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# $^{14}$C AGE OFFSET IN THE MAR PICCOLO SEA BASIN IN TARANTO (SOUTHERN ITALY) ESTIMATED ON *CERASTODERMA GLAUCUM* (POIRET, 1789)

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**ABSTRACT.** The stratigraphic succession of the Mar Piccolo basin (Gulf of Taranto, Southern Italy) is well known in the scientific literature dealing with the last interglacial since its morphological evolution is influenced by sea level changes during Late Pleistocene-Holocene. The local Holocene sea level history is well known thanks to data deriving from peat and ash layers identified in different sediment cores obtained underwater and in coastal areas. Peat sediments are frequently interlayed with muddy-sand beds rich in *Cerastoderma glaucum* (Poiret, 1789). In the literature of the Mediterranean basin, AMS $^{14}$C dating on *C. glaucum* is widely used also in paleo-environmental reconstruction because this bivalve is considered an useful marker of sea level, though in lagoonal systems, large age offsets have been reported in different areas. Due to the availability of precise chronological and geochronological markers, in order to validate the use of *C. glaucum* in paleo sea level reconstruction, AMS $^{14}$C dating campaign was carried out on this bivalve deriving from several cores drilled in the Mar Piccolo basin and its nearby areas. Nineteen AMS $^{14}$C dating analyses carried out on *C. glaucum* sampled from different sediment cores up to a maximum of 30 m from the seafloor are presented. These results show an inconsistency of the ages in relation to a sea-level rise reconstruction model. The interpretation of the data was performed after the estimation of the local age offset calculated by analyzing six live samples, collected in 2017 in Mar Piccolo and in Croatia, and two samples dated to 1968–1969. The results show that for both the classes of samples (2017 and 1960s) an age offset ranging from 600 to 800 yr can be estimated.

**KEYWORDS:** AMS, *Cerastoderma glaucum*, hardwater reservoir, marine reservoir effect, Taranto.

## INTRODUCTION

Paleoenvironmental and paleo-geographic reconstruction are usually carried out through the analysis of facies on cores, high resolution seismic surveys, geomorphological surveys and related morphostratigraphy and archaeological evidence correlation and interpretation. Radiocarbon ($^{14}$C) measurements play a key role since peat levels or fossil shells sampled in cores allows to properly define evolutionary timescales. The reconstruction of the paleogeographic evolutionary model of the Mar Piccolo semi-enclosed sea basin in Taranto (Southern Italy), has been possible thanks to the availability of these data and in particular to the detailed facies analysis carried out on two cores. All together, they allowed to reconstruct the local Holocene sea level curve (Valenzano et al. 2018a). In this area, sandwiched volcanic ash and peat levels represent chronological constraints providing the timing of the different evolution stages. This is in particular possible thanks to the identification of the "*Pomici di Mercato*" a Vesuvius eruption (dated to ca. 8900 BP) on the base of the geochemical features of the associated tephra layer and to $^{14}$C (AMS) analyses carried out on samples indicative of past sea-level found before and after the tephra sedimentation. In the studied cores, peats are always preceded and overlain, in stratigraphic continuity, by muddy-sands levels characterized by the abundant presence of coupled valves in living position of the bivalve *Cerastoderma glaucum* (Poiret, 1789) and *Corbula gibba* (Olivi, 1792).*C. glaucum* is a benthic filter feeder lamellibranchia that lives in

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waters at various depths tolerating widely fluctuating salinities (Carboni et al. 2010). In low salinity waters, for example, it is found at high depth (Boyden 1971, 1972; Krzyminska 1993; Kandeel et al. 2017).

In particular, in the Mediterranean basin, *C. glaucum*, is associated with lagoons/inner basins environments. It is considered a good sea level marker with maximum 2 m of approximation (i.e., Gravina et al. 1989; Scarponi and Kowalewski 2004; Ferranti et al. 2006; Antonioli et al. 2009; Negri 2009; Pavlopoulos et al. 2009; Di Rita et al. 2011; Primavera et al. 2011; Carboni et al. 2010; Taviani et al. 2014; Lambeck et al. 2018). Indeed, in Mar Piccolo some samples can live up to 5 m depth (as shown by modern surveys) meaning that only a detailed facies analysis of sediment cores allows to safely use them as good sea level markers. Due to the abundance of well preserved and complete specimens of *C. glaucum*, some samples extracted from the Mar Piccolo cores were submitted to $^{14}$C age determinations in order to validate peat and tephra indications. Because of the evident inconsistency between peat/tephra ages and *C. glaucum* ones, an extensive accelerator mass spectrometry (AMS) $^{14}$C dating campaign was then planned and carried out on this taxa. Samples from sediment cores, living specimens from Mar Piccolo and from a bay along the SW side of the Ugljan Island (Croatia), as well as specimens collected in the Mar Piccolo in the 1960s obtained from the collection of the Museum of the Department of Biology of the University of Bari were analyzed.

Indeed, though AMS $^{14}$C dating on *C. glaucum* are widely used in paleo-environmental reconstructions, large age offsets and age incongruity have been reported in different coastal areas of the Mediterranean sea (e.g., Sabatier et al. 2010; Orrù et al. 2014). These offsets can be explained as due to the combination of marine reservoir effect (MRE) and hardwater effect (HWE). The origin and mechanisms originating these effects are quite different. Marine effects are associated with the delayed dissolution and mixing of atmospheric carbon dioxide into the oceans and to the interplay of water circulation phenomena such as the upwelling of $^{14}$C-depleted deep waters. These phenomena result in apparently older ages of marine organisms when compared with coeval organism fixing (radio)carbon from the atmosphere. The difference between the $^{14}$C conventional ages of a marine and a coeval "terrestrial" organism is referred as reservoir age, R(t), which is typically time and location dependent. For the calibration of $^{14}$C ages obtained on marine samples, a marine calibration curve is derived from the atmospheric curve by applying a simple box model and by correcting for local effects by using a $\Delta R$ term defined as the difference between the local reservoir offset and the global value (Stuiver et al. 1998; Reimer et al. 2013). As reference, an average modern pre-industrial reservoir age of 400 yr is assumed while an average $\Delta R = 58 \pm 15$ yr was measured for the Mediterranean basin (Siani et al. 2000; Reimer and McCormac 2002). The origin of the hardwater effect (HWE) is more variable and different phenomena have been identified as responsible for it. Among them, one can consider the dissolution of carbonates of geological origin, the input from sediment rich of old organic matter and the melting of glacier ice (Fernandes et al. 2012). In particular, hardwater offset ages as large as 1200 yr have been reported in lacustrine environments (Zoppi et al. 2001). Indeed, similar phenomena are expected for the studied area, at present corresponding to a semienclosed sheltered sea-basin that is supplied by freshwater flows from karst acquifer hosted in Mesozoic units.

