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Evidence of relative sea level rise along the coasts of central Apulia (Italy) during the late Holocene via maritime archaeological indicators

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A B S T R A C T

We investigated archaeological sites located along the coasts of central Apulia (Italy) to estimate the relative sea level changes which have occurred in this region since the Bronze Age, and test the most recent model of predicted sea level for this region. Surveys focused on six sites located on both the Adriatic and Ionian coasts of Apulia at the feet of the carbonatic Murge plateau, a tectonically stable zone as of the last 125 ka. The sites present the remains of ancient settlements, ranging from the Bronze Age (circa II millennium BC), to the Messapian and Magna Grecia Age (c. 2.5 ka BP), the Roman (c. 2 ka BP) and Middle Ages (c. 1 ka BP). The archaeological sea level markers investigated in these sites provided new insight into the history of the relative sea level changes which have occurred in this region during the last c. 3.3 ka BP. Data from 17 archaeological settlements from the above-mentioned sites, placed above or below the present sea level, were analyzed. The intervening relative sea level changes successive to their construction were estimated via the submergence of the functional elevations of significant architectural features related to the mean sea level at the time during which the settlements were functioning. The r.s.l. changes were estimated using detailed topographic surveys, tide analyses and/or hydrodynamic equations. Although not all archaeological markers allowed univocal interpretations, r.s.l. rise at about 2.25 ± 0.20 m as of the Bronze Age, and at least 0.90 ± 0.20 m in the last 2.0/1.5 ka was estimated. A comparison between the elevation of the marker and two different predicted sea level models seems to confirm a tectonic stability of the investigated region in the last c. 3.3 ka BP.

1. Introduction

The coasts of the Mediterranean Sea have been inhabited ever since prehistoric times, and still preserve evidence of ancient maritime installations and coastal settlements that all together testify the widespread occupation of the coastal areas, including those of Apulia. These archaeological sites can be used as indicators of the intervening sea level changes occurring after their construction; fortified coastal villages of the Bronze Age, as well as Messapic, Greek and Romans cities, harbours and fortifications witness the long-lasting life of the settlements up to the Middle Ages.

Anthropisation of the area was, in some cases, conditioned by the natural morphological changes of river mouths and of the coasts, with the eventual disappearing of entire settlements. These sites are currently the subject of shoreline and sea level studies based on geo-archaeological investigations, such as the one at the Roman harbour of Marseille (France), Leptis Magna (Libya), Troy, Miletus and Ephesus (Turkey), Baia (Italy), among others in the Mediterranean basin (Morhange et al., 2001; Goiran et al., 2005; Brückner et al., 2006; Marriner et al., 2006). In other cases, isostatic, tectonic and volcanic land movements, or natural and anthropogenic subsidence, interplayed causing the submergence or the uplift of coastal sites (i.e: Flemming and Webb, 1986; Pirazzoli et al., 1996; Sivan et al., 2001; Morhange et al., 2006; Antonioli et al., 2007, 2009; Stock et al., 2013; Anzidei et al., 2011a, b; 2014 and

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references therein). Exemplary is the case of Falasarna (Crete, Greece) that experienced dramatic co-seismic movements that uplifted the Roman Age harbour to about 8 m (Stiros, 2010). On the other hand, some coastal cities, such as that of Baia (Pozzuoli, Naples, Italy), were subjected to bradyseism that repeatedly raised and submerged the coastal installations subsequent to the volcanic activity of the Phlaegrean Fields (Dvorak and Mastrolorenzo, 1991; Morhange et al., 1999, 2006). Currently, flooding processes, apart from local effects, are a consequence of global changes, such as the eustatic sea level rise and the isostatic vertical land movements. The latter have been occurring since the end of the Last Glacial Maximum (LGM, i.e. 21 ka cal BP) (Lambeck, 2009; Lambeck et al., 2004a, 2004b; 2010a, b, 2011).

Along active tectonic coasts, the eustatic signal is hidden by vertical land movements; while, in those tectonically stable, it is possible to evaluate the eustatic contribution from the observed sea level rise, once the age of the submerged archaeological indicators is known. In the studies aimed to estimate the relative sea level changes, the geo-archaeological contributions play a key role, allowing the estimation of the intervening relative sea level changes along the coasts of the Mediterranean. Therefore, maritime archaeological surveys are crucial in the validation process of the mathematical models aimed towards the reconstruction of the predicted sea levels as a result of global or regional vertical deformations of the Earth's crust and mantle rheology (Lambeck et al., 2004a, 2011; Lambeck and Purcell, 2005).

In the perspective of the acceleration of sea level rise caused by global warming (Knauer, 2007; Veermer and Rahmstorf, 2009; Church et al., 2013; Kopp et al., 2016), and considering the vertical land movements that affect the active tectonic region of the Mediterranean basin (Serpelloni et al., 2013; Anzidei et al., 2014), the maritime archaeological sites play a key role in understanding the local and global causes of their submersion (Lambeck et al., 2004b). In this study, archaeological sea level indicators of coastal installations from the Bronze Age up to the Middle Ages, located between Bari and Taranto (Fig. 1), were used with the aim of collecting new data on the relative sea level changes which have occurred along these coasts during the last c. 3.3 ka. Results were coupled with the most recent interpretation of previous archaeological studies (Auriemma et al., 2004, 2005; Scarano et al., 2008; Alfonso et al., 2012), and with the comparison of the most recent sea level prediction models (Lambeck and Purcell, 2005; Lambeck et al., 2011). Our data will support previous results and new studies on: *i)* the relative sea level rise which occurred during the Holocene in the Mediterranean, and *ii)* trend and rates of vertical tectonics for the Apulia region.

2. Geological and geographic settlements

The Apulia region is a NW trending ridge of continental crust running from central Italy to offshore Greece that constitutes the SW margin of the Adriatic plate (Doglioni et al., 1994, 1996), which is placed in the complex geodynamic basin of the Mediterranean (Serpelloni et al., 2007, 2013). It represents the foreland domain of the southern Apennines to the West and the Dinarides to the East. This region displays a low tectonic activity level (Chiarabba et al., 2005; Battaglia et al., 2004) and was affected by crustal differential uplift and down-lift during the Pleistocene, up to the late Pleistocene (i.e.: Hearty and Dai Prà, 1992; Ferranti et al., 2006; Di Bucci et al., 2011; Mastronuzzi et al., 2011 and references therein).

The surface geology is characterised by the outcropping of a 6 km thick carbonate platform that developed during the Mesozoic, partially overlapped by calcarenite and clay units of the Plio-Pleistocene. Along the coasts, marine terraced deposits outcrop extensively in transgression on the Mesozoic and Plio-Pleistocene units. They are the result of the superimposition of both glacio-eustatic sea level changes and regional uplift, drawing a staircase of marine terraces, recognisable between a 160 m elevation and the present shoreline, which marks the local coastal landscape. Some display a thin sedimentary body composed of calcareous sandstones (locally named *panchina*). In some places, they are associated with dune deposits, whereas others are only abrasion platforms. The last interglacial marine terrace contain Senegalese fauna and fossils of *Persististrombus latus* (Gmelin) marking the oldest deposits of the last interglacial, correlated to the Marine Isotope Substage 5.5, of c. 132–116 ka BP (Ferranti et al., 2006), and allow the estimation of the long-term crustal uplift. The uplift of the Apulian foreland (Doglioni et al., 1994, 1996; Di Bucci et al., 2011) decreased, during the MIS 9.3, of c. 330 ka (Mastronuzzi et al., 2007). Since then, a detailed estimation of the Late Pleistocene uplift has been available only for the Taranto area, calculated at about 0.13 mm/yr. This has been given by the LIT (Last Interglacial Time) deposits (Amorosi et al., 2014; Negri et al., 2015) that decrease to zero in the southernmost part of the region (Ferranti et al., 2006; Mastronuzzi et al., 2007, 2011 and references therein). Therefore, based on these data, an overall tectonic stability of the coastal area of the Murge as of the last 125 ka BP (Ferranti et al., 2006; Antonioli et al., 2009) has been inferred. On the other hand, a few selected geomorphological and archaeological indicators would seem to suggest a very slight subsidence during the Holocene along the Adriatic coast of Apulia, even if some stable areas can be identified (Mastronuzzi and Sansò, 2002; Lambeck et al., 2004a; Antonioli et al., 2009). Unfortunately, the available data are insufficient to discriminate and detail different tectonic behaviours in Apulia, with the exception of the Gargano promontory (Patacca and Scandone, 2004; Piccardi, 2005; Ridente and Trincardi, 2006; Nicolai and Gambini, 2007; Anzidei et al., 1996).

