

Messinian stromatolite-thrombolite associations, Santa Pola, SE Spain: an analogue for the Palaeozoic?

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ABSTRACT

Stromatolite-thrombolite associations are the dominant facies forming large portions of the Santa Pola carbonate platform (SE Spain) during deposition of the Terminal Carbonate Complex (TCC). The TCC, the last period of marine sedimentation in the Western Mediterranean associated with the Messinian Salinity Crisis, comprises a NE–SW trending thrombolite reef with occasionally interlayered stromatolite horizons and a predominantly stromatolite and oolite facies in the back-reef area. The stromatolites are mainly dome shaped, but fine-columnar or wavy-undulose forms can occur. The stromatolites form huge bioherms, extending tens to hundreds of metres. They are finely laminated with alternating layers of dolomicrite and dolomicrospar. The dolomicrite layers appear to be a primary dolomite precipitate, whereas the dolomite crystals in the dolomicrospar layers apparently formed around a meta-stable nuclei which was subsequently dissolved or degraded. The low content of sand-sized particles in the stromatolitic layers indicates formation under low-energy conditions, possibly on a tidal flat. As reported from other areas in the Western Mediterranean, deposition of the TCC at Santa Pola was apparently cyclic, whereby stromatolites generally terminate each depositional cycle. Subtidal *Conophyton* stromatolites, possibly the only known occurrence younger than Palaeozoic, are, however, found on the reef slope at the base of the first TCC depositional cycle. The dolomitic nature of the unadulterated stromatolitic laminations and the association of stromatolites and thrombolites as platform builders were a common feature in the Early Palaeozoic but are unusual in post-Ordovician carbonate facies. We propose that the conditions during TCC deposition were very restricted, possibly reflecting an environment similar to that of the Early Palaeozoic.

INTRODUCTION

Stromatolites are the principal sedimentary feature of carbonate rocks deposited through the first 3000 myr of geological history. Recognized in the field as laminated, commonly domal, columnar or conoidal structures, stromatolites are generally interpreted as the biosedimentary products of sediment trapping, binding, and precipitation by microbial mat communities (Kalkowsky, 1908; Logan *et al.*, 1964; Awramik *et al.*, 1976). While laminated stromatolites became progressively restricted in abundance and environmental range throughout the late Neoproterozoic and

early Palaeozoic, another type of microbialite concomitantly increased in abundance to become a significant biosedimentary constituent of Cambrian and Ordovician marine carbonates (Kennard & James, 1986). Aitken (1967) introduced the term 'thrombolite' for these microbial structures, which are related to stromatolites but without their characteristic lamination. Instead, thrombolites are characterized by a macroscopic clotted fabric which is commonly interpreted to be of cyanobacterial origin (Kennard & James, 1986). Stromatolite-thrombolite associations were significant platform builders in the Early Palaeozoic (Aitken, 1967; Kennard & James, 1986). The

Time (Ma)	Stages	Santa Pola		Mediterranean Sicily
		Lagoon	Reef	
5.1	Zanclean	?	Marine	Trubi
5.15	Messinian	Post TCC		Lago Mare
5.25		Erosion		Upper Evaporites
5.35		Terminal Carbonate Complex		Intra-Messinian Inundation
5.5		Erosion		Erosion Main Salt Lower Evaporites (Calcare di Base)
5.7		Marine Unit (Porites Reef)		
		?		Tripoli

Fig. 1. Diagram showing the Messinian stratigraphic correlation of the successions from la Sierra de Santa Pola and Sicily (Modified after Müller & Hsü, 1987).

stromatolites commonly were interpreted as reefs growing in low-energy peritidal settings, often in waters of elevated salinity, and the thrombolites as reefs growing under higher energy conditions in the subtidal and normal marine waters (Aitken, 1967; Kennard, 1981). Thrombolites progressively declined in abundance during the early Silurian.

Comparable stromatolite-thrombolite associations of Messinian age were described from Western Mediterranean regions, such as Níjar and Santa Pola (Esteban & Giner, 1977; Esteban, 1979; Bernet-Rollande *et al.*, 1980; Vallès, 1986; Riding *et al.*, 1991a; Feldmann, 1995; Calvet *et al.*, 1996). These sediments, referred to as the Terminal Carbonate Complex (TCC) (Fig. 1; Esteban, 1979), indicate extraordinary depositional conditions for this interval, the last period of marine sedimentation in the Western Mediterranean associated with the Messinian Salinity Crisis (Hsü *et al.*, 1973). Stromatolites and thrombolites forming carbonate facies, such as these occurring in the Western Mediterranean, are unusual in the post-Ordovician geological record.

This paper describes and interprets the palaeoenvironment of a Messinian example of a stromatolite-thrombolite association near Santa Pola, Spain that forms the platform sediments of the TCC. This study provides a Miocene analogue for Palaeozoic environments where stromatolites and thrombolites were important platform builders. This geologically young example allows environmental conditions to be more confidently evaluated.

