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Large boulder accumulation on the Algerian coast evidence tsunami events in the western Mediterranean

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ABSTRACT

Evidence of catastrophic mega-block deposition is presented for the Algerian coast from Tipaza to Dellys. The region is prone to large earthquakes, several of which are inferred to be tsunamigenic in origin, as attests the 2003 Zemmouri earthquake (Mw 6.8). It is argued here that several former tsunamis have resulted in the detachment of large boulders from the nearshore zone and their deposition inland. The estimated size, weight (volumetric mass) and distance from the shoreline of more than 100 boulders has enabled estimates to be made of the nature of the hydrodynamic waves responsible for their transport. The boulders weigh up to 200 tons and are scattered along ~150 km of rocky headlands and pocket beaches, in isolated or grouped elements, from the subtidal to supratidal zones. Boulders covered by biogenic incrustations show morphological features which suggest detached, reversed and reworked pieces. Statistical and hydrodynamic analyses indicate that large boulder transport requires either ~30-m-high waves or 5 to 10-m-high waves for catastrophic storm or tsunami events, respectively. Bio-indicators allow us to date two inferred tsunamis as having struck the Algerian coastline between AD 400–600 and ~AD 1700.

1. Introduction

Coastal boulder accumulations are a defining feature of major tsunamis (Bryant and Nott, 2001; Scheffers and Kelletat, 2006). Numerous studies of tsunami-related boulder accumulations have been undertaken in Japan (Nakata and Kawana, 1993), Australia (Bryant and Nott, 2001) and in the southern Caribbean islands (Scheffers and Kelletat, 2003). Although mega-blocks of probable tsunami origin are reported in Greece, southern Italy and the eastern Mediterranean Sea (Kelletat and Schellmann, 2002; Mastronuzzi and Sansò, 2004; Morhange et al., 2006; Vött, et al., 2006; Scheffers and Scheffers, 2007) their evidence is poorly documented in the western Mediterranean.

Striking examples of large boulder deposits associated with tsunamis have been outlined in previous research, for example the AD 1908 catastrophic (Ms 7.5) earthquake in Sicily (Fig. 1a; Heck, 1947). Elsewhere, Mastronuzzi and Sansò (2000, 2004) have attributed Pleistocene calcarenite slabs (up to 80 tons) scattered along the Ionian coast of Apulia (Italy) to three tsunami events between the 15th and 18th centuries AD. More recently, the 2004 Sumatra earthquake (Mw 9.2) and related catastrophic tsunami were responsible for the propagation of large waves and related debris. As evidenced by the widespread transport of large man-made objects in some areas in the zone of highest run-up (around 35 m in W-Sumatra) no significant mega-boulder transportation high enough to lie on emerged marine terraces and far inland have been reported (Kelletat et al., 2007; Goto et al., 2007). However, subsequent to the Sumatra 2004 event at Kalim Beach (Thailand), Kelletat et al. (2007) observed isolated coral boulders debris up to 0.5 ton, and at Khao Lak (Thailand), Umitsu et al. (2006) described two large granite boulders (4 tons and approximately 10 tons) transported over a distance of less than 5 m.

In spite of significant research, the distinction between tsunami-related and storm-related boulders is ambiguous (Dawson, 1994). Analyses of boulder characteristics (size, weight and density), emplacement and transport have been developed by Nott (2003) using statistical analyses and hydrodynamic relationships to determine the origin of coastal deposits. Using linear wave theory and experimental results, Noormets et al. (2004) have calculated wave hydrodynamics and characteristics as a function of local wave and climatic conditions, bathymetry and initial fracturing of cliff rocks. These quantitative approaches provide useful tools to determine the origin and condition of boulder deposits on coastlines although it is also recognized that tsunamis may rework pre-existing boulders across the coastal zone (Imamura et al., 2008).

The Algerian coast has been the site of numerous large earthquakes and tsunamis (Table 1). The AD 1365 and 1773 earthquakes near Algiers were respectively associated with ~5 m and ~2 m tsunami

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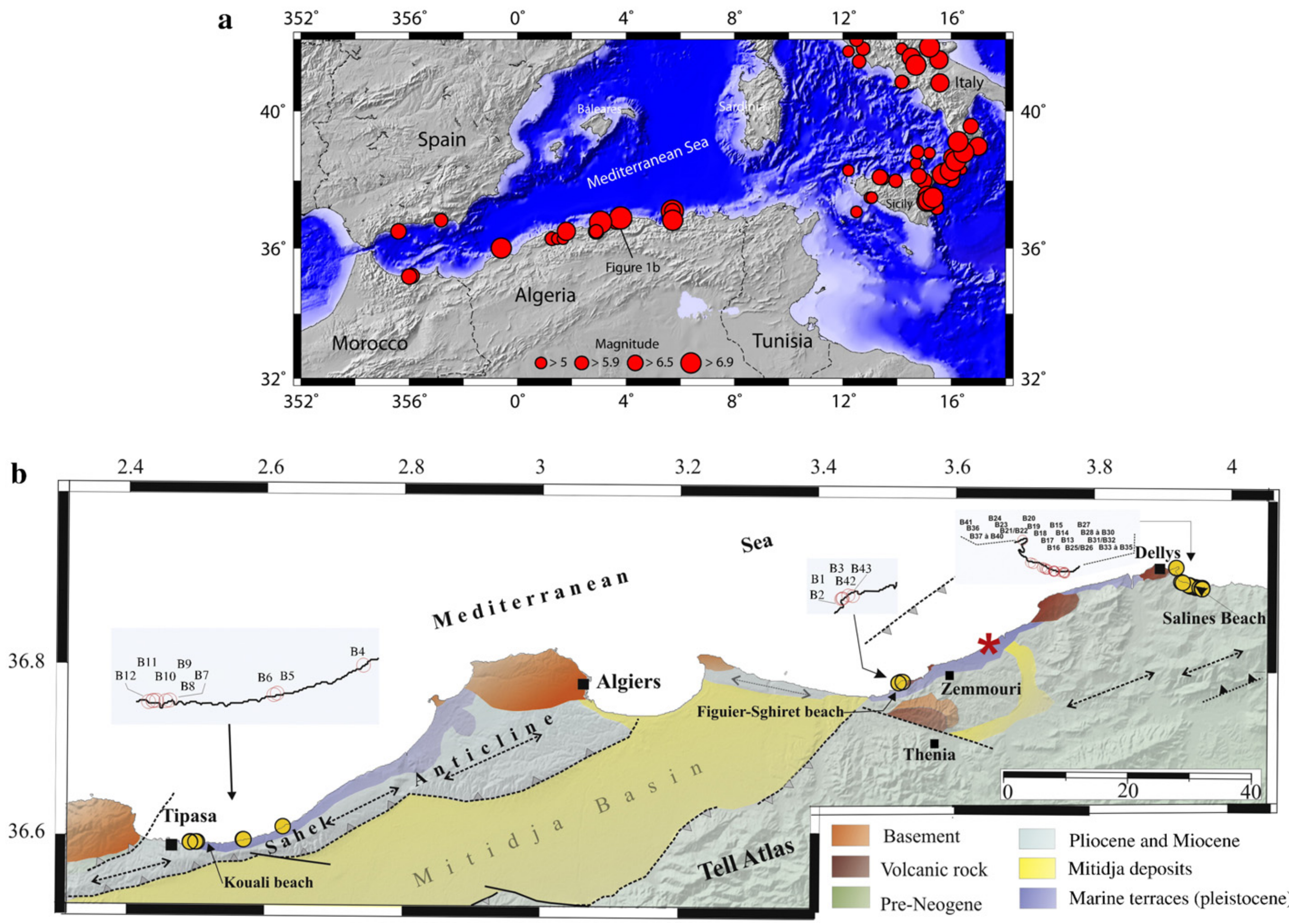

