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THE TYRRHENIAN SECTION OF SAN GIOVANNI DI SINIS (SARDINIA): STRATIGRAPHIC RECORD OF AN IRREGULAR SINGLE HIGH STAND

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Abstract. A new analysis of the most representative Upper Pleistocene (Tyrrhenian, MIS 5e) section of San Giovanni di Sinis (Oristano, Sardinia) has provided a more detailed genetic stratigraphy of a low wave energy beach and temperate lagoon up to emerged peri-lagoonal facies deposits. These peri-lagoonal facies contain remains of fossil vertebrates, which, though few and fragmentary, bear witness to an at least temporary freshwater palaeoenvironment and the presence of deers and terrapins. Besides, the stratigraphy of this outcrop shows shoreface-backshore sandstones overlaying an erosion surface cut on the vertebrate-bearing layers. Facies analysis and sequence stratigraphy of the succession have provided support to a new eustatic interpretation significance. In fact, there appears to be evidence of one irregular single eustatic highstand, rather than two eustatic peaks as previously believed. The facies evolution and the local stratigraphic disconformities are interpreted as being associated with a lateral shift of the depositional environment within the same system formed during the MIS 5e sea level variations. As sea water level continued to rise so an erosional unconformity, caused by wave ravinement, formed between the low wave energy beach-lagoon sequence and the successive wave dominated beach facies sequence. This interpretation is supported by comparison with other sections of the Tyrrhenian in western Sardinia. The maximum sea level attained during the Tyrrhenian stage is a clear indication of a warm-temperate climate which can be correlated to the well known orbital interglacial configuration when the eustatic signal of Greenland's ice sheet melting occurred.

Riassunto. Una nuova analisi stratigrafica del Tirreniano, eseguita sulla sezione più rappresentativa del Pleistocene superiore della Sardegna (San Giovanni di Sinis, Oristano), ha consentito di precisare la transizione delle facies di spiaggia protetta e di laguna temperata fino a facies peri-lagunari emerse. Le facies perilagunari hanno fornito resti fossili di cervo e di tartaruga di acqua dolce il cui significato ambientale, affiancato all'analisi delle litofacies e all'interpretazione genetica e sequenziale della successione degli strati e delle disconformità, ha consentito una nuova interpretazione stratigrafica ed eustatica. Non sarebbero documentati, come finora inteso, due picchi di due separati alti eustatici, ma un unico, anche se irregolare, alto eustatico. L'evoluzione delle facies viene interpretata come conseguenza degli spostamenti degli ambienti all'interno del medesimo sistema deposizionale, instauratosi durante l'*high stand* del MIS 5e. Lo stesso progredire dell'innalzamento eustatico avrebbe causato diverse disconformità e in particolare una netta discordanza di *wave ravinement* tra l'unità stratificata di mare protetto e la successiva di spiaggia esposta al moto ondoso. Tale interpretazione stratigrafica, che trova riscontro nella comparazione con altre sezioni del Tirreniano della Sardegna occidentale, porta ad individuare la presenza di un picco di alto eustatico nella parte medio-tarda del MIS 5e. La sequenza stratigrafica del Tirreniano, documentata in Sardegna, costituirebbe la risposta sedimentaria al segnale eustatico in Mediterraneo causato della fusione di gran parte dei ghiacci della Groenlandia, e di altre parti del globo, correlabile con una configurazione orbitale interglaciale. Durante tale risalita eustatica il Golfo di Oristano ed altre estese aree costiere della Sardegna furono sede della migrazione di ambienti di spiaggia su precedenti ambienti di laguna e paludi fluvio-lagunari.

Introduction

The marine-continental Pleistocene succession cropping out at San Giovanni di Sinis (south-central-western Sardinia; Fig. 1) has been widely studied over the last 30 years, in particularly the stratigraphy of the Tyrrhenian marine depositional sequences, the fossils contained therein and their climatic significance. The stimulating debate among members of the Italian Commission on Stratigraphy during the 2005 FIST-Geoitalia meeting on the Tyrrhenian marine stage and its lithostratigraphic and geochronologic/chronostratigraphic significance, revived researchers' interest in this sedimentary succession. Numerous Tyrrhenian outcrops occur in Sardinia, that bear witness to a eustatic event attaining around $5 \div 6$ m a.s.l. (Ferranti et al. 2006 and references therein), taking as reference Sardinia's tectonic stability by comparison with other parts of the Mediterranean (Lambeck et al. 2004; Antonioli et al.

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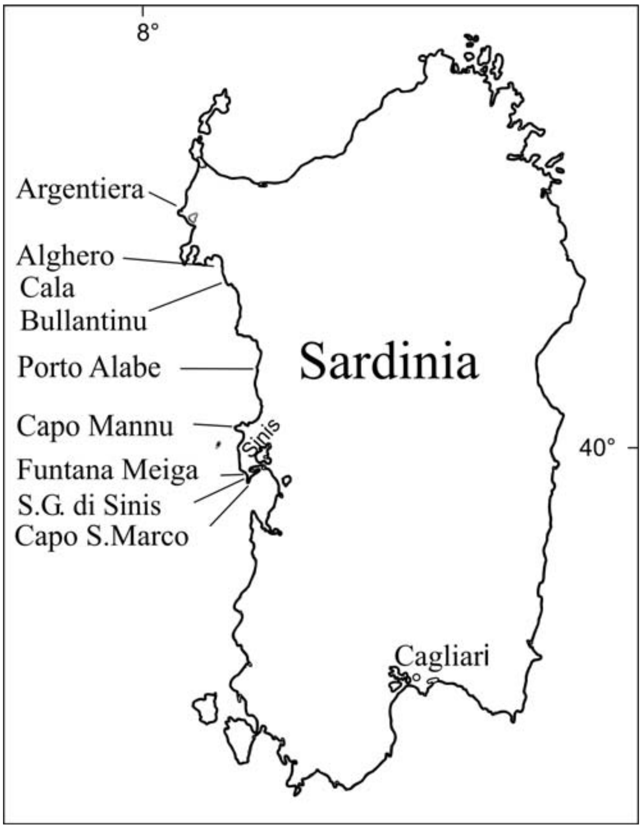

Fig. 1 - Location of the San Giovanni di Sinis and other Sardinian Tyrrhenian outcrops.

2006). In order to identify the most representative sections in Sardinia, current research on the Tyrrhenian event in the Sinis region, as well as in western and southern Sardinia, is focussing on a new stratigraphic analysis. During investigations additional vertebrate fossils were found in the S. Giovanni section (Chesi et al. 2007), that have helped to gain a better genetic understanding of these layers.

The Middle-Upper Pleistocene of San Giovanni di Sinis

Early studies in the San Giovanni di Sinis section identified marine littoral sediments with "warm fauna", correlated to the Tyrrhenian highstand and resting on aeolian sandstones and continental sediments associated with the "Riss glaciation" (Maxia & Pecorini 1968). Other authors attributed part of the section also to the "Würm" glaciation (Vardabasso 1956; Masala 1959; Maxia & Pecorini 1968; Comaschi-Caria 1968; Pomesano-Cherchi 1968; Marini & Murru 1977).

Subsequent studies improved the stratigraphic description of the Tyrrhenian deposits (Ulzega et al. 1980) and correlated these deposits with those of the Tunisian coast (Ozer et al. 1980): Rejiche Formation – Cala Mosca Formation (Eutyrrhenian), Chebba Formation – Santa Reparata Formation (Neotyrrhenian).

Amino acid racemization dating (Wanet et al. 1981) of the Tyrrhenian deposits of San Giovanni di Sinis (67.5 to 56 ka) was considered unreliable because of methodological difficulties (Ulzega & Hearty 1986). Moreover this dating was inconsistent with the findings of later studies (Carboni & Lecca 1985; Davaud et al. 1991; Kindler et al. 1997).

