LATERAL VARIABILITIES OF CYCLE STACKING PATTERNS IN THE LATEMÀR, TRIASSIC, ITALIAN DOLOMITES

ARNDT PETERHÄNSEL
Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge, CB2 3EQ, United Kingdom
Present address: LUKOIL Overseas UK Limited, Charles House, 5–11 Regent Street, London, SW1Y 4LR, United Kingdom
e-mail: arndt@lukoiloverseasuk.com

AND

SVEN O. EGENHOFF
Colorado State University, Department of Geosciences, 322 Natural Resources Building,
Fort Collins, Colorado 80523-1482, U.S.A.
e-mail: sven@warnercnr.colostate.edu

ABSTRACT: The well-known cyclic carbonate succession of the Middle Triassic Latemàr Massif in the Italian Dolomites reveals significant lateral variability in cycle numbers in platform-interior strata. Within an interval of 60 m, a 25% increase in the number of marine flooding surfaces was detected when approaching the several-hundred-meters-wide tepee belt in the backreef area, which represents the maximum elevation of the isolated Latemàr buildup. The impact of high-frequency– low-amplitude sea-level fluctuations on this elevated zone resulted in the development of spatially restricted intermittent emergence and marine flooding surfaces bounding small-scale upward-shallowing cycles. It is postulated that these alternations of submergence and subaerial exposure have favored tepee formation. Sediment collecting in the saucer-shaped tepee megapolygons further expedited upward shallowing of small-scale cycles. Conversely, deeper parts of the lagoon remained largely unaffected by high-frequency, low-amplitude sea-level oscillations: marine flooding surfaces disappear and cycles amalgamate. It is concluded that tepee structures are generally confined to topographically elevated areas where low-amplitude sea-level fluctuations were recorded. Lateral variations in cycle stacking pattern should be commonplace in shallow carbonate buildups throughout the geological record, where paleorelief existed in the platform interior.

INTRODUCTION

In recent years, the spatial distribution of carbonate lithofacies organized in small-scale cycles and related bounding surfaces has received increasing attention given its implications for reservoir architecture, sequence stratigraphy, and cyclostratigraphic interpretations (e.g., Raspini, 2001; Della Porta et al., 2002; Goldhammer et al., 1993; Sonnenfeld and Cross, 1993; Strasser et al., 2005; Borkhataria et al., 2006). Lateral continuity of these cycles and their facies for up to several hundreds of kilometers has been claimed for many pelagic to hemipelagic calcareous sequences (e.g., Maurer and Schlager, 2003) but also for shallow-water carbonate platform environments (e.g., Grotzinger, 1986; Read, 1995; Lehrmann and Goldhammer, 1999; Strasser et al., 2000; Sandulli and Raspini, 2004). Meter-scale cycles with upward shallowing are characteristic features of greenhouse periods and correspond to low-amplitude sea-level fluctuations (Wright, 1992; Read, 1995; Satterley, 1996). However, only few studies have demonstrated this on regionally extensive outcrops where spatial dimensions of facies were determined by physical tracing of beds and surfaces (Sonnenfeld and Cross, 1993; Adams and Grotzinger, 1996; Lukasik et al., 2000). These studies do not rely on facies interpolation and composite sections but are based on walking out beds along outcrops. Egenhoff et al. (1999) applied this technique in the well-exposed Lower to Middle Triassic Latemàr platform of the Italian Dolomites. In the lagoonal succession of this small buildup of 10 km^2, they demonstrated that the complexity of facies architecture was controlled by subtle paleorelief. It was apparent that most cycles are laterally continuous across the buildup interior. However, reconnaissance observations revealed that cycle stacking patterns vary laterally, in particular when approaching the tepee-dominated platform margin. Lateral variations of cycle boundaries are controlled by the magnitude of accommodation changes (Grotzinger, 1986; Read et al., 1986; Adams and Grotzinger, 1996), which in turn may be linked to autocyclic sediment transport (e.g., Pratt and James, 1986; Goldhammer et al., 1990, p. 553–554; Satterley, 1996) and/or high-frequency sea-level changes (e.g., Goldhammer et al., 1990).

We attempt to identify the extent of lateral variations in cycle stacking pattern in the isolated Latemàr carbonate platform (Fig. 1) and the governing factors that account for them. In view of the controversy surrounding the Latemàr's role as a potential cyclostratigraphic measuring stick in the Milankovitch band, the observations presented here highlight the cyclostratigraphic complexity of that buildup.

GEOLOGICAL SETTING

In the Middle Triassic, the area of the Dolomites was located in the tropics at the northwestern margin of the Tethys Ocean, forming part of a continental shelf characterized by the extended carbonate platform of the Contrin Formation (Fig. 2; Masetti and Neri, 1980; Rüffer and Zühlke, 1995). Tectonic movements in the late Anisian (early Middle Triassic; Castellarin et al., 1988) led to the fragmentation of the ramp (Gaetani et al., 1981) with shallow-marine platforms evolving on structural highs. Persisting subsidence resulted in aggrading buildups such as the Latemàr (Schlern Formation) and intervening deep-marine, partly anoxic basins (Buchenstein or Livinallongo Formation; Bosellini and Rossi, 1974). The lagoonal interior of the Latemàr was characterized by subtle paleorelief, which is reflected by lateral facies changes within individual shallowing-upward cycles (Egenhoff et al., 1999). A tepee belt in the immediate backreef formed the topo-

Controls on Carbonate Platform and Reef Development
SEPM Special Publication No. 89, Copyright © 2008
SEPM (Society for Sedimentary Geology), ISBN 978-1-56576-130-8, p. 217–229.

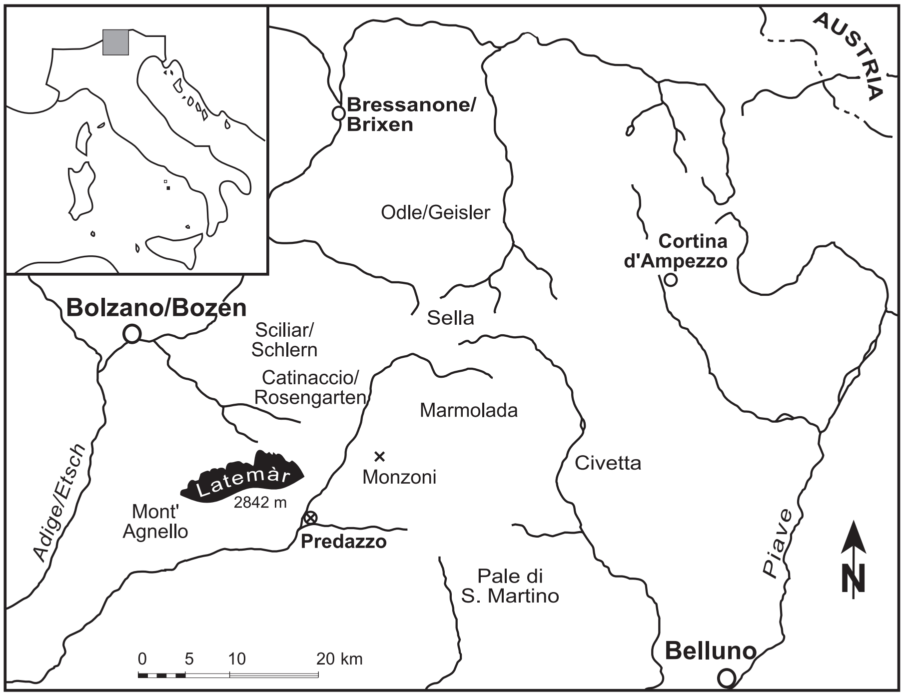


FIG. 1.—Location of the study area and other important Middle Triassic carbonate platforms in the Dolomites. Both German and Italian names are used in the South Tyrol area. Monzoni and Predazzo represent Ladinian magmatic centers (after Bosellini, 1991).

graphic high of the Latemàr platform circumscribing the peritidal lagoon (Egenhoff et al., 1999). This perimeter, 250–500 m wide, is characterized by a higher abundance of tepee structures, both vertical and lateral, than coeval deeper lagoonal areas, where tepees are comparably rare or absent. Interpretations of Latemàr interior facies are listed in Table 1.

In the early late Ladinian a magmato-tectonic event in the central Dolomites terminated a final progradation phase recorded by the youngest deposits of the Latemàr and the neighboring Rosengarten (Viel, 1979; Bosellini, 1984; Brack and Rieber, 1993, Maurer, 2000). Carbonate production ceased as volcanics and volcaniclastics covered many platform tops and partly filled the surrounding basins (Fig. 2; Bosellini and Rossi, 1974).

