

Submerged archaeological sites along the Ionian coast of southeastern Sicily (Italy) and implications for the Holocene relative sea-level change

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Abstract

Precise measurements of submerged archaeological markers in the Siracusa coast (Southeastern Sicily, Italy) provide new data on relative sea-level change during the late Holocene. Four submerged archaeological sites have been studied and investigated through direct observations. Two of them are Greek archaic in age (2.5–2.7 ka) and are now 0.98–1.48 m below sea level; the other two developed during the Bronze age (3.2–3.8 ka) and are now 1.03–1.97 m below sea level. These archaeological data have been integrated with information derived from a submerged speleothem collected in a cave located along the Siracusa coast at –20 m depth. The positions of the archaeological markers have been measured with respect to present sea level, corrected for tide and pressure at the time of surveys. These data were compared with predicted sea-level rise curves for the Holocene using a glacio-hydro-isostatic model. The comparison with the curve for the southeastern Sicily coast yields a tectonic component of relative sea-level change related to regional uplift. Uplift rates between 0.3 and 0.8 mm/yr have been estimated.

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Introduction

Archaeological sites in areas of small tidal range can provide significant information on relative sea-level change during the last millennia using man-made coastal structures whose successful functioning requires a precisely defined relationship to sea level at time of construction. Along Mediterranean shores, in particular, the increasing sophistication of human development has led to there being a number of archaeological remains that can be used to establish constraints on relative sea level (Flemming, 1969; Schmiedt, 1966; 1972; Caputo and Pieri, 1976; Pirazzoli, 1976; Flemming and Webb, 1986; Anzidei et al., 2006; Lambeck et al., 2004a; Antonioli et al., 2007). The interpretation of their former functional height, at the time of their construction provides data on the relative position of land

and sea. These data are compared with predicted Holocene sea-level rise curves (Lambeck et al., 2004b) which take into account eustatic and glacio-hydro-isostatic factors. The eustatic component is global and time-dependent while the isostatic factors vary both with location and time. The accuracy of these predicted values is a function of the model parameter uncertainties that define the earth response function and the ice load history.

The glacio-hydro-isostatic component along the Italian coast has been recently predicted and compared with field data at sites not affected by significant tectonic processes (Lambeck et al., 2004b). By comparing ages and elevations of palaeo-sea level indicators with the predicted curve for the Holocene it is thus possible to accurately evaluate vertical tectonic movements of coastal regions (Lajoie, 1986).

In this paper we show new data on relative sea-level change and vertical rate of tectonic movements along the Ionian coast of southeastern Sicily (Fig. 1), using presently submerged archaeological markers such as docks, piers, quarries, tombs,

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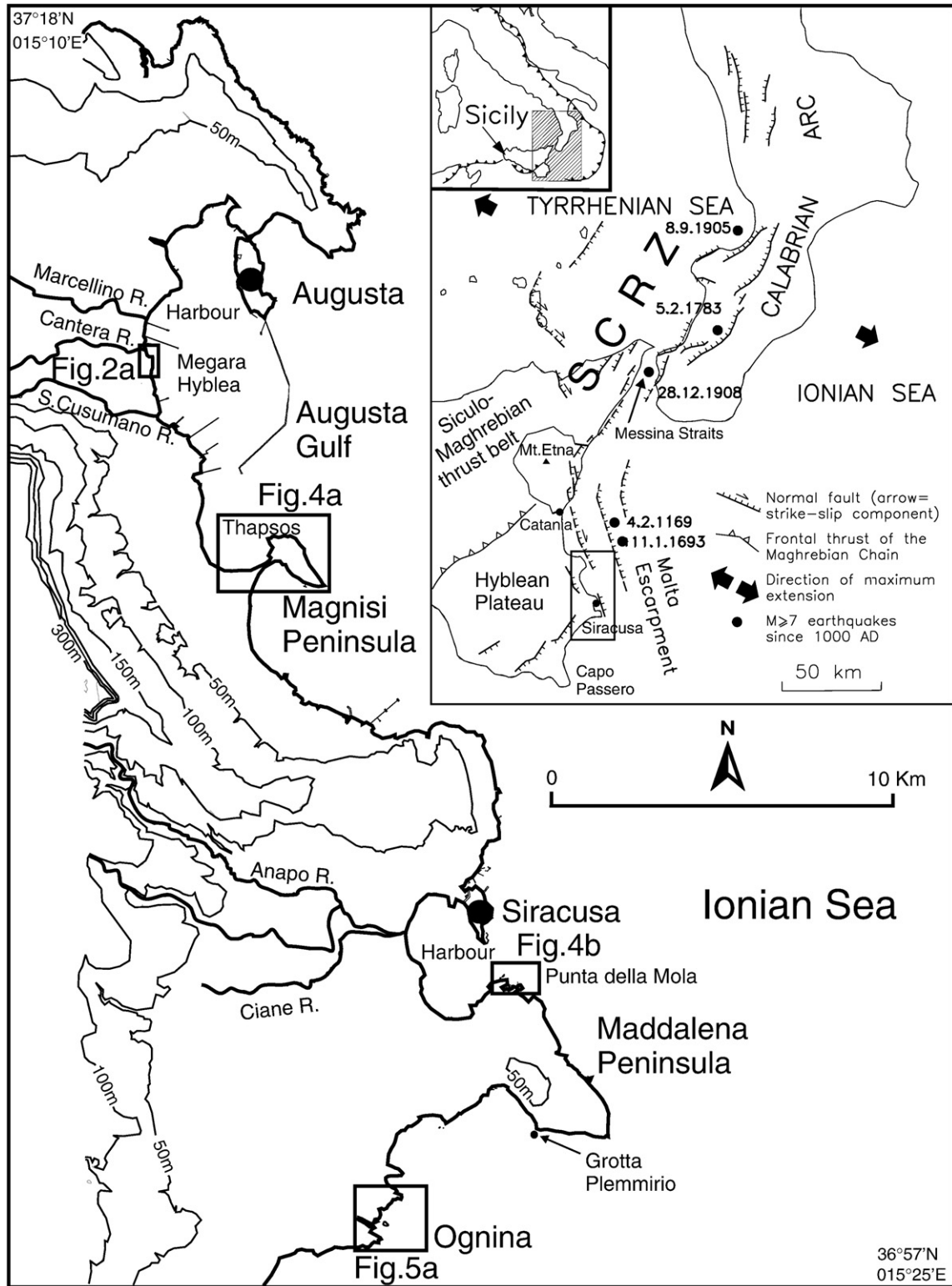


Figure 1. Geographical position of the studied sites along the Ionian coast of southeastern Sicily, in the Augusta–Siracusa area. Inset shows the seismotectonic features of the Siculo–Calabrian rift zone (SCRZ; Monaco et al., 1997; Monaco and Tortorici, 2000) and its location in the central Mediterranean area (line with triangles indicates the frontal thrust of the orogenic belt).

pavements, and bollards. This study has been carried out on four sites, well known in the archaeological literature, located along the coastal area between Augusta and Siracusa. The positions of the archaeological markers are reported with respect to present

sea level, corrected for tide and pressure at the time of surveys. These data are compared to a geomorphologic marker of sea-level position: a submerged continental speleothem covered by calcite secreted by marine organisms, recovered from a

submarine cave south of Siracusa. This study provides new data to constrain the rate of sea-level rise during the late Holocene and on the rate of the vertical movements of a land located in a tectonically active area.

