Tsunami Landfalls in the Maltese Archipelago: Reconciling the historical record with geomorphological evidence

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Abstract

The Maltese Islands lie in the middle of the tsunamigenic Mediterranean domain, around whose margins and islands evidence of historic tsunami landfall has been increasingly recognized in recent years. Critical review of historical evidence of events in 1693 and 1908 indicates extremely modest tsunami impacts. In marked contrast, though, recently discovered geomorphological evidence summarized herein suggests that Malta's coastlines have been overwashed up to elevations of >20 m asl by an exceptional event. A new perspective is provided by a review of the central Mediterranean context within which the Maltese evidence is located. Recent advances in understanding of the Holocene sequence forming the Mediterranean Sea floor present a new stratigraphic and temporal framework within which to elucidate tsunami history. Within 100 km of Malta terrestrial stratigraphy on Sicily also provides supporting evidence of tsunami impact. Review of these advances suggests that the exceptional event required to emplace the most extreme sedimentary and geomorphological signatures on and around Malta is likely to have had a far-field origin. The currently available circumstantial evidence points strongly toward a probability that the AD365 earthquake and tsunami were responsible. This in turn enables critical reassessment of the exposure of Malta to tsunami hazard.

Keywords

Mediterranean; extreme waves; erosion features; boulder deposits; tsunami; Malta

The Maltese archipelago sits on the Malta Plateau atop the Pelagius Platform, a northern promontory of the African plate which extends towards Sicily and separates the deep Ionian Basin from the western Mediterranean. Eastwards at a distance of 120 km the submerged Malta Escarpment forms the steep margin of the Ionian Basin, eastwards of which the sea floor falls to - 4000 m (Galea 2007; Micallef *et al.* 2013). The islands are formed of Neogene sedimentary rocks

31 tilted towards the NE and affected by transverse faults creating horst and graben structures and
32 topography.

33 There is a long and locally detailed history of recorded tsunami linked with tectonically active regions
34 in the Mediterranean, summarized by Guidoboni *et al.* (1994) and Papadopoulos *et al.* (2014). Until
35 quite recently, however, there was a reluctance to believe that tsunami pose a threat in the wider
36 Mediterranean domain (Papadopoulos 2009). The Maltese islands are located at a focal point in the
37 central Mediterranean Sea and, thereby, exposed to marine influences from across the entire
38 Mediterranean including both near-field and far-field sources (Figure 1). Tinti *et al.* (2005) model
39 tsunami originating from these zones and show how those originating from Algeria (~1000 km
40 distant), the Western Hellenic Arc (600-800 km) and especially the Calabrian Arc off Eastern Sicily
41 (250-350 km) have the potential to create significant tsunami impacts on Malta. To the north the
42 near-field tsunamigenic zone of Eastern Sicily and Messina Straits is rated as a threat of intermediate
43 tsunamigenic potential and to the east lies the Western Hellenic arc of high potential (Papadopoulos
44 2009). Even over these distances, a tsunami would have the potential to travel to Malta in
45 approximately 70 minutes and thereby to pose a significant threat to the archipelago and its
46 inhabitants.

47 The tsunami history of Malta is recorded in both historical written records and by geomorphological
48 evidence in the field. The former expresses the human experience of tsunami landfalls in Malta
49 across a span of over 300 years and embraces two events, namely 1693 and 1908. The latter
50 preserves tangible evidence of a tsunami landfall event in the form of recognizable tsunami
51 signatures, of both erosional and depositional origin, which are available for scientific observation
52 and analysis.

53 The objectives of this paper are therefore to:

- 54 • critically review and interpret available documentary evidence of historic tsunami in Malta;
- 55 • summarize recently acquired geomorphological and sedimentary evidence of tsunami
56 landfall on Malta;
- 57 • highlight the apparent contrast between the historical and the geomorphological evidence;
- 58 • interpret the combined Maltese evidence in the context of current understanding of the
59 Holocene and tsunami histories of the Mediterranean;
- 60 • re-evaluate the tsunami threat to Malta.

61

62 **The historical experience of tsunami landfalls in Malta**

63 There are known historical records for two significant tsunami landfalls in Malta; one in 1693,
64 predating the era of scientific understanding of such phenomena, and a second one in 1908, within
65 the modern era.

66

67 *The tsunami of 10/11 January 1693*

68 On 11 January 1693 an earthquake of magnitude (M_{aw}) 7.4 and scoring up to 10 on the Mercalli
69 intensity scale occurred across most of southeast Sicily, devastating many towns and villages and
70 causing an estimated >60,000 deaths (Guidoboni *et al.* 1994; de la Torre 1995). Modern
71 reconstructions of the earthquake event suggest five potential sources ranging from the Malta
72 Escarpment offshore of east Sicily including other nearby faults, to the Sicilian Basal Thrust in east
73 and central Sicily (Visini 2009). It created a tsunami which impacted on a coastline length of 230 km,
74 with a maximum reported run-up to 8m above sea level (asl) at Augusta, and maximum inundation
75 distance of 1.5 km at Mascali (Boccone 1697, in Gerardi *et al.* 2008). Gutscher *et al.* (2006) modelled
76 associated tsunami wave heights of 1-3 m.

