On the Allocyclic Interpretation of the ‘Latemar Cycles’ (M. Triassic, The Dolomites, Italy) and Implications for High-frequency Cyclostratigraphic Forcing


Abstract

The Middle Triassic Latemar Platform is a ca. 5 km wide, 700 m thick isolated carbonate platform containing a succession of over 500 cycles (ca. 1 m av. thickness), which have been attributed to allocyclic forcing by periodic Milankovitchian and/or sub-Milankovitchian composite eustasy. These interpretations are based on the facies composition of the cycles (thicker subtidal units overlain abruptly by thin, cm-scale, subaerial caps), the 5:1 bundling of the ‘fundamental’ m-scale cycles into lower-frequency ‘megacycles’, and spectral analyses of thickness and rank series showing conspicuous matches to predicted Milankovitchian periodicities. The influence of periodic Milankovitchian composite eustasy (whether pure Milankovitch or mixed Milankovitch and sub-Milankovitch) on the development of the Latemar cyclic succession has been questioned based on the dating of ashfall tuffs, paleomagnetic analysis of the platform, and correlation to biostratigraphic markers in nearby basinal deposits. In order to test the interpretation of allocyclic forcing for Latemar cycles, we investigated the cyclic succession preserved at Mendola Pass (located 30 km NW from the Latemar) where Latemar-equivalent cyclic platform interior strata are exposed. The Mendola cycles (av. 0.70 m/cycle) are also bundled into upward-thinning packages with a ca. 5:1 ratio. However, unlike the subtidal deposits immediately overlain by vadose diagenetic caps found at the Latemar, Mendola cycles consist of a mud-rich subtidal unit gradationally overlain by a cryptomicrobial (peritidal) laminitic cap. A measured section from Mendola Pass of 36 cycles correlates biostratigraphically and statistically to a unique interval within the Latemar succession. Although laminitic-capped cycles are often attributed to autocyclicity the similarity of the stacking patterns of the Mendola cycles to those of the Latemar support an allocyclic interpretation. In addition, depositional rates calculated from dated Holocene shallow water carbonate facies equivalent to those at the Latemar and Mendola Pass are shown to be consistent with Milankovitchian or multi-millennial periodicities rather than millennial (ca. 1 kyr) cycle periods. Finally, we consider the question of whether comparative sedimentology can be relied upon for interpretation of relative cycle duration, or if comparative
Sedimentology has reached its useful limit for identifying facies and depositional environments with respect to the middle Triassic. It is our conclusion that statistical and biostratigraphic correlations, in addition to comparative sedimentology, indicate that the Latemar and Mendola cycles were deposited under the control of an allogenic forcing mechanism, and that this mechanism generated depositional cycles with multi-millennial individual periodicities.

Authors’ Note

This manuscript represents the last body of work done by the late Prof. Robert K. Goldhammer in the Dolomite Alps of Northern Italy. Bob had a great love of fieldwork in the Alps due to the excellent preservation of cyclic carbonate stratigraphy at various localities there. Bob also had deep respect for his scientific forebears. Bob would commonly refer to publications and ideas put forth by “the Gins” when teaching to remind students of the many ideas within the scientific community regarding the origin of carbonate rock fabrics and depositional cycles. What we present here is a written attempt to steward Bob’s latest ideas to the geologic and broader scientific community.

Keywords: Middle Triassic carbonates; cyclostratigraphy; high-frequency eustasy

Introduction: The Problem

Investigation of the cyclic succession of platform carbonate deposits at the Latemar began over 20 years ago with Hardie et al. (1986) and has subsequently stirred a vigorous debate regarding the driving mechanisms and depositional environments required to generate the succession. Goldhammer et al. (1987) proposed that the cyclic succession of over 500 depositional cycles (< 1 m av. thickness) at the Latemar platform (the Dolomites, N. Italy) is a sedimentary record of composite glacio-eustasy, driven by Milankovitchian orbital forcing. This interpretation is based on several lines of evidence, including a) the shallowing-upward facies succession within each cycle (thicker subtidal unit overlain abruptly by a thin cm-scale, subaerial cap); b) a prevalent 5:1 bundling of the ‘fundamental’ m-scale cycles into lower-frequency ‘megacycles’, and c) time-series analysis of the cyclic succession showing agreement with predicted Triassic astronomical frequencies (Goldhammer et al., 1987, 1990; Goldhammer & Harris, 1989;
The Goldhammer et al. (1987) interpretation that the high-frequency cyclicity at the Latemar is attributable to Milankovitchian forcing was challenged by the dating of zircons extracted from time-equivalent basinal deposits and ash-fall tuffs preserved in the Latemar platform interior, as well as relative dating provided by biostratigraphy (Brack et al., 1996; Mundil et al., 1996; Mundil et al., 2003; Zühlke, 2004). These authors suggest that the entire Latemar succession was deposited in ca. 2-4 Myr (in contrast to the 9-12 Myr by the Milankovitchian interpretation), which demands much shorter periodicities for composite cyclic drivers (ca. 4.2 kyr/cycle), i.e., the fundamental shallowing-upward cycles are taken out of the Milankovitchian frequency bands (Zühlke et al. 2003). As a result, the driving mechanism for the Latemar cycles was reinterpreted to be a periodic sub-Milankovitchian process and the driver for the megacycle bundling as Milankovitchian (Zühlke, 2004).

Most recently, Kent et al. (2004) has argued that most, if not all, of the 540 m thick Latemar cyclic succession is restricted to a single magnetochron. Since magnetic reversals occur on average every ca. 0.5 Myr, they suggest that the entire succession represents no more than about 0.8 Myrs and that individual Latemar cycles represent 1.7 kyr durations. Independently, Emmerich et al. (2005) attempted to correlate the U-Pb series dates from tuffs in the basinal Buchenstein beds (by Mundil et al., 1996) to dates in the Latemar platform interior (by Mundil et al., 2003) using the biostratigraphic markers of Brack and Rieber (1993). These results suggest that individual Latemar cycles represent 0.9-1.97 kyr (Emmerich et al., 2005). Both works effectively place both the Latemar cycles and megacycles into the sub-Milankovitch band. In particular, the 'millennial model' of Emmerich et al. (2005) is set apart from the previous models in that no link to Milankovitchian forcing of Latemar cycles or megacycles is implied. Since publication of these works, Hinnov (2006) subsequently questioned the interpretation of the paleomagnetic data in Kent et al. (2004) as a primary magnetic polarity signal. Further, the correlation of Emmerich et al. (2005) results in a Latemar chronostratigraphy with two age reversals (see Figure 7b in Emmerich et al., 2005), raising still other questions. These questions, and other issues raised by these millennial models, will be explored further below in the Discussion.
the conclusion that the Latemar cycles are a sedimentological record of an extrabasinal forcing mechanism was never questioned (for a summary of the 3 sets of Latemar cycle period interpretations, see Figure 1). Blendinger (2004), however, challenged the validity of recognizing shallowing-upward cycles in the Latemar altogether, proposing that cycle-capping facies (dolomitic caliches, pisoids, tepees, etc.) are the products of post-burial hydrothermal diagenesis rather than the products of early diagenesis in the vadose zone. Blendinger (2004) states (p. 21) that "an alternative interpretation to eustatically controlled cyclicity and repeated subaerial exposure is provided by diagenesis in a hydrothermal field.” However, the interpretations of Blendinger (2004) are clearly open for discussion (Preto et al., 2005; Peterhänsel & Egenhoff, 2005; Blendinger, 2005 a, b).