In an accurate stratigraphic description of the Pleistocene outcrops in western Sardinia (Carboni & Lecca 1985), on the Sinis coast and the Maldiventre Island, three Middle-Upper Pleistocene marine units have been identified (M1, M2, M3; Fig 2) resting unconformably (δ1) on Messinian marls and limestones of the Capo San Marco Formation (Cherchi et al. 1978). This stratigraphy, as well as the findings of other studies, are reviewed here as they contain evidence which requires new interpretation.

The northern, stratigraphically lowermost part of the San Giovanni di Sinis outcrop displays a shore unit, with foreshore facies evolving into a backshore and aeolian dune (M1; the acronyms used in this study are those of Carboni & Lecca 1985), overlain by a continental sequence (C1, above a faint δ2 surface) with at least 5 layers of aeolian and colluvial sandstones. It should be noted that the elephant fossil remains, described by Maxia & Pecorini (1968) and by Ambrosetti (1972) and discussed by Melis et al. (2001), are from C1 sequence.

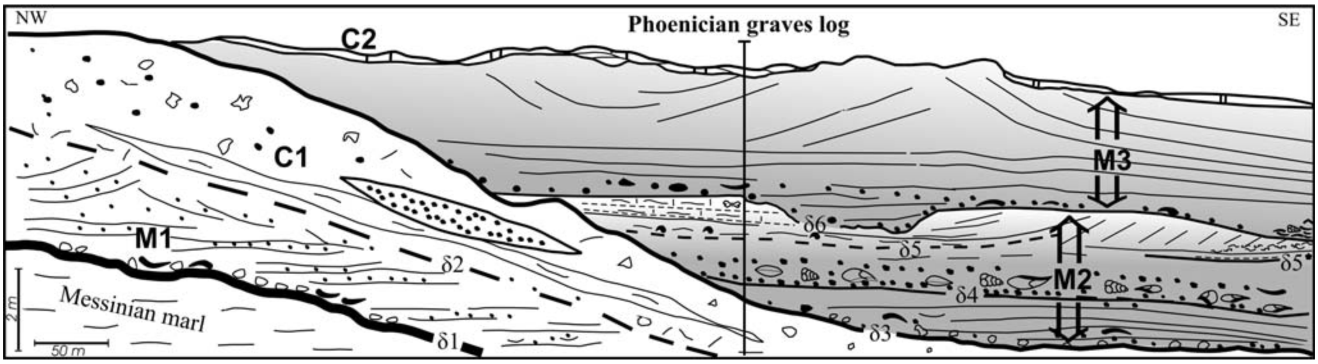

Fig. 2 - Stratigraphic sketch of the marine and continental sequences of the Middle-Upper Pleistocene outcrop in San Giovanni di Sinis. Modified from Carboni & Lecca (1985).

To the north, a normal high angle mesofault occurs in the M1 unit causing an abrupt interruption in the Middle-Upper Pleistocene outcrop and an almost vertical contact with the Messinian marls.

Unit M1, together with the overlying succession, dips slightly south-eastwards. Over an erosional surface (δ3) cut into C1, a second marine unit (M2), of foreshore-lagoonal environment, in a temperate sea, had been deposited east-south-eastward of a promontory of the Sinis palaeo-island (Fig. 3). This unit, characterized by the δ4 and δ5 stratigraphic discontinuities which continue south-eastward, is arranged in several protected shore facies, especially in lagoonal facies of normal marine and brackish water, in transitional facies, some emerged, with remains of molluscs, mammals and reptiles.

A third marine unit (M3) rests on a clear erosion surface (δ6), onlapping both the top of the continental unit C1 and the transitional marine unit M2. The M3 unit has characteristics of shoreface up to foreshore and backshore and is richly fossiliferous (Comaschi-Caria, 1968).

To the north, an isolated outcrop (MX, Fig. 3), correlated with the M3 unit, shows low and high angle cross-lamination with traces of organisms typical of foreshore, backshore and aeolian dunes resting on and extending west of the palaeo-promontory. This MX succession lies unconformably on the Messinian marls.

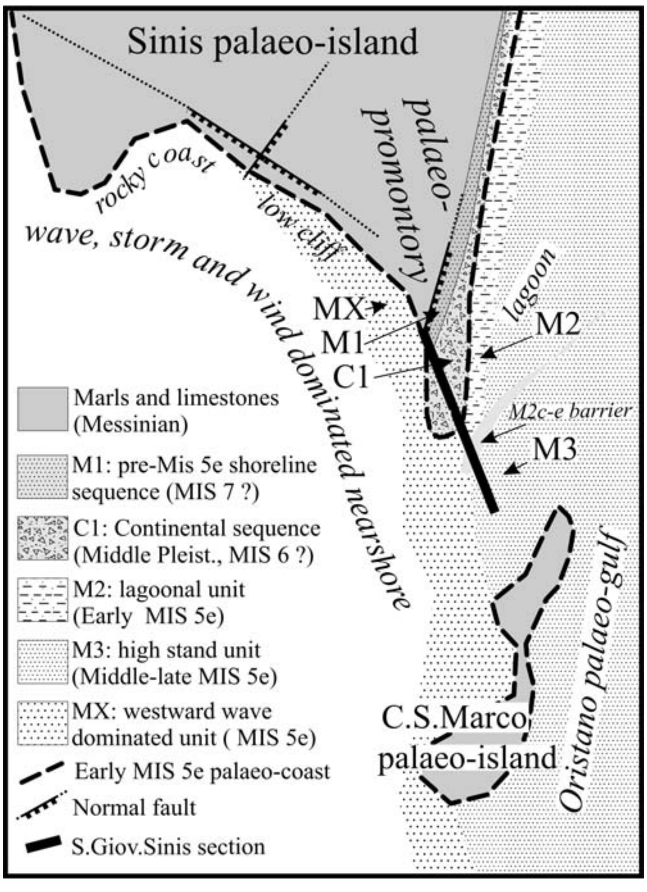

Fig. 3 - Palaeogeographic sketch of the southern Sinis peninsula during M3 unit of the Mis 5e interglacial.

A second continental unit (C2) consists of a basal colluvium, which has reworked the underlying marine unit, followed by 3-4 colluvial beds containing archaeological remains in the upper part. Unit C2 overlays another stratigraphic disconformity surface (δ7) to the north of the previous outcrop, at the Funtana Meiga low cliffs.

Concluding this study Carboni & Lecca (1985) correlated the marine unit M1 to the Palaeo-Tyrrhenian ("Mindel-Riss Interglacial" *Auct.*), considering the significant thickness of the continental succession C1 with mammal remains. On the other hand, based on the stratigraphic interpretation, units M2 and M3 have been correlated to the Eutyrrhenian high stand (i.e. MIS 5e) and the continental C2, containing prehistoric-historic remains, to the Last Glacial ("Wurmian")-Holocene time span.

Later, Ulzega & Hearty (1986) studied Sardinian outcrops and reported U/Th ages of 138 ± 8 and of 149 ± 10 ka for two outcrops near the Cagliari area, at Calamosca and Sa Illetta, respectively. Their work attributed the lower marine unit M1 to the Eutyrrhenian (i.e. MIS 5e) and the upper units M2 and M3 to the Neotyrrhenian (i.e. MIS 5c-5a), dated to between 105 and 75 ka.

A later work, based on the sedimentological interpretation provided by Davaud et al. (1991), also describes the presence of three marine "sequences" interpreted as "*three high sea level phases, corresponding to three highest thermal peaks... during the last interglacial*" but does not advance clear hypotheses concerning their age.

Finally, Kindler et al. (1997) correlated petrographic and sedimentological data in order to interpret the past climatic conditions and sea level forcing mechanism. Their work, carried out on different Tyrrhenian outcrops of Sardinia, confirms Carboni & Lecca's stratigraphic interpretation (1985) and they attribute the lower marine unit (i.e. M1), which they define "*sequence X*" to a pre-Tyrrhenian interglacial and both their "*I and II sequences*" (i.e. M2 and M3) to the MIS 5e.

