LARGE BOULDERS ALONG THE RABAT COAST (MOROCCO); POSSIBLE EMPLACEMENT BY THE NOVEMBER, 1st, 1755 A.D. TSUNAMI

Nadia Mhammdi, Fida Medina
Université Mohammed V-Agdal, Institut Scientifique, Département des Sciences de la Terre, Av. Ibn Batouta, B.P. 703 Agdal, Rabat, Morocco.
mhammdi@israbat.ac.ma; medina@israbat.ac.ma

Dieter Kelletat
Universität Köln, Institut für Geographie, Albertus Magnus Platz 1, Koeln, Germany.
dieter.kelletat@t-online.de

M'Fedal Ahmamou, Lamiaa Aloussi
Université Mohammed V-Agdal, Faculté des Sciences, Département des Sciences de la Terre, Av. Ibn Batouta, B.P. 1014 R.P., Rabat, Morocco.
ahmamou@israbat.ac.ma

ABSTRACT

The rocky coastline south of Rabat (Morocco) shows a large number of boulders lying upon the lithified dune system. The boulders, of 4-100 tons, may be single, in imbricated sets, or forming clusters and ridges. Several of the boulders were lifted and overturned, thus showing pool apertures downwards. Transport distance is generally decametric because of the surface roughness, but it can reach 300 m in flat areas. All boulders have been detached from their initial position at the fractured front of the active cliff. Quantification with the help wave hydrodynamics and rock displacement mechanics shows that dislodgement and transport of these boulders were accomplished rather by tsunami than by storm waves. Although no dating was attempted, post-emplacement bio-erosion by littorinids and the absence of any erosional features below the boulders suggests that they were emplaced during the 1st November 1755 AD Lisbon tsunami.

Key words: Morocco, Rabat coast, tsunami, boulders, 1755 Lisbon earthquake.

1. INTRODUCTION

The northwestern Moroccan coastline is fully exposed to the Gulf of Cadiz (Fig. 1), where the boundary of the North African and European plates becomes convergent near the Gorringe Bank (e.g. Buforn et al., 2004; Stich et al., 2005). This zone, probably one of the most dangerous seismic and tsunamigenic areas in the world, is the source of the Lisbon earthquake (M=9.0) on November, 1st, 1755AD, as well as of other historical events (216-209BC, 881AD, 1731AD), that led to partial destruction of some Moroccan and south-western Iberian coastal cities (Campos, 1991; Elmrabet, 2005). This seismogenic / tsunamigenic area continues to be active, as attested by the occurrence of the large earthquakes of 28 February 1969 (M=7.3), 26 May 1975 (M=7.9), which generated small tsunamis (Baptista et al., 1992; Heinrich et al.; 1994), and 12 February 2007 (M=6.3), strongly felt in Morocco. The calculated return period of tsunami generation is of 200 years in some oceanic sectors around 36°N 10°W (El Alami and Tinti, 1991).

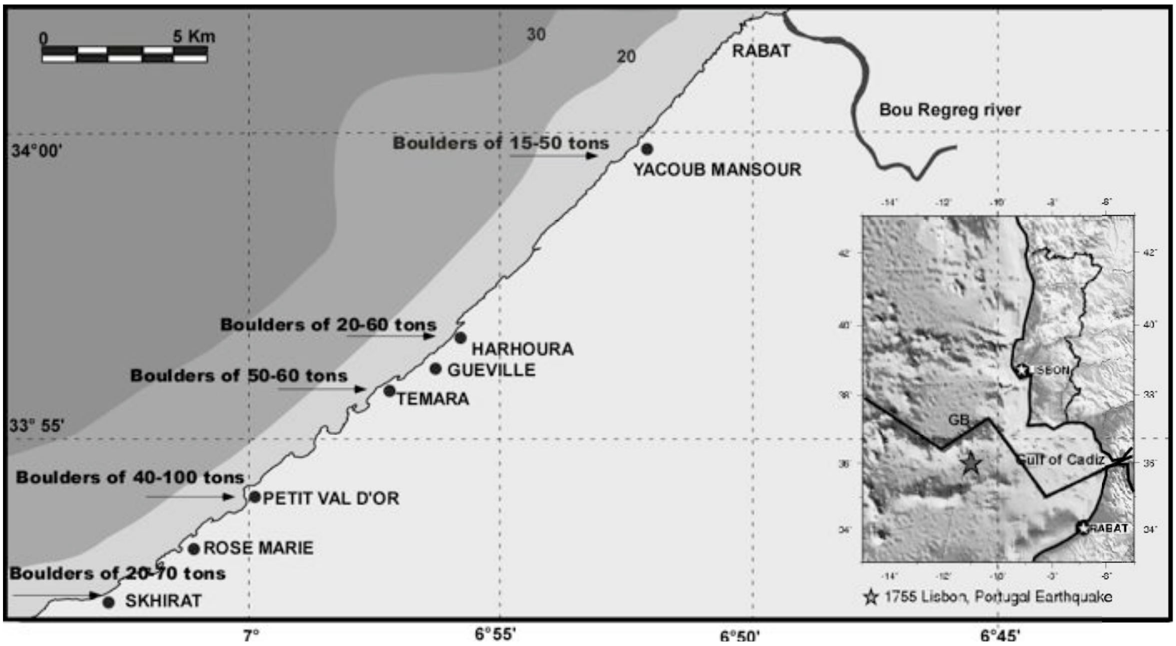

Fig. 1. Map of the coastal area south of Rabat and location of the observation sites (simplified from Milliès-Lacroix, 1974). Inset: map of the Gulf of Cadiz area showing the morphology of the sea bottom and location of the epicentre of the 1755 AD Lisbon earthquake (star). Freely licensed from USGS.