GEOLOGICAL SETTING

La Sierra de Santa Pola is a small carbonate platform of about 20 km² that forms a peninsula

extending eastward into the Mediterranean. It is located about 15 km south of Alicante and is named after the small village of Santa Pola located on its southern boundary (Fig. 2). The platform emerges east of the Elche plain to form a dolomite hill, 144 m above present sea-level at the lighthouse, Faro de Santa Pola (Fig. 2). In the north, the platform gently dips under a cover of Pliocene to Holocene sediments. The eastern margin of the platform is characterized by a N-S trending barrier reef with a steeply dipping fore-reef slope, of which only the upper part is exposed. The reef wall is constructed almost exclusively by *Porites* (Esteban, 1977; Esteban & Giner, 1977; Esteban, 1979). Towards the south, the reef front trends NE-SW and reveals mainly thrombolite facies. These two reef fronts comprise two different reefs separated by an erosional surface. The *Porites* reef matches the descriptions of other *Porites* reefs reported from the Western Mediterranean (Esteban, 1979; Esteban *et al.*, 1996) and is probably laterally equivalent to the Marine Unit (Fig. 1; Esteban, 1979). The erosional surface represents the major drawdown of the Mediterranean during deposition of the Lower Evaporites (Fig. 1). In contrast, the thrombolitic reef, which is occasionally interlayered with stromatolite horizons, is thought to represent the Terminal Carbonate Complex (Fig. 1). The Marine Unit and the TCC are the Lower and Upper Depositional Units described by Vallès (1986) and Calvet *et al.* (1996). The TCC in the lagoonal back-reef area comprises mainly oolite and stromatolite facies, which are well exposed and occur at many sites just north of Santa Pola.

STRATIGRAPHY AND SEDIMENTOLOGY

Marine Unit

Fore-reef area

The lowermost sediments which outcrop in the fore-reef area at Santa Pola primarily comprise very fine grained (10–20 µm) dolomite (Profile IX, Fig. 2). This chalky dolomite can be up to 2 m thick (Profile IX, Fig. 3) and contains centimetre-thick, foraminifera-rich limestone layers which are denser than the surrounding dolomite. These layers preserve a variety of planktonic foraminifera, particularly *Globorotalia acostaensis*, *Globorotalia mayeri*, and *Catapsydrax dissimilis*. Nannofossils such as *Coccolithus pelagicus*, *Dictyococcites antarcticus*, *Reticulofenestra minutula*, *Reticulofenestra pseudumbilicus*,

