# NEW DATA ON THE MID- TO UPPER CRETACEOUS SUCCESSION OF EASTERN SARDINIA IN THE FRAMEWORK OF THE GEOLOGICAL EVOLUTION OF THE TETHYAN REALM

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*Abstract:* Aimed at integrating knowledge of the Mesozoic succession of eastern Sardinia, two sections of Cenomanian and Santonian ages are presented, and their lithostratigraphical, palaeontological, and biostratigraphical features are described in detail. The former section (Lanaittu, Oliena territory), is composed of upper Cenomanian pelagic limestones unconformably lying on Hauterivian shelf limestones through a fossiliferous conglomeratic hardground of middle Cenomanian age; the latter section (Orosei area), consists of Santonian chalk with basal encrinite that unconformably lies on a conglomeratic hardground of late Albian age, in turn erosively resting on a folded substratum of Lower Cretaceous limestones. The mid-Cretaceous and Santonian unconformities present in both sections and in other Cretaceous successions of Sardinia are significant for reconstructing the palaeotectonic history of the island within the geological evolution of the Tethyan domain. The mid-Cretaceous event is interpreted to be related to the SE-directed subduction of the W Ligurian Ocean, which was triggered by the sinistral motion of Iberia with respect to Europe. The Santonian event is attributed to the change to more orthogonal convergence, accompanied by the onset of forebulge development in Sardinia.

## INTRODUCTION

The Upper Cretaceous sedimentary cycle in Sardinia is systematically separated from the Lower Cretaceous one by a gap of variable amplitude, which is the expression of a crucial mid-Cretaceous tectonic event. Transpressional movements are known in the Nurra area (western Sardinia) (Chabrier & Fourcade 1976; Philip & Allemann 1982; Cherchi & Trémolières 1984; Oggiano et al. 1987; Combes 1990; Mameli et al. 2007) and can be indirectly inferred in the eastern part of the island. However, the meaning of this tectonics in the context of the geologic evolution of the Tethyan realm is an open problem.

The palaeotectonic setting of Sardinia in the Late Cretaceous is also poorly known. The successions are represented mainly by platform carbonates in the western sector and pelagic/hemipelagic facies in the eastern sector. The development of a forebulge in the Sardinian block is supported by the emergence of the Mesozoic carbonate platform in western Sardinia since late Campanian time (Massari et al. 2014), in concomitance with relatively deep marine sedimentation on the subsiding eastern side of the island. Comparison of Santonian geological and stratigraphical settings on the eastern and western sides of the island suggests that the birth of the forebulge dates back to the Santonian.

The purpose of this research is twofold. Firstly, new data on the Upper Cretaceous succession of eastern Sardinia are presented through the detailed illustration of the lithostratigraphic, biostratigraphic, and palaeontological features of two new sections of Cenomanian and Santonian pelagites. Secondly, the high-rank discontinuities evidenced in the stratigraphical part are considered in the context of their diffusion and palaeotectonic meaning in Sardinia and surrounding areas. On this basis, an attempt is made to reconstruct the mid- to Late Cretaceous palaeogeography in the context of the eo-Alpine evolution, with special regard to mid-Cretaceous events.

## GEOLOGICAL SETTING

The geological structure of Sardinia is dominated by a Variscan basement overlain by a discontinuous Permo-Cenozoic mixed volcanic and sedimentary succession. The basement comprises Palaeozoic rocks that underwent Ordovician metamorphism overprinted by late-Variscan metamorphism and intruded by large granitoid plutons in multiple events between 340 and 280 Ma (e.g., Casini et al. 2015, and references therein).

Western and eastern Sardinia experienced significantly different geological evolutions for most of their post-Variscan history. The Permo-Mesozoic sedimentary succession of western Sardinia is closely comparable to that of the Pyreneo-Provençal area (Chabrier & Mascle 1975; Azéma et al. 1977; D'Argenio et al. 1985; Cherchi & Schroeder 2002, and references therein), whereas the sedimentary succession of eastern Sardinia is comparable to

that of the autochthonous cover of Corsica and the Briançonnais domain.

In western Sardinia, continental, paralic, and marine epicontinental Permo-Triassic deposits, showing Germanic facies, prelude to the Jurassic intracontinental extensional tectonics (Cassinis et al. 2003), which mirrors that occurring in the Provence and Maritime Alps (e.g.: Bourbon et al. 1973; Bernoulli & Jenkins 1974; Lemoine et al. 1978; Monleau 1986). The Jurassic succession is characterized by platform carbonates, whose deposition was punctuated by several regressions with episodes of local subaerial exposure (Cherchi et al. 2010).

In eastern Sardinia, a major extensional episode during the Early to Middle Jurassic led to the exhumation of the crystalline basement and a pulse of erosion (Dieni et al. 1983; Dieni & Massari 1985; Lemoine et al. 1986; Carmignani et al. 1989; Zattin et al. 2008; Malusà et al. 2016). Extension at that time affected the entire southern European passive continental margin in relation to the opening of the Liguro-Piemontese Ocean (Bourbon et al. 1973; Dieni et al. 1983; Lemoine et al. 1986; Stampfli & Marchant 1997; Dieni et al. 2008). Deposition in eastern Sardinia began in the Middle Jurassic (Bajocian), characterized by continental to marginal-marine lenses overlain by shallow-shelf carbonates, punctuated in the Bathonian to Oxfordian interval by condensed pelagic episodes and gaps marked by hardgrounds with ammonites. Reef facies are diffuse in the Tithonian (Dieni et al. 1966; Dieni & Massari 1985; Cherchi & Schroeder 2002; Costamagna et al. 2007; Dieni et al. 2008; Jadoul et al. 2010; Casellato et al. 2012; Ricci et al., 2018).

The Jurassic to Lower Cretaceous succession is represented by similar facies on both sides of the island, with regressive marginal-marine and lacustrine "Purbeckian" facies (Pecorini, 1965; Colin et al. 1985; Dieni & Massari 1985), and respectively neritic limestones and marls passing upwards to open-platform Urgonian-facies calcarenites (Cherchi et al. 2010; Dieni & Massari 1963).

These successions are not significantly different, except for the outer-shelf radiolarian-rich upper Valanginian marls that crop out at the NE corner of Monte Albo (Siniscola, north-east Sardinia), recording the Weissert palaeoceanographic event (Bottini et al. 2018; Dumitrică 2022).

Significant facies differentiation began in the Aptian, when continuing deposition of platform car-
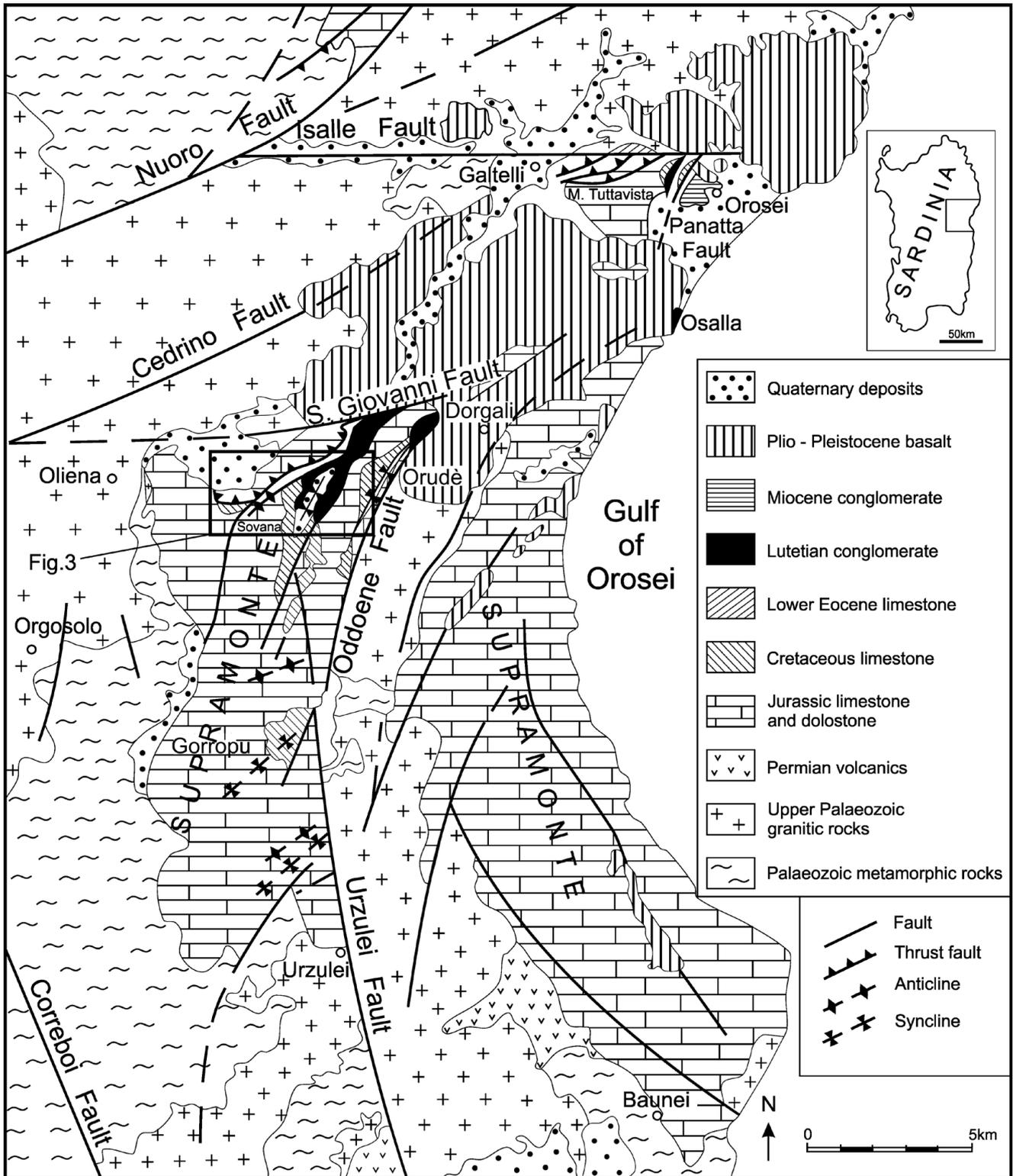
Fig. 1 - Schematic geologic map of central-eastern Sardinia (from Dieni et al. 2008, slightly modified).

bonates in western Sardinia contrasts with rapid deepening on the eastern side of the island (Orosei area) recorded by the sharp transition from Barremian limestones in Urgonian facies to Aptian to lower Albian outer shelf pelagic/hemipelagic limestones and marls, cherty and glauconitic in some intervals, with ammonites and planktonic foraminifera (Dieni & Massari 1963, 1985; Wiedmann & Dieni 1968).