The "Phoenician graves" log

Within the S. Giovanni di Sinis section, the stratigraphic log that displays the most comprehensive relationship between the two marine units M2 and M3, is situated in a small cliff behind the current narrow shore, near the Phoenician-Punic graves cut into the backshore-aeolian sandstones (Section 16 of Carboni & Lec-

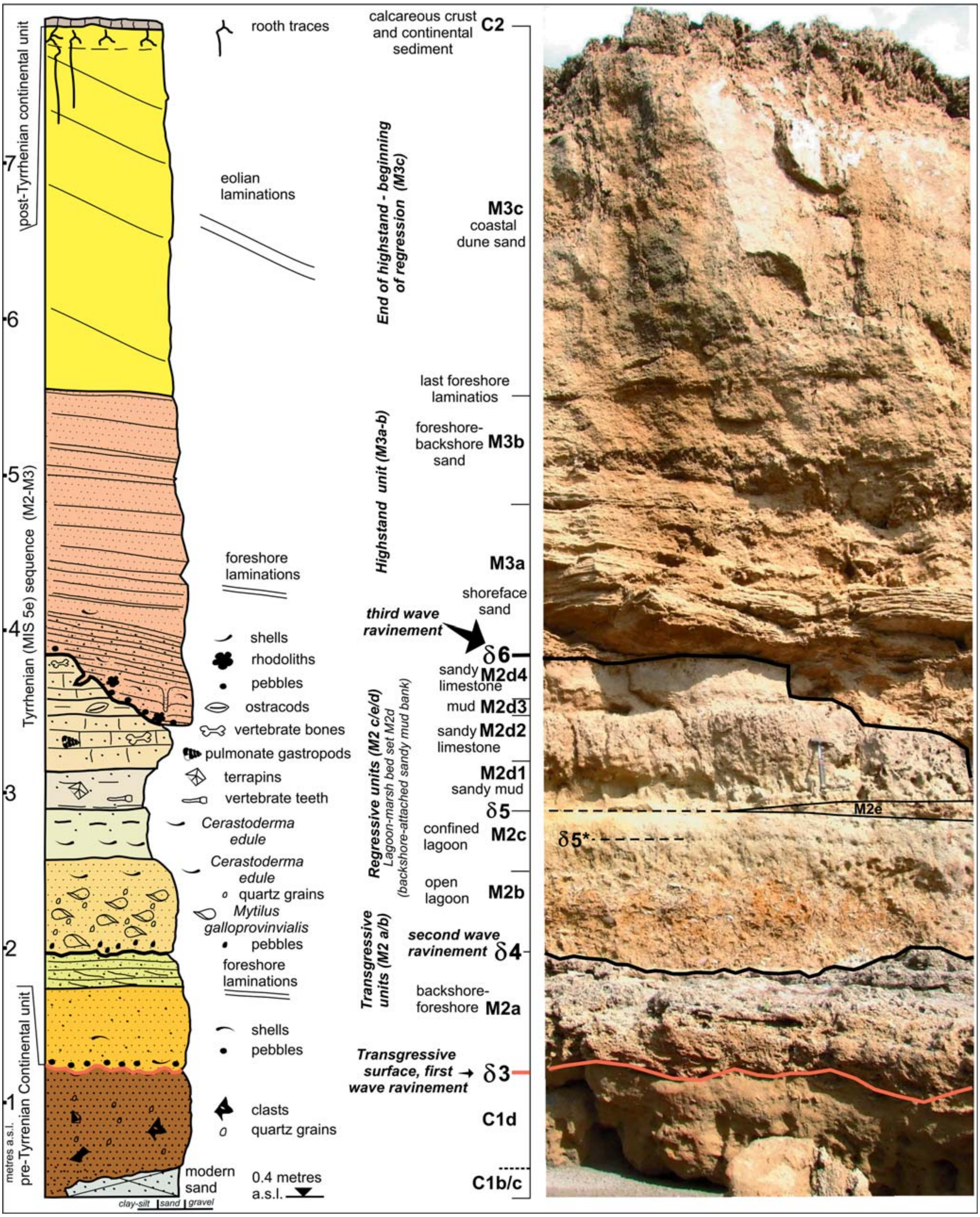

Fig. 4 - The Phoenician graves log and its sequential stratigraphic interpretation. For location see Fig. 6.

ca 1985). The new fossil remains described by Chesi et al. (2007) are derived there from.

This stratigraphic log is characterized by the presence of the erosion-derived truncation on the peri-lagoonal facies of unit M2, overlain by shoreface facies of unit M3. Here the marine unit M1 and the lower part of continental unit C1 (pre-Tyrrhenian) lies below the present sea level and therefore is not described. Between the sea level and about 8 m a.s.l, the following units can be observed from the bottom upwards (Fig 4).

Continental pre-Tyrrhenian (pre-MIS 5) Unit C1

C1b – Fine-medium aeolian sandstone, moderately cemented, mainly quartzose and subordinately bioclastic, with subrounded large quartz grains and pulmonate Gastropods (*Planorbis* sp., *Helix* sp.). The abundant carbonate matrix is characteristic of continental vadose environment, with bioclasts dissolution. The *Mammuthus lamarmorae* (Major) molar found by Maxia & Pecorini (1968) was retrieved from this sandstone.

C1c – Clay-supported aeolian fine-medium sandstone with rare 4 ÷ 8 mm pebbles.

C1d – Massive sandy colluvial deposit, as a result of dune sand input, with moderately reworked quartz and kaolinised feldspars, angular calcareous granules of up to 1 cm size and high percentages of silty matrix. Porosity from biogenic carbonate dissolution, rare marine bioclasts with fragments of pelecypods, sea urchin spines and benthic foraminifers are present.

δ3 Unconformity

This unconformity (1.2 m a.s.l., Fig. 4), that appears as a clear truncation surface on the colluvial deposit C1d, with pebbles from the underlying lithofacies, is interpreted as a wave ravinement surface, the overlying layers being of upper shoreface-foreshore environment.

Tyrrhenian Marine Unit M2a, δ4, M2b-c

M2a – Polygenic conglomerate in very coarse sandy matrix, with high content of benthic microfauna, sandstone clasts of up to 10 cm and reddened clasts of the underlying colluvium, followed by a lithic-bioclastic quartz-feldspar shore sandstone, containing abundant fragments of sea urchin spines. Clasts often appear angular or sub-rounded. The peculiar structure is a plane-parallel lamination, with either sub-horizontal or slightly southward dipping laminas, associated with a large foreshore or with a bar under formation. Laterally backshore facies are also present.

δ4 – This weak disconformity (1.7 ÷ 2.0 m a.s.l., Fig. 5A-B), evidenced both by a clear erosion surface, cut only on M2a, and by the presence of pebbles from the underlying layer, can also be interpreted as having been formed by wave ravinement (wave-related furrows

