Facies (2017) 63:4
DOI 10.1007/s10347-016-0486-4

ORIGINAL PAPER

Coral patch reef system and associated facies from southwestern Gondwana: paleoenvironmental evolution of the Oxfordian shallow-marine carbonate platform at Portada Covunco, Neuquén Basin, Argentina

Matilde S. Beresi[1] · **Nora G. Cabaleri**[2] · **Hannes Löser**[3] · **Claudia Armella**[2]

Received: 28 December 2015 / Accepted: 16 November 2016
© Springer-Verlag Berlin Heidelberg 2016

Abstract During the Middle Oxfordian, the epicontinental shelf of the Neuquén Basin was a site of major coralline evolution and reef building. This work expounds the studies performed on the La Manga patch reefs at Portada Covunco locality, near Zapala city, Neuquén province. Based on the results of 12 facies/microfacies types and the vertical succession of coral morphotypes a shallowing-upward trend ranging from a shallow subtidal-lagoon- to intertidal settings is inferred. The microfacies model suggests an ooidal shoal area in the highest energy zone and various patch reefs on the shallow carbonate platform. Autochthonous reefal facies comprise a low diversity of platy coral and mixed coral-siliceous sponge framestone, ramose coral bafflestone, and microbial bindstone. Non-reefal facies are composed of ooidal packstone, bedded bioclastic wackestone-packstone, and marl levels. Several shallowing-upward episodes are evidenced by local erosional surfaces (main exposure surface-MES). The succession of platy corals (exclusively *Australoseris*) followed by ramose corals (*Etallonasteria*, *Stelidioseris*, and *Stephanastrea rollieri*) probably reflects local environmental changes. The upward change in reefal composition is best interpreted in response to extrinsic physical parameters (local relatively minor sea-level fluctuations). Siliceous sponges occur in low percentages. The La Manga reefal succession could be correlated with the "*global carbonate reef event*". This event occurred in most basins associated with the Tethyan oceanic belt and the North Atlantic Ocean, in low paleolatitude. The Portada Covunco reefs grew at higher paleolatitudes (nearly 39° south), within an embayment of the Neuquén Basin, with open circulation to the paleo-Pacific Ocean on the southwestern margin of the Gondwana realm.

Keywords Middle Oxfordian · La Manga Formation · Coral reefs · Facies/microfacies · Paleoenvironments · Argentina · Neuquén Basin

Introduction

Reefs were abundant and latitudinally widespread in Middle and Late Oxfordian times and became globally distributed and diversified during the Late Jurassic, mainly in the western and northern regions of the Tethyan realm (Leinfelder 2001; Cecca et al. 2005; Martin-Garin et al. 2012). Coral reefs, siliceous sponge reefs, and microbial reefs were the prevailing reef types during these expansions (Leinfelder 2001; Leinfelder et al. 2002).

Corals and sponge facies that developed during the Middle Oxfordian have an extensive presence along the southern margin of the European platform in the Mediterranean Tethys (Gaillard 1983; Leinfelder 2001; Wierzbowski 2002) in relatively deep, neritic environments.

Throughout Earth's history, coral reefs are part of a characteristic geoecological assemblage (Rosen 1992) and developed in warm shallow-water environments of carbonate platforms, which were generally limited to low latitudes. However, reefs extended to considerably higher latitudes (45°4′52″S) during late Oxfordian times

---

✉ Matilde S. Beresi
mberesi@mendoza-conicet.gob.ar

[1] IANIGLA, CCT-CONICET Mendoza, Avda. A. Ruiz Leal s/n Parque Gral. San Martín, 5500 Mendoza, Argentina

[2] CONICET-UBA, Pabellón Ingeis, Ciudad Universitaria, C1428EHA Autonomous City of Buenos Aires, Argentina

[3] Universidad Nacional Autónoma de México (UNAM), Instituto de Geología, Estación Regional del Noroeste (ERNO), Apartado P. 1039, 83000 Hermosillo, Sonora, Mexico

Published online: 29 November 2016

(Martin-Garin et al. 2012) possibly due to subtropical waters reaching farther poleward at those times (Copper 1994) or a wider distribution of warmer surface water than today caused by a more equilibrate, “greenhouse”-type Late Jurassic global climate (Leinfelder 1993). The more equilibrate Late Jurassic global climate may be related to a first- and second-order sea-level rise during the Late Jurassic driven by tectonic-eustatic processes. The general sea level rise increased the carbonate production and the suitable settings for reef growth (Leinfelder 1993; Leinfelder et al. 1994, 1996, 2002).

High-latitude reefs in the Oxfordian are found in the Pacific realm in southern Japan where there are stromatoporoid reefs with corals, algae, and microbes (Tamura 1961; Mori 1963), and along the North American Atlantic coast (mostly sponge-algae limestones) and Argentina (coral-siliceous sponge reefs and some algae or microbes in the Neuquén Basin; Morsch 1990; Matheos and Morsch 1990). These reefs are of moderate-to-high diversity.

Near the paleo-equator, conditions for reef growth were apparently unfavorable for reef developments, since only a few small coral reefs have been found there.

Coral reefs returned relatively rapidly after the Toarcian Oceanic Anoxic Event (OAE), which caused global environmental and biological changes (coral crisis). In the southern hemisphere, the OAE was first observed at the Neuquén Basin, Argentina, having been identified chemostratigraphically, on the basis of a relative increase in marine organic carbon and a characteristic negative carbon-isotope excursion (Al-Suwaidi et al. 2010).

During the Middle–Late Oxfordian, scleractinian corals, siliceous sponges, and algae contributed to an extensive reef-edge development for more than 500 m long and 8–10 m thick, in the southernmost part of the Sierra de la Vaca Muerta, Neuquén Basin. These coral-sponge reefs of the La Manga Formation were first recognized by Matheos and Morsch (1990) and Legarreta (1991) and the taxonomy of corals was reported during the past 25 years (Morsch 1988, 1990; Matheos and Morsch 1990). Two species: *Australoseris radialis* Morsch (family Stylinidae) and *Actinastrea* cf. *piveteaui* Alloiteau (family Actinastraeidae) were the first and only species described by Morsch (1990).

Sponge-bearing facies developed widely in the northern margin of the Tethys during the Late Jurassic (Gaillard 1983; Krautter 1997; Leinfelder et al. 1993, 1994). The facies with sponges have been recorded from the Transversarium Zone (Middle Oxfordian) to the Planula Zone (lowermost Kimmeridgian). Patchy sponge bioherms associated with epibenthic organisms (brachiopods, bivalves, and echinoderms) were developed at the Poti Malal section, in southern Mendoza Province, Neuquén Basin (Beresi and Krautter 2007).

The aim of this paper is to characterize the La Manga coral reefal facies, based on paleontological, sedimentological, and facies/microfacies analysis at the Portada Covunco sections, near Zapala city, Neuquén province. These results can be useful in local and regional stratigraphic correlation and for a better paleoenvironmental interpretation of the Jurassic reefs at a high paleolatitude. The Middle Oxfordian coral-sponge-algae reefs and the coral association from this locality are described here for the first time.

Regional geologic setting and stratigraphic framework

The Neuquén Basin is located in west-central Argentina at a paleolatitude ca. 35–45°S. The Argentine Basin is part of a N–S-oriented extensional system, which developed in a retroarc context along the active margin of South American Plate (Fig. 1). The basin contains more than 6 km of sediments of Late Triassic to Eocene age, deposited in a series of extensional troughs (Legarreta and Uliana 1996). Its history has been controlled by a changing tectonic setting of the western margin of Gondwana. Sedimentation began in the Triassic with volcanic and coarse-grained continental deposits. The Jurassic and Cretaceous marine and continental sediments are fossiliferous and without major hiatuses.

Processes associated with the subduction of the Pacific margin controlled the evolution of the basin. Tectono-eustatically driven first- and second-order sea-level change is responsible for the general sea level rise during the Late Jurassic, which influenced the paleogeography and the sedimentation of the detrital, carbonate, and evaporitic deposits (Legarreta and Uliana 1996, 1999). During the Middle and Late Jurassic, the paleogeography of the Neuquén Basin experienced considerable changes. In the middle Callovian, desiccation of the basin took place, resulting in the evaporitic deposits of the Tábanos Formation (Stipanicic 1966). Later on, between the late Callovian and the early Oxfordian, the depositional system varied from a ramp to a platform with a defined break and an important drop in sea level, which caused the exposition of a vast portion of the platform (Gulisano and Gutiérrez Pleiming 1995; Legarreta and Uliana 1996). The sedimentation continued with the fluvial sediments of the Lotena Formation in the middle Callovian to early Oxfordian (Veiga et al. 2011). The Lotena Formation constitutes the base of the Lotena Group (Leanza 1992), which encompasses the Lotena, La Manga, and Auquilco Formations. The upper part of the Lotena Formation consists of sandstones of marine origin, indicating a return to normal-marine conditions and expansion of the depositional area (Legarreta 1991; Legarreta et al. 1993; Legarreta and Uliana 1999).

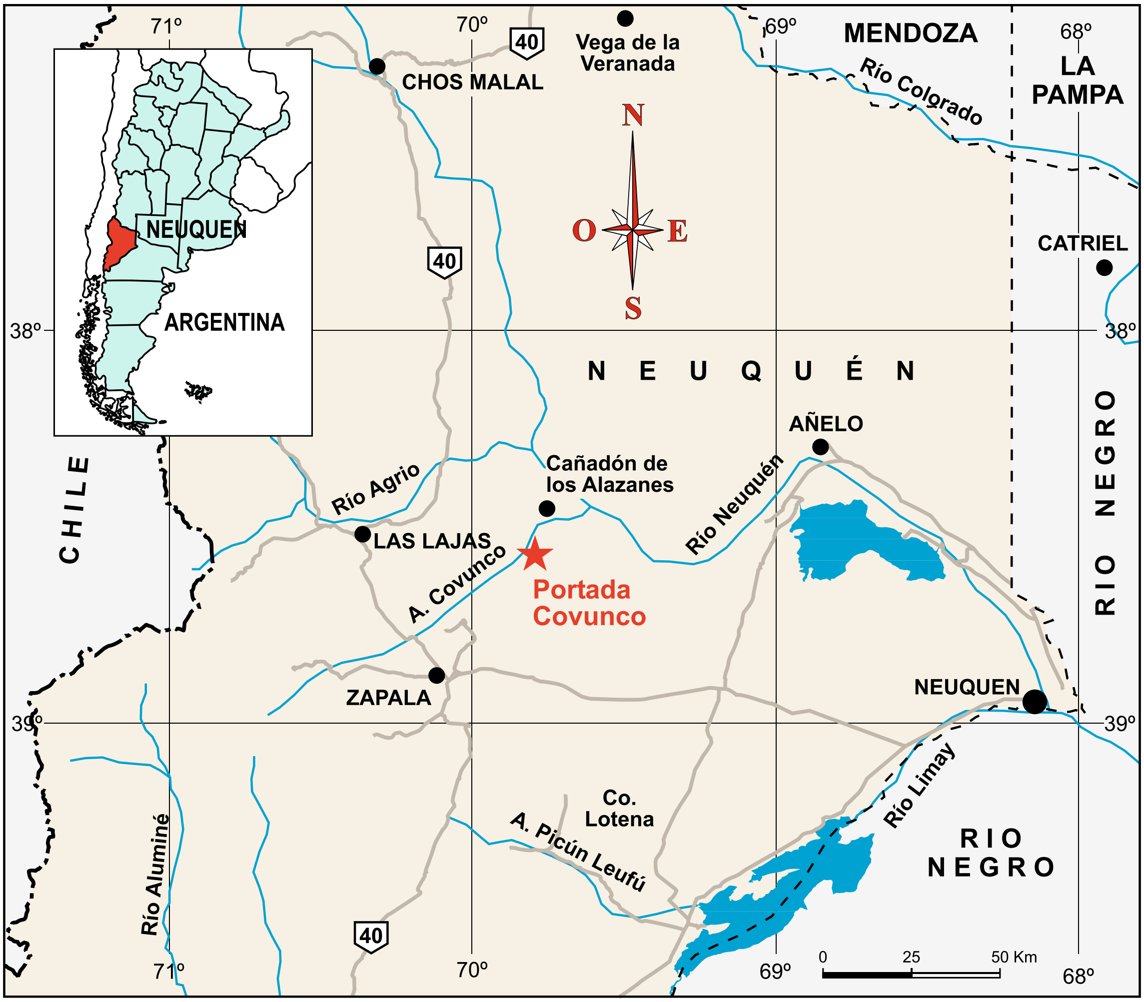


Fig. 1 Map of the Neuquén Province, western Argentina, and close up of the Zapala area showing location of the investigated outcrops at the Portada Covunco

In the middle Oxfordian, siliciclastic sedimentation decreased being replaced by extensive shallow-marine carbonates (Legarreta and Uliana 1999; Leanza and Hugo 2001).

The Oxfordian carbonates of the Neuquén Basin were deposited in an embayment open to Pacific circulation and located at a paleolatitude near 45° south (Legarreta 1991). The late Jurassic (middle Oxfordian) La Manga Formation evidences a shallow carbonate succession, and stretches from the south of San Juan to the center of the Neuquén provinces. The thickness of the La Manga Formation varies between 10 and 120 m (Leanza and Hugo 2001).

Calcareous gypsum sandstones and algal limestones of the Auquinco Formation overlie conformably the La Manga Formation, implying a marked desiccation of the basin during the late Oxfordian.

At Portada Covunco (section 1) the continental facies of the Lotena Formation lies below the La Manga Formation, while in the Portada Covunco Bridge (section 2), red beds of the Kimmeridgian Tordillo Formation (Groeber 1946) overlie unconformably the coral reefal limestones.

The fossil content of the La Manga Formation is characterized by a rich mollusc fauna: *Gryphaea* cf. *calceola* (Quenstedt), *Lucina* sp., gastropods (*Nerinea* sp.) and ammonites. Oxfordian ammonites from the Cordatum–Plicatilis Zone (early–middle Oxfordian) were recognized by Stipanicic (1951) and Stipanicic et al. (1975) in the type locality of La Manga creek. Recently, at the type locality of the La Manga Formation, a new record of ammonite faunas of early Callovian (Bodenbenderi–Proximum zones), early Oxfordian (Peltoceratoides–Parawedekindia zones) to middle Oxfordian ages (Perisphinctes–Araucanites zones) was registered (Palma et al. 2012). These regional zones correlate with the upper part of the Cordatum Zone and the Transversarium Zone, and, probably, across the lower part of the Bifurcates Zone (Riccardi 2008). Meanwhile, deposits of the upper part of the formation have yielded *Mirosphinctes* sp., (Palma and Kietzmann 2008) indicating an early to middle Oxfordian age.

