GRAIN-SIZE AND MORPHODYNAMICAL STATE OF THE BAY-OF-MAHDIA SHOREFACE (TUNISIA). CONTRIBUTION TO THE ASSESSMENT OF COASTAL SENSITIVITY

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Abstract. Improving our knowledge about coastlines worldwide can definitely contribute to understanding how sand coastlines with offshore bar systems operate. The study undertaken on the coastal sedimentary unit on the Bay of Mahdia where moderately active tectonic activity prevails fits into that general approach. This preliminary work presents the morphology and sedimentology of a 15 km long coastline with a sandy beach and an irregular dune ridge bordering the offshore between cape Africa and cape Dimas along the Bay of Mahdia. Morphology displays a sandy sedimentary prism composed of 3 compartments spreading from south to north. At both ends, the prism is poor in sediments along the cape promontory. In the central part, it is more regular for about 7 to 8 km, forming a 1.4 % slope leading, at -10 to -12 m, to a slightly sloping plateau with relief lines highlighting the general contour of the bay. This sedimentary slope is abruptly limited to the north by a relief alignment, located in the extension of the Moknine fault. In the central part, the prism is labeled by the existence of two offshore bars of which the innermost shows instability under the hydrodynamic regime forcing. A bathymetric sounding carried out in August 2006 registered a segmentation of the inner bar, not seen on two sets of previous comparable aerial photos. This segmentation seems to be influenced by the incidence of storms, common during the summer season. A simulated wave refraction diagram of the N to E quadrant swells shows the good relationship of the wave orthogonal deviation with the distribution of the directions of the bar sections observed. The disruption and reorganization of inner bar sections under the influence of average energy storms bear witness to the symptomatic instability of a volume of sand to be displaced that can only be modest in size. Textural analysis and the nature of sediments confirm this diagnosis. The response of sediments to the selection processes shows that grain size assemblage depends on a mixture of sedimentary types in limited numbers, characteristic of the reduction in the number of sedimentary sources. The most important type uses the material from the beach and dune as a reservoir, which is in turn under the influence of reduction processes having required erosion abatement measures. Coarser populations, mainly bioclastic, become incorporated into the fine fraction of the sand whose distribution they modify. The change is however discreet, influencing primarily the asymmetry and leading to bimodality only in rare instances. In the case of Mahdia, the sedimentary sources are therefore exclusively local, rare and in small quantities.

Key words: morphodynamics, littoral zone, grain-size analysis, Tunisia

INTRODUCTION

Sandy coastal systems were studied extensively in the last decades, resulting in a global vision expressed especially in the well-known descriptions of the sequential states of the coastal zone (Wright and Short, 1984; Masselink and Short, 1993). Particular emphasis was put on the existence of sedimentary sand bars, that are, indeed, a special feature. They contain large volumes of sand, play a major role in the nearshore sediment budget and beach variability and also provide a natural barrier to incident wave attack by dissipating wave energy (Van Rijn, 1998). Morphodynamics of sandy bars are therefore a much-studied topic (Greenwood and Davidson-Arnott, 1979; Barusseau and Saint - Guily, 1981; Ruessink *et al*., 2000; Certain, 2002). It refers to the preliminary distinction between three states of sandy coasts: dissipative, reflective or intermediate. The criteria retained, defined by Gourlay (1968), is the parameter Ω which includes a rough description of the wave regime, characterized by the breaker wave height H_b and the period T, and of the sediment grain size, defined by the fall velocity W_s.

However, there is just not enough knowledge about general coastlines worldwide to fully comprehend these systems and even fewer recent studies about the coasts of Tunisia with moderately active tectonics.

This paper will present the results of a preliminary study defining the characteristics of the hydrodynamic regime in the Mahdia region (Fig. 1) and its offshore morphology and sedimentology.

SITE DESCRIPTION

Geological setting

As the foreland of the Atlasic domain, the region of Mahdia was deeply modified by tectonics. Bedir (1988) showed that the structural development is the result of alternating (mainly NE – SW) distensional and (mainly SE – NW) compressional phases. Tectonic activity started in the late Miocene to early Pliocene and distortion continues to the present, result-

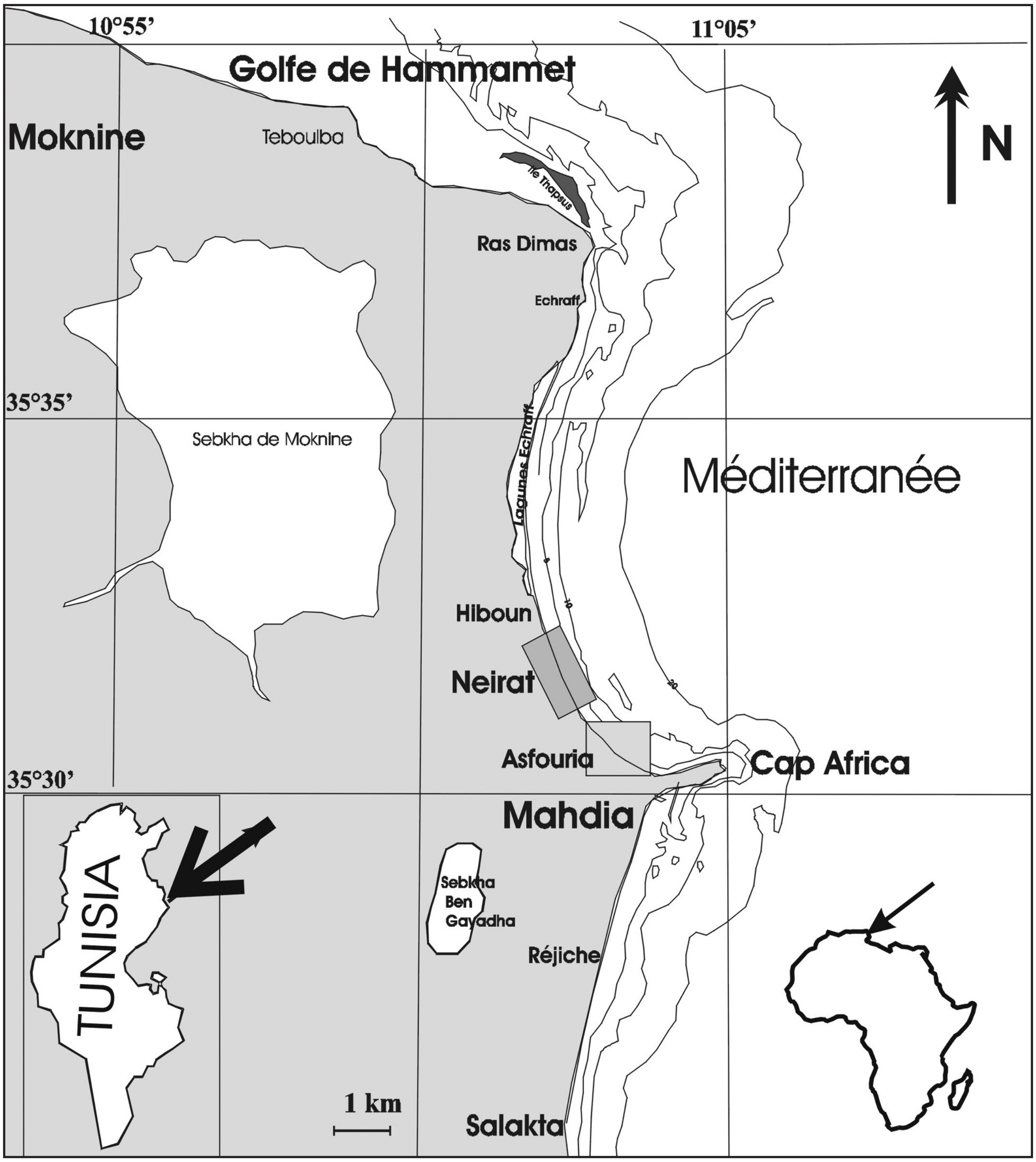

Fig. 1 Location map of the studied area

ing from rifting and east-to-west dextral movements (Martinez and Paskoff, 1984; Klett, 2001). As a consequence, the bay of Mahdia is located in a collapsed tectonic zone (Kamoun, 1981; Amari and Bedir, 1989) between two promontories, cape Africa in the south (upper Pliocene) and Ras Dimas in the north (Tyrrhenian).