Aptian-early Albian transtensional tectonics was active throughout Sardinia, with more conspicuous manifestations in the Nurra area (Rousset 1969; Oggiano et al. 1987; Mameli et al. 2007). In eastern Sardinia, it occurred along faults trending NNE (in modern coordinates), such as the Panatta and Oddoene faults (Fig. 1), causing significant increments in subsidence, as reflected by local stratigraphy.

On a larger scale, this tectonics is believed to represent a far-field effect of the sinistral transtension linked to the eastward motion of Iberia with respect to Europe, active since approximately 130 Ma (Stampfli 1994; Rosenbaum et al. 2002; Stampfli & Borel 2002; Capitanio & Goes 2006; Handy et al. 2010; Le Breton et al. 2021).

A mid-Cretaceous major tectonic episode is recorded in Sardinia and in the Provençal area (Oggiano et al. 1987; Mameli et al. 2007; Schreiber et al. 2011), with apparently similar characteristics. In the Nurra area, sinistral transpression occurred along previous N60-80E normal faults in the frame of compression directed N45°-N60° (in modern coordinates) and was accompanied by *en échelon* folds (Chabrier & Fourcade 1976; Philip & Allemann 1982; Cherchi & Trémolières 1984; Oggiano et al. 1987; Combes 1990; Mameli et al. 2007). In western Sardinia and Provence, this episode is marked by a widespread erosional surface that truncates the Mesozoic succession at various levels and is covered by extensive bauxitic deposits (Cocco & Pecorini 1959; Pecorini 1965; Chabrier 1969; Chabrier & Fourcade 1976; Philip & Allemann 1982; Cherchi & Trémolières 1984; Oggiano et al. 1987; Combes 1990; Combes et al. 1993; Mameli et al. 2007; Bestani et al. 2016).

In contrast, in eastern Sardinia, a shorter hiatus, without evidence of subaerial exposure, is recorded (Dieni & Massari 1963; Busulini et al. 1984). In the Orosei area (Fig. 2), a prominent angular unconformity truncates a folded substratum whose youngest terms are of early Albian age. It is locally capped by a glauconitic-phosphatic calcareous conglomeratic hardground containing plenty of ammonites belonging to several upper Albian biozones (Wiedmann & Dieni 1968). The mid-Cretaceous hiatus lasts longer in the successions of the Oliena-Urzulei carbonate massif (Chabrier 1969; Busulini et al. 1984), suggesting a generally more pronounced depth of erosion of the substratum.

Upper Cenomanian pelagic limestones lie with gentle angular unconformity on Berriasian limestones in "Purbeckian" facies near P.ta Cusidore (Oliena), and on fine-grained lower Hauterivian calcarenites at Mt Uddé, at Cuile Giobbe and in the Gorropu gorge (Orgosolo-Urzulei Supramonte; see Figs. 1, 3 for the location) (Busulini et al. 1984). On the western flank of the Lanaittu syncline, Turonian cherty limestones rest on Hauterivian-?lower Barremian limestones through a discontinuity marked by a glauconitic hardground containing the upper Albian *Desmoceras latidorsatum* (Michelin, 1838) (Busulini et al. 1984).

Facies differentiation between western and eastern Sardinia becomes prominent in the Late Cretaceous. In the Nurra and Anglona regions (north-western Sardinia), the early Coniacian transgression led to the establishment of a rudist-bearing carbonate platform that continued during Santonian (Carannante et al. 1995, 2008; Cherchi & Schroeder 2002, and references therein). In Santonian times, an abrupt drowning episode interrupts carbonate platform deposition in the Nurra (Punta Negra and Uri sections). It is documented by graded breccia layers with calcareous litho- and bioclasts, associated with pelagic marls of the upper part of the lower Santonian (Cherchi et al. 2010). This change in sedimentation regime is attributed to an extensional tectonic episode that disrupted the carbonate platform resulting in a local angular unconformity (Cherchi & Trémolières 1984; Cherchi & Schroeder 1985).

A dominantly pelagic and hemipelagic Upper Cretaceous succession exists in eastern Sardinia. In the Orosei area, precisely in the northern part of the Cuccuru 'e Flores hill (Fig. 2), a thin unit of Santonian pelagic chalk, already quoted by Dieni et al. (1979), unconformably covers the upper Albian conglomeratic hardground (Busulini et al. 1984). A more complete Upper Cretaceous succession crops out in the Gorropu gorge, represented by Turonian to Campanian pelagic and hemipelagic limestones, cherty in some intervals, marly limestones, and marls, all rich in planktonic foraminifera (Fantin 2000). In the Gorropu gorge section, stratigraphic gaps marked by hardgrounds have been identified between the lower Hauterivian and upper Cenomanian and between the lower and middle Santonian. In the Lanaittu valley, arkosic turbidites alternating with marls, previously ascribed to the lower Maas-
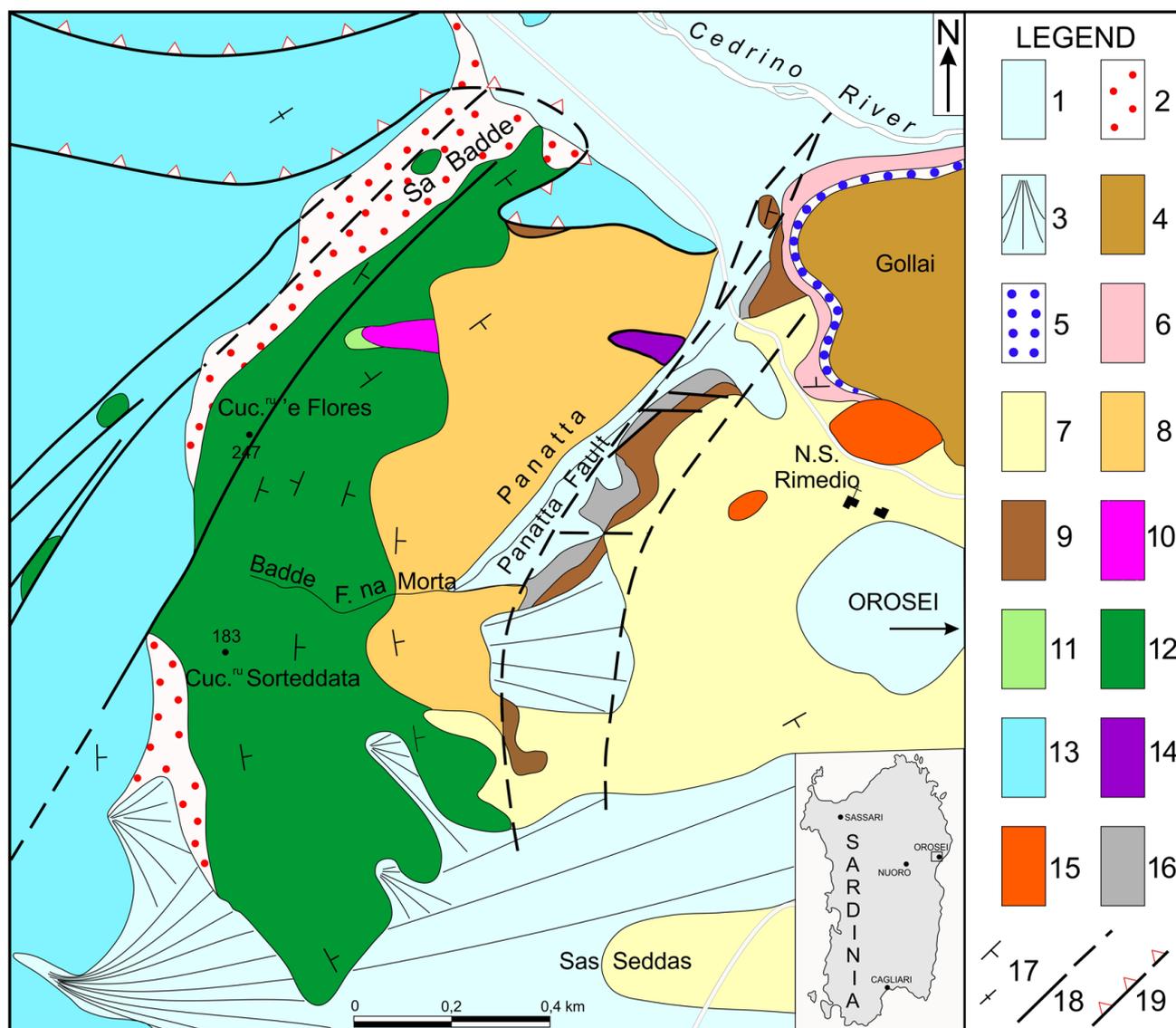
Fig. 2 - Geological map of the area between Orosei and the north-eastern slope of Mt Tuttavista (from Dieni et al. 2008, slightly modified). 1 - Alluvial deposits, locally terraced (*Holocene*). 2 - Scree deposits (*Holocene*). 3 - Alluvial cones, both preserved and dismembered (*Pleistocene - Holocene*). 4 - Giare Basalt: olivine basalt (*Late Pliocene - Pleistocene*). 5 - Nuraghe su Casteddu Formation: alluvial gravel and sand (*Late Pliocene - Pleistocene*). 6 - Fuile Sand: clinostratified, variably clayey sand rich in macro- and microfossils (*Early Pliocene*). 7 - Orosei Formation: alternating polygenic conglomerate, breccia, and sandstone, variably cemented and showing evident clinostratification (fan-delta) (*Middle? Miocene,* possibly *Serravallian*). 8 - Cuccuru 'e Flores Conglomerate: polymictic conglomerate with reworked nummulites and an olistolith of Bathonian dolostone in the Panatta area (*Lutetian*). 9 - Monte Cardiga Formation: limestone and limestone with admixed terrigenous material, containing nummulites and alveolinas (*Ypresian*). 10 - Panatta Chalk: chalk and marly chalk with globotruncanids, with the Orosei Encrinite member at the base (*Santonian*). 11 - Orosei Conglomerate: condensed horizon of glauconitic and phosphatic limy conglomerate very rich in ammonites (*late Albian*). 12 - Lanaittu Formation: marl, marly limestone, limestone, and cherty limestone (*Valanginian - early Albian*). 13 - Monte Bardia Limestone: massive and stratified white limestone (*Berriasian - Kimmeridgian*). 14 - Dorgali Dolostone: brown dolostone (*Bathonian*), as olistolith in the Cuccuru 'e Flores Conglomerate. 15 - Capo Comino Granite: pinky, coarse-grained granite (*Late Carboniferous-Permian*). 16 - Gennargentu Phyllite: grey quartz-phyllite (*?Cambrian - ?Early Ordovician*). 17- Bed attitudes. 18 - Fault. 19 - Thrust. The measured section of the Santonian deposits (Panatta Chalk) is located in the western part of the ouctcrop area of the formation, close to the Orosei Conglomerate.