The aim of this study is to estimate the possible presence of $^{14}$C age offset on *C. glaucum* in the Mar Piccolo basin in Taranto, by analyzing modern and living samples. Throughout the paper, we define *age offset* the difference between the $^{14}$C age measured on a *C. Glaucum* specimen

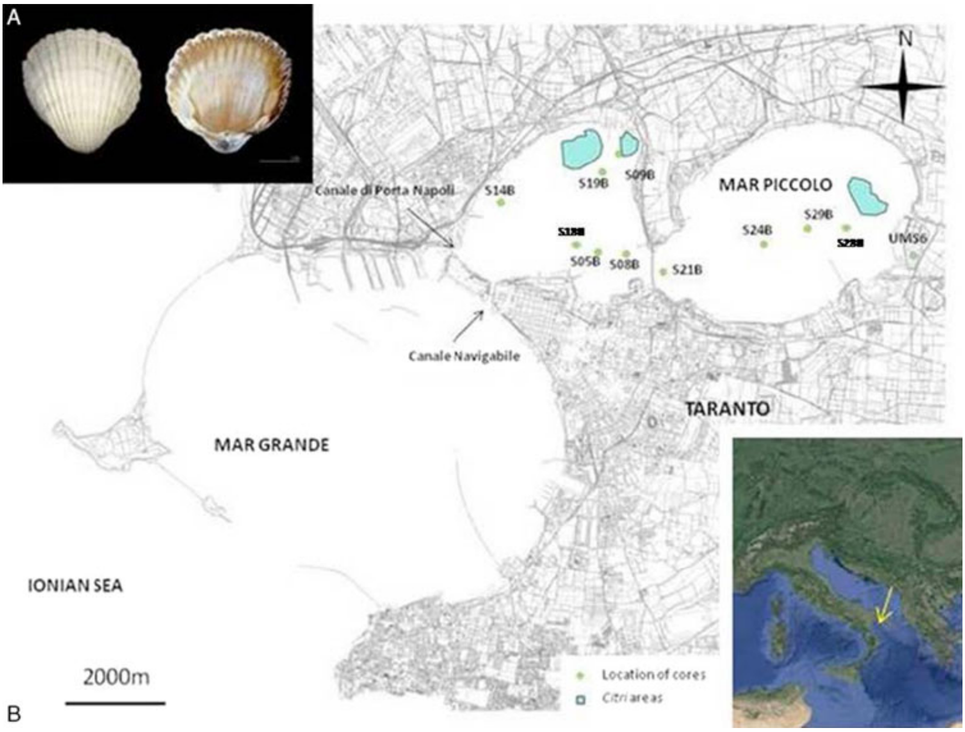

Figure 1 (A) A sample of *C. glaucum* analyzed. (B) The Mar Piccolo basin in Taranto along the Ionian coast of Apulia (Southern Italy) and the location of cores samples (Basemap: Apulian Technical Regional Map).

sampled in the Mar Piccolo in Taranto and the age measured on a coeval marine organism taken in the open sea from the same geographical area. The effect of the measured age offset on the interpretation of sedimentary core sequences obtained from the same area is also highlighted and discussed.

## Geological and Morphological Settings of Mar Piccolo Area

The Mar Piccolo basin (Taranto, Southern Italy) is located on the northern Ionian coast (Figure 1). It is a semi-enclosed sea basin today connected with the Mar Grande and then to Ionian Sea by two channels: the northwestern one, called *Canale di Porta Napoli*, a natural channel today partially filled by human activity, and the eastern one, called *Canale Navigabile*, artificially excavated in the late 19th century (Mastronuzzi et al. 2013).

The stratigraphic succession of the Mar Piccolo basin is represented, from the bottom, by Mesozoic limestone (Calcare di Altamura Fm.) covered in transgression by Upper Pliocene–Lower Pleistocene calcarenite (Calcarenite di Gravina Fm.). The latter passes upwards and laterally, to the interfingered argille subappennine informal unit (Lisco et al. 2016; Valenzano et al. 2018b) (Figure 2).These units are covered by marine terraced deposits. The lowermost overlays the argille subappennine unit and is ascribed to the Last Interglacial Time, corresponding to the Marine Isotope Substage 5.5 (= MIS 5.5; Shackleton 2000) (e.g., Amorosi et al. 2014; Negri et al. 2015). During the following sea

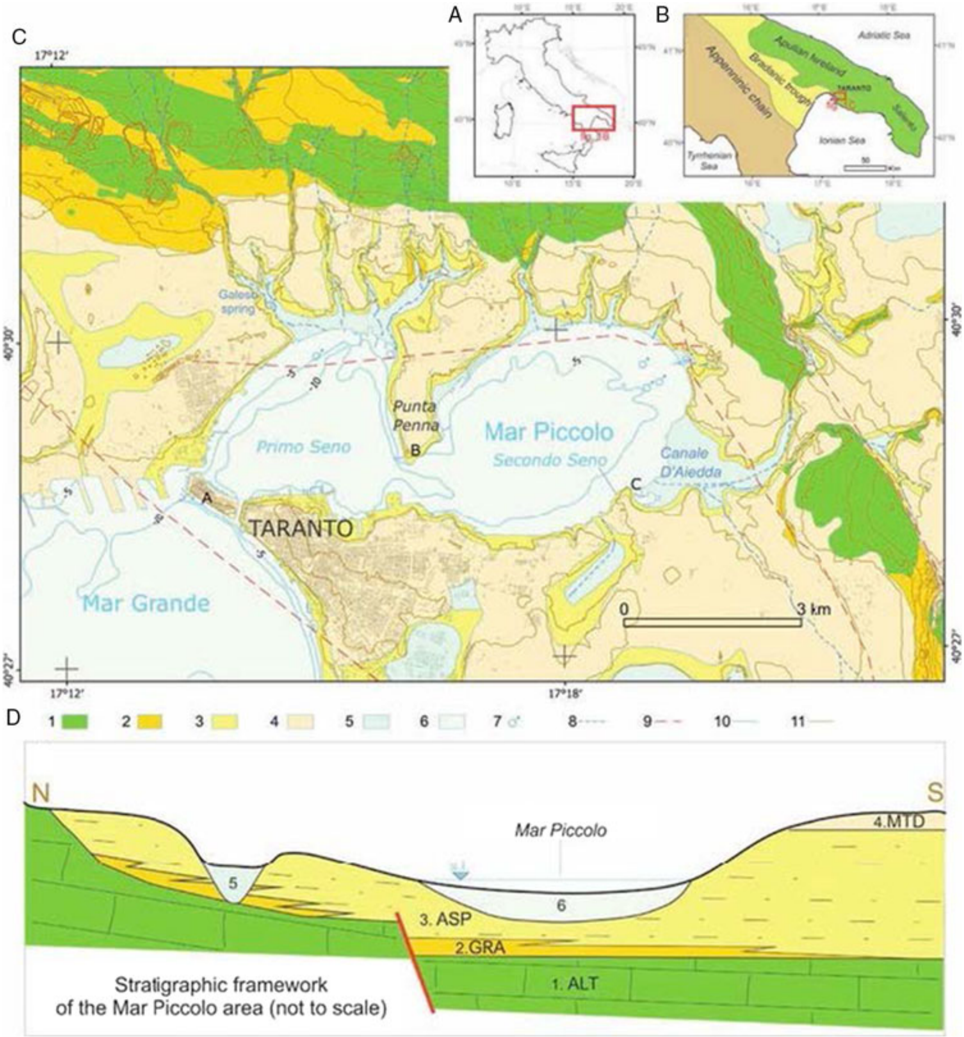

Figure 2 Geological map of the Mar Piccolo basin modified by Valenzano et al. (2018b) after Lisco et al. (2016). (A) and (B) location of the studied area and (C) its geological map:1. Calcare di Altamura Fm (Cretaceous); 2. Calcarenite di Gravina Fm (Upper Pliocene-Lower Pleistocene); 3. Argille subappennine informal unit (Pleistocene); 4. Marine terrace deposits (MIS 5); 5. Alluvial deposits; 6. Holocene marine sediments; 7. Submarine springs; 8. Ephemeral drainage networks; 9. Buried faults; 10. Bathymetric contour, every 5 m; 11. Topographic contour, every 10 m. (D) Stratigraphic sketch of the sedimentary units.