If the deposits at the Latemar (as well as other time-equivalent platforms with similar platform-interior facies successions) cannot be confidently determined to be allogenic through sedimentologic and cyclostratigraphic analysis internal to the platform, the only hope for the validation of an allogenic driver is to identify temporally equivalent deposits elsewhere that are cyclostratigraphically analogous. In this case, a succession of upper Anisian / lower Ladinian cyclic platform interior stratigraphy located 30 km NW of the Latemar at Mendola Pass was measured and analyzed for possible periodic signals. Identification of comparable stacking, bundling, and a cross-correlative statistical fit of Latemar and Mendola sections supports the conclusion that an inter-platformal (hence allocyclic) mechanism drove the development of both cyclic successions. Comparative sedimentologic analysis considering of rates of deposition of equivalent facies in Holocene environments suggests that these cycles accumulated over multi-millennial timescales.

Location and Geologic Setting

The Latemar platform is a ca. 5 km diameter carbonate platform of Anisian/Ladinian age located in the Dolomites of N. Italy near the town of Predazzo (Figure 2). While the platform is of comparative importance in this study, in order to investigate the possibility of an allocyclic driver for the Latemar cycles, the depositional succession at Mendola Pass (located 30 km NW from the Latemar near Bolzano) was analyzed, where over 500 m of Anisian/Ladinian-age cyclic platform interior strata of the Dolomia della Val d'Adige Formation are preserved. Short sections through the Dolomia
The absolute geometry of the Anisian/Ladinian carbonate buildup at Mendola Pass is not known, but appears to have involved a broad shelf that allowed for the deposition of low-energy carbonates (e.g., mud-prone lagoons and tidal flats).

Anisian/Ladinian buildups in the Dolomites are common, most of which are limited to isolated buildups 10s of km² in area. During the Anisian/Ladinian, active faulting related to incipient rifting of Pangaea was ongoing (Doglioni, 1987, 1988). Most of the Anisian/Ladinian-age structures have been interpreted in relation to a regional N70°E structural grain that includes extensive left-lateral strike slip faulting (e.g., Stava fault) and associated flower structures, many of which are cut by Late Ladinian volcanic intrusions (Doglioni, 1988). Such an active tectonic regime almost certainly provided unique subsidence histories from locality to locality. Differential subsidence affecting active carbonate platforms in the Alpine Triassic is discussed in a number of studies spanning middle and late Triassic ages, including Bosellini & Hardie, (1985), Doglioni (1987, 1988), Jadoul et al. (1992), Carulli et al. (1998), Brack & Muttoni (2000), and Cozzi (2000).

Facies and Cycles

The metre-scale platform interior cycles at Mendola Pass and the Latemar share the general trend of having a shallowing-upward facies succession within each cycle. However, the facies internal to the cycles at the two localities are notably different.

Latemar cycles

At the Latemar, facies within cycles “shallow-upward” from a peloidal wackestone/packstone through an oncolitic, lithoclastic grainstone that is capped by a dolomitic caliche crust indicative of subaerial exposure (Goldhammer et al. 1987; Egenhoff et al. 1999; Zühlke et al. 2003; Preto et al. 2001; 2004) (Figure 3). This succession was originally interpreted by Goldhammer et al. (1987) as shallowing up from shallow subtidal through subaerial exposure cap, but without a consistent, well-defined intertidal facies. The absence of a clear intertidal facies was taken as direct evidence of rapid exposure of the platform top to the vadose zone - a "Waltherian skip" in the shallowing-upward facies succession as a direct result of sea-level fall (Goldhammer et
Paleobathymetric relations between the platform interior and reef margin facies estimated the reef top to be 2-3 M deeper than the platform interior (Goldhammer and Harris, 1989). The absence of subaerial exposure diagenesis in the margin therefore constrains the high-frequency sea-level amplitudes to ca. 2-3 M.

This interpretation was modified by Egenhoff et al. (1999) who re-interpreted the oncolitic / bioclastic grainstones beneath exposure caps as possible intertidal deposits (Figure 3, Microfacies 4), although oncoids have been previously associated with subtidal channels (Demicco & Hardie, 1994). Preto et al. (2004) went on to recognize peloidal pack-to-grainstones with weakly developed fenestral cyanobacterial laminae in several cycles (see Preto et al., 2004, Lithofacies 2), interpreting their presence as a record of supratidal conditions.

The recognition of an intertidal facies in the Latemar cycles is important because it affects the fundamental conclusion held earlier (Goldhammer et al., 1987) that the cycles were a record of eustatic oscillations because of the Waltherian skip in facies succession. The interpretation by Egenhoff et al. (1999) for a full shallowing-upward suite of environments allows for Ginsburgian autocyclicity as a possible driver that does not require eustatic oscillations (Ginsburg, 1971). This makes confirmation of an allocyclic driver for the Latemar all the more pertinent.

Mendola cycles

The facies succession internal to the Mendola Pass cycles is fundamentally different than that of the platform interior cycles at the Latemar. Instead of being capped by vadose dolomitic caliche fabrics, Mendola Pass cycles are laminite-capped cycles, similar in many ways to the Late Triassic Dolomia Principale and Lofer cycles of the Dachstein Limestone (Fischer, 1964; Bosellini & Hardie, 1985; Goldhammer et al., 1990; Haas, 1994; 2004; Cozzi et al., 2005). The typical Mendola Pass cycle has an erosive base consisting of mm to cm-scale flat laminated intraclasts ripped up from the underlying cycle cap. Erosion of cycle tops is interpreted to be the result of transgressive reworking or reworking of the substrate during high-energy events prior to the re-initiation of carbonate sedimentation after flooding. Similar base-of-cycle intraclastic breccias can be observed in the laminite-capped cycles of the Dolomia Principale and the Dachstein Limestone, where they are also interpreted as
transgressive or storm reworking of the substrate (Fischer, 1964; Bosellini & Hardie, 1985; Cozzi, 2002).

