Fig. 10. Well-developed domal stromatolites overlying wavy-undulose stromatolites. The length of the hammer is 33 cm.

deposition of the TCC represents the last interval of marine sedimentation in the Western Mediterranean during the late Messinian. Repeated marine inundations followed by periods of isolation led to cyclic deposition of the TCC at Santa Pola (Section A-A', Fig. 4). Within this time span, 7 depositional cycles may have occurred (Esteban, 1979; Müller, 1986). However, Calvet *et al.* (1996) reported three shallowing-upward cycles in the stromatolitic sub-units from Santa Pola. The position of the reef on the shelf might explain the different number of cycles in comparison with the basins. The Santa Pola platform may not have been flooded during each cycle.

With the intra-Messinian inundation, reef growth at Santa Pola resumed but with a different biological composition. The intra-Messinian reef comprises thrombolitic structures and contains variable amounts of gastropods and bivalves. *Porites*, although present, occurring in the lower TCC in patch reefs, did not play a major role as a reef builder (Profile VI, Fig. 4; Profile VII, Fig. 3). Ooid sands are the dominant sediment type in the back-reef area where they formed shoals several metres thick. The ooids indicate shallow but agitated water in a high energy environment. Stromatolites were subordinate, but appear preferentially at the termination of the cycles, as indicated by a gradual upward growth from the underlying sediment generally with a sharp contact to the overlying sediments. They developed in areas with little sand deposition, such as tidal flats or very shallow low-energy environments. They appear to have formed in the zone between low and high tides during relative sea-level high stands and were exposed during the subsequent sea-level drop. The occurrence of *Conophyton* stromatolites on the upper front reef slope is exceptional (Fig. 13) because they probably formed subtidally (Grotzinger, 1989; Hoffman, 1976) at the beginning of the deposition of the first TCC-cycle prior to the settling and growth of eukaryotic organisms.

During later TCC deposition, peloidal sands and biologic diversity decreased, indicating a change in the water conditions towards a higher salinity. Corals disappeared completely while stromatolites dominated in the back-reef area and thrombolites in the front-reef area. Water circulation probably controlled reef growth at Santa Pola. In contrast to the lower Messinian *Porites* barrier reef, which trends almost N-S, the TCC

Fig. 11. Coalesced stromatolite domes forming elongated bioherms indicating the direction of the water currents. The direction of the elongation is approximately north–south. The length of the hammer is 30 cm.

thrombolite reef body and elongated stromatolites developed along the southern edge with the reef front trending ENE-WSW (Fig. 2). Reef growth was reduced in the northern part of the platform, where it appears only along east-facing canyons which cut into the *Porites* reef (Fig. 2).

The formation of the Post TCC stromatolites might have occurred during the short time span of the Lago Mare deposition (Fig. 1), a time of primarily lacustrine sedimentation throughout the Mediterranean (Hsü *et al.*, 1977). There stromatolites appear as patches and may have formed in meteoric water fed ponds on the exposed platform that desiccated from time to time. Their alternating calcite and dolomicrite laminae may reflect seasonal changes in salinity, but clear evidence for this assumption is missing. Stable isotope values indicate the influence of isotopically light meteoric water during calcite (δ^{13}C= −7·90‰, δ^{18}O= −5·00‰) and dolomicrite (δ^{13}C= −4·00‰, δ^{18}O= −1·00‰) precipitation reflecting an environment influenced by fresh water. Later, during the early Pliocene, the Sierra de Santa Pola underwent tectonic uplift and became emergent (Montenat, 1977). The dip of the sediments indicates that uplift at Santa Pola was more or less vertical with a possible tilting of less than 1°.

DISCUSSION

Dolomitic stromatolite layers

The dolomicritic layers of the TCC stromatolites consist of microcrystalline dolomite and are

