SEDIMENT DISTRIBUTION IN A BEACH RIDGE COMPLEX AND ITS APPLICATION TO ARTIFICIAL BEACH REPLENISHMENT

Gordon S. Fraser and Norman C. Hester

ILLINOIS STATE GEOLOGICAL SURVEY

John C. Frye, Chief • Urbana, IL 61801
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ABSTRACT

Severe erosion of much of the beach ridge complex along the Illinois shore of Lake Michigan east of Zion and Waukegan is taking place, especially in the northern half of the area. As much of the area is developed and occupied, methods of restoring and preserving the shoreline are being sought. One proposed method involves replenishing the eroded shore, either by filling or feeding. If this method is used, two factors must be considered: (1) the material supplied should match that now found on the shore, and (2) the material must be available in sufficient quantities near by to make the project economically possible.

A study of the beach ridge complex was made to determine the specific character of the sediments currently being deposited and the grain size of the materials deposited in the past when the complex was being formed.

The sand body that forms the complex along the Illinois shore is approximately 7 miles long and 2.5 miles wide, including a subaqueous platform 1.5 miles wide, and it is as much as 35 feet thick. The subaqueous portion consists of an offshore segment of fine to very fine sand and a nearshore area (in water less than 15 feet deep) where sand and granules occur. The shore material ranges from medium-sized sand to pebbles. West of the shore, medium-sized sands are found in dunes and on eolian sand plains.

Material similar to that currently being deposited on the shore is available within the complex in sufficient quantity for use in a replenishment program. The material was laid down on ancient shores as the sand body prograded south and east from the original shoreline.
INTRODUCTION

Large segments of the shorelines of the Great Lakes consist of Wisconsinan and Holocene sediments that are particularly prone to erosion, especially during periods of high lake level, because they are unconsolidated deposits. This natural process of erosion becomes a problem when it begins to affect shore areas that man has occupied. The Zion-Waukegan area along the Illinois shore of Lake Michigan, which was extensively eroded as a result of the 1952 high lake level, is again undergoing intensive erosion as a result of the recent rise in lake level. Because it is a highly developed area, methods to protect and restore the shoreline are being sought.

Common methods of protection against erosion have made use of man-made structures such as groins, sheet piling, and various types of armoring. Artificial beach replenishment, including both beach feeding and beach filling, also have been used. These methods are discussed in a nontechnical report by the U.S. Army Corps of Engineers (1972).

Geologic processes become important considerations when beach replenishment is selected to retard the erosion. First, how the shore and nearshore processes have acted in the past and how they are now affecting sediments must be understood before the future movement of sediment can be predicted. The behavior of these processes in the Zion-Waukegan area has recently been discussed by Hester and Fraser (1973).

Second, the textural characteristics of the sediments on both the present and ancient shores must be known so that a sediment that has the proper grain-size characteristics can be selected to replenish the shoreline.

Third, a source of usable sediment must be found in the immediate area to make the method economically feasible. Maps delineating the distribution of surface sediments (both subaerial and subaqueous) and subsurface sediments are therefore necessary.

The results of an investigation of the texture of the sediments and of sediment distribution in the area are presented in this paper. This study is one of several investigations of Lake Michigan bottom sediments and shorelines being conducted by the Illinois State Geological Survey.

Acknowledgments

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CULTURAL AND PHYSICAL SETTING

The shoreline east of Zion, Waukegan, and Winthrop Harbor, Illinois, is part of a beach ridge complex on the southwestern shore of Lake Michigan that extends from Kenosha, Wisconsin, to a position just east of Waukegan, Illinois (fig. 1). Its subaerial portion is approximately 14 miles long and ranges from essentially nothing just southeast of Kenosha to 1.1 miles wide in the area of the Illinois Beach Nature Preserve. Only the portion south of the Illinois-Wisconsin boundary is considered in this report. The beach ridge complex is bounded on the east by Lake Michigan and on the west by a bluff composed of glacial material, mostly till.

Except in Illinois Beach State Park and the Illinois Beach Nature Preserve, the complex, particularly along the shoreline, has been occupied by man. Most of the structures in the area are residences, but there are two areas of industrial development, one the Commonwealth Edison Company's nuclear power plant east of Zion and the area to the west along Shiloh Boulevard, and the other an extensive complex of factories and a fossil fuel power station east of Waukegan at the southern end of the beach ridge complex.

