

Dominant processes and sediment mobility on a sandy tidal flat: Martens Plate, German Wadden Sea

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Abstract

Monitoring of bedforms and depth of sediment mobility on Martens Plate in the German Wadden Sea shows that waves are more important processes than tides on a back-barrier intertidal environment subjected to tidal ranges of 3 m. The tidal flat surface is wave-dominated and produces only wave or combined-flow ripples. The depth of sediment disturbance in this area is generally less than 3 cm. At the tidal channel margins, small ebb-oriented dunes are dominant. They exhibit a depth of sediment disturbance of up to 20 cm and migrate less than one wave length during a single tidal cycle.

The areal extent of wave-dominated sedimentation is several times that of tide-dominated processes. Overall depth of disturbance is approximately equal to bedform height regardless of dominant processes or geomorphic location.

Introduction

Tidal flats are generally considered to be tide-dominated with little contribution to sediment mobility from wind-generated waves. The depth to which sediment is disturbed by physical processes during tidal cycles and the nature of the bedforms produced can be helpful in understanding the overall dynamics of tidal flat environments. This report documents a time-series investigation of the depth of disturbance and overall sediment mobility in a sandy tidal flat over one lunar tidal cycle. It also contains important implications for interpreting similar tidal flat sequences in the stratigraphic record.

The size and shape of bedforms have typically been some indication of sediment mobility (e.g. Middleton 1965; Harms 1969; Middleton & Southard 1984). Intertidal environments pose complications that do not occur in many other sedimentary

environments where flow at least approaches steady and uniform conditions. Consequently, what one observes at low tide may not reflect conditions that existed during the tidal cycle but simply the resultant after the ebb cycle. The actual nature of sediment mobility can only be approached through a consideration of the depth to which sediment is moved during the tidal exchange.

Martens Plate is a sand-dominated tidal flat located landward of Harle Inlet between the islands of Spiekeroog and Wangerooge on the East Frisian coast of the German Wadden Sea (Fig. 1). This area of the Wadden Sea is a mesotidal coast with semi-diurnal tides having spring range near 3 m and neap range of about 2.2 m. There is a modest diurnal inequality (Fig. 2).

The intertidal environment in the Wadden Sea extends for several kilometers between the diked mainland and the barrier islands. The tidal flat system in the study area occupies a location typical

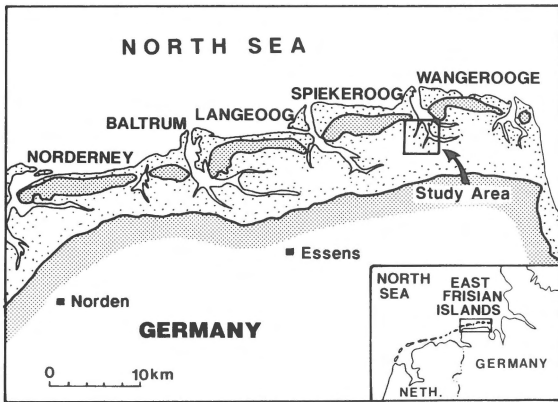


Fig. 1. Location map of the German Wadden Sea and the East Frisian Islands; the study area is situated south of the inlet between the islands of Spiekeroog and Wangerooge.

for a flood tidal delta. In fact, Ehlers (1988) has suggested a flood delta origin for the tidal flat area under consideration. However, as demonstrated by Davis & Flemming (1990), the sand body has formed as the result of seaward progradation, thus mitigating strongly against the flood delta interpretation. The adjacent Harle Inlet which separates the islands of Spiekeroog and Wangerooge, has remained essentially stable during the past few decades but the two subsidiary tidal channels immediately to the west (Fig. 3) have migrated rapidly by up to 1 km during the past few centuries of recorded history (Davis & Flemming 1990).

The surface of Martens Plate has little relief and has remained constant in its elevation, between mean and low water, at least since the 17th century

