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Assessing enigmatic boulder deposits in NE Aegean Sea: importance of historical sources as tool to support hydrodynamic equations

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Abstract. Due to their importance in the assessment of coastal hazards, several studies have focused on geomorphological and sedimentological field evidence of catastrophic wave impacts related to historical tsunami events. Among them, many authors used boulder fields as important indicators of past tsunamis, especially in the Mediterranean Sea. The aim of this study was to understand the mechanism of deposition of clusters of large boulders, consisting of beachrock slabs, which were found on the southern coasts of Lesvos Island (NE Aegean Sea). Methods to infer the origin of boulder deposits (tsunami vs. storm wave) are often based on hydrodynamic models even if different environmental complexities are difficult to be incorporated into numerical models. In this study, hydrodynamic equations did not provide unequivocal indication of the mechanism responsible for boulder deposition in the study area. Further analyses, ranging from geomorphologic to seismotectonic data, indicated a tsunami as the most likely cause of displacement of the boulders but still do not allow to totally exclude the extreme storm origin. Additional historical investigations (based on tsunami catalogues, historical photos and aged inhabitants interviews) indicated that the boulders are likely to have been deposited by the tsunami triggered by the 6.7 M_s Chios-Karaburum earthquake of 1949 or, alternatively, by minor effects of the destructive tsunami produced by 1956's Amorgos Island earthquake. Results of this study point out that, at Mediterranean scale, to flank numerical models with the huge amount of the available historical data become a crucial tool in terms of prevention policies related to catastrophic coastal events.

1 Introduction

Due to the worldwide growth of coastal urbanization, assessment of coastal hazards related to the impact of low frequency-high magnitude events became a fundamental task. With this purpose, several recent studies focused on geomorphological and sedimentological field evidence of catastrophic wave impacts related to historical tsunami events (De Martini et al., 2010; Dominey-Howes, 2002; Goto et al., 2010; Mastronuzzi et al., 2006, 2007; Regnauld et al., 2010; Scheffers and Kellettat, 2003; Scheffers et al., 2007; Vött et al., 2009).

Tsunami deposits have characteristics in common with other kinds of deposits settled by different events. In fact, extreme storms or hurricanes have often been used as alternative interpretations, because their wave energy can be comparable to that of tsunamis (Noormets et al., 2002, 2004). The distinction between tsunami and extreme storm deposits remains a difficult task, addressed by several authors (Barbano et al., 2010; Benner et al., 2010; Goto et al., 2010; Nandasena et al., 2011; Regnauld et al., 2010). However, this distinction is easier in a relatively enclosed basin such as the Mediterranean mainly due to the relatively low waves regime (Mastronuzzi et al., 2006). Among various kinds of deposits, boulder fields represent the most striking geomorphologic evidence of catastrophic events on the coast. Nevertheless, their use as markers of past tsunamis is still debated in literature, mainly with respect to the mechanism of their deposition (Regnauld et al., 2010). In fact, identification of boulders displaced and transported by tsunami or exceptional storm waves plays a crucial role in the assessment of the occurrence of past catastrophic events (Goto et al., 2009). Methods to infer the origin of boulder fields (tsunami vs. storm wave) are presently based on hydrodynamic models (Benner et al., 2010; Goto et al., 2010; Nandasena et al., 2011; Nott, 2003a, b; Pignatelli et al., 2009) and supported by morphological and structural considerations (Goto et al., 2009; Mastronuzzi et al., 2006; Noormets et al., 2002).

In the Mediterranean, historical tsunamis were often reported as consequences of destructive earthquakes and volcanic eruptions (Soloviev et al., 2000). The Aegean sea (eastern Mediterranean), being among the most seismically active regions in the world, has been strongly affected by tsunami in historical times (Papadopoulos, 2009). Hence, geomorphologic and sedimentary records of tsunamis have been described in several areas of the Aegean basin (Dominey-Howes, 2002; Papadopoulos, 2009; Scheffers and Kellettat, 2003).

The aim of this study was to understand the mechanism of deposition of clusters of large boulders (weighing up to 17 tons) which were found on the southern coasts of Lesvos Island (NE Aegean Sea). In order to solve issues dealing with equivocal results of hydrodynamic equations in the study area, a methodology of integrating equations with geomorphological and historical data has been employed to obtain more reliable results.

