# EXTREME WAVES IMPACT ON MALTA (MEDITERRANEAN SEA)

Biolchi, S.[1], Furlani, S.[1], Antonioli, F.[2], Baldassini N.[3], Cucchi, F.[1], Deguara J.[4],Devoto S.[1], Di Stefano A.[3], Evans J.[5],Gambin T.[6], Gauci R.[4], Mastronuzzi G.A.[7], Monaco C.[3], Scicchitano G.[8]

[1] *Department of Mathematics and Geosciences, University of Trieste, Italy, sbiolchi@units.it*
[2] *ENEA, Roma, Italy*
[3]*Departmentof Biological, Geological and Environmental Sciences, University of Catania, Italy,*
[4]*Department of Geography, University of Malta*
[5] *Department of Biology, University of Malta,*
[6]*Department of Classics and Archaeology, University of Malta*
[7]*Department of Earth and Geoenvironmental Sciences, University of Bari, Italy*
[8] *Studio geologi associati T.S.T, Messina, Italy*

## Introduction

The accumulation of large boulders related to waves generated by tsunami and extreme storm events have been observed in different areas of the Mediterranean. Along the NE and E low-lying rocky coasts of Malta tens of large boulder deposits have been recognised and mapped (Furlani et al., 2011; Mottershead et al., 2014). These boulders are detached and moved by the seafloor by the action of sea waves. Reconstructing the history of these blocks and distinguishing events, such as storm waves or tsunami, play a crucial role in assessing the coastal vulnerability and risk. The Maltese coasts are seasonally affected by extreme storm waves: heavy seas are in fact frequent and are originated by the NE and NW winds. Moreover in the past some important tsunami events which occurred in the Mediterranean Sea, such as the 1693 and the 1908, have been reported on the historical chronicles of Malta (Galea, 2007). The seismicity is related mainly to the Malta Escarpment, the Sicily Channel Rift Zone and the Hellenic Arc. In this study we present a multidisplinary approach, which aim to characterize the boulder accumulations in order to assess the natural hazard for the coasts of Malta Island, where extreme waves have been and are able to detach and move large rocky blocks on the coast.

## Study area

The Island of Malta lies in the Sicily Channel, which has been affected during Neogene-Quaternary age (Finetti, 1984; Dart et al., K.R., 1993) by continental rifting. It produced extensive structures, such as the Pantelleria, Malta and Linosa tectonic depressions, which are controlled by NW-SE normal faults.

The tectonic setting of Malta is characterized by two graben systems. The most ancient one, ENE-WSW oriented, has been active since early Miocene and caused the development of a horst and graben system, which is characterized by alternating highlands and lowlands (Alexander, 1988). This system is crossed by faults belonging to the Pantelleria Rift, NW-SE oriented, which developed during the late Miocene and early Pliocene (Reuther &Eisbacher, 1985). The uplift caused by the Pantelleria Rift is responsible for the emergence of the island above sea level during Neogene-Quaternary and it also brought the island to a tilting position towards NNE (Alexander, 1988), with a resulting downlift of its eastern flanks. This tectonic development - with relatively higher topography and steep coasts along the western side of Malta and low-lying coasts along the eastern side - conditioned also the hydrological catchment of the islands during the pluvial Quaternary period, with fluvial channels draining heavily from WSW to a NNE direction. This caused a more intense fluvio-coastal erosion in the eastern part and the removal of a large part of the stratigraphic sequence in the lower topographic regions. These are the reasons why the eastern rocky coast is suitable, from a geomorphological viewpoint, for the accumulation of large boulders, from decimetric to metric in size, which are detached from the sea bottom by the waves and are deposited on the coast, also some tens of meters away from the coastline (Figure 1). Malta is formed by sedimentary rocks, deposited in shallow marine conditions between late Oligocene and Miocene (Pedley et al. 1976). The bedding is mainly horizontal or sub-horizontal.

