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MIS 5e at San Giovanni di Sinis (Sardinia, Italy): Stratigraphy, U/Th dating and "eustatic" inferences

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ABSTRACT

The most representative Late Pleistocene ("Tyrrhenian") outcrop in Sardinia (San Giovanni di Sinis) was re-visited based on detailed sedimentological and stratigraphical analysis supported by U-series dating of fossil corals. The stratigraphy shows shoreface–backshore sandstones overlying an erosional surface cut on vertebrate-bearing layers. Facies analysis and sequence-stratigraphic approaches suggest "eustatic" changes during the overall depositional interval of the marine sequence. Disconformities distinguish two coastal units suggesting a lateral shifts of the depositional environments driven by millennial-scale frequency sea level fluctuations, never exceeding a maximum height +1 to +3 m and by a subsequent rise to +5 ÷ +5.5 m asl.

These deposits have historically been assigned to MIS 5, on the basis of i) their palaeontological content (warm "*Senegalese*" fauna), ii) lithostratigraphic interpretations and iii) amino-acid, geochronological data and generally attributed to the high sea-level episode of MIS 5e sub-stage, through sequential interpretation. U-series measurements in colonies of *Cladocora caespitosa* from the main outcrop of San Giovanni di Sinis and other minor deposits from the eastern side of the isthmus and from Capo San Marco, yielded ^{230}Th-ages confirming an assignment of the embedding sediments to MIS 5e.

Similar measurements in a pelecypod valve (*Cerastoderma* sp.) and a vermetid colony at San Marco yielded much younger apparent ages, tentatively attributed to late "diagenetic" U-uptake processes. Both the first minor pulses and the most important "eustatic" pulse recorded at San Giovanni di Sinis cannot be assigned unequivocally to one of the MIS 5e sea-level oscillations proposed in the recent literature, due to dating inaccuracies and uncertainties, but it seems probable that it occurred during an early part of the interval.

1. Introduction

The interest in the Tyrrhenian (Issel's Piano Tirreno, 1914: "*panchina*", beds bearing "*Senegalese fauna*", i.e. last interglacial outcrops in Sardinia has been renewed by recent diverging opinions suggesting that numerous Tyrrhenian outcrops in Sardinia might actually date from the Late Würmian–Holocene, that Sardinia might not be a stable area and that recent uplift might have occurred (APAT, 2005; Coltorti et al., 2007, 2010, 2012). However, as described in previous literature, and recently confirmed by several studies (Antonioli et al., 2007; Bartolini et al., 2008; Carboni and Lecca, 2008; Andreucci et al., 2009; Carboni and Vacca, 2009; Thiel et al., 2010; Carboni and Lecca, 2010; Orrù et al., 2011a; D'Orefice et al., 2012), the San Giovanni di Sinis sequence and those correlated in the entire island of Sardinia are unquestionably Tyrrhenian (i.e. likely from MIS 5e). Moreover, well-developed tidal notches and of other sea level indicators strongly point to either a relative stability of Sardinia during the Holocene or to weak submergence, if any (Pirazzoli, 2005; Ferranti et al., 2006; Lambeck et al., 2011; Orrù et al., 2011b).

The most complete marine–continental Pleistocene succession in Sardinia crops out along the coast of the Sinis region (central-western Sardinia, Italy; Figs. 1 and 2), at San Giovanni di Sinis. It has been widely studied over the last 40 years, particularly regarding the stratigraphy of the coastal-marine depositional sequence assigned to MIS 5, its fossils content and its palaeo-climatic significance.

The Pleistocene sediments of the Sinis coast (Carboni and Lecca, 1985) rest unconformably on the Messinian marls and limestones of the Capo San Marco Formation (Cherchi et al., 1978) and/or on

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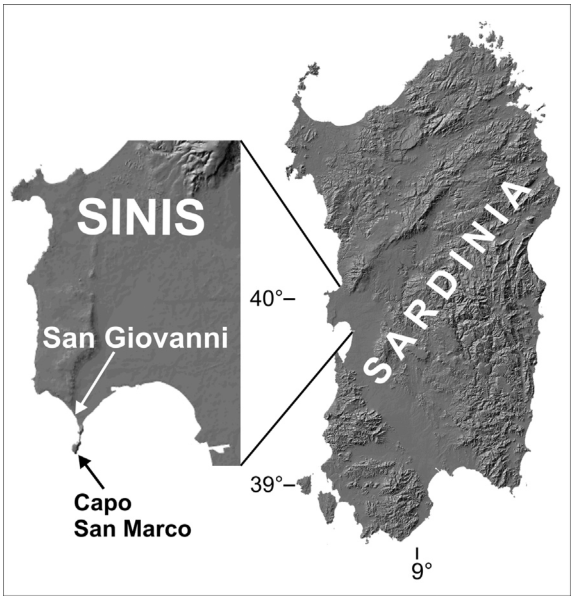

Fig. 1. Location of the San Giovanni di Sinis area MIS 5e outcrops.

Pliocene–lower Pleistocene sediments (Pecorini, 1972; Carboni and Lecca, 1995; Abbazzi et al., 2008). The Tyrrhenian coastal-marine facies exposed mainly illustrates a foreshore–nearshore sedimentary environment followed inland by wide coastal dunes. It consists of sandstones, conglomeratic sandstones and conglomerates locally rich in fossils, with quartz, metamorphic, and volcanic clasts.

These deposits can be recognized almost continuously along the coast at elevations between 0 and ~5.5 m asl. In the inner low areas of Sinis, variously reddish aeolian sandstones, weakly cemented palustrine muds containing pulmonate gastropods, and calcareous evaporitic and/or pedogenic crusts, illustrate continental sedimentation following the last interglacial and preclude any assignment of the underlying unit to the Holocene as suggested by Coltorti et al. (2010).

2. Sampling sites

The samples analysed for the U-series isotopes include colonies of *Cladocora caespitosa* (CLD4, CLD1, CLD3) originating from the lower part of unit M3 which is recognizable along the west coast of San Giovanni di Sinis, that includes the Phoenician graves section (Figs. 2 and 3; Fig. a in Appendix). The other three samples were collected on the eastern coast of the Capo San Marco promontory, in beds correlated to the S. Giovanni M3 unit on the basis of the sedimentary facies and of the stratigraphy (CLD2, Tharros Isthmus; CLD5, at the tip of Capo San Marco; CLD6, next to the Torre Vecchia; Figs. 3–5; see Appendix for the stratigraphic description).