The areas investigated in the present study are located in the central part of the Apulia region, namely the coastal area located at the feet of the Murgia carbonatic plateau where the Piana di Taranto and Brindisi, southward to the Soglia Messapica (Mastronuzzi et al., 2011). From a morphological point of view, they are characterised by the vast presence of gently sloping rocky coasts, inlets, and cliffs generally shaped on a sequence of: *i)* limestone/sandstone along the Adriatic side (Mesozoic Calcare delle Murge and Plio-Pleistocene Calcarenite di Gravina units); or *ii)* sandstone/packstone along the Ionian side (Calcarenite di Gravina and Pleistocene marine terraced deposits units).

The coastal archaeological sites described in this study (Fig. 1) have been partially submerged during the last three millennia circa. Indeed, about 20 ka ago, the sea level was about 130 m below its present position (Lambeck et al., 2004a) and only about 6 ka BP did it rise up to a few metres below its present level (e.g. Lambeck et al., 2004a, b; Auriemma et al., 2004, 2005; Antonioli et al., 2009). The last 6 ka have been characterised by slower rates in sea level rise. However, in the last decades, the global sea level has been rising up to 3.2 mm/yr (Church and White, 2011; Meyssignac and Cazenave, 2012; Jevrejeva et al., 2014 and references therein), while in the Mediterranean, it has been rising at a rate of 1.8 mm/yr (Wöppelman and Marcos, 2012; Anzidei et al., 2014) as a result of global warming.

3. Materials and methods

The study surveyed 17 maritime archaeological artefacts, located in six different sites, providing significant markers for the relative sea level changes along the central coasts of Apulia (Fig. 1; Table 1). Data collection and analyses were performed through five subsequent steps: *i)* elevation measurements of significant maritime archaeological structure markers with respect to the sea level

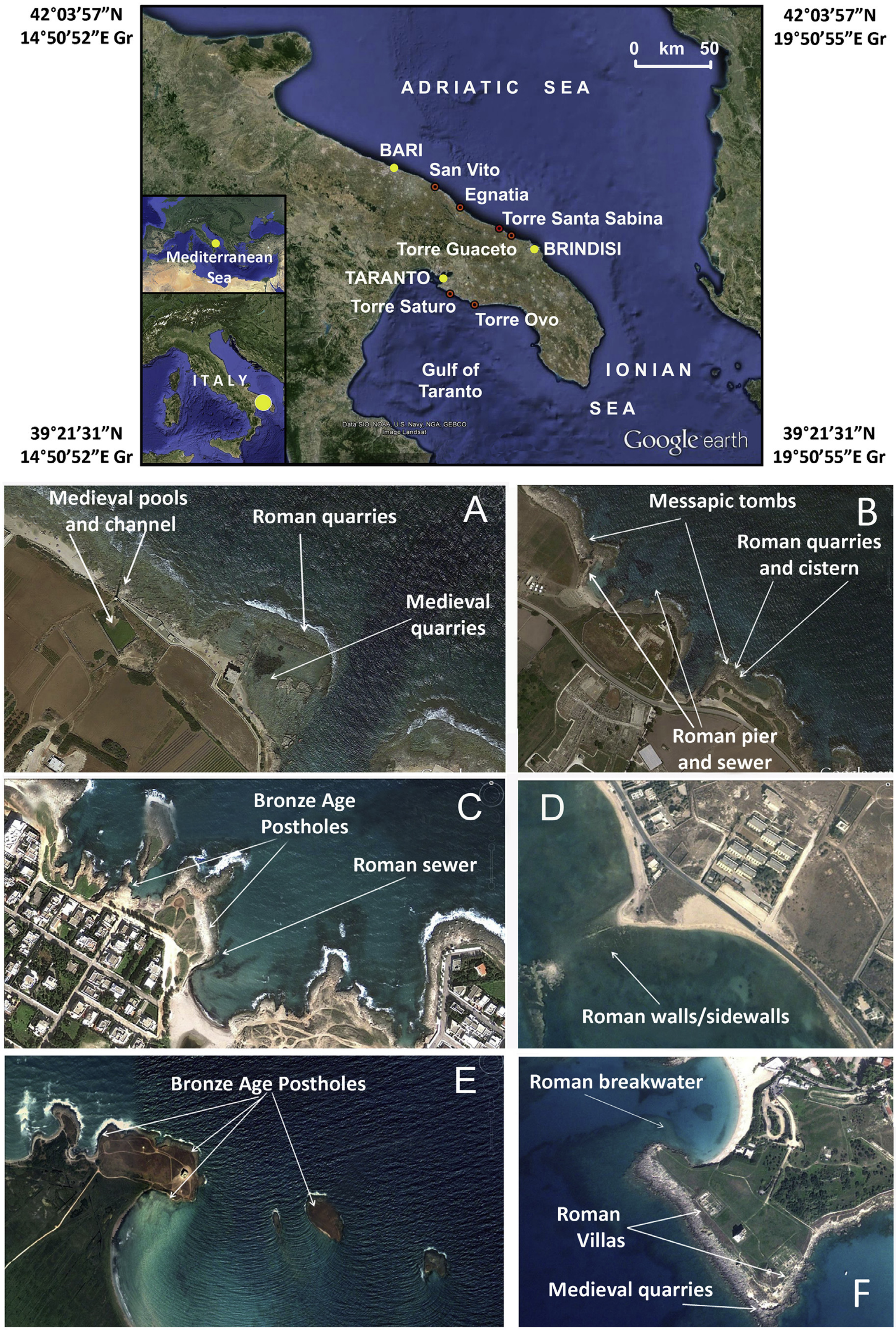

Fig. 1. Location of the studied sites: A - San Vito in Polignano; B - Egnatia; C - Torre Santa Sabina; D - Torre Guaceto; E - Torre Ovo; F - Torre Saturo.

Table 1
Observational data for the investigated archaeological sites. See also Fig. 1 for locations. A, B) site number and name; B) archaeological age (ka BP); C) type of archaeological indicator; D) elevation of the archaeological sea level indicator at the time of surveys; E) functional elevation (estimated according to Lambeck et al., 2004b; Auriemma and Solinas, 2009); F) date and time of surveys; G) local tide amplitude at the time of surveys as reported in the tidal data at the nearby tide gauge station of Bari (data have been retrieved at www.mareografico.it; Z_0 is the reference local mean sea level (cm); H) elevation of the sea level marker after the tidal correction; I) relative sea level changes (RSLC) at the individual sites (with upper and lower limits, when available), with respect to the predicted sea levels for the corresponding age of the archaeological sites as reported in Lambeck et al.(2004a, b, 2011) ; UL = upper level; ML = mean level; LL = lower level.

