"Tsunamis boulders on the rocky shores of Minorca (Balearic Islands)" by Francesc X. Roig-Munar et al.

Anonymous Referee #1

The paper by Roig-Munar et al. is interesting in general. However, the manuscript has some major issues related to the presentation of the data and other more formal aspects. On the one hand the introduction is over-referenced for case studies in the Mediterranean. On the other hand, important references are omitted.
We have removed the references regarding the eastern Mediterranean and we have included new, more relevant and general references (distributed throughout the text).

Statements like "Sedimentary records of tsunamis generated off the North African coast have been identified along the rocky coastline of Minorca,..(l.24-25) come without reference. This sentence is rather a conclusion of the paper already.
We agree. We have changed this sentence.

Page 2 line 1 starts rather abruptly with information on seismicity of Algeria – leaving the reader alone why this would be important. References are missing here as well and also in line 5, line 11.
We have changed this point, reorganizing almost the entire introduction and explaining why seismicity in Algeria is important for the understanding of the presence of this coastal boulders in Minorca.

The introduction concludes with the statement that Roig Munar (2016) [how do you spell your name? with or without dash?] already identified the boulders as tsunamigenic and dated most of them. So what is the aim of this paper here? Later in the text you refer to Roig-Munar et al. (2017). How does the present study differs from this one. I realize that Roig-Munar (2016) is a (unpublished?) PhD-thesis but you treat it as published scientific results. You should clearly outline the aims of this particular study, which could well be the same aims as in the thesis.
The referee is wright. Roig-Munar (2016) is the unpublished PhD Thesis of the first author of this article. We have removed other little and local publications of the author

because are not relevant. We also included some new outcrops to complete the Minorca description of these deposits.

The method section is in part a discussion on volume estimation of boulders – and not a description of the methods that you applied in your study site. Which directly leads to the next problematic formal aspect of the manuscript: you have no paragraph in the study site. The reader does not get any information on the geology, tidal range (negligible?), wave regime, climate, tectonic setting. A description of the study site is mandatory.

We created a new section called "Study site" explaining the geological framework and the maritime climate of Minorca.

The result chapter starts with the statement that 24 areas were analyzed. Which areas? The reader has no idea what you talk about.

We described the results of these areas grouped in tree sectors and display their location in the figures.

The height information on cliffs and boulders have no reference water level. What do talk about? Mean high tide? Mean sea-level?

Height information refers to mean sea level. Tide amplitude is negligible at this effect.

The SI-unit for a metric ton is "t" and not "T".
Corrected.

"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" (p.4, l. 9-10): this is very confusing, why do they not record a single tsunami run-up?
We agree. Is confusing. We removed that sentence.

Line 6: storm wave. 7.5m (reference?) contradicts line 12 (8.5m).
Corrected.

Line 13: the boulders have been interpreted as ... by whom? Or do you mean: we interpret these boulders as...? The same statement occurs in the following paragraphs.
We interpret these boulders is correct.

Line 27: regional wave height 8m – reference is missing here.
We introduced the reference.

Chapter 3.5: how can you 14C date something to 1964 AD? We need a table of your dating results. The last paragraph in this section is not results but discussion. We agree.
The last paragraph is in the discussion now. Referee was right, according to 14C date the age is younger than 1964 AD.

Chapter 4: I do not see a strong relationship with seismic activity. You have not shown this in the manuscript.
Now seismic activity and boulder setting relationship is shown in Figures 9 and 10.

In line 27 you write the following statement: Glacial deposits only register the largest tsunami".
We removed that sentence.

At the moment the conclusions are not backed by the data. We need information in the dating, historical seismicity, historical records of tsunami, etc. Good luck
Now in the article dating, historical seismicity and historical records are more clearly explained.

Anonymous Referee #2

General comments

5

The Authors show several data on boulders deposits on Minorca Island concluding that they were emplaced by tsunamis. The paper could be interesting but methods and results are not well presented, and there are some observations contradicting the conclusion. Therefore, I suggest improving the manuscript showing missing
10 information and reformulating the conclusion.

My first remark regards data presentation. The Authors do not describe the study sites and their surroundings: a map with western Mediterranean area showing seismogenic sources and earthquake distribution would help to understand the
15 location of tsunamigenic areas around Balearic Islands. Moreover, why do you exclude Iberian earthquakes from tsunamigenic sources? No information is shown on tidal range, wave regime, geology and tectonic setting (did your sites undergo to uplift or subsidence?).
We present in the new version the seismogenic sources and earthquake distribution
20 *in the areas around the Balearic Islands. Iberian earthquakes are of too low magnitude to generate tsunamis reaching the Balearic coasts. We also exclude Iberian earthquakes from tsunamigenic sources because the imbricate boulders we have found in Minorca, but also in Mallorca, Ibiza and Formentera (the rest of the Balearic Islands), are mostly located at the south, south-east of these Islands. Only*
25 *in Minorca we have found boulders in the N and W, but these places might be beaten by refracted tsunami waves according to the numerical models simulations from earthquakes at N-Africa. We explain that in the text.*
Maritime climate have been also included in the text.

30 My second remark concerns the data on the maximum wave heights related to historical tsunamis that hit the Minorca Island. Authors show in Table 1 tsunamis observed in the Balearic Islands and their surroundings in the last four centuries, while in Figure 2 tsunami from northern Algeria affecting Balearic Islands modelled by Roger and Hebert (2008). Both show maximum wave heights of 2 m and the May
35 21, 2003 tsunami was 3 m high; it had the highest tsunami waves recorded in recent years in the Balearic Islands. With reference to the studied boulders, Authors affirm that "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". Therefore, neither tsunamis nor storms can have emplaced the boulders you observed in the present coast profile, because in your historical data no tsunami caused waves 13 m high. Probably boulders were deposited when the shoreline was lower than today is. On the other hand, it is possible that storms had higher waves than you observed or that the deposition of boulders by tsunami/s occurred before your historical observation period.

According to our data, the position of the boulders and the results of the hydrodynamic equations require tsunami wave run-ups that multiply, between two and ten times the forecast heights of tsunami waves in the open sea. First of all, the run-up of tsunamis on vertical cliffs is several times higher than that occurring on low coastal areas (Bryant, 2014). Run-up is also enhanced due to several factors (Lekkas et al., 2011): 1) by the distance from the tsunami generation area (only 300 km in our case), 2) by the narrowness of the continental shelf (as in Minorca), 3) by the fact than the tsunami propagation vector is almost perpendicular to the main shoreline direction, and 4) land morphology, characterized by vertical cliffs with entrances (calas). For these reasons we think than run-ups heights in Minorca are several times higher than tsunami wave heights.

The last remark regards your dating methods. How did you date with 14C boulders1964 AD and 1856 AD? Usually the last three centuries are uncertain in 14C dating. These boulders seem to have been recently emplaced, because are among the "five of the analyzed boulders showing marine fauna", therefore they are likely storm boulders. Please show your dating results with calibration and error. Also dating with post-depositional dissolution pans (Fig. 4b) seems not to be very careful. In fact, dissolution rate is not uniform and the range of dispersion of calculated ages makes the values overlapping.

After reviewing the reports corresponding to these dates can only be stated in a case a block moved after 1720 AD, and in the other case it was transported after 1964.

The second dating method used is based on the average dissolution rate of dissolution pans. This requires to identify post-depositional dissolution pans, that is, that have been formed after the movement of the boulders. They can be formed on the same boulder once transported or on the denudation surface that results from the quarry of the boulder. A margin of error can be established based on the variability of the dissolution rate, which is not very high because the boulders are located quite away from the cliff edge, where dissolution rate and their variability is much higher. However in no case the resulting age values can be compatible with marine levels

different from current sea level. Other similar boulders dated by Kelletat (2005) in the neighboring island of Mallorca, corresponds to ages between 565 AD and 1508 AD. Thus, we think the boulders we are dealing were transported in the last centuries, with a marine level equal to the present one.