The stratigraphy at the Phoenician Graves section reveals a single coastal sequence with indications for minor fluctuations of sea level and/or of the coastal dynamics (unconformities: δ3/M2a, δ4/M2b, δ5, δ6/M3a–b, Fig. 2; Appendix). Therefore, the frequent occurrence of *C. caespitosa* L. in the M3a–b "labels" the maximum sea level of this episode (M3) and provides a datum line for the whole MIS 5e sequence. The absence of this fossil in the M2 beds does not allow a more complete dating of the relative sea level fluctuations in the entire MIS 5e sequence of San Giovanni di Sinis.

All samples are deposed in coastal sands and in lumachelles (coquina) of "*Senegalese fauna*", with *Patella ferruginea* Gmel., in the low part of M3, with no *Strombus bubonius* L. (Comaschi-Caria, 1954; Maxia and Pecorini, 1968; Carboni and Lecca, 1985; Ulzega and Hearty, 1986). With the exception of CLD3, sampled in growth position, all the others lay rotated, not abraded, with their latest growth, apices and septa intact. Bearing in mind the knowledge on their growth rates (Peirano et al., 2004, 2009), the ages of the colonies sampled would be between about ten years and up to a maximum of one hundred years.

In the laboratory, the samples were mechanically cleaned as thoroughly as possible, in order to eliminate most of the matrix and cement. The chemical procedures were those described in Goy et al. (2006).

3. Dating

Despite the careful cleaning carried out, all samples show significant amounts of ^{232}Th, highlighting the presence of a detrital fraction contaminating the samples (Table 1). U-contents are relatively low for fossil *C. caespitosa* compared to other Mediterranean sites (e.g. Goy et al., 2006), and lower than values measured in modern unaltered specimens (Montagna et al., 2007). Higher sea-surface temperatures i) during their depositional interval than today, and ii) westwards, in the Mediterranean Sea, were thus likely much warmer based on the U/Ca thermometry proposed by Montagna et al. (2007) for modern *C. caespitosa* colonies.

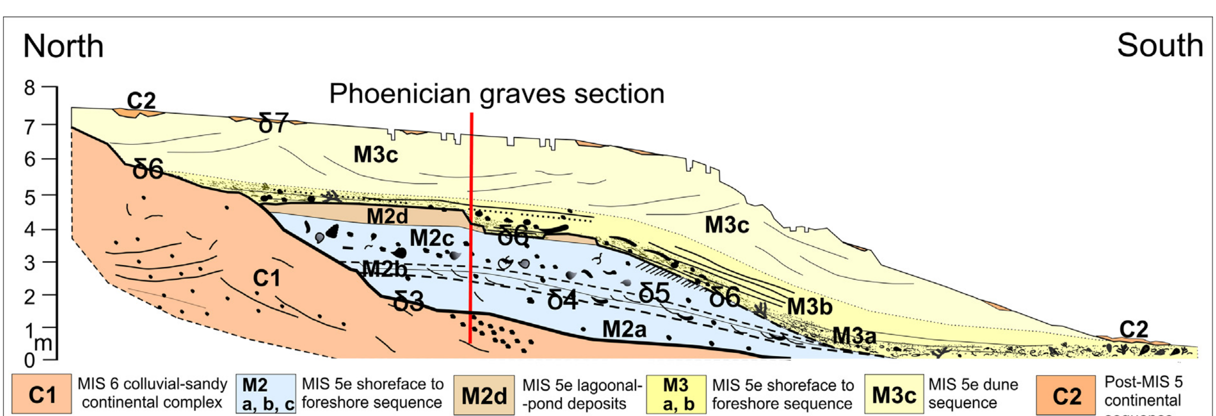

Fig. 2. Stratigraphic cross-section of the marine and continental sequences of the Middle–Upper Pleistocene in San Giovanni di Sinis and location of the Phoenician graves section (from Lecca and Carboni, 2007, modified).

Table 1
U-series systematics of coral samples (errors are ±2σ).

Samples	Site in Fig. 3	Calcite %	[^{238}U] ppm	±	[^{232}Th] ppm	±	(^{234}U/^{238}U)	±	(^{230}Th/^{234}U)	±	Uncorrected age (ka)	±	δ(^{234}U)$_0$
CLD1	S. Giovanni di Sinis section b	51.8	1.891	0.011	0.377	0.005	1.132	0.011	0.767	0.017	151	7.8	202.6
CLD2	Capo S. Marco isthmus section d	7	1.808	0.011	0.083	0.001	1.134	0.009	0.704	0.011	128	4.1	192.5
CLD3	S. Giovanni di Sinis section c	9	2.812	0.011	0.143	0.001	1.111	0.01	0.735	0.013	139	5.6	164.8
CLD5	Capo S. Marco isthmus section e	30	2.437	0.008	0.236	0.001	1.165	0.01	0.729	0.01	135	4	242.2
CLD4	S. Giovanni di Sinis section a	90	1.077	0.01	n.d.	n.d.	1.124	0.008	n.d.	n.d.	n.d.	n.d.	n.d.

