Anatomy of a Transgression Along the Southeastern Shore of Lake Michigan

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ABSTRACT


Landward translation of the shoreline during the post-Chippewa transgression (circa 6,500 yrs BP) of the southern shore of Lake Michigan was dominantly a depositional event and produced a 6.5-m-thick sequence of onshore and upper shoreface deposits. Onshore sediments consist of planar cross-stratified washover and eolian sand and back-barrier lacustrine silty clay. These sediments are distributed in an onlapping sequence of repeated washover to eolian and lacustrine sediments. The onshore sediments are erosionally overlain by upper-shoreface deposits of a moderate- to low-energy barred shoreline. Dominant sediment types are trough cross-stratified longshore-trough and rip-channel sand and parallel-laminated and rippled bar-slope sand. Longshore-trough deposits are common in the more onshore part of the upper-shoreface sequence where they are interbedded with thin beds of bar-slope sediments. In the more offshore part of the upper-shoreface sequence, bar-slope and rip-channel sediments predominate.

ADDITIONAL INDEX WORDS: Depositional transgression, shoreline behavior, beach ridge, lithofacies, nearshore and onshore environments, Indiana.

INTRODUCTION

About 6,500 years ago, lake level in the Lake Michigan basin began to rise from the low level of the Chippewa Phase to the level of the Nipissing Phase of ancestral Lake Michigan and inundated the margins of the lake (Figure 1). Sediment supply was positive to the southern shore of the basin during landward translation of the shoreline and produced a sequence of nearshore deposits over onshore sediments that is more than 6.5 m thick. These depositional-transgression deposits make up the core of the most lakeward dune and beach complex along the southern shore of Lake Michigan, the Toleston Beach. Along the eastern part of the shoreline of Indiana, the Toleston Beach is eroding, and the depositional-transgression deposits within the dune and beach complex are exposed. The outcrop is a low-angle oblique cut of the Toleston shoreline that provides an extended onshore-offshore view of the depositional-transgression deposits. The purpose of this paper is to describe the physical characteristics and lateral and vertical arrangement of lithofacies within the depositional-transgression sequence and to reconstruct their depositional history.

STUDY AREA AND METHODS

The study area is along the southern margin of Lake Michigan in the Indiana Dunes National Lakeshore (Figure 2). The best exposures occur along the lakeward margin of Mt. Baldy, a domal dune near Michigan City, Indiana. High lake levels during 1985 and 1986 enhanced the erosion of the lakeward margin of Mt. Baldy that is caused by the trapping of longshore drift on the eastern (updrift) side of the Michigan City Harbor. Total landward movement of the shoreline on the downdrift side of the harbor since its completion in 1910 is about 0.3 km. The erosion area is concave lakeward near the harbor but is essentially linear and parallel to the depositional strike of the Toleston Beach about 2.2 km away from the western margin of the harbor. Consequently, two views of the early Toleston Beach occur in the exposures: a low-angle oblique view of dep-
Three sections were measured and sampled across the outcrop, and the available exposures were photographed during each inspection. Several vibracores were collected in the marsh south of the Toleston Beach, and lithofacies were traced landward through ditches that crosscut the Toleston Beach to establish the internal architecture of the dune and beach complex. Facies were defined and interpreted on the physical characteristics of the deposits and their relationships with surrounding units.

**LITHOFACIES DESCRIPTIONS**

The sedimentary deposits of the Toleston Beach form part of the Atherton Formation in Indiana (Figure 3). This formation consists of a variety of coastal and paralic sediments, and five lithofacies represent these depositional settings in the outcrop at Mt. Baldy. The transgression sequence of this study is in the lower part of the Atherton Formation and stratigraphically overlies the Lagro Formation, which consists of late Pleistocene till, sand, and gravel.

In the study area, the Lagro Formation is composed of a blue-gray pebbly clay. This clay is the base of the outcrop at Mt. Baldy and forms a flat and nearly horizontal surface on which the Atherton Formation was deposited. The basal pebbly clay currently crops out below the water surface and cannot be examined. WINKLER (1962), however, reported that the clay contained foldlike contortions and vertical cracks that formed polygons as much as 0.34 m in diameter. Compressed wood from the top of the pebbly clay was dated at 6,350 ± 200 years BP (I-363). THOMPSON (1987) traced the clay landward in vibracores and water wells to where it cropped out as part of the Lake Border Moraine.