77 This earthquake is the most intense seismic event to have struck Malta since AD 1500 (Galea 2007).
78 It caused severe damage to many large stone-built structures, including palaces and the Norman
79 cathedral in Mdina (Shower 1693; Galea 2007; Borg *et al.* 2008). In Malta, its magnitude was
80 calculated at K_0 V, and EMS-98 intensity at VII-VIII (Boschi *et al.* 2000). Historical accounts of the
81 Maltese impact of both earthquake and tsunami are provided by Shower (1693) and de Soldanis
82 (1769).

83 In contrast to the earthquake, information specific to the associated tsunami of 1693 is rather more
84 limited. It is presented by Agius de Soldanis (1712-70) in his manuscript 'Il Gozo Antico Moderno e
85 Sacro-Profano', published in Italian (De Soldanis 1750). In 1936 Mgr Giuseppe Farrugia Gioioso
86 published a Maltese translation (De Soldanis 1936), which was itself the basis for a subsequent
87 translation from Maltese into English by Rev Fr A. Mercieca (De Soldanis 1999). In the original text
88 de Soldanis provided two statements which are of potential assistance in gleaning pertinent
89 information from the testimonies of Gozitan inhabitants regarding the tsunami event at Xlendi, Gozo
90 (Figure 2), as follows:

91 'il mare lascio il propio letto, e in fuomi si ritiro per un miglio circa', translated by the authors as 'the
92 sea withdrew for about one mile exposing the sea bed', or by Camilleri (2006) as 'rolled out to about
93 one mile'.

94 'ma poco dopo con grande impeto e mormorio cerco il suo luogo nel tempo stesso', translated by the
95 authors as 'but shortly afterwards returned with great force and noise to its normal position', or by
96 Camilleri (2006) as 'and swept back a little later with great impetus and murmur'.

97 Notably, these statements predate the modern era of quantitative scientific observations and
98 therefore merit some caution in their interpretation, on several grounds. First, it is evident that
99 Agius de Soldanis himself, who was not born until 1712, could not have been an eye witness to this
100 event. Furthermore, he does not reveal his source or sources. If we allow him 21 years to attain
101 adulthood, then it is possible that he acquired his information of the event any time between 1733
102 and 1746. At this time it would have been a memory of between 40 and 53 years, raising the
103 question of how reliable the memory may have been. A sentient 10 year old child witnessing the
104 event would be 50-63 years of age by the time Agius de Soldanis obtained the information; a 30 year
105 old adult would, if still alive, have been 83 years of age. It can only be conjectured how many eye
106 witnesses actually survived to provide valid testimony or how much of that was hearsay from folk as
107 yet unborn in 1693 who had received information from their own elders.

108 Second, there is the accuracy of the observed information, in this case the 'mile'. Certainly, given the
109 circumstances of the moment, the receding sea margin, the lack of landmarks and the sheer
110 practicalities, it would not have been a measured mile. It is also the case that there were many
111 definitions of the mile extant at the time; the international mile was not subject to a standardized
112 definition until 1959. A more practical approach to this issue is to test the plausibility of a tsunami
113 drawdown over a distance of one mile at this site by examining the local bathymetry. At a distance
114 of one mile offshore of Xlendi, bathymetry reveals that the sea floor lies at an elevation of between -
115 100 and -200 m. These values are far in excess of drawdown values reported and/or modelled for
116 Mediterranean tsunami. Piatenese & Tinti (1998), for example, model mareograms for this event
117 which generated four surges. Their thirty minute model portrayed strong withdrawals to -4 m to -6 m
118 respectively at Syracuse (Sicily) with run-ups to between -1 m and +1.5 m. Although the spatial limits
119 of the model did not extend as far as Malta, it is likely that the tsunami effects were not greater than
120 these values on the more distant Maltese shores.

121 The observation concerning the mile could then well be a subjective interpretation, swelled by the
122 memory (conceivably of an awestruck mediaeval peasant lacking the precision equipment to survey
123 it accurately) and the passage of several decades. It is, however, possible to make a reasonable

scientific interpretation based on information on hydrographic charts. From the shoreline at Xlendi an enclosed, elongated (>0.5 km) bay of shallow depth extends seaward beyond the Ras il Badja Point at its entrance, where the depth is still a modest 4 m. It is reasonable, therefore, to suggest that a drawdown to -4 m may have taken place, implying a withdrawal of upwards of 0.5 km prior to the tsunami arrival. This interpretation would appear to place a reasonable constraint on the far less plausible claim of the one mile withdrawal prior to the tsunami advance.

Third, much depends on the quality of the translation. At the detailed level, translation of individual words may affect the sense of the text and there is no guarantee that a particular word has retained an unchanged meaning over a period of 300 years. Translation of the phrase describing the advance of the tsunami wave itself, 'con grande impeto e mormorio', is a case in point: 'Impeto' may reasonably be translated as force; 'mormorio' is more catholic in its implications, depending on context, and to avoid unnecessary and possibly subjective assumptions, we prefer the more general sense offered by the word 'noise'. The significance of this point lies in its influence on and potential value in assessing tsunami magnitude according to subjective scales such as those of Ambraseys (1962) and Iida *et al.* (1967).

Some reasonable inferences, however, can be made from these interpretations. There is no mention of damage and, probably of greater significance, no mention of fatalities. The latter would surely have been reported had any been caused by this event, especially in a scientifically primitive era when such catastrophes were likely to be interpreted as representing the wrath of God. On a very gently shelving inshore seabed, a withdrawal of 0.5 km (startling though it may have appeared to a population of very limited education and experience) is not particularly abnormal as meteorologically induced seiches occur in this area. In terms of current scales of tsunami magnitude (Ambraseys 1962; Iida *et al.* 1967) the advancing tsunami wave with its interpreted rumble falls far short of the 'strong roar' and 'people drowned' characteristics associated with the K₀V category of the modified Sieberg scale of seismic wave intensity. The category III+/-I (Light to Rather Strong) would appear to be a more reasonable for this event on the limited information available, implying run-up values of 1-4m. Conclusions gleaned from the available evidence would appear to be congruent with the interpretation of an intensity of a K₀I-III tsunami.