Erosive bases grade upward into a dolomitized peloidal mud-to-wackestone with fine bioclastic debris and intermittent lenses of dasycladacean grainstone (storm beds), interpreted to have been deposited within a shallow (<10 m) restricted lagoon. Work done in the Holocene by Ginsburg et al. (1977) and Shinn (1986) describes offshore sediment in the modern of Andros Island, Bahamas, that closely matches the description of the peloidal wackestones observed in Mendola Pass cycles. Cores taken 4 km offshore from the tidal flats of Andros Island show well-churned, burrowed sediments that notably lack recognizable physical sedimentary structures (Hardie & Ginsburg, 1977). Texturally, these sediments may be described as highly bioturbated, gray pelletal/peloidal mud to wackestones containing benthic forams and skeletal debris (Shinn, 1986). The modern shallowing-upward tidal flat cycle of Enos and Perkins, (1979) and Shinn, (1986), assigns this subfacies to the subtidal realm, up to ca. 10 metres deep. A similar interpretation applies to the peloidal wackestone facies within the Mendola Pass cycles, with the caveat that a general lack of diversity of faunal remains may be indicative of restriction.

Subtidal wackestone facies within Mendola cycles characteristically coarsen up to a dasycladacean pack-to-grainstone prior to being capped by microbial laminites (Figure 4). Dasycladacean grainstones are interpreted as evidence of shallow-water (perhaps intertidal) reworking resulting from sedimentary fill of accommodation space and aggradation into a comparatively energetic depositional environment. This facies may represent a shallow subtidal depositional setting within the influence of high-energy events (e.g. storms) that reworked algae into semi-articulated bioclasts.

All Mendola Pass cycles are capped by mm-scale, crinkly laminated mud to-wackesone with intercalated discontinuous layers of intraclastic and bioclastic grainstone. Laminae also have rare v-shaped polygonal cracks and horizontal elongate fenestrae. Laminites are interpreted to be evidence of a supratidal flat-type environment similar to the modern tidal flats of Andros Island, Bahamas. Original studies by Black (1933) on Andros Island, Bahamas, identified nearshore surface mats of sticky, filamentous blue-green algae that bind and trap sediment washed in from the offshore subtidal carbonate "factory", creating laminated sediments. Later studies by Hardie and Ginsburg (1977) on Andros Island found that thinly-laminated sediments are typically found in low energy, flat, supratidal environments that are exposed subaerially 85% of
the time or more. Sediments associated with these mats may contain fenestrae of various subtypes, thin-bedded storm deposits, and well-laminated muddy, organic-rich layers (microbial mat) that alternate with layers of soft peloidal sand (Hardie & Ginsburg, 1977; Demicco & Hardie, 1994). By comparison, it is likely that the laminated subfacies within Mendola Pass cycles formed in a supratidal flat-type environment via binding and trapping of transported subtidal sediments onto filamentous microbial mats. Additionally, certain examples (e.g. Mendola Cycle 28 laminites) show evidence of biological origin, including cm-scale gravity-defying stromatolite heads.

Comparison of Latemar vs. Mendola Cycles

The difference in subfacies successions in Mendola and Latemar cycles has several possible explanations. First, it may be that the larger size of the Mendola platform allowed for the development of “protected” tidal-flat environments. Isolation from open marine conditions would have allowed for the accumulation of muddy cycles with flat laminite caps, similar to those observed in the modern tidal flats of Andros Island, Bahamas (Hardie, 1977). This would be in contrast to the Latemar, which appears to have been a smaller isolated platform. By comparison, the interior of the Latemar platform was affected by current and wave energy, winnowing out mud and transporting more sediment off-platform, thereby creating the grainier facies successions preserved there.

It is also possible that differential subsidence affected vertical accommodation space at each location. A slightly lower rate of subsidence at the Latemar during the interval under investigation may have allowed high frequency sea-level oscillations to “touch down” directly onto the subtidal and form diagenetic caps while a slightly faster-subsiding Mendola remained in submerged or in peritidal settings. A slightly faster subsiding Mendola Pass during this interval serves to explain the 0.26 M difference in average cycle thicknesses between the two localities (average cycle thickness of the Latemar interval = 0.52 M; average cycle thickness of the Mendola interval = 0.73 M). A tectonic arrangement of this type would fit with the sinistral transpressive model of Doglioni (1987, 1988), who recognizes compressive tectonic features of both Anisian and Ladinian age near the Latemar platform, which may have limited subsidence at the Latemar as compared to Mendola (see Doglioni, 1988, p. 294, Fig. 1). It should be noted that this phase of compression was both pre- and post-dated by rifting phases that generated differential thickness in sedimentary cover in the Dolomites, resulting in an
overall thickening of the Triassic section by at least 3 times from the west near Mendola pass to the east near Tre Cime di Lavaredo (Laubscher & Bernoulli, 1978; Doglioni, 1987, 1988).

While subfacies within Latemar and Mendola cycles are notably different the cycles nonetheless share several common traits. One distinct similarity is that the facies within both successions “shallow-up”, i.e., the cycles at both localities record a progressive filling of accommodation space prior to being abruptly flooded over. Further, the depositional fabrics preserved within the cycles are indicative of deposition within 0-10 m of water depth (Hardie & Ginsburg, 1977; Shinn, 1986). Deposition in the shallow marine realm made these localities sensitive to environmental shifts, most notably sea-level oscillations. Finally, the Latemar and Mendola cycles are both of similar vertical scale (ca. 1 M), and are “bundled” into thinning-upward packages of predominantly 5 cycles, indicating that the same process driving the development of vertical stacking patterns was recorded at both localities (Figure 5). These patterns are analyzed in further detail below.

Stratigraphic correlation of the Mendola and Latemar sections

The “Mendel Dolomit” was originally defined lithologically by Richtofen (1874), but since that time little published data has become available with reference to its depositional age. However, a recently published geologic map includes clues to the age of the Mendola Dolomite (Avanzini, 2002). Notes from the map indicate that the “Mendola Formation” is a platform carbonate body of Late Anisian-Early Ladinian age (Avanzini, 2002). Portions of the map’s notes are paraphrased below (translated by N. Preto, personal communication).

