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Discussion

Sea level changes versus hydrothermal diagenesis: Origin of Triassic carbonate platform cycles in the Dolomites, Italy: Discussion

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In his recent paper, Blendinger (2004) presents a new and unconventional hypothesis for the formation of the Triassic Latemàr carbonate cycles. He assigned the cycles to intermittent hydrothermal influence alternating with normal marine deposition. Fluids with a composition similar to normal seawater were forced by elevated heat flow from an underlying hydrothermal field to circulate to the seafloor. These fluids are said to produce stratiform diagenetic features including tepees, and they favoured early dolomitization and the growth of cyanobacterial mats. This interpretation deviates strongly from the conventional models where these cycles are considered to be the result of relative sea-level fluctuations in a shallow-marine to subaerially exposed environment (Hardie et al., 1986; Goldhammer et al., 1987, 1990, 1993; Brack et al., 1996; Mundil et al., 1996; Egenhoff et al., 1999; Preto et al., 2001; Mundil et al., 2003; Zühlke et al., 2003).

We welcome this entirely new approach, as it further stimulates a discussion on the validity of criteria used to detect subaerial exposure from carbonate facies. Furthermore, it highlights the importance of microbial growth and cementation processes for the development and the geometrical maintenance of post-extinction carbonate platforms such as the Latemàr.

1. Do we need a new model for the Latemàr cycles?

Blendinger (2004) attacks the conventional model and suggests reinterpretation of the Latemàr cycles based merely on the following presumptions: (1) the Latemàr lacked a marginal energy barrier; (2) the Latemàr cycles appear to reflect low energy depositional conditions; and (3) the stable isotope record of Dunn (1992) argues for a non-vadose origin of the Latemàr cements. We will demonstrate that the assumptions are unfounded (1, 2), the isotope data are ambiguous (3) and, as Blendinger (2004) admits, he presents no new supporting records from the Latemàr platform.

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2. Platform geometry

Blendinger (2004) claims that for the isolated Middle Triassic platforms of the Dolomites "an energy barrier [. . .] is very unlikely given the bedding architecture similar to flattened mounds (Schlager, 2003) and the absence of an elevated reef rim or high-energy sand shoal [. . .]". He argues that platform deposition took place in a deep, but photic environment near the storm wave base.

In order to test these claims, we need to focus on the following crucial questions: (1) what is the geometry of the Latemàr platform. (2) How is the Latemàr margin constructed? (3) And what is the composition of the platform interior?

The Latemàr reef rim and lagoon can be compared with the classical empty bucket morphology for modern tropical carbonate platforms. In this model, Schlager (1981) asked for a stiff reef rim composed of "competent" material and the build-up interior to be filled with "incompetent" lagoonal deposits.

2.1. A "competent" margin

The Latemàr, albeit lacking a major frame-building metazoan community, nonetheless exhibits a stiff margin surrounded by steep slopes that are inclined to a deep basin: the margin is composed mainly of microorganisms such as *Tubiphytes*, calcimicrobes and automicrite, and it is reinforced by abundant amounts of early marine cements providing the necessary rigidity (Harris, 1993; Emmerich, 2001; see also Keim and Schlager, 2001). The Latemàr reef is further subdivided into a deeper water part with fragile, branching corals that were interpreted to have grown below normal wave base, and shallow-water reef areas dominated by encrusting wave-resistant organisms and delimiting the lagoonal interior (Harris, 1993; Emmerich, 2001). A subdivision into reef front, reef crest and backreef is comparable to many other protective carbonate platform margins that formed throughout the Phanerozoic.

The intermittent development of a strongly cemented tepee belt in the outer part of the Latemàr lagoon, several hundred metres wide, with tepee megapolygons several decimetres of relief (e.g., Fig. 12 of Egenhoff et al., 1999), further stabilised the Latemàr margin and added to the energy barrier.

2.2. An "incompetent" lagoon

The Latemàr lagoon is filled with allochemical material including lime mud, peloids, aggregate grains and fragments of a restricted dasycladalean flora (Gaetani et al., 1981; Egenhoff et al., 1999; Preto et al., 2001). These calcareous components are organised in sub-concentric facies belts following the outline of the margin. Lateral facies zoning of mostly allochemical deposits in the lagoon is characteristic of shallow carbonate platforms but argues against a mound-like growth of the entire Latemàr.

