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Giuseppe MASTRONUZZI [1,2*], Maurillio MILELLA [2], Arcangelo PISCITELLI [2],
Oronzo SIMONE [3], Gianluca QUARTA [4], Teodoro SCARANO [5,6],
Lucio CALCAGNILE [4] & Italo SPADA [7]

LANDSCAPE ANALYSIS IN TORRE GUACETO AREA (BRINDISI) AIMED AT THE RECONSTRUCTION OF THE LATE HOLOCENE SEA LEVEL CURVE

Abstract: Mastronuzzi G., Milella M., Piscitelli A., Simone O., Quarta G., Scarano T., Calcagnile L. & Spada I., *Landscape analysis in Torre Guaceto area (Brindisi) aimed at the reconstruction of the late Holocene sea level curve.* (IT ISSN 0391-9838, 2018).

This paper focuses on four different cores drilled in the Area Marina Protetta e Riserva dello Stato di Torre Guaceto (Carovigno, Brindisi). The stratigraphic, sedimentological and paleontological characteristics were related to the geomorphologic features of the whole area and to the radiometric dating of the peaty levels identified in the stratigraphic sequence; the results have been compared with the available geo-archaeological data. The complete data-set allowed to reconstruct the succession of sedimentary environments over time and to place these across the last 2200 years, thanks to radiometric dating. In the stratigraphic sequence, it was possible to highlight layers that indicate coastal areas marked by the presence of inlets in connection with the sea, areas submerged during tides and brackish or continental areas. In particular, the research demonstrated, with good approximation, that the sea level had to be stationed at about -1.1 ± 0.1 m approximately 2200 years BP; then it went to about -0.65 ± 0.1 m about 1900 years BP and continued its rise to the current position. Finally, the comparison of the stratigraphic data with the geophysical predicted sea level curve for the late Holocene indicates that vertical movements in this span of time did not affect this area. This confirms what has recently been established for this area as regards the stability of the Adriatic side of the Apulian foreland.

Key Words: sea level change; coastal landscape, coastal environment, Torre Guaceto, Puglia, Italy

Riassunto: Mastronuzzi G., Milella M., Piscitelli A., Simone O., Quarta G., Scarano T., Calcagnile L. & Spada I., *Analisi del paesaggio di Torre Guaceto (Brindisi) per la ricostruzione delle variazioni tardo oloceniche del livello del mare.* (IT ISSN 0391-9838, 2018).

Nell'Area Marina protetta e Riserva dello Stato di Torre Guaceto, presso Carovigno in Provincia di Brindisi, sono stati realizzati quattro differenti carotaggi. Le caratteristiche stratigrafiche, sedimentologiche e della malacofauna contenuta sono state messe in relazione con quelle geomorfologiche dell'area di studio e con datazioni radiometriche di livelli di torba provenienti dai carotaggi, oltre che correlate con dati geoarcheologici derivanti da studi precedenti. L'insieme dei dati disponibili ha permesso di ricostruire la successione degli ambienti sedimentari nel tempo e di collocare questi, grazie alle datazioni radiometriche, negli ultimi 2200 anni circa. Aree costiere segnate dalla presenza di insenature in connessione con il mare, aree inondate durante le maree e aree salmastre o schiettamente continentali sono riconoscibili nei carotaggi. In particolare, è possibile affermare con buona approssimazione che il livello del mare dovette stazionare a circa -1.1 ± 0.1 m circa 2200 anni dal presente per poi passare a circa -0.65 ± 0.1 m circa 1900 anni e quindi continuare la sua risalita sino alla posizione attuale. Infine, il confronto con le più recenti curve di variazioni del livello del mare relative al tardo Olocene indicano che quest'area non è stata interessata da movimenti verticali in questo intervallo di tempo, confermando quanto recentemente appurato per questa zona dell'avampaese Apulo.

Termini chiave: variazioni del livello del mare, paesaggio costiero; ambiente costiero, Torre Guaceto, Puglia, Italia.

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INTRODUCTION

The instantaneous sea level derives from the equilibrium between the water mass available for the oceanic basins and the land movements. Water quantity is a function of the ice caps extension, which is influenced by climatic changes. At different time scale, geodynamic, tectonic and climatic factors – these last ones, up to the recent, only astronomically conditioned – all together define the global (eustatic) and local (relative) sea level and draw the coastal landscape. Its articulation and extension are both functions of the continental and marine processes that discharge their energy depending on the sea level position, which defines the morphological diversity of the coastal area and a series of condition for the biological activity (e.g.: Cowell & Thom, 1994; Mastronuzzi & *alii*, 2005; 2017a; Mastronuzzi & Sansò, 2006 and references therein). The Earth movements and changing geodynamic and climatic factors cause the constant changes in the sea level: this never stabilizes all along the coasts of the whole world (Mörner, 1986). The coastal landscape records the local (relative) sea level changes; in the case of tectonically stable areas, it corresponds to the eustatic one. Conservative coasts like lagoons, marshes and swamps keep traces of sea level change in the sedimentary sequences, whereas sea movements and bioactivities sculpture rocky coasts. Both those coastal systems derive their structure from a temporary stability of the balance of mass and energy connected to every sea level standing during a long-term eustatic change (e.g.: Antonioli & *alii*, 2015). This is due to ice caps melting, which can cause significant sea level changes, up to one hundred and fifty meters of within some thousands of years. The corresponding sea level defined in a limited coastal area derives from the sum of the eustatic contributions with the glacio-hydro isostasy and tectonics components (Lambeck & Purcell, 2005; Lambeck & *alii*, 2004; 2011). The last 20 ka of the history of the Earth have been characterised by a general warming that caused the melting of the continental ice caps and the world wide rapid eustatic sea level rise from the LGM up to about 6/7 ka BP (e.g.: Antonioli & *alii*, 2009). During the initial phase, the coastal landscape was quickly built, submerged and destroyed, whereas during the last 6 millennia the decrease of the sea level rise rate allowed the gradual submersion of the coastal landscape and, when possible, its slow inland migration.

This last phenomenon – more or less explained by Bruun's model (Bruun, 1962) and other theories (e.g.: Lorenzo-Trueba & *alii*, 2014) – was possible in particular for the "mobile coasts" characterised by the presence of beach-dune systems, lagoons, marshes, swamps, river mouths, coastal plains and lakes, functionally related to each others. The coasts of the Mediterranean basin do not represent an exception and there are several studies that highlight how coastal surveys can identify sea level history, environmental changes, impact of tsunamis and storms in conservative environments (e.g.: De Martini & *alii*, 2003, 2010; Amorosi & *alii*, 2004; Caldara & Simone, 2005; Switzer & Jones, 2008; Vott & *alii*, 2008; Primavera & *alii*, 2011; Di Rita & *alii*, 2011; Smedile & *alii*, 2011; Orru & *alii*, 2014 and references therein). The predictive geophysical model based on multidisciplinary surveys of the sea level markers, chronologically attributed to the Holocene transgression, generally confirms the recent sea level history (Lambeck & *alii*, 2004, 2011). On the other hand, in order to improve the dataset that allowed its construction, more detailed field surveys are needed; geological, geomorphological and archaeological sea level markers together with well defined chronological constrains (radiometric or archaeological ones) can contribute to a better definition of the predictive relative sea level model (e.g.: Auriemma & Solinas, 2009; Anzidei & *alii*, 2011, Mastronuzzi & *alii*, 2017b and references therein). This research approach may be particularly effective if the data used in the study come from areas considered stable at long time scale. In the context of the Mediterranean basin, which is really complex from a geodynamic point of view (e.g.: Anzidei & *alii*, 2014), the Adriatic side of the Murgia plateau – part of the Apulian foreland – might play a key role in the study of the Holocene sea level change due to its stability at medium-long time scale. The presence of archaeological coastal sites and the microtidal regime allow estimating the sea level change along the rocky coasts with a small error bar (e.g.: Mastronuzzi & Sansò, 2002a, Ferranti & *alii*, 2006; Antonioli & *alii*, 2009; Mastronuzzi & *alii*, 2017b). On the other hand, due to the prevalence of rocky coasts in this area, until now there has been no study by using cores derived from wetlands, with the exception of the rich – but local – dataset from the Gargano Promontory, Tavoliere delle Puglia plain to the North (Caldara & *alii*, 2008; Caldara & Simone, 2005; Di Rita & *alii*, 2011) and from the Alimini Lakes in the Southernmost Salento (Primavera & *alii*, 2011). When compared to the Murgia area, both these areas seem to have had different geodynamic behaviours during the Pleistocene and, maybe, also during the Holocene.

