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The contribution of tectonics to relative sea-level change during the Holocene in coastal south-eastern Sicily: New data from boreholes

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ABSTRACT

In order to detect ongoing vertical crustal movement and assess both tectonic instability and marine invasion risk in the south-eastern Sicily coastal area, Holocene sea-level indicators have been compared to the sea-level curve for the same period. A stratigraphical and sedimentological study, accompanied by ^{14}C AMS dating, has been carried out using seven boreholes in the most depressed coastal sectors, the Catania Plain, the lagoonal environments between Augusta and Siracusa and the Vendicari lagoon south of Siracusa. The distinct boreholes showed irregular transitional successions, represented by infralittoral beach sands, lagoon and brackish marsh deposits. Moreover, ^{14}C AMS dating on gastropod and bivalves collected at various depths indicated a Holocene age for these deposits that lie directly on the Lower-Middle Pleistocene substratum. Taking into account that the infralittoral and lagoon sediments occurring in the analysed coastal areas were deposited during the Holocene sea-level rise and that the gastropod and bivalve fragments sampled in the boreholes are, with good approximation, sea-level indicators, the short-term vertical motion undergone by this region during the Holocene can be estimated. Comparing the sampling depth below the present sea level of the dated shells to the sea-level rising curve for the central-eastern Sicily coast, the coastal plains between Catania and Siracusa resulted involved during the Holocene in tectonic uplifting with rates varying from about 1 mm/y in the Catania area to 0.5 mm/y in the Siracusa area. Conversely, in the same period the south-eastern most coastal sector of Sicily can be considered tectonically stable. These results are comparable to uplift rates obtained from geomorphologic and archaeological sea-level markers and are consistent with a remote effect of the active normal fault system located in the Ionian offshore between Catania and Siracusa.

1. Introduction

Sea level is the general reference for detecting ongoing vertical crustal movement and assessing short- and long-term tectonic instability in coastal areas (Lajoie, 1986). As regards Holocene times, short-term estimations include analysis of tide-gauge data and historical and archaeological information that may indicate apparent sea-level change, whereas long-term crustal movements can be detected by mapping and dating palaeo-sea-level markers and separating the tectonic component from the eustatic and hydro-glacio-isostatic components of the relative sea-level change. In Italy, the contributions from the glacio-hydro-isostatic component of post-glacial sea-level rise have been recently predicted and compared with field data at several coastal sites (Lambeck et al., 2004, 2011; Lambeck and Purcell, 2005; Antonioli et al., 2007).

The Ionian coast of south-eastern Sicily (Fig. 1) is subjected to differential vertical movements, as it is located at the footwall of main seismogenic normal fault segments belonging to the Siculo-Calabrian Rift Zone (SCRZ, see inset in Fig. 1; Monaco and Tortorici, 2000). Moreover, between the Catania Plain to the north and Capo Passero to the south, several lagoon environments and fluvial-coastal plains are prone to marine invasion because of climate change and consequent sea-level rise. In particular, the coastal sector of the Catania Plain, lying at places below the present sea level, is believed to be one of the areas in Italy subject to marine invasion in the future.

The aim of this work is to evaluate the Holocene relative sea-level change and the vertical rate of tectonic movements along the Ionian coastal region of south-eastern Sicily (Fig. 1). The palaeo-sea-level markers used are represented by dated mollusc shells, living at sea level, that have been collected at various depths in boreholes carried out in lagoons or in wetland deposits. In order to detect ongoing vertical crustal movement and assess both tectonic instability and marine invasion risk, Holocene sea-level indicators have been compared with the predicted Holocene sea-level curve for the south-eastern Sicily coast (see Lambeck et al., 2011), based on an absence of tectonic movement but including the isostatic contributions.

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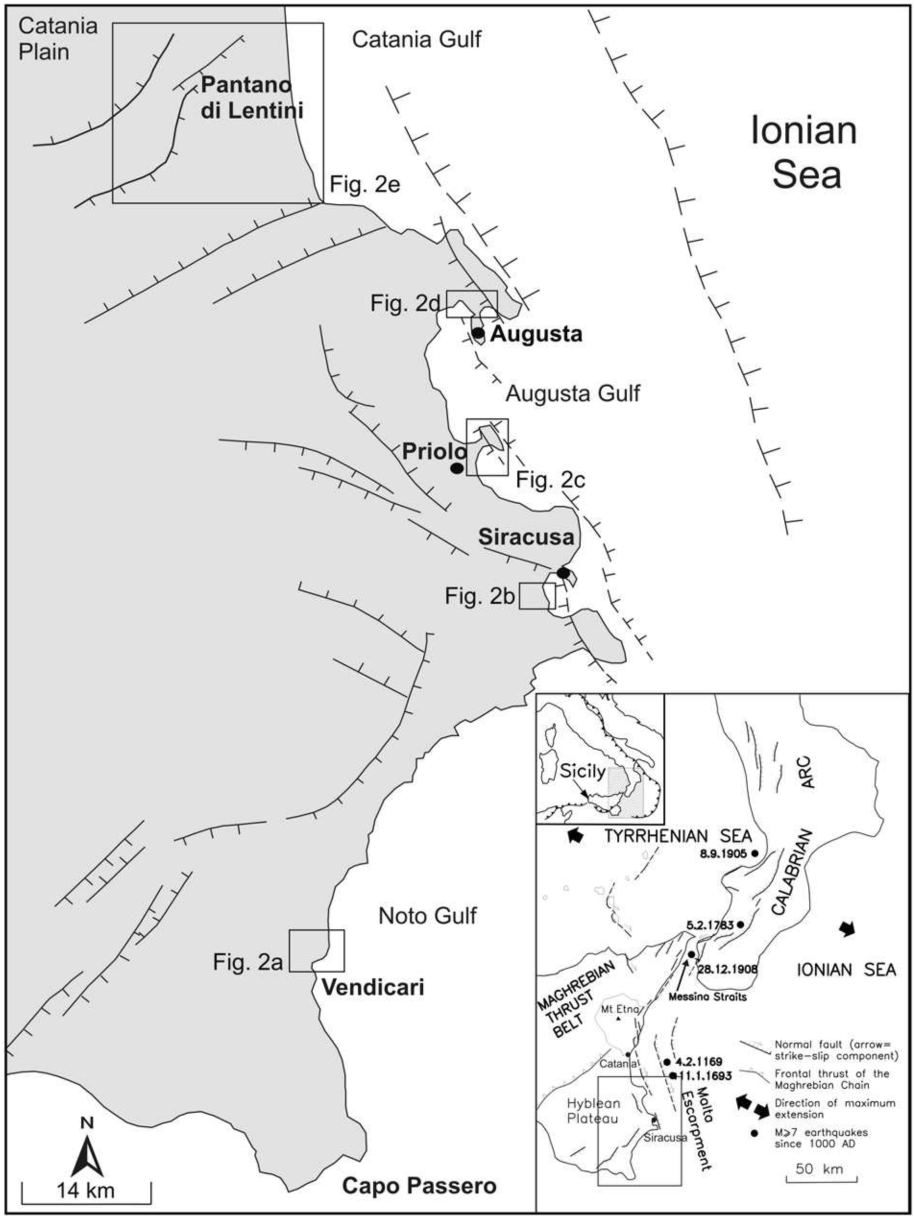

Fig. 1. Geographical position of the studied sites along the Ionian coast of south-eastern Sicily. Inset shows the seismotectonic features of the Siculo-Calabrian rift zone (SCRZ; Monaco et al., 1997; Monaco and Tortorici, 2000) and its location in the central Mediterranean area.

In particular, a stratigraphical and paleoecological study has been carried out using seven boreholes in the most depressed coastal sectors of south-eastern Sicily, from south to north: the Natural Reserve of Vendicari, the Natural Reserve of Ciane River and Saline di Siracusa, the Natural Reserve of Saline di Priolo, the Augusta Saline and the Pantano di Lentini (Figs. 1 and 2). The sedimentary units include lagoonal and coastal deposits that accumulated during the Holocene transgression. Age determinations were obtained by ^{14}C AMS dating of thirteen mollusc shells, representing with good approximation sea-level indicators, collected at various depths in the seven boreholes. This has allowed reconstruction of the Holocene paleogeographic evolution of the investigated coastal areas.

2. Geological setting

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

Since the Early-Middle Pleistocene, active faulting has contributed to continuous extensional deformation from eastern Sicily to western Calabria (Siculo-Calabrian Rift Zone, see inset in Fig. 1; Monaco et al., 1997; Bianca et al., 1999; Monaco and Tortorici, 2000; Jacques et al., 2001). In eastern Sicily, the SSW–NNE striking normal faults are mostly located offshore and control the Ionian coast from Messina to the eastern lower slope of Mt. Etna, joining the NNW–SSE trending system of the Malta Escarpment to the south. This area is marked by a high level of crustal seismicity producing earthquakes with MCS (Mercalli-Cancani-Sieberg)