The tsunami of 28 December 1908

The earthquake of 28 December 1908 was centred on the Straits of Messina, causing at least 120,000 fatalities (Borg *et al.* 2016) in and around the cities of Messina and Reggio di Calabria, the single

greatest loss of life in recorded earthquake history at that time. Its effects were felt over a radius of 200 km from its epicentre. The associated tsunami made landfalls along 100 km of the Sicilian coast and 38 km of that of Calabria with observed maximum run-ups of 11.7 m and 9.7 m, respectively (Omori 1909; Platania 1909). Comerici *et al.* (2008) estimated that 2000 further deaths were attributable to the tsunami, which also destroyed many properties. A contemporary Maltese account of the Messina event is provided by Galea (1909).

In a thorough review Pino *et al.* (2000) summarized studies of the 1908 event. The magnitude of the 1908 earthquake is estimated at $M_w = 7.1$. A majority opinion is that it was caused by strike/slip along a north striking fault located within the Messina Strait (Amoruso *et al.* 2002), whilst Pino *et al.* (2009) affirmed that models to date do not wholly satisfy the observed data. Ridente *et al.* (2014), based on submarine geomorphology, concluded that a blind fault was most likely responsible and that submarine landslides may have locally distorted the run-up pattern, thus confounding attempts to reconstruct the event.

The tsunami impact on Malta, some 250 km from the epicentre, is widely recorded, including numerous contemporaneous newspaper reports (Figure 3) (Borg *et al.* 2016). Official records of tide levels (Qarantena, Grand Harbour Valletta) and daily weather logs (Ġurdan Lighthouse, Gozo, and British naval ships berthed in Grand and Marsamxett Harbours, Valletta) are available for inspection at the National Archives of Malta, Gozo and UK, respectively. Baratta (1910) provided witness observations from 11 localities throughout the Maltese Islands, summarized in Table 1. Not all characteristics were recorded for all stations but it is possible to identify some general patterns. The tsunami made landfall on 28 December, initially at Xlendi (Gozo) at 06.00 and down to Birżebbuġa at 06.50. Characteristic multiple tsunami waves were recorded at Mġarr and Msida. Disturbances of the sea apparently continued at Tigné until 16.00. There is considerable variation in maximum elevations (run-up) of the sea, according to local topographic circumstances, as is characteristic of tsunami waves. Maximum values of >1 m height were observed only at Msida and Birżebbuġa and, within this limited dataset, the total range of sea level variation exceeded 2 m only at Birżebbuġa. The single quantifiable record of inundation (onshore advance) relates to Marsaxlokk (Baratta 1910), suggesting that the tsunami inundated the land up to 300 m inland. Within the broader context of global tsunami events this tsunami impact is of only modest proportion. Although reaching at least X on the Papadopoulos & Imamura (2001) 12-point tsunami intensity scale close to its epicentre at Messina, its intensity was substantially reduced to around point V by the time it arrived at Malta, consistent with a tsunami wave height of <1 m.

It is noteworthy, and perhaps indicative of its limited impact, that no record of this tsunami event was recorded either by the weather observatory at Ġurdan lighthouse, NW Gozo, or in the logs of the many British naval ships at anchor in Grand and Marsamxett harbours, Valletta. The damage that the 1908 event induced in the Maltese islands was apparently limited to the flooding of cellars in Sliema and Msida and the stranding of boats at Quarantena and Marsaxlokk. Relatively minor disruption was caused by the fluctuations of sea level in the form of boats breaking from their moorings and ferry passengers having difficulty in accessing embarkation pontoons. No serious damage was reported and perhaps most significantly there is no record of human fatality or even injury.

The exposure of the Maltese populace to information regarding the 1908 Messina earthquake disaster, including the tsunami, can be assessed from contemporary press reports. These are represented in this study by the two leading Maltese English language newspapers, The Daily Malta Chronicle and The Malta Herald, both available in local archives. The volume of information was assessed in terms of weekly word totals for weeks following the earthquake and tsunami, estimated from the column length of daily articles and their average words per line (Figure 3). Newspapers at this time did not publish photographs but printed articles did, however, include descriptions of the event itself and its aftermath, survivors' tales, reports of ongoing rescue and relief work, charitable requests and donations and obituary notices. It is evident from the material published that the Maltese were exposed to an abundant flow of detailed information following the event. The reportage of these two local papers can be evaluated by comparison with The Times (of London) for the same period (Figure 3), in which individual news items are identified by word length in the online Times Digital Archive (www.thetimes.co.uk/Digital_Archive).

Analysis shows that in the three weeks immediately following the disaster, approximately 96,000 words were published in the two Maltese papers, 60% of them in The Daily Malta Chronicle. The international scale of interest in the Messina disaster is shown by the fact that over a twelve-week period, The Daily Malta Chronicle alone published a word volume amounting to some 56% of that of The Times. In terms of significance, if the total word content (all articles) within each paper at that time is taken into account the 'proportion' of news reporting on the 1908 event within The Daily Malta Chronicle is almost certainly higher than that of The Times.