The subaerial portion of the complex encompasses several major environments, including beach ridges covered with trees and shrubs, dune ridges covered with shrubs and grass, marshes covered with reeds and grass, and the modern shore, which has little or no vegetation.

Fig. 1 - Physical and cultural features of the beach ridge complex along the southwestern shore of Lake Michigan. Except for Illinois Beach State Park and the Nature Preserve, the area has been occupied by man. (Modified from Hester and Fraser, 1973.)
The complex in the area of the Illinois Beach State Park is characterized surficially by an orderly, linear or gently curving arrangement of beach and dune ridges. Relief between the ridge and swale may be so slight, however, that the lineation can be recognized only by subtle changes in vegetative cover that are easily distinguishable on infra-red aerial photographs. North of the park the ridges are poorly defined and discontinuous, the area consisting mainly of low-lying, hummocky sand plains and marshes. North of the Illinois-Wisconsin state line, the marshes are generally absent and the area is covered by an eolian sand plain.

Part of the beach ridge complex lies offshore as a broad apron of sand that slopes gently under the lake east and south of the subaerial portion. It thins toward deeper water and changes in texture with the addition of silt and clay.

The complex is a transitory feature that is now suffering extensive erosion, with associated permanent loss of land to the north and general accretion (with periods of temporary loss) of land to the south. The complex is migrating from north to south and has suffered several periods of extensive erosion (Hester and Fraser, 1973). The geologic record of the migration and the erosion indicates that the same processes will no doubt continue in the future.

METHOD OF STUDY

In an area consisting of 17 square miles (fig. 2), 46 holes were drilled in the subaerial portion of the beach ridge complex with the Illinois Geological Survey's Mobil B-30S, 27 holes were hand augered, 8 beach profiles were trenched, and 10 outcrops were excavated. Data from 128 drill holes were provided by Commonwealth Edison, the Illinois Department of Transportation, District 1, and Soil Testing Services.

Fig. 2 - Sites of the investigations conducted. Cross sections and fence diagrams were constructed from drill hole data to provide a concept of the internal structure of the beach ridge complex. (Modified from Hester and Fraser, 1973.)
Data from 30 holes in the subaqueous portion of the beach ridge complex, were provided by Commonwealth Edison, Soil Testing Services, and the Waukegan Water Company. Thirty-five additional holes were drilled through the sediment body and samples were taken with a jet airlift drill designed by Robert Woolsey of the University of Georgia's Marine Institute, Sapelo Island, Georgia, and constructed by the Illinois Geological Survey. Split-spoon samples from water depths of 15 to 35 feet that ranged from 1\(\frac{1}{2}\) to 2 feet in length were collected at 30 sites. This drilling was done from the R. V. Inland Seas, which is operated by the University of Michigan Great Lakes Research Division under National Science Foundation sponsorship. Altogether, over 900 samples were collected by these various methods and were sieved in the laboratory at a sieve interval of 0.5 \(\phi\).

Topographic maps, soil maps, and aerial photographs of the area were used to delineate geologic provinces and reconstruct the geomorphic development of the beach ridge complex (Hester and Fraser, 1973).

**ENVIRONMENTS OF DEPOSITION**

Hester and Fraser (1973) defined the major environments of the beach ridge system, but only those environments in which sand and/or gravel are the common sediments are discussed here. Dune, shore, nearshore, and offshore environments are included. The shore and nearshore environments extend eastward to the outer slope of the permanent submarine bar, whereas the offshore environment extends lakeward from that bar. Each of these environments may contain sediments ranging in size from very fine sand to pebbles. Usually, however, sediments of one or two size classes predominate, and these size classes are different for each of the environments where sand and/or gravel are being deposited (fig. 3).

The shore environment is characterized by the presence of coarse sand, granules, and pebbles. Dune sediments, on the other hand, contain only medium and fine sand, whereas the offshore sediments are predominantly very fine sand, although a few samples may contain significant amounts of coarse sand and granules. Sediments of the nearshore environment are highly varied, ranging in texture from gravel to silt. In very few samples, however, is the material coarser than coarse sand. Nearshore sediments tend to have less medium sand than dune sediments but more medium sand than offshore sediments.