In the Quaternary, the influence of neotectonics was recognized long ago. There were two successive phases: a post - Villafranchian compression and a Tyrrhenian distension. In the sector under study, a right-lateral strike slip is the most obvious mark of these events, between Moknine and cape Dimas, visible also at sea. The bay itself is a depression occupied by a vast sebkha with recent alluvial deposits. Its western border is a Tyrrhenian relief, the Rejiche barrier, several meters high (Mahmoudi, 1986; Sghaier *et al*., 2006; Paskoff and Sanlaville 1976). Very recent works (Jedaoui *et al*., 2002) indicate that these formations belong to the Eemien interglacial stage 5e.

A number of occurrences of neotectonic movements were listed by Castany (1955), Kamoun (1981) and Bedir (1988). The work of Taher (1979, in Bedir, 1988), compiling the history of earthquakes in Tunisia according to Arabic texts, points to seismicity in Mahdia. This seismicity implies old accidents. Recent activity in the western extension of the fault of Moknine, is responsible for the 1977 earthquake in this locality. The faults are also involved in the earthquake of 1978 at Dimas cape. According to Kamoun (1981) and Bedir (1988), more than fifty earthquakes occurred in the coastal zone or at sea between 1905 and 1986, three of which in the region of Mahdia in 1905, 1906 and 1978. The first two were associated with an EW fault, south of the bay of Mahdia, probably also at the origin of the fracture of the Tyrrhenian ridge of the Rejiche unit (Mahmoudi, 1986).

Geography of the coastal zone

The site under study is located on the eastern coast of Tunisia, south of the Hammamet gulf between the geographical coordinates 35°30'N - 11°03'30E (cape Africa) and 35°36'N - 11°02'25E (Cape Dimas). The latter corresponds to the north end of the vast Tyrrhenian outcrop forming cliffs, west of the plain of Mahdia. It is also the starting point of a long sedimentary sand split spreading out in the direction of the gulf of Hammamet. The bay of Mahdia is a regular coastline with a series of lagoons in its middle part, the Echraf lagoons (Fig. 1). The sandy beach, about fifteen kilometres long and 50 m to 30 metres wide, is lined with fairly well developed coastal dunes up to 4 m in height. This ridge is unevenly spread from south to north; its width varies between 30 to 50 m southwards of the bay, narrows down to just a few meters in the centre and almost disappears in the north. It consists of well-developed vegetated foredunes, invading transverse dunes interrupted by deflation channels, sand-sheets and nebkha to the north of the bay.

In the middle of the bay, based on general morphology and notwithstanding short wavelength variations, the –10 m isobath is 750 m from the beach. In the north, it moves from the coast (1400 m), while in the south it gets closer by less than 500 m (Fig. 2). Erosion of the sandy units of the emerged part of the coast (dunes and beach) justified, particularly in the south, works of restoration or defence: sand fences on sandy ridges (Bouaziz, 2002; Bouaziz *et al*., 2003; 2004) and breakwaters built between 1970 and 1990.

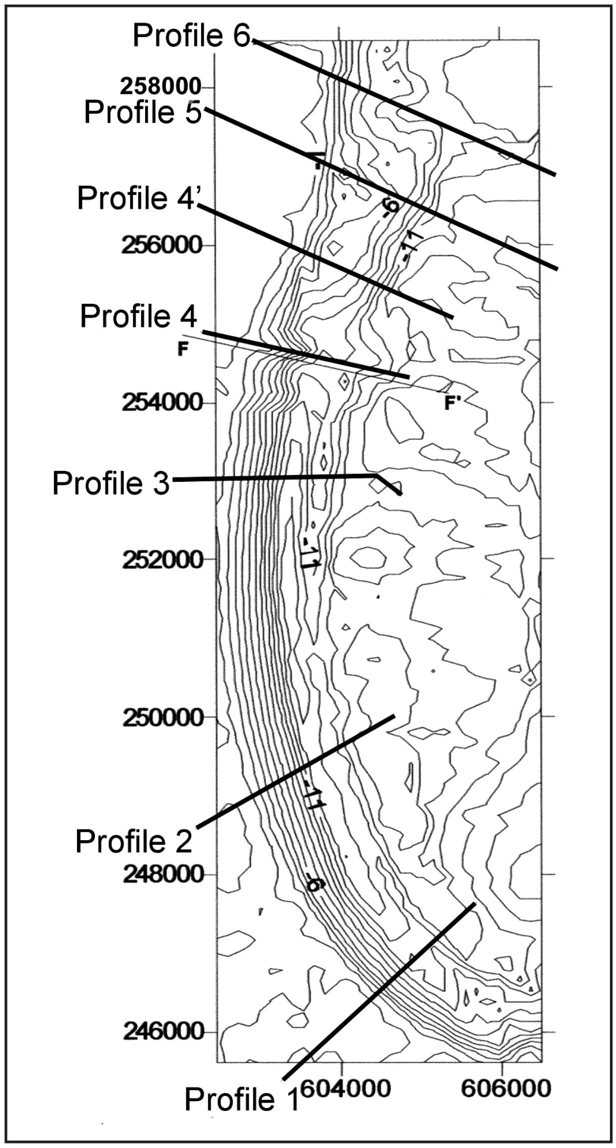

Fig. 2 Gross morphology of the studied area and location of the profiles for sediment sampling. FF': location of the Moknine fault

Dynamic characteristics

The coastal zone of Mahdia is under seasonal wind regime. Local wind data, supplied by the meteorological station of Rejiche harbour, show active directions for each season. Irrespective of zero-wind periods, the results show a large scatter of directions (Table 1). Taking into account directions of the bay shoreline, N20E in the north to N135E in the south, and in the context of littoral drift, the most active winds blow

Table 1 Occurrences of wind on the Mahdia coast

WINTER (Dec-Jan-Feb)

	N	NNE	NE	ENE	E	ESE	SE	SSE	S	Total	SSW	SW	WSW	W	WNW	NW	NNW	Total
[0-5[m/s	8,5	4,5	2,4	1,0	1,3	0,7	1,4	2,8	7,5	30,0	5,2	5,1	4,9	15,2	8,2	6,5	7,7	52,8
[5-10[m/s	4,4	1,8	0,6	0,4	0,4	0,0	0,0	0,3	1,1	9,0	0,8	1,0	1,4	0,4	0,4	2,1	2,0	8,2
Total per sector	12,8		10,7		1,7		5,2		8,6			18,5		15,6		26,9		61,0
				25,9				13,1		39,0								

SPRING (Mar-Apr-May)