trichtian (Dieni & Massari 1982), yielded rare ferroglaucophane grains, interpreted as indicative of the presence of a Late Cretaceous subduction front with Alpine polarity close to the eastern palaeomargin of Sardinia (Dieni & Massari 1982). A well (Lanaittu 1; coordinates: 40°15'33"N – 9°30'05"E), 78.49 m deep, was drilled in 1989 in the axis of the Lanaittu syncline (Fig. 3) to obtain more complete information on the succession. Specifically, a biostratigraphic revision could establish that the suc-
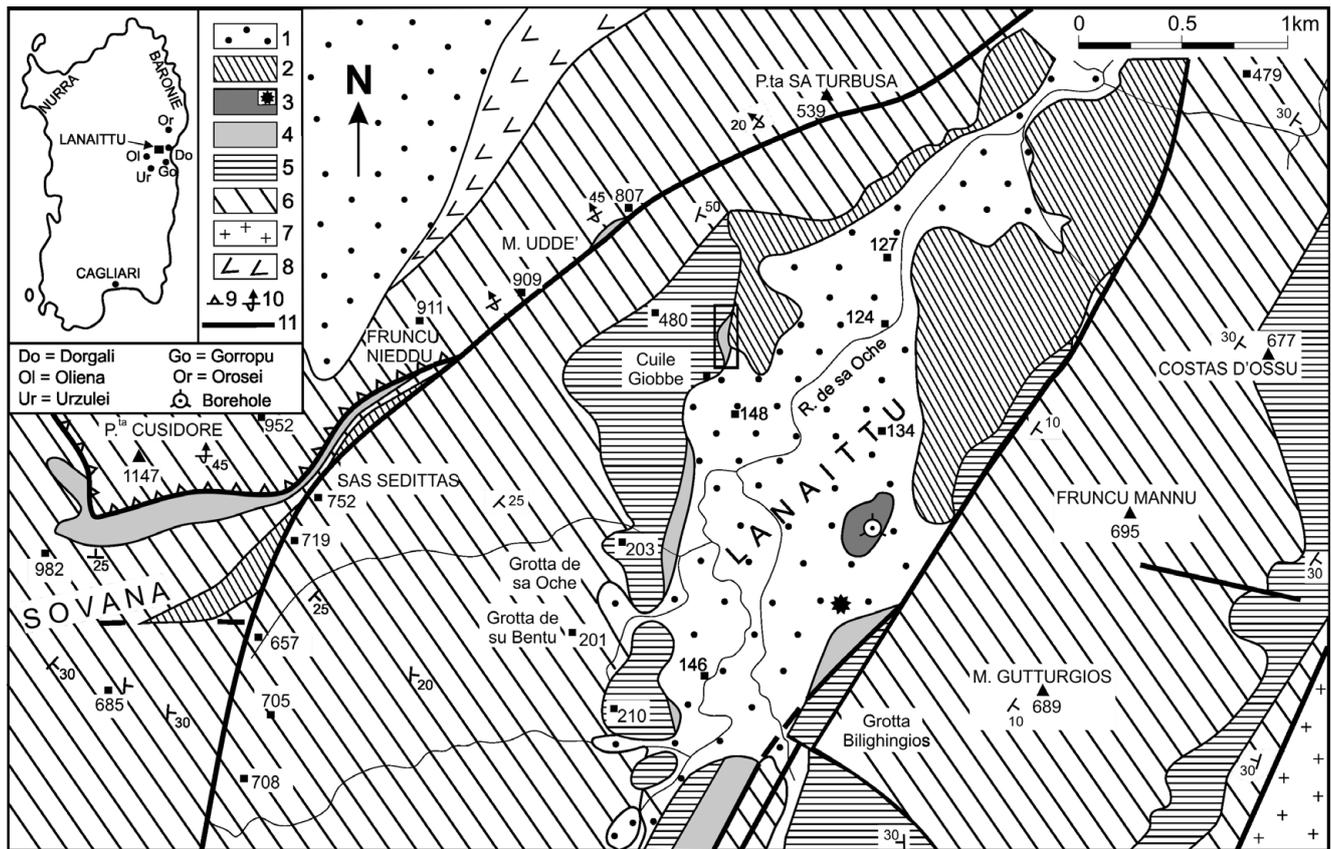
Fig. 3 - Geologic sketch map of the Lanaittu area (from Busulini et al. 1984, slightly modified). 1) Quaternary deposits. 2) Lutetian continental conglomerate (Cuccuru 'e Flores Conglomerate). 3) Upper Campanian marl and turbiditic sandstone and (asterisk) upper Santonian marly limestone; the location of the borehole is indicated in the outcrop area of upper Campanian deposits. 4) Cenomanian to lower Santonian marly limestone and limestone with chert. 5) Lower Cretaceous marl and limestone. 6) Jurassic limestone and dolostone. 7) Granite. 8) Palaeozoic schists. 9) Thrust. 10) Overturned strata. 11) Fault. The rectangular inset shows the location of the Cuile Giobbe section.

cession crossed by the well is comprised between the lower Campanian (*Globotruncanita elevata* Zone) and the upper Campanian (*Globotruncana aegyptiaca* Zone) and that the turbiditic interval ranges in age from the *C. plummerae* to the *G. aegyptiaca* Zone of the middle-upper Campanian.

Emergence of western Sardinia during the latest Cretaceous is documented by Campanian lacustrine marls with ostracods similar to the "Valdo-Fuvelian" facies of Provence, as well as by continental deposits associated with *Microcodium* crusts (Barberi & Cherchi 1980; Oggiano et al. 1987; Barca & Costamagna 2000; Cherchi et al. 2010).

### Repository

All material studied in this research (washed samples, thin sections, micro- and macrofossils, etc.) is housed in the "Museo della Natura e dell'Uomo – Sezione di Geologia e Paleontologia dell'Università di Padova", where the macrofossils figured in Plate 1 are registered under the acronym MGP-PD followed by progressive inventory numbers.

### Results

Two new sections of pelagites, of Cenomanian and Santonian age, are measured in eastern Sardinia, and their litho- and biostratigraphic and micro- and macropalaeontological features are described in detail.

### a) The Cenomanian of Cuile Giobbe

The Cretaceous stratigraphic section of Cuile Giobbe crops out on the western side of the Lanaittu valley (rectangular inset in the central part of Fig. 3). Middle Cenomanian to the lower Coniacian pelagic deposits lie on lower Hauterivian limestones of the *Acanthodiscus radiatus* Zone through an unconformity marked by a conglomeratic hardground (Fig. 4). Here, the focus is on the Cenomanian interval.

