Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2017-313
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Discussion started: 12 September 2017

Tsunamis boulders on the rocky shores of Minorca (Balearic Islands)

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Abstract Large boulders have been found on marine cliffs of 24 study areas of Minorca, Balearic Archipelago. These large imbricated boulders, of up to 229 tonnes, are located on platforms that conform the rocky coastline of Minorca, several tenths of meters from the edge of the cliff, up to 15 m above the sea level, and kilometres away from any inland escarpment. They are mostly located on the southeast coast of the island, and numerical models have identified this coastline as a high tsunami impact zone. The age of the boulders in most of the studied localities show a good correlation with historical tsunamis. Age of the boulders, direction of imbrication and estimation of run-up necessary for their placement, indicate dislodging and transport by North Africa tsunami waves that hit the coastline of Minorca.

1 Introduction

Large boulders accumulations observed and studied on various coastlines of the the Mediterranean have been associated with extreme wave events: France (Shah-Hosseini et al. 2013), Southern Italy (Barbano et al. 2010, 2011; Mastronuzzi et al. 2007; Mastronuzzi and Pignatelli 2012; Pignatelli et al. 2009; Scicchitano et al. 2007, 2012), Greece (Scheffers and Scheffers 2007; Scheffers et al. 2008a), Egypt (Dalal and Torab 2013; Torab and Dalal 2015), Algeria (Maouche et al. 2009) and Malta (Biolchi et al. 2013, 2016; Furlani et al. 2011; Mottershead et al. 2014; Causon-Deguara and Gauci, 2016). The Mediterranean region is a seismically active area with a history of past tsunamis (Soloviev et al. 2000). Sedimentary records of tsunamis generated off the North African coast have been identified along the rocky coastline of Minorca, as inland boulders, in most cases, ripped off a cliff edge. These boulders are placed over coastal rocky cliffs, mainly on the southeast and west coastline of the Island (Fig. 1), and positioned well above the maximum stand of any recorded storm wave, and with no nearby high inland relief that might explain an origin from gravitational fall. Occasionally, boulders found on low cliffs or ramps, have been reworked by storm waves.

Historical and instrumental seismicity indicate that North of Algeria is exposed to relevant seismic hazards and risks. On October 10, 1980, the Asnam earthquake took place with a magnitude of 7.3 Mw (Ambraseys, 1981). The last seismic event recorded was the Zemmouri earthquake that took place on May 21, 2003, with a magnitude of 6.9 Mw. This earthquake was generated by a reverse fault, leading to a significant deformation of the seabed, and creating a tsunami that was observed in Algeria and Spain, and even reached the coasts of France and Italy. This event leaded 3m high waves, the highest tsunami waves recorded in recent years in the Balearic Islands, that damaged some of the harbour facilities of Minorca, Majorca and Ibiza. Tsunami simulations of this event (Fig. 2) were performed by several authors (Hébert and Alasset, 2003; Alasset et al., 2006, Roger and Hebert, 2008).

Alvarez et al. (2011) modelled tsunamis generated near the Balearic Islands, with the purpose of identifying coastal areas where the hazards and impact is greater. Tsunamis generated by earthquakes in the Mediterranean region are expected to have wavelengths between 5 and 20 km, while the maximum water depths are about 3 km. Alvarez et al. (2011) produced a map of tsunami trajectories from nine sources, resembling those responsible of the earthquakes of al-Asnam 1980, and Boummerdes - Zemmouri 2003. The sources of these tsunamis are reverse faults with low-angle dipping to the South and SE, which are capable of generating earthquakes of magnitude 7.3 Mw. These faults delimit the northern belt deformation of Atlas materials from North Africa pushing on the Algerian-Balearic Basin. Tsunami generated by these sources arrive in 30 minutes to Formentera, which is the nearest island to the coast of Algeria, and 45 minutes to Minorca, the most distant island (Roger and Hebert, 2008) (Fig 2).

The presence of large boulders on the rocky shores of the Balearic Islands has been treated by Bartel and Kelletat (2003), Schefers and Kelletat (2003) and Kelletat et al. (2005). The authors linked the presence of large boulders on the coastal platform of Mallorca with storm waves and/or tsunami processes, establishing a simple equation to discern those displaced by a storm wave and a tsunami event. Between 2013 and 2016, the boulders of the south coast of Minorca were analysed, together with those on the south and east coast of Mallorca, and other localities of the Balearic Islands (Roig-Munar, 2016). This study provided different equations to distinguish between boulders moved by storm waves or tsunamis, also relating these larger boulders with tsunamis paths from North Africa. In addition, Roig Munar (2016) could date most of the boulders, establishing a chronology that correlated with the records of historical tsunamis (Table 1).

2 Methodology

In this work, 3.144 boulders located in 24 areas of Minorca Island (Fig. 1) have been analysed. Dimensions were measured, as well as height above sea level, and the distance from the edge of the cliff. Orientation and imbrication was also considered, together with their geomorphological context (Fig. 3). Transport Figure TF (Scheffers and Keletat, 2003) was used to assess the power needed to dislodge and transport each boulder. TF is calculated as the product of the height above sea level, distance from the ledge of the cliff, and weight. Roig-Munar (2016) has estimated a TF> 1000 as indicative of tsunami boulders; this is four times TF value considered previous authors (Kelletal et al. 2005). Additional proof of tsunami dislodgement came from 13 sites with boulders found on cliffs well above the maximum storm wave height recorded in Minorca (Cañellas, 2010).

Calculation of boulder weights requires a good estimation of density and volume (Engel and May, 2012). In most cases the product of the tree axis -a (length), b (width) and c (height)- of each boulder exceeds the true volume of the boulder. Sampling comparisons have been made between Vabc, and a more precise measurement obtained by triangulating the boulder in homogeneous parallelepipeds (Fig. 4a). This procedure produced to the calculation of an average volume Vabc correction coefficient of 0.62 that has been applied to all boulders analysed in this study. Densities of each lithology were calculated using the Archimedean principle of buoyancy in sea water.

In addition to TF, different equations (Table 2) have been applied to all the localities to calculate height of water required to dislodge and/or move each boulder. Nott (2003) has defined pre-settings for transported boulders (submerged, subaerial and joint bounded boulders JBB), and for each boulder type, a different equation for tsunami and storm waves. Most of Minorca boulders were dislodged from cliff edges (Fig. 5), so joint bounded and subaerial scenarios must be considered. Only nine boulders show features (marine fauna or notch fragments) defining they were originally submerged. Pignatelli (2009) defined a new equation to obtain the minimum tsunami height HT that can move a joint bounded boulder (JBB). The Nott derived equation differs from the original in the relevance of the c-axis that indicates the thickness of the boulder directly exposed to the wave impact. Engel and May (2012) reconsider Nott's equations using more accurate volume and density measurements, and defining equations to derive the minimum wave height of a tsunami HT or storm wave HS, that is required to dislodge a submerged, subaerial or JBB boulder (Table 2).