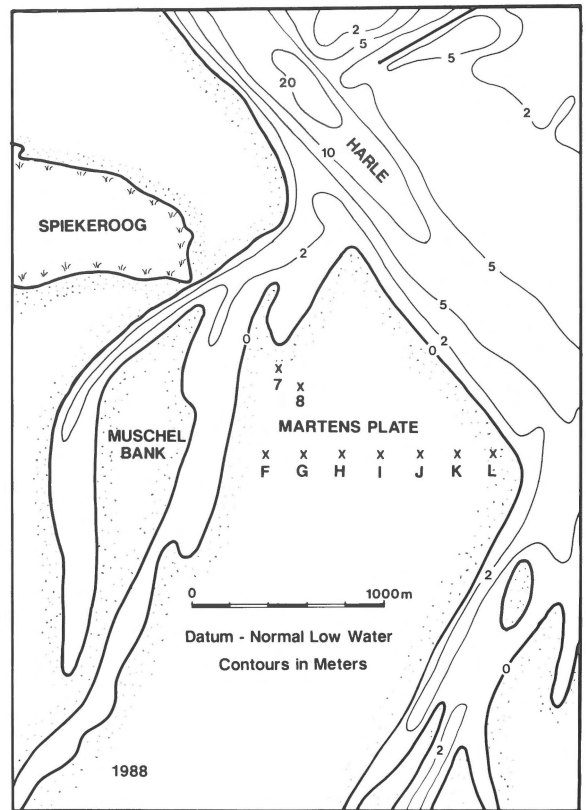


Fig. 3. Generalized map of Martens Plate and adjacent tidal channels and flats showing locations of depth of sediment disturbance observations. Locations 7 and 8 are referred to as G7 and G8 in the text and in Figs 5–7. The datum, Normal Null, is presently about 10 cm below mean sea level.

(Luck 1980). There is apparently an equilibrium elevation which has been maintained during seaward progradation since that time. At the time of the study this level was within about 30 cm in either direction of mean sea level except near the channels where lower elevations persist.

Sediment is dominantly well-sorted, fine, terrigenous sand (2.2–2.5 ϕ) with generally less than 5% shell gravel and less than 2% mud. The tidal flat is covered with small, essentially symmetrical, sinuous to discontinuous ripples. They have a mean wave length of 12–15 cm and a wave height of 1.5–2.5 cm. Bioturbation, especially by the lugworm, *Arenicola marina*, is common locally (Fig. 4). Near the channels the bedforms are dominated by asymmetrical, mostly two-dimensional, dunes with

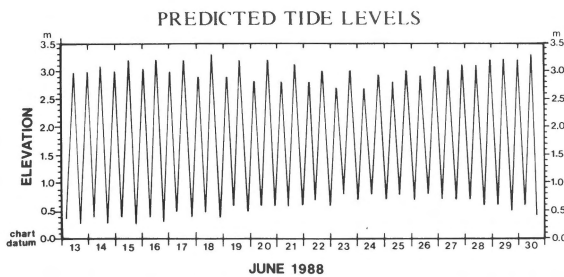


Fig. 2. Predicted tides for the study area during most of the period of observation in 1988. The tidal environment shows modest daily and lunar inequalities. (Data taken from tide tables for Norderney).

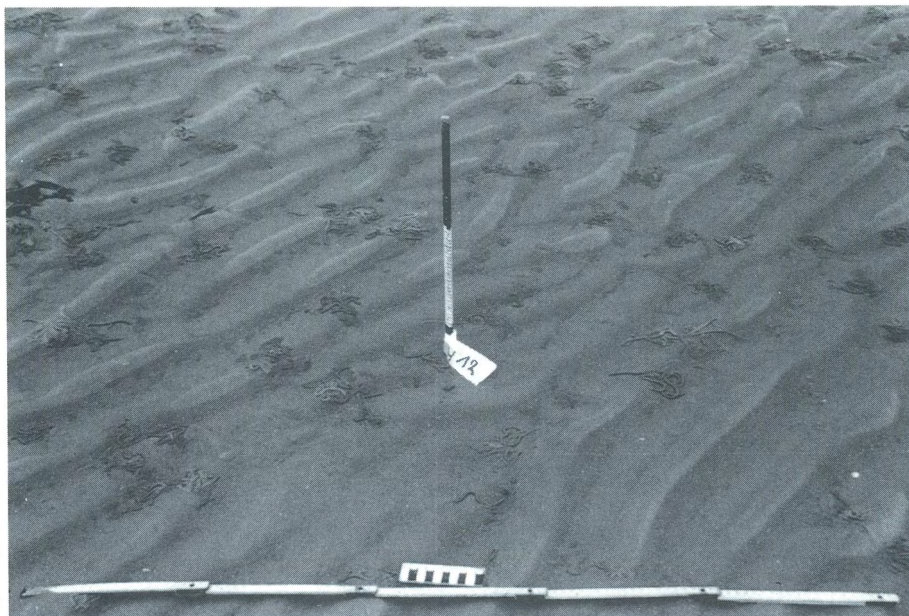


Fig. 4. Photograph of the surface of Martens Plate with the typical small ripples (wave length 12–16 cm; height 2–3 cm) and *Arenicola* burrows at location H. The crests are somewhat flattened as a consequence of ebbing tidal currents.

wave lengths of 2–4 m and wave heights of about 20–25 cm (Fig. 5).

