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GLORIA STORM EFFECTS ON THE COASTAL BOULDERS EAST OF MINORCA (BALEARIC ISLANDS)

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ABSTRACT

The article addresses the analysis of the effects of an extreme marine event, the 2020 storm Gloria, on boulder-field deposits on the eastern coast of Menorca. These deposits were interpreted by the authors as tsunami deposits, formed between the 17th and 19th centuries. Measurements were made of boulders that have been displaced and of the new boulders formed by erosion of the coastal scarp, as well as contrasting all this information with the data of the previous configuration of the boulder fields. These data are complemented with the application of hydrodynamic equations, wave data from buoys and bathymetric profiles in order to verify the limited capacity of even the heaviest storms to modify the position of the boulders in these inland deposits. The Gloria storm, with return periods of more than 200 years, shows the impossibility of moving the thousands of metric blocks to their current positions. Therefore, they require tsunami events such as those that hit these coasts from North Africa.

Keywords: Gloria storm, Minorca Island, boulders, tsunamis

INTRODUCTION

There is a lively debate about the nature of large coastal boulders located at the edges of coastal cliffs. Basically two main schools exist, one attributing the origin of the boulders to heavy storms, basically in places with fetches over thousands of kilometers (Goto et al., 2009, 2011, works focused on Japan; Etienne and Paris, 2011, referring to boulders on Iceland; Cox et al., 2018, 2020, works focused on Ireland) and the other one considering the origin of the boulders to tsunamis. Boulders of tsunami origin has been reported worldwide (Bryant and Nott, 2001; Scheffers and Kelletat, 2003; Nott, 2003, among others), even in the Mediterranean: Kelletat and Schellmann (2002) in Cyprus, Mastronuzzi et al. (2007) in Puglia (Italy), Scheffers and Scheffers (2007) in Crete, Furlani et al. (2014) in Malta.

At the Balearic Islands, tsunami boulders were first reported by Scheffers and Kelletat (2003), followed by Paris et al. (2010) and later widely studied by Roig-Munar et al (2018, 2019). During these studies, our group painted and marked some boulders in order to be allowed to calculate their movement in case of a new tsunami or severe storm.

The occurrence of Gloria storm in January 2020 (19th and 20th) produced the highest wave height (14.8 m at Maó buoy –Minorca Island-) ever recorded at the Balearic Islands, that means during the las 60 years. It was a great opportunity to check if heavy storms play a major role in the quarrying of cliff-top boulders in the east coast of Minorca Island. We want to highlight the fact than the main component of Gloria Storm was the E component. Thus, in this article we analyze the main effects of Gloria storm in two sites of the east coast of Minorca Islands, where coastal boulders already existed. The goals are 1) to show if previous boulders have been moved or new ones have been quarried by the effects of Gloria storm and 2) to the light of the occurrence of this heavy storm, to demonstrate the tsunami origin of the boulders field.

STUDY AREA

The two study areas are located at the E coast of Minorca Island (Figure 1). The lithology of the two areas is similar: horizontal limestones corresponding to the reefal unit of Upper Miocene age (Pomar et al., 2004). The two analyzed boulder deposits (Sant Esteve and Alcalfar) are separated one from the other a distance of 2.9 km, so the waves affect both in the same way.

In Sant Esteve there is a deposit of large boulders –up to 4770 in number, metric ones in size - on a platform of variable height between 1.5 m and 3.3 m, over an approximate area of 30000 m^2 (Figure 2). This part of the coast has a variable height between 0.8 and 1.4 m above sea level and is not properly a cliff. This deposit, consisting of three ridges of overlapping boulders parallel to the coastline, was analyzed by Roig-Munar (2016) and described it as a tsunamitic origin. The direction of the boulders has an E-SE component.

Bathymetry of this study area is shown in figure 2B. The deeper part has a regular slope of 1.8^{o} degrees until the bathymetric level of -25m for both profiles. Nevertheless, as we move to the east, slope differs between the two profiles. Profile A has a gentle slope near the coast whereas it is steeper at the profile B. This small difference in slope in the two profiles can have an unequal influence on the movement of the blocks located in the vicinity of the profiles.

In Alcalfar, over an area of 35000 m^2, there are fields of imbricated boulders (Figure 3) at distances greater than 60 m from the coastline and heights that vary between 4.7 m above sea level in the southern sector and decreasing progressively to 1.5 m to the N. Up to 850 metric boulders exists in this area. The cliff is a hanging cliff with several steps. The boulder ridges are usually concentrated along steps following bedding planes.

