Journal of Coastal Research	7	4	1113–1124	Fort Lauderdale, Florida	Fall 1991

Sediments and Sedimentary Structures of a Barred, Nontidal Coastline, Southern Shore of Lake Michigan

G.S. Fraser[†], T.A. Thompson[†], E.P. Kvale [†], C.P. Carlson[‡], D.A. Fishbaugh[†], B.L. Gruver[‡], J. Holbrook[‡], S. Kairo[‡], C.S. Kohler[†], A.E. Malone[‡], C.H. Moore[†], B. Rachmanto[‡], and L. Rhoades[‡]

[†]Indiana Geological Survey
611 N. Walnut Grove
Bloomington, IN 47405, U.S.A.

[‡]Department of Geological Sciences
Indiana University
Bloomington, IN 47405, U.S.A.

ABSTRACT

FRASER, G.S.; THOMPSON, T.A.; KVALE, E.P.; CARLSON, C.P.; FISHBAUGH, D.A.; GRUVER, B.L.; HOLBROOK, J.; KAIRO, S.; KOHLER, C.S.; MALONE, A.E.; MOORE, C.H.; RACHMANTO, B., and RHOADES, L., 1991. Sediments and sedimentary structures of a barred, nontidal coastline, southern shore of Lake Michigan. *Journal of Coastal Research,* 7(4), 1113–1124. Fort Lauderdale (Florida). ISSN 0749-0208.

A microenergy, nontidal sandy beach along the southern shore of Lake Michigan was studied in detail over a 2-day period that followed a week of storm activity. Box cores, grab samples, trenches, and topographic/bathymetric surveys were used to determine the impact of storm processes on sediment characteristics in the area. The coastal reach consisted of a backshore and foreshore separated by a low berm, a plungepoint at the base of the swash zone, and a bar-trough-rip channel system in the upper shoreface.

Bedforms in the shoreface consisted mainly of 2-D and 3-D ripples with crests oriented subparallel to shore and perpendicular to the incoming waves. Ladderback interference ripples and double-crested ripples occurred on the inshore bar in response to the interaction of incoming waves with shoreface topography. Their occurrence, along with the occurrence of flat-topped ripples and herringbone crossbeds elsewhere in Lake Michigan, reduces the usefulness of these structures in paleoenvironmental reconstructions.

Box cores revealed that granular sands occurred in subparallel lakeward-dipping plane beds landward of the plungepoint and that sediments at the plungepoint consisted of massive to poorly stratified pebbly sands. Moderately coarse-grained sands occurred in longshore-oriented small-scale trough sets, in the interbar troughs, and in lakeward-dipping trough sets in the rip channel. Bars consisted of medium- to fine-grained sands in larger-scale, landward-oriented small-scale crossbeds, and swaley crossbeds on the landward slope and the bar crest, and also contained lakeward dipping, subhorizontal plane beds and swaley crossbeds on the lakeward slope. Internal sedimentary structures bore no relationship to the bedforms that covered the shoreface during the study period and were probably the product of storm-driven processes that operated during the previous week. Although longshore bars in Lake Michigan typically migrate onshore during post-storm periods, the facies sequences observed in box cores indicate that they are not counterparts of ridges on tidally influenced foreshores.

ADDITIONAL INDEX WORDS: *Coastal sedimentary structures, depositional sequences, shoreface bedforms, storm-wave response.*

INTRODUCTION

Purpose

Studies of bedforms, sedimentary structures, and facies relationships of barred, nearshore systems are numerous and well-documented (Davis *et al.,* 1972; Reineck and Singh, 1980; Davidson-Arnott and Greenwood, 1974, 1976; Hunter *et al.,* 1979; Davidson-Arnott and Pember, 1980; Greenwood and Hale, 1980; Shipp, 1984; Short, 1984; Greenwood and Sherman, 1986). The earlier studies consisted of observations of sediment and bedform distribution during low wave energy conditions. Van Den Berg (1977), however, argues that the facies characteristics and associations observed during these studies do not occur in the rock record because sediments deposited during fair weather conditions have relatively little potential for preservation. Later studies addressed this observational bias by using box cores to

---

90152 received 24 December 1990; accepted in revision 25 March 1991.

determine the sedimentary structures preserved beneath the surface veneer of sediments deposited during low wave energy conditions.

These studies, however, did not consistently show the dominance of storm-derived products in coastal sequences. HUNTER *et al.* (1979), for example, found almost a one-to-one correspondence between surface bedforms and internal sedimentary structures on the high energy coast of southern Oregon. On the other hand, storm and fair-weather products were interbedded in the deposits of barred beaches in wave climates of intermediate intensity in Kouchibouguac Bay (DAVIDSON-ARNOTT and GREENWOOD, 1974, 1976; GREENWOOD and HALE, 1980) and on the Atlantic coast of Long Island (SHIPP, 1984).

The entire upper shoreface of a microenergy coast on the southwestern shore of Lake Michigan was covered by oscillatory ripples during fair-weather conditions (FRASER and HESTER, 1977). However, only plane beds and large-scale planar crossbeds were preserved in upper shoreface sequences in raised beaches adjacent to the shoreline. Similarly, THOMPSON (in press) found that ripple beds were relatively uncommon in cores from upper shoreface deposits from the southern shore of Lake Michigan. However, he also found interbedded ripple beds and plane beds in bar slope sequences in a raised beach adjacent to the shoreline suggesting that both storm- and fair-weather deposits were preserved during deposition of the sequence. DAVIDSON-ARNOTT and PEMBER (1980) also found fair-weather structures beneath storm deposits in cores from a barred shoreline at the southeast end of Georgian Bay in Lake Huron.

In order to make a direct comparison between storm- and fair-weather derived products in the sediments of a microenergy shoreface, a coastal reach along the southern shore of Lake Michigan was examined in great detail over a 2-day period immediately following the passage of several large storm systems. The southern coast of Lake Michigan has historically been one of high sediment input (THOMPSON, 1989), but coastal structures have significantly reduced the sediment flux to the area. Typically during the summer, storms pass over Lake Michigan with a 7 to 10 day interval (FOX and DAVIS, 1976), and although the southern coast is at the end of a 500-km (300-mile) fetch, the lakeward slope offshore of the study area is less than 1.1 m/km (6 feet/mile) and storm waves are greatly attenuated by friction. Significant wave heights (average of the highest 33 percent of waves arriving offshore) are about 3.3 m (10 feet) when winds attain speeds of 26 to 30 knots from the north and northwest, but significant wave heights are about half that for winds from the west and northeast (WOOD and DAVIS, 1986).