Dune Environment

Much of the subaerial portion of the beach ridge complex is covered by eolian sands. Dune ridges are well developed just west of the modern shoreline, especially in the southern portion of the complex, but they are less pronounced farther inland. In the northern part of the sand body, the ridges are discontinuous, and many of them have coalesced to form an eolian sand plain. Where extensive marshes are present in the western portion of the complex, dunes are generally absent.
Grain size of the dune material varies only slightly from dune to dune throughout the area. However, grain size may vary considerably in any one dune. Sands in the lee of the dune are the coarsest and show the greatest vertical variability, whereas those of the foredune are finest and vary least vertically. Sand from the dune crest is of intermediate size and degree of variability (fig. 4). In each position the sands generally become finer from the base to the top of the dune (fig. 5).

Fig. 3 - Variation in textures of sediments deposited in the modern shore, dune, offshore, and nearshore environments.

Shore Environment

Shore sediments show the greatest variation in texture of all materials of the sand body. They range from medium sands of the upper shore area to coarse pebbles where waves break and begin to run up on shore (fig. 6). Sed-
iments become finer lakeward of the break point as well as shoreward, in agreement with the theory and observations of Miller and Zeigler (1958, 1964). A bimodal distribution is generally found at the limit of wave run-up.

Variations of this pattern occur, of course, because wave characteristics vary. When waves of higher energy follow lower energy waves, the sediments respond quickly to the new conditions, as sediment distribution and shore profile reach a new equilibrium. However, when the opposite sequence occurs, the sediments and shore profile respond more slowly, and remnants of the responses to former wave conditions may remain under the newer wave regime.

When low-amplitude waves strike the shore after waves of greater amplitude, they form a relatively fine-grained step farther up on the shore from the coarse-grained step formed by the larger waves (fig. 7). The shore sediments become still finer farther up on the shore from the fine-grained step, but they coarsen lakeward to the relatively unmodified coarse-grained wave step.

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Fig. 4 - East-west cross section through a dune illustrates the development of the dune over a core of beach material. Grain-size distribution curves show the vertical variation in textures in the foredune, dune crest, and lee of dune areas.
Lateral accretion by attachment of subaqueous bars to the shore is considered the predominant process responsible for the lakeward (or oceanward) migration of a shore (Currag, Emmel, and Crampton, 1969; Davis et al., 1972).

Although lateral accretion of the shore lakeward is one depositional mode along this coast, the mode responsible for the formation of the successive beach ridges is vertical aggradation associated with the formation of a washover bar. Large waves of long periods can wash entirely over the shore into the swale, or lowland, found behind the shore in many places, carrying material landward and causing migration of the landward side of the bar and upward aggradation. Washover structures associated with this type of deposition may be seen in trenches cut through the shore or in cross-sectional exposures at the mouths of creeks emptying into the lake (Hester and Fraser, 1973, frontispiece).

The surface sediments of a washover bar constructed by a single storm display a size distribution similar to the simple pattern displayed by most shores of the complex. Sediments are coarsest grained where waves break, and they become finer lakeward and farther up on the shore (fig. 8). The finest sediment, approximating that of dune sand, is found in the swale on the landward side of the bar. Frequently, the foreslope of the washover bar is subsequently modified by wave action, and a coarse-grained ridge is formed that is probably similar in origin to the swash bar of Sonu and Van Beek (1971) and Sonu (1972).

Most washover bars, however, are composite structures built by several periods of high wave activity (fig. 9). Internal structures and grain-size characteristics of a bar at the mouth of Kellogg Drainage indicate that at least two periods of bar growth occurred, with intervening periods in which the foreslope of the bar was modified.

The washover bars seen during the field work of 1972-1973 did not exceed 3 feet in height. However, older beach ridges being exhumed during the present period of erosion indicate that such bars can be thicker (fig. 10). In
Fig. 6 -Textures developed on a shore (BP9 on fig. 2) illustrate a continuous gradation from coarse pebbles at the point of wave break (A) to finer sand and granules farther up on the shore. A bimodal texture of sand and pebbles occurred at the limit of wave run-up.

the northern part of Illinois Beach State Park, alternating layers of coarse sand and granules interbedded with coarse gravel occur in a ridge 6 feet above present lake level. It includes 5 feet of shore sediments and 1 foot of dune sand.