Bathymetry of Alcalfar area is shown in figure 3B. This sector of the coast presents a variable bathymetry as we move from the cape located to the N of the study area towards the south (Figure 5). It is characterized by the presence of a positive relief in profiles A and B that it is not present in C. Regarding profile A (Figure 5), it presents similarity in terms of morphology with the profile of the central sector, with a positive relief 400 m from the coast. Regarding profile B, its main characteristic is the presence of a positive relief that has its highest peak 400 m from the coastline. Profile C presents notable differences with the other two. It shows a smooth profile up to 200 m from the coast and from here the slope increases until the last 150 m.

MARITIME CLIMATE

The Mediterranean basin is characterized by a very irregular coastline that creates small well-defined sub-basins, where the wave energy is conditioned by the speed of the wind, its intensity and by a limited fetch (Lionello et al., 2005). In the case of the western Mediterranean, the most intense waves come from the NE (Sotillo et al., 2005), although the NW storms also generate strong waves between the Balearic Islands, Corsica and Sardinia (Bertotti and Cavaleri, 2008). The coastline of the study area is oriented from N to S, so it is directly affected by waves coming from the E, whose fetch extends over 350 km (Figure 4A).

For the present work, the records provided by Puertos del Estado (www.puertos.es) have been considered from the data provided by the Maó Buoy, whose location is about 16 km to the SE of the island (4,422 E longitude and 39,718 N latitude, Figure 1).

In order to assess the wave regime on the eastern coast of Menorca and estimate the height of the storm waves, we used the data provided by the REDTEX set (measurements from the deep water buoy network, www.puertos.es), specifically the Maó Buoy (Figure 1). The data in the present work consist of wave time series (significant height, mean and peak period, maximum height and directional parameters) with a frequency of 60 minutes. With regard to sea level, the data have been extracted from the Port de Maó tide gauge, belonging to the State Port Tide Gauge Network (www.puertos.es).

Gloria storm evolution

The direction of the waves show a NNE component from the beginning of the storm, rolling towards NE until finally reaching the E component from the early morning of January 21, coinciding with the maximum values. Figure 4B shows the evolution of the significant height and maximum height of the swell and how it exceeds the threshold (which is 3.5 m for the overall buoy and 1.5 m for the E direction) from 10 p.m. on January 19, which extends until it falls below it at 6 a.m. on January 23. The duration of the storm was 80 hours, during which a first peak can be observed on day 20 that exceeds 10 m of maximum height (Hmx), decreasing its intensity to, later, reach the maximum of 14.77 m of wave height at 12 noon on January 21, with an associated peak period (Tp) of 12.3 s. Between 7 a.m. and 7 p.m. that same day there were several peaks that exceeded 11 m of Hmax, with five times being the number of consecutive hours that the maximum height exceeded 11 m and two times were above 13 m. Regarding the significant wave height (Hs), the number of hours that exceeded 7 m was 7 hours. The wind showed the same directional behavior as the waves, with a maximum speed of 15.7 m/s. With regard to sea level, it presented the highest values coinciding with the peak of the storm, reaching a maximum height of 0.2 m (www.puertos.es).

METHODOLOGY

A total of 20 boulders have been monitored at Sant Esteve deposit. It is very important to remark than all the monitored boulders are located in the first line of the proximal ridge, which means, we selected the boulders closer to the sea. We have left thousands of boulders located inland unmarked. In 2018, in the Sant Esteve deposit and following the methodology of Naylor et al. (2016), the base of and the lower part of different boulders were marked with yellow paint. The identification of the displaced blocks has been carried out through field work, observing whether they have suffered any type of alteration or whether new ones have appeared. In the case of Alcalfar (where there are no painted boulders), the method has consisted of field work and verification on the ground, based on the difference in color of the rocky substrate in those blocks that have been displaced. Ancient boulders are grey colored at the exposed surfaces due to lichen presence and new boulders are brown colored because of the appearance of new surfaces which have lichen absence. Systematic photographs have been taken in order to determine and quantify their movement. In addition, with the help of a drone, different vertical photographs have been taken.

The morphometry of the boulders was characterized by measuring the three dimensions of the block: the long axis (A), the middle axis (B) and the short axis (C). The volume of each boulder has been inferred by multiplying the three axes and applying a correction factor based on the shape and lithology following the method described in Roig-Munar et al. (2015). The mass of the boulders was determined multiplying the volume of the boulder and the density of the lithology represented (Upper Miocene limestones, with a density value of 2.3 gr/cm^3). Finally, the orientation of each boulder has also been measured.