A	B	C	D	E	F	G	H	I	L
N.	Site name	Age (ka BP)	Type of marker	Elevation (cm)	Functional elevation (cm)	Date and time (GMT) of survey	Tide (cm) BARI TG $Z_0 = -15$	Corrected elevation (cm)	RSLC (cm)
1	San Vito	2000–1500	Submerged channel	−58 −115	0	June 14, 2010 07:40	−18	58 + 3 = −61 115 + 3 = −118	61 ± 20 118 ± 20 mean 89.5 ± 20
2		2000	Quarry	−38	60	07:40	−18	38 + 3 = −41	101 ± 20
3		900–400	Quarry	−65	60	07:40	−18	65 + 3 = −68	128 ± 20
4		900–400	Millstone	−20	20	07:40	−18	20 + 3 = −23	43 ± 20
5		900–400	Channel of the pool with sluice gate	UL -30 ± 20 ML -62 LL -90	Middle of the sluice gate	May 5, 2013 10:30	−19	62 + 4 = −66	79 ± 20
6	Egnazia	2400 ± 100	Classical −hellenistic tombs of coastal necropolis	−85	50 (30 + 20)	June 14, 2010 16:20	+11	−85 + 4 = −81	131 ± 20
7		2050 ± 10	Roman harbour	−280 (top)	0	16:00	+11	−280 + 4 = −276	0
8		2000–1500	Roman cistern	−59 (base)	50	16:20	+11	−59 + 4 = −55	105 ± 20
9		2500–2000	Preroman or roman quarry	−83	50 (30 + 20)	16:25	+11	−83 + 4 = −79	129 ± 20
10		2200–1500	Roman sewerage	−90	0	15:45	+12	−90 + 3 = −87	87 ± 20
11	Torre Santa Sabina	3300 ± 100	Holes of woodenpoles	−30	>200	June 16, 2010 13:30	−8	−30−7 = −38	>238
12		2500–2000	Preroman or roman quarry	−80 −100	50 (30 + 20)	14:00	−5	−80−10 = −90 −100−10 = −110	130 ± 20 160 ± 20
13		2000–1500	Roman sewerage	−90	0	15:30	+7	−90 + 8 = −82	82 ± 20
14	Torre Guaceto	3200 ± 200	Holes of woodenpoles	−20	>200	June 15, 2010, 09:10	−20	−20−5 = −25	>225
15		650 ± 150	Late medioeval quarries	0.0	50 (30 + 20)	June 15, 2010, 09:10	−20	0-5 = −5	55 ± 20
16	Torre Ovo	2200 ± 100	Walls; sidewalk	0.0 top −95 bottom	100	June 16, 2010, 08:00	−10	0−5 = −5 −95 + 5 = −90	5 ± 20 190 ± 20 mean 97 ± 20
17	Torre Saturo	2100 ± 100	Breakwater	−190 top −290	100	June 16, 2010, 12:00	−16	−190 + 1 = −189 290 + 1 = −291	289 ± 20 391 ± 20

at the time of surveys; *ii)* tidal correction of the elevations at the time of surveys, using sea level data from the Italian tide gauge network (www.idromare.it), *iii)* error estimation for age and elevation of the archaeological markers; *iv)* reduction of the elevations for the functional heights of the constructional features, evaluated on the basis of archaeological interpretations; *v)* analysis of the predicted and observed sea levels by comparing the current elevations of the archaeological indicators (i.e. the relative sea level change at each location) with the sea level elevation predicted by the geophysical model for each location (Lambeck et al., 2004a, 2011). Predictions reported in Table 1 derive from previous studies modelling the isostatic signal in the sea level as the result of an ongoing process that can be predicted once the ice and Earth parameters have been established. The ice model used throughout the subsequent predictions derives from Lambeck et al. (2006, 2010a, b; 2011), Lambeck (2009) and includes the most recent developments for the ice sheets in both hemispheres. It includes the major ice sheets back to the penultimate interglacial, as well as an alpine deglaciation model. Rheological parameters were adopted from previous work for the same region (Lambeck et al., 2004a, b) and correspond to the three-layer model with an effective elastic lithospheric thickness of 65 km, with variable upper and lower mantle viscosities. We compared the relative sea level changes obtained in the studied with published predicted sea level curves. In particular, in order to obtain the numbers plotted on Table 1 and Fig. 6 we used the sea level prediction of Lambeck et al., (2004a, b, 2011) published as supplementary material (and downloadable as excell data-set) for the studied sites.

The Apulian coast is situated in a micro-tidal area of the Mediterranean where the tidal range is within 45 cm (www.idromare.it). In order to reduce elevation data to a local mean sea level, during the surveys, tidal data from the nearest tide gauge station located in Bari were used. The time series of tidal data (defined by astronomical plus barometric contribution) collected for this station in the time span 2000–2014 were used and analyzed to estimate a reference local mean sea level in order to reduce the elevations of the surveyed archaeological markers to the local mean sea level at the time of the survey; then, these data were compared with the mean sea level at the time of their construction, as estimated by the functional elevation of the architectural features of the coastal installations. The results are reported in Table 1.

Field surveys and investigations were performed repeatedly in June 2010 and September 2013 using optical or mechanical instruments in condition of calm sea. Coastal measurements were performed by the DGPS technique to locate and georeference each of the investigated sites. The altitude of the archaeological indicators was measured with respect to the sea level at the moment of the surveys, using invar rods and spirit levelling. For those sites located at depths exceeding 1 m, elevations were obtained through digital depth meters, with an accuracy of about 10 cm.

The functional heights of the archaeological benchmarks, used as a comparison with the present sea level to estimate its change in each location, were extensively described for the first time in Lambeck et al. (2004a) and later in other studies (i.e.: Antonioli et al., 2007; Auriemma and Solinas, 2009; Anzidei et al., 2011a,b and references therein). They actually describes the original position of a given archaeological structure by means of specific architectural parts, above or below the supposed mean sea level at the time of their construction. The functional heights depend on the type of structure and its use, as well as on the local tide

Table 2
Expected maximum run-up values (Hr) and maximum horizontal flooding (Xmax) estimated for Torre Santa Sabina and Torre Guaceto localities, due to different impacting waves of supposed height (Hs) in function of the coastal slope and of the Manning's number that represents the coastal roughness (see Fig. 7). Estimates are based on theoretical features from past sea levels as derived by historical series (www.isprambiente.gov.it) and assumed to be indicative for expected events, as reported in Pignatelli et al. (2009, 2010).

	α (slope)	n (Manning)	Hs	X max	Run up (Hr)	Hs	X max	Run up (Hr)
Torre Santa Sabina	1°	0.0497	1 m	25 m	About 1 m	2 m	60 m	About 2 m
Torre Guaceto	4.5°	0.0497	1 m	25 m	About 2.5 m	2 m	60 m	About 4.5 m

amplitudes. They also define the minimum elevation of the structure above the highest local tides, allowing to estimate the error bar. The use of these structures, their age and conservation, the accuracy of the survey and the estimation of the functional heights were used in considering the observational uncertainties at each site. In particular, we used the estimated value of a minimum of 0.3 m above high tide as the functional height of quarries, such as in Tunisia and Libya (Anzidei et al., 2011a) or on Ventotene Island (Lambeck et al., 2004b). In the present study, an approximation range of ± 0.20 m was preferred, based on the constructional features of the investigated indicators, and the shorter tidal range of the Apulian coast compared to that of the Sirte Gulf.

For some of the archaeological indicators used, e.g. huts and post-holes, the approximations are clearly significantly greater and only locally assessible, since the functional heights indicate the minimum elevation which, with the corresponding past sea level, would not have allowed the impacting waves to flood huts. This elevation was evaluated by analysing the present wave climate and the historical series (www.isprambiente.gov.it) - assuming it as indicative of those of the past - and its impact by means of recent flooding models described through hydrodynamic equations (Pignatelli et al., 2009; Piscitelli et al., 2009) (Table 2).

4. Archaeological data

A brief description of the sea level markers from the main archaeological sites is here provided (Table 1).

4.1. S. Vito, Polignano, Bari (41° 0′52.67″N 17°11′34.27″E Gr) (Fig. 2A and B)

The inlet of San Vito is dominated by the homonymous abbey, created by the Basilians, and its first group of monks may date back to the VI or VII century. However, the earliest reliable historical sources date back to 1063. In the XIV century, the abbey began to experience a moment of decline, culminating in the final suppression ordered by Pope John XXII (Favale, 1974; Calderazzi, 1980; Laganara Fabiano, 1981; Romano, 2008).