Specific comments
Page 1. Lines 25: "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...." by whom?
We have changed that sentence.
Page 2. Line 1: "Historical and instrumental seismicity indicates that North of Algeria is exposed to relevant seismic hazard and risk". You are not dealing with Algeria but with Minorca Island. Describe the seismotectonic setting of your study area at local scale and in the general western Mediterranean background.
Now the general seismotectonic setting of the western Mediterranean and its relationship with the setting of Minorca boulders is more clearly described in the article.
Page 2. Line 9: "Alvarez et al. (2011) modelled tsunamis generated near the Balearic Islands". What does it mean "near the Balearic Islands"?
We removed that sentence.
Page 2. Line 15: "Tsunami generated by these sources arrive in 30 minutes to Formentera and 45 minutes to Minorca". This information can be useful for tsunami alert system but not for your study. What about run-up heights predicted on the Minorca coasts? This information can help you to understand if boulders were deposited by tsunamis.
We agree with the referee. We removed that sentence.

Page 3. Lines 26-27. "Transport age of 145 boulders from 12 locations was determined using a combination of these methods." You have just two radiocarbon dating. How did you use this combination? It is not clear what boulders were dated with radiocarbon and the age of the same boulders resulting from dating surface post-transport features.
The two methods are actually independents, but both describe boulders ages just some decades or centuries from present.

Page 4. Line 9. "Since the boulders do not record a single tsunami run-up", what do you mean?
This sentence have been removed.

Page 4. Line15. "In many areas, their origin must be established by a confluence of different criteria", what do you mean?
First we have to discard the blocks coming from gravitational crashes or those clearly wrenched by the waves, then we have to describe their position regarding the morphology and characteristics of the cliff.

Page 4. Line 25. "The average boulder height is 16 m and 40 m from the edge of the cliff", do you mean distance from the edge?
Yes, we describe the altitude of the boulder above mean sea level and their distance from cliff edge.

Page 4. Line 33. "The heights of the boulders of this coastal sector are out of the reach of storm waves, and should be interpreted as tsunami deposits". Why? You have not tsunami run-up so high and it is possible that storm data are incomplete.
Apart from the increase in the run-up due to the impact of the tsunami on the cliff, it is necessary to consider the location of the blocks and the direction of the imbrications, coinciding with the areas of lower swell of Minorca

Page 5. Paragraph 3.4 Biggest boulders. No boulders described in this section could have been deposited by storms and tsunamis. How do you explain them? Maybe they were emplaced when littoral platform was lower or the sea level was higher.
The ages described make it impossible to consider the possibility of different sea levels than the current one. In addition, the run-up obtained for these blocks are compatible with the impact on cliffs of modeled tsunamis.

Page 6. Lines 13-15. "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." I do not understand the 1654 is not a tsunami but a hurricane; therefore, it is likely that in the Balearic Islands some meteorological events was bigger than the storms about you should discuss (?) in the paper.

Already discussed. Even a new word -Medicane- have been created for this events, but waves from medicanes do not reach the altitudes and fluxes needed for quarry and transport analyzed boulders.

5 Use always Majorca or Mallorca Kelletal, Keletat = Kelletat check please.
Corrected.

Please show in a map all the locations mentioned in the text.
Corrected.

10

In addition, I agree with the reviewer1 comments and found them very helpful. If addressed appropriately, the paper could be improved significantly.
We hope that this purpose has been achieved

15 Finally, a revision of written English would be welcomed.
It is done too.

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 on Minorca, in the Balearic Archipelago (Fig. 1). 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 African tsunami waves that hit the coastline of Minorca.

1 Introduction

Large boulder accumulations observed and studied on various coastlines of the ~~the~~ Western Mediterranean have been associated with extreme wave events (tsunamis or storms): 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),~~ and 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 Western 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~~ Large boulders ~~are~~ placed over coastal rocky cliffs on Minorca Island have been found mainly on the southeast and west coastline (Roig-Munar, 2016) (Fig. 1). Some are positioned well above the maximum stand of any recorded storm wave, many show imbricated ridges, and all of them are located away from any high inland relief that might explain an origin from gravitational fall. ~~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.~~

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), but only on the island of Majorca. The authors linked the presence of large boulders on the coastal platform of Majorca with storm waves and/or tsunami processes, establishing a simple equation (Transport Figure) to discern those displaced by a storm wave or a tsunami event. In fact, in many areas of the Western

5 Mediterranean, metric size boulders have been interpreted as remnants of the tsunamis occurred in the last centuries (Pignatelly et al., 2009). However, the distinction between tsunami or storm boulders is not easy nor without controversy, though it is based on a set of sedimentological, morphological and chronological criteria to be treated in each case (Scheffers and Kinis, 2014). Thus, a main objective of this article is to describe the setting of these boulders on the Island of Minorca and discuss their origin.

10 Small recent tsunamis have affected the island of Minorca as stated by local newspapers (Diario de Menorca, 2003, 22nd and 23rd may). The tsunamigenic source is the Algerian coast, which according to the historical and instrumental seismicity is exposed to relevant seismic hazards and risks (Papadopoulos, 2009). 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 that affected Minorca Island was the Zemmouri

15 (Algeria) 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, which damaged some of the harbour facilities on Minorca, Majorca and Ibiza. A fragment of the chronicle about the tsunami in Diario de Menorca (22/05/2003) stated: "In the case of the Port of Mao, the movement

20 of the waters was spectacular: no sooner had it disappeared from the shore, leaving the bottom of the harbour uncovered, than it returned, flooding the seafront and even the road. The same situation was experienced simultaneously in Cala Alcaufar and Cala Sant Esteve, where some hammocks were 300 m from the beach, along with dead fish" (see figure 6 for location). Unfortunately, we did not study the effects of the tsunami on the boulders at that time. Tsunami simulations of this event (Fig. 2) were performed by several authors (Hébert and Alasset, 2003; Alasset et al., 2006, Roger and Hebert, 2008).

25 Thus, there is currently seismic activity at the bottom of the Algerian Basin that gives rise to tsunamis affecting the coast of Minorca. In the recent past, in the last 500 years, there have been tsunamis, affecting the Balearic Islands (Table 1). There are also historical records reporting a flooding event with a run-in up to 2 km inland on the east coast of Majorca (the largest of the Balearic Islands) in 1756 (Fontsere, 1918). Numerical models of tsunami simulation from submarine earthquakes at the North African Coast (i.e. Alvarez et al., 2011; Roger and Hebert, 2008) show that the southeast and west of Minorca would be

30 one of the most affected areas by the tsunami impacts. On the contrary, the fetch length for the southern coast of Minorca is relatively low: 300 km in the S direction and 500 km in the E direction. Thus, in the last 60 years the maximum extremal wave height detected is of 11 m at the 2001 medicane (Jansà, 2013).

The main goal of this article is to demonstrate that some of the boulders located close to the coastal cliffs of Minorca were transported and deposited by tsunamis that occurred in the recent past and mostly originated from submarine earthquakes at the Algerian coast.

5

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 Western 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

10 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).

15 Between Since 2013 and 2016, the boulders of the south coast of Minorca were analysed, together with those on the south and east coast of Majorca, 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).