The news coverage in the press would have been reinforced by visible activity of British naval movements in and out of Valletta in support of the relief effort, and of the arrival in Malta of Sicilian refugees. The Maltese population would have been in no doubt as to the magnitude of its impact on their geotectonically close neighbours along the Sicilian and Calabrian coasts, in sharp contrast with

220 the minimal physical impact on their own island home, as would have also been the case in 1693
221 (Borg *et al.* 2016).

222 In summary, the two tsunami landfalls recorded within more than 300 years of recent Maltese
223 history were consequent upon major seismic events in nearby Sicily, but while each was responsible
224 for an estimated >60,000 human fatalities in their source localities, their impact on Malta was
225 minimal with apparently no human fatalities. Most notably, the legacy of this cumulative experience
226 of local tsunami landfalls would not appear conducive to a belief in a significant tsunami hazard to
227 the Maltese archipelago.

228

229 **Geomorphological evidence of tsunami in Malta**

230 The field evidence for historic extreme wave events in the Maltese islands is concentrated along the
231 east coast, clearly indicating wave attack from that direction (Mottershead *et al.* 2014, 2015). This is
232 not to suggest that such events are exclusive to the east but rather it offers topographies that act as
233 traps for coastal sediment deposition. The cliffed nature of the upfaulted west coast, in contrast,
234 offers few such opportunities and to date no clear evidence of historic extreme wave activity has
235 been observed on that side of the archipelago.

236 A major difficulty in interpreting extreme wave deposits is to discriminate them from regular storm
237 waves. Storm wave height is limited by the available fetch, in the case of Malta up to 2000 km, which
238 in turn limits the maximum height of the storm waves themselves, modelled by Drago *et al.* (2013) as
239 5.5 m. The height of a tsunami, in contrast, is initially dependent on the magnitude of the event that
240 creates it. At the point of landfall on a coastline its height may be magnified up to tenfold by the
241 characteristics of local bathymetry and topography. A coastline will therefore consist of two zones; a
242 lower zone, which receives run-up from both storm and weak tsunami events, and a higher zone
243 beyond the reach of storm wave run-up, which is inundated only by strong tsunami waves. In the
244 former case, both storm and tsunami sediments may accumulate together to form a composite
245 deposit, whereas the latter zone captures and retains only tsunami sediments.

246 Extreme waves, including tsunami, may leave a wide range of both erosional and depositional
247 signatures as evidence of their visitation to a coastline. Depositional signatures may take the form of
248 fine grained sediments deposited in the calm waters of coastal lagoons or estuaries to form sediment
249 sequences susceptible to study by coring or trenching. On exposed terrestrial surfaces coarser
250 material of nearshore origin such as sand, gravel and boulders may be swept ashore to form spreads
251 and in some cases landforms of measurable relief such as ridges and berms.

The range of extreme wave depositional landforms observed across sites widely distributed along the east coast of Malta is shown in Table 2. The majority of signatures are in the form of boulders, characteristic of the rocky shores and coastal platforms and ramps in the coralline limestones of Malta. They may occur as isolated individuals, clusters, or scatters forming a line or berm marking a velocity threshold of a slowing wave riding up a coastal slope. Imbricate boulders, in a cluster or occasionally stacked in a line, are indicative of a linear flow of high velocity. Split boulders, which now consist of two or more closely spaced fragments, are indicative of deposition by a heavy force. Bio-encrusted boulders are indicative of a source within the intertidal or subtidal zone. Sediment sheets are characteristically formed by sand, whereas dump deposits tend to be diamictic. Distinct erosion features are formed by the detachment and removal of bedrock to create a range of features and forms also present along the east coast, as shown in Table 3. The majority of these forms have been described by Bryant & Young (1996) and further defined within the Maltese context by Mottershead *et al.* (2015). Broadly speaking they are arranged in order of diminution of power required for their formation from sockets to swept terrain. Collapsed sea caves are interpreted on the basis that other signatures are indicative of very high energy events and so conceivably are linked to extreme cave breaching events. The identification of a plunge pool is a unique case, at the base of a massive flow evidenced by other signatures (Għemieri, below).

It is doubtful that any single extreme wave signature is itself diagnostic of the activity of tsunamis. It is the case, however, that the signatures occur in assemblages rather than individually, and in patterns relating both to each other and to topography and its interaction with an overwashing flow.

Meaningful relationships can therefore be identified between different signatures, and between signatures and topography. This is particularly the case in areas of varied terrain such as the Maltese Islands. Examples of spatial relationships of this kind are shown in Figure 4 (Aħrax). The headland and the lower slopes facing the NE are the most exposed slopes of the peninsula and exhibit fields of sockets, from whence boulders have been extracted by the decompression effect of a large overwashing wave. These are interpreted as the sources of the boulders now lying deposited further to landward. Two lines of large individual boulders form a funnel leading to a col at 7.3 m asl in the Aħrax Peninsula in the northeastern most corner of the island of Malta. Landward of this line is a spread of other sediment, cobbles diminishing landwards to gravels and sand. The boulders possess a long axis orientation indicating a movement from the coast (Figure 4). This group of signatures is interpreted as a landward-fining sequence of deposition due to a decelerating sheet of water. The boulder line extends to an elevation of >20 m, indicating that the water which transported them attained at least that elevation. Boulders also occur submerged in the bay to the west of Aħrax headland, indicative of refraction of flow around the headland and into the bay. This observation can

286 be linked to the occurrence inland of the bay of a sand sheet terminating in arcuate berms. This is
287 interpreted as being deposited by the flow which entered the bay and ran up the valley to an
288 elevation of 14 m inland of the bay.

