

Oxfordian reef architecture of the La Manga Formation, Neuquén Basin, Mendoza Province, Argentina

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ABSTRACT

The Neuquén back-arc basin is located on the west margin of the South American platform between latitudes 36° and 40° S. The basin is famous for its continuous sedimentary record from the Late Triassic to Cenozoic comprising continental and marine clastic, carbonate, and evaporitic deposits up to 2.600 m in thickness.

The stratigraphical and paleontological studies of the outcrops of the La Manga Formation, Argentina, located near the Bardas Blancas region, Mendoza province (35° S and 69° O) allow the reconstruction of the sedimentary environments of an Oxfordian carbonate ramp, where outer ramp, middle ramp, inner ramp (oolitic shoal), inner ramp margin (patch reef) lagoon and paleokarst were differentiated. The reefs consist of back reef facies and *in situ* framework of coral boundstones that was formed at the top of shallowing-upward succession.

Coral reefs were analyzed by defining coral colonies shapes, paleontological content, coral diversity and taphonomy studies. In some studied sections abundant fragments of gryphaeids, encrusting bryozoans, and isolated sponges provided a suitable substrate for coral colonization; however, other sections show an increase in the proportions of ooids, peloidal and coral intraclasts.

The core reef facies is composed of white-grey unstratified and low diversity scleractinian coral limestone dominated by robust and thinly branching corals with cerioid–phocoid growths and massive coral colonies with meandroid–thamneroid growth forms.

The assemblage is characterized by *Actinastrea* sp., *Australoseris* sp., *Thamneria* sp. and *Garateastrea* sp. Internal facies organization and different types of coral colonies allow to recognize the development of varying framework as well as intercolony areas. A superstratal growth fabric characterizes the coral assemblage. On the basis of coral growth fabric (branche and domal types), the reef of La Manga Formation is considered a typical mixstones. The intercolony areas consist of biomicrites and biomicrorudites containing abundant coral fragments, parautochthonous gryphaeids and another bivalves (*Ctenostreon* sp.), gastropods (*Harpagodes* sp., *Natica* sp.), echinoderms test and spines (*Plegiocidaris* sp.), miliolids, *Cayeuxia* sp., *Acicularia* sp., *Salpingoporella* sp., intraclasts, ooids, peloids and coated grains.

The domal growth forms are probably more protected against biological and physical destruction, meanwhile delicate branching growth forms with very open and fragile framework were more affected and fragmented due to wave action and bioerosion.

The reef fabric shows different intervals of truncation as consequence of erosion resulting from coral destruction by storm waves or currents. The maximum flooding surface separates oolitic shoal facies below from the aggradational and progradational coralline limestones facies above. Subsequent sea-level fall and karstification (148 Ma) affected reef and oolitic facies.

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1. Introduction

The Neuquén Basin is a typical retro-arc foreland basin that developed to the east of the Principal Cordillera between 36° S and

39° S. It was developed at the west margin of South American platform and limited by a magmatic arc to the west and a tectonic foreland to the east. The foreland consisted of the Sierra Pintada belt to the northeast and the North Patagonia massif to the south (Fig. 1a).

Legarreta and Gulisano (1989) described four tectonic episodes of this basin development: 1 – rifting (Upper Triassic–Lower Jurassic), 2 – thermal subsidence (Lower Jurassic–Upper Cretaceous), 3 – subsidence due to magmatic arc and loading (Upper Cretaceous–Early Cenozoic) and 4 – Andean tectonism (Early Cenozoic–Early Quaternary). Much

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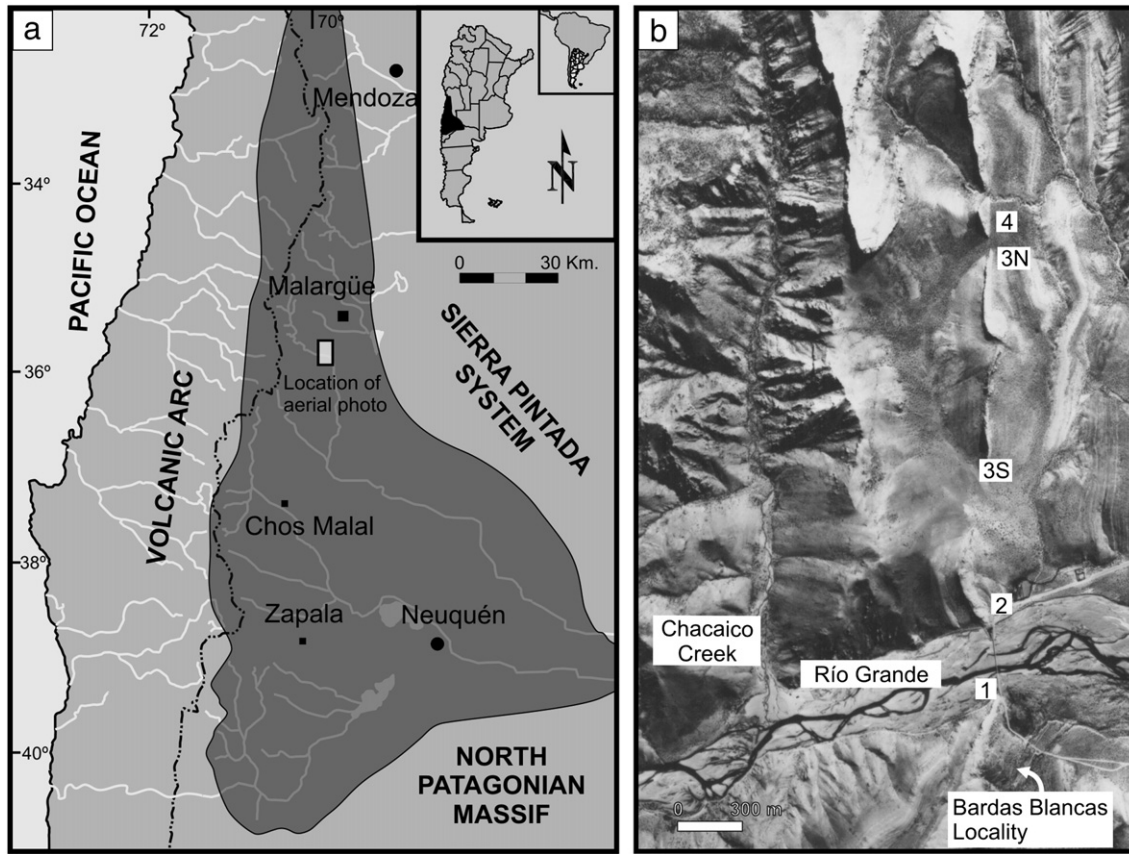


Fig. 1. a – Geological setting of the Neuquén Basin and the study area; b – Aerial photograph of the study outcrops (*barda 1 to barda 4*).

work has been conducted to regional knowledge of the Neuquén Basin (e.g. Legarreta and Gulisano, 1989; Legarreta et al., 1993; among others).

The most important papers describing the geologic setting of the region include those of Digregorio and Uliana (1980), Groeber (1946), Gulisano et al. (1984), Mitchum and Uliana (1985), and Stipanovic and Rodrigo (1970). However, little research has been focused on the carbonate units deposited in the basin.

The Jurassic sequences are part of the lower supersequence of Legarreta and Gulisano (1989) and include three mesosequences:

Precuyo, Cuyo and Lotena. The Lotena Mesosequence consists of five depositional sequences that include marine and continental facies (Lotena Formation), carbonate deposits (La Manga Formation), and evaporites (Auquilco Formation). The Lotena Mesosequence developed from middle Callovian to late Oxfordian–Kimmeridgian times (Fig. 2).

During the Oxfordian time, in the Neuquén Basin a widespread carbonate deposition resulted in a vertical and lateral mosaic of shallow-water facies, adjacent to deep-water, calcareous deposits,

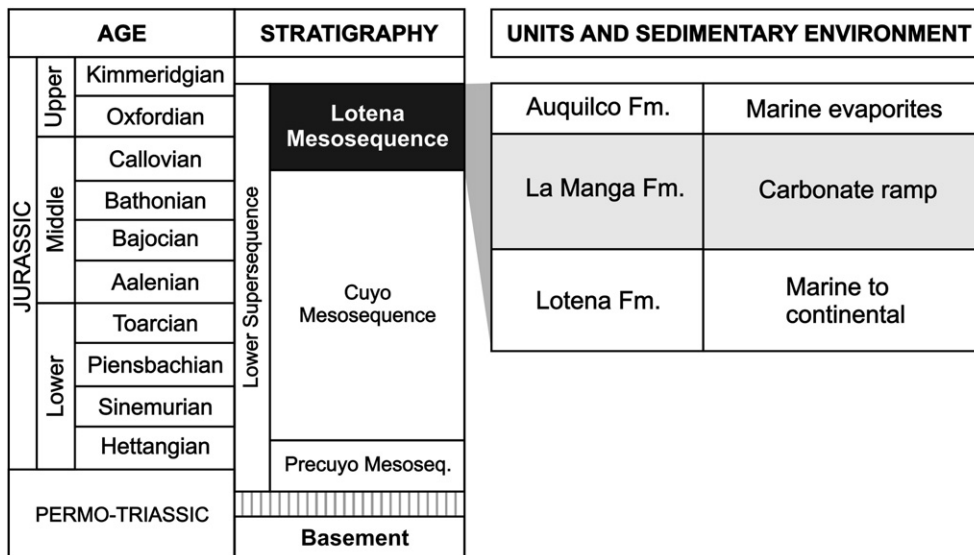


Fig. 2. Stratigraphic chart for the Lower Supersequence and Lotena Mesosequence, in the Neuquén Basin, Mendoza Province (modified from Legarreta and Uliana, 1991).

which are known as La Manga Formation, with recorded sea-level fluctuations and changes in the regional marine hydrographic regime (Palma et al., 2007).