Tectonic setting

Southeastern Sicily (Fig. 1) is characterized by thick Mesozoic to Quaternary carbonate sequences and volcanics forming the emerged foreland of the Siculo–Maghrebian thrust belt (Grasso and Lentini, 1982). This area, mostly constituted by the Hyblean Plateau, is located on the footwall of a large normal fault system which since the middle Pleistocene has reactivated the Malta Escarpment (Bianca et al., 1999), a Mesozoic boundary separating the continental domain from the oceanic crust of the Ionian basin (Scandone et al., 1981; Sartori et al., 1991; Hirn et al., 1997).

Since the early-middle Pleistocene, active faulting has contributed to continuous extensional deformation from eastern Sicily to western Calabria (Siculo–Calabrian rift zone, Figure 1; Monaco et al., 1997; Bianca et al., 1999; Monaco and Tortorici, 2000; Jacques et al., 2001). In eastern Sicily the SSW–NNE striking normal faults are mostly located offshore and control the Ionian coast from Messina to the eastern lower slope of Mt. Etna, joining southwards to the NNW–SSE trending system of the Malta Escarpment (Fig. 1). This area is marked by a high level of crustal seismicity producing earthquakes with intensities of up to XI–XII MCS and $M \sim 7$, such as the AD 1169, 1693 and 1908 events (Postpischl, 1985; Boschi et al., 1995). According to most of published geological data and numerical modelling, the seismogenic source of these events should be located in the Messina Straits and in the Ionian offshore (the Malta Escarpment) between Catania and Siracusa (Postpischl, 1985; Piatanesi and Tinti, 1998; Valensise and Pantosti, 1992; Bianca et al., 1999; Monaco and Tortorici, 2000; Azzaro and Barbano, 2000; Tinti and Armigliato, 2003).

The development of the Siculo–Calabrian rift zone was coupled with a strong regional uplifting of Calabria and Northeastern Sicily, which progressively decreases toward the north and the south, spectacularly documented by flights of marine terraces developed along the coasts (Cosentino and Ghiozzi, 1988; Westaway, 1993; Bordoni and Valensise, 1998; Ferranti et al., 2006). According to Westaway (1993), post-middle Pleistocene uplift of southern Calabria was 1.67 mm/yr, 1 mm/yr of which is due to regional processes and the residual to coseismic displacement. Regional uplifting could result either from stalling of retreat of the Ionian subducted slab and consequent asthenospheric flow into the gap resulting from slab detachment (Wortel and Spakman, 2000; Goes et al., 2004) or from corner flow in the asthenosphere beneath a delaminated crust (Doglioni, 1991; Gvirtzman and Nur, 2001). The uplift has been locally accommodated in the upper crust by repeated coseismic displacement; the highest values have been found in areas located in the footwall of the main active faults where a fault-related component is cyclically superimposed on the regional signal (Valensise and Pantosti, 1992; Westaway, 1993; Bianca et al., 1999; Monaco and Tortorici, 2000; Catalano and De Guidi, 2003; Catalano et al., 2003; Tortorici et al., 2003).

The Augusta–Siracusa area is located at the southern tip of the Siculo–Calabrian rift zone (Fig. 1). In this area the vertical component of deformation has been recorded by several orders of middle–upper Quaternary marine terraces and palaeo-shorelines (Di Grande and Raimondo, 1982), which indicate long-term uplift rates of ~ 0.2 mm/yr in the last 125 ka (Antonioli et al., 2006) and 0.5–0.7 mm/yr in the last 400 ka (Bianca et al., 1999). This uplift rate gradually decreases towards the stable areas of southeastern Sicily (Ferranti et al., 2006). No data reporting Holocene vertical uplift in the studied area are currently available in the literature. Only in the coastal area of the Catania Plain, tens of kilometres to the north, short-term mean values of 0.5 mm/yr have recently been determined (Monaco et al., 2004). New data on late Holocene coastal movements are provided in this paper.

Archaeological markers

Along the southeastern coast of Sicily, between Augusta and Siracusa (Fig. 1), four important archaeological sites, spanning the period from the Bronze Age to the Greek archaic period, have been selected and investigated with the aim of evaluating significant vertical movement along the coast. Evidence of shoreline tectonic movement comes from the Bronze Age settlements of Ognina and Thapsos, from the Greek archaic settlement of Megara Hyblaea and from the coastal quarry of Punta della Mola exploited during the Greek archaic period (Fig. 1). All of these sites contain valuable archaeological markers to deduce sea level change in the last millennia. Except Megara Hyblaea, archaeological knowledge on these sites is based on the work of Orsi (1890, 1895) as no new substantial investigations have been undertaken in recent times (Leighton, 1986 and references therein).

Materials and methods

Measurements of the current heights of significant archaeological markers with respect to the current sea level at the time of the survey were performed by an invar rod mechanical system. Data have been corrected for tides and pressure relative to mean sea level (MSL) using data from the tide gauges of Catania [<http://www.wxtime32.com>] and from the meteorological site www.wunderground.com. We measured quarries, tombs, docks and piers.

To compare the archaeological structures and to relate them to ancient MSL, we defined their former functional height as a parameter to estimate sea-level change at each location. The functional height is defined as the height of a specific architectural part of an archaeological structure with respect to the mean sea level at the time of its construction and use. This depends on the type of structure, its use, and the local tide amplitudes. These parameters also define the minimum height of the structure above the local highest tides. With respect to harbour and dock structures, the functional heights of modern piers and docks are in the range of 0.30 m above high tide, independent of the size of the harbour itself. This estimate is in agreement with the observations collected at other coastal

Table 1
Location, elevation and age of the archaeological and geomorphologic markers

A Site	B Coordinates	C Measurement dd/mm/yy and local time	D Marker type, measured elevation (m.b.s.l.)	E Age (years BP)	F Tide (m)	G Pressure (hPa)/ correction (m)	H Corrected elevation (m)	I Functional height (m)	L Palaeo- sea level (m)	M Predicted sea level (m)	N Uplift Rate (mm/yr)
Megara Iblea	37°12.34'N 15°11.60'E	15/06/06 – 11:36 AM	“Banchinamento Orsi” –0.80	2600±100	–0.01	1020/–0.07	–0.88	0.60	–1.48	–2.25	0.30 +0.03–0.04
Thapsos	37°09.53'N 15°13.92'E	07/07/06 – 12.56 AM	Tomb floor –0.40	3350±150	0.00	1016/–0.03	–0.43	≥0.60	≤–1.03	–3.29	≤ 0.68 ±0.04
Punta della Mola	37°02.47'N 15°18.42'E	14/06/06 – 16:30 AM	Quarries –0.40	2600±100	0.07	1018/–0.05	–0.38	≥0.60	≤–0.98	–2.25	≤ 0.49 ±0.03
Ognina	36°58.76'N 15°15.78'E	15/06/06 – 08:25 AM	Tomb floor (<i>dromos</i>) –1.20	3500±300	0.06	1020/–0.07	–1.21	≥0.60	≤–1.81	–3.5	≤ 0.49 +0.09–0.10
	36°58.80'N 15°15.38'E	06/07/06 – 08:00 PM	Channel sea-bottom –3.00	3500±300	0.11	1021/–0.08	–2.97	≤–1.00	≥–1.97	–3.5	≥ 0.44 ±0.10
Plemmirio cave	37°00.25'N 15°18.74'E	13/12/03 – 06:00 AM	<i>Serpulid</i> overgrowth on stalagmite –20.3	8229±242	0.08	1013/0	–20.22	N/A	≤–20.22	–27.2	≤ 0.78 +0.32–0.33