289 In these ways the patterns of erosional and depositional signatures reflect the interaction between
290 the assailing wave and the terrain over which it flowed. Figure 5 shows a landscape cross section
291 across the col though the Għemieri peninsula at the NE point of the island of Comino. The evidence
292 of erosional and depositional signatures shows that this also acted as a spillway for an overwashing
293 flow. In this case the flow overrode the 4 m high sea cliff and passed over a col just behind the cliff
294 itself from where it was able to flow without hindrance into the bay beyond. Despite the presence of
295 this open routeway, the existence of depositional signatures up to 16.5 m asl on the summit to the
296 north (marked N) and on the slope to the south (marked S) indicates a flow of water up to 10 m deep
297 through this col. The evidence of these depositional signatures is reinforced by the presence of a
298 plunge pool and other erosional signatures on the floor of the col itself, indicative of a local high
299 velocity thread of water concentrated by a canyon at the base of the overwashing flow.

300 A further perspective on the distribution of extreme wave patterns is shown in Figure 6, showing the
301 altitudes attained by extreme wave deposits along the margins of the Comino Channel. At the
302 eastern entrance to the Comino Channel, the upfaulted blocks of land forming the Aħrax peninsula,
303 Comino Island and St Anthony's Head, Gozo, form an eastward-facing bastion to extreme waves from
304 that direction, rising to 35, 75 and 120 m, respectively. This would block the passage of an assailing
305 wave, causing it to back up, thus increasing its hydraulic potential. The wave would then propagate
306 though the limited gaps open to it, namely the North and South Comino Channels. Figure 6
307 demonstrates a steady decline in elevation over a distance of 4 km from east to west; from the
308 highest signatures at 20 m asl, adjacent to the barriers represented by cliffs, down toward 2 m asl at
309 more sheltered sites, declining westwards as the wave propagating along the channel diffracts and
310 attenuates.

311 An alternative approach to the identification of historic events and the processes by which they
312 shaped local landscapes lies in hydrodynamic considerations. Models have been developed both for
313 tsunami run-up and for boulder detachment by wave action, whether storm or tsunami in origin.
314 The run-up equation of Synolakis (1987) models the relationships between shoreline height of
315 tsunami waves, onshore and offshore slope gradients and run-up elevation. Observed values of
316 extreme wave sedimentary signatures provide a minimum estimate of run-up height; this may then
317 be used to retrodict tsunami wave height when bathymetric and topographic gradients are known.
318 For the Maltese sites directly exposed to the NE, the Synolakis equation yields shoreline wave heights

ranging from 1.37 to 3.83 m (Mottershead *et al.* 2014; note that this range now incorporates updating of data following more extensive searching at two sites).

Hydrodynamic considerations can also be applied both to processes of boulder detachment and transportation. These permit the identification of thresholds of force required for the removal of clasts in terms of the height of wave required to do so, whether storm or tsunami. In this way discrimination is possible as to whether a storm wave of plausible height within the Mediterranean context would be capable of removing an observed boulder of specific size from its seating on or within a rock platform surface. If that boulder lies above the maximum storm wave threshold, then a more powerful wave must then be responsible, pointing to the conclusion that it was likely to be a tsunami wave. Applying the models of Nandasena *et al.* (2011), Mottershead *et al.* (2014) showed that at two sites at the shoreline (Water Park, White Tower - Figure 2) 29% and 16%, respectively, of the larger boulders exceed the capacity of the conservatively assumed maximum storm wave height of 9 m, and were thus interpreted as having been detached and transported to their present locations by tsunami waves. The largest boulders in this study implied tsunami wave heights at the shoreline of 4.3 and 3.6 m, respectively. Recent work by Biolchi *et al.* (2015) across a wider range of shoreline sites in the same area produced conclusions not inconsistent with this finding. They also noted that contemporary storms have been capable of moving some large boulders, whilst onshore boulders just above the shoreline show evidence of having been moved onshore from the intertidal zone at dates not inconsistent with known tsunami as far back as the past 1000 years. Although the elevations of the dated boulders are not specifically detailed, the dates appear to relate to shoreline boulders rather than those associated with the higher level (10-20 m asl) overwashing of the landscapes of Ahrax and Ghemieri.

A special case is the model of Hansom *et al.* (2008), which describes clifftop boulder detachment. This was used by Mottershead *et al.* (2015) to model the wave required to detach a ~60 t boulder from a clifftop cornice at ~10 m asl (Figure 4) and revealed the required storm wave to be between 9.1 and 28.4 m (depending on the original but unknown orientation of the boulder), which is clearly unfeasible at this elevation and with maximum sea waves of 5.5 m (Drago *et al.* 2013). However, the required power would be produced by a tsunami wave at 10 m asl of between 2.1 and 7.3 m height, which is a more feasible proposition, particularly for a site with extreme wave signatures present up to 22 m asl.

