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Relative sea level change in Olbia Gulf (Sardinia, Italy), a historically important Mediterranean harbour

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ABSTRACT

Olbia Gulf, located in northeastern Sardinia, is bordered by granite, metamorphic rock, and limestones (Capo Figari and Tavolara Island). It has been an important merchant harbour for three thousand years. Tidal notches in limestone, considered one of the best sea level markers, are present between 5.1 and 8.6 m a.s.l. A fossil beach deposit on Tavolara Island is of Tyrrhenian age (MIS 5.5, 125 ka).

Between 1999 and 2001, during the building of a new Olbia harbour tunnel, many shipwrecks hidden under recent fine sediments have been discovered. The archaeological excavation (380 x 20 m, to the surface of the carbonate bedrock at 4 m depth) was done by the Soprintendenza per i Beni Archeologici per le provincie di Sassari e Nuoro (Olbia branch). During the archaeological excavation campaign, thousands of ceramics, other materials which were not *in situ*, and 24 shipwrecks of different age and size were recovered. Eleven of these wrecks were sunk while they were still in the harbour during an attack by the Vandals in the middle of the fifth century. This attack determined the beginning of a sharp decline of Olbia, and gives a clear picture of one of the turning points of the Mediterranean cultural evolution: the end of the Roman Empire.

Considering −1.4 m as the average altitude of the shipwrecks on the silty bottom of the Olbia Harbour and comparing this value with the predicted sea level curve from the Lambeck model calculated for northern Sardinia (−1 m ca. 1500 cal BP), it appears clear that the ships were at the margin of the harbour in water depth of less than 0.5 m. This confirms: a) the previous archaeological interpretation; and b) that the northern Sardinian coast was stable during the last millennia. Due to the tectonic stability of the coastal area, the evolution of the shoreline from the Bronze age (4 ka cal BP) up to 21.5 ka cal BP (LGM, last glacial maximum) is reconstructed.

1. Introduction

Olbia Gulf and Tavolara Island, located in northeastern Sardinia (Italy, Fig. 1), are sites that are not only historically significant for a human presence dating from the Neolithic period, facilitated by the presence of a bay protected from all winds, but also for a breathtaking coastline with the Marine Protected Area of Tavolara. The objective of this work was to take advantage of the opportunity that presented itself to the Soprintendenza per i Beni Archeologici (archaeological administration), when in 1999–2001, during the construction of a bypass tunnel connecting the ferry harbour with the freeways around Olbia, wreckage of 24 wooden ships was recovered, some of large dimensions, partly at right angles to the coastline and parallel to one another. The archaeological data obtained can be used to measure the paleo-sea level (Fig. 2). During the course of the excavations directed by R. D'Oriano of the Soprintendenza per i Beni Archeologici for the provinces of Sassari and Nuoro, all of the artifacts were studied and dated, and conclusions were reported by D'Oriano (2002). The complex excavation process and subsequent study of the artifacts provided an extremely important series of discoveries. The object of this work was to obtain, on the basis of the work conducted, further information relating to the paleo-sea level during the time at which the ships in question were active and moored at the port of Olbia.

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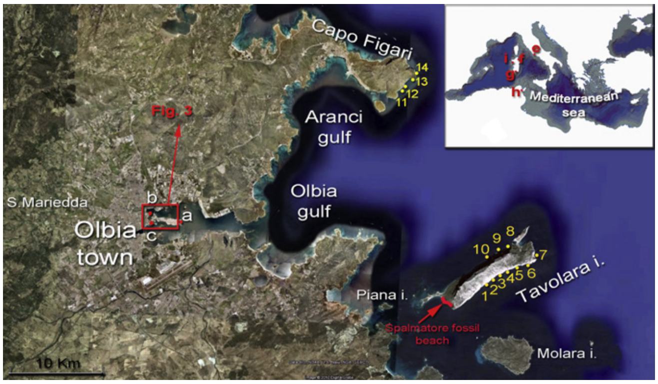

Fig. 1. Olbia gulf and Tavolara Island: topographical and archaeological map. Letters: **a**) Isola Bianca (modern harbour); **b**) *Porto Romano*; **c**) Late Roman harbour (tunnel, wreckage sites); **e**) Rome; **f**) Olbia; **g**) Cagliari (*Karales*); **i**) Porto Torres (*Turris Libisonis*); **h**) Cartagine. Numbers are referred to the distribution and altitude of the tidal notches in Olbia and Aranci gulfs, see also Table 1.

The geomorphological part of this research consisted in the measurement of the tidal notches. Some well-defined tidal notches have been carved out of the limestone ridges of Capo Figari and Tavolara Island (Fig. 1), indicating a paleo-sea level presumed to be of Tyrrhenian age (MIS 5.5) by analogy with the nearby gulf of Orosei, where a notch was measured and studied by Carobene and Pasini (1982) and Antonioli and Ferranti (1992), and subsequently by Mariani et al. (2009). The measurements relating to sea level taken on the wreckage and those of the tidal notches were compared to eustatic values in order to determine whether, both in the long term (last 125 ka) and in the short term (last 1.5 ka), northern Sardinia has remained tectonically stable or undergone vertical movements.

2. Geological background

In the area surrounding Tavolara Island, the basement is a Hercynian intrusive complex, made up of equigranular and inequigranular monzogranites. In the area of Capo Figari, the basement is primarily the Hercynian migmatitic complex, outcropping from leucocratic migmatites with calc-silicate lenses, granodioritic and monzogranitic orthogneisses and amphibolites. The age is attributed to the pre-Cambrian–Cambrian by Franceschelli et al. (1982). During the Jurassic, the overlying eastern Sardinia succession was deposited, which is made up primarily of bioclastic limestones and dolostones and sandy dolostones of littoral to circalittoral environments. The succession of Tavolara and Capo Figari represents the northernmost extremity of the carbonate cover of eastern Sardinia (Dieni and Massari, 1985). Olbia lay at the end of a long plain which is a morphological filling flattened by the flow of rivers.

3. Human settlements

The territory of Olbia, which extends from the gulf of the same name (Fig. 1) thanks to a fertile inland rich in water resources, represented from an early stage one of the most important poles of attraction in the settlement process of northern Sardinia (Lo Schiavo, 1996; Santoni, 1996). Archaeological findings (the oldest date to the middle Neolithic, about 6.5 ka cal BP), such as the renowned female statue portraying the Goddess of Life found in S. Mariedda (Fig. 1), indicate high human traffic from pre-history through the entire Bronze Age (Santoni, 1996).