Site in column **A** are also reported in Fig. 2; **B**: Coordinates (Lat/Long) of the surveyed site; **C**: day month, year, and hour of measurement; **D**: Type and field measurements (before correction) of the archaeological markers; **E**: Archaeological age of the sites; the ^{14}C AMS dating of *Serpulid* fragment collected at the bottom of the Plemmirio Cave stalagmite was carried out at the Research School of Earth Sciences of The Australian National University, Canberra. Calibrated age was calculated using CALIB 5.0.1 (Stuiver et al., 2005); please refer to Dutton et al. (submitted) for raw data and methods. **F**: tidal correction applied for tide amplitude at the moment of surveys; tide data (Catania) from [http://wxtide32.com/version 4.6 \(2006\6\30\)](http://wxtide32.com/version 4.6 (2006\6\30)). **G**: atmospheric pressure and correction values at the time of surveys. Pressure data from <http://www.wunderground.com>; **H**: corrected elevation=D (measured elevation)+F (tide correction)+G (pressure correction); **I**: functional height of the used marker, with respect to the functional mean sea level; for quarries and tombs we assume a minimum elevation at 0.30 m above high tide (0.30 m) to be always dry, whereas the value of ≤–1.0 m for the channel sea bottom depends on the ship draught; **L**: estimated relative sea level at the time of settlement=H (corrected elevation)–I (functional height); **M**: predicted sea level is computed as the average of predictions for Pachino and Catania Plain from the Lambeck et al. (2004b) model. These two sites bracket the location of the studied sites, with Catania plain just to the north and Pachino to the south of the study area; **N**: uplift rates are reported considering the age error bars and uniform uplift over the entire period of time considered, and hence represent time-averaged estimates.

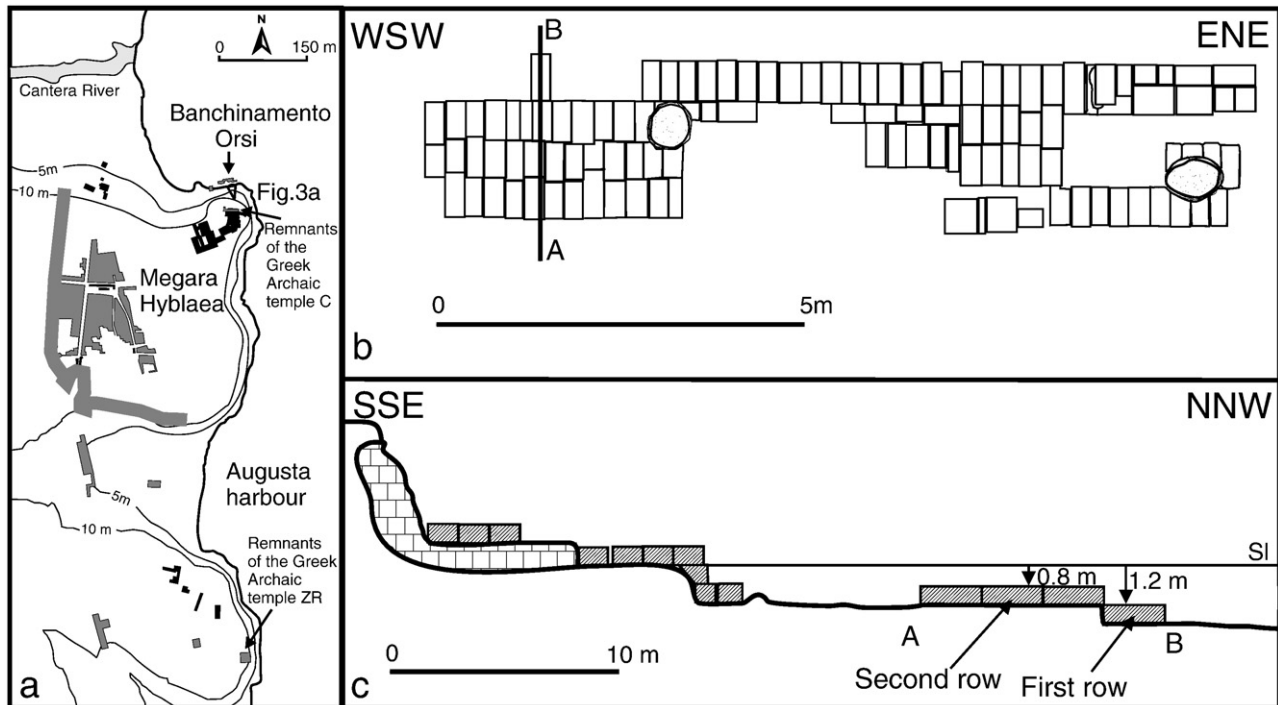


Figure 2. a) Sketch map of the archaeological site of Megara Hyblaea (see Fig. 1 for location); the position of the submerged “Banchinamento Orsi” harbour pier is shown; b) plan and c) cross-section of the “Banchinamento Orsi” harbour pier (from Villard and Vallet, 1953).

archaeological sites (Lambeck et al., 2004a; Antonioli et al., 2007). Taking into account a maximum tide of about 0.30 m in the Ionian coast of eastern Sicily, a functional height of 0.60 m with respect to mean sea level is estimated (Table 1). Moreover these coastal structures were used by ships with a possible draught of about 1.0 m (Kapitaen, 2002; Castagnino Berlinghieri, 2002, 2003). For quarry platforms and rock-cut tombs (presently submerged or partially submerged), we also assume a minimum elevation of their original floor at 0.30 m above high tide to be always dry, which suggests a minimum functional height of 0.60 m with respect to mean sea level.

Further on, the four distinct archaeological sites will be described following their location along the coastline, from the north to the south (Fig. 1).

