Rudist-bearing rhodalgal facies in the post-Turonian recovery of peri-Tethyan carbonate systems: a case history from the Nurra region (northwestern Sardinia, Italy)

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ABSTRACT

The presence of non-geniculate coralline red algae and bryozoans (rhodalgal lithofacies) in association with rudists has been mentioned only rarely in the literature. Nevertheless, because of the significance of rhodalgal facies in the characterization of shallow-water carbonate factories, a correct interpretation of the related ecological factors may improve the palaeo-environmental reconstruction of some rudist-bearing carbonate depositional systems. Uppermost Coniacian-Santonian rhodolith-rich rudist-bearing carbonate successions in the Nurra region (northwestern Sardinia, Italy) record several discrete depositional settings, from autochthonous shallow-water mobile skeletal deposits including coralline algal fragments and rhodoliths, to re-mobilized deposits rich in skeletal components with rhodoliths. The rudist-bearing rhodalgal limestone studied is part of an uppermost Turonian-Campanian transgressive sequence that covers a tectonically-modelled Lower Cretaceous substrate. The recovery of the Upper Cretaceous carbonate factories followed an interval of time during which the Lower Cretaceous carbonate systems, dominated by chlorozoan assemblages and non-skeletal grains, had experienced "Mid-Cretaceous" worldwide crises presumed to have been caused by global climatic/oceanographic perturbations.

In particular, Early-Middle Turonian times, characterized by the hyper-greenhouse conditions then prevailing, witnessed a significant reduction or even complete demise of highly productive carbonate factories. In carbonate settings, biotic assemblages grew in mesotrophic/eutrophic environments. Cyanobacterial consortia, with variable contributions from rudists, largely prevailed in shallow-water domains. Thus far, the latest Turonian-Coniacian recovery of Sardinian carbonate factories with "impoverished chlorozoan assemblages" might be considered as an indication of ameliorated environmental conditions. However, ecological constraints did not allow the tropical "chlorozoan assemblages" to thrive in the Late Cretaceous low-latitudinal carbonate shelves of Sardinia. A Santonian shift toward foramol/rhodalgal depositional systems occurred with sciaphile- (shadow preferring), and mesotrophic-adapted ("rudist-bearing rhodalgal") assemblages flourishing in the new shallow-water domains. In Santonian times relatively cool and mesotrophic to eutrophic conditions are presumed to have become dominant in the water mass impinging on the marginal sectors of the shelf or distal ramp of the Nurra carbonate system. Deterioration in the quality of water presumably caused the demise of large sectors of the Nurra carbonate factory, which underwent local drowning episodes controlled by tectonic activity.

KEY WORDS
Upper Cretaceous,
rudist-bearing limestone,
rhodalgal facies,
Sardinia,
Italy.

RÉSUMÉ

La part des faciès « rhodalgal » à rudistes dans le rétablissement post-Turonien des systèmes carbonatés péri-Téthysiens : exemple de la région de la Nurra (Sardaigne nord-occidentale, Italie).

L'association d'algues rouges corallines encroûtantes et de bryozoaires (faciès « rhodalgal ») avec des rudistes a été rarement mentionnée dans la littérature. Néanmoins, en raison de l'importance que revêt ce faciès « rhodalgal » dans la caractérisation des domaines néritiques de production de sédiments carbonatés (« usines à carbonates »), la détermination exacte des facteurs écologiques connexes peut aider à préciser les reconstitutions paléoenvironnementales des aires peuplées par les rudistes. Dans ce cadre, nous avons étudié les séquences carbonatées à rhodolithes et rudistes d'âge Coniacien terminal à Santonien de la région de la Nurra (NO Sardaigne, Italie). On y identifie une gamme d'environnements de dépôts, distincts, depuis ceux des faibles profondeurs, constitués de débris bioclastiques relativement mobiles, avec notamment des éléments dérivés d'algues corallines et des rhodolithes, jusqu'à ceux resédimentés riches en bioclastes et comportant également des rhodolithes. Le calcaire à rudistes et rhodolithes appartient à un cortège sédimentaire essentiellement transgressif d'âge Turonien terminal à Campanien qui repose en discordance angulaire sur un substratum d'âge Crétacé inférieur. Le rétablissement des usines à carbonates au Crétacé supérieur fait suite à un épisode au cours duquel les systèmes carbonatés du Crétacé inférieur, avec des sédiments caractéristiques d'associations de type « chlorozoan » et où il y a aussi des éléments figurés non bioclastiques, ont subi les répercussions de perturbations globales, probablement d'origine climatique et/ou océanographique, parfois appelées « crises médio-crétacées ». En particulier au cours du Turonien inférieur à moyen, intervalle affecté par un important effet de serre, la sédimentation enregistre une importante réduction, voire localement la disparition totale, des usines à carbonates. Dans les quelques environnements carbonatés restants, les communautés biotiques sont alors représentatives de conditions méso- à eutrophiques : ainsi, si les rudistes contribuent de manière plus ou moins significative à la production carbonatée, ce sont essentiellement les cyanobactéries qui prédominent dans les domaines néritiques. Ces considérations amènent à penser que le rétablissement de la production carbonatée par le biais d'associations de type « chlorozoan », bien qu'appauvries, pourrait témoigner d'une amélioration des conditions du milieu au cours du Turonien terminal-Santonien. Néanmoins en raison de contraintes écologiques, il est peu probable que les associations de type « chlorozoan » présentant un cachet tropical aient pu prospérer au sein des plates-formes carbonatées de basse latitude du Crétacé supérieur de Sardaigne. Au cours du Santonien, un transfert s'est produit vers des systèmes de dépôt de type foraminifère-mollusque (« foramol ») ou algues rouges corallines encroûtantes-bryozoaires (« rhodalgal »), caractérisés par des associations adaptées aux conditions sciaphiles et mésotrophiques (associations de type « rhodalgal » à rudistes), florissantes dans les nouveaux domaines néritiques. Il est admis que ce glissement vers des conditions relativement plus froides et des conditions méso- à eutrophiques affecte la masse d'eau empiétant sur les secteurs marginaux de la plate-forme ou de la rampe distale du système carbonaté de la région de la Nurra. Cette détérioration y est probablement la cause principale de la disparition de nombreuses aires de production de carbonates ; à ce facteur physicochimique, on peut ajouter la réactivation tectonique de la région, responsable d'épisodes d'ennoiement enregistrés dans certains secteurs.

MOTS CLÉS
Crétacé supérieur,
calcaire à rudistes,
faciès rhodalgaire (faciès à algues rouges calcaires),
Sardaigne,
Italie.

INTRODUCTION

Shallow-water limestone characterized by a dominance of sciaphile (low light-adapted) assemblages, and comprised of molluscs (mainly bivalves), bryozoans, benthic foraminifera and coralline red algae (foramol facies *sensu* Lees 1975; Lees & Buller 1972) are common throughout the geological record. Modern and fossil examples (e.g., Nelson 1978, 1988a; Carannante *et al.* 1988, 1995, 1997; Nebelsick 1992; Carannante & Simone 1996; Betzler *et al.* 1997, 2000; Vecsei & Sanders 1999; Halfar *et al.* 2000, 2001; Pedley & Grasso 2002; Braga & Aguirre 2001; Martín *et al.* 2004; Nebelsick *et al.* 2005; Bassi *et al.* 2006; Braga *et al.* 2006; Bassi & Nebelsick 2010, among others) have been shown to develop in carbonate depositional systems under a wide spectrum of environmental, geographical and oceanographic conditions (see Nelson 1988b; James & Clarke 1997; Pedley & Carannante 2006). Their distribution is controlled by multiple factors that include water depth, temperature, salinity, nutrient supply, light intensity and/or availability of suitable substrates which together may yield latitudinal patterns. As a consequence, unlike the modern tropical shelves characterized by zooxantellate-corals (z-corals) and calcareous green algae (chlorozoan facies *sensu* Lees & Buller 1972), foramol-type shelves are not limited to particular latitudinal belts. These "non-tropical" (*sensu* Nelson 1988a) carbonate factories, devoid of limiting rigid frameworks, develop even in tropical/subtropical settings under conditions that involve upwelling of nutrient-rich waters, cold current regimes and/or terrestrial runoff (Carannante *et al.* 1988). In particular, Carannante *et al.* (1988) distinguish a peculiar foramol assemblage (*sensu* Lees & Buller 1972), typically with non-geniculate coralline red algae (locally forming rhodoliths) and bryozoans (rhodalgal facies) as the expression of temperate/transitional belts or tropical/subtropical settings under anomalous water conditions ("temperate-type" open shelves).

Hence, the inception of foramol/rhodalgal carbonate open shelves that replace previous tropical chlorozoan-rimmed shelves in the geological record suggests major turnovers in water mass.