level low stand associated with the global glacial growth, the area today occupied by the Mar Piccolo and the Mar Grande, was incised by a river network that reached, during the Last Glacial Maximum (MIS 2), the past sea level at about 120/140 m below the present one (e.g., Mastronuzzi and Sansò 1998, 2003; Mastronuzzi et al. 2013). The postglacial sea level rise induced the flooding of the river valley that assumed the features of an elongated rias, partially filled by sediments. Indeed, the Mar Piccolo basin was fed mainly by seawater incoming by the present *Canale di Porta Napoli*. In a secondary way, a river catchment

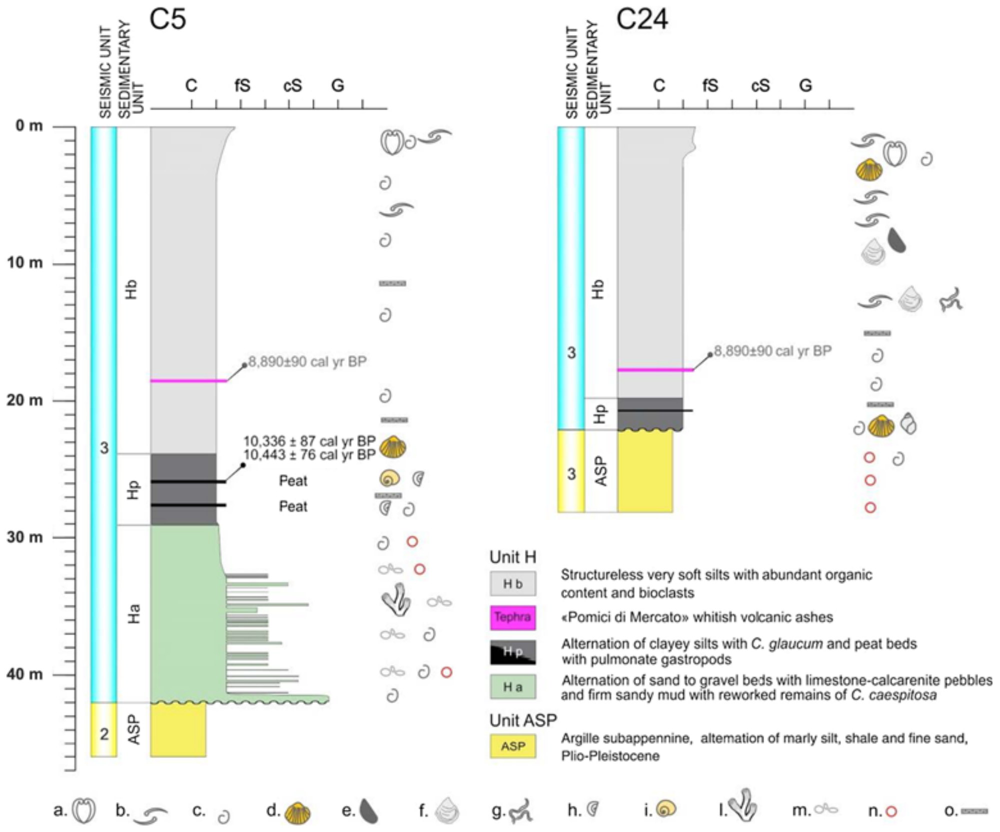

Figure 3 Sedimentary units of cores analyzed by Valenzano et al. (2018a). Key: a. articulated bivalves; b. disarticulated valves; c. unspecified marine mollusc fragments; d. Cerastoderma glaucum; e. Mytilus spp.; f. ostreidae.; g. Polychaeta spp.; h. pulmonate gastropod fragments; i. pulmonate gastropods; l. Cladocora caespitosa fragments; m. carbonatic nodules; n. iron oxides/hydroxides; o. organic matter. Note: The bold black lines indicate peat levels and the bold magenta lines indicate tephra levels. (From Valenzano et al. 2018a.)

shaped on carbonate Mesozoic and Plio-Pleistocenic units, and subaerial and submarine karst springs, nourished by the deep karst water table hosted in the Mesozoic units, supplied the rias of a blend of salt and fresh waters. The process was characterized by two phases. During the first one, from about 15 to 7 ka BP, the fast sea level rise submerged the valley with the formation of beaches and peatlands in the most protected areas; in this phase there was an important contribution of fresh water from springs and tributaries. In the second, with the reduction of the sea level rise at about 7ka BP, and with the stabilization of a warmer, and drier climate, many of the springs were submerged and the waves widened the valley shaping it to the present morphology of an inlets whose flanks are continuously reshaped by wave erosion (Valenzano et al. 2018a).

The reconstruction of Holocene geomorphological evolution has been possible thanks to the availability of 29 different sediment cores drilled in the Mar Piccolo seafloor up to about –50 m from the present mean sea level and by the detailed analysis of two of them (Figure 3). Sandwiched levels of tephra and peat allow to obtain age constraints by mean of $^{14}$C age determinations and geochemical analysis. Moreover, peat levels indicate the past positions of sea level before and after the sedimentation of the tephra layers ascribed to the *Pomici di Mercato* volcanic event, which occurred about 8900 yr BP (Valenzano et al. 2018b). Just above and below the peat levels, massive muddy-sands without any evidence of lamination or reworking are characterized by the abundant presence of *C. glaucum* and *C. gibba*. These dominant taxa are always accompanied by fragments of freshwater lacustrine or continental species, such as *Planorbis*, *Helix, Pomatia* and *Rumina* spp. while brackish/marine species, such as *Bittium reticulatum* (da Costa, 1778) and *Cerithium vulgatum* (Bruguière, 1792) have been found in very low percentages. Anyway they are generally common in eurythermal and euryhaline biocoenoses on hard and/or algal substrata of lagoonal or marine sheltered environments. Taken together, this evidence indicate that the presence of *C. glaucum* in the cores above the peat levels, is connected to sea-level transgression over the peatlands; whereas its presence below the peat levels, is connected to a transgressive muddy-sands above the ravinement surface. Only after a detailed facies analysis, due to its presence in a transgressive system, *C. glaucum* can be used as a marker of sea level. Its presence corresponds to the development of a lagoonal/marine environments characterized by sheltered waters with very low energy.

These paleogeographic features correspond to the present dynamic of the Mar Piccolo which is characterized by a low hydrodynamic and by very slow water circulation, where the exchange velocity with the connected Mar Grande is estimated to be about maximum of 45 days for the eastern part of the basin (De Pascalis et al. 2016).

Today, detailed hydrogeological studies show that the Mar Piccolo basin can be considered a drainage basin for the ground water springs located both along the coast and underwater (locally known as *citri*) (i.e.: Zuffianò et al. 2015; Valenzano et al. 2018b and references therein), influencing the basin salinity whose value is normally around 37 psu (lower than the value of about 38 psu of the close open sea; De Pascalis et al. 2016). In particular, a mean groundwater outflow into the basin was estimated to be as large as $75.2 \times 10^6$ $m^3$ per year (Zuffianò et al. 2015). Chemical analyses also show that groundwater is typically undersaturated with calcite and dolomite produced by Mesozoic and Plio-Pleistocene local geological basement dissolution.