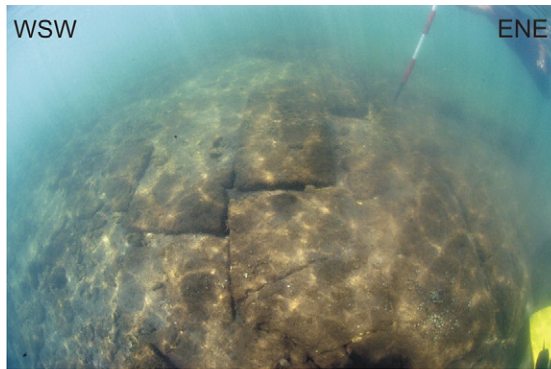
Megara Hyblaea

Megara Hyblaea (Orsi, 1890; Cavallari, 1892) is an ancient Greek colony built alongside a large Quaternary calcarenite plateau (A.A.V.V., 1987) facing the Augusta Gulf, at an elevation of 10–15 m above sea level (Figs. 1 and 2). It is located inside the modern Augusta harbour between two rivers, the Cantera to the north and the San Cusumano to the south. Although debate about the location of the ancient harbor of the

Greek colony still persists, a few considerations about the coastline and its landscape may shed some light on coastal modifications that occurred during the last millennia. Even by simple comparison with 16th to 19th century cartography (Gras, 1995) it is evident that the ancient coastline north of the archeological site formed a more pronounced bay than now. This is mainly due to the construction of two modern piers in the Augusta harbour, which are responsible for a huge accumulation of sediment transported by the rivers Marcellino and Cantera (Fig. 1). Gravity driven processes are also evident along the slope of the plateau, especially in the northeastern and southeastern corners, where the Greek Archaic temples “C” and “ZR” (Gras et al., 2004), respectively, have been partially destroyed by landslides triggered by marine erosion (Fig. 2a).

The most significant archeological marker is a submerged stone structure, at about 4 m off the present coastline near the northeastern corner of the plateau (Fig. 2a), previously observed by foreign visitors (Houel, 1785; Schubring, 1864) and first analyzed by Orsi (1890) who was able to recognize it during an exceptional low-tide episode. This stone structure (“banchinamento”), later reconsidered by Villard and Vallet (1953) and Gras (1995), was interpreted as a harbour pier because of location, block typology, and building technique. It is 24.50 m long and 5.30 m wide (Fig. 2b) and it was built in the so called

Figure 3. a) Underwater view of the “Banchinamento Orsi” harbour pier (see Fig. 2a for location); b) view of the partially submerged tomb of Thapsos (see Fig. 4a for location); c) view of the Punta della Mola partially submerged quarry (see Fig. 4b for location); d) satellite image (from Google Earth) of the Ognina archaeological site (see Fig. 1 for location); the submerged channel and isthmus connecting the islet to the mainland are evident; e) entrance of the partially submerged *dromos* of the tomb in the Ognina islet (see Fig. 5a for location); f) underwater view of the *dromos* of the tomb in the Ognina islet; g) partially submerged bollard along the southern pier of the Ognina channel (see Fig. 5a for location); h) 1-m-high stalagmite in the third room of the Plemmirio cave at ~20 m depth (see Fig. 6 for location).



a



b



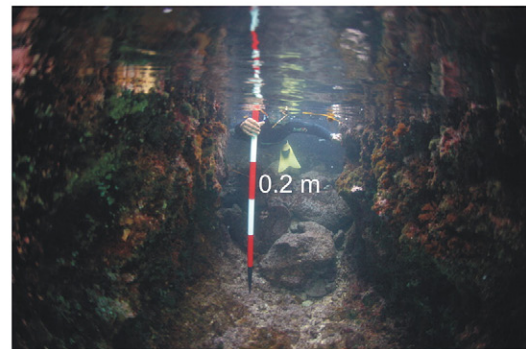
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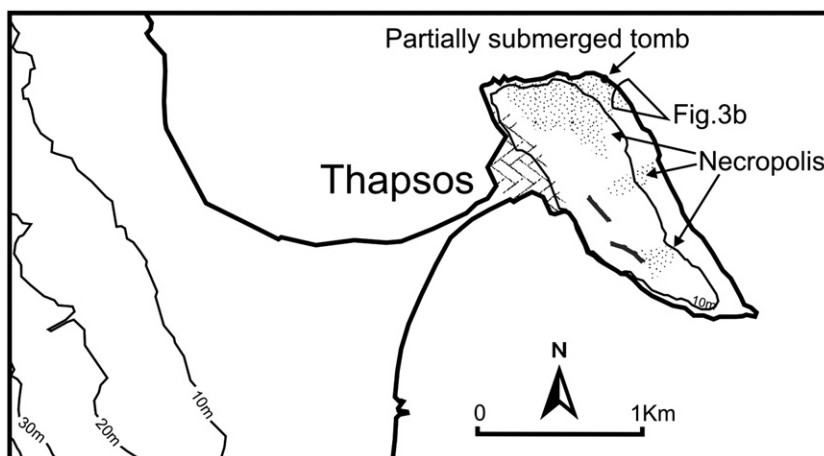
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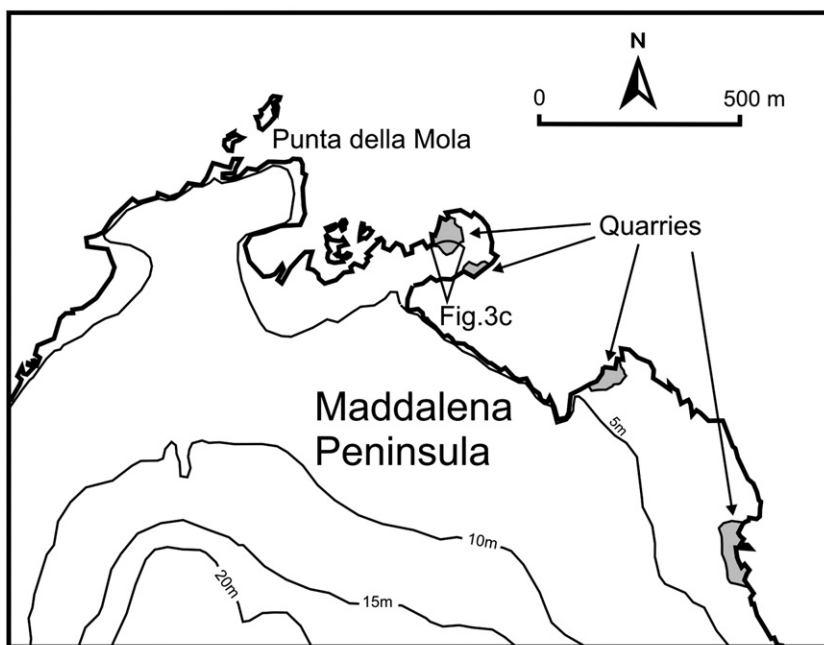
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a



b

Figure 4. a) Sketch map of the archaeological site of Thapsos (see Fig. 1 for location); the position of the partially submerged tomb is shown; b) sketch map of Punta della Mola in the Maddalena Peninsula (see Fig. 1 for location), showing the location of the partially submerged old Greek quarries.

“Greek style” technique that is typical of landing or military structures of the Greek world. This technique is characterised by the use of large parallelepiped calcarenite blocks (Fig. 3a), as long as 1 m and without any joins or transversal blocks, arranged in four overlapping rows (Fig. 2c): the first one seems to be placed straight on the rocky seabed and no foundation level has been detected; the second one forms a large submerged platform. In the eastern sector, the sea bottom relative to the second row is 1.20 m deep at the pier foot and 0.80 m (corrected height -0.88 m) at the pier head (Table 1). Although only part of the four rows of blocks is still in place, one might hypothesize the existence of a complete four-row structure; if we consider the top of the mentioned structure and its original functional surface, the palaeo-sea level should be at -1.48 m depth.