Parent (2006) and Parent et al. (2006) proposed an alternative biostratigraphic zonation for the La Manga Formation at the platform's margin (Fig. 1). The lower part of the La Manga Formation is assigned to the late Callovian (Patagoniensis–Dimorphosus zones) and the upper part to the early Oxfordian (Pressulus Zone). The upper levels may have extended into the lower-most middle Oxfordian, corresponding to the base of the Pseudokranaus Zone (Parent and Garrido 2015).

Several reefs are known from the La Manga Formation: small siliceous-sponge mud mounds (mainly dictyonid hexactinellids and lithistid demosponges) at Bardas Blancas locality, southern Mendoza province (Beresi 2003) and an abrupt coral front reef of 8 m thick, at the southern end of the Sierra de la Vaca Muerta (Morsch 1990). The coral reefs exhibit large debris aprons of corals with robust ramose, dome-shaped and columnar forms accompanied by a variety of gastropods, bivalves, brachiopods, cidarid echinoids, bryozoans, and serpulids.

Study area and methods

The studied sections are at Portada Covunco, near Zapala city in the west-central part of Neuquén province (38°47′778″S, 70°11′781″W). The locality is part of the southernmost outcrops of the La Manga Formation in the Neuquén Basin (Leanza and Hugo 2001). Two stratigraphic sections were measured: Portada Covunco Creek, section 1 (38°47′47″S; 70°11′47″W) and Portada Covunco Bridge, section 2 (38°47′43″S; 70°11′49″W) both at the banks of the Covunco River where it intersects National Route N°22 (Fig. 2). The lateral continuity of both sections was verified. The distance between the sections is 135 m.

A detailed sedimentological analysis of the 8–12-m-thick deposits was carried out in the field in order to study the coral-sponge-microbial reef development in its sedimentary context. The microfacies analysis was performed on samples obtained from the reef limestones and associated facies. The microfacies analysis was based on the classification of Dunham (1962), as modified by Embry and Klovan (1971), and Flügel (2004).

All facies/microfacies types were based on field observations of textures, sedimentary structures, geometric relationship, and petrographic analysis of polished slabs and thin-sections. Corals were cut and polished and thin-sections were prepared. Thin-sections were examined using a Zeiss Axioskop 40 microscope. Microphotographs for illustration purposes were obtained using a transparency scanner Epson Perfection V750-M Pro, with an optical resolution of 6400 dots per inch.

Fig. 2 Generalized stratigraphic columns of the La Manga Formation reefal limestones at Portada Covunco Creek (section 1) and Portada Covunco Bridge (section 2) showing the lithostratigraphy, position of the coral-types, microfacies, main exposure surfaces (MES), regional exposure surfaces (RES), and less exposure surfaces (LES) ▶

Facies associations and depositional environments

A suite of facies associations were defined in order to define the depositional environment and describe the main faunal assemblages with special focus on coral reefs. Twelve facies types are recognized based on compositional and/or textural variations (Table 1). Most of the carbonate facies are limestones; however, some carbonate sandstones are also present. Three facies associations are identified on the basis of different constituents of the facies and microfacies, comparable to other Jurassic carbonate ramp/platform facies elsewhere (Leinfelder et al. 1994, 1996, 2002; Bádenas and Aurell 2001; Cabaleri et al. 2003; Olóriz et al. 2003; Palma et al. 2007; Armella et al. 2013; Wright and Burchette 1996; Flügel 2004; Merino-Tome et al. 2012; Strasser et al. 2012; Chow et al. 2013).

Peritidal facies association

Peritidal facies types **MF1–MF3** are recognized in the Portada Covunco Bridge section (Fig. 3). This section begins with a tabular level (1.8 m thick and 15 m long) of bioclastic wackestone (MF1). The facies overlies a small microbialite mound (0.70–1.15 m of thick and 3 m in width) that forms a domal isolated body. The facies is also covered by bioclastic packstone (MF3) tabular levels (0.40 m thick and 20 m long).

Facies MF1, Bioclastic wackestone (Fig. 3d). Bioclasts (25%) are mainly filamentous dark algae, coral debris, bivalves, brachiopods, calcispheres, ostracods, and vertebrates remains (fish scales). The quartz grains are scarce (<1%). The matrix consists of peloidal micrite which is intensively disrupted by irregular vertical structures (100 µm long and variable width between 6 and 2 µm) filled with sparite crystals. Thin levels of iron oxides (hematite) and microcrystalline quartz have been observed.

Facies MF2, Microbial boundstone (Fig. 3a–c). It is constituted by densely packed fragmented laminae formed by a suite of two layers of dark micrite with a light, interbedded micrite level characterized by a parallel growth pattern and thin contorted dark grey filaments. Between the dark filaments, there are irregular cavities filled with spar crystals. The peloidal matrix is dense and laminated and often attacked by boring bivalves.

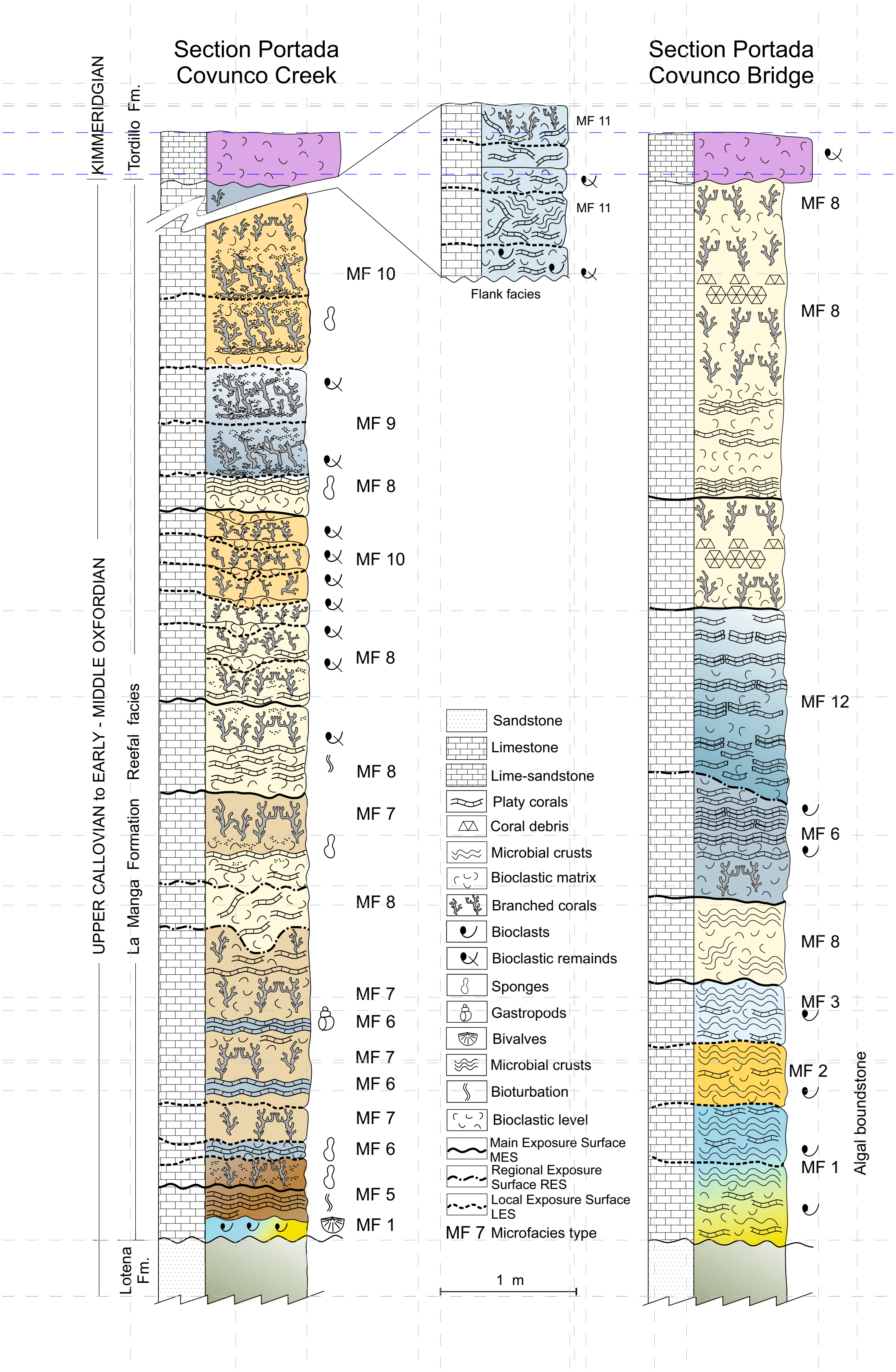

Section Portada Covunco Creek
Section Portada Covunco Bridge
KIMMERIDGIAN
Tordillo Fm.
UPPER CALLOVIAN to EARLY - MIDDLE OXFORDIAN
La Manga Formation Reefal facies
Lotena Fm.
MF 10
MF 9
MF 8
MF 10
MF 8
MF 8
MF 7
MF 8
MF 7
MF 6
MF 7
MF 6
MF 7
MF 6
MF 5
MF 1
MF 11
MF 11
Flank facies
MF 8
MF 8
MF 12
MF 6
MF 8
MF 3
MF 2
MF 1
Algal boundstone
Sandstone
Limestone
Lime-sandstone
Platy corals
Coral debris
Microbial crusts
Bioclastic matrix
Branched corals
Bioclasts
Bioclastic remainds
Sponges
Gastropods
Bivalves
Microbial crusts
Bioturbation
Bioclastic level
Main Exposure Surface MES
Regional Exposure Surface RES
Local Exposure Surface LES
MF 7 Microfacies type
1 m

Table 1 Summary of characteristics of facies/microfacies of the La Manga Formation at the Portada Covunco platform, Neuquén Basin

Facies association	Facies	Physical characteristic	Biota	Bedding	Depositional interpretation
Peritidal	Bioclastic Wackestone (MF1)	Peloidal micrite, intensively disrupted (bioturbation burrows, iron mineral levels)	Algal filaments, coral debris, bivalves, brachiopods, ostracods, and few vertebrate remains	Tabular beds, 1.8 m thick and 15 m of lateral extent	Substrate of MF2. High-energy environment affected by fair weather wave base Periods of subaerial exposure
	Microbial boundstone (MF2)	Laminated peloidal micrite Irregular filaments keep a parallel growth pattern. Fenestral fabric	Filaments, thallus of tabular algae, and radial algae	Domal isolated bodies of 0.70 and 3 m long	Patch reef. Algal filaments could correspond to brackish water environments with free circulation conditions, tide currents, and affected by storm wave base
	Bioclastic packstone facies (MF3)	Peloidal micrite. Siliciclasts: quartz, glauconite, biotite and vulcanite fragments. Intraclasts of sparite and micrite with iron minerals	Coral fragments, mollusks, ostracod shells, sponges, alga filaments, and Dasyclad	Tabular beds, 0.40 m thick and 20 m of lateral extent	Intertidal, free water circulation conditions, with tide currents and affected by storm wave base
Intertidal to shallow subtidal, restricted lagoon	Ooidal packstone (MF4)	The sorting is very well and the fabric is grain-supported. Ooids are type 3. Siliciclasts are grains of quartz, orthoclase, lithics and plagioclase. The intraclasts are of sparite and black pebbles	Ramose and platy-coral fragments	Ooidal shoals. Lenticular carbonate outcrops, 0.20 m thick, and 5 m of lateral extent	Intertidal environment. High energy, reworked by fear weather wave and currents transport
	Peloidal mudstone with bioclasts (MF5)	Algal peloids micrite and clay minerals in the matrix. Ooids type1 and oncoids. Quartz siliciclasts	Coral fragments, mollusks, brachiopods, calcispheres, and filamentous algae	Lenticular beds from 0.8–0.20 m thick, and 05 m long, interdigitated laterally	Back- shoal bars, low energy and protected areas in the lagoon
	Coral and sponges wackestone (MF6)	Peloidal micrite. Ooids and micritic intraclasts	Coral fragments, dictyd and lithistid sponges, crinoids, gastropods, and bivalves	Three beds 0.26, 0.10, and 0.60 m thick and 5 m long, form a domal structure	Lagoon environment with lower energy. Transition between patch reefs and ooid shoals
	Coral-bioclastic packstone (MF7)	Peloidal micrite matrix. Reworked ooids. Micrite or sparite intraclasts, coated by micrite. Micropeloids, quartz, and plagioclase grain	In situ Australoseris, bivalves, gastropods, cephalopods, bryozoans, Dasyclad and radial algae	Lenticular bodies 0.70 m thick and 5 m long	Lagoonal patch reef. The buildup communities are influenced by sediment supply. High sedimentation rate
	Dasyclad bioclastic-packstone (MF8)	The matrix is peloidal clotted micrite. Intraclasts and ooids	Dasyclad algae, solitary corals, gastropods, bivalves, cephalopods, ostracods, serpulids, and algal peloids	Discontinuous laminar levels 0.70 m thick and 10 m long	Lagoonal or coastal bay, with currents action or thick bad weather waves

Table 1 continued

Facies association	Facies	Physical characteristic	Biota	Bedding	Depositional interpretation
Shallow subtidal to intertidal, lagoon	Bioclastic- floatstone with siliciclasts (MF9)	Very fragmented and poorly/very poorly sorting particles. Siliciclasts: quartz crystals, plagioclase, orthoclase, epidote, volcanic and metamorphic grains. Micrite intraclasts. Ooids. The matrix is micrite with sparite patches	Fragments of mollusks, corals, echinoderms, sponges, fish scales, articulated brachiopods	Lentiform beds, 0.35 m thick, 2.5 m lateral extent	Tidal channels in lagoon
	Bioclastic wackestone with corals (MF10)	Peloidal micrite matrix	Coral debris, bivalves, gastropods, foraminifers and algae filaments	Tabular level, 1 m thick and 2.5 m of lateral extension	Lagoon with low-energy environment
	Bioclastic packstone to rudstone (MF11)	The matrix is constituted by micrite and sparite patches with bioturbation	Ramose and platy coral debris, bivalves, gastropods, cephalopods, foraminifers, echinoderms, and Dasyclad algae	Tabular beds, 07.0 m thick and 5 m long	Storm deposits of the patch reef flank
	Siliciclastic mudstone/wackestone with bioclasts (MF12)	Micrite intraclasts. Peloidal micrite matrix	Ramose and laminar coral debris, bivalves, gastropods, sponge spicules, echinoderms, ostracods, filamentous algae and plant remains	Tabular beds, 1.2-m-thick and 15-m lateral extension	Moderate-to-shallow subtidal environment near de costal areas, moderate-to-high energy. The coral bioclasts were transported by currents

Facies MF3, Bioclastic packstone (Fig. 3f). Bioclasts (50%) are composed of coral fragments, mollusc shells, sponges, ostracods, filaments, calcispheres, dasyclad algae, small dasyclad algae, cortoid particles and micropeloids. Siliciclastics (3%) comprise quartz, glauconite, biotite, and volcanic fragments. Intraclasts (2%) consist of homogeneous micrite or sparite, with abundant iron oxides; some of them are black pebbles. The matrix is composed of peloidal micrite and the cement consists of sparite and micrite pendant.

