Uncommonly-deep giant dunes offshore the Moroccan Atlantic Coast

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ABSTRACT: A series of giant dunes (up to 38 m high) have been found offshore of the Atlantic coast of Morocco in water depths between 220 and 120 m. Their internal structure, revealed by high-resolution seismic, indicates that they could be composed of sand. The seismic profiles also display paleodunes presumably fossilized earlier during the Pleistocene. In this abstract, we discuss the setting conditions of these dunes. We also discuss the possibility of these dunes to have been eolian and then transformed in marine dunes. The question of their size and present-day depth opens multiple questions.

1 INTRODUCTION

Marine dunes are typically found on continental shelves when available sand is present and when currents are high enough to shape this type of bedforms. Some authors (e.g. Flemming, 1988) indicate that there is a logarithmic relation between spacing (wavelength) and height. This author in a synthetic article (2000) also put to the fore the existence of some relations between water depth and height. In both case, it is observed that height depends on spacing and/or water depth. Accordingly the sediment is usually coarser in larger dunes (See Mosher and Thomson, 2000). Sand dunes are mostly found in tidal environments meaning that tide is a major dynamic agent even if other processes such as storm can shape efficiently the dunes (Le Bot and Trentesaux, 2004).

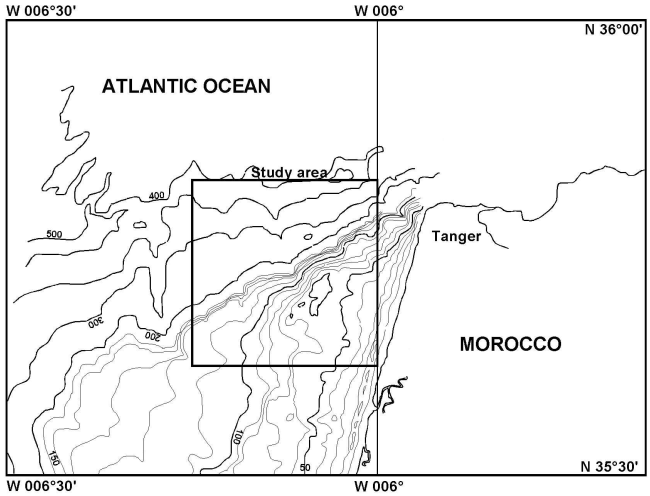

Figure 1. Bathymetric chart offshore the Northern coast of Morocco. Drawing from unpublished data from Vanney 1989.

2 GENERAL SETTINGS AND METHODS

2.1 *Study area*

The study area is located offshore the Northern coast of Morocco on the Atlantic side (Fig. 1). The shelf-break is located at a water-depth close to 120 m. The study area is characterized onshore by a high-relief mountains belonging to the Rifan belt.

2.2 *Data acquisition*

Data were acquired during the NOMADS cruise aboard the French research vessel 'Côtes de la Manche' in July and August 2007. Hundreds of kilometres of high-resolution seismic profiles were shot perpendicular to the coast as it corresponds to the most probable orientation of the geological structures on the Atlantic Moroccan continental shelf. The main purpose of the survey was to study the geological structural setting of the shelf. This is the reason a high-resolution seismic source was used instead of a very-high resolution source maybe more adapted to the objective of looking the bedding of large dunes. The source was a SIG 1 kHz sparker shot with an interval of 0.5 s. The data were digitally acquired using the Delph2 system that incorporates a dGPS signal. The ship speed was about 5 knots allowing a horizontal shooting interval of about 1.3 m.

During the survey, when sailing offshore the harbour of Tangier, a series of dunes were observed on a profile perpendicular to the shore. This observation prompted us to perform a few other seismic profiles parallel to this first one. In total, about 200 km of seismic profile were shot in the area among them 20 km display large bedforms in a limited domain between 120 and 220 m water depth. The data have been digitally recorded, weakly treated (band pass filter) and geographically organised using the Kingdom Suite software.

3 RESULTS

3.1 *Superficial dunes*

Four parallel seismic profiles clearly display sand dunes shaping the sea floor. The dunes have an asymmetric shape, the lee side facing shoreward. The shallowest dunes, however, display a reverse orientation of their lee side.

Their height varies between a few meters in the offshore and shoreward side of the profiles but reaches values as great as 38 metres for the highest dunes (Figure 2).

The dunes have a typical wavelength of 1 km for the greatest and much less for the small ones. The foresets that composed the architecture of the dunes present angles of about 6°. They correspond to second order discontinuities as mentioned in eolian dunes by Brookfield (1977) or by Kocurek (1991) or Mountney (2006) using different nomenclature or also by Berné et al., (1989) in subtidal sand dunes.