The lower Hauterivian limestone is represented by biopelsparite (Fig. 5) with benthic foraminife-
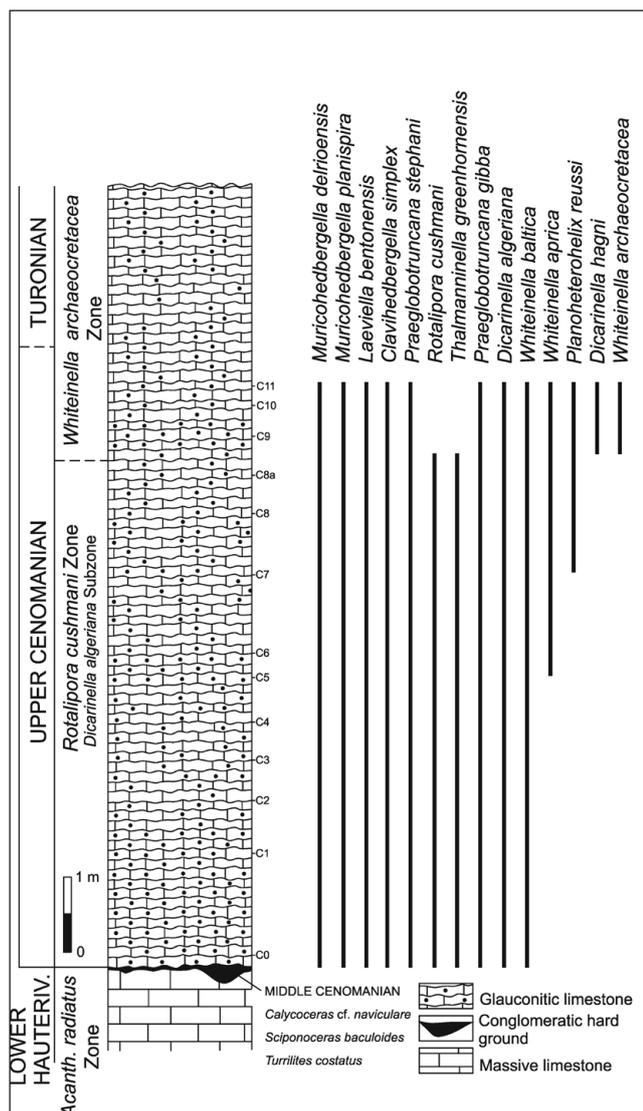
Fig. 4 - The Hauterivian-Turonian interval of the Cuile Giobbe succession: stratigraphic log, biostratigraphy, and distribution of the upper Cenomanian planktonic foraminifera.



Fig. 5 - Thin sections showing: A) Erosional and unconformable contact between the lower Hauterivian shelf limestone and the pelagic upper Cenomanian packstone with glauconite at Cuile Giobbe. The discontinuity is marked (left side) by a thin phosphate coating. B) Boring in the lower Hauterivian biopelsparite lined by phosphatic bands and infilled with upper Cenomanian pelagic sediment.

ra, echinoderm and mollusc debris, and rare ooids, indicating a relatively high-energy carbonate ramp environment. The existence of an angular discordance cannot be perceived at the local scale; however, on a larger scale, a low-angle onlap relationship of the Cenomanian on the Hauterivian substratum is undoubtedly present.

The unconformity is an erosional surface (Fig. 5A), slightly irregular and locally crossed by borings with walls lined by phosphatic bands and fill consisting of pelagic upper Cenomanian sediment (Fig. 5B). The conglomeratic hardground shows variable thickness, locally filling small erosional depressions in the substratum (Fig. 4). It is rich in Fe-oxide coating bored lithoclasts of the Hauterivian limestone and contains phosphate as a discontinuous band draping the unconformity surface (Fig. 5A), as well as authigenic glauconite. The hardground yielded phosphatized and glauconitized ammonites of middle Cenomanian age, among which:

*Calycoceras* cf. *naviculare* (Mantell, 1822) (Pl. 1, fig. 10)

*Eucalycoceras* sp. (Pl. 1, figs. 8, 9)

*Hypophylloceras* sp. (Pl. 1, fig. 6)

*Sciponoceras baculoides* (Mantell, 1822) (Pl. 1, figs. 11, 12)

*Turrilites costatus* Lamarck, 1821 (Pl. 1, fig. 7).

Associated gastropods, preserved as composite moulds, include:

*Avellana incrassata* (Sowerby, 1818) (Pl. 1, figs. 4,5)

*Ceratosiphon retusus* (Sowerby, 1836) (Pl. 1, figs.1-3).
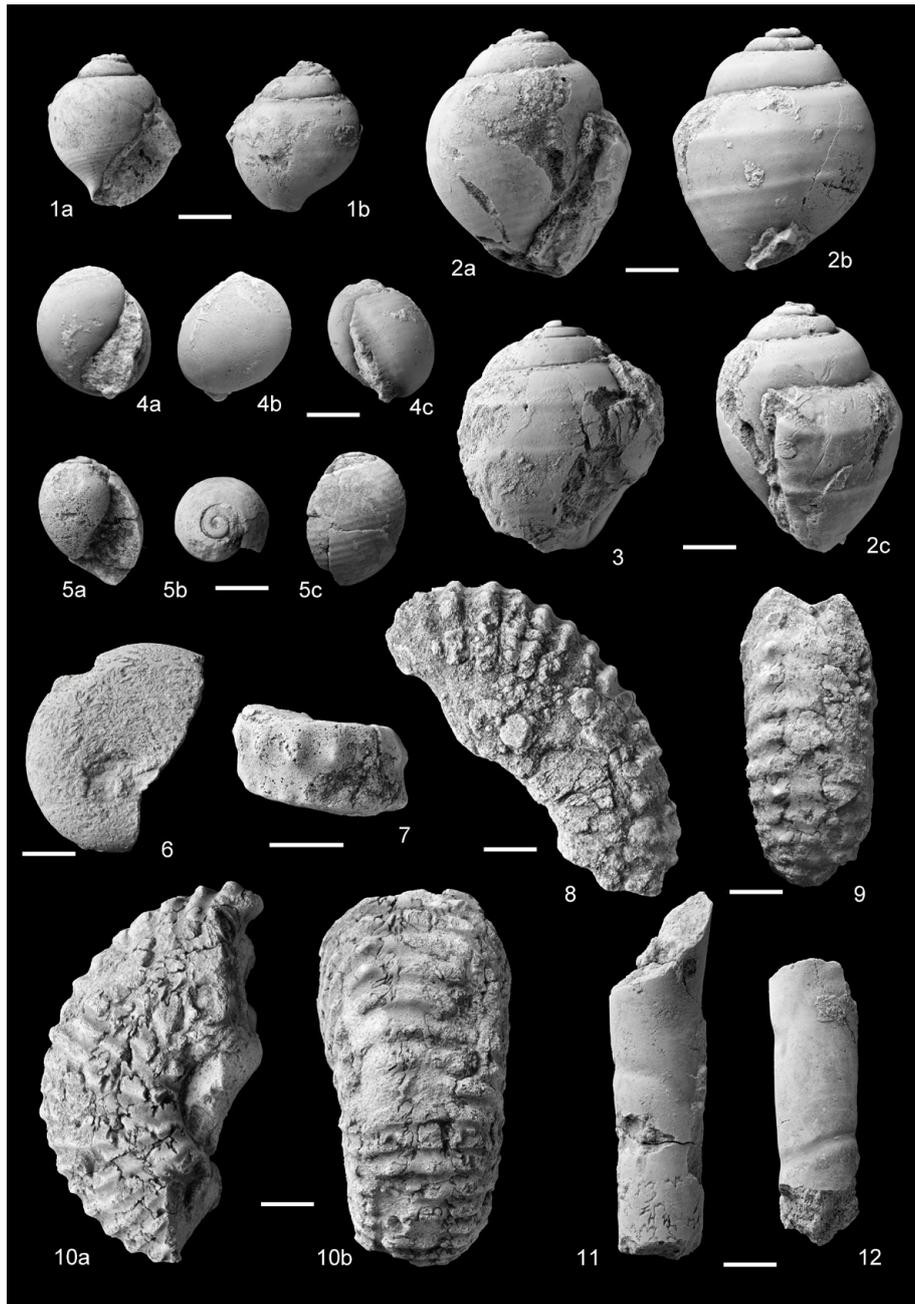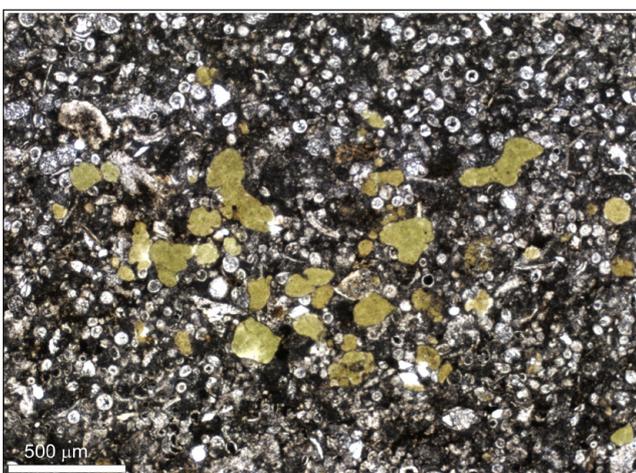
Fig. 6 - Thin section with a detail of the upper Cenomanian pelagic limestone of Cuile Giobbe showing extreme abundance of calcispheres and common glauconite grains.