Archaeological surveys ascribe the founding of the urban settlement of Olbia to the Phoenicians in the middle of the 8th century BC (2.8 ka BP), and clearly show Greek predominance between the Sixth and the Fifth century BC (between 2.7 and 2.5 ka BP). This confirms both the Hellenic origin of the name, *Olbìa polis* (with variants *Ulbia* and *Olbì* during Roman times), and the myth of the city's foundation reported by Pausania (attributed to Iolaus, nephew of Hercules, who arrived with a group of Thespians and Athenians following an indication by the oracle of Apollo at Delphi; (Pausania, *Periegesi della Grecia* (X, 17, 5); Panedda, 1953; D'Oriano, 1996, in press; Mastino, 1996; D'Oriano and Oggiano, 2005; D'Oriano and Marginesu, 2008; D'Oriano, 2010).

From the end of the 6th century BC (2.5 ka BP), the site appears to have been under the control of Carthage (Fig. 1), following its victory at Alalia (AA.VV., 2000) over the Phocaeans in 545 BC (about 2.6 ka BP), which marked a turning point in its favor in the control of the central Mediterranean. However, this did not translate into a conspicuous and stable presence (D'Oriano, 1991, in press).

During the first half of the 4th century BC (2.4 ka BP), there was a gradual transformation in the balance of power in the Tyrrhenian Sea caused by the growth and expansion of Rome, which, as recorded by Polibio in *Storie* (I, 24, 7), had been interested in the control of Sardinia since its first incursions there by sea. This led to the establishment in 386 BC (2.4 ka BP) of a colony near Posada (50 km from Olbia), which is mentioned by Diodoro in *Biblioteca* (XV, 27, 4).

The conflicting interests of Carthage (Fig. 1) and Rome on the Tyrrhenian were regulated by a treaty in 348 BC (2.4 ka BP) that prohibited the Romans from landing and trading in Sardinia. The need to enforce this prohibition required Carthage to found a colony at Olbia sometime around 330 BC (2.3 ka BP). Olbia and its port must have represented for the Carthaginians an ideal outpost for extending control to the north of the island and imposing their presence in the Tyrrhenian Sea at a time – the 4th century BC (2.4 ka BP) – during which a phase of continued colonial expansion was underway (Panedda, 1953). The archaeological data retrieved from the interior and the sea bed in front of the port indicate that the gulf, from the 8th century BC (2.8 ka BP), played an important role in the trade dynamics of northern Sardinia and was an integral part of long-range maritime routes.

A first attempt by the Romans to subdue Punic Olbia is referred in the triumph celebrated in the *Poemi* of *Sardinia* following the campaign of L. Cornelius Scipio against the Carthaginians in 259 BC (2.26 ka BP) (Panedda, 1953; Mastino, 1996). It is, however, probable that no real conquest was achieved (although the sources on this point conflict) but, rather, a naval incursion by the Roman fleet on its return from Aleria (Corsica) was immediately repelled by the arrival of a second Punic squadron led by Hannibal that forced L. Cornelius Scipio to retreat (Panedda, 1953; Mastino, 1996).

Olbia's incorporation into Rome's dominion appears to have already been completed in 210 BC (2.2 ka BP), when, as reported by Livio in *Ab Urbe condita*(XXVI, 6, 13), Romans and Carthaginians once again clashed there, but this time with their roles reversed: the Romans, led by praetor P. Manlius Vulso, defended the city from an attack by the Carthaginian Hamilcar (Panedda, 1953; Mastino, 1996).

The city retained its original layout, but with the empire (1st century AD, 1.9 ka BP) there was a clear process of monumental construction: paved roads, the aqueduct, and baths were built. A number of temple structures were renovated, including the temple of Cerere, dedicated by Acte, the famous mistress of Nero (Panedda, 1953; Mastino, 1996;).

Both written and archaeological sources also attribute an important role to Olbia in Rome's trade and military strategy. Although the city's legal status is not certain, it must have been promoted to the rank of 'municipium' between the end of the republic (2.0 ka BP) and the middle of the 1st century AD (1.9 ka BP) (Panedda, 1953; Mastino, 1996). In any case, the connections