This study is not intended as a definitive description of sedimentation in a barred coastal setting, but it does represent the results of an intensive investigation that gathered a large amount of data in a short period of time. In that sense it is representative of the "instantaneous" response of a barred coast to a particular set of conditions. Moreover, several of the observations made during the course of the survey do impact substantially on the use of certain sedimentary structures or sequences of structures in paleoenvironmental reconstructions.

SETTING

The survey took place along part of the coast in the Lake Street Beach Park along the southern shore of Lake Michigan at Gary, Indiana (Figure 1). This beach is the leading edge of a broad prograding beach ridge complex. The complex began to accrete northward when the water level in the Lake Michigan basin stabilized following the Holocene transgression that ended about 6000 years ago (THOMPSON, 1989).

Lake Michigan experiences a maximum tidal range of about 8 cm (0.25 feet) and the study reach can thus be considered a nontidal environment. The entire southern shore of Lake Michigan is also typically a microenergy environment. Wave amplitude along the coast is less than 0.6 m (2 feet) about 70 percent of the time and waves exceeding 2.4 m (8 feet) occur only 8 percent of the time (U.S. ARMY CORPS OF ENGINEERS, 1975). In addition, the beach is commonly ice-covered in the winter, and is thus protected from much of the intense wave activity that is associated with severe winter storms.

The shoreface of most beaches along the southern Lake Michigan coast consists of an ephemeral bar closest to shore and an inner and outer bar that are relatively stable (WEISHER and WOOD, 1983). The inshore bar systems along the southern shore of Lake Michigan are strongly affected by storm events that may flat-

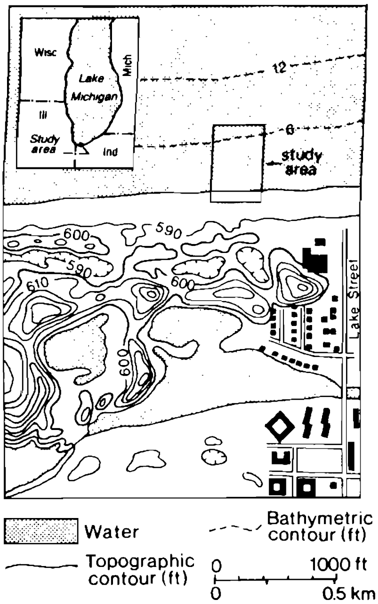

Figure 1. Location map of the study area showing its relationship to the late Holocene coastal sediments landward of the beach.

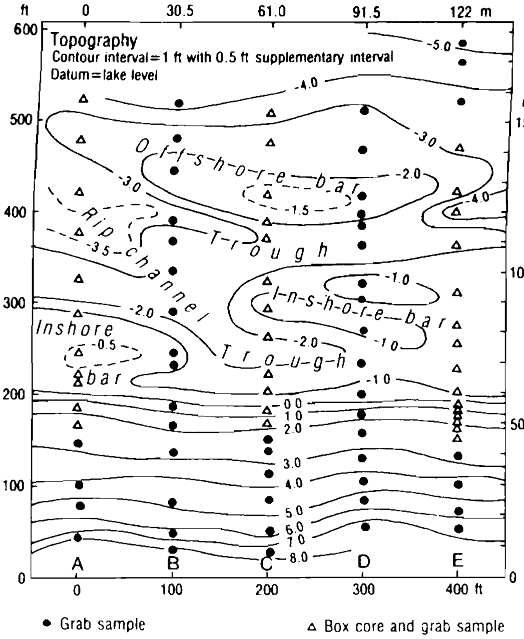

Figure 2. Topography of the study area showing the position of the shoreline at the time of the survey (0.0 elevation), the positions of the inner and outer bars/troughs and the rip channel, and the location of the transects and sampling stations. The inshore and offshore bars correspond to the ephemeral and inshore bars respectively of WEISHER and WOOD (1983).

ten, shift, or erode them entirely (WEISHER and WOOD, 1983), and because the response of the shoreface is profound and rapid, sediments deposited during and immediately after the passage of a storm have the greatest preservation potential.

The shoreface response of most Lake Michigan beaches, to even the dominant low wave-energy conditions, includes the formation of various types of small-scale roughness elements and the modification of existing elements of the macrotopography (DAVIS and FOX, 1972; DAVIS *et al.*,, 1972; FOX and DAVIS, 1976). However, even though storm-driven waves represent only a minor component of the year-round hydrographic climate of Lake Michigan coasts, they produce profound changes in coastal morphology (FOX and DAVIS, 1976) and they are the dominant control on the evolution of coastal sedimentary sequences (FRASER and HESTER, 1977).

During the week preceding the field study (September 23–29, 1988), several low pressure systems passed through the Great Lakes region. Winds of 20 to 40 knots that raised waves of 1.2 to 1.8 m (4 to 6 feet) in the open lake during this period prompted small craft advisories through much of the week. The low pressure systems had cleared the area by the day preceding the survey, but sustained moderate onshore winds were sufficient to produce a 0.3 m (1-foot) set-up along the shore even though wave amplitude through the period of study was consistently less than 0.3 m (1 foot).

METHODS

Five transects, as much as 183 m (600 feet) in length and extending at right angles to the beach, were established at 30.5 m (100-foot) intervals along the study reach (Figure 2). Sample locations were occupied along each transect at intervals ranging from 6.1 to 23 m (20 to 75 feet). At each location, bottom elevation and distance from shore were established with a transit, and grab samples were collected. Box cores were collected at a number of stations along three of the transects (Figure 2) and trenches, oriented both perpendicular and parallel to the transects, were dug in the backshore.

A part of each grab sample was sieved at 0.5 Φ intervals and mean size, coarsest 1-percentile, standard deviation (sorting), and skewness were calculated by the method of moments. Internal structures were identified in trenches in the field and from latex peels taken from the box cores.

Direction of wave propagation was measured by sighting along wave crests with a Brunton compass. Wave height and wave length were measured with a stadia rod, and wave velocity was determined by dividing the wave length by the time interval between passage of successive wave crests.