Based on the skeletal grains and related biological (foramol/rhodalgal vs chlorozoan) assemblages, the organization of the lithofacies (lack of limiting rigid frameworks and/or bars), the geometries of sedimentary bodies, and the shallow-water carbonate system responses to sea-level changes (major lowstand shedding vs highstand shedding), Carannante *et al.* (1995, 1997) and Simone *et al.* (2003; and references therein) proposed a "temperate-type" depositional model ("foramol-rhodalgal open shelves"), devoid of any strictly palaeo-latitudinal and/or water temperature-related implications, for the post-Turonian rudist-bearing carbonate sequences of the central-southern Apennines and northwestern Sardinia (Italy), both constituting a part of the peri-Tethyan Cretaceous realm. In all these sequences, the inception of the post-Turonian shallow-water carbonate factories followed a major Early-Middle Turonian crisis. The re-arrangement of the carbonate platforms succeeded a long interval in which the peri-Tethyan "middle" Cretaceous shallow-water domains were forced repeatedly to change sediment-production modes, patterns of deposition and the internal architecture of the sedimentary succession, all caused by a complex interplay of tectonic, climatic and biotic factors. This interval of time was crucial for the subsequent development of the Upper/post-Turonian shallow-water factories where rudists played a major sediment-producing role, locally in association with coralline red algae and bryozoans (rhodalgal rudist-bearing lithofacies, see Carannante *et al.* 2008).

Rudists thrived on Cretaceous marine shelves, but their evolution and distribution were marked by significant and sometimes dramatic changes involving to considerable degree the mode of production of the carbonate factories. However, to date the ecological constraints on their distribution are still being debated (see Gili *et al.* 1995a, b). Analyses of the complex biotic assemblages that accompanied the main turnovers in the mode of production of the Cretaceous carbonate factories may by improve significantly the palaeoenvironmental interpretation of the rudist-bearing carbonate systems and help to elucidate the ecological meaning of these unique molluscs. We contribute to this debate by focusing on the Upper Cretaceous rudist-bearing limestone which crops out in northwestern Sardinia, Italy (Fig. 1). In the limestone investigated a peculiar biotic rudist-bearing assemblage rich in non-geniculate coralline red algae and bryozoans replaced during the whole of the Coniacian-Santonian transition the antecedent rudist, green algal and coral bearing assemblage.

GEOLOGICAL SETTING

The area studied is in northwestern Sardinia, Italy (Fig. 1). During the Mesozoic, Sardinia was part of the northern Tethyan domain. In latest Oligocene-Miocene times, the Sardinia-Corsica and Balearic Promontory blocks rifted from the European foreland and rotated counterclockwise. This rotation opened the western Mediterranean Sea in relation with the eastward migration of the Apenninic subduction zone (Alvarez 1972; Montigny *et al.* 1981; Cherchi & Montadert 1982; Burrus 1984; Vigliotti & Longenheim 1995; Doglioni *et al.* 1997; Viti *et al.* 2009, among others). The Mesozoic and Palaeogene evolution of Sardinian stratigraphic successions is similar in facies patterns and evolutionary trends to those of the coeval northern margins of the Tethys fronting mainland Europe (mainly northeastern Spain and southern France). Palaebiogeographical research, based mainly on larger foraminifera and rudists, indicate close faunistic relationships between the Cretaceous carbonate platforms of Sardinia and the Pyrenean-Provençal region, thus confirming an assumption that the island was a part of the southern margin of the European plate (Cherchi & Schroeder 1973, 1976a, 2002; Chabrier & Fourcade 1975; Cherchi *et al.* 1981; Masse & Allemann 1982; Philip & Allemann 1982; Cherchi 1989). The Mesozoic succession cropping out in the Nurra region records the inception of an extensive carbonate system following the Tethyan Triassic transgression. During Triassic-earliest Jurassic (pre-rift and sin-rift stages) the northern Tethyan domains were mainly continental-paralic deposits (see Baud *et al.* 1997) passing upward to calcareous-dolomitic Jurassic sequences (the

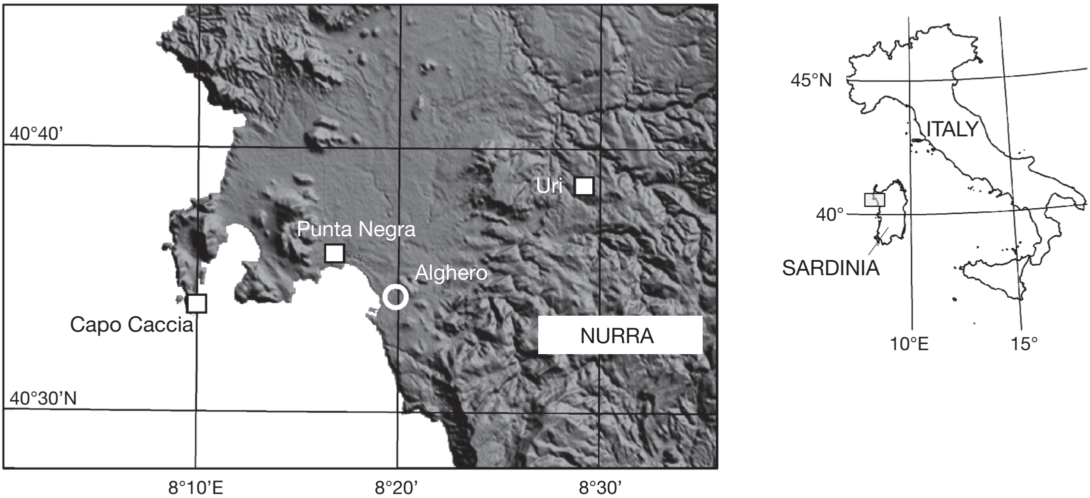

Fig. 1. — Location map of the outcrops investigated in the Nurra region (northwestern Sardinia, Italy).

drifting stage) then, after a major latest Jurassic-earliest Cretaceous regressive event, to Upper Berriasian-Lower Aptian shallow-water limestone (Chabrier & Fourcade 1975; Masse & Allemann 1982; Cherchi & Schroeder 1985; Cherchi *et al.* 2010). In the rapidly recovering Lower Cretaceous carbonate system, chlorozoan assemblages thrived with rudists, corals, larger foraminifera and calcareous green algae; along with abundant non-skeletal grain deposits. However, there were episodes of unhealthiness in the carbonate factory recorded by shallow-water limestone with an impoverished fauna or by foramol assemblages indicating mesotrophic conditions (e.g., Valanginian-Hauterivian limestone, see Simone & Carannante 2008). Albian-Cenomanian tectonic events, in connection with early eoalpine tectonics, caused a complex modelling of the rocky substrate with emersion-related karst-dissolution features and the development of mature palaeosoils with pockets of bauxite (see Pecorini 1965; Cherchi 1985; Cherchi *et al.* 2010; and references therein). This relative stability and a postulated shoreward advance of marine waters that raised hydrostatic pressures resulted in the development on the karstic surface of both fresh water ponds and lakes and brackish marshes (“internal transgression” *sensu* Carannante *et al.* 1994). However in a small area of northern Sardinia a conventional Late Cenomanian marine incursion took place on an eroded Triassic limestone surface, evinced by small erosional remnants in the Anglona area about 40 km east of Nurra (Cherchi & Schroeder 1976b). The remnants are shallow-water micritic limestones rich in larger foraminifera that are overlain by uppermost Turonian-Coniacian rudistid limestone (Philip *et al.* 1978). Finally, after repeated erosion events, an extensive carbonate system recovered once again in the latest Turonian. Regionally, widespread uppermost Turonian-Santonian marine carbonates crop out. In the evolution of the related shallow-water bioclastic facies an interesting example of the change in the mode of production is recorded by the development of peculiar coralline algal and rudist assemblages. (Carannante *et al.* 1995).

MATERIAL AND METHODS

The detailed study of the Coniacian-Santonian transgressive limestone first required a survey to find the most representative localities where the rhodalgal rudist-bearing limestone is best exposed as an aid in mapping the distribution of facies. In the localities selected, several strati-