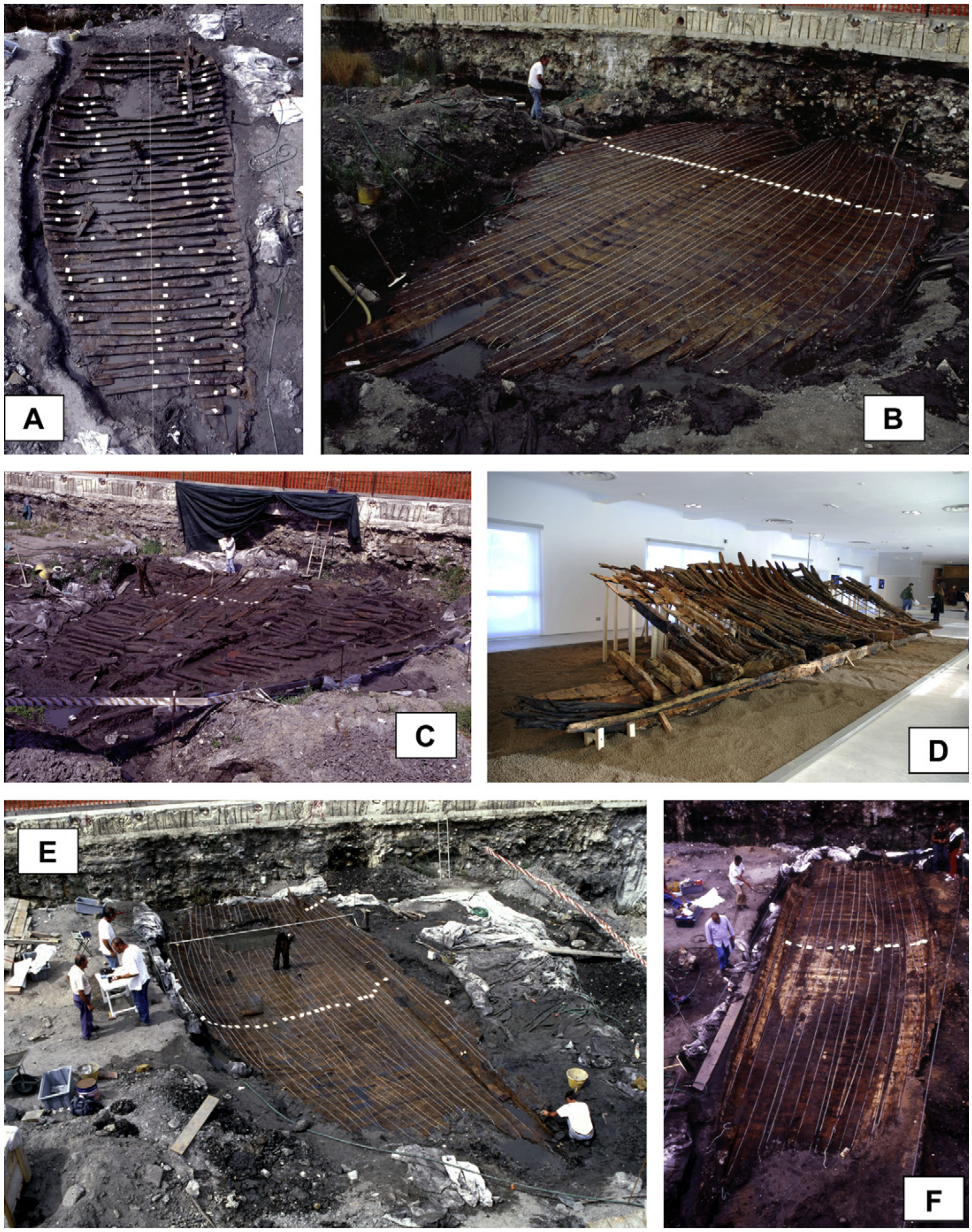

Fig. 2. Photo compilation showing the excavation of shipwrecks described in this paper. Images referred to the late Roman ships sunk in the 5th century. They are all commercial boats, apparently deprived of the cargo and emptied of all the reusable elements. The dimensions vary between 15 m (Wreck n. 13, **B** in this figure) and 30 m (Wreck n.1, **F** in this figure). Wrecks are conserved in the Museo Archeologico Nazionale of Olbia (Figure 5 **D**). **A**: Olbia. Late Roman Harbour excavation, wreckage n 2. **B**: Wreck 13 (about 15 m length). **C**: Wreck 3. **D**: Wreck 2. **E**: Wreck 2. **F**: Wreck 1 (about 30 m length).

between construction, renovation and legal status in Roman cities observed by Gabba (1994) would indicate the early imperial phase.

In the 2nd and 3rd centuries AD (1.8 and 1.7 ka BP), the archaeological evidence indicates widespread affluence in a city which, although no longer at the zenith of its development and beginning to exhibit the first signs of a demographic crisis, maintained an economic role that was important enough to the justify the continued maintenance and reconstruction projects which the main roads leading to the city center underwent in the 4th century (1.6 ka BP) (Panedda, 1953; Mastino, 1996; Meloni, 1996). However, during the 3rd century (1.7 ka BP), and certainly during the 4th century (1.6 ka BP), there are signs of a growing suffering that spread to all sectors of urban life (perhaps excepting the most affluent levels), causing a marked drop in ceramics imports (Meloni, 1996; Pisanu, 1996). One of the last references to the name of Olbia is in a passage of Claudiano's "De Bello Gildonico" (XV, 518–9) which, sometime around 398 AD (1.5 ka BP), briefly mentions the port, which received part of the imperial navy fleet thanks to its masonry constructions, such as the "barrier" built between the shore and the island of Peddona (fig. 3) (Panedda, 1953; Mastino, 1996; D'Oriano, 2002).

The fortunes of ancient Olbia came to a decisive end in the middle of the 5th century AD (1.5 ka BP) following its conquest by the Vandals (Mastino, 1996; Meloni, 1996; D'Oriano, 2002). The

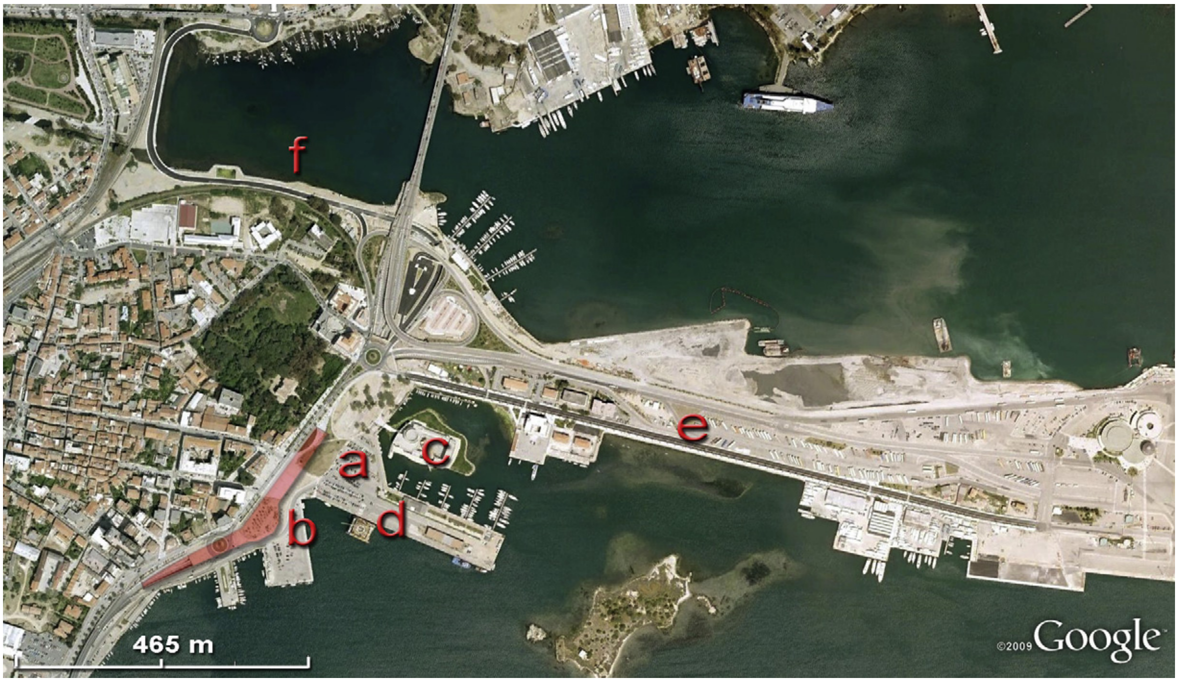

Fig. 3. Town of Olbia, excavation of the ancient harbour **a**) excavation for the tunnel (shaded); **b**) Topographic bench (see also Fig. 7); **c**) Peddona Island (Museo Archeologico Nazionale); **d**) Brin jetty; **e**) Road to the modern harbour (Isola Bianca); **f**) *Porto Romano*.