3. High water-energy deposition

Blendinger (2004) states that a peritidal origin of the cycles at Latemàr is hard to explain: their facies "appear to reflect a low-energy lagoonal environment, which is [. . .] difficult to reconcile with the small platforms lacking marginal energy barriers in a tropical, stormy climate". By contrast, in a different place in his paper (p. 26), he claims that the platform resembled a flattened mound, a build-up architecture that develops where otherwise upward convex deep-water mounds grow into the zone of wave action (Schlager, 2003). The very storms or waves that Blendinger (2004) ruled out initially, he calls on to account, in part, for the build-up's geometry. Notwithstanding this contradiction, there is ample evidence for high-energy deposition on the Latemàr platform top: various facies types, common in many layers of the succession particularly in the marginal tepee belt, have been interpreted as a result of high-energy or storm deposition (Egenhoff et al., 1999). The high-relief tepee megapolygons facilitated the trapping of coarse sediment including gastropod coquina and ammonites, which were likely transported onto the elevated tepee belt during high-energy events. These deposits are only found within tepee cavities. Coarse-grained calciclastic lagoonal facies are more abundant in the outer lagoon, which indicates that high-energy events frequently affected the Latemàr but the marginal barrier attenuated their impact (Egenhoff et al., 1999).

The scarcity of more distinct current-induced sedimentary structures such as scour-and-fill channels or cross bedding (Blendinger, 2004) further argues for an effective energy barrier represented by the forereef and the adjacent tepee belt that sheltered the platform interior. The lack of a protective tepee margin and forereef in other build-ups in a more southerly shelf location (Triassic palaeogeographic position) such as the Marmolada or the Cernera may argue for a deeper depositional environment on these platform tops where tepees were not able to form. A southward overall increasing water depth is possibly related to increasing subsidence(?).

4. Bathymetry

Blendinger (2004) proposes "that the prevailing grainstone depositional fabrics coupled with the scarcity of evidence for sediment transport indicate that the platform tops were generally located within a zone of only minor water energy" near (a comparably shallow) storm wave base. This depositional setting disregards the lagoonal facies architecture of the Latemàr and requires reinterpretation of a number of sedimentary features previously thought to indicate peritidal and meteoric vadose environments (Esteban and Pray, 1983; Kendall and Warren, 1987).

4.1. Pedogenesis

Black pebbles at cycle tops in the Latemàr lagoon (Egenhoff et al., 1999) provide strong evidence for temporary subaerial exposure and argue against deep water deposition of the entire lagoonal succession. These particles originated from reworking of substrate that underwent incipient pedogenesis (see Strasser, 1984). The formation of soil horizons may have indeed been rather uncommon as suggested by Blendinger (2004), although subsequent marine flooding or storms likely removed all signs of soil formation.

4.2. Lagoonal facies architecture

Blendinger's (2004) subtidal interpretation of the lagoonal facies is difficult to reconcile with their architecture (Egenhoff et al., 1999): when, applying semi-quantitative Markov chain analysis to sections measured in the Latemàr lagoon, a systematic vertical and lateral facies distribution becomes apparent. A random origin for this pattern is highly unlikely. Instead, regular bathymetrical changes with a comparably high frequency (< 4 ky per cycle; Mundil et al., 2003) that affected a platform with a subtle palaeorelief (Egenhoff et al., 1999) are a more probable cause. Deep-water deposits with limited storm influence as suggested by Blendinger (2004) would hardly produce a systematic facies architecture with frequent repetitive facies shifts, whereas shallow-water environments are very susceptible to changes in water depth (Shinn, 1983). The existence of this facies pattern per se, however, does neither suggest external nor internal forcing of the cyclicity (for discussion see, e.g., Wilkinson et al., 1998; Rankey, 2002).

Inverse grading, laminar fenestrae, tepees, pisoids, pendent cements, black pebbles and caliche occur in various combinations at cycle tops. The co-occurrence of these features and fabrics is considered indicative of a shallow marine environment with intermittent marine or meteoric vadose conditions during the final phase of cycle deposition.

5. Hydrothermal influence

Blendinger (2004) explains "the stratiform occurrence of the diagenetic features" at the top of the Latemàr cycles by means of "diffuse venting or seeping in the upper, unconsolidated sediment layers". A nearby heat source provided the hydrothermal fluids for this process. In fact, a magma chamber was situated a few kilometres southwest of the platform. Diffuse percolation of fluids through the succession is likely, and some of the small cracks observed in Latemàr strata that have been attributed to Alpine tectonism may be of Triassic age (Blendinger, personal communication, 2004).