Nearshore Environment

The nearshore environment, in water less than 15 feet deep, was the most difficult area to sample. It was too shallow for use of the airlift drill from the R. V. Inland Seas and too deep for taking hand-driven split-spoon samples. However, PONAR grab samples (provided by Julia Badal Graf) and SCUBA samples were taken. The samples indicate that the area consists mainly of medium to medium-fine sand with some gravel that tends to become finer in deeper water (fig. 11).

Offshore Environment

Offshore sediments, found in water deeper than 15 feet, are the finest material found in the beach ridge complex, other than the clayey, silty, marsh sediments. Sediments in the 15- and 20-foot water depth intervals are predominantly fine to very fine sands. However, some coarse material can be found at
Fig. 7 - Textures developed on a shore (BP7 on fig. 2) where a step developed earlier by 2- to 4-foot waves had not yet been modified by 1- to 2-foot waves that formed a step farther up on the shore. Coarsest textures occur at the break point of the earlier waves and they become fine farther up the shore and also lakeward. A bimodal texture is found at the limit of wave run-up.

these depths, especially in the vicinity of the Zion nuclear reactor (samples 1014, 1017, 1019 in fig. 12A) and off the northeast coast (sample 1047, fig. 12A; sample 1048, fig. 12B). The coarse material found off the nuclear reactor is associated with abnormal thickening in that area. The coarse material near the Wisconsin state line occurs off a coast that is constantly being eroded; it may represent a lag deposit.

Samples from 30-foot water depths are fairly uniform, well sorted, very fine sand (fig. 12C), whereas those in depths greater than 40 feet are less well sorted because they contain as much as 50 percent silt and clay (fig. 12D).

SEDIMENT DISTRIBUTION IN THE SUBSURFACE

The original shoreline of the beach ridge complex was once probably near the till bluff that stands approximately a mile west of the present-day shoreline. The sand body, however, has prograded east and south during its development, and sediments deposited in the shore and nearshore environments now
cover sediments once deposited in offshore environments. Marsh and dune sediments have, in turn, been deposited on top of the old shore-nearshore deposits as they prograded east and south. The subsurface of the sand body, therefore, is composed of material deposited in offshore, shore, nearshore, dune, and marsh environments. The last will not be considered here.

It was possible to determine the environment in which sediments recovered from the drilling program were deposited by comparing the grain size of these samples with samples taken of sediments deposited in the various modern environments. Isopach (thickness) maps and isolith (lithology) maps of mean grain sizes were constructed for the whole sand body and for each of the facies of the sand body interpreted as having been deposited in dune, shore-nearshore, and offshore environments.

Total Sand Body

Isopach and isolith maps (fig. 13) show the geometry of the beach ridge complex and the grain-size trends derived from weighted averages of the subsurface samples.* Grain sizes are given in phi (\(\phi\)) units, which are logarithmic equivalents of diameter. The average grain size of each facies was determined by the proportion of the total thickness of the sand body occupied by sediments of that facies. The weighted averages were then added together to give the average grain size of the combined facies at that point.

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* The average grain size of each facies was determined by the proportion of the total thickness of the sand body occupied by sediments of that facies. The weighted averages were then added together to give the average grain size of the combined facies at that point.
Fig. 9 - Textures in the internal portion of a washover bar (BP6 in fig. 2). Both analysis of grain sizes and sedimentary structures indicate at least two periods of bar development, with intervening periods when the portion of the bars toward the lake were modified.

of the millimeter scale. Table 1 gives the conversion from millimeters to phi units. The sand body is elongate north to south and prismatic east to west. It thickens lakeward toward the position of the modern shore, thins abruptly from the shore to the 15-foot water depth line, and then continues to thin more gradually eastward. These trends are interrupted off the shore near the Zion nuclear reactor where abnormal thicknesses of sediment may be attributed to an influx of material from Kellogg Ravine to the west. Some of this material may also be a reflection of

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<tr>
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<tr>
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the disturbance of the southerly longshore drift system created by the pier constructed for the Zion nuclear reactor. The pier was removed before the offshore sampling program was begun, however.

The variation in mean grain size in the beach ridge complex has two causes. First, as not all major environments of sand deposition are present everywhere in the complex, the average grain size in any part of the sand body will be affected by the presence or absence of materials normally deposited in these environments. Second, variable conditions during deposition cause a variation in grain size within a single environment of the sand body.