When evaluating the geomorphological evidence of historic tsunami run-up it needs to be remembered that, for two very good reasons, the observed field evidence is likely to understate the magnitude of the actual event. First, at the point of maximum run-up the tsunami wave itself has

zero velocity and may only be present at that point for a matter of seconds. This means that by that stage it has minimum capacity for sediment transport and will have already deposited much of its sediment load, and during its brief presence at that point will offer minimal opportunity for fine sediment to fall out of suspension. Therefore, any deposition at this point is likely to be floating material such as driftwood and other biodegradable vegetation unlikely to leave any enduring signature. The sediments, especially large boulders, are likely to have been deposited at an early stage during run-up well short of the maximum limit, and will thus significantly underestimate the elevation of the latter. Second, agricultural, residential and industrial development has encroached on many coastal sites, obscuring and/or destroying relevant field evidence. Thus, the encroachment of terraced fields downslope at Żonqor has blurred the boundaries of coastal marine sedimentary deposits; the development of quarrying at Għar Dorf (NE Gozo) has destroyed any surfacial evidence that would corroborate similar deposits near St Anthony's Head; seafront development at Xghajra and Sliema has encroached on deposits evident on the shore platforms beneath; and the coastline flanking the urban concentrations of Sliema and Valletta has seriously obscured natural features of the coastline from Paceville to Xghajra over a distance of more than 7 km. It is perhaps ironic that development, the very phenomenon which obscures and thereby limits the evidence for tsunami attack, is the factor whose very presence actually increases the potential tsunami hazard.

Considering in tandem these two factors, the limited markers emplaced by tsunami at their run-up limit, and the loss of depositional evidence caused by coastal development, point to the conclusion that the remaining surviving and observable evidence is likely to underrepresent significantly the maximum run-up limit and may only serve as a minimum estimate of its true elevation.

The geomorphological evidence presented above contrasts markedly with the historical experiences and current perception of the tsunami history of Malta. The evidence of run-up to >10 m asl at most of the coastal sites directly exposed to wave approach from the NE greatly exceeds anything reported in relation to the 1693 and 1908 events. The notion of a substantial flow of water 2.1-7.3 m in depth flowing over Aħrax col and higher up the peninsula is not easy to comprehend in the field and stretches the imagination of the trained geomorphologist. It is more conceivable, however, that the evidence outlined above alludes to an event of substantially greater magnitude and threat than any in recorded history. It is entirely feasible that this great inundation occurred during an era when Malta was uninhabited or during the many centuries when the population lived well inland with coastal lands far too dangerous to settle under the threat of seaborne marauders. Unfortunately, the authors have not yet been able to establish the dates of the higher altitude deposits, which remains a significant research imperative in resolving the paradox between the historical record and the geomorphological evidence.

386

387 **Maltese tsunami history in the central Mediterranean context**

388 Recent research in the surrounding region offers important evidence regarding the tsunami history
389 of the central Mediterranean zone in which Malta is located. This includes both historic tsunami
390 landfalls on coasts opposed to Malta across the Mediterranean Sea (Mottershead *et al.* 2014) and
391 marine sediments on the seabed.

392 The nearest coastline facing the Maltese archipelago is that of southeastern Sicily. Field evidence of
393 tsunami landfall impacts on this coast has been summarized by de Martini *et al.* (2012), embracing
394 the work of Scicchitano *et al.* (2007), Barbano *et al.* (2010), de Martini *et al.* (2010) and Gerardi *et al.*
395 (2012) and spanning the entire east coast of Sicily from Gurna to Pantano Morghella (including a
396 near-shore seabed study in Augusta Bay). A tsunami event assigned to AD 365 (see Shaw *et al.* 2008)
397 occurred at four sites throughout this geographical range, although it is unclear to what extent the
398 temporally clustered earthquakes of AD 361 in Sicily (M 6.6) and 374 AD (M 6.3) in Reggio, Calabria,
399 may have confounded the interpretation of the sedimentary record. Of particular interest in this
400 case is the study of Pantano Morghella in southeastern Sicily by Gerardi *et al.* (2012), for two
401 geographical reasons. First, of the sites in the study it is the nearest to Malta at only 90 km distant
402 and may, therefore, serve as an analogue for Maltese events. Secondly, it is in the zone
403 characterized by modelling efforts (Tinti *et al.* 2005; Lorito *et al.* 2008) as a focus of impact by high
404 tsunami waves. Gerardi *et al.* (2012) identified two tsunami layers in a coastal wetland site, which
405 they associate with the Hellenic far-field and Messina near-field sources. These are dated at AD 365
406 and AD 1908, respectively. The former reveals an inundation of up to 1200 m distance, and the latter
407 380 m distance. The ingress of the 1908 event at this site was enhanced by an early twentieth
408 century drainage canal, so a more realistic contrast to the AD 365 event is offered by nearby 1908
409 tsunami impacts of 1-3 m run-up and 10-15 m inundation. If these latter values are more
410 representative of the 1908 event, then the AD 365 event assumes an even more outstanding relative
411 magnitude.

412 Studies focused on the continuously accumulating marine sediments on the Mediterranean deep
413 seabed have also revealed some significant insights to better understand the temporally and spatially
414 fragmented terrestrial tsunami evidence. These have been studied both in the Ionian Sea
415 immediately to the east of Malta (Polonia *et al.* 2016a b; Köng *et al.* 2016; San Pedro *et al.* 2016) and
416 in the broader east Mediterranean basin beyond (Polonia *et al.* 2013, 2015, 2016a). Late Quaternary
417 sedimentation in the central and east Mediterranean is dominated by turbidites, formed by
418 seismically triggered mass flows of submarine sediments that are subsequently re-deposited. They

occur both in perched basins, on the floors of submarine canyons and in abyssal plains such as the 4000 m deep Ionian abyssal plain where such beds may attain a thickness of 25 m. The trigger events for the flows may have been seismic shaking, volcanic collapse, or the passage of a tsunami wave. First investigated by Kastens & Cita (1981), the turbidites are both consistent in nature and widespread across the eastern Mediterranean. Recent studies by Polonia *et al.* (2013, 2016a) revealed that they extend from Crete to Sicily and from North Africa to Calabria, reaching as far north as 38° in the Ionian Sea, and extending over an area of >150000 km².