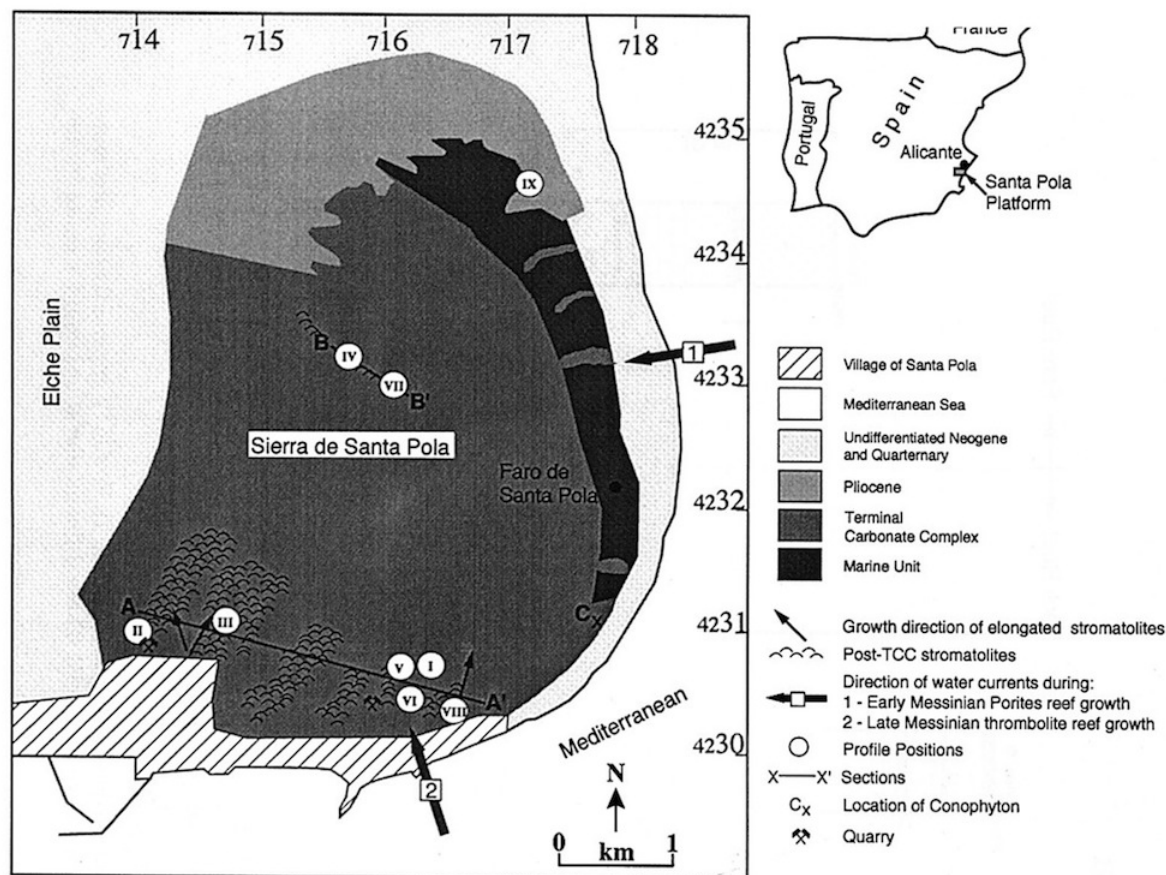


Fig. 2. Location of the study area and geological overview of the units of the carbonate platform, Sierra de Santa Pola, Southeast Spain. The village of Santa Pola marks the southern boundary of the platform. The positions of studied profiles (I to IX) and correlated cross-sections (A-A' and B-B') are indicated. Note the south facing Terminal Carbonate Complex (TCC) thrombolite reef bodies which overgrew the underlying *Porites* reef (Marine Unit), as seen in the E-W trending canyons. The Pliocene marine sediments onlap the carbonate platform at its northern boundary.

Umbilicosphaera sibogae and *Syracosphaera* sp. occur attached to foraminifera but were not found in the fine fraction. This bioassemblage indicates sediment deposition in the late Miocene, possibly late Tortonian to early Messinian (Feldmann, 1995). The foraminifera are well sorted, having a size range between 70 and 200 μm . In sieved fractions <65 μm and >250 μm , no fossil fragments were found. This limited size fraction indicates rapid deposition of the foraminiferal layers, possibly by storm events when energy differences within the water column winnowed the fine sediment leading to deposition of lag deposits rich in foraminifera. In the upper part of the dolomite, a single 2-cm-thick green-black clay-rich layer occurs containing abundant zircons suggesting a volcanic origin. The chalky dolomite is overlain by a 1 m thick sand-rich cryptalgal dolomite which contains stromatolitic beds (Profile IX, Fig. 3). The cryptalgal dolomite terminates in a con-

glomerate layer, which represents the uppermost horizon of the Marine Unit.

Porites reef

The lower Messinian Marine Unit at the platform edge is mainly represented by a *Porites* reef (Fig. 1; Feldmann, 1995). The *Porites* reef consists of several zones which might indicate different growth stages (Esteban, 1977; Esteban & Giner, 1977). A Pinnacle Zone appears above the reef-talus slope with vertical *Porites* sticks up to more than 1 m high. This zone is followed upwards by a Thicket Zone, characterized by *Porites* sticks standing vertical to 30° from the vertical. A Transition Zone with subvertical stick *Porites* and laterally separated convex-downward platy laminar *Porites* follows, leading to the Reef Crest Zone where vertical sticks disappear and highly irregular laminar coral plates dominate (see also Riding *et al.*, 1991b).

Santa Pola - Section B - B'