$^{14}$C measurements also shown a large depletion in the $^{14}$C concentration, which was estimated for one of the spring to be 40.3 ± 0.2 pMC (Zuffianò et al. 2015).

## MATERIALS AND METHODS

In this study, 19 AMS $^{14}$C dating analyses were carried out on *C. glaucum* sampled from different sediment cores up to a maximum of 30 m from the seafloor (Figure 1 and Table 1). Only samples in physiological position with coupled valves were selected and analyzed. The presence of *C. glaucum* in physiological position, can be considered typical of eurythermal and euryhaline biocoenoses on hard and/or algal substrata of lagoonal or marine brackish or shallow water sheltered environments (0–2 m), with low hydrodynamism and absence of redeposition, characterized by different types of soft bottoms. When possible, two or three samples were selected from the same position along each core in order to assess the repeatability of the analyses.

Moreover, three samples collected live in 2017 in the same basin and two specimens sampled in the 1960s from the collection of the Museum of the Department of Biology (University of Bari) were used for the estimation of the local age offset in 2017 and 1968–1969. For the 1968–1969 samples, the museum report clearly indicated that the samples were sampled live. Three more

Table 1 $^{14}$C age obtained on fossil Mar Piccolo's samples. Results are calibrated with Calib 7.0.4 software (dataset: Marine13; ΔR:58 ± 15; Siani et al. 2000; Reimer and McCormac 2002).

| | | | | | | Calibrated age (BP) | |
|---|---|---|---|---|---|---|---|
| ID | Coordinates north; east | Sampling depth from sea level (m) | Lab code | $^{14}$C age (BP) | $\delta^{13}$C (‰) | Marine calibration (1σ) | Age offset corrected calibration (1σ) |
| UMS6E 6.29 | 4483572.16; 697148.4 | –6.29 | LTL17326A | 3514 ± 45 | –2 ± 0.7 | 3325 ± 65 | 2487 ± 208 |
| S9BA 0.86 | 4485261.5; 691751.2 | –9.76 | LTL17343A1 | 5458 ± 45 | –7.5 ± 0.5 | 5782 ± 67 | 4950 ± 245 |
| S9BA 0.86 | 4485261.5; 691751.2 | –9.76 | LTL17343A2 | 4871 ± 45 | –10.8 ± 0.3 | 5117 ± 93 | 4134 ± 231 |
| S9BA 0.86 | 4485261.5; 691751.2 | –9.76 | LTL17343A3 | 4894 ± 45 | –9.2 ± 0.2 | 5140 ± 87 | 4162 ± 232 |
| S14BA 0.78 | 4484323; 689636 | –9.88 | LTL17344A1 | 5484 ± 45 | –0.4 ± 0.2 | 5804 ± 63 | 5006 ± 232 |
| S14BA 0.78 | 4484323; 689636 | –9.88 | LTL17344A2 | 5518 ± 45 | –8.1 ± 2 | 5831 ± 63 | 5029 ± 219 |
| S24AB 1.85 | 4483696.84; 694415.09 | –11.05 | LTL17332A2 | 4603 ± 45 | –17.4 ± 0.5 | 4756 ± 66 | 3765 ± 222 |
| S24AB 1.85 | 4483696.84; 694415.09 | –11.05 | LTL17332A1 | 1294 ± 45 | –5.5 ± 0.7 | 778 ± 63 | 250 ± 125 |
| S8BO 21.10 | 4483462; 691928.1 | –33.47 | LTL17318A1 | 10369 ± 80 | 8.1 ± 0.4 | 11358 ± 172 | 10448 ± 248 |
| S8BO 21.10 | 4483462; 691928.1 | –33.47 | LTL17318A3 | 11437 ± 80 | 6 ± 0.7 | 12835 ± 100 | 12027 ± 385 |
| S28AO 21.13 | 4483997.9; 695199.8 | –33.53 | LTL17321A3 | 10327 ± 80 | 7.1 ± 0.4 | 11269 ± 118 | 10416 ± 247 |
| S28AO 21.13 | 4483997.9; 695199.8 | –33.53 | LTL17321A2 | 9943 ± 65 | 3.5 ± 0.8 | 10830 ± 114 | 9913 ± 247 |
| S28AO 21.13 | 4483997.9; 695199.8 | –33.53 | LTL17321A1 | 9818 ± 50 | 0.8 ± 0.5 | 10655 ± 72 | 9757 ± 239 |
| S21AP 22.23 | 4483159.37; 692605.21 | –35.53 | LTL17320A1 | 13297 ± 85 | 1.9 ± 0.7 | 15303 ± 148 | 14020 ± 331 |
| S21AP 22.23 | 4483159.37; 692605.21 | –35.53 | LTL17320A2 | 13318 ± 85 | –11.7 ± 0.4 | 15339 ± 151 | 14070 ± 345 |
| S5BQ 24.20 | 4483480.6; 691418.5 | –37.15 | LTL17184A | 12912 ± 85 | –1.1 ± 0.5 | 14550 ± 254 | 13585 ± 215 |
| S5BQ 24.20 | 4483480.6; 691418.5 | –37.15 | LTL17316A | 12967 ± 80 | 4.4 ± 0.5 | 14750 ± 250 | 13635 ± 215 |
| S18BR 25,47 | 4484912.9; 691458 | –37.87 | LTL17319A1 | 13342 ± 100 | 5.7 ± 0.1 | 15389 ± 169 | 14131 ± 378 |
| S18BR 25,47 | 4484912.9; 691458 | –37.87 | LTL17319A2 | 12686 ± 80 | –2.4 ± 0.2 | 14118 ± 131 | 13360 ± 212 |

Table 2 Results obtained on museum and 2017 samples.

| Sampling year | Provenance | Lab code | $^{14}$C content (pMC) | $\Delta^{14}$C (‰) |
|---|---|---|---|---|
| 1968–1969 | Taranto | LTL17335A2 | 98.41 ± 0.49 | −18.0 ± 4.9 |
| 1968–1969 | Taranto | LTL17335A2 | 98.52 ± 0.55 | −16.9 ± 5.5 |
| 2017 | Taranto | LTL17609A1 | 98.49 ± 0.55 | −23.0 ± 5.5 |
| 2017 | Taranto | LTL17609A2 | 96.94 ± 0.54 | −38.4 ± 5.4 |
| 2017 | Taranto | LTL17609A3 | 96.21 ± 0.54 | −45.7 ± 5.4 |
| 2017 | Croatia | LTL17610A | 103.03 ± 0.55 | 22.0 ± 5.5 |
| 2017 | Croatia | LTL17610B | 101.56 ± 0.55 | 7.4 ± 5.5 |
| 2017 | Croatia | LTL17610C | 101.64 ± 0.54 | 8.2 ± 5.4 |

Figure 4 (A1 and A2) Location of Croatian samples (Basemap: Google Satellite) and (B) the bay of sampling. (Photo by Paul Leber from Panoramio—Google Earth).

samples collected alive in a bay along the SW side of the Ugljan Island (Croatia) (Figure 4) were submitted to the same analysis (Table 2). Samples derive from the innermost part of an open bay protected by strong winds, but characterized by a continuous change of water with the near deep Adriatic sea. Here *C. glaucum* live up to a depth of about 1 m in a muddy-sandy bottom in association with algae and gastropods like *C.vulgatum* and *B. reticulatum*.