One of the most spectacular effects related to the tsunamis of the Gulf of Cadiz is the displacement of boulders of several tons along the shoreline. Such boulders have been observed in southern Spain at cape Trafalgar (Whelan and Kelletat, 2005) and in Portugal, west of Lisbon (Scheffers and Kelletat, 2005). In Morocco, despite detailed studies on the Quaternary coastal deposits (Guilcher and Joly, 1954; Gigout, 1957; Akil, 1980 among others), only Gigout (1957, p. 10-11, plate II, Figs 3-4), described single boulders in the Rabat coastal area, and interpreted their displacement and overturning as related to storms. On the basis of literature published on Iberia, and within the context of general interest in tsunami research after the December, 26th 2004 catastrophe in the Indian Ocean, we re-visited the coastal area south of Rabat several times during 2007 in order to investigate the existence of comparable tsunami-related boulders. The first results are presented in this paper.

In the following sections, we first review the geology and morphology of the Rabat coastal area in order to set the physical environment, and then we describe the boulders and the style of their arrangement, and discuss the factors that influenced their emplacement according to wave dynamics and transport physics.

2. GEOLOGY AND MORPHOLOGY OF THE COASTLINE NEAR RABAT

The coastal area south of Rabat is dominated by a superimposed dune system and coastal marine deposits of end-Ouljian (70,000 years BP) to present age (Gigout, 1957; Akil, 1980; Saaidi, 1988). This dune system is developed upon the Palaeozoic basement of the western Meseta (Milliès-Lacroix, 1974). A transversal section shows the main morphological elements, which consist of (Fig. 2): (i) an inactive cliff; (ii) a more or less large depression (locally named *Oulja*) with recent beach and older continental deposits; and (iii) the lithified coastal dune system.

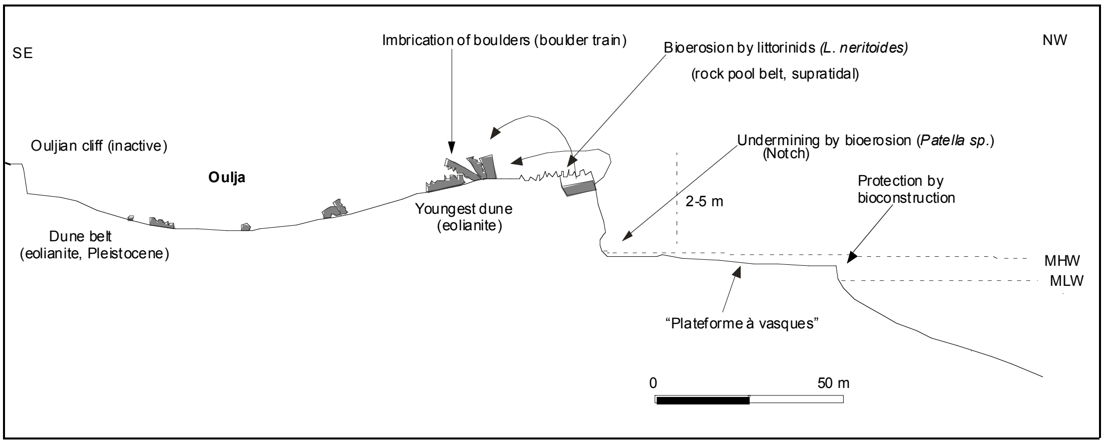

Fig. 2. Schematic transversal section of the Rabat coastal area showing the main morphological units and the type of boulder arrangement. Inspired from Guilcher and Joly (1954), Gigout (1957) and Akil (1980).

According to Gigout (1957), a typical section of the Quaternary deposits of Témara beach comprises, from older to younger (Fig. 3 A): (i) a post-Ouljian consolidated dune system, with generally an eroded top, overlain by (ii) a red clay level, rich in continental Gastropods, capped by (iii) a decimetric-scale grey limestone-sandstone (Flandrian / Mellahian; 5,000-6,000 years BP) which shows the same palaeontological content than the present beach. The latter are overlain by either a *kjoekenmoeding* or by the present-day sand. More recently, Akil (1980) mapped a total of 14 marine and continental formations, the superimposition of which was interpreted as related to alternating episodes of sea level changes. The detail of these subdivisions will not be exposed here because the complex stratigraphic issue is beyond the purpose of this paper. The seaward ridge, consisting of end-Ouljian and post-Ouljian dune complexes separated by Soltanian red clays, most probably belongs to the younger Pleistocene, stade 5e or even 5a. The dune base several meters below sea level points to a sea level of this position or lower during dune accumulation.

Morphologically, the coast south of Rabat consists of relatively small sand beaches (Temara, Sables d'Or, Skhirate...) separated by rocky cliffs and lapiazed platforms (south of Temara, Miramar, Guéville). This area shows great biodiversity (e.g. Lambert, 1985), with several species that contribute to the evolution of the landscape by their constructions or their bioerosional processes, as shown in other areas, especially around the Mediterranean (Kelletat, 1997).

As described by Guilcher and Joly (1957), the morphology of the coastal dune system can be subdivided into two types, depending on the nature of erosional mechanisms: (i) a generally flat "dissolution-driven type" (we use the original term of Guilcher and Joly although we consider that there is no dissolution of limestone in sea water), and (ii) a more abrupt mechanically-driven type.