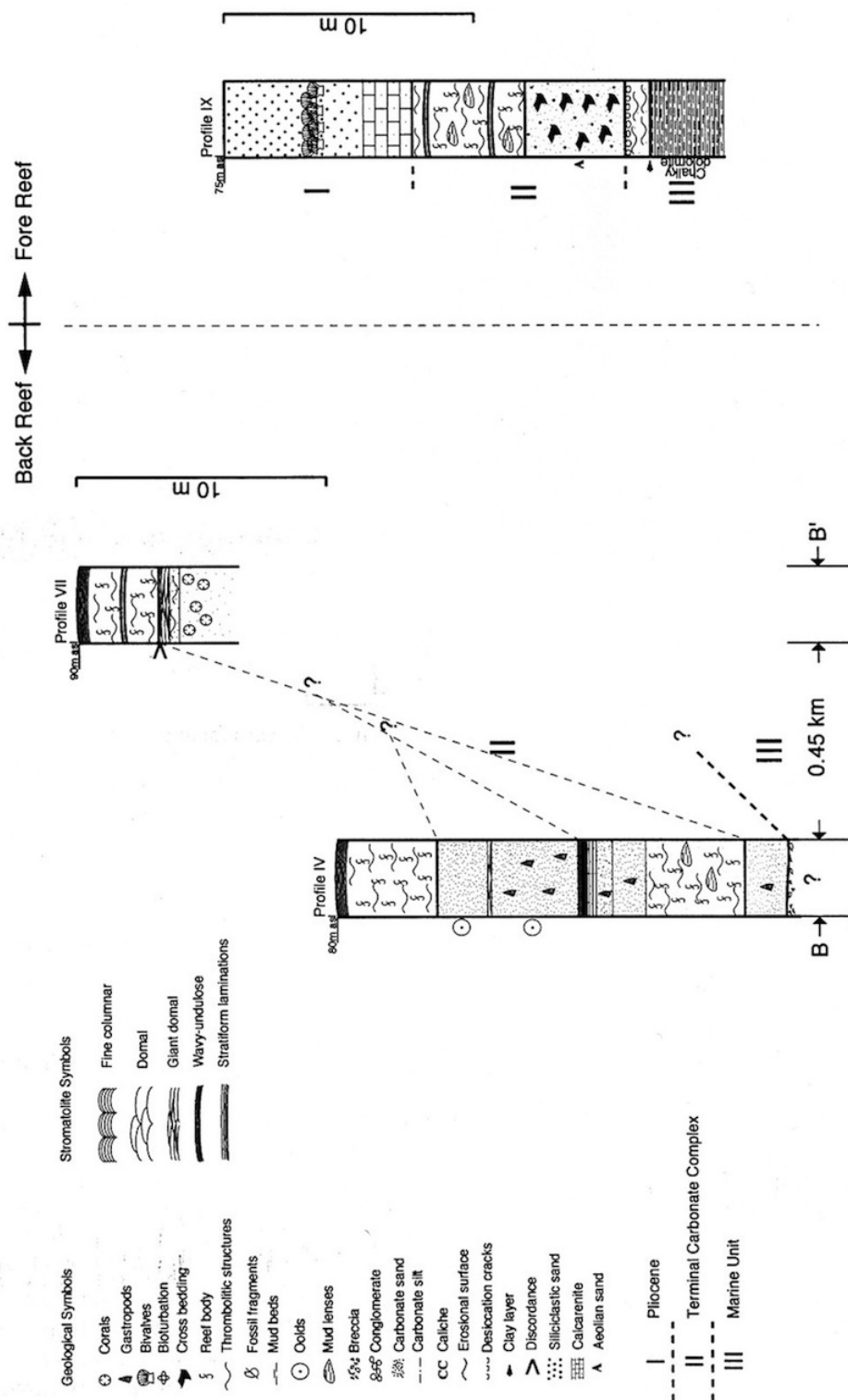


Fig. 3. Cross-section B-B' from the platform centre and Profile IX from the northeastern reef slope (Fig. 2). Profile IV apparently contains more depositional cycles than Profile VII, which is topographically about 10 m above Profile IV. These different elevations could account for the different number of cycles.

Back-reef area

The presence of Marine Unit sediments in the back-reef area cannot be determined with certainty. In an old quarry just north of Santa Pola, a clay layer, with similar composition to the clay layer in the fore-reef chalky dolomite (Profile IX, Fig. 3), occurs within a chalky dolomite outcrop (Profile II, Fig. 4). Unfortunately, the dolomite outcrop of Profile II does not contain interbedded foraminifera-rich layers which would allow dating. However, the lithological similarity of this back-reef unit and the chalky dolomites of the fore-reef area permit a reasonable correlation, suggesting that these back-reef area rocks belong to the Marine Unit. The chalky dolomite is overlain by a weakly lithified, 0.5 m thick, bedded dolomite, which might be time-equivalent to the bedded cryptalgal unit of the fore-reef area (Profile IX, Fig. 3). The upper boundary of this bedded unit is sharply separated from an overlying oolite and this boundary is taken as the top of the Marine Unit in the back-reef area.

Lower Evaporites (Erosional Unconformity)

The Lower Evaporites and/or Main Salt are restricted to the more basal parts of the Mediterranean (Hsü *et al.*, 1977). Thus, marine sedimentation in the Santa Pola area was unlikely since it was probably subaerially exposed during deposition of these evaporites, as indicated by an erosional surface between the Marine Unit and the Terminal Carbonate Complex. The sediments overlying the sand-rich cryptalgal dolomite in the northern part of the platform (Profile IX, Figs 2 & 3) are >4 m thick aeolian sands. These sands are mainly composed of well-rounded and fairly well-sorted peloids (average 200 µm) with abundant angular quartz and calcite grains. The unit has well-developed cross-bedding with high angle foreset dips of about 30°, which are indicative of terrestrial deposition (McKee & Ward, 1983). From their stratigraphic position, these sandstones could be the terrestrial equivalent of the evaporites deposited in the basins. Thus, the erosional unconformity would be age equivalent to the Lower Evaporites (Fig. 1).

Terminal Carbonate Complex (TCC)

The Terminal Carbonate Complex (TCC), first defined by Esteban (1979) in several Western Mediterranean localities, comprises a distinctive

depositional unit delimited by two regionally important erosional surfaces. The TCC of Santa Pola contains several facies types of which only the most prominent are described here. Esteban (1977), Esteban and Giner (1977), Montenat (1977), Esteban (1979), Bernet-Rollande *et al.* (1980), Vallès (1986) and Calvet *et al.* (1996) give fuller descriptions of the Santa Pola facies.

Porites patch reefs

Porites associations repeatedly appear in the lower part of the TCC and outcrop at several sites (Figs 3 & 4). They occur in patch reefs (Fig. 5), up to 12 m across (Calvet *et al.*, 1996) and appear to have grown on peloidal-bioclastic sand (Profile VI, Fig. 4; Profile VII, Fig. 3). *Porites* occurs as vertical or subvertical sticks, up to 50 cm high. The diameter of the TCC *Porites* sticks is generally around 1 cm in contrast to the *Porites* from the lower Messinian reef, which have diameters of 2–3 cm. Their exclusive occurrence in patch-reefs, the smaller stick diameters, and the sandy substrate distinguish them from the lower Messinian *Porites*. They represent the last recognized occurrence of coral reefs in the area.