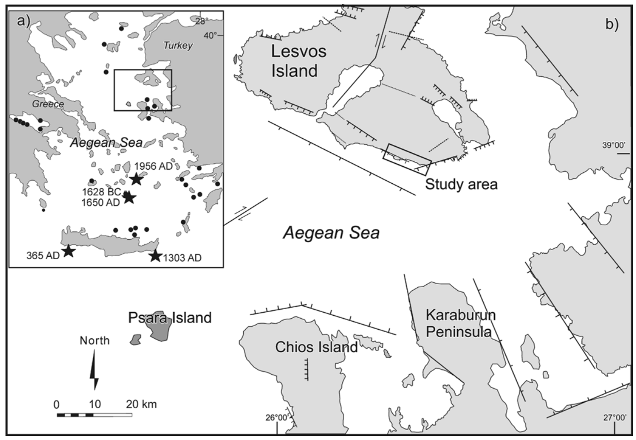

Fig. 1. **(a)** Indicative locations of historical tsunamogenic sources in the broad Aegean area according to Soloviev (1990); Yolsal et al. (2007) and Okal et al. (2009); black stars indicate location and year of the most destructive events. **(b)** Geographical location and simplified tectonic setting of the study area modified from Mascle and Martin (1990) and Pavlides et al. (2009).

1.1 Geological setting

Intense faulting, massive crustal consumption, compressional and extensional plate motions, plate subsidence and volcanic activity are the main components of the complex geotectonic setting of the Aegean region (Dominey-Howes, 2002). Consequently, in this area many large and destructive earthquakes, volcanic eruptions and associated tsunamis have been registered since historical times. In particular, catastrophic waves were generated by the activity of Santorini volcano (1628 BC; 1650 AD) and by large earthquakes in Crete (365 an 1303 AD) and, recently, in Amorgos Island (1956 AD) (Papadopoulos, 2009) (Fig. 1a).

The study area is located in the North Eastern Aegean Sea (Fig. 1a) and its geodynamic status is directly affected both by westward continuation in the Aegean Sea of the North Anatolian Fault Zone (North Aegean Trough) and the West Anatolia Graben System in Asia Minor, with significant historical seismicity (Papazachos and Papazachou, 1997). As a result, the current tectonics of the broad Lesvos area (Fig. 1b) is characterized by the activity of both normal and strike-slip faults (Roumelioti et al., 2011).

1.2 Study area

Lesvos Island (NE Aegean Sea) is the third largest Greek island, covering an area of about 1630 km^2 and bordered by ∼350 km of coastlines (Rovere et al., 2011). The study area is located in the southeastern part of the island (Fig. 1b), near the villages of Plomari and Agios Isidoros. There, the coastline is composed by cliffs alternating with sandy to gravel beaches, often showing beachrock occurrence. The bedrock lithologies are mainly Triassic schists and limestones. Southern Lesvos is generally characterized by a relatively low wave regime because of the protection from the main swells of the Aegean Sea generated by northern winds (Soukissian et al., 2002, 2007). Local studies carried out in the southeastern sector reported maximum fetches slightly exceeding 150 km (Vousdoukas et al., 2009a) and main waves (coming from SE) reaching maximum off-shore wave height of about 1.8 m (Medatlas, 2004; Vousdoukas et al., 2009b).

The whole Lesvos is affected by significant active faults (Pavlides et al., 2009) located both onshore and offshore (Mascle and Martin, 1990). Those located at the southern coast of the island are among the most significant ones: according to their length, their seismic sources and their geometry, a maximum earthquake potential of about 6.6–6.8 M_s was calculated for these faults (Pavlides et al., 2009; Vacchi et al., 2012).

2 Material and methods

Positions and dimensions of the boulders were measured in the study area during three field campaigns carried out in September 2009 and October 2011. Positions were surveyed using a Trimble Juno GPS with external Pathfinder Xh antenna (positioning error < 1 m) and values of the a-, b-, and c-axes of the boulders were measured in order to calculate their volume (Scicchitano et al., 2007). Weight was obtained by multiplying the volume by the density measured with laboratory analyses carried out on fragments of boulders sampled in the field (Barbano et al., 2010). Orientations of the a-axis of the elongated boulders, as well as the distances and elevation of boulders from the shoreline were also measured (following the methodology proposed by Goto et al., 2009; Mastronuzzi and Sansò 2004; Scicchitano et al., 2007).

Detailed mapping of the boulders is the basis for the application of hydrodynamic approaches (Regnauld et al., 2010), that provide a theoretical model for estimating the storm (H_s) or tsunami (H_t) wave height necessary to displace the boulder, starting from different original settings. For this reason, direct observations of small scale geomorphic features of boulders (presence of biogenic encrustation, karst pools, etc.) were carried out in order to define the pre-transport setting (sub aerial., joint bounded or submerged scenario) (Mastronuzzi et al., 2006). As various seafloor features (fracturing, presence of channel and cracks etc.) play a key role in the assessment of the typology of boulder displacement and transport (Pignatelli et al., 2009), seven scuba transects were carried out perpendicular to the shoreline down to −15 m, in order to characterize the underwater morphology of the nearshore zone.