The coastal area surrounding the inlet is marked by the presence of Roman and Medieval quarries with blocks and milestones, ready for extraction, currently located below sea level (Table 1), together with a channel (Fig. 2.1A,B) connected to the quarry still discernible. The large quarry system with accessory channels seems to have been active at least during two different phases: the Roman Age (Fig. 2.1C) and Middle Ages (Fig. 2.1D, E).

Fig. 2. Main archaeological sea level markers in the San Vito, Polignano localities: 1) A and B - two views of the Roman channel; C - detail of the Roman Age quarry; D - Middle Ages quarry; E - location from which two milestones were excavated. 2) A - mouth of the Roman channel; B - sluice gate and its topographic relief; C - seaward located pool; D - plant (above) and section (below) of the sluice gate (measurements expressed in cm); E - complete view of the channel, still partially covered by slabs.

North of the Abbey, lies complex of two - may be three because one other seems to be buried - adjacent tanks, connected to the sea by a network of channels, dating back to 1400 (Romano, 2008) (Fig. 2.2). This chronological attribution, however, seems to be rejuvenated as reported from archive documents by Tavassi La Greca Valentini (2008); in fact the construction of the large tanks (25 × 45 m and 18 × 37 m) is attributed to between 1697 and 1734 A.D. thanks to a document concerning a legal dispute that took place in 1743 between the Chapter of Polignano and the Basilica of SS. Apostles, owners of the abbey at the time. The abbey master builders attest the numerous structural and decorative works carried out in the complex, including a "*fish pond surrounded by farms*", commissioned by Father Lorenzo de Cubellis. Since de Cubellis had been elected commissioner in 1697 and the document dates back to 1743, this time line indicates the construction of the fishponds and the corresponding channel, which at that time were connected directly to the sea level (Tavassi La Greca Valentini, 2008). The channel is still visible (Fig. 2.2A, B), and the fact that some covering slabs are still in their place (Fig. 2.2E) suggests that the sea level was originally below them. The bottom of the channel, in correspondence to the remaining sluice gate, is −0.62 m (Fig. 2.2B, D). Considering a functional height of 0.60 m (Auriemma and Solinas, 2009) arises a sea level change at 0.81 ± 0.30 m.

4.2. Egnazia, Fasano, Brindisi (40°53′18.96″N; 17°23′34.08″E Gr) (Fig. 3)

The Egnatia site experienced various occupation phases, from the protohistoric period to the late ancient and medieval times, through to the Hellenistic and Roman phases.

In the inlet to the north of the acropolis, the remains of two concrete piers of the port basin (Auriemma, 2003; Auriemma et al., 2004) (Fig. 3A,B,C) lie submerged. At the end of the destroyed north-western mole, originally extending for a length of 105 m, two, large, unaligned, parallelepiped concrete blocks (*pilae*), in *opus reticulatum* (Auriemma, 2003, 2004 and references therein), emerge from the sandy seafloor at a depth of 6.2 m. The internal plinth close to the coast is the highest, emerging from 2.40 to 3.1 m. Its upper face is irregular and the highest point is found at −3 m. The external plinth is about 0.60 m high.

The remaining part of the southern pier, facing SSW-NNE, is made of concrete with multiple castings of wooden caissons. The

Fig. 3. Main archaeological evidences in Egnatia: A - northern part of the pier; B and C two aspects of the southern pier; D - sewer channel; E - Roman quarry; F - pseudo-sargophagus tomb.

surrounding rocky area is located at −4.60 m, while the top of the structure is at −3 m. The total length of the visible block is 23 m, although three different-sized blocks can be clearly distinguished. These show the imprints of the constructional parts constituting the internal wooden frame of the caisson into which the concrete was poured (Fig. 3B). The caisson had external poles whose metal pins with traces of wood were also found still fixed into holes in the rock. During the Roman Imperial Age (i.e. as of the I century BC), harbour structures made of hydraulic concrete using *pozzolana* (Brandon et al., 2014) poured into wooden caissons were widely used across the Mediterranean. In particular, this building technique can be dated back to the time of Augustus. The port of Egnatia was built for military use and can be dated to around 2050 BP, a period in which an inscription in honor of M. Agrippa, *patronus of the municipium of Egnatia*, admiral and son-in-law of Augustus, was attributed and to whom the military planning of the port is ascribed.

Additional archaeological evidences can be found in the area: tombs of the coastal necropolis excavated in the rock, drainage canals (Fig. 3D), quarries (Fig. 3E), tombs (Fig. 3F), cisterns, seats for wall lines, today partially or completely submerged by the sea. The quarries were excavated with benching methods. However, some blocks, previously prepared for extraction, but not detached, are often still *in situ*. Close to the large quarry area, next to the remaining part of the boundary wall, regular cuttings were found underwater up to −1 m. The quarry area is located between −0.5 and −1.00 m.

Although dating is not yet certain, the presence of tombs with pseudo-sarcophagi (i.e. with lowered edges to install cover slabs), dated back to the V and IV centuries BCE, cut from the bottom of the quarries, provide the age of the bedrock exploitation. A network of small channels is connected to a larger one, NE–SW trending, likely used to sewer and/or drain rainwater from the town. It was excavated in the bedrock and still shows the offset for the bearing of the slabs. At present, its bottom is at −0.70/0.80 m below sea level. Finally, near these structures, a cistern made of waterproof mortar