The "dissolution (see above) type" comprises several zones:

Lapiez and pools: a very significant aspect of the surface in reach of sea water splash and spray is a dark colour and numerous pits, potholes or *marmites,* pools with very sharp rock pinnacles in between (*lapiez*), the depth of which may reach 1.5 m in places (Fig. 3 B, C). The deepening and widening of the pools was interpreted by Guilcher and Joly (1957, p. 86) as related to dissolution (see above) by water, not to mechanical erosion; however, they could be only related to bio-erosion by littorinids of the species *Littorina neritoides* L. – (Fig. 3 D), very common in the Moroccan coast (Lambert, 1985) –, grazing on endolithic algae (Cyanophyceae and Chrolophyceae) as described by Kelletat (1997) and others. Measurements of the intensity of bio-erosion on these carbonate rocks in other areas have resulted in 1-2 mm/year (e.g. Trudgill, 1987), but it is not possible to determine the number of generations of rock pools with flat bottoms and sharp notches that have been developed and destroyed by the grazing process of the littorinids. There is no doubt that these bioerosional features are of younger Holocene ages, when sea-level was close to the modern one and seawater spray and splash again reached the eolianite surface. Some remnants of old red soils or even caliche point to an old soil surface on the dune belt, most probably from the time of a lower sea level during the youngest Pleistocene.

"Plateforme à vasques": seaward of the lapiez zone appears a 10 to 40 m wide platform that has been cut out of the eolianite (Fig. 3 E), comprising large pools which are generally 25 cm deep, bounded by narrow crests and rims with bio constructions by barnacles and vermetids. This platform may display steps up to 50 cm in height, pouring seawater into each other, and is bounded by the mean high tide cliff. Its lower boundary appears at half tide. Between the two cliffs, and in particular the seaward fringe of the platform, where the stronger waves break, the platform shows significant bio construction and no fresh signs of plucking or quarrying. We interpret this platform as the result of coastal abrasion and bio-erosion in notches by limpets (*Patella* psp.) during the higher Holocene (Mellahian; 5,000-6,000 BP) sea-level, which – according to the levelling topography of the platform – should be rather stable, and at the modern level for a longer time of the Younger Holocene.

Area of break-up of the Plateforme à vasques. This area, only exposed at low tide, is characterized by basins that are deeper than those of the plateforme à vasques (25-80 cm), and is bounded seawards by the low tide cliff.

In the mechanical-driven type, the seaward slope of the dune system breaks and forms a generally highly fractured high tide cliff, with large blocks tilted seawards, or fallen at the base of the cliff (Fig. 3 E). However, the *plateforme à vasques* and the basin break-up areas are present although with a smaller width