Interpretation

Bioclastic wackestone is the substrate of the microbial boundstone. Reworked bioclastic material indicates an environment affected by a fair weather wave base. Coral fragments proceed from the destruction of the patch reefs. The iron mineral levels may indicate periods of subaerial exposure or secondary process. The vertical structures have been interpreted as bioturbation. Over the bioclastic wackestone developed a microbial boundstone in the shallow zones with low sedimentation rate. The microbialite development is related to conditions of high nutrient availability (Leinfelder et al. 1994). The microbial boundstone form a true framework and share the common features of peritidal carbonates as well as the special textural features of fenestral matrix (Shinn 1983). Molds of very large algal filaments correspond to brackish water environments (Monty 1967; Monty and Hardie 1976; Schneider et al. 1983). The widespread occurrence of microbialites suggests mesotrophy and eutrophy, with arguably more nutrients and the more humid local climatic conditions of the Late Oxfordian (Olivier et al. 2004).

The boundstone growth was interrupted by the bioclastic packstone facies formed in an environment characterized by open circulation conditions, with significant influence from the wave base, which has fragmented and reworked the bioclasts. The pendant cement indicates vadose diagenesis in shallow environments.

Intertidal to shallow subtidal, restricted lagoon

This facies association **MF4–MF8** is present in the Portada Covunco Bridge section. The ooidal packstones (MF4) form lentiform outcrops of 0.2-m thickness and 5 m of lateral extent with trough cross-bedding stratification and wave-ripple cross-lamination at the top of the levels (Fig. 4).

The peloidal mudstones (MF5) are composed of beds (0.8–0.2 m thick, 0.5 m long), laterally interdigitated. The bioclastic mudstones consist of three beds (0.26, 0.10, and

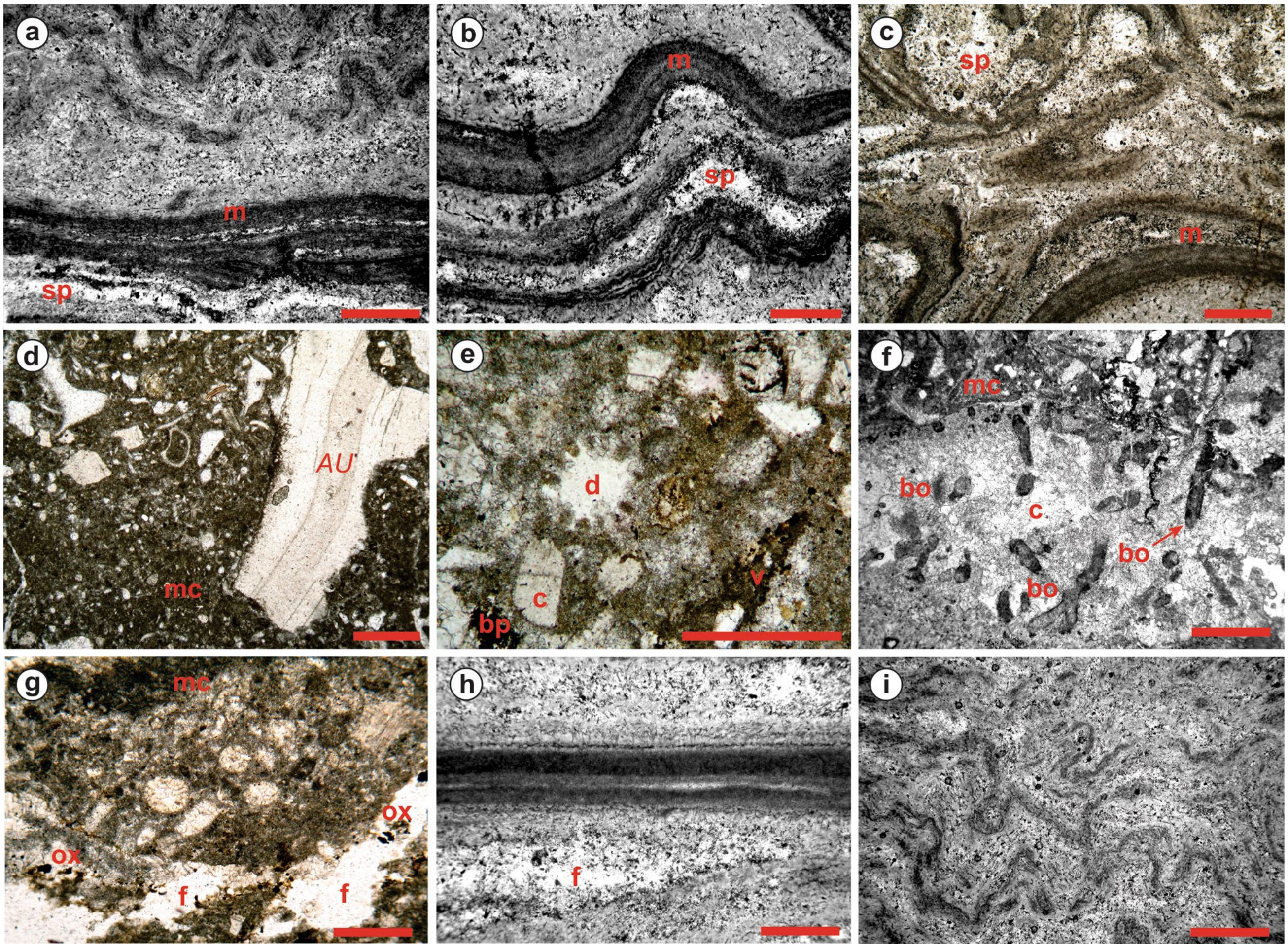


Fig. 3 Photomicrographs of peritidal microfacies of the La Manga Formation at Portada Covunco, Neuquén Basin. **a**–**c** MF2 microbial boundstone. Densely packed fragmented laminae are formed by layers of dark micrite (*mc*) and sparite (*sp*), keeping a parallel and contorted growth pattern. Thin dark-grey are discontinuous filaments. **d** MF1 fossil fragments, platy-coral debris very fragmented (*Au*) and microbial crust (*arrow*) in a micritic matrix (sample LMPC 16). **e** MF3 dasyclad alga (*d*) coral (*c*) with iron oxides coating (*ox*), intraclasts and black pebbles (*bp*). Part of the cement is pendant. In addition, a silt-sized volcanic grain (*v*) with iron oxides, and altered plagioclase grain (sample LMPC20). **f**, **g** MF3, **f** white coral fragment (*c*) intensively bored (*bo*) and microbial crusts (*mc*), **g** fenestral pores (*f*), iron oxides (*ox*). **h**, **i** MF2 microbial boundstone, **h** laminated fabric characterized by flat dark micrite, and fenestral pores (*f*), **i** distinctive contorted very large algal filaments. *Scale bar* is 0.5 mm for all figures

0.60 m in thickness), which form a domal structure (5 m in long, laterally wedged up to 0.20 m thick). The coral and sponge wackestone (MF6) and the coral bioclastic boundstone (MF7) form lenticular bodies (0.70 m thick and 5 m long). The dasyclad-bioclastic packstone facies (MF8) forms discontinuous levels (0.70 m thick and 10 m long) with ripples and swaley cross-stratification.

Facies MF4, is distinguished by ooidal-packstone levels (Fig. 4a), which are formed of superficial ooids (35–40%) type 3 (Steinhoff and Strohmenger 1996) with different core compositions. Nuclei include siliciclasts (quartz and plagioclase crystals), skeletal grains (bryozoan or coral fragment) and micritic grains. Bioclasts (3%) are fragments of recrystallized scleractinian corals, bryozoans; some remains present surfaces covered with iron oxides. Well sorted siliciclasts (3%), generally very angular, consist of feldspar, quartz, plagioclase and, to a lesser degree, lithoclasts. The intraclasts (1%) are sparite with iron oxide and some are black pebbles. Particles are very well sorted and the matrix is peloidal grumose micrite without clayish minerals.

Facies MF5, is characterized by peloidal mudstone and bioclasts (Fig. 4b–d). The facies is composed of peloids (45–50%) and bioclasts (10%). Bioclasts (10%) are composed of coral fragments with borings of incrusting organisms, molluscs and brachiopod remains, calcispheres and filamentous algae. The type 3 ooids and type 1 oncoids (Steinhoff and Strohmenger 1996) are scarce and only appear in the lower levels. Quartz grains are more abundant

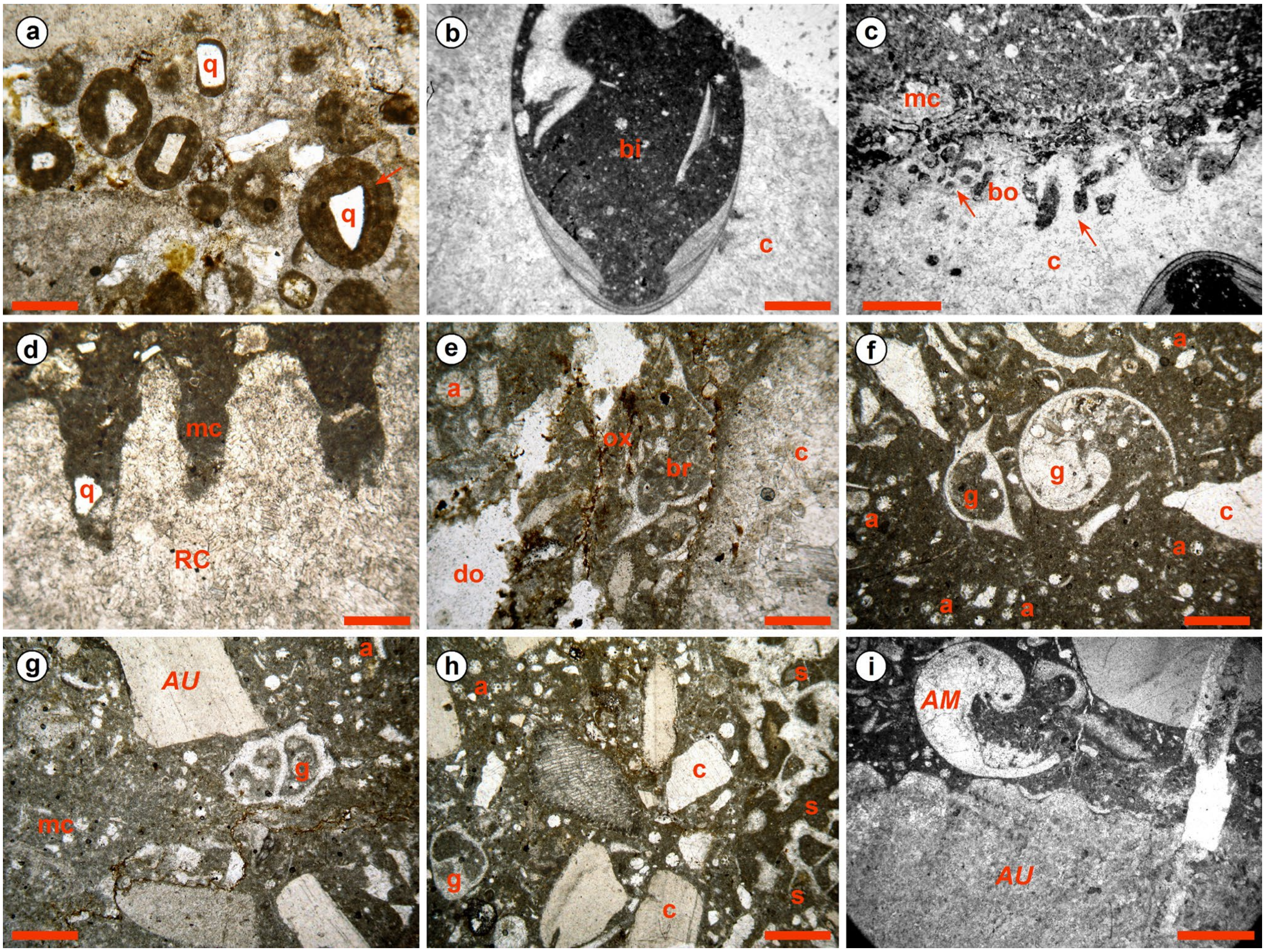


Fig. 4 Photomicrographs of the intertidal shallow lagoonal microfacies. **a** MF4 ooids, some of which have detrital quartz nuclei (*q*) (sample LMPC1). Plane-polarized light. **b–d** MF5 boring lithophag bivalve (*b*) within a coral, **b** bivalve shell (*bi*) in the borehole partly preserved and infilled with micropeloidal micrite (sample LMPC 4), **c** the upper part of the coral exhibit dark microbial crusts (*mc*) and small boreholes by boring (*bo*) activity of organisms, **d** ramose-coral type (*RC*) encrusted by dense microbialite (*mc*); parts of the coral are recrystallized, (*q*) detrital quartz. **e** MF6 coral (*c*) coating of iron oxides (*ox*), calcispheres (*a*) and volcanic grains (*v*) in a dense micritic matrix. A void is filled with dolomite (*do*) (sample LMPC5). **f** MF7 recrystallized gastropod (*g*), calcispheres (*a*), dasyclad algae (*d*) fossil fragments and small undifferentiated bioclasts within micritic matrix (sample LMPC 6). **g** MF8 platy-coral debris (*Au*), gastropods (*g*), and microbial crusts in a matrix of silt-sized biotic debris (sample LMPC9). **h**, **i** MF6 part of the skeleton of a siliceous demospongе (upper right) partly disintegrates (*s*), platy-coral debris (*c*), calcispheres (*a*), and gastropod occur together within a mud-rich bioclastic matrix (sample LMPC5), **i** *Australoseris* fragment (*Au*) overgrowth with microbial crust and *Ammonitella* (*Am*) within a bioclastic matrix. *Scale bar* is 0.1 mm for **d**; 0.5 mm for **a–c**, **e–i**

in the microfacies lower levels (2%) and their average frequency decreases toward the upper levels (0.1%). Clay minerals are frequent in the matrix.

Facies MF6, consists of coral and sponge wackestones (Fig. 4e). The fragmented remains correspond to scleractinian corals (10%) and siliceous sponges (mainly hexactinosan and lithistid) (5%). It was possible to recognize crinoids (2%), molluscs (3%): gastropods, bivalves, and calcispheres (2%). Intraclasts of peloidal micritic composition (5%) are frequent. The ooids (2%) are reworked. The matrix is composed of peloidal micrite.