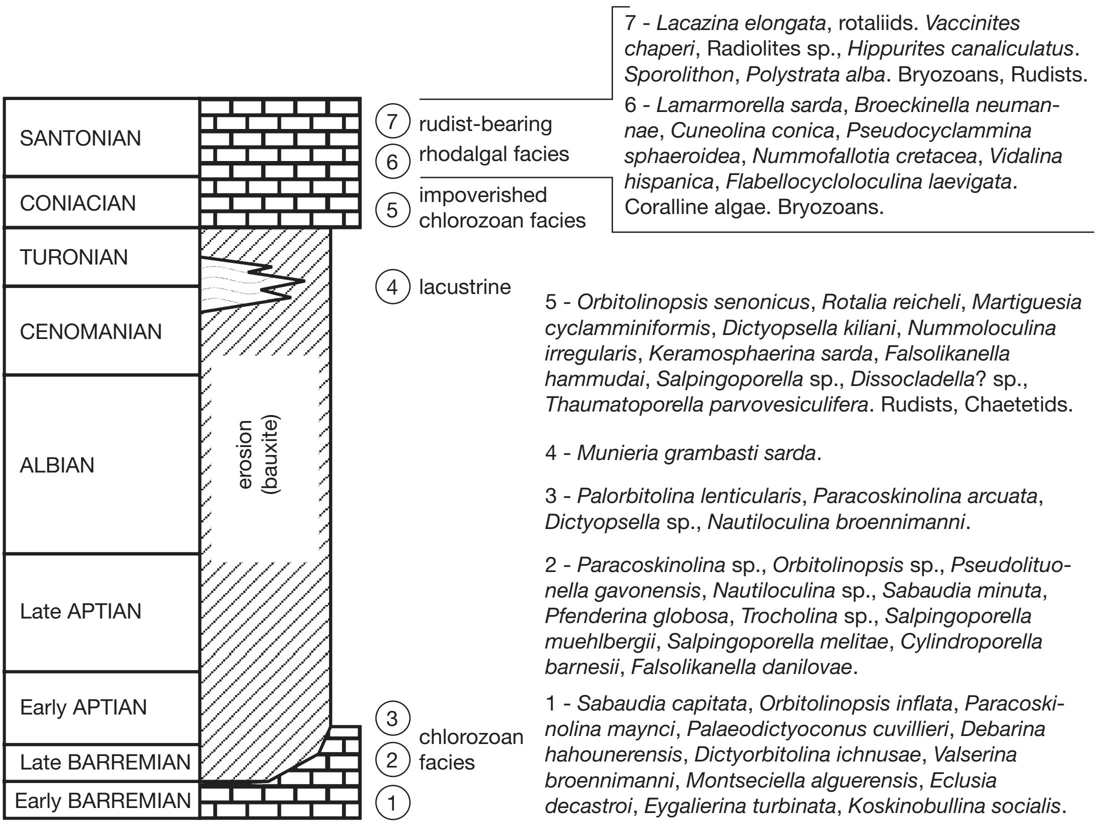

FIG. 2. — Capo Caccia section, Nurra region (northwestern Sardinia). Simplified stratigraphy showing the main biostratigraphic markers and the positions of the rhodalgal vs chlorozoan facies. Not to scale.

graphic sections were considered and studied with a combination of detailed field observations and sedimentological/palaeontological analyses. In particular, three sections were measured and sampled because of their significant, although not necessarily dominant, content of non-geniculate coralline red algae. Textures and sedimentary structures were analysed in the field on a cm/dm scale along with follow-up laboratory analyses by thin-sections (more than 500) and polished slabs. Most of the outcrops analysed had been previously studied from a biostratigraphic point of view (see Philip & Allemann 1982; Cherchi 1985; Cherchi *et al.* 2010, and references therein). Additional bio-stratigraphic analyses were carried out in this study, on the collected specimens and related thin sections.

THE NURRA RUDIST-BEARING RHODALGAL LIMESTONE

Preliminary sedimentological descriptions of the Nurra Upper Cretaceous stratigraphic succession had been published by Philip & Alleman (1982) and Cherchi (1985), and reconsidered for facies analysis by Carannante *et al.* (1995, 1997), Philip & Gari (2005) and Simone & Carannante (2008). The studied localities are located (Fig. 1): 1) on the Capo Caccia promontory (Capo Caccia section, F°192 IV S.E.-Capo Caccia-I.G.M.); 2) along the coast between the village of Fertilia and Punta Negra, north of the town of Alghero (Punta Negra section, F°192 I S.W.-Fertilia-I.G.M.); and 3) on the southern slope of Monte Miale Ispina, west of the village of Uri (Uri section, F°192 I N.E.-Olmedo-I.G.M.).

FIG. 3. — Capo Caccia section, Nurra region (northwestern Sardinia). Upper Cretaceous rudistid limestone (**Cr$_2$**) disconformably overlying the gentle karst surface of the pre-bauxite Lower Cretaceous limestone of the "Urgonian facies" (**Cr$_1$**). Bauxitiferous clay (**bx**) fill the fault-related karst network that cuts into the bedrock.

CAPO CACCIA SECTION

The Coniacian-Santonian rudist-bearing sequence, transgressive on a Lower Cretaceous calcareous bedrock (Fig. 2), is well exposed on the western side of the road to the Capo Caccia promontory (Figs 1; 3).

The pre-Coniacian substrate is massive, light beige to whitish bioclastic grainstone of the "Urgonian facies" with slightly opaque marine cement, that had been originally aragonitic. The biogenic components are corals, hydrozoans, chaetetids, pelecypods, echinoids, larger foraminifera (Orbitolinidae) and green algae which are particularly abundant ("chlorozoan assemblage" *sensu* Lees & Buller 1972). In the uppermost part of the interval, the matrix limestone may be silty. The dissolution of originally aragonitic shells and the occurrence of intra- and inter-granular clear calcitic cement is detectable. The rich and diversified microflora and microfauna of the uppermost 10 m suggests well oxygenated, open marine waters, Early Barremian in age (see Cherchi 1985; Cherchi *et al.* 2010; and references therein). Locally, lower Aptian limestone constitutes the pre-Coniacian substrate. A fracture network, with superimposed karst phenomena, cuts the "Urgonian limestone". Reduced, whitish to reddish, pellettiferous bauxite and angular Urgonian lithoclasts fill the karst cavities (Figs 3; 4A).

The overlying transgressive Upper Cretaceous limestone, sampled in continuity for about 50 m, begins with a discontinuous level of breccia (up to 1 m thick). The elements of this breccia are mainly blackish angular calcareous clasts and reworked bauxite fragments (Fig. 4B). The black fragments contain fresh-water gastropods, abundant charophytes (*Munieria grambasti* subsp. *sarda* Gušić) and/or thin-shelled miliolids. All these elements are embedded in a muddy-silty matrix with larger miliolids and *Dicyclina* sp.

Lateral variation in the basal transgressive deposits is shown in adjacent outcrops. Not far from the main sampled section but not in stratigraphic continuity due to repeated faulting ("Belvedere" area), the pre-Coniacian Urgonian substrate appears to have been bored locally by lithophagous bivalves. Only weak evidence of palaeosol-related deposits have been found. Reddish silty fillings of thin fracture networks are very rare, whereas a thick breccia interval marks the first few metres of the transgressive Coniacian rudist limestone. In the basal interval, blackish clasts (?Cenomanian-Turonian lacustrine or brackish limestone) are very common. They are found in association with Coniacian elements resulting from the reworking of early hardened shallow-water deposits containing scattered small individuals of radiolites such as *Biradiolites* cf. *angulosus* d'Orbigny and *Bournonia* sp. In contrast, black limestone, rich in fresh-water gastropods and charophytes (*Munieria grambasti* subsp. *sarda* Gušić), crops out along the sea coast (Punta del Frara), preserved in lens-shaped bodies, up to 7 m thick. This lacustrine-fresh water to brackish limestone overlies eroded, dolomitized Jurassic limestone (Bathonian in age) and on its bauxite cover. A Turonian age for the lacustrine-brackish *Munieria* limestone may be envisaged according to palynofloral data coming from carbonaceous clays present between Albian bauxite and Coniacian limestone in the eastern Nurra (Medus pers. comm. 1987). However, a latest Cenomanian age cannot be excluded. The *Munieria* limestone passes into Coniacian rudist limestone, through a bioeroded and fissured hard-ground.

In the Capo Caccia section, the Coniacian-Santonian stratified bioclastic limestone is grey to beige or blue-grey. In the first few metres of the section, constituted of muddy-silty wackestone/packstone rich in miliolids, impressive burrow systems cause the texture of the strata to appear to be nodular (pseudo-breccia). The pseudo-breccia nodules (intraclasts) are very similar in composition and texture to the embedding matrix; this can be interpreted as more or less developed firmgrounds with local evidence of early weak diagenetic processes (incipient hardgrounds). A *Durania* sp. biostrome follows: individuals in upright growth position, alternate with bioclastic sands locally rich in upper valves of rudists. Echinoids and chaetetids, benthic foraminifera, calcareous green algae, and rare corals as well as annelid tube fragments are present in the overlying muddy/silty beds (Fig. 5B, C). According to Philip *et al.* (1978), the basal portion of the Upper Cretaceous rudistid limestone overlying the emersion-related deposits, contains *Vaccinites giganteus* (d'Hombres-Firmas), *Vaccinites moulinsi* (d'Hombres-Firmas) and *Radiolites* cf. *sauvagesi* (d'Hombres-Firmas). Rudists and larger benthic foraminifera (see Fig. 2) indicate this limestone to be of Coniacian age (Pecorini 1965; Philip *et al.* 1978; Philip & Allemann 1982; Cherchi & Schroeder 2002; Cherchi *et al.* 2010).

Up section the rudist-rich limestone alternates with bioclastic floatstone/rudstones in which parautochthonous (near *situ*) rudist (radiolitids and small hippuritids) shells often remain articulated and occur together with large skeletal fragments in a coarse grainstone matrix. The resulting bioclastic bodies locally form flat lenses with sharp and erosive bases. In the overlying Coniacian beds a sharp change in lithofacies occurs: above a stratum of about 5 m of wackestone, grainstone and rare packstone with a silty matrix tend to predominate. Beds of well sorted, rounded and washed skeletal sand locally show cross lamination. Echinoids and benthic foraminifera (which include very large and thick-shelled miliolids) increase in occurrence in the overlying beds in which bryozoans and non-geniculate coralline red algae first appear, becoming dominant in the overlying limestone in which green algae and hermatypic corals totally disappear. The skeletal limestone, approximately 20 m above the base of the transgressive Upper Cretaceous rudist limestone, is Santonian in age (see Cherchi & Schroeder 1985).