THE LATEMÀR CONTROVERSY

The Latemàr buildup is one of the most thoroughly studied carbonate platforms. Milankovitch-band eccentricity and superimposed precession rhythms were thought to be the controlling mechanism to account for the stratal pattern of the 720-m-thick lagoonal interior of the buildup (Hardie et al., 1986; Goldhammer et al., 1987, 1990; Goldhammer and Harris, 1989; Hardie et al., 1991; Hinnov and Goldhammer, 1991; Goldhammer et al., 1993). An allocyclic origin of the more than 600 “basic Latemàr precession cycles”, which are bounded by marine flooding surfaces and are usually of meter scale, has been further advocated by more recent studies of Preto et al. (2001), Zühlke et al. (2003), and Zühlke (2004). These authors used time-series analysis and Fischer diagrams (Fischer, 1964; but see also Sadler et al., 1993) to support their allocyclic model for the Latemàr lagoonal succession. For these rocks, orbital forcing and cycle deposition in bundles of five, or “pentacycles”, has been widely embraced by the sedimentological community, and the Latemàr has been persistently quoted in textbooks as the premier example (Tucker and Wright, 1990; Reading, 1996). However, this interpretation has been challenged or modifications have been suggested by various authors since it was first proposed: detailed biostratigraphic calibration of platform-to-basin evolution combined with radiometric age dating of zircons from volcaniclastic beds in both basinal and platform deposits reduce the average Latemàr cycle duration to less than 8 kyr (Brack et al., 1996; Mundil et al., 1996), less than 3 kyr (Mundil et al., 2003) or less than 2 kyr (Emmerich et al., 2005) instead of 20 kyr (Goldhammer et al., 1987, 1990; Goldhammer et al., 1993). This indicates partly sub-Milankovitch control,

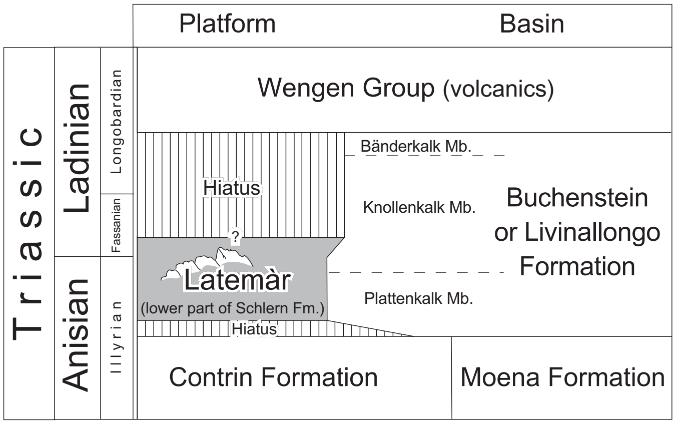


FIG. 2.—Stratigraphic relationship of the Latemàr succession to adjacent units in the central western Dolomites (stratigraphic correlations based on Maurer, 1999; Mundil et al., 2003).

TABLE 1.—Comparison of facies interpretations of the Latemàr interior presented by various authors.

	Goldhammer et al. (1987,1990, 1993)	Preto et al. (2001)	Zühlke et al. (2003)	Blendinger (2004)	Egenhoff et al. (1999); this paper
(1) Cycle type	Depositional cycle with diagenetic cap	Shallowing-upward facies cycles	Shallowing-upward accommodation cycles	Depositional cycle with top overprinted by hydrothermal fluids	Shallowing-upward cycles bounded by marine flooding surfaces
(2) Depositional environment	Shallow subtidal deposition	Deeper subtidal to subaerial	Shallow subtidal to supratidal	Subtidal deposition in photic water around storm wave base	Shallow subtidal to supratidal deposition.
(3) Vertical and lateral cycle completeness	**All** cycles with various thicknesses of solely subtidal facies and capped by thin dolomitic crust (or tepee); individual cycles are not studied for lateral variability	Vertical facies variations are detected through subfacies-ranking approach.	Most cycles are laterally continuous and can be physically traced across the platform “layer-cake” geometry).	Refers to Egenhoff et al. (1999)	Not every facies is (fully) developed in every cycle; lateral changes in cycle thickness and facies (partly pinching out)
(4) Microfacies arrangement	Basal cycle member: bioturbated shallow subtidal (within the photic zone) skeletal–lithoclast packstone or grainstone with coarsening-upward trend; occasionally storms produced graded “tempestites	Cycles show four sub-environments: (1) Deep subtidal packstones to grainstones with abundant and various fossils, overlain by (2) restricted subtidal fine-grained wackestones with scarce and/or oligotypic biota, overlain by (3) weakly laminated supratidal-flat deposits, apped by (4) caliche soils consisting of yellow dolostones with vadose pisoids and pendant/ meniscus cements.	Cycles consist of subtidal facies, overlain by intertidal- to supratidal floatstones, rudstones, bindstones and teepees, supratidal residual sediment orperitidal dolomitic caps.	Subtidal facies with coarsening-upward trend; refers to Gaetani et al. (1981) and Goldhammer et al. (1990)	Shallow subtidal dasycladalean-bearing pelois packstone to wackestone overlain by a peritidal fenestral packstone to wackestone with peloids and lumps, occasionally oncoids; coarse storm deposits in andaround teepees; lagoonal facies are organized in subconcentric belts following the outline ofthemargin
(5) Diagenetic overprinting	Upper cycle member: thin yellow dolomitic cap of subaerial origin with vadose cements, solution vugs, and caliche fabrics; tepees indicate continuous subaerial exposure and represent two or more cycles	Caliche and meniscus cements as well as dolomitization of cycle tops indicate early diagenetic overprinting during late stages of cycle evolution.	Intertidal and supratidal tepees, supratidal residual sediment and intertidal to supratidal dolomitic caps represent diagenetic overprint	Cycle top consists of thin dolomitic cap of subtidal origin with hydrothermally induced dripstone cements, subtidal tepees, and hydrothermal dissolution features resulting in reddening of carbonates.	Upper part of cycle **may be** diagenetically overprinted during peritidal (dolomitic cap and tepees) and subaerial conditions (calichification and karstification): peritidal conditions lead to dolomitization (Carballo et al., 1987), sheet cracks and cementation to tepee formation, eolian transport of ferruginous material and/or dissolution to red internal sediment (terra rossa), calichification to enlargement of components.

which according to Zühlke et al. (2003) may be related to rapid paleoceanographic and atmospheric changes. They attributed a bundle of four to five Latemàr cycles to precessional forcing (20 kyr) in contrast to Goldhammer et al.'s (1987, 1990) and Goldhammer et al.'s (1993) short-eccentricity interpretation (100 kyr) of these pentacycle sets. Kent et al. (2004), based on lithostratigraphic, biostratigraphic, and magnetostratigraphic correlations, proposed millennial-scale tidal-amplitude variations an order of magnitude faster than the Milankovitch band to explain the meter-scale basic Latemàr cycles. Also, they saw striking coincidence of subaerial exposure surfaces about every 10 m (Egenhoff et al., 1999) and the most prominent spectral peak of Preto et al.'s (2001) untuned time-frequency analysis centered at 10 m. This correlation would suggest precessional forcing for these recurring events (Kent et al., 2004) and, yet again, for a thicker depositional interval than in Zühlke et al. (2003). The two sequences making up the general facies units (LCF–MTF–UCF–UTF; Fig. 3; Egenhoff et al., 1999) then correspond to long-eccentricity forcing (400 kyr), which would imply a total duration of 800 kyr for the entire cyclic succession at Latemàr (Kent et al., 2004). Despite the heterogeneity of the recent interpretations with respect to cycle duration, there appears to be strong concurrent evidence against pure orbital forcing of the meter-scale basic Latemàr cycles.

Blendinger (2004) questioned sea-level changes and eustasy as the governing factors for cycle formation at Latemàr and offered an alternative interpretation involving intermittent hydrothermal influence alternating with normal marine deposition. On the basis of correlation between abundance of cycles and younger volcanic dikes crosscutting the buildup, he hypothesized that fluids with a composition similar to that of normal seawater were forced periodically by elevated heat flow from an underlying magma chamber to circulate to the seafloor. These fluids produced stratiform diagenetic features, including tepees, and favored growth of cyanobacterial mats and early dolomitization. However, the Latemàr facies and its distribution patterns argue against Blendinger's (2004) hydrothermal model, and stable-isotope data from Latemàr are equivocal (Preto et al., 2005; Peterhänsel and Egenhoff, 2005).