	N	NNE	NE	ENE	E	ESE	SE	SSE	S	Total	SSW	SW	WSW	W	WNW	NW	NNW	Total
[0-5[m/s	7,8	6,2	4,5	2,4	6,0	4,4	4,1	6,9	5,8	48,1	2,7	1,3	2,3	5,1	1,5	2,8	4,0	19,7
[5-10[m/s	8,1	4,9	2,6	1,8	1,4	0,5	1,2	4,5	4,2	29,1	0,4	0,0	0,0	0,8	0,3	0,1	0,5	2,1
> 10 m/s	0,4	0,4	0,0	0,0	0,0	0,0	0,0	0,1	0,0	0,9	0,1	0,0	0,0	0,0	0,0	0,0	0,0	0,1
Total per sector	16,3		22,7		7,4		21,7		10,0			6,8		5,9		9,2		21,9
				51,3				26,8		78,1								

SUMMER (Jun-Jul-Aug)

	N	NNE	NE	ENE	E	ESE	SE	SSE	S	Total	SSW	SW	WSW	W	WNW	NW	NNW	Total
[0-5[m/s	6,6	6,7	5,4	5,0	10,9	6,7	2,8	5,7	8,8	58,7	4,7	2,3	1,2	2,9	0,9	2,8	2,2	17,0
[5-10[m/s	2,9	3,1	1,6	2,9	0,7	0,6	0,9	6,5	4,0	23,2	0,3	0,4	0,3	0,0	0,0	0,1	0,0	1,2
Total per sector	9,5		24,8		11,6		23,2		12,8			9,2		2,9		6,0		18,2
				53,2				28,6		81,8								

AUTUMN (Sep-Oct-Nov)

	N	NNE	NE	ENE	E	ESE	SE	SSE	S	Total	SSW	SW	WSW	W	WNW	NW	NNW	Total
[0-5[m/s	8,9	6,0	3,8	2,1	5,6	2,8	2,5	4,0	9,2	44,9	7,0	4,0	3,5	6,7	4,5	5,7	7,5	39,0
[5-10[m/s	3,2	1,8	0,6	0,3	0,3	0,1	0,3	2,9	2,6	12,2	0,4	0,7	0,6	0,0	0,4	0,7	1,0	4,0
Total per sector	12,2		14,5		5,9		12,6		11,9			16,3		6,7		19,9		43,0
				35,5				21,6		57,0								

from the east. They are the generally dominant winds (57 to 81.8% of the time), except in the winter when the offshore winds are the most frequent ones (61% of the time). In fact, considering the directions of littoral drift likely to be activated by marine winds, it is necessary, for the largest part of the bay, to distinguish between N to E winds or even ESE winds maintaining a southward drift and ESE winds in the south of the bay that generate a northward drift. The former are most frequent in all seasons, even though their dominance is only clear in spring and summer. The N to ENE quadrant is also the most active one (23.5% in winter, 39 % in spring, 34.3% in summer and 26.7% in the autumn).

The speed of the offshore winds is chiefly below 5 $m.s^{-1}$ (71% of cases); they exceed 10 m.s-1 in only 0.5% of the cases or, in average, less than 2 days per year, generally at the end of spring under N to NNE winds. Maximum storm speeds of about 40 $m.s^{-1}$ were however recorded.

The most frequent waves landing on the Tunisian coast come from the north east sector with dominating winds as well as from the north sector. They are responsible for 75% of the activity observed. However, waves from E to SSE were recorded too. This distinction also reflects seasonal distribution of winds, with a decrease in E to SSE wind speed in winter (6.4% active winds) against nearly 20 to 35% during the other seasons (Table 1).

The SE sector also presents a relatively short fetch preventing the formation of long and regular waves. The east sector, on the other hand, has a much extended fetch but the winds in this sector are not regular enough to generate strong waves. The N to NE sector has a fetch several hundred kilometres long (minimum 250 km in the direction of the coast of Sicily) resulting in the formation of a fully-developed swell.

Table 2 Medium and exceptional active waves in the bay of Mahdia (1964-2002) (LCHF, 1978; DGSAM, 2006)

Offshore direction	Ordinary storm		Exceptional storm	
	Amplitude (m)	Period (s)	Amplitude (m)	Period (s)
N	1.2	7	2.8	11
NNE	1.1	8	2.6	12
ENE	1.1	9	2.5	14
E	1.4	9	2.9	13
ESE	1.4	8	4	14
SE	1.1	9	2.8	13

Table 2 indicates wave characteristics (height and period) according to their origin, based on yearly sea states respectively exceeded by 50% and 1%. These visual data, observed on board commercial vessels come of the database of COADS (International Understanding Ocean - Atmosphere Dated Set), a North American project which has been gathering together information dating back to 1784. The available compilation for the Tunisian coast takes into account information dating from 1964.

The tide is mixed, predominantly semi diurnal and microtidal, with a tidal range lower than 0.6 m during spring water.

METHODOLOGY

Classic morphology and sedimentology methods were used in this study. The morphological survey was based on field measurements and examination of two sets of aerial pictures taken in 1968 and 1997.

In addition to beach topographic surveys by total station, a complete assessment of the bay of Mahdia based on bathymetric sounding was completed in August 2006 between the coastline and the 12-m depth line. 67 profiles perpendicular to the coastline, of an average length of 800 meters, were carried out. The density of mapped points in x, y, z is higher than 500 km^{-2}. The document was mapped in Lambert north coordinates and processed under Surfer. Meteorological conditions which prevailed before the survey indicate an east to south-east regime of wave with a few strong squalls. On the aerial pictures, particular attention was devoted to offshore bars as they appear in shallow waters along the coastline. According to the information collected from the Office of Topography and Cartography, prevailing meteorological conditions in the period preceding these shots indicated a north east wave regime.

Sediment analysis was carried out on samples of submarine sands taken between -1 and -12 m. Seven profiles were sampled (Fig. 2). A total of 42 samples underwent a grain-size analysis by sieving, using an AFNOR column of sieves. Grain size distribution was characterised by using classic indexes (average mean size Mz and/or median value Q2, sorting index σ, asymmetry index SK_I and kurtosis index K_G), according to Folk and Ward (1957). The sorting index gives an idea of the global extent of the distribution while the asymmetry and kurtosis indices quantify to some extent the relative sorting of some parts of the distribution in relation to others, becoming relative sorting indexes. Asymmetry indicates sorting of the fine half-distribution in relation to the coarse half-distribution; peakedness corresponds to the estimated relative sorting of the central part of the distribution in relation to the fine and coarse tails. Besides, modal analysis was developed to emphasize elementary populations constituting the grain-size assemblage and sedimentary types to which they belong (Barusseau, 1973). To this end, modal values were classified according to the AFNOR geometric progression. The result is a cumulative frequency curve assigning each mode to a population of modal values. Every population is considered as a sedimentary type. Therefore, any given modal value characteristic of a sediment, for a given profile at a given level, solely represents the local variety of that type.

We also tried to show how the mixture of sedimentary types recognized on the Mahdia shoreface can be at the root of the asymmetry observed. To this end, we simulated under Mathcad® software mixtures of lognormal populations for which we had control of their central value (mode), standard-deviation (sorting index) and proportions of the mixture.

Finally, to characterize the three types of materials constituting the sediment, samples were examined under the binocular magnifier. The beach rock outcrops located in the coastal zone were also examined by petrographic study on thin sections to test their potential ability to supply sand to the coastline.

RESULTS

Bar morphology

This part is based on the bathymetric survey undertaken in August 2006 (Fig. 3). The aerial photographs add to the knowledge about the offshore bars, for depths 0 to -3/-4 m (Fig. 5).