The sequence of transgression deposits is capped by planar cross-stratified fine-grained sand, and these sediments are the source for part of the active dune field of Mt. Baldy. The entire dune land is migrating landward at a rate of 1.2 to 1.5 m per year in response to strong northwesterly winds that occur during storms. This migration exposes older eolian sediments, soil horizons, and buried trees stratigraphically above the sequence of deposi-
Figure 2. Map of the study area showing physical and cultural geographic features. Note the low-angle oblique orientation of the outcrop to the strike of the Toleston Beach.

Fossiliferous Silty Clay

The pebbly clay at the base of the outcrop is overlain by 1 to 1.5 m of blue-black to gray silty clay (Figure 3). The clay is calcareous, carbonaceous, and highly fossiliferous. Dominant fossil types are gastropods, pelecypods, ostracods, turtles, and fish (GUTSCHICK and GONSIEWSKI, 1976). Disseminated and compacted plant debris occurs throughout and produces a crude horizontal layering. The clay is exposed along the shoreline for about 3 km, and has been traced beneath the Toleston Beach in vibracores and ditches to just north of Beverly Drive (Figure 2). The top of the clay has been radiocarbon dated at 4,690 ± 200 years BP (W-3246, GUTSCHICK and GONSIEWSKI, 1976) and is at an altitude of about 177 m. This surface rises about 0.5 m from west to east along the outcrop.

A second fossiliferous silty clay occurs higher in the section and is separated from the lower clay by 0 to 1 m of fine-grained sand (Figure 4). This upper clay is 0.3 to 0.5 m thick and siltier and sandier than the lower clay and contains less plant debris. The upper clay is not horizontal but dips 5° to 10° to the east-southeast. It joins the lower silty clay in the eastern part of the outcrop and pinches out updip into the
sands described below. The upper silty clay has been radiocarbon dated at 5,475 ± 250 years BP (1-362, WINKLER, 1962).1

Planar Cross-Stratified Medium-Grained Sand

The fossiliferous silty clays are overlain by and interbedded with planar cross-stratified medium-grained sand (Table 1). The planar cross-beds form sets 2 to 2.5 m thick (Figure 5). Like the upper silty clay, the planar cross-beds dip to the east-southeast with dips near 25°. The foresets of the planar cross-beds are slightly concave upward and contain discontinuous layers of flat pebbles. The pebbles are commonly imbricate and are concentrated at low-angle truncations between cross-sets. Foresets are defined by alternations in grain size, but some inversely and normally graded laminae are present.

Planar cross-beds can be traced downdip where they pinch out into the silty clays, but commonly foresets flatten out above the silty clays and grade into subcritical and critical climbing-ripple cross-stratification (Figure 6). Within the climbing ripples, mud drapes and flasers are common. Thick wavy mud laminae (0.5–1.5 cm thick) can be traced across the outcrop and updip into the planar cross-beds.

Planar Cross-Stratified Fine-Grained Sand

The planar cross-stratified medium-grained sand is replaced laterally (eastward across the outcrop) and upsection by well-sorted, planar cross-stratified fine-grained sand (Table 1, Figure 5). Contacts between these units are generally sharp. Foresets of the fine-grained sand dip parallel to the direction of dip of the medium-grained sand and generally contain fewer or no low-angle truncations. As in the planar cross-stratified medium-grained sand, laminae are defined by slight alternations in grain size, but commonly the laminae are indistinct. Foresets can be traced downdip into the silty clay where they become intercalated with organic-rich clay or thin (< 1.5 cm thick) layers of allochthonous peat. Within these tosets beds, micro-trough cross-stratification and wavy, ripple, and flaser bedding are common.

Along one part of the shoreline, peat layers within the cross-beds of fine-grained sand are very common. They extend updip along the foresets and are commonly wavy (Figure 5). Unlike the fine-grained sand, these layers do not extend into the silty clay but flatten out above the clay. The entire unit is truncated by another planar set of cross-beds of medium-grained sand.
Figure 4 Photograph of the upper fossiliferous silty clay. The clay is interpreted as a back-barrier lacustrine deposit and represents stable lake level (without overwash) during the post-Chippewa transgression.