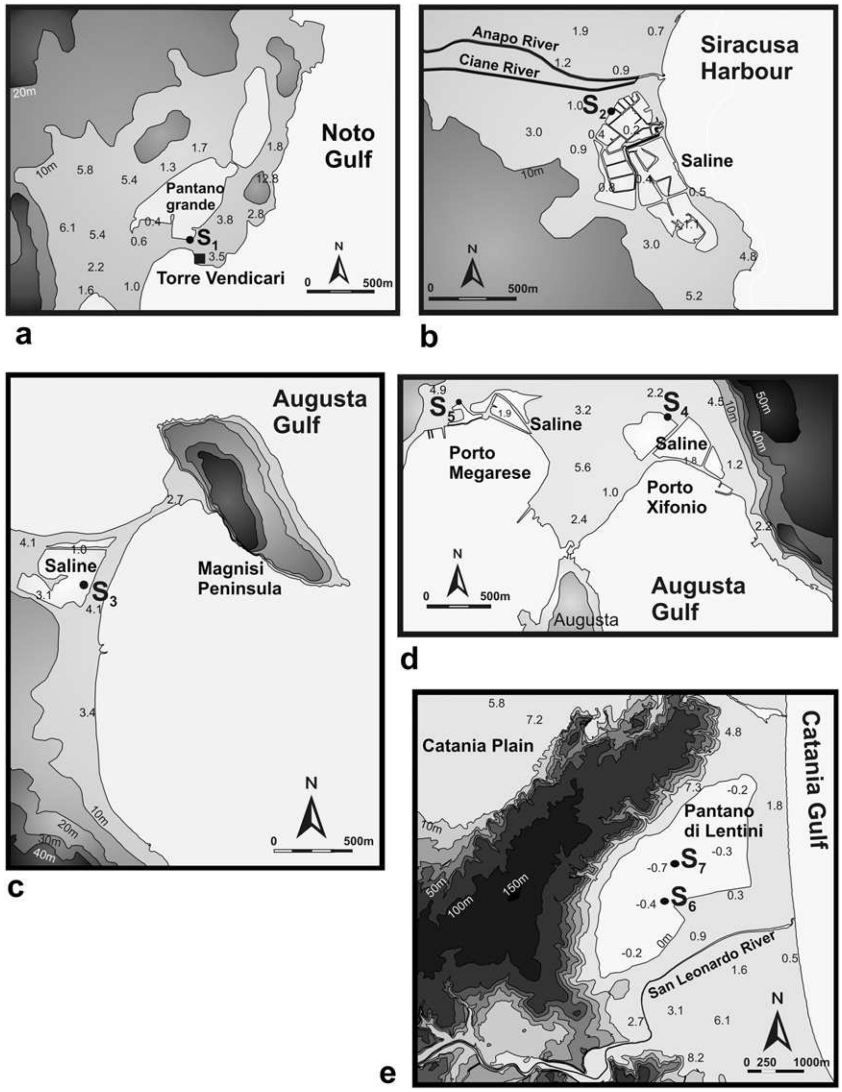

Fig. 2. Sketch maps of the five study areas discussed in the text (see Fig. 1 for location). a) Natural Reserve of Vendicari; b) Natural Reserve of Ciane River and Syracuse Saline; c) Priolo Saline; d) Augusta Saline; e) Pantano di Lentini.

intensities of up to XI–XII and $M \sim 7$, such as the 1169, 1693 and 1908 events (Postpischl, 1985; Boschi et al., 1995). According to most published geological data and numerical modelling, the seismogenic source of these events should be located in the Messina Straits and the Ionian offshore (the Malta Escarpment) between Catania and Siracusa (Postpischl, 1985;Valensise and Pantosti, 1992; Piatanesi and Tinti, 1998; Bianca et al., 1999; Monaco and Tortorici, 2000; Azzaro and Barbano, 2000; Tinti and Armigliato, 2003).

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

The south-eastern Sicily coastal area is located at the southern tip of the Siculo-Calabrian Rift Zone (Fig. 1). In this area, the vertical component of deformation has been recorded by several orders of Middle-Upper Quaternary marine terraces and palaeo-shorelines (Di Grande and Raimondo, 1982), which indicate long-term uplift rates ranging between 0.4 and 0.7 mm/y (Bianca et al., 1999; Dutton et al., 2009). This uplift rate gradually decreases toward the stable areas of the south-eastern corner of Sicily (Antonioli et al., 2006; Ferranti et al., 2006). No data reporting Holocene vertical uplift in the studied area are currently available. Only in the coastal area of the Catania Plain, short-term mean values of 0.5 mm/y have recently been determined (Monaco et al., 2004). New data on Holocene coastal movements are provided in this paper.

3. Borehole data

Seven boreholes have been cored along the Ionian coast of south-eastern Sicily (Fig. 2). The location was dictated by the necessity to cross Holocene lagoon or transitional sediments in order to sample palaeo-sea-level markers such as mollusc shells living at sea level. A stratigraphic and paleoecological study has been carried on the continuously cored boreholes that reached depths ranging between −11.70 and −41.00 m below sea level. Calcareous nannofossils and foraminifera determinations have been carried out in order to recognize the Pleistocene substratum. Stratigraphic analysis was initially based on sediment colour and texture, vertical and lateral lithofacies relationships and on the occurrence of organic matter. Paleoecological analysis was performed on 63 samples, collected at various depths in the seven boreholes, in order to determine the biocoenosis sensu Pères and Picard (1964). The distribution of mollusc thanatocoenoses has been compared with the model of Guelorget and Perthuisot (1983), that considers the paralic environment as an independent ecological domain controlled by the effective distance from the marine domain. Subsequently, the geochronological correlations were verified using the ^{14}C AMS shell dates.

Below, the five distinct lagoon sites where boreholes have been carried out will be listed following their location along the coastline, from south to north (Fig. 2).

3.1. Natural Reserve of Vendicari

The Vendicari lagoon site (Fig. 2a) is one of the most important wetlands in south-eastern Sicily. It extends parallel to the coast for a total length of about 7 km (Amore et al., 1994) and represents the northernmost segment of a paralic system located on the south-eastern border of the Iblean Plateau, along a coastal belt characterized by flat landscape.

At the southernmost sector of one of the lagoons (the Pantano Grande) the borehole S1 (Fig. 3) was cored. The S1 well is located at an altitude of +0.40 m a.s.l. and reaches a depth of 19.90 m below sea level (b.s.l.). Stratigraphic study has shown that the upper 0.50 m consists of brown muds, typical of soil. They overlie infralittoral beach deposits constituted by greyish fine sand with dark brown muddy sand horizons, rich in shell fragments of *Loripes lacteus*, *Venerupis aurea*, *Acanthocardia tuberculata*, *Chamelea gallina*, *Rissoa* spp., *Gibbula* sp., *Cerithium vulgatum* and *Bittium reticulatum.* Below the sand interval, between −4.80 and −14.10 m, brown sandy muds rich in bivalves and gastropods shell fragments, dark brown muddy sands containing gravels and dark organic silts rich in brackish water shell fragments were observed (Fig. 4a). The paleoecological analysis (see below) suggests that this interval is indicative of a lagoon environment. The ^{14}C AMS dating of a *Cerastoderma glaucum* sampled at −5.40 m and of a *C. vulgatum* sampled at −6.90 m yielded calendar ages of 4711–4948 and 5049–5304 cal BP, respectively (samples A and B in Table 1).

The lagoon sediments overlie a deposit of yellowish cemented gravels; at −16.90 m a few decimetres-thick lime layer was observed. The dark clays and silts Pleistocene substratum was reached at a depth of −17.40 m. Sample 13, collected at a depth of −19.40 m, showed an oligotypic fauna of lagoon facies. The ^{14}C AMS dating of a *C. glaucum*, collected at the bottom of this interval, indicates an age not older than 47,000 ± 2000 BP (sample C in Table 1).

3.2. Natural Reserve of Ciane River and Siracusa Saline

The Natural Reserve of Ciane River and Siracusa Saline (Fig. 2b) includes a marshy coastal environment (the Saline) that periodically

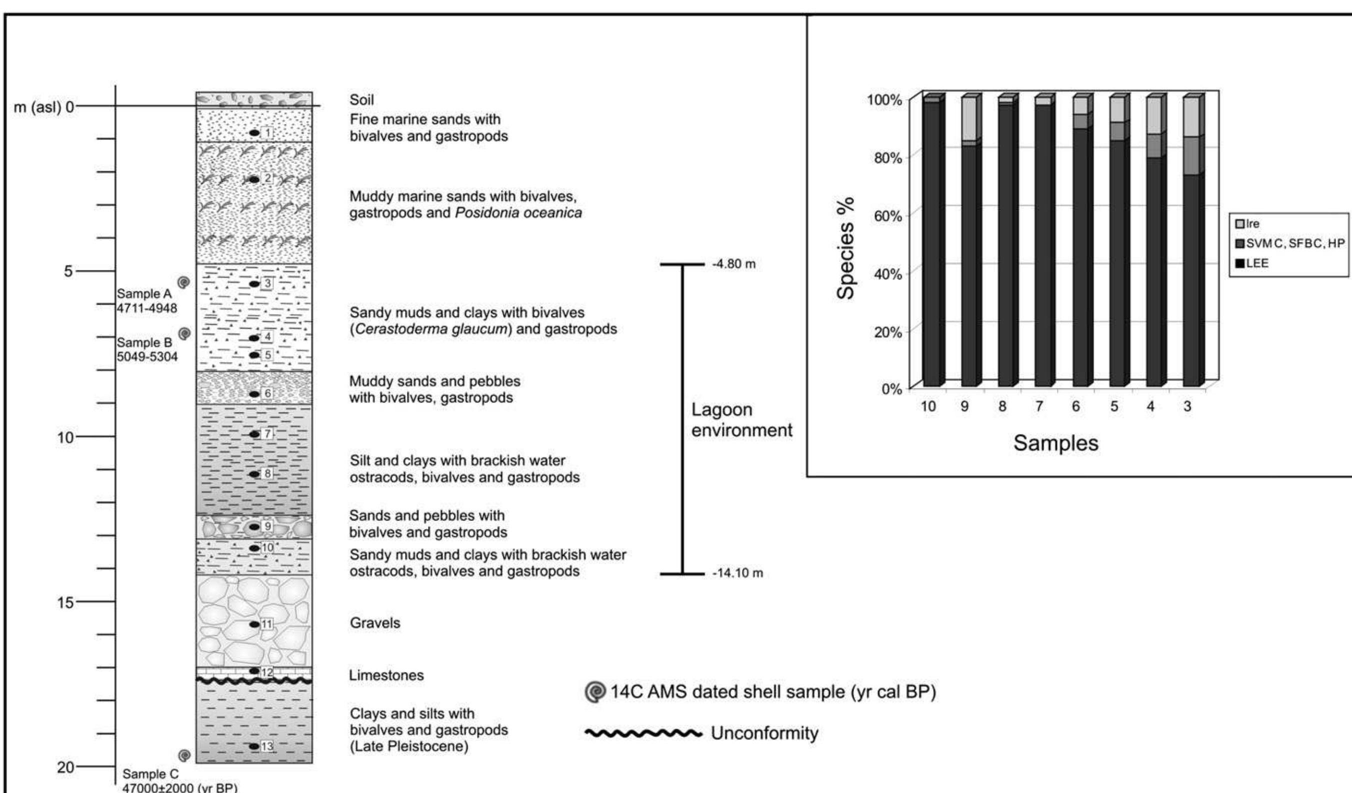

Fig. 3. Stratigraphic cross section of the Natural Reserve of Vendicari area (S1; see Fig. 2a for borehole location) showing lithofacies distribution. Inset shows the frequency distribution of the fossiliferous content (referring to lagoonal malacofauna) found in samples 3–10.