Thrombolite reef

The thrombolite reef occurs throughout the front-reef area in the southern part of the peninsula and, also, covers portions of the south-facing *Porites* reef wall (Fig. 2). The thrombolites are dolomitized and generally have a clotted fabric, distinct from the laminated structures of the stromatolites (Aitken, 1967; Kennard & James, 1986). In thin-section, abundant filamentous structures, possibly algae, about 100 µm across occur (Fig. 6). In the northern fore-reef area, a dolomite bed with thrombolitic structures and abundant mud lenses overlies the aeolian sand and probably represents the TCC in this region of the platform (Profile IX, Fig. 3). Occasional laths of gypsum, 500 µm long and 100 µm wide, locally fill cavities in the dolomite. The lower part of the thrombolite reef contains abundant carbonate sand and bioclasts; bivalves and gastropods, in the size range of up to several centimetres, are also common. In the upper part, the sand content decreases, fossil fragments become rarer and alternations of the thrombolite reef with stromatolitic layers occur. In a few cases, the thrombolite reef contains abundant lime mud lenses of unknown origin. Along the reef front, several bulbous thrombolitic reef bodies overgrew the underlying

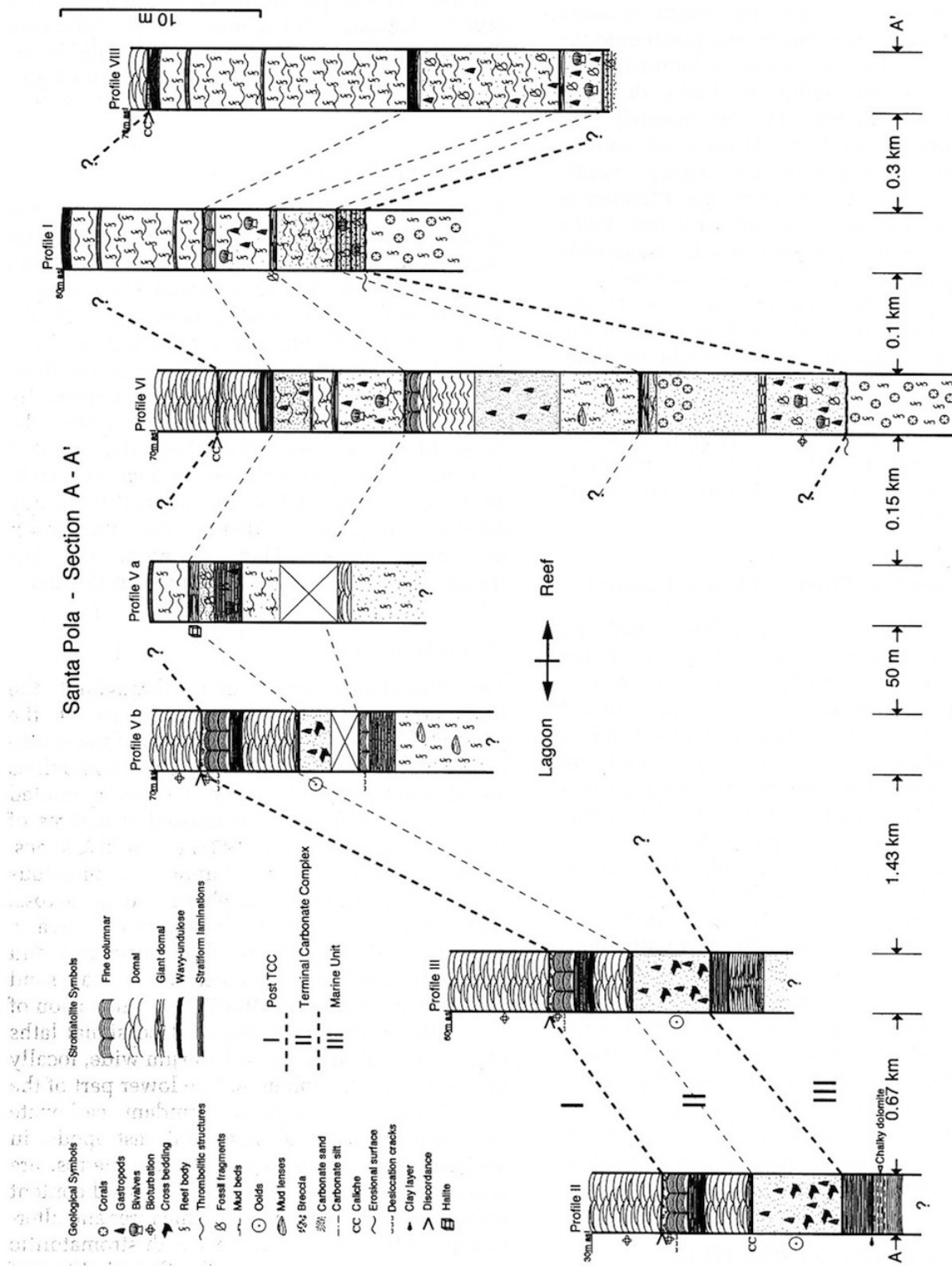


Fig. 4. Cross-section A-A' correlated from the back reef (Profile II) to the front reef (Profile VIII) area (Fig. 2). These seven profiles correlate the facies development within the TCC depositional cycles. Note that the dominant thrombolite facies occurs in the front-reef area and the oolite and stromatolite facies in the back-reef area.