According to Villard and Vallet (1953), the submerged stone structure, named “Banchinamento Orsi”, should be a portion of a bigger complex (“portique à ailes”) connected with another structure transversally located onshore (Fig. 2a), which is built by stone blocks similar in size, but rather differently arranged in technique. Recent studies (Gras, 1995; Tréziny, 2002; Gras et al., 2004) interpreted the entire complex as a monumental fountain (“fontaine du Cantera”) by comparison with similar old Greek structures. Regardless of the interpretation of the entire structure, the “Banchinamento Orsi” could well be a harbour pier area arranged since the Greek Archaic Age (2.5–2.7 ka) in order to support a channel-harbour on the ancient mouth of the Cantera river. In this context, the occurrence of the Greek Archaic temple “C” near the “Banchinamento Orsi” and the recent hypothesis of reconstruction with its entrance from the

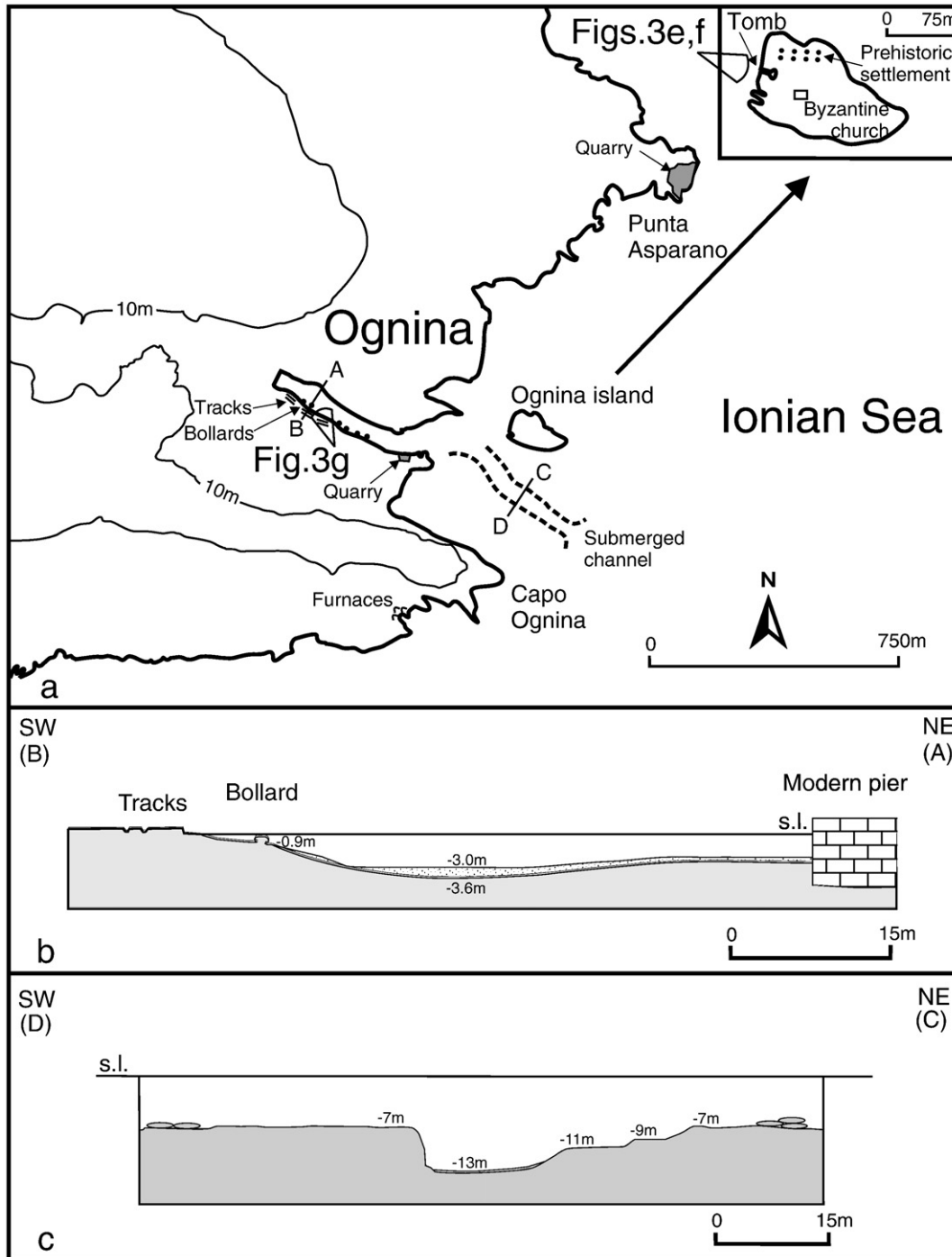


Figure 5. a) Sketch map of the archaeological site of Ognina (see Fig. 1 for location); inset shows the islet with the position of the partially submerged tomb; b) cross sections of the emerged (A–B) and submerged (C–D) sectors of the Ognina channel.

coastline (Gras et al., 2004) should be reconsidered. Recent analysis (Guzzardi et al., 2007) of votive offerings recovered close to the temple “C” have ascertained that this religious complex was a sanctuary dedicated to Hera Ilithyia, the goddess of childbirth, and that it was almost certainly connected with an harbour located on busy maritime routes.

It is possible that a more accurate investigation with ultra-sound equipment, of the multi-beam profiling type, might find

something under the huge seaweed cover which hides possible archaeological remains or architectural details, which are currently difficult to identify. Further underwater archaeological prospecting carried out along this stretch of the sea floor has revealed the occurrence of an irregular structure, still under study, built by means of several remnants of blocks and rough stones fully covered by seaweeds (Basile, 1995). It is located about 22 m to the north of the “Banchinamento Orsi” at 1.20–

1.40 m depth and has been interpreted as a sort of L-shaped jetty, but it could represent a break-water in front of the Cantera river mouth.

Thapsos

The Bronze Age settlement of Thapsos (Orsi, 1895; Bernabò Brea, 1958, 1966a; Voza, 1972, 1973a,b) is located on the Magnisi Peninsula, in the middle of the Augusta Gulf, on the south of the harbour (Fig. 4a). The peninsula is formed by a flat and low (maximum 20 m above sea level [a.s.l.]) calcareous horst (A.A.V.V., 1987), gently tilted to the east-northeast. It is connected with the mainland by a low-lying sandy isthmus, which provides the site with sheltered leeward anchorages and landing places.

In the eastern portion of the peninsula, three main clusters of necropolis of the Middle Bronze Age (3.5–3.2 ka) are scattered on a rocky platform placed between 5 and 2 m a.s.l and gently sloping towards the sea. In the northern sector (Fig. 4a) numerous tombs, which yielded local grey hand-made pottery together with Mycenaean vessels, are partially flooded due to a combination of winds, waves, and currents that generate rough seas. This particular circumstance was first perceived by Orsi (1895) and recently reconsidered (Basile et al., 1988) but no detailed investigation has been undertaken on site. The best known type of necropolis is the one of rock-cut tomb carved directly into the bedrock to create a small artificial cave with one, or sometimes more, sub-circular chambers with domed ceilings, which is evocative of an Aegean beehive tomb of the *tholos* type (Alberti, 2004). The architectural structure has a rectangular opening with perimeter groove for fitting the stone slab which shuts the tomb and is characterised by the presence of a *dromos* (narrow corridor) in front of the entrance facing the sea. The majority of these tombs have been desecrated by tomb robbers; hence the original position of the grave goods remains unknown. The architectural structure will eventually be ruined by the waves on the eastern and northeastern side of the peninsula.