The stratigraphic sequence starts with the Lower Coralline Limestone Formation (Upper Oligocene: Chattian, thickness: 140 m), which is characterized by bioclastic, bedded, grey limestones. It is followed by the soft and yellowish Globigerina Limestone Formation (late Oligocene – middle Miocene: late Chattian - Langhian, thickness: 20-207 m, Giannelli&Salvatorini, 1972; Baldassini et al., 2013) which is composed by massive fine-grained biomicrites. The sequence continues with the Blue Clay Formation (middle Miocene: late Langhian - early Tortonian, thickness: 20-75 m), mostly formed by alternating layers of dark-grey and pale-grey marls. The upper part of the sequence is made up of the Upper Coralline Limestone Formation (Upper Miocene: late Tortonian – early Messinian, thickness: 10-170 m), which is very similar to the oldest carbonate unit (Pedley et al., 1976).

## Matherials and methods

The eastern low-lying coasts of Malta have been surveyed in order to identify and map all the boulder accumulations. Some of the them have already been described by Furlani et al. (2011) and Biolchi et al. (2014) at Armier Bay, and by Mottershead et al. (2014), at Ahrax Point, Water Park, Xghajra and Zonqor.

The most representative boulders, in term of size, shape and distance to the coastline, were chosen for further analysis. The candidate boulders include the largest observed blocks, slab-like, roughly cubic and rectangular, as well as assembled andisolated ones.

In order to verify if the boulders are compatible with the storm wave regime of the area or if tsunami waves were responsible for their detachment, transport and deposition, we applied a hydrodynamic approach. In particular, the

Pignatelli et al. (2009), Nandasena et al. (2011) and Engel and May (2012) equations were applied in order to calculate the minimum tsunami and storm wave heights required to detach a boulder from the cliff-edge. Direct observations on each boulder were carried out, regarding size, direction and distance from the shoreline, whereas the unit weight was determined by means of the Schmidt Hammer (SH).

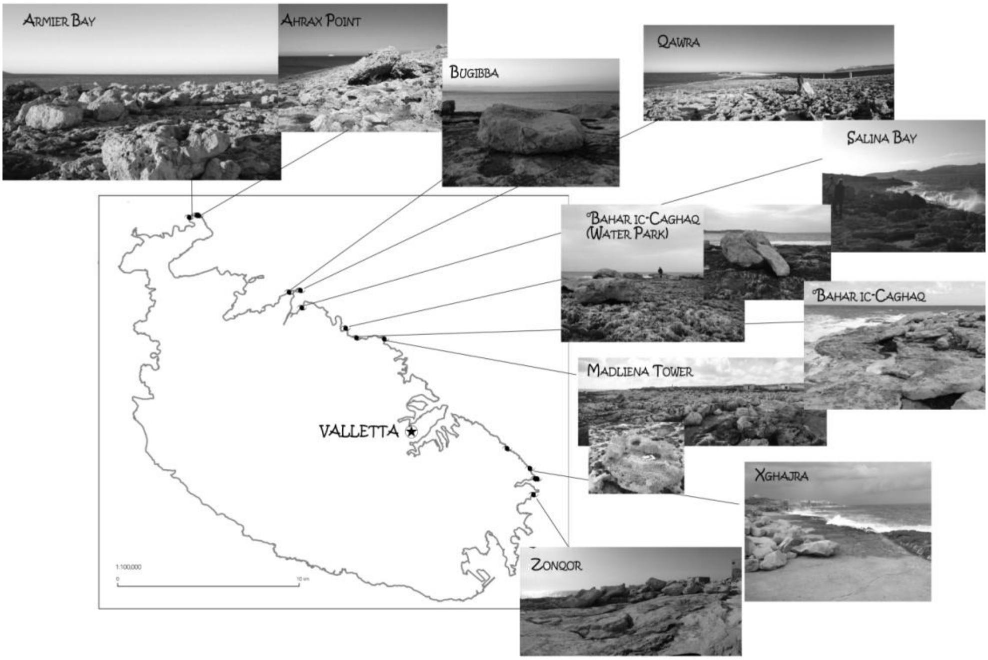

*Figure 1.Location of the coastal boulder deposits and relative pictures.*

As this approach also depends on the pre-transport environment, the most probable setting (submerged, sub-aerial, etc) prior to transportation has been determined. Moreover, detailed submerged profiles of the four coastal sites have been carried out by direct scuba surveying. The onshore megaboulders at each site were inspected to check for the presence of any biological structures, which can serve as a definite indicator of a marine (submerged) origin of the boulders since died just after their removal from underwater environment.

Finally, collected data have been compared to the Maltese wave data (Malta Maritime Authority, 2003; Malta Environment and Planning Authority, 2007;http://www.capemalta.net/maria/pages/waveforecast.html).