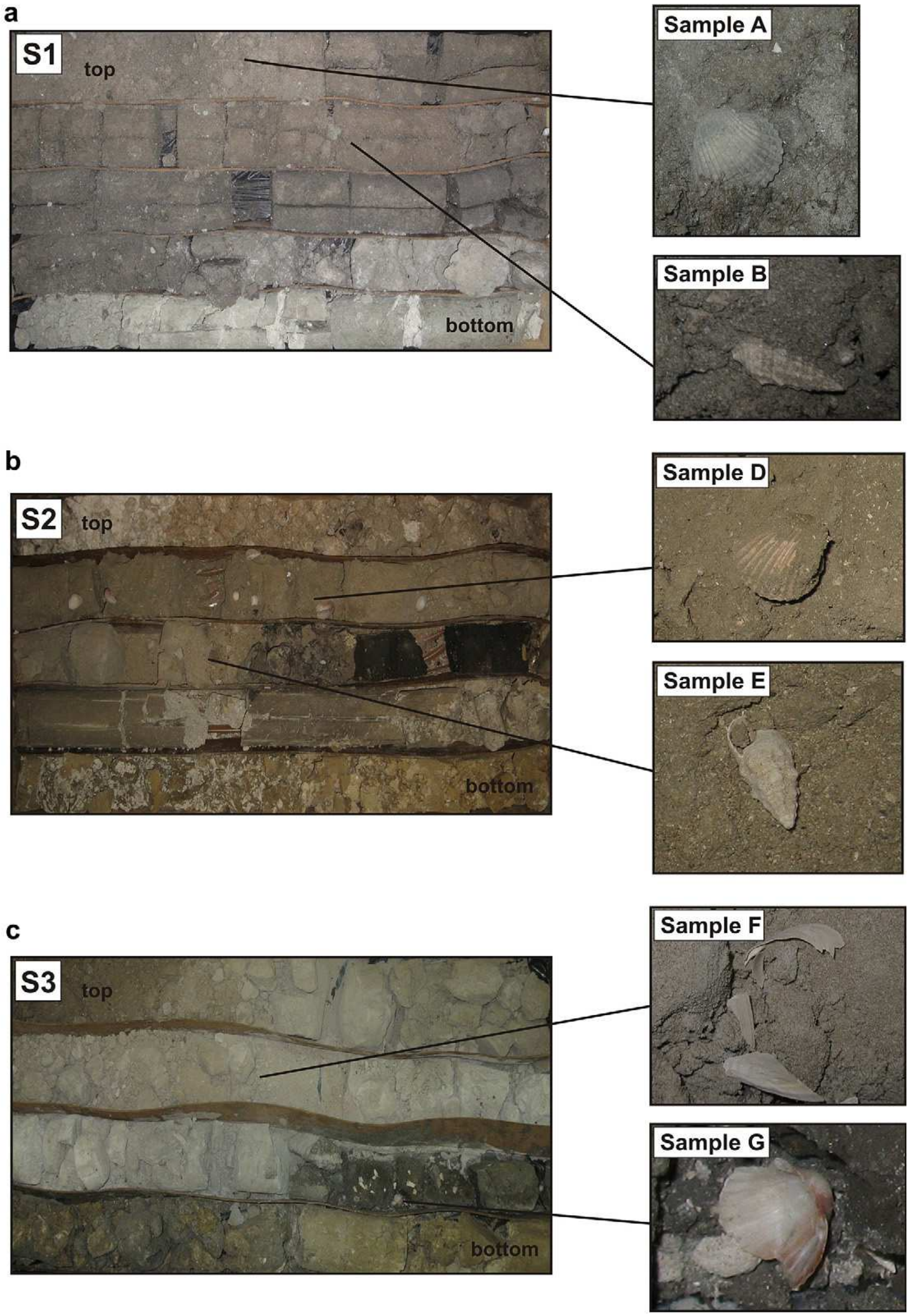

Fig. 4. Some representative examples of lagoonal deposits. a) Vendicari (in the box fossils of *Cerastoderma glaucum* and *Cerithium vulgatum*); b) Ciane (in the box fossils of *Cerastoderma glaucum* and *Cerithium vulgatum*); c) Priolo (in the box fossils of *Loripes lacteus* and *Cerastoderma glaucum*).

is flooded by the sea. Abundant remains of *Posidonia oceanica* significantly contribute to the formation of a sandy coastal barrier.

At the Natural Reserve of Ciane River and Siracusa Saline, the borehole S2 (Fig. 5) has been cored. The S2 well is located at an altitude of +0.50 m a.s.l. and reaches a depth of −16.00 m b.s.l. The stratigraphic analysis showed that the upper 1.60 m is dark muds with gravels that have been interpreted as soil. Below the soil, between −1.10 and −5.60 m, brown muddy sands and dark greyish sandy muds with brackish water shells have been observed (Fig. 4b). Paleoecological analysis suggests that these sediments are representative of lagoon environment. The ^{14}C AMS dates of a *C. glaucum* sampled at −1.40 m b.s.l. and of a *C. vulgatum*

Table 1
^{14}C dating results of shell fragments collected in the seven boreholes drilled in the lagoon areas of south-eastern Sicily and estimated uplift rates. Age determinations by Poznan Radiocarbon Laboratory (Poz) and R.J. Van de Graaff Laboratorium of the Utrecht University (Utc). All samples were calibrated using the program CALIB 5.0.1 (2-sigma, marine entry; Stuiver et al., 2005). Predicted sea-level points from the Lambeck et al. (2011) model; uplift rates provide for the average calendar age, the depth range in which the molluscs association lived (see text) and uniform uplift over the entire period of time considered.

Sample	Lab. number	Locality	Borehole	Coordinates of the borehole	Fossil species	Depth (m b.s.l.)	^{14}C age (BP)	Calendar age (cal BP)	Predicted sea level (m)	Uplift rate (mm/y)
A	Poz 17907	Vendicari	S1	36°48′13.25″N 15°05′53″E	*Cerastoderma glaucum*	−5.4	4610 ± 40	4711–4948	−5.083	−0.07 to 0.35
B	Poz 17906	Vendicari	S1	36°48′13.25″N 15°05′53″E	*Cerithium vulgatum*	−6.9	4890 ± 40	5049–5304	−5.465	−0.28 to 0.11
C	Poz 20403	Vendicari	S1	36°48′13.25″N 15°05′53″E	*Cerastoderma glaucum*	−19.9	47,000 ± 2000			
D	Poz 17757	Ciane	S2	37°03′05.94″N 15°16′04.06″E	*Cerastoderma glaucum*	−1.4	4055 ± 35	3966–4212	−3.622	0.54–1.03
E	Poz 20409	Ciane	S2	37°03′05.94″N 15°16′04.06″E	*Cerithium vulgatum*	−3.3	4230 ± 35	4211–4432	−3.978	0.16–0.62
F	Poz 20406	Priolo	S3	37°8′42.78″N 15°13′9.09″E	*Loripes lacteus*	−0.7	3970 ± 30	3863–4073	−3.386	0.68–1.18
G	Poz 25139	Priolo	S3	37°8′42.78″N 15°13′9.09″E	*Cerastoderma glaucum*	−1.9	4150 ± 35	4094–4353	−3.718	0.43–0.90
H	Poz 17759	Priolo	S3	37°8′42.78″N 15°13′9.09″E	*Ostrea* sp.	−10.2	33,300 ± 400			
I	Poz 20407	Augusta Saline (Xifonio)	S4	37°14′35.07″N 15°13′58.97″E	*Cerithium vulgatum*	0.0	3200 ± 35	2881–3136	−2.237	0.74–1.40
J	Poz 25138	Augusta Saline (Megarese)	S5	37°14′57.99″N 15°12′51.53″E	*Cerastoderma glaucum*	−0.2	3590 ± 35	3380–3581	−2.77	0.74–1.31
K	Utc 11548	Pantano di Lentini	S6	37°20′36.06″N 15°03′23.27″E	*Cerastoderma glaucum*	−37.9	9110 ± 50	9676–10,094	−45.465	0.76–0.96
L	Utc 11844	Pantano di Lentini	S7	37°20′53.56″N 15°03′9.54″E	*Cerastoderma glaucum*	−26.6	8787 ± 46	9368–9534	−37.479	1.15–1.36

sampled at −3.30 m b.s.l. revealed calendar ages of 3966–4212 and 4211–4432 cal BP, respectively (sample D and E in Table 1).

The lagoon sediments overlie beach deposits consisting of yellowish medium sands and gravels that are rich in shell fragments including *A. tuberculata*, *C. gallina*, *V. aurea*, *Dosinia lupinus*, *Dosinia exoleta*, *Rissoa* spp., and *B. reticulatum.* The substratum, made up of Lower Pleistocene blue-greyish clays and Middle Pleistocene yellowish clays, was reached at a depth of −7.30 m. A clay sample, collected at −8.05 m, showed a nannofossil association characterized by *Helicosphaera carteri*, *Helicosphaera selli*, *Pseudoemiliana lacunosa*, *Gephyrocapsa* "Medium size", *Pantosphaera* spp. and *Gephyrocapsa* sp.*3.* This fossil content suggests a Middle Pleistocene age, more precisely the MNN 19f zone. A clays sample, collected at −13.20 m, showed a foraminifera association characterized by *Hyalinea baltica* and *Globigerinoides rubber*, and a nannofossil association characterized by *H. carteri*, *H. selli*, *P. lacunosa*, *Gephyrocapsa* "Medium size" and *Pantosphaera* spp. This fossil association suggested a Lower Pleistocene age, more precisely the MNN 19b zone.