Facies MF7, is composed of coral-bioclastic packstones (Fig. 4f, g). The main bioclastic constituents (55%) are laminar coral remains, siliceous sponges, bivalves, gastropods, cephalopods, bryozoans, echinoderms plates, calcispheres and cross section of small spherical and ovoidal calcified dasyclad algae filled with clear calcite. The micritic intraclasts (5%) occasionally are re-coated by micrite. Micropeloids are abundant (15%). Reworked and recrystallized ooids (2%) were observed together with scarce quartz and plagioclase grains (1%). The matrix is composed of peloidal micrite with pores filled with dolomite crystals are scarce.

Facies MF8, is comprised of dasyclad packstones (Fig. 4h, i). Bioclasts (75%) mainly represented by dasyclad algae, and are followed in importance by fragments of reworked corals, solitary corals, gastropods, bivalves, cephalopods, ostracods, serpulids, calcispheres, undetermined algae and algal peloids. Algal remains constitute several transverse sections of dasycladaceans and short broken lengths, which are probably sections of the stem of these algae. The hollow cylinder, which is usually either micrite calcite or a sparry calcite cast, is perforated by tubes that make up the positions of the branches. Dasyclads are associated with micritic peloids and cemented by sparry calcite. Intraclasts and ooids are not over 1%. The matrix is peloidal clotted micrite. Some particles are cortoids.

Interpretation

The ooids were formed in shoal bars. The facies is comprised of progradating accretional sigmoid structures. Bioclast remains are the consequence of mechanic destruction caused by the action of currents and waves. Ooids, together with the fragmentation degree of the bioclasts, suggest a high-energy environment above the fair weather wave base in which currents transported material that originated in the lagoon and the coastal zone. The siliciclasts sorting degree and the presence of black pebbles indicate transport from marginal areas and deposition in the shoal bar.

Back-shoal bars limited the lagoon environment, which is composed of low energy and protected areas, and formed among the topographic elevations of the shoals. The protected environment was optimum for the development of filamentous algae, molluscs, and brachiopods (Armella et al. 2007). The corals and disarticulated shells, both of which exhibit limited abrasion, indicate storm reworking, limited transportation from the patch reef, and transportation by tide currents (Armella et al. 2008). Algal peloids were formed by micritization of algal particles (Riding 2000).

The transition between patch reefs and ooidal shoals is evidenced by bioclasts with severely worn out corals and sponges, indicating reworked material coming from the patch reefs. The ooids themselves were transported from shoals and deposited in lower-energy environments. The matrix of the patch reefs consists of a bioclastic wackestone.

The patch reefs were recognized for their lenticular geometry and the presence of constructors' organisms (corals, sponges, and algae). These framebuilders were accompanied by a great variety of encrusting, boring, and free-living epibenthic metazoans. The build-up communities are influenced by sediment supply, energy and oxygenation, which provide light and nutrients (Hallock and Schlager 1986; Carannante et al. 1995; Dupraz and Strasser 2002; Götz et al. 2005; Armella et al. 2007, 2008). Conditions are relatively quiet and protected by the development of coral structures allowing for the formation of micritic mud with predominance of micropeloids, thus resulting in an optimum environment for the development of the molluscs and bryozoans associated fauna (Armella et al. 2008). Filamentous algae would have come from the destruction of algal mound. The intraclasts, ooids, and siliciclasts were transported from the marginal areas. An erosional surface has been recognized on the top of the patch reefs. This body was large enough to reach sea level under intertidal conditions, and was affected by the wave action that produced the redistribution of sediment on shallow-marine shelves (Peters and Loss 2012) and erosion episodes. The dasyclad algal facies developed at the top of the patch reefs. This facies covers some coral reef bodies and fills the depressions among the boundstones. Spherical dasyclad algae probably belong to the *Acicularia-Terquemella* group. According to Bucur et al. (2008), if the shape of the dasycladaceans is spheroidal, ovoidal, or discoid an affiliation with the genus *Terquemella* is much more probable than with the genus *Acicularia*. The abundant presence of dasyclad algae points to the free circulation of water coming from the lagoon (Gabrig Turbay et al. 2013). They are commonly associated with a calm lagoonal or coastal bay environment, and indicate tropical to subtropical water temperatures (Flügel 2004). The coral fragments corroborate the presence of currents and the contribution of material from bodies destroyed by waves. The molluscs, gastropods, and bivalves, represent forms occupied by the reefs that were then removed post-mortem. The peloids formed in protected zones back of reef bodies. The presence of dasyclads, ostracods, and micropeloids indicate a shallow, proximal depositional setting on the carbonate ramp/platform (Vincent et al. 2006).

Shallow subtidal to intertidal, lagoon

The facies association **MF9–MF12** formed between the back reef and the ooid shoals is recognized in both sections of the Portada Covunco (Fig. 5). Bioclastic floatstone facies (MF9) occur as lenticular beds (0.35 m thick and 2.5 m long). Bioclastic wackestone facies (MF10) is composed of a tabular level (1 m thick and 2.5 m of lateral extension). Bioclastic packstone to rudstone facies (MF11) are constituted by two tabular beds (0.7 m thick and 5 m long, which are wedged laterally). Mudstones and wackestones with bioclasts (MF12) are comprised of tabular beds (nearly 1.2 m thick and 15-m lateral extension).

Facies MF9, Bioclastic floatstones with siliciclasts are constituted by very fragmented and poorly/very poorly

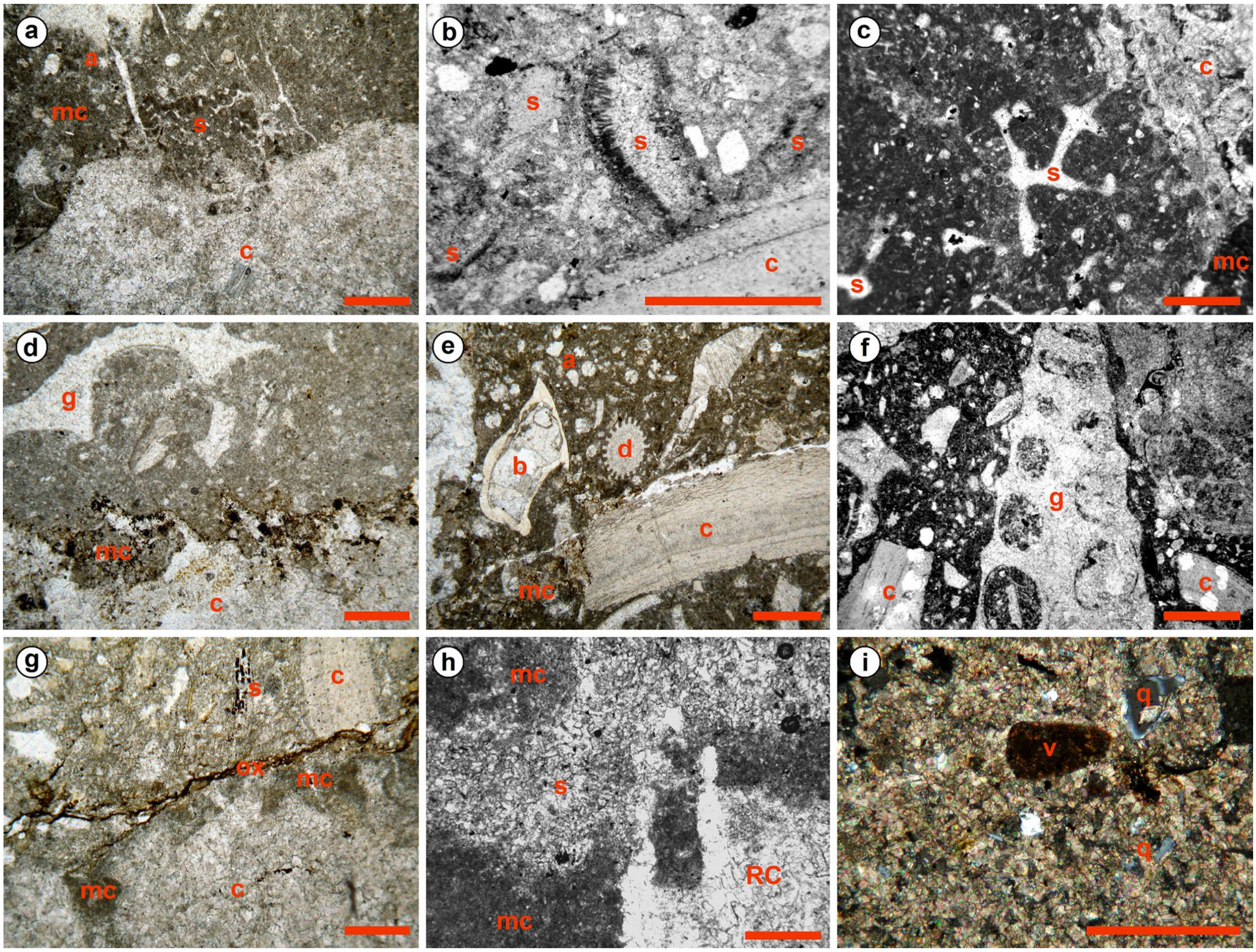


Fig. 5 Photomicrographs of intertidal to shallow subtidal to intertidal lagoon microfacies. **a**–**c** MF9, **a** relic of encrusting "lithistid" sponge (*s*) on the upper surface of coral (*co*). Other bioclasts are algae and calcispheres (*a*), and microbial crust (*mc*) within a micrite matrix, **b** Cylindrical "lithistid" sponge on a coral (*co*) and small sponges occur with platy-coral debris (sample LMPC 10), **c** small part of a dictyonal skeletal framework of a hexactinosan sponge (*s*) in the center of the picture within a micritic matrix with microbial crusts (*mc*). **d** MF10 coral debris (*c*) with a thin dark microbial crust, and cavities filled with micrite iron-oxide surface (*ox*). Section perpendicular to the axis of a gastropod (*g*), external projections indicate ornamented shell, occupied by calcite cement (sample LMCM 12). **e**–**f** MF11 **e** articulation of pelecipod valves at hingeline (*pe*), shell is filled with coarse sparry calcite. Platy-coral fragment (*c*), dasyclad alga (*d*), calcispheres (*a*) and a volcanic grain (*v*), within a micrite matrix. Bioturbation affected the bioclasts (sample LMPC 14). **f** coral debris (*c*), a chambered shell of a gastropod (*g*), matrix is a bioclastic wackestone. **g**, **h**, **i** MF12 **g** coral surface with iron oxides (*ox*) that was later exposed. The upper part of coral (*c*) exhibits small borehole caused by organism activity, partly filled with dark peloidal micrite (*pm*). In addition, biotite (*b*), plagioclase altered (*pl*) to opaque minerals, and numerous siliciclasts (si) (sample LMPC 15). **h**, part of the skeleton of a sponge (*s*) partly disintegrated and substituted by sparite cement, and, ramose coral debris (*RC*) with microbial crusts (*mc*). **i** volcanic rock (*v*) and siliciclastic grains (*q*) (sample LMPC 19). *Scale bar* is 0.1 mm for **h**; 0.5 mm for **a**–**g**, **i**

sorted particles (Fig. 5a, b, c). Bioclasts (15%) are sponges, molluscs, corals, echinoderms, articulated brachiopod valves, thin fish scales and undetermined fragments. The siliciclasts (10%) are represented by quartz crystals, plagioclase, orthoclase, epidote, and fragments from volcanic and metamorphic rocks. Intraclasts of irregular form (9%) are composed of recrystallized micrite. The ooids are scarce and are replaced by iron oxide. The matrix is micrite with sparite patches. Parallel irregular cavities filled with sparite crystals disrupted the matrix.

Facies MF10, Bioclastic wackestones with corals (Fig. 5d). Bioclasts (15%) are composed of corals, bivalves, gastropods, foraminifer shells, and badly preserved algae filament remains. Coral surfaces are covered by iron minerals. The matrix is peloidal micrite.

Facies MF11, Bioclastic packstones to rudstones (Fig. 5e, f). Bioclasts (35%) are platy and finger corals, bivalves, gastropods, cephalopods, foraminifers, echinoderms, and dasyclad algae. Siliciclasts (3%) are of quartz, plagioclase, biotite, and volcanic lithoclasts. Oncoids are scarce (<1%). The matrix is constituted of micrite and sparite patches and is disrupted by vertical and sub-horizontal cavities infilled by sparite.

Facies MF12, Siliciclastic mudstones wackestones with bioclasts (Fig. 5g–i). They are characterized by siliciclasts (15%) quartz, metamorphic quartz, feldspar, plagioclase, clay, muscovite, glauconite, biotite, volcanic glass and volcanic lithoclasts. Bioclasts (8%) correspond to branching and laminar corals, bivalves and gastropod shells, demosponge monaxon spicules, echinoderms, ostracods, filamentous algae, vertebrate (fish) and plant remains. Scarce intraclasts (1%) are micritic. The matrix is peloidal micrite. Irregular cavities infilled with sparite are very frequent.

Interpretation

Bioclastic floatstones with siliciclasts (**MF9**) correspond to channel facies formed in a lagoon with a contribution of terrigenous particles from the hinterland and reworked autochthonous elements deriving from the destruction of the patch reefs and from adjacent environments. Metazoan activity produced bioturbation.

Bioclastic wackestones with platy-corals (**MF10**) correspond to the matrix of the reefs formed in the protected lagoon. The low-energy environment favored the formation of micritic mud with the presence of cyanobacteria formed by the micropeloids (Armella et al. 2013). The coral fragments come from the destruction of the reefs, while the algae come from the lagoon.

Bioclastic packstones to rudstones (**MF11**) facies were produced by the destruction of bodies and correspond to storm deposits in the patch reef flank environment.

In facies **MF12**, siliciclastic mudstone wackestones with bioclasts, the presence of terrigenous and plant remains is indicator of the closeness to coastal areas with a significant contribution of particles in subtidal environment. Bioclasts correspond to forms that inhabited the reefs and were buried post-mortem. The cavities comprise bioturbation that originated in burrowing organisms. Coral remains were exposed and covered by micrite and siliciclastic grains.

The inter-reef channels are floatstones with siliciclasts (**MF9**) and, flanks facies are composed of bioclastic- packstones to rudstones with coral debris (**MF11**). In platform non-reefal facies carbonates are composed of bedded bioclastic wackestone-packstone (**MF10**).

Patch reef types of the La Manga Formation

Reefs in the La Manga Formation consist of a series of small patch reefs preserved in situ, extending from shallow subtidal to intertidal-lagoonal-settings on a wide carbonate ramp. Small patch reefs are intergrowths of coral colonies, siliceous sponges and microbialites and associated organisms. They are elongated rigid skeletal structures separated by narrow sandy channels. In plain view, they are ellipsoidal to irregular in shape and may be up to 6 m across and 1–3 m in height above the surrounding sand-floored interareas.