Tidal currents over Martens Plate itself are sluggish with maximum spring velocities of about 20 cm/sec whereas maximum spring velocity in the channels is up to 130 cm/sec (Davis & Flemming 1991). Fetch may be up to several kilometers during high tide causing waves to be important factors on the tidal flat. Frequent winds of Beaufort 3 or more cause wave heights to reach 50 cm with a water depth of only about 1.0 m during neap and near 1.5 m during spring high-tide conditions.

Objectives

The objectives of this study were to monitor the scale and nature of bedforms and the depth of regular sediment mobility due to physical processes over the tidal flat environment in order to determine: 1) the relative importance of tide- and wave-generated processes on the sandy tidal flats, and 2) if there is a relationship between bedform size and depth of sediment mobility over a tidal cycle.

Methodology

The primary data base is repetitive measurements of changes along an east-west transect across the central part of Martens Plate. This transect consisted of seven locations spaced at 200 m intervals. Two channel-margin sites north of the primary transect (Fig. 3) were also investigated. The dunes at each of these channel-margin sites were monitored for their mobility, geometry and size as well as the depth of sediment mobility.

A vertical metal rod was placed at each monitoring location and surveyed for location and elevation with respect to Normal Null, the German standard datum which is currently about 10 cm below mean sea level. Using the technique described by Greenwood & Hale (1980), steel washers (3 cm diameter) were placed at the sediment surface over each of the vertical rods. The length of the rod that protruded above the sediment surface was then measured. The net change in elevation of the tidal flat surface, if any, is determined by monitoring the length of the rod above the sediment. The depth of sediment disturbance over a given time interval is determined by measuring the depth of burial of the

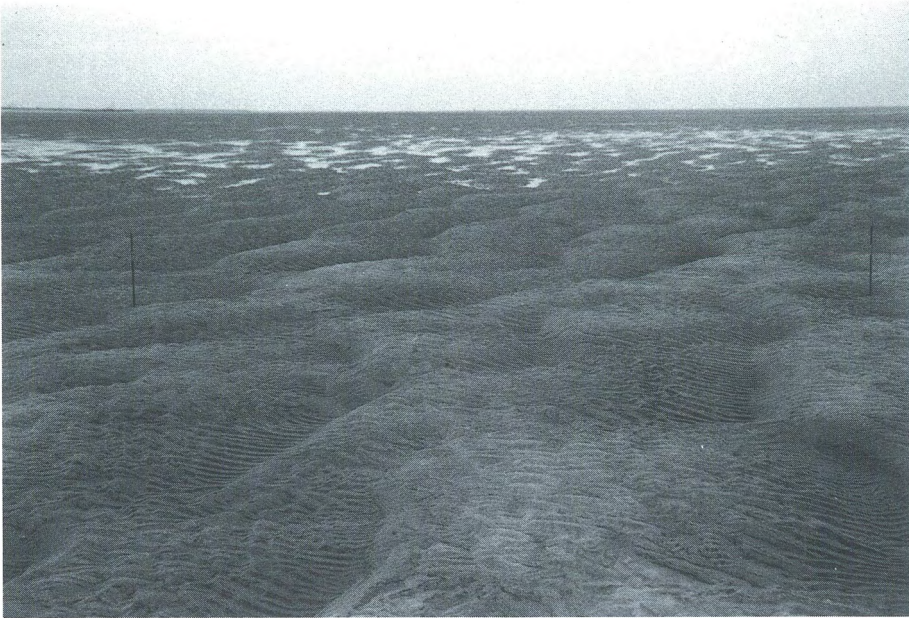


Fig. 5. Photograph of small dunes at monitoring site G8. These are 3-D bedforms with heights of about 20 cm and wave lengths of 2–4 m. Rod at the right extends 62 cm above the sediment.

washer. The washers are excavated and placed around the rod on the surface each time the measurements are made. This technique provides net change at low tide over one or more tidal cycles and does not include any differences that may exist at high tide. The absence of scouring (Figs 4, 7) as well as the continuity of the ripples at and away from the stakes and washers indicate that these items did not significantly affect local sedimentary processes.