Although the hydrodynamic approach developed by Nott (Nott, 2003a, b) has commonly been used to quantify the waves necessary to displace the boulders in Mediterranean areas (Maouche et al., 2009; Mastronuzzi and Sansò, 2004; Mastronuzzi et al., 2006; Scicchitano et al., 2007), issues about its applicability have been recently raised by Benner et al. (2010), Goto et al. (2009, 2010), Nandasena et al. (2011). For this reason, we processed boulders data using two recently published hydrodynamic approaches (Benner et al., 2010; Pignatelli et al., 2009) both of which make significant advancements with respect to Nott's original approach. The following equations were thus used:

For a submerged pre-transport scenario (SMBS) (Benner et al., 2010):

$$H_t \geq \{0.5\mathrm{bc}[\mathrm{b}g(\rho_s-\rho_w)/\rho_w-\rho_s C_m uc\,(\rho_w g)\}/C_D \mathrm{c}^2+C_L \mathrm{b}^2 \quad (1)$$

$$H_s \geq \{2\mathrm{bc}[\mathrm{b}g(\rho_s-\rho_w)/\rho_w-\rho_s C_m uc\,(\rho_w g)\}/C_D \mathrm{c}^2+C_L \mathrm{b}^2 \quad (2)$$

For a Joint bounded boulder scenario (JBBS) (Pignatelli et al., 2009)

$$H_s \geq [2\mathrm{c}(\rho_s-\rho_w/\rho_w)]/C_L \quad (3)$$

$$H_t \geq [0.25\mathrm{c}(\rho_s-\rho_w/\rho_w)]/C_L \quad (4)$$

where a, b and c are the axis of the boulder, ρ_w is the density of water (1.03 g ml^{-1}), ρ_s is the density of boulder = 2.6, C_m and C_D are the mass coefficient = 1 and the coefficient of drag = 1.2, respectively, C_L is the coefficient of lift (typically 0.178), $g = 9.81$ m s^{-1} (Benner et al., 2010; Pignatelli et al., 2009).

In order to gather chronological constraints for the deposition event, AMS ^{14}C radiocarbon age determinations were performed on marine biological encrustations (Suerc Radiocarbon Lab., Glasgow, UK) and historical insights were obtained by interviews of local people and analysis of historical photographs.

Fig. 2. Topographic sketch of the surveyed sites; **(a)** and **(b)** examples of large boulders mapped in the site of Plomari; **(c)** and **(d)** examples of large boulders mapped in the site of Agios Isidoros.

3 Results

3.1 Boulder characteristics

A total of 47 boulders were found in the study area. Some of them are organized in clusters, others are scattered along the shoreline (Fig. 2). After a first general mapping, more detailed surveys were carried out on the 26 boulders with a major axis ≥1 m (Table 1). No significant differences in boulder position were noticed among the 2009, 2010 and 2011 survey.

The boulders consisted of beachrock slabs (Fig. 2) of which the unit weight was calculated in 2.6 t m^{-3}. The boulders had a maximum size of 4.5 × 2.5 × 0.6 m with a volume of about 7 m^{3}and a maximum weight of about 17 t (P 15, Table 1). Some peculiar features are constant on the majority of the beachrock boulders:

i. the boulders are scattered up to about 20 m from the shoreline and their elevation does not exceed 0.5 m above the mean sea level;

ii. most boulders are upside down, as proved by erosive features normally cut upon the upper surface of a beachrock and presently facing the ground (Fig. 2a and d);

Table 1. Structural features of the 32 boulders showing an axis ≥1 m and relative H_s and H_t values calculated with the hydrodynamic equations (Benner et al., 2010; Pignatelli et al., 2009).

Boulder	a (m)	b (m)	c (m)	Vol. (m^3)	Weight (t)	Distance (m)	height a.s.l. (m)	Submerged boulder scenario (SMBS)	
								H_t	H_s
I1	1.85	1.3	0.2	0.5	1.3	0	0	0.8	3.4
I2	1.7	1.3	0.2	0.4	1.1	0	0	0.8	3.4
I4	2.6	1.6	0.3	1.2	3.2	0	0	1.2	4.7
I5	1.3	1	0.3	0.4	1.0	0	0	0.9	3.4
I6	3.1	2.1	0.3	1.9	5.1	1.0	0	1.3	5.2
I7	2	1.2	0.2	0.5	1.2	4.1	0.2	0.8	3.3
P2	1.4	1.2	0.25	0.4	1.1	11.0	0.4	0.9	3.7
P4	2.1	1.4	0.2	0.6	1.5	0	0.4	0.9	3.5
P6	1.7	0.9	0.2	0.3	0.8	18.7	0.4	0.7	2.9
P9	1.6	1.3	0.4	0.8	2.2	10	0.4	1.1	4.5
P10	3.5	2.2	0.7	5.4	14.0	14	0.4	1.9	7.6
P11	2.1	1	0.4	0.8	2.2	11.1	0.4	0.8	3.4
P13	2	1	0.4	0.8	2.1	7.0	0.4	0.8	3.4
P14	1.2	1.2	0.3	0.4	1.1	7.0	0.4	1.0	4.0
P15	4.5	2.5	0.6	6.7	17.6	8.0	0.4	2.0	8.1
P16	1.2	1.5	0.4	0.7	1.9	9.0	0.4	1.3	5.0
								Joint bounded boulder scenario (JBBS)	
								H_t	H_s
I3	2.5	1.9	0.6	2.8	7.4	0	0	2.6	10.4
I8	1.1	0.5	0.4	0.2	0.6	8.0	0.3	2.0	7.8
I9	2.9	2.7	0.5	3.9	10.2	0	0	2.2	8.7
I10	2.5	1.8	0.4	2.0	5.3	4.5	0	2.0	7.8
P1	1.6	0.8	0.4	0.5	1.3	6.7	0.4	1.7	7.0
P3	2.4	1.3	0.4	1.2	3.2	13.0	0.4	1.7	7.0
P5	1.1	0.9	0.5	0.5	1.3	11.0	0.4	2.2	8.7
P7	1.1	0.5	0.3	0.2	0.5	15.0	0.4	1.5	6.1
P8	1.1	0.9	0.4	0.4	1.2	15.9	0.4	2.0	7.8
P12	2.0	1.5	0.5	1.5	3.9	13.9	0.4	2.2	8.7