5.1. Spatial distribution of syngenetic features

It is quite possible that hydrothermal activity augmented the saturation state of carbonate ions in lagoonal waters, thus favouring cementation, tepee and pisolite formation. However, it is difficult to explain why this seeping should have generated a subconcentric distribution of these features in the outer lagoon following the contours of the Latemàr margin. This pattern corroborates Egenhoff et al.'s (1999) palaeorelief model. Additionally, if syngenetic features formed by upward flowing diagenetic fluids, they should be found at various levels of individual cycles or associated with different facies types. Instead, they are usually associated with facies forming the cycle top (see also Egenhoff et al., 1999).

If fluids that produced the syngenetic features of the Latemàr cycles were related to the nearby igneous centre, the frequency of tepees together with the intensity of cementation should either decrease away from the volcanic centre or be evenly distributed across the platform within individual stratigraphic intervals. However, this is not the case. Conversely, the tepee belt at Latemàr is best developed in the present-day north and northeast, which is the platform margin opposite the one facing the location of the magmatic centre. Egenhoff et al. (1999) ascribed this platform facies asymmetry to storm-driven sediment redistribution and palaeowinds from present-day south and west (Blendinger and Blendinger, 1989).

5.2. Stable isotopes

Blendinger (2004) calls on Dunn's stable isotope data to support a marine or hydrothermal origin, and rejects a meteoric origin for the Latemàr cements. The data collected from bulk rock and separated components by Dunn (1992) show $\delta^{13}C$ values from +2‰ to +4‰ and $\delta^{18}O$ values from −2‰ to −8‰. The small range in $\delta^{13}C$ values can be explained as being derived entirely from a marine source and remained unchanged even when recycled into diagenetic products. ^{13}C-depleted values (up to −12‰) often associated with pedogenic calcite are absent. The ^{18}O-depleted values can be related to high temperatures or ^{18}O-depleted waters. The 6‰-range in $\delta^{18}O$ values is found in many limestones and is commonly interpreted as due to the addition of late cements precipitated at high temperatures due to burial (Dunn, 1992). These data do not uniquely support or discount hydrothermal activity.

The distribution of the isotope data is interesting. $\delta^{18}O$ values from rocks below the Latemàr cyclic sequence, closer to the igneous body, are less depleted than those from the overlying cement-rich cyclic sequence. Dunn (1992) takes this to indicate that burial or hydrothermal waters did not pass from the lower to the overlying cyclic rocks, as their cements are isotopically different. Also, it might be expected that hydrothermal fluids would cool with distance from the heat source resulting in increasing $\delta^{18}O$ values but the reverse occurs.

6. Conclusions

Our observations and literature data indicate that the interior of the Middle Triassic Latemàr carbonate platform was indeed protected by an energy barrier represented by a strongly cemented reef rim and tepee belt. The growth anatomy of the Latemàr reflects Schlager's (1981) bucket model with a stiff competent reef and a non-competent calciclastic lagoon, even though the Latemàr's palaeorelief is rather low compared with modern carbonate platforms. The composition of the Latemàr reef margin, dominated by microorganism and reinforced by abundant cements, resembles a mound facies (see also Blendinger et al., 2004; Wood, 2001). This is likely related to microbial flora assuming the role of shallow-water frame-builders from metazoans in the aftermath of the Permian mass extinction.

The systematic lateral and vertical facies distribution and frequent repetitive facies shifts argue against deep-water sedimentation of Latemàr interior deposits and favours deposition in shallow water, which is much more susceptible to environmental changes. This is corroborated by (1) the occurrence and distribution of high-energy related deposits, (2) the distribution and co-occurrence of tepees and other syndepositional diagenetic features and (3) the preservation of black pebbles. However, Blendinger's (2004) bathymetrical interpretation may be valid for other platforms likely situated in deeper bathymetries in the present-day east of the Latemàr such as the Cernera (Blendinger et al., 2004).

The distribution of tepees and other early diagenetic attributes along a sub-concentric zone following the contours of the Latemàr margin is difficult to reconcile with an exclusively hydrothermal, deep-water origin for these features, which should decrease in abundance away from the heat source, an igneous centre situated a few kilometres southwest of the platform (present-day southeast). Stable isotope data do not uniquely support hydrothermal activity. Higher $\delta^{18}O$ values of cements from the cyclic sequence compared to underlying limestones would indicate increasing temperatures away from the heat source, which argues against upward percolation of hydrothermal fluids.

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