Data acquisition

The various locations were visited and measurements taken 8 or 9 times between 15 June and 19 July, 1988. The sampling intervals range from a single tidal cycle of 12.5 hrs to a period of 20 days. Neap and spring tidal conditions (Fig. 2) were included.

Depth of sediment disturbance

Measurements of the depth of sediment mobility

over the period of study showed distinct patterns which can be related to both location and environmental conditions. Because of the distinct difference in conditions and bedforms between the tidal flat surface and the channel margin area, each will be considered separately.

Tidal Flat Surface

In general, the nature of the changes observed across the east-west transect on Martens Plate displays a marked uniformity. Five of the seven locations exhibited a depth of sediment disturbance of less than 3 cm. This depth is similar to the average height of the symmetrical, wave-generated bedforms that cover this environment. The two locations L and J (Fig. 3) showed deviations from this pattern.

In the case of location L, the cumulative depth of disturbance was 10 cm over a period of four days and 26.5 cm over the 20-day interval (Fig. 6). During low tide the bedforms at this location were similar to those across the surface of the tidal flat. Location L is adjacent to the main tidal channel

and it is subjected to strong currents causing development of small dunes. Moreover, only slight changes in the channel would modify the elevation at location L.

Location J is well away from the tidal channel but showed an anomalously high depth of sediment disturbance during the 21–24 June sampling period (Fig. 6A). The only explanation offered is that this location is higher than most of the locations and that storm conditions persisted during the period when there were successive days of winds at or above a Beaufort 4 level (Fig. 6C).

The amount of change at the various locations is not a function of the time involved except at the channel margin and perhaps at location J. Whether after a single tidal exchange or a period of several days, the depth of disturbance was limited to less than 3 cm in five of the seven transect locations. In contrast, location L at the channel margin and to a lesser extent, Location J showed substantial increases and decreases in depth of disturbance through time (Fig. 6A). The above observations indicate that at most locations depth of disturbance is wave induced and is related to bedform size. It is not time or tide dependent. Numerous box cores and vibracores taken from Martens Plate show no indications of tidalites except in demonstrable channel sequences (Davis & Flemming 1990; 1992).

Channel margin

Small dunes dominate the upper channel margin environment. Two areas of dunes were monitored in concert with the locations on the tidal flat. The sites were chosen so as to monitor well-developed dunes with crest spacing of 2–4 m and with ebb orientations at low tide. Each of the two sites consisted of two or more stakes originally placed on the crest of adjacent bedforms (Fig. 7). Both depth of disturbance and bedform migration were measured.

Measuring bedform migration is not really possible without closely spaced observations within a given tidal cycle. Some investigators have indicated bedform migration rates by observing only low-tide

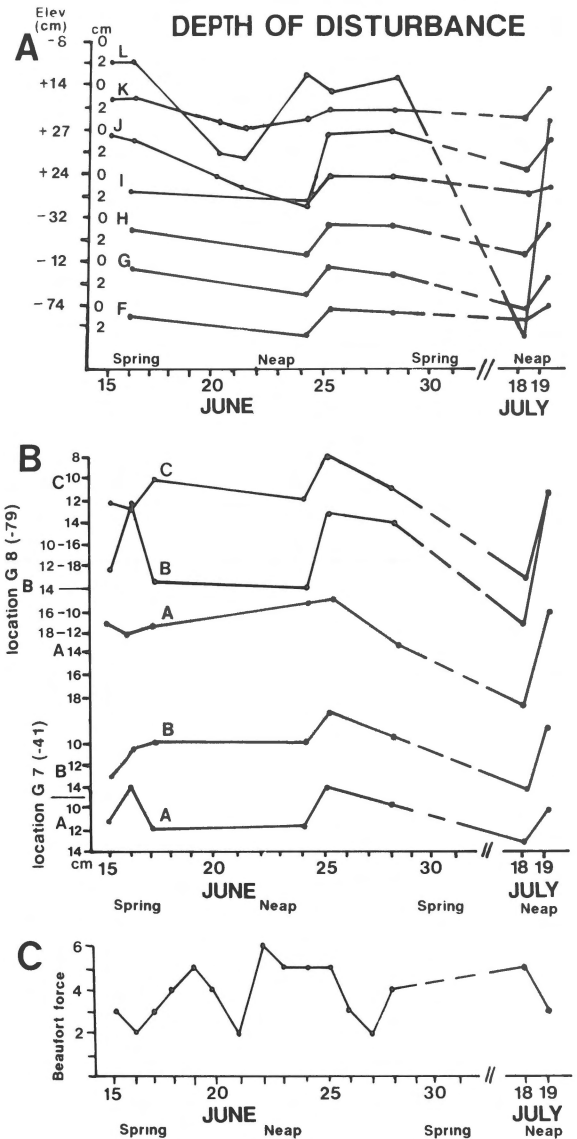


Fig. 6. Plots of the depth of sediment disturbance data over the period of the study: A) the ripple-dominated upper tidal flat; B) channel margin areas where small dunes dominate; C) wind force as recorded at Norderney.