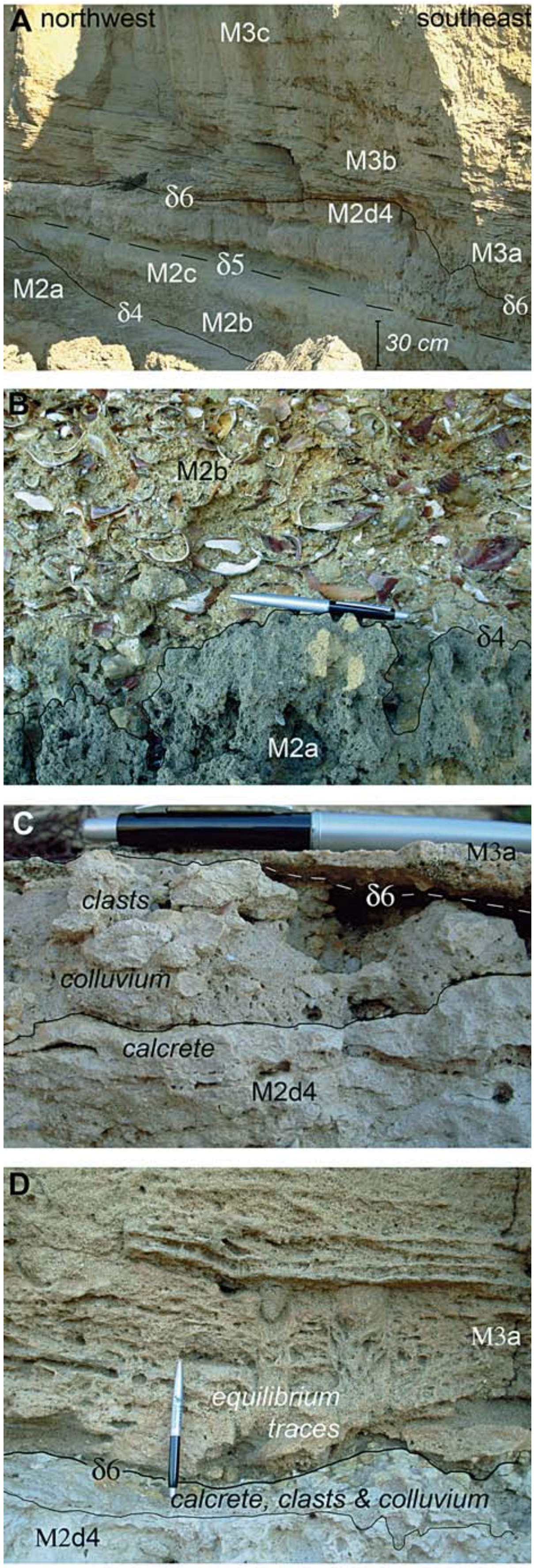

Fig. 5 - Peculiar contacts of Phoenician graves log and surroundings. A: about 1m palaeo-cliff of δ6 erosional surface; B: d4 erosional surface; C and D: details of δ6 erosional surface.

and ridges on a beach rock). Neither subaerial processes nor continental deposits are evident, therefore it can be attributed to an open lagoon (or protected palaeo-gulf beach) setting on a former precociously lithified beach.

M2b – Overlying the δ4 disconformity is a conglomeratic very coarse poorly sorted sandstone, with dominant quartz and feldspar with well- or sub-rounded grains. Well rounded pebbles of marine sandstone and of continental colluvium (C1d) are also frequent. The significant bioclastic component forms a "lumachella" with *Mytilus,* often containing whole valves, and rare articulated valves of *Cerastoderma edule* L. (Fig. 5B).

M2c – Silty, locally clay-silty sand, with *Cerastoderma edule* L. with frequently articulated valves and with *Tapes* sp., ostreids and venerids, rare marine ostracods, marine benthic foraminifera, fragments of calcareous plates and spines of irregular sea-urchins (Spatangidae), rare plates of *Balanus* sp. Small Pulmonata Gastropoda are also found. The abundant detrital fraction consists of transparent and opaque quartz granules, with various degrees of reworking, and lithic granules, both of up to 1 cm size. This bed is massive and the carbonate mud of the matrix is locally moderately cemented.

Unlike the south-eastern part, which will be described later, here M2c is homogeneous and does not exhibit lateral variations.

Lagoon bed set M2d

M2d1 – Fine silty sand containing silt-sized hypohaline microfauna represented by prevailing oligotypic ostracods and some benthic foraminifera, in a carbonate mud matrix, with rare sea-urchin fragments and spines, quartz granules and subordinate plagioclase, mica and metamorphic lithic grains. This bed bears the remains of terrapin (*Mauremys* sp.) and deer (bones and teeth) (*Praemegaceros cazioti* D.), witnessing episodic fresh waters at this level (Chesi et al. 2007).

M2d2 – Sandy limestone, originated from soil-forming processes (calcrete), with rare small ostreids and *Mytilus galloprovincialis* Lmk. shells. Small Pulmonata Gastropoda (Planorbidae, *Lymnaea* sp.), fragments of vertebrate bones (artiodactyls), burrows and thin root traces which, together with small dissolution cavities, result in widespread porosity.

M2d3 – Carbonate mud with fine sandy component, angular hyaline quartz, subordinately opaque and well rounded and feldspar grains. The biogenic carbonate component consists of rare smooth and ornamented ostracods, rare benthic foraminifera, and reworked Miocene planctonic foraminifera. Abundant shells of Planorbidae (*Armiger crista* L.), fragments of *Lymnaea* sp., and fine carbonate annelid tubes are also present.

M2d4 – Marly-sandy limestone and superficial calcrete, with internal molds of Pulmonata Gastropoda (Planorbidae), fragments of vertebrate bones (artiodactyls), rare *Mytilus galloprovincialis* Lmk. fragments, burrows and continental annelid tubes. Root colonization, with local carbonate crusts and some centimetres of colluvial sediments, are observed in the upper part (Fig. 5C-D).

M2e – Between M2c and M2d, this log contains a pinchout of a sandstone layer (M2e) clearly recognizable in the southern part of the section which will be described later.

δ6 Unconformity

This erosion surface (2.7 ÷ 3.7 m a.s.l., Fig. 5A-C-D), visible south-eastward for about 130 m, vertically exposed for about 1 ÷ 1.5 m and locally changing to a paraconformity before disappearing beneath actual beach, can be interpreted as a wave ravinement surface cut on the M2d bed set. Locally, on this δ6 unconformity the M2d4 layer displays *Trypanites* ichnofacies.

Tyrrhenian marine Unit M3

M3a – Very coarse-coarse quartz-rich sandstone of upper shoreface-foreshore wave-dominated environment with pebbles and cobbles originating from underlying sandy colluvium C1d and from other previous sandstones and marly limestones M2d. In the lower part this bed contains a significant bioclastic component, algal balls of coralline red algae, *Patella (Patellastra) ferruginea* Gml., *Conus testudinarius* Mart., small molluscs, regular sea urchin spines and benthic foraminifera. Laterally, at a step in δ6, is a sandy filling with shoreface lamination burrowed by S*kolithos* ichnofacies (retrusive equilibrium and escape structures of bivalves in an accreting sand situation, *sensu* Bromley 1996; Fig. 5D).

M3b – Very coarse sandstone of upper shoreface-foreshore wave-dominated environment, dominantly biogenic with subordinate quartzose and feldspar-rich, with abundant fragments of sea urchin spines, coralline red algae, small mollusc shells and, locally, valves of *Loripes lacteus* L. The depositional structures are represented by plane-parallel south-eastward dipping laminas at angles of 5 ÷ 7 degrees and by sets of 10 cm thick south-eastward prograding sigmoidal low angle laminas. The upper part of the structure tends to become massive for backshore episodes.

M3c – Coarse-medium moderately sorted bioclastic and quartzose sandstone with calcite cement, of backshore and coastal dunes, with internal structure showing high angle, tangential downlapping, south-eastward prograding laminations.

Continental post-Tyrrhenian unit C2

Polygenic carbonate crusts with *Helix* sp. shells, minor colluvium and aeolian sand and silt.