Fig. 1. a - Major tsunami earthquakes along the North Africa coastline and western Mediterranean Sea (data are from the European Tsunami Catalogue and recent publications: Soloviev et al., 2000; Tinti et al., 2004; Alasset et al., 2006; Harbi et al., 2007a,b). b - Location of the studied sites (circles) along the coastal region of Algiers with simplified geology and geomorphology. The epicenter of the 2003 Zemmouri earthquake (Mw 6.8, Bounif et al., 2004) is on the coastline NE of Zemmouri.

waves (Ambraseys and Vogt, 1988; Harbi et al., 2007a). Although traces of historical tsunamis in northern Algeria have not been well studied, previous works report the existence of coastal or offshore seismic hazards that can be linked to past tsunamis (Ambraseys, 1982; Meghraoui, 1991; Harbi et al., 2007a). Most recently, the 2003 Zemmouri earthquake (Mw 6.8) and related coastal fault rupture generated a significant tsunami with 1 to 2-m-high run-up that affected the Balearic Islands of Spain (Alasset et al., 2006).

In this paper, we describe the location, size and morphology of boulder accumulations in the coastal region of Algiers and investigate

Table 1
Large historical earthquakes on the Algerian coastline associated with tsunamis.

Year	Mon	D	H	M	S	Lat °N	Lon °E	INT	Au	QG	RMK	Wave height	Site
42 AD								?	HAR		de		Dellys
1365	Jan	3	18	0	0	36.77	3.05	X EMS	HAR	II	Lc, de, *i*, o Tsunami	5 m	Algiers
1522	Sep	22	–	–	–	36.91	2.5	IX MM	ETC	–	lc, o		N. Tipasa
1716	Feb	3	9	45	0	36.67	2.95	IX EMS	HAR	II	lc, *i* Tsunami		Algiers
1716	May	–	–	–	–	36.7	3.1	VIII MM	SSIS	–	A		Algiers
1722	Nov	29	3	0	0	36.77	3.05	VII MM	SSIS	III	lc		Algiers
1773	May							?	HAR	–	o, Tsunami	2 m	Tipaza
1790	Oct	09	10					IX-X MM	MOK		De		Oran
1804	Aug	25	8	30	0	36.8	2.8	IX MM	ETC	–	M,o		N. Sidi Fredj
1856	Aug	22	11	40	0	36.82	5.79	VIII+ EMS	HAR	I	M,o,I,de	2–3 m	Djijelli
1860	Sep	22	0	0	0	36.8	2.5	VIII MM	ETC	–	M, o		N. Tipasa
1885	May	25	2	0	0	36.8	2.5	V MM	ETC	–	M, o		N. Tipaza
1891	Jan	15						IX MSK	MAO		M,de,i	30 cm	Gouraya
2003	May	21						X EMS	HAR		i	1 m (in Europe)	Zemmouri

INT: intensity (EMS: European Macroseismic Scale, MM: modified Mercalli scale, MSK: Medvedev-Karnik-Sponhauer scale). Ref: reference (HAR: Harbi et al., 2007a and 2007b; ETC: European Tsunami Catalogue; SSIS: Seccion de Sismologia e Ingeniera Sismica "Spanish catalogue"; MOK: Mokrane et al., 1994; MAO: Maouche et al., 2008); QG: quality grade (I: earthquakes with abundant macroseismic, II: earthquakes with fairly sufficient macroseismic information, III: earthquakes with poor information or a single observation, no: events with poor or no tsunami information). RMK: remarks on events (M: macroseismic location, lc: location coordinates, o: offshore, de: destructive, i: availability of macroseismic information).

whether their detachment, transport and accumulation can be correlated to storm wave regimes or tsunami events. The quantitative analysis of boulders enabled the calculation of potential wave heights responsible for the boulder transport. Radiocarbon ages of marine incrustations on mega-blocks deposited above the limit of present-day storm waves are concurrent with historical and catastrophic seismic tsunami events on the Algerian coast.

2. Geological, geographical and wave climate contexts

The area of Algiers is characterised by the coastal Sahel anticline bound to the south by the Mitidja Quaternary basin and attributed to the Tell Atlas fold-thrust belts of North Africa (Fig. 1b). The Mitidja basin trends E–W parallel to the coast and is associated with Quaternary compressive deformation and thrust focal mechanisms of recent earthquakes (Meghraoui et al., 1996). The basin is separated from the sea to the north by the Sahel anticline, probably related to a hidden reverse fault where the westernmost section is associated with the 1989 Tipasa earthquake (Mw 6.0; Meghraoui, 1991). The basin's eastern region corresponds to the site of the large 2003 Zemmouri coastal earthquake and related offshore tsunamigenic fault rupture (Meghraoui et al., 2004; Alasset et al., 2006; Fig. 1b).