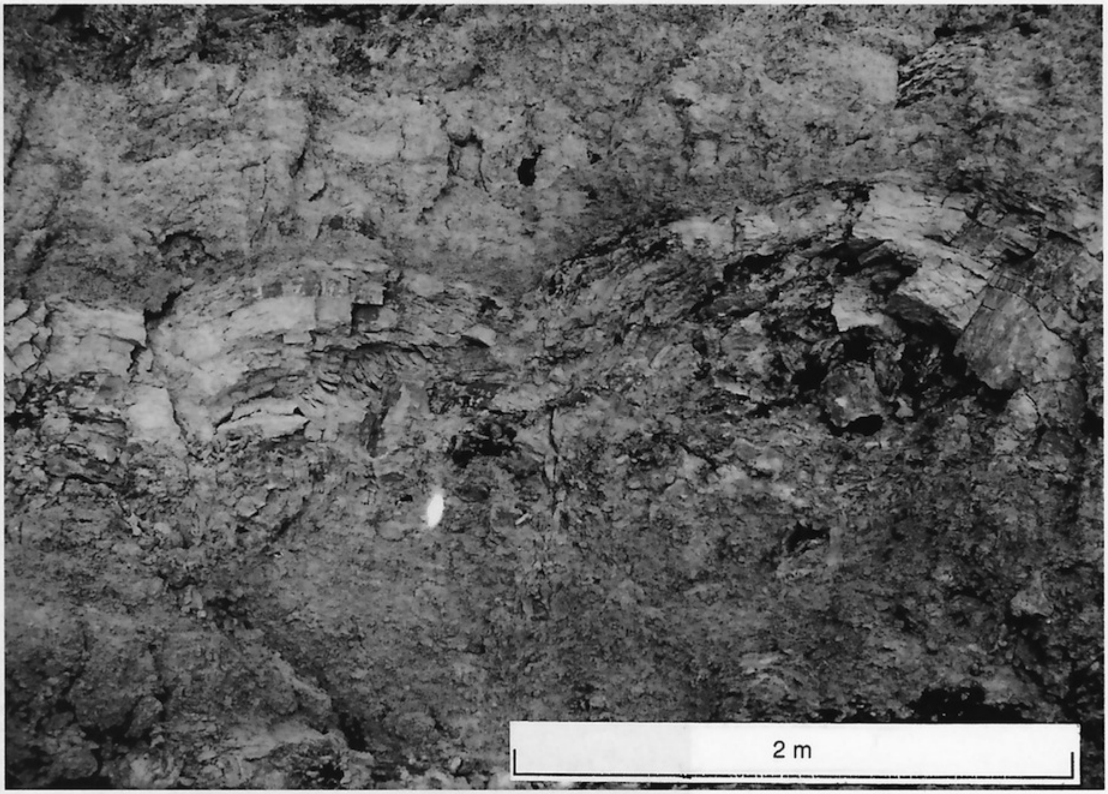

Fig. 12. Giant domal stromatolites interbedded in peloid-ooid sandstones in the quarry to the west of Profile VI.

organic carbon-rich, as indicated by a dark, olive green to brown appearance in thin section (Fig. 14). With the exception of the mineralogy and microtexture, these layers show no significant difference to micritic carbonate layers from modern stromatolites, as observed in the Bahamas (Dill *et al.*, 1986; Reid & Browne, 1991; Browne, 1993; Feldmann, 1995; Reid *et al.*, 1995). Based on comparison with modern micritic layers in Bahamian stromatolites, the dolomitic nature of the micritic layers of the Santa Pola stromatolites is interpreted to be a primary or a very early diagenetic feature of primary microbial mat layers. The process leading to micrite-crust formation appears to be rapid, as indicated by the very small crystal sizes, whereby organic matter becomes embedded within the precipitated microcrystals.

Although the micritic dolomite layers in the Santa Pola stromatolites are interpreted as primary features, modern analogues are rare. Lagoa Vermelha, in Brazil, is a modern example where primary dolomite and calcite precipitate in association with microbial mats (Vasconcelos *et al.*, 1995; Vasconcelos & McKenzie, 1997). In this lagoon, the water chemistry is seasonally controlled, with freshwater flooding during the rainy season in winter and intense evaporation with seawater inflow during the dry summer. The precipitate produced in association with organic matter during the wet season is low-magnesium calcite, whereas the evaporative conditions lead to precipitation of primary dolomite during the dry season when the salinity of the lagoon reaches twice that of seawater.