The average texture of the sand body increases in size westward toward the position of the modern shoreline. This is in part due to an increase in grain size westward in sand deposited in the offshore portion of the sand body, and to the addition of coarse shore-nearshore sediments (fig. 14). At the position of the modern shoreline, the shore-nearshore sediments are thickest, and the average texture of the complex in the vicinity of the modern shore is a medium sand. West of the modern shore, however, dunes are present that effect a reduction in the average grain-size of the sand body in that area.
Fig. 11 - Range in textures of samples from the nearshore area taken at water depths of from 4 to 12 feet along the coast from the Wisconsin-Illinois line to the Commonwealth Edison fossil fuel power plant east of Waukegan. The samples generally are composed of medium to very fine sand, although some contain substantial amounts of coarse sand, granules, and pebbles.

Dunes are not present in the south-central portion of the complex. Instead, the western part of the area is occupied by extensive marshes and bogs (Hester and Fraser, 1973). The only sediments present other than marsh deposits are those that formed in the shore-nearshore and offshore environments. As a result, the sand body in that area has an average texture of medium sand, similar to that of the sediments of the modern shore. Discontinuous sand dunes are found on the western margin of the sand body, and, wherever they appear, these dunes tend to lower the over-all sediment size to that of a medium-fine sand.

Textures in areas A and B in figure 13 are somewhat finer than would be expected from their positions in the sand body, and the texture in area C is considerably coarser than would be expected. Areal variations in the textures of the shore materials account for these differences.

Shapes and Sediments of the Facies in the Subsurface

Dune Facies

Because of the irregular topography of the upper surface of the dunes, it is difficult to prepare a standard isopach map of the dune deposits. However,
Fig. 12 - Range of textures in samples of offshore sediment, taken at water depths of 15 feet or more, from the Wisconsin-Illinois line to Waukegan. Samples are generally in the fine to very fine sand size range, although some contain appreciable amounts of coarse sand, granules, and pebbles. The coarser samples are associated with the abnormal thickness of the sand body in the vicinity of the Zion nuclear reactor (samples 1017, 1019, 1014 in A) or are from the erosional coast on the northern part of the complex (sample 1047 in A and sample 1048 in B).
Fig. 13 - Isopach and isolith maps of complete sand body. The beach ridge complex thickens eastward to the position of the present-day shoreline, where it begins to thin eastward into the lake basin. The coarsest textures of the complex are found in the area of the modern shore. Both east and west of this area textures are finer.
Fig. 14 - Idealized east-west cross section through the beach ridge complex illustrates the effect that the presence or absence of various units of the complex have on the average textures in any one part of the sand body. The sand body texture is coarsest near the modern shore and where marshes are present, because fine sands of the dunes are absent. The sand body texture is finest from the subaqueous bar eastward because only fine to very fine sands of the offshore facies are present.

The area of dune development can be divided, on the basis of thickness, into three areas (fig. 15), based on the province map in Hester and Fraser (1973) and the soils map for Lake County prepared by Pashke and Alexander (1970).

The first area consists of the modern shore. Dune material is thin or absent and is confined to a zone beyond wave run-up where vegetation has acted to trap wind-blown sand. The second area is the high dune field, generally found just west of the modern shore and in an extensive area in the southern portion of the sand body. The dunes may be up to 15 feet higher than the adjacent swales. However, the dune sand does not exceed 10 feet thick because the dunes have formed around a core of shore material (fig. 4). The third dune area consists of the low dunes plain in the northern portion of the complex, where dune sands range to only 5 feet thick.

**Shore and Nearshore Facies**

Because shore and nearshore facies are difficult to differentiate in the subsurface, the sediment distributions of these two environments were analyzed together.

The subsurface shore and nearshore sediments thicken from nothing near the till bluff to a maximum of 15 feet in the vicinity of the modern shore and then thin rapidly into the lake (fig. 16). A cross section through the sand body illustrates the variation in the thickness of the shore and nearshore sediments and shows the prismatic shape of these deposits (fig. 17).

