Submerged speleothem in Malta indicates tectonic stability throughout the Holocene

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Abstract

Submerged caves represent potential archives of speleothems with continental and marine biogenic layers. In turn, these can be used to reconstruct relative sea-level changes. This study presents new data on the tectonic behaviour of the island of Malta during the Holocene. These data were obtained from a speleothem sampled, during an underwater survey, at a depth of −14.5 m, inside a recently discovered submerged cave. Since the cave was mainly formed in a subaerial karst environment, the presence of a speleothem with serpulids growing on its continental layers permitted the reconstruction of the chronology for drowning of the cave. The radiocarbon dates obtained from the penultimate and last continental layers of the speleothem, before a serpulid encrustation, were compared with synthetic aperture radar (SAR) and global positioning system (GPS) data, together with published sedimentological and archaeological data. The radiocarbon analyses provided an average age of 7.6 ka BP that perfectly aligns with the Lambeck's model of Holocene sea level. Morevoer, long-term data agree with published archeological and sedimentological data as well as with SAR interpherometric and GPS trends on a decadal scale. We conclude that the Maltese islands were tectonically stable during the Holocene, and this tectonic behaviour still persists nowadays. On the contrary, new informations on older deposits, such as MIS5e (Maritime Isotope Stage, corresponding to 125 ka ago) were not found in the study area, confirming the lack of older Quaternary marine deposits in these islands.

Keywords

Malta, radiocarbon age, SAR, sea level change, speleothem, submerged cave

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Introduction

The relationship between sea level change and the tectonic setting of coastal areas can be derived by comparing eustatic and glacio-isostatic adjustment (GIA) models with data derived from sea level markers (e.g. Antonioli et al., 2007; Shennan et al., 2015). Submerged speleothems, in particular, can be successfully used to evaluate relative sea level changes (Dutton et al., 2009a; Surić et al., 2009). They keep track of past sea-level fluctuations because their growth may be interrupted during inundations (Surić and Juračić, 2010). Therefore, the dating of speleothems, in particular inside caves, which develop in the phreatic zone, allows the assessment as to when their development stopped because of flooding with seawater or when cave dripwater was scarce. These dates provide additional constraints on the timing and elevation of the past shoreline. In some cases (Antonioli et al., 2004; Dutton et al., 2009b; Furlani et al., 2017a; Scicchitano et al., 2008; Surić and Juračić, 2010), thanks to studies of the overgrowth on lithophaga or serpulids, it was also possible to accurately date the drowning of the speleothems. The latter are also widely used to reconstruct climate and environmental changes, as discussed in many case studies compiled by Fleitmann et al. (2008).

The tectonic setting of the Maltese archipelago was tentatively reconstructed first by Paskoff and Sanlaville (1978) using coastal geomorphological observations. They proposed that the island of Malta is tectonically stable or slightly subsiding towards the NE. Furlani et al. (2013), using the study of underwater archaeological remains along the southern and eastern coast of Malta, confirmed the late-Holocene stability of the island. Using GPS data, Anzidei et al. (2014), also suggested that Malta, as well as Lampedusa, are both tectonically stable. Deposits belonging to the MIS5e (125 ka ago) stage have not yet been observed on the archipelago, as suggested by Furlani et al. (2013, 2017b).

Paleo environments and coastal lagoon deposits were studied by Marriner et al. (2012) in the context of an ancient silted harbour at Burmarrad (NE Malta). Gambin et al. (2016) investigated the vegetation history from the Neolithic to the Roman Age in the same area. Assuming the stability of Malta, Furlani et al. (2013) hypothesized the position of the sea for the 21, 14.5, 13.8, and

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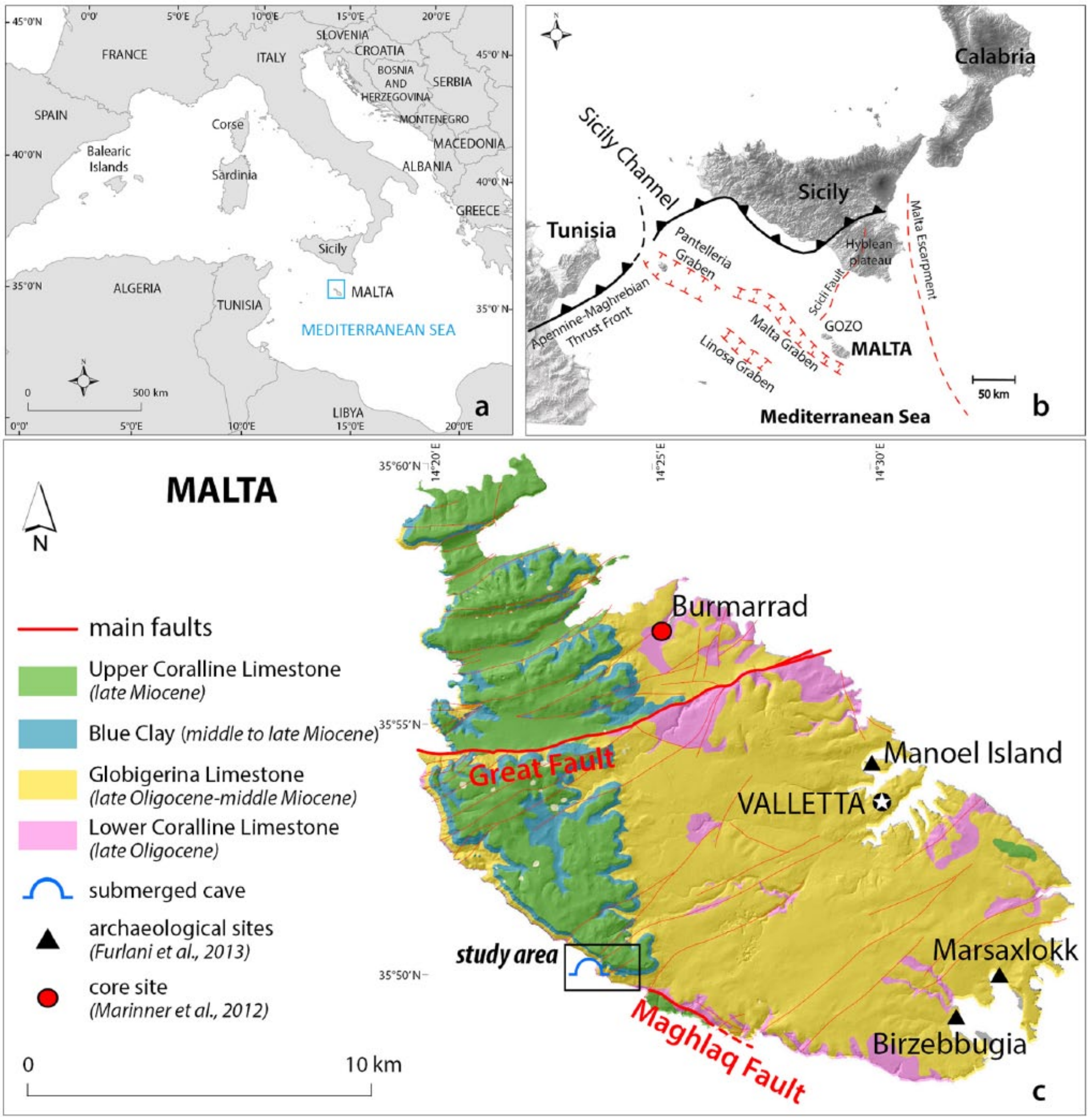

Figure 1. The island of Malta in the central Mediterranean context. (a) geographical setting with the location of Malta Island in the Mediterranean Sea, (b) geodynamical setting of the Sicily Channel, and (c) geological map of the Island of Malta and location of the published coastal archaeological sites (Furlani et al., 2013), sedimentological markers (Marriner et al., 2012) and the submerged cave studied in this research. Greensand Fm. has not been represented due to the poor and too much small outcrops for this scale.