In the following page, an interdisciplinary dataset (geological, radiometric, paleontological and morphological) deriving from news surveys performed in the wetlands of the Natural Reserve and Protected Marine Area of Torre Guaceto (Carovigno, Brindisi) (fig. 1) is presented and analyzed together with some data deriving from the geoarchaeological studies carried out recently along the Adriatic side of the Murgia Plateau (Milella & *alii*, 2006; Scarano & *alii*, 2008; Scarano & Guglielmino, 2017; Mastronuzzi & *alii*, 2017b and references therein). The following pages aim to:

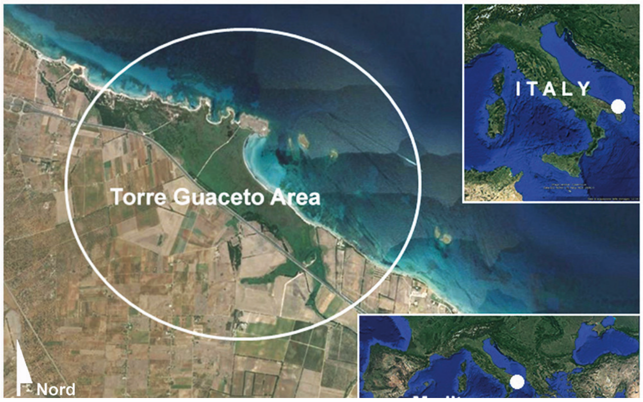

FIG. 1 - Location of studied area.

i) recognize the change in physical landscape; ii) reconstruct the sea level history of the South Adriatic; iii) validate the efficiency of the most recent regional geophysical model of relative sea level changes.

GEOMORPHOLOGIC FEATURES AND HUMAN SETTLEMENTS

The Natural Reserve and Protected Marine Area of Torre Guaceto (fig. 2) extends for about 1000 ha inland and 2000 ha seaward along 8 km of the Adriatic coast of Apulia on the limit between three well defined morphological areas: the Murge plateau inland and the pediment of Fasano and the Brindisi plain seaward; these last two are separated by the Canale Reale river that crosses over the Torre Guaceto area (Mastronuzzi & *alii*, 2011; Mastronuzzi & Sansò, 2017).

To the North of Canale Reale, the landscape is dominated by a low climbed surface which extends from the feet of the Murgia scarp to the sea level shaped on the Mesozoic unit of the Calcari di Bari and on the Cenozoic unit of Calcarenite di Gravina Fm (Late Pliocene - Early Pleistocene); seaward, the surface is covered discontinuously by more recent deposits which consist of a cemented beach-dune system ascribed to the last interglacial time (LIT), in turn ascribed to the high sea level stand occurred on 125 ka (Late Pleistocene, MIS 5.5). The surface and the body of Calcarenite di Gravina Fm are crossed by well-defined incisions that show the features of "box valleys" due to sapping processes (Mastronuzzi & Sansò, 2002a), locally named "lame". Seaward, sapping valleys cut the Pleistocene sedimentary cover and the LIT dune belts – beach sediments; this indicates that they were formed due to the increase of the relief energy, caused by the lowering of the sea level, which was connected to the cooling of the last glacial time (LGT). Sapping valleys are well distinct also below the present sea level, as for example just below the tower that gives the name to the studied area. They extend up to a depth probably corresponding to the interface between the Mesozoic and Cenozoic units. Their maximum shaping may correspond to the lowermost sea level stand occurred about 20 ka BP during the Last Glacial Maximum (LGM). The relative frequency of these incisions draws a very indented coastline locally named "*costa merlata*" (= crowned coast) marked by narrow and deep inlets (fig. 2). Usually, they host small beaches, surrounded inland by low dunes (Mastronuzzi & Sansò, 2002b).

FIG. 2 - The promontory of Torre Guaceto is sculptured on a sequence of Calcarenite di Gravina (Late Pliocene - Early Pleistocene) overlayered by a younger calcarenite ascribed to the Late Pleistocene - Tyrrhenian (generic MIS5). On the left is the marsh-swamp area and in the back is the inlets with pocket beaches.

To the south of the Canale Reale, Calcarenite di Gravina Fm is covered by Middle Pleistocene sandy-silt units and, on top of those, by the beach-dune system of the LIT. In this area the coastline is more regular and marked by cliffs, not higher than 3 m, in rapid regression. The relict of the beach system of the MIS 5.5 constitutes the top of the small islands placed along the Torre Guaceto area, since they were isolated by the sea level rise during the last phases of the Holocene transgression. Where inlets are larger, poliphasic stationary beach-dune systems tend to isolate coastal lakes; they are represented by aeolianites partially cemented, ascribed to three phases of dune shaping occurred since the Middle Holocene (Mastronuzzi & Sansò, 2002b).

During the Bronze Age and the historical time, inlets facilitated the maritime traffic allowing the use of sheltered areas to load/unload ships used for coastal trade and supply of fresh water. The uninterrupted human occupation from the Bronze Age up to the Middle Ages along the Adriatic coasts of the Murge plateau allows us to collect numerous archaeological markers of the past sea level stands useful in the reconstruction of its history (e.g.: Auriemma & *alii*, 2005; Scarano & *alii*, 2008; Mastronuzzi & *alii*, 2017b). In particular, Torre Guaceto has been well known as a safe harbour since ancient times; the name seems to derive from the arabic word *gawsit* that means "place of the fresh water" supplied by the springs, the extended marshes and the Apani and Reale streams (Scarano & *alii*, 2008). In the 2nd millennium BC walled settlements were placed in the areas of the present Torre Guaceto promontory and Scogli di Apani islets that towered over the salt and swampy territories (Mastronuzzi & *alii*, 2017b). Hundreds of postholes of varying shapes and sizes occur along the washed and eroded coastal profiles, now some centimetres below the current mean sea level, testifying to the presence of large villages during the Bronze Age. In most recent times, sandstone quarries dating to the Late Middle Ages were carved in coastal zones and right now they are some centimetres below the mean current sea level. Both these archaeological remains suggest that mean sea level was about 2.25 ± 0.2 m below the current one at 3.5 ka BP and about 0.9 ± 0.2 m below the current one between the 1st Century BC and 1500 AD (Mastronuzzi & *alii*, 2017b).

MATERIAL AND METHODS

Immediately behind the promontory that hosts Torre Guaceto (fig. 2), there is a marsh area limited by beaches with low dunes. The area was extensively reclaimed during the last century; so, stratigraphically, it does not contain natural features although the wildness of its current biological environments. The only area never involved in the reclamation process is placed on its southern limit, at the border of Canale Reale. This area has been chosen to coring up to the local basement. In the entire area, four different cores (fig. 3; tab. 1) have been drilled; only in correspondence of the site TGS3 and TGS4 it was possible to reach the Calcarenie di Gravina formation. Cores have been drilled using a "Peatsampler set Eijkelkamp"; this tool allows to collect different samples of 0.5 m each. The longest core (TGS4 – about 2.5 m below the present topographic surface = b.p.t.s.) is the sum of three different segments made by levelling each base to the top of the closest and deepest one (fig. 4).

