

Architecture, dynamics and preservation of marine sand waves (large dunes)

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Abstract: A synthesis of the main characteristics of sand waves is proposed, based on investigations in modern tide- and wave-dominated environments. The use of very high resolution seismics and vibrocores allows to examine the internal structures and preservation of sand waves, which may provide clues for comparison with the stratigraphic record.

Geometry of marine sand waves

The largest sand waves that we have observed are 22m high. They are located in a place where water depth is about 65m and tidal current near the floor about 1m/s. It seems that many very large sand waves reported in the literature (40m,) are actually sand banks. Among different empirical equations relating sand wave heights (H) and water depth (h), that of Allen ($H = 0.086 h^{1.19}$) matches the best our observations, but values are very scattered. In general, the measured heights of sand waves are slightly higher than that calculated from the spacing (L) using the equation of Flemming

$$H = 0.0677 L^{0.8098}$$

For a given spacing, the highest sand waves are those with symmetrical shape, as predicted by numerical models (Taylor and Dyer, .

Migration rates of large sand waves

Large (6-8 m high) sand waves in tidal seas have migration rates of 0 to 70m/year. The migration rate is increasing as an inverse function of bed form height. Three-dimensional, barchan-like sand waves have the fastest rates. They represent the ultimate stage of large bed forms resting on coarse lags in environments where current velocity 1m above the bed is more than 1m/s during spring tides. In contrast, "moribund" or fossil sand waves formed during the early post-glacial sea-level rise (or during stillstand during this overall rise) are found on wave-dominated shelves such as the Western Mediterranean Sea, the Adriatic and the Black Sea.

Reversing sand waves

Instead of migrating in one given direction, some sand waves reverse their path according to long-term changes in the net bedload transport. Recent investigations with repeated surveys demonstrate that this phenomenon is ubiquitous in estuaries , tidal inlets and straits [.

Internal structure of sand waves

The most popular conceptual model for sand wave internal structure is that of Allen . It is based on the tidal time-velocity pattern, which is characterized by a strength index and a velocity symmetry index. Six classes of internal structures are determined, from a symmetrical one, characterized by medium-scale cross-beds with opposite directions of dipping, up to a very asymmetrical one, with large scale-unidirectional cross-beds. These structures match very well the geometry of sand waves described in the stratigraphic record or the seismic structures of modern sand waves. However, the processes at the origin of the "master bedding" of modern sand waves are not those proposed by Allen (1980). First, it appears that the asymmetry of the tidal current over one single semi-diurnal cycle is not at the origin of sand wave asymmetry. Because of their large size, sand waves have a response time of several days or weeks, and the asymmetry during spring tides, or the combination of tidal currents with seasonal or episodic unidirectional flows, control their architecture. Secondly, the "master bedding" of large sand waves does not result from erosion by reversing (subordinate) currents, in contrast with what is observed in small bedforms

(megaripples). Two factors have been identified for creating such bounding surfaces. One is related to the migration of superimposed megaripples, climbing at a negative angle. The other process is particularly important on the open shelf, where storms are rounding sand waves and creating major bounding surfaces, whereas cross-beds are eventually reconstructed by tidal processes during fair-weather periods.