Table 1. Comparison of textures between lithofacies

<table>
<thead>
<tr>
<th>Lithofacies</th>
<th>Mean (phi)</th>
<th>Lithofacies</th>
<th>Mean (phi)</th>
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<tbody>
<tr>
<td>Medium-grained planar cross-stratified sand</td>
<td>1.93</td>
<td>Medium-grained trough cross-stratified sand</td>
<td>1.73</td>
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<tr>
<td>(washover)</td>
<td></td>
<td>(longshore trough and rip channel)</td>
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<tr>
<td>Fine-grained planar cross-stratified sand</td>
<td>2.31</td>
<td>Medium- to fine-grained parallel-laminated and</td>
<td>2.23</td>
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<tr>
<td>(eolian)</td>
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<td>rippled sand (bar slope)</td>
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Trough Cross-Stratified Medium-Grained Sand

Foresets of the planar cross-stratified medium- and fine-grained sands are truncated upward by 1.0 to 2.0 m of trough cross-stratified, parallel-laminated, and rippled sand (Figures 3 and 5). The contact is very irregular, erosional, and locally marked by a flat-pebble lag. The troughs are 0.8 to 1.8 m wide and 0.2 to 0.5 m thick. They are medium grained (Table 1) with scattered pebbles along foresets and at the trough bases. A variety of foreset dip directions occur in the trough cross-beds, but commonly
the troughs face alongshore and offshore. Alongshore-facing troughs predominantly indicate a west to east sediment-transport direction. Offshore-facing troughs are coarser grained and larger than the shore-parallel troughs and make up most of the basal part of the troughed, parallel-laminated, and rippled sequence. Alongshore-facing troughs are more common in the upper part of the sequence where they are interbedded with parallel-laminated sand.

Parallel-Laminated and Rippled Medium-to Fine-Grained Sand

Parallel laminae are horizontal to subhorizontal (Figure 5) and have been traced as much as 21 m across the outcrop. Beds are commonly less than 0.25 m thick and medium to fine grained, and laminae are defined by alternations in grain size. In the upper and eastern part of the troughed, parallel-laminated, and rippled sequence, the parallel-laminated beds are interbedded with alongshore-facing troughs (Figure 7), but in the lower and western part of the sequence, the parallel-laminated beds are interbedded and interleaved with rippled fine-grained sand (Figure 8).

The rippled sand occurs as isolated pods or ripple forms of fine grained sand within parallel-laminated beds (Figure 5) or as distinct beds of subcritical and critical climbing-ripple cross-stratification. Beds of climbing-ripple cross-stratification are in the basal part of the sequence and commonly overlie offshore-oriented troughs (Figure 8). Like the trough cross-stratification, the climbing-ripple cross-stratification indicates a predominant west to east sediment-transport direction.

INTERPRETATION AND ARCHITECTURE

The fossiliferous silty clays are believed to have formed in a freshwater lacustrine environment (WINKLER, 1962; GUTSCHICK and GONSIEWSKI, 1976) on the landward side of a low-relief barrier beach. Owing to the interbed-
ded relationship between beach and lacustrine deposits, the radiocarbon dates from the lower and upper fossiliferous silty clays and the upper surface of the basal pebbly clay suggest that the barrier beach existed for about 1,500 years. During this time, lake level was rising from the level of the Chippewa Phase to the level of the Nipissing Phase (HANSEL et al., 1985), and the barrier beach migrated landward into the back-barrier lacustrine setting.

Landward migration of the barrier beach across the present outcrop locality is recorded by the planar cross-stratified medium-grained sands. These sands are interpreted as washover deposits, and they contain many of the characteristics described by SCHWARTZ (1975, 1982) and DEERY and HOWARD (1977) for delta foreset strata of washover fans. The planar cross-stratified medium-grained sands are, however, about 3 to 5 times thicker than washover deposits described in the literature and have well-developed toset beds (climbing-ripple cross-stratified sands at the base of foresets) that have not been described for washover fans.