Within the Mendel Dolomit, Ogilvie Gordon (1927) recognized a lower member with dasycladacean alga *Diplopora annullatissima* and *Physioporella paucifoliata* corresponding with the Sarl-Dolomite, and an upper member with *Diplopora annulata* corresponding with the Schlern-Dolomit. These conclusions were later corroborated by von Klebelsberg (1935) and Van Hilten (1960). Further stratigraphic studies carried out for the purpose of geological mapping of the area distinguished two informal units within the Mendola Formation. The first is the subtidal member, corresponding to the Upper Serla Dolomite and Contrin Dolomite of the eastern Dolomites. The second is the Peritidal Member. The lower boundary of the Peritidal Member is marked by a paleosol and sometimes associated with tepee horizons. The upper boundary is more variable. At Mendola pass, strongly karstified portions are infilled with andesitic and basaltic volcanics that are laterally equivalent with the basinal Roen Limestones. Additionally, a
few ammonoids of the *avisianum* subzone occur at the base of the Peritidal Member (N. Preto, *personal communication*). The sedimentary environment is that of an aggrading, periodically exposed carbonate platform.

The section measured in this study belongs to the “Peritidal Member” of the Mendola Formation, which overlaps with Latemar platform interior biostratigraphy (Figure 6). The assemblage of dasycladacean algae extracted from the Mendola section includes *Physoporella leptotheca* (Cycle 7), *Diplopora annulata annulata* (Cycles 7, 8, and 20) and *Gyroporella ladinica* (Cycle 20). Dasycladacean algae of the subtidal member of the Mendola formation, including *D. annullatissima* and *P. paucifoliata* were not found within the study interval (N. Preto and O. Piros, personal communication). In terms of correlation to the Latemar, *D. annullatissima* occurs only in the lowermost part of Latemar (Gaetani *et al.*, 1981), and *P. paucifoliata* is even older. However, *D. annulata* was found within the study interval and is consistent with the biostratigraphy of Ogilvie Gordon (1927) for the upper Peritidal Member of the Mendola formation. The lowermost portion of the Peritidal Member is reported to contain ammonoids of the *avisianum* subzone indicating late Anisian age, which is consistent with a 175 m thick succession of cycles in the Latemar that includes the upper portion of the Lower Tepee Facies, the entirety of the lower cyclic facies, and the lower half of the Middle Tepee Facies (*see* Manfrin *et al.*, 2005, p. 480, fig. 3). The upper portion of the Peritidal Member of the Mendola formation may correlate to portions of the Latemar stratigraphy above this interval, including the upper portion of the middle tepee facies and/or the upper cyclic facies. In sum, while biostratigraphy does not tie the Mendola succession to a specific interval within the Latemar, it does indicate that there is a biostratigraphic overlap of the Mendola and Latemar cyclic successions.

*Statistical correlation of the Mendola and Latemar sections*

Statistical time series analysis of the Latemar and Mendola cycles sheds light on the stratigraphic patterns in the sections and their interrelationships. *Running cross-correlation analysis* pinpoints the most likely position of the Mendola section within the Latemar’s extended cyclic stratigraphy. Importantly, this sets up a common time origin for the two sections, and an opportunity to investigate specific cyclic patterns shared by the two sections.
The assessment of stratal frequencies (i.e., bundling frequencies) common to the two sections is extremely challenging due to the short length of the Mendola measured section (36 cycles). Multiple graphical and statistical signal analysis techniques are needed to focus on different aspects of the Mendola's stratal patterns and its corresponding Latemar counterpart. To present a full range of views, Fischer plots, harmonic analysis, spectral coherency and cross-phase analysis, were used as follows.

Running cross-correlation analysis

To study the similarity of stacking between cyclic sections, a running cross-correlation procedure may be applied. This technique was developed by Anderson and Kirkland (1966) to correlate intra-basinal sequences of varves in the Permian Castile Formation. Subsequently, the technique was formalized in Dean and Anderson (1974). Running cross-correlation was later used by Holland et al. (2000) as an independent means to correlate regional stratal patterns and to corroborate biostratigraphic correlations.

Preto et al. (2004) applied this "semi-automated" technique to the Latemar platform, successfully correlating their Cimon del Latemar (CDL) cycle thickness series to the Cima Forcellone cycle thickness series; the results are replicated here in Figure 7A. The results give a perfect match for the "marker horizon M" that Egenhoff et al. (1999) observed in their field measurements of both localities (Figure 7C).

In like spirit, the same technique was applied to the Mendola and Cima Forcellone cycle thickness series, shown in Figure 7B. With the Mendola series being only 36 points long, the running cross-correlation values are more variable ("noisier") than the comparatively highly organized cross-correlation curve between the two Latemar localities (compare Figure 7A and 7B). In addition, the Mendola Pass locality is ca. 30 km distant from the Latemar platform, and may be associated with a separate tectonic block, if not a unique subsidence history, as several of the carbonate platforms of the mid-Triassic of the Dolomites are reported to be (Doglioni, 1987, 1988; Brack and Muttoni, 2000). This alone would be expected to minimize the chances for a positive Mendola-Latemar correlation at the metre-scale level of this analysis. Nonetheless, an extremely high correlation coefficient value of +0.6, greatly exceeding the 95% confidence limit of 0.375 for 36 degrees of freedom, occurs between the Mendola and the Cima Forcellone series from Cycles 351-386. This serves as strong support that we
have discovered the stratigraphic placement of the Mendola section within the Latemar platform.

**Fischer plots**

Charts plotting the cumulative deviation from mean cycle thickness (i.e., "Fischer plots", after Fischer, 1964) highlight relative accommodation trends in platform cycle successions. The Fischer plot of the Mendola section (Figure 8A) shows clear bundling of cycles into megacycles with an average grouping of 5 fundamental cycles into 1 megacycle (5:1). The Fischer plot of the correlative Latemar section (Figure 8B) is remarkably similar, with both bundling and overall stacking trends synchronized with those at Mendola Pass. Both Fischer plots suggest a regressive interval over the first 15 cycles (cycles thinning upward). This trend is particularly pronounced in the Latemar section and is followed by the deposition of a 2.5 metre-thick tepee-capped cycle (a.k.a., Cycle 366, see Goldhammer et al., 1987) that is the thickest cycle in the study interval. The equivalent cycle at Mendola Pass is also the thickest in the study interval (3.06 metres-thick), but is laminite-capped. The remaining upper 21 cycles are the most strongly bundled in both sections, and both have a long-term trend suggestive of transgressive to high-stand conditions.