Discrimination between boulders transported by tsunamis or heavy storms, poses some difficulties in most cases (Kelletat, 2008; Barbano et al, 2010). Nevertheless, in many areas of the Mediterranean, metric size boulders have been interpreted as remnants of the tsunamis occurred in the last centuries (Pignatelli et al., 2009).

Age of the boulders was determined using two methods: a) radiocarbon dating of marine incrusting fauna, and b) dating surface post-transport features. Most of the boulders show unconformable post-depositional solution pans on the surface, related to karstic dissolutions after the transport of the boulder. Some (Fig. 4b) of these post-depositional solution pans are intersecting pre-existing ones developed conformably with stratification. Karstic dissolution rate of these pans was estimated at average of 0.3 mm/y (Emery, 1946. Gómez-Pujol et al, 2002). Transport age of 145 boulders from 12 locations was determined using a combination of these methods (Fig. 9).

3 Results

The 24 areas analysed have been grouped into three sectors: SE, W and N. All the boulders were processed, but those with a TF lower than 1.000 were excluded from the final analysis. Our results are based on the analysis of 720 boulders.

3.1 Southeast sector

Although 1.766 boulders have been analysed in six areas of the SE sector, only 274 (16%) had a TF>1000 (Fig. 6). These boulders have an average size of 3.1 m along their longest axis (a), 2.16 m along the intermediate axis (b) and 0.9 m along the shortest axis (c), which almost always corresponds to the thickness of the source strata. Mean weight is 11.62 T, with a maximum of 229 T from the coastal islet of *l'Aire*. Average cliff height is 6.8 m, and average height of the boulders is 6.19 m, and 61.4 m from the edge of the cliff, with extremes of 18.5 m and 136 m. The highest regional storm wave registered was 7.5 m.

Engel and May (2012) formulations show that the boulders with a TF> 1000 from this sector require a column of water between 8.8 m (subaerial) and 14,4 m (JBB) to explain storm wave run-ups, and between 7.3 and 8.7 m for the tsunami run-ups. Since the boulders do not record a single tsunami run-up, these figures can be estimated for the latest and most intense tsunami run-up, the one that overrides the cliff with floods above 15 m. Previous lower magnitude events have very little chance of being registered, because of the reworking by the most intense and latest tsunami wave.

We calculated that 33 % of the TF>1000 boulders are in areas above the maximum stand of the waves registered (8.5 m), and many of them show imbrication patterns. These boulder deposits have been clearly interpreted as produced by tsunami events. However, 79 % of all the boulders are positioned at a height at which they can be reworked by storm waves (Roig-Munar et al., 2017 in press). In many areas, their origin must be established by a confluence of different criteria.

Boulder setting of this sector can be characterized by the presence of several ridges of imbricate boulders (five of the eight sites show this setting) (Fig. 6), as well as sub-rounded boulders (5 of 8), and isolate groups of imbricate boulders (4 of 8). Although cliff altitude of this sector is quite low, and many sites show sub-rounded blocs (5 of 8), there is not any clear relationship between these characters. As an example, some of the lower cliffs do not show any ridge, meanwhile some with higher cliffs do have ridges.

3.2 Western Sector

Along the cliffs of the Western 1.043 boulders were measured (Fig. 1 and 7), and 232 boulders (22%) showed a TF>1000. These boulders have an average size of 2.38 m along the longest axis (a), 1.86 m along intermediate axis (b) and 0.68 m along the shortest axis (c), which mostly corresponds to the thickness of the source strata. Mean weight of these boulders is 4,6 T, with a maximum of 21,9 T. Average cliff height is 12 m, and the average boulder height is 16 m and 40 m from the edge of the cliff, with extremes of 31 m and 65 m. The highest regional wave registered was 8 m.

Formulations of Engel and May (2012) show that the boulders with a TF> 1000 require a column of water between 13.7 m (subaerial) and 18.6 m (JBB) to explain storm wave run-ups, and between 12.4 and 13.6 m for the tsunami run-ups. Almost all the TF>1000 boulders are positioned above the maximum stand for waves registered along the West coast of Minorca (8 m). These deposits have been clearly interpreted as originated by tsunamis waves. Only 16 % of all the boulders are positioned at a height at which they can be reworked by storm waves. The heights of the boulders of this coastal sector are out of the reach of storm waves, and should be interpreted as tsunami deposits.

Boulder setting of the Western sector of Minorca is characterized by higher cliff altitudes and imbricate boulder ridges at half of the sites analysed (4 of 8). Only two of the sites show sub-rounded boulders –the lower sites– and just one has isolated groups of imbricate boulders.

3.3 Northern sector

Along the North coast of Minorca 338 boulders have been measured (Fig. 8), and 214 (63%) showed a TF>1000. The boulders have an average size of 2.56 m along longest axis (a), 1.94 m along the intermediate axis (b) and 1.3 m along the shortest axis (c). Mean weight of these boulders is 12.07 T, with a maximum of 128.3 T at *Illa dels Porros*. Average cliff height is 7.81 m, and the average boulder height is 11.7 m, and 66.2 m from the edge of the cliff, with extremes of 27 m and 129 m. Highest regional wave height was calculated at 11 m (Cañelles, 2010).
Formulations of Engel and May (2012) show that the boulders with TF> 1000 require a column of water between 9.8 m (subaerial) and 21.6 m (JBB) to explain storm wave run-ups, and between 8.3 and 11.3 m for the tsunami run-ups. Most of the TF>1000 boulders (74%) are positioned above the maximum wave height registered along the North coast of Minorca (9 m). The boulders of this sector have been interpreted as originated by tsunami waves, although, 24 % of the boulders are positioned at a height at which they can be reworked by storm waves. The heights of the boulders of this sector are out of the reach of storm waves, and must be interpreted as tsunami deposits.
The setting of the Northern boulders is characterized by few imbricate ridges (just two of the eight sites), only one site with isolate imbricate groups of boulders, and a greater presence of sub-rounded blocs (6 of 8).

3.4 Biggest boulders

The results for each area indicate the average size and weight for all the boulders with a TF>1000, but we will consider some our findings about the largest boulders of each area. The largest boulders of the SE area of Minorca are located on the islet of *l'Aire*, just 960 m off the SE coastal tip of Minorca. The largest boulders of this area weigh 228 T, 154 T and 114 T. Engel and May (2012) equations provide storm run-ups estimations of 39 m, 28 m and 27 m respectively, meanwhile for a tsunami run-up they required 13 m, 11 m and 10 m.
The largest boulders of the Western area of Minorca weigh 21.9 T, 18.2 T and 17 T, but they are located higher and more inland than those of the SE coast. The results of Engel and May (2012) equations of this area show storm run-ups of 33.4 m, 31.5 m and 30.9 m and tsunami run-ups of 24 m, 23.6 m and 22 m. They are located on a littoral platform at 31 m above the sea level (*Punta Nati*, Fig. 7).
The North coast largest boulders weigh 128.3 T, 56.5 T and 53.7 T. They are found on the small islet of des Porros, just 426 m off the Northern tip of Minorca (Fig. 8). According to the equations of Engel and May (2012), storm run-ups of 54.8 m, 33.9 m and 39.7 m are required to transport these boulders, and heights of 28.3 m, 11.1 m and 18.6 m for a tsunami run-up.