The hardground is overlain by a succession of grey nodular limestones about 8 m thick, referred to the upper Cenomanian based on the planktonic foraminiferal content (Fig. 4). The lower part contains remains of fish, debris of echinoids, fragments of ammonites, and the gastropod *Avellana incrassata* (Sowerby, 1818). In thin section, limestones are packstones and wackestones containing extremely abundant calcispheres such as *Pithonella ovalis* (Kaufmann, 1865) and *P. sphaerica* (Kaufmann, 1865) (Fig. 6), associated with sponge spicules, planktonic and benthic foraminifera, debris of echinoderms and bivalves, authigenic glauconite decreasing in abundance upward, phosphate, sparse small grains of angular quartz, plagioclase,
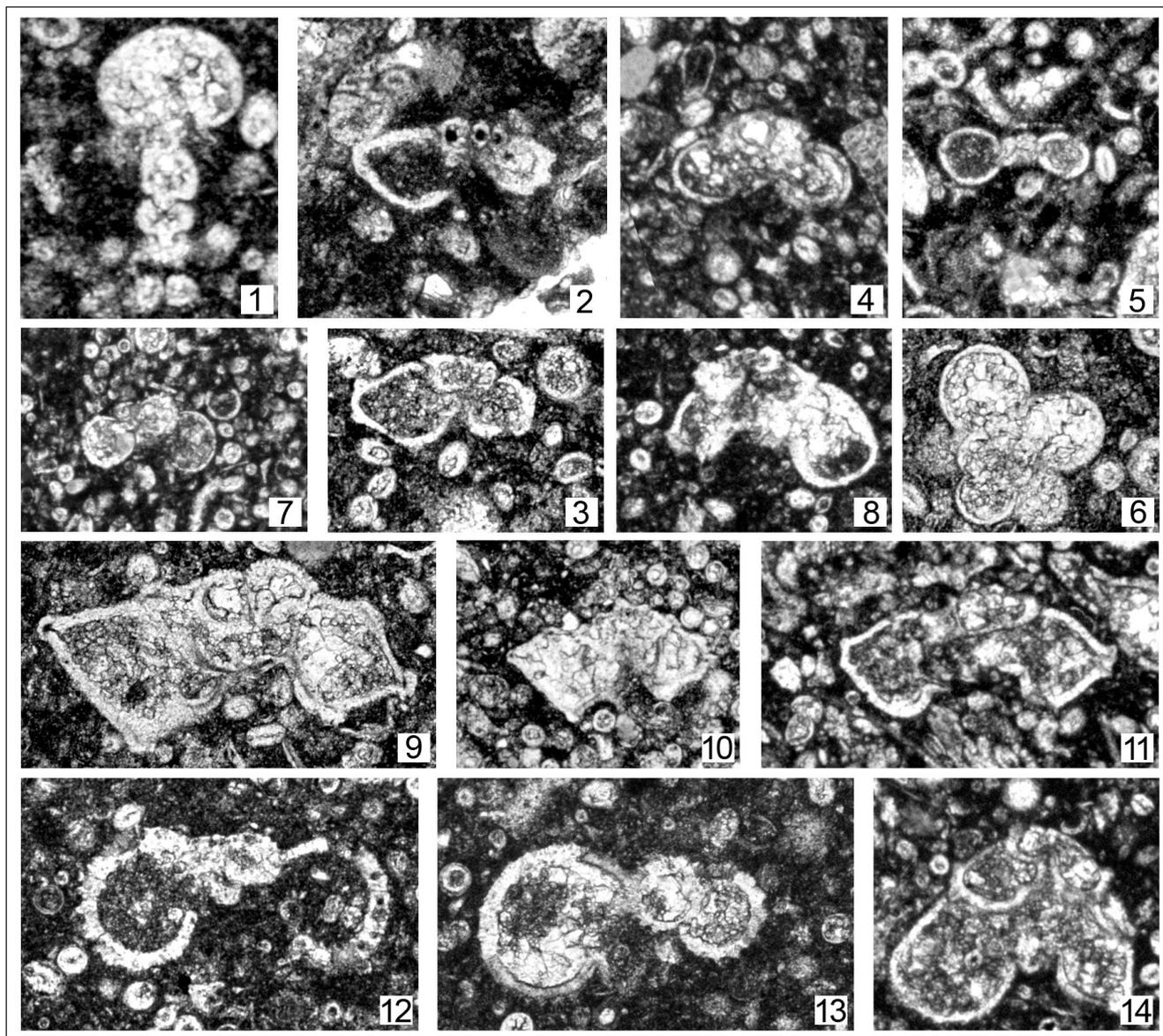
Fig. 7 - Upper Cenomanian planktonic foraminifera of Cuile Giobbe. 1) *Laeviella bentonensis*. 2, 3) *Dicarinella algeriana*. 4) *Whiteinella archaeocretacea*. 5, 6) *Clavihedbergella simplex*. 7) *Whiteinella baltica*. 8) *Praeglobotruncana stephani*. 9) *Rotalipora cushmani*. 10) *Thalmanninella greenhornensis*. 11) *Dicarinella hagni*. 12) *Whiteinella aprica*. 13) Transitional form between *Whiteinella baltica* and *Whiteinella praehelvetica* (Trujillo, 1960). 14) *Praeglobotruncana gibba*. Scale bars: 100 µm.

and chert. The facies shows the characteristics of a condensed, pelagic deposit.

In the interval comprised between samples C0-C11 (log of Fig. 4), planktonic foraminifera, determined in thin section (Fig. 7), are represented, in order of appearance, by:

*Muricohedbergella delrioensis* (Carsey, 1926)
*Muricohedbergella planispira* (Tappan, 1940)
*Laeviella bentonensis* (Morrow, 1934)
*Clavihedbergella simplex* (Morrow, 1934)
*Praeglobotruncana stephani* (Gandolfi, 1942)
*Rotalipora cushmani* (Morrow, 1934)
*Thalmanninella greenhornensis* (Morrow, 1934)
*Praeglobotruncana gibba* Klaus, 1960
*Dicarinella algeriana* (Caron, 1966)
*Whiteinella baltica* Douglas & Rankin, 1969
*Whiteinella aprica* (Loeblich & Tappan, 1961)
*Planoheterohelix reussi* (Cushman, 1938)
*Dicarinella hagni* (Scheibnerova, 1962)
*Whiteinella archaeocretacea* Pessagno, 1967,
indicating the upper Cenomanian *Rotalipora cushmani* Zone and the *Whiteinella archaeocretacea* Zone (Fig. 4).
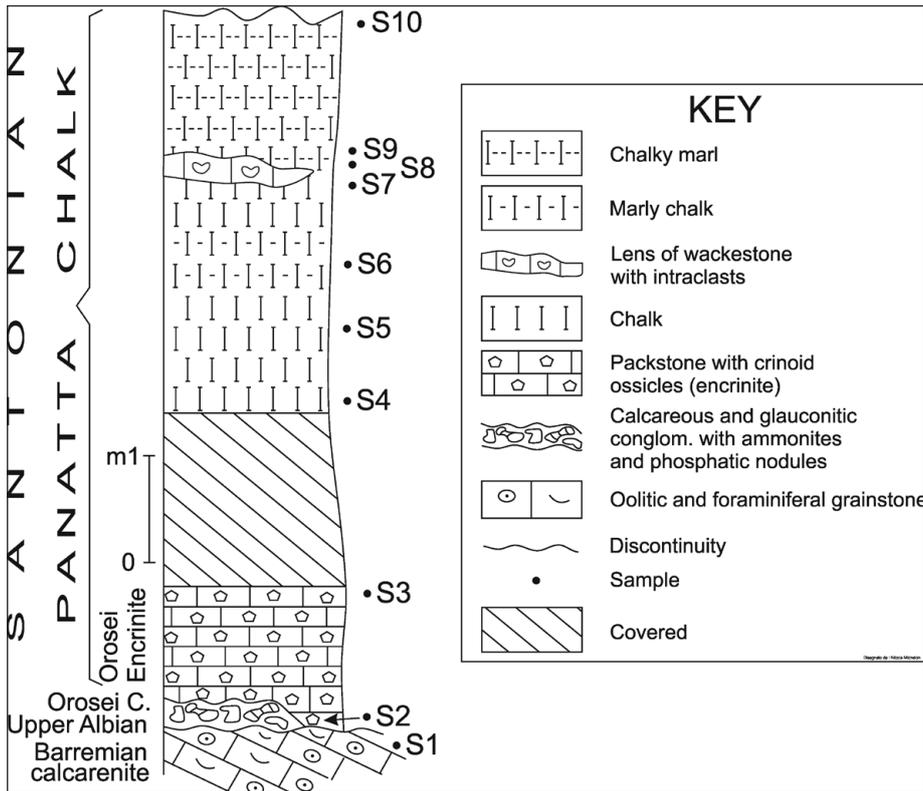
Fig. 8 - Litho- and chronostratigraph-
ic log of the Cuccuru 'e
Flores section, with position
of studied samples.

The section continues with Turonian nodular and marly limestones and Coniacian cherty limestones (the latter not represented in the log) dated according to the planktonic foraminiferal content.

Concerning the depositional environment, the presence of herbivorous gastropods such as *Ceratosiphon* and *Avellana* in the hardground faunal assemblage suggests that sea floor was characterized by the growth of algae, which provided food for these molluscs. The succession overlying the hardground shows a rapidly deepening transgressive trend. The water column should have been rich in nutrients, probably due to upwelling processes, that favour the bloom of calcispheres and the precipitation of phosphate. The extreme abundance of calcispheres is typical of the upper Cenomanian drowning platforms (Jenkyns 1991; Hernandez-Romano et al. 1997; Dias-Brito 2000), and their association with planktonic foraminifera is generally considered indicative of a shallow-bathyal depositional setting. Furthermore, the scarcity of benthic foraminifera can be interpreted as a signal of high environmental stress reflecting poor oxygenation of the sea floor.

b) The Santonian of Orosei

In the Orosei area, and precisely in the northern part of the Cuccuru 'e Flores hill, a thin unit of Santonian pelagic chalks, here formally designed as Panatta Chalk, unconformably covers the upper Albian calcareous conglomeratic hardground (Busulini et al. 1984), here named Orosei Conglomerate (Figs. 2, 8). The latter marks a prominent angular unconformity that truncates a folded substratum whose youngest units are of early Albian age. Interestingly, besides plenty of ammonites belonging to several biozones of the upper Albian (Wiedmann & Dieni 1968), the conglomeratic hardground also includes a specimen of *Anahoplites planus sulcatus* (Spath, 1925) (Wiedmann & Dieni 1968). This middle Albian specimen shows a high level of corrosion, in contrast to the excellent state of preservation of the associated upper Albian ammonites. This suggests the original existence of middle Albian marine sediments predating the mid-Cretaceous tectonics. The hiatus in the Orosei area is therefore minimal, in contrast with significant gaps occurring in western Sardinia, and indicates a probable late Albian age for the mid-Cretaceous tectonics.