Vandals, after conquering Carthage and making it their capital (439 AD, 1.5 ka BP), began a series of incursions into Roman territory. The most important centers of the Mediterranean islands were occupied and taken from the direct control of Rome (fig. 1), which was itself sacked in 455 AD (1.5 ka BP) (Meloni, 1996).

Olbia was one of the centers most affected by these incursions and was hit much harder than other Sardinian cities such as Karales and Turris Libisonis (fig. 1). In contrast to Olbia, the latter two cities figure among the dioceses convened in Carthage in 484 for the council called by Huneric, a sign that not only were they not abandoned, but that they maintained pre-eminent roles in their respective territories. The archaeological record of this event is represented, in addition to many traces of fire and violent destruction identified both within the city and port area and in the necropolis of "Su Cuguttu", by 11 honorary ships (fig. 3a) burned and sunk in the port (Mastino, 1996; D'Oriano, 2002). Without discussing in detail the different hypotheses surrounding the events affecting Olbia between the 5th and 10th centuries AD (between 1.5 and 1.0 ka BP), it can be affirmed with certainty that the city thus entered a long period of recession during which the ancient center decreased drastically in size, but was not completely abandoned, probably in favor of less exposed and safer areas (Mastino, 1996; Meloni, 1996).

When Olbia, with the name of Civita, and later Terranova, reappears in the written record (11th century, 0.9 ka BP, after the period of Arab invasions), it is already the capital of the Giudicato of Gallura, one of the four independent realms into which Sardinia is divided following the end of Byzantine rule (Castellaccio, 1996; Meloni, 1996). The fading threat of Arab invasion (VIII- XII centuries, between 1.2 and 0.8 BP) and the resumption of maritime traffic, thanks to an alliance between the Giudicato of Gallura and the Republic of Pisa, was a strong impulse for the rebirth of the city, fostering rapid demographic growth and re-launching activity in the port (Panedda, 1953; Castellaccio, 1996). To this end, the Roman port was reclaimed in order to achieve greater depth, because the depth of the ancient port had been reduced because of the mud retained by the wreckage the Vandals had left in their wake (D'Oriano, 2002).

4. Materials and Methods

4.1 Tidal notch

Taking measurements of the tidal notch on Figari and Tavolara cliffs (Fig. 1) was not an easy procedure. These erosional morphologies were found between 5.1 and 8.6 m asl (Fig. 1, Table 1), carved out of a very compact and steep limestone face, and exhibit good lateral continuity. In some cases, climbing made it possible to take measurements with a surveyor's wheel (Fig 5). In other cases that was not possible, and so a 3-m Invar pole was used, and the remaining part was measured using photographs (Fig. 6). The small organogenic terrace found at the base of the modern tidal notch at mean sea level was compared with the corresponding geomorphological fossil markers (see Fig. 6). Using this procedure, it was not necessary to

Table 1
Altitude of the tidal notch at the Olbia and Aranci gulfs.

number	coordinates	Altitude (m)
Southern portion Tavolara Island		
1	40 53 56 N – 9 42 12 E	7.3
2	40 54 09 N – 9 42 57 E	7.45
3	40 54 20 N – 9 43 22 E	7.6
4	40 54 28 N – 9 43 44 E	7.3
5	40 54 32 N – 9 43 55 E	7.25
6	40 54 36 N – 9 44 15 E	6.5
7	49 54 47 N – 9 44 29 E	7.5
Northern portion Tavolara Island		
8	40 55 02 N – 9 43 30 E	6.8
9	40 54 52 N – 9 43 04 E	6.5
10	40 54 41 N – 9 42 46 E	6.8
Capo Figari promontory		
11	40 59 16 N – 9 30 17 E	5.07
12	40 50 24 N – 9 39 26 E	5.10
13	40 59 36 N – 9 39 43 E	5.03
14	40 59 46 N – 9 39 50 E	5.10

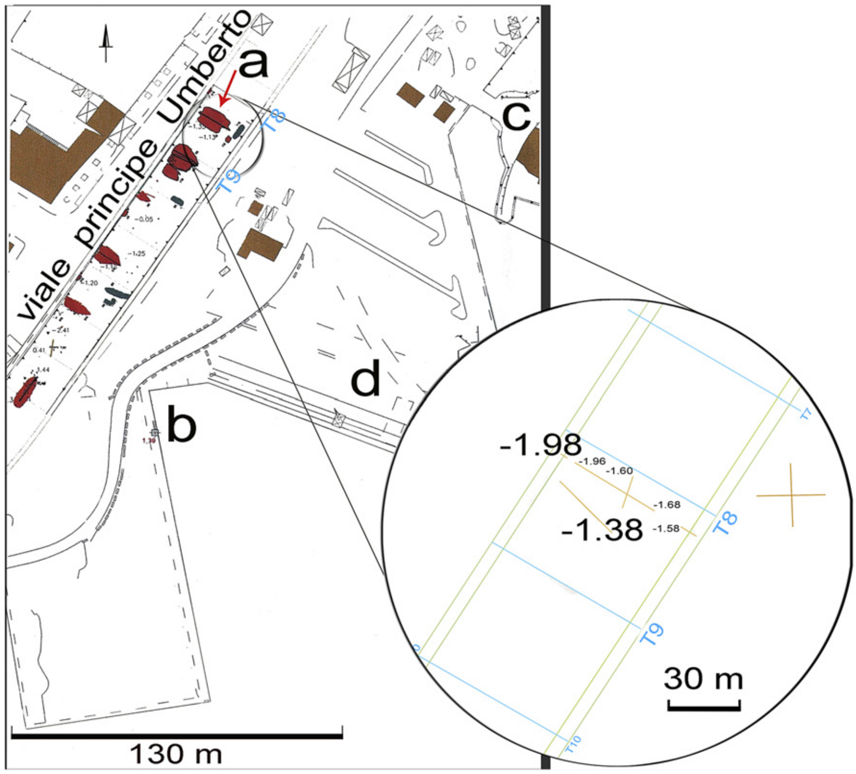

Fig. 4. Topographical plant of the area of excavation (sector north) with indication of figwrecks the position of the wrecks **a**) wreck R1; **b**) Topographic bench (see also Fig. 7); **c**) Peddona Island (Museo Archeologico Nazionale); **d**) Brin jetty. In the circle, the altitude b.s.l of the 5 long shafts for rudders documented under wreck R1 (with indication of the high). Topographical plot of the area of excavation (sector north) with indication of the position of the wrecks.

screen the measurements with tide and barometric pressure. The measurements were carried out in September 2007 and May 2008.