3.3. Natural Reserve of Saline di Priolo

The Natural Reserve of Saline di Priolo is located in the central sector of the Augusta Gulf, between Siracusa and Augusta (Fig. 2c). It consists of a shallow lagoon enclosed between coastal sandy bars forming a tombolo that attaches the Magnisi Peninsula to the mainland. Since the ancient Greek colonization until the 1960s, it was used for salt production.

At Priolo Saline, borehole S3 (Fig. 6) has been cored. S3 is located along the inner sector of the southern bar, at an altitude of +0.80 m a.s.l. and reaches a depth of −12.70 m b.s.l. The stratigraphic study showed that the upper 0.28 m is constituted by dark brown muds that can be classified as soil. They overlie infralittoral beach deposits consisting of yellowish fine sands rich in bivalves and gastropod shell fragments including *L. lacteus*, *A. tuberculata*, *C. gallina*, *D. lupinus*, *Gibbula ardens*, *Caecum trachea*, *Alvania* sp., *C. vulgatum* and *B. reticulatum.* Below the sand interval, between −0.40 and −4.50 m, dark brown muddy sands rich in bivalve shell fragments and blackish clays and sandy muds rich in brackish water shell fragments have been observed (Fig. 4c). The paleoecological analysis (see below) suggests that this interval is representative of a lagoon environment. The ^{14}C AMS dating of a *L. lacteus* sampled at −0.70 m and of a *C. glaucum* sampled at −1.90 m yielded calendar ages of 3863–4073 and 4094–4353 cal BP, respectively (samples F and G in Table 1).

The lagoon sediments overlie a beach deposit of yellowish muddy sands containing gravels and rich in bivalve and gastropod shell fragments. The Pleistocene substratum, reached at a depth of −7.70 m, is 3.80 m of yellowish marine clays containing, at a depth of −10.70 m, a few decimetres-thick gravel layer. The ^{14}C AMS result for an *Ostrea* sp. fragment sampled at −10.20 m indicates an age of 33,300 ± 400 BP (sample H in Table 1). The yellowish marine clays overlie blue-greyish marine clays. A sample, collected at −12.50 m, showed a nannofossil association characterized by *H. carteri*, *H. selli*, *P. lacunosa*, *Gephyrocapsa* "Medium size", *Pantosphaera* spp. and *Gephyrocapsa* sp.*3.* This fossil content suggests a Middle Pleistocene age, more precisely the MNN 19f zone.

3.4. Augusta Saline

The Augusta peninsula, in the northern sector of Augusta Gulf (Fig. 2d), separates two bays where ancient lagoon environments were exploited until the past century for salt production. Boreholes S4 and S5 have been cored in the eastern (Porto Xifonio Saline) and

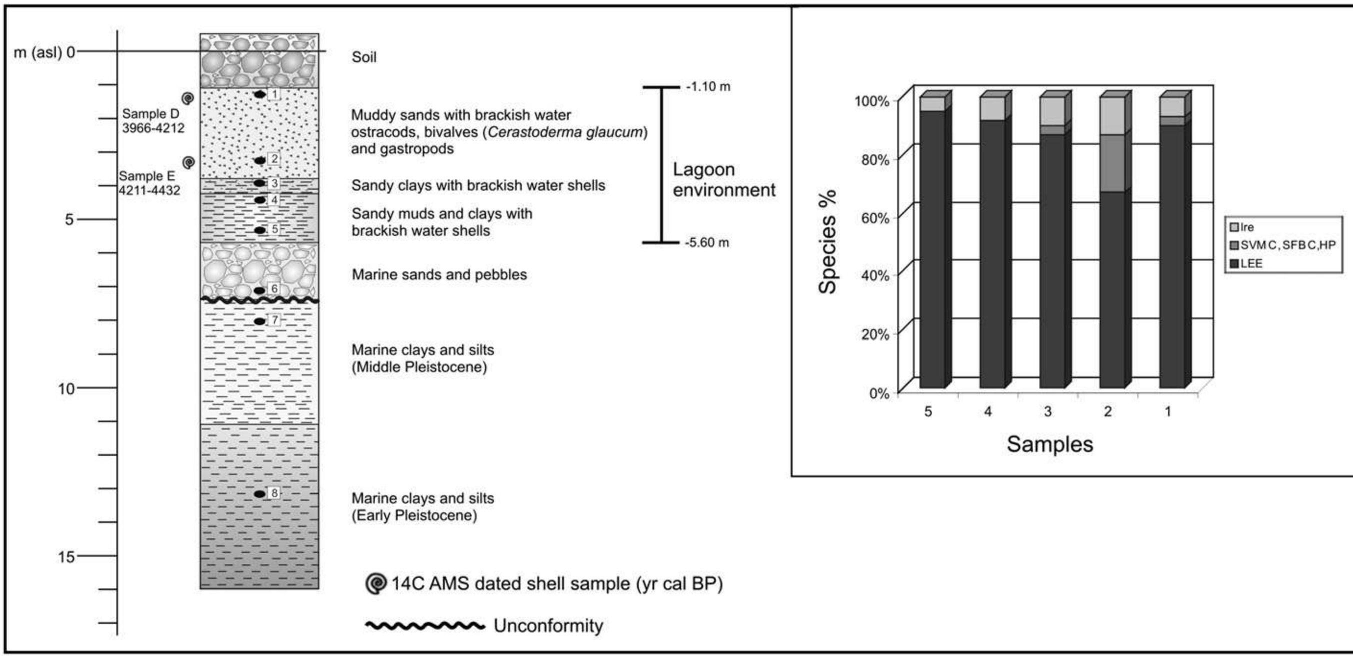

Fig. 5. Stratigraphic cross section of the Natural Reserve of Ciane River area (S2; see Fig. 2b for borehole location) showing lithofacies distribution. Inset shows the frequency distribution of the fossiliferous content (referring to lagoonal malacofauna) found in samples 1–5.

in the western bay (Porto Megarese Saline), respectively, where the wetlands have been partially reclaimed.

The S4 well is located in the Porto Xifonio area (Fig. 2d) at an altitude of +1.00 m a.s.l. and reaches a depth of −15.00 m b.s.l. (Fig. 7). The upper 0.35 m is dark muds with pebbles and is interpreted as soil. Below the soil, between +0.65 and −2.40 m, a brown sandy mud and clay level containing brackish water shells, was observed. The ^{14}C AMS dates for a *C. vulgatum* sampled at 0.00 m yielded 2881–3136 cal BP (sample I in Table 1). At depths between −2.40 and −4.20 m, a dark brown clay and sandy mud level, containing brackish water shells, occurs. The paleoecological analysis (see below) suggests that all these sediments are representative of lagoon environments. The lagoonal sediments overlie alluvial coastal sediments consisting of greyish polygenic gravels in a silty matrix. The substratum, composed of Lower Pleistocene blue-greyish clays and Middle Pleistocene alternating layers of sandy muds and muddy marine sands with pebbles rich in shell fragments, was reached at a depth of −6.00 m. Two mud samples, collected at −6.30 and −9.45 m, respectively, showed a nannofossil association characterized by *H. carteri*, *H. selli*, *P. lacunosa*, *Gephyrocapsa* "Medium size", *Pantosphaera* spp. and *Gephyrocapsa* sp.*3*. These fossil contents suggest a Middle Pleistocene age, more precisely the MNN 19f zone. A clay sample, collected at −12.20 m, showed a nannofossil association characterized by *H. carteri*, *H. selli*,

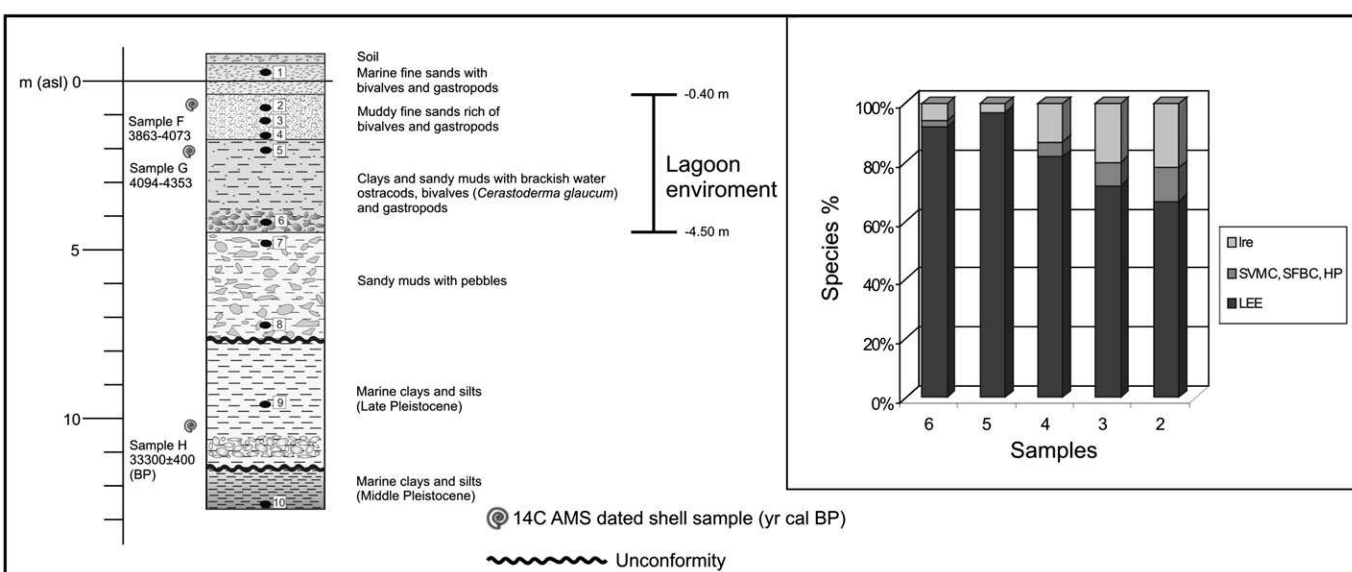

Fig. 6. Stratigraphic cross section of the Priolo Saline area (S3; see Fig. 2c for borehole location) showing lithofacies distribution. Inset shows the frequency distribution of the fossiliferous content (referring to lagoonal malacofauna) found in samples 2–6.