Fig. 5. Lower TCC *Porites* patch reef. *Porites* sticks, up to 50-cm length, forming a patch reef a few metres across in the back-reef area at Profile VII. *Porites* is mainly dissolved away and the moulds are partly infilled by calcite cement. The length of the hammer is 33 cm.

Porites reef in a manner which resembles an onion skin-like structure (Fig. 7). The individual reef bodies, which are frequently separated by later infillings of travertine, indicate several growth stages.

Peloid and bioclast facies

The dominant rock types in the lower part of the TCC are peloidal and bioclastic dolomites, which are distributed over the whole platform. In the central part of the platform (Profile IV, Fig. 3), they form layers up to several metres thick. In the transition zone between the front reef and back reef, they overlay the lower Messinian *Porites* reef. Peloids and bioclasts are also common components in the lower portions of the thrombolite reefs, although they disappear with increasing

distance from the front reef toward the back-reef area.

Oolite facies

The oolites, best exposed in a small quarry just north of Santa Pola (Profile II, Fig. 2), are cross-bedded and contain variable amounts of unidentified monospecific gastropods. Except for these gastropods, fossils are rare. The oolites comprise a prominent depositional horizon in the back-reef area with a thickness >4 m (Profile II, Profile III & Profile Vb, Fig. 4). The ooids have diameters up to 500 µm and are heavily micritized and dolomitized. In some outcrops, the oolites have a foamy mouldic texture because the ooids have been dissolved leaving the surrounding dolomitized micritic cement, which forms a

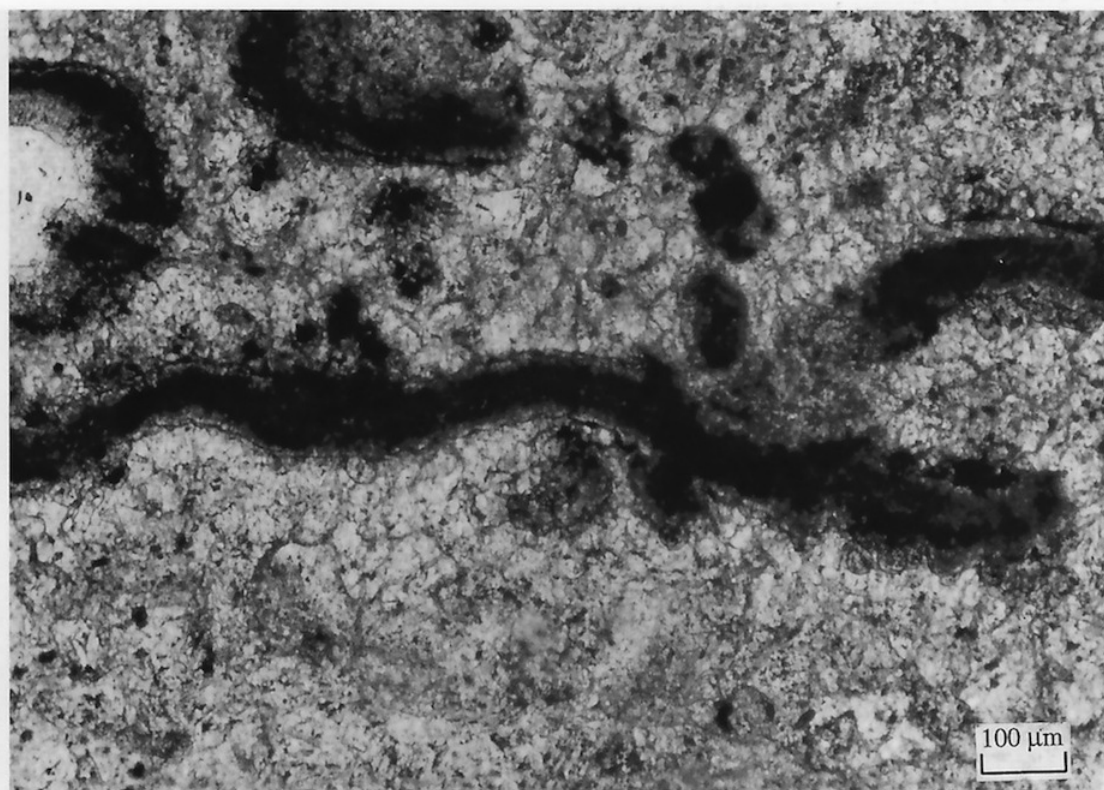


Fig. 6. Thin-section photomicrograph showing filamentous structures of unidentified algae which are possible framework builders of the thrombolites.

mesh-work pattern. Occasionally, the upper surface of the oolites has been calcretized (Profile II, Fig. 4).