The Santonian limestone consists mainly of locally cross laminated, bioclastic grainstone, alternating with silty packstone in which bryozoans (both Cyclostomata and Cheilostomata) and non-geniculate coralline algae (*Sporolithon* Heydrich) are characteristic components. In particular, non-geniculate coralline algae are present in quantity as algal debris in the biogenic sands that comprise the Santonian sedimentary succession but they also form small and scattered rhodoliths (Fig. 6A). These rhodoliths

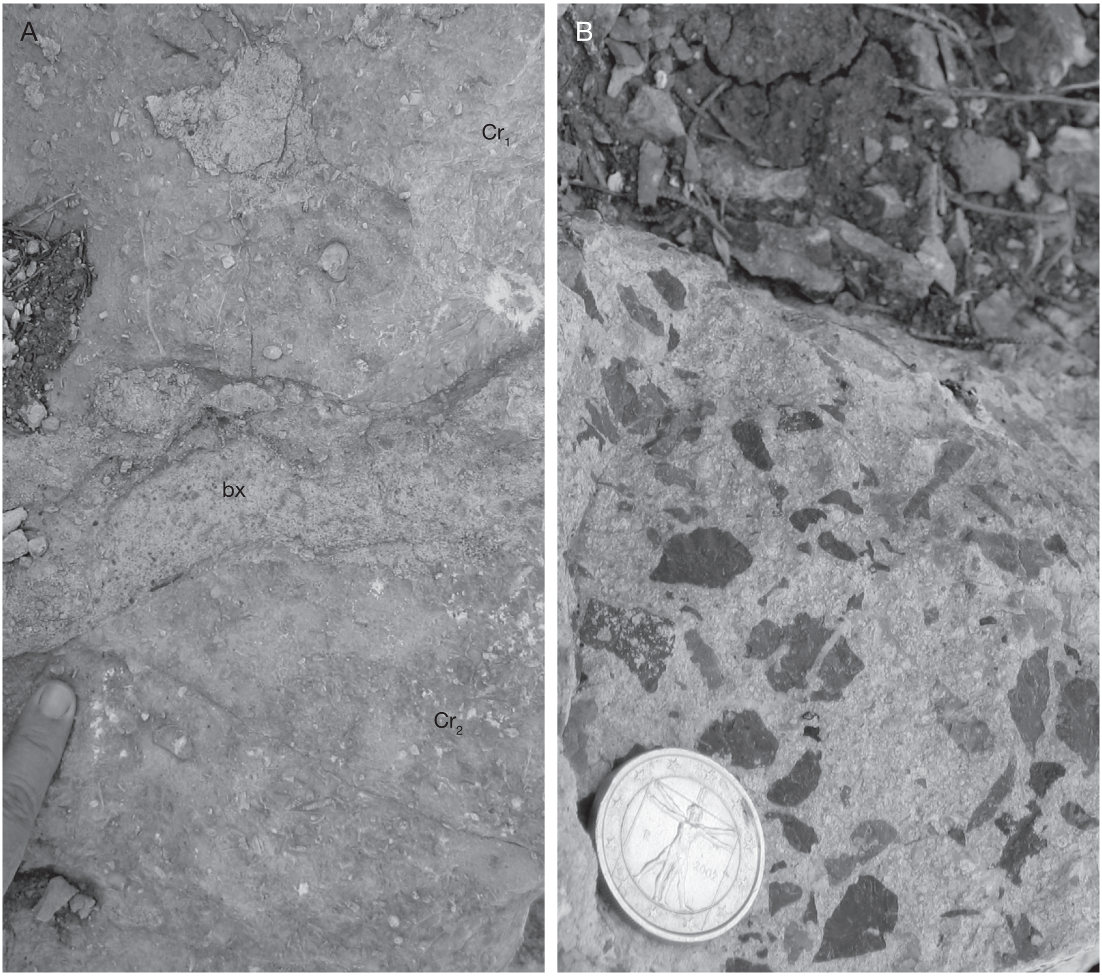

Fig. 4. — Capo Caccia section, Nurra region (northwestern Sardinia): **A**, reduced, whitish to reddish, pellettiferous bauxite (**bx**) filling the fracture network-related karst cavity system cutting into the Urgonian bedrock; **B**, ?Cenomanian-Turonian muddy black clasts with characean remains, fresh water ostracods and small clasts of bauxite from the first post-tectonic deposit above the bauxite lenses. These clasts fill surficial karst cavities.

are spherical/sub-spherical in shape, ranging in size from 1 to about 10 cm in mean diameter, and show mainly lumpy and fruticose outer growth-forms. Nuclei are often made up of small bryozoan colonies.

Levels containing large radiolitids and hippuritids occur, the fossils are embedded in a matrix of bioclastic grainstone (rudistid floatstone) or locally form impressive banks with well preserved *in situ* shells (“primary shell concentration” *sensu* Kidwell *et al.* 1986).

Depositional setting and related benthic assemblage

On the whole, the lower part of the limestone at Capo Caccia is muddy and silty and includes assemblages of rudists. At the base, the ubiquity of a complex network of burrows indicates a low energy environment in which the sea floor was essentially stable, a firmground subject to repeated bioturbation and local reworking. Higher in the succession sediments are mobile bioclastic blankets periodically subject to higher energy. Rudists are mainly elevator forms (*sensu* Gili *et al.* 1995a) dwelling in the soft substrate that only locally became site of intensive growth for rudists. In the maximum expression of this development, rudist (hippurites) banks grew without building true reefs (see Carannante *et al.* 1995 for details).

The main skeletal components of the bioclastic beds tend to change markedly throughout the Coniacian-Santonian section. An "impoverished chlorozoan facies" (*sensu* Carannante *et al.* 2008) prevails in the first Coniacian beds. The increase of filter-feeder bivalves, bryozoans and non-geniculate coralline red algae in the following Coniacian-Santonian transitional beds in which green algae and hermatypic corals totally disappear, clearly testimony to the expansion of the rhodalgal facies (*sensu* Carannante *et al.* 1988) that replaces chlorozoan forms and is dominant in Santonian strata (see Fig. 2).

Punta Negra section

North of Alghero at the Punta Negra promontory (Fig. 1), 60-70 m of Coniacian-Santonian bioclastic and bio-lithoclastic limestone lies on eroded Jurassic dolomitized limestone (Fig. 7).

The colour of this Upper Cretaceous stratified limestone is grey to beige. In the first few metres (about 8 m), intensive burrow traces produce a nodular texture. At the top of this interval a particularly strong burrowed level, rich in clay components, mimics a clastic texture (pseudobreccia layer) and passes to a thin marly layer (about 10 cm in thickness) with planktonic foraminifers. Above the Jurassic contact chaetetid colonies (*Blastochaetetes flabellum* Michelin), rudistid shells and fragments are common throughout, along with corals and mollusc and echinoid fragments as well as benthic foraminifera and calcareous green algae. At the upper limit of this interval a level of particularly strong burrowing (pseudobreccia layer), rich in clay, passes into a thin planktonic foraminifera-rich marly layer (about 10 cm thick). The assemblage of benthic foraminifera suggests a Coniacian age for this interval as well as for the overlying 12 m thick-bedded bioclastic limestone which also contains *Orbitolinopsis senonicus* Gendrot and *Keramospherina sarda* Cherchi & Schroeder (Cherchi & Schroeder 1985). This limestone grades upward from silt- supported wackestone to grainstone with rudist debris (that includes fragments of large shells of radiolitids), along with echinoids, chaetetids, sponge, benthic foraminifera, calcareous green algae, and rare coral fragments. Calcareous green algae become fewer and non-geniculate coralline red algae are present locally in the overlying Coniacian-Santonian transitional interval. Red algae dominate in the overlying coarse grainstone which passes upward into fine-grade Santonian grainstone containing abundant, well-differentiated benthic foraminifera that indicate a Santonian age (Fig. 7). On this Santonian grainstone is a 7 m graded breccia of calcareous lithoclasts derived from the erosion of the Coniacian substratum which had been disrupted by synsedmentary faults (Cherchi & Trémolières 1984). These lithoclasts are interspersed with mollusc shells and fragments**,** mainly rudists, and red algae (Fig. 5D, E), along with skeletal debris with intragranular green glauconitic infillings and fragments of reddish peloidal crusts. A thin marly level with planktonic foraminifera separates this graded breccia from a 2 m fine-grade breccia containing abundant non-geniculate coralline algae (*Sporolithon*), bryozoan, mollusc and echinoid fragments. In this interval non-geniculate coralline algae form small rhodoliths (Fig. 6b). The rhodoliths are spherical/sub-spherical, and range from 1 to 5 cm in mean diameter. Most of the outer growth forms of the rhodoliths are lumpy and fruticose. Commonly, their nuclei are made up of bryozoan colonies or rudistid fragments.