Through the LIDAR flight 1st coverage 2008-15 (www.cnig.es) it has been determined the height of the boulders in relation to sea level, the distance they are from the edge of the cliff, as well as the most representative topographic profiles (three in Alcalfar and two in Sant Esteve).

The Transport Figure (TF) equation has been applied to each boulder, according to Sheffers & Kelletat (2003):

TF = P x A x D (1)

Where P is the mass of the boulder (in tons), A the height (in meters) above sea level and D corresponds to the distance (in meters) of the boulder to the edge of the cliff. The Transport Figure is a simple way that refers us to the wave energy needed to move any boulder: the larger the transport figure of a boulder, the larger the wave energy need to move the boulder. Scheffers and Kelletat (2003) establish a threshold from which boulders of tsunamis can be discriminated from those deposited by storms. These authors set the threshold at Transport Figure higher than 250. Roig-Munar (2016) rise the threshold value at TF higher than 1000.

In order to evaluate if storms are capable to transport boulders from its present position, we use the Noormets et al. (2004) equation:

Xmax = [T x (g) 0.5 x (R-E) 0.5 x Cosα]/5 (2)

Where Xmax is the maximum flooding distance by waves, T is the period of the wave, g is gravity, R is the height of breaking wave, and E is the cliff height and α is the angle of deposit.

RESULTS

Sant Esteve

At Sant Esteve 20 boulders were marked, before Gloria storm, with paint marks for monitoring, all of them located in the frontal part of the boulder ridge. After Gloria storm, 4 boulders have moved (Figure 5). The average displacement is of 0.4 m, with boulder 14 being the one with large displacement (0.56 m). The weight of the displaced boulders is notably lower than the weight of the boulders not displaced (Table 1). Also the Transport Figure value of the displaced boulders is considerably lower than the TF of boulders not displaced (2 and 715 respectively, Table 1).

After the storm a new boulder appear (Fig. 6 left). It is located at the edge of the cliff and it was formed by a wave strike, overturning the boulder and leaving a clear scar in the rock (pale brown colored). This new boulder has a weight of 3.6 T, it is at a height of 1.2 m above sea level and 2 m away from the edge of the coastline. Its Transport Figure value is of 9, considerably lower than transport Figure value of boulders without displacement (715). This boulder, in the process of removal and deposition, has been fragmented into several smaller blocks, which are scattered inland, within a radius of 5 m with respect to the boulder from which they were detached.

The maximum flooding distance from the coastline to inland (Xmax) yields values around 23-24 m for the swell conditions that occurred during the Gloria storm. These are insufficient values to affect most of the blocks, since the average distance of Sant Esteve boulders from the sea is 38.1 m. Within the group of displaced blocks, we observe that only boulder 10 is within the range of this maximum flood distance, as well as the new formed boulder. These values of maximum flooding distance are not enough for boulder displacement but enough for the erosion of thin rock sheets located close to the coastline. Waves also moved and returned this rock sheets into the sea (Fig. 6 right).

Regarding their topographic distribution, the displaced boulders are located in the southern half of the Sant Esteve deposit, where the average height of the cliff in this sector is around 0.8 m while, in the northern sector, where we have not detected boulder movements, the height of the cliff is 1.4 m. This fact can be explained not only by the different height between sectors but also by a different bathymetric profile. Because the depth of wave break in this area is of approximately -10m, the wave will break at a distance of 130 m from the coast in profile A (northern sector, Figure 2), whereas it will break at 60 m distance in profile B (southern sector). There is more than double the distance at which the waves begin to dissipate their energy. Thus, there is an important reduction of wave energy in sector A, where there has been no boulder movement, with respect to sector B.

Alcalfar

In this location 9 boulders have been displaced (with an average of 1.4 m) and 3 new boulders have been quarried from the cliff hanging edge (Fig. 7) giving an average displacement of 5.7 m. Boulders numbers 1 and 2 have been detached from the higher southern sector. Boulders from 4 to 13 have been displaced at the lower northern sector. Along the area, there are hundreds of boulders unmoved located at steps in bedding planes.

The maximum flood value at the southern sector of the area (average cliff height of 4.7 m) corresponding to the hydrodynamic conditions of the storm is of 18 m. In the northern area (with cliff height average of 3.2 m), the maximum flood value corresponding to hydrodynamic conditions of the storm is of 21 m. This northern area, represent the most dynamic sector, with an average displacement of 1.4 m, with block 11 corresponding to the longest distance traveled with 4.4 m. Of this group of blocks, only boulder 13 is within the flood zone and boulder 7 is close to it, with the average distance from the blocks to the ledge of 26.3 m. In figure 7 (right) we see the displacement of blocks 8, 10 and 13, and the drag mark can be seen on the surface of the cliff. The yellow arrows on the photographs of each block show the starting point of the block before its displacement. In the northern area, the boulder displacement is imperceptible because boulders are 30 m away of the cliff, whereas the maximum flood value according Noormets equation is of 23 m.