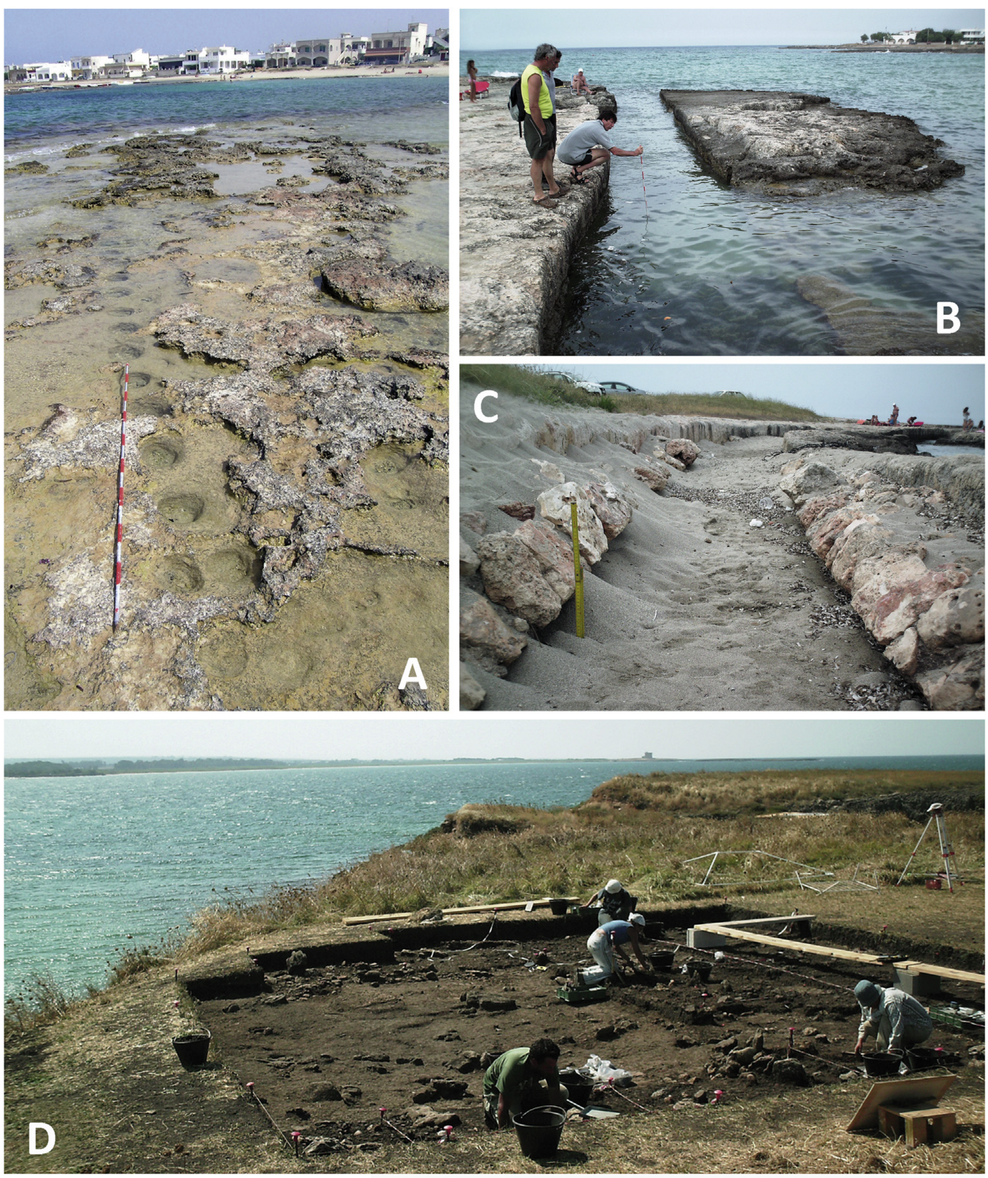

Fig. 4. Main archaeological evidences in Torre Santa Sabina (A,B,C) and Torre Guaceto (D): A -Bronze Age postholes and, in the background, a Middle Ages millstone; B and C - two views of the Roman channel; D - Archaeological surveys performed on the Apani Islands highlight the presence of a Neolithic village; here, the Bronze Age postholes and Middle Ages quarry have been surveyed in the intertidal zone.

(*coccio pesto*), shows its bottom up to 60 cm below the present sea level.

4.3. Torre Santa Sabina, Carovigno, Brindisi (40°45′31.62″N; 17°42′13.94″E Gr) (Fig. 4A–C)

The site of Torre Santa Sabina was a large and long-lived coastal Bronze Age settlement, as documented by Mycenaean grave goods (Onnis, 2010 and references therein). The survey carried out in the coastal area provided evidence of tens of postholes excavated into the bedrock and arranged in different alignments, placed at sea level or at a few centimetres below (Scarano et al., 2008) (Fig. 4A). The long history of the ancient Camerini inlet is testified by the thick stratigraphic sequence of wooden wrecks and rich cargos still preserved on the sea bottom (Auriemma et al., 2005; Auriemma, 2004). Later on, the Torre Santa Sabina site would have preserved its role as a harbour site for a long time, albeit on a smaller scale. The limestone quarry in the outcropping bedrock further west can probably be dated back to the Hellenistic and Roman Ages, and can be related to a few groups of large blocks located nearby on the seabed. The quarry is about 50–60 m long (NE-SW) and 15 m wide. Currently, its bottom, that is the bedding plane of the blocks, is between 0.50 and 1 m below sea level. A posthole is located at about 1 m below sea level. On the other side, a quarry of small blocks is found in the bedrock area outcropping further east, which can be dated to the Middle Age and, at present, is located between about 0 and 0.50 m below sea level. Finally, further north, a drainage canal flows into the Mezzaluna inlet (Fig. 4B, C). The offset rim for the covering slabs is still preserved and, at present, the bottom of the canal close to its end is about −0.80 m (Auriemma, 2004; Auriemma et al., 2004, 2005).

4.4. Torre Guaceto, Carovigno, Brindisi (40°42′50.42″N; 17°48′1.45″E Gr) (Fig. 4D)

This site has been well known as a safe harbour ever since ancient times supplying abundant freshwater from springs fed by large marshes and two main streams (Canale Apani and Canale Reale) (Scarano et al., 2008). Currently, archaeological remains dated back to the Bronze Age are the most important testimonies identified in this area, such as protohistoric evidence of a stretch of coast about 3.5 km long, including five islets (namely, Torre Guaceto and Scogli di Apani, Fig. 4D) as well as large sea bottom zones. In this area, many postholes of varying shapes and sizes (often arranged in rows and spaced out quite regularly) occur uninterruptedly along the eroded and washed out coastal profiles (of both the mainland and islets). They are also present in the intertidal zones, lying on the neighbouring rocky seabed to a depth of at least 2.5 m below sea level. A remarkable cluster of postholes, some of which likely spaced in rows, was also discovered at 3.5 and 4.5 m below sea level on a large sector of Torre Guaceto (direction 330° E). With regards to the archaeological markers relating to the Late Middle Ages, it is worth mentioning two adjoining limestone quarries (100 and 160 m^2 wide, respectively) lying at the bottom of a pocket beach to the north of the Torre Guaceto peninsula. The bedding plane of the blocks in the smaller one is at least 50 cm below the present sea level; on the other hand, the bigger one (clearly visible in the 1943 aerial photos) was completely filled by the sand both in the underwater and emerging sections.

4.5. Torre Ovo, Maruggio, Taranto (40°18′13.18″N; 17°29′59.32″E Gr) (Fig. 5A–C)

In this bay, significant traces of the Roman era have also been preserved. The settlement, interpreted as a fishing village, is believed to have obtained sustenance from fishing activities; it is likely that boats travelling along a cabotage route docked in this area (Alessio, 2001). In the inlet, alignments of currently submerged squared blocks placed perpendicularly to each other in one or two rows, probably coeval, are recognisable (Fig. 5A–C). They form a sort of caisson type foundation, or "*vespaio*", dated III or II centuries BCE, of a service building associated to this landing place, built when the whole area was above sea level. The main alignment appears perpendicular to the coast facing the small island. This last line may be the foundation of an embankment used solely to reach the small island serving as a landing and mooring point around which other similar blocks lie.

4.6. Torre Saturo, Pulsano, Taranto (40°22′21.58″N; 17°18′12.88″E Gr) (Fig. 5D,E)

This bay, located south east of Taranto, offers an example of a breakwater structure, built using a typical rubble jetty technique (Auriemma, 2004; Auriemma and Solinas, 2009), projecting from the southern headland and tracing a curved path. It appears to be an embankment with a trapezoidal section, having a total length of 105 m and a width of 11 m in the middle of the path (the width of the baseline varies from 14 but 18 m). The bottom is at 1–3 m in the initial part near the beach, between 4 and 5 m in the central part, and gradually decreases in the last part, up to 7 m (Fig. 5D).

The included archaeological materials seem largely referable to the Hellenistic or late Republican Ages (III-II cent. BCE), while near the breakwater structure and on its surface, materials of a later period are present (Fig. 5E). Due to its simplicity and ergonomics, the loose stone cast is a type of underwater building used throughout all ages and coastal areas to create large dam bulwarks, not requiring the "*firmissimum opus*" docks passable.

In order to fulfil their task, these defensive structures were originally above sea level. Currently, the upper surface of these breakwater structures is between −2.30 and −2.5 m. On the surface of the structure in *Saturo*, the remains of a brick load, probably sunk between the end of the II and I century BCE, along with archaeological material useful for dating the site (Fig. 5E), were found. At the time of the shipwreck, the seawall probably emerged just above or was just below the sea level (Auriemma, 2004; Colucci, 2014).

5. Discussion

The archaeological data collected along the Adriatic coast (four localities) and the Ionian coast (two localities) of Apulia span between the Bronze Age, here corresponding to c. 3.3 ka BP, and the late Middle Ages (Table 1). Geologically, the coasts extend along the foot of the Murge plateau, up to the Brindisi - Taranto alignment, also known as Soglia Messapica (Mastronuzzi et al., 2011).