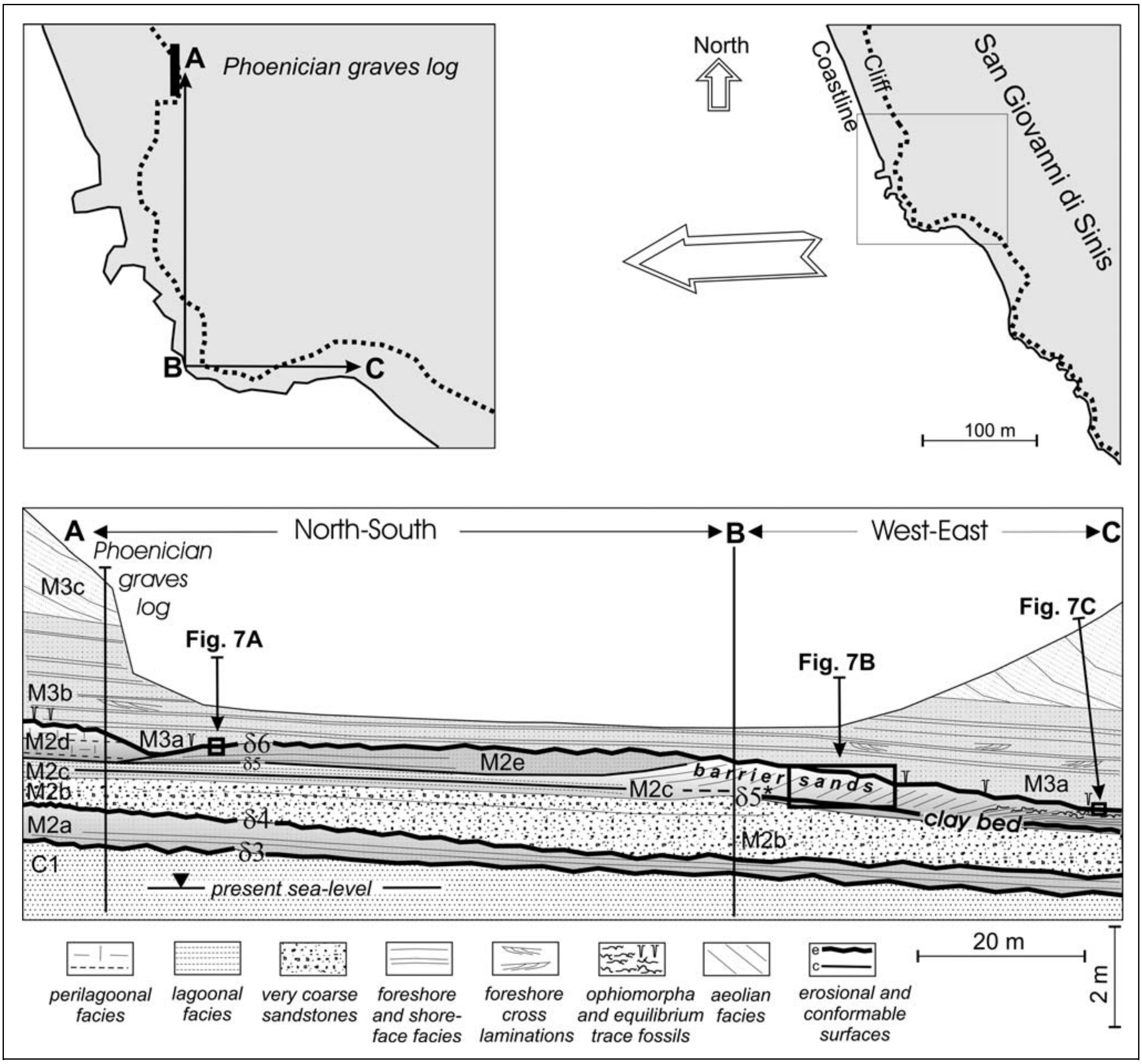

Fig. 6 - Cross section of south-eastern part of the S. Giovanni outcrop.

South-eastern part of the S. Giovanni section

In an earlier study Carboni & Lecca (1985) have described 24 logs of the entire S.Giovanni of Sinis outcrop (as well as 14 logs from other sites). These are not included herein, but for a better understanding of our interpretation it is necessary to describe the south-eastern part of this section because it shows a 3D depositional architecture (Fig. 6).

Firstly, southward of the Phoenician graves log, between M2c and M2d and slightly south-east dipping, is interbedded a sandstone layer (M2e, Figs. 4, 7A) with low angle plane-parallel laminae of foreshore-shoreface and massive texture of backshore environment. The δ5 stratigraphic discontinuity, underlying the M2e unit, indicates a local lagoonal environment. In fact, this surface disappears southward as the M2b and M2c rise and these two layers are in turn buried by the backshore facies of M2e.

Another peculiarity of this part of the section is the lateral facies variation of layer M2c, which in the Phoenician graves log appears as a simple layer with upward increasing matrix. South-eastwards it is divided into several facies which are difficult to schematise in the cross-section. Initially M2c exhibits a lagoon facies, evolving eastwards into a beach and finally into barrier sands.

Further south-eastward between M2c and M2b (δ5*, Figs. 6, 7A, 7B) are interbedded plastic unlaminated greenish clays (10-30 cm, eastward-dipping about 1 m/50 m). The clay contains sparse smooth quartzose granules, fine-very fine quartzose sands, micaceous

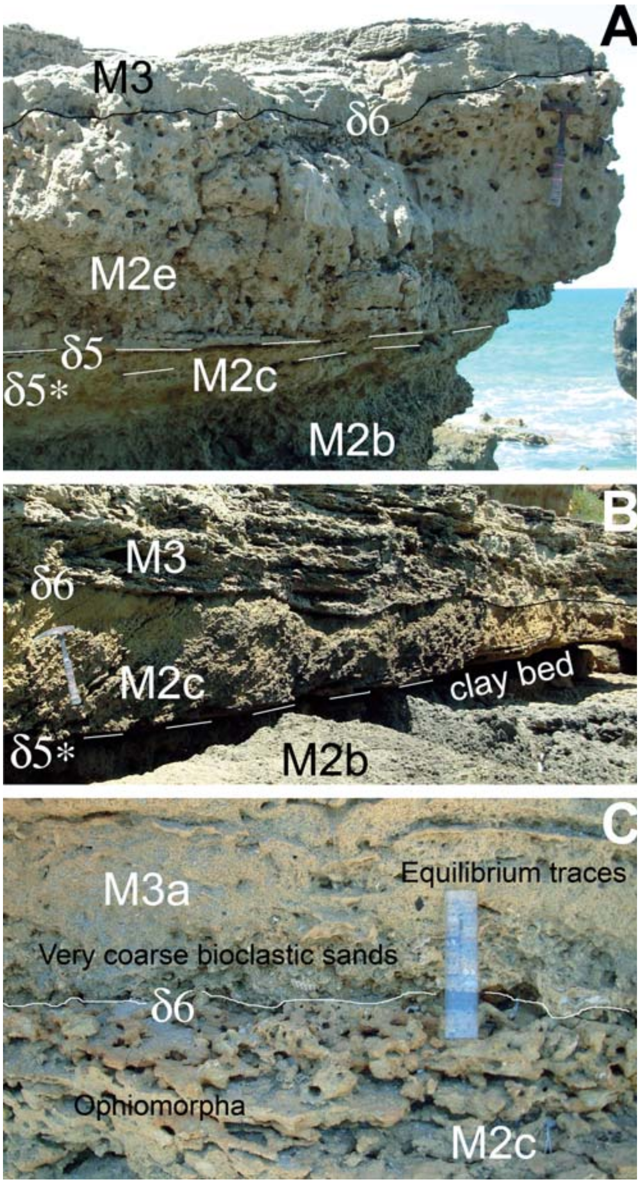

Fig. 7 - Erosional surfaces of south-eastern part of the S. Giovanni section. A: M3 unit and δ6 ravinement surface on M2e barrier sands; B: M3 unit and δ6 ravinement surface on M2c barrier sands; C: M3 on bioturbated sandstone M2c, note the faint δ6 ravinement surface. For location see Fig. 6.

grain, calcareous benthic foraminifera (Miliolidae, Nonionidae, Rotalidae), ostracods, faecal grains, fragments of pelecypods, millimetre size burrows and rhizocretions. This bed can be interpreted as a restricted paralic microenvironment (in the order of one to a few metres deep) emplaced on a former open lagoon or a protected palaeogulf, during a local normal regression or a forced regression caused by a minor sea-level drop. A very short time span elapsed between this regression and the following sedimentation, as only locally is the δ5* surface unconformable, and it disappears northwards (Figs. 6, 7A-B, 4).