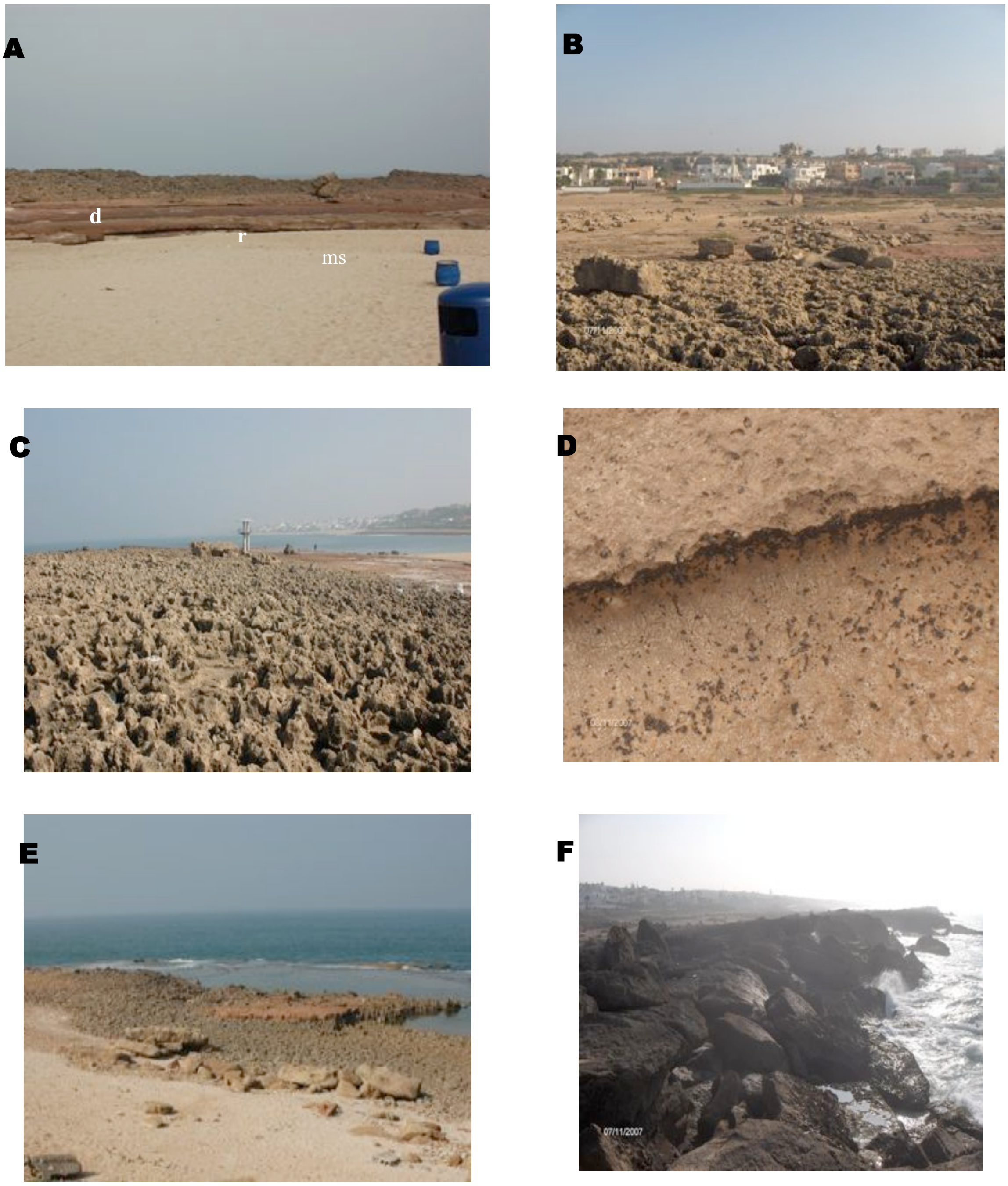

Fig. 3. Some geological and morphological features of the coastal area south of Rabat. **A**, Main Quaternary formations at Témara; successively from the foreground: present-day beach sands, then Mellahian (5,000-6,000 years BP) marine sandstones (ms), overlying red clays (r) and the lithified coastal dune (d). View to the northwest. **B,** successively from the foreground: lapiez, *Oulja* depression with boulders, and inactive cliff in the background behind the constructions at Harhoura (view to the south-east); **C,** Lapiez landscape at Temara (view to the north); **D**, example of a pool showing a concentration level of littorinids at Témara; **E,** Promontory of a partly submerged platform at Témara (view to the southwest); **F,** Highly fractured cliff in the dune belt at Harhoura (view to the southwest).

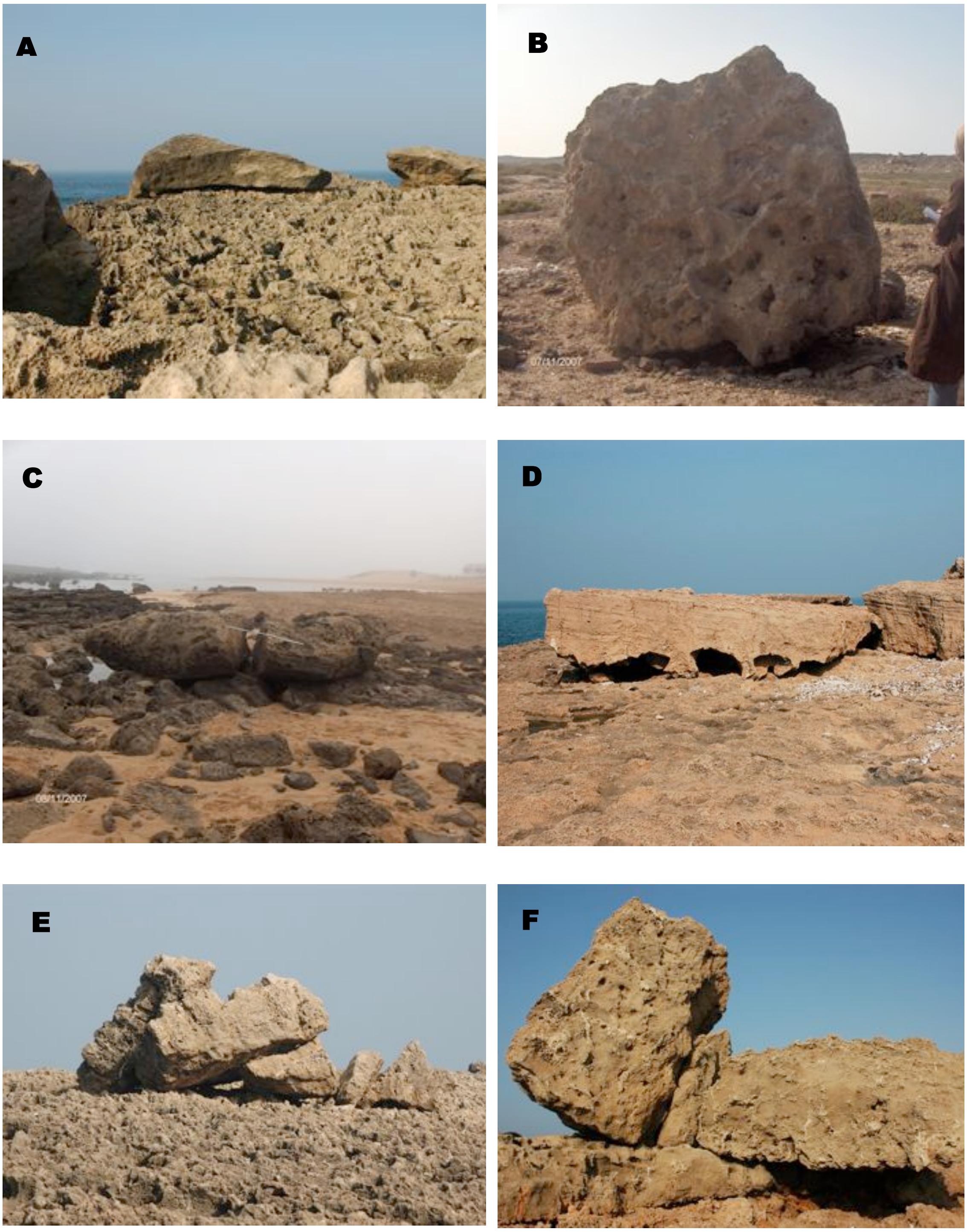

Fig. 4. Most conspicuous examples of boulder arrangement observed along the Rabat coast. **A**, Single boulders laying on cliff top at Harhoura; **B**, single fragment at Skhirate transported over 300 m; **C**, a large boulder dislocated into two fragments at Petit Val d'Or (view to the north); **D,** Two overturned boulders at Témara, showing pool openings downwards (view to the north); **E**, blocks in clusters at Harhoura (view to the southeast); **E, F**, trains of imbricated boulders at Témara (E) and Harhoura (F), view to the northwest in both.

3. THE BOULDERS

A striking aspect of this coastline of more than 40 km in length is the occurrence of large boulders upon the coastal formations, especially eolianite. Observation of aerial photographs shows that they extend from the southwest of the city of Rabat (municipality of Yacoub El Mansour) to Skhirat plage. As our study is preliminary, the description of the boulders is mainly qualitative, since we have just noted the dimensions and the weight of the largest blocks, and the maximum transport distance. The statistical orientation of their axes is under study.