As noted above, the chalk forms the infill of a presumably syntectonic gentle syncline with axis oriented NNE-SSW and dipping gently NNE-ward (Fig. 2).

A transgressive soft encrinite with "*Isocrinus?*" sp. (described and discussed in the palaeontological ap-
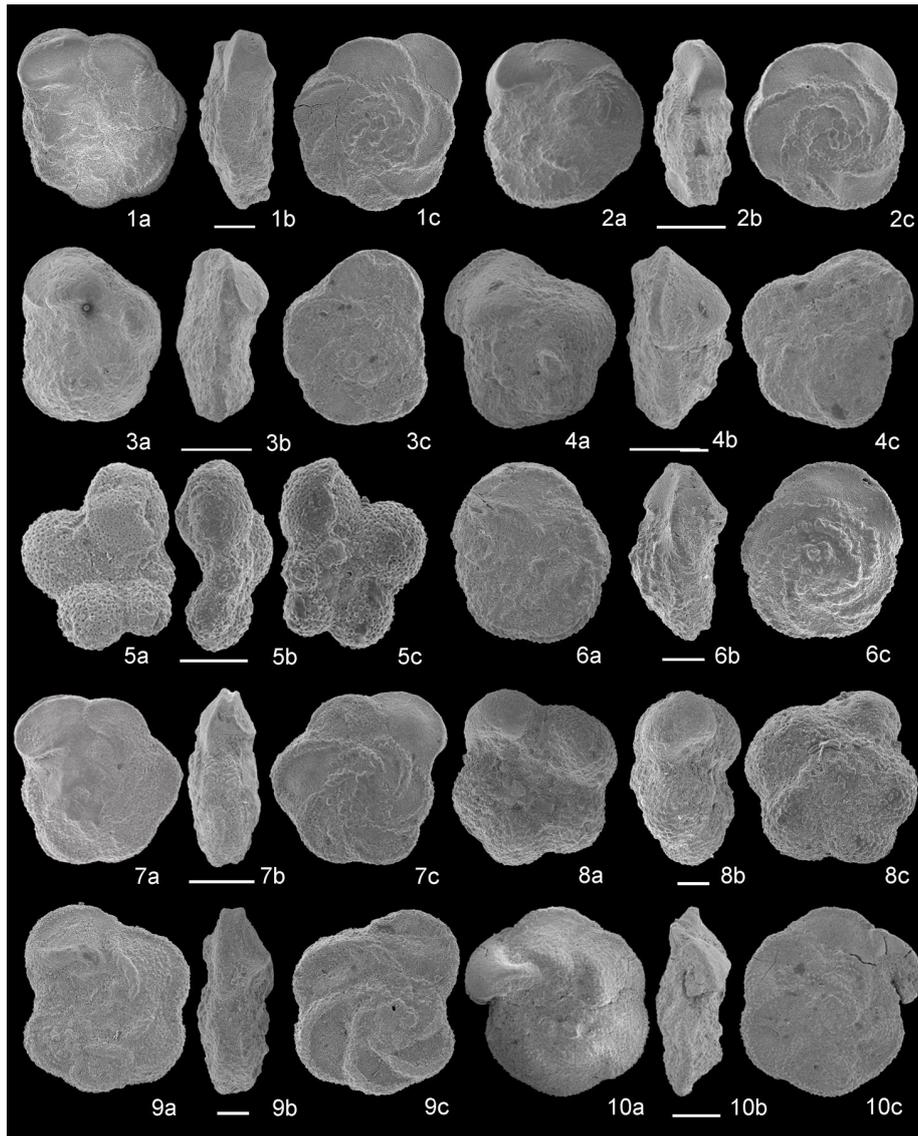
Tab. 1 - Distribution chart of the Santonian planktonic foraminifera in the Panatta Chalk section.

| Sample code | Planktonic foraminifera | Benthic foraminifera | Radiolaria | Inoceramids | Glauconite | Calcispheres | Marginotruncana sinuosa Porthault, in Donze et al., 1970 | Marginotruncana angusticarenata (Gandolfi, 1942) | Marginotruncana pseudomarginata Neagu, 2012 | Dicarinella concavata (Brotzen, 1934) | Marginotruncana paraconcavata Porthault, in Donze et al., 1970 | Marginotruncana tarfayaensis (Lehmann, 1963) | Globotruncana linneiana (d'Orbigny, 1839) | Contusotruncana fornicata (Plummer, 1931) | Marginotruncana coronata (Bolli, 1945) | Dicarinella asymetrica (Sigal, 1952) | Archaeoglobigerina cretacea (d'Orbigny, 1840) | Planoheterohelix globulosa (Ehrenberg, 1840) | Muricohedbergella simplicissima (Magne & Sigal, 1954) | Pseudotextularia nuttalli (Voorwijk, 1937) | Laevoheterohelix pulchra (Brotzen, 1936) | Globotruncanita stuartiformis (Dalbiez, 1955) | Marginotruncana pseudolinneiana Pessagno, 1967 | Laeviella bollii (Pessagno, 1967) | Archaeoglobigerina sp. | Muricohedbergella simplex (Morrow, 1934) | Dicarinella marginata (Reuss, 1845) | Planohedbergella prairiehillensis (Pessagno, 1967) | Planohedbergella ultramicra (Subbotina, 1949) | Planoheterohelix moremani (Cushman, 1938) | Muricohedbergella tradinghousensis (Pessagno, 1967) | Globotruncana neotricarinata Petrizzo, Falzoni & Premoli Silva, 2011 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S 10 | A | F | R | F |  |  | x | x | x | x |  | x | x | x | x | x | x | x | x | x |  |  | x |  |  |  | x |  |  |  | x | x |
| S 9 | C | F | R | F | F | F | x | x | x |  | x | x | x | x | x | x | x | x |  |  |  | x | x | x |  |  | x | x | x |  |  |  |
| S 7 | A | F | R |  |  |  | x | x | x | x | x | x | x | x | x | x | x |  | x |  | x |  | x | x |  |  |  |  |  |  |  |  |
| S 6 | A | R | R |  |  |  | x | x | x | x | x | x | x |  | x | x | x | x | x |  |  | x | x | x | x |  |  |  |  |  |  |  |
| S 5 | A | F |  | F |  |  | x | x | x | x | x | x | x | x |  | x | x | x | x |  |  | x | x | x |  |  |  |  |  |  |  |  |
| S 4 | A | R | R |  |  |  | x | x | x | x | x | x | x | x | x | x | x | x | x | x |  |  |  |  |  |  |  |  |  |  |  |  |

Abbreviations: x = present; A = Abundant; C = Common, F = Frequent; R = Rare.

pendix), occurring in the basal part of the succession, is here designated as Orosei Encrinite, a member of the Panatta Chalk (Fig. 8). It contains lumps of glauconite grains and very rare, small, and poorly preserved brachiopods. The encrinite is overlain by 4-5 metres of white, chalky limestone and chalky marl (Fig. 8), which generally exhibit scarce cohesiveness.

## The foraminiferal assemblages

Planktonic foraminiferal taxonomy follows the pforams@mikrotax database at http://www.mikrotax.org/pforams (Huber et al. 2016; Petrizzo 2000; Petrizzo et al. 2017; Huber et al. 2022). The planktonic foraminiferal biozonation follows the schemes of Robaszynski & Caron (1995), Premoli Silva & Sliter (1995), Petrizzo et al. (2020), and Petrizzo & Gilardoni (2020).

Planktonic foraminiferal assemblages (Tab. 1 and Pl. 2) show high diversity and are composed of large marginotruncanids, dicarinellids, *Contusotruncana fornicata* and *Globotruncana linneiana* that are especially abundant in the large-sized fraction (> 250 µm). Biserials (*Planoheterohelix globulosa*) and muricohedbergellids are more common in the fine fraction (< 125 µm) together with frequent planispiral taxa (*Laeviella bollii* and *Planohedbergella prairiehillensis*).

Benthic foraminifera are common in all samples. Rare radiolarians are recorded in the small-sized fraction of most samples. Inoceramid debris is found in samples S5, S9, and S10. Sample S9 also contains calcispheres and glauconite (Tab. 1).

The associations studied are assigned to the *Dicarinella asymetrica* Zone because of the consistent occurrence of the marker species. A Santonian age is inferred for all samples based on the co-occurrence of *Dicarinella asymetrica* and *Globotruncana linneiana*, the latter being a secondary marker for identifying the base of the Santonian Stage in the GSSP (Lamolda et al. 2014). Sample S10 yields *Globotruncana neotricarinata*, a species that first occurs in the uppermost part of the *Dicarinella asymetrica* Zone (Petrizzo et al. 2019), allowing its assignment to the late Santonian.

## DISCUSSION AND CONCLUSIONS

### The new stratigraphic sections

Aimed at integrating knowledge of the Mesozoic succession of eastern Sardinia, the lithostratigraphical, palaeontological, and biostratigraphical features of two sections of Cenomanian and Santonian ages are described in detail. The data presented contribute to the knowledge of the Upper Cretaceous succession in eastern Sardinia. The Cuile Giobbe section offers the record of a stratigraphical situation quite common in the Oliena-Urzulei Supramonte, where, unlike the more complete record in the Orosei area, a large part of the Lower Cretaceous succession is missing in the

mid-Cretaceous gap, with Hauterivian neritic limestones unconformably overlain by Cenomanian or Turonian pelagic limestones. In this section a conglomeratic hardground with a middle Cenomanian fauna, unconformably lying on Hauterivian neritic limestones, is overlain by condensed upper Cenomanian pelagic limestones with authigenic glauconite, showing a rapid deepening in a shallow-bathyal depositional setting, where calcisphere bloom, phosphate precipitation, and low benthic foraminifera content suggest high environmental stress in a context of poor oxygenation of the sea floor and water column rich in nutrients, probably due to upwelling processes.