12.4 ka BP time slices. Based on the same assumption of tectonic stability, also Micallef et al. (2013) and Foglini et al. (2016) produced maps of past sea levels. The latter authors provided a more detailed reconstruction of the Maltese paleo-landscape after the LGM until present thanks to combined multibeam surveys, Light Detection And Ranging (LiDAR)-derived digital terrain models (DTMs), Chirp sub-bottom profiler records and seabed samples.

The aim of this paper is to confirm the Holocene tectonic stability of the Maltese islands, which until now has only been hypothesized. We do this through the use of radiocarbon dating on the last continental layer of a speleothem present in a submerged marine cave and sampled at −14.5 m below mean sea level (b.m.s.l.). This cave has only recently been discovered along the southwestern coast of Malta. GPS and synthetic aperture radar (SAR) data further permitted the evaluation of the present-day tectonic setting of the island thus providing the basis for a discussion on the relationships between long-term and short-term data.

Geological and geomorphological setting

The Maltese Islands are a group of central Mediterranean Islands located about 96 km South of Sicily and 290 km from North Africa. Located on a shallow shelf, the Malta-Ragusa Rise, they are part of the submarine ridge, which extends from the Ragusa peninsula of Sicily southwards to the North African coasts (Schembri et al., 2009; Figure 1a).

From a geodynamical viewpoint, the Island of Malta, which is the largest of the archipelago, lies on the northern flank of the NW-SE striking Pantelleria Rift system, in the Sicily Channel, which was affected by continental rifting during Neogene-Quaternary age (Dart et al., 1993; Finetti, 1984). It produced extensive structures, such as the Pantelleria, Malta and Linosa tectonic depressions, controlled by NW-SE striking normal faults. The Pantelleria Rift is an elongate fault-controlled trough within the foreland of the Apennine-Maghrebian thrust and fold belt (Figure 1b) and was mainly developed during the late Miocene and lower Pliocene (Reuther and Eisbacher, 1985).

Malta is characterized by two tectonic settings. The most ancient one, ENE-WSW oriented, has been active since the lower Miocene and caused the development of a horst and graben system. It is characterized by alternating highlands and lowlands (Alexander, 1988), which are crossed by faults belonging to the Pantelleria Rift. The Maghlaq Fault (Figure 1c) is the largest fault outcropping in Malta with a NW-SE trend (Bonson et al., 2007). The Neogene-Quaternary uplift, caused by the Pantelleria Rift activity, is responsible for the emergence and subsequent tilting towards the NNE of the island (Alexander, 1988), with a resulting downdrop of its eastern flanks.

The Maltese Islands have a low seismicity and are exposed to the effects of earthquakes originating in the Sicily Channel due to the rifting processes and in eastern Sicily due to the activity of the Malta Escarpment and the Scicli strike-slip fault (Figure 1b). Earthquake activity is generally characterized by small magnitude events (Pedley et al., 2002), the strongest, Mw = 7.4 (Armigliato et al., 2007), being recorded in Sicily in 1693 (Galea, 2007).

Malta is formed of sedimentary rocks, with sediments being deposited in shallow marine conditions between late Oligocene and Miocene (Pedley et al., 1976). The stratigraphic sequence, recently revised by Baldassini and Di Stefano (2017), includes five geological formations (Figure 1c), which are, from the oldest, Lower Coralline Limestone (late Oligocene), characterized by bioclastic, bedded, grey limestones; Globigerina Limestone (late Oligocene – middle Miocene), composed of soft and yellowish massive fine-grained biomicrites; Blue Clay (middle to late Miocene), mostly formed by alternating layers of dark-grey and pale-grey marls; Greensand (late Miocene), composed of marly-clayey sands and arenites; Upper Coralline Limestone (late Miocene), consisting of bioclastic limestones. Quaternary deposits are scarce and include a sequence of vertebrate remains that were found in in Ghar Dalam cave and are datable to the Pleistocene Epoch (Hunt, 1997). Poorly sorted slope debris deposits cover hillsides and extend into the graben margins while terra rossa soils fill the valleys, graben bottoms and dolines, fan deposits and aeolian deposits (Pedley, 2011).

Paskoff and Sanlaville (1978), Magri (2006), Devoto et al. (2012), Micallef et al. (2013), Biolchi et al. (2016) and Prampolini et al. (2017) all described the geomorphology of the island and its surrounding seabed, which are strongly controlled by the two aforementioned fault systems. Interaction between the lithological and tectonic characteristics with the weathering processes favoured the development of several coastal features such as sea caves, notches, arches and gorges. The southwestern coast is characterized by continuous limestone plunging cliff and the present-day tidal notch can be observed (Biolchi et al., 2016; Furlani et al., 2013).

Although Malta is an island connected to southwestern Sicily by a submerged ridge, it remained completely isolated throughout most of the Upper Pleistocene. Paleo-biogeographical evidence (see, for example, Foglini et al., 2016; Furlani et al., 2013; Hunt and Schembri, 1999; Palombo, 1986; Savona-Ventura and Mifsud, 1998; Storch, 1974; Zammit-Maemple, 1989; Zammit-Maemple and de Bruijn, 1982) suggest the occurrence of an emerged land bridge connecting Sicily and Malta during Last Glacial Maximum (LGM).

Boreholes

Two cores drilled by Marriner et al. (2012) at the Burmarrad ria (Figure 1c) along the NE coast of Malta, provided the chronostratigraphic record of the Holocene transgression related to the post-glacial change of the sea level. Data show a fluvial-dominated upper estuarine environment between 7.5 ka cal. BP and 7.0 ka cal. BP. After 7.0 ka cal. BP, sediments highlight the transition to a marine environment until 4.0 ka cal. BP, when salt marshes and fluvial facies, which are related to the accretion of the ria infilling.

Estuarine facies are characterized by lagoonal and upper muddy-sand assemblages in sheltered areas. The transition between estuarine to marine environment is marked, in particular, by a layer of peat at about −11 m b.m.s.l. with an age of 7.0 ka cal. BP (Marriner et al., 2012). The marine transgression is highlighted by microfossils, ostracods and dominant molluscan species, such as *Loripes lacteus, Cerastoderma glaucum, Bittium reticulatum* and *Rissoa ventricosa*.