**Harmonic analysis, coherency and cross phase spectra**

The full suite of stratal patterns in the sections is revealed through statistical time series analysis. We turn to the multitaper method (MTM), which is an exceptional tool for frequency assessment of short, highly noisy time series (Thomson, 1982). The MTM harmonic analysis procedure evaluates signal-to-noise ratios in spectra, and searches for statistical outliers indicative of the presence of lines, at ultra-high frequency resolution. The MTM also provides averaged spectral coherency and cross-phase estimators that outperform others, harvesting more information (degrees of freedom) from the data, and with less bias, than other methods (see Hinnov & Goldhammer, 1991 for an example pertaining to the Latemar cycles).

MTM harmonic analysis of the Mendola and Latemar sections (Figures 9A and 9B) shows that some of the bundling frequencies are shared by the two sections, although their relative amplitudes are quite different. This may be due to different, very low-frequency tectonic influences on the development of the Mendola vs Latemar cycles or the presence of differential cycle thicknesses resulting normal sedimentary processes.
(e.g., lateral sediment erosion and transport) on Mendola tidal flats. The lowest frequency bundling term, Mendola at 1/18.9 and Latemar at 1/27, while measured with a high F-test in both sections, is based on only two repetitions of the term in the 36-cycle long Mendola, and less than two repetitions for the Latemar, thus may not represent a true, sustained bundling at this frequency. The next to lowest bundling term, Mendola at 1/8.5 and Latemar at 1/9.8, are only 1/8.5-1/9.8=1/64 apart, i.e., less than the elementary bandwidth Δf=1/36, and so this line may represent the same process in both sections. Examination of the Fischer plots (Figure 8) indicates that one source of this peak in both of the sections appears to involve a single bundle of 8 to 9 cycles (Cycles 7 to 15). Surprisingly, the 5:1 bundling frequency has a very low F-test (ca. 60-75%) in both sections; in both, the line is slightly broader than Δf, and in the Latemar has a substantially lower amplitude (Latemar’s 0.2 m vs Mendola’s 0.35 m). This suggests that this bundling component, while quite visible in the Fischer plots of both series, is somewhat variable about 5:1, causing the F-test to fail. Finally, both sections show a bundling at 1/2.4; again, these bundles can be observed in the Fischer plots (Figure 8, e.g., Mendola Cycles 19 to 20, or Latemar Cycles 14 to 15); some of the power at this frequency could also be a spectral artifact from asymmetry in the 5:1 bundling.

Magnitude-squared coherency (MSC) and cross phase spectral analysis identify significant frequency components shared by two time series, i.e., frequencies present in both series that are consistently coordinated over the duration of the series. MSC spectra measure correlation coefficients between time series as a function of frequency; to maximize the d.o.f.’s of MSC estimates, averaging over two or more sampled frequencies is necessary. Cross-phase spectra indicate the phasing of frequency components between the two series; for example, when cross-phase registers 0º at a particular frequency, the two series are said to be "in phase" at that frequency.

In Figure 9C 2π multitapers were applied, which preserves the narrowest possible averaging bandwidth (β=3Δ), while gathering a substantial 5 to 6 d.o.f’s across most of the frequency range (see d.o.f. curves, Figures 9A and 9B). To be on the conservative side, the significance levels for zero coherence for 5 d.o.f.'s are indicated. Three bands of non-zero coherence are present, centered at 1/10, 1/5 and 1/2.4. The double-peak nature of the MSC at 1/10 could be artifacts, from excessive weighting imposed by one of the higher order 2π multitapers on the outer edges of the averaging bandwidth β, and magnified by the frequency interpolation (zero-padding). The other
striking MSC peak is centered at f=1/5, which indicates that 5:1 bundling is present and coordinated between the series at a statistically significant level.

The cross-phase spectrum (Figure 9D) can be interpreted at frequencies where MSC values indicate significant non-zero coherence. The cross-phase of 20° at 12:1 bundling may indicate that the two series are phase-shifted relative to each other at this frequency; in the "time" domain, this would correspond to a shift of (20°/360°)*12=0.67 cycles, i.e., less than a one cycle lead of the Latemar series over the Mendola series. Similarly, at 9:1, the Latemar series leads the Mendola series by ca. 1 cycle; at 5:1, Mendola leads the Latemar by ca. 0.5 cycles; and at 2.4:1, the two series are statistically in-phase. Taken together, the Mendola and Latemar series show close coordination to within ca. ±1 cycle at all significant bundling frequencies, constituting powerful evidence of a broadband statistical fit and phase lock between them.

**Results**

The following results were derived from the analysis of the cyclic successions:

**Shallowing-upward theme of the cycles**

The Mendola and Latemar cycles are late Anisian / early Ladinian-aged shallowing-upward, metre-scale peritidal platform carbonate cycles that formed as a result of repetitive environmental changes over time. The presence of the shallowing-upward cycles allows for physical measurement and statistical analysis of their stacking trends (i.e., trends in the vertical arrangement of cycle thicknesses). The cyclic successions have stacking patterns that not only appear similar to the eye (see Figure 8), but cross-correlate with a correlation coefficient exceeding 95% (see Figure 7), suggesting a shared external driver. Site-specific controls (e.g., autogenic sedimentary processes, local subsidence) exerted comparably less influence on the development of the cyclic successions, but could explain the differing average cycle thicknesses between the successions (average cycle thickness of the Latemar interval = 0.52 m; average cycle thickness of the Mendola interval = 0.73 m).

**Recording of cyclic processes**

Both Mendola and Latemar successions formed in environments conducive to recording rhythmic, cyclic sea-level oscillations. The shallow marine realm (0 to 5 m water depth) is almost certainly the depositional environment that these deposits formed
in, where repeated flooding and exposure of the sediment-water interface was recorded within each depositional facies succession. This is especially true at Mendola Pass, where facies within shallowing-upward cycles are consistent with those found on modern carbonate tidal flats (e.g., Hardie & Ginsburg, 1977). Strong and consistent sedimentologic evidence for early subaerial exposure of Latemar cycle caps provides evidence for a similar facies/water depth relationship at the Latemar (Preto et al., 2004). The significant statistical correlation between the Mendola and Latemar stacking patterns provides additional support for the same sea-level oscillations affecting both depositional environments. This observation is important, because constantly deep-submerged environments, as favored by Blendinger (2004) for the Latemar cycles, would "miss beats", not have a non-random bundling pattern, and not be readily correlatable to a clearly-peritidal counterpart at Mendola (Preto et al. 2005). The presence of Mendola cycle cap laminites and Latemar cycle cap dolomite crusts indicating subaerial exposure during sea-level fall means that the Latemar was not only able to “keep up” with subsidence, but also undergo extended periods of time with the platform top in peritidal and supratidal conditions, environments not known for exceptionally fast accumulation rates.