Generally, the shape of the boulders is platy (Figs. 4 and 5). Their maximum length (A-axis) reaches 8.4 m at Val d'Or, and their weight ranges from a few tons to 100 tons. A weight of 20-30 tons is general for the larger ones, nearly all along the coast. Approximate weight was calculated using a density of 1.54-1.715 (Asebriy et al., 2007).

These boulders lay in cliff-top or landward slope (Fig. 4 A), in the landward following swale or even several meters uphill on the next eolianite ridge (Fig. 3 B). The distance to the active cliff is from a few meters to about 300 m (Fig. 4 B), and the height above high water, i.e. the rate of vertical transport, may reach more than 5 meters.

Several types of arrangement were observed:

– Single boulders (Fig. 4 B), which may be fractured by probable vertical slamming (Fig. 4 C). Some of them have been displaced in their original position, i.e. with the rock pool topography on the upper surface, whereas others have been overturned and show the rock pools at their base, with the openings to downwards (Fig. 4 D).

– Imbricated boulder trains, with up to 7 platy boulders leaning one on the other, steeper inclined to seaward (Figs. 4 E, F and 5 A).

– Large chaotic clusters (Fig. 5 B), or, more rarely, ridges.

However, the amount and arrangement of the boulders are quite variable from one site to another:

(1) At Harhoura, the boulders are either scattered or arranged in small clusters; maximum displacement of a block is 150 m (Fig. 3 B).

(2) Southwards, Témara beach shows beautiful examples just beside the promenade alley, which is almost 2 km long. Here, the boulders may be single, imbricated, or in clusters. Maximum estimated weight is 50-60 tons. The horizontal displacement towards the continent is small (20 m), but the blocks are located at relatively high altitude (5 m), as shown in Figures 3C and 4E.

(3) The Petit Val d'Or shows the most spectacular features. In this lagoon-like beach, the boulders are very numerous and occupy a ridge of ca. 500 m x 60 m = 30,000 m^2 (Fig. 5 B). Maximum weight and displacement of the boulders are respectively 100 tons and 150 m. The boulders show all types of arrangement, and imbrication occurs along N110 and N160 trends (Fig. 5 A). To the south, this lagoon connects with the sea by a swale, the elevated shoulders of which also show isolated boulders, some of which reach 70 tons, are overturned, and located at relatively high altitude (2 m).

(4) In the southern area of Skhirat plage, we also observed a ridge of relatively small blocks which are isolated or imbricated along a N130 direction. Here, a 4 ton block was displaced as much as 300 m from the shoreline, along a flat platform (Fig. 4 B).