Polonia *et al.* (2013, 2016a) studied short (1-3 m) seabed cores which provide a record of late Holocene sedimentary events in the Ionian abyssal plain east of Malta. In particular, they reveal the presence, only 160 km from Malta, of a major megaturbidite unit, the Homogenite/Augias Turbidite (Polonia *et al.* 2013, hereafter HAT). This unit, on account of its uniformity and its breadth of occurrence, is interpreted as a consequence of a single basin-wide event of magnitude unmatched elsewhere within the late Holocene. Both Polonia *et al.* (2016a) and San Pedro *et al.* (2016) presented models that demonstrated that each turbidite emplacement comprises up to four identifiable phases, consistent with the disturbance caused by the passage of a tsunami wave.

Radiometric dating evidence from a wide distribution of sites in differing topographic circumstances reveals a widespread synchronicity of deposition, confirming that emplacement was the consequence of a single widespread major event. Calibrated ¹⁴C dating places the event in the interval AD 364-415. This associates it with the M_w 8.4 earthquake event of 21 July AD 365, the greatest seismic event known to have occurred in the Mediterranean domain during the historical period, and the associated tsunami. Polonia *et al.* (2013; 2015) identified a turbidite layer similar to the above in both its sedimentary character and wide distribution, which was interpreted in relation to a tsunami event of similar magnitude of impact to the HAT. This bed was dated as at least 15 ka BP. Köng *et al.* (2016) studied long (10-15 m) cores from the Ionian basin embracing a sedimentary record extending back 60 ka. They identified a siliclastic megaturbidite which they correlated with the HAT and a further similar layer dated 21 ka BP which they interpreted as evidence of a tsunami. This latter deposit could relate to the post 15 ka BP basin-wide turbidite layer reported by Polonia *et al.* (2013) for which only a minimum date could be estimated.

In cores retrieved from canyons and basins in the western Ionian Sea below the Malta Escarpment, some 190km east of Malta, Polonia *et al.* (2016b) were able to identify turbidites assigned to the 1693 and 1908 tsunami, confirming the capability of these events to displace submarine sediment some 200 to 300 km from the seismic event of their origins. In addition, Köng *et al.* (2016) have identified some 75 comparable turbidites within their cores on the Calabrian arc, dated within the past 60 ka.

Nonetheless, these studies document regional (near-field) and not basin-wide events. In the case of the Messina 1908 event, it was estimated that seismic shaking caused several large submarine landslides that contributed significantly to the tsunami that was generated (Polonia *et al.* 2016b). Conceivably, if the 1908 tsunami were landslide generated/augmented then much of its energy would have comprised shorter period waves that would attenuate significantly with distance from their origin. This might provide one plausible explanation for the limited historical impacts of this tsunami on the Maltese islands. This could explain the limited historical impacts of this tsunami on the Maltese islands.

A further approach to interpreting AD 365 or equivalent palaeotsunami events, and their impacts, is via modelling efforts (Tinti *et al.* 2005; Lorito *et al.* 2008; Shaw *et al.* 2008; Pararas-Carayannis & Mader 2010; Pararas-Carayannis 2011). Such models uniformly show that the AD 365 tsunami could have reached as far west as the Sicily Channel, though without significantly penetrating the western Mediterranean basin. Modelled tsunami wave amplitude at the longitude of Malta ranges from 2-7 m. Lorito *et al.* (2008, p. 11), in commenting on local extreme values of absolute maximum water height (HMAX) attained during tsunami propagation, noted that shoaling effects (as they approach along their propagation path from the NE) can create 'local extreme HMAX values at Malta and along the southeastern coasts of Sicily, Calabria and Apulia'. It is thus likely that tsunami waves approaching from the NE are transformed by shoaling as they pass over the major submarine obstacle represented by 3500 m high Malta escarpment, as clearly shown by England *et al.* (2015).

Conclusion

A new perspective on the tsunami risk to Malta is now provided by recent studies of Holocene events in the eastern Mediterranean basin. It is evident that tsunami of near-field origin from the Calabrian Arc making landfall at Malta in historical time have caused little recorded damaging impact. There is certainly good public awareness of these events as a result of the 1908 earthquake and associated tsunami. Both devastated the cities of Messina and Reggio Calabria, yet the latter had only modest impact on Malta. Earthquake events of similar magnitude along the Calabrian Arc are not uncommon, with an estimated recurrence interval of 100-700 years (Polonia *et al.* 2015) or 450-1000 years (Köng *et al.* 2016), yet on the basis of recorded history do not apparently constitute a significant threat to Malta.