20 **2 Methodology**

In this study, 3.144 boulders located in 24 areas of Minorca Island (Fig. 1) have been analysed. Dimensions were Boulder size was measured, as well as height above sea level, and the distance from the edge of the cliff. Orientation and imbrication were also considered, together with their geomorphological context (Fig. 3). Transport Figure TF (Scheffers and Kelletat, 2003) was used to assess the power needed to dislodge and transport each boulder. TF is calculated as the product of the height above

25 sea level, distance from the edge of the cliff, and weight. Scheffers and Kelletat (2003) consider boulders with TF>250 as indicative of tsunami boulders. In this paper we focus our study on boulders with TF>1000 and at boulders Roig-Munar (2016) has estimated a TF> 1000 as indicative of tsunami boulders; this is four times TF value considered previous authors (Kelletat 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, which is 11 m (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 three 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~~ a correction

5   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 both tsunami and storm waves. Most of

10   Minorcan 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

15   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).~~

20   Age of the boulders was determined using two different 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

25   was determined using ~~a combination of~~ these two methods (Fig. 9).

Other qualitative observations were taken into account: a) relation of the boulders with their source area and presence of fractures that can promote detachment of the boulders, b) presence of incrusting or boring marine fauna indicating the origin of the boulder before its displacement, c) presence of pre-detachment and post-detachment solution pans which have been used as date indicators of boulder emplacement, d) degree of rounding of the boulders, presence or absence of other type of sediment

30   as well as presence of abrasion surfaces due to boulder quarrying and transport and, e) presence of "flowouts" which are areas with denudated beds forming channels over the cliff favouring the entry and acceleration of the water flows and leaving a boulder ridge in its front.

3. Study site

3.1. Geology of the study areas

Both from a geological and geomorphological point of view, Minorca is divided into two parts separated by an imaginary line WNW-ESE that extends from Mao to Cala Morell (Fig. 1): a) the Migjorn, which covers the southern half of Minorca, is formed by undeformed calcareous materials from the upper Miocene forming a nearly horizontal platform; and b) the Tramuntana, which includes all the outcrops of Palaeozoic, Mesozoic and Oligocene age. These materials are faulted and folded by the alpine orogeny and constitute the northern half of the island characterized by gentle hills and valleys.

The eight study sites of the southern sector (Figure 1) and the eight study sites of the western sector are located on carbonated, horizontal, well-developed bedding, Upper Miocene rocks forming a marine cliff with heights between 4.5 and 20 m. On the other hand, five of the eight study sites of the northern sector correspond to outcrops of massive Jurassic limestones, forming sea-cliffs between 2 and 20 m height. The other three study sites of the northern area are located on Plioquaternary eolianites: Tirant and Tusqueta sites constituting a gentle ramp where cliffs are absent; nevertheless, in Punta Grossa (Fig. 8), eolianites conform an 8 m high coastal cliff.

3.2. Maritime climate

The coast of Minorca island is subject to a maritime climate characterized in the last 50 years by a maximum wave height of 10 m from a NNE dominant direction (Cañellas, 2010). The eastern coast of the island is characterized by a maximum wave height of 8.5 m with a dominant N component (Cañellas, 2010). At the northern sector of the Island, the maximum wave height recorded since 1958 was 11 m height from a NNE direction. The Hs50 is estimated at 9.88 m (Cañellas, 2010). The tidal regime in Minorca is of very low amplitude (30 cm), almost negligible for this study.

Mediterranean hurricanes, called medicanes in the Mediterranean, generated by intense tropical cyclones may be a more likely extreme wave form reaching the coast of Minorca. The remarkable the medicane of 10-11 November 2001 was associated with the seventh most intense cyclone around the Mediterranean, throughout the period ERA-40 (1957-2002) and is the most intense of all detected in the westernmost Mediterranean, near the Balearic Islands (Genovés et al., 2006). The wind exceeded 150 km / h, affecting a large marine extension and causing waves up to eleven meters of significant height (Jansà, 2003). The number of intense cyclones affecting the Balearic Islands during the period 1957-2007 is between 5 and 10 (Homar et al., 2007).

4. Results

The 24 areas analysed (Figure 1) 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~~ Therefore, results are based on the analysis of 720 boulders.

4.1. Southeast sector

Although 1.766 boulders have been analysed in ~~six~~ eight areas of the SE sector (Fig. 1 and 6), only 274 (16%) had a TF>1000. 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
5 a maximum of 229 t on ~~from~~ the coastal islet of Illa de l'Aire. Average cliff height is 6.8 m, ~~and~~ average height of the boulders is 7.19 m, and average distance from the edge of the cliff is 61.4 m ~~from the edge of the cliff~~, with extremes of 18.5 m and 136 m respectively. The highest regional storm wave registered was 7.5 m (Cañellas, 2010).

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~~
10 ~~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~~ 7.5 m), and many of them show imbrication patterns. Due to these two reasons we interpreted these boulder deposits ~~have been clearly~~
15 ~~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).
20 Although cliff altitude of this sector is quite low (6.8 m, average), 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.

4.2. Western Sector

Along the cliffs of the western area (Fig. 1 and 7) 1.043 boulders were measured, and 232 boulders (22%) showed a TF>1000.
25 These boulders have an average size of 2.38 m along the longest axis (a), 1.86 m along the 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 at a distance of 40 m from the edge of the cliff, with extremes of 31 m and 65 m. The highest regional wave registered was 8 m (Cañellas, 2010). Formulations of Engel and May (2012) show that the boulders with a TF> 1000 require a column of water between 13.7 m
30 (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 storm run-up heights for these 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.

4.3. Northern sector

Along the North coast of Minorca 338 boulders have been measured (Fig. 1 and 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, the average boulder height is 11.7 m and at a distance of 66.2 m from the edge of the cliff, with extremes of 27 m and 129 m. The 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, In addition, 24 % of the boulders are positioned at a height at which they can be reworked by storm waves. The storm run-up heights for these 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 isolated imbricate groups of boulders, and a greater presence of sub-rounded blocs (6 of 8).

4.4. 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 Illa de l'Aire (Fig. 6), 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-up estimations of 32 m, 23 m and 22 m respectively, meanwhile for a tsunami run-up they required 12 m, 9 m and 9 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 20.2 m, 16.4 m and 16.5 m and tsunami run-ups of 9.9 m, 10.5 m and 10.5 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 Illa des Porros (Fig. 8), just 426 m off the Northern tip of Minorca (Fig. 8). According to the equations of Engel and May (2012), storm run-ups of

46.3 m, 45.4 m and 37.7 m are required to transport these boulders, and heights of 19.8 m, 22.6 m and 16.6 m for a tsunami run-up.

4.5. Dating Age of the deposits

Five of the analysed boulders show marine fauna, indicating that they have been dislodged from the submerged area and
5 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~~ at a distance of 18.4 m from the cliff edge, with a weight of 4.75 t. ~~and~~ Radiocarbon ~~14C~~ dating determined an age younger than ~~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 younger than ~~of~~ 1856 AD.
10 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).
15 ~~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 chronicles written by Fontseré (1918) 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 (Fontseré, 1918). Data The records of~~
20 ~~the National Geographic Institute of Spain (Martinez-Solares, 2001 and Silva and Rodríguez, 2014) record in 1756 the presence of a tsunami at the southern coast of Majorca the Balearic Islands.~~

5. Discussion

In interpreting the cause of extreme wave events, there are two feasible hypotheses, namely tsunami waves or storm waves. The former are long period waves (up to 10^2 minutes) of long wavelength (>100 km), the latter characterised by much shorter period (max. 15 secs) and length (10^2 m).
25 On account of their long wavelength, tsunami waves possess a minimum factor of 4x greater power in relation to their height than storm waves (Mottershead et al. 2014). This greater power enables tsunami to achieve both detachment of significantly larger bedrock clasts and also much also greater run-up heights and distances. Due to this reason, imbrication of very large boulders (at a distance of the cliff edge and at a height above any recorded wave) seems impossible through wave action whereas it seems plausible through tsunami waves.