Upward in the succession are alternations of fairly coarse breccias and marly intervals were recognised. The sequence end with blackish marls and clays housing benthic and planktonic foraminifera and nannoplankton dated Santonian (Cherchi & Schroeder 1985). Among the planktonic tests are *Heterohelix reussi* (Cushman), *Archeoglobigerina blowi* Pessagno and whiteinellids. In the nannoplankton assemblage, *Lucianhorabdus cayeuxi* Deflandre occurs (Fig. 7).

Depositional setting and related benthic assemblages

In the first few metres of Punta Negra section, short deepening episodes are recorded. Presumably they

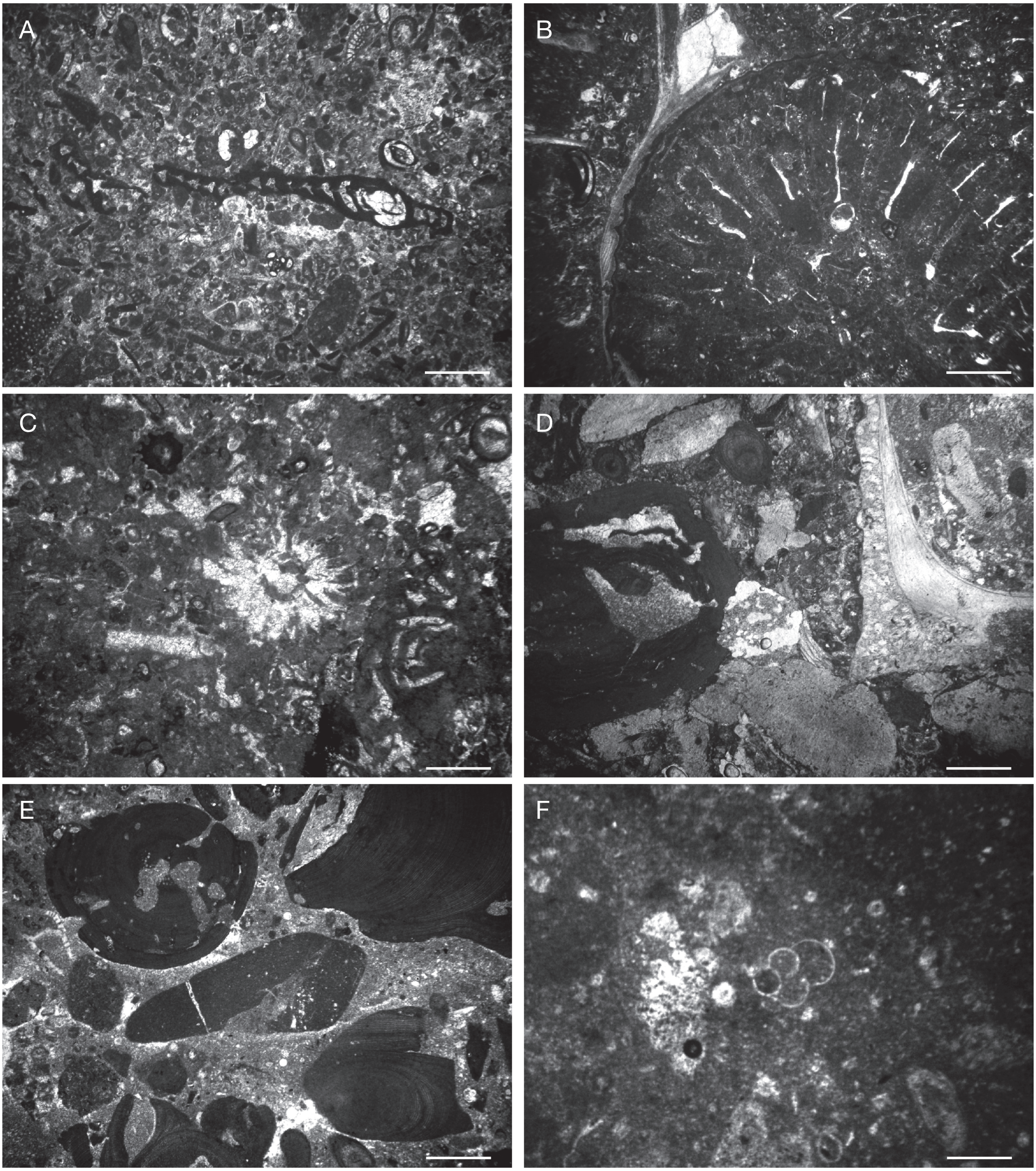

FIG. 5. — Nurra region, northwestern Sardinia: **A**, Capo Caccia section: Santonian fine-grade bioclastic grainstone with *Lamarmorella sarda* Cherchi & Schroeder, 1975; **B**, Capo Caccia section: coral fragment in the Coniacian rudistid limestone along with impoverished chlorozoan assemblages; **C**, Capo Caccia section: green algal fragment in the Coniacian rudistid limestone with impoverished chlorozoan assemblages; **D**, Punta Negra section: rudist and coralline algal debris in resedimented Santonian rhodalgal grainstone; **E**, Punta Negra section: silt-supported bioeroded coralline debris in resedimented Santonian rhodalgal limestone; **F**, Uri section: r-strategist planktonic foraminifera in reddish-pink marly re-sedimented deposits with abundant relict rhodalgal debris. Scale bars: A, C, 0.5 mm; B, D, E, 1 mm; F, 0.2 mm.

were linked to synsedimentary tectonic instability. Low energy regimes and sediment-starvation episodes resulted in impressive bioturbated banks rapidly evolving to hemipelagic marly deposits. These low energy episodes pass upward into higher energy deposits. However, subsequent tectonic activity induced repeated episodes of mass flow. The clasts of the breccias indicate their source was an unstable rocky limestone substrate swept by high-energy currents. Sciaphile assemblages of "rhodalgal facies" provided their skeletal fraction to this milieu.

The main skeletal components of the beds changed markedly as the Punta Negra Coniacian-Santonian succession was deposited. The first beds of Coniacian age laid down on a Jurassic substrate are considered to be "impoverished chlorozoan facies" (*sensu* Carannante *et al.* 2008) beds, in a rapidly drowning succession. An "impoverished chlorozoan facies" still characterizes the following limestone that shows a significant change at the Coniacian-Santonian transitional interval in which encrusting coralline algae and bryozoans first appear. Finally, non-geniculate coralline algae (*Sporolithon*) become more abundant, along with bivalve filter-feeders and bryozoans as relict rhodalgal skeletal debris. These rhodalgal skeletal elements are incorporated with the lithoclasts of the Santonian graded breccias that alternate with marly limestone and marls in the re-sedimented Santonian Punta Negra succession. Among the planktonic foraminifera tests, the abundance of *Heterohelix reussi* and whiteinellids suggest they have adopted r-strategy to dysaerobic conditions. Finally, the presence among the nannoplankton of *Lucianhorabdus cayeuxi* Deflandre suggests, according to Henriksson & Malmgren (1993), that the water was relatively shallow (not more than 300 m) and cold (9-11°C) thus suggesting a marginal outer shelf or distal ramp setting.

URI SECTION

The Upper Cretaceous limestone crops out in an abandoned quarry on the southern slope of Monte Miale Ispina (west of Uri village; Fig. 1). In the Uri section the Jurassic substrate (Tithonian) is made up of dolomitized oolitic grainstone grading upward to packstone and wackestone rich in green algae (*Salpingoporella annulata* Carozzi). Upper Cretaceous limestone lies unconformably on this surface. Such a basement is unconformably overlain by Upper Cretaceous limestone. In some places the Jurassic erosional surface was deeply bored by lithophagous bivalves. Locally, coarse rudstone containing Jurassic lithoclasts and large rudistid (mainly hippuritid) fragments and shells lies on this substrate. Upward the rudstone gives way to coarse, slightly graded grainstone with *Lamarmorella sarda* Cherchi & Schroeder. Nearby, Santonian bioclastic rudstone in a reddish-pink silty-marly matrix rests directly on the bioeroded Jurassic bedrock (Cherchi & Schroeder 1985). The reddish cover is particularly rich in non-geniculate coralline algae and contains abundant bryozoan colonies, rudistid fragments, echinoids, sponges and larger foraminifera, among which *Lamarmorella sarda*, *Broeckinella neumannae* Gendrot and *Flabellocyclolоculina laevigata* Gendrot (Poignant *et al.* 1982; Cherchi & Schroeder 1985) and *Lacazina elongata* Munier-Chalmas (Pecorini 1965). Small bauxite fragments as well as green glauconitic and brown phosphatic grains also occur in the reddish matrix.

The main skeletal components of the Santonian graded calcareous beds and of the reddish-pink marly deposits are bryozoans, molluscs (bivalve filter-feeders), benthic foraminifera and in particular non-geniculate coralline algae (Fig. 8). Planktonic foraminifera also occur: small tests of heterohelicids and whiteinellids (Fig. 5F). There are no calcareous green algae, z-corals and non skeletal grains.