The reef framestones are made up of platy-coral colonies with a more lateral extension on one side, and ramose forms on the top, with a more vertical growth direction on the other side.

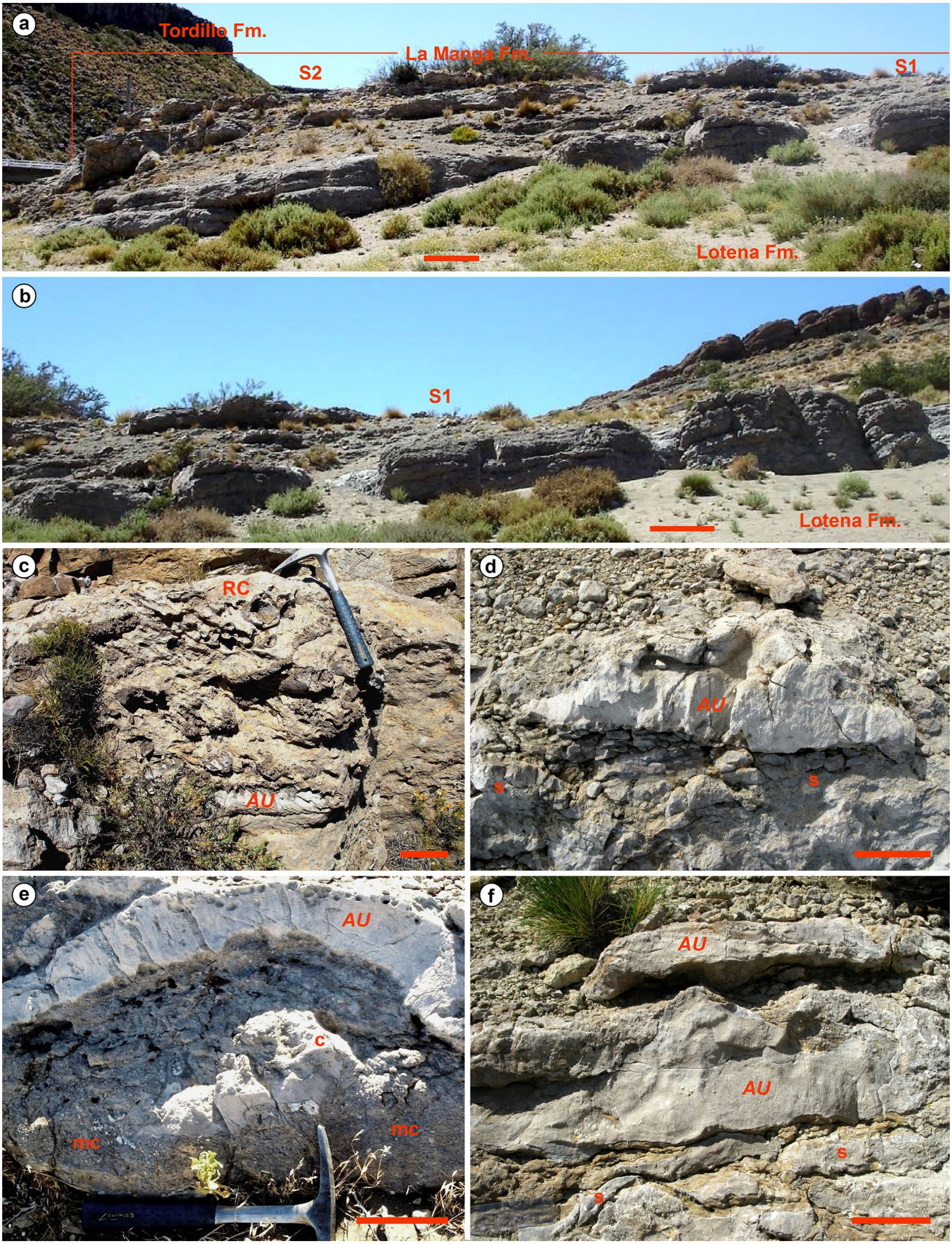
Fig. 6 The Oxfordian typical reefal outcrops of the La Manga Formation, at Portada Covunco, **a** section 1 (S1) and 2 (S 2), **b** section 1(S1). **c** *Australoseris* (*Au*) and silicificated ramose-coral type (*RC*) at the top, section 2. **d** Small patch reef constructed by white meandrinoid platy corals (*Au*) and siliceous sponges (*s*), section 1. **e** *Australoseris* colony (*Au*) and microbialites (*mc*) at section 1. **f** *Australoseris* (*Au*) and siliceous sponges (*s*) at section 2. *Scale bar* is 1 m for **a**–**b**; 10 cm for **c**–**f** ▶

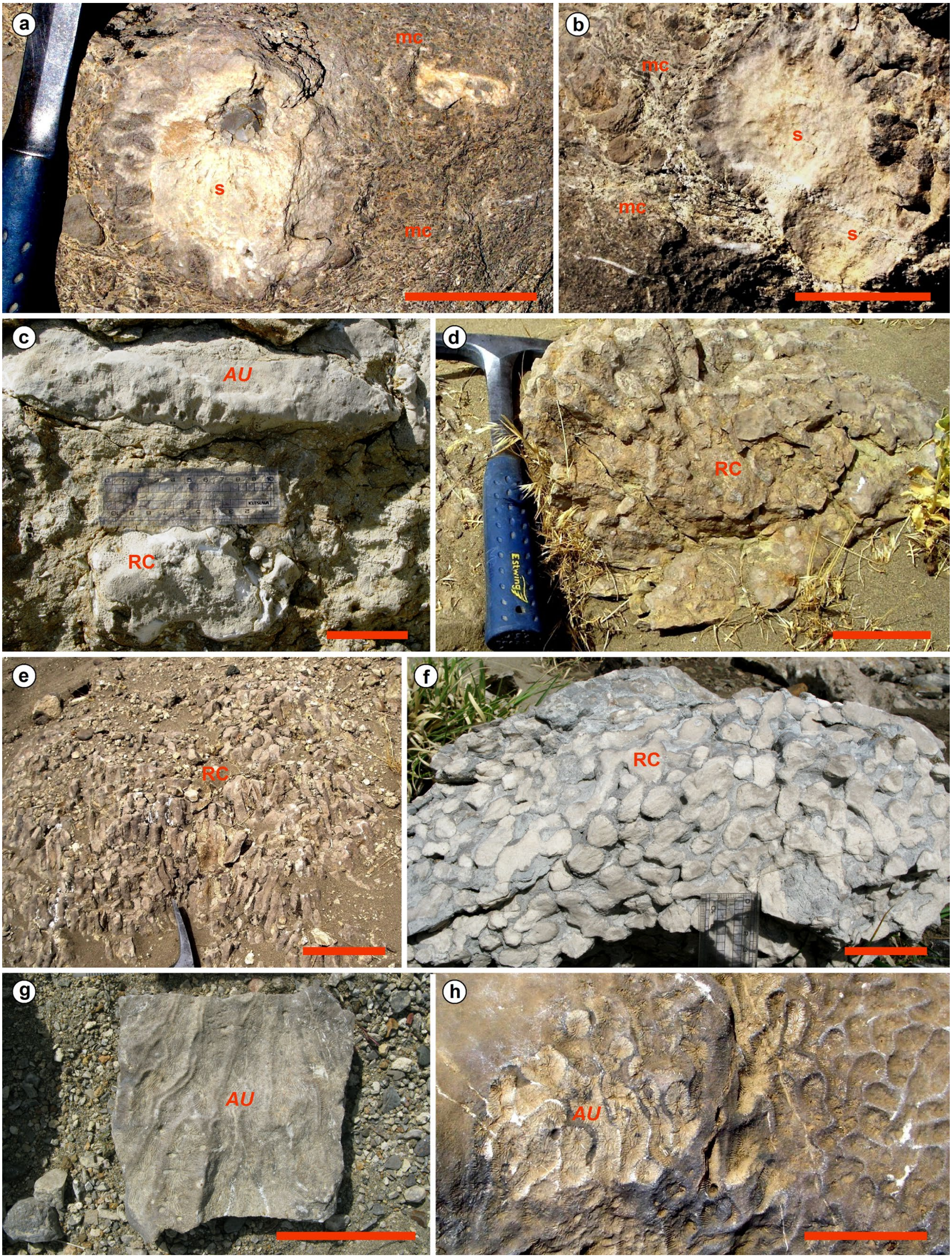
Reefal facies types. The coral patch reefs are comprised of framework constructors and framework fillers, and a consolidated matrix. Major framework constructors are primarily massive and branching corals, siliceous sponges, and microbial crusts (Fig. 6). Reefal facies types are composed of framestone containing large platy and massive corals in growth position, bafflestone which contain in-place stalked ramose corals that trapped sediment by baffling, siliceous sponge-coral framestone (Fig. 6a, b) and microbial bindstone (Figs. 6, 7). The framework fillers are frequently massive and encrusting forms dominating. Coral framestone exhibits a large number of cryptic habitats between and below reef-building organisms and in small reef cavities. Encrusting serpulids and borings are frequent. Bioconstructions with a high biogenic contribution comprise 35% of the reef structure.

Non-reefal facies types. About 55% of the reef structure consists of non-reefal facies. This facies is composed of ooid packstone, bioclastic wackestone-packstone levels and marly limestones with abundant skeletal thin-shelled bivalves, echinoid spines, bryozoans, gastropods, and serpulids worms deposited on inter-reef areas. Limestones are well stratified in beds 15–50 cm thick.

The marly intervals with irregular stratification surfaces are characterized by abundant bioclasts and few dish-shaped sponges and corals and bedding thicknesses vary from 20 cm to thin layers less than 12 cm.

The major difference in the community structure of the inter-reef area is a decrease in the abundance of corals. Texturally, the grains from this facies show a greater degree of abrasion and breakage. The large number of complete,


a
Tordillo Fm.
La Manga Fm.
S2
S1
Lotena Fm.
b
S1
Lotena Fm.
c
RC
AU
d
AU
s
s
e
AU
c
mc
mc
f
AU
AU
s
s


a
mc
s
mc
b
mc
s
mc
s
c
AU
RC
d
RC
e
RC
f
RC
g
AU
h
AU

◂**Fig. 7** Coral-sponge facies at section 1, **a**, **b** siliceous hexactinosan sponge (*s*) surrounded by microbial crusts (*mc*); diameter of sponges: 13 and 11 cm. **c** silicified ramose-coral colonies (*RC*) and massive platy-coral (*Au*). **d**–**f** overview of ramose coral colonies (*RC*). **g**, **h** meandrinoid platy-coral colonies (*Au*). *Scale bar* is 10 cm for **a**, **b**, **d**, **e**; 5 cm for **f**–**h**

unbroken corals shows that the most grew in situ, whereas a smaller number of broken corals appear to have been transported from nearby patch reefs. The inter-reef channels are floatstone with siliciclasts and flanks facies are composed of bioclastic-packstones to rudstones with coral debris. In addition, the peri-reefal areas are comprised of coarse-grained rudstones and floatstones.

Corals

Four scleractinian coral growth forms comprise the coral-dominated patch reefs at Portada Covunco: massive, platy, and thin or thick ramose corals. The corals may reach 1 m in width and height, with branches of 5–60 mm in diameter. The platy corals may reach 50 cm in diameter and 5–20 cm in thickness. Massive corals may reach 50 cm in diameter. Platy coral associations are always sediment-supported, with the exception of a small portion in section 2.

Bioclastic wackestone-packstone with abundant thin-shelled bivalves and small biotic fragments, as well as ooids and coated grains, are all interbedded with the coral colonies. Corals are often iron-stained. Bioerosion on the upper surface of the laminar coral by worm tubes and lithophagid bivalves is frequent, and they are often coated with dark microbial crusts and the boring has been filled by a complex suite of marine sediments and cement.

The reef patches exhibit very low diversity of scleractinian corals. Massive and platy corals are only represented by *Australoseris radialis* (Fig. 7c, g, h), whereas the ramose corals (Fig. 7d–f) represent the genera *Etallonasteria* (Fig. 8a, b), *Stelidioseris* (Fig. 8c, d) and *Stephanastrea* (Fig. 8e, f).

Australoseris is a colonial coral with a meandroid calicular arrangement and relatively large calicular dimensions. The other three genera have a cerioid (*Stephanastrea*) or plocoid (*Stelidioseris*, *Etallonasteria*) calicular arrangement. The plocoid corals have a very narrow coenosteum and therefore appear cerioid. The calicular dimensions—except for *Australoseris*—are small.

Australoseris is only known from the Late Jurassic of the Neuquén Basin. *Etallonasteria* is a relatively rare genus that has its main distribution in the Late Jurassic of Europe, but there is also one occurrence in the early Aptian (Morycowa and Decrouez 2006). Only one species is known—*Etallonasteria minima* (Etallon 1864). The present material has larger dimensions than the type specimen of *Etallonasteria minima* but compares well to material from the Late Jurassic of Europe.

Stelidioseris (as *Actinastrea* or *Astrocoenia*) is a very common Middle Jurassic to early Late Cretaceous genus and widely distributed. It is one of the most common coral genera of the Late Jurassic to Early Cretaceous. Approximately 50 species are known from the Jurassic and another 70 from the Cretaceous. The *Stelidioseris* specimens from the study area cannot be assigned to any Jurassic species because morphometric data of corresponding type material was not available to us. Our specimens are comparable to *Stelidioseris whitneyi* (Wells 1932), which was originally described from the Early Cretaceous of Texas but has a wide stratigraphic distribution from the Late Jurassic to early Late Cretaceous worldwide. The specimens compare well to *Actinastrea* cf. *pivetaui* in Morsch (1990), but the type of *A. pivetaui* belongs to *Actinastrea*, not to *Stelidioseris*.

Stephanastrea is restricted to the Bajocian to the Kimmerdgian and is common in Europa. The present material may belong to *Stephanastrea rollieri* (Koby 1885).

The three latter genera are abundant in shallow-marine environments, as shown from the Late Jurassic of southern Germany (Lauxmann 1991), the Swiss Jura (Koby 1880–1889), the Holy Cross Mountains in Poland (Roniewicz 1966), the Stramberk area in the Czech Republic (Geyer 1955), or Portugal (Koby 1905).

Apart from the above-mentioned material, two large specimens of solitary corals were found within the marl layer of the middle part of section 2 that did not allow determination. The marl layer is accumulated in depressions between the colonial coral patch reefs.

Microbialites

Microbialites are defined as “organo-sedimentary deposits that have accreted as a result of a benthic microbial community trapping and binding detrital sediment and/or forming the locus of mineral precipitation” by Burne and Moore (1987).