Materials and methods

In November 2012, a speleothem was collected from the aforementioned submerged cave (Figure 2). The speleothem was retrieved following a visual survey and analysis of the cave. Two samples of the penultimate and the ultimate continental layers (Figure 4d), with a thin overgrowth of serpulids, sponges and tetracoral from a stalactite were sampled and analysed.

The analysis was carried out using established analytical protocols for radiocarbon dating, which was performed by accelerator mass spectrometry (AMS) at the CEDAD Laboratory, University of Salento, Lecce, Italy. Conventional radiocarbon dates were calibrated by using the last internationally accepted atmospheric dataset (Hua, 2013), specifically the IntCal13 curve (Reimer et al., 2013). The calibrated dates are reported as time ranges thus including the uncertainty of the measurement and calibration (Table 1). It is well known in scientific literature (e.g. Hendy, 1970; Goslar et al., 2000) that the use of speleothems for obtaining ^{14}C-based chronologies can have a limiting factor in the possible contribution of ^{14}C-depleted carbon from dissolved carbonates in the speleothem's formation. The magnitude of this effect, which is strongly dependent on site characteristics (Hendy, 1970; Goslar et al., 2000), is typically expressed through a Dead Carbon Fraction (DCF) term. The occurrence of a large number of draperies and curtain-like stalactites in the studied cave strongly points towards a rapid flow of meteoric water which support a negligible dissolution of carbonate. On the basis of this consideration, we assumed a DCF = 0 in the radiocarbon dating calculation.

Depths inside the cave bottom were measured using an 'Aladin Pro' dive computer with a 10 cm measurement error bar with the local tide.

Data published by Marriner et al. (2012) from the two cores recovered from the NE coast of Malta, at Burmarrad (Figure 1c), were used to compare the radiocarbon dating of marine and estuarine deposits with the dates obtained from the speleothem. This was done in order to reconstruct the Holocene transgression along the Maltese coast. In order to establish the tectonic behaviour of the studied area, the radiocarbon dates obtained were finally compared to sea-level predictions for Malta (Lambeck et al., 2011).

Moreover, tide gauge data were analysed from the tidal station located at Marsaxlokk for the period 1991–2002 (http://www.psmsl.org/data/). The uncertainty corresponds to the standard deviation of the trend.

Recent surface deformations of Malta were analysed comparing our data with SAR, GPS and tide gauge data. SAR interferometry is a well-established remote sensing technique used to detect and measure Earth surface deformations caused by natural and anthropic processes. The exploitation of European Space Agency (ESA) archives allows the analysis of long temporal series of datasets, and hence, the reconstruction of deformation history over large spatial scales. The interferometric analysis was carried out by processing two datasets, acquired by the ENVISAT mission, with the Parallel Small Baseline Subsets algorithm (P-SBAS; Casu et al., 2014), integrated within the ESA's Grid Processing On Demand (G-POD; https://gpod.eo.esa.int/). Specifications of the images used and the parameters applied are summarized in Table 2.

Data

The submerged cave and the speleothem

The area where the speleothem was collected is located in the southwestern coast of the island, below Gebel Ciantar, at the foot of Dingli Cliffs (Figure 3a). This coastal sector is characterized by high plunging cliffs, which extend down to 40 m below the sea level (Figure 3b). The cave opens in the horizontal beds belonging to the Lower Coralline Limestone, at the depth ranging between

Figure 2. Collage of images of the submerged cave and sampling operations. (a) the plunging cliff in the surroundings of the studied cave. The cave develops in correspondence of a normal fault, which occurs on the cliff; (b) scuba diver during sampling operations; (c) speleothems on the roof of the cave; and (d and e) the inner wall of the cave enlightened by headlights.

Table 1. Radiocarbon datings: (a) site name and laboratory number; (b) typology of sea-level marker; (c) coordinates of the site; (d) depth of the sample; (e) radiocarbon age; (f) calibrated or archaeological age; (g) depth corrected with tide gauge data; (h) functional height (following Antonioli et al., 2007); (i) predicted past sea level (following Lambeck et al, 2011); (l) vertical tectonic rate calculated in the site.

a Site name and sample lab. Name	b Type of marker	c WGS84 coordinates	d Depth (m b.s.l.)	e Radiocarbon age	f Calibrated age (Calib 7.0.4*) or Archaeological age	g Corrected measured Depth (m b.s.l.) and reference	h Functional height (m)	i Predicted sea level (Lambeck et al. 2011) (m b.s.l.)	l Vertical tectonic rates (mm/a)
Gebel Cjantar LTL14449A2 Penultimate continental layer	Submerged speleothem	35.8428 14.3958	−14.5	6844 ± 45	7705–7618	−14.5 ± 0.1 This paper	/	16,8	0.0
Gebel Cjantar LTL14449A3 Last continental layer before marine serpulids	Submerged speleothem	35.8428 14.3958	−14.5	6774 ± 45	7657–7592	−14.5 ± 0.1 This paper	/	15,2	0.0
Burmarrad	*Peat*	35.9409 14.4209	−11.2	6115 ± 30	6940–7015	Marriner et al. (2012)	/	−11,4	0.0
Manoel Island	Garum tanks	35.9039 14.4962	−0.84 ± 0.1	/	2000 ± 100	−0.86 ± 0.1 Furlani et al. (2013)	0.5	−1.37 ± 0.1	0.0
Marsaxlokk	Walking service surface	35.8384 14.5491	−0.54 ± 0.1	/	1000 ± 200	−0.56 ± 0.2 Furlani et al. (2013)	0.0	−0.56 ± 0.2	0.0

Table 2. P-SBAS processing specifications.

Dataset				
Track	Orbit	Number of images processed	Number of interferogram generated	Period of analysis
494	Descending	22	57	2003–2010
401	Ascending	20	46	2003–2009
Processing parameters				
Max perpendicular baseline (m)	Max temporal baseline (days)	Ground pixel dimension (m)	Coherence threshold	Atmospheric phase screen time window (days)
400	1500	80	0.7	200