The case for allocyclicity

The fact that correlated cycle stacking patterns are recognized at separate locations that are constrained by biostratigraphy is strong evidence for the existence of a common allocyclic mechanism driving the development of both successions. The presence of allocycles at the Latemar and Mendola Pass requires that mechanisms existed during the mid-Triassic that acted to generate both sea-level oscillations and resultant carbonate depositional cycles at both localities. In the case of the Latemar controversy, what can be established to a first order is that shallowing-upward depositional cycles have been identified and cross-correlated to Mendola Pass, implying that the driving mechanism is at the very least regional in its stratigraphic influence.

Discussion

Comparative Sedimentology

The comparison of Holocene and Pleistocene dated allocycles to the ancient is useful for several reasons. First, composite sea-level oscillations regarded as drivers for shallow marine carbonate sedimentation in the Holocene and Pleistocene are grouped
into 5 ca. 20 kyr oscillations per 100 kyr oscillation (Broecker et al., 1968; Bloom et al., 1974), a bundling pattern that conspicuously matches the cycle stacking at the Latemar and Mendola Pass. The fact that sea-level oscillations within the Milankovitch band form dateable carbonate depositional cycles demands consideration. Second, if the composite allocyclic forcing mechanisms that formed depositional cycles in the mid-late Triassic are still active today, then those same mechanisms ought to be recorded as depositional cycles today. Discovery of modern or recent depositional cycles with millennial periodicities and bundling patterns similar to that of the Latemar would better point the cyclostratigraphic community toward identifying the correct forcing mechanism.

Third, shallowing-upward facies successions similar to those found at Mendola Pass can be found in Florida Bay, the Bahamas and, to an extent, in the Persian Gulf. By comparing the rates at which these deposits form in the modern, one may better understand average cycle durations for similar deposits in the geologic past.

Recent publications offer new insights into sea-level change during the past 20 kyr. Two compilations are provided here. Table 1 summarizes Pleistocene and Holocene cyclic climatic processes operating at sub-Milankovitch periodicities. While many types of variations are listed, not every process is tied (observationally or otherwise) to metre-scale sea-level change at these periodicities, and none are tied to the formation of shallowing-upward depositional cycles in modern marine carbonate sedimentary settings. Table 2 compiles literature involving the dating of Pleistocene and Holocene carbonate shallowing-upward successions. This suggests that in most cases, the sediments making up the Holocene carbonate successions- most of which are not yet complete shallowing-upward cycles- formed over the past 5-7 kyr as the result of a longer-term sea-level rise over the past 10-20 kyr. While a few examples of dated shallowing-upward facies successions from the modern appear to have formed within the last 1,000 years (Strasser & Samankassou, 2003), dating and analyses of Holocene and Pleistocene carbonate successions from around the world has not yet produced a correlatable stack of metre-scale shallowing-upward carbonate depositional cycles with millennial (1-2 kyr) periodicity.

Holocene and Pleistocene “icehouse” conditions, so-called due to the presence of major land-locked ice sheets, store and release large amounts of seawater, and allow for high-frequency sea-level oscillations with amplitudes of several 10s of metres. As an example, dating of coral reef terraces in Barbados by Bloom et al. (1974) suggests that six major sea-level oscillations have occurred over the past 130 kyr, with rise/fall
amplitudes of 20-100 metres (Bloom et al. 1974; Chappell and Shackleton, 1986). Shallow marine carbonate cycles produced by sea-level oscillations of these magnitudes are also comparatively thicker than those found in the Alpine Triassic (Goldhammer et al., 1990). Pleistocene depositional cycles identified in Florida and the Bahamas are on the order of 5 – 15 metres thick, and consist of subtidal carbonate capped by laterally correlative red soil crusts (Goldhammer & Kaufman, 1995). Both modern carbonate shallowing-upward successions as well as the record of Pleistocene and Holocene sea-level oscillations operate at cyclic frequencies that are in tune with known orbital periodicities (Table 2; Logan et al., 1969; Bloom et al., 1974; Tudhope, 1989; Parkinson, 1989; Goldhammer & Kaufman, 1995; Strasser & Samankassou, 2003).

The early to mid-Triassic is thought to have occurred during a greenhouse (or possibly transitional icehouse-greenhouse) climatic regime, lacking major continental ice sheets and to therefore have comparably low amplitude (ca. 10 m or less) high frequency sea-level oscillations (Vail et al., 1977; Goldhammer et al., 1990; Wright, 1992; Read, 1995). Consequently, shallowing-upward depositional cycles are relatively thin (1-2 M), but in many cases still form stacks that seem to reflect orbitally driven composite eustasy. Many workers have suggested that Triassic depositional cycles formed as the result of Milankovitch-band high-frequency/low-amplitude eustatic oscillations related to rhythmic orbital perturbations that affected the spatial and temporal distribution of solar energy to the Earth’s surface (Fischer, 1964; Schwarzacher, 1975; 1993; 2005; Goldhammer et al., 1990; Goldhammer & Kaufman, 1995; Yang & Lehrmann, 2003; Zühlke, 2004; Maurer et al., 2004, Cozzi et al., 2005).

Obviously, the geoclimatic conditions of the Holocene and Pleistocene stand in contrast to those of the early to mid-Triassic. However, observations from modern sediments suggest that cyclic climatic perturbations with millennial periodicities are not being recorded as shallowing-upward carbonate depositional allocycles, even in areas where carbonate sediments have infilled available accommodation space (e.g. tidal flats of Andros Island). Instead, most shallowing-upward facies successions dated from the Holocene and Pleistocene seem to have formed with periodicities that are commensurate with Milankovitchian and/or other multi-millennial processes. It is certainly possible that the processes driving Triassic depositional cycles were unique to that period of geologic time and that comparison between modern and ancient is not warranted. However, the presence of Triassic allocycles that have an apparent statistical profile that is consistent with Milankovitchian orbital parametres- a link that is
temporally justified through comparative rate studies of Holocene facies successions-leaves us with two main options regarding their origin, discussed as follows:

I. The successions of carbonate depositional cycles at the Latemar and Mendola Pass record periodic, allogenic processes directly linked to Milankovitchian composite eustasy.