TOPOGRAPHY/BATHYMETRY

The sandy coasts of Lake Michigan are typically barred shorelines, and a considerable body of literature exists that describes the morphology, dynamics, and sediment characteristics of such coasts in both marine and lacustrine settings (see summary articles by GREENWOOD and DAVIDSON-ARNOTT, 1979; GREENWOOD, 1982). The beach in the study area at Gary is no exception. During the period of observation it contained two bar/trough couplets (the two innermost bars of WEISHER and WOOD, 1983) cut by a rip channel extending obliquely to the northwest away from the shore (Figure 2). The inshore bar was nearly attached to the beach at its western end where it was separated from the shore by a trough less than 3 m (10 feet) wide and less than 15 cm (0.5 feet) deep. This bar extended away from the beach at a slight angle so that at the eastern end of the study area the trough was about 30.5 m (100 feet) wide and 30 to 60 cm (1 to 2 feet) deep. The inshore bar was cut by a rip channel that merged with the inshore trough where it was slightly in excess of 60 cm (2 feet) deep.

The water depth over the crest of the offshore bar was slightly less than 45 cm (1.5 feet) deep (Figure 2). This bar was separated from the inshore bar by a trough (60 to 90 cm) (2 to 3 feet) deep, and it was terminated at its western end by the rip channel which was 1.1 m (3.5 feet) deep at that point. The lakeward part of the outer bar sloped uniformly lakeward to depths in excess of 1.5 m (5 feet) at the northern margin of the study area.

Landward of the shoreline the foreshore rose relatively steeply up from the plungepoint to a poorly developed berm. The backshore landward of the berm sloped more gently upward to the southern margin of the study area where the slope increased abruptly onto the foredune.

SEDIMENT TEXTURES

The coarsest sediments, both in terms of mean size and coarsest 1-percentile, occur at the plunge point (Figures 3a, 3b), and these are also the most poorly sorted sediments in the system (Figure 3c). Relatively coarse and poorly sorted sediments also occur in the longshore troughs and in the rip channel, and the finest-grained sediments occur on lakeward slope of the outer bar. The best-sorted sediments in the system occur on the backshore where the sands are medium to fine-grained in size.

In general, dune and backshore sediments were positively skewed, whereas upper shoreface sediments were negatively skewed. This distribution is in general agreement with other studies of coastal sediments which have stressed the effect of subaqueous traction transport in producing negatively skewed grain size populations (FRIEDMAN, 1961). However, sediments deposited subaqueously on part of the inner bar were positively skewed and sediments deposited subaerialy on parts of the backshore were negatively skewed. THOMPSON, *et al.*and HESTER (in press) also noted that skewness was unreliable in identifying foreshore deposits in cores taken landward of the study area. The processes responsible for this departure from previously reported studies of skewness in coastal sediments (*cf.* FOX *et al.*, 1966) is not presently understood. Nonetheless, its occurrence should prompt careful reconsideration of the traditionally held concepts regarding characteristics of grain size distributions in coastal systems.

BEDFORMS

Description and Interpretation

The entire foreshore in the swash zone between the berm and the plungepoint in the

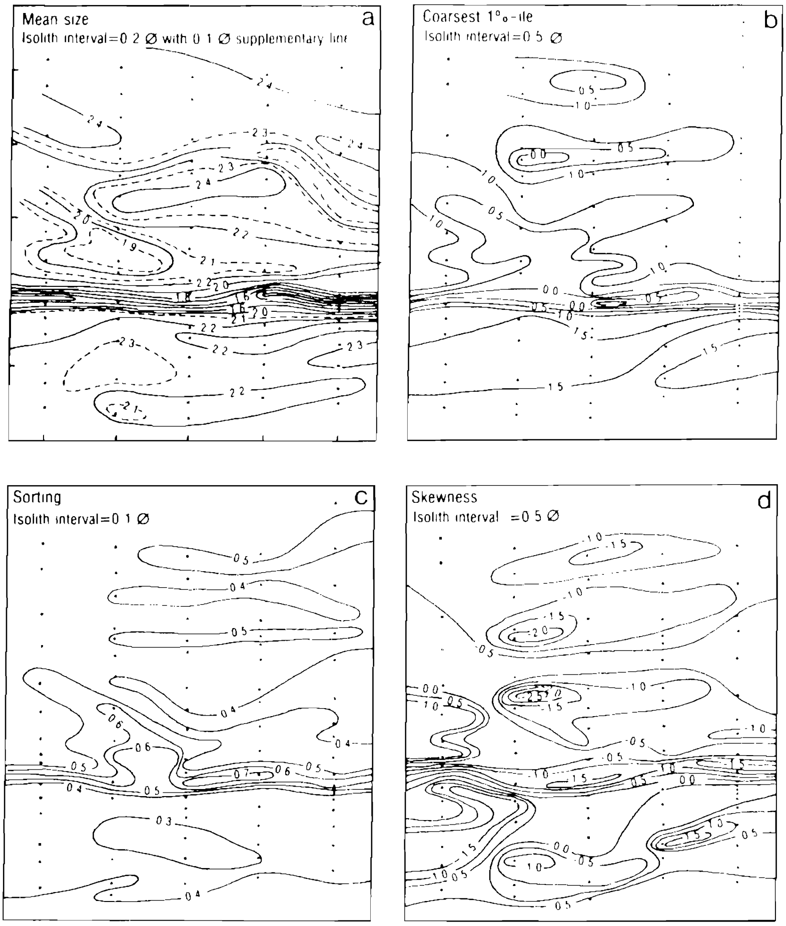

Figure 3. Maps of the study area showing textural parameters of the sediments: (a) mean size; (b) coarsest one-percentile; (c) standard deviation (sorting); (d) skewness.

study area was covered with a flat surface in response to wave runup and return. Much of the backshore between the berm and the limit of storm wave runup was also covered by a flat surface except in places where adhesion ripples and flat-topped millimeter-sized ripples occurred.

Sand transport by wind was not evident on the backshore under the low wind conditions that existed during the study period, but landward of the limit of storm wave runup, remnant wind ripples, with wavelengths of about 60 mm and amplitudes of 1 to 2 mm, occurred.

Besides the bar and trough macroforms, the active bedforms observed in the shoreface under the conditions that prevailed during the period of observation consisted mainly of long-crested 2-D ripples oriented subparallel to shore in broad ripple trains. These ripples were formed and maintained by oscillatory flow established under the prevailing wave conditions at the time of the study, and their occurrence is in agreement with other studies of barred shorelines in Lake Michigan (DAVIS, 1965; FRASER and HESTER, 1977).