–

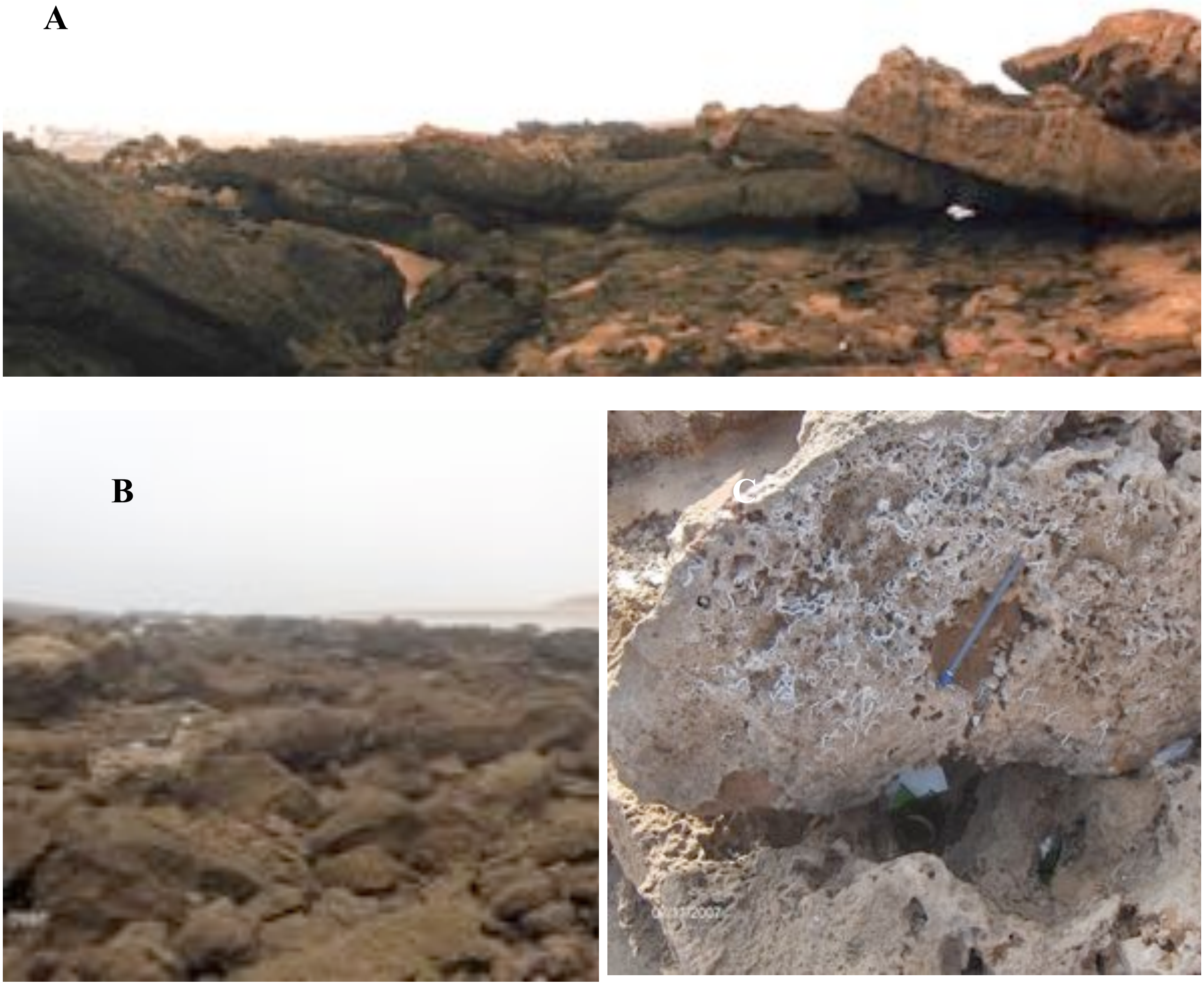

Fig. 5. A, Spectacular train of seven imbricated platy boulders at Petit Val d'Or, the uppermost being overturned, with the pool openings to downwards (view to the southwest); **B,** chaotic assemblages of blocks at Petit Val d'Or (view to the north); **C**, boulder with vermetids at Témara, attesting for uplift and transport from an infratidal area.

4. INTERPRETATION / DISCUSSION

4.1. *Provenance of the boulders*

As the lithology and morphology of most boulders is identical to that of the coastal eolianite, their source is the fractured rock pool belt close to the active cliff (Fig. 3 F), and their way of transport always is to the SE, which means perpendicular to the general coastline trend. Some boulders display small vermetids (Fig. 5 B), carvings of sea urchins or borings of bivalves (Lithophaga sp.), documenting their dislodgement from an area below sea-level; however, most of the boulders derive from the fractured cliff top itself, and only in the case with no signs of bio-erosion and rock pools on them, their sources are the positions of cliff rock below the rock pools belt, i.e. in the lowermost sections of the profile.

The amount of displaced boulders in a given area seems to be directly related to the density of fractures in the nearby active cliff. Thus, highly fractured cliffs as those at Harhoura (Fig. 3A) or Petit Val d'Or, would have provided more boulders than Témara or Skhirat.

4.2. *Emplacement of the boulders*

The emplacement of large boulders on shoreline platforms has been a matter of debate concerning the phenomenon to which it is related (hurricane or tsunami), especially for old unobserved or undocumented events (see discussion in Nott, 2003 and Noormets et al., 2004). Modelling of wave and tsunami hydrodynamics and rock displacement mechanics show that large waves as well as tsunami can lead to the detachment of a block from its cliff rock because the pressure may be very high, reaching 130 t/m^2 for a breaking wave, 70 t/m^2 for a tsunami (Noormets et al., 2004); however, its lift, overturning and emplacement at a distance can only be accomplished by tsunami waves because they yield greater energy and act during a longer time. In this section, we review the mechanical aspects related to boulder dislodgement and transport in order to understand the emplacement mechanisms of the Rabat boulders.

4.2.1. Dislodgement

First, the role of breaking waves in the dislodgement of the boulders can be assessed using the general formula of wave breaking (see Noormets et al., 2004, p. 47):

$$H_b / h_b = 0.72 + 5.6 \tan \beta \qquad (1)$$

where H_b is the height of the breaking wave, h_b is the water depth at the breaking point and $\tan \beta$ is the bottom slope. Above a flat bottom ($\beta = 0$), waves will break if water depth is 1.39 of their height. Therefore, an 18 m-wave will break in about 25 m of water depth, or an 8 m wave in 11 m of water.

In the case of the coast south of Rabat, the available bathymetric maps are not accurate enough (Fig. 1); however, we can infer from equation (1) that even wave heights may reach 10 m during storms (e.g. on 5 and 6 January 2008), only waves or swell of less than 6-7 m can approach the cliffs to release their full energy without breaking.

As a large number of boulders are upside-down, an increased energy is required to dislodge, lift and overturn them. Among the several cases exposed by Nott (2003), the joint bounded block scenario seems the most appropriate to the Rabat coast, and the main force acting on the boulder is the lift force F_L, expressed by (Nott, 2003, and modified version by Noormets et al., 2004):

$$F_L = [0.5\ \rho_w\ C_l\ (bc)\ u^2]\ b / 2 \qquad (2)$$

where C_l is the lift coefficient (0.178), b and c are the length of the B-axis and the C-axis of boulder respectively, ρ_w is the mass of unit volume of water and u is flow velocity.

This force can exert a moment with a pivot point around which the boulder may rotate (Fig. 8A of Noormets et al., 2004).

Following equation (2), a 10-ton boulder would require a storm wave height of at least 18.5 m (Table 1 of Nott, 2003). Because the weight of the observed boulders is in the range 20-100 tons, storm waves can be already excluded for the coastal boulders south of Rabat, and tsunami waves with their much higher mass, velocity and energy are required.

It can also be readily seen from equation (2) that for blocks of the same size, the lift force mainly depends on the velocity of flow, which is much higher for tsunamis. Therefore, the overturning of the boulders is best explained by the lift force exerted by tsunamis.

4.2.2. Transport of blocks

The transport distance of a block on a platform can be expressed by the formula (Noormets et al., 2004, p. 57):

$$X = [T.\ g^{1/2}\ .\ ((R - E)^{1/2} - H^2)] / 5 \qquad (3)$$

where X is the transport distance (m); T is the wave period (s); g is the acceleration due to gravity (m/s^2); R is the run-up elevation (m); E is the revetment crest elevation (m); and H is the bore height (m) at distance X.

