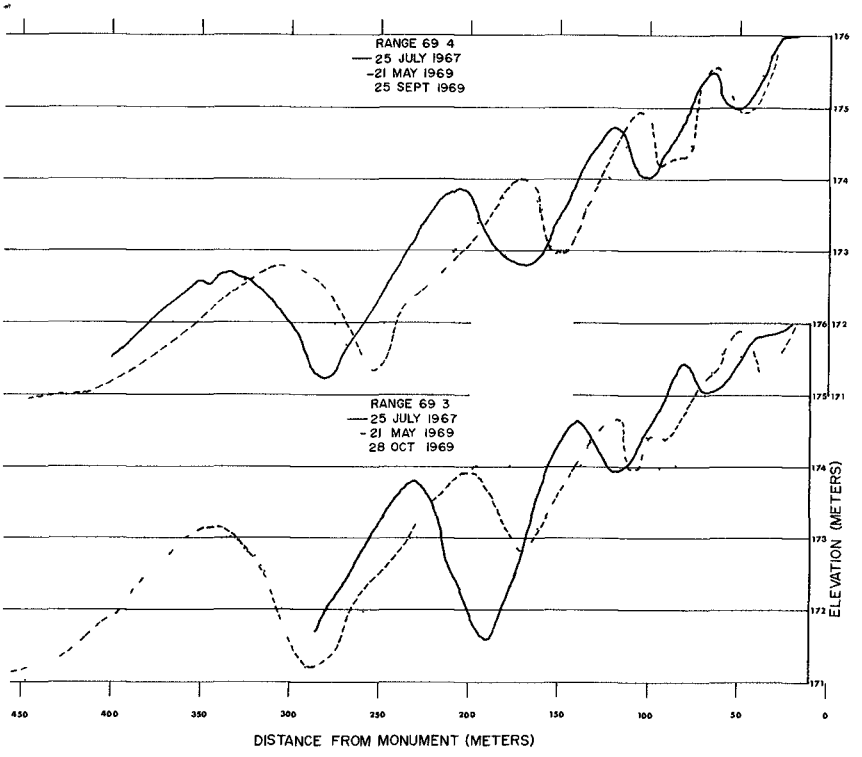

Fig 5 Movement of bars and troughs

tures, they would simply have been drowned during the subsequent rise in lake level, i e , the 1969 depths would merely plot 0 31 m above the 1967 depths But this is not what occurs The bars have responded to the rising lake level by building upward in a manner to preserve fixed depths below the water surface Discrepency between the 67 and 69 depths increases toward deep water (where the response is slower), but even on the deeper bars the difference in depth is less than the change in lake level

The most rapid movements of bottom material are associated with the spring and fall intervals of frequent high wave intensities The fall season is most important because wind across the lakes is accelerated due to unstable air stratification above the warm lake surface, whereas stable stratification occurs in spring and summer over the cold lake surface Thus, lake elevation during the fall months is perhaps the determining factor in the establishment of equilibrium nearshore topography, and in this sense the profiles measured during the summer of 1967 and the spring of 1969 are probably representative, at least for the deep water ends of the profiles, of conditions established during fall of the previous year For a considerable part of the ice-free season, an increase in water surface elevation allows higher amplitude waves to propagate to the shoreline than would be possible if the profiles were fully adjusted to an equilibrium state These non-equilibrium stages are associated with extensive beach erosion and structural damage Conversely, during low lake levels the longshore bars are more effective in dissipating the incident wave energy, and the shallow-water areas are unusually stable Noting the annual cycle of water surface elevation in Lake Michigan as shown in Figure 4, it is to be expected that the beach is most vulnerable to erosion during the early summer months of peak water level

TEXTURE OF BOTTOM SEDIMENTS

A fine grain, very well sorted quartz sand is the typical bottom sediment from the water's edge out to a depth of 9 m and from range 1 to range 29, 45 km south While diving with the aid of SCUBA, a few pools of colloidal clay (about a meter in diameter and a few centimeters in thickness) were noted, resting gently over scattered depressions in the bottom None of the more than 270 bottom samples had so much as 1% by weight in the silt-clay size range, i e , $<4\phi$, where $\phi = -\log_2$ diameter in mm Toward the other end of the size range granules and pebbles, though uncommon, did occur at the strandline along some reaches of the coast and they appeared in a few samples from specific troughs