The succession is capped by pink to red silty limestones and is terminated by an ignimbrite dated Oligocene-Early Miocene.

Coralline red algae are present both as fragments of fruticose plants and as small lumpy rhodoliths (Fig. 6C, D). These are mainly sub-spherical in shape and up to 10 cm in mean diameter. Nuclei are often bryozoan colonies. Poignant *et al.* (1982) identified ten species of coralline red algae including *Polystrata alba* (Pfender) and nine species of *Sporolithon*. Like some other 20th century authors, Poignant *et al.* (1982) used the invalid

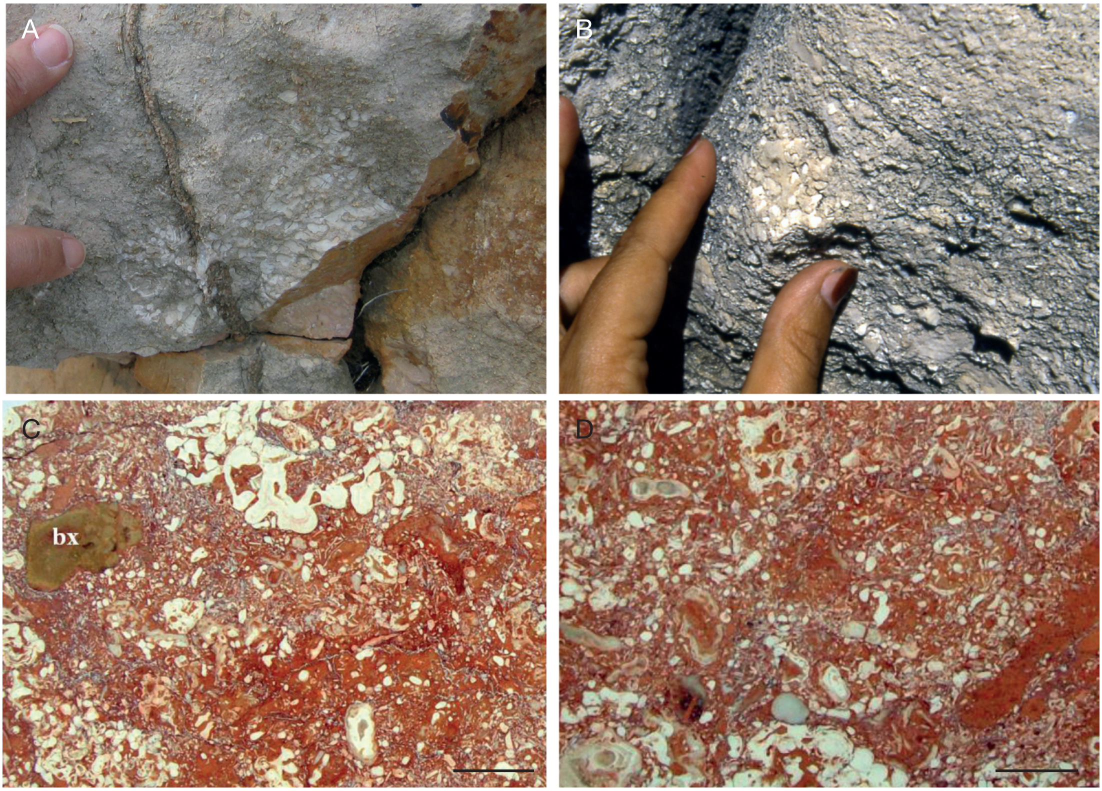

FIG. 6. — Nurra region, northwestern Sardinia; **A**, Capo Caccia section: small algal nodule in Santonian rudistid limestone with rhodalgal assemblages; the rhodolith is sub-spheroidal and shows lumpy and fruticose outer growths; **B**, Punta Negra section: small algal nodules in a gravity deposit of which the plankton-bearing matrix includes plankton. It also contains non-geniculate red algae and bryozoan fragments. The rhodolith is sub-spheroidal and shows lumpy and fruticose outer growths; **C**, **D**, Uri section: coralline algal debris with lumpy rhodoliths and fragments of fruticose corallines in reddish-pink marly resedimented deposits with bauxite fragments (**bx**), relict rhodalgal components and planktonic foraminifera. Scale bars: C, D, 2 cm.

name *Archaeolithothamnium* Rothpletz rather than the valid name *Sporolithon*, considering that the Rothpletz name was correctly published. Poignant *et al.* (1982) applied that name to all species in which sporangia were grouped in concentric rows (sori) rather than occurring in conceptacles. Iryu *et al.* (2009) provide additional information on *Sporolithon*, its heterotypic synonym *Archaeolithothamnion* Rothpletz *ex* Foslie, the invalid orthographic variant *Archaeolithothamnium* coined by Rothpletz (1891), the non-fossil genus *Heydrichia* Townsend *et al.*, and other fossil genera referable to the Sporolithaceae but requiring further assessment (see also Braga & Bassi 2007).

Depositional setting and related benthic assemblages

The state of neglect of the analyzed quarry and the related low quality of outcrops did not permit a valid reconstruction of the relationships between the several lithologies seen in the outcrops. Nevertheless, the graded litho- and bioclastic beds that include Jurassic lithotypes and a rich quantity of relict skeletal material suggest that in Santonian times, the Uri area was the site of re-sedimentation of both marginal and relatively deep deposits. Lithoclasts from the tectonically unstable rocky substrate, and the reworked relict skeletal debris of sciaphile (shadow preferring) assemblages of the rhodalgal facies favor this interpretation. Chlorozoan photophylous (light preferring) assemblages as well as non-skeletal grains are in fact totally absent.

EVOLUTION OF THE ENVIRONMENT ON THE NURRA CARBONATE SHELF

In the localities selected, Upper Cretaceous rudist-bearing rhodalgal lithofacies crop out in discrete palaeo-depositional settings ranging from autochthonous/parautochthonous shallow-water mobile skeletal covers ("faciès à pralines" of the "détritique côtier" Biocenosis of Pérès & Picard 1964) of the Capo Caccia promontory to the re-mobilized deposits in the tectonically-controlled settings of Punta Negra and Uri. According to Carannante *et al.* (1995), starting in Coniacian times a shallow sea encroached on the previously moderately accidented Nurra platform, the first step of a significant transgression. An earlier transgressive phase (?Cenomanian-Turonian) produced a rise of the water table into the network of karst cavities ("internal transgression" *sensu* Carannante *et al.* 1994) that gave rise to fresh-water, brackish and/or schizohaline pools). The Coniacian restoration of fully marine conditions is documented by the bioclastic content of the transgressive strata, rich in rudists, which covered large sectors of the shelf with their own detritus.

The lower part of the transgressive succession provides evidence of low energy, shallow, inner shelf environments where rudists grew locally, either isolated or in clusters. Z-corals and calcareous green algae which characterized the previous Lower Cretaceous systems, are present although rare in the Coniacian recovering factories ("impoverished chlorozoan assemblage" *sensu* Carannante *et al.* 2008). Upward in the succession, more open, deeper and dimly lit (lower photic zone) conditions prevailed in which coralline red algae and bryozoans become more and more abundant ("rhodalgal assemblage" *sensu* Carannante *et al.* 1988) in an environment that still supported rudist growth. Higher energy events are demonstrated by grainstones made up of clean, well rounded skeletal grains that are intercalated locally with bioclastic strata in which the bioclasts are frequently deeply bioeroded. As a whole, the transgressive Coniacian/Santonian succession shows that mobile bioclastic substrates were subjected to repeated high energy events (e.g., storm waves and currents). Locally, these substrates supported densely-packed rudist communities. Their shells and fragments contributed conspicuously to the bioclastic content of the sediments. Rudists grew as several superimposed generations. The rudist banks so formed did not make a rigid framework but produced primary shell concentrations *sensu* Kidwell *et al.* (1986) that are not true reefs (Carannante *et al.* 1995). Non-geniculate coralline red algae and bryozoans were the dominant biogenic components on these open shelves that lacked reefs, thriving in the middle-outer shelf areas from which high energy events moved them shoreward. During the Santonian, in some localities, the sea floor sank rapidly, presumably because of tectonic activity and the consequent instability of the rocky substrate. As a consequence, gravitational processes displaced the sediments, both lithoclasts and shallow-water skeletal debris rich in non-geniculate coralline algae and bryozoans (Punta Negra and Uri sections). The hemipelagic blackish deposits of Punta Negra and the reddish marls of Monte Miale Ispina in the Uri section, rich in shallow-water rhodalgal skeletal debris and in r-strategist planktonic foraminifera, are evidence of drowning episodes under meso-eutrophic conditions in some parts of the Nurra platform.