METHODOLOGY AND OBSERVATIONS

When "walking out" or tracing lagoonal flooding surfaces (e.g., Rogers, 1998; Rankey et al., 1999), Egenhoff et al. (1999) detected facies variations in individual platform-wide meter-scale cycles (now assigned to sub-Milankovitch sea-level oscillations; see above discussion), which reflect paleorelief on the depositional surface. A tepee belt near the platform margin was thought to represent the paleotopographic high circumscribing the peritidal lagoon. The tepee belt is characterized by intermittent tepee formation. In contrast to Egenhoff et al. (1999), who investigated lateral facies variations in intervals with laterally continuous meter-scale Latemàr cycles, this study focuses on strata that split laterally into several smaller-scale cycles. An approximately 60-m-thick section forming the base of the relatively tepee-poor Upper Cyclic Facies (UCF, Fig. 3; Egenhoff et al., 1999) is characterized by a lateral increase in cycle numbers. It was analyzed to characterize these cycles and to unravel the circumstances that resulted in their formation. This interval represents the lower 60 m of the section that was used for time-series analysis by Hinnov and Goldhammer (1991) and Preto et al. (2001). This section was said to "contain the longest uninterrupted sequence of cycle couplets [, subtidal base and subaerial exposure cap,] in the [Schlern] Formation that was measured at a single location" (Hinnov and Goldhammer, 1991).

The measured interval is stratigraphically well constrained: it is marked at its top by a distinct tuffite, which has been dated to 241.5 Ma (LAT 32 of Mundil et al., 2003), and it is internally controlled by various continuous marker beds, which are characterized either by prominent weathering or by subaerial emergence features. They are easily recognizable in the field and can be walked out within structural blocks of the buildup and correlated across faults or scree cover. A minimum of 10 carbonate beds above and below the markers were traced and correlated (e.g., marker bed N in Figures 3 to 5). The interval represents the base of the upper cyclic facies (Egenhoff et al., 1999) and includes strata that exemplify platform-wide continuity without splitting of cycles.

In the upper part of the 60 m interval, half a dozen zones, 2–3 m thick, display lateral splitting of meter-scale cycles into two to six centimeter- to decimeter-scale (small-scale) cycles, for example at 32–34 m, 39–41 m, and 43–46 m (Figs. 6 and 7). In the lower part of the measured section, tepees with discontinuous small-scale cycles are comparatively rare, for example at 17 m. Small-scale cycles are associated with abundant tepees belonging to the backreefal tepee belt, but obviously they are also restricted to certain episodes within the 60 m interval (Fig. 4), thus implying a spatial and temporal restriction of variation in numbers of lateral cycles.

Small-scale cycles are composed of shallowing-upward facies successions bounded by flooding surfaces. The bases of such cycles are usually composed of wackestones to packstones with varying amounts of dasycladalean algae, which grade upwards into peloid-lump wackestones and packstones, which are in turn overlain by oncoid packstones to grainstones (cf. Goldhammer et al., 1990; Egenhoff et al., 1999; Preto et al., 2001). A dolomitic cap forms the topmost part, if the cycle is fully developed. This facies succession, with a decrease in mud content towards the top, characterizes both the meter-scale cycles that are laterally traceable throughout the platform interior (Egenhoff et al., 1999) and the centimeter- to decimeter-thick cycles that are discontinuous and developed exclusively in association with tepees. Many of these very thin cycles can be followed throughout the tepee belt. Within the detailed measured interval of 60 m at Cimón Latemàr, 105 shallowing-upward cycles are recorded compared to 79 at the Cima del Forcellone, a decrease of some 25%.

DISCUSSION

Lateral Distribution and Origin of Discontinuous Small-Scale Cycles

There appears to be unanimous consensus on external forcing of the basic meter-scale Latemàr cycles, even if the specific driver has not yet been agreed upon (see controversy above). For the discontinuous centimeter- to decimeter-scale cycles, both, allocyclic and autocyclic forcing has to be considered:

Autocyclicity.—

Lateral variations of cycle stacking patterns in carbonate deposits have been attributed to lateral sediment transport: theoretical approaches of Ginsburg (1971) and Burgess et al. (2001) advocated shoreline and island progradation as possible cycle-producing mechanisms. Pratt and James (1986) and Satterley (1996) provided outcrop data supporting these interpretations. At Latemàr, distinct progradation geometries and lateral accretion in small-scale cycles, usually seen as an indicator of autocyclic influence, are absent, which argues against exclusive autocyclic control. Small-scale cycles are concentrated in the tepee belt

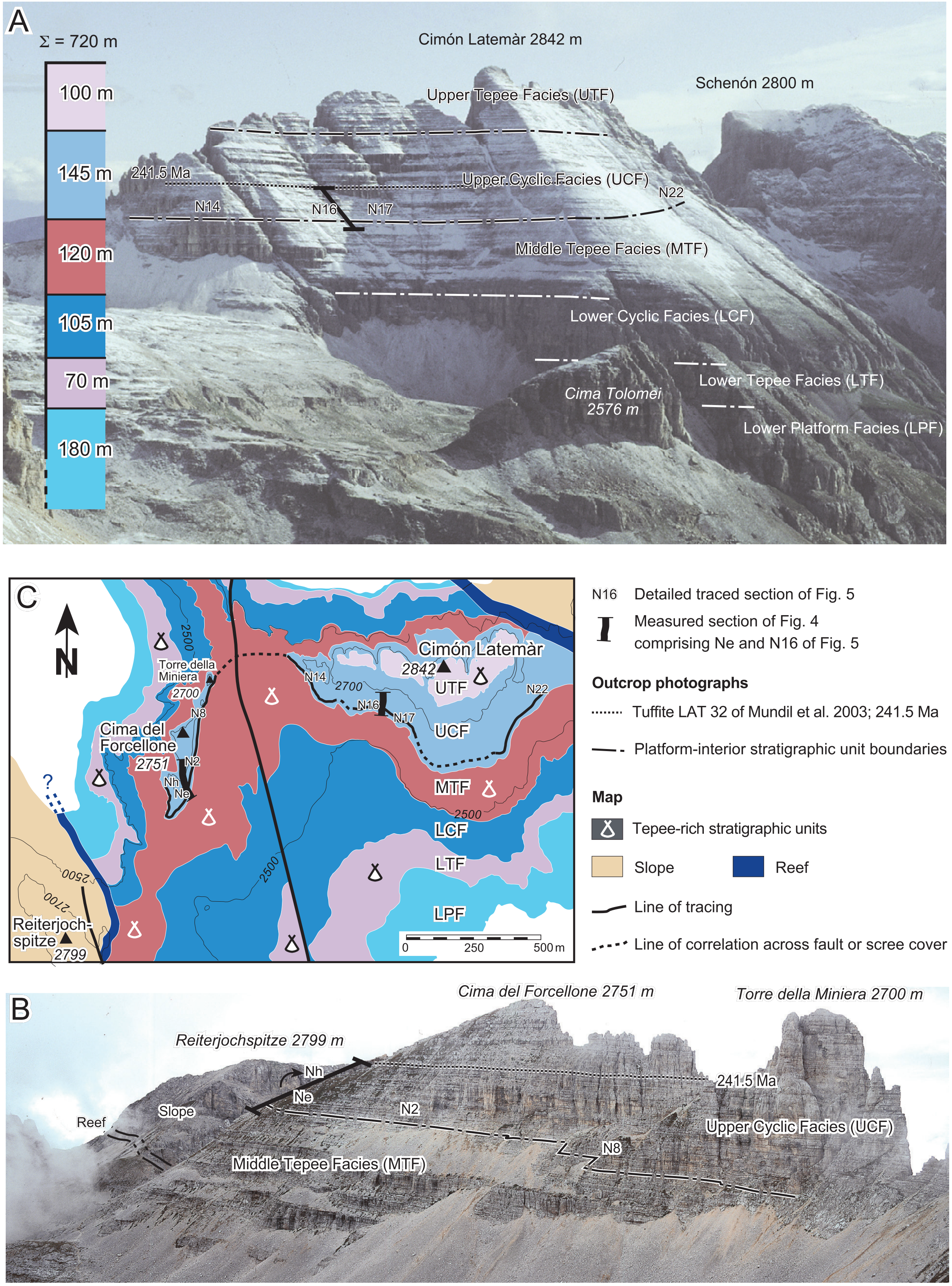


FIG. 3.—Location of traced and correlated interval displayed in Figure 4, linking Cimón Latemàr (A) and Cima del Forcellone (B). Stratigraphic units are in accordance with Egenhoff et al. (1999). The section is capped at the top by a distinct tuffite (LAT 32 of Mundil et al. 2003; 241.5 Ma). Locations of individual segments Nh, Ne, N2, N8, N14, N16, N17, and N22 composing the curved cross section in Figure 5 are indicated. The Forcellone and Latemàr blocks are separated by a fault with a displacement of 35 m (C).