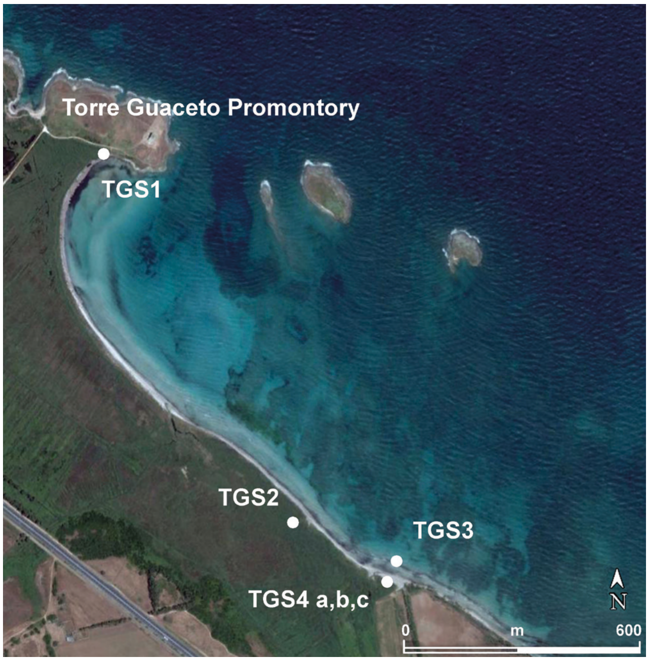

FIG. 3 - Coring sites location.

Both data collection and analysis were carried out through six succeeding steps: i) elevation measurements of the topographic surface on which core were drilled; 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) paleontological analysis of the level documented in the core; iv) AMS age determinations of the peat documented in the level that suggested a sea level stand; v) correlation of the observed sea levels with the bibliographic data on sea level changes supplied by archaeological indicators; vi) comparison of the obtained sea level curve with the geophysical models (Lambeck & *alii*, 2004, 2011).

The elevation of the top of the cores has been determined with respect to the instantaneous sea level using optical and mechanical instruments in condition of calm sea; this aimed at the georeferencing by DGPS technique of each core that was performed.

The studied area, as all the Apulian coast, has the micro-tidal features of the majority of the Mediterranean basin; here the tidal range is within 0.45 cm (www.idromare.it). In order to reduce the topographical elevation data to a local mean sea level, tidal data from the nearest tide gauge station located in Bari were used during the surveys. The mean sea level of the Bari tide gauge station has been chosen after a correction of the instantaneous sea level in function of the barometric features surveyed at the time of the coring, according to the methodology proposed by Anzidei & *alii* (2011). In particular, core TGS4 was drilled at 09.45 local time (07.45 London GMT) on 2015, June 23 (fig. 5); the top of the core was at + 0.52 m above the instantaneous sea level in condition of high pressure (about 1017 hPa). The hydrometric sea level in tide gauge station of Bari is lower of that ISPRA of about 0.25 m. This means that at the moment of the sampling the core top was 0.12 m above the local mean sea level. Considering the local tidal range, the core was sampled in the intertidal area. Moreover, the compaction due to the coring activities suggests that the depth of the samples could be considered with respect to the local mean sea level with a vertical error bar of ± 0.1 m.

In the third phase, the stratigraphic description of the sampled corers has been limited to the core TGS4 (for a total lenght of about 2.5 m) and to the core TGS3 (for a lenght of 1.0 m corresponding to the lowest section of core TGS4)

TABLE 1 - Observational data for the analyzed sites; depth must be considered with an error bar of about ± 0.1 m (see text) (a.i.s.l. = above instantaneous sea level; a.p.m.s.l. above current mean sea level referred to the ISPRA).

Core	Latitude (N)	Longitude (E Gr)	Environment	Surveyed elevation (m a.i.s.l.)	Corrected elevation (m a.p.m.s.l.)	Depth (m)	Local basement
TGS4c	40° 42' 17"	17° 48' 22"	dune crest	1.5	1.12	-	TGS4b
TGS4b	40° 42' 17"	17° 48' 22"	dune base	0.7	0.32	-	TGS4a
TGS4a	40° 42' 17"	17° 48' 22"	shoreface	0.52	0.12	1.15	Calcarenite di Gravina Fm
TGS3	40° 42' 18"	17° 48' 23"	submerged beach	-0.3	-0.42	1.0	Calcarenite di Gravina Fm
TGS1	40° 42' 53"	17° 47' 54"	back beach	0.6	0.2	0.35	Late Pleistocene calcarenite
TGS2	40° 42' 24"	17° 48' 12"	marsh	0.7	0.3	-	vegetation

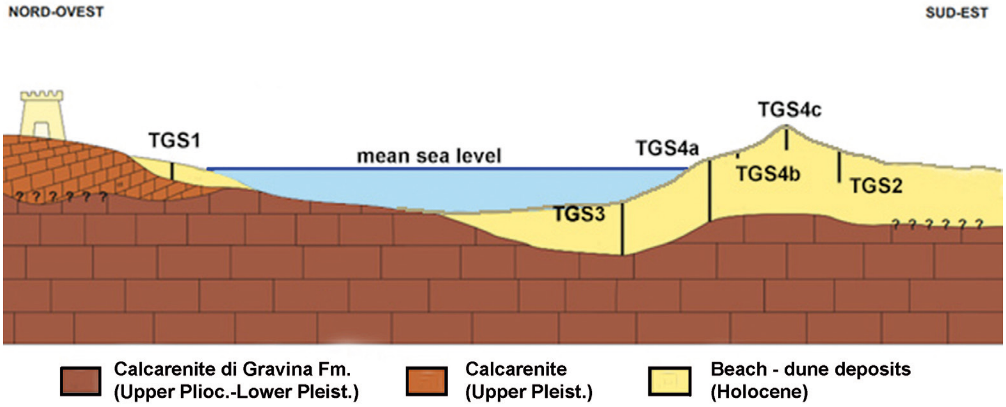

FIG. 4 - Schematic relation between different cores.

FIG. 5 - Area in which core TGS4 was drilled; in the insert a sketch of the relations between TGS4a, b and c segments are shown (horizontal scale is only indicative).

(figg. 6 and 7). They have been collected respectively on the present shore face/dune area and in the submerged beach. Afterwards, detailed descriptive analyses were carried out on the TSG4 core, due to the complete correspondence between the stratigraphy identifiable in the TGS4c segment and to the TGS3 core. Different levels have been identified due to their macroscopic features like difference in colour and granulometry, content in malacofauna, etc. Samples have been collected for every change in these features and, in particular, in correspondence of presumable organic levels marked by dark grey/black colour or shells. When apparent homogeneity represented a significant thickness of the stratigraphy, more samples at different depth were collected. A total of 25 samples were analysed for an average distribution of 1 sample every 0.1 m (fig. 6b) investigating faunal assemblage for environmental reconstruction and, in case of environments indicative of the sea level, to identify materials which could be useful for ^{14}C age determinations. Samples have been wet-sieved in fresh water without any use of chemicals to avoid the destruction of the organic components. They were sifted using 500 µm and 63 µm pore sieves. The coarsest fraction was used for the study of macro-fossiliferous assemblages, essentially malacofauna; the finest was examined for the study of the microfauna represented by foraminifera and ostracods. The entire assemblage allowed identifying four different levels that suggest the sea level with an elevated approximation and a low error bar. Samples of "peat" derived by them were submitted for AMS age determinations (tab. 2).

Their age has been established by means of AMS (Accelerator Mass Spectrometry) radiocarbon determinations performed at CEDAD (Centre for Dating and Diagnostics), at the University of Salento (Calcagnile & *alii*, 2004).