Previous studies of the La Manga Formation have been focussed mainly on the lithostratigraphy, biostratigraphy and paleontology (Leanza, 1981; Riccardi, 1984; Groeber et al., 1953; Westerman, 1967; Westerman and Ricardi, 1984; Riccardi, 1992; Stipanovic, 1965, 1996, among others) and its sedimentological interpretation (Legarreta, 1991; Lo Forte and Palma, 2002; Palma et al., 1997, 2004, 2005), as well as on diagenetic aspects of the succession (Palma and Lo Forte, 1998; Palma et al., 1997).

During the Late Jurassic scleractinian corals flourished in the tropical and subtropical Tethys region (Stanley, 1998, 2001; Leinfelder, 1993; Leinfelder et al., 1994; Insalaco et al., 2007) meanwhile reefs in South America, specially in Argentina are poorly represented (Gerth, 1928; Matheos and Morsch, 1990; Morsch, 1990; Legarreta, 1991). Even though the middle Oxfordian sequence from La Manga Formation in South Mendoza province, has been the subject of several stratigraphic, sedimentological and palaeontological studies, the reef facies cropping out near Bardas Blancas area have received little attention (Legarreta, 1991). In fact, this publication did not give any details on coral fossil associations, and discussions on controls of fundamental importance that might operate in reefal environment. More recently, from outcrop studies, Palma et al. (2005, 2007) carried out detailed analyses of the facies and the reef distribution from these sections, that show remarkable differences in development of facies as well as in the content of coral associations. The reef succession in Bardas Blancas area is spectacularly exposed and provides an excellent opportunity to examine reef facies development that have not yet been studied in detail. Detailed information on sequence stratigraphy allows to recognized two phases of reef development: an initial aggradational phase following by a second aggradational–progradational phase (Palma et al., 2007). In fact, early publications on corals from the Upper Jurassic La Manga Formation have also been reported from other areas, but it is important to recognize that emphasis has been put only on taxonomy (Morsch, 1990).

In this paper, we describe details of reef architecture, spatial biotic diversity and interaction between sedimentation rate and palaeoecology of reef organisms. Particular attention is given to sedimentological conditions deduced from different coral growth forms, and taphonomic observations. Consequently, a new coral assemblage is recognized.

2. Geological setting

La Manga Formation (60 m) consists of peloidal–skeletal wackestones–packstones and oolitic packstones–grainstones with an abundant fauna of bivalves, echinoderms, corals, forams, and calcareous algae. These components are associated with a variable content of siliciclastic grains (Palma et al., 2007). In the Bardas Blancas studied area (Fig. 1b) the deposits of the La Manga Formation have been observed in four different *bardas* (or promontories, in the local tongue): *barda* 1 to 4, with *barda* 3 subdivided in north (3N) and south (3S) (Fig. 3). These deposits have been divided into six informal units (A to F) representing outer ramp (A), middle ramp (B), inner ramp–oolitic shoal (C), inner ramp margin (patch reef) (D), lagoon deposits (E), and a paleokarst surface (F) (Palma et al., 2007) (Fig. 3).

Unit A consists of greyish well-bedded wackestone–packstone rich in well preserved bivalve shells. Stratal geometry is tabular with beds up to 70 cm-thick (mean of 30 cm). Lithofacies association in the unit A was deposited in the outer ramp, below mean storm-weather wave base. Storm waves and/or current action were likely responsible for the reworking and transport of shells.

Unit B consists of greyish grainstone–packstones with local wackestones, and siltstones. Stratal geometry is subtabular with beds up to 40 cm-thick. In this unit different lithofacies have been recognized. They include parallel-laminated packstones, wave ripples peloidal wackestones, planar cross-stratified packstone–grainstones, massive packstone–grainstones, swally cross-stratified grainstone–packstones, hummocky cross-stratified grainstone–packstones, and siltstones. These deposits are interpreted as a typical coarsening

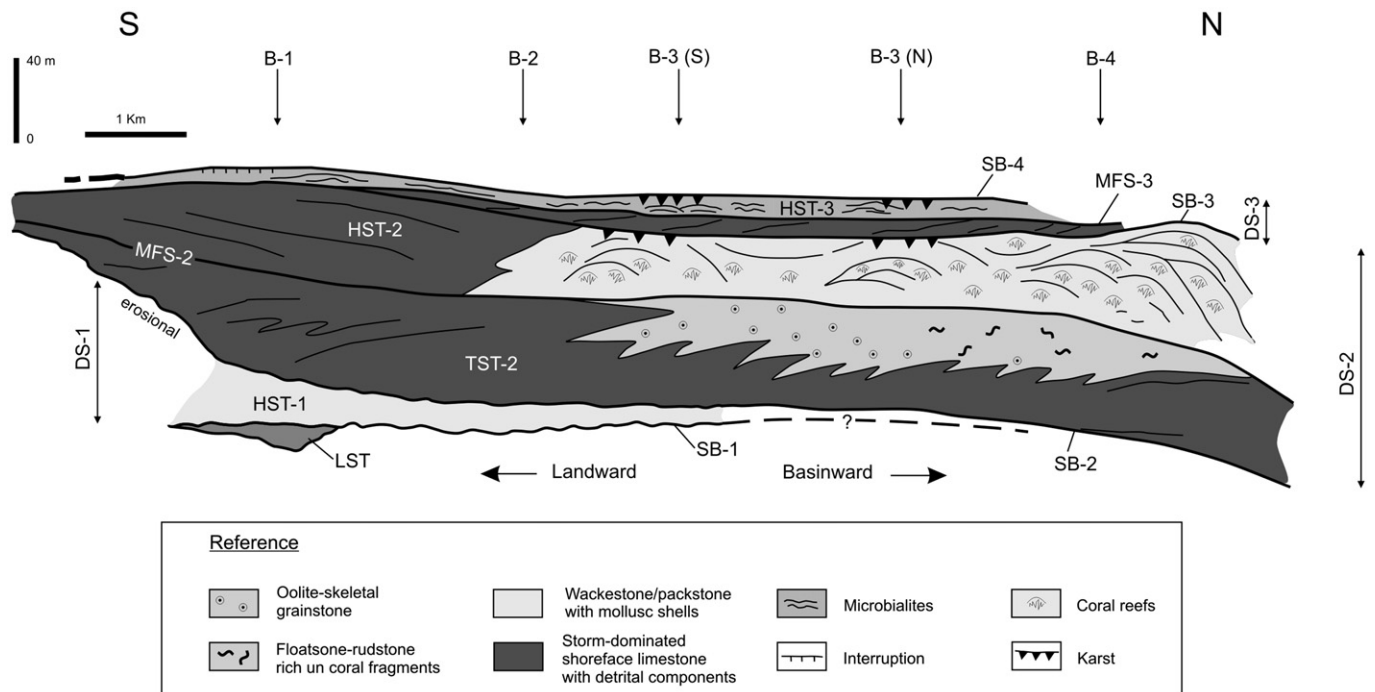


Fig. 3. Depositional sequences (DS-1, DS-2, DS-3), their systems tracts and general differentiated facies distribution in the studied area. B-1 to B-4 represent *barda* 1 to *barda* 4 (see Fig. 1b for their location) (modified from Palma et al., 2007).

upward sequence accumulated on a middle-ramp storm-dominated shoreface deposits.

Unit C is represented by light grey, generally well-sorted grainstone with locally subordinate packstone. Ooids, peloids, and coated grains are dominant. Skeletal fragments, usually moderately to well rounded, included echinoid spines, bivalves, gastropods and some corals. Intraclasts derived from the surrounding facies are also present in certain levels. Stratal geometry consists of thin to medium tabular beds. Sedimentary structures are represented by parallel lamination or tabular planar cross-stratification. Lithofacies and microfacies studies suggest a high energy and shallow-water depositional setting.

Unit D consists of reef core facies, fore and back reef facies. These are characterized by scleractinian community of relatively low generic diversity. The rich associated fauna is represented by bivalves, echinoids, serpulids, bryozoans, dasycladacean algae and cyanophytes, as well as forams and ostracods. The build-up occurs in the top of shallowing-upward succession and reaches a thickness of 18 m approximately.