The coastal area of Algiers essentially constitutes sand beaches, flat rocky headlands and cliffs. Sand beaches are less than 50 m wide and 5-km-long (e.g., Figuier, Salines, Zeralda, Kouali in Fig. 1b); they are generally bound by dune belts that crown emerged Holocene and Pleistocene marine terraces. In the Tipasa area, pocket beaches are separated by gently sloping rocky headlands that consist of stepped Pleistocene calcarenite and sandstone outcrops, probably linked to episodes of tectonic uplift similar to the 2003 Zemmouri vertical coseismic movements (Meghraoui et al., 2004).

Using the WAM (Wave Prediction Model) the extreme wave at the site (latitude 37.1°N, longitude 2.9°E) was estimated from annual surge (RTP10.10/TR/IE's/04 1.2 report). A period of calculation extending over 9 years (1993–2002) was used to perform a simple statistical analysis to estimate the return period of the highest waves. The following calculations are validated by satellite observations (Topex, ERS 1–2):

- Annual wave height; Hsig = 6.3 m Tp = 11 s Hmax = 11.8 m
- 10-year wave height; Hsig = 7.8 m Tp = 12 s Hmax = 14.6 m
- 100-year wave height; Hsig = 9.3 m Tp = 14 s Hmax = 17.4 m

where H(sig) is the significant surge height, Tp is the peak period and H(max) is the possible maximum height. It is important to bear in mind that the centennial swell only gives an order value of magnitude. It represents the maximum surge height that can occur. This value is high and can only exist far from the shore. According to de Valk and Wensink (2004), wave height and wind data from the north Algerian coast (offshore Skikda) have been collected and modeled in an attempt to estimate the maximum height of waves generated by storms (Fig. 2). The different analyses are consistent with 8 to 12-m-high sea waves caused by strong northern storm winds reported from Skikda (1970), Oran (1985) and Algiers (2001) where large waves flooded coastal roadways and the seafront of Algiers causing severe damage and casualties (Algerian Meteorological Office). However, no transport of large boulders was observed during these storms, probably due to the effects of bottom friction and long-distance wave propagation over the shallow offshore zone of the Tipasa–Algiers area.

By contrast, tsunami wave propagation is directly related to the water depth, and is governed by the equation $v = \sqrt{g \cdot h}$, where v is the wave velocity vector, h is the water depth and g the gravity acceleration (Holmes, 1965; Synolakis and Bernard, 2006). Although v decreases with decreasing water depth, wave height and propagation conserve their energy and velocity until they meet the coastline. As a result, seismogenic tsunamis with 5 to 10-m-high waves are able to transport 200 ton boulders (Nott, 2003).

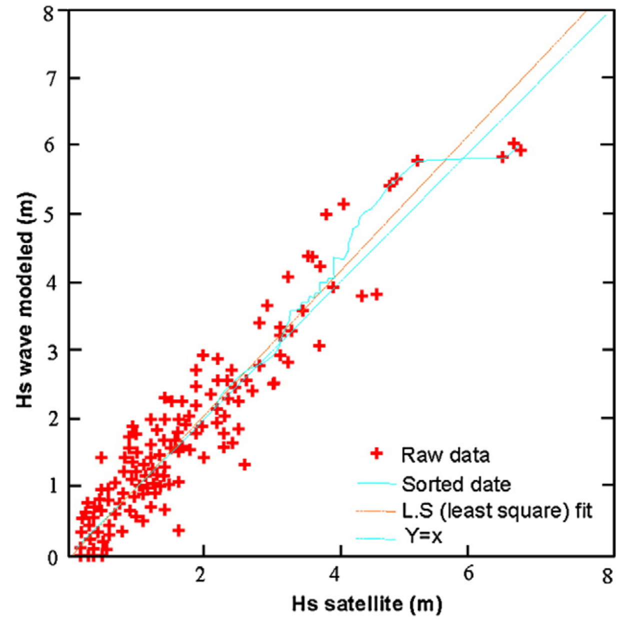

Fig. 2. Modeled local wave storm from hind cast and significant altimeter wave height in the western Mediterranean near Algeria (de Valk and Wensink, 2004; station 38.00° N 5.25° E).

3. Large boulder accumulation along the Algiers coast

The existence of large boulder accumulations raises the following question: what size waves are capable of detaching 200 ton boulders from the coastal zone inland? Large calcarenite, sandstone and calcareous mega-blocks have been observed along a 150 km-long coastal zone between Tipasa and Dellys (Fig. 1b). They are arranged in isolated elements, small groups or walls with 50–200 m^3 and >200 tons (see Table 2). Biogenic marine incrustations (Serpulids, Balanids, Vermetids) and boring bivalves (e.g. *Lithophaga*) on boulder surfaces suggest offshore (sublittoral zone) to inland transportation. Other boulders with traces of mid-littoral erosion (e.g. notches, benches and pools) also suggest a coastal or nearshore origin.

3.1. West of Algiers (Tipasa region)

East of Tipasa, an accumulation of boulders is observed along the coastline in a ~50 m wide strip for about ~10 km. Adjacent to steep seaward slopes, large boulders in vertical or inclined positions reach 2 to 3 m above mean sea level (MSL). Blocks weighing up to 10 tons cover promontory surfaces stretching from the coastline to the front of the first ridge. Analysis of imbrication axes indicates that the waves responsible for the boulder accumulations were most likely propagated from the NW to SE.

Between Kouali beach and “Rocher Plat” boulder fields are observed with calcarenite slabs up to 227 m^3 in volume (Table 2, Fig. 3a, b, c and d). In some cases, boulders are also fractured and broken. Large isolated fragments of calcarenite at distances of up to 30 m from the coastline can be attributed to their original ‘rip-up’ locations (Figs. 4 and 5). 200 m^3 and 100 m^3 boulders (e.g., B07 in Fig. 3d) show bio-eroded surfaces that attest to displacement from north to south. In several cases, these boulders have induced fractures of the underlying rocks, consistent with a violent impact during deposition. The sublittoral origin of the blocks is attested by bio-constructions, notably marine algae and *Dendropoma* of which the higher limit represents the top of the subtidal zone of biological mean

Table 2
Size and weight of boulders surveyed in the Algiers coastal area and tsunamis and storm wave heights required for their transport using the equations of Nott (2003).