## Results and conclusions

The three axes of the most representative boulders, together with their volume and their density are listed in Table 1. Density has been evaluated by means of the Katz et al. (2000) formula, which relates the rebound values of a rock to the uniaxial compressive strength and its density. Moreover, the height of tsunami and storm waves required for detaching and moving a boulder from the coast edge, calculated with Nandasena et al. (2011), Pignatelli et al. (2009) and Engel and May (2012) approaches, are reported.

*Table 1.Physical parameters of the boulders (axis a, b and c, volume and density) and results of the application of the hydrodynamic equations provided by Nandasena et al., 2011; Pignatelli et al., 2009 and Engel and May, 2012 respectively for Tsunami wave (T) and Storm wave (S)*

| SITE | BOULDER | a *(m)* | b *(m)* | c *(m)* | V *$(m^3)$* | δ *$(g/cm^3)$* | $N_T$ *(m)* | $N_S$ *(m)* | $P_T$ *(m)* | $P_S$ *(m)* | $E_T$ *(m)* | $E_S$ *(m)* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AHRAX POINT | AA1 | 4.1 | 2.4 | 1.1 | 10.82 | 1.39 | 1.18 | 4.71 | 1.11 | 4.46 | 0.80 | 3.21 |
| | AA2 | 2.8 | 1.2 | 1.1 | 3.70 | 1.70 | 2.18 | 8.71 | 2.06 | 8.24 | 0.49 | 1.97 |
| | AA3 | 1.8 | 0.8 | 0.8 | 1.15 | 1.70 | 1.58 | 6.34 | 1.50 | 5.99 | 0.33 | 1.31 |
| | AA4 | 3 | 2.2 | 0.65 | 4.29 | 1.70 | 1.29 | 5.15 | 1.22 | 4.87 | 0.90 | 3.61 |
| | AA5 | 2.25 | 1.9 | 0.3 | 1.28 | 1.70 | 0.59 | 2.38 | 0.56 | 2.25 | 0.78 | 3.11 |
| | AA7 | 1.7 | 1 | 0.8 | 1.36 | 1.70 | 1.58 | 6.34 | 1.50 | 5.99 | 0.41 | 1.64 |
| | AA8 | 2 | 1 | 0.5 | 1.00 | 1.70 | 0.99 | 3.96 | 0.94 | 3.75 | 0.41 | 1.64 |
| | AA9 | 2 | 1.2 | 0.45 | 1.08 | 1.62 | 0.78 | 3.13 | 0.74 | 2.96 | 0.47 | 1.87 |
| ARMIER BAY | AB1 | 4.2 | 2.8 | 0.5 | 5.88 | 1.78 | 1.10 | 4.41 | 1.04 | 4.17 | 1.20 | 4.80 |
| | AB2 | 3.5 | 1.6 | 0.55 | 3.08 | 1.85 | 1.33 | 5.32 | 1.26 | 5.03 | 0.71 | 2.85 |
| | AB3 | 2 | 1.6 | 0.8 | 2.56 | 1.62 | 1.39 | 5.57 | 1.32 | 5.27 | 0.62 | 2.50 |
| | AB4 | 1.9 | 1.4 | 1.4 | 3.72 | 1.81 | 3.24 | 12.95 | 3.06 | 12.24 | 0.61 | 2.45 |
| | AB6 | 1.6 | 1.2 | 0.5 | 0.96 | 1.70 | 0.99 | 3.96 | 0.94 | 3.75 | 0.49 | 1.97 |
| | AB7 | 3.4 | 1.6 | 1.15 | 6.26 | 1.70 | 2.28 | 9.11 | 2.15 | 8.61 | 0.66 | 2.62 |
| | C16 | 0.9 | 0.8 | 0.25 | 0.18 | 1.80 | 0.57 | 2.27 | 0.54 | 2.15 | 0.35 | 1.39 |
| | AB5 | 2.56 | 1.06 | 0.92 | 2.50 | 1.70 | 1.82 | 7.29 | 1.72 | 6.89 | 0.43 | 1.74 |