The case for Milankovitchian composite eustasy driving the deposition of either fundamental cycles and/or megacycles at the Latemar and Mendola Pass is substantial, and is based on extensive sedimentological and statistical analyses. While the two main models supporting the presence of Milankovitchian composite eustasy involve different time scales (see Figure 1), both studies strongly argue for the presence of multi-millennial astroclimatic forcing in the development of carbonate depositional cycles. Here, we recognize that both of these models, Goldhammer et al. (1987) and (Zühlke et al. (2003) argue that the development of Latemar cyclicity is linked to orbital forcing.

From a comparative-sedimentological standpoint, Latemar and Mendola cyclic stratigraphy agrees with known parametres of Milankovitch band sedimentation. Dating of shallowing-upward successions from modern carbonate settings indicates that most have formed (most of which are not yet complete ‘cycles’) over the past 5-7 kyr in response to Holocene sea-level rise (Table 2). The fact that many platforms have not yet aggraded to sea-level and/or formed exposure caps suggests that the periodicity associated with the cyclic driver is longer than the time in which the depositional cycle actually forms. Additionally, sea-level oscillations inferred from coral reefs and deep-sea sediments confirm that 5 oscillations with amplitudes of 20-100m occurred over the past 100 kyr (Broecker et al., 1968; Bloom et al., 1974; Chappell & Shackleton, 1986). The frequencies of these oscillations match those of the precession and eccentricity, and they provide a driver for the bundling of depositional cycles that is fundamentally linked to carbonate sedimentation.

Additional sedimentological evidence for Milankovitch band forcing of depositional cycles relates to the rates at which complete carbonate cycles form, particularly vadose diagenetic facies. While the cycles measured at Mendola Pass do not have diagenetic caps, many of the cycles in the equivalent Latemar succession do have well-developed diagenetic caps. The presence of these diagenetic caps must be accounted for in a temporal sense for the Latemar cycles and in a time-correlative sense for Mendola cycles. If Holocene examples are used as a temporal benchmark, rapid,
millennial scale sea-level oscillations do not provide adequate time for observed vadose diagenetic features to form. Radiocarbon-calibrated rates of Holocene caliche formation average 2-4 cm/kyr (James, 1972; Robbin & Stipp, 1974; Handford et al. 1984; Demicco & Hardie, 1994), and several studies suggest even lower rates, at 0.4-1 cm/kyr (Lucia, 1968; Davies, 1970; Evamy, 1973). The caliche that caps Latemar cycles ranges in thickness from 1-30 cm, averaging 6 cm in thickness (Goldhammer et al. 1987). In order for diagenetic caliche caps to form within a millennial cyclic framework (entire cycle in 0.9-1.97 kyr), rates of caliche formation must operate at least an order of magnitude faster (20-40 cm/kyr), if not more, than those in the Holocene. Additionally, studies of Holocene tepees at Lake MacLeod, Western Australia by Handford et al. (1984) show that sediment buckles and is tilted into tepee antiforms at an average rate of 4 cm/kyr, and void-filling aragonite cements within tepees grow at extremely slow rates of 0.2-0.4 cm/kyr. Hardie et al. (1986) and Goldhammer et al. (1987) report tepee zones at the Latemar with thicknesses varying from 1 to 13 M, with individual cement bands up to 20 cm thick. Individual tepee antiforms are typically onlapped by sediments from subsequent cycles, suggesting that tepees were completely formed prior to the deposition of the next cycle(s). If Holocene rates of tepee formation from Lake Macleod are even close approximations of rates of tepee development at the Latemar, the multi-metre tepee structures at the Latemar alone represent several hundreds of kyr of time.

In order for these same tepee structures to have formed caps on millennial cycles, both tepee antiforms and cements would have to form at rates that are at least two orders of magnitude faster (40-400 cm/kyr antiform; 20-40 cm/kyr cement) than those documented at Lake MacLeod.

In addition to sedimentologic evidence, spectral analysis of Latemar cycle thickness and rank series indicates a close match between bundling frequencies of Latemar cycles and Milankovitchian orbital cycles. The clarity of the record and the non-trivial nature of the match is especially apparent in studies using rank series analysis, where plots of depth ranked units appear to have formed in lock-step synchronicity with Milankovitchian insolation (see Figure 8 of Preto et al. 2004). However, tuning the Latemar cycles to a sub-Milankovitch component (i.e., 4.2 kyr, Zühlke et al., 2003) also preserves Milankovitchian frequency components, but at a different order (see Figures 11 & 12 and Table 2 of Zühlke, 2004), pointing to a “fractal-like” aspect of the different orders of the Milankovitch rhythms (first noted by Schwarzacher, 1998). The difference lies in the assignment of the precession: the pure Milankovitch interpretation suggests
that the precession has driven fundamental cycle formation (i.e., 20 kyr Latemar cycles / 100 kyr megacycles), while the mixed Milankovitch/sub-Milankovitch interpretation suggests that precession drove formation of megacycles (i.e., 4 kyr Latemar cycles / 20 kyr megacycles).

In light of this "fractal" equivalence, the mixed Milankovitch/sub-Milankovitch model deserves closer attention. Thus far, no specific proposal has been offered for the required eustatic driver operating at a millennial scale of ca. 4 kyrs. However, we note recent work on Pleistocene eustasy that may lead to the identification of such a driver: Chappell (2002) reports ca. 6 kyr recurrent coral terraces uplifted in the Late Pleistocene of Papua, New Guinea suggestive of sea-level oscillations with amplitudes as large as 15 m. Possibly this is the analog to the 4.2 kyr Latemar driver. There is also evidence of similar eustatic behavior in the uplifted Pleistocene coral terraces of Barbados (Thompson & Goldstein, 2005). However, both locations are situated in tectonically active areas, involving rapid uplift of the islands related to the geodynamics of adjacent convergence zones. In particular, the rather large (>10 m) amplitudes that have been suggested for these millennial eustatic changes depend on the accuracy of the uplift rates that have been estimated for these islands. It is also important to note that these measurements were taken from fast-growing corals, not from stacked peritidal depositional cycles.

In either case, (pure Milankovitch or mixed Milankovitch/sub-Milankovitch) both models rely on an astroclimatic forcing mechanism as a cyclic driver for carbonate sedimentation. The hallmark of this forcing is recognized via statistical analysis of Latemar cycles and cross-applied to the Mendola succession. Comparative sedimentology indicates that Holocene carbonate successions formed at rates commensurate with multi-millennial processes, providing further evidence for a link between an allocyclic, Milankovitchian process and the sedimentary record.