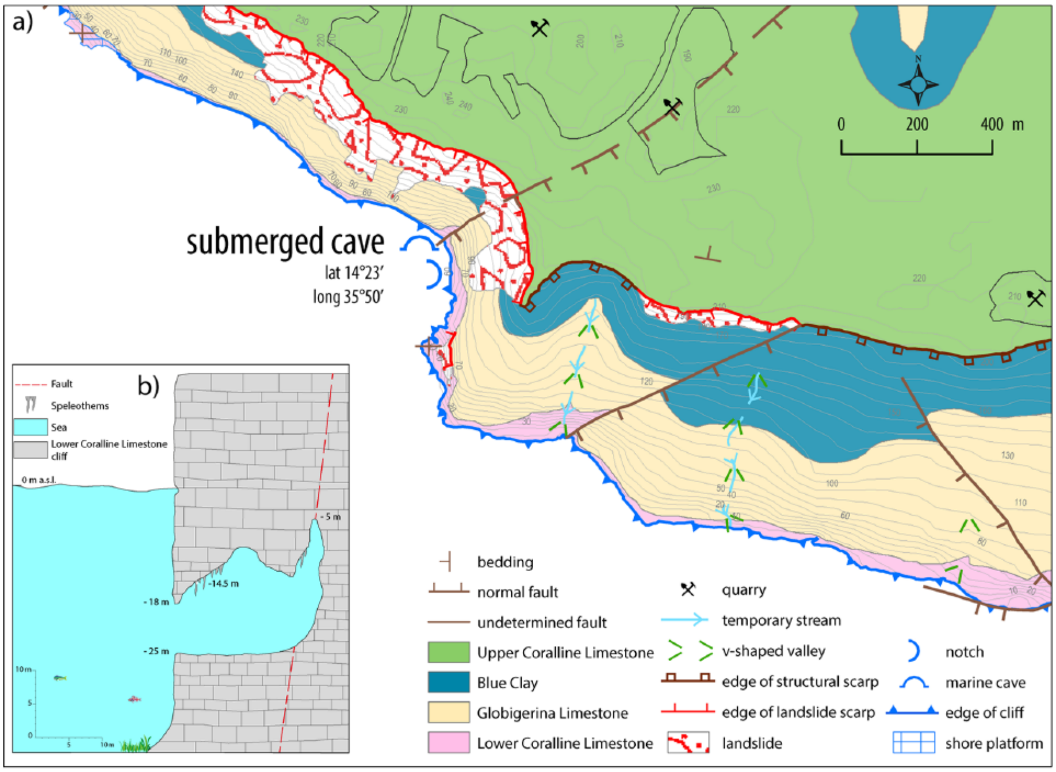

Figure 3. (a) Geomorphological map of the surrounding of the submerged cave (redrawn from Biolchi et al., 2016) and (b) sketch of the submerged cave.

−18 m and −35 m b.m.s.l., and developed in a system of joints and fractures related to a vertical NE-SW oriented normal fault.

The cave is approximately 25 m long and 15 m wide. The roof is indented and irregular with two chimneys: the first one is wider, at −10 m b.m.s.l., whereas the latter is narrower and steeper, at −5 m b.m.s.l. (Figure 3b). Limestone beds are hidden by weathering processes, which produced very smooth surfaces (Figure 2c). The bottom of the cave (at a depth of 35 m) is flat and is covered by sandy deposits. The walls are covered by algal coats, Serpulids as well as coloured sponges (Figure 2e).

The roof and the upper part of the lateral walls are characterized by the occurrence of several speleothems and flowstones, partially colonized by marine encrustations. The stalactite was sampled at −14.5 m b.m.s.l. (Figure 4).

The studied speleothem shows the accretion of continental layers with subsequent marine overgrowth. The last layer is mainly composed by carbonate tubes of polychaete worms and other benthic organisms such as sponges.

The age of two layers (penultimate and ultimate continental layers, see Figure 4) provided the following radiocarbon calibrated ages (Table 1): 7705–7618 cal. BP and 7657–7592 cal. BP, respectively, with a probability of 67.5% for the younger level immediately before the complete flooding of the cave (Figure 5).

SAR data

The outcomes of SAR analysis are graphically reproduced in Figure 6 (De Luca et al., 2015). The island of Malta appears to be stable with a rate of deformation null except for restricted coastal areas in the north-western sector, where several landslides have been detected (Devoto et al., 2012, 2013; Mantovani et al., 2013; Piacentini et al., 2015).

Considering that for the ENVISAT mission, the image acquisition geometry is nearly vertical and that the results obtained by processing the ascending and descending datasets are consistent, we can safely assume that, during the investigated period, no tectonic-related displacements occurred along the vertical and E-W directions.

Discussion

Many authors considered the island of Malta tectonically stable at least since Roman period through the use of archaeological remains as indicators (Furlani et al., 2013) and geomorphological

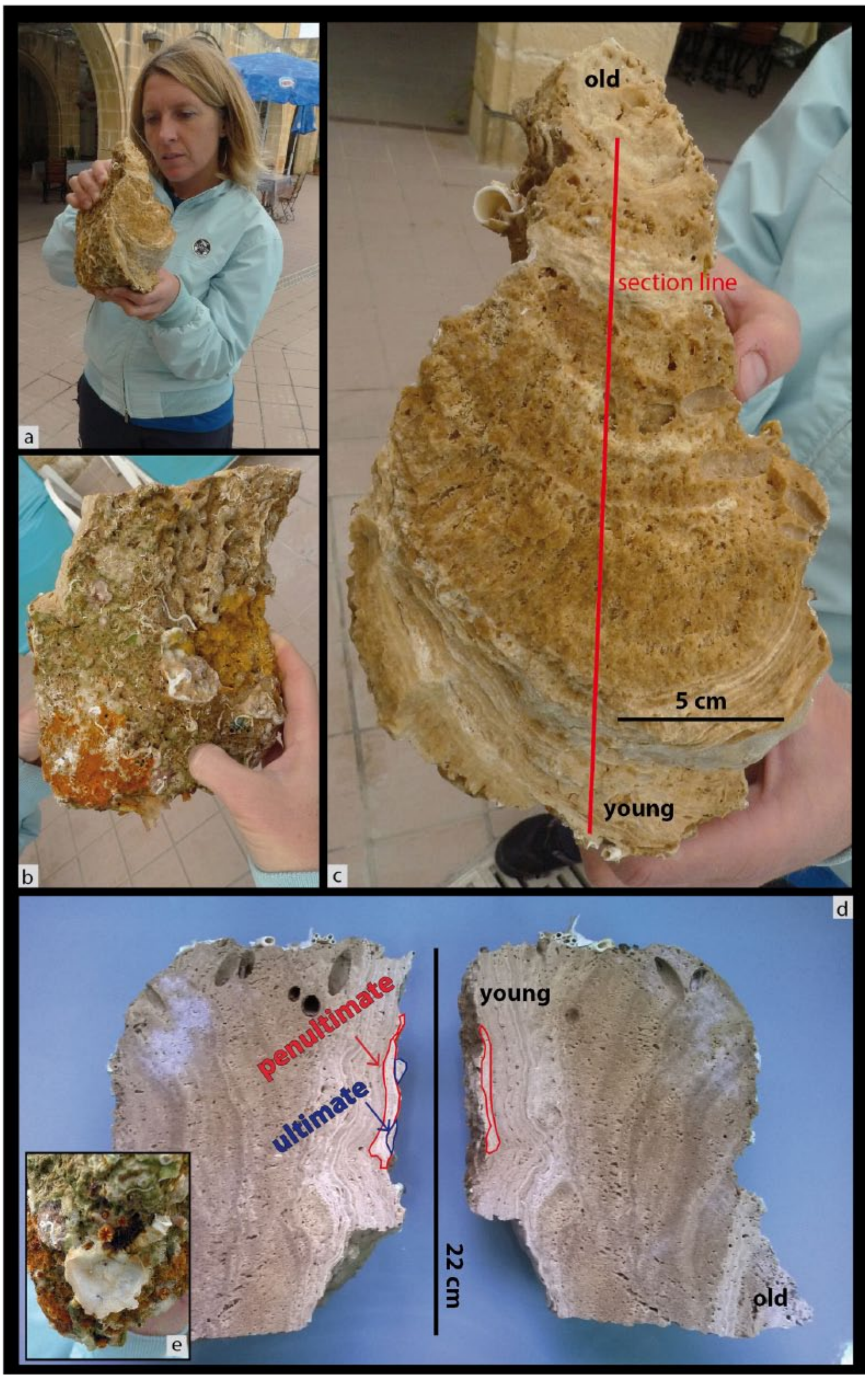

Figure 4. The speleothem sampled at Gebel Ciantar. (a) the size of the sample, (b) view of the stalactite, (c) direction of growth of the stalactite, (d) view of the central part of the stalactite, and (e) the main marine overgrowth of the speleothem: serpulids, sponges and parazooanthus. The red line highlights the portion of the speleothem sampled for radiocarbon dating (penultimate layer), while the blue line highlights the last continental layer (Table 2).