The Murge plateau, an extended tectonic structure defined during the Pleistocene, is enclosed between the horst/semi-graben system - composed of the Gargano Promontory and the Tavoliere (Plains) of Apulia - and the southernmost part of Apulia (namely, the Salento Peninsula), characterised by horst and graben structures (Di Bucci et al., 2011; Mastronuzzi et al., 2011 and references therein). This is considered a tectonically stable area during the Upper Pleistocene – Holocene; low uplift rates have been recognised along the Ionian coast ranging from about 0.13 mm/yr in the Taranto area to zero in the southernmost part of the region, although low rates subsidence along the Adriatic coast during the Holocene may have occurred (i.e.: Hearty and Dai Prà, 1992; Mastronuzzi and Sansò, 2002; Amorosi et al., 2014; Negri et al., 2015). The Murge themselves are marked by tectonic and karstic structures with the occurrence of possible recent neotectonic activity (Iurilli et al., 2009).

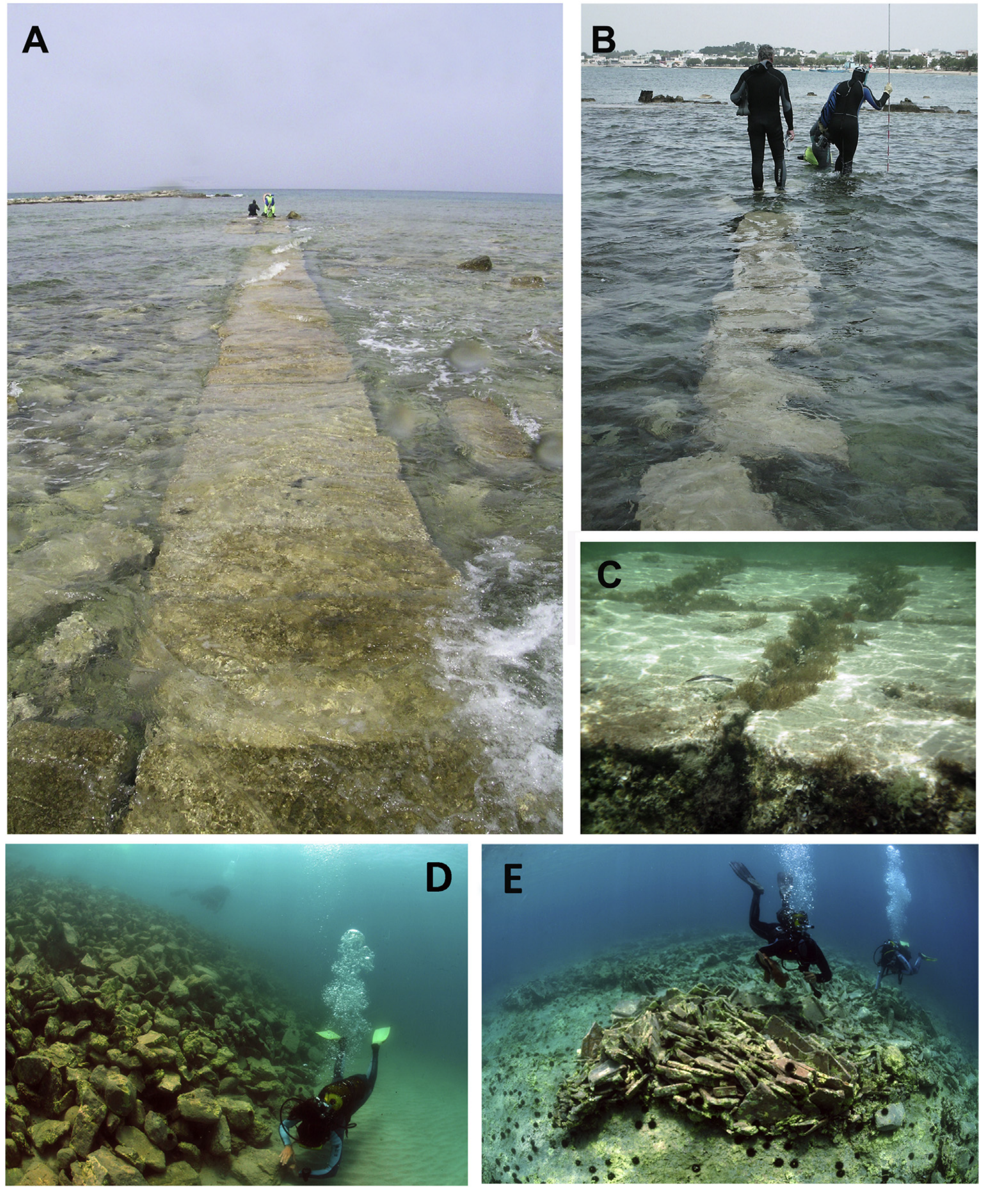

Fig. 5. Archaeological markers of the sea level in the Torre Ovo (A,B,C) and Torre Saturo (D,E) localities: The main block alignment view, seaward (A) and landward (B), in the Torre Ovo locality; C - detail of the limestone blocks used to build them; D - The "*pietre perse*" breakwater structure of Torre Saturo; E - remains of a Roman wreck at its top.

To the south of the Soglia Messapica, the landscape is shaped locally in a sequence of Mesozoic and Cenozoic carbonate units showing a substantial stability (Mastronuzzi et al., 2007) and in an extended area in which Cenozoic and Neozoic units outcrops; the latter seems to be subjected to differential vertical movements, as suggested by recent studies along the west coast of the Salento peninsula at Torre Pali (Mastronuzzi and Sansò, 2014) and Porto Cesareo (Alfonso et al., 2012), and along the eastern coast in the Alimini Lake district (Primavera et al., 2011). Here, archaeological indicators and paleontological observations in the Alimini lakes suggest a complex sea level history during the last 4500 years, with higher sea level rise rates (when compared with predictions) during the Bronze Age as well as in the last 500 years. Assuming that the sea level rose with the same velocity in nearby sites, these anomalies have been interpreted as differential vertical land movements by poor observations and, consequently, as approximate interpretations of archaeological and palaeo-environmental data.

Fig. 6 has been built using data shown in Table 1; the site elevations are plotted against the predicted sea level curves of two model solutions by Lambeck et al. (2004a and 2011). The position of each site has been reduced for the functional elevation, while different coloured dots indicate the position and age of the archaeological indicators with respect to the current sea level.

Sites 14 and 11 correspond to the two areas of Torre Guaceto and Torre Santa Sabina, both characterised by the remains of hut postholes. We used the hydrodynamic equations by Pignatelli et al. (2009) and Piscitelli et al. (2009) to reconstruct the possible past positions of the sea level considering the impacting waves of the past as being similar to those of the present. In particular, the Pignatelli et al. (2009) equation has been used to calculate the maximum flooding (X max in Table 2 and Fig. 7A). The slope of the rocky coast (α) has been derived from a digital terrain model (DTM), made available by the Apulia Regional Administrative Offices, considering an average slope for 10 m wide buffers. The Manning number (n) of the calcarenite-shaped coastal landscape (showing