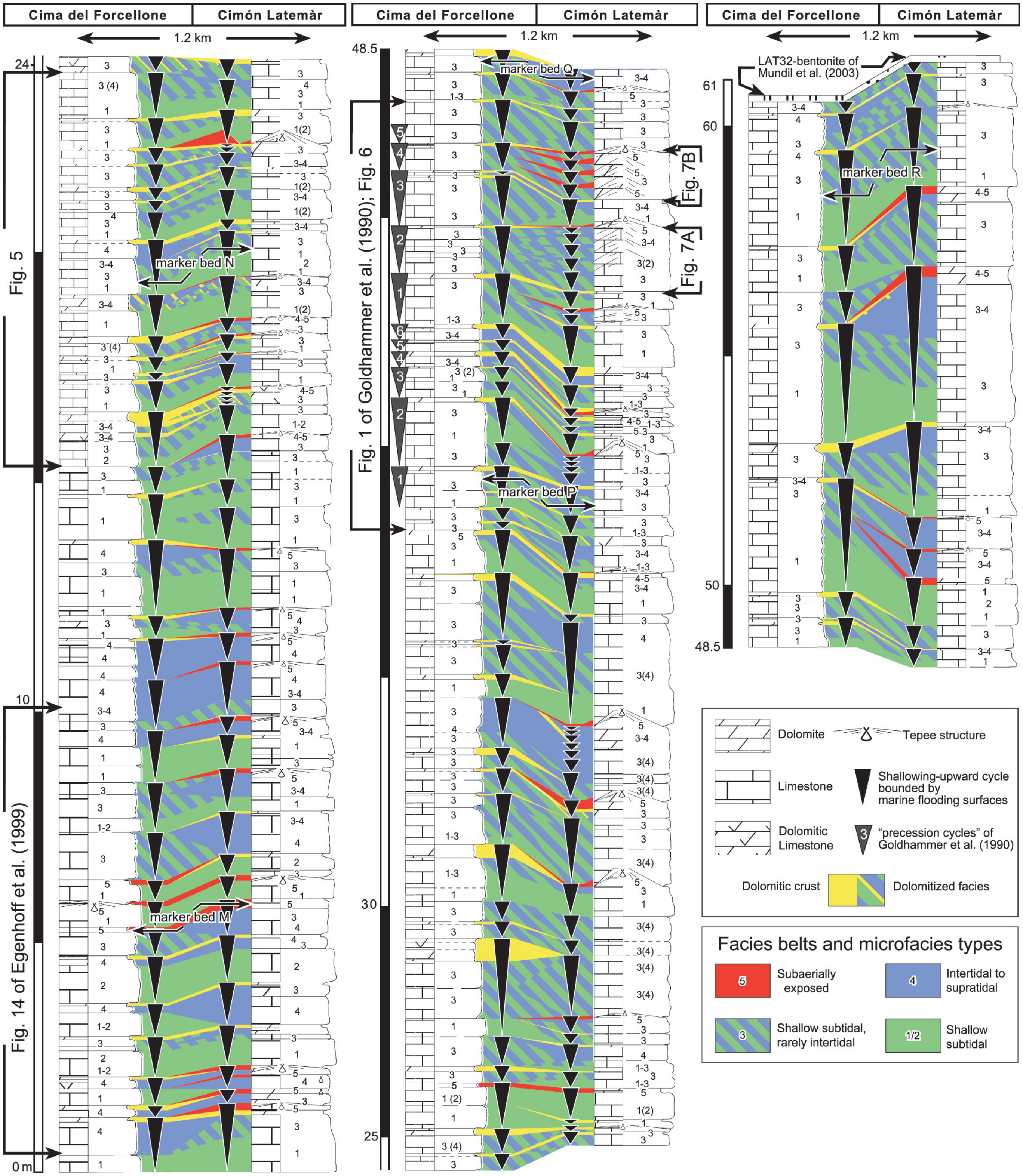


FIG. 4.—Vertical and lateral facies of a detailed traced and correlated interval illustrated with time-equivalent sections from Cima del Forcellone and Cimón Latemàr including detailed traced segments Ne and N16 of Figure 5 at 15–24 m. Locations of measured sections are shown in Figure 3. Cycle stacking pattern represented by black triangles is based on vertical facies development. Two sets of "pentacycles" measured at the same locality by Goldhammer et al. (1990) are indicated at 38–47 m and are portrayed in Figure 6. The interval comprising discontinuous small-scale cycles associated with tepees shown in Figure 7 is equivalent to part of the upper "pentacycle" set.

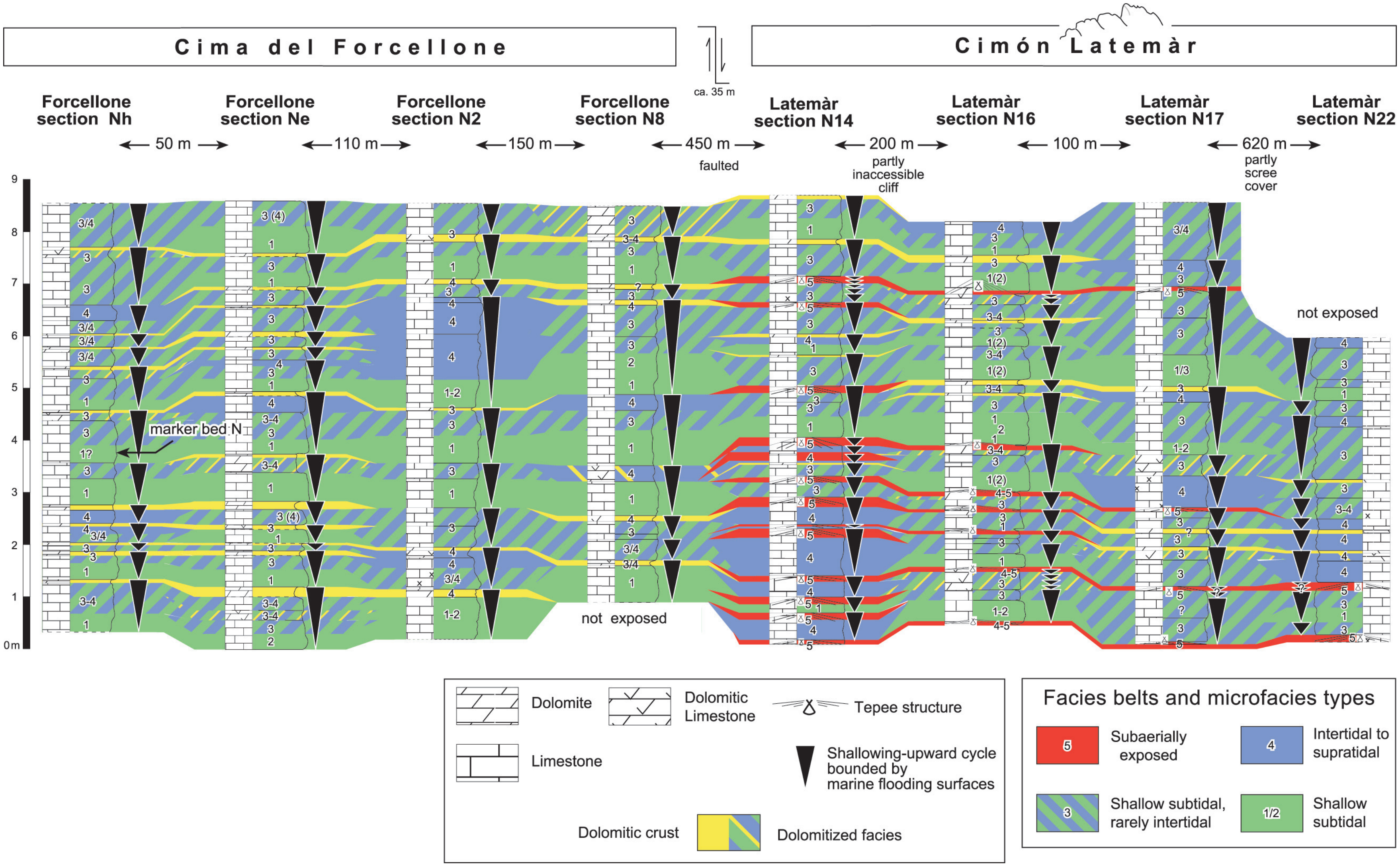


FIG. 5.—Lateral changes in facies and cycle stacking pattern within traced and correlated beds from the basal Upper Cyclic Facies (Fig. 3). Segments Ne and N16 form part of the sections portrayed in Figure 4, 15–24 m. The profile represents a curved cross section connecting the tectonic blocks of the Cima del Forcellone in the west and the Cimón Latemàr in the north, which are divided by a fault with 35 m offset. All beds were traced except where indicated (see also map Fig. 3). The four Forcellone sections (left) represent the outer lagoon whereas the four Latemàr sections (right) are situated in proximity to or within the tepee belt. Black triangles indicate shallowing-upward cycles bounded by marine flooding surfaces. Cycle numbers vary throughout the measured sections owing to amalgamation or splitting; lateral variation is greatest in sections with abundant tepees. Locations of individual segments Nh, Ne, N2, N8, N14, N16, N17, and N22 are in Figure 3.