conditions and assuming that migration is less than a wave length (e.g. Dalrymple et al. 1978, Lambiase 1980). This represents only minimum distance of migration during successive tidal cycles. Detailed multiple tidal cycle studies of this type were conducted by Allen & Friend (1976) on similar dunes in a similar tidal setting. In the case of the dunes on the channel margins of Martens Plate, the

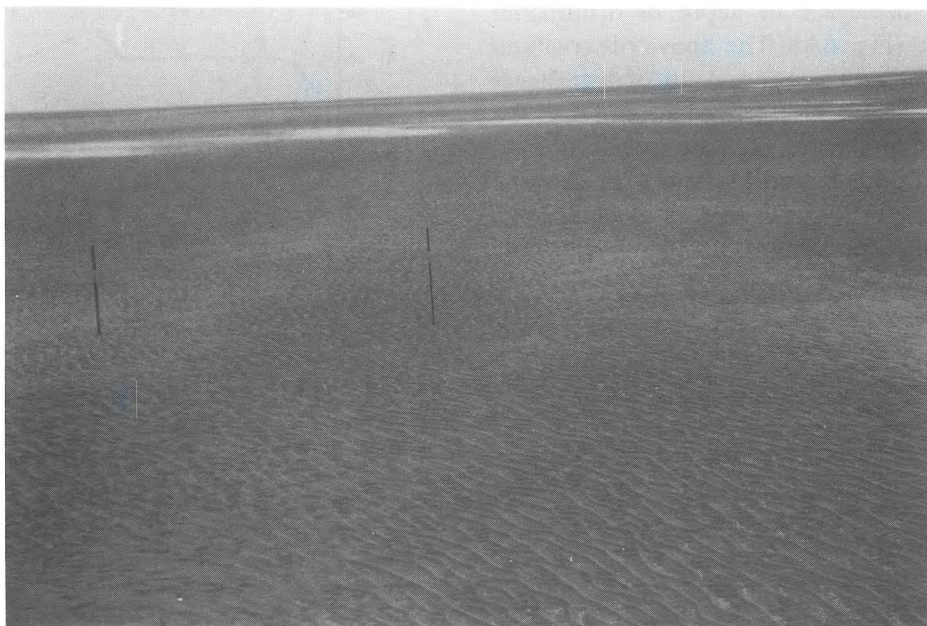
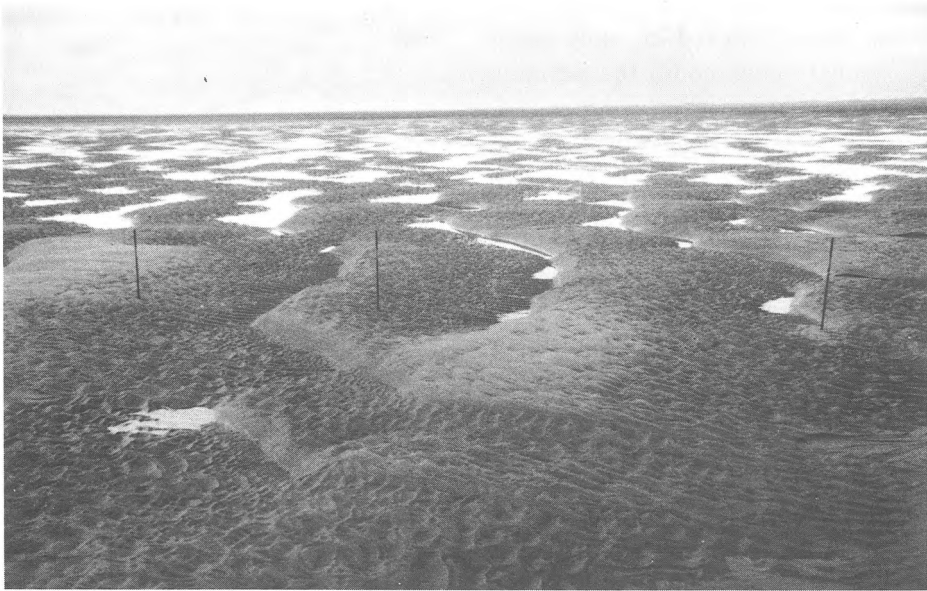