The analysis of the selected samples by means of an optical microscope allowed highlighting the possible presence of particles of contaminants and exogenous mate-

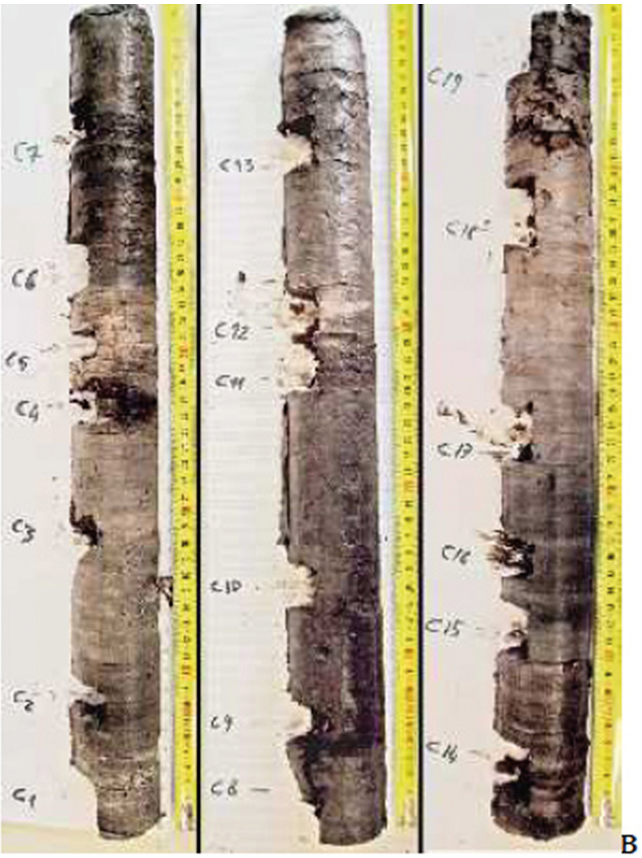

FIG. 6 - A) part of the TGS4 core still in the peat sampler and B) the entire TGS4a core from the bottom (left) to the top (right) on which analyzed samples are indicated.

rials, which were removed by handpicking. The samples were then chemically processed following the protocol employed for organic sediments and consisting in a first strong acid attack with HCl in order to remove the inorganic, carbonatic fraction followed by an alkali (NaOH) and a final acid (HCl) attack. From all the selected samples it was possible to extract a quantity of organic material sufficient for the AMS analysis. The AMS analysis were carried out with the 3MVTandetron accelerator installed at CEDAD (Calcagnile & *alii*, 2005) on the graphite obtained through the catalytic reduction of the carbon dioxide obtained from the combustion at 900 °C of the purified fraction of the samples (D'Elia & *alii*, 2004). Conventional radiocarbon ages were calculated from the measured $^{14}C/^{12}C$ ratios after correction for machine and processing background and isotopic fractionation as detailed by Stuiver & Polach (1977). Measurement uncertainty was calculated as the largest between the scattering of the ten repeated measurements carried out on each sample and the radiocarbon counting error (tab. 2).

STRATIGRAPHY AND ENVIRONMENTS RECONSTRUCTION

The core TGS4 (fig. 6) cuts a Holocene sediment succession overlying the local basement (Calcarenite di Gravina Fm). The succession (fig. 7) could be split in two intervals; the lower (up to about 0.4 m a.p.m.s.l., samples 1-18) is characterised by a succession of alternating clay, silty clay, silt and fine sand, interbedded with thin dark horizons, mostly made of vegetal organic matter, whose aspect recalls a peat accumulation. The most recent part of the succession (samples 19-25) turned out to be made of loose fine and medium-sized sand.

The stratigraphic sequence is described from the bottom to the top as follows. Several among the most representative biological remains are shown in figg. 8-11.

1) *Section 1 (samples 1-4)*: shallow brackish water environment.

Grayish mud and fine sand horizons thickly interbedded with organic deposits. Locally the sediment is made up of partially decomposed vegetal material (e.g., samples 1 and 4).

Mollusc assemblages are rich in individuals belonging to few species. The gastropods found are mainly attributable to the Hydrobiidae Family, among which were identified *Hydrobia acuta* and *Ecrobia ventrosa*. Young specimens of *Cerastoderma glaucum*, *Abra* cf. *segmentum* and fragments of Lucinidae represent bivalves; rounded (worn-out) fragments of larger valves testify to the presence of adult individuals of these species.

The microfauna is characterised by poor assemblages (few individuals and few species). Foraminifera are mainly

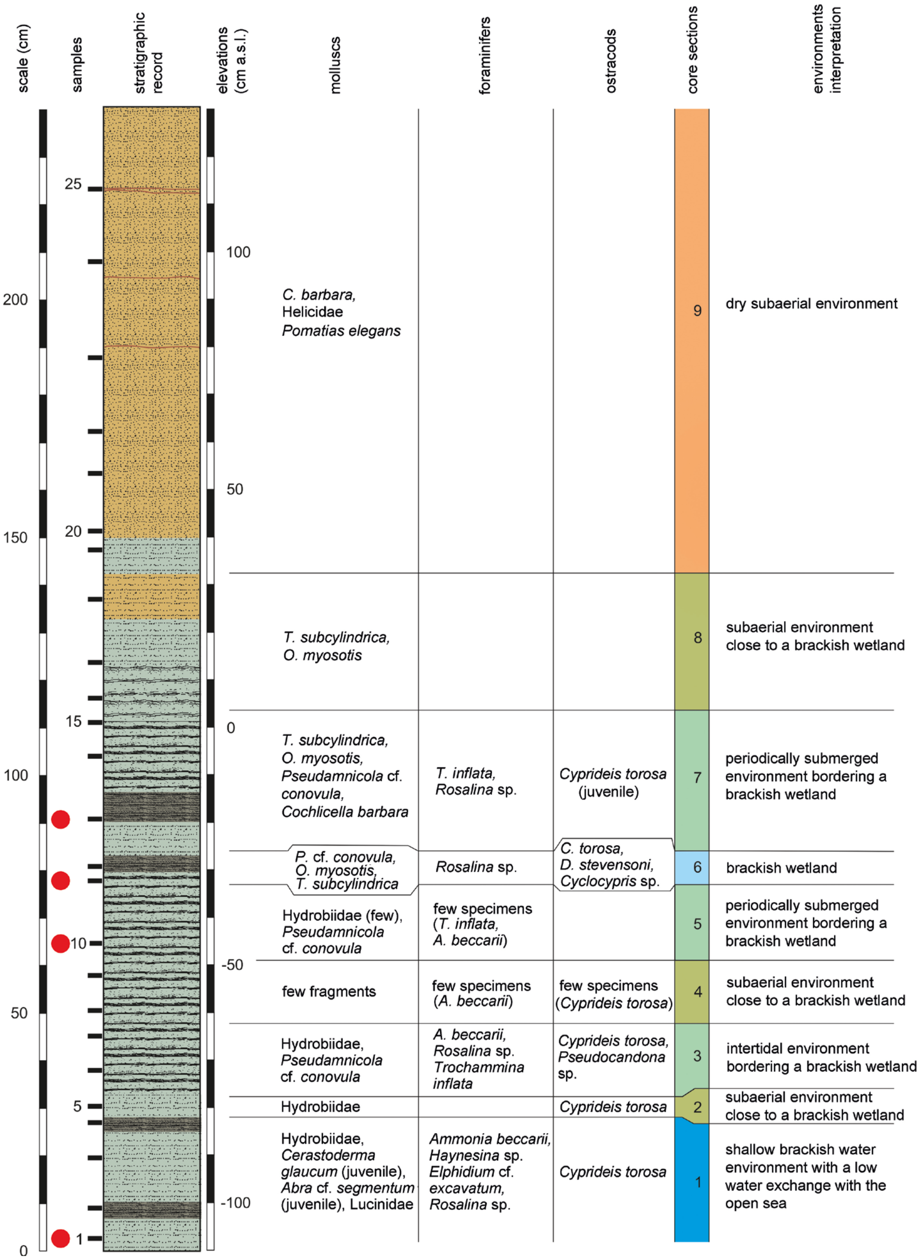

FIG. 7 - Stratigraphy, paleontological data and paleogeographic reconstruction of the entire TGS4 sequence. Red dottes indicate the position of dated samples.

TABLE 2 - Summary of radiocarbon dating analyses. Calibration were performed using CALIB 7.1 (Stuiver & *alii*, 2018).