Equation (3) readily shows that, for the same conditions of run-up and revetment height, the transport appears to be much longer by tsunami waves because of their longer period. For instance, for the same wave/bore heights, and taking a period of 15 s for waves and 15 min for tsunami, the distance is 60 times longer for tsunamis.

A simpler method in quantifying the energy of displacement of a boulder is calculating the "transport figure" (Scheffers, 2005, p. 39) which is given by the equation:

$$Tf = W \times D \times V \qquad (4)$$

where Tf is the Transport figure; W is the weight (tons) of the block; D is the distance moved (m), and V is the vertical distance (m). The value 2,000 is regarded as to be the uppermost limit of storm wave transport energy.

At Petit Val d'Or, we found 20-ton blocks transported 150 m away from the shoreline, some of which were overturned. This gives a Tf of 3,000 without taking into account the height reached. In average, blocks of 30-60 tons are common at 10-20 m inland, so this gives Tf values of 1,500-6,000 for a +5 m elevation.

It should be noted that the value of topographic elevation is a minimum, as many blocks have been overturned, so their centre of gravity attained a higher elevation which depends on the boulder dimensions (e.g. 3 m for a 6 m large block). This leads to a large increase of the V values, and then in those of Tf.

4.3. ***Age of boulder dislocation***

Since this study is preliminary, we have not yet collected any marine organisms at or in the boulders to absolutely date the time of their displacement out of the sea, but there are some indirect or relative age indicators for this process: nearly all boulders have been settled on a ripe bio-erosive topography, balancing on rock pinnacles in an unstable position, or leaning one against the other with touching only at 1,2 or 3 small points, e.g. in imbrication trains. Neither the surface under the boulders nor beside them shows any significant differences in weathering or erosion, and the rock pools remnants on or below the boulders are nearly exactly the same as on the rock surface aside. Pools on the boulders with inclined bottoms, however, may display the formation of a new horizontal pool bottom after deposition. The dimensions of this transformation is in the size of centimetres to 1-2 decimetres, and regarding the bio erosive process being in the order of 1-2 mm/year, the age of dislocation may be only a few hundred (100-400) years as a maximum.

4.5. ***Concluding remarks***

Summarizing, we can state that swell waves along the Rabat coast generally break before impacting with the cliff, and when they do not break, their energy appears to be insufficient for dislodgement, overturning and long transport of boulders ≥ 10 tons. Moreover, the unstable arrangement of boulders cannot be the result storms and hurricanes as successive wave trains should have destroyed the imbricates. Therefore, there is little doubt that tsunami was the cause of the present-day pattern.

As this part of the Moroccan coastline is exposed to the Gulf of Cadiz with well known large tsunamis in former centuries, and as a tsunami wave of far more than 10 m in height (or with a run-up of more than 10 m in places) has been reported or calculated for the Lisbon tsunami of November, 1st, 1755 AD (Baptista et al., 2003; Gutscher et al. 2006), it is highly likely that this tsunami was responsible for the boulder accumulations and transport at the NW Moroccan coastlines. This is in accordance with the amount of weathering and the general aspect, that all the boulders have been dislodged and transported by the same (i.e. only one) event. Taking into account the observations along the southern Atlantic coastline of Spain near Cabo de Trafalgar (Whelan and Kelletat, 2005), where boulders of up to 100 tons have been transported on up to 300 m by the Lisbon tsunami and the Cabo de Trafalgar, 19 m high, has been overrun by the tsunami waves, this conclusion may be supported by all observations available so far.

4.6. Tsunami hazard in the Rabat coast

All the observations along the coast south of Rabat show that in the rocky zones, the boulders remain between the shoreline and the inactive cliff (Fig. 2), so their transport was restricted to the flat Oulja when the latter is present, or to the platforms in lower areas. In addition, the inactive cliff has certainly acted as a barrier against the tsunami wave and protected the eventual constructions and population uphill. On the basis of the formulas exposed by Nott (2000, 2004), which use rock density and dimension of boulders, the calculated tsunami wave heights seem to have been relatively small, in the range 3-5 m; however, the tsunami coincided with a period of high tide (+2.83 m at 14.00), thus increasing the energy.

This may have not been the case in estuaries, where the largest damage was reported by Al Kadiri from the area of Rabat and Salé (text reproduced by Elmrabet, 2005, p. 264-265). We have no data on the estuarine formations of the Bouregreg river between Rabat and Salé for the moment, but recent surface boring of the Loukkos estuary (Aloussi, 2008), located 100 km to the north, has revealed centimetric to decametric-thick, Foraminifera-bearing, marine sands intercalated within muddy deposits at shallow depths, up to 10 kilometers inland. This attests for a probable tsunami-related invasion by seawaters. As datings are still unavailable, we cannot ascertain that these marine sands are related to the 1755 tsunami or to previous ones; however, they attest for the existence of such events in past times.

5. CONCLUSIONS

1. A survey of the rocky coastline south of Rabat (Morocco) has led to the first description of the emplacement of a large number of boulders laying upon the post-Ouljian lithified dune system along the shoreline.

2. The boulders, weighting 4-100 tons, may be single, arranged in imbricated sets, or forming clusters of hundreds. Some of the boulders have been overturned, thus showing pool apertures downwards. Transport distance is generally of some tens of meters because of the surface roughness, but some of them were found at 300 m from the shoreline.

3. All boulders have been detached from their initial position at the fractured front of the active cliff. Wave hydrodynamics and rock mechanics quantification show that dislodgement and transport of these boulders were accomplished by tsunami rather than by storm waves.

4. Although no datings were attempted, the unstable position of the boulders, the post-emplacement bio-erosion by littorinids and the absence of any erosion at the base of the boulders or in the basement rocks suggests that they were emplaced in recent times, most likely during the 1755 AD Lisbon tsunami.