The sedimentary accretion continues with low angle laminated foreshore-upper shoreface sandstones strongly bioturbated by *Ophiomorpha* fabric. Upwards the laminae diverge up to a high angle aeolian lamination of a low, westward accreting dune. In the lower part of the diverging laminae sparse *Ophiomorpha* fabric is again observed between each lamina. Another new beach is recognised above both the bioturbated layer and the high angle aeolian sandstone (M2c) and the overlapped M2e (Fig. 7). The new beach is laterally correlated to the M3 unit of the Phoenician graves log and the basal surface to the δ6 unconformity.

Again in this part of the section the M3 unit shows the same depositional features observed in the northern part (M3a,b,c facies), upper shoreface related to a new sea-level rise with coarse-very coarse, poorly sorted terrigenous and fossiliferous sands, wavy or discontinuous low angle laminations bearing retrusive equilibrium traces, upward it exhibits foreshore low angle and cross lamination and finally in the upper part the high angle aeolian lamination documents the regression of the beach sedimentation. Towards the south these facies (M3a-b) grade into layers with unsorted, highly fossiliferous sandy matrix (lenses with *Loripes lacteus* L.) and finally a massive *Pinna nobilis* L. bearing *lumachella*. These facies can be related to a protected shoreface opening east – south-eastwards into the Oristano palaeo-Gulf.

The stratigraphical architecture cannot simply be interpreted as an unconformity of a transgressive event after a major regression. Rather it appears to be the result of minor regressions followed by minor transgressions. Indeed, eastward the δ5* surface is the most striking unconformity (Figs. 6, 7B), but to the north it becomes an almost imperceptible paraconcordance within M2c.

Palaeoenvironment evolution and interpretation

Evolution

Pre-Tyrrhenian phase - The lower part of the stratigraphic log described indicates a continental environment (C1b-c-d) where the aeolian sediments are derived, at least partially, from a previous shore. These materials are mixed with mud, very coarse sand and lithic pebbles and cobbles. The diagenetic processes of these sediments appear to be affected by the temporary presence of a water table, in climatic conditions suitable for inducing the dissolution of carbonate grains. The continental facies indicate a progressive lowering of the sea level, and the onset of an increasingly continental environment, closing the marine pre-Tyrrhenian sequence M1-C1 (pre-MIS 5e, possibly MIS 7-6).

Tyrrhenian transgressive and highstand systems tracts - The subsequent sea level rise is responsible for the first ravinement surface δ3 and the deposition of the transgressive conglomeratic sandy fossiliferous unit M2a. The plane-parallel laminations and the contained fossils indicate a foreshore environment and a protected upper shoreface evolved to a backshore. The layer M2a is in turn affected by the δ4 erosional surface buried beneath very coarse sandstone, where neither subaerial processes nor continental deposits are evident. Since the erosion surface incises only M2a it is interpreted as a discontinuity surface with a very short hiatus, produced by a second wave ravinement after rapid lithification. Thus it may have been formed, after a brief hiatus, by an open lagoon environment setting on a former beach transgression. The *Mytilus galloprovincialis* Lmk. *lumachella* M2b, contained in the very coarse sandstone, can be interpreted as a temperate climate lagoon (or a protected palaeo-gulf) deposit, evolving to a very low energy setting indicated by the common shells with articulate valves and by the mud matrix in the upper part.

The sedimentation continues in a confined environment, beginning with M2c layer (consisting of sandy and silty mud with *Cerastoderma edule* L.) until such time as the lagoon becomes completely separated from the sea (south-eastward) by barrier sands (Fig. 6). The clay bed, located seaward beneath the δ5* unconformity, may represent an early lagoonal episode of this M2b-M2c-M2d- δ6 transgressive-regressive phase.

The M2d bed set follows (with its four sub-facies, containing vertebrate and reptilian remains) indicating the presence of brackish waters marsh and episodic fresh waters.

The presence in M2d1 of artiodactyls and reptiles typical of fluvial marginal environment with fresh marsh and lagoon with salty waters, is evidence of an environment rapidly evolving, already in M2d2, towards an episodically emerged environment (carbonate pedogenesis), the hypohaline ostracods rapidly disappearing to be replaced by limivorous, reptiles and Pulmonata gastropods. This environment continues in M2d3 and M2d4, as indicated by the presence of *Lymnaea* sp. and, particularly, *Armiger crista* L. (already described by Carboni & Lecca 1985 and Esu 1986), and by the traces of continental worms, vertebrate bones, roots and thin carbonate crusts.

The M2d bed set certainly underwent erosion, but it is important to emphasize that there are only a few centimetres of carbonate crust and of continental sediments below the erosion surface δ6 (Fig. 5C-D), which is instead directly overlain by open shore wave-dominated conglomeratic sandstones of unit M3a.

Evidence of the subsequent open shore conditions of M3 is the biogenic shoreface sediment with transported algal balls of *Lithophyllum* sp. (M3a-b), characterized by common trace fossils (*Skolithos* ichnofacies) and covered with roughly plane-parallel laminas, low angle sets and cross lamination typical of foreshore. This conglomeratic-sandy deposit indicates a rise in sea level in a warm-temperate climate up to about + 5-6 m, submerging the promontory, creating a less protected gulf.

The superposed sandstone M3c contains high-angle laminations and belongs to backshore and dune environment, denoting the end of the high stand.

Finally, the carbonate crusts C2 and the associated sedimentary products, indicate the onset of the continental post Tyrrhenian environment.

Interpretation

As mentioned above, the presence of the surface erosion δ6 between M2 and M3 is differently interpreted in the literature. The most important aspect of the interpretation is whether this erosion can be attributed to a significant global sea level drop. In fact, were this true, then the Sardinian Tyrrhenian successions would certainly have been represented usually by two separate marine sequences, contrarily only the S. Giovanni di Sinis shows two objective sequences.

The simplest interpretation of the S. Giovanni di Sinis section (Phoenician graves part) would suggest associating units M2 and M3 to two MIS 5 eustatic peaks, and to attribute the stratigraphic discontinuity surface δ6 to a global, though minor, regressive phase between the two units (Carboni & Lecca 1985; Davaud et al. 1991). Likewise, Kindler et al. (1997) related this unconformity with a climate modification during the MIS 5e, but their global comparison allowed to correlate this climatic change to two palaeo-sea level highstands separated by a roughly 9 metres lowstand (Kindler & Hearty 1997), well known in the Bahamas MIS 5e sequence (Berger 1978; Chen et al. 1991).

However, stratigraphic discontinuities in a coastal system, whether they are manifested as erosion truncations or appear as paraconformities, are not always caused by a significant global lowering of the sea level. Likewise, a coarse conglomerate does not necessarily occur at the base of a new eustatic-related sequence. This question has been widely debated in the literature for many years (Curray 1964; Boyd et al. 1992) and is described in numerous sections with the various stratigraphical and environmental combinations (e.g. Fischer 1961; Swift 1975; Rampino & Sanders 1980; Kraft et al. 1987; Ward & Ashley 1989; Bardaji et al.1990; Embry & Johannessen 1992; Zaitlin et al. 1994; Catuneanu 2002).

On the basis of our sequence stratigraphic and genetic analyses, it is believed that the stratigraphic discontinuity δ6 does not unequivocally indicate two sharply distinct marine sequences. Were this stratigraphic discontinuity the result of a significant drop in sea level, then it should show much deeper erosion in the underlying layers. This erosion should be evidenced by continental sediments formed during the eustatic fall, like is represented in the continental sequence C1 resting on M1 unit or in the unit C2 resting on M3 unit. The only facies with pedogenesis are present in M2d which formed in the innermost environment where fresh water and episodic emersion occurred. On the contrary in the other layers M2c and M2e, δ6 (Fig. 7) does not cover other facies that have undergone pedogenesis or other continental sub-aerial processes. Besides, the difference in eight of the erosion surface is about 1 ÷ 1.5 m, but as the beds dip, the stratigraphic thickness eroded is only 0.5 ÷ 1 m. This stratigraphic relationship is fully compatible with a ravinement surface produced by wave erosion during the final stage of the sea level rise on a previous coastal deposit, presumably a barrier-lagoon system (e.g. Ward & Ashley 1989).