Sample	Section	Laboraty Code	Material	Elevation m (m.s.l)	Conventional ^{14}C age (BP)	δ^{13} (‰)	Calibrated ^{14}C age (2s)
TGS4 C13	7	LTL16023	peat	-0.3 ± 0.1	1782 ± 45	-21.3 ± 0.6	128 AD - 356 AD (93.6%) 366 AD - 380 AD (1.8%)
TGS4 C11	5	LTL17353A	peat	-0.65 ± 0.1	1895± 45	-24.9 ± 0.1	79 BC - 220 AD (95.2%)
TGS4 C10	5	LTL16022A	peat	-0.75 ± 0.1	2416 ± 45	-25.3 ± 0.5	752 BC - 682 BC (18.1%) 669 BC - 612 BC (9.6%) 593 BC - 399 BC (67.7%)
TGS4 C1	1	LTL16021A	peat	-1.10 ± 0.1	2220 ± 45	-23.3 ± 0.5	390 BC - 184 BC (95.4%)

represented by young tests referable to opportunistic taxa. In particular*, Ammonia beccarii* is dominant on *Haynesina* sp., *Elphidium* cf. *excavatum* and *Rosalina* sp.; frequently, *A. beccarii* tests show irregular coiling and an abnormal proloculus size.

Ostracods are mainly represented by valves of *Cyprideis torosa* belonged to organisms of different ages.

A few vegetal remains have been found scattered within the clayey deposits. These are mainly represented by a few oogonia of the Characeae green algae and seeds of *Ruppia maritima* water plant (samples 3 and 4).

The assemblages found in this section could suggest the main features of the original accumulation environment. *H. acuta* is herbivorous and feeds on aquatic plants, sandy and muddy bottoms (Evagelopoulos & *alii*, 2009). Due to its adaptability, this species can thrive under a large range of salinity conditions and it is commonly found in coastal water bodies such as lagoons, estuaries, hyperhaline ponds and fully marine conditions (Britton, 1985; Evagelopoulos & *alii*, 2007, 2009). *E. ventrosa* (= *Hydrobia ventrosa*) is frequently found in mesohaline waters, such as brackish lagoons (Giusti & Pezzoli, 1984). These two Hydrobiidae species frequently live together (Barnes, 2005) in water basins characterised by a salinity ranging from 2‰ to 34‰, even if they prefer the narrower range 6‰ - 25‰ (Fretter & Graham, 1978).

Bivalves *C. glaucum* and *A. segmentum* are widespread in brackish waters (Pérès & Picard, 1964; Picard, 1965; Pérès, 1967). In particular, *C. glaucum* commonly lives in water bodies characterised by a salinity between 18‰ and 37‰ (Vatova, 1981); *A. segmentum* lives in waters whose salt content is between 14‰ and 27‰. Both species tolerate water salinity as low as 5‰ (Cognetti & Maltagliati, 2000).

The foraminiferal assemblages are dominated by the opportunistic *Ammonia beccarii.* The most represented accompanying species are *Rosalina* sp., *Haynesina* sp. and *Elphidium* cf. *excavatum*.

These foraminifers commonly live in brackish lagoons and river mouths, but are also found in littoral marine waters (Murray, 1991a, 1991b). In particular, A. *beccarii* is considered an opportunistic species, capable to live (and reproduce) in extreme environments, such as polluted areas, water bodies characterised by salinity fluctuations and hyper saline basins (Boltovskoy & *alii*, 1991; Almogi-Labin & *alii*, 1992, 1995; Stouff & *alii*, 1999, Pascual & *alii*, 2002).

The ostracoda are mostly represented by the dominant euryhaline taxon *C. torosa*, usually considered a brackish organism capable to live in environments characterised by varying salinity over short (diurnal) timescales, as well as adjusting to longer-term changes (Boomer & *alii*, 2017). The other accompanying species are represented by a very small number of individuals.

The plant *R. maritima* (whose presence is testified by seeds; fig. 11) grows in clean, well oxygenated and shallow water basins characterised by low hydrodynamics. Considered a brackish plant, it colonises water bodies with salinity conditions ranging from 0‰ to 70‰ (Kantrud, 1991), but do not tolerate quick fluctuations (La Peyree Rowe, 2003).

The Characeae algae (represented by a few oogonia) are generally considered freshwater species.

All these pieces of evidence suggest that the original accumulation environment was a brackish water body characterised by the presence of sea grass meadows. The presence of submerged vegetation is suggested by the occurrence of the foraminifer *Rosalina* sp., an epiphytic taxon that lives attached to flat leaves and stems.

The occurrence of *Characeae oogonia* shows that freshwater environments were not too far from the sampling place.

The collected evidence highlights that possible stress factors affected the deposition environment. In fact, abnormal coiling patterns and few other growth anomalies have been observed on a number of *A. beccarii* tests (fig. 9). Specific studies proved that such kind of phenomena are directly connected to a stressed environment (Boltovskoy & *alii*, 1991; Almogi-Labin & *alii*, 1992; Stouff & *alii*, 1999; Samir, 2000; Geslin & *alii*, 2002). Unfavourable life conditions are also suggested by the structure of faunal assemblages, characterised by few opportunistic species often represented by juvenile individuals that were not able to develop the adult stage.

In brief, the first investigated core section could have been originated in a brackish water body characterised by limited water exchange with the open sea, characterised by environmental instability, possibly due to both natural pollution (decomposing organic matter, low oxygen levels) and rapid fluctuations of salinity and bathymetry.

2) *Section 2 (sample 5)*: subaerial environment close to a brackish wetland.

This section is characterised by greyish silt with secondary weakly cemented calcium carbonate encrustations. Scattered within the sediment, few shell fragments have been found mostly belonging to the Hydrobiidae group. Microfauna is represented by young specimens of the foraminifer *A. beccarii* and few *C. torosa* ostracods. The organisms found occur in small numbers, suggesting an environment not suitable to water life.

These horizons have been interpreted as accumulated in a subaerial environment bordering a brackish wetland.

3) *Section 3 (samples 6-7)*: intertidal environment bordering a brackish wetland.

Dark mud alternating with thin organic horizons made up of vegetal detritus whose aspect recalls a somewhat peaty deposit. The analysed samples (6 and 7) yielded a macrofaunal assemblage characterised by a few species belonging to the Hydrobiidae Family, among which the brackish *H. acuta*, *E. ventrosa* and several *Pseudamnicola* cf. *conovula*.

Microfauna is scarce, mostly represented by *A. beccarii* and *Rosalina* sp.; these species are accompanied by few specimens of *Trochammina inflata*, several of them buried in the early stages of life.

Ostracods are mainly represented by *C. torosa* at different stages of development, several exoskeletons still preserve coupled valves; a few shells of the freshwater species *Pseudocandona* sp. have also been found.

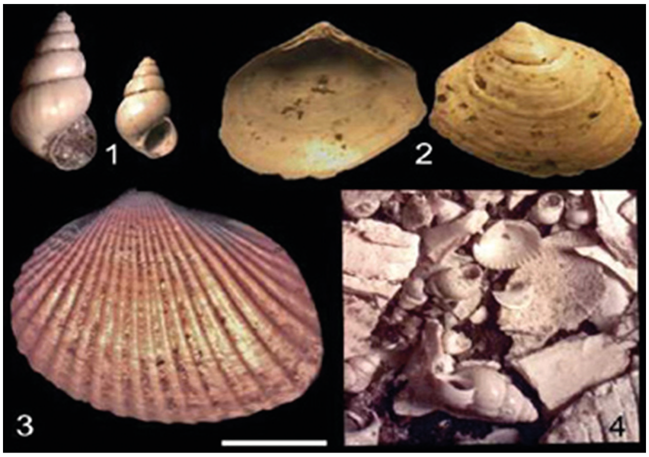

FIG. 8 - The main recognised mollusc species that form the section 1 assemblages are: 1) Hydrobiidae; 2) *Abra segmentum*; 3) *Cerastoderma glaucum*; the inset 4) shows how the samples appear after their preparation (scale: 2 mm).