~~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.~~

5 ~~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.~~

Taking into account the hydrodynamic equations of Engels and May, Nott and Pignatelly, for joint bounded boulders (JBB),

10 ~~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.~~

15 ~~Our findings~~ Results 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

20 plausible, while the height of a 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).~~

25 According the position of the boulders and the results of the hydrodynamic equations, it seems clear than the large boulders cannot be transported by a single storm event, neither by a series of storms. On the other hand, hydrodynamic equations require run-ups of the tsunami wave that multiply, between two and ten times, the models forecast heights of tsunami waves in the open sea. First of all, the run-up of tsunamis on vertical cliffs is several times higher than that occurring on low coastal areas (Bryant, 2014). Run-up is also enhanced due to several factors (Lekkas et al., 2011): 1) by the distance from the tsunami

30 generation area (of only 300 km in our case), 2) by the narrowness of the continental shelf (as in Minorca), 3) by the fact than the tsunami propagation vector is almost perpendicular to the main shoreline direction, and 4) byland morphology, characterized by vertical cliffs with entrances (calas). For these reasons we think than run-ups heights on Minorca would have been several times higher than tsunami wave heights. On the contrary, as they shoals, wave heights increase run-up heights in a much lesser way and thus, it is impossible to reach the run-up values obtained from the hydrodynamic equations.

According to Papadopoulos (2009), the major tsunamigenic source in the Western Mediterranean is located north of Algeria (Figure 10), although the Alboran region has to be taken into account too. In other areas as the Liguro-Provençal basin and the Valencia Trough (Fig. 10) the seismicity is too low to be taken into account as tsunamigenic areas. The seismicity of the northern region of Algeria is dominated by thrust focal mechanisms to the west and central part of this area and by strike-slip faults to the east (e.g., Bezzeghoud et al., 2014). The Alboran region is dominated by strike-slip focal and extensional focal mechanisms where largest magnitudes are usually low to moderate (Vanucci et al., 2004).

If we focus in North Algeria, since 1716, there have been 7 seismic events (Fig. 9) with intensity greater than X recorded by Ayadi and Besseghoud (2014) capable of originating a tsunami that, according to the numerical models, will directly hit the coast of Minorca (especially the southern one). According to the same authors, only one seismic event of high intensity is recorded prior to 1716: Algiers, third of January of 1365. Thus, between the period 1716-2017 seven high magnitude events have been recorded, whereas between 1365 and 1715 only one high magnitude event has been recorded. This fact is probably due to the lack of information as we go back in time and probably the frequency of the first period must be hidden in some way.

Regarding the dating of the boulders, although only two blocks with embedded marine fauna have been radiocarbon dated, such dates serve as a reference to the second dating method used. Our C14 results show than in one case a block was moved earlier than 1720 AD, and in the other case was transported after 1964.

The second dating method used is based on an average dissolution rate of dissolution pans. This requires identifying post-depositional dissolution pans, that is, those that have been formed after the movement of the boulders. They can be formed on the same boulder once transported or on the denudation surface that results from the quarry of the boulder. A margin of error can be established based on the variability of the dissolution rate, which is not very high because the boulders are located away from the cliff edge, where dissolution rate is more variable. However, in no way do the resulting values (age values) match with marine levels different from the current one. Other similar boulders dated by Kelletat (2005) on the neighbouring island of Majorca, correspond to ages between 565 AD and 1508 AD.

Estimations using dissolution rates of surface pans are coherent with the two macro-fauna radiocarbon C14 dates. Historic records of earthquakes and associated tsunamis (Fontseré, 1918; Martinez-Solares, 2001; Silva and Rodriguez, 2014) are also consistent with our chronology (Figure 9). Among the historical records of huge wave phenomena that have affected the Balearic Islands, there are also some episodes that can be attributed to tsunamis. In 1856, the chronicles written by Fontseré (1918) 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 offshore the Algerian coast (Fontseré, 1918). The data of the National Geographic Institute of Spain (Martinez-Solares, 2001 and Silva and Rodríguez, 2014) record in 1756 the presence of a tsunami that flooded more than 2.4 km inland at the southern coast of Majorca (Fontseré, 1918).

Finally, 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. Up to 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 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 just 25 % of the sites have imbricate ridges. Weight, distance inland and height of some

5   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 but we don't exclude submarine landslides occurring off the Catalan platform or at the Liguro-Provençal basin platform (Fig. 10).

~~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,~~

10   ~~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 (the ones with larger Transport Figure values) 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

15   boulders have also 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 tsunami wave impact ~~coastal impacts on~~ along the coast of the Balearic Islands. These models have been supported by the

20   historical chronicles of tsunami events ~~and impacts~~ hitting ~~on~~ the ~~Balearic~~ Islands ~~has also been recompiled~~. The last 2003 tsunami episode caused important damages in some ports of the Balearic Islands.

Despite the location of the boulders being an important issue, ~~Setting of the boulders do not only explain local aspects of the coast,~~ further information obtained from boulder orientations and the presence of imbricated ridges and/or isolated groups of imbricated boulders, is evidence of a continuous flow which can only be originated by a tsunami ~~flood~~. Distance from local

25   escarpments can exclude that any of the boulders analysed had its origin ~~in~~ from a rock fall.

Hydrodynamic equations applied to these boulders give wave run-up values which are very far from the reach of the waves recorded in the last 50 years ~~show in most cases a TF>1000~~, which is a clear indication that a tsunami wave was the cause of their dislodgement, transport and setting. Weights up to 228 t (Illa de l'Aire, fig. 6), altitudes reaching 31 m (Punta Nati, fig. 7) above sea level, and distances from the cliff edge of up to 136 m (Illa de l'Aire), confirm the results obtained in our

30   calculations. Historic data of storm waves, or even medicane (11 m) events, cannot explain the size and positioning of the boulders.

Dating by 14C, and ~~dates~~ obtained from pan dissolution rates establish ==an age range for tsunami emplacement of the studied boulders== ~~a tsunami chronology of historical events impacting Minorca~~ between the 17th and 19th centuries. ==During this period, seven earthquakes with intensities larger than X have been documented along the North Algerian coast and also 11 historical tsunami phenomena have been described from historical records in the Balearic Islands.== ~~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.~~