iii. several boulders, especially in the area of Agios Isidoros, are completely buried in the sand (Fig. 2c).

The presence of biogenic encrustations (mainly vermetids and serpulids) suggested a mid-sublittoral pre-transport position of the boulders (as these organisms usually live within this environment: Laborel, 1987).

These settings were validated by the underwater transects carried out along the whole seaward extension of the beachrock outcrop: the high degree of fracturing coupled with the presence of scattered broken pieces at the seaward edge of the beachrock outcrop (about −3 m depth) confirmed the hypothesis of an original submerged position (SMBS) or a submerged joint bounded scenario (JBBS). In fact, geometrical analysis of the boulders and of large holes in the submerged part of the beachrock itself often revealed a close correspondence between the shapes of the boulders and the shapes of the holes (Fig. 3a). When this correspondence was recognized on the field, boulders were processed using the JBBS equation; in the remaining cases, boulders were processed using SMBS equation (see methods, Table 1).

On the basis of the individuated pre-transport settings, values of storm wave height (H_s) and tsunami wave height (H_t) theoretically required for the boulder displacement were calculated (Table 1).

Mapping of the a-axis of the boulders did not reveal a defined pattern of orientation. The frequency of a-axis directions indicated a sector between 130 and 220° N (Fig. 3b). The largest boulders are often almost perpendicular to the shoreline (170 to 200° N).