FIG. 6.—Outcrop photograph of a part of the section measured at Cima del Forcellone (38.5–47.5 m of Figure 4) looking to the north with Rosengarten/Catinaccio massif in the background. The portrayed interval comprises the two "fourth-order cycles" or "pentacycles" of Figure 1 of Goldhammer et al. (1990). The numbers and dashed lines reflect their "fifth-order precession cycles". Cycles 2 and 4 in the upper part of the photograph correspond to tepee beds at Cimón Latemàr comprising several small-scale cycles (Figure 7).

rather than distributed more randomly across other areas of the Latemàr interior. This may be a further argument against pure internal forcing. However, redistribution of sediment towards the up to 500-m-wide tepee belt, for example during storms, may have contributed to shallowing of facies, particularly inasmuch as this elevated area may have functioned as a suitable sediment trap: laterally extensive tepee megapolygons, up to several meters in diameter and several decimeters in relief (Fig. 7), easily collected lagoon-derived sediment with only limited possibilities of it being removed again. Ammonite specimens, which are important for biostratigraphic analyses, were found in increased abundance within the megapolygons as well. Storm derivation of the small-scale cycles would imply that storm deposits or their preservation are causally related to tepee formation. Conversely, in the Latemàr succession tepees do exist that do not comprise small-scale cycles (Fig. 4), and storm layers have been identified in non-tepee strata forming part of a meter-scale Latemàr cycle (Egenhoff et al., 1999). This observation argues against a storm origin of the small-scale cycles. Furthermore, gradational upward coarsening of carbonate particles and decreasing portions of micrite within the small-scale cycles question deposition during a single storm event. Some small-scale cycles, however, do show sharp contacts between basal wackestones to packstones and overlying grainstones, reflecting local erosion during high-energy events.

Allocyclicity.—

Lateral variations in cycle stacking pattern may be related to high-frequency sea-level changes with comparably low amplitude, which are recorded only on topographic highs. This high zone is commonly represented by an entire platform or isolated buildup where surrounding basinal areas remain unaffected by sea-level changes. However, cycle recording across the interior of a buildup could also vary, if topographic relief exceeds the amplitude of the sea-level changes. Then, deeper lagoonal parts remain largely untouched by fluctuations in water depth. At Latemàr, superimposed high-frequency, low-amplitude sea-level fluctuations may have affected only the elevated tepee belt area, where reduced accommodation resulted in the formation of laterally discontinuous cycles (Figs. 8A, B3, C3, D3). Deeper parts of the lagoon remained largely unaffected and thus show no intermittent subaerial exposure and/or deposits of marine flooding caused by this allocyclicity (Goldhammer et al.'s subtidal missed beats).

With respect to the above discussion, small-scale cycles in the Latemàr tepee belt likely formed as a result of external forcing. Upward shallowing may have been further expedited by sediment redistribution towards the tepee belt.

In essence, the paleotopography of the buildup with the elevated position of the tepee belt and its saucer-shaped sedimentary structures can be seen as the foremost reason for the restriction of small-scale cycles to that area.

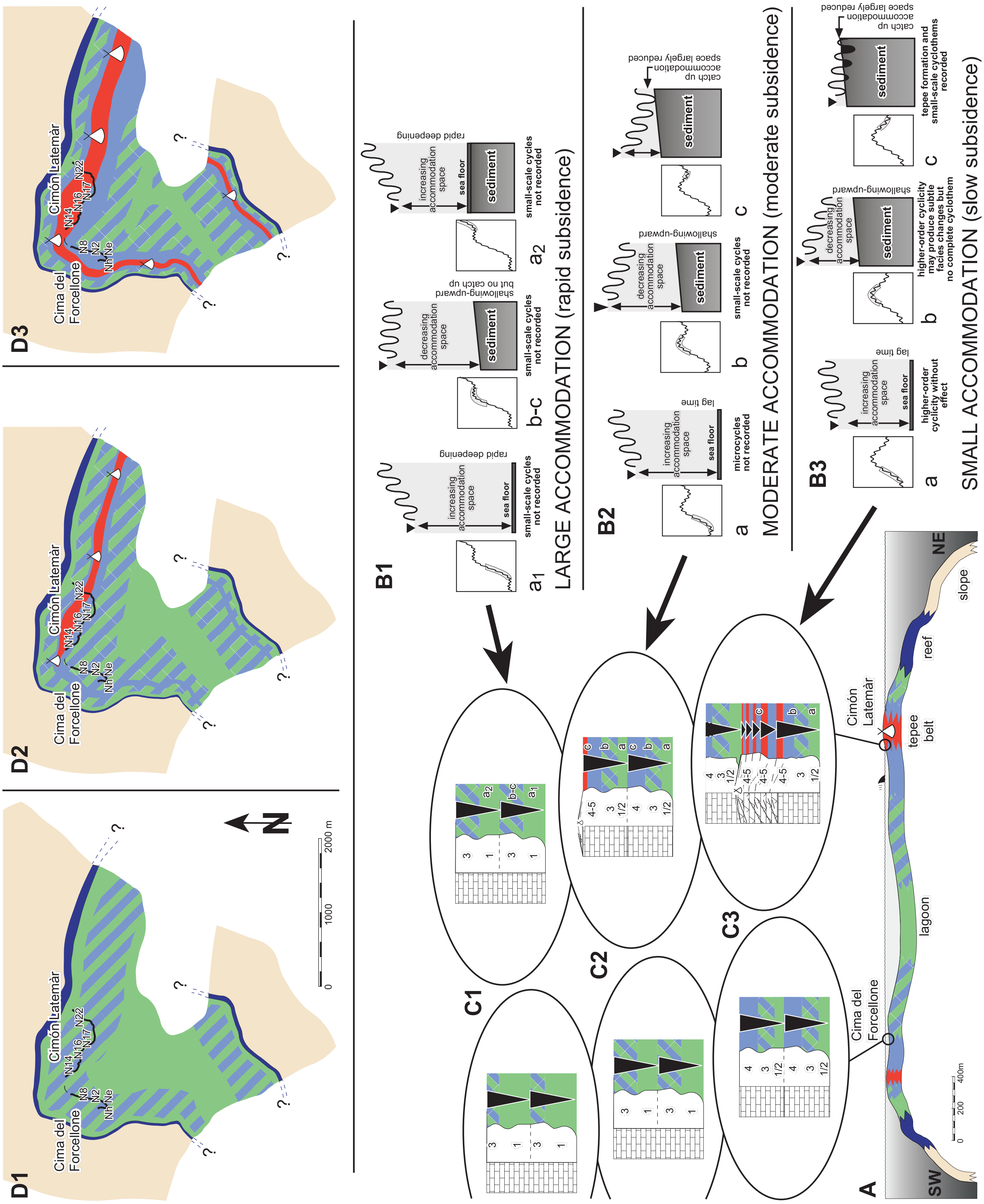
Vertical Distribution of Discontinuous Small-Scale Cycles

Small-scale cycles form clusters of discontinuity surfaces (Goldhammer et al., 1990; see also Hillgärtner, 1998) associated with tepees, and they occur intermittently throughout the middle and upper part of the Latemàr section measured in the immediate backreef (Fig. 4). Although tepee formation may have been influ-

FIG. 7.—Tepee structures from the Upper Cyclic Facies at Cimón Latemàr comprising several small-scale cycles. These strata grade laterally into one basic Latemàr shallowing-upward cycle. Figure 7A corresponds to 43.5–45 m of Forcellone section, and Figure 7B is equivalent to 47–47.5 m. The numbers represent "fifth-order precession cycles" of Goldhammer et al. (1990) portrayed in Figures 4 and 6. The vertical part of the measuring stick has a length of 1.6 m.

enced or advanced by the redistribution of lagoonal deposits (see discussion above), there is further evidence for predominant allocyclic forcing: in intervals with increased occurrence of tepee stacks, the meter-scale basic Latemàr cycles are often thinner than average, indicating a period of reduced overall accommodation (Goldhammer et al., 1990).