Samples were processed at the chemical laboratories of CEDAD (Centre for Applied Physics, Dating and Diagnostics), Department of Mathematics and Physics "*Ennio de Giorgi*" University of Salento in Lecce (Italy). After a preliminary observation at the optical microscope, they were treated with $H_2O_2$ to remove the uppermost layer and then converted to $CO_2$ by acid hydrolysis with $H_3PO_4$. Extracted carbon dioxide was then reduced to graphite at 600°C with high purity hydrogen on Fe powder (Calcagnile et al. 2004, 2005).

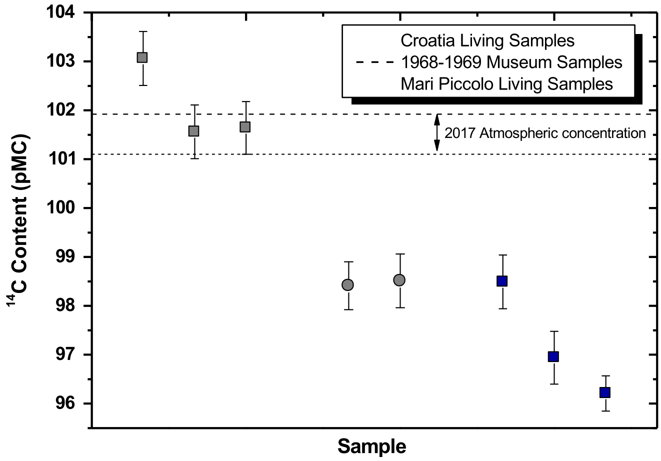

Figure 5 $^{14}$C concentrations measured for the modern samples. The atmospheric $^{14}$C concentration as derived from Hammer and Levin (2017) is given for comparison. The range takes into account the seasonal variability.

AMS measurements were carried out at CEDAD using the $^{14}$C beamline installed on the 3 MV Tandetron accelerator (Mod. 4130 HC by High Voltage Engineering Europa BV). IAEA (International Atomic Energy Agency) C6 (sucrose) samples were used for normalizing the measured $^{14}$C/$^{12}$C isotopic ratios. The measured isotopic ratios were corrected for isotopic mass fractionation by using the $\partial^{13}$C term measured on line with the accelerator and for machine and sample processing background estimated by measuring IAEA C1 samples (Carrara Marble), completely depleted in $^{14}$C, using the same processing used for the samples. $^{14}$C ages (in yr BP: before present, 1950 AD) and $^{14}$C content (in pMC = percent modern carbon) were then calculated according to Stuiver and Polach (1977).

## RESULTS AND DISCUSSION

The data obtained for the samples collected in 1968–1969 and collected live in Taranto and Croatia are shown in Figure 5 and summarized in Table 2. In the same Figure, the 2017 atmospheric concentration estimated from the Hammer and Levin (2017) data is also shown as a range which includes the seasonal variability. It can be observed that the samples collected in Taranto (both the 1968–1969 and 2017 ones) have $^{14}$C concentrations below 100 pMC. In order to correctly interpret these data, the current available literature data on $^{14}$C distribution across the Mediterranean basin were considered.

For the Western Mediterranean basin, in the Ligurian subbasin, a significant uptake of bomb $^{14}$C was measured in the period between 1953 and 1963 with $\Delta^{14}$C value above zero after 1961–1962. In particular in the period between 1963 and 2000, $\Delta^{14}$C values ranging between 50 and 90‰ were measured with the maximum value of 90 ‰ reached in 1972 on the coral *Cladocora caespitosa* (Linnaeus 1767; Tisnérat-Laborde et al. 2013). Indeed, a significant variability has to be expected between different locations across the Mediterranean which has been recently well simulated by high resolution regional models which predicts for the Ionian Sea in the Taranto region $\Delta^{14}$C values higher than for the Ligurian Basin (Ayache et al. 2017).

According to the output of these models, calculated in Ayache et al. 2017 for the year 1977, we assumed a $\Delta^{14}C = 90 \pm 10‰$ for Taranto in 1968–1969.

For the estimate of the present-day expected $^{14}C$ concentration in the Taranto surface water we used recent data obtained for the Mediterranean surface water obtained in 2011 during the R/V Meteor MT84_3 Mediterranean Sea Cruise (Tanhua et al. 2012, 2013). The closest data point available from these data set is $\Delta^{14}C \approx 44$ ‰for the open Ionian Sea. This value is consistent with the output of the high resolution regional model by Ayache et al. (2017) and predicting for the Taranto area a slightly higher $\Delta^{14}C$ of about 65 ± 5‰ (Ayache et al. 2017). Considering a decreasing rate of the $^{14}C$ concentration of ≈2‰ per year this would correspond to an expected value for Taranto in 2017 of 53 ± 5‰. The results obtained for both the 1968–1969 and the 2017 samples clearly indicate a local depletion of the $^{14}C$ concentration since the measured values are significantly lower than the expected one.

In order to analyze the results obtained for the Croatian samples, the data published by Macchia et al. (2013) were considered. In this case the $^{14}C$ in DIC (Dissolved Inorganic Carbon) extracted from sea water in 2010 obtained from Northern Adriatic surface water correspond to a $\Delta^{14}C = 31.8 \pm 2.7‰$. In this case, the 2017 value of 17.8‰ was derived from the 2011 data by considering a decline rate of 2‰ per year.

In particular, the two samples from Mar Piccolo gave statistically consistent results with an average $\Delta^{14}C = -17.5 \pm 0.8‰$ which is much lower than the expected value of 90‰ estimated above.

In addition, the 2017 samples from Mar Piccolo show a significant depletion in the $^{14}C$ content with all the measured values below 0‰. For these samples, an average $^{14}C$ content corresponding to $\Delta^{14}C = -37.5 \pm 11.5‰$ can be estimated, where the uncertainty was estimated as scattering of the three data points.

The average $^{14}C$ concentration for the Croatian samples corresponds to 12.5 ± 8.2‰ which overlaps within one standard deviation with the value of 17.8‰ expected for 2017.

We also observe here that the average $^{14}C$ concentration measured for the Croatian samples corresponds to 102.1 ± 0.8 which overlaps within one standard deviation with the 2017 atmospheric concentration ~101.5 estimated on the base of the data by Hammer and Levin (Hammer and Levin 2017). The results obtained on these samples can be easily explained by the particular local geomorphological and hydrological features. The bay is shaped in a Mesozoic rocky body but: (1) no river supply is present, (2) no important underwater springs are present, and (3) it is characterized by a continuous exchange of deep water. Our data then indicate a significant offset in the $^{14}C$ ages for the *C. glaucum* specimens sampled in 2017 and 1968–1969 in Taranto which is not detected (at least within the level of uncertainty achievable in this study) for the Croatia samples. This seems to point towards a site-dependent aging effect more than to a phenomenon dependent on the species (for instance related to the feedings habits).