DISCUSSION

The presence of non-geniculate coralline red algae in association with rudists has been mentioned only rarely in the literature. Santonian strata including both rhodolith- and rudist-bearing successions have been described in detail from the Nurra region (northwestern Sardinia, Italy, Carannante *et al.* 1995) and from Provence (southeastern France, Philip & Gari 2005). Both areas are on the margin of the north Tethyan domain. In northeastern Spain, there are Santonian limestone in which a rich rudist fauna co-exists with corals, green algae, red algae and bryozoans (Gili *et al.* 1995b; Skelton *et al.* 1995; Pomar *et al.* 2005). Others associations of rudists and rhodoliths are reported in the Maastrichtian Simsima Formation of Oman ("*Dictyoptychus* facies", Skelton *et al.* 1990) and in the Lower Maastrichtian of Mexico (Götz & Mitchell 2009). In addition, red algal and rudist limestone has been described by Cherchi & Schroeder (1984) from northwestern Spain in Cenomanian successions on the European margin of the Atlantic Ocean.

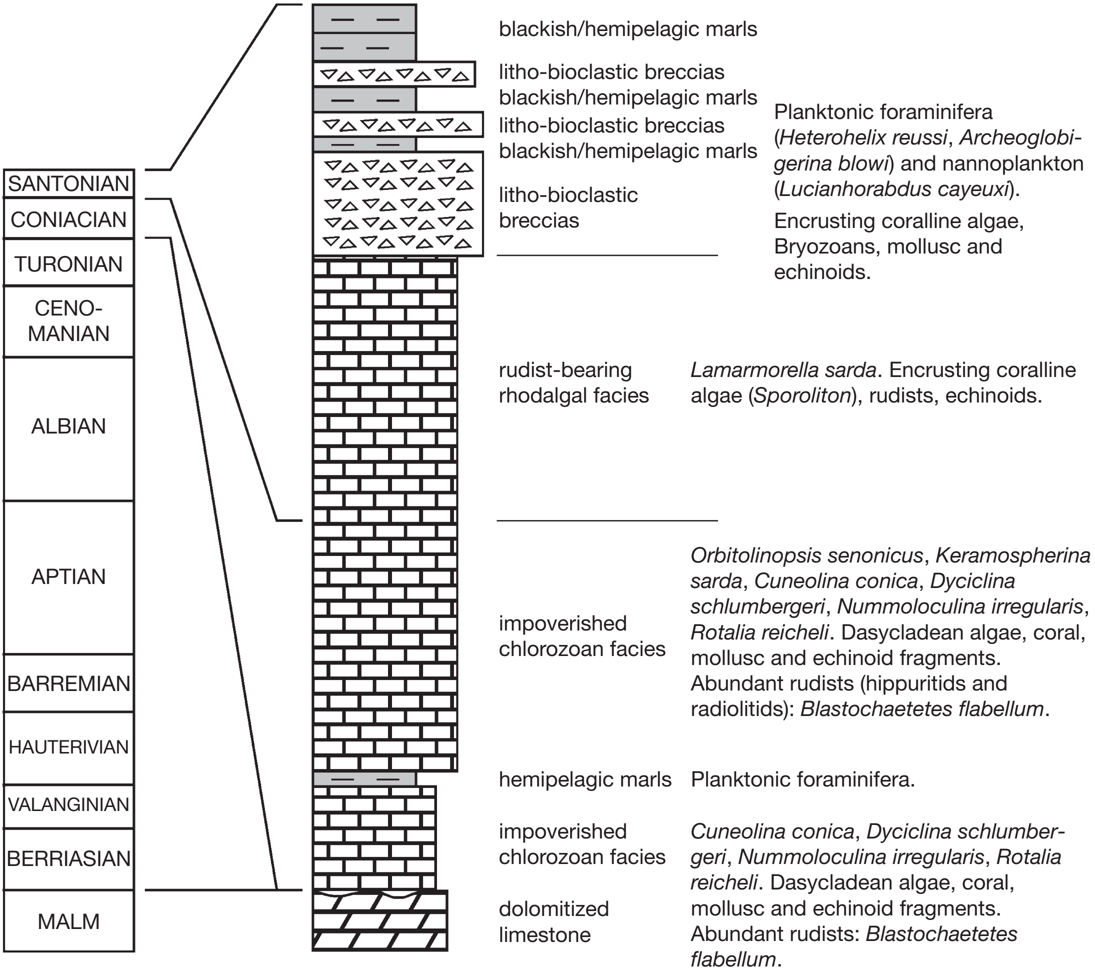

FIG. 7. — Punta Negra section, Nurra region (northwestern Sardinia). Simplified stratigraphic column with the main biostratigraphic markers and the location of the rhodalgal and chlorozoan facies. Not to scale.

However, the significance of the non-geniculate coralline and rudist association has been frequently underestimated or misinterpreted. Carannante & Simone (1987) and Carannante *et al.* (1995) correlated the inception of the Upper Cretaceous rudist-bearing rhodalgal carbonate factories of the Nurra region with stress conditions in the water mass that during the Coniacian-Santonian transition affected the pertinent carbonate system. The paper by Philip & Gari (2005) which deals with coeval red algal-bryozoan and rudist limestone from the Provence Platform area, briefly reconsiders the Coniacian-Santonian section at Nurra. They find only a limited and local mixing of heterozoan skeletal debris with rudist and coral fragments and describe a well-defined alternation of "heterozoan carbonate" (*sensu* James 1997) rich in red algae and bryozoan fragments ("rhodalgal facies" in this paper), with rudist-coral biostromal bodies considered as an expression of shallow, warm-water depositional settings ("photozoan carbonates" *sensu* James 1997). Philip & Gari (2005) consider the red algal and bryozoan lithofacies as indicative of a cool-water, deeper environment in accordance with the "heterozoan" definition by James (1997). According to Philip & Gari (2005), during the Coniacian transgression the availability of hard substrates was the major cause for the development of heterozoan associations, because a hard sea floor was considered unfavourable to the constratal soft-bottom dweller radiolititids and hippuritids (expression of "photozoan"). In their analysis of the Sardinian outcrops, Philip & Gari (2005) did not take into sufficient account the first transgressive interval on the rocky pre-Coniacian substrate; it shows corals and green algae along with rich radiolitid assemblages. In contrast, red algae, bryozoans and benthic foraminifers mainly characterize the overlying Santonian interval in which large rudist shells float in a rhodalgal skeletal, locally silty matrix or locally built banks. Although hard substrates are required for encrusting and for branched red algae and bryozoans to grow, their debris normally makes loose-mobile bioclastic covers (soft sediments of the "détritique côtier" Biocenosis *sensu* Pérès & Picard 1964) in recent sea bottoms. The "détritique côtier" sediments from the Mediterranean Sea, so well-described in the French literature (see Pérès & Picard 1964), are denominated as discrete facies on the basis of different biotic components. In particular, rhodoliths characterize the "faciès à pralines" (*sensu* Pérès & Picard 1964).These are dimly lit soft bottoms (oligophotic settings *sensu* Pomar 2001; Pomar & Hallock 2008). Similar bioclastic substrates have been the sites of rudistid dwelling in Santonian carbonate systems coeval with other peri-Tethyan shallow-water carbonate systems (e.g., southern Italy Cretaceous carbonate platforms pertaining to the middle, southern Tethyan belt) where radiolitites and hippurites contributed very largely to the carbonate factories. In the Upper Cretaceous limestone of southern Italy, rudistids provided up to 90% of the skeletal fraction with minor contributions from benthic foraminifera and echinoids and even less from bryozoa and non-geniculate coralline algae. It should be of particular interest to discriminate the ambient factors that were presumably responsible for the flourishing rudistid-rhodalgal facies in the shallow-water systems of the northern margin of the Tethys (e.g., Sardinia, Provence) from the ambient factors controlling the rudist-dominated facies along the western and northern shores of the Adriatic central-southern Tethyan domains (e.g., Apulia, Apennines). These latter areas did not develop a rhodalgal facies although deepening there was coeval (latest Turonian-Santonian) with that in Sardinia and southern France.