Microbialites form a small reef body with approx. 1.70 m thickness and 3-m lateral extension occurring at the basal part of section 2 of the Portada Covunco (Fig. 2). Microscopically, microbialites (Fig. 3a–c) are composed of alternating dark-colored dense micritic filaments and light-colored thin laminae of mm to cm scale, laterally variable and fragmented. Dark micritic filaments form crusts up to several millimeters thick within a clotted to peloidal micrite, with differences in colorations and dispersed black micro fragments. Dense or laminated peloidal micritic areas

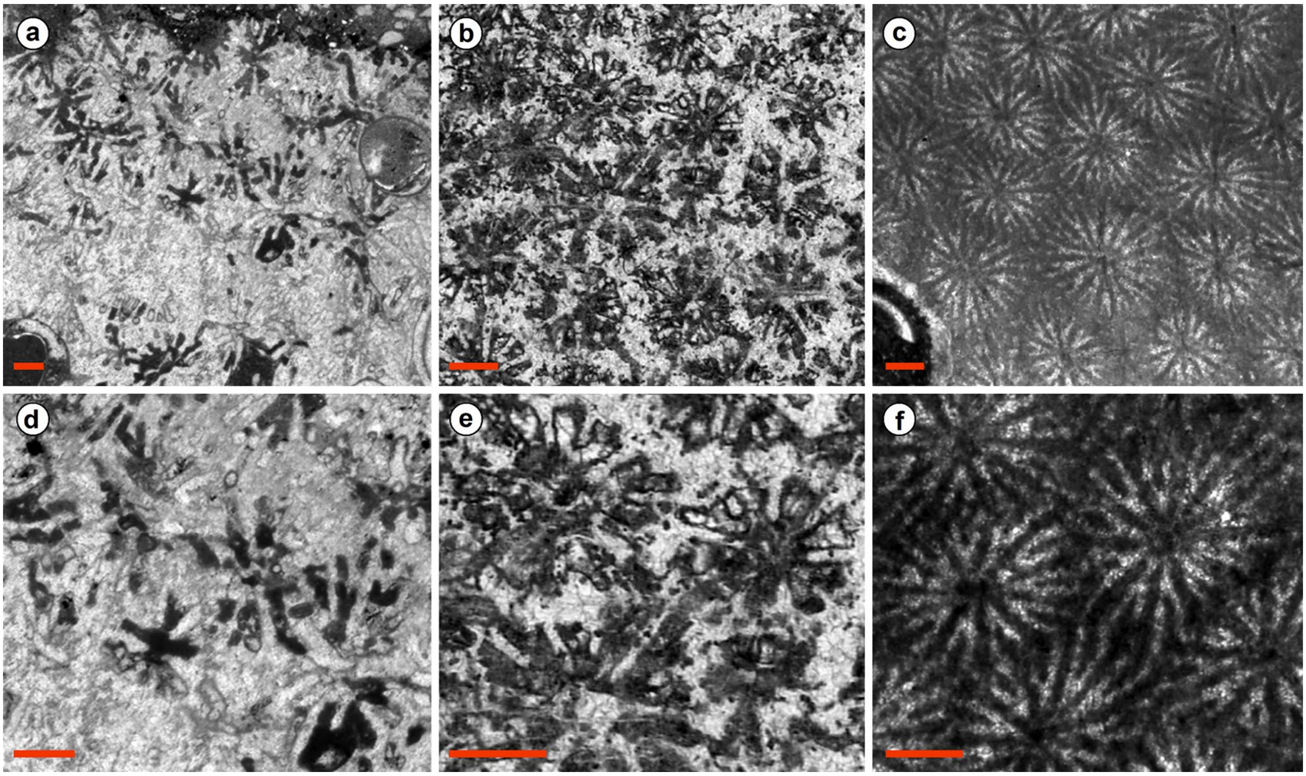


Fig. 8 Thin-sections of corals at the La Manga Formation, Portada Covunco. **a** *Etallonasteria* sp. IANIGLA-PI 992. **b** Detail of **a**, IANIGLA-PI 992. **c** *Stelidioseris* sp. IANIGLA-PI 996. **d** Detail of **c**, IANIGLA-PI 996. **e** *Stephanastrea rollieri* (Koby 1885), IANIGLA-PI 991. **f** Detail of **e** IANIGLA-PI PI 991. *Scale bar* is 1 mm for all figures

prevail. Locally, the common and distinctive contorted laminations resemble stromatolitic structures. Inside the laminae there are no encrusting components, such as foraminifera, bryozoans, or others skeletal or algal elements.

In the coral-sponge patch reef, microbialites encrust mainly the lower surfaces of the corals, forming overgrowths on skeletal hard parts, and are particularly common between corals, on siliceous sponges or on sediments (Fig. 7a, b). It is also possible that microbial crusts developed on dead portions of coral colonies.

Microbialites occur in low- and, more rarely, in high-energy regimes, in shallow and deep water as well as in oxygenated and oxygen-depleted environments (Leinfelder et al. 1994, 1996). They are very eurytopic, tolerating a wide range of habitats and are widely distributed. Reduced background sedimentation is the most important prerequisite for the development of microbial mats (Leinfelder 1993). The widespread occurrence of microbialites suggests mesotrophy and eutrophy, with arguably more nutrients and a local more humid climatic condition in the Late Oxfordian (Pittet et al. 2000). Between the microbial community and coral reefs, irregular channels were infilled with bioclastic serpulid wackestone and oriented white thin-shelled pelagic bivalves (“filaments”).

Sponges

Siliceous sponges are a rare component of the La Manga reef framework, and never developed biogenic structures at Portada Covunco sections. Dish and cup-shaped hexactinellids (mainly dictyonal skeleton), platy “lithistid” demosponges and uncertain coralline sponges, are all poorly preserved. Specimens of dictyonid sponges were mostly calcified but sometimes show partial dissolution or micritization. The skeleton of “lithistid” sponges is altered by crystallization. Siliceous sponges are commonly overgrown by dense microbial crusts (Fig. 7a, b) in association with serpulids. Some crustose forms could indicate coralline sponges on the upper side of corals.

Hexactinellids, with their dictyonal skeletons include the Hexactinosa and Lychniscosa. These groups are restricted to a few levels within the mixed coral-sponges facies. They can reach a diameter of 15–33 cm width and 30 cm high, and within one level, the diameter is more or less constant. The majority belong to the Dictyida (cf. *Stauroderma* and *Cribrospongia*).

There is a predominance of siliceous, dish-shaped sponges with respect to other morphotypes. Dictyonid sponges, growing upright as small cylinders on corals

(Fig. 5b), and isolated spicules can be observed in some thin-sections (Fig. 5c).

In the outcrops of the Portada Covunco Bridge—section 2—(Fig. 6b), "lithistids" and lychniscoid sponges occur embedded in a marl-limestone layer (less than 30 cm thick). Large cup-shaped hexactinellids from coral-sponge framestone distinguish from the marl layer dominated by platy and small tube-shaped sponges. Marl layers with irregular stratification surface also bear white filaments and isolated spicules, indicating quiet and deeper-water conditions. Marl-dominated intervals alternate with coral-bioclastic wackestone-packstone facies.

Accompanying faunas

Invertebrates account for approximately 15% of fauna. Together with the corals, the benthic community included suspension feeders, grazing herbivores, and scavenger organisms. The most conspicuous benthic fossils are bivalves, brachiopods (some rhynchonellid?), crinoids, cidaroid echinoids, disarticulated ostracods, siliceous sponges, uncertain coralline sponges, and foraminifera. A variety of micro-encrusting organisms such as algae, serpulids, and crustose bryozoans are found to cover parts of corals and sponges, boring metazoans (lithophagid bivalves, sponges and serpulids) and *Crescentiella?* (Senowbari-Daryan et al. 2008) are constituents of the community.

Among algae, dasyclads are the most abundant. Spherical dasyclad algae (Figs. 3e, 5e) probably belong to the *Acicularia-Terquemella* group. These algae are considered as the reproductive bodies (gametophores) of some dasyclad algae in deposits of Late Jurassic–Early Cretaceous age (Bucur et al. 2008).

Boring organisms and lithophagid bivalves (Fig. 4b) produce lime mud. Bivalves required a hard, or at least firm, substrate for colonization. Bryozoans and foraminifers with poor preservation of the wall structure, sponge spicules, and, rarely, fragment of coralline sponges occur in the assemblage. These organisms grow in the many nooks and crannies, between larger skeletal metazoan and corals. Clusters of the thin-shelled pectinacean bivalves, gastropods (Fig. 4f)-as internal moulds—and bryozoans ("*Berenicea*"?) are less important constituents, occurring embedded within the micrite matrix. Boring organisms and serpulids are very frequent (Fig. 3f). White dots are possibly the microproblematicum *Crescentiella* occurring as one or more internal cavities in the intertidal facies. *Crescentiella (Tubiphytes* in old literature) and similar organisms are a microproblematic group of Mesozoic shallow-water carbonates.

Discussion

Evidence of the evolution of the Oxfordian La Manga reefal facies and their associated paleoenvironments is present at the Portada Covunco sections (Fig. 9). In these sections, we identified several shallowing-upward episodes as evidenced by local erosional surfaces (main exposure surface-MES) (Fig. 2). These succession records are 0.32–2.20 m in thickness. The thinner succession corresponds to Portada Covunco Creek, while the thicker is observable at Portada Covunco Bridge. Nevertheless, the less exposure surfaces (LES) are related to storm waves or current actions, which indicate local redistribution of sediments due to the water motion and sediment entrainment. Both sections exhibit a regional exposure surface (RES), which were identified in other localities of the Sierra de la Vaca Muerta. The regional exposure surface (RES) situated at 2.35 m from the base at Portada Covunco Creek and 3.5 m from the base at Portada Covunco Bridge are linked to one regional sea level change (Howell et al. 2005).

Based on results of 12 facies/microfacies types and the vertical successions of coral morphotypes and fossil assemblages we infer a shallowing-upward trend ranging from a shallow subtidal-lagoon- to intertidal settings (Table 1).

The transgressive sequence above the fluvio-deltaic and marginal marine facies (Lotena Formation) enabled the development of a carbonate platform with oolitic shoal bars (MF4) in the intertidal zone; back shoal carbonates (MF5) and the development of reefs (Fig. 9). Reefs consist of small patch reefs with related lagoonal facies (MF6; MF7), and a microbial boundstone (MF2). Framework constructors are primarily massive and branching corals, siliceous sponges and microbes. Reefal facies developed in shallow intertidal, subtidal (MF6; MF7), and peritidal (MF2) environments (Table 1).

The Neuquén coral patch reefs display a transition from deeper platy-colonies to shallower ramose-coral colonies as the reefs grew, which has been observed several times (Beresi et al. 2008, 2010).

The concept of "ecological succession" has been frequently applied in the study of ancient reefs. Most successional models are based on ancient fossil reef complexes, which differ in several aspects from modern coral reefs (Kiessling et al. 1999). An "ecological succession" sensu Walker and Alberstadt (1975) with pioneering (stabilization and colonization), diversification and domination stages was documented rigorously for the first time in the Late Jurassic reefs in the Western High Atlas of Morocco (Olivier et al. 2012). In contrast to classical examples of ecological successions, many studies emphasize the role of physical environmental factors for vertical successions. The morphological and biological variability of reefs involve

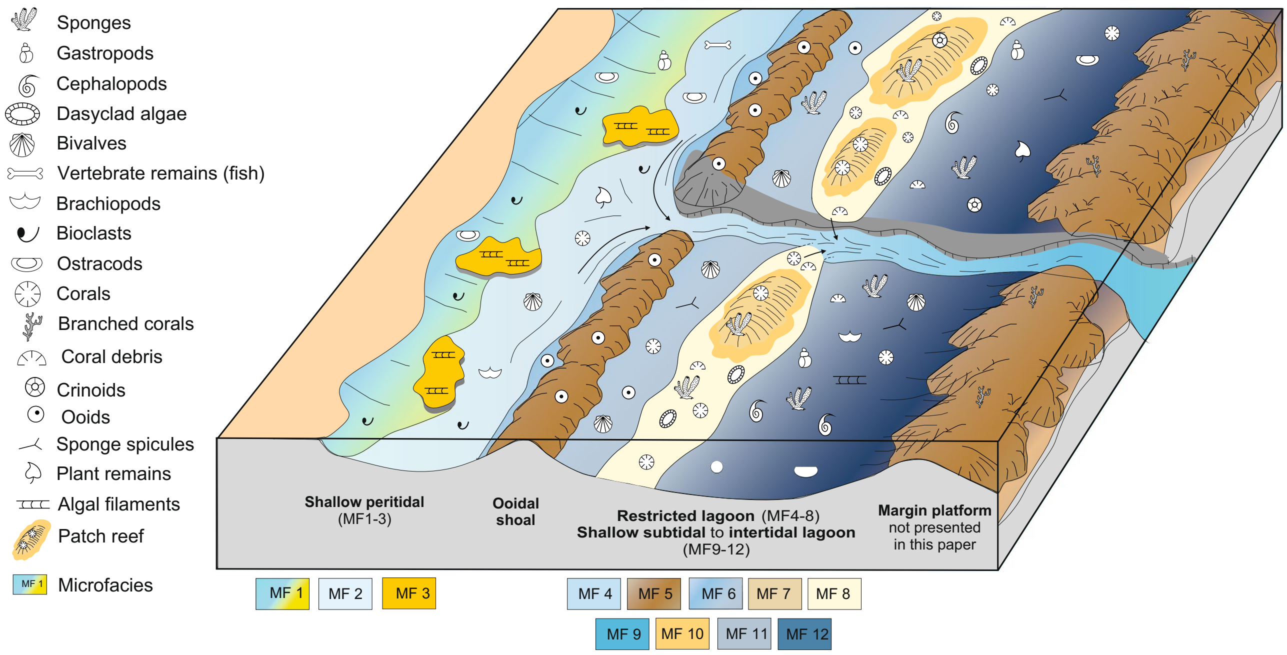


Fig. 9 A schematic block-diagram of the Mid-Oxfordian La Manga Formation, summarizing the general carbonate facies/microfacies distribution, the position of patch reefs, shoal *bars* and associated reef fossil assemblages in a platform setting. Outer platform deposits are not studied in the present paper

interactions between chemical, biological, and physical processes. Biological factors affecting spatial competition are thus probably more important than geologic controls on reef evolution (Kiessling 2009).

It is well established that corals and other benthic organisms distribute themselves on the reef in response to ambient environmental parameters (Done 1983). Studies of such controlling factors include the water depth in Pleistocene reefs from the Caribbean (e.g., Geister 1984b); wave energy (Hubbard 1997); light intensity and water flow velocity (Kruszyński et al. 2007); and, an allogenic, sea-level controlled community change in a late Pleistocene coral reef from Sinai Peninsula, Egypt (Mewis and Kiessling 2013).