The conditions which produced micritic dolomite in the Santa Pola stromatolites remain speculative to a certain degree. Gebelein and Hoffman (1973) suggest that micritic dolomite layers in stromatolites are secondary. Their assumption is that magnesium ions can be found in high concentrations in organic complexes in microbial mat layers. When the organic matter decomposes, the magnesium is released to form dolomite in the micro-environment of the relict microbial mat layers. However, degradation of organic matter under favourable (anoxic, hypersaline) conditions can lead to primary precipitation of dolomite, as shown in Lagoa Vermelha (Vasconcelos *et al.*, 1995; Vasconcelos & McKenzie, 1997). In modern Bahamian stromatolites the formation of a micritic stromatolite layer may be a process within the micro-environment of a microbial mat, which is associated with boring activity of endolithic microbes

Fig. 13. *Conophyton* stromatolites (arrows) that separate the overlying TCC thrombolite unit from the early Messinian *Porites* reef at the base of this first TCC depositional cycle. The length of the hammer is 30 cm.

resulting in dissolution and reprecipitation of carbonate previously produced (Feldmann, 1995; Feldmann, in press). Therefore, the composition of the resultant carbonate precipitate is strongly dependent on the degradation of organic matter and/or the chemical conditions within the microbial mat. Degradation of organic matter by sulphate reducing bacteria can cause the increase of both alkalinity and pH in the pore waters, providing the necessary conditions for dolomite precipitation to occur (Andrews, 1991; Slaughter & Hill, 1991).

The micritic layers of the TCC stromatolites alternate with microsparry dolomite layers, which are considered to be equivalent to the sediment-rich laminae of modern stromatolites. The presence of cylindrical holes, with average diameters of 10 μm in most of the dolomite crystals (Fig. 15) indicates that dolomite growth may have nucleated around minute particles which were subsequently dissolved. These nuclei may have been an earlier meta-stable dolomite precipitate or fine-grained detritus of unknown origin. The growth of the dolomite crystals proceeded outward from the now missing nuclei with the precipitation of discrete layers. Qualitative EDX examination of the layers of an individual crystal shows that the magnesium content tends to increase toward the outer rim (Fig. 16a–d) implying an increase in the stability of each succeeding dolomite layer as stoichiometric dolomite composition is approached. The microspar layers are porous and permeable and, thus, promote circulation of dolomitizing fluids.