An on-going debate concerns the possibility that rudists hosted zooxanthellate algae (see Gili *et al.* 1995a). The ecological constraints of the rudists are still not defined but they are frequently referred to as photophilous assemblages (photozoan assemblage *sensu* James 1997) owing to their hypothetical but undocumented symbiosis with zooxanthellate algae. Rudists were bivalve filter-feeders with a variety of forms and an ubiquitous distribution on Cretaceous carbonate shelves that might be taken to indicate that they lived in many discrete shallow-water habitats each with its own temperature, nutrient content, salinity and oxygen level. Their coexistence with mesotrophic assemblages favoureded by a low intensity of light (foramol/rhodalgal assemblages) suggest an adaptability allowing them to thrive even in slight oligophotic settings where the supply of nutrients may be significantly (Carannante *et al.* 1997, 2008; see also Philip & Gari 2005). Although in existing seas non-geniculate coralline algae and bryozoans occur from the tropics to the polar areas, the related rhodalgal facies is found mainly in temperate/transitional areas where encrusting coralline algal and bryozoan assemblages thrive. The profile of the depositional surface and local hydrodynamic conditions as major factors controlling sedimentary facies (Carannante *et al.* 1988). In addition, shelves in the lower latitudes are more welcoming to rhodalgal assemblages when the ambient water is "anomalous" (e.g., upwelling of cold, nutrient-rich waters on the shelf marginal sectors, hyperproductivity by terrestrial runoff, cold currents and/or low light penetration due to increased terrigenous input). All these factors must be taken into account in any interpretation of the mega- and microfacies of the Cretaceous rudist and rhodalgal limestones of the lower latitudes where coralline algae are commonly accompanied by bivalve suspension-feeders (radiolitids and hippuritids), bryozoa and foraminifera. Among the benthic foraminifera, large thick-shelled miliolids when present suggest an increased nutrient supply (see Hallock 1985). Among the planktonic foraminifera of the Santonian hemipelagic marls of Punta Negra and Uri, opportunistic forms predominate and suggest mesotrophic to eutrophic conditions (Hallock

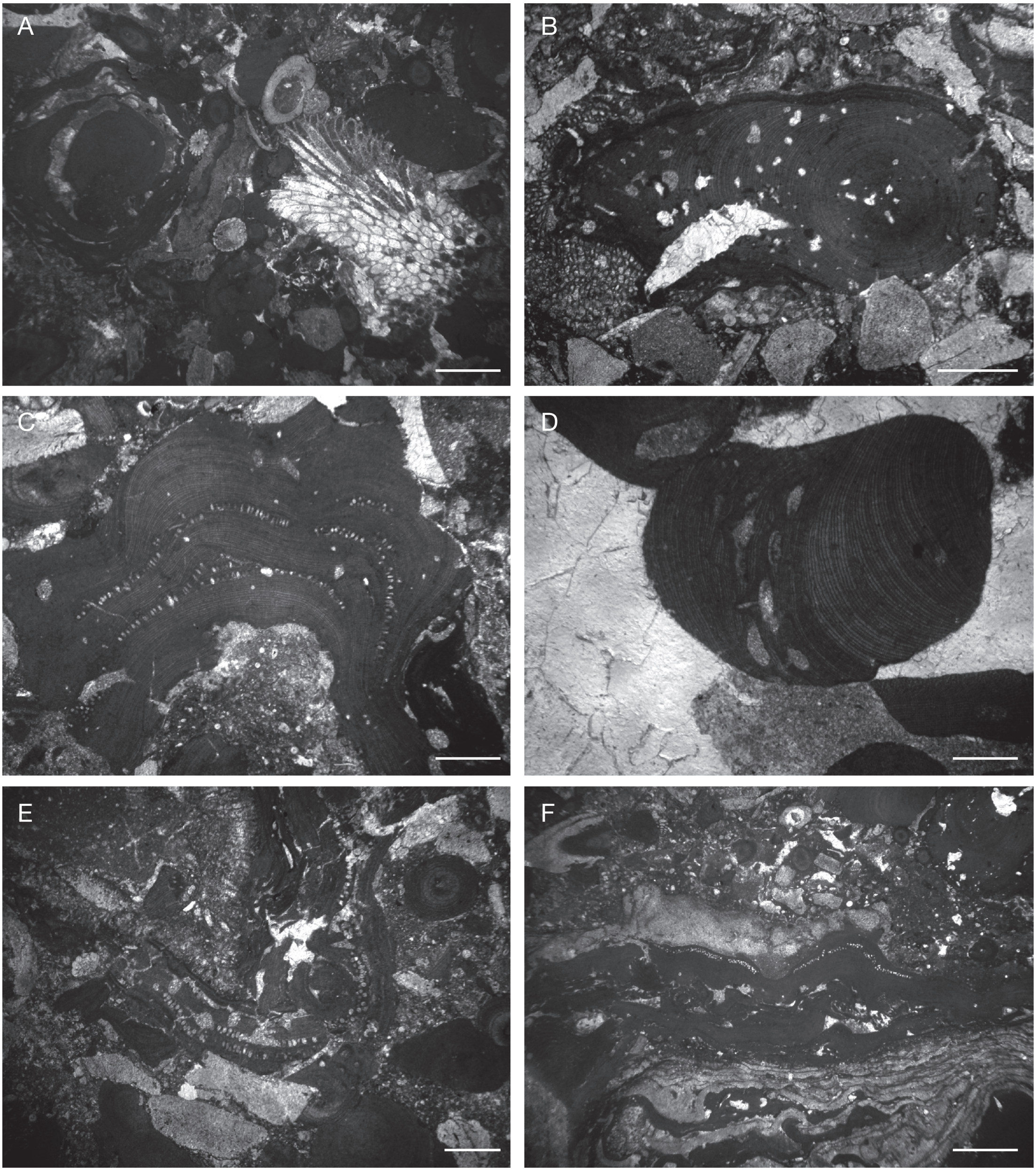

FIG. 8. — Uri section, Nurra region (northwestern Sardinia). Coralline algal debris and small rhodoliths in resedimented rhodalgal limestone rich in rudist fragments, bryozoans and planktonic foraminifera: **A**, **B**, non-geniculate coralline and bryozoan fragments; **C**, oblique transversal section of superimposed plants of *Sporolithon* Heydrich showing several sori; **D**, transverse section of an abraded fragment of an indeterminate non-geniculate alga; **E**, encrusting sequence of superimposed non-geniculate coralline algae and bryozans; **F**, several alternations of superimposed plants of *Polystrata alba* (Pfender) and indetermined non-geniculate corallines. Scale bars: A, B, 1 mm; C-F, 0.5 mm.

et al. 1991). In addition, r-strategist foraminifera characterize the Santonian pelagic wackestones in these and other Sardinian successions (Carannante *et al.* 1995; see also Dieni & Massari 1985). That the Cretaceous Sardinian platform was in an anomalous environment in a low latitude is consonant with the criteria mentioned above and is consisent with our interpretation of developments after the complex middle Cretaceous emersion events.

Although post-emersion conditions probably controlled the recovery and the following evolution of the Nurra carbonate factory (*via* terrestrial runoff, changed circulation with local upwelling, suitable substrates and/or complex local causes), a more general control cannot be ruled out. In Cenomanian-Turonian times climatic/oceanographic perturbations were world wide causing oceanic crises and marked declines in the output of shallow-water carbonate factories. Impoverished biotic assemblages with cyanobacterial consortia and variable contributions from rudists, largely prevailed in the shallow-water settings during the Early-Middle Turonian times when hyper-greenhouse conditions prevailed (Graziano *et al.* 2007). In this view, outcrops of uppermost Cenomanian shallow-water limestone (inner shelf muddy lithotypes) in the Anglona area (central-northern Sardinia) contain larger benthic foraminifera: *Cisalveolina fraasi* (Gümbel), *Chrysalidina gradata* d'Orbigny, *Pseudolituonella reicheli* Marie, *Pseudorhapydionina casertana* (De Castro), *Pseudorhapydionina dubia* (De Castro), among others (Cherchi & Schroeder 1976b). Some species appear to be not strictly dependent on symbionts (i.e. morphologically simple tests like *Chrysalidina gradata*, *Pseudorhapydionina dubia*, *Pseudolituonella reicheli*, see Parente *et al.* 2008). They may be r-strategist assemblages adapted to mesotrophic to mildly eutrophic conditions. These conditions presumably recurred several times during the Cenomanian, interacting with emergences caused by faulting. Excluding the fresh water blackish limestone of Punta del Frara, no Turonian sediments crop out in studied areas. The uppermost Turonian-Coniacian recovery of the Nurra carbonate factory begins with "impoverished chlorozoan assemblages" with subordinate corals. This might indicate improved environmental conditions related to a decrease in the severity of the thermal maximum of the Early-Middle Turonian (see Simone & Carannante 2008). Although modern hermatypic corals are commonly considered as light dependent, Aptian corals thriving in low-light and nutrient-rich waters have been described by Tomas *et al.* (2008). These Aptian corals show sheet-like and platy morphotypes and a low diversity; they are encrusted by coralline red algae and foraminifera or veneered by films of cyanobacteria. Microbialites together with other accessory forms (e.g., calcispheres, ostreid bivalves) suggest that this Aptian limestone was deposited under mesotrophic conditions. If so, how corals became adapted to that environment should be investigated thoroughly, but that topic is beyond the scope of the paper.

In the Nurra region, sciaphile and mesotrophic-adapted (rudist and rhodalgal) assemblages flourishing in shallow-water domains marked a shift toward foramol/rhodalgal depositional systems. A relative cooling trend and mesotrophic to eutrophic conditions presumably became dominant in the water mass impinging on the marginal sectors of the Nurra Santonian carbonate system (for details Carannante *et al.* 1995, 1997). This view is confirmed by the nannoplankton of the Punta Negra marls. Presumably, waters inimical to chlorozoan assemblages thus favoured rhodalgal assemblages and filter-feeder molluscs (rudists). The deterioration continuing, it reached a point beyond which it became harmful to rudist-rich rhodalgal assemblages causing the demise of large sectors of the Late Santonian Nurra carbonate factory. This latter underwent local drowning episodes in a depositional context controlled by tectonic activity.

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