In climatic conditions able to induce a rapid carbonate diagenesis, such as the beach rocks, calcretes and continental clastic sediments of M2d4 (1-4 centimetres), the presence of *Trypanites* ichnofacies may be entirely compatible with the palaeogeographic hypotheses provided. The evidence of barrier-lagoon facies, up to sebka facies, from the present coastal sector of the Oristano Gulf and Sinis, as described by Plaziat (1982), during the current eustatic highstand, support the validity of this palaeogeographic interpretation.

This new interpretation of the Tyrrhenian S. Giovanni section recognizes depositional discontinuities between beds of adjacent environments within the same depositional system, in a complex and rapidly changing eustatic-related palaeoenvironmental context (Figs. 3, 6). Thus, in contrast with the earlier interpretation, here it is pointed out that the discontinuity surface δ6 (as well as δ4, δ5 and δ5*) represents at the most a small eustatic variation, only capable of a transgressive erosion, triggering facies migration within a lagoon-shore system controlled by a single eustatic phase.

The eustatic behaviour in this erosional phase (δ6) can be interpreted as a slowing down of the rising or a stationary trend at about + 2.7 ÷ 3.7 m or, at the most, as a minor drop in sea level of a few metres, before reaching the maximum highstand at about + 6 m above the present sea level.

Thus, the whole San Giovanni di Sinis succession can be attributed to a south-eastward accretion of coastal sediments over a small promontory composed of Messinian marls, where the retreat in the west-facing coast produces a small west-facing cliff with a foreshore-shoreface at its base (Fig. 3).

Elevation above present sea level

Currently Sardinia belongs to a microtidal area, with low sea-level variations (monthly ± 20 cm, annual ± 30 cm; APAT 2007), and a similar tidal behaviour is suggested during the Tyrrhenian time. Thus ± 30 cm would be the least inaccurate estimate, but considering sea level variations during storms, ± 50 cm is a more realistic value. To this one needs to add the different elevations maintained by the sedimentary products (which depends on the energy of the depositional environments related to the same sea-level), with general inaccuracies that can be estimated as a minimum at around ± 1 m in the correlation of the sections.

The facies in the outcrops studied do not provide reliable sea level indicators and their evaluation is fairly subjective. The only morphological structure providing reliable indications would be the notches on limestone, but none have been observed in the available lithofacies, with the exception of Miocene marly limestones of S'Archittu (Lecca et al. 1983) where large notches are present +5 ÷ 6 ms a.s.l. Morevoer, hydro-isostatic movements certainly occurred that could have altered elevations. Thus, notwithstanding all the above considerations, and in spite of a recent well documented regional synthesis (Ferranti et al. 2006) and a detailed description of the Alghero-Argentiera sector (Andreucci et al. 2006), an accurate study is warranted.

Currently, the palaeo-elevations are referred to the actual sea level, the present coast of Sinis peninsula being almost stable, indeed the Tyrrhenian outcrops on the west coast of Sinis and at S. Marco promontory are observed between the present sea level and +5 ÷ 6 m, likewise the greater part of western Sardinia.

In the S. Giovanni section in particular, a maximum level of 5 ÷ 5.5 m a.s.l. is well evidenced by foreshore laminations, while the ravinement surface (δ6) attains around 3.7 m. Westwards, where the section is no longer observable because of erosion of the present cliff, the M3b foreshore laminations rise up to an estimated elevation of around 6.0 m a.s.l., (plus the above mentioned inaccuracy of ± 1 m).

Regarding fault movement in the northern part of the section, this appears to concern M1 and C1 alone, as MX (MIS 5e) is not affected.

Discussion and correlation to other Sardinia sites

As mentioned earlier, researchers do not concur on a common geochronological interpretation of the Pleistocene succession of San Giovanni di Sinis. Thus, at the moment, as no precise radiometric date is available for these marine units, the geochronological interval is inferred from the regional knowledge of numerous Pleistocene coastal deposits observed in other areas of Sardinia and attributed to the MIS 5e. This attribution is generally well supported by a large amount of data from amino acid racemization (Belluomini et al. 1985, 1986, 1993, 2001; Ulzega & Hearty 1986; Kindler et al. 1997; Tomassi et al. 2005).

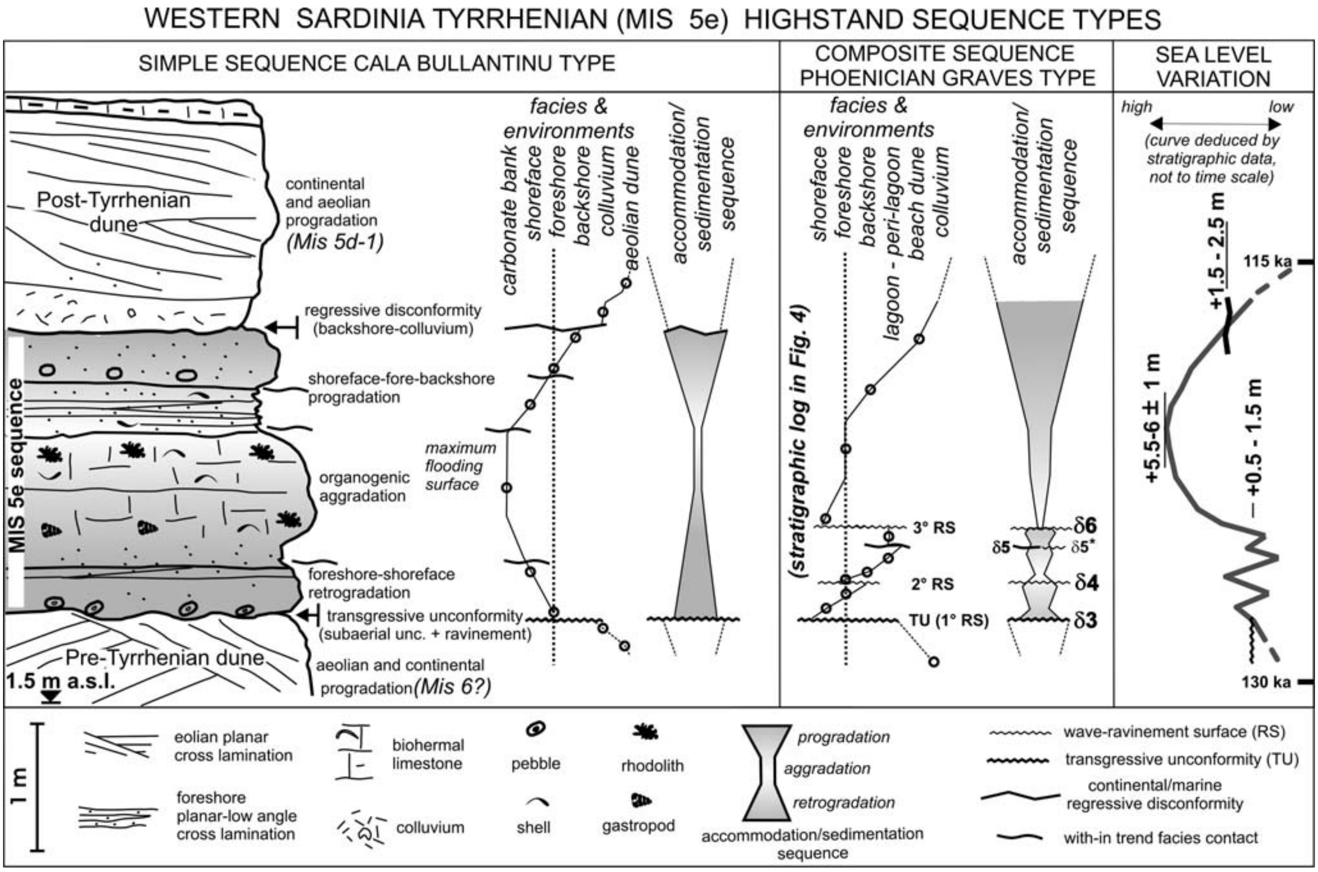

Fig. 8 - Sequential stratigraphic and genetic interpretation of the Tyrrhenian outcrops in western Sardinian, interpreting the facies variations as small eustatic variations within the Mis 5e high stand. The ages are from Kukla (2000) and from Shackleton et al. (2003).