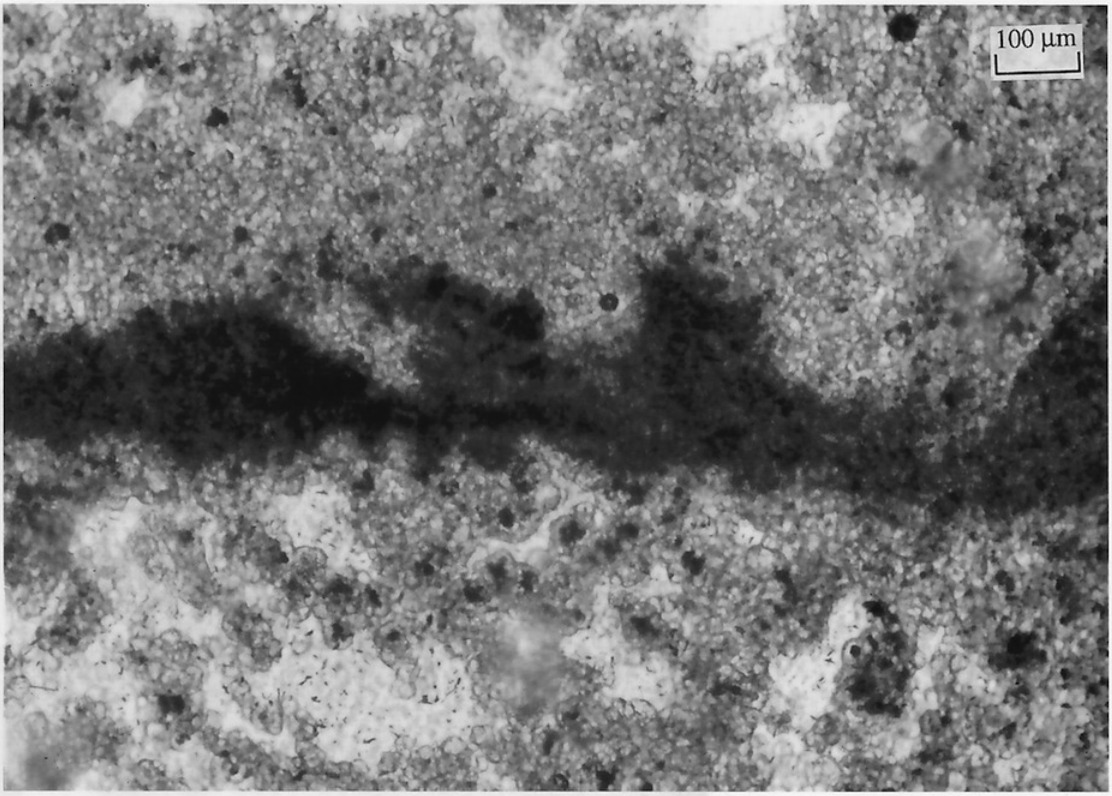

Fig. 14. Thin-section photomicrograph showing alternating dolomicrospar (lower) and dolomicrite laminae (middle) in a TCC stromatolite. The dolomicritic layer has a bushy top-relief and a relatively sharp bottom line. These features generally allow the determination of the growth direction of a stromatolite. Note the dense, dark appearance of the dolomicritic layer in contrast to the porous, light appearance of the microsparry layer.

Under the assumption that stromatolite formation was coupled with cyclic flooding, which was associated with mat growth and carbonate deposition and precipitation, dolomitization of the microsparry layer could be explained by evaporative dolomitization after flooding (Shinn *et al.*, 1965; Behrens & Land, 1972; McKenzie, 1981). With the decomposition of organic matter under anoxic and evaporative conditions discrete dolomite layers may have formed around nuclei which were subsequently dissolved by circulating fluids.

Cyclicity of stromatolites and thrombolites

Stromatolite-thrombolite associations dominating carbonate facies, such as those at Santa Pola, are unusual in the post-Ordovician. Stromatolites with a wide range of growth forms, such as columns, branching columns, and domes were abundant in the Proterozoic (Hoffman, 1976). These forms represent a variety of environments from subtidal to intertidal and supratidal (Hoffman, 1976). With the increasing occurrence of thrombolites and the evolutionary explosion of eukaryotes in the Early Palaeozoic (Knoll, 1992; Feldmann & McKenzie, in press) stromatolites, in particular the subtidal forms such as *Conophyton,* which are well known from early Mid-Proterozoic to Early Palaeozoic (Grotzinger, 1989; Hoffman, 1976), declined or disappeared. Subsequently, the abundance of thrombolites declined with the evolution of reef-forming organisms towards the Middle Ordovician (Kennard & James, 1986).

Considering the various stromatolites and thrombolites which have formed during TCC deposition, we propose that the first TCC cycle, containing *Conophyton* stromatolites, reflects an environment similar to that of the Proterozoic prior to the evolutionary explosion of the eukaryotes. The subsequent TCC cycles represent an environment similar to that of the Early Palaeozoic when stromatolites were intertidal to supratidal forms, which grew in highly saline environments, and thrombolites subtidal features, which developed in agitated and less highly saline waters.

Fig. 15. SEM photomicrograph showing dolomite crystals in a microsparry layer of a TCC stromatolite. Note the characteristic holes centred in the isodiametric shapes of the rhombohedral crystals.

The stratigraphic position of the stromatolites indicates changes in environmental conditions related to the conditions under which the surrounding rocks were deposited. In the front-reef area at Santa Pola, stromatolites are interbedded between thrombolites and commonly terminate depositional cycles (Fig. 17). Calvet *et al.* (1996) reported three episodes of deposition in the Santa Pola stromatolitic sub-units indicating a cyclic deposition of the TCC probably closely related to an intermittent entrance of marine waters in the Mediterranean. These cycles can be traced from the lagoonal back-reef to the front-reef area and can be separated from each other by sharp contacts, dramatic changes in lithology, or erosional surfaces. In general, with each subsequent cycle up-section in the thrombolite reef, the faunal assemblage becomes poorer and the carbonate sand content of the sediments decreases, whereas stromatolite abundance increases. Analogous depositional cycles within the TCC, which are associated with relative sea-level falls and subsequent rises of at least 30 m, were also reported from Las Negras, Spain (Whitesell *et al.*, 1993). Thrombolites are commonly regarded as subtidal forms which develop in agitated water (Aitken, 1967; Kennard, 1981). If the thrombolites at Santa Pola grew under turbulent high energy conditions acting as a wave breaker, the conditions must have changed during the period of stromatolite formation. Observational studies on modern mats (Feldmann, 1995) demonstrate that very strong wave activity scours and damages stromatolitic structures by removing microbial mats and weakly lithified stromatolite layers. Therefore, the formation of a stromatolite primarily requires a laminar water flow, where scouring is low such as in tidal currents, or a relative decrease in high energy conditions. Such conditions would occur with a shallowing caused by a sea-level drop or during initial flooding of a platform during a sea-level rise.