     The other described section (Cuccuru 'e Flores section), cropping out in the Orosei area, consists of unconformably-based pelagic and hemi-

pelagic Santonian deposits with a soft, lowermost layer of transgressive encrinite grading upward with a deepening trend to a chalky facies (Panatta Chalk), unknown elsewhere. This unit unconformably lies on a calcareous conglomeratic hardground containing ammonites belonging to several biozones of the upper Albian (Wiedmann & Dieni 1968), which rests erosively on a folded substratum of Lower Cretaceous deposits.

### The mid-Cretaceous and Santonian tectonics

     Although important palaeotectonic conclusions cannot be inferred from the essentially stratigraphic data presented in this work, we attempted, starting from the analysis of the unconformities and integrating our information with inputs from the literature, to interpret the mid- to Late Creta-

Fig. 9 - Comparison between selected Cretaceous successions of western Sardinia (Nurra area, from Cherchi & Schroeder, 1985, slightly modified) and eastern Sardinia (Gorropu gorge and Lanaittu 1 borehole; Orosei, from Dieni et al., 1987, slightly modified). Upper part: schematic stratigraphic logs; lower part: relative chronostratigraphy. HG: hardground; Cgl. HG: glauconitic phosphatic calcareous conglomeratic hardground; lmst: limestone; biocl.: bioclastic; U.: Upper; Cret.-Cen. bound.: Cretaceous-Cenozoic boundary. The oblique lines mark the stratigraphic gaps. The question mark in the Gorropu-Lanaittu section indicates that the thickness of the interval between the mid-Santonian and the lower Campanian is unknown.
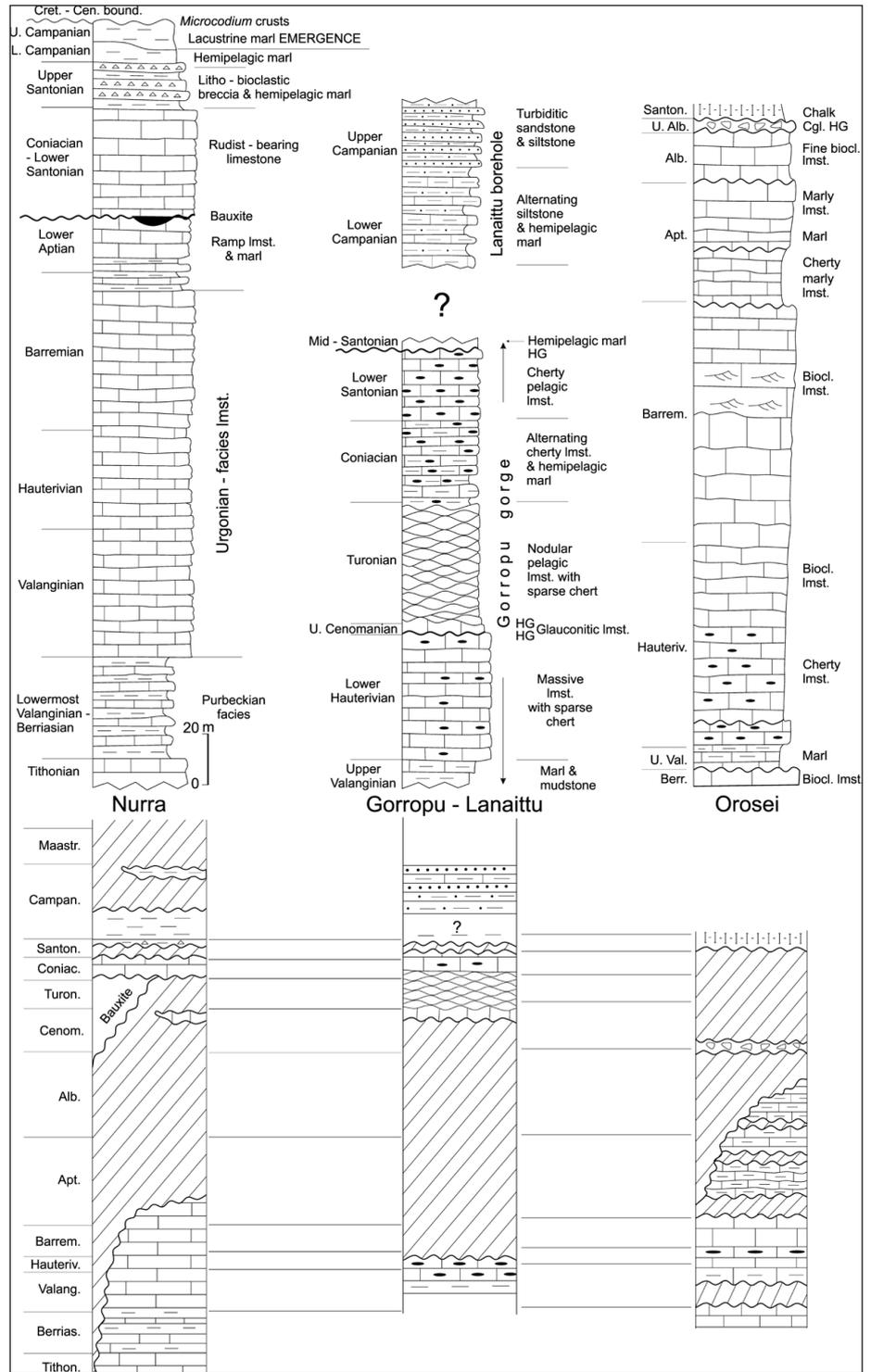
ceous geologic setting of Sardinia in the frame of the geodynamic situation of the surrounding Tethyan areas.

Following an episode of diffuse transtension in the Aptian – early Albian, a major tectonic event near the end of the Early Cretaceous produced deformations and stratigraphic gaps of variable amplitude throughout Sardinia (Fig. 9). In eastern Sardinia the impact of the mid-Cretaceous tectonics is highlighted by the change from platform/outer shelf limestone successions to pelagic deposits without evidence of subaerial exposure, a situation contrasting with that of W Sardinia, where the Upper Cretaceous succession lies on a surface of long-lasting subaerial exposure and continues the trend of the Lower Cretaceous shallow-water sedimentation.

In the north-western Sardinia (Nurra area) a mid-Cretaceous left-lateral transpressional tectonics associated with the unconformity is well documented (Chabrier & Fourcade 1976; Philip & Allemann 1982; Cherchi & Trémolières 1984; Oggiano et al. 1987; Combes 1990; Mameli et al. 2007). In eastern Sardinia, although the unconformities are accompanied by angular unconformities and by erosion that locally removes a large part of the Lower Cretaceous succession, producing hiatuses of various amplitudes, the nature of the involved tectonics can only be inferred. Possible clues for its transpressional nature include local fault-associated folding (Orosei) and stratigraphic gaps of varying amplitude even in nearby locations, pointing to a variable relief and depth of erosion of the substratum. The fact that the maximum amplitude of the stratigraphical gap is recorded near P.ta Cusidore (Fig. 3) suggests that the ENE-WSW San Giovanni Fault (Fig. 1) was actively involved in the mid-Cretaceous transpressional movements. This assumption is supported by the analogy to the N60°- 80°E transpressional faults of the Nurra area. Moreover, it is compatible with the AFT age of 117.3 Ma detected close to the fault (Zattin et al. 2008).

Mid-Cretaceous deformations in the Nurra area are thought to exhibit features similar to those of the coeval tectonics in Provence, which was probably in a position close to Sardinia at that time. Deformations in Provence have been variously interpreted. They were attributed to rifting similar to that active in the Pyrenean area (e.g., Bestani et al. 2016), or compression (Bilau et al. 2023), or transpression (e.g., Schreiber et al. 2011). The latter reconstruction, which we share, entails a frame of transpressional tectonics along a system of sinistral N30° and dextral N140° faults in a context of sinistral oblique convergence, with a peak in the late Albian-early Cenomanian. This tectonics in Provence was concomitant with the rise of a broad subaerially-exposed kilometric antiformal structure trending approximately E-W, the so-called "Isthme Durancien" (Combes et al. 1993, and references therein) or "Durance High". The linked subaerial exposure, comparable to that which occurred in W Sardinia, was associated with a stratigraphic hiatus lasting from the latest Albian to the earliest Cenomanian at least (Combes 1990; Combes et al. 1993; Bestani et al. 2016).

The mid-Cretaceous is known to have been a key period of evolution in the Atlantic-Tethyan sy-stem, where a drastic change of plate motion occurred (e.g., Stampfli et al. 2001, and references therein). The reconstruction proposed here partly follows the scissor-like model of Schreiber et al. (2011), implying that the driver of the mid-Cretaceous changes in the Tethyan area is the eastward shift of Iberia relative to Europe, accommodated by sinistral motion along the northern Pyrenean transform. According to this model, the transtensional tectonics in the Pyrenean domain, which occurred in concomitance with late Albian mantle exhumation (e.g., Asti et al. 2019), changed eastward into oblique compression (Fig. 10). The latter is assumed by Handy et al. (2010) to have been determined by the activation of SE-directed subduction of the western Ligurian Ocean beneath Alkapeca, triggered by the sinistral motion of Iberia (Fig. 10). We propose that the similarity of transpressional tectonics affecting Sardinia and Provence may represent a far-field effect of the onset of oblique convergence linked to this major change. The reconstruction implies a likely kinematic link between the SE-directed subduction of the western Ligurian Ocean and the Eo-Alpine Orogeny within the Alcapa unit (Handy et al. 2010) (Fig. 10).