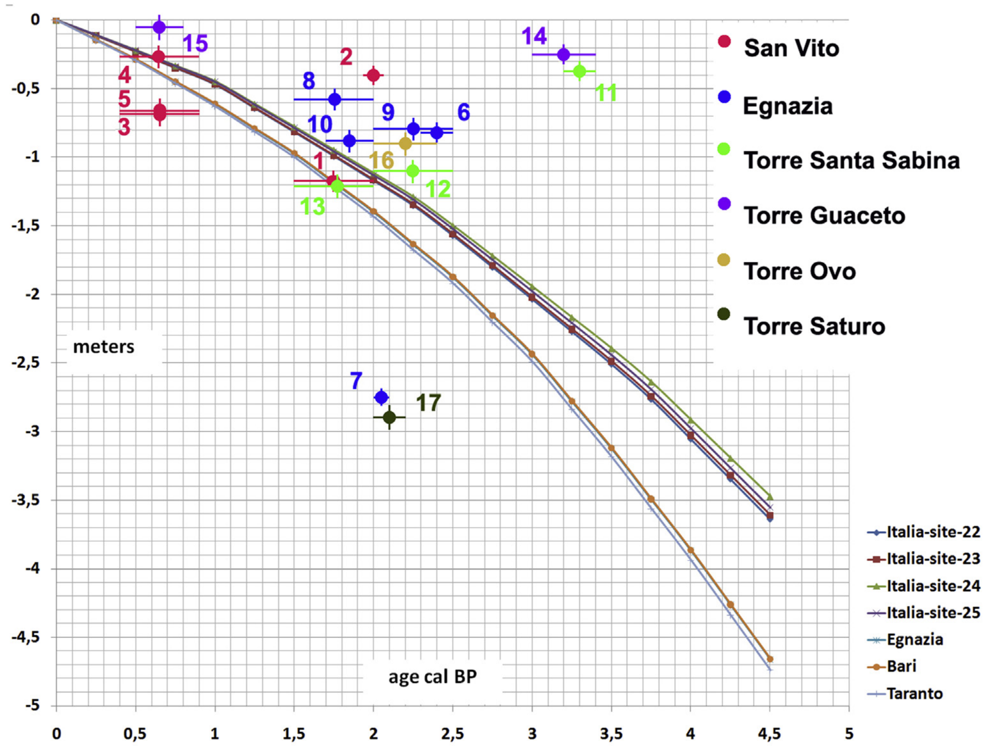

Fig. 6. Sea level predictions against the topographic elevation and age of the investigated sites. The elevation of the surveyed sea level markers with respect to the present mean sea level and to the predicted sea level by Lambeck et al. (2004a, b, 2011) derived from data synthetically reported in Table 1.

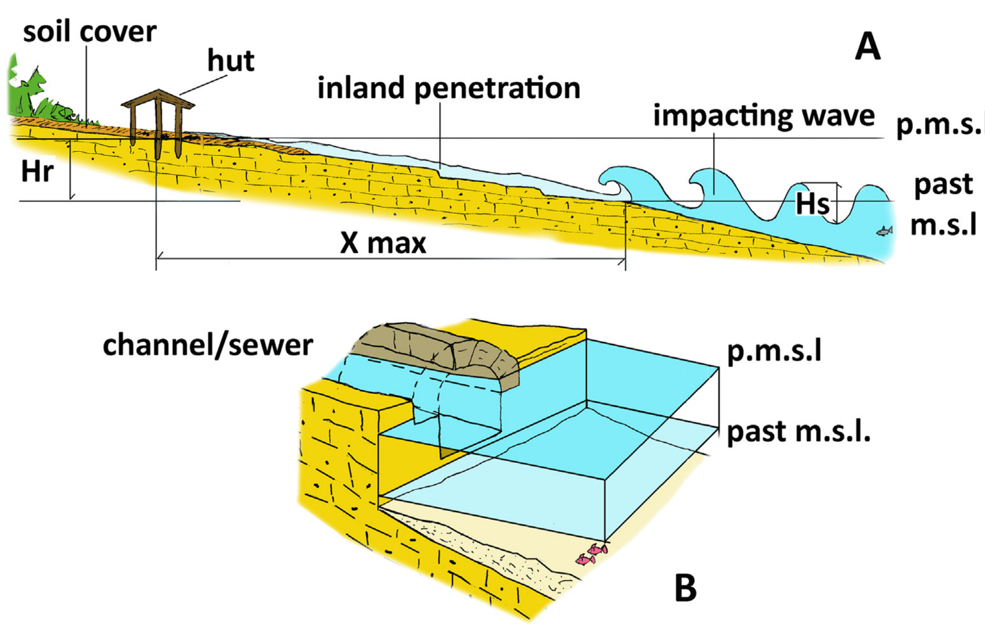

Fig. 7. Comparison between the Bronze Age hut postholes of c. 3.3 ka BP (A), and the Roman Age channel of 2.0/1.5 ka BP (B) with the present and past sea levels. Local basement is represented as a generic "calcarenite", the most highly represented lithotype in the surveyed areas; p.m.s.l.: present mean sea level; past m.s.l.: past mean sea level (related to the age of the artefact); Hr: Run-up; Hs: impacting wave height; Xmax: maximum horizontal flooding.

the roughness of the coastal area and its capability to dissipate impacting wave energy) has been obtained by the elaboration of direct surveys performed using a laser scanner (Pignatelli et al., 2010).

The high impacting wave value has been inferred from the largest storms frequently occurring along this coast. Considering the wave amplitudes from the RON (www.idromare.it), it can be hypothesised that the height of the set-up corresponds to impacting waves < 2 m in height (Hs). The maximum run-up estimated for Torre Santa Sabina is at about 2 m, and for Torre Guaceto at about 4.5 m. The hydrodynamic equation do no permit to obtain an error bar but only an height; the error bar can be considered that deriving from the local tidal range (±0.20 m). As the ground slope is low, the run-up is not significant, thereby inferring that hut postholes were placed at least 2 m above sea level in Torre Santa Sabina and 4.5 m at Torre Guaceto. While the data from Santa Sabina are in good agreement with the predicted sea level (Fig. 6), those from Torre Guaceto are not. In the latter, the hut poles pertain to an area which, during the Bronze Age, was placed in the back dune, whereas, in recent times, was flooded due to sea level rising (Scarano et al., 2008); therefore, it is reasonable to believe that the remains of the hut pole holes correspond to the lower part of the original poles excavated in the local basement below the soil cover.

The position of site 16 at Torre Ovo, with respect to the predicted sea level curves (Fig. 6), suggests that the observed structures did not pertain to marine port facilities, but most probably to land harbour facilities. At present, they stand at an elevation lower than 0.90 m below sea level, and, at the time of their use, the estimated elevation was between 0.4 m and 0.70 m, according to the predicted sea levels estimated by Lambeck and Purcell (2005) for the Mediterranean basin, and Lambeck et al. (2011) for the Italian coasts.

Sites 7 and 17 correspond to the structures of the Roman harbours of Egnatia and Torre Saturo, respectively. These areas are largely submerged and suggest that their history may be marked by at least one episodic severe marine event. The bases of the isolated plinths (*pilae*) of the destroyed northern pier at the Egnatia harbour are at −6 m, while the structure tops are at −2.80 m, marking the ancient sea level. This would correspond to the imprints still present in the concrete of the horizontal wooden poles. Many of them are displaced with respect to their original position suggesting that the breakwater structure may have suffered the impact of severe storms that eroded the lower part and the pebble level placed at its foundations on the bedrock. It is likely that these events might have contributed to the socio-economic collapse of Egnatia during the late-Roman - early Middle Age.

On the contrary, the harbour at Torre Saturo shows a raw stone rubble breakwater structure overlain with the remains of a scattered cargo (tiles) from a ship, presumably pushed onto the breakwater structure by waves, causing it to sink bottom side up; this corresponds to the mean sea level. Its present position is about 1.90 m below sea level.

Although the preservation and typology of these two sites provide valuable archaeological information on the construction techniques, they cannot be used successfully for the intents and purposes of the present study.

The land indicators of sites 6, 8 and 9 are presently submerged, thereby indicating the sea level since the time of their construction. Moreover, the slope of the piezometric surface of the coastal aquifer intercepted by the fresh water wells of Egnatia (Milella et al., 2006) is indicated as roughly 1‰ by Polemio (2015, pers. comm.). Considering the present coastal slope, it is reasonable to suppose that this surface is almost parallel to the sea level for at least the first 200 m. These data and the maximum run-up (Hr) (similar to those of Torre Santa Sabina, as reported in Table 2), indicate that the structures were built in an area where the bottom was just above the coastal aquifer, but occasionally surfed by impacting waves.