Long-term variations in accommodation may be responsible for vertical, that is, temporal, constraints for formation of small-scale cycles (see Lehrmann and Goldhammer, 1999). With changes in overall accommodation, various facies and cycle stacking patterns should form which are all represented in the Latemàr succession. Figure 8 demonstrates the influence of different levels of overall accommodation (B) on cycle stacking patterns (C) and facies distribution across the Latemàr platform (A and D). Vertical variability of formation of small-scale cycles and thus long-term variations in accommodation can be explained if a lower-order sea-level fluctuation with comparably larger amplitude is invoked (Vail et al., 1977; Haq et al., 1987). This interpretation largely follows the model for vertical cycle stacking of Goldhammer et al. (1987, 1990) and Goldhammer et al. (1993) but on a different scale and with important repercussions for tepee formation. Possible variations in the subsidence rate also have to be taken into account as a controlling factor for long-term accommodation (Fig. 8B). The nearby Predazzo and Monzoni magmatic


D1
D2
D3
Cima del Forcellone
Cimón Latemàr
N14
N16
N17
N22
N8
N2
Nh Ne
?
N
0
1000
2000 m
B1
increasing accommodation space
sea floor
rapid deepening
small-scale cycles not recorded
a1
decreasing accommodation space
sediment
shallowing-upward but no catch up
b-c
a2
LARGE ACCOMMODATION (rapid subsidence)
B2
microcycles not recorded
lag time
a
shallowing-upward
b
catch up accommodation space largely reduced
c
MODERATE ACCOMMODATION (moderate subsidence)
B3
higher-order cyclicity without effect
higher-order cyclicity may produce subtle facies changes but no complete cyclothem
tepee formation and small-scale cyclothems recorded
SMALL ACCOMMODATION (slow subsidence)
C1
C2
C3
1
3
1/2
4
4-5
A
SW
NE
0
200
400m
lagoon
tepee belt
reef
slope

centers (Fig. 1) were controlling regional subsidence and accommodation, producing deep faults and doming (Doglioni, 1988). Emmerich et al. (2005) have modeled subsidence variations for the Latemàr to fluctuate between 330 and 450 m Myr^{-1} between the central (MTF; Fig. 3) and upper (UTF) cyclic part of the lagoonal succession. Local changes in subsidence would imply that the assumed long-term accommodation changes are not only eustatic in origin. It is thus reasonable to assume that long-term accommodation changes in the Latemàr lagoonal succession are a composite of low-order sea-level oscillations and subsidence variations. With high levels of accommodation, high-frequency, low-amplitude sea-level oscillations are not recorded across the platform. Instead, meter-scale basic Latemàr cycles are deposited across the platform interior (Fig. 8—C1). It is noteworthy that rapid subsidence reduces the regressive time interval owing to convergence of the accommodation high and the onset of a new cycle (Fig. 8—B1), thus potentially shortening the period formation of small-scale cycles. Moderate accommodation levels result in the formation of thin tepees on a narrow backreef belt in the north and northeast (Fig. 8—B2, C2, D2). This distribution is related to the asymmetric paleorelief of the Latemàr buildup (Egenhoff et al., 1999). Centimeter- to decimeter-scale cycles are generated with comparably small accommodation levels when high-frequency, low-amplitude sea-level changes affect the elevated tepee belt (Fig. 8—A, B3, C3, D3). Further reduced overall accommodation space would shift the Goldilocks window (term of Goldhammer et al., 1990) of small-scale cycle and tepee formation to a deeper area on the buildup, thus widening the tepee belt to topographically lower areas, whereas higher areas would face somewhat longer subaerial exposure.

Tepees, Cycle Formation, and Missed Beats

Accommodation space varies in time and also laterally owing to paleorelief. At Latemàr, backreef strata characterized by tepees grade laterally lagoonward into layers without tepees, suggesting such paleorelief (Egenhoff et al., 1999; Fig. 8). Thus, Goldhammer et al.'s (1987, 1990) and Goldhammer et al.'s (1993) subaerial missed beats associated with tepee structures, although unrecorded on the elevated part of the platform, should be represented by carbonate deposits in deeper parts of the lagoon where enough accommodation space is provided. Cycle numbers in the deeper parts of the platform should therefore exceed the number of cycles recorded on elevated areas, and meter-scale basic Latemàr cycles should pinch out when they are traced from the paleotopographically deeper outer lagoon (Cima del Forcellone) into the elevated tepee belt. This is in contrast to our observations, in which cycle numbers increase laterally towards the elevated tepee belt by splitting of meter-scale cycles into several centimeter- to decimeter-scale cycles within the tepee belt (Figs. 5, 8). Thus, more sea-level changes, which means more marine flooding surfaces, are recorded in the tepee belt than elsewhere on the platform. Many of the small-scale cycles are of a higher order than the coeval meter-scale cycle of the deeper areas in the lagoon. It is therefore concluded that tepee stacks in general do not correspond to subaerial missed beats or represent more than one condensed basic Latemàr cycle as envisioned by Goldhammer et al. (1987, 1990) and Goldhammer et al. (1993) or Zühlke et al. (2003). An estimate of cycle numbers following their assumptions results in a significant overestimation of cycle numbers and corresponding time when measuring sections situated in the tepee belt. However, during subaerial exposure of the whole platform some cycles may have not been recorded, resulting in emergence horizons (Egenhoff et al., 1999).

Conversely, the recordability of centimeter- to decimeter-scale cycles in the tepee belt implies that tepees at Latemàr respond to relatively short pulses of sea-level fluctuations: brief phases of sedimentation likely enhanced by sediment redistribution from deeper lagoonal areas resulted in deposition of small-scale cycles separated by marine flooding surfaces. This involves a multistage process of deposition and syndepositional diagenesis including pervasive cementation. Once the tepee belt has been established, it forms a "symbiotic" relationship with small-scale cyclicity: centimeter- to decimeter-scale cycles are recorded only within the tepee belt and the related high-frequency sea-level fluctuations enhance alternations of diagenetic processes that favor tepee formation.

CONCLUSIONS

The cyclic Latemàr platform interior is characterized by meter-scale paleorelief, with a tepee belt in the immediate backreef representing its topographic high. Tepee formation is spatially limited and further temporally restricted to certain intervals. The number of cycles increases in the vicinity of these tepee zones, owing to a fanning out of cycles where discontinuous marine flooding surfaces appear. A laterally traced section from a relatively tepee-poor interval in comparison to the entire succession, that is, the Upper Cyclic Facies (UCF in Figure 3) reveals a 25% variation in cycle numbers. Low-amplitude sea-level fluctuations are likely responsible for the increase of cycle numbers in tepee zones. These oscillations influenced only the paleotopographically elevated tepee belt, whereas deeper parts of the lagoon remained largely unaffected owing to facies amalgamation without intermittent subaerial exposure and/or marine flooding. Sediment redistribution towards tepee areas, for example during storms, likely contributed to shallowing of facies as these saucer-shaped megapolygons acted as suitable sediment traps. The lateral increase in cycle numbers and the occurrence of tepee structures are indicators of subtle paleorelief on the Latemàr platform top.

Given the correlation between cycle-number increase and tepees, cycle-number variation in tepee-rich intervals of the succession, which are the Middle Tepee Facies (MTF) and Upper Tepee Facies (UTF),

FIG. 8 (facing page).—**A)** Paleotopography in the immediate backreef is attributed to higher amounts of carbonate fixation and enhanced growth in the tepee belt area likely related to small-scale cyclicity and sediment trapping in tepees and inter-tepee depressions and favored by microbial binding and cementation. Asymmetric paleorelief generated a broader tepee belt in the north and northeast of the buildup (Egenhoff et al., 1999). Influence of different levels of accommodation **(B)** related to two orders of superimposed sea-level oscillations and subsidence on cycle stacking patterns **(C)** and facies distribution across the Latemàr platform **(D)**. Long-term accommodation changes in the Latemàr lagoonal succession may be a composite of low-order sea-level oscillations and subsidence variations. B1–D1) High accommodation levels result in largely continuous deposition of meter-scale basic Latemàr cycles across the platform interior. Small-scale cycles are absent. B2–D2) With moderate accommodation levels, thin tepees may form on a narrow backreef belt in the north and northeast. B3–D3) Low levels of accommodation facilitate recording of high-frequency, low-amplitude cycles in the high areas of the platform during falling low-order sea level. The generated centimeter- to decimeter-scale cycles are associated with tepees and restricted to the tepee belt. Individual segments of traced section (Nh, Ne, N2, N8, N14, N16, N17, and N22) are in Figure 4.

should exceed variations in cycle numbers in tepee-poor units at Latemàr, which are the lower and upper cyclic facies (Fig. 3) and thus amount to even larger variations than the reported 25%. The vertical variations of cycle stacking patterns are likely to be responding to long-term accommodation changes, whereas small-scale cycles associated with tepees form during overall regressive periods. Long-term accommodation was probably a composite of low-order eustatic sea level and regional subsidence.