The connections between the different profiles spaced about 800 m apart could be hazardous. Nevertheless, using the dune parameters such as depth, height, internal structure and geographic location, it is possible to link the dunes from one profile to its neighbour. It then appears that at least 7 dunes are present in the study area, some of them having no connection from one profile to the next one. The dunes have a SW-NE 2D (Ashley, 1990) shape and seem to be more or less parallel to the isobaths. The deepest one (7 to 12 m high) is lying in more than 220 m water depth while the shallowest one is located around 115 m water depth. As far as we can follow the dune crests, they have a maximum extent of a few kilometres but due to the limited study area, it is probable that they extend further NE and SW.

3.2 *Paleodunes*

Some of the highest dunes clearly display a core made of an ancient bedform that can explain their size. This series of bedforms is buried and appear as fossil dunes (Figure 2).

This second group of dunes can be divided in different superimposed sub-units of different ages. The highest dune reaches 52 m (Figure 2) but the smallest ones generally have a height of 15 to 40 metres. Other smaller bedforms having the same external shape, but with an internal structure difficult to depict due to their size, are also present in the study area. Most of these bedforms have very similar structure than the most recent dunes. They are asymmetric with a lee side mostly facing shoreward; the wavelength is usually smaller but can reach 1 kilometre. It is more complicated to connect the dunes from one profile to the next one but it appears that they also have a 2D shape that is more or less parallel to the present-day shoreline.

4 DISCUSSION

This survey showed two units (superficial and buried paleodunes) of uncommonly deep and high dunes having similar characteristics than typical shelf dunes set in a much shallower water depth.

4.1 *Superficial dunes*

The first striking point concerning these dunes is their large height. Depending on the authors, the dune height in deep water can be correlated with water depth with a water-depth/height ratio smaller but reaching 10 (Allen, 1968) or uncorrelated (Flemming, 2000). In our case, this ratio reaches 5 that is greater than any observations except some places like the gravel dunes from the Juan de Fuca Strait (Mosher and Thomson, 2000) or Dover Strait (Le Bot and Trentesaux, 2004). The conditions are here radically different. It may be possible that at such depths, the dune height is not limited by the water depth but by the depth of the thermocline that control the displacement of internal oceanic waves. The second problem concerns the water depth. As far as it is known from the literature, if we exclude the possibility of these dunes being due to oceanic internal waves, the present-day depth is not compatible with the local oceanic conditions.

Neither superficial sediment nor any core has been sampled from the study area, and it is still difficukt to be to be sure about the sandy nature of the dunes. Even if they possess all the characteristics of sand dunes, their unusual great depth open some questions about their precise setting.

If the dunes cannot be set in present-day conditions, there is a need to change the relative water-depth of the area. The water depth can change as it changed during the Pleistocene with amplitudes as great as 120 metres. In these conditions, the deepest dunes having an amplitude of 12 m were formed in a minimum 100 m water depth. Taking into account the Pleistocene oscillations, the greatest dunes (amplitudes of 38 m) could have been set in water depths comprised between 50 and 75 m. For both dunes, the height is extremely large compared to usual water depths. One must also consider high energetic currents that are sometimes observed close to the shelf break. This has been described for example along the western border of the Celtic Sea (Reynaud et al., 2003).

When the sea-level change amplitude is not sufficient to explain the depth of the dunes, one can consider the changes in the sea-floor position that can evolve in case of uplift or subsidence. The vertical movements are usually 2 to 3 orders of magnitude slower than the glacio-eustatic Pleistocene sea-level changes. Nevertheless, Northern Morocco is a rather active region on a tectonic point of view. This region experienced the consequences of the collision between the African and the European plates that started more than 10 millions years ago (Tortonian) and has been responsible for the creation of relief on both sides of the Gibraltar Strait Piqué et al., 2007). The history of this collision evidences a succession of compressive and extension phases that were accompanied by high subsidence rates. The Gibraltar sector is supposed to have been uplifted by 15 m during the last 100 Ky (Cadet et al., 1977). Nevertheless, 40 km further south, the Rharb plain is a subsiding zone. Along the coastal plain, the subsidence rate has been evaluated to 100 m/Ma using data from Flinch (1993), but on the external shelf a maximum value of 1000 m/Ma can be proposed (Flinch and Vail, 1998). In these conditions, it seems possible to greatly modify the depth of the dunes if they are ancient enough to be subsided a greater depth. Unfortunately, the timing of this subsidence has to be combined with petrography data and dating of the sediments. That is still unachieved.