The magnitude of the age offset has been estimated according to Coularis et al. (2016) and Keaveney and Reimer (2012) as:

$$R_{year} = -8033 \ln\left(\frac{F^{14}C_{Taranto,year}}{F^{14}C_{ref,year}}\right)$$

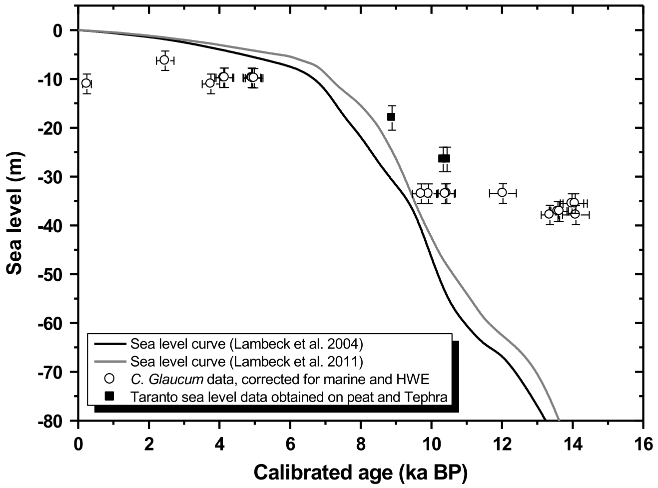

Figure 6 Results obtained on fossil samples from the mar Piccolo cores in comparison with sea level model curves elaborated by Lambeck et al. (2004, 2011).

Where $F^{14}C_{\text{Taranto,year}}$ corresponds to the $^{14}C$ concentration measured for the Taranto samples either in 2017 or 1968–1969 and $F^{14}C_{\text{ref,year}}$ is the corresponding reference value for the same year estimated as described above. In this way, the local age offset effect was estimated to be 642 ± 100 yr for 2017 and 820 ± 100 yr for 1968–1969. These values overlap between each other and indicate and average offset age of 730 ± 125 yr.

The origin of this age offset, which has to be considered additional to the marine reservoir effect, is probably found in the presence of hardwater flows of karst origin.

The results obtained for the sediment core samples are given in Table 1. The obtained conventional $^{14}C$ ages have been then calibrated to calendar ages by using the Marine13 curve and a ΔR value of 58 ± 15 yr (Siani et al. 2000; Reimer and McCormac 2002). In the same table, we also list the calibrated ages obtained after correcting for the age offset estimated for the modern samples. In Figure 6, the data obtained, corrected for both the marine and the hardwater effects by using the value estimated for the modern samples, are plotted as a function of their depth.

In Valenzano et al. (2018a), in order to reconstruct the Taranto area paleo-environmental evolution, two time-constraints were identified in the same cores containing *C. glaucum* analyzed in this study. They were a peat level, immediately preceded and overlayed by levels containing C. Glaucum (Figure 3), (which can be considered a good sea level marker) at –26.5 ± 2.5 m and a tephra level at –18.5 m attributed to the "*Pomici di Mercato*". For the first one, two consistent $^{14}C$ dates, obtained on atmospheric samples, are available to 9188 ± 75 (LTL17186A and LTL17186B) and 9255 ± 75 BP which can be calibrated to 10,336 ± 87 and 10407 ± 110 cal BP. Tephra level is dated to 8890 ± 90 cal BP (Figure 3). It was found at a mean depth of –32.4 m msl (19 m bsb), suggesting that it deposited in a very shallow basin (at a depth of about 6–7 m); its use in the present study can be considered only for chronological purposes. When these data (black squares in

Figure 6) are compared with the available sea level rise curves (Lambeck et al. 2004, 2011; gray and black curves in Figure 6) different considerations can be made.

Data derived from the use of the peat levels indicate a very slow uplift that is in agreement to that already known for the area of Taranto and corresponding to about 0.128 mm/yr (Mastronuzzi et al. 2017, 2018). On the other hand, for this part of the Mediterranean basin no other deterministic sea level curves are available except for Sibari (Ferranti et al. 2011; Cafaro et al. 2013). Unfortunately, the plain of Sibari corresponds to a semigraben in the Appenine chain (Ferranti et al. 2011; Cafaro et al. 2013), which means that a direct correlation between the curve extrapolated for the Appenine Chain (Sibari) and another for the stable foreland (Taranto) is not possible.

When comparing the data obtained for the *C. glaucum* samples (after correcting them for both the marine and hardwater effects) with the available sea level rise curves, two different time ranges have to be considered. The most recent samples, dated between ~10 ka BP to the present, shows results which are in acceptable agreement with the Lambeck curve. On the other hand, the samples extracted from the lower levels give inconsistent data: their age is essentially not related to the sampling position. In particular, they gave $^{14}$C ages significantly older than expected.

The observed differences between the upper and lower level can be explained when considering the evolution of the Mar Piccolo Basin. According to Valenzano et al. (2018a), the Mar Piccolo evolution can be interpreted as result of erosional and depositional processes in transitional low-energy settings of an incised-valley system during last sea-level cycle, due to the interplay of fluvial incisions and reduced magnitude wave-tide action.

This means that when the oldest specimens lived, the Mar Piccolo had the characteristics of a rias, fed mainly by fresh water rich of fossil calcium carbonate dissolved in the groundwater deriving from the dissolution of Murge limestones, coming from karst springs and from streams of Murge, giving rise to a significantly larger hardwater effect.

## CONCLUSIONS

Samples of *C. glaucum* from the Mar Piccolo basin, Ionian Sea, Southern Italy, were submitted to AMS $^{14}$C dating analyses. Both fossil samples, selected from sediment cores and modern, post bomb samples were dated. The modern samples were both collected live in 2017 and obtained from museum collections. The obtained $^{14}$C results show a significant offset towards older $^{14}$C ages. The aging effect, additional to the marine one, is estimated to be 730 ± 125 yr. The comparison of the data obtained on the Taranto samples with those obtained on *C. glaucum* samples collected live in the NorthernAdriatic sea suggests that the measured effect is related to the site and not to the specie. The most probable explanation of the effect is related to the presence in the studied basin of hardwater flows, which are depleted in $^{14}$C as the results of the dissolution of carbonate rocks of geological age.

The results obtained on known-age samples of *C. glaucum* allowed to better explain, the data obtained from samples extracted from sediment core. Indeed the comparison of the data obtained on *C. glaucum* with reference sea-level rise curves point towards a time dependency of the measured offset effect.

The results of the analysis performed on these mollusca coming from this area indicate that *C. glaucum* is not always a suitable $^{14}$C samples for sea-level rise studies. To use it as good indicator of sea level marker, it is necessary that (1) its meaning as sea level markers should be assessed through a preliminary facies analysis and (2) any possible age offset on $^{14}$C determination can be excluded.

This study confirms the importance of a detailed knowledge of the sources of carbon for the organisms which are submitted to $^{14}$C dating analyses as already proved previously for other mollusca as for example the continental gastropod *Helix* sp. (Quarta et al. 2007; Mastronuzzi and Romaniello 2008; Romaniello et al. 2008).

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## REFERENCES

Amorosi A, Antonioli F, Bertini A, Marabini S, Mastronuzzi G, Montagna P, Negri A, Rossi V, Scarponi D, Taviani M, Angeletti L, Piva A, Vai GB. 2014. The middle-upper Pleistocene Fronte section (Taranto, Italy): an exceptionally preserved marine record of the last interglacial. Global and Planetary Change 119:23–38.

Antonioli F, Ferranti L, Fontana A, Amorosi A, Bondesan A, Braitenberg C, Dutton A, Fontolan G, Furlani S, Lambeck K, Mastronuzzi G, Monaco C, Spada G, Stocchi P. 2009. Holocene relative sea-level changes and tectonic movements along the Italian coastline. Quaternary International 206:102–133.