4.2 Wreckage of the port of Olbia

Rather complex, on the other hand, was the task of reconstructing the relative palaeo sea level from the data collected during the excavation performed by the Soprintendenza per i Beni Archeologici of Sassari and Nuoro (Olbia branch) on the site of the tunnel connecting the port and suburban roadways (D'Oriano, 2002; fig. 2, 3a). The measurements referring to the depth of the keels of the ships, identified during the surveys and reported on the topographic maps (fig. 3a), were critically examined in order to determine the paleo-seabed depth at the time of their sinking.

The excavation brought to light the wreckage of 24 ships (dated to between the 1st century AD [1.9 ka BP] and late antiquity [1.5 ka BP] and the medieval period), traces of an arsenal (naval shipyard) located on a sandy peninsula which possibly divided the area around the port into two sectors, which during the excavation were identified as the "northern sector" and "southern sector", and countless ceramic artifacts (D'Oriano, 2002; Riccardi, 2002; fig. 2, 3a, 4).

In the evaluation of sea level changes, only the ships from the 5th century AD (1.5 ka BP) were considered to be significant markers. The attitude in which these wrecks were found (fig. 3a), all parallel to one another and at right angles to the ancient coastline (as indicated by the discovery of corresponding remains with wooden wharfs), confines the analysis to a single, homogeneous context, well-defined both in its topography and in its chronology (D'Oriano, 2002). For the same reason the decision was made to exclude measurements pertaining to wreckage studied at the same site but belonging to other time periods (fig. 3a, Riccardi, 2002).

In particular, in coherence with the dates proposed (D'Oriano, 2002; Riccardi, 2002), the attitude recorded for wreck R1 (shown on the map in fig. 3, sector T8, and fig. 2f) was adopted as significant. The choice was determined by the necessity of confirming the effective relevance of the measure to the depth of the keel. Some values shown on the topographic map (fig. 3a) which cannot be attributed with certainty to the attitude level of the wreckage could have led to gross errors of evaluation. In this case, in contrast, the effective correspondence between wreck R1 and the depth of the keel is supported by the presence of 5 long shafts for rudders (datable to the 1st century AD, 1.9 ka BP), discovered directly beneath (between −138 and −198 cm, fig. 3b; Riccardi, 2002).

All the measurements taken during the excavation were compared to the sea level and connected with a "zero value" measured on the Brin jetty, marked by the presence of a topographic bench mark (fig. 7). It was thus possible to proceed with a new measurement of the height of the benchmark in order to verify the margin of error caused by the sea level and atmospheric pressure (found at *http://www.wxtide32.com* and *www.wunderground.com*). The difference obtained was then added to the value indicated on the topographic map in order to obtain the height of the plane measured with respect to the current average sea level.

5 Data

5.1 Archaeology

5.1.1 Porto Romano

In 1989, on the occasion of an excavation for laying a sewer line parallel to the shoreline of the area known as Porto Romano (fig. 1), a layer of sand was found between −100 and −80 cm asl, containing ceramic materials dated to the middle of the 4th and 3rd