Tepees do not comprise subaerial missed beats but instead form within a topographic range where low-amplitude sea-level fluctuations were recorded, in contrast to topographically lower lagoonal areas, which remained unaffected by them. It is postulated that such alternations of submergence and intermittent emergence favored tepee formation on the Latemàr platform.

Lateral variations in small-scale cycle stacking patterns are almost certainly a common feature of the interiors of carbonate buildups throughout the rock record: on these platforms, paleorelief delimited the recording of low-amplitude shallowing-upward cycles to topographically elevated areas. This cyclic setting may be further added to scenarios favoring tepee formation.

ACKNOWLEDGMENTS

This research has been supported by a Marie Curie individual fellowship from the European Community Programme "Improving Human Potential" to AP under contract number HPMF-CT-2002-01912. We are indebted to Thilo Bechstädt and Rainer Zühlke for introducing us to the Latemàr during our M.Sc. projects, and to Jürgen Grötsch and Volker Vahrenkamp for calling our attention to lateral issues in platform strata. We thank André Strasser, Brian Pratt, Guy Spence, Adrian Immenhauser, Wolfgang Blendinger, Dan Lehrmann, Tony Dickson, Isabel Montañez, David Osleger, and Ali Jaffri for discussion and valuable suggestions on an earlier draft. Dan Bosence and Mark Harris provided helpful reviews of the manuscript. Grappawarm thanks go to our friend Tonio Gabrielli at the Rifugio "Torre di Pisa". This is Cambridge Earth Science Contribution 8867.

REFERENCES

Adams, R.W., and Grotzinger, J.P., 1996, Lateral continuity of facies and parasequences in Middle Cambrian platform carbonates, Carrara Formation, southeastern California, U.S.A.: Journal of Sedimentary Research, v. 66, p. 1079–1090.

Blendinger, W., 2004, Sea level changes versus hydrothermal diagenesis: origin of Triassic carbonate platform cycles in the Dolomites, Italy: Sedimentary Geology, v. 169, p. 21–28.

Borkhataria, R., Aigner, T., and Pipping, K., 2006, An unusual, muddy, epeiric carbonate reservoir: The Lower Muschelkalk (Middle Triassic) of the Netherlands: American Association of Petroleum Geologists, Bulletin, v. 90, p. 61–89.

Bosellini, A., 1984, Progradation geometries of carbonate platforms: examples from the Triassic of the Dolomites, northern Italy: Sedimentology, v. 31, p. 1–24.

Bosellini, A., 1991, Geology of the Dolomites—an introduction: Dolomieu Conference on Carbonate Platforms and Dolomitization: Sankt Ulrich/Ortisei, Tourist Office Grödental/Val Gardena, 43 p.

Bosellini, A., and Rossi, D., 1974, Triassic carbonate buildups of the Dolomites, Northern Italy, *in* Laporte, L., ed., Reefs in Time and Space: Society of Economic Paleontologists and Mineralogists, Special Publication 18, p. 209–233.

Brack, P., Mundil, R., Oberli, F., Meier, M., and Rieber, H., 1996, Biostratigraphic and radiometric age data question the Milankovitch characteristics of the Latemar cycles (Southern Alps, Italy): Geology, v. 24, p. 371–375.

Brack, P., and Rieber, H., 1993, Towards a better definition of the Anisian/Ladinian boundary: New biostratigraphic data and correlations of boundary sections from the Southern Alps: Eclogae Geologicae Helvetiae, v. 86, p. 415–527.

Burgess, P.M., Wright, V.P., and Emery, D., 2001, Numerical forward modelling of peritidal carbonate parasequence development: implications for outcrop interpretation: Basin Research, v. 13, p. 1–16.

Castellarin, A., Lucchini, F., Rossi, P.L., Selli, L., and Simboli, G., 1988, The Middle Triassic magmatic–tectonic arc development in the Southern Alps: Tectonophysics, v. 146, p. 79–89.

Della Porta, G., Kenter, J.A.M., Immenhauser, A., and Bahamonde, J.R., 2002, Lithofacies character and architecture across a Pennsylvanian inner-platform transect (Sierra de Cuera, Asturias, Spain): Journal of Sedimentary Research, v. 72, p. 898–916.

Doglioni, C., 1988, Examples of strike-slip tectonics on platform-basin margins: Tectonophysics, v. 156, p. 293–302.

Egenhoff, S., Peterhänsel, A., Bechstädt, T., Zühlke, R., and Grötsch, J., 1999, Facies architecture of an isolated carbonate platform: tracing the cycles of the Latemàr (Middle Triassic, northern Italy): Sedimentology, v. 46, p. 893–912.

Emmerich, A., Glasmacher, U.A., Bauer, F., Bechstädt, T., and Zühlke, R., 2005, Meso-/Cenozoic basin and carbonate platform development in the SW-Dolomites unraveled by basin modelling and apatite FT analysis: Rosengarten and Latemar (Northern Italy): Sedimentary Geology, v. 175, p. 415–438.

Fischer, A.G., 1964, The Lofer cyclothems of the Alpine Triassic: Kansas Geological Survey, Bulletin 169, p. 107–149.

Gaetani, M., Fois, E., Jadoul, F., and Nicora, A., 1981, Nature and evolution of Middle Triassic carbonate buildups in the Dolomites (Italy): Marine Geology, v. 44, p. 25–57.

Ginsburg, R.N., 1971, Landward movement of carbonate mud: new model for regressive cycles in carbonates (abstract): American Association of Petroleum Geologists, Bulletin, v. 55, p. 340.

Goldhammer, R.K., and Harris, M.T., 1989, Eustatic controls on the stratigraphy and geometry of the Latemar buildup (Middle Triassic), the Dolomites of northern Italy, *in* Crevello, P.D., Wilson, J.L., Sarg, J.F., and Read, J.F., eds., Controls on Carbonate Platform and Basin Development:, SEPM, Special Publication 44, p. 323–338.

Goldhammer, R.K., Dunn, P.A., and Hardie, L.A., 1987, High-frequency glacio-eustatic sea level oscillations with Milankovitch characteristics recorded in Middle Triassic platform carbonates in northern Italy: American Journal of Science, v. 287, p. 853–892.

Goldhammer, R.K., Dunn, P.A., and Hardie, L.A., 1990, Depositional cycles, composite sea-level changes, cycle stacking patterns, and the hierarchy of stratigraphic forcing: examples from Alpine Triassic platform carbonates: Geological Society of America, Bulletin, v. 102, p. 535–562.

Goldhammer, R.K., Harris, M.T., Dunn, P.A., and Hardie, L.A., 1993, Sequence stratigraphy and systems tract development of the Latemar Platform, Middle Triassic of the Dolomites (northern Italy): outcrop calibration keyed by cycle stacking patterns, *in* Loucks, R.G.,and Sarg, J.F., eds., Carbonate Sequence Stratigraphy: Recent Developments and Applications: American Association of Petroleum Geologists, Memoir 57, p. 353–387.

Grotzinger, J.P., 1986, Cyclicity and paleoenvironmental dynamics, Rocknest platform, northwest Canada: Geological Society of America, Bulletin, v. 97, p. 1208–1231.

Haq, B.U., Hardenbol, J., and Vail, P.R., 1987, Chronology of fluctuating sea levels since the Triassic: Science, v. 235, p. 1156–1167.

Hardie, L.A., Bosellini, A., and Goldhammer, R.K., 1986, Repeated subaerial exposure of subtidal carbonate platforms, Triassic, northern Italy: Evidence for high-frequency sea level oscillations on a 10^4 year scale: Paleoceanography, v. 1, p. 447–457.

Hardie, L.A., Wilson, E.N., and Goldhammer, R.K., 1991, Cyclostratigraphy and dolomitization of the Middle Triassic Latemar buildup, the Dolomites, northern Italy: Conference on Carbonate Platforms and Dolomitization: St. Ulrich / Gröden, Guidebook Excursion F, 56 p.

Hillgärtner, H., 1998, Discontinuity surfaces on a shallow-marine carbonate platform (Berriasian, Valanginian, France and Switzerland): Journal of Sedimentary Research, v. 68, p. 1093–1108.

Hinnov, L.A., and Goldhammer, R.K., 1991, Spectral analysis of the Middle Triassic Latemar Limestone: Journal of Sedimentary Petrology, v. 61, p. 1173–1193.