Between the two capes limiting the sedimentary unit of the bay of Mahdia, the nearshore looks like an arched slope, NW-SE oriented in the south but NNE-SSW oriented in the north, and can be seen as three different compartments. To the south, leaning on the north edge of the cape of Africa, the slope is rather regular but steep, between 1.7 and 1.9%, and leads to a serrated rocky plateau, tilted toward the NNE. A vast central zone exhibits, for over 9 km of coastline, a more gentle but still regular slope, of about 1.4%, ending at depths -10 to -12 m in a slightly tilted plateau, marked by relief underlining the general curve of the bay. Finally, to the north, the sedimentary slope narrows suddenly while the sea bed become jagged and chaotic, suggesting a change to a rocky substrate, confirmed by the observations made by divers at the time of sampling. The transition between the last two zones is marked by a relief alignment situated in the extension of the Moknine fault (Fig. 3) of which it constitutes the trace.

The rocky beds are made of more or less fine sandstone generally containing shell debris and presenting ancient facies of coastal sands. Those still undated beach-rocks, often badly consolidated, could be relatively recent. The fact that they are not covered by sandy sediments from the shoreface could indicate some sedimentary shortage, also emphasized by the emergence, in a small number of sectors, of limited outcrops of beach-rocks towards -2 m.

The sandy sedimentary prism is well developed in the central part of the bay. Calculation of parameter Ω and surf similarity index ξ (Table 3) indicates values respectively ranging from 5 to 10.4 and 0.10 to 0.21; beaches are therefore predominantly dissipative, exceptionally intermediate but still close to the dissipative regime (Short, 1999).

Table 3 Ω and surf similarity index in the south and central parts of the bay of Mahdia

Ω (Gourlay, 1964)				Irribaren number (surf similarity index)			
Ws (m/s)	Hb (m)	T (s)	Ω	L	tanβ	L0	ξ
0,03	1,5	8	6,3	South part	0,0158	100	0,13
0,03	1,5	10	5,0	South part	0,0158	156	0,16
0,03	2,5	8	10,4	South part	0,0158	100	0,10
0,03	2,5	10	8,3	South part	0,0158	156	0,12
				Central part	0,0205	100	0,17
				Central part	0,0205	156	0,21
				Central part	0,0205	100	0,13
				Central part	0,0205	156	0,16

These beaches are chiefly characterized by the presence of offshore bars between the coastline and -4 m, two of them located in the centre of the prism (Fig. 4); but only one to its north and south ends. This could be explained by the average slope, weaker in the centre than at the ends. The outer bar, about 5 km long, develops in a continuous and rather linear way at a depth of -3 to -4 m with the crest toward -2/-2.5 m. The inner bar, the only one which extends along the entire bay, is segmented in oblique sections to the shore, at variable angles. Rather NNW oriented in the south, those segments tend to become NS to NNE in the north. The angle they form (Table 4) with the coastline varies from 12 to 43° with an average of 24° in the south and 30° to the north. Their average length is of the order of 288±107 m (n=23), shorter at both ends of the bay than in the central part.

The shape of the inner bar observed on the aerial photos of 1968 and 1997 is very different in the middle of the bay. In fact, it forms a continuous ridge, straight to weakly crescentic (Fig. 5). The shape and siting of the outer bar remain unchanged.

Meteorological conditions preceding both sets of field surveys (bathymetry and aerial pictures) are not known precisely enough to correlate them with two different types of marine climate conditions. The difference recorded between the positions of the inner bar doesn't however result from the type of analysis which determined them. The density of bathymetric measurements (>500.km^{-2}, 1 point per square of 40 to 50 m in length) and the geometry of the bars (width of 50 to 200 m; length of 140 to 540 m) are such that the network of points used to prepare the field numeric model provides correct mapping which leaves no doubt as to the reality of the segmentation and orientation of the inner bar. Therefore, it follows that the inner bar forms an unstable structure where breaking and segment reorientation can occur depending on changes, albeit brief, of swell conditions.

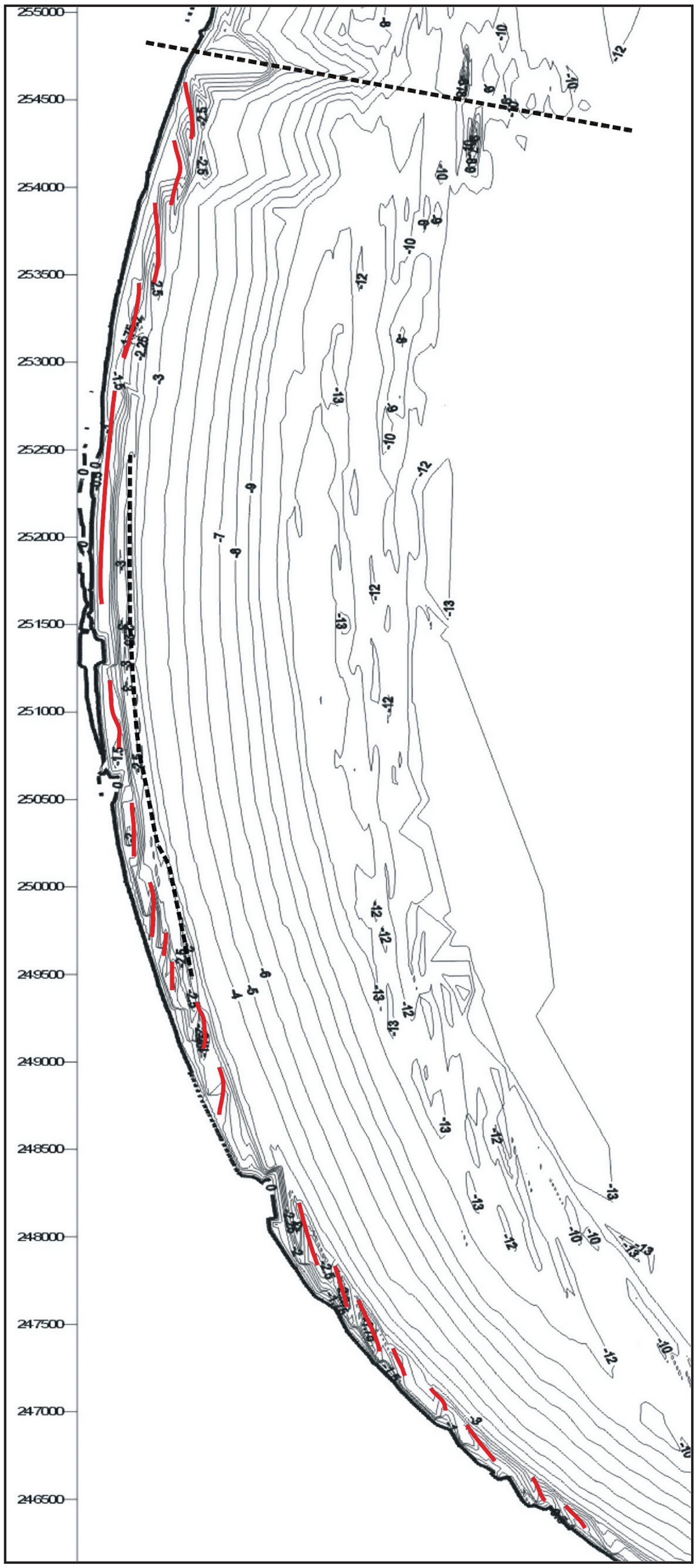

Fig. 3 Location of the bars on the nearshore zone of the Bay of Mahdia according to the bathymetric survey on Aug. 2006

