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Late Cretaceous Foramol Carbonate factories of the Nurra region (North-western Sardinia, Italy)

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Rudist-bearing Cretaceous limestones cropping out in the Nurra region (northwestern Sardinia, Italy) document that, during the lower Senonian (Coniacian-Santonian interval), sediments characterized by assemblages dominated by molluscs, with variable amounts of red algae, bryozoa, echinoids, substitute sediments including hermatypic corals, green algae and variable amounts of non-skeletal grains (Carannante *et al*., 1995). These latter components were largely dominant in the previous carbonate-shelf contexts of the Nurra during the Jurassic-lower Cretaceous times, becoming less numerous until they disappear in the transgressive deposits that followed the tectonically inducted middle Cretaceous emersion phase.

On the whole, the Nurra rudist-bearing limestones show how, in the Late Cretaceous, a shallow sea encroached on the previously fairly deformed Nurra platform during a rapid and significant transgressive event following a tectonic-related mid-Cretaceous regressive event. During this latter, the basement in the Nurra region was widely exposed. A karst surface developed with complex morphologies, partially controlled by faults. The exposed lowland had a shallow relief where bauxite deposits accumulated over more deeply eroded sectors. Cenomanian?-Turonian brackish limestones rich in algaeremains ("*Munieria*" limestones) are the first post-tectonic sediments overlying bauxite and substratum limestones (Cherchi, 1985). They are preserved (Cherchi *et al*., 1981) in lens-shaped bodies exposed in limited outcrops (e.g. Punta del Frara locality) as well as in the clasts, rich in Charophyte oogonia and stems, occurring in the lagoon sediments that mark the first marine transgressive deposits (e.g. Capo Caccia, Olmedo localities). These lacustrine and marsh deposits (fresh, brackish and/or schizoaline pools) record, according to the model proposed by Carannante *et al*. (1994), the first transgressive phases and the consequent rise of the water table via the karst cavity system, followed by repeated and complex erosive events. Finally, the Coniacian restoring of definite marine conditions is documented by the bioclastic deposits, rich in rudists, that covered large sectors of the shelf with their own detritus.

The Senonian transgressive limestones may reach up to 140 m in thickness and are locally capped by Oligo-Miocene ignimbrites. The first interval (up to 20 m thick) of these rudist-bearing limestones is determined as Coniacian in age on the basis of rudist and foraminifer assemblages (Philip *et al*., 1978; Cherchi, 1985; Cherchi & Schroeder, 1987). In this interval a sharp change in the grain association occurs: in the first few meters benthic foraminifers (among which are large and thick-shelled miliolids), green algae (Dasycladaceae), echinoid, chaetetid and rudist fragments dominate along with a few corals. In the remaining Coniacian strata, the coralline red algae and the bryozoans became episodically present and, at times, very abundant. The subsequent Santonian limestones are made up essentially of bioclastic grains in which echinoid fragments and benthic foraminifers increase; bryozoans and red algae, which may form small rhodoliths, become dominant, whereas the green algae totally disappear. A complete list of the recognized species is given in Cherchi (1985). A decline in the mean aragonite-shelled bioclast producers may be noted (Carannante *et al.*, 1995). A parallel decline in the aragonite cements (*versus* the dominance of calcite cements) also characterizes these Senonian limestones (Ross, 1991). In the Santonian strata of some localities an upwards evolution to gravitative deposits rich in red algae and bryozoans and/or to planktonic-rich, dark and probably anoxic sediments may be observed.

Owing to their peculiar environmental significance (see Premoli Silva & Sliter, 1995; Henricksson & Malmgren, 1993) the occurrence among the planktonic forams of numerous heterohelicids and hedbergellids and among the calcareous nannoplankton of *Lucianhorabdus cayeuxi* Deflandre is worthy of mention (Cherchi, 1985).

LITOLOGY

A peculiar trend can be distinguished in the depositional features of these rudist limestones which, even though they present some lateral variations, are generally characterized by a vertical transition from:

a) bioclastic wackestones and packstones with benthonic foraminifers, molluscs (rudists), chetetids, some green algae and few corals in a pellet-rich, muddy and marly matrix, with a very limited contribution of non-skeletal grains passing to:

b) bioclastic grainstones, among which are:

b') fine bioclastic grainstones with benthic foraminifers, molluscs (rudists) and intraclasts. Some bryozoans and coralline red algae are detectable and seem to be associated with the reduction (or disappearance) of green algae and chaetetids.

b") bioclastic grainstones to rudstones (and subordinate packstones with silty matrix, with abundant coralline red algae, bryozoans, echinoids, molluscs and benthonic foraminifers.

Where unbroken rudist shells are abundant the following can be recognized:

c) rudist floatstones in a matrix of (a) or (b). The isolated rudists may be preserved in growth position, or fallen, but only barely reworked or not at all;

d) rudist rudstones/bafflestones in a matrix of (a) or (b). Rudists, clustered in growth position, are subordinate.

Locally, the above-described lithofacies may pass upward to:

e) litho-bioclastic rudstones (sometime graded breccias) with calcareous lithoclasts associated with coralline red algae, bryozoans, echinoids and green grains in a matrix of bioclastic packstones rich in benthic and planktonic foraminifers; locally a more abundant red-stained matrix with reworked bauxite grains is detectable;

or to:

f) bioclastic wackestones and packstones with planktonic foraminifers and calcareous nannoplancton.