Bathymetry also has its influence on Alcalfar (Figure 3). Because the depth of wave break in this area is of approximately -10m, the wave will break at a distance of 400 m from the cliff in profile A and B. Profile C it presents notable differences with the other two. It shows a smooth profile up to 200 m from the coast and from here the slope increases until the last 150 m. The depth of -10m is at a distance of approximately 90 m from the coastline. Thus, the emerged area close to profile C receive most powerful waves than areas offshore profiles A and B because the distance to the coast and the place where waves break is lower in profile C.

The boulders that have had the most movement are those that were previously isolated, while those that were grouped or in clusters, has been displaced less due to the plug of the blocks located inland. Also, those blocks closest to the coastline and at the lowest elevation are the most susceptible to being displaced.

The new boulders correspond to sea wave hits, quarrying individual boulders in areas with a hanging cliff. (Figure 8, upper right). The only boulders torn from the cornice, boulders 1 to 3, are those that present lower values in their three axes and the lowest in terms of TF (Table 2).

It is important to remark than hundreds of already imbricated boulders have not been moved by Gloria storm (Figure 8, lower left and right). Displaced boulders constitute a minimum percentage respect to the total of boulders (less than 2 per thousand). The average movement of the displaced boulders is 1.4 m and corresponds to boulders located at the front of the ridge, many of them were isolated, below average in size and far below in Transport Figure values. The new formed boulders have this same characteristics: isolated, not imbricated, and with dimensions and Transport Figure values below average.

DISCUSSION AND CONCLUSIONS

Our data measure the low ability of storms like Gloria to generate geomorphological changes in elevated areas above sea level and far from the coastline, previously highly underestimated. In fact, it is proven how storm surge is just capable of moving very few boulders several meters from the shoreline, or reorienting them, on the roof of lower cliffs. But it is also evident that a single storm (or a recurrence of many storms over centuries) of this type cannot explain the formation of this type of boulder deposit.

The stronger storm ever recorded (Gloria) shows than just some new boulders can be quarried from the edges of cliffs. New boulders only occur if previously exists a small hanging cliff. The storm hits from below the hanging rock, the boulder is torn from the edge of the cliff, flips and fall on top of the cliff, resulting in new smaller fragments and the larger one remaining overturned. But these new boulders are located at a maximum distance of 6 m from the edge of the cliff and have Transport Figure values lower than 150, whereas tsunami boulders have Transport Figure values higher than 1000.

There is historical evidence that a tsunami occurred in 1756 affecting the east coast of Mallorca Islands (Fontseré, 1918), with a run-in up to 2km and a run-up up to 40 m. That was a very high energetic process which could create a boulder field at cliff top places higher than 7 m and at a distances over 100 m from the edge of the cliff. Storms like Gloria, not even with thousands of years can create the boulder field observed at Alcalfar and Sant Esteve.

In detail, the great storms (as Gloria) with recurrences of hundred years, produce the centimeter transport of a few boulders at cliff top surfaces no higher than 4-5m, break some cornice to the highest hanging cliffs and wash most of their top surfaces. The Transport Figure of the boulders carried by the storms does not usually exceed 150, whereas boulder already existing has Transport Figure values higher than 700.

In contrast, the tsunami boulders are in overlapping ridges, at average heights of 7.6 m ranging from a few to more than two tens of meters. They respond to one or more events that occurred about 250 years ago and present Transport Figures over 1000 (Roig-Munar et al., 2018)..

Therefore, we must conclude that the storms, even the strongest one as Gloria, cannot be responsible for the deposition of the tsunami boulders. They must have been originated by totally different processes. Storms move boulders effectively, but at distances and heights far less and incomparable to tsunami flows. They do not form overlapping clusters of hundreds of boulders, but just rather hit the upper part of the cliffs and cause collapses on the edges of the cliffs. They withdraw more materials to the sea than they bring inland.

Can we imagine any other flow to explain the arrangement of the tsunami boulders other than this event? It should be a powerful stream that would come from North Africa and be able to build cords of thousands of large imbricated boulders at significant heights inland, above the cliffs and in a process that took place more than two centuries ago. In the light of the effects recorded from the largest storm in the Balearic Islands, it is clear that a recurrence of such storms would not be enough to explain the disposition of the tsunami boulders. Thus, the most obvious conclusion is to consider the tsunami origin of the analyzed boulders and rule out their origin by large storms.