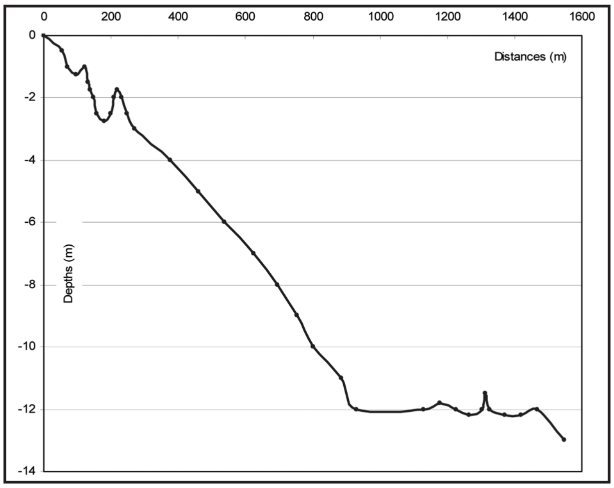

Fig. 4 Bathymetric crosshore profile in the central part of Bay of Mahdia

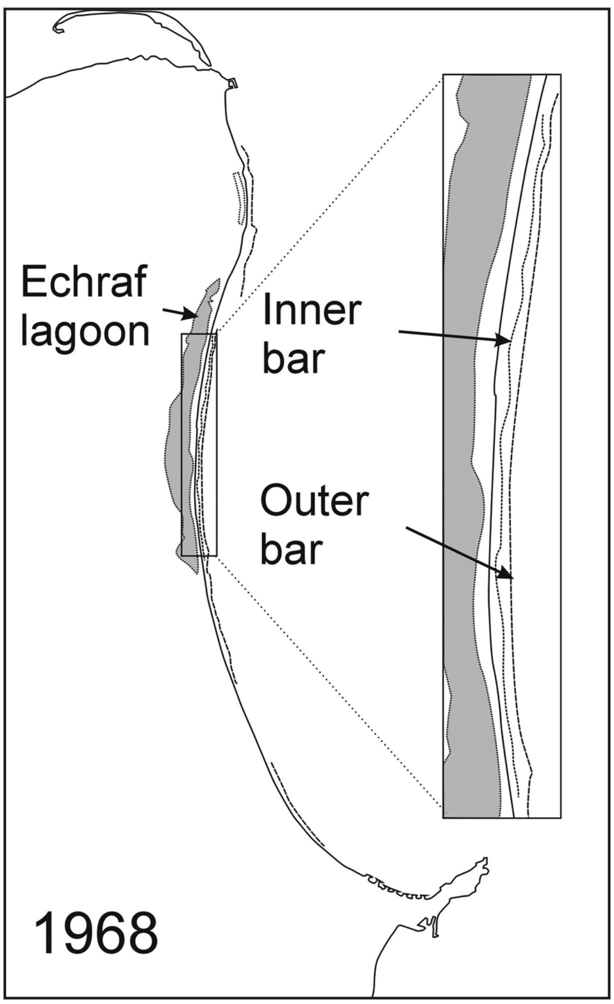

Fig. 5 Location of the bars on the nearshore zone of the Bay of Mahdia according to the air photographs. The map is a synthesis of both surveys in 1968 and 1997

Table 4 Angular deviation of segmented inner bars from the adjacent shoreline direction.

Bar direction (°) South part of the bay (from S -top- to N -bottom)	Bar length (m)
-34	143
-25	167
-34	262
-24	190
-18	238
-14	310
-12	381
-16	500
-4	190
1	286
9	333
12	238
0	381
-3	405
6	310
	Mean = 289m±100m

Central part of the bay (end)	Bar length (m)
-4	South end of a continuous bar
2	North end of a continuous bar

North part of the bay (from S -top- to N -bottom)	Bar length (m)
34	286
-2	548
-8	333
-20	262
0	190
0	214
0	167
	Mean = 285m±129m
	General Mean = 288 m±107 m

Grain size characteristics of the sands

Grain size analysis (Table 5) reveals a majority of unimodal sands (86% of the cases), rather well sorted, showing, in 60% of the cases, asymmetry of the coarse fraction of constitutive grains; leptokurtic in 62% of the samples (KG> 1.11), mesokurtic in 29% of them and platykurtic in just a few samples (9%). Some deep samples can also display bimodality.

Examination of the samples uncovered the presence of three types of constitutive material, distributed according to depth. Inshore samples (-1 to -6 m) made of a mixture of small size quartz and white bioclasts of molluscs, sea urchins and foraminifers. Sediments between -6 and -8 to -10 m, are entirely composed of small size bioclasts, like a pie made of minced tests (molluscs and foraminifers) with very little quartz. The deepest sediments are totally made of large size bioclasts (0.5 to 1 cm), of an oxidized colour, with quite a lot of intact gastropods, broken lamellibranches, sea urchin radioles and numerous foraminifers. This facies is only found in the north sector (Fig. 2), north of the Moknine fault (profiles 4, 5 and 6), and in the southernmost part, in Asfouria (profile 1). These locations provide an explanation to bimodality observed on some grain size curves. Petrographic analysis of beach rocks sampled at -2 m at cape Dimas and in Asfouria shows a strong correlation with a coarser bioclastic beach rock facies composed of molluscs and foraminifers and well-sorted quartz. The beach rocks sampled at -8m on profile 4 and -12 m on profile 1, offer a different facies with fine to medium heterometric grains of quartz, and finer and rarer bioclastic fraction.

Modal value statistical analysis (Tables 6 and 7; Fig. 6), shows that grain size distribution is controlled by the mixture of three sedimentary types: a finer type forming the majority group, (about 75% of the cases) regrouping all sediments with a mode between 95 and 220 µm (ST I with a representative value of 0.145 mm); a middle type associating the modes between 220 and 400-500 µm (ST II for which the representative modal value is 0.28 mm - approx. 10% of the cases); finally, a coarse type for modal values higher than 500 µm (ST III with a representative modal value of 0.850 mm) corresponding to 15% of the cases. Apart from obvious bimodalities, the aspect of grain size curves in the coarsest dimensions of the sediment range (above 0.5 mm) indicates that ST III type could modestly contribute to the distribution without being graphically visible on the curve.

In 4 samples showing bimodality or asymmetric unimodality, we simulated mixtures of the three Gaussian populations, each population being defined by the central value (the mode) and standard deviation (the sorting index) of the corresponding fundamental sedimentary types ST (Table 8). The test aims at obtaining empirically the proportions of the three components of the mixture likely to reproduce the characteristics of the cases under study. Attention concentrated mainly on the SKI parameter. Table 9 lists the four retained cases and the results obtained. It must be emphasized that the mix of those three fundamental populations (ST) reflects precisely the asymmetry it entails. However, it appears difficult to reconcile the three indexes; peakedness seems particularly sensitive, in this respect. This could be explained by the fact that, for each simulation, it is the value of the characteristic mode of the sedimentary type defined (Table 8) which is retained and not the local value which can slightly deviate considering the conditions surrounding the formation processes of the sand deposit where and when it accumulated.