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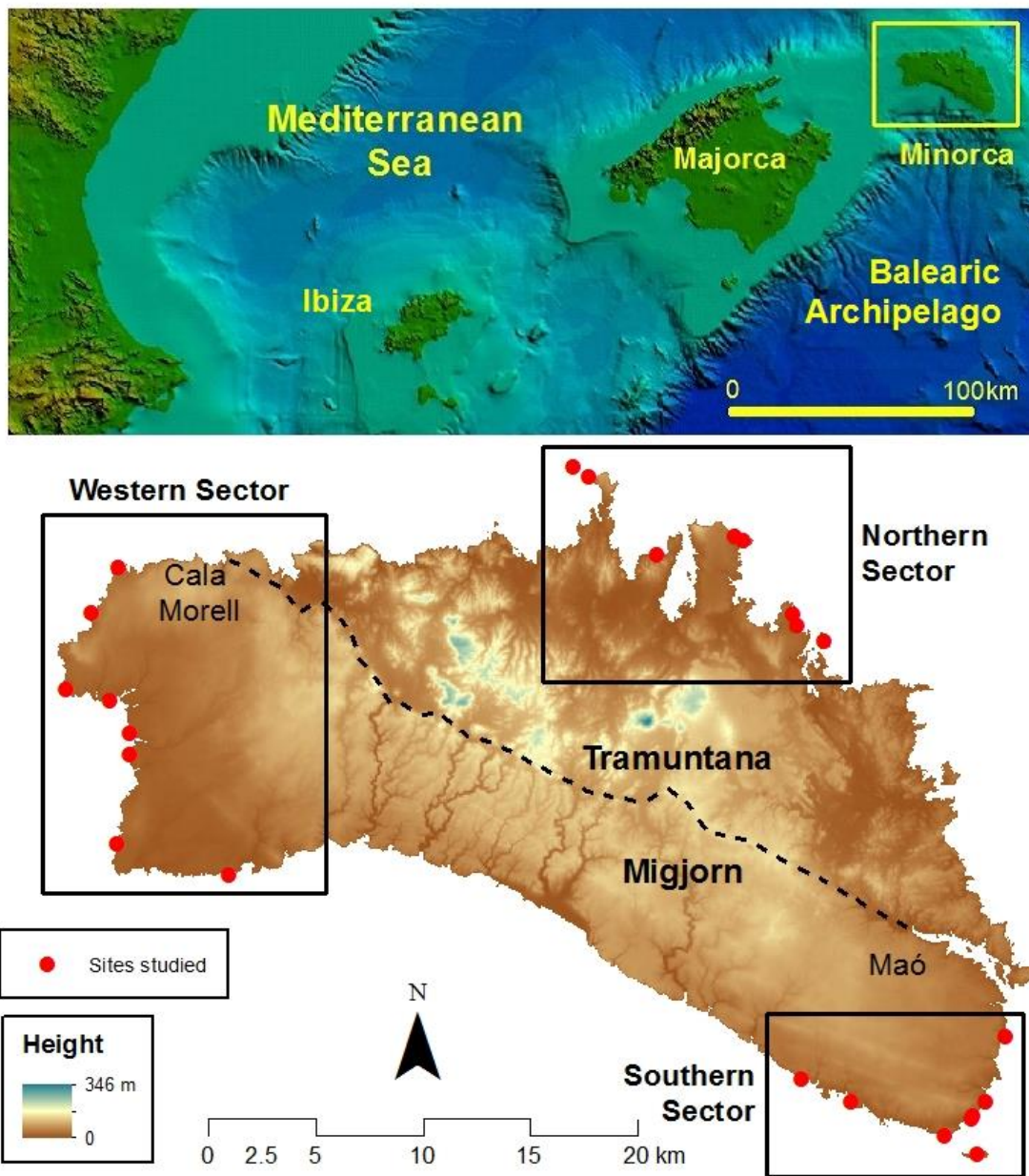
Figure 1: Situation of the sampled areas: A) West, B) North and C) Southeast of Minorca. Most of the northern coast doesn't have littoral platforms able to preserve boulders and most of the southern central cliffs show altitudes out of reach of tsunamis (up to 70 m)
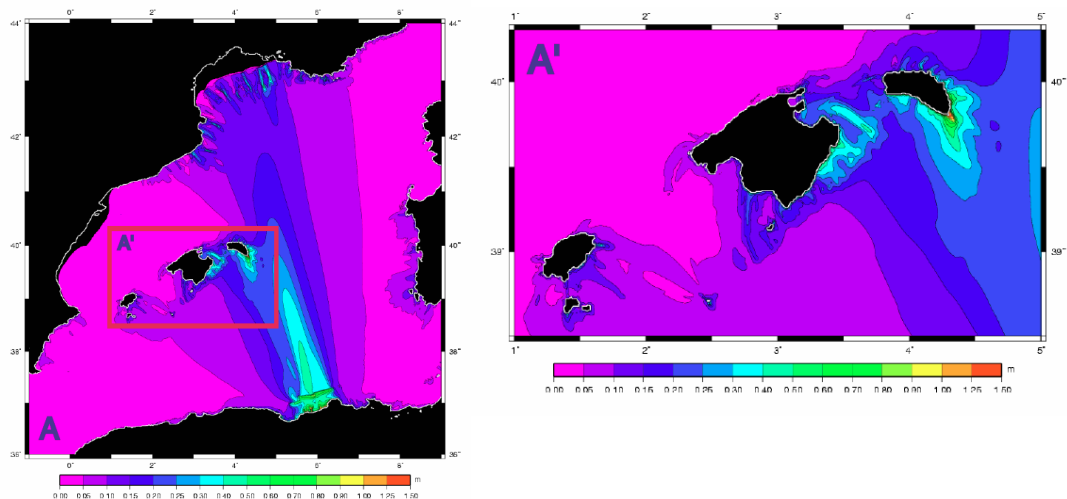
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Figure 2: Tsunami simulation from northern Algeria impacting Balearic Islands. Accumulated maximum height 1.5 h after the break of the fault, 3 segments at a time, with a deviation of 80 °. Source: Roger and Hebert (2008).

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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) (see fig.10, for location).