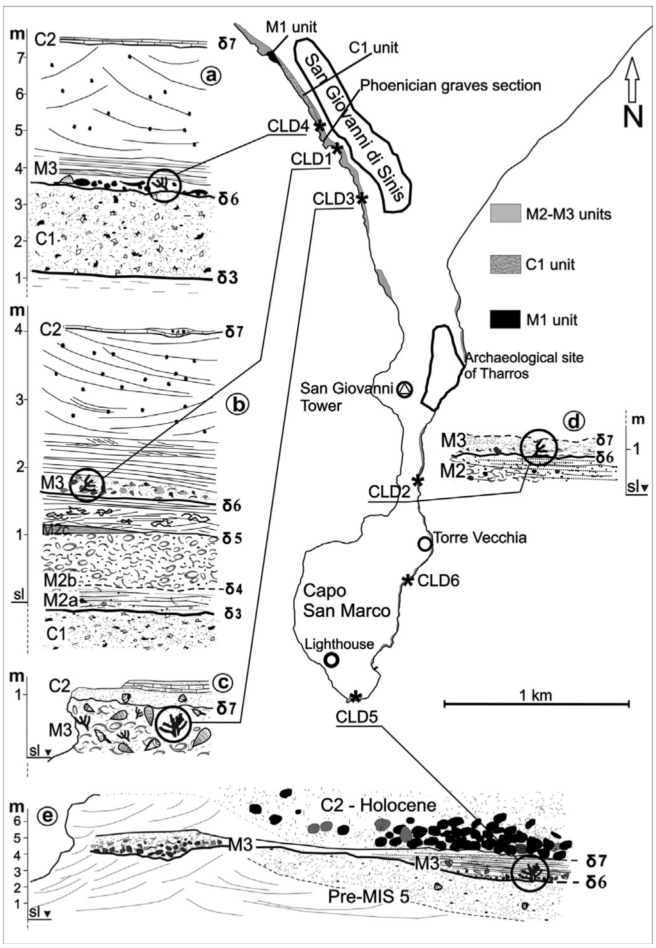

Fig. 3. Sampling sites and stratigraphic position of the samples (Phoenician graves section.kmz; CLD4.kmz; CLD1.kmz; CLD3.kmz; CLD2.kmz; CLD5.kmz; CLD6.kmz).

As illustrated by calcite percentages in Table 1, most samples have undergone diagenetic changes marked by the replacement of large parts of the aragonite of skeletons into calcite and also by a significant loss in U. When made of 100% pristine aragonite, such corals should contain about 3 ppm of U as observed in modern Mediterranean specimens (Montagna et al., 2007). Due to the significant amount of ^{232}Th (Table 1), correction for the detrital contribution to the ^{238}U-series isotope abundances, may be attempted using a 3-dimensional isochron diagram (Ludwig and Titterington, 1994).

As illustrated in Fig. 6, the isochron does indicate an age of 126 ± 25 ka, but the data points define a relatively large scatter. Nonetheless, all samples suggest a Last Interglacial assignment (note that the age uncertainty corresponds to a ±2σ error). The least contaminated sample (CLD2, see Table 1), as indicated by its very low ^{232}Th-content, yielded an uncorrected age of 128 ± 4 ka in agreement with the isochron age.

Unfortunately, the number of data points available does not permit documentation of the diagenetic effect on U–Th series isotope concentrations, and thus to better assess the age of the samples, as proposed for example by Thompson and Goldstein (2005), based on ^{234}U/^{238}U *vs* ^{230}Th/^{238}U trends. Here, there is no unequivocal relationship between the calculated initial ^{234}U-excess (*vs.* its parent ^{238}U-activity), and the uranium content (Table 1). On another hand, the purely statistical approach proposed by Ludwig and Titterington (1994) which we use here, gives *a priori* an even statistical weight to all samples whereas mineralogical and geochemical properties indicate that some samples have experienced lesser diagenetic alteration and a lesser contamination by detrital fractions (e.g. CLD2; Table 1). These are likely to yield ^{230}Th-ages (128 ± 4 ka) much closer to the true age than the more contaminated and diagenetically evolved samples. Thus, the age-uncertainty calculated from the isochron approach (Fig. 6) must be seen as overestimated. Nonetheless, an attribution of the above samples and of the embedding unit M3 to MIS 5e seems plausible.

Sample CLD6 allows comparison of three ages of fossils originating in the same sample and discussion of the meaning of the ages. Three biogenic carbonate remains (*C. caespitosa*, *Cerastoderma* sp. and vermetids) were sub-sampled (Fig. 7). Following usual procedures (mechanical cleaning, grinding, X-ray analysis, spiking and chemical extraction of U and Th), all samples were analysed on a Triton™ TIMS instrument. Despite evidence of a relatively open system, the analytical data from this *C. caespitosa* colony CLD6 (137 ± 4 ka, Table 2) appears in good agreement with the ones (CLD1, 2, 3, 4, 5, M3a–b) dated in the entire San Giovanni di Sinis – Capo San Marco area (Fig. 8a, b), whereas the *Cerastoderma* and vermetid samples from the same site (Fig. 9), illustrate much larger departures from the concordias as expected from diagenetically U-enriched samples (e.g., Zazo et al., 1999).

Table 2
U-series systematics of *C. caespitosa* CLD6, *Cerastoderma* and vermetids samples (errors are ±2σ) of the sequence south-west of Torre Vecchia.

Samples	[U ± 2σ ppm]	[Th ± 2σ ppb]	(^{234}U/^{238}U)* ± 2σ	(^{230}U/^{234}U) ± 2σ	Th age ± 2σ (ka)	(δ ^{234}U)$_0$ ‰
Coral CLD6	2.557 ± 0.010	90.6 ± 7.9	1.124 ± 0.006	0.730 ± 0.011	137 ± 4	183 ± 9
Cerastoderma	0.781 ± 0.003	5.968 ± 0.003	1.225 ± 0.007	0.463 ± 0.005	66 ± 1	271 ± 8
Vermetids	0.076 ± 0.004	12.97 ± 0.68	1.201 ± 0.008	0.517 ± 0.007	77.4 ± 1.5	250 ± 9

*: including recently-uptaken diagenetic U.

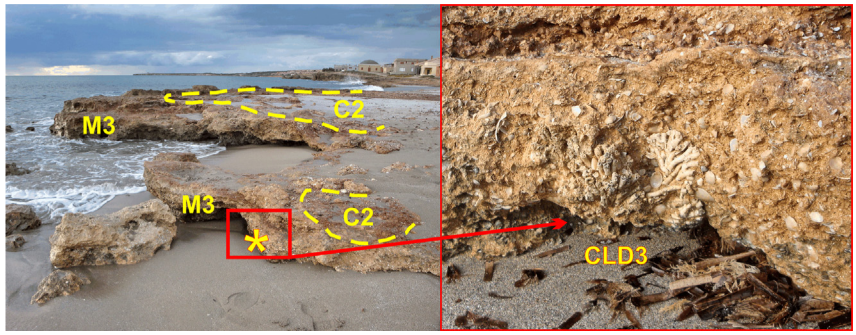

Fig. 4. *C. caespitosa* CLD3 sampled in the M3 unit, south of the San Giovanni di Sinis.