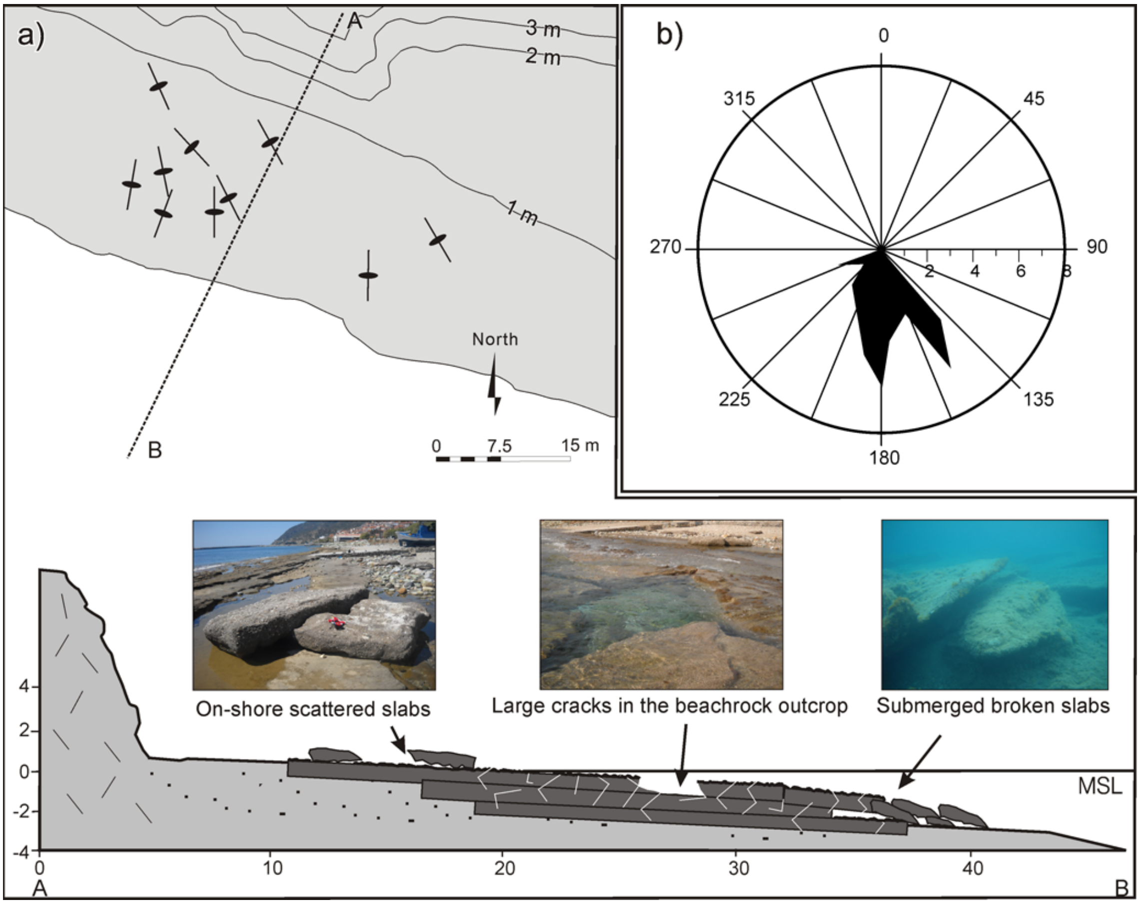

Fig. 3. **(a)** A-axis orientation and schematic sketch of deposition pattern of a cluster of boulder in Plomari: elevation and distance are expressed in meters. **(b)** Frequency of a-axis direction of the mapped boulders.

3.2 Exceptional storm waves or tsunami?

For the submerged boulders (SMBS), the calculated maximum storm wave values (H_s) slightly exceeded 8 m whereas for the joint bounded boulders (JBBS) H_s values reached maximum values of about 10 m (Table 1). The Aegean Sea is characterized by relatively short fetch and relatively small swells, mainly generated from northern winds (Soukissian et al., 2007). It is very unlikely that waves exceeding 9–10 m could be generated in this sector of the Aegean, especially in a south-facing area. In addition, southern waves affecting the southeastern sector of Lesvos are characterized by maximum fetches of about 100 nautical miles and by maximum off-shore significant wave height (H_s) not exceeding 2 m (Medatlas, 2004). However, the possibility that extreme events caused the displacement of the boulders was tested using the wave data available for the Aegean Sea (Medatlas, 2004; Soukissian et al., 2007; Derebay, 2007; http://poseidon.hcmr.gr/). Statistical models proposed by Inghilesi et al. (2003) and Persson and Rydén (2010) allowed for the calculation of off-shore wave heights (H_0) and period (T_0) values with long return period (50–100 yr). The results provided values of H_0 and T_0 ranging respectively from ∼4.5 to ∼6.5 m and ∼9 to ∼11 s (50 to 100 yr return time). These wave parameters are in agreement with those proposed in the long term forecasting (based on 10-yr wind and wave observations) proposed in the Wind wave atlas of the Hellenic seas (Soukissian et al., 2007).

In order to test if the hydrodynamic equations applied to the largest boulders produced H_s values compatible with extreme storm events, we processed the long term wave parameter to calculate the wave heights at breaking point (H_b) using the following equation

$$H_b/H_0 = (\tan\beta)^{0.2}(H_0/L_0) \quad \text{(Sunamura and Horikawa, 1974)} \qquad (5)$$

where H_0 is the off-shore wave height, L_0 the wave length ($L_0 = gT^2/2\pi$), β is the mean slope of the seafloor deduced merging the official bathymetry of the Hellenic seas (Greek Navy Hydrographic Office) with the detailed underwater profiles carried out through SCUBA transects. The average mean slope ranges from 2° and 2.5° from −30 m depth to the shoreline.

According to these results, H_b values with long return periods (50–100 yr) in this sector are between 7.5 and 8 m, only slightly less than the values calculated with the hydrodynamic equations (Table 1). Thus, even if the equations calculated storm wave heights (H_s) exceeding 8 m, hydrodynamic results did not provide unquestionable evidence allowing to exclude one between extreme storm or tsunami wave as depositional mechanism.