During Santonian, gentle synsedimentary folding in the Orosei area occurred in concomitance with an episode of extensional tectonics in western Sardinia (Nurra area), where it caused an abrupt drowning episode interrupting carbonate platform deposition (Cherchi & Trémolières 1984; Cherchi & Schroeder 1985; Cherchi et al. 2010). Judging from the age of the involved sediments and stratigraphic gaps, tectonics should have been active in the early Santonian. It is thought to reflect the change from oblique convergence to a setting of more orthogonal convergence, known to have occurred everywhere along the Tethys margin since ~ 84 Ma. Based on the assumption that a NW-directed Alpine subduction front existed off the eastern palaeo-margin of Sardinia during the Late Cretaceous (Cello et al. 1996; Handy et al. 2010; Le Breton et al. 2021) (Fig. 10), it is suggested that the observed Santonian changes reflect the onset of the formation in Sardinia of a forebulge, due to the approach of an eo-Alpine accretionary wedge to the Sardinian palaeo-margin. The extensional event documented in the Nurra area is interpreted to have resulted from tensile stresses triggered by bending close to a forebulge crest (e.g., Reis et al. 2017). The forebulge becomes more manifest in a later time, when the subaerial exposure of the Me-

Fig. 10 - Proposed schematic late Albian palaeotectonic map of the Tethyan domain, partly based on Handy et al. (2010), Schreiber et al. (2011), and Hinsbergen et al. (2020). DH: Durance High. Br: Briançonnais. Grey: oceanic areas; white: emerged lands.
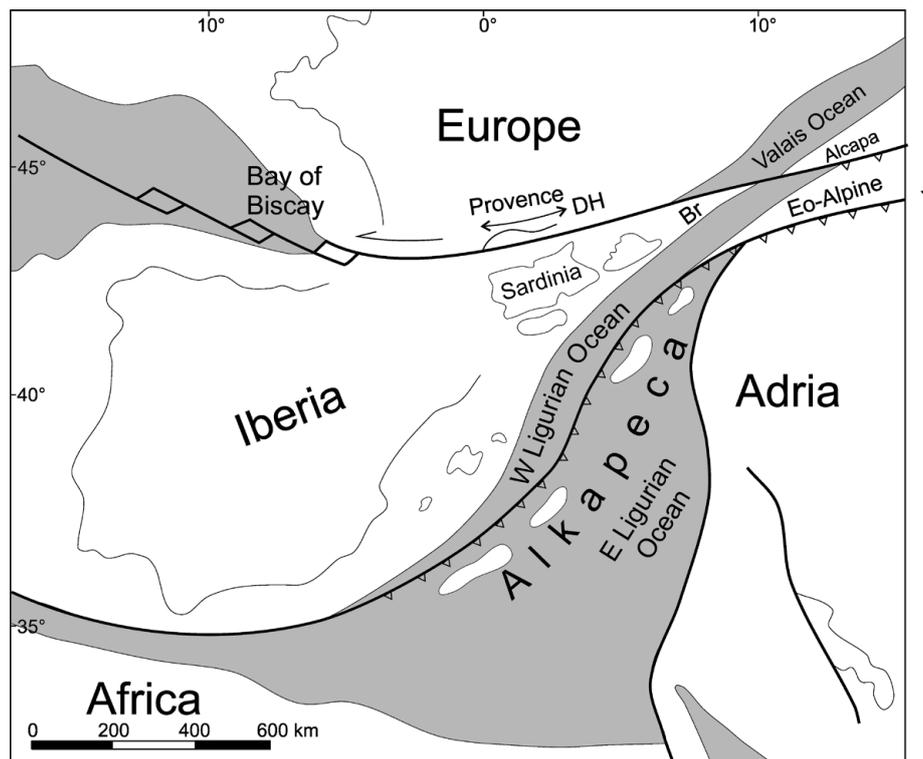
sozoic carbonate platform in western Sardinia since late Campanian (Barca & Costamagna 2000) occurred in concomitance with relatively deep marine sedimentation on the subsiding eastern side of the island. At this stage, incipient collision is envisaged to have occurred (Cello et al. 1996; see also Marroni and Pandolfi 2003 for the Corsica margin). This reconstruction is similar to the one proposed by Mueller et al. (2018) for the Upper Cretaceous Bordighera Sandstone of Ligurian Alps, and is supported by the presence of detrital glaucophane in the middle-upper Campanian arkosic turbidites of the Lanaittu valley.

## PALAEONTOLOGICAL APPENDIX

Class CRINOIDEA Miller, 1821
Family Isocrinidae Gislen, 1924
Genus *Isocrinus* von Meyer, 1836

The proposal of Rasmussen (1961) is adopted to use the preliminary genus name "*Isocrinus*?" for most Cretaceous species of Isocrinidae known only from stalk fragments.

### *"Isocrinus?"* sp.
Fig. 11

**Material**: 72 internodal columnals and 17 cirrals (MGP-PD 33309A).

**Description**. Columnals oval, pentagonal, pentalobate, and substellate, with diameter increasing with height (1.9 - 3.4 mm). Small columnals, oval and pentagonal, with sharp interradia sometimes occurring in larger specimens. Articular faces with broad areolae of variable width. Petal floors drop-like, sometimes ellipsoidal, and becoming larger in the proximalmost columnals, surrounded by a maximum of 18 crenulae.

Crenulae short and thin. Lumen small and circular. Latera smooth, straight, sometimes slightly convex. Cirrals of different sizes with lengths varying from short to long in the distal parts. Long cirri sometimes curved. Cirrals smooth, elliptical, and rarely circular in section. Nerve canal surrounded by a distinct perilumen.

**Discussion**: Rasmussen (1961, and the literature therein) documented only three Santonian 'isocrinid' taxa in central and southern Europe: "*I.*?" *carinatus* (Roemer, 1840), "*I.*?" *minutus* (Valette, 1917), and "*I.*?" *nodulosus* (Roemer, 1840), all with lateral surfaces covered with granules, nodules or even having a keel. In the material examined, no such structures were observed in any of the specimens, as all of them were smooth. However, it cannot be excluded that at least some of the columnals from Orosei should be related to another genus of Late Cretaceous isocrinids, such as *Nielsenicrinus* Rasmussen, 1961, whose diagnostic feature is the presence of
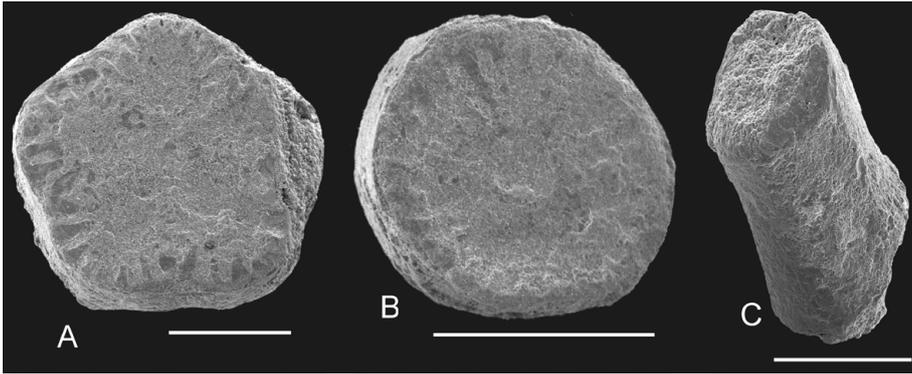
Fig. 11 - "*Isocrinus*?" sp.: A) medial? columnal articular face. B) juvenile distal? columnal articular face. C) medial/proximal cirral, oblique view. Scale bar: 1 mm.

cryptosyzygy occurring between secundibrachials 3 and 4 (Oji et al. 1996). Other isocrinids present in Santonian sediments of Europe include *Austinocrinus* de Loriol, 1889, *Balanocrinus* Desor, 1845, and *Doreckicrinus* Rasmussen, 1961. However, the morphology of their columnal articular facets is so unique that it is impossible to confuse the Sardinian specimens with them.

In summary, the studied ossicles do not refer to any of the isocrinid forms of the Upper Cretaceous of Europe listed above. It may be hypothesized that they belong to one or more new taxonomic entities which, however, cannot be formally defined because of the lack of significant morphological characters from the diagnostic point of view, owing to the extreme disarticulation suffered by the skeletons.

**Remarks**. All Santonian crinoid ossicles of Orosei belong to isocrinids. According to Baumiller et al. (2010) and Gorzelak et al. (2012) these echinoderms should be restricted to deep-water refugia after the Mesozoic marine revolution. However, Salamon et al. (2009) and Lach (2016) pointed out that isocrinids recorded from the lower part of the Upper Cretaceous are pretty common and remained in shallow-water settings for some time after the initiation of this major change.

**Distribution**. According to Hess & Messing (2011) *Isocrinus* ranges from the Upper Triassic (?Carnian) to the Lower Cretaceous of Europe and Asia; however, according to Rasmussen (1961) its stratigraphic range extends to the Danian and the distribution area includes Denmark, Sweden and eastern Europe [e.g., "*I.*?" *divergens* (Nielsen, 1913), "*I.*?" *echinatus* Rasmussen, 1961, "*I.*?" *gocevi* (Sieverts-Doreck, 1951), "*I.*?" *longus* (Nielsen, 1913)].

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