features (Antonioli et al., 2015; Biolchi et al., 2016; Furlani et al., 2017b). Until this present study, the lack of significant older sea level markers did not allow to unequivocally confirm the local tectonic behaviour before Roman period. Many authors, such as Furlani et al. (2013, 2017b), Micallef et al. (2013), Foglini et al. (2016) and Prampolini et al. (2017) reconstructed the evolution of the sea level rise of Malta assuming the tectonic stability of the island. Recently, Marriner et al. (2012) provided a description of the evolution of a small ria along the NE coast of the island. They suggested that between 7500 and 7000 cal. BP, the small bay was dominated by an estuarine environment (Marriner et al., 2012). From 7000 cal. BP, the marine transgression affected the bay, as testified by the increased amount of marine organisms. Subsequently, the relative sea level stability of the late Holocene coupled with the increase of sediment input from inland initiated the progradation of the deltaic sequence. Marriner et al. (2012) provided a detailed reconstruction of the sea level rise, but they did not discuss the tectonic setting of the island through the comparison of the elevation of the sea level markers with sea level rise models. The lack of MIS5e deposits has been explained by Furlani et al. (2013) as being due to the exposure of the high energy waves and local weathering that prevent the preservation of rocks and deposits. In addition to this, the weakness of the geological units could have completely eroded the MIS5e deposits.

The discovery of a submerged speleothem encrusted by marine organisms at a depth of −14.5 m b.m.s.l. and the subsequent study of the radiocarbon dates from the penultimate and ultimate continental layers (Figure 4d) provides a new sea level

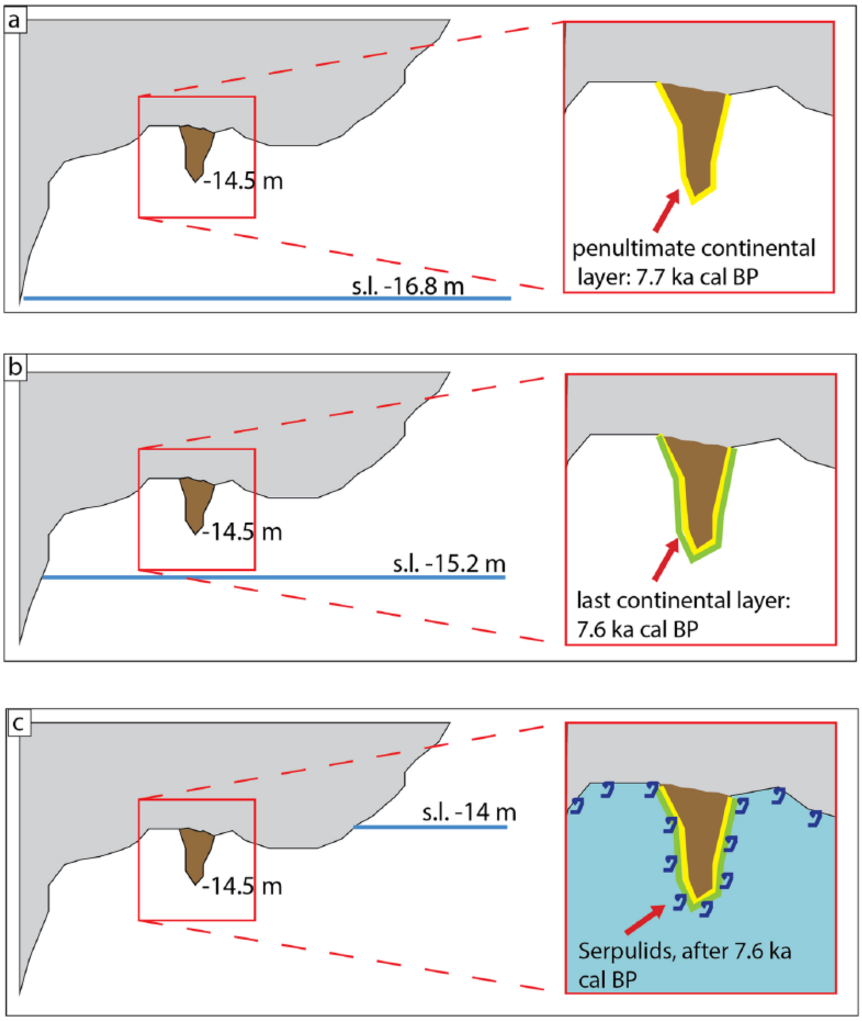

Figure 5. Sketch of the speleothem flooding: (a) at 7.7 ka cal. BP the speleothem was growing and sea level was at − 16.8 m (Lambeck et al., 2011); (b) at 7.6 ka cal. BP the speleothem was growing and sea level was at − 15.2 m; (c) after 7.6 ka cal. BP sea flooded the cave and marine organism began to overgrow the speleothem.

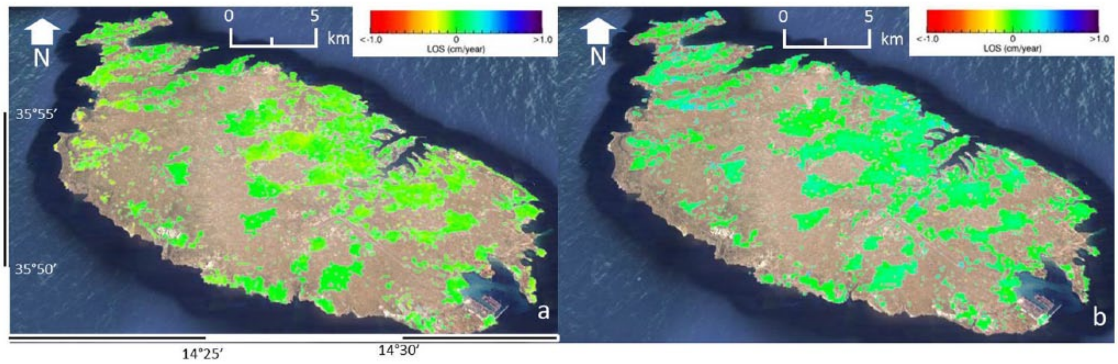

Figure 6. Colour coded line of sight (LOS) displacement rate over the island of Malta as result of the P-SBAS processing of the (a) track 949; (b) track 401 SAR dataset (see Table 2).

marker to evaluate the tectonic behaviour of the island. The carbonate concretion on speleothems and flowstones, which developed in subaerial conditions, stopped when seawater entered in the cave and flooded it. The growth of the speleothem could also have stopped for other reasons, such as changed hydrology or climate, and so on. Subsequently, marine encrustations caused by serpulid worms started to colonize the submerged speleothems forming concretions that protected the layers of spelean calcite, which lies below. In some cases, it forms a thick overgrowth that can be used for dating the flooding process (Antonioli et al., 2001, 2004; Dutton et al., 2009b; Furlani et al., 2012; Scicchitano et al., 2008). The studied cave was originally a subaerial karst void that developed in correspondence to a fault (Figure 3b), in a subaerial environment. After LGM, and as the relative sea level rose, waves increasingly remodelled the cave with abrasion processes, which enlarged it. At the same time, the speleothems were submerged. The accretion of marine encrustation is mainly controlled by biological and physical parameters (Antonioli et al., 2001).