Hydrodynamic approaches have been often used as a tool to discriminate boulders deposited by tsunami or storm waves (Barbano et al., 2010; Maouche et al., 2009; Mastronuzzi and Sansò, 2004; Scicchitano et al., 2007) even if local seafloor morphology, initial setting of the boulder and type of waves could produce complexities that are difficult to incorporate into hydrodynamic models (Goto et al., 2010). Therefore, further observations focused on geomorphological indicators and on seismotectonic sources must be considered in order to test the reliability of both hypotheses:

i. the geomorphological and lithostructural settings of the coastal area play a crucial role in boulder detachment and transport by catastrophic waves (Noormets et al., 2004). Mastronuzzi et al. (2006) indicated the presence of layered units and bedrock fracturing as important preconditions for boulder displacement. Coastal sectors characterized by beachrocks and affected by tsunami wave impact often show on-shore broken slab accumulation (Nott, 2004; Vött et al., 2009; Scheffers and Scheffers, 2007). In the study area, the slabs were probably torn out from the original beachrock unit which appears considerably fractured (Fig. 3a). Moreover, on the majority of boulders, a fragile layer of biogenic encrustation was observed. Its preservation is a clear indicator of short transport generated by a single wave (Mastronuzzi et al., 2006). Such single pulse transport is also suggested by the primary position of the biggest boulders, as confirmed by the strict correlation between the geometry of the large holes observed underwater and the polarity of displaced boulders (Noormets et al., 2002). However, a large storm wave, amplified by topographic factors, could also act as single pulse wave. In addition, in presence of large fracturing, both tsunamis and large storm waves are capable of quarrying large boulders (Noormets et al., 2002, 2004) but tsunamis are more likely to displace and transport such boulders onto the coastal platform because of the longer duration of the wave action (Mastronuzzi et al., 2006);

ii. significant additional information was provided by the literature dealing with Mediterranean regions most frequently affected by tsunamis (Altinok and Ersoy, 2000; Altinok et al., 2011; Papadopoulos and Chalkis, 1984; Papadopoulos and Foakefs, 2005; Soloviev et al., 2000; Yolsal et al., 2007). These papers provide spatial distribution of tsunami hazard in the Aegean area based on the historical occurrence of tsunami events as well as on the triggering seismic sources. The area located among Chios, Lesvos and Karaburum peninsula (Fig. 6) was included in the first-degree hazard zone in the Official Earthquake Hazard Regionalization map of Turkey and its seismic activity is currently increasing (Altinok et al., 2005). Destructive earthquakes and related tsunamis in this area have been reported by several authors (Papazachos and Papazachou, 1997; Altinok et al., 2005, 2011) and, on the basis of the distribution of tsunamogenic earthquakes, southern Lesvos was listed as a tsunami affected area (Fig. 4) (Papadopoulos and Chalkis, 1984; Papadopoulos and Foakefs, 2005; Yolsal et al., 2007);

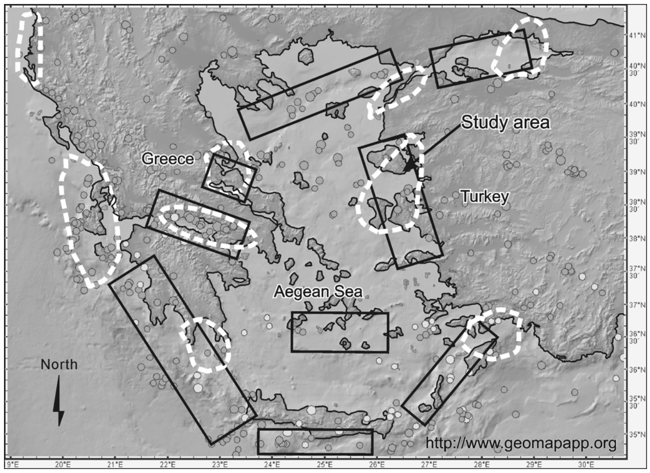

Fig. 4. Tsunamogenic zones in the broad Greek area. Black squares are redrawn after Papadopoulos and Foakefs (2005) and Yolsal et al. (2007) whereas white dashed lines after Papadopoulos and Chalkis (1984). Dots indicate location and epicenter depth (grey ≤ 50 km; white 50–200 km) of recent earthquakes ($M \geq 5$; 1964–1995) modified from http://www.geomapapp.org.

iii. further indications can be gathered by subdividing the a-axis orientation of the boulders on the basis of the relative H_s values. Most of the boulders presenting H_s values exceeding 7.5 m (i.e. not compatible with calculated extreme storm events) have their elongated axis almost perpendicular to the shoreline oriented between 170° N and 200° N. However, other boulders are oriented mainly between 130° and 150° N (Fig. 6), which is the direction of the major swells in the area (Vousdoukas et al., 2009a, b). This orientation pattern reflects a scheme already recognized in other Mediterranean boulder accumulations (Mastronuzzi and Sansò, 2004; Scicchitano et al., 2007) and was explained with re-orientation by storm waves after a tsunami event.

Based on the previous considerations, we assume that a single tsunami wave displaced all the boulders from the submerged position to the shore. Subsequent storm wave events, coming from S–SE, affected the deposited boulders but were able to re-orient only the smaller ones.