Stromatolite facies

Extensive bioherms of stromatolites are the most prominent feature of the back-reef sediments of the Santa Pola platform. The transition from the underlying sediments into stromatolites is usually gradual, whereas the upper boundary of each stromatolite unit generally is sharp, indicating cyclic deposition. Stromatolites also occur repeatedly in the front-reef area. Their abundance increases in the upper part of the front-reef section, where they alternate with thrombolitic reef structures. Throughout the platform, stromatolites appear in various forms and have a variety of textures, indicating distinct growth conditions. Based on their forms, the stromatolites of Santa Pola are divided into five distinctive types. Stromatolites rarely occur as individual mounds but appear as bioherms or biostromes extending for several hundred metres laterally. Five types are distinguished:

1 *Small columnar stromatolites* commonly occur within domal and tabular biostromes, which are 30–100 cm thick (Fig. 8). These biostromes are generally composed of a series of coalesced, gently convex domes, 0.5–2 m in diameter, and exhibit synoptic reliefs of 10–25 cm. In the back-reef area (Profile II, Profile III & Profile Vb, Fig. 4) they overlie biostromes with wavy-undulose stromatolites and are overlain by thin layers of fine-to-medium peloid and ooid grainstone or flat-pebble conglomerate. In the front-reef area, they overlie domal stromatolites (Profile VI, Fig. 4) or thrombolite reef bodies (Profile I, Fig. 4) and are overlain by thrombolite reefs. Small columnar stromatolites generally range from 2 to 3 cm in diameter, are closely packed with parallel branches, and have crinkled gently convex laminae. They form surfaces which resemble 'egg carton' structures and often display desiccation cracks (Fig. 9).

2 *Domal stromatolites* form gently domed biostromes, up to 2.5 m thick and with an average synoptic relief of 5 cm (Fig. 10). The lithologies underlying and overlying these stromatolites in the back-reef area are oolites and wavy-undulose

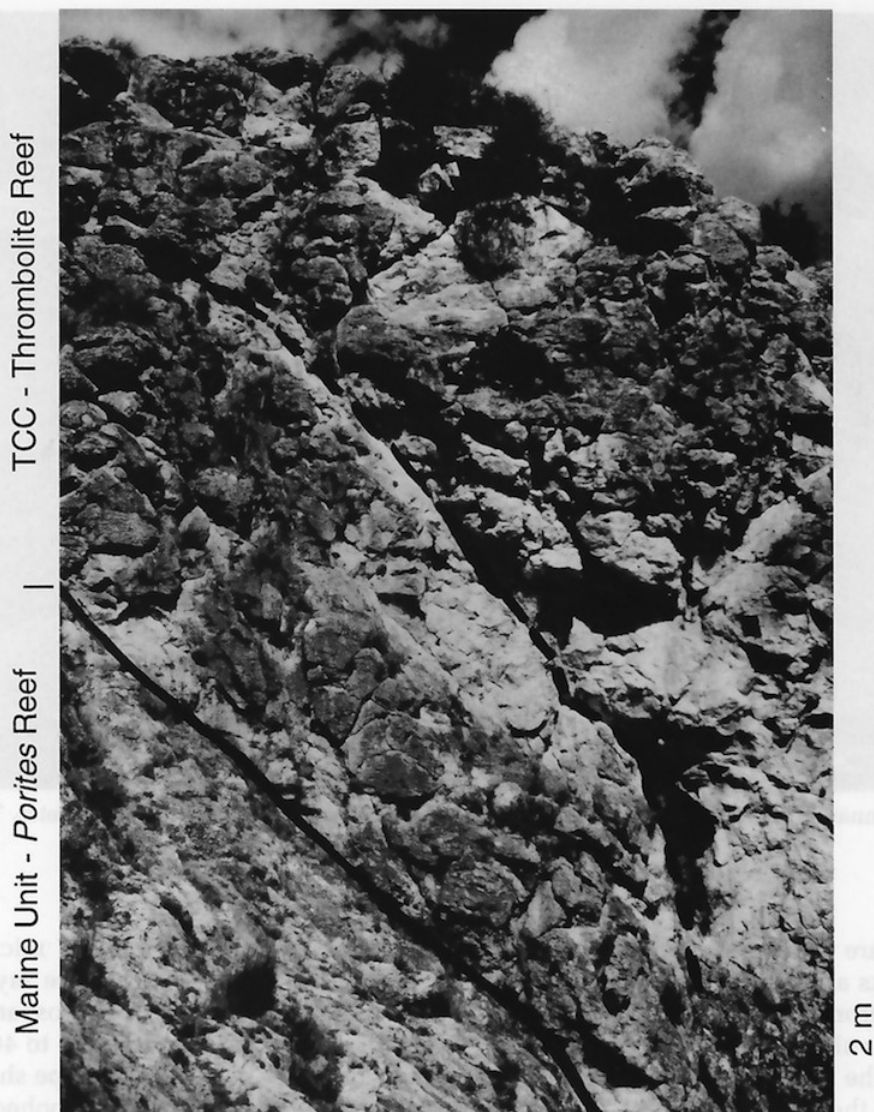


Fig. 7. Thrombolite reef body of the TCC (background) overgrowing erosional surface of the early Messinian *Porites* reef (foreground). The solid line on the drawing indicates the boundary between the two formations. The thrombolite reef bodies overgrew the *Porites* reef. Each of the layers (separated by the dashed line) could represent a depositional cycle.

stromatolites, respectively (Profile II, Profile III & Profile Vb, Fig. 4). In the front-reef area, they overlie thrombolite bioherms or wavy-tabular stromatolites (Profile VI, Fig. 4). The columns and domes are parallel and unbranched, ranging from 10 to 100 cm in diameter. They are either linked or tightly packed. Occasionally, these stromatolites appear as coalesced domes to form elongated bioherms, indicating the direction of the water currents (Fig. 11).