Table 5 Grain-size indices of the sediments of Bay of Mahdia

Profile nb	Depth (m)	Q2 (mm)	σ	SKI	KG	
Profile #1	1	0.18	0.52	-0.23	1.38	
	2	0.18	0.56	-0.27	1.57	
	4	0.15	0.51	-0.18	1.23	
	6	0.14	0.48	-0.14	1.24	
	8	0.11	0.41	-0.20	1.09	
	10	0.10	0.62	-0.46	1.35	bimodal
	12	0.50	0.71	0.12	0.88	
Profile #2	1	0.13	0.27	0.08	1.10	
	2	0.14	0.34	-0.28	1.14	
	4	0.13	0.52	-0.40	2.63	bimodal
	6	0.14	0.40	-0.21	1.24	
	8	0.86	0.86	0.00	1.01	
	10	0.13	0.27	0.09	1.15	
	12	0.13	0.37	-0.03	1.17	
Profile #3	1	0.16	1.50	-0.77	1.76	bimodal
	2	0.18	0.33	0.23	1.17	
	4	0.19	0.37	0.06	1.32	
	6	0.19	0.38	-0.05	1.36	
	10	0.15	0.40	0.01	0.80	
	12	0.15	0.40	-0.03	0.80	
Profile #4	1	0.13	0.27	0.25	1.10	
	2	0.13	0.25	0.15	1.01	
	4	0.12	0.28	0.11	1.01	
	6	0.26	0.36	0.32	1.04	
	8	0.12	0.46	-0.12	1.55	
	10	0.70	0.80	0.08	1.22	
Profile #4’	1	0.15	0.39	-0.33	0.99	
	2	0.14	0.31	-0.22	1.62	
	4	0.14	0.40	-0.19	1.37	
	6	0.13	0.30	-0.04	1.33	
Profile #5	1	0.13	0.25	-0.15	1.24	
	2	0.11	0.36	-0.38	0.97	
	4	0.13	0.28	-0.23	1.11	
	6	0.12	0.20	0.13	1.03	
	8	0.78	0.56	-0.03	0.99	
	10	0.48	0.66	0.12	0.97	
Profile #6	1	0.13	0.30	0.06	1.59	
	2	0.13	0.27	0.06	1.46	
	4	0.10	0.38	-0.52	1.60	
	6	0.12	0.34	-0.02	1.36	
	8	0.10	0.36	-0.48	3.73	bimodal
	12	0.16	1.25	-0.49	0.77	bimodal

Table 6 Grain-size assemblages according to the modal analysis (The modal values are given in mm. In the complex formulae, the modal value is followed by a figure between brackets indicating the percentage of the population)

	1	2	4	6	8	10	12
Profile #1	0.16	0.16	0.16	0.14	0.115	0.095(85)+0.28(15)	0.5
Profile #2	0.125	0.13	0.13(90)+0.32(10)	0.14	0.28(10)+>1(90)	0.13	0.13
Profile #3	0.15(80)+>2(20)	0.21	0.19	0.195		0.15	0.15
Profile #4	0.13	0.13	0.125	0.24	0.125	0.3(15)+0.7(85)	
Profile #4'	0.16	0.135	0.135	0.13			
Profile #5	0.13	0.11	0.15	0.12	1.6	0.8	
Profile #6	0.13	0.13	0.095	0.12	0.095(85)+0.26(15)		0.13(55)+0.8(45)

Table 7 Statistical analysis of grain-size modal values

D (mm)	n	Σ(n)	Σ (%)
4	0		0
2	1	1	2.1
1	2	3	6.3
0.8	2	5	10.4
0.63	1	6	12.5
0.5	1	7	14.6
0.4	0	7	14.6
0.315	1	8	16.7
0.25	3	11	22.9
0.2	2	13	27.1
0.16	6	19	39.6
0.125	23	42	87.5
0.1	4	46	95.8
0.08	2	48	100

Fig. 6 Distribution of grain-size modal values

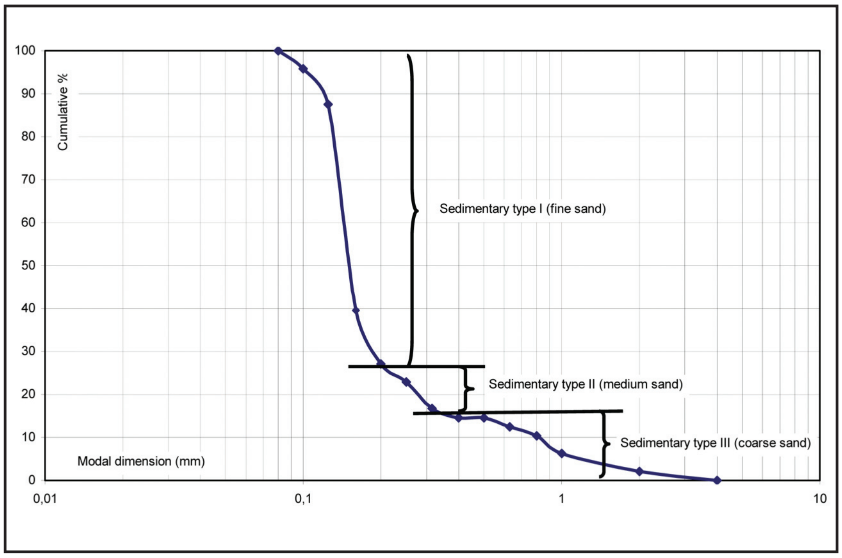

Table 8 Characteristics of the three sedimentary types (ST) resulting from the modal analysis of the grain-size distributions

Sedimentary Type	Median in Φ units (mm)	Sorting σ (Φ units)
I	2.80 (0.143)	0.20
II	1.85 (0.277)	0.25
II	0.23 (0.852)	0.50

Table 9 Simulation of ST mixing and comparison of the grain-size parameters calculated viz. grain-size parameters observed

Sample	Distribution type	Calculated indexes			Simulated indexes					
		σ	SKI	KG	TS I (%)	TS II (%)	TS III (%)	σ	SKI	KG
P5-10	Unimodal	0,36	-0,38	0,97	84,7	12,7	2,6	0,38	-0,39	1,75
P6-4	Unimodal	0,38	-0,52	1,60	80,6	16,9	2,5	0,46	-0,50	1,57
P1-10	Bimodal	0,62	-0,46	1,35	70,4	28,2	1,4	0,50	-0,48	0,80
P3-1	Bimodal	1,50	-0,77	1,76	71,4	7,2	21,4	1,08	-0,76	1,29

DISCUSSION

Several questions are raised by the morphological and grain size observations made on the barred beach of the bay of Mahdia. They are articulated around the two following lines:

- Instability of the bar shapes depending on the wave regime and the small available sedimentary pool,
- The sediment response to the sorting processes and reduction of the number of sedimentary sources.

Morphologically, the available sand volume in the nearshore zone of the bay of Mahdia is probably limited. This limitation is expressed in two different ways, in area and in volume. In area, because the sedimentary prism is only fully developed in the central part of the bay. To the south and to the north, it narrows down to the point where it tends to disappear, particularly north of the Moknine fault. Sedimentary accumulation therefore takes place where there was a tendency to subsidence during the Quaternary. Recent seismicity in the region, following documented neotectonic movements (Castany, 1955, Kamoun, 1981, Bedir, 1988, Klett, 2001, Jedaoui *et al*., 2002), shows that the tectonic component of local evolution cannot be ignored. However, it cannot be mentioned as a direct cause for the more clearly marked development of sedimentation observed in the central part. The chronological and causal correlations between neotectonic events and transportation and depositional processes are not proven or even probable. There is just spatial coexistence and time consistency of two sets of facts which must be underlined.

The second limitation is better established even though, in the absence of information on the thickness of the inshore sandy prism, it is impossible to estimate the volume of that prism. It can be argued that it is limited because the sedimentary cover is incomplete. The rocky substrate becomes visible near both capes through increased steepness of the topographic slopes and outcrops of subtidal sandstone around -8/-10 m water depth. In discontinuous sectors, similar sandstones emerge at shallower depths (Dimas cape, Echraff, Asfouria).