FIG. 9 - Microfauna is characterised by a few species; the most represented are the foraminifers 1) *A. beccarii*; 2) several *A. beccarii* individuals show abnormal tests; 3) *T. inflata*; 4) *Haynesina* sp.; 5) *Rosalina* sp.; 6) the ostracod *Cyprideis torosa* (scale: 1 mm).

The faunal assemblage is characterised by few brackish species accompanied by freshwater organisms. This information, together with the laminated aspect of the deposit, suggests that this part of the succession accumulated in an intertidal zone periodically flooded by brackish waters.

The presence of *T. inflata*, one of the few intertidal foraminifers that live in flat muddy grounds slightly above the mean sea level, covered by halophilic vegetation and periodically submerged by tide, allows a comparison with the "barene" areas of the lagoon of Venice (Favero & Serandrei Barbero, 1981; Serandrei Barbero & *alii*, 2004, 2011).

Finally, the occurrence of freshwater species suggests the occasional inundation by inland waters, possibly channelled.

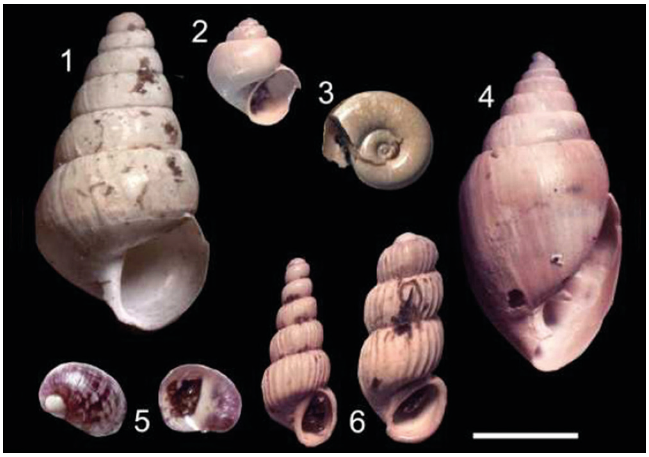

FIG. 10 - Molluscs that characterise sections from 2 to 8; 1) *Cochicella barbara*; 2) *Pseudamnicola* cf. *conovula*; 3) Planorbidae; 4) *Ovatella myosotis*; 5) *Theodoxus fluviatilis*; 6) *Truncatella subcylindrica*, juvenal (left) and adult (right) (scale: 2 mm).

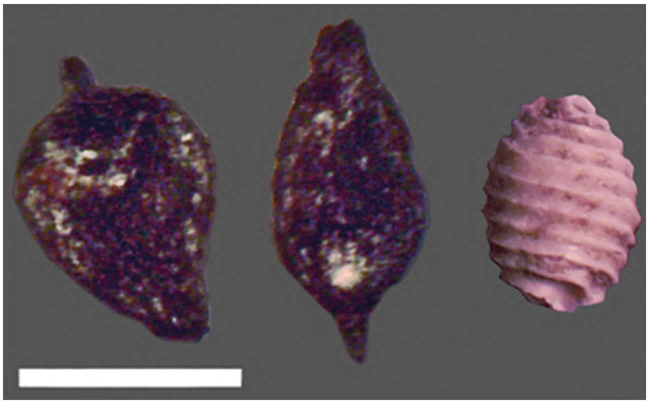

FIG. 11 - Seeds of plant like *R. maritima* and Characeae algae represented by a few oogonia from the TGS4 core (scale: 1 mm).

4) *Section 4 (samples 8-9)*: subaerial environment close to a brackish wetland.

This section shows alternating greyish mud and vegetal detritus laminae with scattered biological remains (a few tests of *A. beccarii*, most likely displaced).

5) *Section 5 (sample 10)*: periodically submerged environment bordering a brackish wetland.

Light greyish mud with scattered lumps of partially decomposed vegetal detritus. The molluscs found are scattered shells of the Hydrobiidae *P.* cf. *conovula*. Foraminifers occur with small sized specimens of *T. inflata*. Several juvenile ostracod valves (*C. torosa*) have been found. Characeae oogonia and *R. maritima* seeds represent few identifiable vegetal remains.

The poor biological assemblages suggest that the original accumulation environment was occasionally (perhaps seasonally) submerged. The occurrence of *T. inflata* suggests the nearby presence of an intertidal area.

6) *Section 6 (samples 11-12)*: brackish wetland.

This section could be subdivided into two intervals a few centimetres thick. The lowest appears thickly laminated due to the presence of thin dark accumulations of partially decomposed vegetal detritus (sample 11); the upper part is mainly constituted by greyish mud (sample 12).

The molluscan assemblages are dominated by the gastropod *P.* cf. *conovula*, the accompanying taxa are *Teodoxus fluviatilis*, *Ovatella myosotis* and *Truncatella subcylindrica.* The Planorbidae Family and the species *Cochlicella barbara* are represented by just one specimen each.

Among the recognised molluscs, two taxa are capable to bear extreme conditions. *O. myosotis* is commonly considered a typical inhabitant of saline environments (Cesari 1976; 1988). This gastropod is widespread, in emerged wetlands not far from water bodies (ponds, lagoons etc.), hiding under stones or dead vegetal remains; adult individuals could tolerate a wide range of salinity (between 0‰ and 90‰). *T. subcylindrica* lives (often buried) on soft muddy bottoms, in either subaqueous or occasionally submerged environments whose salinity ranges from 18‰ to 40‰. It can also be found under hips of decomposing vegetal remains (Fretter & Graham, 1978).

T. fluviatilis is considered an opportunistic species capable to thrive in fresh, brackish and fully marine waters, feeding on flat surfaces such as stones or logs; it easily tolerate low oxygen conditions, but cannot stand long dry periods (Falkner & *alii*, 2001; Zettler & *alii*, 2004; Bunje, 2005).

Among the microfauna, the foraminifer *Rosalina* sp. occurs in numbers; ostracods are mainly represented by *C. torosa*, few individuals of *Cyclocypris* sp. and *Darwinula stevensoni* have been also found.

Characeae algae are represented by few oogonia.

Aside from the occurrence of *Rosalina* sp., microfaunal assemblages seem originated from a somewhat fresh (or slightly brackish) wetland.

In brief, all these pieces of evidence suggest that the original environment was a brackish wetland subjected to periodic inundations from adjacent water bodies (either fresh or saline). In particular, saltwater contribution is testified by the occurrence of brackish molluscs. The presence of the sole foraminifer *Rosalina* sp. (a form living attached on flat surfaces) could be supposed as due to the stranding, from an adjacent brackish or marine environment, of either algae or aquatic plants carrying foraminifers attached to their leaves.

On the other hand, the occurrence of the ostracods *Cyclocypris* sp. and *Darwinula stevensoni* and of the green algae Characeae suggests freshwater inputs from the inland.

7) *Section 7 (samples 13-15)*: periodically submerged environment bordering a brackish wetland.

Greyish mud horizons alternating with partially decomposed dark vegetal detritus. Part of the inorganic components of the deposit is formed by calcium carbonate granules, in some cases encrusting marine shells fragments (sample 14).

Malacofauna is dominated by *T. subcylindrica* and *O. myosotis*, several of them juvenile; a few *P. cf. conovula* shells and *C. barbara* fragments have also been observed. The number of shell fragments seems to decrease upward (sample 15).

Foraminifers (*T. inflata*, *Rosalina* sp. and a number of young unidentifiable individuals) are more represented in the upper part of the section (samples 14 and 15).

Apart from several *C. torosa* specimens, most of ostracod valves belonged to some juvenile individuals not easily identifiable.

Overall, faunal assemblages suggest that the paleoenvironment was a brackish wetland, possibly periodically submerged by tide or by wave overflooding (compare to Section 5).