Ayache M, Dutay JC, Mouchet A, Tisnérat-Laborde N, Montagna P, Tanhua T, Siani G, Jean-Baptiste P. 2017. High-resolution regional modelling of natural and anthropogenic radiocarbon in the Mediterranean Sea. Biogeosciences 14:1197–1213.

Boyden CR. 1971. A comparative study of the reproductive cycles of the cockles *Cerastoderma edule* and *C. Glaucum*. Journal of the Marine Biological Association of the United Kingdom 51:605–622.

Boyden CR. 1972. The behaviour, survival and respiration of the cockles Cerastoderma edule and C. Glaucum in air. Journal of the Marine Biological Association of the United Kingdom 52:661–680.

Cafaro F, Cotecchia F, Lenti V, Pagliarulo R. 2013. Interpretation and modelling of the subsidence at the archaeologicalsite of Sybaris (Southern Italy). In: Bilotta E, Flora A, Lirer S, Viggiani C, editors. Geotechnical engineering for the preservation of monuments and historic sites. Boca Raton (FL): CRC Press. p. 199–206.

Calcagnile L, Quarta G, D'Elia M, Rizzo A, Gottdang A, Klein M, Mous DJW. 2004. A new accelerator mass spectrometry facility in Lecce, Italy. Nuclear Instruments and Methods in Physics Research 223–224:16–20.

Calcagnile L, Quarta G, D'Elia M. 2005. High resolution accelerator-based mass spectrometry: precision, accuracy and background. Applied Radiation and Isotopes 62(4): 623–629.

Carboni MG, Bergamin L, Di Bella L, Esu D, Pisegna Cerone E, Antonioli F, Verrubbi V. 2010. Palaeoenvironmental reconstruction of late quaternary foraminifera and molluscs from the ENEA borehole (Versilian plain, Tuscany, Italy). Quaternary Research 74:265–276.

Coularis C, Tisnérat-Laborde N, Pastor L, Siclet F, Fontugne M. 2016. Temporal and spatial variations of freshwater reservoir ages in the Loire river watershed. Radiocarbon 58(3): 549–563.

De Pascalis F, Petrizzo A, Ghezzo M, Lorenzetti G, Manfè G, Alabiso G, Zaggia L. 2016. Estuarine circulation in the Taranto seas. Environmental Science Pollution Research 23:12515–12534.

Di Rita F, Simone O, Caldara M, Gehreles RW, Magri D. 2011. Holocene environmental changes in the coastal Tavoliere Plain (Apulia, southern Italy): a multiproxy approach. Palaeogeography, Palaeoclimatology, Palaeoecology 310:139–151.

Fernandes R, Bergemann S, Hartz S, Grootes PM, Nadeau MJ, Melzner F, Rakowski A, Hüls M. 2012. Mussel with meat: bivalve tissue-shell radiocarbon ages differences and archaeological implications. Radiocarbon 54(3–4):953–965.

Ferranti L, Antonioli F, Mauz B, Amorosi A, Dai Pra G, Mastronuzzi G, Monaco C, Orrù P, Pappalardo M, Radtke U, Renda P, Romano P, Sansò P, Verrubbi V. 2006. Markers of the last interglacial sea level high stand along the coast of Italy: tectonic implications. Quaternary International 145–146:30–54.

Ferranti L, Pagliarulo R, Antonioli F, Randisi A. 2011. "Punishment for the sinner": Holocene episodic subsidence and steady tectonic motion at ancient Sybaris (Calabria, Southern Italy). Quaternary International 232:56–70.

Gravina MF, Ardizzone GD, Scaletta F,Chimenz C. 1989. Descrptive analysis and classification of benthic communities in some Mediterranean coastal lagoons (central Italy). Marine Ecology 10(2):141–166.

Hammer S, Levin I. 2017. Monthly mean atmospheric $\Delta^{14}CO_2$ at Jungfraujoch and Schauinsland from 1986 to 2016. heiDATA V2. Available from: https://heidata.uni-heidelberg.de/dataset.xhtml?persistentId=doi:10.11588/data/10100

Kandeel EK, Saad ZM, Afaf MM, Marwa EA. 2017. Population dynamics of the cockle cerastoderma glaucum. A comparison between Lake Qarun and Lake Timsah, Egypt. Turkish Journal of Fisheries and Acquatic Sciences 17:945–958.

Keaveney EM, Reimer PJ. 2012. Understanding the variability in freshwater reservoir offsets: a cautionary tale. Journal of Archaeological Science 39:1306–1316.

Krzyminska J. 1993. The distribution of *Cerastoderma glaucum* (Poiret), *Macoma balthica* (Linnaeus), *Mya arenaria* (Linnaeus) and *Mytilus edulis* (Linnaeus), in Holocene bottom sediements of the southern Baltic Sea. Scripta Geologica – Special Issues 2:269–273.

Lambeck K, Antonioli F, Anzidei M, Ferranti L, Leoni G, Scicchitano G, Silenzi S. 2011. Sea level change along the Italian coast during the Holocene and projections for the future. Quaternary International 232:250–257.

Lambeck K, Antonioli F, Purcell A, Silenzi S. 2004. Sea-level change along the Italian coast for the past 10, 000 yr. Quaternary Science Reviews 23:1567–1598.

Lambeck K, Anzidei M, Antonioli F, Benini A, Verrubbi V. 2018. Tyrrhenian sea level at 2000 BP: evidence from Roman age fish tanks and their geological calibration. Rendiconti Lincei 29:69–80.

Lisco S, Corselli C, De Giosa F, Mastronuzzi G, Moretti M, Siniscalchi A, Marchese F, Bracchi V, Tessarolo C, Tursi A. 2016. Geology of Mar Piccolo, Taranto (Southern Italy): the physical basis of remediation of a polluted marine area. Journal of Maps 12:173–180.

Macchia M, D'Elia M, Quarta G, Gaballo V, Braione E, Maruccio L, Calcagnile L, Ciceri G, Martinotti V, Wacker L. 2013. Extraction of dissolved inorganic carbon (DIC) from seawater samples at CEDAD: Results of an intercomparison excercise on samples from Adriatic shallow water. Radiocarbon 55(2–3): 579–584.

Mastronuzzi G, Romaniello L. 2008. Holocene aeolian morphogenetic phases in Southern Italy: problems in $^{14}C$ age determinations using terrestrial gastropods. Quaternary International 183:123–134.

Mastronuzzi G, Sansò P. 1998. Morfologia e genesi delle Isole Chéradi e del Mar Grande (Taranto, Puglia, Italia). Geografia Fisica e Dinamica Quaternaria 21:131–138.

Mastronuzzi G, Sansò P. 2003. Quaternary coastal morphology and sea level changes. Field Guide. Puglia 2003, Final Conference– Project IGCP 437 UNESCO - IUGS, Otranto / Taranto– Puglia (Italy) 22–28 September 2003, GI2S Coast– Gruppo Informale di Studi Costieri, Research Publication 5. Taranto: Brizio srl. p. 184.

Mastronuzzi G, Boccardi L, Candela AM, Colella C, Curci G, Giletti F, Milella M, Pignatelli C, Piscitelli A, Ricci F, Sansò P. 2013. Il Castello Aragonese di Taranto in 3D nell'evoluzione del paesaggio naturale. Bari: DIGILABS. p. 171.