Overwash is primarily a storm phenomenon and is promoted by a high storm surge, a high lake level, and a low-relief beach or barrier island. The facies relationships suggest that the early Toleston Beach was only slightly above lake level and had few established dunes. Therefore, the early Toleston Beach was overtopped by storms that eroded the nearshore and transported coarse detrital material into the back-beach setting. The rising lake level during the post-Chippewa transgression certainly promoted this process.

A period of beach stability with little or no lake-level rise is represented by the planar cross-stratified fine-grained sand. These sands are interpreted as eolian deposits that formed principally by grain fall along the landward margin of the washover fan. Important characteristics for this interpretation are the fine grain size, good sorting, indistinct laminae, and
Figure 8. Offshore-facing trough cross-beds and subcritical to critical climbing-ripple cross-stratification at the base of the troughed, parallel-laminated, and rippled sequence. The coarse-grained trough cross-beds are interpreted as rip-channel deposits that are interbedded with distal bar-slope sediments. Offshore-facing troughs commonly occur in the base of the upper-shoreface sequence.

tabular nature of the cross-sets (cf. HUNTER, 1977). Stable lake level is also suggested by the wave reworking and intercalation of organic clays and allochthonous peats with the toesets of the eolian sediments. The amount of reworking is dependent on the depth of the water in the back-barrier basin and the time between overwash events.

Five washover to eolian/lacustrine transitions (Figure 5) were observed from west to east along the length of the outcrop. More cycles may exist, but the entire outcrop was never entirely exposed during this study. The repeated sequences indicate that the landward translation of the shoreline was not a continuous process but episodic and strongly dependent on storms to erode the beach face and transport sediment into the back-barrier basin. The landward migration produced an onlapping sequence (horizontal stratigraphy) with little vertical stacking of onshore sediments.

The sedimentary structures and textural characteristics of the parallel-laminated, trough cross-stratified, and rippled sands overlying the washover to eolian/lacustrine sequences are similar to sedimentary features found in upper shoreface deposits of modern moderate- to low-energy barred shorelines (cf. DAVIDSON-ARNOTT and GREENWOOD, 1974, 1976; FRASER and HESTER, 1977; VAN DEN BERG, 1977; GREENWOOD and DAVIDSON-ARNOTT, 1979; HUNTER et al., 1979). Barred shorefaces are composed of three geomorphic elements: a trough, a bar, and a rip channel. Studies of DAVIDSON-ARNOTT and GREENWOOD (1974, 1976), GREENWOOD and DAVIDSON-ARNOTT (1979), and HUNTER et al. (1979) demonstrate that the trough, the bar, and the rip channel are influenced by different processes (i.e. oscillatory vs. unidirectional flow, fair-weather vs. storm wave-climate, etc.). These varying processes produce assemblages of structures and textural characteristics that are indicative of each environment.

Trough cross-stratification is, in part, produced in response to the migration of three-
dimensional small- and large-scale ripples in longshore troughs between bars. Longshore-trough deposits are generally coarser than adjacent bar sediments and may be preferentially preserved during onshore or offshore migration of the shoreline (FRASER and HESTER, 1977; HUNTER et al., 1979). The alongshore-facing trough cross-stratification observed in the outcrop at the Indiana Dunes is interpreted as having formed in longshore troughs by the migration of three-dimensional ripples. The predominance of eastward-dipping foresets in the trough cross-stratification suggests that the dominant longshore currents were west to east during the early development of the Toleston Beach. This paleoflow direction is opposite to the dominant flow direction today, which is east to west.

Longshore bars are primarily influenced by wave oscillation. Orbital flow velocity increases up the offshore slope of the bar as waves shoal. Consequently, there is a change from small-scale, two-dimensional wave ripples to plane bed, and possibly megaripples, from the bar base to its crest (DAVIDSON-ARNOTT and GREENWOOD, 1974, 1976). The ripples migrate up the back of the bar or are washed out in response to the prevailing wave conditions. Therefore, the offshore slope is characterized by interbedded horizontal to subhorizontal parallel-laminated sands and truncated ripple cross-stratification (CAMPBELL, 1966; DAVIDSON-ARNOTT and GREENWOOD, 1974, 1976). This assemblage of structures is similar to the parallel-laminated and rippled sands observed in the Indiana Dunes outcrop, and they are believed to have accumulated along the lakeward slopes of longshore bars.