The comparison of inner bar directions on the bathymetric surveys and aerial photos indicate that the accumulated sand can become organized *en echelon*, if there has been first a disruption, then a reorientation. Such a change implies a limited sedimentary volume, easy to swiftly move under the hydrodynamics forcing. The nature of this forcing remains speculative at the moment for lack of sufficient data on marine meteorological conditions preceding the bathymetric and photographic surveys. All free sedimentary forms (aeolian bedforms, offshore bars) are aligned to maximize gross sediment transportation normal to their crests (Rubin and Hunter, 1987; Lancaster *et al*., 2002). Consequently, it can be reasonably assumed that the crests tend to shift in order to be normal to the ray trajectories of waves propagating toward the beach after the refraction process took place. In this context, simulations of waves propagation directions using the SMC model (González *et al*., 1999; González and Medina, 2001; Garcia, 2004; Bouaziz, unpublished report) show that NE sector waves can generate such a directional adjustment of the inner bar which is the most sensitive to even small amplitude waves common in summer when they are most active (Fig. 7). Qualitative information concerning marine meteorological conditions for the period preceding the bathymetric survey gives a dominance of an E to SE regime and indicates the occurrence of several sea storms. In the summer period, they generally come from the N to E sector, accompanying the then dominant winds (Table 1). The dispersion of bar segment directions in the bathymetric survey (Table 4) would match a refraction diagram of such waves with an approximate height of 1.2 m and a 7-second period.

We can conclude that a small volume of sand in the bars is a favourable condition for the emergence of varied types of bars. The shape of bars can then be a circumstantial state reflecting a given marine meteorological situation rather than a characteristic state of the bar itself. This criterion is not taken into account in the usual bar classifications reporting as a characteristic state the fact that a bar is linear or transverse (Wright and Short, 1984; Short, 1999). This inconsistency in the bar direction associated with an insufficient sedimentary reservoir was described in Sète (France) by Certain (2002) who also observed a rapid adjustment in the direction of the bar under the effect of a change in the direction of the waves.

Another reason for the scant volume in the sedimentary reservoir which could feed the coastal sandy prism is the poor diversity of existing sedimentary types, symptomatic of limited sources.

Three sedimentary types were identified. The ST I, extensively represented, is the essential constituent of the prism in the shallowest zones. It is also the type found on the beach and in the beach barriers (Bouaziz, unpublished report). Although it dominates down to -6 m, it is not possible to define a fining offshore gradient based on the distance to the beach and increase in depth. Beyond that depth, the grain size assemblage becomes coarser and richer in large bioclasts. Therefore, the coarse fractions in the deep zones originate from the biogenic material supplied by the epiphytic fauna found in the Posidonia meadows further offshore (ca -15 m). However, the sometimes unconsolidated coastal outcrops of beach rocks could also play a role in supplying the upper shoreface.

In the grain size assemblages presented in the samples under study, the coarseness of the sediment can increase in different ways indicating the increasing influence of the proportions of ST II and ST III. A modest influence materializes through the discreet addition of both populations blending with the coarse distribution tail of ST I; the consequence of this contribution is a change in the asymmetry of the sediment (P1-1; P1-2; P1-4; P1-6; P2-2; P5-2....). When the coarse grain contribution is more significant, the grain size distribu-

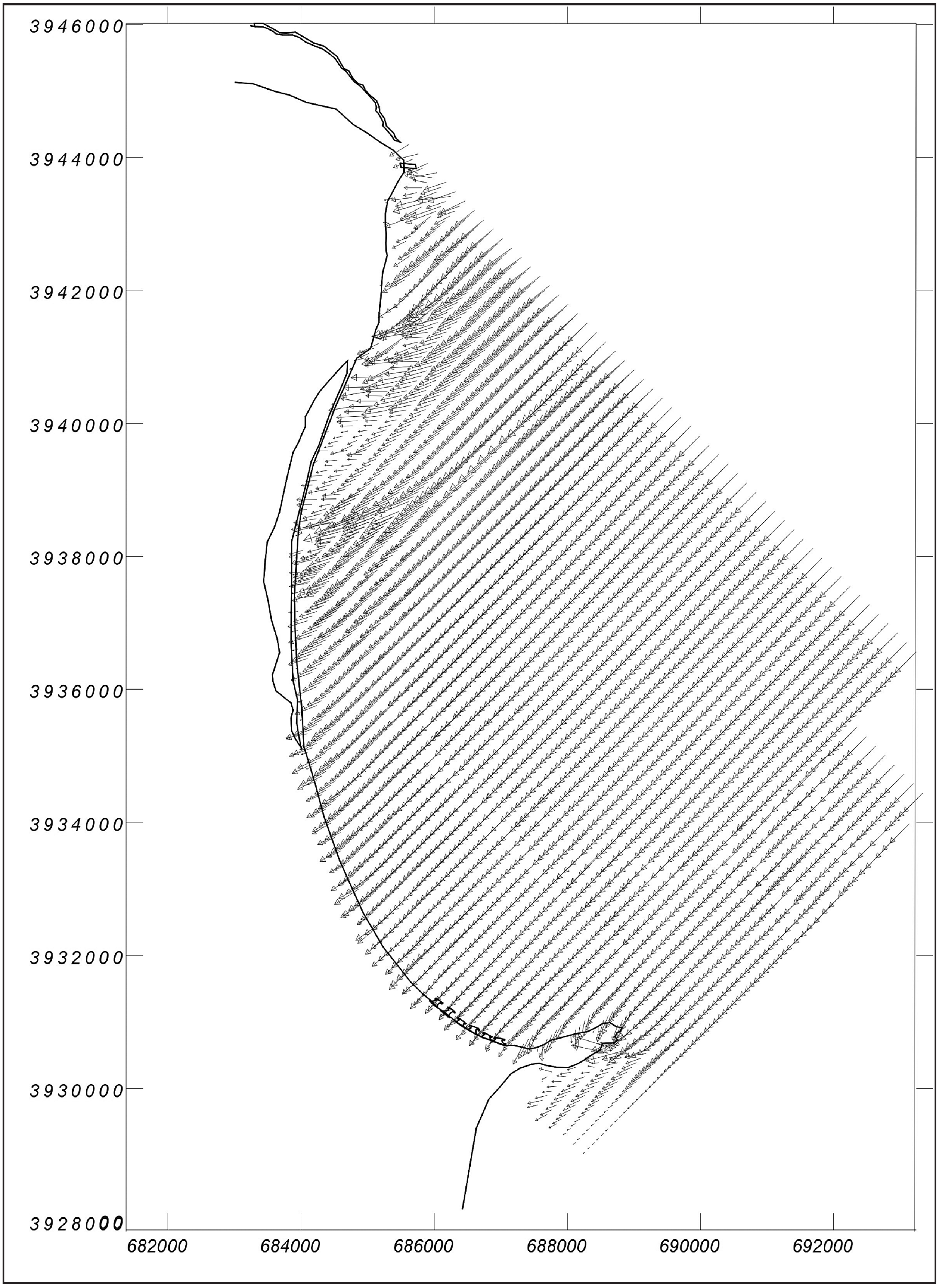

Fig. 7 Propagation diagram of NE waves (H = 1.2 m; T = 7 s) showing the good agreement of the wave rays direction after refraction and the orientation of inner bar segments (see Fig. 3).

tion clearly shows a second population coexisting with the generally dominating ST I. This situation occurs particularly near -2 m beach rock outcrops and produces bimodal distributions in P2-4 and P3-1, for instance. Finally, in rare cases, bimodality can be induced by the abundance of type ST III (P3-1) populations. The epiphytic bioclasts of the sea meadows supply this type which can even form the totality of the sediment (P1-12; P2-8; P4-10; P5-8; P5-10).