Unit E consists of bioturbated wackestone, peloidal wackestone, bioclastic wackestone–packstone, oncoidal packstone, and floatstone/rudstone rich in bioclastic debris. Stratal geometry is tabular with beds up to 60 cm-thick, some of them laterally discontinuous. These facies contain a diverse fauna represented by gryphaeids, some another bivalves, echinoderms, bryozoan, forams and calcispheres, as well as green algae (dasycladacean), cyanobacteria (*Cayeuxia* sp.), and scleractinian corals forming isolated patch reefs. Lithofacies and microfacies studies suggest a shallow subtidal and intertidal environments, under intermittently agitated and episodically turbulent water.

Unit F is represented by a stratiform breccia with both matrix and clasts supported fabrics, with clasts derived from affected facies corresponding to Units C and D. The thickness of the breccia is variable ranging from a few centimeters up to 1.30 m. Breccia fabric is disorganized without clasts orientations, and does not show internal stratification. The breccia is related to a paleokarst surface. The episode of emergence and karstification is related to a sea-level fall and a stratigraphic break (148 Ma; Legarreta, 1991) which is represented throughout the area, from the Bardas Blancas section to the Sierra Azul outcrops, 60 km southward.

The units are included into three third-order depositional sequences (DS-1, DS-2, DS-3) mainly represented by transgressive and highstand systems tracts stages (Palma et al., 2007) (Fig. 3). The sequence boundaries are represented by important discontinuities that separate the depositional sequences and can be laterally followed tens of kilometres. These boundaries are separating different lithologic characteristics and also constitute the limits of different stratal geometries. The DS-1 shows an important erosive surfaces at its top and base and crops out only partially in the study area. DS-1 consists of greyish wackestone–packstones (Unit A) that only represents part of the HST of the whole sequence. This sequence reaches its maximum thickness in *barda* 1 being thinner progressively northward, in the *barda* 4, where it is difficult to differentiate. The base of this sequence consists of an erosive surface, SB-1, probably related to the intra-Callovia discontinuity (Legarreta, 1991; Legarreta and Uliana, 1996).

The DS-2 develops on SB-2. The process or processes that created this erosive surface still remain unclear. The beginning of DS-2 is characterized by a rapid sea-level rise and represented by Unit B. First sedimentation of this sequence develops on transgressive surface (Ts-1) by means of shoreface sandstones. These sediments are characterized by a clear retrogradation with the presence of small sponges and corals fragments as well as transgressive facies in the basinward area directly deposited on the Ts-1. Oolitic grainstones, floodstones and rudstones rich in coral fragments represented by Unit C constitute the upper part of the TST-1 in *barda* 3 and *barda* 4.

The ultimate deepening stage of DS-2 is represented by the maximum flooding surface 1 (Mfs-1). This surface separates Unit C below from Unit D above in the study area, except for the landward area (*barda* 1), where high sea-level period still preserve shoreface

facies from Unit B deposited both below and above the Mfs-1. This surface indicates the boundary between a transgressive unit or retrogradational set of Unit C and the lower part of Unit B and an overlying regressive unit or progradational set represented by Unit D and the upper part of Unit B.

The transgressive and later HST-2 reestablished carbonate production over the shelf area (*barda* 3 and *barda* 4). Highstand progradation in the study area brought shoreface facies from Unit B to a position approximately 2 km shelfward of the underlying TST-1. The new shelf scenario dominated by carbonate bank shows aggradational characteristics during the first stages of the deposition of Unit D, while in a second stage of the HST-2 shelf change in character marginwards to aggradational–progradational characteristics. This new situation could be related to the response of the organisms from reef facies of Unit D to the opening of new living space once population growth is limited by the rate of growth in living space. Development of a paleokarst (Unit E) at the top of Unit D marks the upper part of DS-2 and the beginning of the DS-3.

The DS-3 starts on SB-3, a boundary representing the flooding surface between the HST-2 and the overlying TST-2 of the new DS-3. This surface is type 3 sequence boundary from Schlager (1999) and well developed on the drowned reef of *barda* 3 and *barda* 4. This new highstand–transgressive system tracts (HST-2–TST-2) boundary indicates again a major stratigraphic turning point and a new level of reorganization of the sedimentation pattern related to the drowning of the carbonate platform and the subsequent continental influence (Palma et al., 2007). After deposition of DS-3, the Neuquén Basin experienced a drastic change in deposition. A thick pile of evaporites (Auquilco Formation) (Fig. 2) covered the basin. This new basin configuration could result from extensional stress fields related to fragmentation of southwestern Gondwana and the Atlantic opening (Vergani et al., 1995).

The HST-2 of the La Manga Formation shows evidence of flourishing coral growth (Palma et al., 2007), thus offering the opportunity to investigate the framework and study the internal composition and successions. On the basis of several perisphinctid ammonites found in the region (Palma and Kietzmann, 2008; Palma et al., 2007), the age of the La Manga Formation is middle Oxfordian (Riccardi, pers.comun.).

The study area is located 63 km south of Malargüe city, in southern Mendoza province, western Argentina, a few kilometres northwest of the village of Bardas Blancas (Fig. 1b). Detailed facies and microfacies studies of the La Manga Formation were carried out in particular sites located immediately in the *bardas* 1, 2, 3, and 4 of Palma et al. (2007), although a similar trend in facies evolution was also recognized in the nearby Coihueco Creek succession, 45 km to the south of the Bardas Blancas locality (Palma et al., 2005).

3. Materials and methods

Facies analysis were carried out through the study of different stratigraphic sections that crop out across the *bardas* 1, 2, 3, and 4 (Fig. 1b). Excellent outcrop conditions across a km-scaled profile allow the study of lateral and vertical facies variations. The reef coral structure was documented by different transects on the reef framework (Fig. 4) according to the methodology of Weidlich et al. (1993). Detailed measuring in the field was followed by both taphonomic observations and thin-sectioning of the corals. During this work, sedimentologic characteristics of the intercolony areas, and coral types (massive or branching) were measured in order to estimate the relative importance of the reef builders and the framework density, as well as to identify the growth fabric, according to the recent terminology proposed by Insalaco (1998). Detailed field investigations on the reef framework were carried out taking into account observations of sedimentation rate and energy level. Reef and associated macrofauna were recorded; neither state of preservation

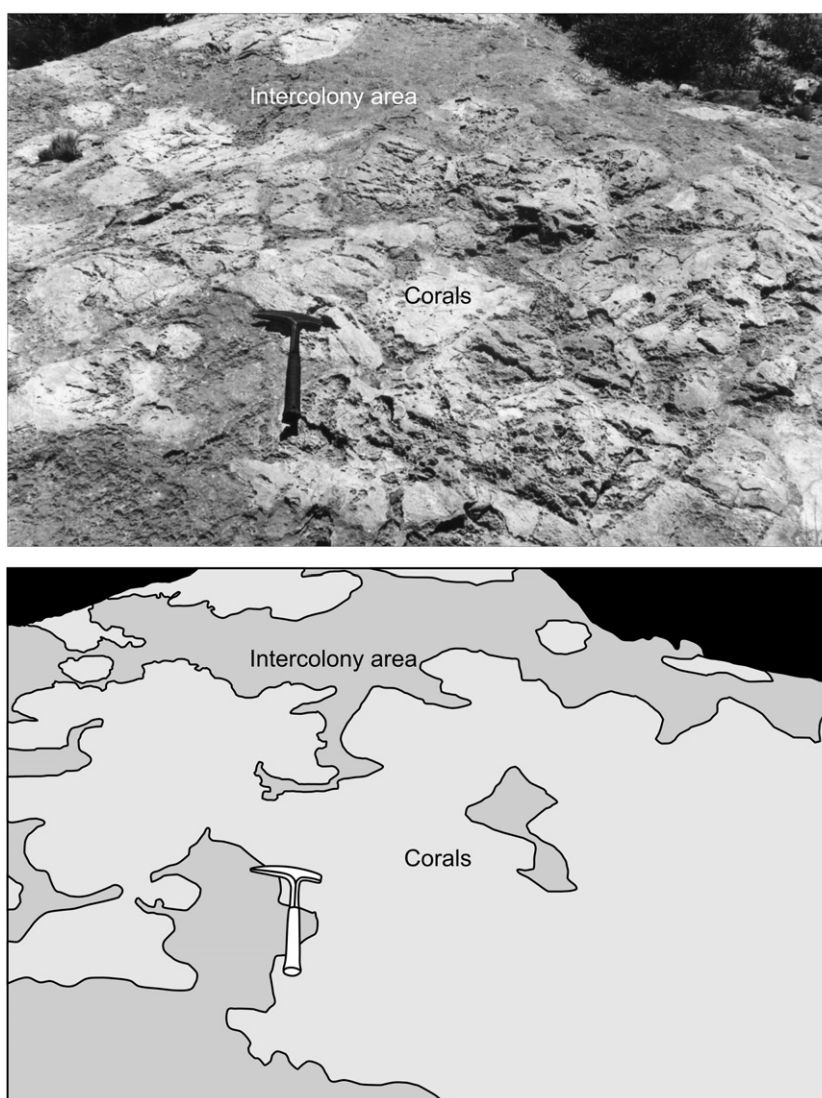


Fig. 4. Photograph and tracing of outcrop surface at *barda 4* locality showing distribution of coral framework and intercolony areas.