The landward slopes of longshore bars are characterized by medium-scale, high-angle planar cross-stratification (DAVIDSON-ARNOTT and GREENWOOD, 1974, 1976), but the bar-crest and landward-slope sediments are probably not preserved in nearshore sequences of barred shorelines, owing to erosion by migrating longshore troughs (HUNTER et al., 1979). The absence of high-angle, landward-dipping planar cross-stratification in the outcrops supports HUNTER et al.’s (1979) conclusion.

There is a net landward movement of water as waves shoal, and a mass imbalance with an offshore-directed pressure gradient is created along the shoreline. This imbalance is relieved by offshore jetting of water (rip currents) through breaks in shore-parallel longshore bars or gaps between oblique bars. Flow velocity in the rip channels is higher than the current velocity in longshore troughs and is strictly unidirectional. Offshore-dipping trough cross-stratification due to the migration of lunate megaripples is the most common sedimentary structure in rip channels (DAVIDSON-ARNOTT and GREENWOOD, 1974, 1976; HUNTER et al., 1979). During storms, rip channels may erode through the entire active sedimentary prism and channel sediment from the beach face to the basal part of the upper shoreface and into the lower shoreface. Moreover, the sediment that fills the rip channels is coarser than the adjacent shoreface deposits (DAVIDSON-ARNOTT and GREENWOOD, 1976) and differs structurally from the parallel-laminated and rippled sands. In the shoreline exposures of the Indiana Dunes, offshore-oriented trough cross-stratified sands are interpreted as rip-channel deposits because of their structure and orientation, coarser grain size, and position at the base of the upper shoreface sequence.

Because the exposure at Mt. Baldy is slightly oblique (5° to 10°) to the strike of the early Toleston Beach, a more landward view of the paleoshoreline is produced from west to east across the outcrop. Variations in the abundance and occurrence of lithofacies in the exposure are related to the lithofacies position relative to the paleoshoreline. Longshore-trough deposits (alongshore-facing trough cross-stratified sands) are more abundant in the eastern (landward) part of the exposure where they are interbedded with a small amount of bar-slope deposits (parallel-laminated sand) (Figure 7). Westward (offshore), the bar-slope deposits compose most of the stratigraphic sequence (Figure 5), and rip-channel deposits (offshore-facing trough cross-stratified sands) are more prevalent.

The contact between the upper-shoreface deposits and underlying onshore deposits is erosional and irregular and truncates the washover and eolian foresets, so that no subaerial topset beds are preserved. The contact is horizontal across the outcrop, and irregularities are primarily caused by rip channels cutting into the top of the onshore sequence (Figure 8). Gravels occur only locally and usually at the
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base of rip channels. This erosional contact is interpreted as a ravinement that formed by the landward migration of the shoreface through the onshore sequence. No foreshore, backshore, or foredune deposits were preserved between the onshore and upper-shoreface sequences. Gravel and sandy gravel of probable beach origin, however, have been recovered in vibracores and water wells drilled into more landward parts of the Toleston Beach. These sediments mark the most landward point of shoreline translation during the post-Chippewa transgression.

DISCUSSION AND SUMMARY

A water-level rise commonly causes the shoreline to migrate landward. During this migration, the shoreface of the equilibrium profile migrates through the onshore and upper nearshore sedimentary prism (SWIFT, 1975). But, if the rate of sediment supply to the system is great enough to cause the equilibrium profile to translate above the regional slope of the pre depositional surface, a sequence of onshore deposits may be preserved (DAVIS and CLIFTON, 1987). Therefore, two conditions are required to produce a depositional transgression: a coastal system enriched with sediment and a rising water level.

The southern shore of Lake Michigan during the post-Chippewa transgression satisfied both of these needs. The southern shore is a sediment sink that receives longshore drift from both margins of the lake. The approximately 400 km² of dune and nearshore deposits in the Toleston Beach attests to the long-term southward supply of sediment to the area during the development of the coastline. Moreover, the directions of sand spit migration for older dune and beach complexes (cf. SCHNEIDER and KELLER, 1970) also indicate that sediment was supplied from the margins to the southern coastline throughout most of the history of the basin. Although no modern sediment budget studies have been conducted to support this argument, it is highly probable that sediment supply increases to the southern shore of Lake Michigan during a lake-level rise, because a part of the sediment eroded from the margins of the lake is transported to the southern coastline. Thus, a positive relation probably existed during the post-Chippewa transgression between rising water level and increased sediment yield to the area.