a (m)	*b* (m)	*c* (m)	Volume (m^3)	Weight (ton)	ρs (g/cm^3)	Hs joint-bound (m)	Ht joint-bound (m)	Ht submerged (m)	Hs submerged (m)	
12.0	9.0	1.0	108.0	178.2	1.7	41.6	10.4	12.2	48.6	Bloc 7
13.0	7.0	2.5	227.5	375.4	1.7	45.1	11.3	4.2	16.6	Bloc 8
3.5	2.5	0.8	7.0	11.6	1.7	12.1	3.0	1.7	6.9	Bloc 9
5.0	3.0	0.7	10.5	17.3	1.7	17.3	4.3	2.8	11.1	Bloc 19
4.0	2.5	0.7	7.0	11.6	1.7	13.9	3.5	2.0	7.9	Bloc 20
4.0	2.6	1.2	12.5	20.6	1.7	13.9	3.5	1.3	5.3	Bloc 21
6.0	5.0	2.3	69.0	113.9	1.7	20.8	5.2	2.5	9.9	Bloc 25
6.0	5.0	4.0	120.0	198.0	1.7	20.8	5.2	1.5	6.1	Bloc 27
4.0	6.0	2.0	48.0	79.2	1.7	13.9	3.5	3.4	13.6	Bloc 28
5.0	4.6	1.7	39.1	64.5	1.7	17.3	4.3	2.7	10.8	Bloc 33
10.0	3.0	0.9	27.0	44.6	1.7	34.7	8.7	2.2	8.8	Bloc 42

a, *b* and *c* are the boulder axes, *ρs* is the boulder density, Ht and Hs are the tsunami and storm wave heights respectively, and *d* is the coastline distance.

sea level of Laborel and Laborel-Deguen (1994). Finally, the Roman quarries of Tipasa (Fig. 1b) are covered by boulders which suggest that at least one of the flood events took place during post-Roman times.

3.2. East of Algiers (Zemmouri–Boumerdes region)

This coastal area experienced the Mw = 6.8 Zemmouri 2003 tsunamigenic earthquake. However no run-up was observed along the coast and several rapid sea-level variations (<0.4 m) were measured along the western Mediterranean coast (Alasset et al., 2006).

Several mega-blocks were observed to have been deposited 30 to 70 km east of Algiers (see examples B3, B21, B25 and B30 in Fig. 4a). Three of the slabs (B1, B2 and B3, Figs. 1b and 4a) are characterised by marine biogenic incrustations (e.g. balanids and serpulids). The presence of bio-indicators (Vermetids, Balanids and Serpulids) associated with marine erosion features suggest that these blocks were derived from the subtidal zone. In some cases, the boulders were also overturned up to 50 m from the coastline.

At "Les Salines" beach near Dellys two boulder accumulations show significant differences in block size along the coastline (Fig. 4a). East of "Les Salines," the boulders (B25, B27 and B35 characterised by a volume of 69 m^3, 120 m^3 and 135 m^3, respectively) are scattered at a

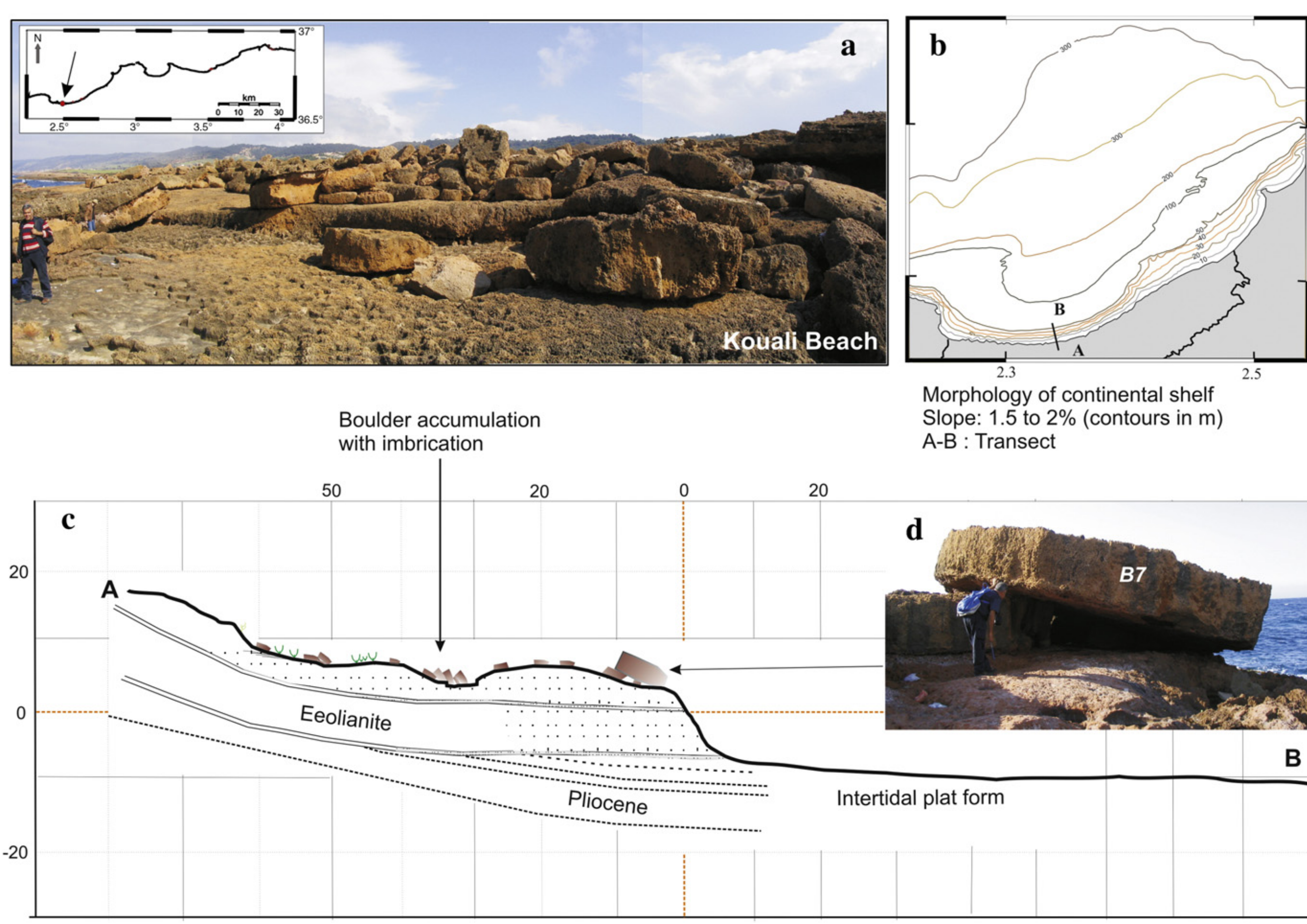

Fig. 3. a - Kouali (Tipasa) boulder accumulation and geomorphical context; b - morphology of the continental shelf showing 1.5 to 2% average slope and location of the A–B Transect (Fig. 3c); c - cross section AB of shoreline with location of boulder accumulation; d - near shore boulder B7 at Kouali Beach.