3.5 Dating Age of the deposits

Five of the analysed boulders show marine fauna, indicating that they have been dislodged from the submerged area and deposited above the cliff. Two of these boulders have been sampled for 14C dating: A boulder from Son Ganxo (SE of Minorca, Fig. 6) is a fragment of shoreline notch (wave-cut notch); located 2.5 m above sea level and 18.4 m from the cliff edge, with a weight of 4.75 T, and 14C dating determined an age of 1964 AD. Another boulder in Sant Esteve (SE of Minorca, Fig. 6) is situated about 19 meters from the waterfront and 1 m above sea level, with a weight of 43.15 T, and 14C dating determined an age of 1856 AD.

Some of the boulders in the spray areas show post-depositional dissolution pans (Fig. 4b). Although dissolution rate for these pans is not uniform (it increases near the cliff edge), we have considered an average of 0.3 mm/y (Emery, 1946. Gómez-Pujol et al, 2002). This rate has been used to date the age of 145 pans found on the surface of the boulders (Fig. 9).

Radiocarbon dating and estimating dates using dissolution ratios, provided a range of ages for 12 locations between 1574 and 1813 AD, although 8 of the 12 dates are situated around the year 1790 AD (Fig. 9).

Among the historical records of huge wave phenomena that have affected the Balearic Islands, there are some episodes that can be attributed to tsunamis. In 1654, the chronicles written by Fontseré (1918), record a hurricane in the sea that crossed the island of Minorca, destroying the foundations of buildings and uprooting trees (sic). In 1856, the same chronicles record an extraordinary sea rise in the Port of *Maó* that destroys several moorings. In 1918 a new 'seismic wave' floods the Port of *Maó*, following an earthquake off the Algerian coast. The records of the National Geographic Institute of Spain (Martinez-Solares, 2001 and Silva and Rodríguez, 2014) record in 1756 the presence of a tsunami that floods the south coast of the Balearic Islands.

4. Discussion

The presence of tsunami boulders has been described on a great number of Mediterranean islands, but at the Balearic Islands we have found a strong relationship with seismic activity off the North coast of Algeria. A tsunami wave generated in Algeria will have its main impact on the SE coastline of the Balearic Islands, and with a high incidence on the island of Minorca. Both the effects of the last registered tsunami of 2003, and those recorded in the historical chronicles confirm this relationship.

Storm waves that impact on the rocky coast of Minorca can move and transport smaller boulders, particularly, those located at the top of cliffs. Many of these large boulders cannot be transported by a single storm event, neither by a series of storms. Hydrodynamic equations show that these large boulders can only be dislodged with tsunami run-ups, and many of these boulders are even located beyond the reach of storm wave run-ups. For joint bounded boulders (JBB), the Nott, Engels and May and Pignatelli equations, show that storm run-ups of 14 m are needed to dislodge the boulders, while tsunamis run-ups of only 8 and 13 m would explain their position. Along the SE sector of coastline, storm run-ups of 14.4 m are required to explain the position of the boulders, while only 8 m tsunami run-ups can explain the same positions. Because the calculated storm run-ups of this height seem improbable, not even those generated by extreme events such as medicanes (Jansà, 2013), seems reasonable to believe that the boulders have been dislodged by tsunami waves that reach 8 m run-ups. Our findings along the higher cliffs of the W coastline, requires tsunamis run-ups 13 m high and / or storm run-ups of 18.6 m. It is evident that neither the fetch, nor the available storm wave records reach these values, and that tsunami waves seem to be the most plausible explanation. Despite the results of these hydrodynamic equations, it should be noted that the model simulation does not place this area as the preferred impact target coastline for tsunamis originated off the Algerian coastline (Fig. 2). The calculations along the northern coast sector require storm run-ups of more than 21 m that are not plausible, while the height of tsunami run-up required to position the boulders is only 9 meters. It is difficult to understand this magnitude of tsunamis along the north coastline of Minorca, although the 2003 tsunami generated a wave with a run-up height of 3 m in Sant Antoni, on the north coast of Ibiza. A submarine landslide off the Catalan platform could also be considered as a generator of tsunamis hitting the NE of Minorca, (Canals et al, 2004; Iglesias et al., 2012; Iglesias, 2015), but the estimated age for this event is much older (11.500 BP).

Settings of the boulders depend on local physiography and on the characteristics of the flow that transported them. Most of the imbricate ridges are found along the SE sector, with lower cliffs and a bigger impact of potential tsunamis. We discovered that 62 % of the boulders along the SE coastline are sub-rounded, indicating reworking by storm waves. Boulders along the western sites are positioned higher, and only 25% are sub-rounded, overlapping with the presence of flow-out morphologies. Most of the boulders of this sector have been dislodged and transported by tsunami flows, and with storm wave reworking them only locally. The position of the boulders along the North coast sector shows evidences of both tsunami, and storm wave flows: 75 % of the sites have sub-rounded blocs and, although just 25 % of the sites have imbricate ridges, weight, distance inland and height of some boulders, cannot be explained by storm waves (Roig-Munar et al, 2017 in press). The tsunamis hitting the north coast of Minorca could be caused by a refraction of a tsunami wave originated off the North Africa coast, or a submarine landslides occurring off the Catalan platform.

Estimations using dissolution rates of surface pans are coherent with the two macro-fauna radiocarbon C14 dates. Historic record of earthquakes and associated tsunamis (Fontseré, 1918; Martinez-Solares, 2001; Silva and Rodriguez, 2014) are consistent with our chronology. The last major tsunami recorded by the boulders on the coasts of Minorca took place about two hundred and fifty years ago; all later tsunamis did not reach this magnitude. Like glacial deposits, coastal boulders only register the last largest tsunami, and earlier records of smaller magnitude are almost completely obliterated by the largest and more recent wave event.

Conclusions

More than three thousand large boulders have been analysed on the coastal platforms of Minorca, of which 720 have been selected for this study. Weight, height above sea level and distance from the edge of the cliff, indicate that they have been dislodged and positioned by the action of tsunami waves, although some of these boulders have been later reworked by storm waves. Our data and our conclusions are largely supported by different evidence and analysis.