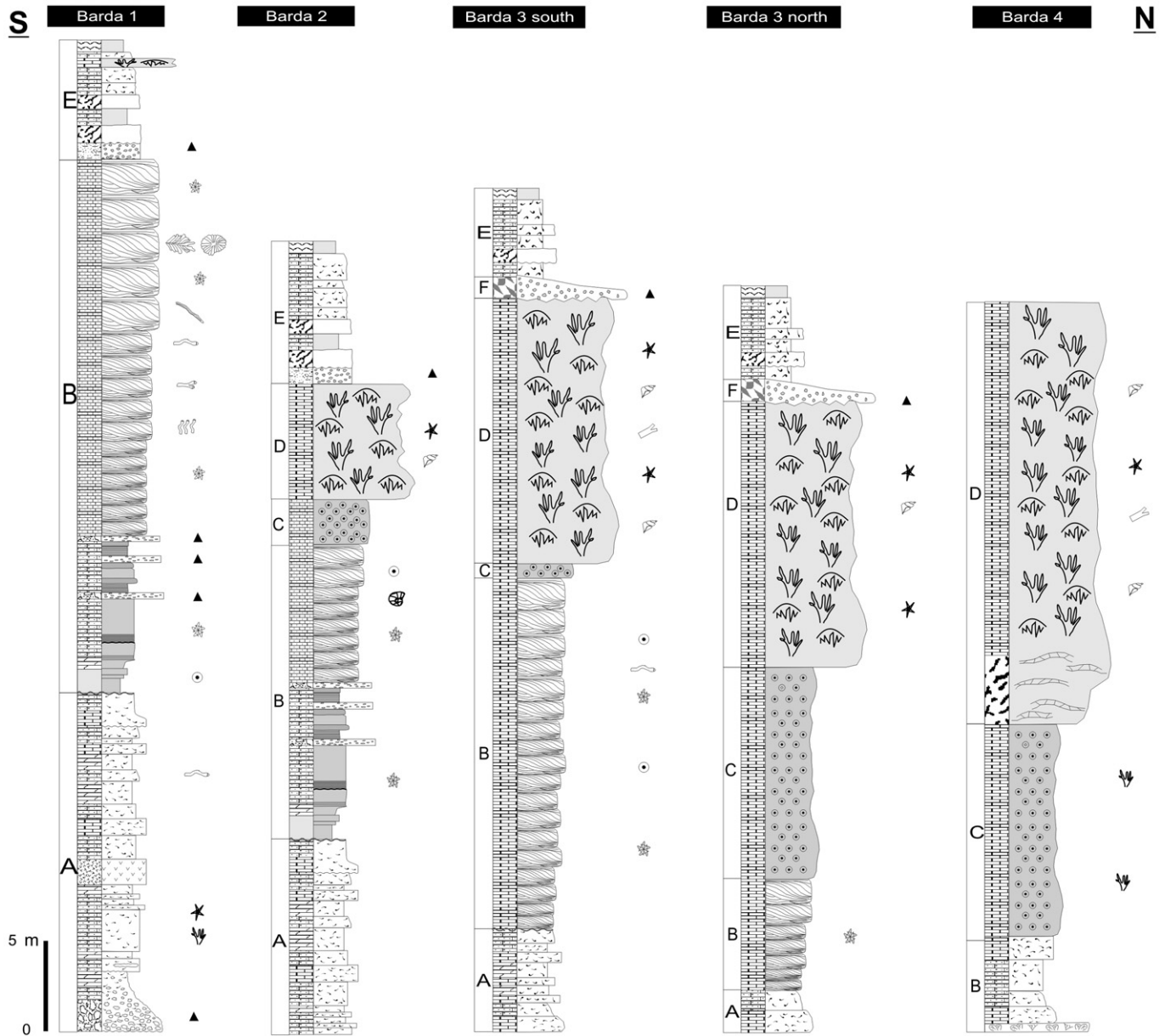
and abundance, as well as additional material was collected from loose rubble in order to increase the number of specimens available for taxonomic identification. The relative importance of reef builders was visually estimated in outcrop sections.

4. Reef facies

Reefs in the depositional sequence DS-2 of the La Manga Formation outcrop from the village of Bardas Blancas (*barda 1*), in the south, to just beyond *Portal de Barda (barda 4)* in the north (Fig. 1b). *In situ* reef development occurs in small-localized patches throughout the sections. The reef patches tend to be domal in form, of relatively small size, approximately 18 m high and 20 m across, and dominated by branching and dome-shaped corals. This facies consists of *in situ* reef framework coral mixstones that occur along the inner ramp margin (Palma et al., 2007). This core reef facies is composed of a white unstratified coral limestone dominated by branching and domal coral in growth position. The size of the branching colonies varies between 10 to 80 cm in height, with massive or domed shape colonies reaching between 15 and 20 cm across and 8 cm in high. The build-up formed on the top of shallowing-upward succession and reaches a thickness of 18 m approximately. New studies made up in different

sedimentary sections (Fig. 5) reveal that the coral fauna characterize similar biotic conditions.

The base of the reef structure is formed by a substratum of densely packed gryphaeids (Fig. 6a) which attains a maximum thickness of 20 cm in the *bardas 1* and 2. Overlying the fragmented gryphaeids substrate, the basal part of the reef shows a combination of thin branching and massive coral-growth forms. These colony shapes, allow to bind and stabilize the substratum and show sheet-like to gently domal shapes. Observations made in other places (*bardas 3* and 4) allow an interpretation that the coral framework started on oolitic shoal (Fig. 6b). During the initiation and early stages of reef growth, the lateral transition from the oolitic shoal (Fig. 6c) to *in situ* reef is sharp to gradational. From a biological point of view, the main body of the coral reef structure of the La Manga Formation is composed of *Actinastraea* sp. and *Australoseris* sp. (Morsch, 1990, 1996; Palma et al., 2007). The reef structure exhibits two corallum growth forms: ramose and massive respectively. New data on the coral fauna assemblage allow to recognized that the level of integration within colonies is shown by ceriod/thamnasteroid forms which shows the degree of soft tissue continuity between individuals in the colony, although processes such as dissolution, recrystallization, and replacement by silica sometimes prevent taxonomic identification. Nevertheless some corals show typical characteristics



References

- | | | |
|-----------------|--------------------------------|----------------------------------|
| Grainstone | Microbialite & sponges | <i>Dactyloidites ottoi</i> |
| Packstone | Ammonite | <i>Damesonichnites beinberge</i> |
| Wackestone | Bryozoan | <i>Skolitus isp.</i> |
| Mudstone | Gastropod | Ooid |
| Conglomerate | Echinoids spines and sclerites | Siliciclastic material |
| Stromatolites | Gryphaea | Anelids |
| Float/ Rudstone | Corals | Intraclast |
| Andesite | <i>Thalassinoides isp.</i> | Peloid |
| Breccia | <i>Gyrochorte isp.</i> | |

Fig. 5. Oxfordian general stratigraphic succession of the studied localities (barda 1 to barda 4) (modified from Palma et al., 2007).