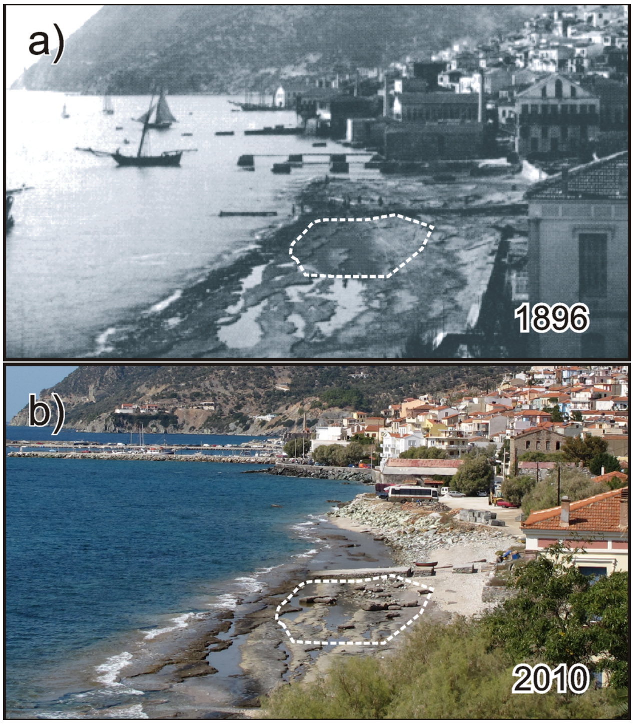

Fig. 5. Plomari in the 1896 **(a)** and today **(b)**. Boulder deposits are missing in the 1896's photograph. The 1896's photo is extracted from the book "Maritime tradition, boatyards and wooden vessels" (To Polion, 2010).

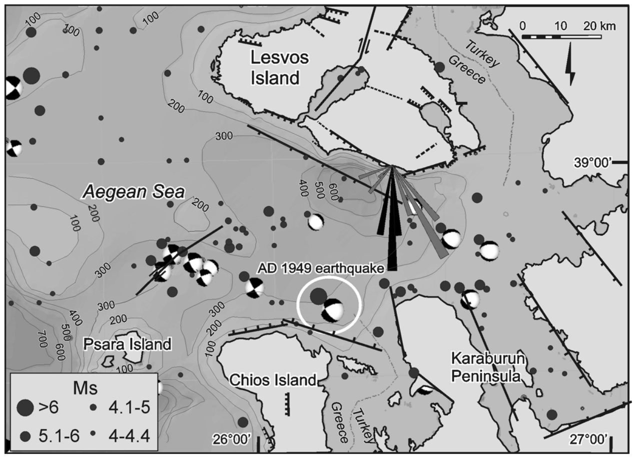

Fig. 6. Epicenter location and focal mechanism of the $M_S > 4$ earthquakes after the 1928 in the study area (data modified from http://naseismic.geo.aegean.gr/). White circle indicates the 1949's $M_S = 6.7$ event triggering a tsunami wave recorded in Chios and in the Karaburun peninsula. The map also shows the a axis orientation of the larger (black) and smaller (grey) boulders. Faults are modified after Mascle and Martin (1990) and Pavlides et al. (2009).

This integrated approach, ranging from geomorphological to seismotectonic data, indicated a tsunami as the most likely cause of displacement of the boulders but still does not allow to totally exclude the extreme storm origin.

3.3 Historical investigations and chronological constraints of the event

At Mediterranean scale, historical sources represent a key tool in tsunami-related research (De Martini et al., 2010; Papadopoulos and Foakefs, 2005). Very detailed catalogues (about 300 events) are available starting from about 1000 BC (Papazachos and Dimitriou, 1991; Yolsal et al., 2007; Soloviev et al., 2000). Among them, a major focus is represented by Greece and the surrounding area where catalogues (enriched with information from Greek, Byzantine, Arabic, and Latin texts) were compiled by several authors including only the reliably known major tsunamis with names, epicentral distances and intensity (Altinok et al., 2005; Papadopoulos, 2009; Papadopoulos and Foakefs, 2005; Papazachos and Papazachou, 1997).

The high seismic activity affecting the NE Aegean Sea often triggered tsunami waves that caused damage to the surrounding coastal areas (Altinok et al., 2011). For the area located among Lesvos, Chios and Karaburum peninsula, historical data are available on six main events which took place on 20 March 1389, 24 November 1772, 13 November 1856, 19 January 1866, 3 April 1881 and 23 July 1949 (Altinok et al., 2005; Soloviev et al., 2000).

Therefore, AMS ^{14}C radiocarbon dating was performed on two samples of biological encrustation (*Vermetidae* spp., boulder P15 and *Serpulidae* spp., boulder I9) trying to collocate chronologically the boulder displacement (Table 2). The obtained ages did not completely solve our issues because they only indicated that both samples were of recent origin (Table 2) and probably close to 1950. Because of this, we carried out an historical investigation, which was made with the help of the local cultural association of Plomari. Interviews of aged inhabitants of the village confirmed the sudden appearance of the boulders on the shoreline but the people who were interviewed could not recall precise dates. In addition, further data were obtained by using an historical photograph of Plomari taken in 1896. In the same area where boulders are presently found, the photograph shows no traces of deposited material (Fig. 5).