Finally, from calcium carbonate encrustations that characterise the sample 14 it is possible to hypothesize an episodic super saturation of the interstitial waters caused by a marked evaporation.

8) *Section 8 (samples 16-18)*: subaerial environment close to a brackish wetland.

The section 8 can be subdivided into three parts. The lower tract is characterised by a thick succession of alternating greyish mud and thin dark organic laminae (sample 16). The middle part is made up of greyish laminated mud that, upward, gradually becomes reddish in colour. Under the stereo microscope the sample 18 (upper part of the section) resulted characterised by a number of scattered reddish lumps of residual red earth.

In the whole section the number of shell fragments decreases upwards; the malacofauna resulted mainly composed of the brackish species *O. myosotis* and *T. subcylindrica* whose shells appear often intact and not worn, suggesting a negligible displacement.

Microfauna resulted scarcely represented; the few individuals found belong to the species *A. beccarii* and *C. torosa.*

Faunal assemblages suggest an accumulation occurred in a subaerial environment very close to a shallow brackish water body.

The horizons of this section recorded the early phases of accumulation of sediments originated inland (red earth lumps) and washed inside the basin. The study of the very upper part of the TGS4 core has confirmed this hypothesis.

9) *Section 9 (samples 19-25)*: dry subaerial environment.

The most recent deposits of the studied succession are made up of well-sorted loose fine sands. Bedding surfaces are virtually invisible in the lower part of this interval (samples 19-22) but become apparent upcore (samples 23-25).

Biological remains are scarce and limited to the terrestrial *O. myosotis*, *C. barbara*, *Pomatias elegans* and fragments of Helicidae. Small charcoal fragments represent the vegetal component. The nature of the sediment and the concomitant occurrence of *C. barbara* (lives in dry and vegetated sandy environments not far from the coastline), *P. elegans* (lives on calcareous grounds and sand dunes) and Helicidae suggest that this section accumulated in a back beach-sand dune environment.

DISCUSSION

The palaeontological, geochronological and topographic dataset derived by the TGS4 core, the most representative of the entire drill campaign, allows the morphodynamics evolution of the studied area also thanks to the possible direct correlation with geoarchaeological data deriving from the area of Torre Guaceto and the not far Torre Santa Sabina locality (Carovigno), San Vito (Polignano) and Egnatia (Fasano), all placed at the foot of the Murgia plateau (Scarano & *alii*, 2008; Mastronuzzi & *alii*, 2017b) (fig. 12).

The TGS4 core results from the sum of TGS4a, TGS4b and TGS4c cores; it recorded the local evolution of the sedimentary environments. The lower part of the succession (section 1) originated in an apparently well-established brackish water body characterised by a low but perhaps continuous water exchange with the open sea. The accumulation continued through a series of environments settled at the edge of a brackish wetland. In several cases, these were muddy grounds periodically submerged by shallow brackish waters in intertidal area or by waves flooding exceeding the beach and the embryonal dune (sections 3, 5, 7). In some cases, the accumulation occurred in subaerial (muddy) grounds bordering a brackish wetland (sections 2, 4, 8). A single section of the investigated core originated in a very shallow and brackish water body (section 6). The upper part of the core (section 9) was created in a dry terrestrial environment.

In particular, the lower part of the sequence (sections 1-8) is characterised by soft fine and organic deposits containing remains of opportunistic species whose life is closely related to the paralic domain (either brackish shallow water bodies or somewhat wet environments).

The undisturbed flat laminations, at some levels rich in vegetal organic matter (often assuming the aspect of peaty deposits), the lack of bioturbation (and/or deposit homogenisation), seem to point to a calm environment subjected to rather reducing conditions that hampered the oxidation of the organic compounds. In brief, collected evidence suggests that these sediments accumulated in a wetland dominated by low energy deposition processes. The section 8 recorded the early phases of changing accumulation mechanisms at the coring place. In the upper part of the TGS4 sequence the deposit became a fine reddish loose sand poor in biological remains. The occurrence of terrestrial gastropods and charcoal fragments shows that these deposits accumulated in a dry coastal environment either a beach or dune. The transition between wet and dry environments appears gradual, clearly appreciable, but seems not marked by any erosion surface. Thus, it might be hypothesised that the reddish sand accumulated directly above the brackish horizons without significant interruptions of sedimentation processes.

Actually, the reconstruction of the original sedimentary environments allowed identifying some levels that should correspond to the sea level stands with an error bar of ± 0.1 m. The lowermost (section 1) seems to correspond to an environment that had a continuous, although low, exchange with the open sea. A peaty sample was collected from the lowermost part of this section. Peaty sample submitted to AMS age determinations on the section 1 (TGS4 C1) is the most representative of the position of past sea level stands. This may confirm the identifications of past sea levels with an approximation of ± 0.1 m. The general features indicate with good approximation the sea level. On the other hand, sections 3, 5 and section 7 keep evidence of an environment periodically submerged at the border of brackish wetland suggesting a possible connection to the open sea during the main tide.

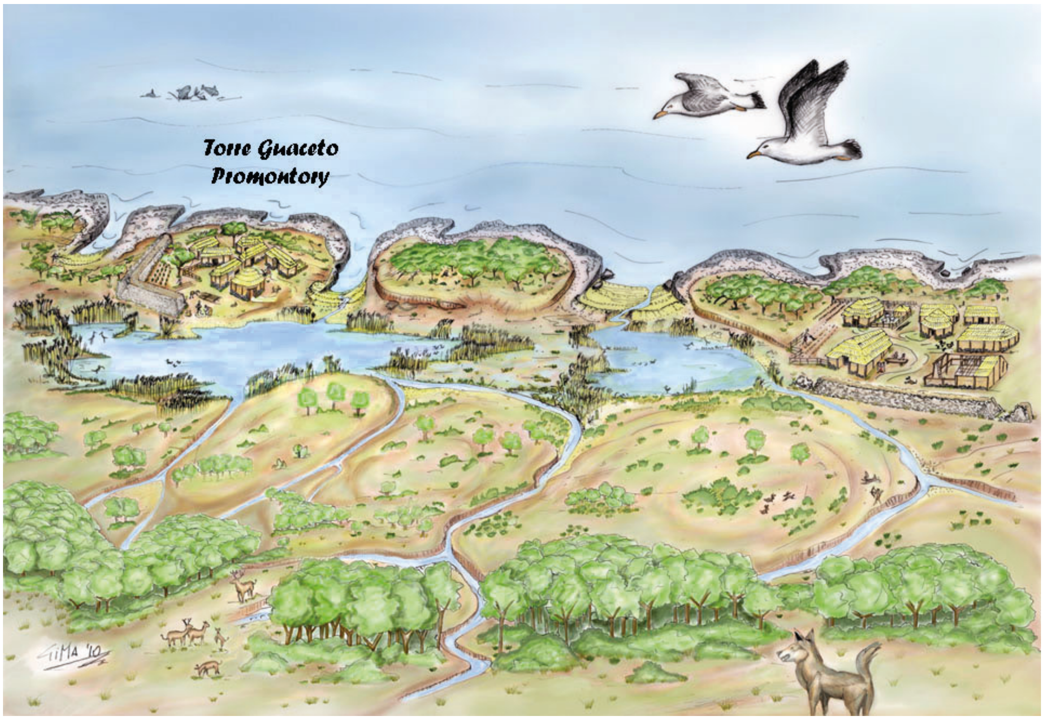

FIG. 12 - Reconstruction of the paleogeography of the Torre Guaceto area during the Bronze age (about 3.5 ka BP).