The stromatolites formed in the front-reef area generally appear to have grown upward from the underlying reef body with a sharp boundary to the overlying sediments. They repeatedly appear as elongated bioherms (Fig. 11). These features suggest that they formed during falling relative sea-level under agitated water conditions, possibly produced by tidal currents. Beside these physical conditions, the chemical conditions may have changed as indicated by the different

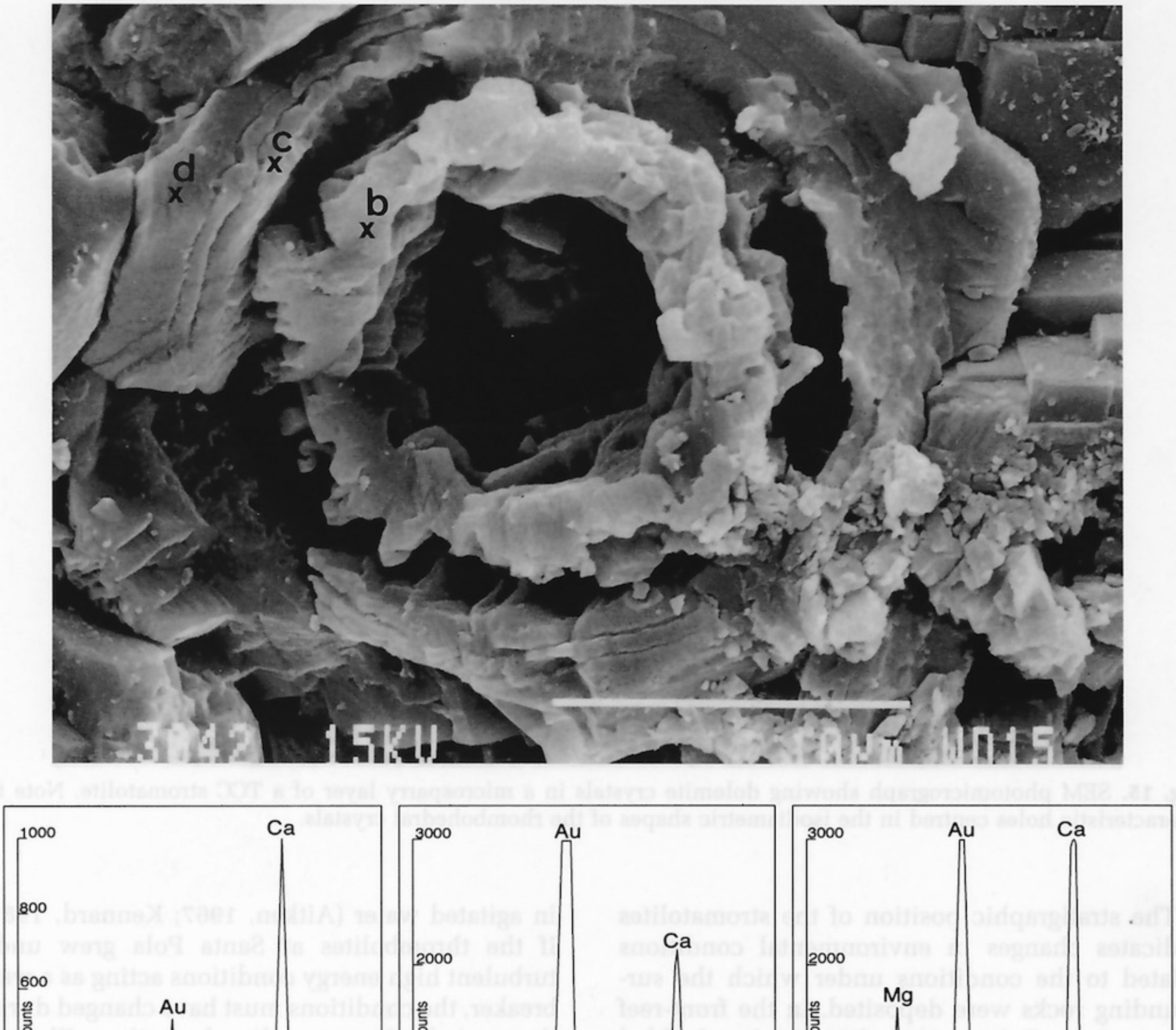

Fig. 16. (A) SEM photomicrograph showing a cross-section through a dolomite crystal from a microsparry layer in a TCC stromatolite. Note the growth of the crystal by precipitation of discrete layers. The x markers (b, c, and d) indicate the sites of EDX examination. (B)–(D) EDX-plots, qualitative chemical analyses, showing that the Mg content tends to increase from site B to D. Site B, appears to be a low magnesium calcite; Site C, a high magnesium calcite; and site D, a dolomite. This zonation indicates secondary dolomitization.