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

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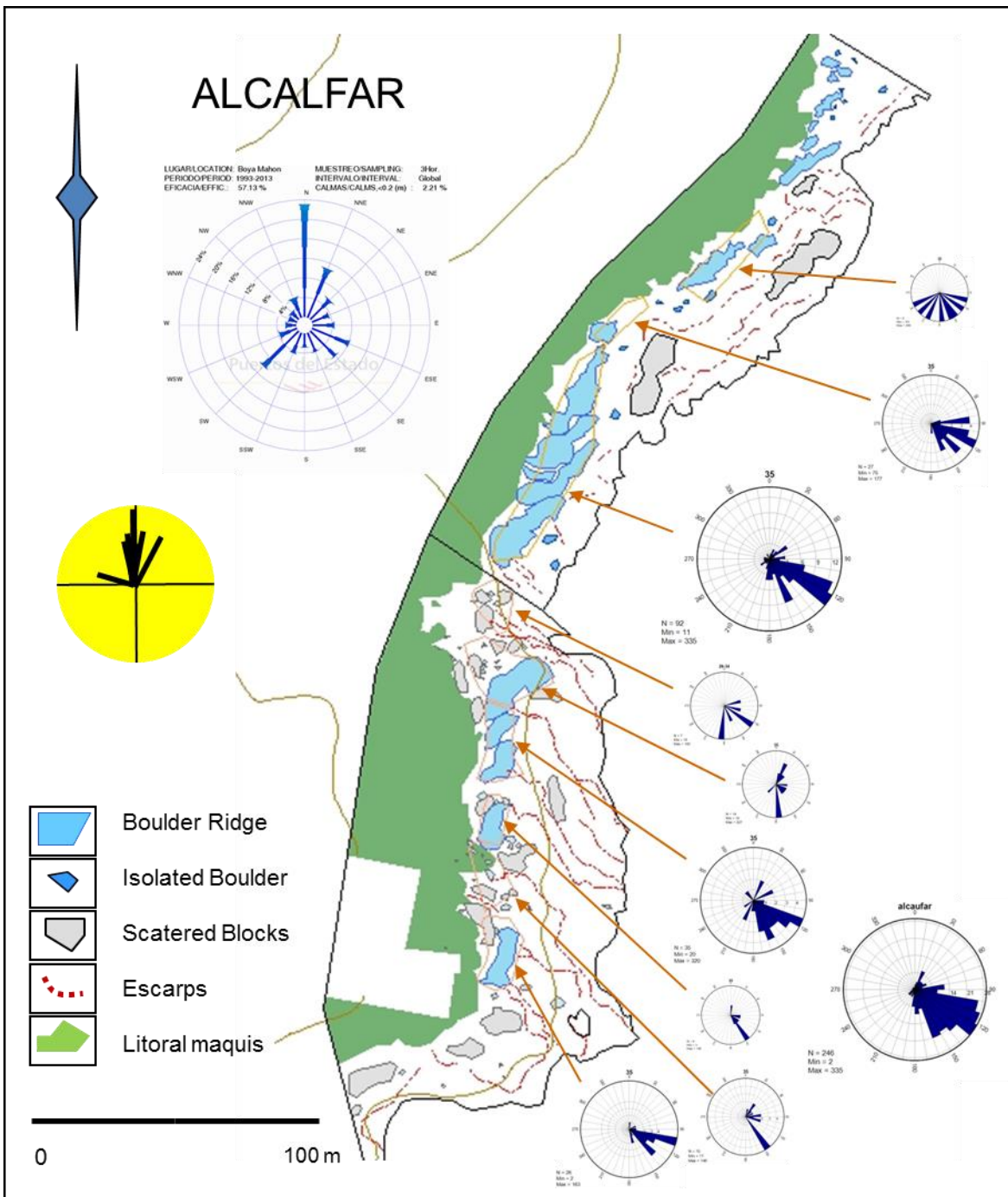
Figure 3: Geomorphology Map of Alcaufar area (SE of Minorca) White circles show boulder orientation for each site. Main circle shows mean wave directions recorded at Maó Buoy. Yellow circle shows mean extreme wave directions
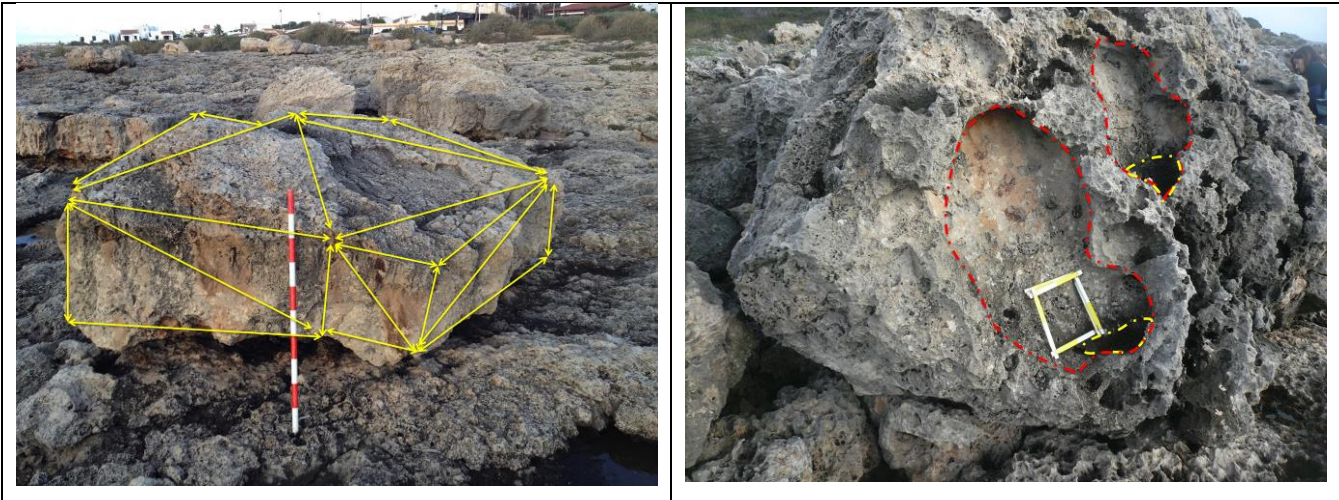
Figure 4: a) Example of triangulation of a boulder to obtain the actual volume (*sa Caleta, Minorca*). b) Unconformable post-depositional morphologies (yellow) over pre-existing solution pans (red) (*Son Ganxo*, Minorca).

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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	$Ht = [0{,}25\,(\rho_s - \rho_w / \rho_w)\,[2a - C_m\,(a/b)\,(\ddot{u}/g)] / [C_d\,(ac/b^2)+ C_l]$	$Hs = [(\rho_s - \rho_w / \rho_w)\,[2a - 4C_m\,(a/b)\,(\ddot{u}/g)]\,] / [C_d\,(ac/b^2)+ C_l]$
	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	$Ht = (\rho_b - \rho_w) \cdot V \cdot (\cos\theta + \mu \cdot \sin\theta) / 2 \cdot \rho_w \cdot C_L \cdot a \cdot b \cdot q$	$Hs = (\rho_b - \rho_w) \cdot V \cdot (\cos\theta + \mu \cdot \sin\theta) / 0.5 \cdot \rho_w . C_L \cdot a \cdot b \cdot q$

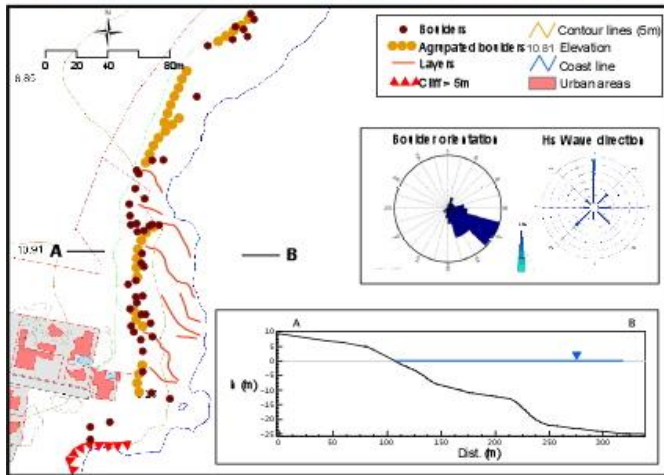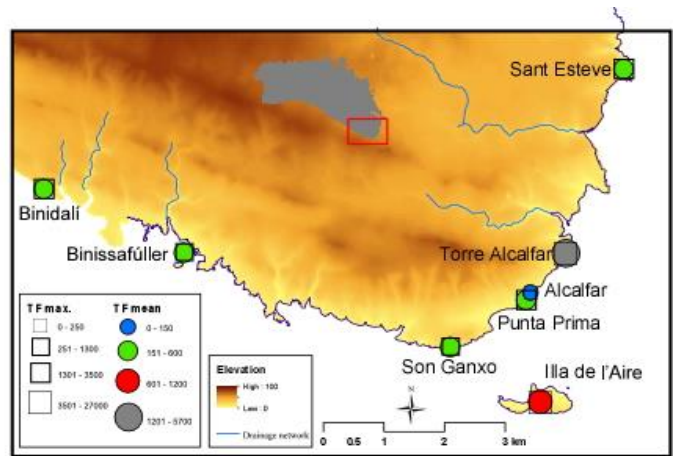|						
Ht	tsunami height	a	large axis of the boulder	C_d	coefficient of drag
Hs	storm wave height	b	medium axis of the boulder	C_l	coefficient of lift
ρ_s	boulder density	c	short axis of the boulder	C_m	coefficient of mass
ρ_w	sea water density	g	force of gravity	$\ddot{u}$	speed of water flow
V	Volume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