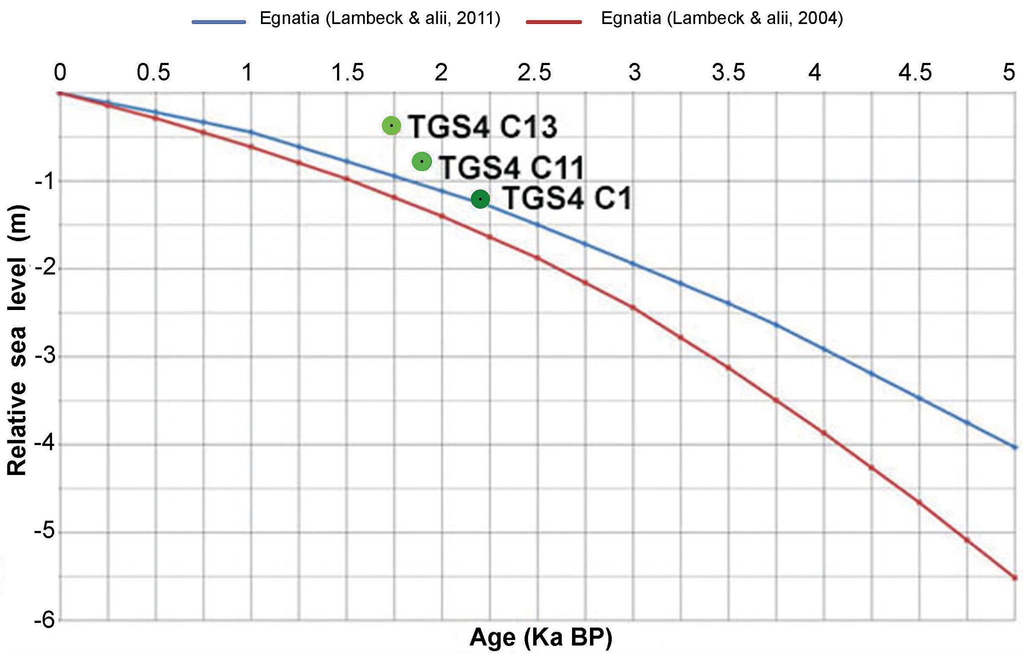

Fig. 13 - Aged samples that indicate possible position of the sea level reported on the relative sea level curve for the studied area fit with the geophysical predictive models. The tonality of green dottes indicates the largest (dark green) or less (light green) significance in the indication of sea level; horizontal diameter indicates the error in the age definition (± 45 years); vertical diameter indicates the error bar in elevation determination (± 0.1 m) (for explanation see text).

Samples were collected in these two sections but not in the section 3 because of lack of material to be analyzed. Samples from these levels were submitted to AMS age determinations; results are shown in tab. 2. Ages obtained from samples TGS4 C1, C11 and C13 seem to be validated by their gradual rejuvenation upward in the core stratigraphy; unluckily, sample TGS4 C10 gave an age that seems to be invalidated by possible re-accumulation. Moreover, it is important to underline that sample TGS4 C13 seems to be less indicative of an intertidal area because of the presence of fragments of marine shell may be re-accumulated not by tide but, probably, by waves that exceeded the beach-dune system or imposed a temporary sea surge in the more sheltered areas of a back dune/lagoon area derived by waves impact.

The chronological correlation with regional geoarchaeological data (Mastronuzzi & *alii*, 2017b) and to the geophysical model of the relative sea level history during the last thousands of years derived by the entire Mediterranean basin (e.g.: Lambeck & *alii*, 2004; 2011; Antonioli & *alii*, 2009; Anzidei & *alii*, 2014), allows to extend the affirmation that during the last two millennia the entire coasts at the foot of Murgia plateau were characterised by a substantial tectonic stability validating the predictive geophysical models (fig. 13). No direct comparisons seem to be possible with sea level curves obtained in the Gargano and Tavoliere delle Puglie areas at the North of Torre Guaceto and respect to that obtained in the Alimini area at the South (Caldara & *alii*., 2008; Caldara & Simone, 2005; Di Rita & *alii*, 2011; Primavera & *alii*, 2011). In fact, these basins are located in geological contexts characterized by different tectonic behaviors.

On the other hand, the correlation with the geophysical models suggests the following reconstruction of the sea level rise:

- the hut postholes surveyed in the near area of Torre Santa Sabina together with those of Torre Guaceto suggest a sea level rise from the Bronze Age (3.5 ka BP) of at least 2.25 ± 0.2 m
- approximately 2200 years BP the sea level stand at about -1.1 ± 0.1 m below the present position; the area of Torre Guaceto was marked by a constellation of islands and inlets already well-identified;
- about 2000 years BP the sea has been stationed at a level of -1.0 ± 0.1 m from the present as suggested by archaeological remains; at this time the coastal strip of Torre Guaceto, was marked by the presence of a beach with a low embrional dune and typical back-beach environments;
- about 1900 years BP the sea level stand at about -0.65 ± 0.1 cm; the presence of a beach may be in progradation allowed the development of a coastal environment with the characteristics of a brackish area;
- approximately 1700 years BP the sea level probably stands for a very short span of time around -0,3 ± 0,1m below the present one; the back beach-dune system, marked by the presence of discontinuous dry area, likely temporarily flooded by waves probably during severe storms;
- from this time and up to about 150 years ago, with the continuous slow rise of the sea level, the coastal area was marked by the vertical and lateral variation between occasionally submerged environments, always close to a brackish area, and a more appropriately emerged environment; the presence of a brackish area is, however, a dominant character in the vertical succession;
- approximately 150 years ago, the rising sea level determined the beach's accumulation that persists up to the present.

CONCLUSIONS

From the study of the palaeontological association, considerable changes in physical landscape have been highlighted. Such changes were characterized by the slow adaptation of the sedimentary environments to the slow sea level rise and to the dynamics imposed in a coastal environment by every change in the hydraulic regimes connected to the rain events and exceptional waves impacts. As a matter of fact, data indicate a natural coastal system – free from any constraint associated with anthropic activity aimed at controlling its physical dynamics – which is particularly prone not only to any sea level change but also changes in wave energy or of drying or humidifying caused by meteorological events on limited areas. They determine the vertical and horizontal expansion/contraction of the biological environments that can persist in a limited span of time up to a new change in the meteorological or in wave climate conditions. At the same time, the malacofauna association together with sedimentological analysis have shown different levels connected to sea level stand, in turn highlighted by salt water features.

Finally, the complete dataset composed of the data deriving from the cores drilled in the Torre Guaceto area and from the archaeological markers as the hut postholes seem to indicate a sea level rise from the Bronze Age at a rate of about 0.6 mm a^{-1}. In more recent times, core TGS4 suggests a sea level rise of about 1,10 m during the last 2200 at a rate of 0.5 mm a^{-1} and finally a sea level rise of about 0.65 m during the last 1900 years (0.3 mm a^{-1}) confirming the sea level position at 0.9 ± 0.2 m about 2.0/1.5 ka inferred geoarchaeological data from this side of Murgia. These data indicate only an average rate for the last 2000 years; they are useful to confirm the trend of sea level changes during the analyzed time span. Nevertheless, the IPCC AR5 curve indicates an impressive increase of the sea level rise since the industrial time at the middle of XIX century; the correspondent sea level rise is assessed at about 2.3 mm a^{-1} between the 1870 and the 2000 AD. At planetary scale, the present sea level rise is valued at about 3 mm a^{-1} with an impressive increase up to 1.8 mm a^{-1} during the last two centuries for the Mediterranean basin. These data highlights the flooding of the Adriatic coastal areas that may occur in the next decades as consequence of the continuous sea level rise induced by the global warming, which has been dramatically increasing in recent years.

With regards to point iii, compared to the predicted sea level, the data available correspond to the supposed tectonic stability/low rate uplift of the Adriatic sides of the Murge area in opposition to the still invaluable Holocene tectonic behaviour of the far area of the Tavoliere delle Puglie or of the Salento area at the south of Canale Reale. Actually, in both case the geodynamic behaviours can be reasonably considered different due to the difference in the geological context; geological, paleontological and geoarchaeological data seem to be in contrast with the data of the Adriatic side of Apulia along the Murge plateau; in particular, additional data on the Salento region could highlight interesting aspects of its recent history in the complex context of the Euroasia and Africa plate kinematics.

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