Over the crest of the outer bar, however, 3-D ripples and 2-D ripples with discontinuous crests were observed. The direction of movement of these ripples was also parallel to that of wave approach, and the change in morphology apparently was in response to increasing current velocity concommitant with decreasing water depth over the crest of the bar.

DAVIDSON-ARNOTT and GREENWOOD (1976) report the occurrence of a change from 2-D ripples to plane beds over bar crests in response to increasing current velocities, and bedform stability diagrams for sand beds under oscillatory flow conditions indicate that a transition from wave-ripples to plane bed occurs with increasing wave orbital velocity. As that transition occurs, the vertical form index (length/height) of the ripples increases (ALLEN, 1984). Our observations suggest that a transitional bedform, consisting of sinuous-crested ripples or linguiod ripples may exist under conditions of low wave orbital energy. DAVIDSON-ARNOTT and PEMBER (1980) noted a similar change in ripple form on longshore bars in Georgian Bay, Lake Huron. Straight-crested ripples occurred during periods of low wave-energy, but as wave heights increased the ripples were irregular in shape with discontinuous crests. They also suggested that the irregular ripples represented a stage just prior to the formation of a plane bed under conditions of high energy asymmetric oscillatory flow.

The cause for the shape change of ripples on the shoreface bars in the study area may be a simple increase in wave orbital velocity as waves shoaled over bar crests, but we noted no consistent change in the vertical form index that should accompany such a velocity increase. On the other hand, a transition from symmetrical oscillatory flow to more unidirectional flow that would accompany the movement of a wave into shallower water over bar crests might also affect ripple shapes. CLIFTON, HUNTER, and PHILLIPS (1971) noted a change from long-crested to more short-crested forms into shallower water on a non-barred coast, and they attributed this to a shoreward increase in landward-directed current velocity. It may be that, under conditions of low wave orbital energy, the hydrodynamic environment of the lakeward flank of the offshore bar of our study area is similar to the inner offshore of CLIFTON, HUNTER, and PHILLIPS (1971) where sinusoidal waves produced asymmetric orbital velocities and onshore migrating ripples.

Ripples of a distinctly different character were observed over the crest of the inner bar. Double-crested ripples (Figure 4a) were observed on the lakeward slope of the inshore bar west of the rip channel at the point of its closest approach to the shoreline (Figure 5a), and ladderback interference ripples (Figure 4b) occurred along the crest of the inshore bar but landward of its brinkpoint (Figure 5a). Both ripple types were active under the prevailing hydraulic conditions. Vortex plumes of fine sand were observed after the passage of dominant and subordinant wave crests, and the ladderback ripples reformed within 30 minutes after parts of the bar surface were smoothed.

Wave propagation lakeward of the outer bar during the study period was nearly at right angles to the shoreline (Figure 5b). As the waves entered shallower water, the part of the wave travelling in the rip channel maintained these deeper water characteristics, but wavelength decreased, wave velocity slowed, and wave height increased for that part of the wave that moved over the outer bar causing it to refract around the bar during its approach. The angle of refraction increased as the wave moved over the inshore bar to the point where two wave crests, oriented perpendicularly to each other, were simultaneously propagated across and down the length of the bar. It was this wave pattern that formed and maintained the interference ripples.

The double-crested ripples formed only on the inshore bar where it closely approached the shoreline. Complex wave patterns at this point resulted both from refraction around the end of the bar adjacent to the rip channel as well as from reflection of the wave against the shoreline and against the point where the bar was closest to the shore (Figure 5b). Non-rhythmic patterns forced by these complex wave interactions complicated observations, but it appeared that the double-crested ripples were the product of the interaction of dominant shoreward-directed oscillatory currents caused by deep-water wave approach, and lakeward-directed oscillatory flow set up by wave reflection off the shoreline (Figure 5b). One crest was formed and maintained by the incoming waves and the second crest was a product of the reflected wave.

Alternatively, the overnight change in wave climate from 0.3 to 0.6 m (1 to 2 foot) waves of the preceding day to waves with amplitudes of less than 0.3 m (1 foot) during the time the double-crested ripples were observed may also have

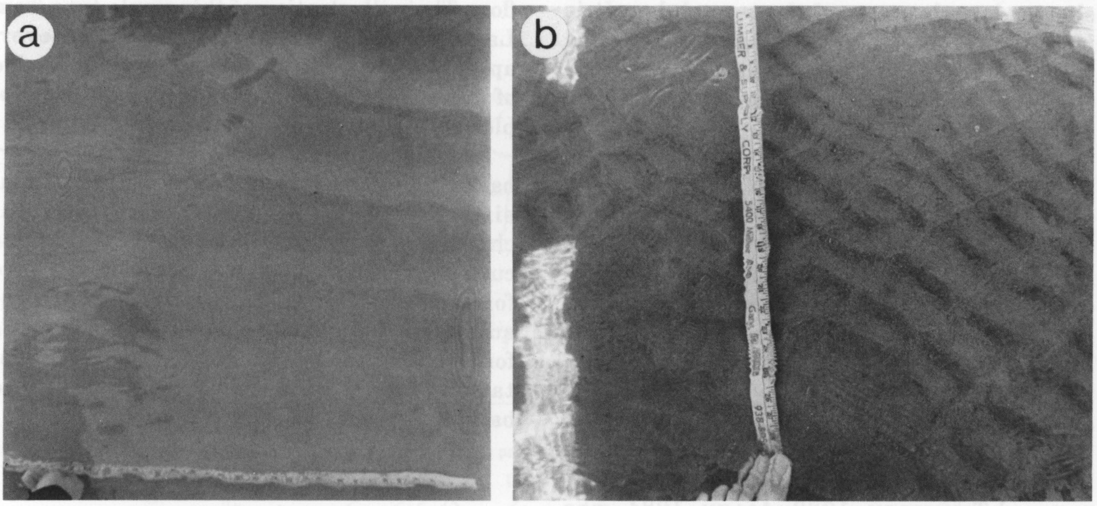

Figure 4. Photographs showing (a) ladderback interference ripples, and (b) double-crested ripples on the inner bar of the study area. Scale shown in photographs is graduated in inches.