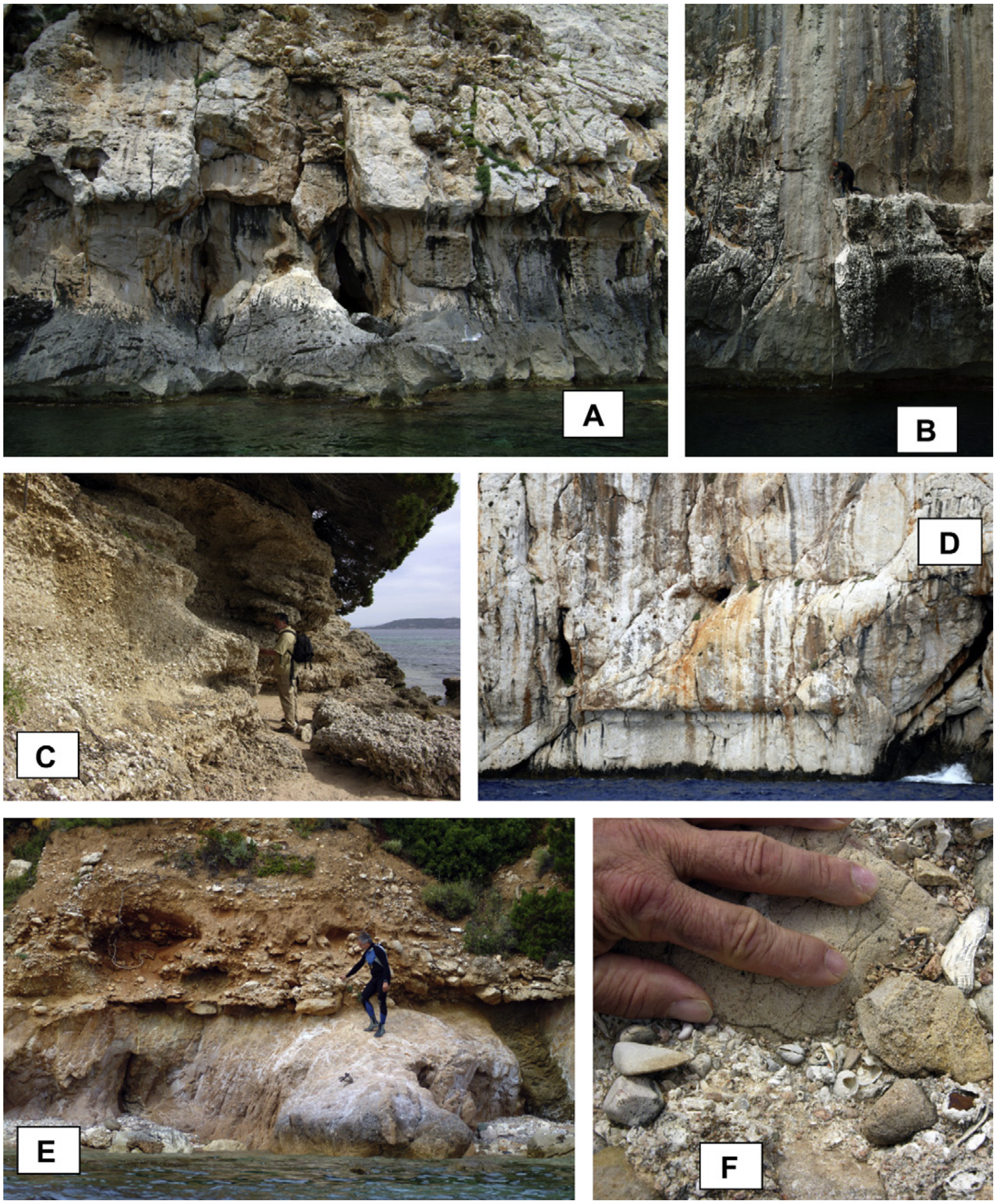

Fig. 5. Photo collection showing the tidal notches measured at Tavolara island and Capo Figari. **A**) The tidal notch in southern portion of Tavolara island (Fig. 1). **B**) Measuring tidal notch in southern portion of Tavolara island. **C**) Marine sediments from Punta La Mandria in the southwestern part of Tavolara Island. **D**) The tidal notch at Capo Figari (Fig. 1). **E**) The marine conglomerate outcropping on the granite of Spalmatore southwestern part of Tavolara Island (Fig. 1). **F**) Particular of the fossil marine shell outcropping at Punta La Mandria (Fig. 1)

centuries BC (2.4 and 2.3 ka BP) (D'Oriano, 1990). In particular, the oldest context was identified as an ancient beach limit now submerged (−100 cm), and, in spite of the wide margin of error that characterizes this type of indicator, it would not be inappropriate to evaluate the indication offered by this context in order to have another point for comparison with the high tide curve.

5.1.2. Late Roman wrecks

Based on the information provided by this excavation, partly in the literature and partly acquired specifically for this study, it is possible to make some observations on the environmental conditions in which the ships sank.

The many traces of fire, identified in the wood of the keels near the ship's line of buoyancy, indicate that at the moment of the disaster causing them to sink (one of many attacks by the Vandals on Roman territories; D'Oriano, 2002), the ships were not beached, but, although in very shallow water, must have been floating (fig. 8). This information is confirmed by the discovery of biological concretions on some portions of the hulls, a sign that for a certain period, presumably a couple of years, the now abandoned vessels, before becoming definitively submerged in the mud, continued to offer a habitat suitable for the growth of organisms (Riccardi, personal communication).

Archaeological findings indicating subsequent phases are extremely unreliable. After this event, the port, although probably not completely abandoned, must have lost its functionality, compromised by the presence of wreckage in the primary landing area (D'Oriano, 2002). Only many centuries later, in the 13th–14th

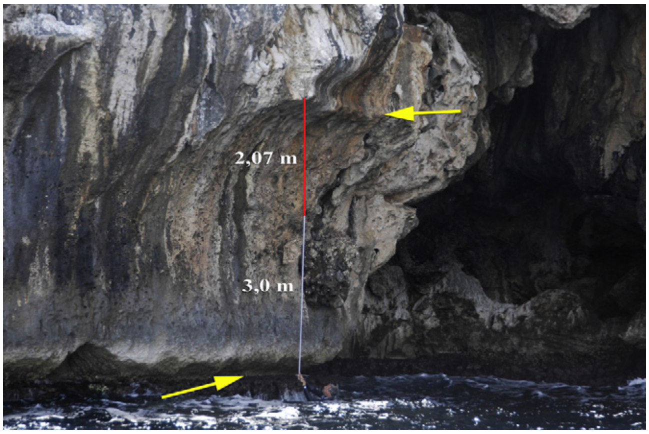

Fig. 6. Measuring a tidal notch at Figari promontory (Fig. 1). The arrow indicates the base of the notch. The present day notch has a vermetid zone 2–3 cm thick.

centuries (between 0.7 and 0.6 ka BP), was the port made accessible once again, thanks to costly reclamation works over an area made unapproachable not so much by the wreckage itself as by the mud and debris that it accumulated (D'Oriano, 2002).

Therefore, when the ships sank, they must have been moored, probably with the prow partially beached and facing the shore. They were moored in a primary landing area equipped with wooden quays, characterized by water that is very shallow, but deep enough to partially float the ships, which in spite of their large dimensions, had a draught of ca 0.50 m.

The definition of the time period in which the 5th century wrecks sank was made possible by the study of the naval construction techniques (Riccardi, 2002), in addition to the incidence of ceramic materials. Although the site did not exhibit a well-defined stratification (due to the re-mobilization of the bottom, whose dynamics were reconstructed by Giovani Tilocca in D'Oriano, 2002) and only a limited number of the artifacts could be definitively established as cargo (D'Oriano, 2002), a first indication of the timeframe was deduced from the study of the most recent artifacts (many of which were already in circulation from the 4th

Fig. 7. The topographic bench mark measured on the Brin jetty of Olbia harbour. The box shows the piton used during the 2000–2001 archaeological excavation.

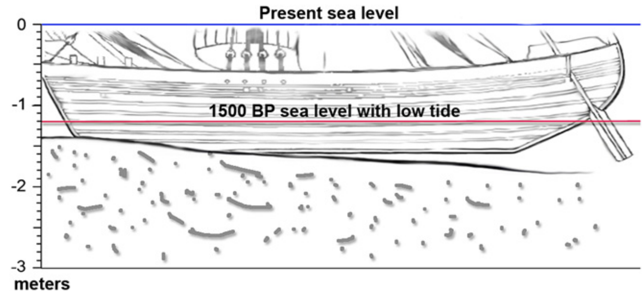

Fig. 8. Hypothetical sketch of a ship in the late Roman harbour of Olbia.