Since the sand body is prograding eastward, it was expected that the sediments would become finer eastward. The sediments, however, coarsen eastward from the till bluff, reaching a maximum near the modern shore, and only then
show the expected fining trend into the lake (fig. 16). This initial coarsening lakeward of the shore-nearshore sediments can possibly be accounted for by the variation in the wave energy that occurs along a curved shore.

As King (1972) indicated, variation in wave energy along a shoreline is, at least in part, responsible for variations in grain size parallel to the shore. The component of wave energy parallel to shore is at a minimum when waves approach the shore at angles of 0° or 90°, and it reaches a maximum when waves approach at an angle of 45°. Because the shoreline along the beach ridge complex is curved, wave energy varies considerably along the coast. The winds of greatest velocity measured along the southwestern shore of Lake Michigan are generally from the north and west. Because of the north-northeast south-southeast elongation of Lake Michigan, however, the direction of longest fetch (the continuous area of water over which winds blow) is from the north-northeast, so that waves of greatest energy approach the southwestern shore from the northeast quadrant. These waves hit the north-south oriented shoreline of the northern two-thirds of the beach ridge complex at an approximately 45° angle, although the pattern may show some variation (Collinson, 1973, personal communication).

Transport energy along the beach ridge complex, therefore, is at a maximum when the strong waves from the northeast hit the north-south oriented part of the shore. However, at the distal end of the sand body the shoreline curves to the southwest, and waves from the northeast approach this part of the shore at an angle somewhat greater than 45°, causing a reduction in transport energy and possibly a reduction in the size of material that can be transported.

Hester and Fraser (1973) indicated that as successive beach ridges were built they followed a north-south line for most of their length but curved to the southwest at their distal or southern ends, joining the till bluff at angles of up to 25° from a north-south line. The beach ridges near the till bluff, therefore, have a north-south trend only in the northern portion of the sand body, which was built first, and they join the till bluff at an increasing angle southward. Where the beach ridges curved to the southwest, wave energy decreased and finer grain sizes were transported around the curve. Therefore, the shore-nearshore

Fig. 15 - Thickness of the dune facies. Because of the irregularity of the topography, a standard isopach map could not be prepared. Instead, the area of dune development was divided into three areas based on the thickness of the dunes in those areas.
Fig. 16 - Isopach and isolith maps of shore-nearshore facies. Sediments thicken and coarsen eastward from the till bluff to the position of the present-day shore. They then thin abruptly and become finer eastward.
Fig. 17 - East-west cross section along Shiloh Boulevard (CS4 in fig. 2) illustrating the variation in thickness of the shore-nearshore facies. The facies thickens eastward to the position of the modern shore and thins rapidly from there into the lake. The plan view of the lineaments formed by the beach ridges along this cross section are curved to the southwest, as much as 20° from a north-south line near the western margin but only about 10° near the present-day shore.

Sediments near the bluff, especially at the southern portion of the sand body, are finer grained than those near the lake where the ridges nearly parallel a north-south line.

The fine textures found in the shore-nearshore sediments on the western side of the sand body may be due to a decrease in longshore transport energy along the curved portion of the shore. This concept is illustrated in figure 17. The beach ridges gradually become more parallel to a north-south direction going eastward from the till bluff, and the sediments in the shore and nearshore facies become coarser with the addition of pebble layers and coarse sand and granules. The concept also accounts for the anomalously fine textures in areas A and B in figure 13, which are on the southwesterly curving portions of the beach ridge system. The mechanism may not operate on the modern shoreline because it has been artificially modified by man.

The isolith map in figure 16 also shows two areas that are coarser than would be expected. The areas coincide with topographic disconformities in the
beach ridge lineaments formed during former periods of erosion. The disconformities are expressed on the surface by truncations of curved portions of beach ridges (Hester and Fraser, 1973). The subsurface expression of these disconformities is a concentration of gravel that was probably left as a lag deposit when beach ridges were eroded.

A plan view section of the beach ridges shown above the cross section indicates where such a disconformity occurs (fig. 18). Thick sections of gravel are found to the east of the erosional boundary, and much finer material is found to the west because of the high angle the lineaments make with a north-south line. Concentrations of gravel left as a lag after an episode of erosion account for the anomalously coarse area C in figure 13, which lies along a pronounced topographic disconformity.