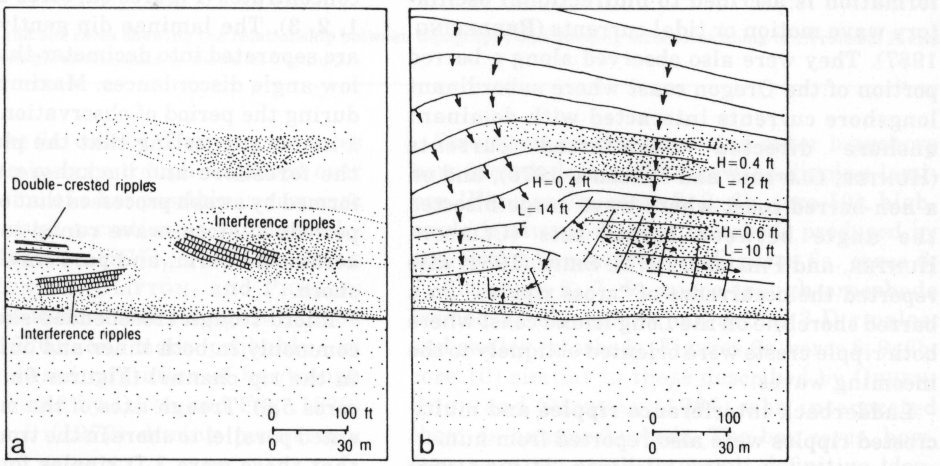

Figure 5. Maps of the study area showing the relationships between (a) topography and bedform in the study area, (b) topography and angle of wave approach. Interference ripples occurred along the crest of the inshore bar and double-crested ripples occurred on its lakeward slope.

been responsible for their formation. The more lakeward of the crests in each couplet was normally subordinant in amplitude to the landward one and it also tended to be less continuous. In addition, amplitude and continuity of the subordinant ripple crest increased into shallower water (Figure 4a), suggesting that the subordinant crest was in equilibrium with the existing wave climate and that it was climbing the stoss side of a ripple that was relict from the wave conditions of the preceding day. For this to occur, however, the lower amplitude and longer length waves of the second day would have to produce ripples with spacings the same as those produced by the larger amplitude, shorter length waves of the second day. It is more likely, therefore, that the double-crested ripples were hydrodynamically stable under the wave conditions prevailing on the second day of the study.

DISCUSSION

The common occurrence of both ladderback interference ripples and double-crested ripples on tidal flats has led to their use as indicators of deposition in intertidal environments (see REDDERING, 1987, for literature review). In fact, most sedimentology textbooks are unequivocal on this point (*e.g.* KOMAR, 1976; FRIEDMAN and SANDERS, 1978; REINECK and SINGH, 1980; BLATT, MIDDLETON and MURRAY, 1980; COLLINSON and THOMPSON, 1982; ALLEN, 1984, who ascribe their formation to late runoff directed down trough axes during ebb stage, or to modification of oscillatory action of waves during ebb stage).

Ladderback interference ripples, however, were observed in subtidal settings where their formation is ascribed to bidirectional oscillatory wave motion or tidal currents (REDDERING, 1987). They were also observed along a barred portion of the Oregon coast where subordinant longshore currents interacted with dominant onshore directed wave-forced currents (HUNTER, CLIFTON, and PHILLIPS, 1979), and on a non-barred coast where wave surge bisected the angle between ripple sets (CLIFTON, HUNTER, and PHILLIPS, 1971). SHIPP (1984) also reported the occurrence of "cross ripples" on a barred shoreline on the Long Island coast where both ripple crests were oriented obliquely to the incoming waves.

Ladderback interference ripples and multicrested ripples were also reported from numerous locations in Lake Michigan. DAVIS (1965) ascribed interference ripples to changes in the direction of wave approach caused by shifting wind patterns. He also noted that double- or triple-crested ripples compose over 10 percent of all ripple varieties. DAVIS *et al.* (1972) noted the occurrence of interference ripples in bar/trough systems along the eastern shore of Lake Michigan. They compared the ripples to similar ones that form in runnels of ridge-and-runnel systems on tidal coasts and suggested that they formed in response to the interaction of longshore currents and onshore directed oscillatory flow. Their illustration of this ripple-type from Lake Michigan (their Figure 8b), however, appears to show the ripples on the leading edge of a bar, similar to the occurrence of such ripples during the present study.

Although previous interpretations of ladderback ripples and double-crested ripples emphasize their origin in response to temporal changes in water depth, wave orientation, or current direction, visual observation of ripple formation and migration during the present survey revealed that these types of ripples formed simultaneously in response to reorientation of wave patterns by complex inshore bathymetry.

SEDIMENTARY STRUCTURES

Description

Sedimentary structures in the upper 20 cm of sediment (depth limit of box cores) landward of the plungepoint consist of planar strata delineated by layers of granules and dark mineral concentrates (Figures 6a, cores 1, 2, 3; 4b, cores 1, 2, 3). The laminae dip gently lakeward and are separated into decimeter-thick packages by low-angle discordances. Maximum wave runup during the period of observation did not exceed 1 meter suggesting that the planar strata on the foreshore and backshore were probably formed by swash processes that operated during periods of storm-wave runup to the foreshore, across the berm, and part way onto the backshore.

Micro-trough crossbedded sands occur most commonly in both inner and outer troughs and in the rip channel (Figures 6a, cores 5, 9; 4b, cores 5,8). Trough axes of the ripples were oriented parallel to shore in the troughs indicating that these were 3-D ripples formed by longshore-directed currents. Straight-crested ripples migrating onshore occupied the troughs during the survey, however, indicating that longshore currents capable of sustaining longshore ripple movement did not occur during the fair weather intervals between storms.