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Figure and tables captions

Figure 1.-Location of the two study areas. Red dot in upper left sketch corresponds to the Maó Buoy location.

Figure 2- Boulder field at Sant Esteve on a platform with a variable height of 1.5 to 3.3 m. the area is of 3 Ha, approximately and the number of boulders is larger than 4700.

Figure 3- Bathymetric profiles at Sant Esteve (Source bathymetry: www.ideib.cat).

Figure 4- Boulder fields at Alcalfar. Red arrows indicate the direction of boulder transport, parallel to bedding steps.

Figure 5-Bathymetric profiles at Alcalfar (Source bathymetry: www.ideib.cat).

Figure 6- Fetch length in the E direction from Minorca. Inset left: Wave direction at the Maó Buoy for the period 1993-2019. Inset right: Wave height and direction of Gloria Storm between 20 and 24 January 2020 (www.puertos.es).

Figure 7- Significant wave height (Hs), Maximum wave height (Hmax) and wave period (Tp) from the Maó Buoy (www.puertos.es) during Gloria storm. The horizontal blue line is the leave threshold of 3.5m, the vertical line indicates the moment of change of direction of the waves. Blue arrow indicates wind from NE and red arrow indicates wind from the E.

Figure 8- Plant distribution of analyzed boulders at Sant Esteve. Yellow dots correspond to boulders with visible displacement. Arrows on the right indicate the original place for boulders. Scale bar is 1 m.

Figure 9- Left: New boulder created by a wave strike which overturned the boulder with no displacement involved. Right: Marks of rock sheets eroded by the storm and returned to the sea.

Figure 10- Plant distribution of boulders at Alcalfar. Red dots correspond to boulders with some displacement. Blue dots correspond to new boulders. Yellow arrows indicate the places from where the boulder was moved.

Figure 11- Southern sector of Alcalfar before (left) and after (right) Gloria storm. Cliff erosion enhanced and a unique new boulder (boulder 1 of figure 12) appeared which will problaly be dragged to the sea with future storms.

Figure 12- Large boulder imbrication at Alcalfar (6 meters above sea level). No new boulders formed, no boulders movement at this place during Gloria storm.

Table 1- Main boulder characteristics at Sant Esteve, east of Minorca.

Table 2- Main boulder characteristics at Alcalfar, east of Minorca.

Figures

Figure 1

Location of the two study areas. Red dot in upper left sketch corresponds to the Maó Buoy location.

Figure 2

A) Boulder field at Sant Esteve on a platform with a variable height of 1.5 to 3.3 m. the area is of 3 Ha, approximately and the number of boulders is larger than 4700. B) Bathymetric profiles at Sant Esteve (Source bathymetry: www.ideib.cat).

Figure 3

A) Boulder fields at Alcalfar. Red arrows indicate the direction of boulder transport, parallel to bedding steps.B) Bathymetric profiles at Alcalfar (Source bathymetry: www.ideib.cat)

Figure 4

A) Fetch length in the E direction from Minorca. Inset left: Wave direction at the Maó Buoy for the period 1993-2019. Inset right: Wave height and direction of Gloria Storm between 20 and 24 January 2020 (www.puertos.es).B) Significant wave height (Hs), Maximum wave height (Hmax) and wave period (Tp) from the Maó Buoy (www.puertos.es) during Gloria storm. The horizontal blue line is the leave threshold of 3.5m, the vertical line indicates the moment of change of direction of the waves. Blue arrow indicates wind from NE and red arrow indicates wind from the E.

Figure 5

Plant distribution of analyzed boulders at Sant Esteve. Yellow dots correspond to boulders with visible displacement. Arrows on the right indicate the original place for boulders. Scale bar is 1 m.

Figure 6

Left: New boulder created by a wave strike which overturned the boulder with no displacement involved. Right: Marks of rock sheets eroded by the storm and returned to the sea.

Figure 7

Plant distribution of boulders at Alcalfar. Red dots correspond to boulders with some displacement. Blue dots correspond to new boulders. Yellow arrows indicate the places from where the boulder was moved.

Figure 8

Southern sector of Alcalfar before (upper left) and after (upper right) Gloria storm. Cliff erosion enhanced and a unique new boulder (boulder 1 of figure 12) appeared which will probably be dragged to the sea with future storms. Lower left and right: Large boulder imbrication at Alcalfar (6 meters above sea level). No new boulders formed, no boulders movement at this place during Gloria storm.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Table1.png
- Table2.png