Fig. 7. Photographs of a) well-developed dunes at location G8 during spring tidal conditions and b) washed out dunes at the same location during neap tidal conditions. The two vertical rods in the left part of the photo are the same in both pictures. They are 2.62 m apart.

minimum distance of migration ranges from 0.3 up to 2.7 m for a single tidal cycle. Allen & Friend (1976) found much slower rates on the Norfolk coast of England.

The depth of sediment disturbance of these small dunes is another indication of sediment mobility along the tidal channel margins. Two sites were monitored simultaneously with the sites of the tran-

sect on the upper tidal flat (Fig. 3). The elevation at site G7 was -0.41 m (Normal Null) and site G8 was -0.79 m (Fig. 6B). In general, the depth of disturbance for each site followed similar patterns and also showed parallel changes with the upper tidal flat. The depth of disturbance over diurnal periods ranged from 6 to 14 cm. Over the extended sampling period it ranged up to 19 cm. The depth to which sediment is mobile reflects the height of the bedform at the location of the rod. The rather wide range is due to the fact that some rods were near a crest and others some distance from it. Actual bedform height observed averaged 20 cm during spring tide conditions. During neap tide conditions the dunes were washed out and approached plane bed conditions (Fig. 7b). The depth of disturbance during these neap conditions reached a maximum of 11 cm.

These data help to provide information on both depth of disturbance and bedform migration. The long-term depth of sediment disturbance value reflects passage of several bedform crests past the monitoring stake. This value is equivalent to the average height of the bedforms. The fact that observed values are without exception less than the average bedform height, indicates that the migration of the bedforms per tidal cycle is probably less than the crest to crest distance of the individual dunes. This leads to the conclusion that both depth of sediment disturbance and crest positions must be monitored on the basis of single tidal cycles if accurate information on migration rates is to be obtained.

Discussion

A time-series monitoring of bedforms and depth of disturbance on a sandy tidal flat at Martens Plate shows significant differences in bedform mobility and in dominant physical process between the tidal flat surface and the adjacent channel margin.

Observations at Martens Plate demonstrate three important aspects of tidal sedimentation: 1) depth of disturbance of sediments across the tidal flat, 2) rate of bedform migration over an individu-

al tidal cycle, and most importantly 3) dominant processes over the intertidal sand body.

Channel margin

The depth of sediment disturbance at the channel margins is directly related to bedform height with some differences over the lunar monthly tidal cycle. During spring conditions bedform height is maximum and the observed depth of disturbance more or less approaches this height which is about 20 cm. Neap tidal conditions cause a severe reduction in bedform height to about 5 cm or less. During neap tidal conditions the depth of disturbance ranged from 5 to 11 cm (Fig. 6B). Ripples showed a direct relationship between depth of disturbance and bedform height throughout the lunar cycle. In all cases ripple height is equal to or slightly less than the depth of disturbance.

Bedform migration for the small channel-margin dunes was determined from a combination of the depths of disturbance and crest positions over successive tidal cycles. Although there was considerable range in the distance of migration per tidal cycle, it seems typically less than one wavelength but may be over 2 m.

Tidal flat

The tidal flat surface is characterized by only ripple-size bedforms that are essentially symmetrical but have orientations other than what would be generated by ebbing tidal currents. These apparently combined-flow ripples are the result of wave-dominated conditions in view of their orientation and symmetrical profile. High-tide conditions provide for water depths of 1.0–1.5 m over this surface. Several kilometers of fetch are available in most directions and wave heights of 0.5 m are common thus producing wave processes that dominate weak tidal currents over the tidal flat surface.

These conditions lead to a stratigraphy that includes a combination of homogenized, structureless sand produced by the bioturbation by *Arenicola marina* and smallscale, ripple cross-stratifica-

tion. The latter reflects the domination of wave processes on the tidal flats. It is likely that the bioturbated sections were originally subjected to the same wave processes.

These data and the absence of any tidal signatures in tidal flat sediments away from the tidal creeks suggest that many tidal flat sediments may not carry a tidal signature into the stratigraphic record. These observations also are in contrast to a flood delta origin of the northern Martens Plate, as proposed by Ehlers (1988).

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