In most cases ripples were the only bedding structures observed in box cores from either the inner or outer trough. In several cores from the inner trough, however, ripples overlie larger scale crossbeds with landward-directed dip ori-

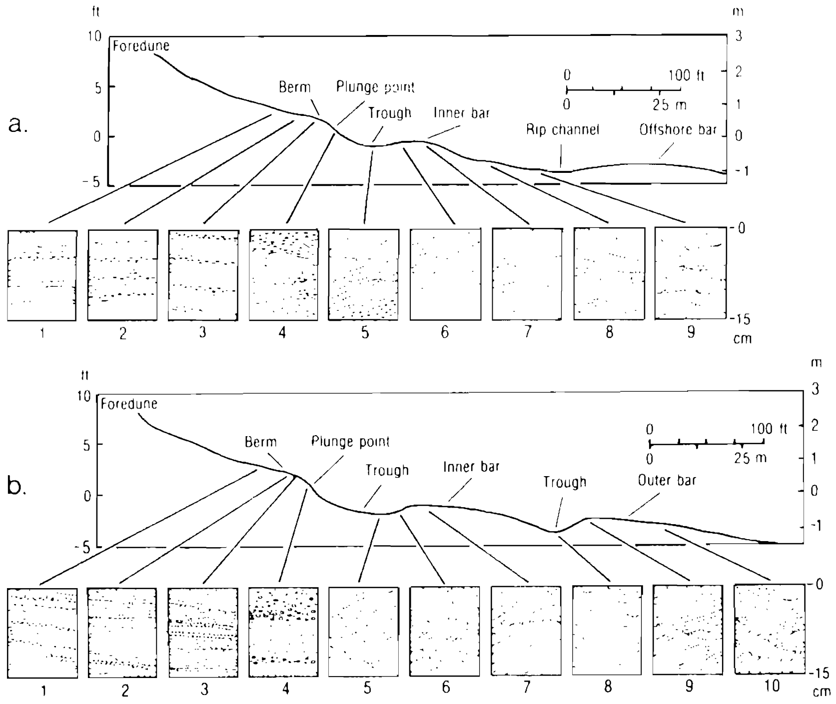

Figure 6. Profiles and box cores showing the relationship between topography and bedding structures along (a.) Transect A and (b.) Transect E. Locations of transects is shown in Figure 2.

entations (Figure 6a, core 5). These occurrences suggest that the inshore trough migrated over the former position of a bar possibly in response to long-term coastal accretion as suggested by FRASER and HESTER (1977), VAN DEN BERG (1977), and HUNTER, CLIFTON, and PHILLIPS (1979); seasonal water level changes (SAYLOR and HANDS, 1970); or, more probably, in response to landward migration of bar/trough couplets documented by DAVIS and FOX (1972) and DAVIS *et al.* (1972) during post-storm periods.

Deposits at the plungepoint are massive or display only crudely developed vertical textural segregation (Figures 6a, core 4; 6b, core 4). In one case, however, granular and pebbly sands with incipient bedding overlie ripple bedded granular sands (Figures 6a, cores 4), suggesting that the toe of the beach accreted over sands deposited in the inshore trough. Shoreline accretion leeward of inshore bars during post-storm periods was also noted by DAVIS and FOX (1972) from several Lake Michigan beaches.

Structures on the inner and outer longshore bars include low-angle lakeward-dipping laminae (Figures 6a, cores 8, 9; 6b, core 10), high-angle landward-dipping crossbeds produced by shoreward bar migration (Figures 6a, cores 6, 7; 6b, cores 6, 7, 9) micro-trough crossbeds formed by alongshore migrating 3-D ripples, and swaley crossbeds (Figures 6a, cores 8, 9; 6b, core 10) similar to those described by GREENWOOD and SHERMAN (1986) who interpreted them as hummocky beds. The box cores, however were too small to permit definitive identification of hummocky cross stratification.

DISCUSSION

DAVIS *et al.* (1972) postulated a similarity in processes and morphologies between ridge and runnel systems in tidal environments and bar and trough systems in Lake Michigan. Although direct observations by trenching were not made in the shorefaces they studied in Lake Michigan, DAVIS *et al.* (1972) postulated that similar sequences developed in both settings as ridges (bars) migrated shoreward and welded onto the beach. The sequence produced by such a process was postulated to consist of a coarse-grained storm layer overlain by ripples formed in the runnel (trough). The ripples should be succeeded upward by large-scale landward-dipping crossbeds of the ridge, and the sequence should be capped by low-angle, seaward (lakeward) dipping laminae of the welded beach face.

Observations elsewhere in Lake Michigan have failed to confirm the presence of such a sequence, however. The only high angle, landward-dipping crossbeds that occurred along the southwestern shore of the lake belonged to overwash fans that overlay backshore sediments, and the beach deposits consisted entirely of lakeward-dipping subhorizontal strata (FRASER and HESTER, 1977). Furthermore, in over 60 vibracores of foreshore sediments from beach ridges along the southern shore of Lake Michigan, landward dipping laminae were observed at the base of the foreshore sequence less than 5 percent of the time, and the bulk of such strata occurred in backshore sediments immediately below dune sands (THOMPSON *et al.,* 1991).

Likewise, the present survey failed to confirm the presence of the sequence postulated by DAVIS *et al.* (1972). The inshore bar was observed to migrate landward during the period of observation, and the westernmost part of the inshore bar was, in fact, nearly welded to the beach face. However, all excavations made in both the backshore and foreshore revealed a consistent sequence composed solely of subparallel, subhorizontal laminae overlying a gravel-rich storm layer. The only exception occurred where the foreshore stepped down to the plungepoint and ripple bedded sands were overlain by coarse grained sediments deposited when the plungepoint had migrated lakeward into the trough. Only at the leading edge of the inshore bar were high angle beds seen to overlie rippled beds.

Although the mechanism of shoreward migration and beach face welding of longshore bars is a commonly observed phenomena in Lake Michigan, the sequence of sedimentary structures supposedly produced by such a process is only rarely encountered. Either the process itself does not produce such a sequence because some intrinsic mechanism prevents its formation (FRASER and HESTER, 1977), or because some pervasive erosional process prevents its preservation as the inshore bar is welded to the beachface.

CONCLUSIONS

Even though micro wave energy conditions occur most commonly along the southern shore of Lake Michigan, this study has shown that the products of the dynamic processes that occur during low wave energy conditions are not represented in the sedimentary sequences evolving along this coast. Instead, the products of storm-driven processes are preserved in the subsurface. If this is true of other coastal settings care must be taken when inferences about paleohydraulic regimes are made from coastal sedimentary sequences in the rock record. It is apparent that the degree of preservation of fair-weather products in coastal sequences is not simply a matter of wave-energy level but rather is an interrelationship between wave climate and storm frequency.

This study has also shown that even the differentiation of wave- and tide-dominated regimes represented in the rock record should not casually be made. In addition to the double-crested ripples and ladderback interference ripples discussed above, flat-topped ripples and rounded ripples (DAVIS, 1965) and herringbone crossbeds formed by reversing longshore currents (FRASER and HESTER, 1977) have also been observed in Lake Michigan. The occurrence in a nontidal setting of these structures, supposedly indicative of tidally-influenced deposition, reinforces the point that paleoenvironmental reconstructions based on the occurrence of one or even several "diagnostic" sedimentary structures can lead to serious errors in interpretation.