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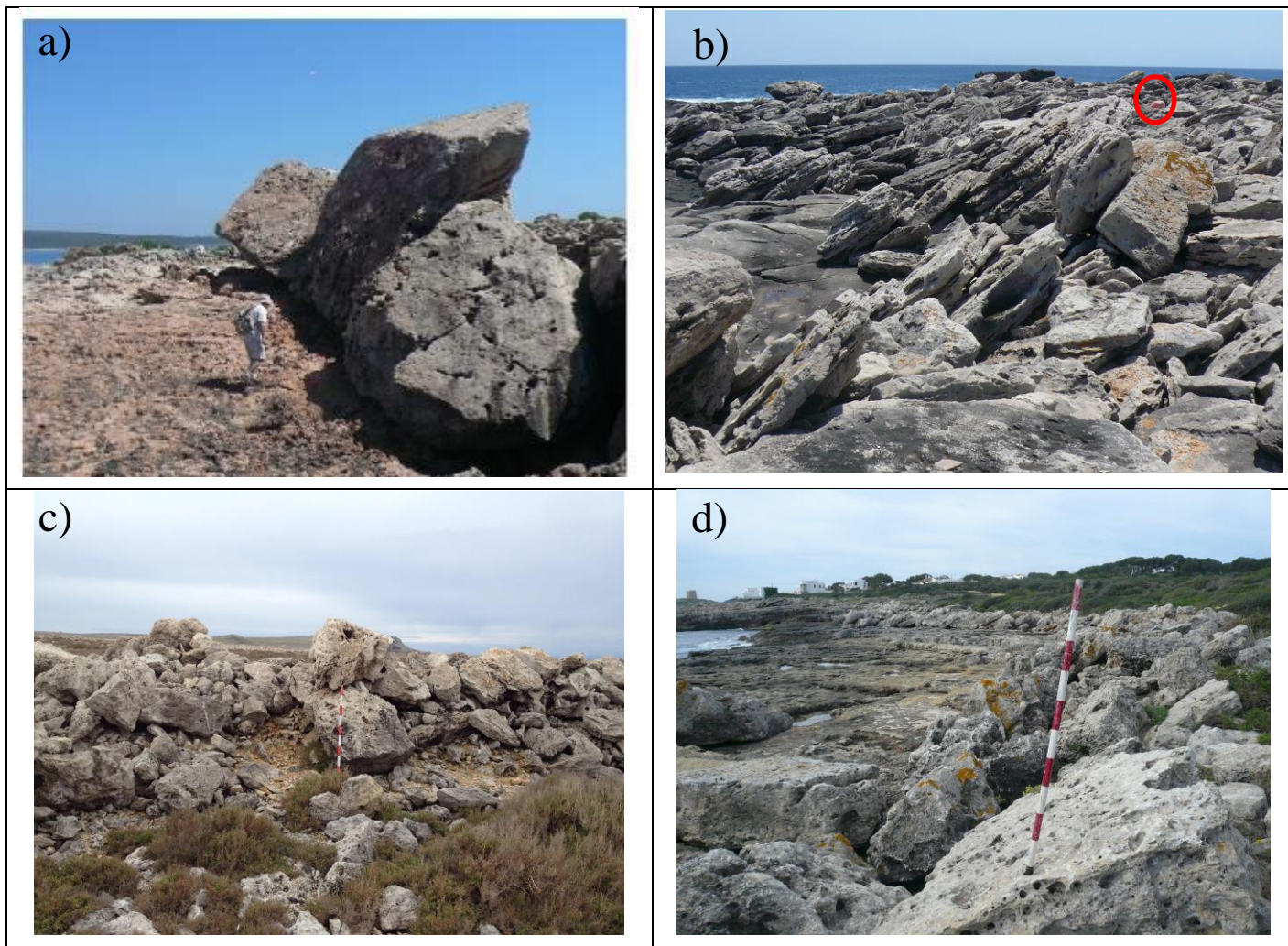
Figure 5: a) Examples of mega-boulders displaced from the edge of the cliff at Illa de l'Aire, SE of Minorca, 15 m asl., b) Set of imbricate boulders at Sant Esteve, SE of Minorca, buoy in circle is 60 cm long c) Boulder ridge at Punta Nati, W of Minorca, 21 m asl. d) Ridge of imbricate boulders at Alcaufar, E of Minorca, 4.5 m asl. See fig 6 and 8 for location.

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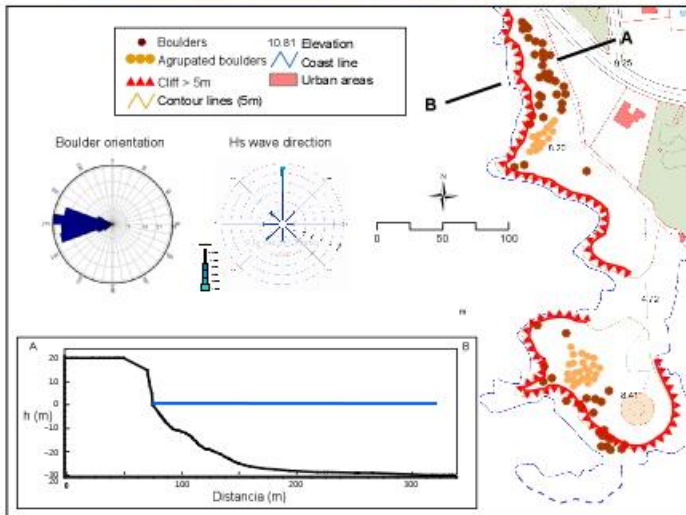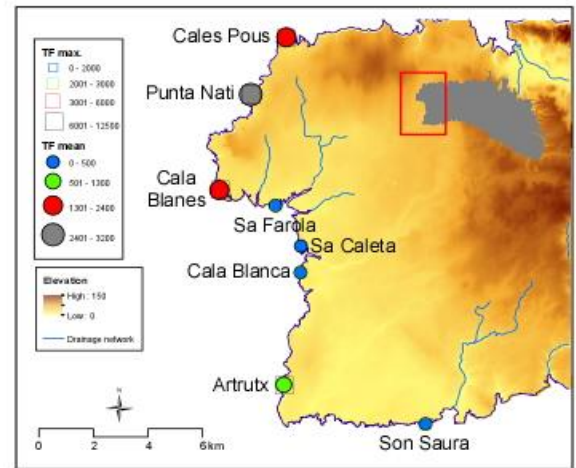
	Total	TF > 1000		Hp 12	JBB	Subaerial
N. Boulders	1.043	232				Engel & May
Distance av.	23.5	40		St.	18.6	13.7
Height av.	9.8	16		Ts	13.6	12.4
Weight av.	2.6	4.6				Pignatelli
TF av.	752	2.404		Ts		14.5

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*..

Figure 8. Location and main characteristics of N Minorca boulders. Picture corresponds to Caballeria boulders. Geomorphological sketch shows boulders distribution at Illot d'Adaia.
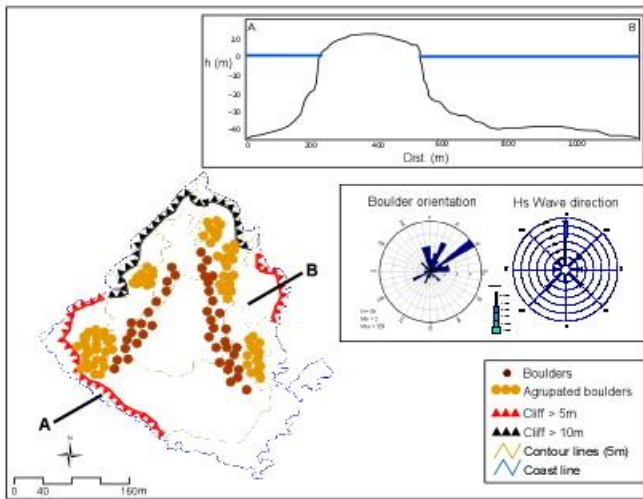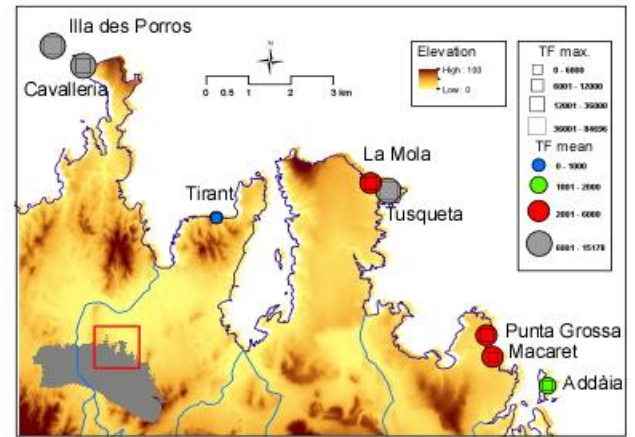
	Total	TF > 1000	Hp 12	JBB	Subaerial
					Engel & May
N. Boulders	338	214			
Distance av.	50.2	66.2	St.	21.6	9.8
Height av.	9.4	11.7	Ts	11.3	8.3
Weight av.	8.4	12.1			Pignatelli
TF av.	5.479	8.501	Ts		13.2