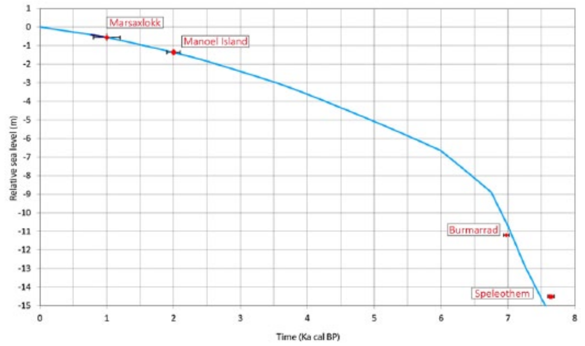

Figure 7. Predicted sea level curve from Lambeck et al., 2011, with datings quoted in Table 1.

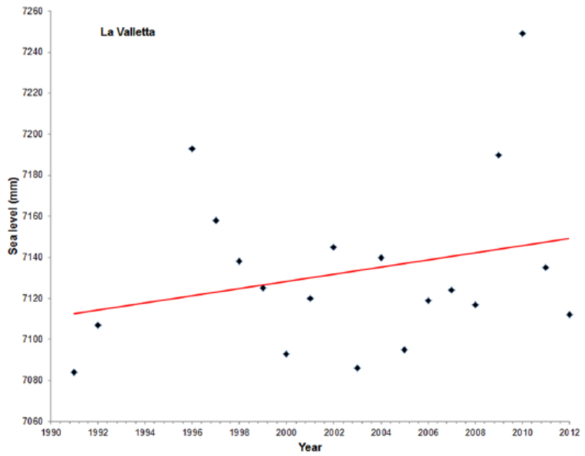

Figure 8. Sea level at La Valletta tide gauge station during the time span 1991–2012. The red line is the linear fit of the tidal time series corresponding to a trend at 1.7 ± 1.0 mm/a, which is consistent with the mean eustatic sea level rise in the Mediterranean, as recently estimated by Wöppelmann and Marcos (2012) and Anzidei et al. (2014).

Radiocarbon dates from the last continental layers (covered by the first marine serpulid encrustation) provided the environmental transition between the subaerial environment and marine environment with a reduced error bar (Table 1, Figure 5), showing the local transgression at −14.5 m m.s.l. occurring about 7.6 ka cal. BP. The magnitude of contribution of both ^{14}C-depleted from the limestone and/or the contribution from soil ^{14}C can be dependent on the site characteristics (Goslar et al., 2000; Hendy, 1970). In the studied cave, the occurrence of a large number of draperies and curtain-like stalactites strongly points towards a rapid flow of meteoric water and then to negligible dissolution of carbonate inside the cave. As a matter of fact, a humid mid-Holocene phase was described by Magny et al. (2011) by studying lake-level fluctuations in nearby southern Sicily, between 9.8 and 4.5 ka BP, with a precipitation maximum before ca. 7.5/7.0 ka BP.

The new radiocarbon results presented in this study, together with published data, provide ground for discussing the tectonic behaviour of the island and the timing of the relative sea level change. In particular, the comparison between the age and elevation of the speleothem with the predicted sea level rise model published by Lambeck et al. (2011) shows that our field data fit perfectly with the curve. In particular, Lambeck et al. (2011) calculated that the sea level ranged between −14.7 m and −15.8 m at an age of 7.5 cal. BP. This means that the speleothem sample confirms the model (Figure 7) and that the sea was some decimeters below the speleothem. Moreover, the radiocarbon dates from the speleothem (Figure 5), which is considered a good sea level marker (e.g. Dutton et al., 2009b), agree with the reconstruction of the transition between estuarine and marine environments, 10 km north from our cave, provided by Marriner et al. (2012). The latter Authors dated a sample of peat at about −11.2 m that gave back an age of about 7.0 ka cal. BP (Table 1), very similar in age of the speleothem. Other samples, such as *Loripes lacteus*, a bivalve very common in shallow-water environments (Petersen, 2011) collected above, at −9.5 m b.m.s.l., provided an age of 5.8 ka cal. BP. Core samples have larger error bars with respect to the speleothem, but results obtained fit well with the Lambeck's model that provides a depth ranging between −6.3 m and −7.1 m at 5.75 ka cal. BP. In the same way, archaeological data, in particular the submerged Roman Age tanks at Manoel Island discussed by Furlani et al. (2013), also fit the model for the late Holocene

Our results suggest that no vertical tectonic movements occurred at least during the last 7.6 ka cal. BP in SW Malta. As suggested by Antonioli et al. (2015 and references therein), Malta is located in an area of the central Mediterranean characterized by a vertical displacement comprised between −0.15 and +0.15 mm/year. These rates differ from neighbouring eastern Sicily that is a tectonically complex region where heterogeneous tectonic processes, generally related to Europa-Africa convergence coexist in a small area (Cultrera et al., 2015). Here, uplift rates of 0.61 and 0.90 (even over + 1.41 mm/year) are observed. Moreover about 200 km northwest of the Maltese archipelago, Pantelleria and Ferdinandea island are subactive. In particular, the latter raised from the Graham Bank in 1831 (Aissi et al., 2015). The tectonic behaviour of the island of Malta seems to be confirmed also for the short-term period. This behaviour corresponds with current GPS data that show a null movement along the vertical component at the MALTA station (Anzidei et al., 2014; Serpelloni et al., 2013). Results indicate the absence of any deformation of Malta within the resolution of this technique. Concerning sea level data, we have retrieved and analysed tidal data from the tidal station located at Marsaxlokk for the period 1991–2012 (Figure 8). Although the time period is indeed too short to establish a significant sea level rate for this location, the analysis shows a local trend of sea level rise at 1.7 ± 1.0 mm/yr. This value roughly corresponds to the mean sea level rise in the Mediterranean Sea estimated for the last decades (Anzidei et al., 2014; Wöppelmann and Marcos, 2012). In addition, SAR data collected between 2003 and 2010 (Figure 6) suggest, in fact, that there are no significant vertical movements of the island. Short-term series provided by instrumental data, such as SAR, GPS and tide gauges, can hardly be correlated to the long-term tectonic contexts suggested by radiocarbon dates. They can, however, be compared in order to explore and establish changes in vertical movements (Anzidei et al., 2014), in particular recent ones. It means that no vertical movements were recorded, both in the long- and short-term periods.