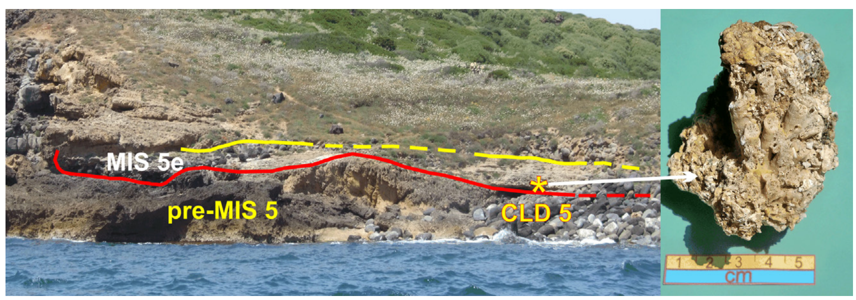

Fig. 5. The Capo San Marco outcrop and the *C. caespitosa* CLD5.

In contrast to scleractinian corals such as *C. caespitosa*, where uranium is mostly "authigenic", the U in *Cerastoderma* and vermetid shells is of "diagenetic" origin (often occurring in the vadose zone with some inputs of "continental" uranium, indicated by an excess in ^{234}U vs ^{238}U well above that expected for uranium of "marine" origin). The ^{230}Th-ages provided by such samples therefore relate to a "diagenetic U-uptake phase" (Fig. 9). In most rapidly cemented littoral deposits, U-uptake generally occurs during an early diagenetic phase (a few tens of thousands years; e.g. Zazo et al., 2002) resulting in diagenetic-U ages relatively close to the true ages of the embedding units.

In the case of the *Cerastoderma*, sp. and vermetids analysed here, the high porosity and weak cementation of the deposit might have been responsible for a long-duration diagenetic U-uptake phase (e.g. Zazo et al., 1999), possibly still active. This would explain the ~50 ky difference in "apparent" ^{230}Th-ages between the coral and the mollusc samples. However, the facts that the embedding unit is a thanathocenotic accumulation, and the fair agreement between the ^{230}Th-ages of the *Cerastoderma*, sp. and vermetids, leave the door open to questioning the true age of the unit. In this regard, indications for high relative sea-levels at about 70–75 ka are reported elsewhere (e.g. Schellmann and Radtke, 2004; Dogan et al., 2012). Some uncertainty is thus required with respect to this issue, although a sea-level at a height near the present one during this time interval might be considered as much unlikely, based on the continental-ice volume estimates (e.g. Waelbroeck et al., 2002). However, the stratigraphic and sedimentologic relationships between the colony of *C. caespitosa* CLD6, the growth of vermetids, and the bioclastic *Cerastoderma*-bearing unit exclude the possibility of large hiatuses in this unit and the whole MIS 5e sequence (Fig. b, Appendix).

4. Discussion

U-series data assign the M3a–b deposits from several sections of San Giovanni di Sinis and Capo San Marco area to MIS 5e. Stratigraphic correlation extends the same age to many other deposits of the Sinis coast. These data exclude any assignment to the Holocene, as recently put forth (see Coltorti et al., 2010, 2012; Thiel et al., 2010). Similarly the attribution of the section near Torre Vecchia that yielded sample CLD6, to MIS 5a as proposed by D'Orefice et al. (2012), seems unlikely based on the apparent age (Table 2). Sample CLD2, which shows little evidence for any significant diagenetic evolution, yielded an age of 128 ± 4 ka, compatible with those of marine deposits of early MIS 5e at the global scale (e.g. Kopp et al., 2009).

The sedimentary unconformities, the discontinuities and the changes of facies in several sections where marine MIS 5e deposits are exposed led to the identification of different cyclothems

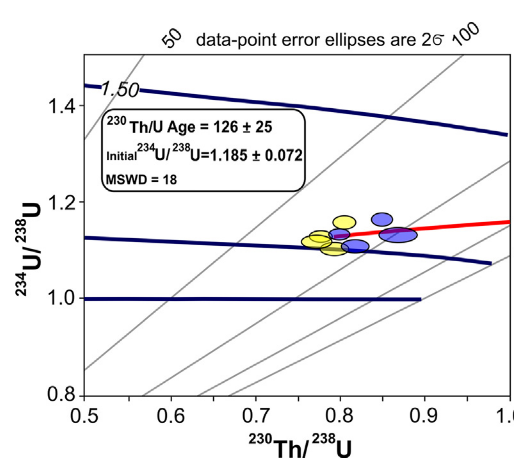

Fig. 6. 2 D-projection (ellipses) of a 3D-Abaca illustrating the systematics of U-series data in samples (CLD1, 2, 3, 5) from the present study, using the Isoplot 3 from Ken Ludwig (USGS). The scatter data point around the isochron line is quite large, illustrating diagenetic effects on ^{238}U-series isotopes and the variable detrital contamination of samples.

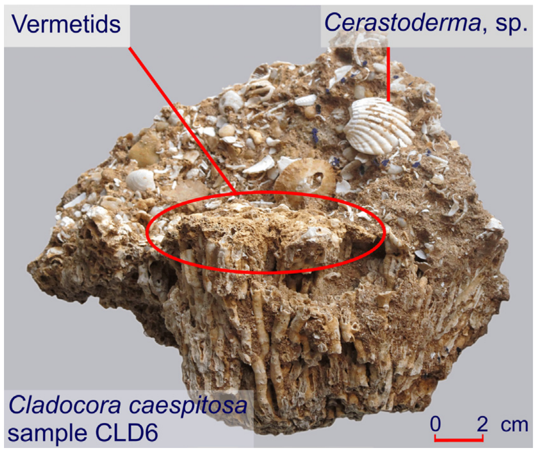

Fig. 7. Detail of the *C. caespitosa* CLD6, originating from bed 5 of Torre Vecchia sequence. The Vermetidae encrusted the colony of *C. caespitosa, the Cerastoderma* sp. shell was deposed about 2–4 cm above the colony, about 10 cm laterally.