Tsunamis generated off the Algerian coast are quite well known. What was little known is the potential impact of these waves on the coastline of the Balearic Islands, including Minorca. Tsunami simulation models have confirmed the high probability of coastal impacts on the Balearic Islands. The historical chronicles of tsunami events and impacts on the Balearic Islands has also been recompiled. The last 2003 tsunami episode caused important damages in some ports of the Balearic Islands.

Setting of the boulders do not only explain local aspects of the coast, further information obtained from boulder orientations, imbricated ridges and isolated groups of imbricated boulders, are evidences of a continuous flow originated by a tsunami flood. Distance from local escarpments can exclude that any of the boulders analysed had its origin in a rockfall.

Hydrodynamic equations applied to these boulders, show in most cases a TF>1000, a clear indication that a tsunami wave was the cause of its dislodgement, transport and setting. Weights up to 228 T (*Illa de l'Aire*), altitudes reaching 31 m (*Punta Nati*) above sea level, and distances from the cliff edge of up to 136 m (*Illa de l'Aire*), confirm the results obtained in our calculations. Historic data of storm waves, and medicane (11 m) events, cannot explain the size and positioning of the boulders.

Dating by C14, and dates obtained from pan dissolution rates establish a tsunami chronology of historical events impacting Minorca between the 17th and 19th centuries. The last great tsunami that affected the coast of Minorca occurred about 250 years ago. Boulders deposits also record tsunamis of smaller dimensions, and reworking of the boulders by important storm waves on the lower cliffs.

Acknowledgments

This work was made was with the support of the CHARMA Project (MINECO, Ref .: CGL2013-40828-R).

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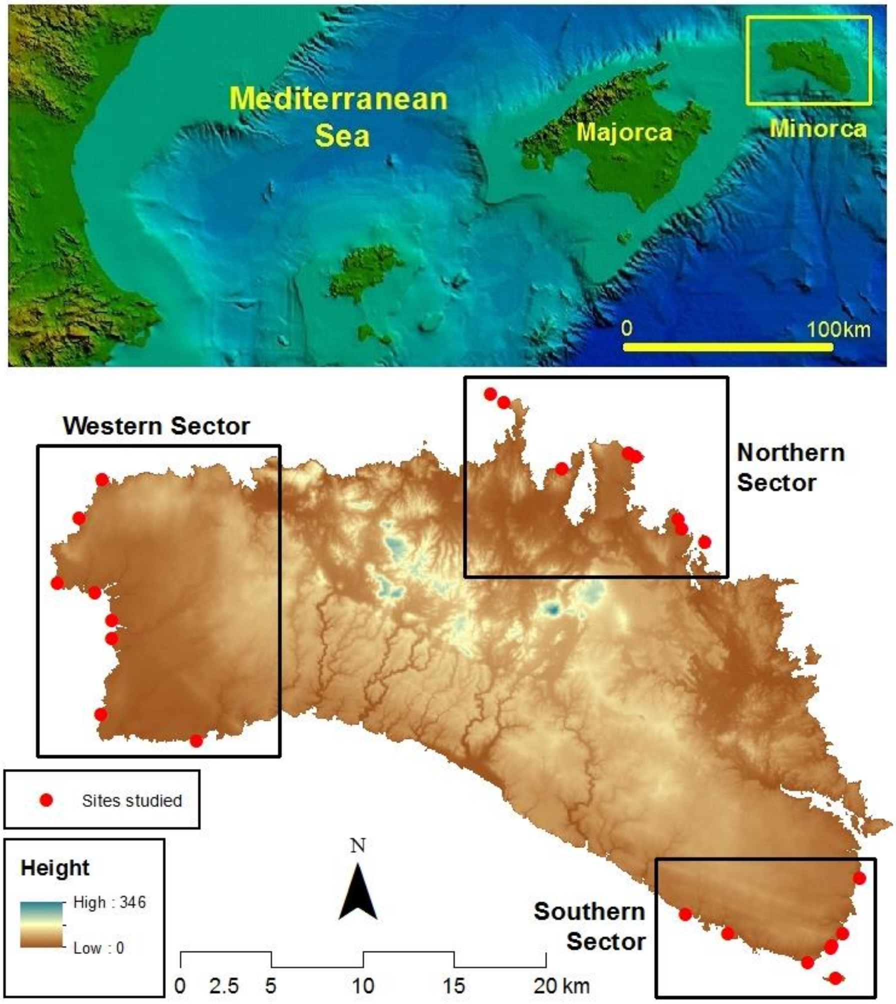

Figure 1: Situation of the sampled areas: A) West, B) North and C) Southeast of Minorca. Most of the northern coast doesn't have littoral platforms able to preserve boulders and most of the southern central cliffs show altitudes out of reach of tsunamis (up to 70 m)

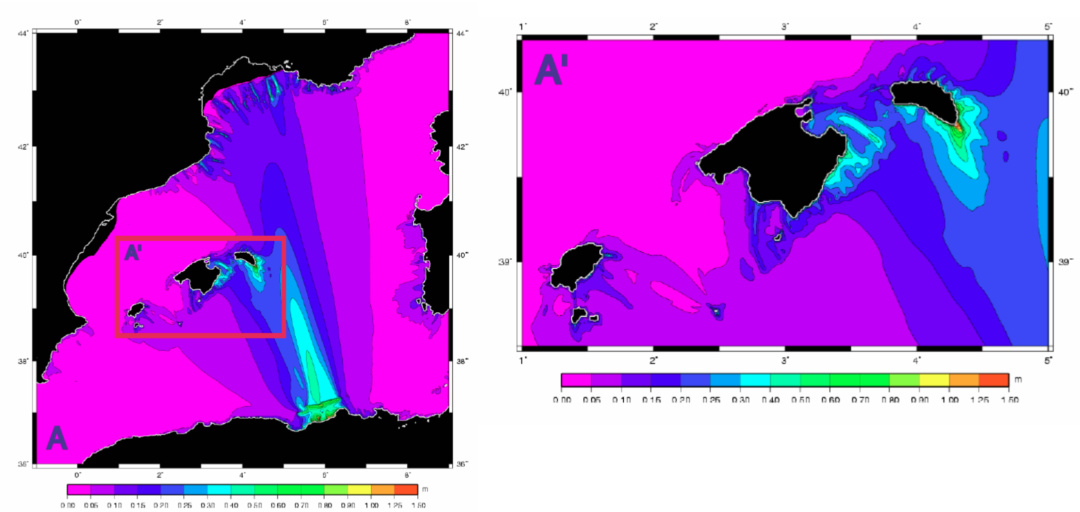

Figure 2: Tsunami simulation from northern Algeria impacting Balearic Islands. Accumulated maximum height 1.5 h after the break of the fault, 3 segments at a time, with a deviation of 80 °. Source: Roger and Hebert (2008).