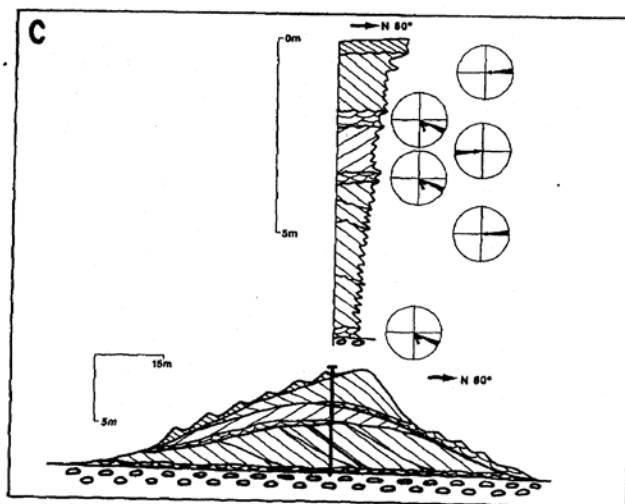
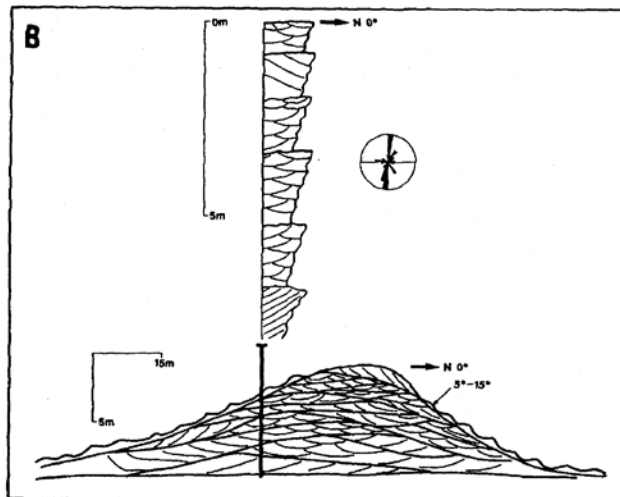
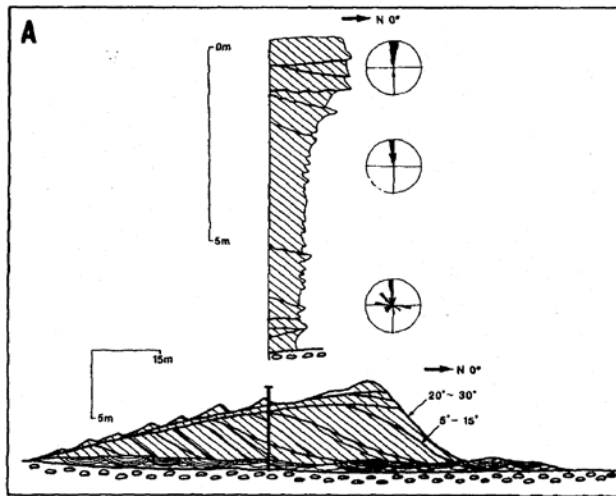


Figure 1: Scenarios for the internal structure of sand waves.

A/ Asymmetrical sand wave on the continental shelf with cosets several meter-thick. The master bedding results from erosion surface formed during storms. The cross-beds within each coset may have an angle of dip as high as 34° . Superimposed bedforms create an erosion surface at the top of the sand wave, and have dip angles in the same range as that of the large sand wave. Medium-scale cross-beds at the bottom of the sand wave have dip angles almost perpendicular to that of the sand wave, due to the secondary circulation along the lee-side.

B/ Symmetrical sand wave in a site where net sediment transport is almost balanced in flood and ebb directions (for instance along the axis of a sand ridge). Medium-scale cross-beds with divergent directions constitutes the core of the sand wave. Major bounding surfaces are related to megaripple migration.

C/ Reversing sand wave. This structure corresponds to sand waves where seasonal changes create inversion of net bedload transport. Large-scale cross beds corresponds to periods when asymmetry of the sand wave is well pronounced. Major bounding surfaces form during periods of reversal of net bedload transport, when the bed form becomes symmetrical. Because no avalanche occurs at that time, megaripple cross-beds (usually oriented parallel or oblique to the sand wave axis) may be preserved.

Erosional sand waves

Bedforms migrating with a negative angle of climb scour a wavy surface in the underlying surface . Ultimately, these bed forms have a core which has nothing to do with the process at their origin. Most of the described examples are from small-scale bed forms such as ripples, but the same process may occur at any scale. Sand waves remolding estuarine or shoreface sands are described from different settings. A similar may account for the internal structure of many sand ridges.

Figures 2: Seismic section across partly or completely buried sand waves in the Pertuis Breton (North of Ile de Ré, SW of France)

Preservation of sand waves in the Quaternary

Relatively few references are made to preserved sand waves on modern continental shelves. One major reason is that the best studied areas are accommodation-dominated environments around western Europe and North America, where the sediment is reworked during each glacio-eustatic cycle . However, in particular settings such as the Pertuis breton (SW France), we have observed early-Holocene sand waves partly burried by estuarine muds. Similarly but at larger water depths (80-90m), sand waves formed during the early transgression on the outer shelf in the Black Sea are now covered by a veneer of prodeltaic muds supplied by the Danube. The best examples of Pleistocene sand waves and sand ridges are from the East China Sea, due to high sedimentation rate and important subsidence. In addition to the modern sand ridges, up to 3 sets of sand bodies, related to Middle and Late Quaternary transgressions, have been identified in this area. These sand bodies are perfect analogs to Neogene reservoirs identified by 3D seismics in the South China Sea).



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