Apart from some burials, which might show features caused by irregularities in the bedrock, in one case a tomb located on the northeastern necropolis facing the sea (Fig. 4a) provides clear evidence of sea-level change. Similar to the other rock-cut tombs belonging to the northeastern cluster of necropolis, this tomb is now partially submerged (Fig. 3b) and its shape has been heavily modified by various natural elements. The edge of the main sub-circular chamber and the series of niches cut out of the bedrock are clearly detectable, even if wave action has partially eroded the ground plan and enlarged the original profile. The presence of part of the markedly arched vault, which is still visible in one side of the chamber, suggests that the ceiling was domed. Since the vaulted ceiling is partially collapsed and the ground plan eroded, we can infer an altitude of -0.40 m below the present day sea level for the ground plan by comparison with other tombs of the same typology. Considering the corrected value of -0.43 m and the functional height, the palaeo-sea level should have been at ≤ -1.03 m depth (Table 1).

Punta della Mola (Maddalena Peninsula)

The Maddalena Peninsula (Fig. 1) is a calcareous horst gently tilted to the east-northeast, located south of the Siracusa natural harbour and formed by Miocene sediments that along the coast are unconformably covered by Pleistocene calcarenites (A.A.V.V., 1987). On the northeastern sector of the peninsula (Punta della Mola, Fig. 4b), conspicuous evidence of extracted parallelepiped blocks reveals the existence of stone quarries (Fig. 3c) which were exploited during the Greek Archaic period (2.7–2.5 ka). Remnants of stone quarries down to a -1 m depth have been reported by Lena and Basile (1986). Our survey in this area revealed the occurrence of four quarries whose floor is located at maximum corrected depths of 0.38 m below sea level, suggesting that the palaeo-sea level should have been at ≤ -0.98 m depth (Table 1).

Ognina

The Ognina area is located 10 km south of Siracusa and is formed by two small promontories (Fig. 5a). The coast is mostly characterized by rocky platforms, carved on Pleistocene calcarenites (A.A.V.V., 1987), placed between 3 and 0.5 m a.s.l. and gently sloping seaward. The archaeological site was mostly located on a former small peninsula (the main part is the Ognina island, Fig. 5a), connected to the mainland by a narrow rocky isthmus, which is now submerged (Fig. 3d). It is a complex site with remnants of several archaeological phases, spanning the period from Neolithic to Byzantine. The positive structures survive to a height of only 3 m on the top of the islet, whereas negative structures (carved straight out of the rock) endure both on the island as well as on the coastal mainland. Some of the archaeological evidence found at Ognina in a partially modified position with respect to the time of use has already been discussed in considerable detail as a signal for sea-level change (Kapitaen, 1970; Castagnino, 1993–1995; Basile et al., 1988). The submerged rocky isthmus provided in the antiquity the settlement with sheltered leeward anchorages and beaching places, and it is still in place, from -0.20 m down to -3.30 m relative to the present sea level.

On the tiny offshore island of Ognina (Fig. 5a) a series of post-hole structures arranged in parallel alignments suggest the presence of a settlement established during the Neolithic Age, while a stable Maltese trading center (Bernabò Brea, 1966b; Parker, 1980) flourished during the Bronze Age (3.8–3.2 ka). Close relationships with Malta are suggested by certain vessels which are matched with *Tarxien* (3.8–3.4 ka) and *Borg in Nadur* (3.4–3.2 ka) cultures (Bernabò Brea, 1958) and which reflect a series of long-distance contacts within an organised system of maritime trade. Material evidence seems to suggest that during the Bronze Age the island of Ognina was a genuine trading post under the control of Malta. In the western sector of the islet (see inset in Fig. 5a), a partially submerged Bronze Age tomb of the rock-cut chamber type is carved in the calcarenites (Fig. 3e). This chamber is preceded by a long *dromos* with an elliptical opening, the floor of which is at -1.20 m (corrected height -1.21 m) below the present sea level (Fig. 3f). Taking

into account the functional height, the palaeo-sea level should have been at ≤ -1.81 m depth (Table 1).

Further meaningful indicators of sea-level change come from the adjacent coastal mainland and are located along the channel as well as along the coast southward of Capo Ognina. Alongside the channel, several partially submerged bollards are carved into the rock (Fig. 3g). Below the sea surface a bollard has been detected which forms a small artificial mushroom shape, the foot of that is 0.9 m below the present sea level (Fig. 5b). The sea bottom inside the channel has been detected at maximum -3.00 m (-2.97 m corrected for tide and pressure; Table 1). Taking into account at least 1.0 m of ship draught (Castagnino Berlinghieri, 2003), the palaeo-sea level should have been ≥ -1.97 m depth. These two last data points are very significant if we relate them with the Bronze Age (3.8–3.2 ka) activity at the site by the Maltese and other seafaring people, as attested by archaeological evidence. It is worthwhile to note that the channel extends to the east where it is completely submerged, with bottom reaching a depth of -13 m b.s.l. (Figs. 5a and c).

Along the edge of the channel (Fig. 5a) there are tracks (*carraie*), previously discussed by Castagnino (1993–1995), that show clear sign of erosion and part of which are collapsed by the southern side of the channel border. Although shapeless shards of amphorae and common ware have been recovered from the submerged channel, it is rather difficult to assess the chronologic range of use, but it seems feasible to surmise that this road system was built to support the intense activity along the channel. Stone quarries are in fact located both on the north and on the south side of the present channel mouth; these are of uncertain age and currently partially submerged with floor located at maximum depths of 0.30 m below sea level. In addition, a partially submerged furnace of uncertain age has been found south of Capo Ognina (Fig. 5a).

Geomorphological markers

The coastal area of southeastern Sicily is characterized by the occurrence of several strands of marine terraces formed by wave-cut surfaces and/or thin depositional platforms (Di Grande and Raimondo, 1982; Bianca et al., 1999). The inner edge of the terraced surfaces and the alignments of marine caves, litophaga holes and notches carved in the coastal cliffs, often linked to palaeo-karstic levels, represent a remarkable record of the palaeo-shorelines formed at sea level during marine stillstands. The Quaternary period was marked by cyclic glacio-eustatic relative sea-level changes, which have been reconstructed on the basis of variations of benthic foraminifera oxygen isotopic ratios (Waelbroeck et al., 2002, and references therein). The eustatic sea level calculated for the last 450 ka reached ~ 6 m above the present sea level during the last interglacial and about 130 m below the present sea level during the last glacial climax. This implies that strands of palaeo-shorelines may occur both inland, especially in uplifted regions, and in submerged areas if not buried by sediment accumulation.