Kent, D.V., Muttoni, G., and Brack, P., 2004, Magnetostratigraphic confirmation of a much faster tempo for sea-level change for the Middle Triassic Latemar platform carbonates: Earth and Planetary Science Letters, v. 228, p. 369–377.

Lehrmann, D.J., and Goldhammer, R.K., 1999, Secular variation in parasequence and facies stacking patterns of platform carbonates: a guide to application of stacking-patterns analysis in strata of diverse ages and settings, *in* Harris, P.M., Saller A.H., and Simo, J.A., eds., Advances in Carbonate Sequence Stratigraphy: Application to Reservoirs, Outcrops and Models: SEPM, Special Publication 63, p. 187–225.

Lukasik, J.J., James, N.P., McGowran, B., and Bone, Y., 2000, An epeiric ramp: low-energy, cool-water carbonate facies in a Tertiary inland sea, Murray Basin, South Australia: Sedimentology, v. 47, p. 851–881.

Masetti, D., and Neri, C., 1980, L'Anisico della Val di Fassa (Dolomiti occidentali): sedimentologia e paleogeografia: Universitá di Ferrara, Annali, Nuova Serie, Sezione IX. Scienze Geologiche e Mineralogiche, v. 7, p. 1–19.

Maurer, F., 1999, Wachstumsanalyse einer mitteltriadischen Karbonatplattform in den westlichen Dolomiten (Südalpen): Eclogae Geologicae Helvetiae, v. 92, p. 361–378.

Maurer, F., 2000, Growth mode of Middle Triassic carbonate platforms in the Western Dolomites (Southern Alps, Italy): Sedimentary Geology, v. 134, p. 275–286.

Maurer, F., and Schlager, W., 2003, Lateral variations in sediment composition and bedding in Middle Triassic interplatform basins (Buchenstein Formation, southern Alps, Italy): Sedimentology, v. 50, p. 1–22.

Mundil, R., Brack, P., Meier, M., Rieber, H., and Oberli, F., 1996, High resolution U–Pb dating of Middle Triassic volcaniclastics: Time scale calibration and verification of tuning parameters for carbonate sedimentation: Earth and Planetary Science Letters, v. 141, p. 137–151.

Mundil, R., Zühlke, R., Bechstädt, T., Peterhänsel, A., Egenhoff, S.O., Oberli, F., Meier, M., Brack, P., and Rieber, H., 2003, Cyclicities in Triassic platform carbonates: synchronizing radio-isotopic and orbital clocks: Terra Nova, v. 15, p. 81–87.

Peterhänsel, A., and Egenhoff, S.O., 2005, Sea level changes versus hydrothermal diagenesis: origin of Triassic carbonate platform cycles in the Dolomites, Italy: Discussion: Sedimentary Geology, v. 178, p. 145–149.

Pratt, B.R., and James, N.P., 1986, The St George Group (Lower Ordovician) of western Newfoundland: tidal flat island model for carbonate sedimentation in shallow epeiric seas: Sedimentology, v. 33, p. 313–343.

Preto, N., Hinnov, L.A., Hardie, L.A., and De Zanche, V., 2001, Middle Triassic orbital signature recorded in the shallow marine Latemar carbonate buildup (Dolomites, Italy): Geology, v. 29, p. 1123–1126.

Preto, N., Hinnov, L.A., Hardie, L.A., and Harris, M.T., 2005, Sea level changes versus hydrothermal diagenesis: origin of Triassic carbonate platform cycles in the Dolomites, Italy—Discussion: Sedimentary Geology, v. 178, p. 135–139.

Rankey, E.C., Bachtel, S.L., and Kaufman, J., 1999, Controls on stratigraphic architecture of icehouse mixed carbonate–siliciclastic systems: a case study from the Holder Formation (Pennsylvanian, Virgilian), Sacramento Mountains, New Mexico, *in* Harris, P.M., Saller A.H., and Simo, J.A., eds., Advances in Carbonate Sequence Stratigraphy: Application to Reservoirs, Outcrops and Models: SEPM, Special Publication 63, p. 127–150.

Raspini, A., 2001, Stacking pattern of cyclic carbonate platform strata: Lower Cretaceous of Southern Apennines, Italy: Geological Society of London, Journal, v. 158, p. 353–366.

Read, J.F., 1995, Overview of carbonate platform sequences, cycle stratigraphy and reservoirs in greenhouse and ice-house worlds, *in* Read, J.F., Kerans, C., Weber, L.J., Sarg, J.F., and Wright, F.M., eds., Milankovitch Sea Level Changes, Cycles and Reservoirs on Carbonate Platforms in Greenhouse and Icehouse Worlds: SEPM, Short Course Notes 35, p. 1–102.

Read, J.F., Grotzinger, J.P., Bova, J.A., and Koerschner, W.F., 1986, Models for generation of carbonate cycles: Geology, v. 14, p. 107–110.

Reading, H.G., 1996, Sedimentary Environments, Third Edition: London, Blackwell Science, 704 p.

Rogers, R.R., 1998, Sequence analysis of the Upper Cretaceous Two Medicine and Judith River formations, Montana: nonmarine response to the Claggett and Bearpaw marine cycles: Journal of Sedimentary Research, v. 68, p. 615–631.

Rüffer, T., and Zühlke, R., 1995, Sequence stratigraphy and sea-level changes in the Early to Middle Triassic of the Alps: a global comparison, *in* Haq, B.U., ed., Sequence Stratigraphy and Depositional Response to Eustatic, Tectonic and Climatic Forcing: Amsterdam, Kluwer, p. 161–207.

Sadler, P.M., Osleger, D.A., and Montañez, I.P., 1993, On the labeling, length, and objective basis of Fischer plots: Journal of Sedimentary Petrology, v. 63, p. 360–368.

Sandulli, R., and Raspini, A., 2004, Regional to global correlation of lower Cretaceous (Hauterivian–Barremian) shallow-water carbonates of the southern Apennines (Italy) and Dinarides (Montenegro), southern Tethyan Margin: Sedimentary Geology, v. 165, p. 117–153.

Satterley, A.K., 1996, The interpretation of cyclic successions of the Middle and Upper Triassic of the Northern and Southern Alps: Earth-Science Reviews, v. 40, p. 181–207.

Sonnenfeld, M.D., and Cross, T.A., 1993, Volumetric partitioning and facies differentiation within the Permian Upper San Andres Formation of Last Chance Canyon, Guadalupe Mountains, New Mexico, *in* Loucks, R.G., and Sarg, J.F., eds., Carbonate Sequence Stratigraphy: Recent Developments and Applications: American Association of Petroleum Geologists, Memoir 57, p. 435–474.

Strasser, A., Aurell, M., Badenas, B., Melendez, G., and Tomas, S., 2005, From platform to basin to swell: orbital control on sedimentary sequences in the Oxfordian, Spain: Terra Nova, v. 17, p. 407–413.

Strasser, A., Hillgärtner, H., Hug, W., and Pittet, B., 2000, Third-order depositional sequences reflecting Milankovitch cyclicity: Terra Nova, v. 12, p. 303–311.

Tucker, M.E., and Wright, V.P., 1990, Carbonate Sedimentology: London, Blackwell Science, 496 p.

Vail, P.R., Mitchum, R.M., Jr., and Thomson, S., III, 1977, Seismic stratigraphy and global changes of sea level, Part 4: Global cycles of relative changes of sea level, *in* Payton, C.E., ed., Seismic Stratigraphy—Applications to Hydrocarbon Exploration: American Association of Petroleum Geologists, Memoir 26, p. 83–97.

Viel, G., 1979, Lithostratigrafia ladinica: una revisione. Riconstruzione paleogeografica e paleostrutturale dell' area dolomitica–cadorina (Alpi Meridionali), I. e II. Parte: Rivista Italiana di Paleontologia, v. 85, p. 88–125 and p. 297–352.

Wright, V.P., 1992, Speculations on the controls on cyclic peritidal carbonates: icehouse versus greenhouse eustatic controls: Sedimentary Geology, v. 76, p. 1–5.

Zühlke, R., 2004, Integrated cyclostratigraphy of a model Mesozoic carbonate platform—the Latemar (Middle Triassic, Italy), *in* D'Argenio, B., Fischer, A.G., Premoli Silva, I., Weissert, H., and Ferreri, V., eds., Cyclostratigraphy: Approaches and Case Histories: SEPM, Special Publication 81, p. 183–212.

Zühlke, R., Bechstädt, T., and Mundil, R., 2003, Sub-Milankovitch and Milankovitch forcing on a model Mesozoic carbonate platform—The Latemar (Middle Triassic, Italy): Terra Nova, v. 15, p. 69–80.