Table 1. Historical tsunamis phenomena impacting in the Balearic Islands, modified from Roig-Munar (2016). Information sources (IS): (1) Fontseré (1918) and (2) Martinez-Solares (2001) and Silva and Rodriguez (2014).

Data	Affected area	Phenomenon	IS
1660	Majorca, Palma, Campos	Earthquake and tsunami	1
1721	Balearic Islands	Earthquake and sea water withdrawal	1
1756	Majorca, Santanyí	Tsunami and big waves	1
1756	Balearic Islands	Tsunami and flooded coasts	2
1790	Alboran Sea	Tsunami	2
1804	Alboran Sea	Tsunami	2
1856	Minorca, Maó	Tsunami and seismic wave	1
1856	Algeria	Tsunami	2
1885	Algeria	Sea level changes	2
1891	Algeria	Tsunami	2
1918	Minorca, Maó	Seismic wave	1
2003	Algeria	Earthquake (7.0) and tsunami	2

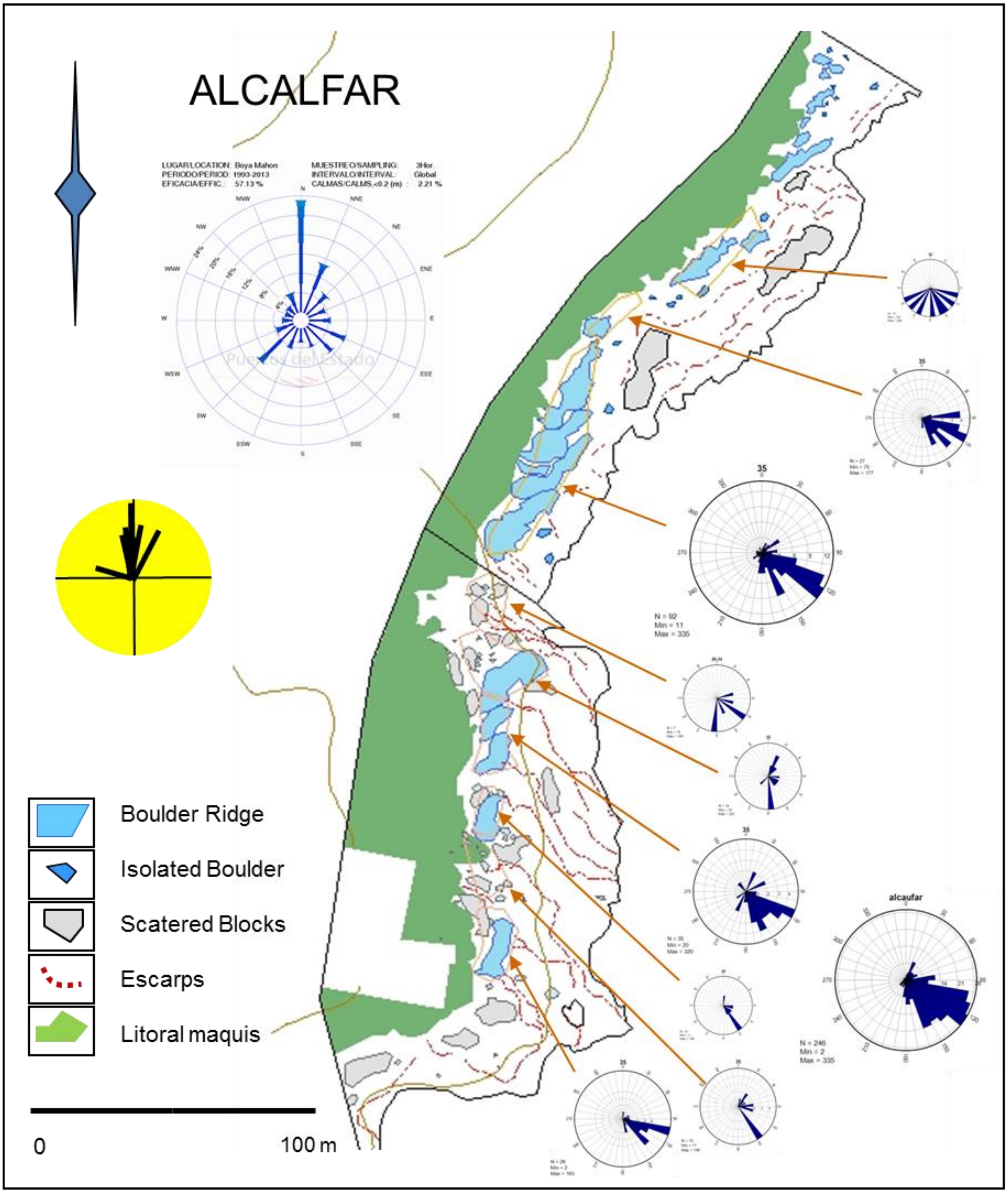

Figure 3: Geomorphology Map of Alcaufar area (SE of Minorca) White circles show boulder orientation for each site. Main circle shows mean wave directions recorded at Maó Buoy. Yellow circle shows mean extreme wave directions

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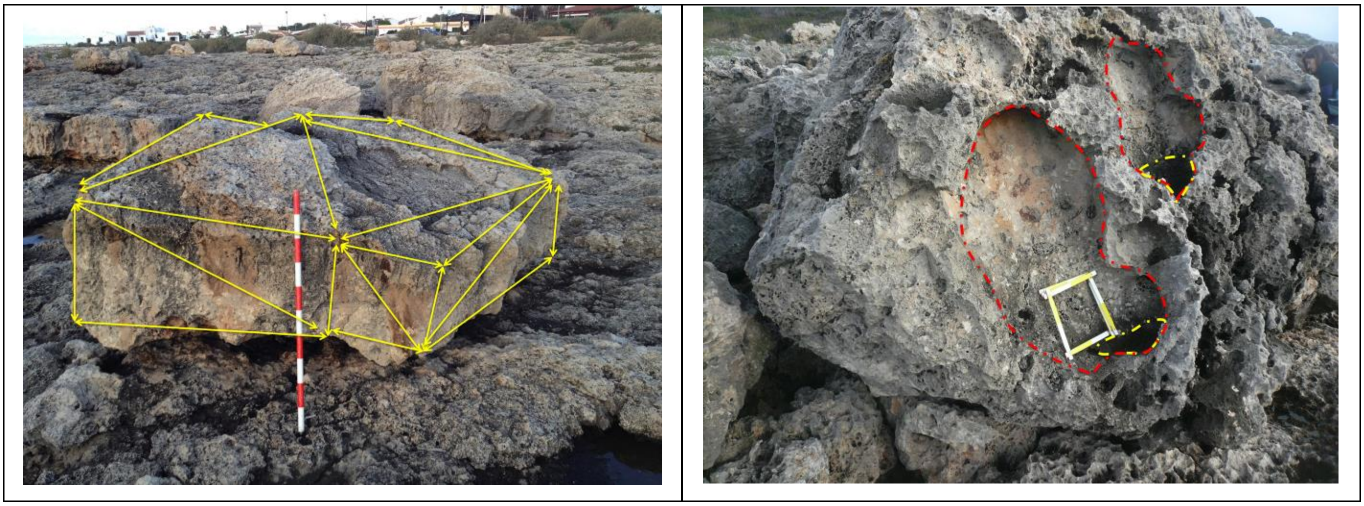

Figure 4: a) Example of triangulation of a boulder to obtain the actual volume (*sa Caleta, Minorca*). b) Unconformable post-depositional morphologies (yellow) over pre-existing solution pans (red) (*Son Ganxo*, Minorca).