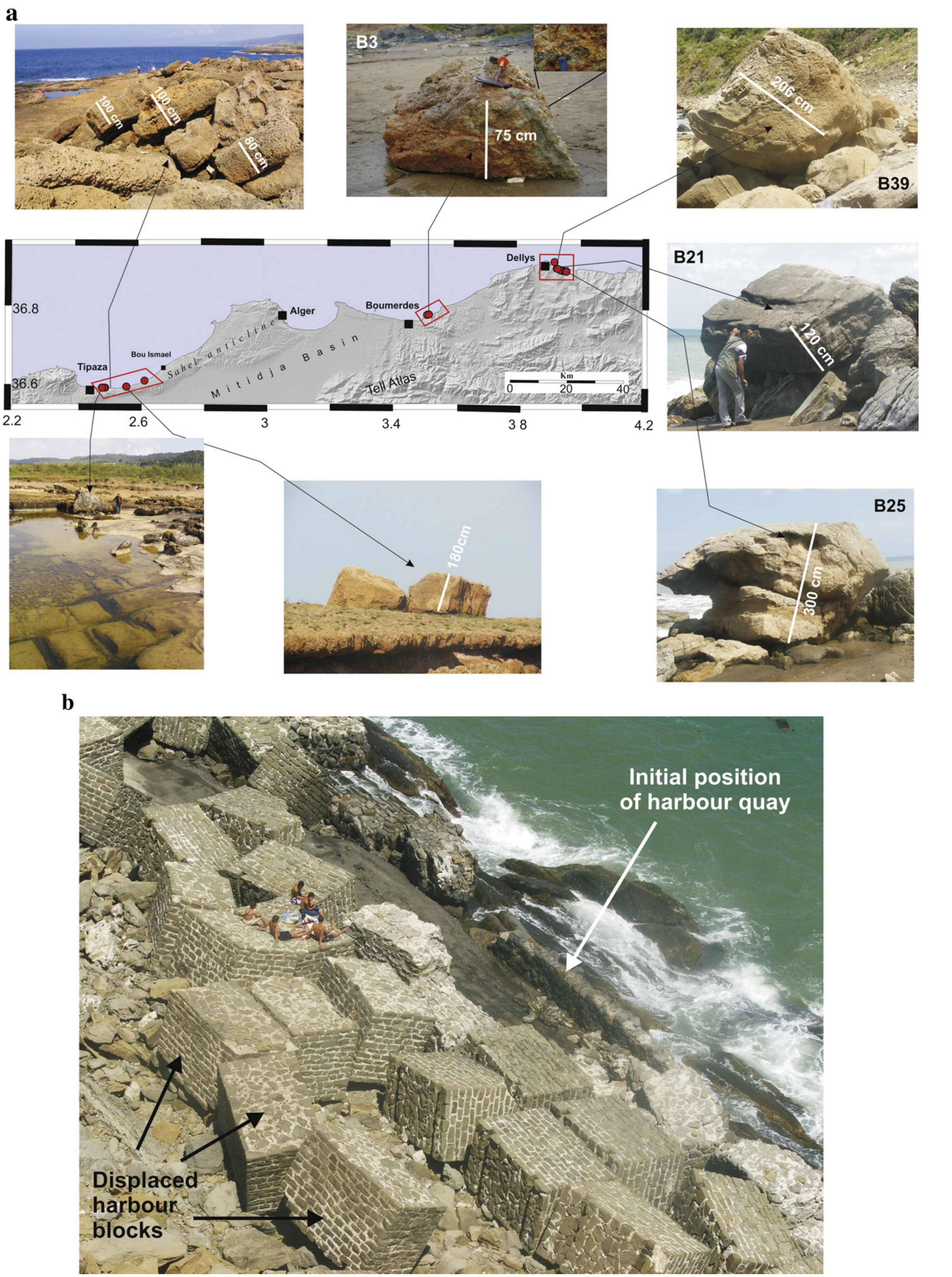

Fig. 4. a - Boulder accumulation deposited at different locations along the Algiers coastline; b - picture showing the destruction of the Dellys Ottoman harbour (Marsa Lekdim) by catastrophic waves, the blocks have been displaced ~2 to ~6 m from their initial position.