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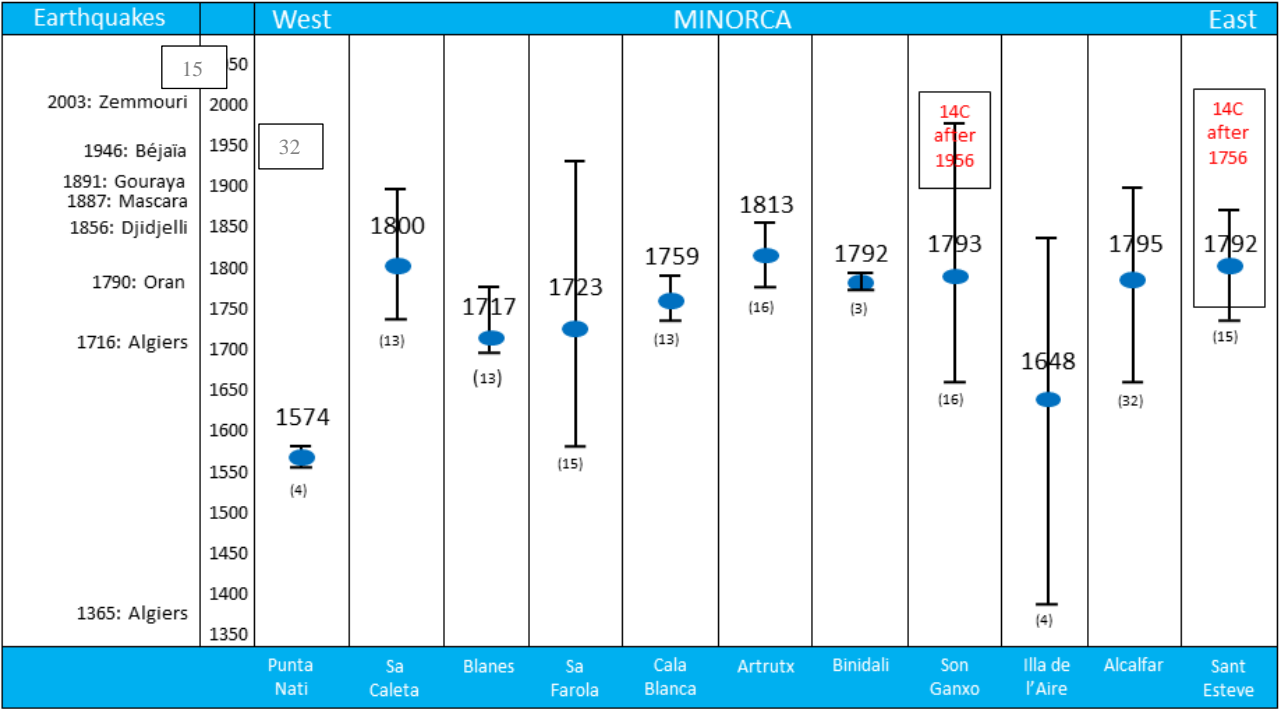St: Average Storm wave run-up
Ts: Average Tsunami wave run-up

Figure 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 numbers in parentheses ~~the box~~ show the number of measured pans at each area. The left column display the earthquakes with intensity >X occurred in North Algerian Coast, since 1365. Rectangles indicate the age obtained through 14C.
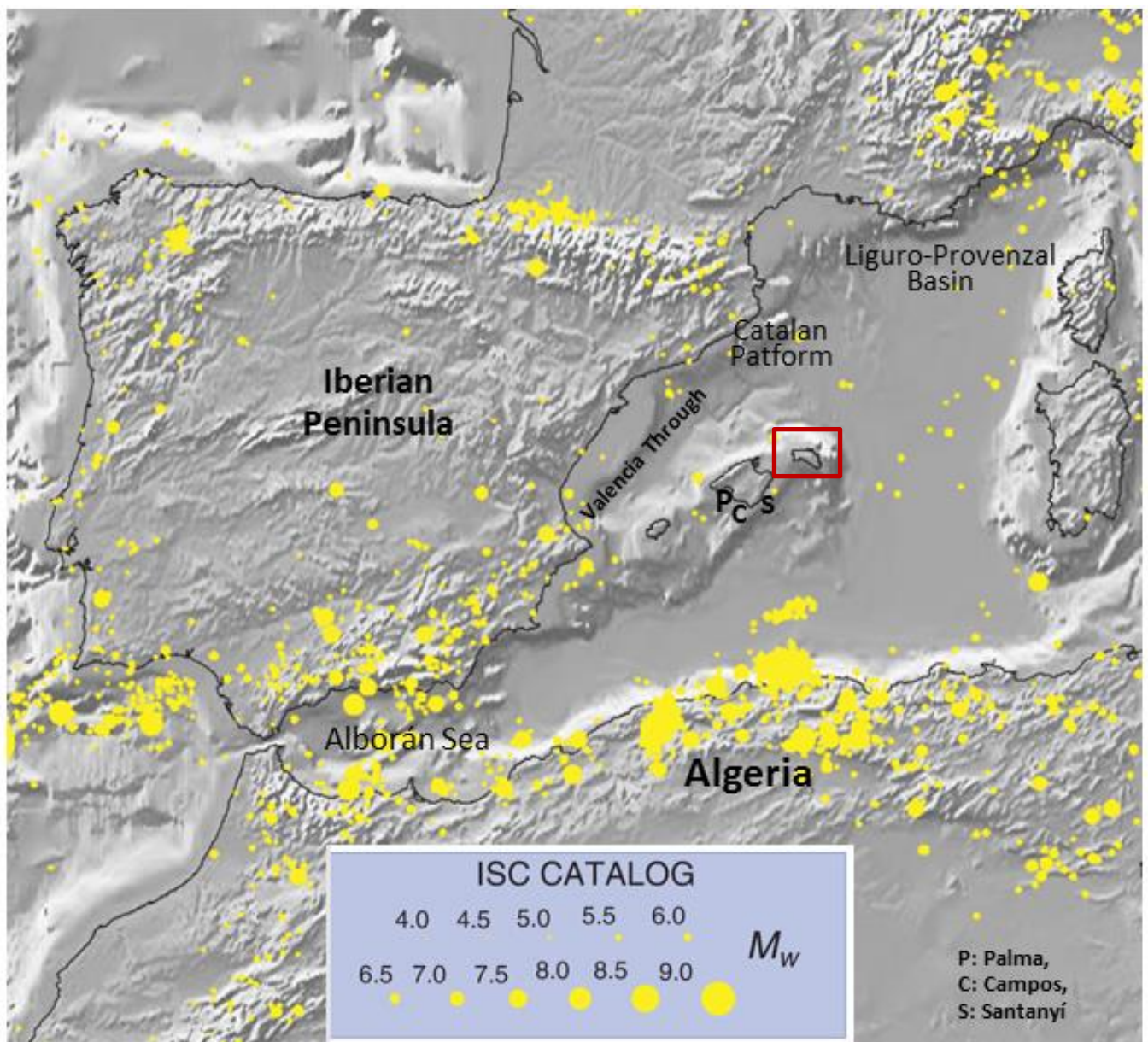
Figure 10. Instrumental seismicity of the Western Mediterranean Region (from ISC Catalog) for depth interval 0-50 km. Modified from Vanucci et al., 2004

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