Table 2: Equations used in the analysis of Minorca boulders

		Ht	**Hs**
Nott (2003)	**submerged**	$Ht = [0,25(\rho_s - \rho_w / \rho_w)\ 2a] / [(C_d\ (ac/b^2) + C_l]$	$Hs = [(\rho_s - \rho_w / \rho_w)\ 2a] / [(C_d\ (ac/b^2) + C_l]$
	subaerial	$Ht = [0,25\ (\rho_s - \rho_w / \rho_w)\ [2a - C_m\ (a/b)\ (ü/g)] / [C_d\ (ac/b^2) + C_l]$	$Hs = [(\rho_s - \rho_w / \rho_w)\ [2a - 4C_m\ (a/b)\ (ü/g)]\ ] / [C_d\ (ac/b^2) + C_l]$
	joint bounded boulder	$Ht = [0,25\ (\rho_s - \rho_w / \rho_w)\ a] / C_l$	$Hs = [(\rho_s - \rho_w / \rho_w)\ a] / C_l$
Pignatelli (2009)	**joint bounded boulder**	$Ht = [0,5 \cdot c \cdot (\rho_s - \rho_w / \rho_w)] / C_l$	
Engel and May (2012)	**subaerial**	$Ht = 0,5 \cdot \mu \cdot V \cdot \rho_b / C_D \cdot (a \cdot c \cdot q) \cdot \rho_w$	$Hs = 2 \cdot \mu \cdot V \cdot \rho_b / C_D \cdot (a \cdot c \cdot q) \cdot \rho_w$
	joint bounded boulder	$Ht = (\rho_b - \rho_w) \cdot V \cdot (\cos\theta + \mu \cdot \sin\theta) / 2 \cdot \rho_w . C_L \cdot a \cdot b \cdot q$	$Hs = (\rho_b - \rho_w) \cdot V \cdot (\cos\theta + \mu \cdot \sin\theta) / 0.5 \cdot \rho_w . C_L \cdot a \cdot b \cdot q$

Ht	tsunami height	a	large axis of the boulder	C_d	coefficient of drag
Hs	storm wave height	b	medium axis of the boulder	C_l	coefficient of lift
ρ_s	boulder density	c	short axis of the boulder	C_m	coefficient of mass
ρ_w	sea water density	g	force of gravity	ü	speed of water flow
V	Volume abc of the boulder	q	boulder area coefficient	θ	cliff top steepness
μ	coefficient of friction				