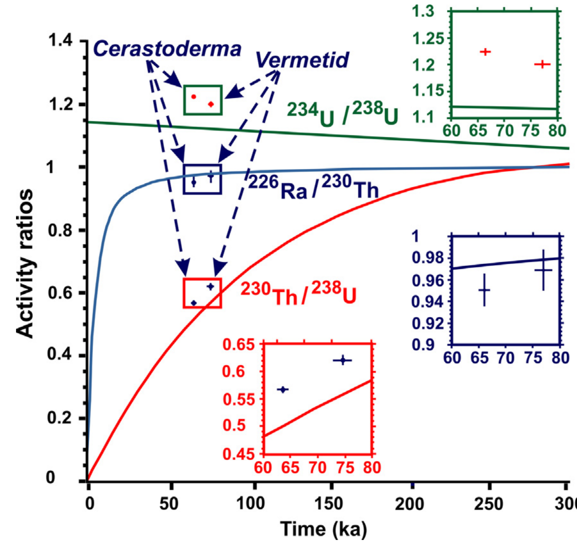

Fig. 9. Evolution of activity ratios versus time of $^{234}U/^{238}U$, $^{230}Th/^{238}U$ and $^{226}Ra/^{230}Th$ for a closed-system with 100% authigenic "marine uranium": vermetids and *Cerastoderma*, sp. samples pointing to an age of ~70 ka for a diagenetically-uptaken uranium (cf. the excess of ^{234}U *vs* ^{238}U, well above that expected for a "marine-U", suggesting U-uptake with some "continental" water U-influence).

associated with several relative sea-level oscillations, as illustrated by Hearty et al. (2007) and O'Leary et al. (2008). Whether they related to major "eustatic" fluctuations of MIS 5e (e.g. Kopp et al., 2013), is another issue.

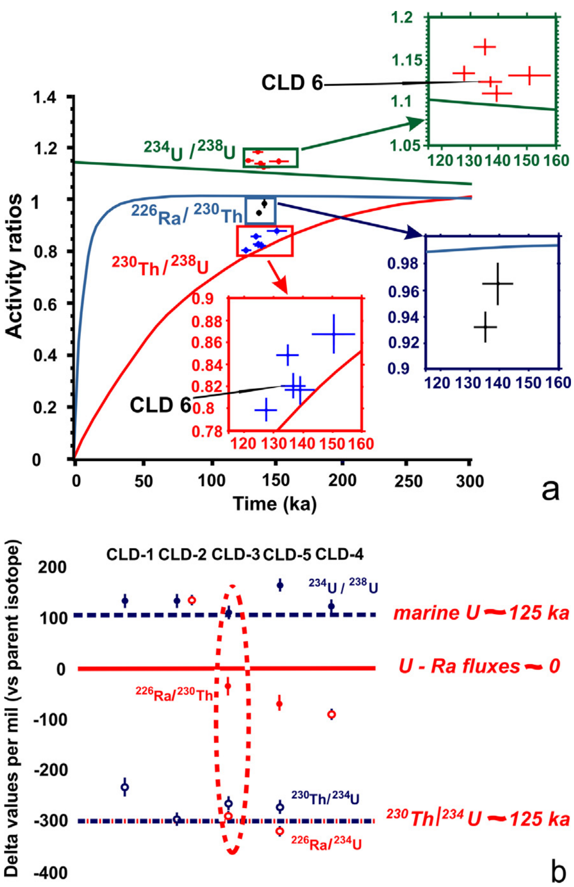

Fig. 8. Evolution of activity ratios versus time of $^{234}U/^{238}U$, $^{230}Th/^{238}U$ and $^{226}Ra/^{230}Th$ for a closed-system with 100% authigenic "marine uranium": the *C. caespitosa* samples point to an age of ~125 ka with indication for some U-mobility (see offsets from the concordias in the blow-up sketches), b) Option 1: Age-model assuming constant U-fluxes with constant $^{226}Ra/^{234}U$xs ratios, Option 2: Selecting the most likely representative sample (within the dashed-ellipse).

The large scatter of ages assigned to high sea-level stands of MIS 5e in the circum-Mediterranean (cf. Coltorti et al., 2010; Andreucci et al., 2009; Thiel et al., 2010; Hillaire-Marcel and Ghaleb, 2012), does not permit unequivocal correlations between such "high stands". The presence of one, two or more eustatic peaks, or fluctuations at the millennial scale, during the MIS 5e interglacial has thus been a matter of much debate at the global scale (Hillaire-Marcel et al., 1996; Schellmann and Radtke, 2004; Hearty et al., 2007; O'Leary et al., 2008) and in the Mediterranean area (Davaud et al., 1991; Kindler et al., 1997; Jedoui et al., 2003; Zazo et al., 2003; Zazo et al., 2007; Bardají et al., 2009; Zazo et al., 2010; Dabrio et al., 2011; Ginés et al., 2012; Zazo et al., 2013), although the statistical assessment of MIS 5e sea level of Kopp et al. (2009) supports the scenario of a twin MIS 5e sea-level recording.

Investigations on the San Giovanni sequence (Lecca and Carboni, 2007; Carboni and Lecca, 2010) led to the proposal of a sea level high stand, dating probably from the early MIS 5e, based on the above chronological data (Fig. 10). In this sequence, the highest sea-level of M3a–b is preceded by short-entity sea-level oscillations, probably at millennial scale pacing, responsible for significant changes in the morphology of the coastline. This interpretation would thus correspond with conclusions from other stratigraphic studies in the Mediterranean realm (Dabrio et al., 2011).

In San Giovanni di Sinis, the upper part of the M3 unit consists of an aeolian deposit of backshore (M3c) and any late MIS 5e high

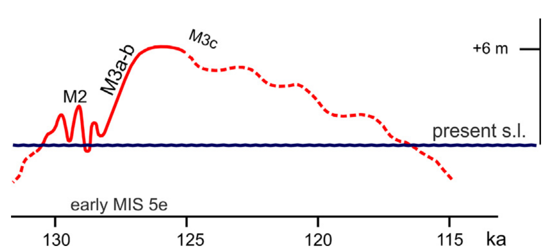

Fig. 10. Tentative sea level curve of MIS 5e deduced from stratigraphic data of San Giovanni di Sinis, (from Lecca and Carboni, 2007 modified) and from U-series data of this work.

eustatic peak produced some wave ravinement. The absence of a new overlying shore cyclothem or a truncating surface above M3 unit represents a stratigraphic evidence that after the deposition of the M3a–b the shore has been conditioned by a forced regression and the sea must have lowered.

5. Conclusions

The recent U-series data from samples of *C. caespitosa* sampled at the very base of the M3 marine unit of the main outcrop at San Giovanni di Sinis and from other minor southern outcrops located on the eastern side of the isthmus and at the tip of Capo San Marco, support previous assignments of the sequence to MIS 5e. Unit M3 is related to a sea level pulse that reached about +5.5 m above modern sea level at San Giovanni di Sinis. The six coral colonies of *C. caespitosa* dated yielded an isochron age of 126 ± 25 ka (±2σ), and the age of the best preserved sample points to an age of 128 ± 4 ka (±2σ). The deposition of both M2 and M3 units occurred within an MIS 5e high "eustatic" sea level interval. Several outcrops along the present coast of the Sinis region correlative of M2 and M3 also document the MIS 5e sequence above heterochronous and possibly polyphasic erosional surfaces up to a maximum level of +4 to +5.5 m asl (M3 unit), preceded by several fluctuations of lower intensity (M2 unit).