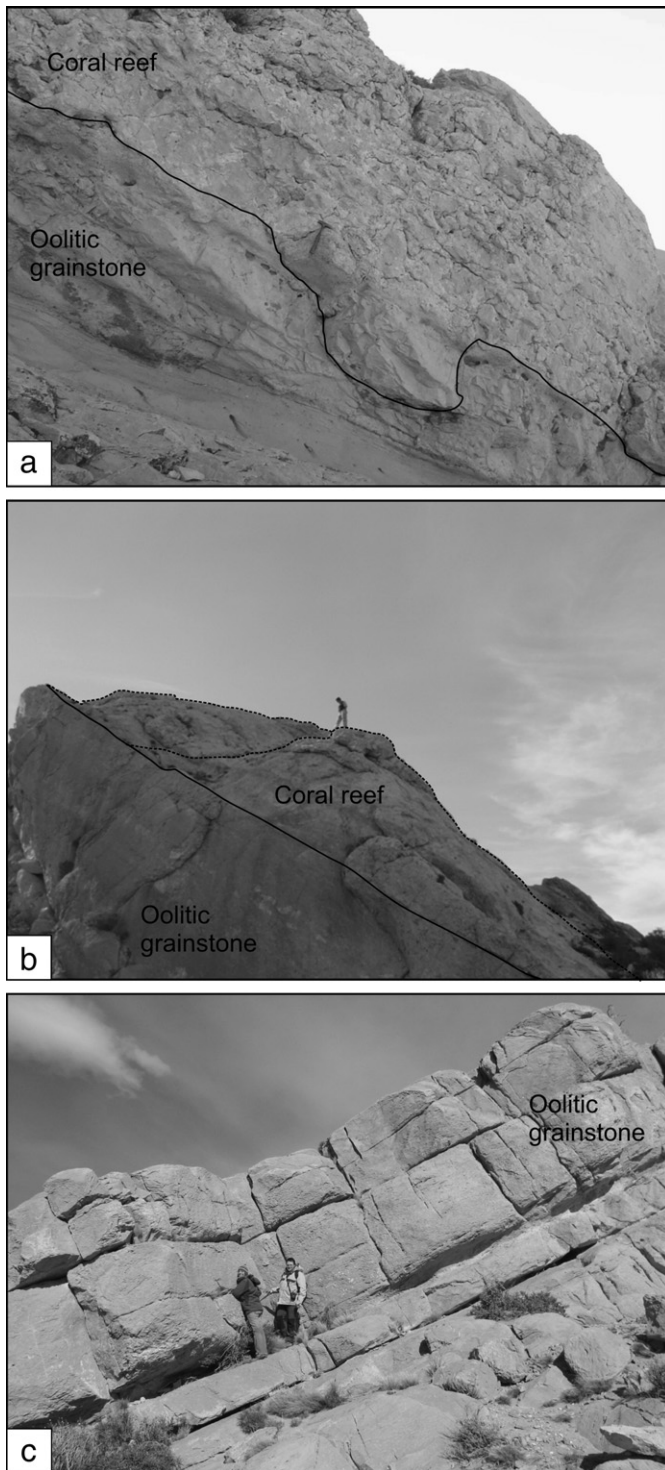


Fig. 6. a – The initial phase of coral growth on grypheid shell fragments substrate at *barda 2* locality; b – Panorama of the Oxfordian reef exposed at *barda 4* locality. The initial phase of corals growth on oolitic grainstone substrate.; c – Aspects of cross-stratified oolitic shoal substrate at *barda 4* locality.

that resemble those of the ramose *Actinastraea* sp. (Fig. 7a,b). These are a colonial corallum, cerioid, ramose to incrusting, non costate with prismatic and closely packed coralites, calices (CD: 0.8–1.2 mm) monocentric and with septa typically 12 in number arranged in two cycles (Filikorn et al., 2005). Other corals resemble *Thamnasteria* sp. (Fig. 7c). This colonial corallum exhibits ramose growth forms with corallite centers closely united by confluent septocostate (Wells,

1956). On the basis of a cerioid and massive corallum colonial with calices mono (DC: 8–10 mm) or polycentriques and 64–74 septa can be assigned to *Garateastrea* sp. (Fig. 7d). Although some morphological features are not visible, the preserved features of the specimens studied are most similar to those described for *Thamnasteria* sp. These specimens resemble those found in the Lajas Formation (Neuquén Basin, Bajocian) in central west Argentina described by Morsch (1996). Finally, massive thamnastero-meandroid growth forms resemble *Australoseris* sp. (Fig. 7e).

The corals exhibit a wide range of specializations as demonstrated by their range of skeletal structures. The branching ramose coral forms such as *Actinastraea* sp. and *Thamnasteria* sp. show thin and thick branches (Fig. 8a). The last form have colonies of different sizes suggesting more rapid growth. Dense thickets of robustly branching colonies can reach 80 cm high and possess thick branches, generally between 5.6 and 8 cm-thick, with higher branch packing density. On the other side, thinly branched forms generally between 0.5 and 1.5 cm developed a close packing density. Although there may be some gradation between the branch shapes, outcrops observations show a bimodal distribution in terms of branch diameter, which resulted in the formation of a rigid framework. According to Geister (1995) and Insalaco (1996) *Thamnasteria* sp. could have had a high rate of growth controlled by calcification and light levels (Bertling and Insalaco, 1998).

The massive colonies are generally dome-shaped. In some cases they are widely spaced, reaching a height of 8 cm, but in others developed a dense and intergrowing framework. These massive colonies are represented by *Australoseris* sp. which is abundant, and by the massive cerioid *Garateastrea* sp. The massive colonies and the thick branching ramose coral were constructors, while small branch colonies functioned as secondary framebuilders and bafflers. Most colonies were affected by erosion where a truncation surface is recognized (Fig. 8b). The coral growth fabrics are closely related with the sea-floor topography, oceanography and ecology of coral species, which allow to recognized different types of coral growth fabrics. Following the terms introduced by Insalaco (1998), the growth fabric of this coral assemblage should be designated as a superstratal rigid pillarstone and domestone, low uniform and discontinuous. Even though both coral communities produce different framework and growth fabric types, the coral framework reveals an internal zonation. The presence of both pillarstone and domestone fabric together allows to consider the framework like mixstone type fabric (Insalaco, 1998). Some colonies are intensely bored by lithophagid bivalves (Fig. 8c) but others coral specimens are poorly preserved because they have suffered considerable recrystallization during diagenesis precluding confident identification. In fact, aragonite was mainly affected by dissolution and the moldic porosity that resulted from the processes is filled by non-ferroan granular calcite cement; meanwhile some septae are filled by peloids or micrite (Fig. 8d).

Other contributors included bivalves such as *Ctenostreon* sp., echinoids, gastropods (*Harpagodes* sp. and *Natica* sp.) and serpulids, which are considered as reef dwellers, and siliceous sponges. Echinoderms are represented by *Plegiocidarid* sp. from the Middle Jurassic (Bajocian) to Lower Cretaceous (Aptian) of Europe, which represented the first mentioned in South America (Rodríguez, 2007).

Some small coral-sponge were found at the base of bedded parts of the principal reef facies (Palma et al., 2004, 2007). These bioherms are up to 20 cm high, and a maximum width might be as much as 40 cm. The presence of microbialites associated with the coral-sponge assemblage (Palma et al., 2007) is considered as binders (Bourque, 1997). Microbialites appear affected by bioerosion as well as sponge bodies (Fig. 8e). Microbialite fabrics included classical micropeloidal, densely micritic, or agglutinated textures (Riding, 1991) or simple crusts of clotted micrite presumably related to physical reworking and bioerosion (Neuweiler, 1993; Olivier et al., 2008), which indicates periods of microbialite growth interruptions (Olivier et al., 2004).