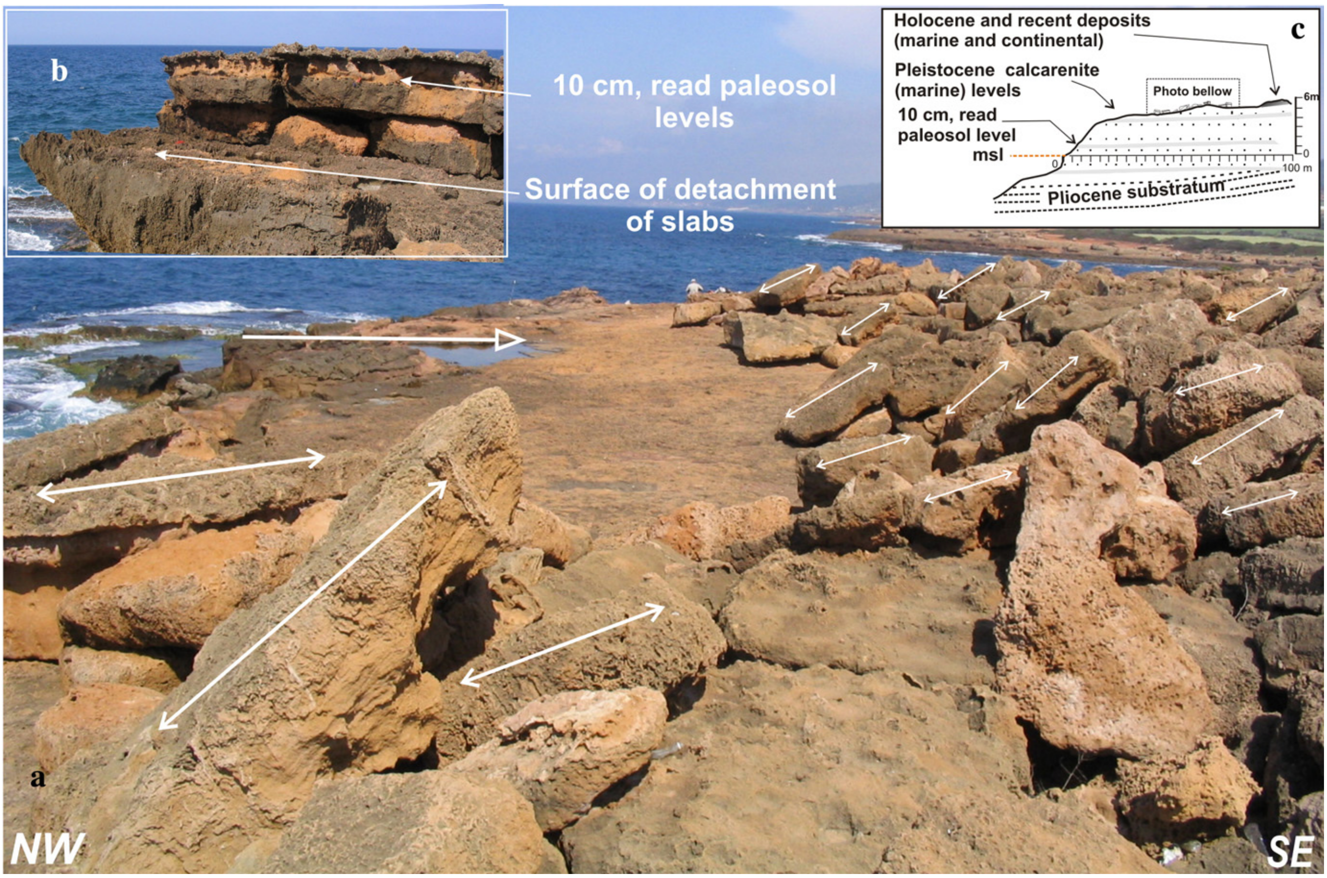

Fig. 5. Example of boulder accumulation at Kouali Beach (see Figs. 1b and 3d); a - boulder accumulation with double arrows as axis orientations; b - detachment zone (subtidal and supratidal); c - cross section showing the local lithological units.

distance of up to 10 m from the coast. The weights range between ~10 and 200 tons. The blocks are imbricated and oriented (*a*-axes) perpendicular to the coast line (mostly in a SE direction). In some areas, the presence of a cliff-line has acted as an obstacle to boulder transport inland.

West of "Les Salines," boulders weighing up to 50 tons lie 30 m from the shoreline and show dispersed "*a*" axes indicating deposition perpendicular to the coastline. Some mega-clasts also show fractures and are covered by balanids, vermetids and serpulids (B19, B20 and B21, Fig. 4a). Other reworked boulders display characteristic supratidal karstic pools on their surfaces.

The damaged quay of the Ottoman harbour of Dellys (Marsa Lekdim, Chaid-Saoudi, 2008) show more than 18 fallen wall blocks with ~1 m^3 in size that attest to 2–6 m of transport (Fig. 4b). The harbour blocks displacement is therefore post-16th century which corresponds to the date of its construction. The dislocation of the harbour by swells and storms (as reported from local archives) and the quay blocks accumulation suggest, by comparison with the nature of boulders, that the displacement and accumulation of large calcareous, calcarenite and sandstone boulders on the coast between Tipasa and Dellys require catastrophic waves or tsunamis.

4. Tsunami or storm deposits?

Several studies of boulder accumulations around the Mediterranean have been carried out (Scheffers and Kelletat, 2003; Mastronuzzi et al., 2006). Extreme wave events inundating low-lying coastal zones are responsible for the transportation and deposition of clasts, cobbles and boulders. The scientific interest in boulder accumulation on the Algerian coast is important in terms of near shore deposits related to palaeo-tsunamis that occurred in the Mediterranean basin as reported in southern Italy, Greece and the eastern Mediterranean Sea (Kelletat and Schellmann, 2002; Mastronuzzi et al., 2006). The carving and transportation of large boulders require specific wave height and energy-level thresholds (Noormets et al., 2004). In this study only the boulders that display high-energy signatures have been selected. These types of deposit are distinguished using the criteria of Nott (1997): (a) the boulders display clear imbrications; (b) the majority of boulders have their *A*-axes aligned perpendicularly to the shoreline direction; (c) the boulders are deposited in such a fashion as to form imbricated boulder trains displaying sorting with distance inland or upslope; (d) the boulders are deposited in preferential locations; and (e) in some cases the boulders have a different lithology to the underlying shore platform and backing sea-cliff, and in several cases the boulders are recognized by the marine sublittoral fauna attached on their surface.

According to Nott (2003), different forces act on a boulder impacted by a wave depending upon the pre-transport position. When submerged, a boulder experiences drag and lift forces when impacted by a wave and it will resist to movement through the force of restraint. In the joint bounded block scenario, the boulder will only experience lift and drag force (Nott, 2003). Moreover, substantial fracturing in the rock body is required in order to extract large clasts from the platform edge (Noormets et al., 2004). In our study, we assume that only blocks that were submerged or joint bounded prior to transportation have been identified. The lithological conditions and fracturing observed in the local sandstone favored the detachment of lithic blocks from their joint bounded position on the shore platform.