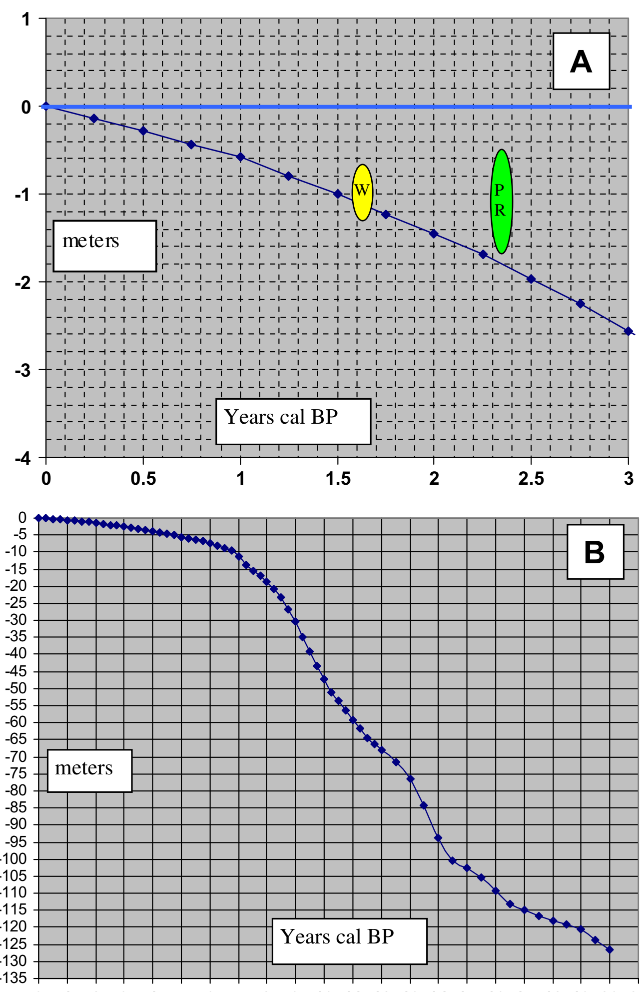

Fig. 9. Predicted sea level curve from Lambeck et al., this issue, for Olbia. **A**: last 3 ka cal BP curve compared with observed data and relative error bars (**W**: wrecks and **PR** Porto Romano beach, **B** last 20 ka cal BP predicted sea level curve.

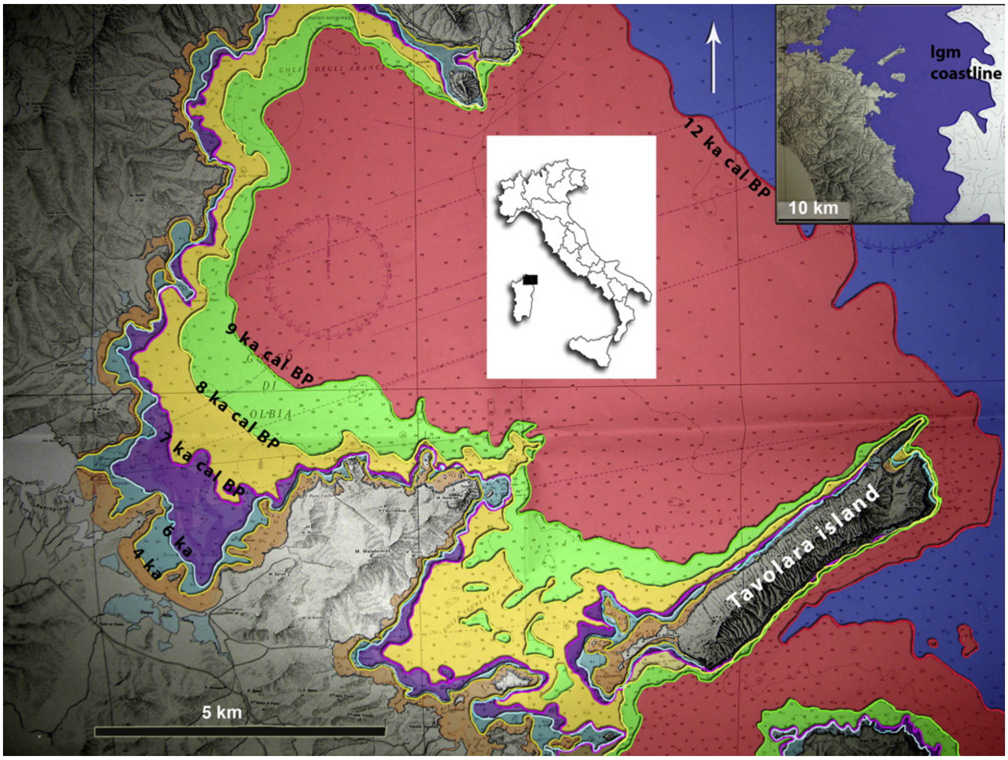

Fig. 10. Palaeocoastline reconstruction in Olbia Gulf since last Glacial. In the box on the right the palaeocoastline during LGM (last glacial maximum) 21.5 ka cal BP with the sea level at -130 m. Palaeocoastlines: −68 m, 12 ka cal BP; −30 m, 9 ka cal BP; −19 m, 8 ka cal BP; −11.5 m, 7 ka cal BP; −7.2 m, 6 ka cal BP; −4 m, 4 ka cal BP. map of Istituto Idrografico Militare Della Marina, 1966.

century AD, 1.6 ka BP. The discovery of a Theodosius I coin from 396, and therefore in circulation in the 5th century AD (1.5 ka BP), found among the planking and frame of one of the ships (and hence definitely onboard when the ship sank), excludes the low end of the time spectrum.

Another time constraint is represented by the well-known passage of Claudius Claudiano in *De bello Gildonico* (XV, 518–9). The author noted that in 397, due to the conflict with Gildo, a part of the imperial navy fleet made a stop in the port of Olbia, evidently still functional and free of encumbrances large enough to impede access to a large number of warships of medium-large dimensions (D'Oriano, 2002). However, the port of Olbia was in a state of dilapidation from the middle of the 5th century. Further studies on the ceramics that can be correlated to the wrecks, in particular the most recent ones found directly beneath the wood of the ships, have demonstrated with certainty that the timeframe of the event can be set at around 450 AD, 1.4 ka BP (Pietra, 2006, 2008). Therefore, the ship sinking took place 1560±10 BP (between 440 and 460 AD).