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Appendix A

1. Early stratigraphic interpretations

The early studies of the San Giovanni di Sinis outcrops identified marine littoral sediments with "*Senegalese fauna*", resting on aeolian sandstones and continental sediments associated with the marine regression related to the "Riss glaciation" (Maxia and Pecorini, 1968). Other authors attributed part of this succession also to the "Würm glaciation" (Comaschi-Caria, 1954; Vardabasso, 1956; Masala, 1959; Maxia and Pecorini, 1968; Pomesano-Cherchi, 1968; Marini and Murru, 1977). Later studies improved the stratigraphic "Tyrrhenian" identification (i.e. MIS 5) (Ulzega et al., 1980) and suggested their correlative nature with similar deposit from the Tunisian coast (Ozer et al., 1980: Rejiche Formation–Cala Mosca Formation, "*Eutyrrhenian*"; Chebba Formation–Santa Reparata Formation, "*Neotyrrhenian*").

A detailed stratigraphic study of the Pleistocene outcrops along the coast of Sinis and the Mal di Ventre island (Carboni and Lecca, 1985) identified and described, for the first time, a Middle–Late Pleistocene marine and continental composite succession, composed of three shoreface to foreshore–backshore units (named M1, M2, M3) and two continental units (named C1, C2), resting unconformably on Messinian marls and limestones of the "Capo San Marco Formation" and locally presenting neotectonic evidences. M1 is correlated to the "Palaeo-Tyrrhenian" ("Mindel-Riss" *Auct*., i.e. MIS 7 interglacial). C1 is correlated, given its considerable thickness, to pre-MIS 5. M2 and M3 are correlated, on the basis of the stratigraphic interpretation, to the "*Eutyrrhenian*" highstand (i.e. MIS 5e) and, on the northern side, an isolated outcrop (named MX) is correlated to the M3 unit as well; C2, containing prehistoric - historic remains in the highest part, is correlated to the Late Pleistocene marine regressions (i.e. MIS 4–2) and to Holocene).

Some of the earlier ages of the "Tyrrhenian" beach deposits at San Giovanni di Sinis, between 67.5 ka and 56 ka by Amino Acid Racemization dating (Wanet et al., 1982), were considered unreliable because of methodological difficulties (Ulzega and Hearty, 1986). By means of further racemization dating, Ulzega and Hearty (1986) attributed the San Giovanni di Sinis lower coastal unit to the "Eutyrrhenian" (i.e. MIS 5e) and the upper units, dated between 105 ka and 75 ka, to the "Neotyrrhenian" (i.e. MIS 5c–5a).

Davaud et al. (1991), applying a fine sequential and petrographic analysis, identified three coastal marine sequences interpreted as three high-sea level phases, corresponding to the three highest thermal peaks during the last interglacial but did not propose a precise age for these high sea levels, only tentatively hypothesizing an age between 130 and 70 ka. Kindler et al. (1997) attributed the lower marine unit (i.e. M1), to a pre-Tyrrhenian interglacial and both their "I and II sequences" (i.e. M2 and M3) to MIS 5e. The II sequence was correlated to a significant increase in carbonate facies linked to the 128-ka insolation maximum.

Carboni and Lecca's later field investigations led to the discovery of further remains of reptiles and artiodactyls in the upper part of unit M2, including a terrapin (*Mauremys*, sp.) and the endemic Sardinian deer (*Praemegaceros cazioti*, Chesi et al., 2007). These data documented the presence of an emerged marsh environment with episodic fresh waters.

A subsequent study of this Pleistocene succession provided a detailed facies analysis of the micro-tidal low wave energy beach and temperate lagoon in its transition to emerged perilagoonal facies containing vertebrate remains involved by an erosion surface (Lecca and Carboni, 2007). At least three wave ravinement surfaces and one paraconformity of the MIS 5e sub-stage are described. There appears to be evidence of an irregular single highstand, rather than two eustatic peaks as previously believed (Carboni and Lecca, 1985; Ulzega and Hearty, 1986; Davaud et al., 1991; Kindler et al., 1997). The local stratigraphic unconformities/disconformities/paraconformities are interpreted as a consequence of the lateral shifts of the depositional environments.

In a further recent study, Andreucci et al. (2009) proposed a stratigraphic sketch using both new and prior (Carboni and Lecca, 1985) local terms and concepts identifying four unconformity-bounded units. In comparison to Carboni and Lecca (1985) several differences in recognising the facies, the stratigraphic surfaces and the architecture are present. The δ6 disconformity is traced at different stratigraphic levels, as in the Log 5 – Phoenician tombs ("Phoenician graves section" of Lecca and Carboni, 2007, "Tombe Romane" in Carboni and Lecca, 1985). The δ4 ravinement surface and the clay lens bearing benthic foraminifera and ostracods are not mentioned. These different interpretations confirm the critical importance of the stratigraphic recognition to decode the signal contained in these main outcrops and to correctly attribute the datings and the sequential and eustatic interpretation. Optical stimulating luminescence (OSL) age dating attributed to the depositional unit named U3a (corresponding to our M3 unit) an age of 120 ± 10 ka and to U3b (apparently corresponding to the M3 unit as well) an age of 100 ± 5 ka (MIS 5c).

Despite all the different interpretations and using δ6 as a maximum flooding surface, most of the outcrop is described as a single cycle of a marine transgression and related highstand that developed during MIS 5e, not that dissimilar from Lecca and Carboni's (2007) irregular single high stand, though this study is not quoted in Andreucci et al. (2009).

Coltorti et al. (2010), in contrast with all the other studies and arousing doubts of interpretation (Catto, 2010), hypothesize that the lagoonal layers M2d mentioned in Lecca and Carboni (2007) belong to "… an interdunal lacustrine environment…" and ascribe the M3 shoreface–foreshore–backshore unit to … "the basal part of a dune system." Furthermore, for the "Tyrrhenian" outcrop at Capo San Marco, the same authors suggest a Holocene age, "… although this is in contrast with the OSL dating results". Thiel et al. (2010) obtained conflicting results using OSL and ^{14}C dating performed on the San Giovanni di Sinis and Capo San Marco outcrops. These hypotheses are incompatible with the Amino Acid Racemization dating reported in the older literature, and with other dates published recently (OSL, Andreucci et al., 2009; U/Th ages in Carboni and Lecca, 2010; ESR, Orrù et al., 2011a).