Among these hypotheses, the possibility of these dunes being ancient coastal eolian dunes could be a matter of discussion as the dune heights are usually great compared to shelf dunes and similar to what we observe. The subsidence rate has to be even greater to move these dunes from a continental setting to water depths of 220 m. Such littoral dunes are abundant along the Moroccan coast and are then lithified (Plaziat et al., 2007).

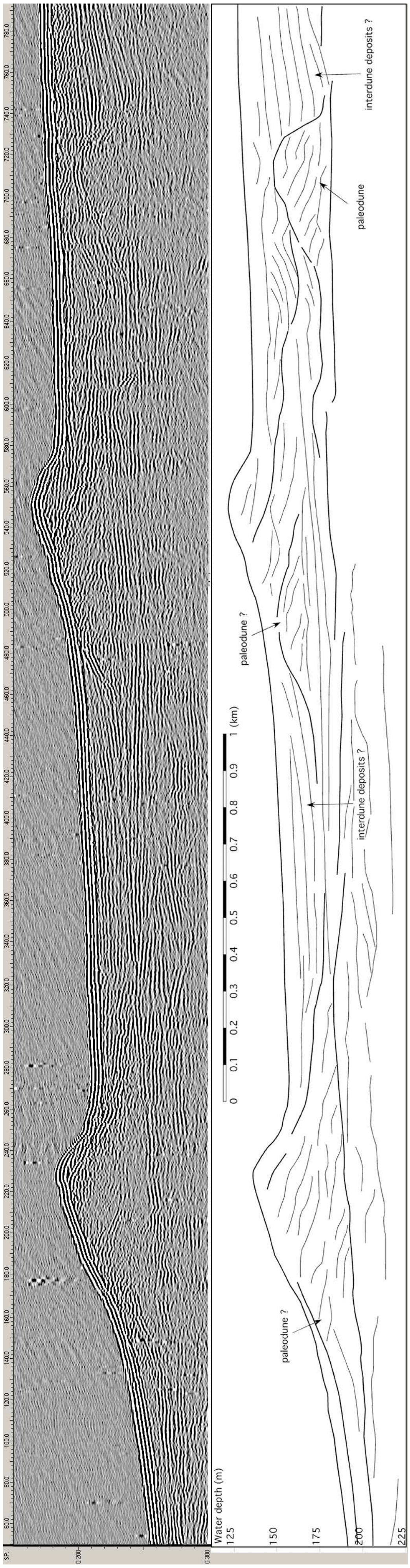

Figure 2. Profile Nr 13 and its line drawing displaying Superficial and paleodunes. First order discontinuities are outlined with bold lines. Vertical total height corresponds to 0.15 sec, i.e. 112 m in water. Notice the foresets within the dune bodies and the low-angle reflectors between the dunes maybe corresponding to interdune deposits. Superficial dune clearly used paleodunes to develop.

They are organised in a series of parallel dunes that become younger shoreward and separated by inter-dune deposits. If this possibility is addressed, then we need to envisage a series of processes that: 1) consolidated the dunes preventing them for further marine erosion, 2) moved the dunes at such a depth, and, 3) continued to shape these bedforms.

Early cementation, quite common under these latitudes, can be at the origin of the preservation of Pleistocene dunes that are now in an offshore position. This phenomenon can be observed offshore the Mediterranean Israel Coast. In this region a series of eolianite ridges composed of lithified, shore-parallel calcareous sand dunes occurs down to 50 m water depth (e.g. Eytam & Ben-Avraham, 1992 or Almagor, 1993). These ridges were resistant enough to erosion and mark Quaternary marine stillstands or regressions. Such a scenario can be kept in mind for our observations as long as we are lacking sediment dating.

4.2 *Paleodunes*

Every question that was addressed for the superficial dunes can also be discussed for the underlying dune units. In these units, some dunes reach a height of 50 m. Especially, the preservation phenomenon had to be efficient enough to fossilize such large bedforms in changing sea-level conditions. In the absence of dating, it would be too preliminary to discuss the origin of this succession. Do we need to consider that every sub-unit of the dunes is part of a motif related to oscillating sea level, as it is observed in the East China Sea (e.g. Liu et al., 2007) in quite different conditions? The question is still open.

5 PRELIMINARY CONCLUSIONS

Seismic data that were obtained offshore the Northern Atlantic Morocco display anomalously high dunes at water depths that seem incompatible with present-day conditions. At the moment, the data are too preliminary to be sure about the environment that allowed the setting and the preservation of dunes having tens of meters heights in up to 220 m water depth.

There is a crucial need of multibeam bathymetry to be done in the area to better precise the morphology of these dunes. There is also a great need to sample sediment from the dunes and from the inter-dunes. The seismic profiles also display in some places the possibility to attain the deposits that are just under the dune sediments. This could be a precious help for dating the setting of these large bedforms.

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