This photograph allows us to place another chronological constrain on the date of the boulders deposition. In 1896 there is no evidence of scattered broken beachrock slabs on the shoreline. This is consistent with the theory of a single pulse wave as the depositional mechanism as opposed to a continuous action of the waves on the beachrock outcrops. Furthermore, major swells (events longer than a single tsunami wave) with waves higher than 8 m were not remembered by the aged inhabitants of Plomari and were not retrievable in the historical waves database (Soukissian et al., 2007). These historical data corroborated the tsunami hypothesis and ruled out extreme storms as the cause of

Table 2. AMS ^{14}C dating results. Both samples yielded modern age.

Sample ID	Boulder n. (see Table 1)	Lab. N.	Specimen	δ^{13} ‰	Fraction modern carbon
Plo	P15	27340	*Vermetidae* spp.	−2.6	1.0088 ± 0.0032
Vag	I9	27341	*Serpulidae* spp.	0.4	1.0713 ± 0.0038

transport and displacement of the boulders; according to the photographic documentation, the tsunami event cannot be earlier than the year 1896.

In 1949, the Chios-Karaburum earthquake $M_s = 6.7$ (Papazachos and Papazachou, 1997) was registered offshore of Chios Island (location of the epicenter, Fig. 6, Altinok et al., 2005) at about 40 km from Plomari. In this date, historical reports describe a tsunami wave affecting both the Turkish coast (town of Çeşme) and the Greek one where significant flooding was observed in the Chios beaches (Altinok et al., 2005, 2011).

The elongated a-axis of the mapped largest boulders is reasonably compatible with the 1949 event (Fig. 6) that was characterized by a tsunami wave height (H_t) of about 2 m. This value fits with the tsunami wave height (H_t) calculated for the largest boulders (Table 1). In fact, Altinok et al. (2005) and Papadopoulos (2009) report tsunami intensity ranging between III and IV of Papadopoulos and Imamura scale. According to this 12-points intensity scale, the wave could have been observed by the people on the coast but it would not have been able to damage the buildings. The absence of damages could explain why the aged inhabitants of Plomari were not able to recall the precise date of the tsunami.

Therefore, the 1949 event could have been responsible for the boulders deposition. However, we cannot completely exclude the possibility that the tsunami wave was triggered by one of several seismic events which occurred in the last century and are listed in the earthquakes catalogs of this sector of the Aegean Sea (http://naseismic.geo.aegean.gr). In fact, even if no other seismic events in the broader vicinity reached a magnitude comparable to the 6.7 of 1949, the exceptional amplitude the tsunami produced by the 1956's Amorgos Island earthquake is still arising the interest of the scientific community (Okal et al., 2009). It was the largest one in Greece in the 20th century ($M_s = 7.8$) with the epicenter located in central-southern Aegean Sea (about 150 km from the southern coast of Lesvos) (Fig. 1a). In the night of the 9 July, it triggered a tsunami that destroyed hundreds of houses and killed more than 50 people (Yolsal et al., 2007). On the basis of the 1956's dislocation source, recent numerical simulations (Okan et al., 2009) seems to be in agreement with the hypothesis of a minor impact of this destructive wave on the southern Lesvos coastline. Therefore, the 1956's event must be necessarily considered as alternative cause of the boulders displacement in the study area.

4 Conclusions

Even though the main aim of this study was to present and discuss the results obtained in the study area in terms of processes of boulder deposition, it also gives some insight on the methods for the assessment of historical tsunamis. The hydrodynamic approaches often used to assess the origin of boulder deposits in the Mediterranean are not sufficient to provide unambiguous evidence for the mechanism responsible for boulder deposition in the study area. According to Goto et al. (2010) hydrodynamic approaches tend to simplify environmental complexity, and in the case of low-energy tsunamis they must be integrated with further data.

This study pointed out that supporting numerical models and geomorphologic data with other kind of records becomes essential when facing ambiguous results. The interviews of local people and analyses of historical photographs, together with the data provided by radiocarbon analyses and by the tsunami catalogues, indicated that the boulder accumulation is likely to have been deposited by the tsunami triggered by the 6.7 M_s Chios-Karaburum earthquake of 1949 or, alternatively, by minor effects of the destructive tsunami produced by 1956's Amorgos Island earthquake. In both cases, these deposits represent the first field evidence of tsunami wave impact in this sector of the Aegean Sea that, according to the seismic sources, has been affected by several tsunami events since the antiquity.

At Mediterranean scale, the huge amount of historical data could provide significant support to numerical models becoming a crucial tool in order to confirm results that are critically important for local coastal communities to prepare tsunami and storm wave disaster prevention policies.

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