ACKNOWLEDGMENTS

This study was funded by the U.S. Geological Survey through the NOAA Sea Grant Program (Grants 88-125, 89-134) as part of the USGS southern Lake Michigan Erosion Study. Special thanks to the Gary Parks and Recreation Department for permission to work at the Lake Street Beach. Previous versions of the manuscript have been read by Ned Bleuer, John

Comer, Denver Harper, and Jeff Williams and their comments are appreciated.

LITERATURE CITED

ALLEN, J.R.L., 1984. *Sedimentary Structures.* Their Character and Physical Basis: Developments in Sedimentology, No. 30. New York: Elsevier, 663p.

BLATT, H.B.; MIDDLETON, G.V., and MURRAY, R.C., 1980. *Origin of Sedimentary Rocks.* Englewood Cliffs, N.J.: Prentice Hall, 782p.

CLIFTON, H.E.; HUNTER, R.E., and PHILLIPS, R.L., 1971. Depositional structures and processes in the non-barred high-energy nearshore. *Journal of Sedimentary Petrology,* 41, 651–670.

COLLINSON, J.D. and THOMPSON, D.B., 1982. *Sedimentary Structures.* London: Allen and Unwin, 194p.

DAVIDSON-ARNOTT, R.G.D. and GREENWOOD, B., 1974. Bedforms and structures associated with bar topography in shallow-water wave environment, Kouchibouguac Bay, New Brunswick, Canada. *Journal of Sedimentary Petrology,* 44, 698–704.

DAVIDSON-ARNOTT, R.G.D. and GREENWOOD, B., 1976. Facies relationships on a barred coast, Kouchibouguac Bay, New Brunswick, Canada. *Society of Economic Paleontologists and Mineralogists, Special Publications No. 24,* pp. 149–168.

DAVIDSON-ARNOTT, R.G.D. and PEMBER, G.F., 1980. Morphology and sedimentology of multiple parallel bar systems, southern Georgian Bay, Ontario. *In:* MCCANN, S.B., (ed.), *The Coastline of Canada.* Geological Survey of Canada, Paper 80-10, pp. 417–428.

DAVIS, R.A., Jr., 1965. Underwater study of ripples, southeastern Lake Michigan. *Journal of Sedimentary Petrology,* 35(4), 857–866.

DAVIS, R.A., JR. and FOX, W.T., 1972. Coastal processes and nearshore sand bars. *Journal of Sedimentary Petrology,* 42(2), 401–412.

DAVIS, R.A., JR.; FOX, W.T.; HAYES, M.O., and BOOTHROYD, J.C., 1972. Comparison of ridge and runnel systems in tidal and non-tidal environments. *Journal of Sedimentary Petrology,* 42, 413–421.

FOX, W.T. and DAVIS, R.A., JR., 1976. Weather patterns and coastal processes. *In:* DAVIS, R.A., JR., and ETHINGTON, R.L., (eds.), *Beach and Nearshore Sedimentation.* Society of Economic Paleontologists and Mineralogists Special Publication 24, pp. 1–23.

FOX, W.T.; LADD, J.W., and MARTIN, M.K., 1966. A profile of the four moment measures perpendicular to a shore line, South Haven, Michigan. *Journal of Sedimentary Petrology,* 36, 1126–1130.

FRASER, G.S. and HESTER, N.C., 1977. Sediments and sedimentary structures of a beach-ridge complex, southwestern shore of Lake Michigan. *Journal of Sedimentary Petrology,* 47, 1187–1200.

FRIEDMAN, G.M., 1961. Distinction between dune, beach, and river sands from their textural characteristics. *Journal of Sedimentary Petrology,* 31, 514–529.

FRIEDMAN, G.M. and SANDERS, J.E., 1978. New York: Wiley. *Principles of Sedimentology,* 782p.

GREENWOOD, B., 1982. Bars, *In:* SCHWARTZ, M.L., (ed.), *Encyclopedia of Beaches and Coastal Environments.* Stroudsburg, PA: Dowden, Hutchinson, and Ross, pp. 135–139.

GREENWOOD, B. and DAVIDSON-ARNOTT, R.G.D., 1979. Sedimentation and equilibrium in wave-formed bars: a review and case study. *Canadian Journal of Earth Sciences,* 16, 312–332.

GREENWOOD, B. and HALE, P.B., 1980. Depth of activity, sediment flux, and morphological change in a barred nearshore environment. *In:* MCCANN, S.B., (ed.), *The Coastline of Canada.* Geological Survey of Canada Paper 80-10, pp. 89–109.

GREENWOOD, B. and SHERMAN, D.J., 1986. Hummocky cross-stratification in the surf zone: flow parameters and bedding genesis. *Sedimentology,* 33, 33–45.

HUNTER, R.E.; CLIFTON, H.E., and PHILLIPS, R.L., 1979. Depositional processes, sedimentary structures, and predicted vertical sequences in barred nearshore systems, southern Oregon coast. *Journal of Sedimentary Petrology,* 49, 711–726.

KOMAR, P.D., 1976. *Beach Processes and Sedimentation.* Englewood Cliffs, N.J.: Prentice-Hall, 429p.

REDDERING, J.S.V., 1987. Subtidal occurrence of ladderback ripples: their significance in paleoenvironmental reconstructions. *Sedimentology,* 34, 253–257.

REINECK, H.-E. and SINGH, I.B., 1980. *Depositional Sedimentary Environments.* New York: Springer-Verlag, 549p.

SAYLOR, J.H. and HANDS, E.G., 1970. Properties of longshore bars in the Great lakes. *Proceedings of the 12th Coastal Engineering Conference,* pp. 839–853.

SHIPP, R.C., 1984. Bedforms and depositional sedimentary structures of a barred nearshore system, Eastern Long Island, New York. *Marine Geology,* 60, 235–259.

SHORT, A., 1984. Beach and nearshore facies variability south-east Australia. *Marine Geology,* 60, 261–282.

THOMPSON, T.A., 1989. Anatomy of a transgression along the southeastern shore of Lake Michigan. *Journal of Coastal Research,* 5, 711–724.