A last result that stimulates a review of this section is provided by the "*minimum age*" of 70 ± 4 ka of a colony of *C. caespitosa* L. on the eastern coast of Capo San Marco (D'Orefice et al., 2012). This age, on the one hand is in contrast with the Holocene age hypothesized in Coltorti et al. (2010), on the other hand sustains the possibility of the presence of a cyclothem of the MIS 5a high stand.

2. The "Phoenician graves" type section (Phoenician graves section.kmz).

The most representative MIS 5e section in Sardinia is exposed next to the village of San Giovanni di Sinis (Fig. 2; Fig. a), on the small cliff behind the present narrow shore, in the central part of the outcrop (near Log 16 of Carboni and Lecca, 1985, the "Phoenician graves" section of Lecca and Carboni, 2007; the new name of this section, near "Tombe Romane", was preferred for a new discovery of older Phoenician graves inland (Del Vais and Fariselli, 2009)).

The facies sequence of this section can be summarized as follows:

- *Upper part of unit C1, continental pre-MIS 5e:* fine-medium moderately cemented aeolian sandstone and massive sandy colluvial deposit. This continental complex, which also contains dwarf elephant teeth, is attributed to the middle Pleistocene because it is buried by Tyrrhenian sediments (Maxia and Pecorini, 1968; Ambrosetti, 1972; Melis et al., 2001; Palombo et al., 2012). Northward, this complex covers an upper shoreface–backshore sequence, probably MIS 7 interglacial (Carboni and Lecca, 1985; Andreucci et al., 2009).
- *δ3 unconformity*: continental surface interested by the MIS 5e transgressive wave ravinement on the C1 unit.
- *MIS 5e foreshore to lagoonal units, M2a–δ4–M2b–M2c:*
  M2a – polygenic conglomerate and lithic-bioclastic quartz feldspar foreshore plane-parallel laminated sandstone.
  δ4 – disconformity: surface (1.7–2.0 m asl) modelled by subaerial erosion and wave ravinement of a limited sea level fluctuation.
  M2b – lagoonal lumachelle of M. galloprovincialis Lmk, and rare Cerastoderma edule L.
  M2c – lagoonal silty, clayey-silty sand, with *C. edule* L. *Tapes* sp., ostreids and venerids.
- *MIS 5e perilagoonal bed set M2d:*
  M2d1 – clayey silt very rich in ostracods, with terrapin (*Mauremys* sp.) and deer (*P. cazioti* Dep.) remains (Chesi et al., 2007).
  M2d2 – carbonate silt, locally well lithified limestone, containing artiodactyl bone fragments.
  M2d3 – carbonate mud and silty fine sand.
  M2d4 – well-lithified marly-sandy limestone, with internal pulmonate moulds.

To the south-east of Phoenician graves section, the M2c–d bed set begins a thin sequence of low energy, clay bed, interbedded sandstones (M2e) locally with trace fossils (complex tiering of *Planolites* ?) and lagoon–backshore–foreshore–upper shoreface environments.

- *MIS 5e δ6 unconformity*: erosional surface with clear macroborings (*Gastrochaenolites*) on the M2d hardground, interpreted as a wave ravinement surface of a significant sea level fluctuation (2.7 ÷ 3.7 m asl), changing to a paraconformity southeastward.
- *MIS 5e upper shoreface–backshore – aeolian sequence, unit M3:*
  M3a – foreshore–upper shoreface sandstone bearing *corallinae algae*, *Patella (Patellastra) ferruginea* Gml., *Conus testudinarius* Mart. in the lower part. Upward and laterally there is a sand bar with foreshore–shoreface laminations, sand mounds, equilibrium structures, burrows (*Skolithos*, *Monocraterion* and others traces in aggrading sands).
  M3b – terrigenous and highly biogenic sandstone of foreshore–upper shoreface, with low and high angle cross-laminations.
  M3c – bioclastic and quartzose backshore and dune sandstones.
- *Continental unit* C2, *post-Tyrrhenian*: polygenic carbonate crusts, minor colluvium and aeolian sand and silt.

It is important to underline the presence, near the Phoenician graves section, of the δ3, δ4 and δ6 erosional surfaces, the third being a clear erosional truncation before the M3 shore sediments, with colonies CLD1, 3, 4.

On the basis of this stratigraphic reconstruction, the discontinuity δ6 is not thought to be a separation of two distinct and significant sequences, but is interpreted as a discontinuity between beds of adjacent environments within the same depositional shore-lagoon system, in a complex and rapidly changing palaeogeographic context related to a small sea level fluctuation, because the shift of the depositional facies recognised is not compatible with an important sea level fall. The sea level behaviour of this erosional phase (δ6), therefore, can be interpreted as a slowdown in the sea rise or a stationary trend at about +2.5 to +3.0 m or, at the most, as a minor drop of a few metres in sea level, before reaching the maximum highstand at about +4.5 to 5.5 m above the present sea level.

The San Giovanni di Sinis outcrop thus preserves the sedimentary response to the high frequency climatic and sea level variations, not identifiable in sections of less receptive environments. Using this new sequence stratigraphy for San Giovanni, it can be reasonably suggested that the beginning of the highstand phase (about +3.5 m) of the temperate climate was followed by a phase with a warm and drier climate that favoured carbonate production (Kindler et al., 1997), with a sea level rise to about +5 m or, with higher intervening events, perhaps storm events, to about +6 m.