| | new | 2.39 | 1.69 | 0.82 | 3.31 | 1.58 | 1.33 | 5.31 | 1.26 | 5.02 | 0.64 | 2.57 |
| | Q2 | 0.75 | 0.55 | 0.5 | 0.21 | 1.70 | 0.99 | 3.96 | 0.94 | 3.75 | 0.23 | 0.90 |
| BAHAR IC | B1 | 2.3 | 0.6 | 0.36 | 2.55 | 1.70 | 1.14 | 4.55 | 1.12 | 4.49 | 0.76 | 3.03 |
| | B10 | 3.1 | 1.6 | 0.6 | 2.98 | 1.39 | 0.66 | 2.62 | 0.61 | 2.43 | 0.54 | 2.14 |
| | B11 | 3.3 | 1.8 | 0.69 | 4.10 | 1.39 | 0.75 | 3.01 | 0.70 | 2.80 | 0.60 | 2.41 |
| | B12 | 3.1 | 2.35 | 0.5 | 3.64 | 1.39 | 0.55 | 2.18 | 0.51 | 2.03 | 0.79 | 3.15 |
| | B13 | 4.3 | 3.4 | 0.7 | 10.2 | 1.39 | 0.76 | 3.06 | 0.71 | 2.84 | 1.14 | 4.55 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CAGHAQ | B14 | 3.2 | 2.1 | 1.1 | 7.39 | 1.39 | 1.20 | 4.81 | 1.11 | 4.46 | 0.70 | 2.81 |
| | B2 | 4.35 | 3.65 | 0.4 | 6.35 | 1.80 | 0.87 | 3.48 | 0.86 | 3.44 | 1.58 | 6.33 |
| | B3 | 2.4 | 1.8 | 0.55 | 2.38 | 1.80 | 1.20 | 4.78 | 1.18 | 4.73 | 0.78 | 3.12 |
| | B4 | 2.6 | 1.7 | 0.7 | 3.09 | 1.80 | 1.52 | 6.09 | 1.50 | 6.01 | 0.74 | 2.95 |
| | B5 | 2.15 | 1.93 | 0.7 | 2.90 | 1.80 | 1.52 | 6.09 | 1.50 | 6.01 | 0.84 | 3.35 |
| | B6 | 2 | 1.5 | 0.55 | 1.65 | 1.80 | 1.20 | 4.78 | 1.18 | 4.73 | 0.65 | 2.60 |
| | B7 | 2.3 | 1.6 | 0.36 | 1.32 | 1.80 | 0.78 | 3.13 | 0.77 | 3.09 | 0.69 | 2.78 |
| | B8 | 3 | 2.4 | 1 | 7.20 | 1.80 | 2.17 | 8.70 | 2.15 | 8.59 | 1.04 | 4.17 |
| | B9 | 3.3 | 1.65 | 0.6 | 3.27 | 1.39 | 0.66 | 2.62 | 0.61 | 2.43 | 0.55 | 2.21 |
| BUGIBBA | LB1 | 4 | 2 | 1.2 | 9.60 | 1.70 | 2.44 | 9.78 | 2.25 | 8.99 | 0.82 | 3.28 |
| | LB10 | 2.4 | 2.3 | 0.5 | 2.76 | 2.05 | 1.50 | 5.98 | 1.41 | 5.66 | 1.13 | 4.54 |
| | LB2 | 2.9 | 1.65 | 1.05 | 5.02 | 1.98 | 3.03 | 12.13 | 2.79 | 11.15 | 0.79 | 3.16 |
| | LB3 | 2.6 | 1.8 | 1.1 | 5.15 | 2.08 | 3.54 | 14.17 | 3.20 | 12.81 | 0.90 | 3.60 |
| | LB4 | 3.3 | 2.8 | 0.6 | 5.54 | 1.62 | 1.09 | 4.37 | 0.99 | 3.95 | 1.09 | 4.37 |
| | LB6 | 2.02 | 1.12 | 0.35 | 0.79 | 1.85 | 0.89 | 3.54 | 0.80 | 3.20 | 0.50 | 2.00 |
| | LB7 | 1.98 | 1.8 | 1.1 | 3.93 | 2.02 | 3.34 | 13.35 | 3.02 | 12.07 | 0.87 | 3.50 |
| | LB8 | 1.74 | 1.6 | 0.85 | 2.37 | 1.74 | 1.86 | 7.45 | 1.68 | 6.73 | 0.67 | 2.68 |
| | LB9 | 2.5 | 2.15 | 0.8 | 4.30 | 1.70 | 1.63 | 6.52 | 1.50 | 5.99 | 0.88 | 3.52 |
| QAWRA | Qa1 | 1.8 | 1.4 | 1.3 | 3.28 | 1.80 | 2.95 | 11.81 | 2.79 | 11.17 | 0.61 | 2.43 |
| | Qa2 | 2.2 | 1.2 | 0.65 | 1.72 | 1.80 | 1.54 | 6.18 | 1.40 | 5.58 | 0.52 | 2.08 |