The next steps of investigation should be to look for absolutely datable material to exactly date the boulder dislocation, to extend the observations along the Moroccan coastlines to the south and the north, and to try to evaluate the tsunami history of the area by coring in the sediments trapped in the swales behind the first eolianite ridge.

6. ACKNOWLEDGEMENTS

This work was initiated within the activities of the team “Marges méso-cénozoïques marocaines” at the Institut Scientifique of Rabat, and in part funded by the University Mohammed V-Agdal.

7. REFERENCES

Akil, M. 1982. Contribution à l'étude sédimentologique des formations littorales quaternaries de la région de Rabat. Mém. Dipl. Etudes Sup., Université Mohammed V, Fac. Sci. Rabat, 139 p., 7 pl., 1 map.

Aloussi, L. 2008. Evolution spatio-temporelle de l'estuaire du Loukkos; étude préliminaire. DESA Memoir, Fac. Sci. Rabat, 58 p. + append.

Asebriy, L., Bucci, C., El Amrani, I.-E., Franchi, R., Guerrera, F., Martin-Martin, M., Patamia, C., Raffaelli, G., Robles Marin, P., Tejera de Leon, J. and Tentoni, L. 2007. Etude intégrée de la dégradation des monuments historique Romains et Islamiques de la ville de Rabat (Maroc): proposition de solutions durables de prévention et restauration. Science and Technology for Cultural Heritage, Pisa-Roma, 16 (1-2), 45-65.

Baptista, M.A., Miranda, P. and Mendes Victor, L. 1992. Maximum entropy analysis of Portuguese tsunami data ; the tsunamis of 28.02.1969 and 26.05.1975. Sci. Tsunami Haz., 10(1), 9-20.

Buforn, E., Bezzeghoud, M., Udias, A. and Pro, C. 2004. Seismic sources on the Iberia-African plate boundary and their tectonic implications. Pure Appl. Geophys., 161(3): 623-646.

Campos, M.L. 1991 Tsunami hazard on the Spanish coasts of the Iberian peninsula. Sci. Tsunami Haz., 9(1): 83-90.

El Alami, S.O. and Tinti, S. 1991. A preliminary evaluation of the tsunami hazards in the Moroccan coasts. Sci. Tsunami Haz., 9(1): 31-38.

Elmrabet, T. 2005. The great earthquakes in the Maghreb region and their consequences on man and environment. Imprimerie Beni Snassene, Rabat, 428 p. (in Arabic + English summary and table).

Gigout, M. 1957 Recherches sur le Pliocène et le Quaternaire atlantiques marocains. Trav. Inst. Sci. Chérif., Rabat, sér. Géol. et Géogr. Phys., 7, 77 p.

Guilcher, A. and Joly, F. 1954. Recherches sur la morphologie de la côte atlantique du Maroc. Trav. Inst. Sci. Chérif., Rabat, sér. Géol. et Géogr. Phys., 2, 140 p.

Gutscher, M.-A., Baptista, M.A. and Miranda, J.M. 2006. The Gibraltar Arc seismogenic zone (part 2): Constrains on a shallow east dipping fault plane source for the 1755 Lisbon earthquake provided by tsunami modeling and seismic intensity. Tectonophysics, 426: 153-166.

Heinrich, Ph., Baptista, M.A. and Miranda, P. 1994. Numerical simulation of the 1969 tsunami along the Portuguese coast. Preliminary results. Sci. Tsunami Haz., 12(1): 3-23.

Kelletat, D.H. 1997. Mediterranean coastal biogeomorphology : processes, forms and sea-level indicators. In : Transformations and evolution of the Mediterranean coastline. Bull. Inst. Océanogr., Monaco, n° sp. 18, and CIESM Sci. series, 3 : 209-226.

Lambert, A. 1987 Animaux de la côte atlantique marocaine. Librairie Nationale, Casablanca, 207 p.

Milliès Lacroix, A. 1974 Carte géotechnique de la région de Rabat. Notes et Mémoires du Service géologique du Maroc, n°238.

Noormets, R., Crook, K.A.W. and Felton, E.A. 2004. Sedimentology of rocky shorelines: 3. Hydrodynamics of megaclast emplacement and transport on a shore platform, Oahu, Hawaii. Sedim. Geol., 172: 41-65.

Nott, J. 2000. Records of prehistoric tsunamis from boulder deposits. Evidence from Australia. Sci. Tsunami Haz., 18, 1, 1-14.

Nott, J. 2003. Waves, coastal boulder deposits and the importance of pre-transport setting. Earth and Planet. Sci. Letters, 210: 269-276.

Saaidi, E. 1988. Géologie du Quaternaire marocain. Ed. SMER, Rabat, 439 p.

Scheffers, A. and Kelletat, D. 2003. Tsunami relics on the coastal landscape west of Lisbon, Portugal. Sci. Tsunami Haz., 23(1): 3-15.

Scheffers, A. and Kelletat, D. 2004. Bimodal tsunami deposits – a neglected feature in paleo-tsunami research. In: Schernewski, G. and Dosch (Editors) – Geographie der Meere und Küsten. Coastline Reports, 1: 67-75.

Stich, D., Mancilla, F. and Morales, J. 2005. Crust-mantle coupling in the Gulf of Cadiz (SW-Iberia). Geophys. Res. Lett., 32, L13306, doi:10.1029/2005GL023098.

Trudgill, S.T. 1987. Bioerosion of intertidal limestone, Co. Clare, Ireland. – 3: Zonation, Process and Form. Marine Geology, 74: 111-121.

Whelan, F. and Kelletat, D. 2005. Boulder deposits on the southern Spanish Atlantic coast: possible evidence for the 1755 AD Lisbon tsunami. Sci. Tsunami Haz., 23(3): 25-38.