bio-assemblages. The thrombolites always contain a variety of organisms, such as bivalves and gastropods, even if their diversity decreased with time during cyclic TCC sedimentation. In contrast, the stromatolites are fossil-poor. An explanation for this change in biological abundance may be falling relative sea-level leading to a restricted environment. The thrombolites may have formed in a subtidal environment a few metres deep and under more or less normal marine conditions. With falling sea-level, the reef environment changed from subtidal to peritidal, and, during low tides, high evaporation led to hypersaline conditions. Under these conditions,

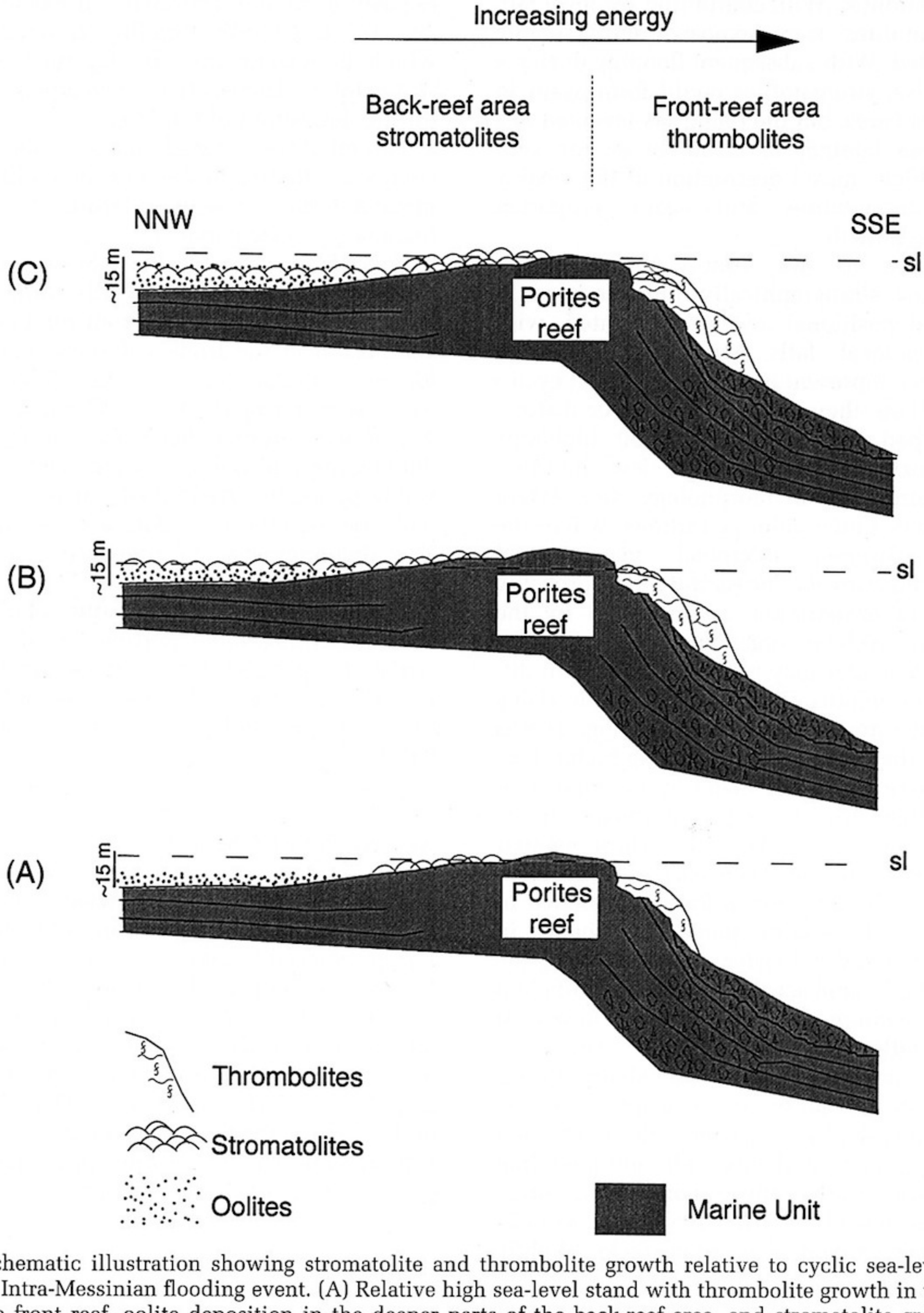

Fig. 17. Schematic illustration showing stromatolite and thrombolite growth relative to cyclic sea-level changes during the Intra-Messinian flooding event. (A) Relative high sea-level stand with thrombolite growth in the subtidal zone at the front reef, oolite deposition in the deeper parts of the back-reef area, and stromatolite growth in the intertidal zone of the back-reef area. (B) Relative low sea-level stand promoting thrombolite growth in the basinward migrated subtidal zone at the front reef and stromatolite growth in the intertidal zone on both the previously deposited ooid sands and thrombolites. (C) Relative high sea-level stand with thrombolites growing over the preceding stromatolites in the subtidal zone at the front reef, stromatolite growth in the intertidal zone of the back-reef area, and sand deposition in the deeper water of the back-reef area.

the reef builders of the thrombolites disappeared, whereas the salinity resistant microbes thrived to form stromatolites. With continuing sea-level fall, the stromatolites were exposed and possibly partly eroded. With subsequent flooding during a sea-level rise, stromatolites could form again in the front-reef area, but the rising sea-level led to a change from laminar to turbulent energy conditions, which caused destruction of the weakly lithified stromatolites and again supported thrombolite growth.

In contrast to the front-reef area where stromatolites stratigraphically indicate termination of depositional cycles associated with relative sea-level falls, stromatolites in the lagoonal area represent entire depositional cycles (Fig. 17). Here, they occur as tabular or distinctively shaped domes forming giant bioherms covering extended areas of a few hundred square metres. Their morphology and extent imply growth under calm conditions, where the stromatolite-forming microbial mats could develop undisturbed. The salinity was