An altitude of −135 cm asl is considered be valid for the 5th century wreckage. This elevation, as stated above, refers to the depth of the keel of wreck R1 (Fig. 2f), located in sector T8 of the topographic map (Fig. 4a). Correcting this measurement for the sea level re-measured by the topographic bench mark (+10 cm) obtains a value of −145 cm asl (water depth in the 5th century AD, 1.5 ka BP; Fig. 8).

5.2 Geomorphology

Table 1 integrates the measurements with the tidal notch values measured at Tavolara and Capo Figari (Fig. 1). However, their utility depends exclusively on the age.

Sediments between Spalmatore (Fig. 1) and Punta La Mandria in the southwestern part of Tavolara Island were studied in a previous investigation by Segre (1954). In the description provided by this author, only one stratigraphic section is indicated, conveying the idea of substantial uniformity along the ca. 100 meters of outcrop. In contrast, the new survey undertaken for this study found a rather diverse stratigraphy of sediments, indicating a rather articulated coastal paleography.

In the part of the beach near Spalmatore, above the red brick granite exposed just below sea level, a layer of well-cemented biogenic calcarenite circa 1.6 m wide is overlain by a 20 cm layer of weakly cemented sand. Above the sand is a well-cemented conglomerate 3.4 m thick. Clasts of varying sizes indicate episodes of differing energy in the conglomerate. The maximum height recorded was ca. 5.5 m asl.

Towards Punta La Mandria, the calcarenite tends to diminish in width before disappearing after 50 m. Nearby, the outcrop appears very different from the first part. The granite is exposed approximately 1.5 m asl, overlain by a layer of large calcareous masses 40 cm thick. This is overlain by a layer of sand 1.6 m thick, with a highly fossiliferous layer with marine mollusks in the upper part. The entire outcrop is covered, at about 5 m asl, by colluvium made up of a heterogeneous sediment containing 1–100 cm calcareous and granite clasts and terrestrial molluscs.

In the fossiliferous sandy layer, the following are very frequent: *Conus mediterraneus, Conus vayssieri, Hexaplex trunculus, Cerithium vulgatum, Cerithium rupestre, Bittium reticulatum, Thais haemastoma, Columbella rustica, Arca noae, Barbatia barbata, Spondylus gaederopus, Loripes lacteus, Pycnodonta squarrosa, Patella ferruginea, Chama gryphina, Venus verrucosa, Chamelea gallina,* and *Tapes sp.* Based on the values and fauna contained, this association is attributed to the Tyrrhenian stage (MIS 5.5, 125 ka BP). The material recovered is not well-preserved, often exhibiting abrasions and fractures. This is probably due to the high energy that accompanied deposition. Both those species connected with the solid substrates and those connected with mobile substrates contributed to the thanatocoenosis. This heterogeneity should be considered in light of a rather diversified environment, probably a seabed partly a mobile substrate and partly a solid substrate, probably formed by clastic sedimentary rock due to the cementation of organogenic debris. The deposit is essentially a thanatoceonosis of molluscs, and organogenic rocks produced by the action of builder organisms, especially bryozoa, serpulidae and calcareous algae. Based on these observations and on the presence of *Conus* and *Patella ferruginea*, this deposit is attributed to the Tyrrhenian (125 ka BP). The highest marine sediments are at 4.5 m asl. The thickness of the deposit does not exceed 5 m. The tidal notches of Tavolara and Capo Figari can therefore be attributed to the Tyrrhenian.

6. Discussion and paleocoastline reconstruction

Several lines of reasoning are used to determine the paleo -sea level of 1500 BP. The value at which wreck R1 was found on the bottom of the port (−35 cm) was corrected in terms of the tide and brought to -1.45 m asl. From this number, ca 40 cm must be subtracted for the functionality: although the ships had an average draught of about 50 cm, the possibility that when they were abandoned their prows were partially beached does not permit exclusion of the possibility that the functional depth was not fully guaranteed. As the ships would not be moored in water shallow enough to cause grounding at low tide, approximately 20 cm must be added to this value. In the meantime we cant exclude that in case of low tide boats could not sink into the mud of 25–30 cm. The combined estimate suggests mean sea level at between −0.85 an −1.15 m asl.

This value is a few centimeters below the predicted sea level curve for Olbia (Lambeck et al., 2011; Fig. 9A). Evidently, this is due to compaction of the sediment. The data establishes that from 1500 BP the coast of this area was tectonically stable.

Comparing the tidal notch values (5 m asl at Capo Figari and 8.50 at Tavolara) with the eustatic sea level value of 125 ka (6 m, Ferranti et al., 2006) also indicates stability. The 3.5 m of difference between Tavolara and Capo Figari are interesting. A few metres over 125 ka is geologically insignificant, but this difference confirms a small degree of mobility related to disturbances analogous to those recorded for the Gulf of Orosei and Capo Caccia, also in Sardinia (Ferranti et al., 2006).

In light of the fact that the area has remained stable, and assuming minimal movement of the sediments loosened at the bottom of Olbia Gulf, it is possible to reconstruct the evolution of the shoreline from 21.5 ka cal BP (Last Glacial Maximum) with a sea level of −130 m for the subsequent time slices of 10, 8, 7, 6 and 4 ka cal BP, as shown in Fig. 10 using the Lambeck model, Lambeck et al., in this issue. Wide palaeocoastline variation is evident, including the formation of Tavolara Island after 8 ka cal BP.

7. Conclusions

Based on the surveys carried out on the numerous wrecked ships found near the port of Olbia, and in particular on the location at which a 5th century AD (1500 BP) ship (R1) was discovered, it was possible to reconstruct the sea level between −0.85 and −1.15 asl. This value is in agreement (with a limited occurrence of sediment compaction) with the predicted sea level curve calculated with the Lambeck model for Olbia (Fig. 9 A).

Some tidal notches carved out of the limestone of Tavolara Island and Capo Figari at values between 5.1 and 8.6 meters were measured and attributed to the Tyrrhenian. Comparing these values with the eustatic value of the Mediterranean Sea, it is possible to establish that Olbia has been stable at least since 125 ka.

Considering the stability of the area, and assuming a minimal quantity of sediment on the seabed, the rising of the sea level from the last ice age (LGM, 21.5 ka cal BP) to the present has been reconstructed, demonstrating large topographic variations.

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