We used the formulas of Nott (2003) for the physics of boulder movement, in particular equations for the joint bound and the submerged scenario to calculate wave heights. Because the boulders have always been broken off a hard rock (conglomerate and sandstone

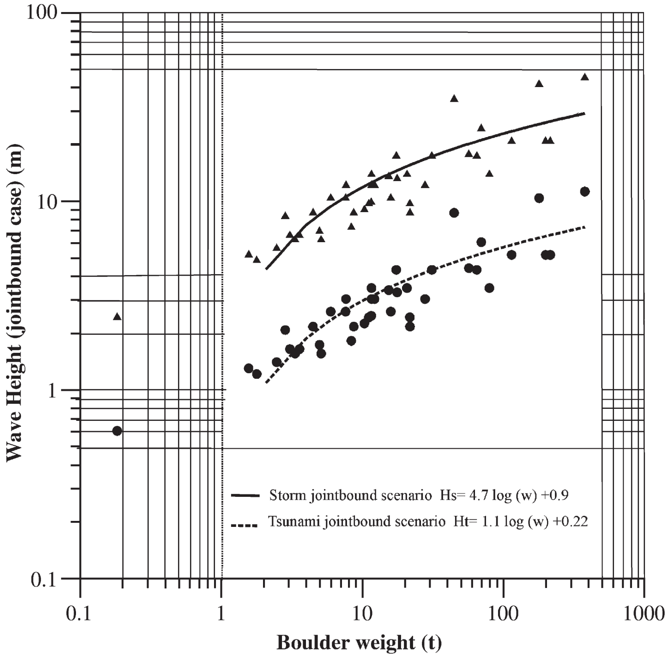

Fig. 6. Storm and tsunami wave height (h) and boulder weight (w) relationships following Nott's standard equations (Nott, 2003). Data of Table 2 given for a tsunami scenario Ht = 1.24 * log(w) − 0.22 and for a storm scenario Hs = 7 * log(w) − 0.9.

stratum), we assume that the joint-bound scenario is more indicative. The result for some examples is presented in Table 2.

1) For a submerged boulder scenario

$$Ht > [0.25\,(\rho s - \rho w/\rho w)2a] / \left[cd\left(ac/b^2\right) + cl\right]$$

$$Hs > [(\rho s - \rho w/\rho w)2a] / \left[cd\left(ac/b^2\right) + cl\right]$$

2) For a joint-bound block scenario, the equations can be simplified as:

$$Ht > [0.25\,(\rho s - \rho w/\rho w)a] / cl$$

$$Hs > [(\rho s - \rho w/\rho w)a] / cl$$

where *Ht* is the tsunami wave height and *Hs* is the storm wave height at a breaking point, ρw is the constant sea water density 1.03 g/ml, ρs the boulder density, *cd* the coefficient of drag (typically 2), *cl* the coefficient of lift (typically 0.178), *a*, *b* and *c* are the boulder axes. The log–linear regressions presented in Fig. 6 describe the wave height characteristics and related boulder transport using our data from Algiers. On the basis of Nott's equations, Table 2 presents the largest boulder size and weight (density = 1.65 g/cm^3) in conjunction with the tsunami and storm wave heights required for their transport. The application of Nott's joint-bound scenario equations to the deposits selected in the Algiers area allowed us to calculate variable storm wave heights ranging from 2.43 m to 45.18 m and tsunami wave heights from 0.6 m to 11.28 m (Table 2). The wave height estimated for the transportation of boulders indicates that tsunami waves only need to be a quarter the size of a storm wave to transport the same size boulder (Fig. 6). Indeed, the largest boulders (>25 tons) that may have undergone an earthquake-induced tsunami for transport need a tsunami wave of 1 to 5-m-high. In contrast, storm-induced transportation of large boulders (>25 tons) requires 20 to 40-m-high waves which are unlikely to occur in the Mediterranean Sea (Wind and Wave Atlas of the Mediterranean Sea, 2004).

5. Dating the boulder depositions

In order to link the boulder deposits to past tsunami events in the western Mediterranean Sea, and particularly on the Algerian coast, radiocarbon ages of marine biogenic incrustations have been compared to historical earthquake catalogues, archives and ancient chronicles for the Mediterranean area. We collected samples of Serpulids, Balanids, Lithophaga and Vermetids from different boulders. The calibration of radiocarbon dates was carried out using the program Calib 5 (Stuiver et al., 2005) for the marine environment with a reservoir age of 468 years and DeltaR = 165 realized offshore Bou Ismail (formerly Castiglione, Fig. 4a; see also http://intcal.qub.ac.uk/marine/index.html). Two groups of samples (B5, B6 and B10, B11) provide the estimated age of boulders deposits. Calendar ages of boulders B5 and B6 are respectively 440–674 AD and 419–661 AD. Sample B9 yielded a recent age (106 years BP), while boulders B10 and B11 were respectively dated to AD 1712 to <1950 and AD 1704 to <1950 (Table 3).

The largest boulders were moved 10 m to 50 m from the shoreline and are located at an average ~30 m distance. Whereas the clear origin of large boulders from the border of the supratidal zone is supported by numerous marine biological incrustations and other geomorphological features, identifying the original location of small boulders is problematic due to the scarcity of ^{14}C datable material (marine bioconstruction) on their surface. There is no difference in the type of incrustation or other features showing different periods of transportation. Indeed, smaller boulders covered sometimes by recent barnacles show more eroded surfaces indicating shoreline transportation possibly during recent storms. This is corroborated by the age of boulder B9 that yielded 106 ± 0.35 years BP. However, surface barnacles and bio-erosion indicate that small and large boulders may have been transported during the same event from the subtidal and/or infratidal zones. The different geomorphological features and sedimentological observations on large boulders suggest that the different biological organisms grew in their natural habitat. These biological organisms must have died just after their displacement beyond the sublittoral zone and the ^{14}C dating results might correspond to the immediate post-transport age. Therefore, it is likely that both groups of data cited above might be related to two high-energy events that occurred in this zone. According to the national meteorological center of Algeria, no large storms have taken place

Table 3
Dating results of shell fragments collected from biogenic incrustations on boulders and calibrated using Calib5 (Stuiver et al., 2005), for the marine environment we use 468 year reservoir age and DeltaR = 165 undertaken at Castiglione (Bou Ismail now) within the range considered by Stuiver et al., 2005; marine shells are characterised by Serpulids, Balanids, Vermetids and boring bivalves (e.g. *Lithophaga*); *d* is the coastline distance.