The described sediments are essentially made up of skeletal debris in which the molluscs (rudists) assume a dominant role. Their fragments are intensely bioeroded and may show widespread micritization. Unbroken shells of rudists are only partially preserved in growth position. In some cases they may form clusters and bouquets. The superimposition of several clusters results in complex rudist accumulations which laterally grade into bioclastic sheets. Detailed observations of the growth pattern suggest the progressive colonization of loose sediment by dense monospecific congregations. No evidence of associated encrusting forms has been found. The relief on the surrounding surface was slight, limited to the last generation of individuals which had grown partially buried in the loose sediment ("constratal growth" *sensu* Gili *et al.*, 1995a, b). Coralline red algae and bryozoan fragments contribute significantly to the sediment. The former may form well-developed rhodolits (up to a few centimetres in diameter) which are associated with isolated rudists or mixed with lithoclasts of the substratum in gravitative deposits. Current- and storm-induced sedimentary structures (e.g. basal erosive surfaces, cross laminations) are common in the coarse grainstones (lithofacies b”) that locally mark the transition from lithofacies (a) to lithofacies (b’).

Depositional environment

According to Carannante *et al*. (1995, 1996), the Coniacian sediments of the lithofacies (a) give evidence of low energy, shallow, inner shelf environments where rudists grew locally, either isolated in the sediment (lithofacies c), or in clusters (lithofacies d). Within a few meters they pass up to the bioclastic grainstones of lithofacies (b), typical of more open, deeper and poorly lit marine conditions, still characterized by the growth of rudists both isolated (lithofacies c) and clustered (lithofacies d). As a whole these transgressive sediments affirm the development, in Coniacian-Santonian times, of a bioclastic sheet that covered the sea-floor, locally occupied by densely-packed rudist communities. The rudist communities, which contributed conspicuously to the bioclastic fraction, locally grew in several superimposed generations, subsequently colonizing increasingly larger areas. There is no evidence of any original significant difference in relief with respect to the surrounding sediment in which the rudists grew. No rigid frameworks characterized these rudist accumulations that did not develop true reefs.

A rapid deepening of the depositional setting locally occurred in Santonian times, leading to the deposition of hemipelagic (lithofacies f) and gravitative (lithofacies e) deposits. The source area of the resedimented deposits was represented by the faulted substratum (abundance of calcareous lithoclasts) supporting sciaphile communities typical of open shelf sea floors (reworked skeletal fraction).

The presence of very thick-shelled miliolids among the benthic forams which characterize lithofacies (a), but which are also present in the more open and high energy sediments of lithofacies (b), seems to document, according to Hallock & Schlager (1986) an increased nutrient supply in the waters. In addition, the opportunistic planktonic foraminifers (e.g. heterohelicids, hedbergellids) that characterize the Santonian pelagic fraction, seem to indicate, according to Premoli Silva & Sliter (1995), mesotrophic to nearly eutrophic conditions in the water whereas the occurrence among the nannoplankton of *Lucianhorabdus cayeuxi* Deflandre indicates, according to Henricksson & Malmgren (1993), relatively shallow (not more than 300 m) and cold (9°-11°C) conditions in marginal outermost shelf sectors or in distal ramps.

As a whole, the described Senonian lithofacies and the palaeoenvironments reconstructed on the basis of the facies analysis indicate a large and winnowed carbonate foramol open shelf passing upward (in the Santonian) to a more articulated shelf complex, characterized by relatively deeper and/or darker environments, where presumably cooler, nearly eutrophic conditions prevailed.

Discussion

On the whole, the Cretaceous succession in northwestern Sardinia shows a pronounced evolutionary trend. The substratum of the studied upper Cretaceous succession is formed by eroded pre-Urgonian dolomitized limestones and/or massive limestones of Urgonian facies which in their succession indicate the development of a carbonate platform supporting well developed chlorozoan-chloralgal assemblages and abundant non-skeletal grains. Sediments in which the green algae are still significant, chetetids and corals are sporadically present and non-skeletal grains are exceptionally found, characterize the first Senonian transgressive limestones. Later a gradual change in biological assemblages occurred. In the Coniacian deposits, characterized by chlorozoan/chloralgal associations, an increase in red algae and bryozoa and the disappearance of green algae and of non-skeletal grains corresponded to the strong predominance of the molluscs. Similar deposits, rhodalgal (*sensu* Carannante *et al*., 1988) on the basis of the characterizing presence of red algae (rhodophyta), result more generically ascribable to deposits of foramol *s.l.* (without the salinity value significance in Lees & Buller, 1972).The above variation could be consistent with a change, during the early Senonian, of the water parameters prabably linked to conditions of stress (e.g. inducted upwellings on the marginal sectors of the shelves, increased oceanic overturns, hyperproductivity due to terrestrial runoff on post-emersive transgressed substrata) in the waters impinging on the Nurra carbonate platform during the Coniacian-Santonian transition. There, the more opportunistic forms of the foramol assemblages might flourish, in depositional contexts considerably changed, with respect to the previous ones.

The changed environmental conditions, by controlling the biological assemblages (demise of the chlorozoan/chloralgal associations *versus* the spreading of the foramol *sensu lato* associations) and by preventing non-skeletal production, resulted in a substantial variation in the sediment components such as to give a foramol (temperate-type) carbonate factory. In this latter, as a response to the different producing communities, a different organization of the sediment developed. In this view, a depositional model for the upper Cretaceous rudist associated deposits can be found neither in the recent coralgal build-ups, nor in the classic tropical bioclastic bars and. These sediments correspond better to the modern foramol open shelf deposits in which scattered and limited organogenic concentrations, which only reach a low relief, are associated with bioclastic debris accumulated in a sheet of loose sediment The resulting temperate-type carbonate shelves were characterized by a low growth potentiality essentially due to a higher dispersion rate that could have facilitate their drowning.

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