Benthic zonation within a single reef is to a large extent determined by the relative abilities of various organisms to survive the turbulent conditions of breaking waves (Hubbard 1997).

The vertical succession of coral morphotypes of massive meandrinoid platy-corals (exclusively *Australoseris*) followed by ramose-corals (*Etallonasteria*, *Stelidioseria*, and *Stephanastrea*), probably represents local changes in environmental conditions such as water depth, caused by sea-level fluctuations or reef growth. Therefore, we interpreted the change as the replacement of one community of reef building by another (cf. Olivier et al. 2012) controlled by extrinsic physical (episodic sea-level fluctuations) parameters according to a community replacement rather than an ecological succession (Aronson et al. 1998; Mewis and Kiessling 2013).

According to Rosen et al. (2000), the platy-coral stratigraphically "lowest facies" also equate to the greatest water depths relative to the other coral assemblages, and/or more turbid environments with slow sedimentation rates. The decreasing light intensity (e.g., due to suspended sediments) induced the growth of the plate-like colonies, which were able to remove the unwanted particles of their calicular surface (Matheos and Morsch 1990). The decreasing bathymetry and high sedimentary input induce the dominance of branching corals and sediment-adapted colonial structures (Thornborough and Davies 2011). The dominance of ramose coral colonies is indicative of shallower, well-illuminated waters (Morsch 1990; Insalaco 1996).

The biotic zonation of recent reefs is commonly used as a powerful proxy to reconstruct Cenozoic fluctuations of sea-level (e.g., Geister 1984a), while the zonation of Jurassic reefs is poorly explored (Lathuilière et al. 2005). Good examples of coral zonation are the coral associations of the Late Jurassic reef complex at Cape Ghir, Atlantic High Atlas, Morocco (Martin-Garin et al. 2007) and the Oxfordian reef tract in the northern French Jura (Lathuilière et al. 2005). In the French Jura, the slow-growing corals appear first (lamellar microsolenid corals adapted to poor light conditions), dome-shaped and branching fast-growing corals appear later with high light requirements. Both the reduction in growth rate and change in growth form have been interpreted as a response to a reduction in light availability in the deep-water reefs (Insalaco 1996). The transition between these two reef growth phases has been interpreted as a reflection of a crisis in the coral ecosystem (Olivier et al. 2004).

The study of drill cores (Thornborough and Davies 2011) also reveals that the coral-dominated reef flat is composed of an initial stage of massive coral growth in water depths of approximately 10 m, followed by mixed massive and branching biofacies, with branching corals dominating as the reef approaches sea level.

It is probable that the vertical succession of coral morphologies at Portada Covunco represents a zonation similar to the late Oxfordian reef tract in southern France (Lathuilière et al. 2005). In this case, the position of platy-coral colonies constitutes the first stage of each shallowing-upward episode (pioneering assemblages) for the colonization of the patch reefs (Fig. 2) and evolved toward ramose corals when suitable ecological conditions were present. The rapid growth of ramose corals can cause them to rise above the seafloor (Hubbard 1997).

The successive change in coral morphotypes may probably be interpreted as a bathymetric trend, linked mainly to local sea-level fluctuations. It seems plausible that local sea-level fluctuations might have affected the composition of coral reef communities and controlled the coral diversity at Portada Covunco. Where the rate of local sea-level fluctuations is faster than the rate of growth of corals formed in place, the coral type could change, in response to the fluctuations (e.g., Insalaco et al. 1997). Nevertheless, superimposed larger scale sedimentary cycles might also be due to sea level change, as Legarreta states (1991), assuming eustatic sea-level control (second-order sea level fluctuations) of the Late Jurassic La Manga in high paleolatitudes (ca. 38° south).

We also note that the laminar platy and massive coral colonies show a more lateral extension on one side, and ramose forms on the top show a more vertical growth direction on the other side. As coral reefs serve as natural breakwaters against wave energy, it is probable that the distribution of these morphotypes changed from windward to leeward. Based on a modern example, this pattern could be interpreted as an expression of prevailing energy conditions. This is the case of the modern flat reef—One Tree Reef—in the Capricorn Bunker Group in the southern Great Barrier Reef (Marshall and Davies 1982; Thornborough and Davies 2011). In this reef, the branching coral cover is greatest in the leeward section, while the windward section is dominated primarily by massive corals, and secondarily by low-branching forms. The distribution of these forms changes transversally across and longshore the coral flat.

On the other hand, rigid siliceous sponges ("lithistid" demosponges and dictyd hexactinellids), together with, for the most part, platy-corals, are restricted to the mixed coral-sponge reefal facies, where sponges are strongly recrystallized. Like most modern hexactinellids, Jurassic sponges occupied relatively distal and deepest-water environments with low-energy conditions; meanwhile "lithistids" and possibly lychniscosans tolerate shallower environments (Krautter 1997; Leinfelder et al. 1993). The widespread occurrence of siliceous sponge facies depends on periods of regionally lowered sedimentation rate, short-term oxygenated conditions, and high sea levels (Leinfelder et al. 1994, 1996).

Within the coral facies of Portada Covunco, these sponge groups occur in low percentages, with only few individuals. It is probable that the sea-floor conditions and the shallow intertidal and lagoon settings offered poor conditions for a wider siliceous sponge facies development.

Conclusions

This study documents the microfacies and the vertical successions of coral morphotypes and proposes a depositional model for the La Manga Formation at Portada Covunco locality, Neuquén Basin. The vertical succession displays a general shallowing-upward trend, evidenced by the associated microfacies (lagoonal facies from shallow subtidal to peritidal), the vertical successions of coral morphotypes and fossil assemblages whose growth pattern is enclosed by the main exposure surfaces (MES). Reefs had relatively low coral diversity at the Portada Covunco locality.

The vertical succession starts with meandrinoid platy-corals made entirely of *Australoseris radialis* followed by ramose corals (*Etallonasteria, Stelidioseris*, and the species *Stephanastrea rollieri*). It is probable that the distribution of these morphotypes changed from windward to leeward.

We propose here, for the first time, that the Portada Covunco coral reefs show the replacement of one community of reef building by another as the reefs grew. The upward change in reefal composition (zonation) is best interpreted as a response to episodic local fluctuations of the sea level (MES); shallowing-upward episodes were determined. Otherwise, the minor episodes (LES) suggest erosion and sedimentation events.

Siliceous sponges (mainly dictyonine hexactinellids and "lithistid" demosponges) and calcimicrobes appear to be a sign of short-lived communities within the shallow-carbonates coral facies.

In spite of the particular characteristics of the La Manga reefal carbonates, they can be correlated with the Late Jurassic "*global carbonate reef event*" or *"reef age"*. The event occurred throughout the Jurassic epicontinental seas, bordering the northern margin of the Tethyan Ocean and the marginal basins of the young North Atlantic Ocean, in low paleolatitude. However, the coral facies of la Manga Formation occurred in high paleolatitude (near 39° south), within an embayment of the Neuquén Basin, with open circulation to the paleo-Pacific Ocean on the south-western margin of the Gondwana realm.

Acknowledgements MB, NC, and CA were financially supported by CONICET. HL received a travel grant within the Academic Interchange Program of the Universidad Nacional Autónoma de México. We are especially indebted to Dr. W. Volkheimer for his continuous support of our work and to Dr. P. Narváez and Dr. J. D´Angelo (IANIGLA, Mendoza) for their assistance during the field work. We thank R. Cocca (Dirección Provincial de Minería, Zapala) for his friendly assistance to HL during field work. Thin-sections were prepared at the INGEIS, University Buenos Aires and coral sections at the Universidad Nacional Autónoma de México, IGL, ERNO (Hermosillo, Sonora, Mexico). The figures were prepared by R. Bottero (IANIGLA, CONICET-Mendoza) and G. Giordanengo (INGEIS, CONICET-UBA). We thank T. Helm for his help correcting the English. Dr. N. Olivier and an anonymous reviewer are thanked for their helpful comments and suggestions.

References

Al-Suwaidi AH, Angelozzi GN, Baudin F, Damborenea SE, Hesselbo SP, Jenkyns HC, Manceñido MO, Riccardi AC (2010) First record of the early Toarcian Oceanic anoxic event from the southern hemisphere, Neuquén Basin, Argentina. J Geo Soc 167(4):633–636

Armella C, Cabaleri N, Leanza HA (2007) Tidally dominated rimmed-shelf facies of the Picún Leufú Formation (Jurassic/Cretaceous boundary) in southwest Gondwana, Neuquén Basin, Argentina. Cretac Res 28(6):961–979. doi:10.1016/j.cretres.2007.01.001

Armella C, Cabaleri N, Leanza HA (2008) Facies de *patch reef* del Jurásico superior (Formación Picún Leufú) en la región de Zapala, Cuenca Neuquina. Rev Mus Argent Cienc Nat 10(1):63–70

Armella C, Cabaleri N, Cagnoni MC, Panarello H (2013) Early Callovian ingression in southwestern Gondwana. Palaeoenvironmental evolution of the carbonate ramp (Calabozo Formation) in southwestern Mendoza, Neuquén Basin, Argentina. J South Am Earth Sci 45:293–315

Aronson RB, Precht WF, Macintyre IG (1998) Extrinsic control of species replacement on a Holocene reef in Belize: the role of coral disease. Coral Reefs 17:223–230

Bádenas B, Aurell M (2001) Proximal–distal facies relationships and sedimentary processes in a storm-dominated carbonate ramp (Kimmeridgian, northwest of the Iberian Ranges, Spain). Sediment Geo 139(3):319–340. doi:10.1016/S0037-0738(00)00151-2

Beresi MS (2003) Oxfordian sponge association from the Neuquén Basin, Mendoza, west-central Argentina. J South Am Earth Sci 16(3):105–112. doi:10.1016/S0895-9811(03)00047-6

Beresi MS, Krautter M (2007) Oxfordian siliceous sponge facies from the southern Mendoza, Neuquén Basin, Argentina. In: 3th Simposio Argentino del Jurásico, Mendoza, Argentina, p 30

Beresi MS, Cabaleri N, Armella C (2008) Coral facies of the La Manga Formation at the Portada Covunco, Neuquén Basin. In: 12th Reunión Argentina de Sedimentología, Buenos Aires, p 42

Beresi MS, Cabaleri N, Armella C (2010) Characterization of the Oxfordian coral-reef types, at Portada Covunco, Neuquén Basin. In: 18th International Sedimentological Congress, Mendoza, Argentina, p 171

Bucur I, Granier B, Sâsâran E (2008) Upper Aptian calcareous algae from Pâdurea Craiului (northern Apuseni Mountains, Romania). Geol Croat 61(2–3):297–309

Burne RV, Moore L (1987) Microbialites: organo-sedimentary deposits of benthic microbial communities. Palaios 2:241–254

Cabaleri N, Armella C, Cagnoni M, Ramos A, Valencio S (2003) Carbonate ramp facies at the Calabozo Formation (Middle Jurassic), Mendoza, Argentina. Andean Geol 30(2):205–221

Carannante G, Cherchi A, Simone L (1995) Chlorozoan versus foramol lithofacies in Upper Cretaceous rudist limestones. Palaeogeog Palaeoclim Palaeoecol 119:137–154

Cecca F, Martin- Garin B, Marchand D, Lathuilière B, Bartolini A (2005) Paleoclimatic control of biogeographic and sedimentary events in Tethyan and peri-Tethyan areas during the Oxfordian (Late Jurassic). Palaeogeog Palaeoclim Palaeoecol 222:10–32. doi:10.1016/j.palaeo.2005.03.009

Chow N, George AD, Trinajstic KM, Chen Z (2013) Stratal architecture and platform evolution of an early Frasnian syn-tectonic carbonate platform, Canning Basin, Australia. Sedimentology 60:1583–1620. doi:10.1111/sed.12041

Copper P (1994) Ancient reef ecosystems: expansions and collapse. Coral Reef 13:3–11

Done TJ (1983) Coral zonation: its nature and significance. In: Barnes DJ (ed) Perspectives on Coral Reefs. Australian Institute of Marine Sciences, Townsville, pp 95–147

Dunham RJ (1962) Classification of carbonate rocks according to depositional texture. In: Ham WE (ed) Classification of carbonate rocks. Amercan Association of Petroleum Geologist, Memoir, vol 1, pp 108–121

Dupraz C, Strasser A (2002) Nutritional modes in coral-microbialite reefs (Jurassic, Oxfordian, Switzerland): evolution of trophic structure as a response to environmental change. Palaios 17:449–471

Embry AF, Klovan JE (1971) A late Devonian reef tract on northeastern Banks Island, Northwest Territories. Bull Can Pet Geol 19:730–781

Etallon A (1864) Classe des Polypes. In: Thurmann J, Etallon A (eds) Lethea Bruntrutana, ou études paléontologiques et stratigraphiques sur le Jura bernois et, en particulier, sur les en virons de Porrentruy. Neue Denkschriften der allgemeinen Schweitzerischen Gesellschaft für Naturwissenschaften 20, 357–464

Flügel E (2004) Microfacies of carbonate rocks. Analysis, interpretation and application. Springer, Berlin, p 976

Gabrig Turbay CV, De Cesero P, Vasconcelos M, Garcia AJ, Carvalho Silva R (2013) Depositional, diagenetic and stratigraphic aspects of microfacies from Riachuelo Formation, Albian, Sergipe Basin, Brazil. Rev do Inst de Geociências-USP 13(4):2–48. doi:10.5327/Z1519-874X201300040002

Gaillard C (1983) Les biohermes à spongiaires et leur environnement dans l´Oxfordien du Jura Méridienal. Doc Lab Géol Lyon 90:515

Geister J (1984a) Holozäne westindische Korallenriffe: geomorphologie, Ökologie und Fazies. Facies 9:173–284

Geister J (1984b) Récifs pleistocenes de la mer des caraibes: aspects géologiques et paléoécologiques. In: Geister J, Herb R (eds) Géologie et Paléoécologie des Récifs. Inst Géol I'Universite Berne, pp 3.1–3.34

Geyer OF (1955) Beiträge zur Korallenfauna des Stramberger Tithon. Paläont Z 29:177–216

Götz S, Löser H, Schmidt D (2005) Reef development on a deepening platform: two early Cretaceous coralgal patch reef (Catí, Llacova Formation, eastern Spain) compared. Cretac Res 26:864–881. doi:10.1016/j.cretres.2005.05.008

Groeber P (1946) Observaciones geológicas a lo largo del meridiano 70. 1. Hoja Chos Malal. Revista de la Sociedad Geológica Argentina 1(3):177–208