Long	Lat	Specimen	Laboratory	Lab num	Nature	Sample	Volume (m^3)	Altitude	*d*	C14 age (BP)	Calibration (AD)
2.5678	36.5955	2007-9	Col, Beta Anal,	T1	Marine shell	B5	1.72	4 m	27 m	2000 ± 40	440–674
2.5679	36.5956	2007-10	Col, Beta Anal,	Ti2	Marine shell	B6	4.62	5 m	26 m	2030 ± 40	419–661
2.4983	36.5925	2007-13	Poznań RL	Poz-20873	Marine shell	B9	7	1 m	17 m	106.91 ± 0.35	modern
2.4901	36.5926	2007-14	Poznań RL	Poz-20768	Marine shell	B10	9.6	2 m	50 m	530 ± 30	1704–< 1950
2.4902	36.5925	2007-15	Col, Beta Anal,	Ti3	Marine shell	B11	6.24	2 m	57 m	500 ± 40	1712–< 1950

during the past 100 years, except the events of Skikda, Oran and Algiers (see section 2). The Wind and Wave Atlas of the Mediterranean Sea (2004) indicates a maximum winter swell of ~7 m in the vicinity of Algiers. Therefore, one may conclude that large boulder movements at this site are not related to large storm events but rather to tsunamis. This is attested by the historical seismicity records of Algeria and the tsunami catalogue of the western Mediterranean Sea (Table 1, Ambraseys and Vogt, 1988; Soloviev et al., 2002; Tinti et al., 2004; Harbi et al., 2007a; Maouche et al., 2008) that report the occurrence of large earthquakes (Io ≥ IX, EMS) in 1365, 1716, and 1773, associated with >2 m sea waves; other earthquakes (Io<IX, EMS) took place in 1724, 1755 and 1756 (Table 1).

The seismic history of coastal Algeria and the western Mediterranean Sea is poorly known, in particular that of the pre-1800 period. Tsunamis can derive from either the coastal area of Algeria, southern Spain or the Balearic Islands (Soloviev et al., 2000; Harbi et al., 2007a).

The tsunami dated from samples B10 and B11 (Table 3) may be related to: (1) the large earthquake of 3rd February AD 1716 that induced severe damage and killed more than 20,000 people in the area of Algiers (Ambraseys and Vogt, 1988); or (2) the 6th May AD 1773 earthquake that generated ~2-m-high tsunami waves (Harbi et al., 2007a). Bearing in mind the regional seismotectonic context of the western Mediterranean region, the tsunami events of AD 1522, AD 1680 and AD 1804 (Soloviev et al., 2000) might also have been generated from seismic sources of southeast Spain. According to Gracia et al. (2006) the 50-km-long offshore extension of the NE–SW trending Carboneras fault is a potential source of large magnitude earthquakes (Mw ~7.2), possibly responsible for the AD 1522 tsunami. Therefore, major earthquakes in the western Mediterranean, particularly off SE Spain may generate tsunamis responsible for boulder deposition on the coasts of Algeria and Morocco.

6. Discussion

The impact of tsunamis on coasts has been neglected in coastal geomorphology, even though low-frequency large magnitude events have played an important role in coastal morphogenesis (Dawson and Shi, 2000; Scheffers and Kelletat, 2003). This is particularly true for the Algerian coast that is located along active seismogenic structures and plate boundaries and therefore prone to tsunami flooding. Using field observations along the coastal zone of Algiers and characteristics of more than 100 boulders, we have identified historical tsunami deposits at circa AD 419 and circa AD 1700. Although no historical accounts report these events so far, seismic sources of these tsunamis may be related to earthquake faults off the Algerian coast or from the tectonically active zones of SE Spain. Further field investigations and the study of palaeo-tsunamis deposits and historical documents are, however, needed to complete the historical tsunami catalogue for the region.

This study suggests that the deposition of the biggest boulders can be attributed to tsunami events and not to storm waves. In particular, the boulders' weight and physical dimensions suggest that the Algiers coastal area was struck by consecutive tsunami waves coming from the NW. A well documented tsunami event with sea wave >2 m is the AD 1365 Algiers earthquake that struck the city and caused severe damage in the region (Delphin, 1922; Ambraseys and Vogt, 1988; Al Djillali, 1995). The high-energy coastal deposits indicate that the region has been affected by historical tsunamis triggered by earthquakes that occurred in the Mediterranean Sea near the Algerian coast and also by regional earthquake activity (western Mediterranean Sea, southern Spain). The 1856 Djidjelli earthquake, which also affected the Balearic Islands, Sardinia and southern France is a good example of a large offshore tsunami event (Ambraseys, 1982).

Recent studies (Noormets et al., 2004; Scheffers, 2005) demonstrate that the impact of extreme storm waves is less effective than tsunami waves in the detachment and transport of large boulders. In particular, Noormets et al. (2004) indicate that tsunamis are capable of quarrying large boulders, provided that: (1) sufficient initial fracturing is present; and (2) erosive action on the outcrop is long enough; or (3) that boulders already exist in the nearshore zone. Moreover, tsunamis can mobilize an impressive amount of material, in contrast to storm waves that only cause the detachment and transport of isolated boulders. Our study of a large number of mobilized boulders, allied with their great weight and position along the Algiers coastline, implies a tsunami origin. Hydrodynamic calculations were made using the equations of Nott (2003) and indicate a tsunami wave height for the largest boulders ranging from ~5 to more than 10 m (Table 2). By contrast, the mobilization of such large boulders requires wind-breaking (storm) waves of 20 to 40 m wave height.

7. Conclusions

Large boulder accumulations along the coastal area of Algiers characterise the rocky morphology zones and imply the existence of large and possibly catastrophic sea waves in the past. Field evidence shows the presence of large and small boulders in several areas along the shoreline between Tipaza and Dellys. An analysis of physical parameters such as the size, weight and boulder distribution, coupled with a comparison of other studies in the Mediterranean Sea, suggests storm or tsunami origin for waves. The radiocarbon results highlight two groups of boulders dated to around AD 419 and AD 1700. The large and small boulders studied using Nott's equation reveal a difference between the storm-induced and tsunami-induced block deposition along the shoreline. The earthquake catalogue of Algeria indicates two destructive earthquakes in 1716 and 1773 which are the best candidates for the generation of the AD 1700 tsunami event. A second finding is the dating of boulders to around AD 419, for which there is apparently no historical account in Algeria. Tsunamigenic sources off SE Spain and the Balearic islands may be responsible for boulder deposition on the coasts of Algeria and Morocco. Further studies of coastal boulders and palaeo-tsunamis will help to improve our understanding of tsunami hazards and coastal vulnerability in the western Mediterranean Sea.

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