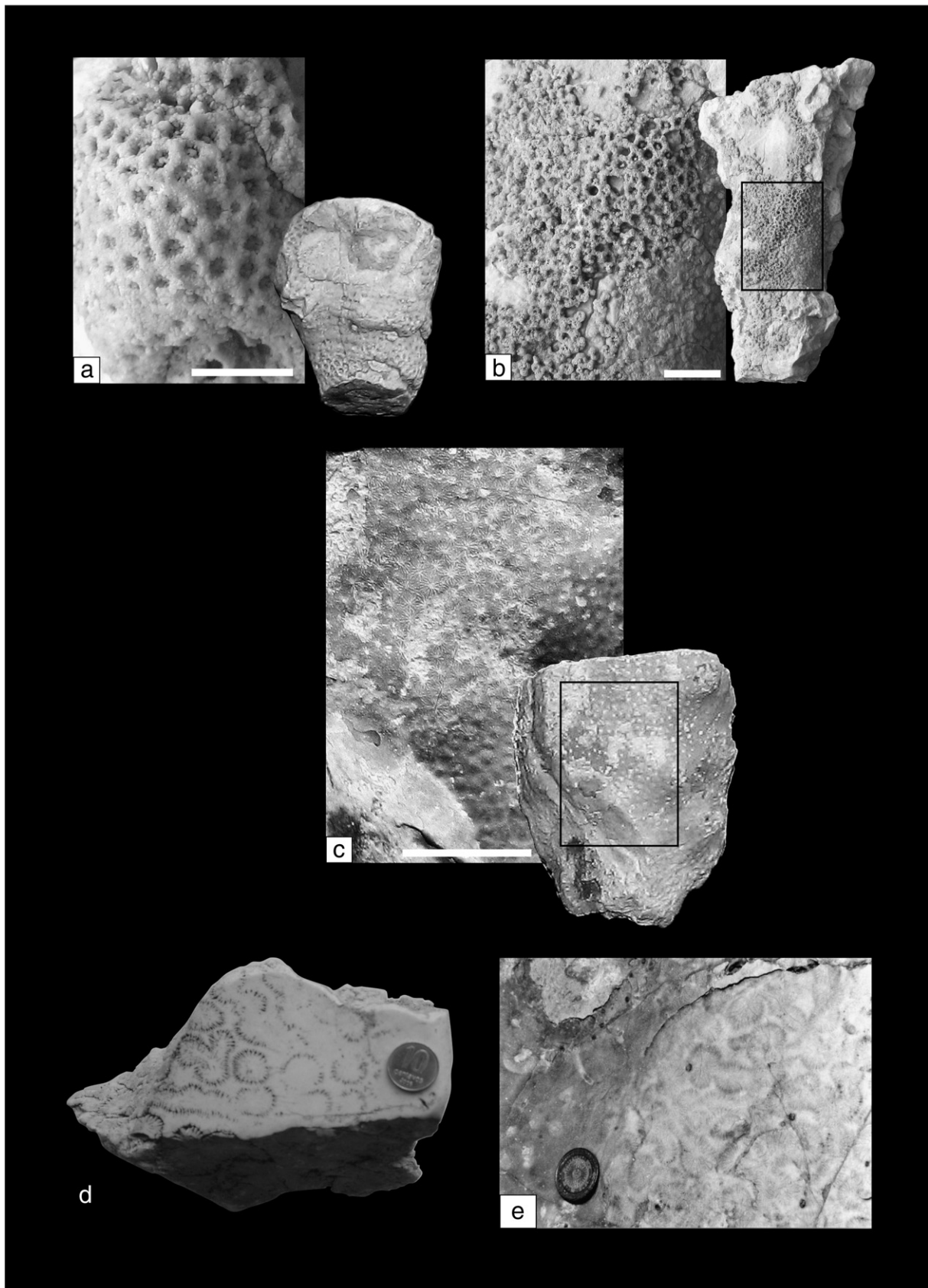


Fig. 7. Coral from the Oxfordian strata of the La Manga Formation. a,b – Lateral view of branch fragments of *Actinastraea* sp. Scale bar 1 cm.; c – Branch of *Thamnasteria* sp. and close view of calicular details. Scale bar 1 cm; d – *Garateastrea* sp. polished cross-section showing the cerioid to meandroid growth form. Coin diameter = 1 cm; e – *Australoseris* sp. cross-section showing the thamnastero-meandroid growth forms. Coin diameter = 2 cm.

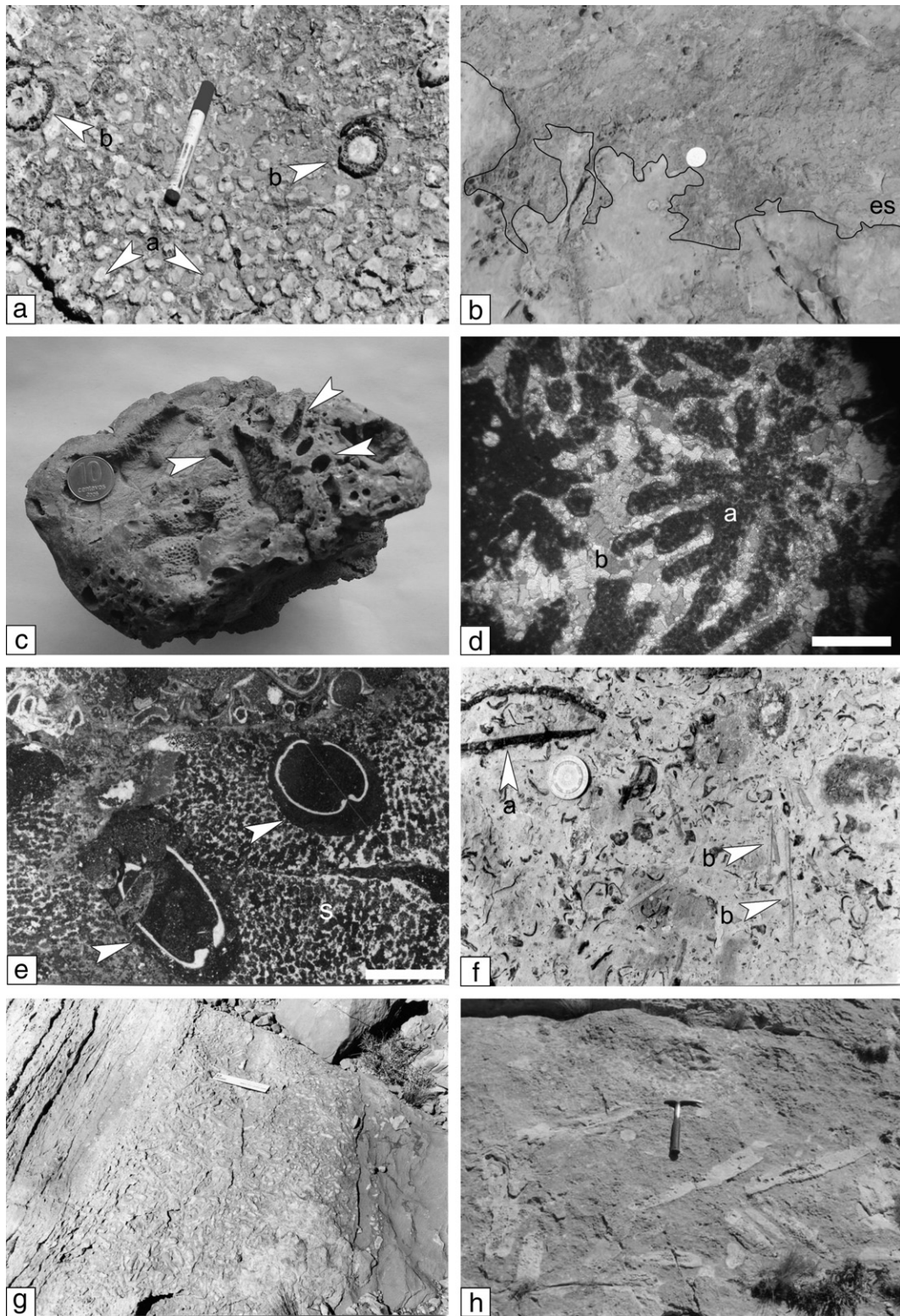


Fig. 8. a – Cross-section of *Actinastraea* sp. showing thin (a) and thick (b) branches. Pen for scale: 15 cm; b – Erosion surface on coral framework (es). Coin diameter = 2 cm; c – Abundant lithophag borings (arrows) within domal coral. Coin diameter = 1 cm; d – Dissolved coral septae filled by peloidal micrite (a) and granular calcite cement (b). Scale bar 0.5 mm; e – Detailed of sponge bodies (s) showing the peloidal aspects and bioerosion cavities filled by micrite and articulated lithophags (arrow). Scale bar 0.5 mm; f – Intercolony area rich in mollusc fragments (a) and echinoderm spines (b). Coin diameter = 2 cm; g – Rudstone–floatstone facies with abundant coral fragments. Scale 20 cm; h – Large coral fragments affected by little evidence of abrasion.

5. Intercolony areas

Space between framework elements are filled by bioclastic wackestone–packstone (Fig. 8f). The bioclasts consist of angular,

very poorly sorted grains ranging from less than 0.01 to 10 cm in size (average approximately 2 cm). They show a considerable taxonomic richness, with bivalves, reef-frame builders, echinoids, gastropods, benthic foraminifera, green algae, cyanobacteria and peloids. The

peloidal material is polygenic, comprising pellets and highly micritised bioclasts. Microborings are common, specially associated with molluscs and coral fragments. On a microfacies scale the sediment is a bioclastic wackestone and locally packstone (biopelmicrite). Micrite matrix was probably formed by accumulation of very small and indetermined bioclast debris. Thin sections show that at least some micrite can be considered as automicrite and their heterogeneous texture reveals diffuse masses of peloidal to clotted micrite. The clotted or grumous texture is commonly attributed to microbial activity (Chafetz, 1986; Riding, 2000). Similar textures have been described from reef and mud mounds throughout the geological record (Riding, 2000; Riding and Tomas, 2006) and it has been interpreted as resulting calcification of partially decomposed cyanobacteria (Pratt, 1982; Turner et al., 2000).

6. Rudstone–floatstone reef facies

The rudstones to floatstones bed shows massive stratification of 40 to 60 cm-thick. This facies is characterized by bioclasts ranging in size from 2.5 to 12 cm (Fig. 8g). The coral fragments increase in size upward. Dense, peloidal micrite binds the reef debris together. The transition from bioclastic floatstones to rudstones is gradual. The aragonite skeletons of scleractinian corals are always replaced by calcite. In addition, this facies includes bivalves, some gastropods and echinoids. Some cavities are lined by rims of dog-tooth cements indicating a late meteoric–phreatic conditions. The rudstones to floatstones facies are the result of coral destruction during storms.

7. Lagoonal patch reef

A low coral diversity exclusively represented by *Actinastrea* sp. and *Thamnasteria* sp. was observed in the lagoon. Coralstone growth fabric should be designated as suprastratal pillarstone, uniform and discontinuous, according to Insalaco (1998). A protected lagoon with low-energy facies is represented by Unit E (Palma et al., 2007) where bioclastic wackstones increase in abundance of pelecypods, gastropods, miliolid foraminifers, oncoids and *Cayeuxia* sp. fragments. Many components are highly micritised and micrite matrix was formed by accumulation of very small and indetermined bioclast debris. Some of the bioclastic wackstones are normally bioturbated by *Thalassinodes*.