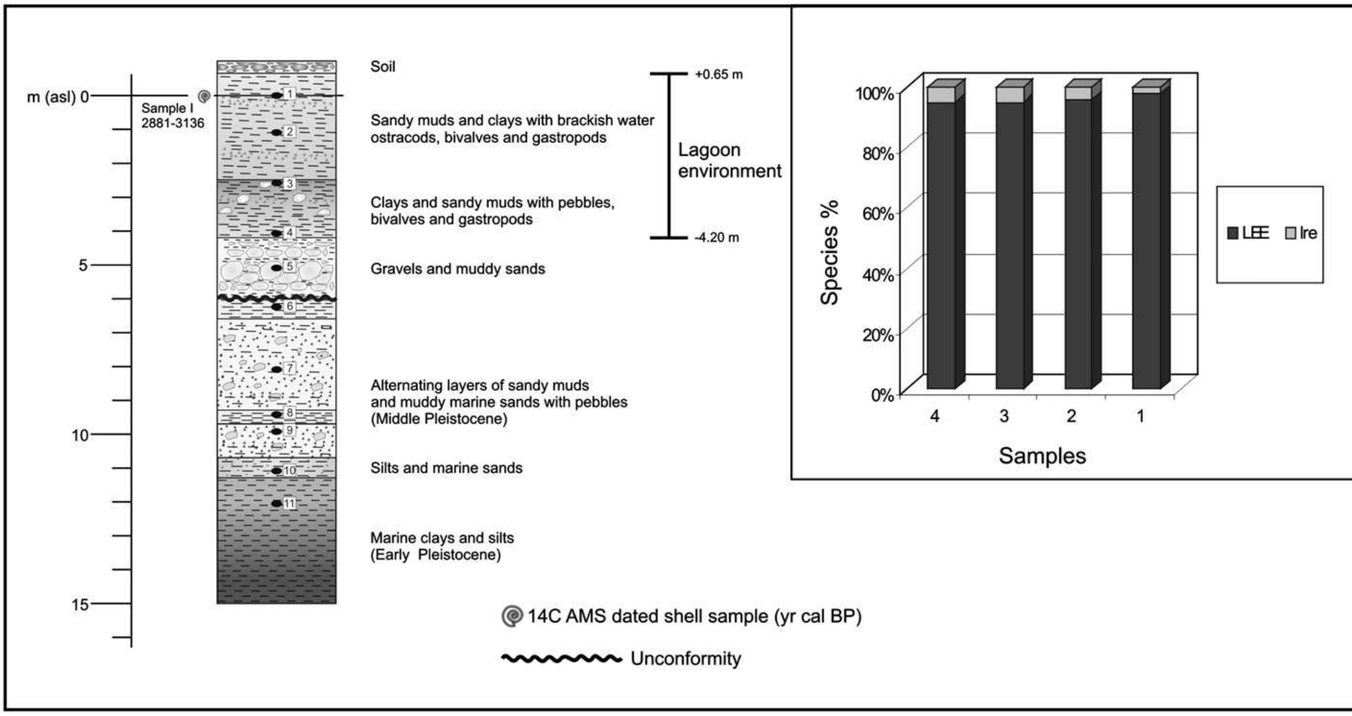

Fig. 7. Stratigraphic cross section of the Augusta Xifonio Saline area (S4; see Fig. 2d for borehole location) showing lithofacies distribution. Inset shows the frequency distribution of the fossiliferous content (referring to lagoonal malacofauna) found in samples 1–4.

P. lacunosa, *Gephyrocapsa* "Medium size" and *Pantosphaera* spp.. This association suggests a Lower Pleistocene age, more precisely the MNN 19b zone.

The S5 well is located in the Porto Megarese area (Fig. 2d) at an altitude of +0.80 m a.s.l. and reaches a depth of −11.70 m b.s.l. (Fig. 8). The stratigraphic study showed that the upper 0.15 m is constituted by dark mud with pebbles that can be interpreted as soil. Below this interval, between +0.65 and −2.50 m, a brown clay and sandy mud level with brackish water shells, has been observed. The ^{14}C AMS dates for a *C. glaucum* sampled at −0.20 m a.s.l. yielded a calendar age of 3380–3581 cal BP (sample J in Table 1). At depths between −2.50 and −4.20 m, dark greyish clays and muds with brackish water shells occur. The paleoecological analysis (see below) suggests that all these sediments are representative of lagoon environments. The lagoonal sediments, similar to that observed in S4, overlie alluvial coastal deposits consisting of greyish polygenic gravels in a silty matrix. The substratum, made up of marine clays and silts, was reached at a depth of −5.20 m. A sample

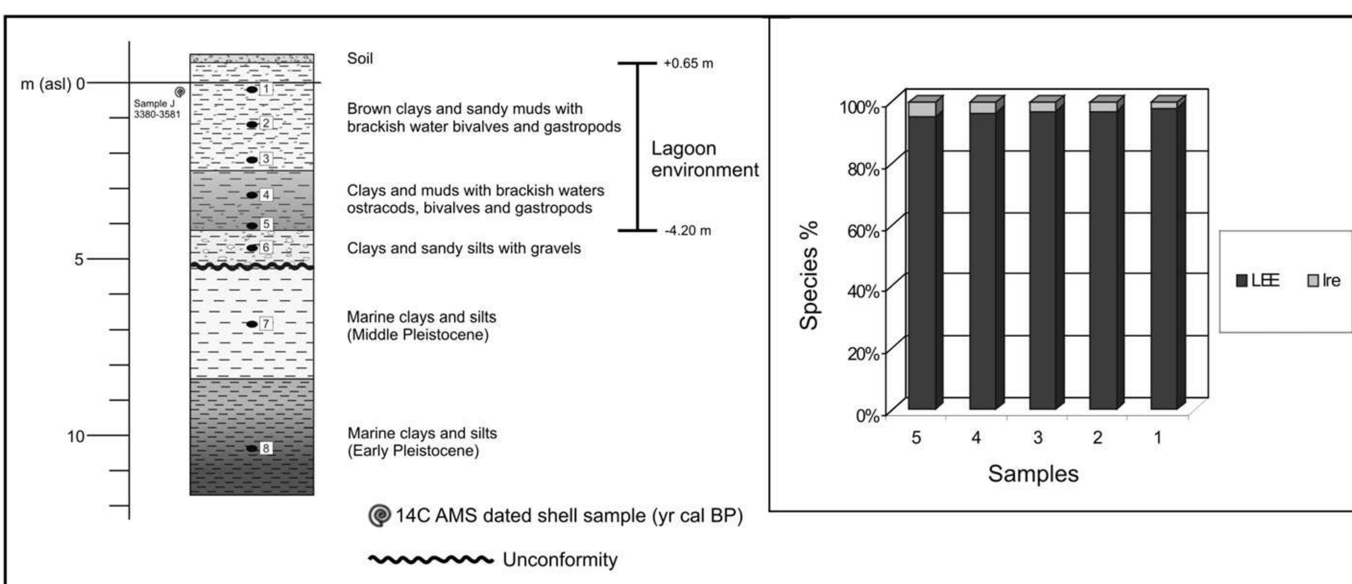

Fig. 8. Stratigraphic cross section of the Augusta Megarese Saline area (S5; see Fig. 2d for borehole location) showing lithofacies distribution. Inset shows the frequency distribution of the fossiliferous content (referring to lagoonal malacofauna) found in samples 1–5.

of yellowish clays, collected at −6.80 m b.s.l., showed a nannofossil association characterized by *H. carteri*, *H. selli*, *P. lacunosa*, *Gephyrocapsa* “Medium size”, *Pantosphaera* spp. and *Gephyrocapsa* sp.*3*. This fossil content suggests a Middle Pleistocene age, more precisely the MNN 19f zone. A sample of blue-greyish clays, collected at −10.40 m, showed a nannofossil association characterized by *H. carteri*, *H. selli*, *P. lacunosa*, *Gephyrocapsa* “Medium size” and *Pantosphaera* spp., suggesting a Lower Pleistocene age, more precisely the MNN 19b zone.

3.5. Pantano di Lentini

The Pantano di Lentini is the most depressed sector of the Catania Plain, a Holocene fluvial-coastal plain facing the Ionian Sea mostly fed by the Simeto River (Fig. 2e). This area is an ancient lagoon fed by San Leonardo River, and it is bounded seaward by a sand dune barrier of a few hundred meters. This area was reclaimed during the 1950s and at present it lies below sea level (to 2.5 m depth), having been drained by a system of channels. Two continuous boreholes (S6 and S7) have been cored in the central portion of the Pantano di Lentini.