Sieving the sediment on $1/4\phi$ intervals disclosed a small but clear trend toward finer material on the crests away from shore Superimposed on this classical pattern is a tendency for trough samples to be coarser, more poorly sorted, and more negatively skewed than samples from the adjacent bar (Figure 7) Changes in these three textural parameters can most simply be viewed as expressing the absence, on crests, of some material from the coarse end of the normal size distribution

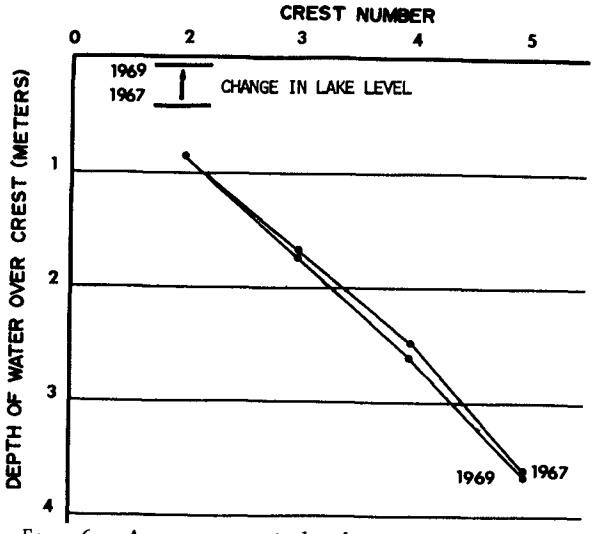

Fig 6 Average crest depths measured at ten sites in 1967 compared with the results of 1969 measurements from the same area

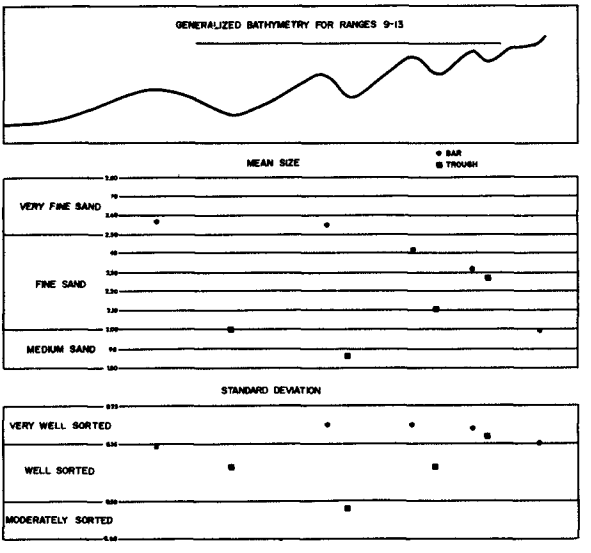

Fig 7 Average textural parameters of crest and trough samples from ranges 9-13 Trough samples are coarser and more poorly sorted than samples from adjacent troughs

These observations are in accord with the principal theories on bar genesis, in as much as the various theories all envision some winnowing action at trough sites with concomitant deposition on a bar site located immediately lakeward