8. Taphonomy

The coral framework and coral fragments are described in terms of the relative degree of alteration by processes such as fragmentation, bioerosion, micritization, abrasion and diagenesis (cf. Scoffin, 1992).

8.1. Fragmentation

The massive growth forms are resistant to mechanical destruction, but not to the biological one. On the other hand, branching coral shapes contribute to the strength of the framework, but they are not intensely affected by bioerosion, such as domal corals. Some truncation surfaces were observed (Fig. 8b), origin of which is the consequence of storm actions that influenced on the coral reef geomorphology and community compositions (Perry, 2001). Amounts of *Actinastrea* sp. and *Australoseris* sp. rubble remained angular and unrounded, in and around the principal reef structure.

8.2. Bioerosion

It was observed that domal coral morphologies appear to be more affected by bioerosion, and principally bored by lithophagids. These observations suggest that the type of growth fabric can be considered another important factor controlling distribution of bioeroders. In fact, Scoffin and Bradshaw (2000) mentioned that macroborers can display

niche preferences that can result in the intense degradation of coral morphologies.

According to Hallock and Schlager (1986), the activities of macroborers are recognized as a significant influence in reef accretion and development. On the other hand, they are responsible for the direct destruction of the reef framework and the increase of physical damage during storms (Sammarco and Risk, 1990).

Bioerosion on coralla surfaces is between grade 1 to grade 4 according to the Ketcher and Allmon (1993) scale. The domal coral shapes are the most affected by bioerosion of lithophagids (Fig. 8c) but the scarcity of borings in branching forms indicates either a high rate of sedimentation or an unfavourable environment for the boring organisms. Bivalves and worms played an important role in the coral framework degradation (Perry, 1988), and the high degree of bioerosion by lithophaga is probably related to a high sedimentation/turbid settings in the fossil record (Smithers and Lacombe; in Macdonald and Perry, 2003).

Bioerosion of skeletal material is represented in corals and shells also by microborings, which might be attributed to endolithic algae, bacteria or fungi, and by larger borings, assigned to bivalve molluscs (Tudhope and Risk, 1985). According to Macdonald and Perry (2003), the lower grade of bioerosion is related to the greater amount of the substrate dominated by sediments, probably related to a rapid burial of coral framework. Nevertheless, other factors like coral skeletal morphologies and densities could vary with sedimentation and light so that they are also important controls on boring (Barnes and Lough, 1999; Pandolfi and Greenstein, 1997). Bioerosion cavities are filled by peloidal micrite (Fig. 9a,b) or showing geopetal features, partially occupied by micrite and granular calcite (Fig. 9c).

8.3. Micritization

The micritization is a very common process on grain surfaces as a consequence of microboring and filling of skeletal cavities by micrite and sediment. The origin of micritization is related to the influence of lower energy conditions (Scoffin, 1987) and the abundance of organic fragments derived from the breakdown of coral framework and associated fauna. All particles exhibit evidence of micrite envelopes but gastropod and bivalve shells are more susceptible to micritization.

8.4. Abrasion

The material has not been transported far away since much of the material is composed of large coral fragments (Fig. 8h) and occasionally whole coral colonies showing very little evidence of abrasion. The grades of smoothing on individual coralla surfaces vary among grade 2 and grade 4 of the Ketcher and Allmon (1993) classification. Although abrasion features vary between allochems particles, coral and molluscan grains include rounding of grain margins as well as plates and spines of echinoderms.

Corals with abraded surfaces are scarce in the study area, although fragmentation is common as a consequence of transport by a turbulent regime that commonly produced fragments, but very rarely abraded skeletal surfaces. Likewise, some of the fragmented corals occur in lithoclasts, indicating that they were reworked after first being transported buried and lithified. Hence this material can be considered as parautochthonous reef debris that has been deposited at, or very close to, the site of reef development.

8.5. Diagenesis

During the development of the reef sequence reef cementation phase was characterized by early marine phreatic diagenesis that included micritization and precipitation of micrite and fibrous calcite in some primary cavities. Syndepositional cements are common and fill primary porosity. These marine carbonates were probably formed

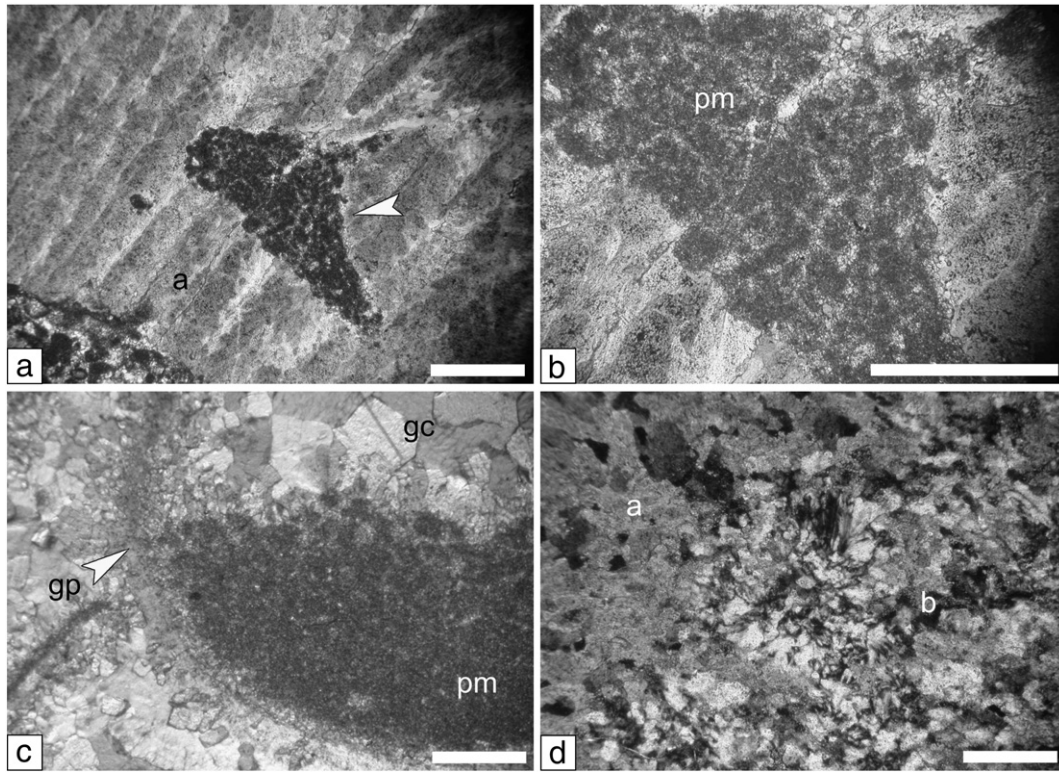


Fig. 9. a – Longitudinal coral section (a) affected by microboring (arrow). Scale bar 0.5 mm; b – Close view of microboring (a) containing peloidal micrite (pm). Scale bar 1 cm; c – Detailed of geopetal cavity (gp) containing geopetal peloidal micrite (pm) overlain by granular calcite cement (gc). Scale bar 0.5 mm; d – Thin-section photomicrograph of dissolution cavity on coral (a) filled by silica cements (b). Scale bar 0.5 mm.

by aragonite or high magnesium calcite that was subsequently neomorphosed; this was the major diagenetic process that contributed to early lithification of the reef.

The reef skeletons are affected by a complete dissolution of all aragonite skeletons that have been replaced by calcite, presumably due to early diagenetic aggrading neomorphism and dissolution and precipitation of granular calcite in the meteoric–phreatic diagenetic environment (James and Choquette, 1990). Diagenetic events in this environment included neomorphism of micrite and grains, including stabilization of Mg-calcite, and extensive dissolution of aragonitic allochems. Scleractinians, gastropods, and aragonitic bivalves are represented only by external moulds filled by fibrous spar and granular calcite cement. Syntaxial cements are commonly observed on echinoderm fragments. Some skeletal structures, matrix, and cements are partially replaced by silica that occurs as microcrystalline quartz or calcedonite precipitated in the voids created by the dissolution of carbonate (Fig. 9d). Nevertheless in some cases when skeletal carbonate grains are silicified, they retain their original microstructure, as is the case of oysters and ostracods that have retained their microstructure. Petrographic evidence shows that this process was not selective. The silica required for silicification must have been derived from silica-supersaturated pore waters derived from the outside of the carbonate host rocks (Williams et al., 1985). The replacement of carbonate by silica represents the most obvious indication of meteoric diagenesis.

The exposure of reefs is concomitant with the development of a paleokarst in response to sea-level fall (Palma et al., 2005, 2007).

9. Discussion

The reefs exhibit a very low diversity of scleractinian corals. The gryphaeid fragments as well as oolitic shoal represent the substrate over which the reef start-up to growth with thin branching growth

forms with a loose open framework at the base, and to more thickly branching and massive growth at the top where a change of energy conditions might be interpreted from the internal zonation of the coral framework. It is probable that the reef growth started during phases of reduced sandwave mobility as well as in areas slightly protected by oolitic bars, as we can see in the *bardas* 3 and 4.