The mechanism behind these mixtures, ST I + ST II + ST III, leading to the formation of a negatively asymmetric fine unimodal sediment, like P5-10 or P6-4, or of a type P1-10 and P3-1 bimodal sediment, is illustrated in Fig. 8. From a unimodal population (mode = 2.8Φ; σ=0.2Φ), the simultaneous addition of ST II and ST III in increasing proportions to the ST I dominant sediment type, first increases the asymmetry of the sediment which apparently remains unimodal. The negative skewness indicates the intermixing with a coarser sediment fraction, as also observed by Bartholomä and Flemming (2005). It then triggers off the graphic image of bimodality. Hence, asymmetry and bimodality are the two facets of one and the same phenomenon, the blending into a dominant grain size population of normally distributed stocks.

In the framework of this approach, the dimensional structure of the grain size assemblage is interpreted as a mixture of stocks, the origin of which cannot be found in their transport mode, contrary to Visher or Passega's idea, but in local sources. In this case, local sources are scarce and in small quantities. ST I is connected to the reservoir constituted by beach and dune which both suffer from gradual depletion discernible in the erosion which justifies the adopted protection measures (breakwater and sand fences). The case of the two coarse types (ST II and ST III) is slightly more complex. Two potential sources were identified: on one hand, a limited pool of consolidated sandstone at -2 m and a large reservoir towards -10/-12 m, and, on the other hand, the fragments from the epiphytic fauna bound to the Posidonia meadow located around -15 m. In both cases, their inclusion in the sediment is subject to the dynamic conditions of the reworking, difficult in the case of consolidated materials and inevitably limited as depth increases.

CONCLUSION

The results of the preliminary survey of the offshore hydrodynamic regime, morphology and sedimentology, illustrate the manner in which the sedimentary response to the sorting processes and reduction in the number of sedimentary sources evidence the limited sediment availability and explain the instability of offshore bar shapes according to the wave regime.

The shortage of available sand is perceptible morphologically, in extent as well as in volume. The sedimentary prism is only fully developed in the central part of the bay where a sandy depocenter reflects the subsidence observed during all the whole Quaternary era and in particular following the

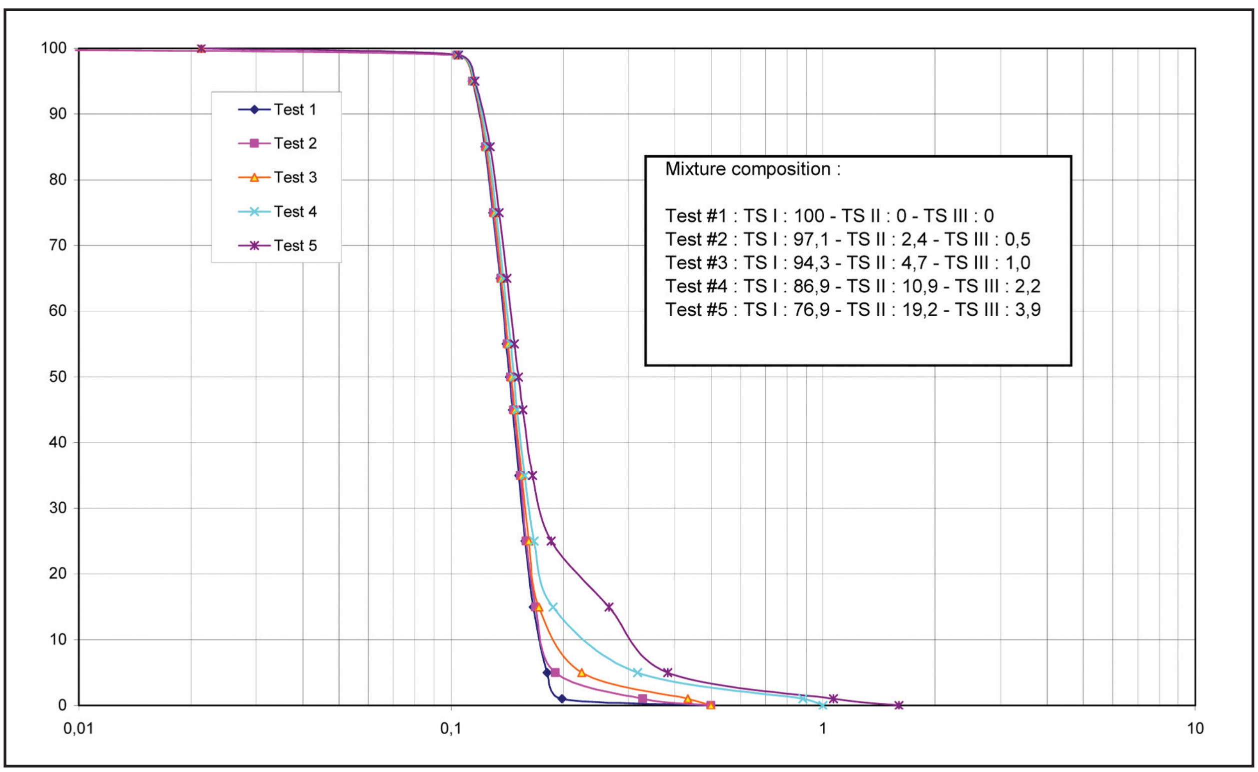

Fig. 8 Simulation of the occurrence of asymmetry or bimodality according to the proportion of the various components of a mixture (proportions in the caption are not percentages but absolute values intervening in the mixture; corresponding proportions in % are given in Table 9)

Tyrrhenian distension. The two sedimentary bars marking its upper part are submitted to reworking mainly discernible in the inner bar. Comparing the directions of this offshore bar indicates that sand accumulation, normally linear on both sets of available aerial pictures, can become segmented under the influence of the waves, as seen on a bathymetric survey dated August 2006. Modelling the wave refraction pattern emphasizes a significant correlation with the segment directions observed under N to E waves, normally prevailing in summer, particularly during a number of squalls in 2006. This capacity to become organized *en echelon*, following disruption and reorienting, prompts the thought of a limited sedimentary volume, more mobile than a larger entity. This typological diversity, not accounted for in standard bar classifications points to the introduction of a distinction between coastlines provided with plenty of sandy material and those which endure a sedimentary shortage. It also underlines how useful it is to survey the typological variety of bar shapes as a sensitivity indicator for the erosion of sandy coastal zones. One reason behind the reduction in volume of the sedimentary reservoir contributing to feeding the offshore sandy prism is the restricted sources, manifest in the poor diversity of sedimentary types. Three sedimentary types were identified. ST I, a well-sorted fine sand, is the main constituent of the prism in the shallowest zones, also present on the beach and in dune ridges. Beyond -6 m, the grain size assemblage becomes coarser and a lot richer in thick bioclasts, supplying two sedimentary types, a medium one (ST II) and a coarse one (ST III). These bioclasts derive from the epiphytic fauna of the Posidonia sea meadows situated further offshore towards -15 m and maybe also from coastal beachrock outcrops.

In the grain size assemblages, the coarseness of the sediment can increase in several ways translating the growing influence of the part taken by the ST II and ST III. A modest influence materializes through a change in the asymmetry of the sediment; a more significant influence entails coexistence of both populations, ST II or ST III with the generally dominating ST I.

The mechanism of the mixture, ST I + ST II + ST III, was modelled to substantiate the consequences observed. Based on a unimodal population of ST I type (mode = 2.8Φ; σ=0.2Φ), simultaneous addition of ST II and ST III in growing proportions increases at first, the asymmetry of the sediment apparently remaining unimodal but later, triggers off bimodality. Asymmetry and bimodality are the two facets of one and the same phenomenon, the blending of normally distributed stocks into a dominant grain size population. In this approach, the dimensional structure of the grain size assemblage is interpreted as a mixture of stocks, the origin of which cannot be found in their transport mode but in local sources. In this case, local sources are scarce and in small quantities. Grain size analysis confirms the sedimentary shortage in the compartment of the bay of Mahdia .

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