The sea bottom offshore of the present Siracusa coastline is characterized by several submerged karstic caves, aligned at the base of two main escarpments, the shallower one located at depth between -9 and -12 m and -20 and -22 m, the deeper one located at depth between -20 and -25 m and -40 and -45 m (Scicchitano and Monaco, 2006). These morphological elements have been interpreted as the effect of late Pleistocene sea-level stillstands that are presently submerged as a consequence of Holocene sea-level rise. Several speleothems have been found inside the caves (Scicchitano and Monaco, 2006), which may have been cyclically submerged during the Quaternary sea-level change. A stalagmite (Fig. 3h) was collected from the “Plemmirio” cave (Fig. 6; Leonardi, 1994;

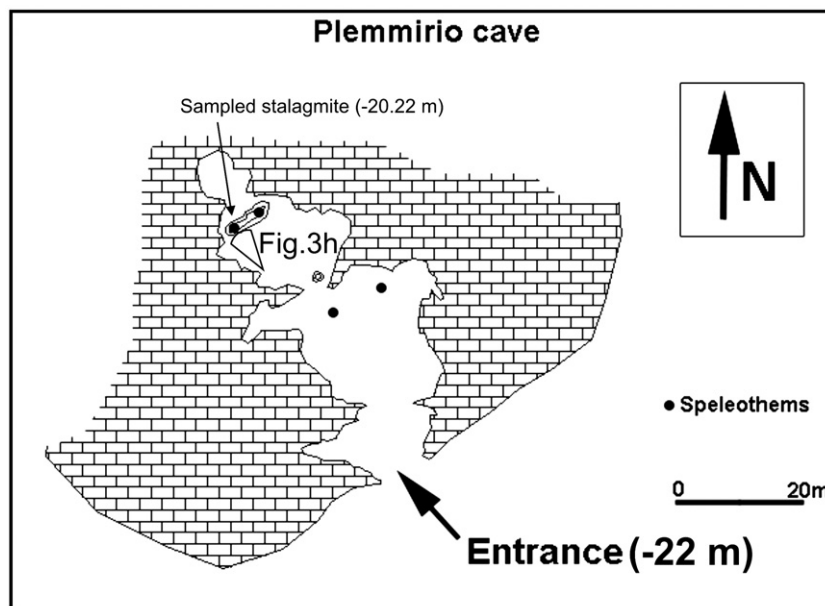


Figure 6. Planimetric map of the Plemmirio cave (see Fig. 1 for location; from Leonardi, 1994), showing the location of the sampled stalagmite.

Scicchitano and Monaco, 2006), located at a depth of -22 m at the southeastern corner of the Maddalena Peninsula (Fig. 1). Absolute age determination of the last marine encrustation on this speleothem was established using ^{14}C AMS on a sample taken from the base of the *Serpulid* crust coating the stalagmite at -20.22 m corrected depth (8229 ± 242 cal yr BP, Table 1). Because *Serpulids* colonize quite quickly after a cave becomes inundated (Antonioli et al., 2001), this age represents a precise time estimate of cave submergence during the last transgression.

Implications with the Holocene relative sea level change and estimation of tectonic uplift

Sea levels along Italian coastlines, like elsewhere in the Mediterranean, are subject to the isostatic response of the crust to glacial unloading of high-latitude continental ice sheets during the last deglaciation as well as to the loading of the ocean floor by the meltwater (glacio-hydro-isostasy). This process occurs at rates that are functions of the glacial history of the ice and of the rheology of the mantle (Lambeck and Purcell, 2005). In the Mediterranean, the glacio-isostatic response is one of an ongoing collapse of a broad bulge that formed around the ice sheet at the time of glacial loading and which extends into the eastern Mediterranean region. The hydro-isostatic response is one of the loading of the sea floor by glacial meltwater and superimposes a shorter wavelength spatial variability on the more regional glacio-isostatic response. The predominant consequence of the isostatic rebound is that sea level has continued

to rise up until the present time along the entire length of the Italian coast at a rate that is a function of distance from the centres of former maximum glacial load but that is also a function of the coastal geometry. Note that we have not considered the numerical uncertainty in the sea-level prediction in our calculations because quantitative estimates through time for each site are not available. These predictions should be considered robust, because they have been rigorously tested at many sites, but are of course not entirely without error.

Last interglacial shorelines (e.g., marked by fossils, tidal notches, and terraces) along tectonically stable coasts of Italy are found at an altitude of 6 ± 3 m (Ferranti et al., 2006). Using this benchmark, the extreme tip of southeastern Sicily appears to be a stable region, whereas eastern Sicily coastal areas underwent strong uplift (up to 1.4 mm/yr), gradually decreasing towards the south. During the Holocene, palaeo-shoreline observations along the Ionian coasts of northeastern Sicily (Firth et al., 1996; Stewart et al., 1997; De Guidi et al., 2003) and analyses from the lagoonal fossils sampled in the Catania Plain (Monaco et al., 2004), yield age–altitude results that suggest uplifting in the order of 2.0 mm/yr (northeastern Sicily), 3.0 mm/yr (Mt. Etna active volcanic area) and 0.5 mm/yr (Catania Plain).

In the Siracusa area, submerged archaeological and geomorphological markers indicate that in the last 8 ka, sea-level rise was faster than tectonic uplift. The tectonic contribution can be evaluated as the difference between the observed local palaeo-sea-level positions (Table 1) and the predicted sea-level curve for the same locality (Lambeck et al., 2004b). Figure 7 illustrates

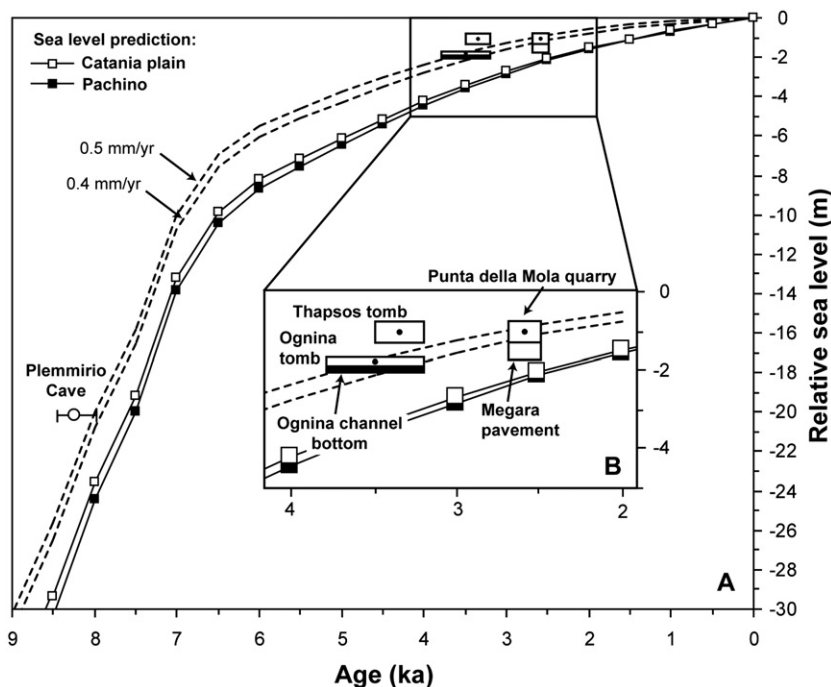


Figure 7. Comparison between predicted sea level curves calculated by Lambeck et al. (2004b) for southeastern Sicily coast and elevation of observed archaeological and geomorphologic markers (this study, Table 1). Sea level predictions are shown for the Catania plain (open squares, north of studied sites) and Pachino (filled squares, south of sites) to bracket the geographic position of the study area. Sea level predictions for various uplift rates (dashed lines) are calculated using the average sea level of the Catania plain and Pachino predictions. Inset (B) shows close up of archaeological markers. Width of rectangles represents age uncertainty; height of boxes bears no spatial significance. Rectangles containing a dot in the center represent maximum estimates of sea level and should sit at or above the dashed lines.