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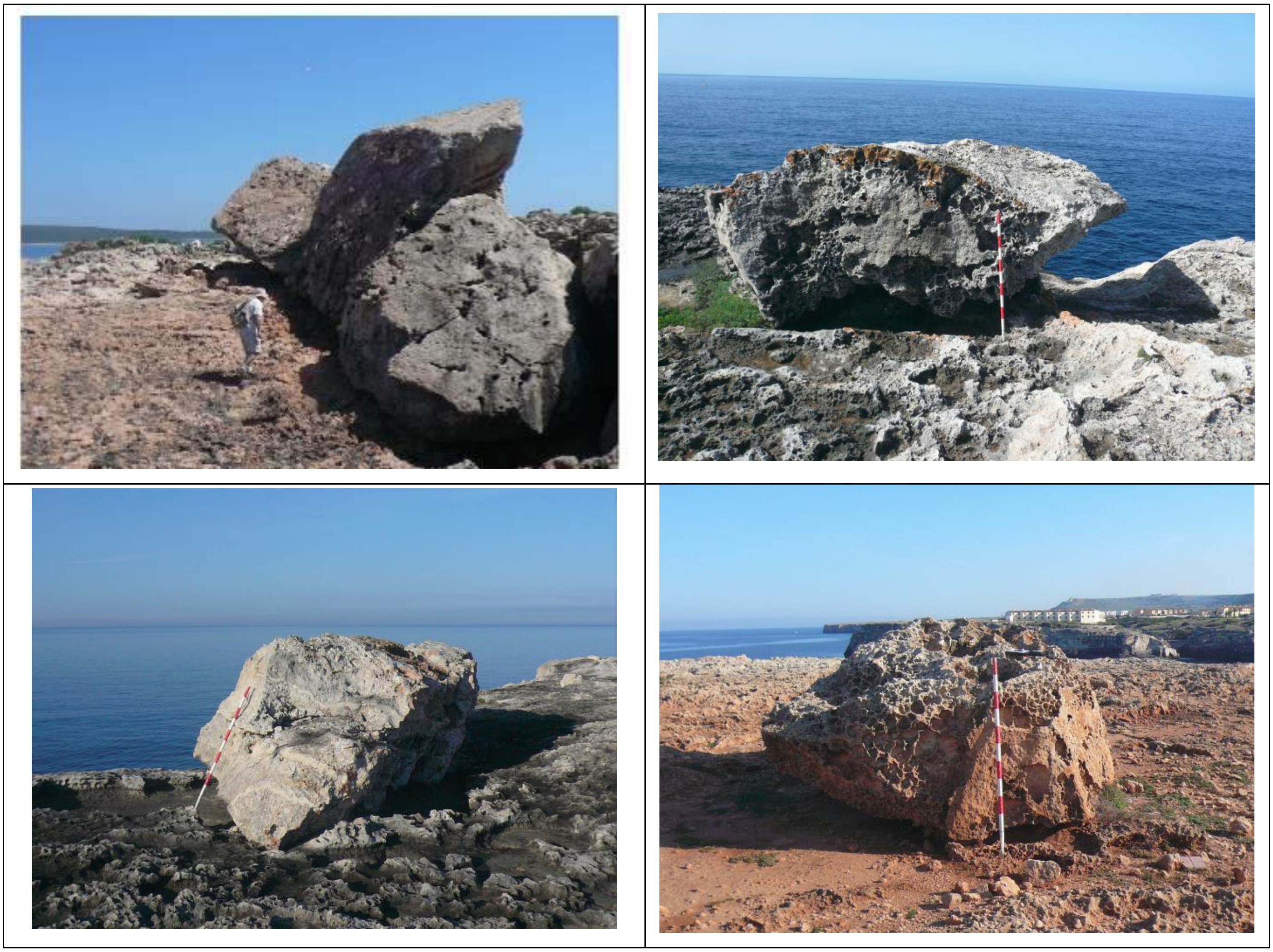
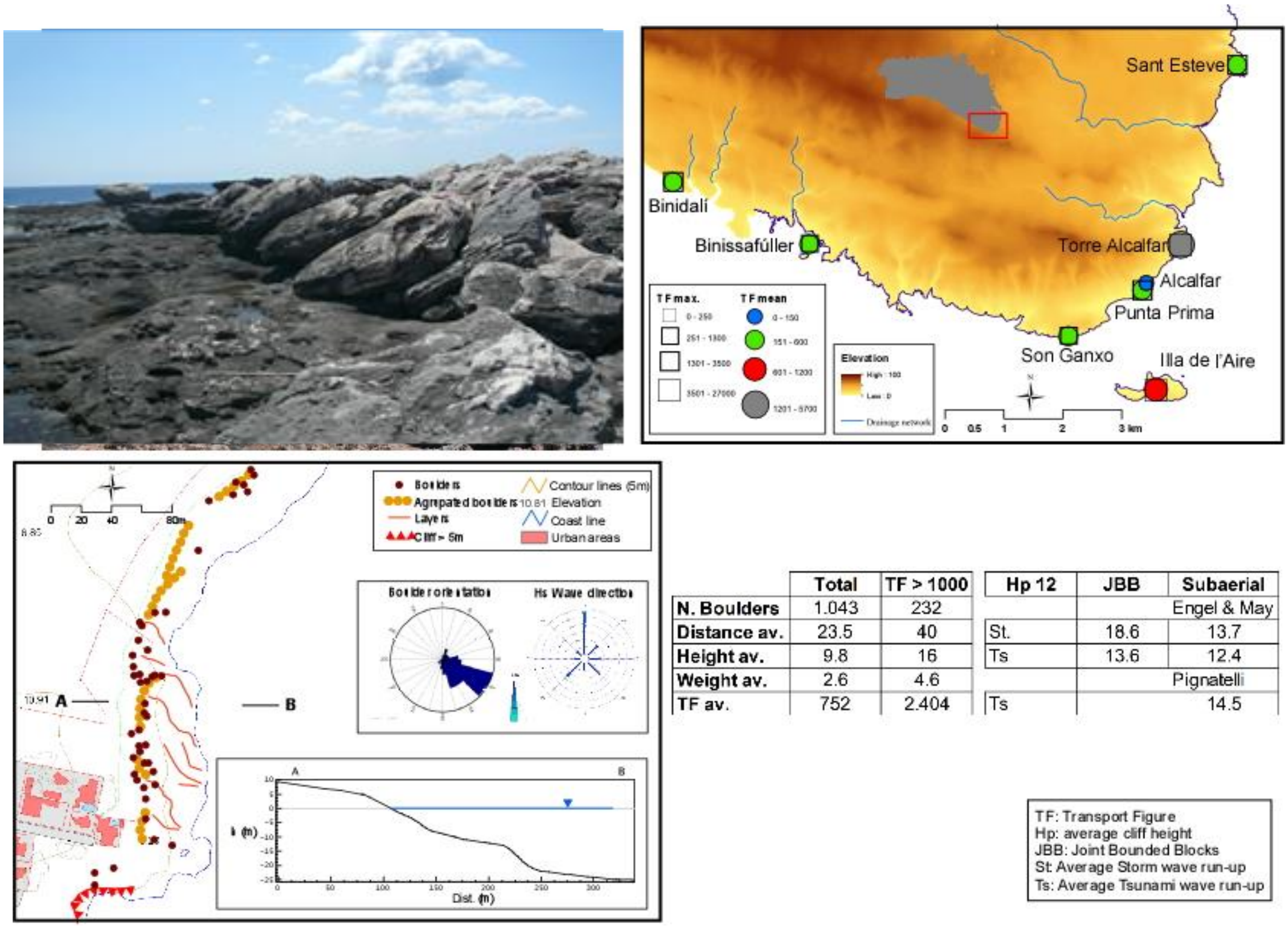


Figure 5: Examples of mega-boulders displaced from the edge of the cliff a) Illa de l'Aire, SE of Minorca 15 m asl., b) Binidali, SE of Minorca, 12 m asl, c) sa Farola, W of Minorca, 9 m asl and c) Cala en Blanes, W of Minorca, 18 m asl.



	Total	TF > 1000	Hp 12	JBB	Subaerial
N. Boulders	1.043	232			Engel & May
Distance av.	23.5	40	St.	18.6	13.7
Height av.	9.8	16	Ts	13.6	12.4
Weight av.	2.6	4.6			Pignatelli
TF av.	752	2.404	Ts		14.5

Figure 6.- Location and main characteristics of SE Minorca boulders. Picture corresponds to an imbricate ridge of boulders in *Sant Esteve*. Geomorphological sketch shows boulders distribution at *Alcaufar*.

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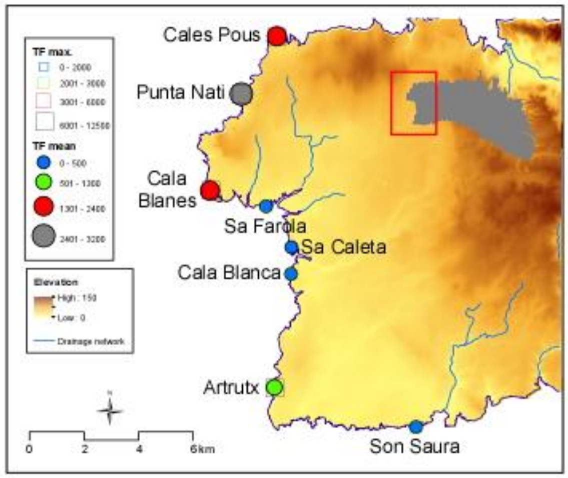