Biolchi *et al.* (2015) showed that modern storms are capable of moving and depositing shoreline boulders on Malta and it is possible that some of these deposits may be associated with known

historic tsunami. In contrast, however, we are concerned here with the patterns of signatures in Maltese coastal landscapes extending upwards to >20 m asl. Their recent recognition in Malta (Mottershead *et al.* 2014, 2015) represents a much more severe landfall impact and would appear to require a different explanation. The recent evidence of Polonia *et al.* (2013, 2016a, b) and Köng *et al.* (2016) implies stratigraphic and temporal support for the AD 365 tsunami and at least one previous basin-wide event originating in the Hellenic Arc, as potentially responsible agencies. As such they represent low frequency events of very high magnitude and a potentially highly damaging threat to the Maltese archipelago. However, since only two basin-wide events of this type separated by some 19,000 years have been identified from studies covering the past 60 ka, it is very difficult to estimate a return period with any confidence.

While this paper has sought to reconcile the apparent paradox between the historical record and the geomorphological evidence, the dating of the higher altitude landfall deposits is still a prerequisite to the verification of the AD 365 tsunami as the primary formative agent, and this remains an important near-term research objective. It is concluded, therefore, that the populated NE shores of the Maltese islands are exposed to moderately frequent severe storms and infrequent near-field tsunami capable of major impacts along the shoreline. By contrast, evidence of high run-up and long inundation distances are tentatively linked to very infrequent, far-field basin-wide events with long though as yet uncertain return periods. If this type of event does represent the major tsunami hazard in the Maltese archipelago, then there may be some solace in the interpretation that it is likely to be of very low frequency of occurrence and, with its origin in the Western Hellenic Arc, would provide at least 60 to 70 minutes warning to Malta.

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668

Location	Time (hr)	Rise (m)	Fall (m)	Range (m)	Waves (no.)	Run-up (m)	Inundation (m)
Xlendi	06.00	/	/				
Mġarr	06.10	+0.91	/		4		
Marsalforn		+0.72	-0.38	1.10			
Francesi	06.30	+0.32	-0.23	0.55			
Sliema	06.50	+0.92					
Msida (Valletta)		+1.40	/		5		
Quarantena (Valletta)	06.45	/	/				
Sliema Marina	07.45	0.92					
Tigné	<16.00	vortices					
Birżebbuġa	06.30	+1.50	-1.20	2.70			
Marsaxlokk						+2.80*	300*

Table 1: Summary of tsunami observations on Gozo and Malta from 1908 presented by Baratta (1910). Values indicated by * were reconstructed by ground surveys in this study from descriptions by Baratta. The locations are illustrated in Fig. 2.

Location	Boulders					Sediment sheet	Dump deposit
	Isolated	Line/Berm	Imbricate	Split	Bio-encrusted		
Aħrax	/	/	/			/	
Għemieri	/	/	/		/		/
N Comino coast	/		/		/		
Qorrot	/		/	/			/
Quarry	/	/	/				
Water Park	/		/		/		
White Tower	/		/		/	/	/
Xghajra	/		/	/	/		
Żonqor	/	/	/		/		

Table 2: Distribution of depositional extreme wave signatures at Maltese sites. The locations are illustrated in Fig. 2.

Location	Sockets	Eroded scarps	Clifftop detachment scar	Scoured terrain	Swept terrain	Collapsed sea cave	Plunge pool
Aħrax	/	/	/	/		/	
Għar Għana	/	/		/	/		
Għemieri	/	/	/	/		/	/
N Comino coast	/			/			
Qorrot		/			/		
Quarry					/		
St Paul's Island	/				/	/	
Water Park	/						
White Tower	/	/					
Xghajra		/			/		
Żonqor		/			/		

Table 3: Distribution of erosional extreme wave signatures at Maltese sites (modified after Mottershead *et al.* 2015, with permission from John Wiley & Sons, Inc.) The locations are illustrated in Fig. 2.

Figure Captions

Fig. 1. Distribution of field sites around the Mediterranean with published evidence of extreme wave impacts linked to tsunami. Near-field sites are clustered around Sicily with the most relevant far-field sites located from western Greece to Crete comprising the western Hellenic arc.

Fig. 2. Malta site locations covering locations of historical tsunami reports (*italics*) and geomorphological evidence (underlined). Modified after Mottershead *et al.* (2014), with permission from Schweizerbart Science Publishers (www.schweizerbart.de).

Fig.3. Weekly newspaper wordage covering the Messina earthquake and tsunami disaster of 28 December 1908 in the immediate aftermath of the event.

Fig. 4. Aħrax study site showing distributions of boulder deposits, erosional features and inferred directions of direct and refracted wave impacts. The location of this site is illustrated in Fig. 2. Modified after Mottershead *et al.* (2014), with permission from Schweizerbart Science Publishers (www.schweizerbart.de).

Fig. 5. Composite N-S section across Għemieri col, Comino, showing reconstructed levels of overwashing as follows: 1. maximum known storm wave of 5.5m would marginally overtop the crest of the col; 2. a large imbricate boulder on Għemieri summit indicates a high energy flow overwashing the peninsula to at least 11.5 m asl; 3. a scatter of small boulders on the southern slope suggests that the outlying overwashing flow attained a minimum level of 17 m asl. The location of this site is illustrated in Fig. 2. Modified after Mottershead *et al.* (2015), with permission from John Wiley & Sons, Inc.

Fig. 6. Sites along the channels to the north and south of Comino plotted according to their relative exposure to the NE. (Triangles show highest depositional boulder signatures; bars show the height range of erosional signatures).

Direction of wave attack

Key individual boulder

Flow direction inferred from boulder "a" axis orientation

Erosion scarp

Eroded cliff top

Concentration of medium and large boulders

Spread of small and medium boulders

Scattered small boulders and cobbles

Sand sheet

Area of sockets

Dune crests