**Offshore Facies**

Offshore sediments thicken to the east toward the area of the modern shore (fig. 19A), as would be expected because the till surface on which the offshore sands are deposited slopes gently downward to the east. In the vicinity of the modern shore, this trend reverses itself, and offshore sediments begin to thin eastward. In the vicinity of the nuclear reactor the sediment is abnormally thick, probably filling in an irregularity in the till surface.

Sand size tends to decrease lakeward and silt and clay content to increase (fig. 19B). The offshore sands may grade laterally eastward into the silty-clayey facies of the Waukegan Member, which was described by Lineback and Gross (1972).

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**Fig. 18** - East-west cross section through the beach ridge complex along Wadsworth Road (CS3 in fig. 2). The plan view of the lineaments formed by the beach ridges along the cross section show a topographic disconformity near the position of PA5, where ridges oriented at a 24° angle to a north-south line are truncated by ridges oriented in a nearly north-south direction. Gravel layers in the offshore portion of PA7 may be lag deposits formed when erosion truncated the beach ridges.
Fig. 19 - Isopach and isolith maps of the offshore facies. Sediments deposited in the offshore portion of the sand body thicken eastward toward the position of the modern shoreline. They thin and become finer eastward from there.
A cross section (fig. 20) of the offshore facies along Wads- worth Road that continues eastward into the lake also demonstrates the initial thickening eastward to the area of the modern shore, followed by a thinning of the facies from the present shoreline eastward. It also shows the general trend of fining eastward and coarsening upward.

Figure 20 also shows the relation of grain size and depth. The texture of the offshore facies becomes coarser toward the west where the sand was deposited in progressively shallower water. The facies also becomes coarser upward as the offshore sands aggrade and cause a decrease in water depth.

The relation of depth to grain size is explained by the null point theory proposed by Cornaglia (1887) and tested and at least partly verified by Ippen and Eagleson (1955), Eagleson, Dean, and Peralta (1958), and Miller and Ziegler (1958). The null point theory describes the motion of sand grains in the nearshore environment in response to the transport energy of shoaling waves. A discussion of the null point theory and its implication for sediment textures can be found in King (1972).

RESOURCES FOR BEACH REPLENISHMENT

Studies of beach replenishment and behavior of fill materi- al have revealed that the stability of the added materials in the shore environment depends largely on their similarity in textural characteristics to the in-place shore materials. In the study of
requirements for beach nourishment at Presque Isle Peninsula, Erie, Pennsylvania, Berg (1965) discussed the importance of using the proper grain size. He found that the sand fill used for replenishment had a finer mean size than the original shore material. Because much of the fill material proved to be more compatible with processes characteristic of the zone immediately offshore than it was with those of the shore, it was easily eroded and was redeposited in the offshore environment.

Krumbein and James (1965) proposed a formula for estimating the amount of borrow material with specific sorting and grain-size parameters that would remain on a shore composed of native materials of known specific parameters. By varying the parameters in the formula independently, they determined the compatibility of the materials on a scale of five possibilities, ranging from complete loss of the borrow material, through various conditions of its partial retention, to its stability in the shore environment, which resulted when parameters were matched.

In the Zion beach ridge complex, three textural types are present. Two of these, the dune and offshore sands, are finer and better sorted than the shore material. If they were to be used as fill on the shore area, a considerable transformation of the shore profile would be necessary before much of this fine material would remain on shore. The shore-nearshore sands and gravels of the complex, however, would be well suited for artificial shore replenishment purposes. Thick deposits of this material exist in the subsurface of the beach ridge complex, built up as the sand body has prograded south and east away from the original shore near the till bluff.

CONCLUSIONS

Because of present high water levels in Lake Michigan, erosion is a serious problem along the coast of the beach ridge complex near Zion, Illinois. Beach replenishment, either by fill or feeding methods, can be used to control this erosion. If beach replenishment is used, the fill must be a material similar in composition to the present shore. Of the three major environments in the beach ridge complex where sand and/or gravel are currently being deposited, the shore sediments have the coarsest grain size. The finer material from the dune or offshore environments, consequently, would be unsuitable for replenishment material. Fortunately, because the shore is part of a sand body that has prograded east and south, coarse material that was once a shore deposit and was subsequently buried is abundantly available in the subsurface of the beach ridge complex.
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(Exclusive of Lake Michigan Bottom Studies)

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