Figure 7, illustrating textural variations in an offshore direction, is based on the average values from the various bars on ranges 9-13 during 1969 In addition to the accumulation of slightly coarser sand at the troughs, which appears to be a general rule, we found a few troughs floored with a relict, immobile material Therefore, to examine size variations of just the mobile fraction in the longshore direction, the crest samples were averaged for the three persistent bars which occur on each range, and the results are shown in figure 8 A regional trend emerged, the finest material in littoral transit and stable within the surf zone accumulates in the area just north of Little Sable Point (in the vicinity of range 10) This reach of the coast occupies an intermediate position between shore bluffs that mark the intersection of the modern shoreline with glacial moraines A high bluff (>50m) to the north is subject to periodic slumping as indicated by the presence of recently uprooted trees in the shallow water at the toe of the bluff and by the testimony of residents This source of new material to the littoral system lies about 5 km beyond the northern limit of the area sampled, but as shown by the pattern of accretion and recession around the Pentwater jetties the net longshore drift is from the north in this region and the bluff appears to be a source of sediment to the nearshore zone as far south as Little Sable Point Cobbles lie at the toe of the bluff and the finer constituents eroded from the morainal debris are redistributed by littoral drift Clays and silts in suspension evidently move considerable distances alongshore, but are ultimately diffused into deeper water prior to burial The sand load becomes gradually finer in its direction of flow away from the bluff toward Little Sable Point, Figure 8 The transport of some of the coarse sand reaching Pentwater may be arrested by the jetties there South of Little Sable Point the moraine again meets the shoreline, and in the past has contributed fresh material to the shore environment However, because of the configuration of the coast (Figure 1) the northwesterly storms are less important here than southwesterlies which cause littoral drift in this region toward the north The finer sediments in the vicinity of range 10 are protected somewhat from northerly drift by the Point Northwesterly storms likewise fail to induce strong littoral flow at this point since the waves approach normal to shore Therefore, it is not unreasonable that moving away from glacial bluffs to the north and south toward this zone of converging littoral currents, increasingly finer and more mobile sediments are encountered It should be pointed out that the spatial variations in texture, (alongshore, offshore, and bar verses trough) are small ($\sim 3/4\phi$) and would not have been disclosed by the still common practice of sieving at $1/2\phi$ intervals

BAR GEOMETRY AND COMPOSITION

A relationship between sand size and slope of the beach has been demonstrated by Bascom (1951) Moreover, wave tank experiments at the Coastal Engineering Research Center (Saville and Watts, 1969) have

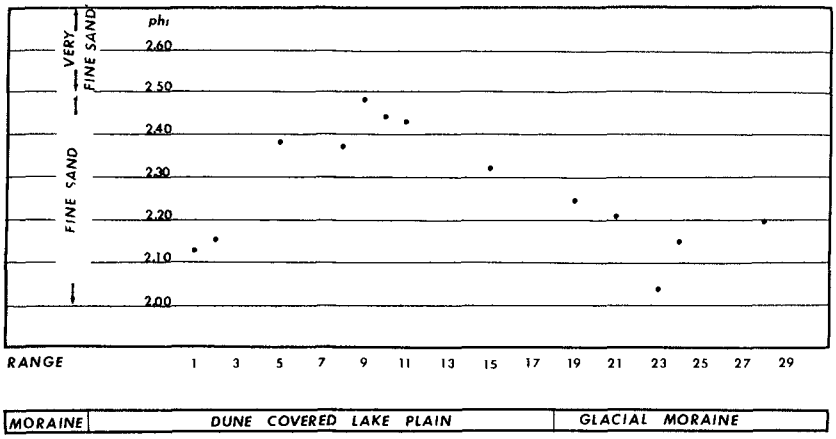

Fig 8 Longshore variation in mean diameter of mobile sediment

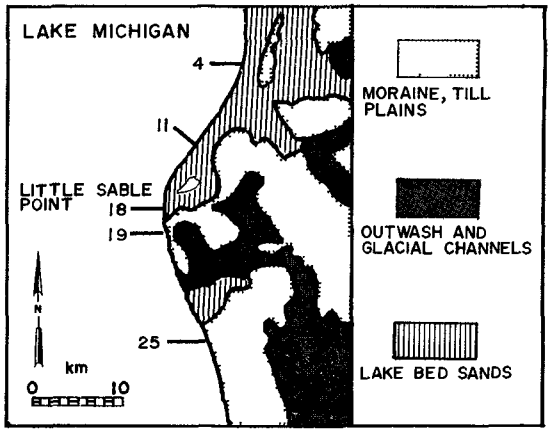

Fig 9 Location of ranges with boulder-paved troughs and their relationship with glacial formations onshore (From Michigan Geological Survey, 1955)

shown a tendency for bars to build slightly farther offshore as the grain size of the sediment is decreased The textural variations discussed in the preceding section are, however, too small to relate to changes in bar morphology The response of profile configuration to radical changes in bottom composition, several orders of magnitude greater than the variations revealed by sieve analysis, will be discussed here