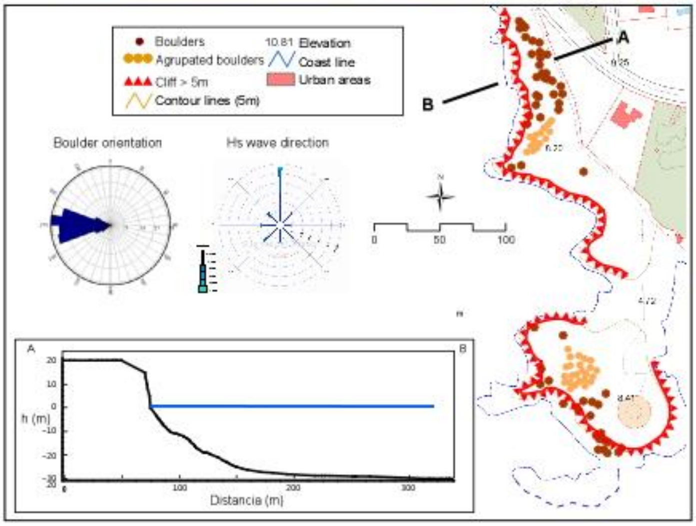

	Total	TF > 1000		Hp 12	JBB	Subaerial
N. Boulders	1.043	232				Engel & May
Distance av.	23.5	40	St.		18.6	13.7
Height av.	9.8	16	Ts		13.6	12.4
Weight av.	2.6	4.6				Pignatelli
TF av.	752	2.404	Ts			14.5

TF: Transport Figure
Hp: average cliff height
JBB: Joint Bounded Blocks
St: Average Storm wave run-up
Ts: Average Tsunami wave run-up

Figure 7. Locations and main characteristics of W Minorca boulders. Picture corresponds to isolated boulders from *Punta Nati* (31 m above sea level). Geomorphological sketch shows boulders distribution at *Sa Caleta*..

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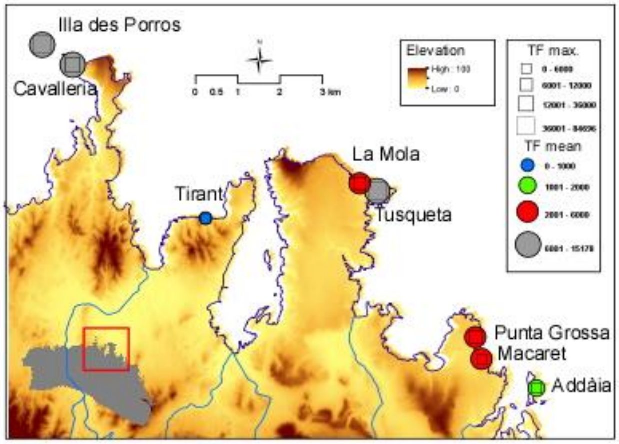

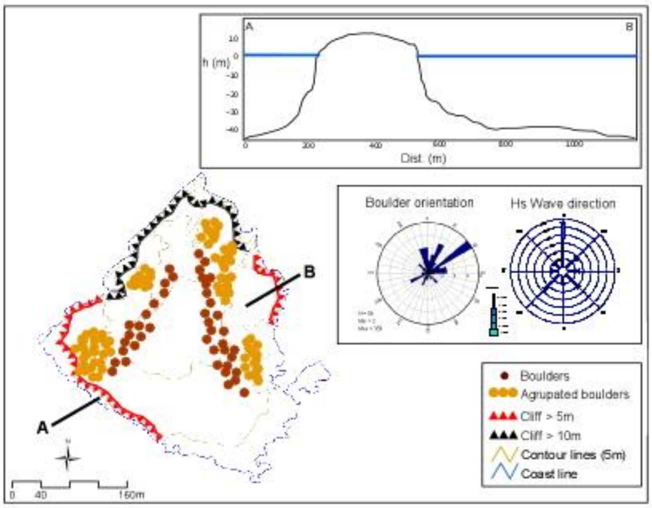

	Total	TF > 1000
N. Boulders	338	214
Distance av.	50.2	66.2
Height av.	9.4	11.7
Weight av.	8.4	12.1
TF av.	5.479	8.501

Hp 12	JBB	Subaerial
		Engel & May
St	21.6	9.8
Ts	11.3	8.3
		Pignatelli
Ts		13.2

TF: Transport Figure
Hp: average cliff height
JBB: Joint Bounded Blocks
St: Average Storm wave run-up
Ts: Average Tsunami wave run-up

Figure 8. Location and main characteristics of N Minorca boulders. Picture corresponds to Caballeria boulders. Geomorphological sketch shows boulders distribution at Illot d'Adaia.

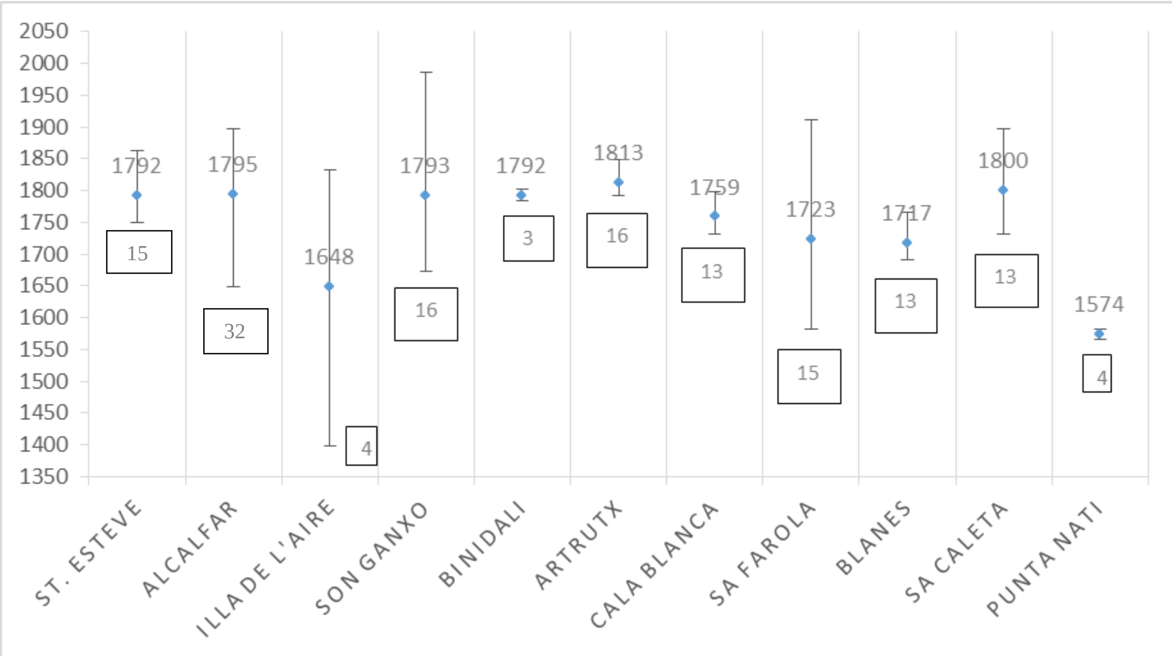

Figure 9: Chronology of the post-depositional dissolution pans found on the surface of South Minorca boulders: The ages, in years AD, correspond to the post depositional dissolution pans measured on the boulders of the sampled localities. The blue dots indicate the average age of each locality. The bar indicates the range of dispersion of calculated ages, and the figures into the box show the number of measured pans at each area.