Sites 1, 10 and 13 correspond to the mouth of the sewer/drainage channels located at the San Vito, Egnatia, and Torre Santa Sabina localities, respectively and are located near the sea level predicted by Lambeck et al. (2004a). At site 10 (Egnatia), the channel is at a higher elevation compared to the other sites, possibly due to the excavation of the medieval quarries that destroyed part of the installation. In the proposed reconstruction, sites 1 and 13 are optimal sea level indicators, in good agreement with the predicted sea levels (Lambeck et al., 2004a, 2011) (Fig. 7B).

Sites 2, 4 and 15 are also land indicators, originally positioned above sea level; they confirm the further evidence of the sea level rise since the time of their construction.

Sites 3 and 5 correspond to the San Vito (near Polignano) channel sluice gate and quarries, respectively. Based on previous studies, sluice gates are usually the best archaeological sea level change indicators (Lambeck et al., 2004b; Auriemma and Solinas, 2009). Unfortunately, in the case of San Vito, the dating is still complicated to interpret; based on a historical source of archival reliability (a legal act), the fish pond complex has been dated to the period 1697–1743. This, however, contrasts sharply with the predicted curve. On the other hand, the attribution of the fish tank to the Roman Age is not corroborated by the architectonic evidence; i.e. the fish tank does not present typical features like the Roman fish tanks located along the Tyrrhenian coast of Italy or the eastern coasts of the Adriatic sea in Croatia and Slovenia (Lambeck et al., 2004b; Antonioli et al., 2007; Anzidei et al., 2013). In fact, the San Vito fish tank shows registered or juxtaposed plant tubs, cement structures in or dug into the local calcarenitic bedrock. Only the channel resembles those of typical Roman fish tanks. These features exclude the possibility that this fish tank had been built between the I century BCE and the II century CE, a period during which most of these maritime installations were built. In addition, a few kilometres north of this site, late Imperial Roman maritime structures with evidences of fishing activities have been identified (Pers. communication of Dr. Ciancio and Sanseverino, Apulian Archaeological Commission). Presently, neither surveys nor analyses of historical sources provide a convincing explanation of the validity of this channel as a sea level indicator.

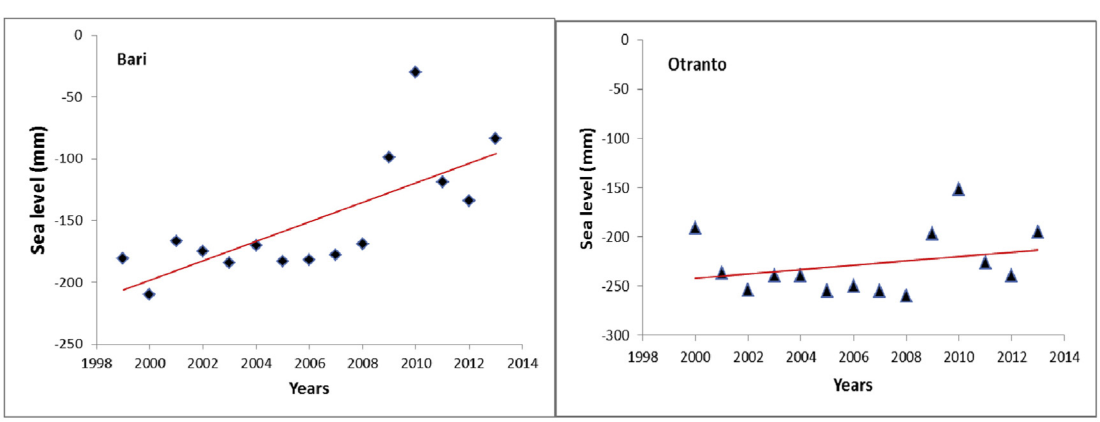

Fig. 8. Graph of the annual mean sea level recordings collected at the tidal stations in Bari and Otranto between 1999 and 2013. Data show sea level trends at 7.9 ± 0.1 and 3.9 ± 0.1 mm/y, respectively (red line is the linear fit). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The sea level curve estimated by Lambeck et al. (2004a, 2011) predicts a relative sea level rise for this region in the range of 0.3 and 2.3 m, between 500 and 3200 years cal BP, at a mean rate of 0.75 mm/y. Besides the long-term geological data, recent geodetic observations have become available along the coasts and inner areas of Apulia, showing the present-day land movements of this region (Serpelloni et al., 2013; Anzidei et al., 2014). The tide gauge stations located in Bari and Otranto, the nearest to the investigated archaeological areas, have recorded a sea level trend of $7.9 \pm 0.1$and 3.9 ± 0.1 mm/yr, respectively, during the time span 1999–2013 (Fig. 8). Although the duration of the sea level recordings for these stations is still too short to provide a reliable estimation, this value can be considered a preliminary indication that should correspond to an excess of about 2 and 5 mm/yr in the sea level rise with respect to recent estimates for the Mediterranean region. Moreover, the available GPS data for the last two decades show a weak subsiding trend for Apulia at about −1 mm/yr (Serpelloni et al., 2013; Anzidei et al., 2014). Therefore, the rate of vertical crustal movements inferred from the marine archaeological sites provides evidence of the combination of land subsidence and sea level rise, in agreement with recent instrumental observations. The whole dataset seems to hypothesise tectonic stability during the late Holocene at these sites where the elevations of the markers are in agreement with the predicted sea-levels, and, conversely, tectonic subsidence or uplift is inferred when the elevations of the markers are respectively below or above the predicted sea-level values.

6. Conclusions

The extensive data-set provided by our surveys was used to estimate the rates of relative sea level changes occurring along the coasts of the Murge plateau within the Mediterranean basin, as well as the rates of sea level rise as of the late Holocene. The studied sites have provided a number of indications that contribute to *i)* validate sea level predictions and estimate sea level rise as of the Late Holocene for the studied region and *ii)* estimate the vertical land movements of the southern Murge plateau with respect to the nearby Apulia areas.

With regards to point *i)*, the mouths of the drainage and sewer channels in Egnatia, San Vito, and Torre Santa Sabina have small functional heights providing good constraints on the past sea levels. The last column in Table 1 shows the predicted relative sea level change in the studied sites from the time of their construction. In particular, the data from the study of the hut pole-holes surveyed in Torre Santa Sabina and in Torre Guaceto suggest a sea level rise from the Bronze Age of at least 2.25 ± 0.20 m, at a rate of about 0.6 mm/yr^{-1}. Moreover, for more recent times, sites 1 and 13 suggest a sea level rise of $0.87\div0.90 \pm 0.20$ m during the last 2000/1500 years, at the same rate of 0.6 mm/yr^{-1}. Unfortunately, only few data are available for the past 1000 years. The sluice gate in the San Vito channel provided the most significant archaeological constraint for sea level reconstruction, but is still difficult to interpret. The incongruity between the chronology provided by the historical sources, its elevation, and the predicted sea levels for this location is debated. The elevation of the San Vito channel, which has been carved into the bedrock and connecting the fish tank with the open sea, suggests the Roman Age, rather than the Middle Ages, although the archival, historical, and architectural evidence does not support this interpretation. Therefore, this channel remains an open question requiring further investigation.

With regards to point *ii)*, the available data, compared to the predicted sea level, are in agreement with the vertical tectonic stability/low rate uplift of the Ionian and Adriatic sides of the Murge area. The recognised behaviour is in contrast with paleontological, morphological, and archaeological data available for the nearby Salento area. On the other hand, the geology and the recent tectonic history of the Salento area in the context of the Euroasia and Africa plate kinematics is still a question of debate (Serpelloni et al., 2005). Therefore, a comparison with similar data from the facing coasts of Albania should be useful to support our investigations.

Finally, the archaeological sea level indicators of this region contributed to fill the gap between geological and instrumental data to estimate local sea level changes. Results will also contribute to drawing future coastal flooding scenarios, indicating that, in the absence of significant vertical land movements, possible flooding of the Murge coastal areas that may occur in the next decades as a result of global warming, will be mainly conditioned by the eustatic sea level rise, which has been dramatically increasing in recent years.

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