probably high due to evaporation, as indicated by the absence of skeletal organisms. Each of the stromatolite shapes may represent growth in different water depths. For example, with rising sea-level, the area around Profile II (Fig. 4) was flooded (at the beginning only during high tides), and the surface was colonized by microbes and tabular stratiform to wavy-undulose forms developed on these tidal flats. These tabular stromatolites could not keep pace with continuing sea-level rise and domal forms developed in the new subtidal environment. This change in morphology permitted faster growth allowing the mat forming cyanobacteria to receive sufficient light for maximum growth. With the subsequent sea-level fall, renewed peritidal conditions dominated, causing a return to tabular forms. With supratidal conditions, disruption of the extended microbial mats by periodic desiccation caused the formation of small adjacent microbial mat patches. Under these conditions, small columnar stromatolites may have formed as indicated by the abundant desiccation cracks. Slightly elongated stromatolites probably formed in channel depressions, where stronger laminar water flow controlled their growth direction.

CONCLUSIONS

1 The Santa Pola platform is composed of two reef types which are separated by a major erosional surface: (a) an early Messinian N–S striking *Porites* reef which formed prior to the deposition of the Terminal Carbonate Complex and (b) a NE–SW trending thrombolite reef, which is accompanied by lagoonal oolite and stromatolite facies, that developed cyclically during deposition of the TCC.

2 Thrombolites formed under subtidal high-energy conditions. Back-reef stromatolites, having distinct forms, grew in intertidal to supratidal low-energy environments.

3 *Conophyton* stromatolites, to our knowledge the only representatives of this form that have been recognized in rocks younger than Palaeozoic, occur at the front-reef slope and probably formed subtidally prior to the colonization of eukaryotes during the first TCC cycle.

4 The stromatolites have alternating layers of dolomicrite and dolomicrospar. The dolomicrite is interpreted to have formed primarily associated with the bacterial degradation of organic matter. The dolomicrospar is probably a product of evaporative dolomitization.

5 The Santa Pola stromatolite-thrombolite associations, forming large portions of the platform sediments, possibly reflect an environment similar to Palaeozoic environments where stromatolites and thrombolites were important platform builders.

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