Conclusion

Radiocarbon dates together with GOS and SAR measurements as well as published sedimentological and archaeological data permitted the accurate reconstruction of the vertical tectonic behaviour of the island of Malta during the Holocene. Underwater geomorphological surveys were carried out to sample the speleothem as well as to frame it in the local geomorphological context. Radiocarbon dates from the speleothem have been combined with GPS and SAR measurements with these data subsequently compared and integrated with published geomorphological, sedimentological and archaeological data. This was done in order to provide the limits of the tectonic framework of the archipelago.

The cave provided for the first time in this sector, useful information on the drowning of a hypogean karst environment. Radiocarbon dates from the last continental layers of the stalactite provided the position of the sea level at 7.6 ka cal. BP, exactly when the cave was drowned by the sea. The drowning event was proved by the colonization of serpulids just above the dated layers.

The analysis of our radiocarbon dates were integrated with those from lagoonal peats and marine shells sampled from two cores in the northeast of Malta (Marriner et al., 2012) as well as with the elevation of underwater archaeological coastal structures in the south of the island (Furlani et al., 2013). The comparison of these markers with the Lambeck's model (Lambeck et al., 2011) confirmed the tectonic stability of Malta during the mid-Holocene. SAR interpherometric analysis and GPS data suggest that this tectonic pattern persists to the present day. This framework is in contrast with surrounding tectonically active areas, such as eastern Sicily, the Malta Escarpment and the Etna volcano to the north, as well as the volcanic islands of Pantelleria and Ferdinandea to the northwest.

Future fieldwork and research should focus on the unsolved question of the lack of older marine deposits, belonging to the MIS5e stage. Such a study is needed as it will provide a solid constrain to the tectonic behaviour of the island also during the Upper Pleistocene.

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References

Aissi M, Rovere M and Wurtz M (2015) Seamounts and seamount-like structures of Sardinia Channel, Strait of Sicily, Ionian Sea and Adriatic Sea. In: Rovere M and Wurtz M (eds) *Atlas of the Mediterranean Seamounts and Seamount-Like Structures*. Malaga: MAVA Fondation pour la nature, IUCN, pp. 187–225.

Alexander D (1988) A review of the physical geography of Malta and its significance for tectonic geomorphology. *Quaternary Science Reviews* 7: 41–53.

Antonioli F, Anzidei M, Lambeck K et al. (2007) Sea level change during Holocene from Sardinia and northeastern Adriatic (Central Mediterranean sea) from archaeological and geomorphological data. *Quaternary Science Reviews* 26: 2463–2424.

Antonioli F, Bard E, Silenzi S et al. (2004) 215 KYR history of sea level based on submerged speleothems. *Global and Planetary Change* 43: 57–68.

Antonioli F, Lo Presti V, Rovere A et al. (2015) Tidal notches in Mediterranean Sea: A comprehensive analysis. *Quaternary Science Reviews* 119: 66–84.

Antonioli F, Silenzi S and Frisia S (2001) Tyrrhenian Holocene palaeoclimate trends from spelean serpulids. *Quaternary Science Reviews* 20(15): 1661–1670.

Anzidei M, Lambeck K, Antonioli F et al. (2014) Coastal structure, sea-level changes and vertical motion of the land in the Mediterranean. In: Martini IP and Wanless HR (eds) *Sedimentary Coastal Zones from High to Low Latitudes: Similarities and Differences*. London: Geological Society of London (Special Publications 388), pp. 453–479.

Armigliato A, Tinti S, Zaniboni F et al. (2007) New contributions to the debate on the cause of the January 11th, 1693 tsunami in eastern Sicily (Italy): Earthquake or offshore landslide source (or may be both)? *Transactions of the American Geophysical Union* 88(52): Fall Meeting Supplement, Abstract S53A-1019.

Baldassini N and Di Stefano A (2017) Stratigraphic features of the Maltese Archipelago: A synthesis. *Natural Hazards* 86: 203–231.

Biolchi S, Furlani S, Devoto S et al. (2016) Geomorphological recognition, classification and spatial distribution of coastal landforms of Malta. *Journal of Maps* 12(1): 87–99.

Bonson CG, Childs C, Walsh JJ et al. (2007) Geometric and kinematic controls on the internal structure of a large normal fault in massive limestones: The Maghlaq Fault, Malta. *Journal of Structural Geology* 29: 336–354.

Casu F, Elefante S, Imperatore P et al. (2014) SBAS-DInSAR parallel processing for deformation time-series computation. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 7(8): 3285–3296.

Cultrera F, Barreca G, Scarfì L et al. (2015) Fault reactivation by stress pattern reorganization in the Hyblean foreland domain of SE Sicily (Italy) and seismotectonic implications. *Tectonophysics* 661: 215–228.

Dart CJ, Bosence DWJ and Mcclay KR (1993) Stratigraphy and structure of the Maltese Graben system. *Journal of the Geological Society* 150: 1153–1166.

De Luca C, Cuccu R, Elefante S et al. (2015) An on-demand web tool for the unsupervised retrieval of Earth's surface deformation from SAR data: The P-SBAS service within the ESA G-POD environment. *Remote Sensing* 7(11): 15630–15650.

Devoto S, Biolchi S, Bruschi VM et al. (2012) Geomorphological map of the NW coast of the Island of Malta. *Journal of Maps* 8(1): 33–40.

Devoto S, Biolchi S, Bruschi VM et al. (2013) Landslides along the north-west coast of the Island of Malta. In: Margottini C, Canuti P and Sassa K (eds) *Landslide Science and Practice, Vol. 1: Landslide Inventory and Susceptibility and Hazard Zoning*. Berlin: Springer, pp. 57–64.

Dutton A, Bard E, Antonioli F et al. (2009a) Phasing and amplitude of sea-level and climate change during the penultimate interglacial. *Nature Geoscience* 2: 355–359.

Dutton A, Scicchitano G, Monaco C et al. (2009b) Uplift rates defined by U-series and ^{14}C ages of serpulid-encrusted speleothems from submerged caves near Siracusa, Sicily (Italy). *Quaternary Geochronology* 4: 2–10.

Finetti IR (1984) Geophysical study of the Sicily Channel Rift Zone. *Bollettino di Geofisica Teorica ed Applicata* 26: 3–28.

Fleitmann D, Spötl C, Newmann L et al. (2008) Advances in Speleothem Research. *Pages News* 16(3): 40.

Foglini F, Prampolini M, Micallef A et al. (2016) Late Quaternary coastal landscape morphology and evolution of the Maltese Islands (Mediterranean Sea) reconstructed from high-resolution seafloor data. In: Harff J, Bailey G and Lűth F (eds) *Geology and Archaeology: Submerged Landscapes of the Continental Shelf*. London: Geological Society of London (Special Publications 411), pp. 77–95.

Furlani S, Antonioli F, Biolchi S et al. (2013) Relative sea level change in Malta. *Quaternary International* 288: 146–157.

Furlani S, Antonioli F, Cavallaro D et al. (2017a) Tidal notches, coastal landforms and relative sea-level changes during the Late Quaternary at Ustica Island (Tyrrhenian Sea, Italy). *Geomorphology* 299: 94–106.