In Sardinia, a single Tyrrhenian coastal clastic marine sequence is usually documented, though not always with the complete sequence. Unlike S. Giovanni di Sinis, this single sequence was deposited mainly at the base of wind dominated cliffs where transitional and confined environments were not present. In particular, a regional comparison is possible, with the outcrops along the central and north western Sardinian coasts, in Cala Bullantinu, Porto Alabè, Capo Mannu, Maldiventre and Alghero-Argentiera sites (Malatesta 1954; Mezzadri & Vinci 1968; Lecca et al. 1983; Zammarano 2000; Andreucci et al. 2006).

In the sandy sediments observed in these sites, it is possible to identify (even with local lateral changes of shore, bars and cliff-base facies) a single depositional sequence corresponding to one sea level high stand, though with frequent variations in terrigenous and bioclastic lithofacies.

Especially in the Cala Bullantinu outcrop (Figs. 1, 8), several sections display a sequence related to a single sea level highstand with a basal ravinement surface overlain by a sandy conglomerate followed by boundstone containing red algae (*Lithophyllum* sp.) and molluscs. After the high stand, the onset of sea level fall is evidenced by foreshore conglomeratic sandstones and backshore sandstones, followed by red sandy colluvium with some reworked marine fossils and, finally, by a thick succession of coastal aeolian dune sandstones interlayered with colluvium and palaeosols.

On the aeolian Pliocene deposits at the Capo Mannu outcrop (Fig. 1; Pecorini et al. 1973; Carboni & Lecca 1995; Tegas 2000), it is possible to observe a Tyrrhenian section with a single sequence of one eustatic highstand.

In the Porto Alabè site (Zammarano 2000), the sequence shows evolutionary characters similar to those at Cala Bullantinu and likewise contain a red algae boundstone. In both outcrops, amino-acid dating methods (Tomassi et al. 2005) indicate an MIS 5e age.

The deposition in the middle part of the Tyrrhenian sequence of bioclastic sediments, up to boundstone facies, has been observed in many other outcrops in south-western and southern Sardinia and is described in detail in the M3a-b facies of the San Giovanni di Sinis section. This peculiar warm-temperate facies could be correlated with the maximum solar radiation recorded during the MIS 5e (~128 ka BP, Berger 1978; ~125 ka, Kukla 2000; 132 -115 ka BP, Shackleton et al. 2003).

Comparison of all the Sardinian sections analysed enables to summarize a Tyrrhenian eustatic trend characterised by a single high stand of irregular shape (Fig. 8), with a maximum during the middle-late part. A similar trend, evidenced by a multi-stage reef development, has also recently been described in the Barbados and Bahamas (Blanchon & Eisenhauer 2001; Hearty & Neumann 2001).

Based on this comparison, two types of Tyrrhenian section have been recognized in western Sardinia, deposited under two different conditions (Fig. 8). One (Cala Bullantinu type) with more stable available space for the organogenic aggradation during the maximum flooding. The other (Phoenician graves type) characterized by the continuous accretion of sands from upper shoreface-backshore-lagoon, where depositional environments migrate landward in the wave erosion zone during sea level rise. In S. Giovanni section, four eustatic-sedimentary phases related to Tyrrhenian high stand can be identified: i) the eustatic sea level rise (early high stand: accommodation > sedimentation) produces a first transgression beach with facies retrogradation; ii) the subsequent sedimentary response (sedimentation > accommodation), contemporary to minor drops in sea level, produces normal regression and minor transgression: barrier islands, lagoons and marshes; iii) the major sea level rise (maximum high stand: accommodation > sedimentation), responsible for wave-ravinement and a second transgression beach; iv) finally, the onset of sea-level lowering (sedimentation > accommodation) causes beach and dune progradation of an initiating forced regression.

The S. Giovanni section, reinterpreted in this way, preserves the sedimentary response to the high frequency variations not recognizable in the sections of less sensitive environments, locally with less sedimentary input and more available space.

Moreover, comparing our sequence stratigraphy with the Eemian interglacial climate data for continental Europe (Kukla et al. 2002; Turner 2002) and Greece (Tzedakis et al. 2002), notwithstanding the uncertainty surrounding its age, we can deduce that the entire high-stand phase during which the M2 and M3 marine units of S. Giovanni deposited lasted in the order of 11 ÷ 15 ka, from about 130 to 115 ka B.P. This means, using the new sequence stratigraphic interpretation of S. Giovanni, that an early high stand phase (about +3 m) of temperate climate, was followed by a phase with a warm-temperate climate and with a sea level rise up to about +6 m, which is comparable with the consequences of the Greenland ice cap melting (Huybrechts et al. 1991; Cuffey & Marshall 2000). A similar sequence is also described in Tunisia that evidences a recession of wet conditions during the second half of the Last Interglacial which favoured carbonate sedimentation (Jedoui et al. 2001).

This event, in the orbital forcing concept of the chronostratigraphy (Hays et al. 1976; Imbrie & Imbrie 1980; Berger et al. 1981; Kukla et al. 1981; Martinson et al. 1987), may be associated with the result of high eccentricity, high inclination and northern summer at perihelion, the precession half cycle lying well within the Tyrrhenian time span. Therefore, the single irregular high stand and the maximum at around 6 m above the present sea-level recognised in the S. Giovanni section may well represent a eustatic indicator, preserved in the Mediterranean area, coming from Greenland melting ice as well as from other small ice sheets. The highest sea level caused the flooding of the Oristano palaeo-alluvial plain, by foreshore-shoreface environments landwards setting on marsh-lagoon environments. The same occurred in other several Sardinian coastal plains as already reported by Maxia & Pecorini (1973).

Concluding remarks

The distinctive feature of the Upper Pleistocene San Giovanni di Sinis section is that it preserves two coastal marine deposits correlated with the MIS 5e high-stand, with clearly distinct lithostratigraphy. The genetic-sequential analysis and comparison with other outcrops in western and southern Sardinia, enable us to attribute the coastal marine units M2 and M3 to a single eustatic event of MIS 5e. The ravinement surface δ6 separating them, as well as the underlying δ4 and δ5*, likely represents a lithological discontinuity within the MIS 5e high stand systems tract, and can therefore be interpreted as an intraformational disconformity. Thus, the complexity and arrangement of the whole succession here would provide sedimentary evidence for a rapid palaeogeographical evolution of a depositional system extremely sensitive to eustatic variations, even of a meter, within the same high stand. The lower unit M2 provides evidence of the first temperate sea ingressions (δ3, δ4), raising sea levels up to 3 m. Contrary to earlier reconstructions, the eustatic behaviour of the ravinement surface δ6 can be interpreted as a slowing down of the Tyrrhenian sea level rise, as a stationary phase or as a minor fall of few metres. The upper unit shows that the maximum highstand was attained at about +6 metres during the warmest climatic phase. This result of the stratigraphic genetic-sequential analysis, enables identification of a warm-temperate signal also in Sardinia during the middle-late Tyrrhenian high-stand (MIS 5e). At a global scale, these stratigraphic data could be correlated with an interglacial orbital configuration, within which the eustatic indicator of the melting Greenland ice sheet can be placed.

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