THOMPSON, T.A., in press. Beach ridge development in the Indiana Dunes National Lakeshore and Indiana Dunes State Park. *Indiana Geological Survey Special Report 51.*

THOMPSON, T.A.; FRASER, G.S., and HESTER, N.C., in press. Lake-level variations in Lake Michigan: Magnitude and timing of past fluctuations. *Illinois-Indiana NOAA Sea Grant Special Report IL-IN-SR-91-2.*

U.S. ARMY CORPS OF ENGINEERS, GREAT LAKES BASIN COMMISSION, 1975. *Shore Use and Erosion.* Great Lake Basin Framework Study, North Central Division, Appendix 12, 174p.

VAN DEN BERG, J.H., 1977. Morphodynamic development and preservation of physical sedimentary structures in two prograding recent ridge and runnel beaches along the Dutch coast. *Geologic en Mijnbouw,* 56, 185–202.

WEISHER, L.L. and WOOD, W.L., 1983. An evaluation of offshore and beach changes on a tideless coast. *Journal of Sedimentary Petrology,* 53, 847–858.

WOOD, W.L. and DAVIS, S.E., 1986. *Indiana Dunes National Lakeshore Situation Report.* Great Lakes Coastal Research Laboratory, Purdue University, West Lafayette, Indiana, 205p.

□ RÉSUMÉ □

Pendant deux jours, a la suite d'une semaine de tempête, on a étudié une plage sableuse de régime non tidal située sur le lac Michigan. On a réalisé des carottages, des trappes à sable, des tranchées et des campagnes bathymétriques et topographiques pour déterminer l'impact des processus de tempête sur les caractères sédimentaires de cette zone. Le système littoral comprend une arrière plage et une avant plage séparés par une berme basse, une rupture de pente à la base de la zone de déferlement et un systéme de chenaux à crêtes et sillons et de refente sur le haut de plage. Les formes du haut de plage sont principalement des rides à deux ou trois dimensions dont les crêtes sont orientées quasi- parallèlement à la plage et perpendiculaires aux houles. Des rides interférentes en échelle et des rides à double crête se produisent sur la barre interne, en réponse aux interaction de la houle et de la topographie du fond. Leur présence, tout le long avec celle de rides à sommet arrondi et d'interstratification en arête de poisson sur tout le lac Michigan, réduit considérablemente l'utilite de telles structures pour reconstituer le paléo-environnement. Des tubes à carotte montrent la présence de sables granulaires en lits horizontaux quasi-parallèles et plongeant vers le lac, situés en amont du point de rupture de pente. Elles montrent aussi que les sédiments en ce point sont des sables à galets, massifs ou faiblement stratifies. On a des sables modérément grossiers dans les dépressions de petite taille orientés parallèlement au rivage, dans les sillons entre les barres et dans les chenaux de refente qui plongent vers le lac. Les barres sont constituées par des sables fins dans les interstratifications à grande échelle, ou à petite échelle orientées vers la terre, et les interstratifications des dépressions dont les pentes sont orientées vers la terre ou sur la crête des barres. Elles comportent aussi des lits plans sub-horizontaux qui plongent vers le lac et des interstratifications de dépression sur la pente tournée vers le lac. Il n y a pas de lien entre les structures sédimentaires internes qui couvrent la plage au moment de la période d'étude. Elles sont probablement le produit des processus de tempête qui ont opéré durant la semaine précédente. Bien que les barres prélittorales du lac Michigan migrant vers le rivage durant les périodes de tempête, les séquences de faciès observées dans les carottes indiquent quélles ne sont pas la contrepartie de crtes des avant-plages observées sur les mers à marée.—*Catherine Bousquet-Bressolier, Laboratoire de Géomorphologie EPHE, Montrouge, France.*

□ ZUSAMMENFASSUNG □

Ein energiearmer, nicht-gezeitenbeeinflußter Sandstrand entlang des Südufers des Michigan Sees wurde über eine 2-tägige Periode, die einer Woche mit Sturmaktivitäten folgte, im Detail untersucht. Durch Gebrauch von Kernkästen, Greiferproben, Gräben und topographisch/bathymetrischen Messungen wurde die Wirkung von Sturmprozessen auf Sedimenteigenschaften in dieser Region ermittelt. Die Küste setzt sich aus "backshore" und "foreshore" zusammen, getrennt durch einen niedrigen Wall, einem Abtauchpunkt an der Basis der Spülzone und einem Barren-Ripp-Rinnenkanal-System in der oberen Brecherzone. In der Brecherzone bestanden die Schichtformen hauptsächlich aus 2-D und 3-D Rippeln mit subparallel zur Küste verlaufenden Scheiteln, und senkrecht zu den ankommenden Wellen. An küstennahen Barren erschienen leiterförmige Interferenzrippeln und Rippeln mit Doppelscheiteln als Antwort auf die Wechselwirkung von ankommenden Wellen mit der Brecherzonen-Topographie. Ihr Vorkommen zusammen mit dem Vorkommen flachkämmiger Rippeln und; Fischgrätenmuster-Diagonalschichtungen anderswo im Michigan See reduziert die Nützlichkeit dieser Strukturen für die Rekonstruktion früherer Zustände. Kernkästen zeigten, daß körnige Sande landeinwärts von dem Abtauchpunkt in subparallelen seewärts eintauchenden flachen Bänken vorkommen und daß am Abtauchpunkt Sedimente aus massiv bis schlecht geschichteten kiesigen Sanden bestehen. Mäßig grobkörnige Sande traten in küstenparallel orientierten klein-maßstäbigen Rinnen und in Gräben zwischen den Barren auf, seewärts eintauchende Gruppen von Rinnen im Rippkanal. Barren bestanden aus mittel- bis feinkörnigen Sanden in landeinwärts orientierten kleinmaßstäbigen Diagonalschichtengen und Diagonalschichtungen auf der landwärtigen Böschung und dem Barrenscheitel, und außerdem seewärts eintauchendenm,subhorizontalen flachen Bänken und Diagonalschichtungen auf der seewärtigen Böschung. Innere Sedimentstrukturen zeigten keine Beziehung zu Schichtformen, welche den Strand während der Untersuchungsperiode bedeckten and waren wahrscheinlich das Produkt von Sturmprozessen, die während der vorherigen Woche wirksam wurden Obwohl Küstenbarren während Perioden nach Stürmen in Michigan See typischerweise landwärts wandern, zeigt die in Kernkästen beobachtete Fazies-Abfolge, daß sie Keine Ebenbilder zu Kämmen eines gezeitenabhängigen Strandes sind.—*Gabriele Lischewski, Essen, Germany.*