Mastronuzzi G, Antonioli F, Anzidei M, Auriemma R, Alfonso C, Scarano T. 2017. Evidence of relative sea level rise along the coast of central Apulia (Italy) during late Holocene from maritime archeological indicators. Quaternary International 439:65–78.

Mastronuzzi G, Antonioli F, Anzidei M, Bruckner H, De Martini PM, Ferranti L, Monaco C, Moretti M, Pagliarulo R, Scicchitano G, Smedile A, De Giosa F, Fago P, Lisco S, Lo Presti V, Pignatelli C, Milella M, Piscitelli A, Scardino G, Spampinato CR, Valenzano E. 2018. Crossing Southern Italy: a travelling meeting from Taranto to Siracusa. Taranto - Siracusa (Italy), 16–23 September 2018. Bari: Digilabs s.r.l. p. 108.

Negri A, Amorosi A, Antonioli F, Bertini A, Florindo F, Lurcock PC, Marabini S, Mastronuzzi G, Regattieri E, Rossi V, Scarponi D, Taviani M, Zanchetta G, Vai GB. 2015. A potential Global Stratotype Section and Point (GSSP) for the Tarentian stage, upper Pleistocene: work in progress. Quaternary International 383:145–157.

Negri PM. 2009. An experimental mapping method by means of fossil mollusk faunas: the Holocene Thai paleogulf. Bollettino della Società Paleontologica Italiana 48(1):41–50.

Orrù PE, Mastronuzzi G, Deiana G, Pignatelli C, Piscitelli A, Solinas E, Spanu PG, Zucca R. 2014. Sea level changes and geoarchaeology between Malfatano Bay and Piscinnì Bay (SW Sardinia) in the last 4 ky. Quaternary International 336:180–189.

Pavlopoulos K, Triantaphyllou M, Karkanas P, Kouli K, Syrides G, Vouvalidis K, Palyvos N, Tsourou T. 2009. Paleoenvironmental evolution and prehistoric human environment, in the embayment of Palamari (Skyros Island, Greece) during middle-late Holocene. Quaternary International 216:41–53.

Primavera M, Simone O, Fiorentino G,Caldara M. 2011. The palaeoenviornmental study of the Alimini Piccolo lakes enables a reconstruction of Holocene sea level changes in southeast Italy. The Holocene 21(4):553–563.

Quarta G, Romaniello L, D'Elia M, Mastronuzzi G, Calcagnile L. 2007. Radiocarbon ages anomalies in pre- and post-bomb land snails from the coastal area of the Mediterranean basin. Radiocarbon 49(2):817–826.

Reimer P, McCormac F. 2002. Marine radiocarbon reservoir corrections for the Mediterranean and Aegean Seas. Radiocarbon 44(1):159–166

Reimer PJ, Bard E, Bayliss A, Beck JW, Blackwell PG, Bronk Ramsey C, Buck CE, Cheng H, Edwards RL, Friedrich M, Grootes PM, Guilderson TP, Haflidason H, Hajdas I, Hatté C, Heaton TJ, Hoffmann DL, Hogg AG, Hughen KA, Kaiser KF, Kromer B, Manning SW, Niu M, Reimer RW, Richards DA, Scott EM, Southon JR, Staff RA, Turney CSM, van der Plicht J. 2013. IntCal13 and Marine13 radiocarbon age calibration curves 0–50, 000 years cal BP. Radiocarbon 55(4):1869–1887.

Romaniello L, Quarta G, Mastronuzzi G, D'Elia M, Calcagnile L. 2008. $^{14}$C age anomalies in modern land snails shell carbonate from Southern Italy. Quaternary Geochronology 3:68–75. doi: 10.1016/j.quageo.2007.01.006.

Sabatier P, Dezileau L, Blanchemanche P, Siani G, Condomines M, Bentaleb I, Piquès G. 2010. Holocene variations of radiocarbon reservoir ages in a Mediterranean lagoonal system. Radiocarbon 52(1):91–102.

Scarponi D, Kowalewski M. 2004. Stratigraphic paleoecology: bathymetric signatures and sequence overprint of mollusk associations from upper Quaternary sequences of the Po Plain, Italy. Geology 32:989–992.

Shackleton NJ. 2000. The 100, 000-year ice-age cycle identified and found to lag temperature, carbon dioxide, and orbital eccentricity. Science 289(5486):1897–1902.

Siani G, Paterne M, Arnold M, Bard E, Mativier B, Tisnerat N, Bassinot F. 2000. Radiocarbon reservoir ages in the Mediterranean Sea and Black Sea. Radiocarbon 42(2):271–280.

Stuiver M, Polach HA. 1977. Discussion: reporting of $^{14}$C data. Radiocarbon 19(3) 355–363.

Stuiver M, Reimer PJ, Braziunas TF. 1998. High precision radiocarbon age calibration for terrestrial and marine samples. Radiocarbon 40(3):1127–1151.

Tanhua T, Alvarez M, Mintrop L, McNichol A, Key R. 2012. Carbon Dioxide, Hydrographic, and Chemical Data Obtained During the R/V Meteor MT84_3 Mediterranean Sea Cruise (April 5-April 28, 2011). Oak Ridge, Tennessee: Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy. doi: 10.3334/CDIAC/OTG.CLIVAR_06MT20110405. http://cdiac.ornl.gov/ftp/oceans/CLIVAR/Met_84_3_Med_Sea/

Tanhua T, Hainbucher D, Cardin V, Alvarez M, Civitarese G, McNichol AP, Key RM. 2013. Repeat hydrography in the Mediterranean Sea, data from the Meteor cruise 84/3 in 2011. Earth System Science Data 5–2:289–294.

Taviani M, Angeletti L, Çağatay MN, Gasperini L, Polonia A, Wesselingh FP. 2014. Sedimentary and faunal signatures of the post glacial marine drowning of the Pontocaspian Gemlik "lake" (Sea of Marmara). Quaternary International 345:11–17.

Tisnérat-Laborde N, Montagna P, McCulloch M, Siani G, Silenzi S, Frank N. 2013. High resolution coral based $\Delta^{14}$C record of surface water process in the western Mediterrenean Sea. Radiocarbon 55(2–3):1617–1630.

Valenzano E, Scardino G, Cipriano G, Fago P, Capolongo D, De Giosa F, Lisco S, Mele D, Moretti M, Mastronuzzi G. 2018a. Holocene morpho-sedimentary evolution of the Mar Piccolo Basin (Taranto, Southern Italy). Geografia Fisica e Dinamica Quaternaria 41:119–135.

Valenzano E, D'Onghia FM, De Giosa F, Demonte P. 2018b. Morfologia delle sorgenti sottomarine dell'area di Taranto, mar Ionio, Inventario ad ampia scala delle emissioni fluide sommerse. Memorie Descrittive della Carta Geologica d'Italia (accepted).

Zoppi U, Albani A, Ammerman AJ, Hua Q, Lawson EM, Serandrei Barbero R. 2001. Preliminary estimate of the reservoir age in the Lagoon of Venice. Radiocarbon 43(2A): 489–494.

Zuffianò LE, Basso A, Casarano D, Dragone V, Limoni PP, Romanazzi A, Santaloia F, Polemio M. 2015. Coastal hydrogeological system of Mar Piccolo (Taranto, Italy). Environmental Science and Pollution Research 23(13):1–13.