Longshore bars occur on tidal as well as tideless bodies, inland lakes as well as open oceans The resulting forms are quite variable, reflecting local sediment response to a particular energy environment In spite of this variability, longshore troughs in sandy material are characteristically U-shaped It was therefore surprising to find on the fathograms several profiles exhibiting flat and even convex upward trough floors In each instance investigation using SCUBA revealed the presence of a rock pavement at these sites of anomalously shaped troughs

The rocks were from cobble to boulder size (0 1 to several meters in diameter) and ran the gamut of lithologies through sedimentary, igneous, and metamorphic types This indicates the necessity of glacial transport to explain their occurrence on the shore of Lake Michigan Three of the five ranges with flat bottom troughs are indeed directly offshore from truncated glacial moraines The occurrence of boulders on these three southern ranges is thus readily explainable as an effect of post glacial coastal erosion Boulders also floor troughs on ranges 4 and 11, and these are separated by kilometers from the nearest boulder clay deposit Evidently the glacial moraines formerly extended considerably farther westward (Figure 9)

The correlation between atypically shaped troughs and the presence of boulder pavements seems well established by this study The use of grab samplers (VanVeen, 1936, Shipek, 1965), so routinely employed in surveys of shallow-water sediments, fail to reveal the rock pavements due to the large size of individual rocks (0 1-2m) and the elongate, patchy distribution of the deposit Likewise, Hough's method (1952) for identifying bottom composition by interpreting the density and thickness of fathogram traces also failed to reveal these substantial changes in bottom type Rock pavements do however reveal their presence by effecting profile configuration They interrupt normal profile development, causing abrupt changes in slope and flat to convex upward troughs (Figure 10) This previously unrecognized relationship permits the use of fathograms to infer the presence of clay, gravel, boulder, or bedrock substratum and the thickness of mobile sediment

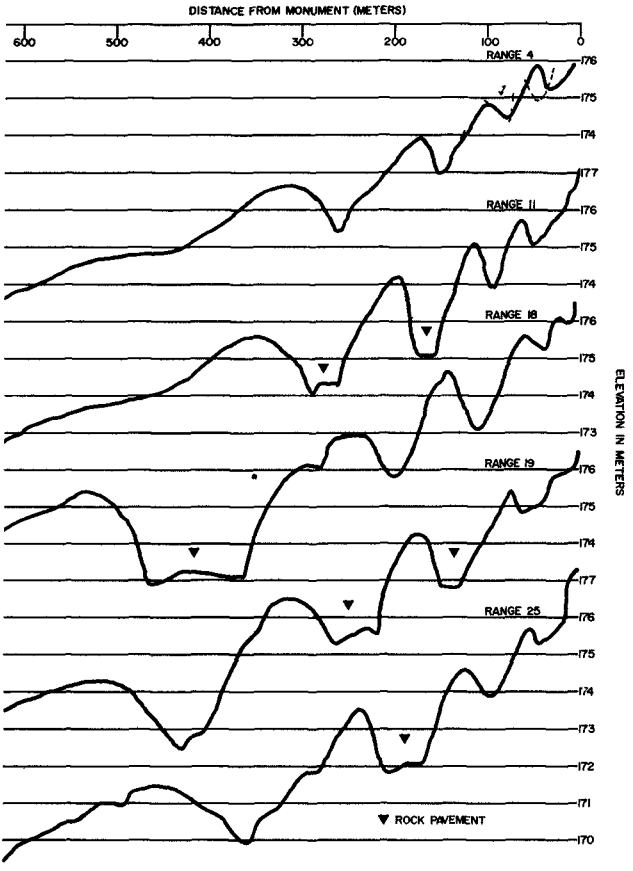

Fig 10 Atypical, flat-bottom troughs arise where immobile strata interrupt normal profile development

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