The S6 well is located at an altitude of −0.40 m and reached a depth of 40.40 m b.s.l. (Fig. 9). The stratigraphic study has shown that the upper 1.50 m is dark brown sandy muds and clays rich in shell fragments typical of brackish marsh. At about 0.60 m, a few decimetres-thick ash layer was observed. The lagoonal sediment overlies beach deposits constituted by yellowish fine sands containing coarse sands levels, rich in shells of bivalves and gastropods such as *A. tuberculata*, *C. gallina*, *Mactra corallina*, *Glycymeris glycymeris*, *Astarte fusca*, *Tellina* sp., *Conus mediterraneus*, *G. ardens*, *Tricolia pullus,* and *C. vulgatum*. Below the sand interval, between 33.60 and 37.90 m b.s.l., a dark greyish sandy silt level with bivalve shell fragments (*L. lacteus*, *Gastrana fragilis*, *V. aurea*, *C. glaucum*) occurs. The ^{14}C AMS dates for a *C. glaucum* sampled at the bottom of this interval yielded a calendar age of 9676–10094 cal BP (sample K in Table 1). Below, at depths between 37.90 and 39.00 m, alluvial polygenic gravels in a silty matrix marks the transgression above the Pleistocene substratum, represented by blue-greyish marly

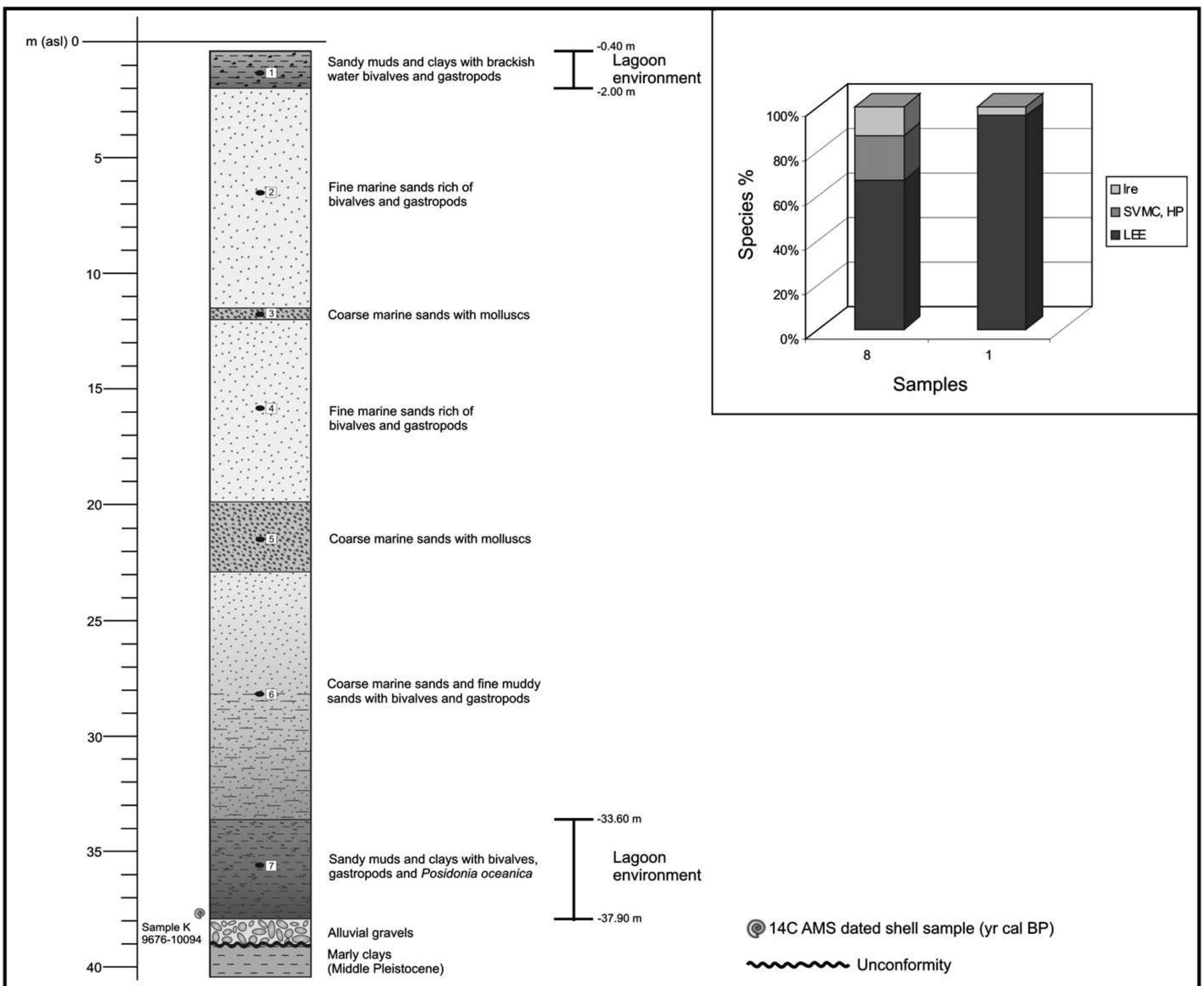

Fig. 9. Stratigraphic cross section of the Pantano di Lentini area (S6; see Fig. 2e for borehole location) showing lithofacies distribution. Inset shows the frequency distribution of the fossiliferous content (referring to lagoonal malacofauna) found in samples 1, 7 and 8.

clays. A clay sample, collected at 39.40 m, has a foraminiferal association characterized by *H. baltica*, *Uvigerina peregrina*, *Globigerinoides ruber*, *Brizalina dilatata*, *Bolivina alata*, *Globorotalia inflata*, *Spheroidina bulloides*, *Bulimina marginata,* and *Cassidulina neocarinata.* In the same sample, abundant nannofossils were represented by *Calcidiscus macintyrei*, *H. carteri*, *Gephyrocapsa* “Small-size”, *Gephyrocapsa oceanica*, *Syracosphaera* spp., *P. lacunosa*, *Pantosphaera* spp. and *Gephyrocapsa* sp.*3.* These fossil contents suggest a Middle Pleistocene age, more precisely the MNN 19f zone.

The S7 well is located at an altitude of −0.70 m b.s.l. and reaches a depth of 30.70 m b.s.l. (Fig. 10). The stratigraphic study showed that the upper 1.6 m consists of dark brown sandy muds and clays rich of brackish water typical of lagoon environment. These sediments overlie beach deposits constituted by yellowish fine sands containing coarse sand levels, rich in shell fragments of bivalves and gastropods such as *A. tuberculata*, *C. gallina*, *M. corallina*, *D. lupinus*, *G. glycymeris*, *Venus casina*, *G. ardens*, *T. pullus,* and *C. vulgatum.* Below the sand interval, between −21.20 and −26.60 m, dark brown sandy muds and dark greyish sandy muds and clays rich in shell fragments of bivalves (*L. lacteus*, *G. fragilis*, *V. aurea*, *C. vulgatum*), have been observed. The ^{14}C AMS dating of a *C. glaucum* fragment collected at the bottom of this interval at −26.60 m yielded 9368−9534 cal BP (samples L in Table 1). The transgressive deposits, made up of alluvial polygenic gravels in a silty matrix, similar to that of the S6 well, were reached at a depth of 26.60 m.

4. Paleoecological analysis of Holocene deposits

4.1. Natural Reserve of Vendicari

The paleoecological analysis of the S1 Holocene deposits showed an environmental evolution from lagoonal deposits to infralittoral beach deposits. In the interval between −9.05 and −14.10 m, the lagoon thanatocoenoses are more oligotypic (see inset in Fig. 3): samples 7−10 are dominated by *Hydrobia ventrosa* followed by *C. glaucum* and *Abra ovata,* typically associated in the “Euryhaline and Eurythermal Biocoenosis in brackish water” (LEE of Pères and Picard, 1964). Rare marine influence is indicated by *C. vulgatum,* a species of wide ecological distribution within the infralittoral zone also common in the sandy-muddy lagoonal facies, and by *L. lacteus* in sample 9, typical of the “Biocoenosis of superficial muddy sands in sheltered areas” (SVMC of Pères and Picard, 1964). The benthic foraminiferal component is more

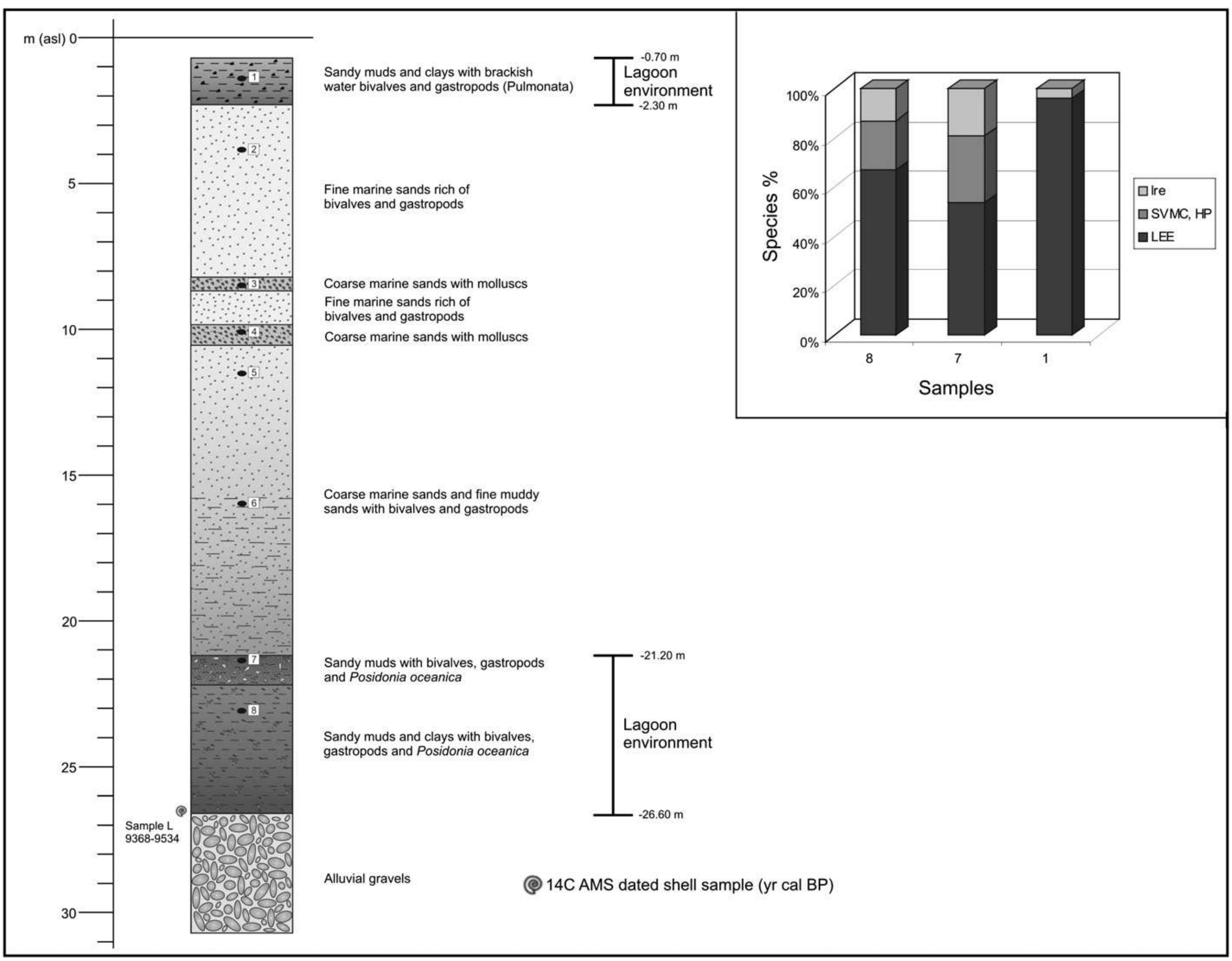

Fig. 10. Stratigraphic cross section of the Pantano di Lentini area (S7; see Fig. 2e for borehole location) showing lithofacies distribution. Inset shows the frequency distribution of the fossiliferous content (referring to lagoonal malacofauna) found in samples 1 and 8.