3 Giant domal stromatolites form gently domed biostromes, up to 70 cm thick. Adjacent lithologies are peloid-oid grainstones (Profile IV, Fig. 3). Giant domal stromatolites commonly form a

series of coalesced, gently convex domes ranging from 0.5–2 m in diameter (Fig. 12) and exhibit synoptic reliefs of 10–30 cm.

4 Wavy-undulose stromatolites form tabular or sheet-like bodies up to 1 m thick. These biostromes have a synoptic relief of less than 5 cm (Fig. 10). Adjacent lithologies can be small columnar stromatolites, domal stromatolites, thrombolite reef bodies, and rarely peloid-oid grainstones or flat-pebble conglomerates. The laminations of these stromatolites are planar to slightly wavy. They may be either laterally continuous or discontinuous forming an unconformity-like pattern. Irregular and laminoid



Fig. 8. Small columnar stromatolites forming convex domes which can be up to 2 m in diameter. The length of the hammer is 33 cm.

fenestral fabrics are widespread, and shrinkage or desiccation cracks are locally common.

5 *Conophyton* stromatolitic structures (Fig. 13) were found at one site in the front-reef slope (Fig. 2) at the base of the first TCC-cycle separating the *Porites* reef from the thrombolite reef. They have closely spaced vertical columns, up to 5 cm across and 40 cm high, which apparently formed a low-relief bioherm. To our knowledge, these *Conophytons* are the only representatives of this form that have been recognized in rocks younger than Palaeozoic age.

Examination of the internal structure of the Santa Pola stromatolites, which show distinctive growth forms in different stratigraphic horizons, indicates that their microfabric is not related to their morphologic shape. Within similarly shaped stromatolites, distinct microstructures can occur, whereas similar microstructures can occur within differently shaped stromatolites. The Santa Pola stromatolites generally have laminations consisting of couplets of which at least one is dolomite enriched in amorphous organic matter. These micritic layers appear dense, bushy, or clotted in thin-section (Fig. 14). They usually contain no detrital grains, although occasionally,

at their base, remnants of micritized detrital grains are found. The micrite layer is generally overlain by a distinctive microspar dolomite layer with crystals ranging from 10 to 40 μm . The crystals have an isodiametric shape showing, more or less, the characteristic rhombohedral outlines of dolomite. The crystals contain hollow centres, which sometimes appear as multiples (Fig. 15). At the boundary between the two layers, subspherical fenestral fabrics, up to 300 μm across, frequently occur. The small cavities are occasionally filled with blocky calcite, indicating a later stage diagenesis. The thickness of the dolomitic and microsparry layers can vary considerably, even within a single thin-section, ranging from 100 μm to 1 mm. The microsparry layer of a couplet often is somewhat thicker than the micritic layer, but there are cases where the opposite is true.

Post TCC (?)

In the back-reef area, stromatolites were found which are separated from the TCC by an angular unconformity (Profile II, III, and Vb, Fig. 4). These stromatolites have laminations with layers of sparry calcite with crystal sizes of 20–50 μm



Fig. 9. Exposed upper surface of the small columnar stromatolites which form 'egg-carton' structures with desiccation cracks. The length of the pencil is about 5 cm.

alternating with layers of dolomicrite. Both layers may be up to 1 mm thick but usually measure about 0.5 mm or less. Small cavities or fenestral fabrics are occasionally filled with fibrous calcite, which is orientated perpendicular to the cavity walls. These stromatolite bioherms occur as patches of several tens of square metres. The calcitic layers and the underlying unconformity indicate that these stromatolites may post-date the TCC.

Pliocene

Pliocene sediments are well exposed in the northern part of the Sierra de Santa Pola (Fig. 2; Profile IX, Fig. 3), where they onlap the reef slope and unconformably overlie the TCC. The lower part of these sediments is a yellow calcarenite. The calcarenite is unconformably overlain by a reddish siliciclastic sandstone which is interbedded with coquina shell beds. A more detailed description of these deposits is given by Montenat (1977). In contrast to the deposits of the TCC, these sediments are not dolomitized and their fossil content is well preserved.

DEVELOPMENT OF THE SANTA POLA PLATFORM

Esteban (1979) described Santa Pola as an asymmetric atoll-like platform isolated on the margin of an open shelf. Analogous to other lower Messinian *Porites* reefs of the Western Mediterranean, the barrier reef of Santa Pola probably developed during the late early Messinian in several stages, possibly as a consequence of a relative sea-level fall (see Haq *et al.*, 1988). The poor diversity of lower Messinian reefs, built almost exclusively by *Porites*, probably indicates stress conditions with falling sea level.

When the Mediterranean became isolated, triggering a dramatic sea-level fall during the Messinian Salinity Crisis (Hsü *et al.*, 1977; Müller & Hsü, 1987), deposition of the Lower Evaporites occurred in the deeper basins. The Santa Pola reef was exposed and an erosional surface formed as indicated by calcrete and palaeosols in several outcrops (Profile I & Profile VI, Fig. 4). The Santa Pola *Porites* reef probably remained subaerially exposed as indicated by the aeolian sand dunes until the intra-Messinian inundation (Fig. 1, Müller & Hsü, 1987). With rising sea level,