Furlani S, Antonioli F, Gambin T et al. (2017b) Marine notches in the Maltese islands (central Mediterranean Sea). *Quaternary International* 439: 158–168.

Furlani S, Cucchi F and Biolchi S (2012) Late-Holocene widening of karst voids by marine processes in partially submerged coastal caves (northeastern Adriatic Sea). *Geografia Fisica e Dinamica Quaternaria* 35: 129–140.

Galea P (2007) Seismic history of the Maltese Islands and considerations on seismic risk. *Annals of Geophysics* 50(6): 725–740.

Gambin B, Andrieu-Ponel V, Medail F et al. (2016) 7300 years of vegetation history and climate for the NW Malta: A Holocene perspective. *Climate of the Past* 12: 273–297.

Goslar T, Hercman H and Pazdur A (2000) Comparison of U-series and radiocarbon dates of speleothems. *Radiocarbon* 42(3): 403–414.

Hendy CH (1970) The use of ^{14}C in the study of cave processes. In: Olsson IU (ed.) *Radiocarbon Variations and Absolute Chronology*. New York: Wiley Inter-Science Division, pp. 419–443.

Hua Q (2013) Radiocarbon dating of marine carbonates. In: Rink WJ and Thompson J (eds) *Encyclopedia of Scientific Dating Methods*. Dordrecht: Springer, pp. 1–6.

Hunt CO (1997) Quaternary deposits in Maltese Islands: A microcosm of environmental change in Mediterranean lands. *GeoJournal* 41(2): 101–109.

Hunt CO and Schembri PJ (1999) Quaternary environments and biogeography of the Maltese islands. In: Mifsud A and Savona Ventura C (eds) *Facets of Maltese Prehistory*. Malta: The Prehistoric Society of Malta, pp. 1–39.

Lambeck K, Antonioli F, Anzidei M et al. (2011) Sea level change along the Italian coasts during Holocene and prediction for the future. *Quaternary International* 232(1–2): 250–257.

Magny M, Vannière B, Calo C et al. (2011) Holocene hydrological changes in south-western Mediterranean as recorded by lake-level fluctuations at Lago Preola, a coastal lake in southern Sicily, Italy. *Quaternary Science Reviews* 30: 2459–2475.

Magri O (2006) A geological and geomorphological review of the Maltese Islands with special reference to the coastal zone. *Territoris* 6: 7–26.

Mantovani M, Devoto S, Forte E et al. (2013) A multidisciplinary approach for rock spreading and block sliding investigation in the north-western coast of Malta. *Landslides* 10: 611–622.

Marriner N, Gambin T, Djamali M et al. (2012) Geoarchaeology of the Burmarrad ria and early Holocene human impacts in western Malta. *Palaeogeography, Palaeoclimatology, Palaeoecology* 339–341: 52–65.

Micallef A, Foglini F, Le Bas T et al. (2013) The submerged paleolandscape of the Maltese Islands: Morphology, evolution and relation to Quaternary environmental change. *Marine Geology* 335: 129–147.

Palombo MR (1986) I grandi mammiferi pleistocenici delle isole del Mediterraneo: tempi e vie di migrazione. *Bollettino della Società Paleontologica Italiana* 24(2–3): 201–204.

Paskoff R and Sanlaville P (1978) Observations geomorphologiques sur les cotes de l'archipel Maltais. *Zeitschrift fur Geomorphologie* 22: 310–328.

Pedley HM, Clarke MH and Galea P (2002) *Limestone Isles in a Crystal Sea: The Geology of the Maltese Islands*. Malta: PEG Ltd.

Pedley HM, House MR and Waugh B (1976) The geology of Malta and Gozo. *Proceeding Geological Association* 87: 325–341.

Pedley M (2011) The Calabrian Stage, Pleistocene highstand in Malta: A new marker for unravelling the Late Neogene and Quaternary history of the islands. *Journal of the Geological Society of London* 168: 913–925.

Petersen KS (2011) Marine molluscs as indicators of former sea-level stands. In: van de Plassche O (ed.) *Sea-Level Research: A Manual for the Collection and Evaluation of Data*. Dordrecht: Springer, pp. 129–156.

Piacentini D, Devoto S, Mantovani M et al. (2015) Landslide susceptibility modelling assisted by Persistent Scatterers Interferometry (PSI): An example from the north-western coast of Malta. *Natural Hazards* 78(1): 681–697.

Prampolini M, Foglini F, Biolchi S et al. (2017) Geomorphological mapping of terrestrial and marine areas, northern Malta and Comino (Central Mediterranean sea). *Journal of Maps* 13(2): 457–469.

Reimer PJ, Bard E, Bayliss A et al. (2013) IntCal13 and MARINE13 radiocarbon age calibration curves 0–50000 years cal BP. *Radiocarbon* 55(4): 1869–1887.

Reuther CD and Eisbacher GH (1985) Pantelleria Rift crustal extension in a convergent intraplate setting. *International Journal of Earth Science* 74(3): 585–597.

Savona-Ventura C and Mifsud A (1998) Ghar Dalam cave, a review of the sediments on the cave floor stratigraphy. *Xyenza* 3(1): 5–12.

Schembri PJ, Hunt C, Pedley M et al. (2009) The environment of the Maltese Islands. In: Malone C, Stoddart S, Bonanno A et al. (eds) *Mortuary Customs in Prehistoric Malta*. Oxford: Oxbow Books, pp. 17–39.

Scicchitano G, Antonioli F, Castagnino Berlinghieri EF et al. (2008) Submerged archaeological sites along the Ionian Coast of south-eastern Sicily and implications for the Holocene relative sea level change. *Quaternary Research* 70: 26–39.

Serpelloni E, Faccenna C, Spada G et al. (2013) Vertical GPS ground motion rates in the Euro-Mediterranean region: New evidence of velocity gradients at different spatial scales along the Nubia-Eurasia plate boundary. *Journal of Geophysical Research: Solid Earth* 118(11): 6003–6024.

Shennan I, Long AJ and Horton BP (2015) *Handbook of Sea-Level Research*. Chichester: AGU, Wiley.

Storch G (1974) Quartare Fledermaus-faunen von der Insel Malta. *Senckenbergiana Lethaea* 55: 407–434.

Surić M and Juračić M (2010) Late Pleistocene-Holocene environmental changes – Records from submerged speleothems along the Eastern Adriatic coast (Croatia). *Geologia Croatica* 63(2): 155–169.

Surić M, Richards DA, Hoffmann DL et al. (2009) Sea-level change during MIS 5a based on submerged speleothems from the eastern Adriatic Sea (Croatia). *Marine Geology* 262: 62–67.

Wöppelmann G and Marcos M (2012) Coastal sea level rise in southern Europe and the nonclimate contribution of vertical land motion. *Journal of Geophysical Research* 117: C01007.

Zammit-Maemple G (1989) *Ghar Dalam Cave and Deposits*. Malta: Mid-Med Bank.

Zammit-Maemple G and de Bruijn H (1982) The Plio/Pleistocene Gliridae from the Mediterranean islands reconsidered. *Proceedings of the Koninklijke Nederlandse Akademie van Wetenschappen B* 85: 113–128.