oligotypic with dominating *Ammonia beccarii* and rare specimens of *Elphidium crispum*. The distribution of the macro- and micro-faunal components show that this interval is representative of a lagoon protected from the open sea by a sand barrier with limited marine influence (class IV confinement according to Guelorget and Perthuisot, 1983). In samples 3–6, the thanatocoenoses showed a major presence of marine species. *H. ventrosa* is still dominant, followed by *C. glaucum* and *A. ovata*. The marine component is formed of species transported from infralittoral biocoenoses, among which are *Ctena decussata*, *L. lacteus*, *G. fragilis,* restricted to the SVMC, *A. tuberculata* and *C. gallina*, typical of the "Biocoenosis of fine well sorted sands" (SFBC of Pères and Picard, 1964), *C. trachea*, typical of the "Biocoenosis of the Posidonia meadows" (HP of Pères and Picard, 1964) and *C. vulgatum*. Foraminiferal assemblages increase in abundance and diversity, and consist of *A. beccarii*, *E. crispum*, *Quinqueloculina* sp. and *Triloculina* sp.. The distribution of the macro- and micro-faunal components show that the interval between −4.80 and −9.05 m is representative of a lagoon protected from the open sea by a sand barrier with a major influence from the sea (class IV–III confinement according to Guelorget and Perthuisot, 1983). The interval between −0.10 and −4.80 m includes infralittoral beach deposits, and samples 1 and 2 are rich in shell fragments belonging to the SVMC, SFBC, HP and to the "Biocoenosis of coarse sands and fine gravels under the influence of bottom currents" (SGCF of Pères and Picard, 1964).

Stratigraphic and paleoecological data suggest that the Vendicari area (Fig. 2a), during the Last Glacial Maximum, was the site of chemical precipitation of calcium carbonate ($CaCO_3$), as evaporation was not balanced by provision of marine and/or river waters. Subsequently, rapid sea-level rise and the simultaneous development of a sand barrier isolated the area from open sea, favouring the development of a lagoon environment. About 4000 years ago, it was partially invaded by beach deposition.

4.2. Natural Reserve of Ciane River and Siracusa Saline

The paleoecological analysis of the S2 Holocene deposits (see inset in Fig. 5) show an environmental evolution from infralittoral beach deposits (e.g. sample 6), rich in shell fragments belonging to the SVMC, SFBC, SGCF and HP, to lagoon deposits (e.g. samples 1–5) rich in brackish water shell fragments belonging to the LEE. The lagoonal thanatocoenoses are oligotypic and show a high number of specimens of *H. ventrosa*, a paralic vagile species, followed by *C. glaucum* and *A. ovata,* typically associated in the LEE. Rare marine influence is indicated by rare specimens of *L. lacteus,* typical of the SVMC and *C. vulgatum,* a species of wide ecological distribution within the infralittoral zone, common also in the sandy-muddy lagoonal facies.

The benthic foraminiferal component is oligotypic with *A. beccarii*. In sample 5, the thanatocoenoses shows mixing of brackish and typically marine species. The former *H. ventrosa* is dominant, followed by *C. glaucum* and *A. ovata.* The marine component is formed by *L. lacteus* and *G. fragilis,* typical of the SVMC, *A. tuberculata*, typical of the SFBC, *C. trachea,* typical of the HP, and *C. vulgatum* and *B. reticulatum,* species of wide ecological distribution. The benthic foraminiferal component increases in abundance and diversity with *A. beccarii*, *E. crispum*, *Quinqueloculina* sp. and *Triloculina* sp.. The distribution of the macro- and micro-faunal components show that the interval between −1.10 and −5.60 m is representative of a lagoon protected from the open sea by a sand barrier (class IV–III confinement according to Guelorget and Perthuisot, 1983).

Stratigraphic and paleoecological data suggest that in the Siracusa Saline area (Fig. 2b), the formation of a coastal barrier fed by the Ciane and Anapo river deposition occurred during the early stage of the Holocene transgression. It rapidly isolated the system from the open sea, with the subsequent development of a lagoon environment.

4.3. Natural Reserve of Saline di Priolo

The paleoecological analysis of S3 Holocene deposits (see inset in Fig. 6) showed an environmental evolution from infralittoral deposits (e.g. samples 7 and 8), rich in bivalve and gastropod shell fragments belonging to the SVMC, SFBC, SGCF, HP and to the "Biocoenosis of the photophilic algae" (AP of Pères and Picard, 1964), with a foraminiferal assemblage composed of both benthic (*Quinqueloculina* sp., *Triloculina* sp., *Uvigerina* sp. and *Elphidium* sp.) and planktonic forms (*Globigerina* sp., *Globigerinoides* sp. and *Orbulina universa*), to lagoon deposits (e.g. samples 2–6), rich of brackish water shell fragments belonging to the LEE and, finally, back to beach deposits (e.g. sample 1) rich in bivalve shell fragments belonging to the SVMC and SFBC with rare specimens belonging to the LEE. In samples 5 and 6, the lagoon thanatocoenoses are strongly oligotypic with dominating *H. ventrosa*, with a few specimens of *C. glaucum* and *A. ovata*, typically associated in the LEE. Rare marine influence is indicated by a few specimens of *C. vulgatum,* a species of wide ecological distribution within the infralittoral zone also common in the sandy-muddy lagoonal facies, and rare specimens of *L. lacteus* (sample 6), a species typical of the SVMC. The benthic foraminiferal component is oligotypic with *A. beccarii*. The distribution of the macro- and micro-faunal components show that this interval is representative of a lagoon protected from the open sea by a sand barrier with limited marine influence (class IV confinement according to Guelorget and Perthuisot, 1983).

In samples 2–4, the thanatocoenoses show a major marine influence due to mixing of lagoon and marine species. In particular, *H. ventrosa* is still dominant but shows a decrease in numbers, followed by *C. glaucum* and *A. ovata*. The marine component is formed of temporarily immigrating species transported from infralittoral biocoenoses, including *L. lacteus* and *G. fragilis,* typical of the SVMC, *C. vulgatum* and *B. reticulatum.* The benthic foraminiferal component showed an increase in abundance and diversity. The distribution of the macro- and micro-faunal components show that this interval is representative of a lagoon closely connected with the sea (class IV–III confinement according to Guelorget and Perthuisot, 1983).

Stratigraphic and paleoecological data suggest that at the beginning of the Holocene transgression, in the Priolo Saline area (Fig. 2c) a shallow marine environment occurred. Subsequently, a tombolo connected Magnisi Island to the mainland and a large lagoon environment developed. The lagoon maintained its characteristics until about 4000 y ago, when it was partially invaded by beach deposition.

4.4. Augusta Saline

The paleoecological analysis of S4 and S5 Holocene deposits (see inset in Figs. 7 and 8, respectively) showed an environmental evolution from alluvial coastal deposits (e.g. sample 5 in S4, sample 6 in S5), constituted by polygenic gravels in a silty matrix with few shell fragments, to lagoonal deposits (e.g. samples 1–4 in S4, samples 1–5 in S5) containing brackish water shell fragments, belonging to the LEE. In these samples the lagoonal thanatocoenoses are strongly oligotypic and represented only by *H. ventrosa*, a paralic vagile species, followed by rare specimens of *C. glaucum* and *A. ovata,* typically associated in the LEE, and rare specimens of *C. vulgatum,* a species of wide ecological distribution within the infralittoral zone common in the sandy-muddy lagoonal facies. The benthic foraminiferal component is oligotypic with *A. beccarii*. The distribution of the macro- and micro-faunal components show that the interval between +0.65 and −4.20 m in both boreholes is representative of a lagoon unaffected by marine influx (class V confinement according to Guelorget and Perthuisot, 1983).

Stratigraphic and paleoecological data suggest that during the Holocene transgression, the Augusta coastal area (Fig. 2d) was rapidly isolated from the open sea with the development of a complex lagoon system. At present, the Augusta Saline lagoons represent the remains of a larger paralic system, partially reclaimed and filled.

4.5. Pantano di Lentini

The paleoecological analysis of S6 and S7 Holocene deposits (see inset in Figs. 9 and 10, respectively) showed an environmental evolution from shallow-water deposits in sheltered areas (e.g. sample 7 in S6, samples 7 and 8 in S7), rich in bivalves and gastropods belonging to the SVMC, HP, LEE, to infralittoral beach deposits (e.g. samples 2–6 in both boreholes) rich in shell fragments belonging to the SVMC, SFBC, SGCF, HP, AP, and finally to lagoonal deposits, (e.g. sample 1 in both boreholes), rich in brackish water shell fragments. In the samples collected from the basal interval (between −33.60 and −37.90 m in S6, between −21,20 and −26,60 m in S7), the mollusc thanatocoenoses are characterized by mixing of lagoonal and marine species, due to marine influence. *H. ventrosa* is dominant followed by *C. glaucum*. The marine influence is indicated by *L. lacteus* and *G. fragilis* typical of the SVMC and by *C. vulgatum*. The distribution of the macro- and micro-faunal components suggest that this interval is representative of a lagoon with a large marine influence (class III–IV confinement according to Guelorget and Perthuisot, 1983).