The thin and loosely branched corals with cerioid to phocoid forms could have been occupied by a quiet and shallow-water environment with higher sedimentation rate. Conversely, dense and thick branched corals with cerioid forms could have been adapted to higher-energy setting, whereas the relatively small size of the massive dome shape forms suggests slower growth rate, low sedimentation rate and a moderate to high energy (Bertling and Insalaco, 1998).

The back reef is characterized by abundant fragment of corals intensive reworked by currents or storms. The rudstone/flotastone beds can be interpreted as a storm deposit similar to one described by Ball et al. (1967). Corals with abraded surfaces are scarce although fragmentation is common as a consequence of a dense flux that may cause breakage, but rarely produces abrasion (Lowe, 1982). Thus probably the result of transportation agents that affected these corals was discontinuous.

The large fragments of corals has not been transported far away from the core reef area because of their size and low abrasion grades, so that these materials can be considered as parautochthonous reef debris. The intensive micritization suggests that the bioclastic material was not rapidly buried, nevertheless we can assume for that a long time as resident on the sediment surface.

The different species of gastropods and bivalves indicate clear and turbulent waters (Dodd and Stanton, 1981); likewise grazing gastropods point to the presence of algal mats, which are common micrite producer (Bathurst, 1976).

The presence of small coral colonies in the growth position in the lagoon suggests a close relationship with reef facies. The fossil content

of the lagoon consists of an assemblage represented by molluscs, dacyclacean algae (*Acicularia* sp. and *Salpingoporella* sp.) miliolids, and abundance of *Cayeuxia* sp. often encrusting oncoids, reflecting a shallower environment within the lagoon.

According to James (1983) the coral succession suggests an upward shallowing of the environment, since branching growth is often interpreted as typical of low energy (James, 1983) and well illuminated waters (Insalaco, 1996). The abundant associated fauna represents a benthic community that included suspension feeders, grazing herbivores, and scavenger and is suggestive of oxygenated conditions. There is no evidence of a persistent barrier and the reef probably formed small patches on the contemporary sea floor (cf. James, 1983).

The origin of microbialites remains a topic of discussion. In fact, microbialites are generally interpreted to be the result of carbonate precipitation induced by phototrophic and heterotrophic bacteria (Pentecost and Riding, 1986; Reid et al., 2000). Nevertheless, other authors point out that organomineralization could play a notable role (Neuweiler et al., 1999).

As mentioned by Olivier et al. (2007) and Leinfelder et al. (1993) many factors such as nutrients, sedimentation rate, oxygenation salinity, temperature, and sea-level change can be controlled, microbialite development.

The presence of small coral–sponge at the base of the principal reef facies may be related to differences in nutrient conditions. According to Krautter (1998) the reef coral facies are related to stable, moderately oligotrophic conditions while the sponges could be related to oligotrophic to mesotrophic settings. As mentioned by Dupraz and Strasser (2002) the amount of nutrients in the water played an important role. In fact, an increase in nutrient availability favours the development of abundant microbialites, but in this particular case study, microbialites are not frequent, probably a consequence of nutrient level fluctuations (Olivier et al., 2007).

According to Leinfelder et al. (1993) a low sedimentation rate is a requirement for the development of microbialites, which are incrustated by bryozoans, serpulids and foraminifera, suggesting a period of time before a new generation of sponges or corals (Palma et al., 2004). Possibly, the presence of interruptions in the microbialites growth would indicate a low rate of sedimentation and poor light conditions (Olivier et al., 2007).

The absence of glauconite or iron impregnations in the microbial crust suggests a well oxygenated water column. Furthermore, fossil diversities indicated stenohaline conditions.

In the reefs studied there were no detected changes in sea level that could have influenced the development of sponge–microbialite, as suggested in similar bioherms of Germany by Pawallek and Aigner (2003). According to Insalaco (1998) and Braga and Aguirre (2004) these microbialites played a role similar to that of the coralline algae in present day reefs.

The reef from the La Manga Formation provides a good example of the interaction between reef growth, facies development, and sea-level changes. Even though the coral assemblage is not well represented by high diversities, a well-developed internal facies reflected varying degrees of framework development; from thin to thick branches coral shape followed by massive coral at the top. The vertical biotic zonation is interpreted as a consequence of physical factors such as sedimentation rate and water energy level. The dominance of branching to domal or massive coral colonies in the succession indicates that conditions were initially just quite or positive for branching coral growths. In addition, an increase in net sediment accumulation affected the growth of these forms but was favorable for massive domal corals. The evidence of erosive surfaces on the reef development suggests that these reefal units were deposited between storm- and normal wave base (around 5–10 m). Besides that the micritization of allochems particles implies that they were not rapidly incorporated into the reef framework.

From the comparative study of reef-bearing sections in central western Europe (Insalaco et al., 1997) described a diversity in Oxfordian coral reef types according to their sedimentological, palaeoecological and constructional characteristics.

The small patch reef located in area of *bardas* 1 and 2 developed within mixed carbonate/siliciclastic facies with low coral species richness probably are reflecting a palaeobathymetry from below normal wave base through to very shallow water, and correspond to Type VI reefs of Insalaco et al. (1997). Likewise, the relative abundance of thinly and thickly branching colonies suggests that energy levels were lower than in the massive coral growth forms, that are commonly interpreted as response to the increase in water energy. On the other hand, sediment supply to the reef was higher as suggested by the abundance of bioclastic-dominated areas, and by physical erosion of the reef and bioerosive self-sedimentation.

Energy levels were not so high as to inhibit the development of branching ramose corals, nevertheless some episodic storm events, with moderately high energy levels, affected the coral reef. Thick branch ramose colonies and small dome-shaped colonies associated with mobile oolitic shoals and a diverse molluscan fauna are similar to the Type VIII reefs of Insalaco et al. (1997).

The full utilization of accommodating spaces by the continuous succession of coral framework of up to a thickness of 18 m reflects a catch-up scenario, which was influenced by sea-level changes and the progressive lost of accommodation space, which resulted in a progradation of the reef structure during a keep space scenario, in northwest direction probably influenced also by terrigenous input.

Different factors might have influenced the reef development in the La Manga Formation during the Oxfordian. These environmental changes included reduction of salinity, input of siliciclastic material, elevated nutrient level, or climatic cooling. Reduced salinity level appears improbable because of the presence of stenohaline forms. Considering the presence of dasycladacean algae (*Acicularia* sp. and *Salpingoporella* sp.) and calcareous oolites (Palma et al., 2007) climatic cooling is also improbable. Likewise, a lower nutrient level is probable because a lack of encrustation is observed (cf. Hallock, 1988), so that an input of siliciclastic material could affect the coral assemblage (Sanders and Baron-Szabo, 2005; Dupraz and Strasser, 2002). The growth of the reef phases in *barda* 3 and *barda* 4 is a consequence of a deceleration of rate of sea level resulting in a thick aggradational and later progradational architecture (Palma et al., 2007). Finally, a sea-level fall resulted in widely karstification process that affected the top surface of some reefs and previous deposited facies (see Palma et al., 2007).

10. Conclusions

In the Bardas Blancas area coral reefs from the La Manga Formation are constituted by a low diversity of scleractinian corals which are represented by *Actinastraea* sp., *Australoseris* sp., *Thamnasteria* sp., and *Garateastrea* sp. probably. The Oxfordian coral reefs of La Manga are represented by coral assemblages closely similar to those of the Upper Jurassic European coral faunas.

The growth fabrics of this coral assemblage is a superstratal rigid pillarstone and domestone with low uniformity and low discontinuity. In spite of this, coral communities produced different framework and growth fabric types, and the coral framework reveals an internal zonation. The presence of both pillarstone and domestone fabric allows to interpret the framework as a mixstones-type fabric.

The coral associations are mainly dominated by thin and thick branches forms, as well as by massive forms. The initial reef development appears to have developed on the fragmented gryphaeids substrate or on oolitic shoal. Both substrate types were followed by a similar coral succession that represents the main reef-growth phases. The vertical transition from the thin to the thick branch coral shapes suggests that energy levels were lower than

massive coral growth forms, that are commonly interpreted as a response to the increase in water energy. During the reef development the water energy commonly was moderate to low, punctuated by episodic high energy events.

These reefs contain a moderate diversity of skeletal organisms, including bivalves, echinoderms, gastropods, forams, ostracodes, sponges, and dasyclad algae, cyanophytes as well as microbialites.

During the development of the reef facies, the relative sea-level rose causing aggradation of the reef framework. This aggradation took place through thickening of the framework coral facies. This indicates that the sea-level rise was initially very rapid and then reef growth kept pace with the rise, resulting in the development and progradation. A mantiform breccia composed primarily of clasts from the reef and oolitic facies is interpreted as paleokarst.

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