| | Qa3 | 1.5 | 1.5 | 0.7 | 1.58 | 1.85 | 1.77 | 7.08 | 1.60 | 6.40 | 0.67 | 2.68 |
| | qawra_2 | 2 | 1.05 | 0.6 | 1.26 | 1.74 | 1.24 | 4.97 | 1.19 | 4.75 | 0.44 | 1.76 |
| | qawra_3 | 2.3 | 1.5 | 1.1 | 3.80 | 1.88 | 2.74 | 10.95 | 2.62 | 10.47 | 0.68 | 2.72 |
| PEMBROKE | P1 | 2.55 | 1.2 | 0.6 | 1.84 | 2.24 | 2.18 | 8.72 | 2.02 | 8.09 | 0.65 | 2.60 |
| | P10 | 2.55 | 1.5 | 0.35 | 1.34 | 2.08 | 1.07 | 4.26 | 1.02 | 4.08 | 0.75 | 3.00 |
| | P16 | 2 | 1.3 | 0.4 | 1.04 | 1.80 | 0.90 | 3.60 | 0.86 | 3.44 | 0.56 | 2.26 |
| | P2 | 2 | 1.5 | 0.65 | 1.95 | 2.20 | 2.28 | 9.11 | 2.11 | 8.45 | 0.80 | 3.18 |
| | P3 | 2.85 | 2.7 | 0.8 | 6.16 | 2.19 | 2.78 | 11.11 | 2.58 | 10.31 | 1.43 | 5.70 |
| | P4 | 2.5 | 1.8 | 0.7 | 3.15 | 2.08 | 2.20 | 8.79 | 2.04 | 8.15 | 0.90 | 3.60 |
| | P5 | 2.8 | 1.5 | 0.7 | 2.94 | 2.08 | 2.20 | 8.79 | 2.04 | 8.15 | 0.75 | 3.00 |
| | P6 | 2.4 | 2.1 | 0.7 | 3.53 | 2.08 | 2.20 | 8.79 | 2.04 | 8.15 | 1.05 | 4.21 |
| | P7 | 2.55 | 1.4 | 0.5 | 1.79 | 2.08 | 1.52 | 6.09 | 1.46 | 5.82 | 0.70 | 2.80 |
| | P9 | 2.55 | 1.5 | 0.6 | 2.30 | 2.08 | 1.83 | 7.31 | 1.75 | 6.99 | 0.75 | 3.00 |
| Z | Z1 | 2.8 | 2.2 | 0.8 | 4.93 | 1.53 | 1.17 | 4.66 | 1.13 | 4.50 | 0.81 | 3.25 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ONQOR | Z10 | 4.1 | 2.2 | 0.7 | 6.31 | 1.74 | 1.47 | 5.86 | 1.39 | 5.54 | 0.92 | 3.69 |
| | Z11 | 5.3 | 2.6 | 1.5 | 20.7 | 1.74 | 3.20 | 12.81 | 2.97 | 11.88 | 1.09 | 4.36 |
| | Z12 | 2.3 | 1.2 | 0.7 | 1.93 | 1.49 | 0.97 | 3.86 | 0.90 | 3.59 | 0.43 | 1.72 |
| | Z13 | 2.4 | 0.86 | 0.7 | 1.44 | 1.85 | 1.72 | 6.90 | 1.60 | 6.40 | 0.38 | 1.53 |
| | Z14 | 5.1 | 1.55 | 1 | 7.91 | 1.78 | 2.25 | 8.99 | 2.08 | 8.34 | 0.66 | 2.66 |
| | Z15 | 2.8 | 1.1 | 1 | 3.08 | 1.75 | 2.17 | 8.69 | 2.02 | 8.06 | 0.46 | 1.86 |
| | Z2 | 2.7 | 1.8 | 0.5 | 2.43 | 1.70 | 0.97 | 3.88 | 0.94 | 3.75 | 0.74 | 2.95 |
| | Z3 | 3.3 | 2.8 | 0.9 | 8.32 | 1.70 | 1.83 | 7.33 | 1.69 | 6.74 | 1.15 | 4.59 |
| | Z4 | 4.35 | 3 | 0.7 | 9.14 | 1.74 | 1.51 | 6.03 | 1.39 | 5.54 | 1.26 | 5.03 |
| | Z5 | 2.6 | 1.5 | 0.7 | 2.73 | 1.74 | 1.51 | 6.03 | 1.39 | 5.54 | 0.63 | 2.52 |
| | Z6 | 8.5 | 4 | 1.2 | 40.8 | 1.74 | 2.46 | 9.84 | 2.38 | 9.50 | 1.68 | 6.71 |
| | Z7 | 3.45 | 1.45 | 0.7 | 3.50 | 1.70 | 1.36 | 5.43 | 1.31 | 5.24 | 0.59 | 2.38 |
| | Z8 | 3.3 | 2.2 | 0.7 | 5.08 | 1.88 | 1.76 | 7.04 | 1.67 | 6.66 | 1.00 | 4.00 |
| | Z9 | 3.1 | 1.45 | 1 | 4.50 | 1.74 | 2.09 | 8.37 | 1.98 | 7.92 | 0.61 | 2.43 |