In the samples collected from the uppermost interval (between −0.40 and −2.00 m in S6, between −0.70 and −2.30 m in S7), the lagoonal thanatocoenoses are strongly oligotypic and showed a high number of specimens of *H. ventrosa*, followed by few specimens of *C. glaucum*, and *A. ovata*, typically associated in the LEE, and rare specimens of *C. vulgatum*. Also the benthic foraminiferal component showed a strongly oligotypic association represented only by *A. beccarii*. The distribution of the macro- and micro-faunal components show that this interval is representative of a lagoon protected from the open sea by a sand barrier with limited marine influence (class IV confinement according to Guelorget and Perthuisot, 1983).

Stratigraphic and paleoecological data suggest that in the Pantano di Lentini area (Fig. 2e) a lagoon environment existed during the early stage of the Holocene transgression. The subsequent rapid sea-level rise favoured the marine invasion of a large and shallow marine bay bounded by two structural highs. This configuration, together with prevailing sea currents, favoured the southwards migration of a sand barrier fed by the alluvial coastal sediments of the Simeto and San Leonardo rivers. About 3000 y ago, when the continuous sand barrier isolated the bay from the open sea, a lagoon environment developed (Monaco et al., 2004). The occurrence of an ash level in the upper part of the lagoon sediments probably relates to the huge 122 B.C. Mt. Etna volcano explosion (Gemmellaro, 1858) and confirms the Late Holocene age of these deposits.

5. Contribution of tectonics to relative sea-level change during the Holocene

The stratigraphic and paleoecological study carried out in the lagoon areas of south-eastern Sicily, accompanied by ^{14}C AMS dating, allows reconstruction of the Holocene geological and morphological evolution and definition of the vertical movements undergone by these areas, in relation to Holocene sea-level rise. The relative sea-level change along the coasts represents the combined result of eustasy, glacio-hydro-isostasy and vertical tectonic motion. The contributions from eustasy and the concomitant isostatic adjustments have been predicted for the south-eastern Sicily region using the calibrated model parameters of Lambeck et al. (2011). The tectonic contribution can then be evaluated as the difference between the observed local palaeo-sea level positions and the predicted sea-level curve for the same locality. Tectonic stability is deduced at sites where the elevations of the markers are in agreement with the predicted sea-level curve; conversely, tectonic subsidence or uplift is indicated where the elevations of the markers are below or above of the predicted sea-level curve, respectively. Fig. 11 illustrates this comparison for south-eastern Sicily: data on relative sea-level change have been obtained by ^{14}C AMS (Table 1) dating of fossil specimens belonging to lagoon mollusc associations typically living from sea level down to about 2 m depth. Consequently, an error bar between 0 and +2 m from the sample depth has been adopted. All the observed data points, except for samples A and B, fall above the predicted values,

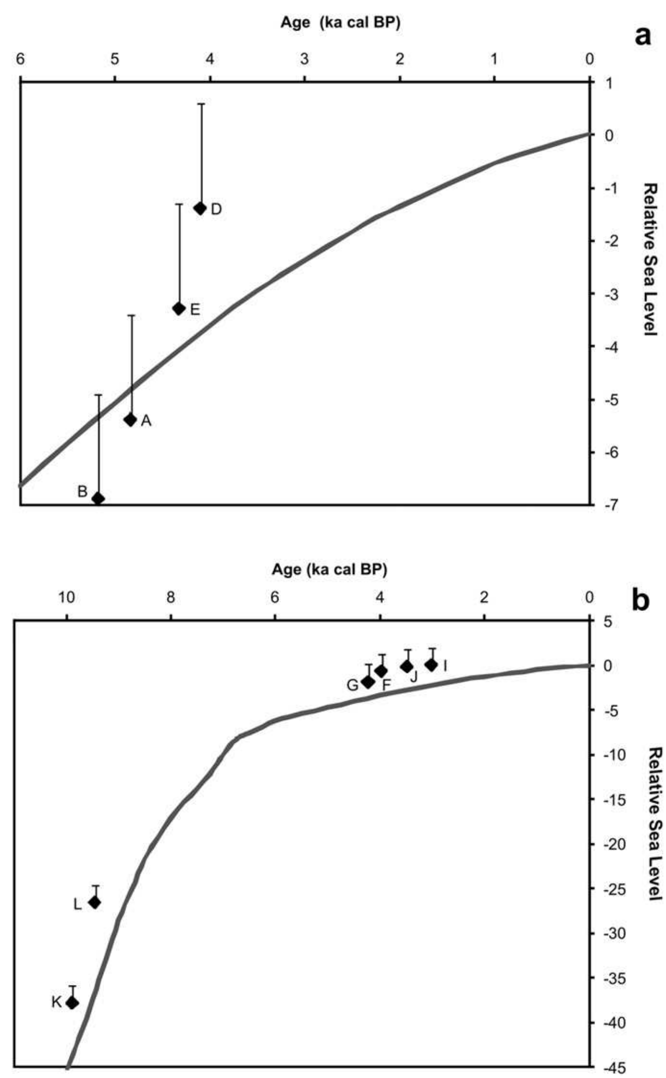

Fig. 11. Comparison of depths below present sea level of aged fossils shells sampled in the seven boreholes with the predicted eustatic-isostatic sea-level curve for (a) Capo Passero and (b) Catania (Lambeck et al., 2011). Letters indicate the samples. An error bar between 0 and +2 m from the sample depth has been adopted (see text).

indicating that the region has been subjected to a general uplift during the Holocene (Table 1).

The ^{14}C AMS dates for sample A (*C. glaucum)* and B (*C. vulgatum)*, gave ages of 4711–4948 cal BP and 5049–5304 cal BP, respectively. Comparing the depths below present sea level of the aged fossil shells with the predicted eustatic-isostatic sea-level curve (Fig. 11a) gives subsidence rates of −0.07 to 0.35 and −0.28 to 0.11 mm/y, respectively. These values suggest a slight subsidence of the Vendicari area during the last 5000 y, probably related to sediment compaction, even if the south-eastern corner of Sicily has been considered stable since the Middle-Late Pleistocene (Ferranti et al., 2006). To the north, in the Siracusa area (Fig. 1), the ^{14}C AMS dates for a *C. glaucum* and a *C. vulgatum* gave ages of 3966–4212 al BP and 4211–4432 cal BP, respectively (samples D and E in Table 1). Comparison of the depths below present sea level of the aged fossil shells with the predicted eustatic-isostatic sea-level curve (Fig. 11a) gives uplift rates of 0.54–1.03 and 0.16–0.62 mm/y, respectively. To the north, in the central sector of the Augusta Gulf (Fig. 1), two samples have been collected: sample F, a *L. lacteus*, was dated at 3863–4073 cal BP and suggests an uplift rate of 0.68–1.18 mm/y (Fig. 11b). Sample G, a *C. glaucum,* was dated at 4094–4353 cal BP and suggests an uplift rate of 0.43–0.90 mm/y (Fig. 11b). At the northern corner of Augusta Gulf, the ^{14}C AMS result for a *C. vulgatum* (Sample I) and a *C. glaucum* (Sample J) yielded calendar ages of 2881–3136 cal BP and 3380–3581 cal BP, respectively. Taking into account the predicted sea level at those times and the age error bar, uplift rates of 0.74–1.40 mm/y and 0.74–1.31 mm/y can be calculated (Fig. 11b). Finally, in the Catania Plain (Fig. 1), the northernmost area, the present elevation of a *C. glaucum* (sample K; calendar age: 9676–10,094 cal BP), and a *C. glaucum* fragment (sample L; calendar age: 9368–9534 cal BP) suggests uplift rates ranging from 0.76–0.96 mm/y to 1.15–1.36 mm/y when compared to the local sea-level prediction of Lambeck et al. (2011) (Fig. 11b). All these values are conservative because they do not take into account the possibility of sediment compaction, but they are consistent with the short- and long-term uplift rates estimated in the coastal areas of the Hyblean Plateau (Bianca et al., 1999; Scicchitano et al., 2008; Dutton et al., 2009) and in the Catania area (Monaco et al., 2004).

6. Conclusions

Taking into account that the lagoonal sediments occurring in the analysed coastal sectors of south-eastern Sicily areas were deposited during the Holocene sea-level rise and that the gastropod and bivalve fragments sampled in the boreholes are, with good approximation, sea-level indicators, this study allows estimation of the short-term vertical motion undergone by this region. Comparing the sampling depth below the present sea level of the dated shells to the sea-level rising curve for the central-eastern Sicily coast (i.e. Lambeck et al., 2011), the coastal sectors between Catania and Siracusa resulted involved during the Holocene in tectonic uplifting with rates varying from about 1 mm/y in the Catania area to 0.5 mm/y in the Siracusa area. Conversely, in the same period the south-eastern most coastal sector of Sicily can be considered tectonically stable. Unlike the northeastern Sicily and Calabrian Arc, where Holocene sea-level markers are usually above the present sea level (Antonioli et al., 2006), in south-eastern Sicily they are all below the sea level because of slower rates of tectonic uplift.

These data are comparable with uplift rates recently obtained by geomorphologic and archaeological sea-level markers and are consistent with a remote effect of the active normal fault system located in the Ionian offshore between Catania and Siracusa. For the Augusta–Siracusa coastal sector, the results agree with the uplift values of 0.3–0.8 mm/y determined by precise measurements of submerged archaeological markers and speleothems (Scicchitano et al., 2008) and with the long-term uplift rate of 0.4 ÷ 07 mm/y for the last 400 kyr estimated by marine terraces (Bianca et al., 1999) and by speleothems from submerged caves (Dutton et al., 2009). The southward decreasing Holocene uplift pattern broadly confirms the spatial trend previously recognized in Late Pleistocene uplift (Ferranti et al., 2006). Taking into account that both short- and long-term values estimated in the Catania area by previous authors are between 1 and 2 mm/y (Monaco et al., 2002; Antonioli et al., 2009), these data confirm a general southward decrease of both the regional uplift and of the remote effect of the active normal fault system located in the Ionian offshore between Catania and Siracusa, at the bottom of the Malta Escarpment (Bianca et al., 1999; Argnani and Bonazzi, 2005).

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