Lake level was rising during the post-Chippewa transgression at a rate of about 4 mm/yr in response to isostatic rebound of northern outlets from the basin and cooler and wetter climatic conditions throughout the Great Lakes. At this rate and an estimated regional slope of 1/2°, the rate of landward translation was about 0.5 m/yr. LARSEN (1985) has shown that the rise to the Nipissing Phase of ancestral Lake Michigan was not a continuous process, and periods of stable lake level or falling lake level occurred during the transgression (cf. LARSEN, 1985, Figure 11).

During one of these deflections from the overall lake-level rise, the early Toleston beach ridge probably formed slightly lakeward of the present coast as a mainland-attached beach (Figure 9). Landward migration of the shoreline and newly formed barrier beach occurred as a rising lake level was reestablished. At this time, the supply of sediment was large enough to cause the equilibrium profile not to traverse the pre depositional surface, and onshore sediments began to be preserved between the pre depositional surface and the ravinement.

The process of landward migration was by shoreface erosion and overwash during storm events (Figure 9). Between periods of overwash, eolian and lacustrine sediments accumulated on the washover fans and in the back-barrier basin. An onlapping sequence of repeated washover to eolian and lacustrine sequences was formed. Translation of the equilibrium profile through the onshore and upper nearshore eroded the foreshore and backshore, truncated the subaerial topset beds of the washover and eolian deposits, and permitted the upper-shoreface sediments to accumulate above the onshore sequence (Figure 9).

FRASER and HESTER (1977) studied deposits of the post-Chippewa transgression along the southwestern shore of Lake Michigan and found that upper-shoreface sediments erosionally overlie back-barrier marsh deposits or the forested pre depositional land surface. The upper-shoreface deposits are dominated by high-angle trough and planar cross-beds that are interpreted as longshore-trough deposits. Low-angle tabular cross-beds occur only in the upper part of the upper-shoreface sequence and are interpreted as longshore-bar deposits. They
suggest that longshore-trough sediments will dominate upper shoreface sequences formed during depositional transgressions. This suggestion is unsupported in the outcrops at Mt. Baldy, where longshore-trough and bar-slope deposits are equally represented. Major differences in the abundance of longshore-trough and bar-slope deposits at Mt. Baldy are apparently related to the onshore-offshore position of the exposure, with longshore-trough deposits occurring in the more onshore regions and longshore-bar deposits in the more offshore reaches.

Alternatively, it is possible that differences between the Mt. Baldy and Illinois State Beach nearshore areas are more related to the amount of sediment supplied to the two systems during the post-Chippewa transgression. The preservation of a thick onshore sequence beneath the upper-shoreface deposits at Mt. Baldy indicates that the southern end of the lake received more sediment than the southwestern margin. The greater sediment supply and upward deflection of the equilibrium profile would have promoted more aggradation along the bar slopes and less erosion by migrating longshore troughs. Therefore, both a thicker onshore sequence and a greater abundance of bar-slope deposits should occur in depositional transgressive systems that are highly enriched with sediment.

The point at which lake level stopped rising (beginning of the Nipissing Phase) and began its slow fall to its present altitude cannot be determined from the exposures at Mt. Baldy. Elsewhere along the southern shore of Lake Michigan, the lowering of lake level is represented by a 6.5-km-wide dune/beach complex of about 150 beach ridges. In the study area, however, this drop caused a vertical translation of the shoreline through the deposits of the post-Chippewa transgression. Except for the sediments described here for the core of the Toleston Beach, most of the early Nipissing Phase deposits were eroded.

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Figure 9 (Facing page). Schematic diagram illustrating the post-Chippewa transgression along the southern shore of Lake Michigan.

(A) Initial development of the Toleston Beach about 6,300 years BP.

(B) Landward migration of the barrier beach into the back-barrier lacustrine setting by nearshore erosion and overwash.

(C) Late-stage migration of the barrier beach with the shoreface translating through the onshore sedimentary prism.