Concerning the pre-dislodgement setting of the boulders, a joint-bounded, submerged scenarioois the most frequent, while for some blocks at Zonqor, Bugibba and Baharic-Caghaq, a subaerial joint bounded scenario is suggested.
Underwater surveying highlighted at Zonqor and Armier Bay a submerged scenario characterized by isolated boulders, both with fresh contours and coveredby algae and populated by marine organisms, niches and fresh detachment scarps. The sea bottom is similar to the subaerial geomorphological setting, being characterized by a gentle sloping platform, interrupted by small scarps which correspond to the bed planes.

The application of the hydrodynamic equations (Table 1) has highlighted that there are no correlation between density and volume values and the obtained results. As a consequence, the larger boulders do not necessarily require high waves to be detached from the cliff edge. Results from Nandasena et al. (2011) and Pignatelli et al. (2009) are very similar: the highest values are up to reach 14 and 13.35 m using Nandasena et al. (2011) and up to 12.8 and 12.7 m (Pignatelli et al. (2009), thus differing between them of less than 1 m. For all other values, the decrease of the storm wave height, decreases also the difference between the obtained results. Among the 77 selected boulders, the storm wave heights of 21 of them exceed 8 m. Conversely, the calculated tsunami wave heights are very low and range between 3.5 m (3.2 m for Pignatelli) and 0.55 m (0.51 m for Pignatelli). Engel and May (2012) equations provided very much lower values, suggesting storm wave heights ranging between 1 and 6 m. Most of storm wave heights are congruent with those measured on the Maltese Arcipelago (Malta Maritime Authority, 2003; Malta Environment and Planning Authority, 2007;

http://www.capemalta.net/maria/pages/waveforecast.html).During the stormiest months, the maximum wave values range between 5 and 5.5 m. However we can suppose that in correspondence to the coast, the run-up height can exceed 10 m, as testified by the cliff top storm deposits (CTSD) observed at significant elevations at Ahrax Point.

Biolchi et al. (2014) provided three Radiocarbon datings, performed on three marine organisms sampled from three boulders (AB5, C82 and Q2 of this study): 1083-1205 BP, 558-639 BP and post 1950 AD. These results suggested the possible occurrence of ancient extreme events, somehow correlated to historical tsunami events but also a very recent storm event.

Additional proof of recent extreme waves is provided by the tracks of freshly damaged karst surface, which were generated by rolling/saltation boulder transport, leading directly from the fresh scarp at the terrace edge to the boulder’s current position.

While new radiocarbon dating are in progress, this preliminary study suggests the frequent occurrence of extreme storm waves on the island of Malta. This occurred especially along the north-eastern and eastern coasts, where the geomorphology of the coast, the sub-horizontal attitude of the strata and the low geomechanical properties of the rocks favoured the detachment of large boulders from the coast edge, both in submerged and subaerial conditions.

However, the possibility that also one or more tsunami events have affected these coasts is not excluded.

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