Gulisano CA, Gutiérrez Pleiming AR (1995) The Jurassic of the Neuquén Basin, Neuquén Province, Field Guide. Asoc Geol Argent Ser E 2:111

Hallock P, Schlager W (1986) Nutrient excess and the demise of coral reefs and carbonate platforms. Palaios 389–398

Howell JA, Schwarz E, Spalletti LA, Veiga GD (2005) The Neuquén basin: an overview. Geo Soc Lond Sp Pub 252(1):1–14

Hubbard DK (1997) Reefs as dynamic systems. In: Birkeland C (ed) Life and death of coral reefs. Chapman and Hall, New York, pp 43–67

Insalaco E (1996) The use of Late Jurassic coral growth bands as palaeoenvironmental indicators. Palaeontology 39:413–431

Insalaco E, Hallam A, Rosen B (1997) Oxfordian Upper Jurassic Coral reefs in Western Europe: reef types and conceptual depositional model. Sedimentology 44(707):734

Kiessling W (2009) Geologic and biologic controls on the evolution of reefs: annual review of ecology. Evol Syst 40:173–192

Kiessling W, Flügel E, Golonka J (1999) Paleo reef maps: evaluation of a comprehensive database on Phanerozoic reefs. Am Assoc Pet Geol Bull 83:1552–1587

Koby F (1880–89) Monographie des polypiers jurassiques de la Suisse. (1880–1889). Abh Schweiz Paläont Ges 7–16: 1–582

Koby F (1885) Monographie des polypiers jurassiques de la Suisse, cinquième partie. Abh Schweiz Paläontol Gesell (Mém Soc Paléont Suisse) 12:213–304

Koby F (1905) Description de la faune jurassique du Portugal, polypiers du Jurassique supérieur.Commission du Service Géologique du Portugal, pp 1–167

Krautter M (1997) Aspekte zur Palaokologie postpalaozoischer Kieselschwamme. Institut Geologie und Palaontologie, Stuttgart. Profil 11:199–324

Kruszyński KJ, Kaandorp JA, van Liere R (2007) A computational method for quantifying morphological variation in scleractinian corals. Coral Reefs 26:831–840

Lathuilière B, Gaillard C, Habrant N, Bodeur Y, Boullier AR, Hanzo MD, Thierry J, Werner W (2005) Coral zonation of an Oxfordian reef tract in the northern French Jura. Facies 50(3–4):545–559

Lauxmann U (1991) Revision der oberjurassischen Korallen von Württemberg (SW-Deutschland), exclusive Fungiina. Palaeontogr A 219:107–175

Leanza HA (1992) Estratigrafía del Paleozoico y Mesozoico anterior a los Movimientos Intermálmicos en la comarca del Cerro Chachil, provincia del Neuquén. Rev Asoc Geol Argent 45(3–4):272–299

Leanza HA, Hugo C (2001) Hoja Geológica 3969-I, Zapala, Provincia del Neuquén (1:250.000) Programa Nacional de Cartas Geológicas, Instituto de Geología y Recursos Minerales. Bol 275, Serv Geol Min Arg, Buenos Aires

Legarreta L (1991) Evolution of a Callovian–Oxfordian carbonate, margin in the Neuquén Basin of west central Argentina: facies, architecture, depositional sequences and global sea-level changes. Sed Geo 70:209–240

Legarreta L, Uliana MA (1996) The Jurassic succession in west-central Argentina: stratal patterns, sequence and paleogeographic evolution. Palaeogeog Palaeoclim Palaeoecol 120:303–330

Legarreta L, Uliana MA (1999) El Jurásico y Cretácico de la Cordillera Principal y de la Cuenca Neuquina. 1. Facies Sedimentarias. In: Caminos R (ed) Geología Argentina, Anales 29. Serv Geol Min Arg, Buenos Aires, pp 399–416

Legarreta L, Gulisano CA, Uliana MA (1993) Las secuencias sedimentarias jurásico-cretácicas. In: Relatorio 12th Cong Geol Arg, Mendoza, vol 9, pp 87–114

Leinfelder RR (1993) Upper Jurassic reef types and controlling factors. A preliminary report. Inst Geol Pal Univ Profil 5:1–45

Leinfelder RR (2001) Jurassic reef ecosystems. In: Stanley GD Jr (ed) The history and sedimentology of ancient reef systems, topics in geobiol series 17. Kluwer/Plenum Press, New York, pp 251–309

Leinfelder RR, Nose M, Schmid DU, Werner W (1993) Microbial crust of the Late Jurassic: composition, palaeoecological significance and importance in reef construction. Facies 29:195–230

Leinfelder RR, Krautter M, Laternser DGR, Nose M, Schmid DU, Schweigert G, Luterbacher H (1994) The origin of Jurassic reefs: current research developments and results. Facies 31(1):1–56

Leinfelder RR, Werner W, Nose M, Schmid DU, Krautter M, Laternser R, Takacs M, Hartmann D (1996) Paleoecology, growth parameters and dynamics of coral, sponge and microbolite reefs from the Late Jurassic. In: Reitner J, Neuweiler F, Gunkel F (eds) Global and regional controls on biogenic sedimentation: i. reef evolution, research reports. Gfttinger Arb Geol Paleont Sb 2, pp 227–248

Leinfelder RR, Schmid DU, Nose M, Werner W (2002) Jurassic reef patterns-The expression of a changing globe. In: Flügel E, Kiessling W, Golonka J (eds) Phanerozoic reef patterns, SEPM Sp P 72, Tulsa, pp 465–520

Marshall JF, Davies PJ (1982) Internal structure and Holocene evolution of one tree reef, Southern Great Barrier Reef. Coral Reefs 1:21–28

Martin-Garin B, Lathuilière B, Geister J, Chellai EH, Huault V (2007) Geology, facies model and coral associations of the Late Jurassic reef complex at Cape Ghir (Atlantic High Atlas, Morocco). CR Geosci 339:65–74

Martin-Garin B, Lathuilière B, Geister J (2012) The shifting biogeography of reef corals during the Oxfordian (Late Jurassic). A climatic control? Palaeogeo Palaeocl Palaeoec 365:136–153

Matheos SD, Morsch SM (1990) Geochemistry and paleoecological aspects of coral bearing limestones from the Upper Jurassic at the Southern end of Sierra de La Vaca Muerta, Neuquén Basin, Argentina. Neues Jahrbuch Geologisches Paläontologische Abhandulgen 181:159–169

Merino-Tome O, Della Porta G, Kenter JAM, Verwer K, Harris P, Adams EW, Playton T, Corrochano D (2012) Sequence development in an isolated carbonate platform (Lower Jurassic, Djebel Bou Dahar, High Atlas, Morocco): influence of tectonics, eustacy and carbonate production. Sedimentology 59:118–155. doi:10.1111/j.1365-3091.2011.01232.x

Mewis H, Kiessling W (2013) Environmentally controlled succession in a late Pleistocene coral reef (Sinai, Egypt). Coral Reefs 32:49–58

Monty CLV (1967) Distribution and structure of recent stromatolitic algal mats, eastern Andros Island, Bahamas. Ann Soc Géol Belgique 90(3):55–100

Monty CLV, Hardie LA (1976) The geological significance of the freshwater blue–green algal Calcareous Marsh. In: Walter MR (ed) Stromatolites. Developments in Sedimentology 20. Elsevier, Amsterdam, pp 447–477

Mori K (1963) Geology and paleontology of the Jurassic Somanakamura Group, Fukushima Prefecture, Japan. Science Report of Tohoku University, 2nd Series (Geology), vol 35, pp 33–65

Morsch S (1990) Corales (*Scleractinia*) de la extremidad sur de la Sierra de La Vaca Muerta, Formación La Manga (Oxfordiano), Provincia del Neuquén, Argentina. Ameghiniana 27(1–2):19–28

Morycowa E, Decrouez D (2006) Early Aptian scleractinian corals from the Upper Schrattenkalk of Hergiswil (Lucerne region, Helvetic Zone of central Switzerland). Revue de Paléobiologie, Genève 25:791–838

Olivier N, Pittet B, Mattioli E (2004) Palaeoenvironmental control on sponge-microbialite reefs and contemporaneous deep-shelf marl-limestone deposition (Late Oxfordian, southern Germany). Palaeogeog Palaeoclim Palaeoecol 212:233–263

Olivier N, Martin-Garin B, Colombie C, Cornee JJ, Giraud F, Schnyder J, Kabbachi B, Ezaidi K (2012) Ecological succession evidence in an Upper Jurassic coral reef system (Izwarn section, High Atlas, Morocco). Geobios 45(6):555–572

Olóriz F, Reolid M, Rodríguez-Tovar FJ (2003) A Late Jurassic carbonate ramp colonized by sponges and benthic microbial communities (External Prebetic, Southern Spain). Palaios 18(6):528–545. doi:10.1669/0883-1351

Palma R, Kietzmann DA (2008) Ciclos de somerización en facies peritidales de la Formación La Manga: tipos, origen y controles. Dissertation, 12th Reunión Argentina de Sedimentología, Buenos Aires, pp 133

Palma R, López-Gómez J, Piethé RD (2007) Oxfordian ramp system (La Manga Formation) in the Bardas Blancas area (Mendoza Province) Neuquén Basin, Argentina: facies and depositional sequences. Sediment Geo 195(3):113–134. doi:10.1016/j.sedgeo.2006.07.001

Palma R, Kietzmann DA, Martín-Chivelet J, López-Gómez J, Bressan G (2012) New biostratigraphic data from the Callovian–Oxfordian La Manga Formation, Neuquén Basin, Argentina: evidence from an ammonite condensed level. Rev Paléobiol Genève Vol Spéc 11:345–356

Parent H (2006) Oxfordian and Late Callovian ammonite faunas and biostratigraphy of the Neuquén, Mendoza and Tarapacá basins (Jurassic, Ammonoidea, western South America). Inst Fisiog Geol (Rosario) Bol 76(1–2):1–70

Parent H, Garrido AG (2015) The ammonite fauna of the La Manga Formation (Late Callovian–Early Oxfordian) of Vega de la Veranada, Neuquén Basin, Argentina. N Jb Geol Paläont Abh 275(2):163–217. doi:10.1127/njgpa/2015/0461

Parent H, Schweigert G, Melendez G (2006) Oxfordian perisphinctid ammonites from Chacay Melehué, Argentina. Paläontologische Zeitschrift 80(4):307–324

Peters SE, Loss DP (2012) Storm and fair-weather wave base: a relevant distinction?. Geology. Geological Society of America, pp 511–514

Pittet B, Strasser A, Mattioli E (2000) Depositional sequences in deep-shelf environments: a response to sea-level changes and shallow-platform carbonate productivity (Oxfordian, Germany and Spain). J Sediment Res 70:306–321

Riccardi A (2008) El Jurásico de la Argentina y sus amonites. Rev Asoc Geol Arg 63(4):625–643

Riding R (2000) Microbial carbonates: the geological record of calcified bacterial-algal mats and biofilms. Sedimentology 47:179–214

Roniewicz E (1966) Les madréporaires du Jurassique supérieur de la bordure des monts de Sainte-croix, Pologne. Acta Palaeont Polonica 11:157–264

Rosen BR (1992) Empiricism and the biogeographical black box: concepts and methods in marine palaeobiogeography. Palaeogeogr Palaeoclimatol Palaeoecol 92:171–205

Rosen BR, Aillud GS, Bosellini FR, Clarke NJ, Insalaco E, Valldeperas FX, Wilson ME (2000) Platy coral assemblages: 200 million years of functional stability in response to the limiting effects of light and turbidity. In: 9th international coral reef symp, Bali, vol 1, pp 255–264

Schneider J, Schröder HG, Le Campion-Alsamard T (1983) Algal micro-reef-coated grains from fresh water environments. In: Peryt T (ed) coated grains. Springer, Berlin, pp 284–298

Senowbari-Daryan B, Bucur II, Schlagintweit F, Matyszkiewicz J (2008) *Crescentiella*, a new name for "*Tubiphytes" morronensis* Crescenti, 1969: an enigmatic Jurassic–Cretaceous microfossil. Geol Croatica 61(2–3):185–214

Shinn EA (1983) Birdseyes, fenestrae, shrinkage pores, and loferites: a reevaluation. J Sediment Petrol 53(2):619–628

Steinhoff I, Strohmenger C (1996) Zechstein 2 carbonate platform subfacies and grain-type distribution (Upper Permian, northwest Germany). Facies 35:102–132

Stipanicic PN (1951) Sobre la presencia del Oxfordense superior en al arroyo de La Manga, provincia de Mendoza. Rev Asoc Geol Argent 6(4):213–242

Stipanicic PN (1966) El Jurásico en Vega de La Veranada (Neuquén), el Oxfordense y el diastrofismo Divesiano (Agassiz-Yaila) en Argentina. Rev Asoc Geol Argent 20(4):403–478

Stipanicic PN, Westermann GE, Riccardi AC (1975) The indo-pacific ammonite Mayaites in the Oxfordian of the southern Andes. Ameghiniana 12:281–305

Strasser A, Vedrine S, Stienne N (2012) Rate and synchronicity of environmental changes on a shallow carbonate platform (Late Oxfordian, Swiss Jura Mountains). Sedimentology 59:185–211. doi:10.1111/j.1365-3091.2011.01236

Tamura M (1961) The geologic history of the Torinosu epoch and the Mesozoic reef limestones in Japan Japanese. J Geol Geogr v 32:253–277

Thornborough KJ, Davies PJ (2011) Reef flat. In: Hopley D (ed) Encyclopedia of modern coral reefs. Structure, form and process. Springer, Berlin, pp 869–875

Veiga GD, Schwarz E, Spalletti LA (2011) Stratigraphic analysis of the Lotena Formation (upper Callovian-lower Oxfordian) in central Neuquén Basin, Argentina. Andean Geol 38(1):171–197

Vincent B, Rambeau C, Emmanuel L, Loreau JP (2006) Sedimentology and trace element geochemistry of shallow-marine carbonates: an approach to paleoenvironmental analysis along the Pagny-sur-Meuse Section (Upper Jurassic, France). Facies 52:69–84. doi:10.1007/s10347-005-0026-0

Walker KR, Alberstadt LP (1975) Ecological succession as an aspect of structure in fossil communities. Paleobiology 1:238–257

Wells JW (1932) Corals of the trinity group of the commanchean of central Texas. J Paleontol 6(3):225–256

Wierzbowski H (2002) Detailed oxygen and carbon isotope stratigraphy of the Oxfordian in Central Poland. Int J Earth Sci (Geologische Rundschau) 91:304–314

Wright VP, Burchette TP (1996) Shallow-water carbonate environments. In: Reading HG (ed) Sedimentary environments: processes, facies and stratigraphy. Blackwell, Oxford, pp 325–394