3. Stratigraphy of the sampling sites (locations in Fig. 3; CLD4.kmz; CLD1.kmz; CLD3.kmz; CLD2.kmz; CLD5.kmz; CLD6.kmz).

CLD4

About twenty metres north of the Phoenician graves section, the section (Fig. 3 a) shows:

- at the base, the loamy-sandy-detrital colluvial deposit, rich in moderately rounded quartz grains and angular limestone fragments (C1 *pre-MIS 5e* continental unit);
- over a clear wave ravinement surface (δ6 unconformity), the fossiliferous basal conglomerate of the M3 unit with well-rounded pebbles from the underlying lithofacies, and *Patella*

(*Patellastra*) *ferruginea* Gmel., *Conus testudinarius* Mart., frequent red coralline algae, provided the solitary *C. caespitosa* colony of sample CLD4. In its upper part, this fossiliferous bed is transitional to laminated foreshore sands and backshore dune deposits;
- at the top is a red polygenic carbonate crust and very thin sandy-loamy colluvium layers, *post-Tyrrhenian*, sometimes with *Helix* sp. pulmonate shells (δ7 disconformity).

CLD1

South of the *Phoenician graves*, the section (Fig. 3 b) shows from the bottom:

- loamy–sandy–detrital colluvial deposit, rich in moderately rounded quartz grains and angular carbonate fragments (C1 continental *pre-MIS 5e* unit);
- M2a foreshore conglomeratic, lithic-bioclastic quartz-feldspar sandstone, scarcely fossiliferous;
- M2b coarse-very coarse, poorly sorted, sandstone forming lumachelle with *M. galloprovincialis* Lmk. and rare *C. edule* L., overlying the δ4 disconformity;
- lagoonal thin lens of green clays with benthic foraminifera and ostracods, faecal grains, fragments of pelecypods;
- thin beds of thinly laminated upper shoreface–foreshore sandstones and of strongly bioturbates sandstones, very rich in horizontal burrows, overlying the δ5 paraconformity;
- lumachelle deposit of the basal M3 unit overlying the δ6 disconformity, with a rich content of fauna of the protected bay, containing *C. caespitosa* racemes and a complete colony (CLD1);
- smooth transition to a gently south-eastern dipping foreshore sandstone with plane parallel laminations and to aeolian sandstone with both low and high angle accretion;
- at the top, *post-Tyrrhenian* red polygenic carbonate crusts and very thin sandy-loamy colluvium layers, sometimes with *Helix* sp. pulmonate shells (δ7 disconformity).

CLD3

Towards the south-east, along today's beach in the southern part of the San Giovanni di Sinis coast, the MIS 5e outcrop is progressively eroded, and only the M3a–b unit crops out (Fig 3 c) showing layers with *Loripes lacteus* L. and a massive lumachelle containing abundant shells of *Pinna nobilis* L., often with articulated valves, and other fauna (molluscs, red algae and *C. caespitosa*). From this lumachelle comes sample CLD3 (Fig. 4).

CLD2

On the eastern side of the isthmus between the archaeological site of Tharros and the Torre Vecchia, an irregular and exiguous outcrop (Fig. 3d) shows:

- massive medium-size grained sandstone (correlated to M2), poorly bioclastic, laterally changing to microconglomeratic locally fossiliferous sandstone;
- erosional surface correlated to δ6 disconformity;
- lumachelle usually containing *Cerastoderma* sp. and a very rich fauna of small gastropods and pelecypods (correlated with M3 unit), where a colony of *C. caespitosa*, CLD2, was collected.

CLD 5

Based on the highest elevation (about +4.5 ÷ 5.5 m) of the marine terrace and on its faunal content, the outcrop at the end of Capo San Marco was previously attributed to the *Tyrrhenian* (i.e. MIS 5e; Comaschi-Caria, 1954; Ulzega et al., 1980; Sanna, 1986; Carboni and Lecca, 1985; Belluomini et al., 1993; Carboni and Lecca, 2010); only recently it has been dubiously attributed to the Holocene (Coltorti et al., 2007, 2010; Thiel et al., 2010; Coltorti et al., 2012).

The outcrop from the bottom shows (Fig 3e):

- pre-MIS 5e dune, composed of at least three benches of up to about 8–10 m in thickness of cross laminated aeolian sandstone, dipping eastward, containing some mammal bone fragments and rhizocretions; late-dune or interdunal medium-coarse sandy deposits with a muddy component, rich in moderately rounded quartz granules, *Helix* shells and root traces. Consistently with the age of the stratigraphic literature, OSL dating for the quartz of the third bank of these dunes indicated pre-MIS 5e (174 ± 13 ka, Thiel et al., 2010).
- resting in a notch and on an erosional platform gently dipping to the south, carved in the upper bank of a previous dune, at a height between 3.0 m and 5.5 m, is a conglomerate composed of basalt spheroidal blocks and cobbles in biocalcarenitic matrix containing marine shells and encrusting coralline algae. This conglomerate dips eastward where it becomes 1.50 m thick, with a 20 cm thick conglomeratic bed at the base and coarsely laminated upwards, containing red coralline algae biohermes, pelecypods and gastropod shells including *M. galloprovincialis* Lmk, *Glycymeris* sp, *C. edule* L., *Ostrea edulis* L., *Barbatia barbata* L., *Patella (Patellastra) ferruginea* Gmel., *Patella (Patella) coerulea* L., *Bittium reticulatum* da Costa, *Thais haemastoma* L., *Conus (Lautoconus) ventricosus* Gmel. and the *C. caespitosa* of the CLD5 sample (Fig. 5).
- overlying a disconformity surface, a post MIS 5e deposit of basalt spherical cobbles and blocks, in a slightly reddish-brown loamy matrix.

CLD 6

Along the eastern rocky coast of the C. S. Marco promontory, the MIS 5e coastal sediments crop out almost continuously. A representative section, near Torre Vecchia (Fig. 3), shows six beds (Fig. b) forming a sequence correlatable to the San Giovanni one.

Beds 2–3–4a–4b and beds 5–6 respectively show the sedimentary framework and the biofacies comparable and correlatable to the M2 and M3 units of the San Giovanni di Sinis Phoenician graves section.

Below unconformity U2, correlated to the δ6 unconformity of the San Giovanni outcrop, bed 4b contains typical fauna of a littoral confined environment, composed of large *C. edule* shells and a very high amount of *M. galloprovincialis* Lmk shells.

Resting on unconformity U2, bed 5, in turn correlated to M3 of San Giovanni, constitutes a chaotic thanatocoenosis composed mainly of pelecypods and rare colonies of coral. A large colony of *C. caespitosa*, CLD6, originates from this bed, a sub-sample of *Cerastoderma* was located 10 cm nearby, whilst another sub-sample of Vermetidae encrusted the upper part of the colony CLD6. Between these three sub-samples, no sedimentary discontinuity was present.

Appendix B. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quaint.2013.12.052.

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