this comparison. The age of the marine encrustations on the Plemmirio stalagmite suggests that the cave was last submerged during the Holocene transgression. The ^{14}C date of the *Serpulid* calcite collected at the base of the biogenic crust implies that the relative sea level was at or above -20.22 m depth by 8229 ± 240 cal yr BP. Taking into account the predicted sea level at that time (Table 1; Fig. 7) and the age error bar, a maximum uplift rate of $0.78 + 0.32 - 0.33$ mm/yr can be calculated dividing the obtained corrected elevation by the calibrated age of the *Serpulid* sample.

The age and palaeo-sea level of the studied archaeological indicators have also been compared to the predicted sea-level curve. All uplift rates represent time-averaged values as they were estimated assuming uniform uplift over the entire period of time considered. A significant marker for identifying sea level comes from the Bronze Age tomb of Ognina islet, the floor of which is at -1.21 m below the present sea level (Table 1). Taking into account that the palaeo-sea level was at least 0.60 m lower than the original floor, 0.30 m above high tide ($+0.30$ m) to be always dry, the relative sea level 3.5 ± 0.3 ka ago should have been at -1.81 m depth. Comparing this value with the predicted sea level (Table 1; Fig. 7), we obtain a maximum uplift rate of $0.49 + 0.09 - 0.10$ mm/yr for the last 3500 yr. The ≤ -1.03 m palaeo-sea level of the Thapsos tomb suggests a maximum uplift rate of 0.68 ± 0.04 mm/yr.

These values can be compared to the Ognina channel topography, which is characterized by sea-bottom maximum depths of -2.97 m (corrected for tide and pressure) (Table 1; Fig. 5b). Given that in the Bronze Age (3.5 ka ago) the sea level was 3.5 m lower than the present (Lambeck et al., 2004b), it means that the channel bottom should have been emergent, unless tectonic uplift has occurred in the intervening time. Taking into account that the ships that used these coastal structures could have had a possible draught of about 1.0 m (Kapitaen, 2003; Castagnino Berlinghieri, 2002) and assuming negligible sedimentation accumulation since the Bronze Age, the relative sea level should have been not more than 1.97 m lower than the present, which might fit with the maritime topography analysed. Correcting this value for the predicted sea level (Table 1; Fig. 7), we obtain a minimum tectonic uplift rate for this case of 0.44 ± 0.10 mm/yr.

Another important marker is represented by the “Banchinamento Orsi” in the archaeological site of Megara Iblea. The pier head is located at -0.88 m and considering a functional height of 0.6 m, the relative sea level should have been at -1.48 m depth 2.6 ± 0.1 ka ago. Comparing this value with the predicted sea level (Table 1; Fig. 7), we obtain an uplift rate of $0.30 + 0.03 - 0.04$ mm/yr for the last 2.6 ka. For that time period, the Punta della Mola quarries can also be used for determining a tectonic component in the relative sea level change. Their floor is located at a corrected maximum depths of 0.38 m below sea level and considering that the palaeo-sea level was at least 0.60 m lower than the anthropogenic platform (0.30 m above high tide to be always dry), the relative sea level should have been at -0.98 m depth 2.6 ± 0.1 ka ago. Correcting this value for the predicted sea level (Table 1; Fig. 7), we obtain a maximum uplift rate of 0.49 ± 0.03 mm/yr for the last 2.6 ka.

All the observed data (Fig. 7) fall above the predicted sea level curve of Lambeck et al. (2004b), indicating that the area has been subjected to general uplift during the last 8 ka. The present elevation of most of these archaeological sites implies an uplift rate of ~ 0.4 mm/yr, with estimates from individual sites ranging from 0.30 to 0.68 mm/yr when compared to the local sea level predictions of Lambeck et al. (2004b). The consistency of calculated uplift values between sites indicates that they reflect a regional process and not localized settling or collapse of structures. In contrast, the ^{14}C age of the *Serpulid* calcite encrusting the speleothem indicates a higher uplift rate of 0.78 mm/yr, but note that this estimate has a larger error than any of the archaeological sites.

The large range of possible uplift rates (between 0.46 and 1.11 mm/yr, Table 1) that is calculated for this geomorphologic sea-level marker is mostly due to the fact that the sea-level curve has a much steeper slope near 8 ka. Hence, our ability to constrain a precise uplift rate on this data point is limited because the sea level is changing rapidly during this period. Therefore, we are left with two possible interpretations: (1) if we consider the low end-member (0.46 mm/yr) uplift rate calculated for the *Serpulid* calcite, then this sea-level marker is in excellent agreement with the late Holocene archaeological data; or (2) if we consider the best estimate (0.78 mm/yr) or upper end-member (1.11 mm/yr) uplift rate calculated from the ^{14}C data, then this scenario indicates that the uplift history in this region is punctuated by episodic coseismic events superimposed upon the longer-term gradual uplift. In general, the uplift values we have calculated are similar to the Holocene uplift rate of 0.5 mm/yr recently determined in the coastal sector of the Catania Plain (Monaco et al., 2004) and with the long-term uplift rate of 0.65 mm/yr estimated for the last 400 ka (Bianca et al., 1999).

Conclusions

Precise measurements of submerged archaeological markers along the southeastern Sicily coast, integrated with information derived from a submerged speleothem, provide data on the relative movement between land and sea level during the Holocene. The main source of uncertainty is the depth range of the former functional heights of the submerged archaeological markers at the time of their construction. We consider our inference that the minimum height of the archaeological structure must sit above the local highest tides to be always dry to be a robust parameter to determine the former functional heights (see also Lambeck et al., 2004a; Antonioli et al., 2007).

While there is some heterogeneity in the uplift rates we have calculated based on geomorphologic and archaeological observations, we emphasize that these estimates are essentially the same if we consider the errors in associated ages and in the position of the predicted sea level from the model. If, however, the heterogeneity in uplift rates is in fact real, it would confirm the tight connection between long-term tectonic uplift and abrupt fault-related displacement in controlling recent crustal instability in this area, which is located at the footwall of one of the most active seismogenic structure of the central Mediterranean (see also Bianca et al., 1999).

Finally, the estimation of recent relative sea level movement is useful to provide a flooding hazard scenario for those civil and industrial settlements of the studied region located near the present sea level, where little relative sea level rise movement could produce extensive coastline sea-flooding.

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