II. The successions of carbonate depositional cycles at the Latemar and Mendola Pass record periodic, allogetic processes operating at millennial periodicities.

In their recent work, Emmerich et al. (2005) write "radiometric age dating on detrital zircons in air-borne tuff layers intercalated within the cyclic succession of the Latemar solved the controversy" (Emmerich et al., 2005, p. 11). This statement, however, is by no means an agreed-upon fact. Indeed, their correlation scheme (see Fig. 7b in Emmerich et al., 2005) results in two conspicuous age-reversals (i.e. older-
upward rather than younger-upward) the first occurring from "Tc" (241.2+0.8/-0.6 Ma) to LAT-31 (242.6±0.7 Ma) and the second occurring between the platform-interior ash beds LAT-30 (241.2+0.7/-0.6 Ma) and LAT-32 (241.7+1.5/-0.7 Ma). If these age reversals in zircon crystal ages are accurate, then these ages cannot possibly reflect the age of the sediments they bracket in an absolute sense, as successive layers of stratigraphy do not become increasingly older upward in undeformed settings.

Emmerich et al. (2005), and independently, Kent et al. (2004), suggest that both cycles and megacycles at the Latemar operate at sub-Milankovitchian frequencies, i.e., ca. 0.9-1.97 kyr/cycle and ca. 3.5-10 kyr/megacycle. As a result, the accumulation of the entire Latemar buildup was calculated to have occurred over approximately 1 Myr. Indeed, the prevalent 5:1 megacycle bundling originally identified by Goldhammer et al. (1987) is not recognized by Kent et al. (2004).

Periodic drivers for Triassic millennial shallowing-upward cycles are difficult to identify because no such drivers have yet been linked to the deposition of stacked shallowing-upward cycles in the Holocene or Pleistocene (see previous discussion). Kent et al. (2004) argue for tidal forcing operating at ca. 1.8 kyr, citing a theoretical tide at the periodicity identified by Munk et al. (2002). However, Munk et al. (2002, p. 382) state that "the equivalent tidal amplitude of the millennial term is estimated at 0.04 mm-" which is clearly not enough to generate the metre-scale Latemar cycles. Similarly, there is a disconnect between millennial-period Dansgaard-Oeschger climate cycles and Heinrich-type warming events cited by Emmerich et al. (2005) as possible cycle drivers. No link has yet been established between these cycles and formational periodicities of shallowing-upward carbonate successions of the Holocene and Pleistocene. Recently, Roth and Reijmer (2005) identified oxygen isotope excursions in a 30-m long core from the leeward margin of the Great Bahama Bank that have both centennial and millennial (ca. 1.7 kyr) periodicities. While this discovery establishes a link between centennial and millennial cyclic processes and carbonate sedimentation, the cycling has yet to be linked to the depositional periods of platform-interior shallowing-upward depositional cycles. The identification of periodic megacycle drivers within the millennial model is likewise problematic. Studies from the Holocene and Pleistocene have yet to identify a lower-frequency (ca. 5-10 kyr) cyclic process by which millennial tides, Bond cycles, or other climatic processes will produce bundled shallowing-upward carbonate megacycles.

While the rates of eustatic rise and fall required for millennial cyclic carbonate deposition are rapid, rates for subsidence and sediment accumulation required for the
development of depositional cycles within this context are likewise very high. The subsidence required to generate 700 m of section in ca. 1 Myr is approximately 0.7 m/kyr. As both the Latemar and Mendola sections preserve cyclic successions of similar stacking and bundling trends, subsidence would have operated at near-equal rates at both localities during the study interval in question. In addition, accumulation rates (including time for sedimentation and subaerial exposure) of platform interior and tidal flat sediments would need to be extraordinarily high in the millennial framework – requiring a sustained accumulation rate in excess of 0.7 m/kyr, approaching the growth rates of Holocene corals - to generate both successions (see Schlager, 1981 for rates). If one considers low energy carbonate tidal flats as sediment sinks rather than sediment sources (e.g., Ginsburg et al., 1977), source sediments would need to be produced at rates that are yet again even higher than 0.7 m/kyrs in order to generate enough sediment to fill the tidal flat sink.

The paucity of evidence for millennial cyclicity of shallowing-upward carbonate successions in the Holocene and Pleistocene, however, must be tempered with the realization that biotic, climatic, and oceanic conditions have changed throughout geologic time. It is possible that the cyclic drivers in the Triassic were unique to that period and cannot be compared to those operating in the Holocene and Pleistocene. Indeed, it may be that in this case comparative sedimentology has met its useful limit as a temporal reference, and that its only appropriate use in mid-Triassic carbonates is as a tool for identifying facies and depositional environments.

The conclusion that processes with millennial periodicities formed the depositional cycles at the Latemar is the result of paleomagnetic analysis, the dating of platform interior ash beds, and the correlation of these dates to basinal deposits proximal to the Latemar platform. The decision to rely on these techniques to a greater degree than comparative sedimentology and/or statistical analyses of the cyclic succession is one that must be made in order to accept the millennial model.

Conclusions

This work has undertaken a new examination of the issue of allocyclicity in the origin of the Latemar platform cycles of the Middle Triassic of the Dolomites, northern Italy. This involved the measurement and analysis of a coeval cyclic platform carbonate formation external to the Latemar locality, 30 km to the northwest at Mendola Pass. The
objective was to determine if the Mendola Pass succession contained a stratigraphic signal comparable to the one found in the Latemar succession. Both successions have metre-scale cyclic bedding with a shallowing-upward depositional theme, with each cycle exhibiting subtidal (<10 m water depth) to supratidal successions of subfacies. Biostratigraphic ties were established between the two successions; statistical correlation analysis of measured cycle thickness series from the two localities allowed for stratigraphic placement of the shorter Mendola Pass section within the Latemar succession. Harmonic analysis identified the full suite of stacking pattern frequencies in both sections, and spectral coherency and cross-phase analysis confirmed significant coherency and phase-locking between the cyclic signals of both localities.

These results have the following implications for high-frequency cyclostratigraphic forcing of the Latemar platform:

• The current state of knowledge regarding Holocene and Pleistocene composite eustasy, the formation of shallowing-upward cycles, and the rates at which these cycles and their component facies form indicate that carbonate allocycles in the modern form as the result of multi—millennial processes (Table 1, Table 2). If the drivers and depositional rates that have been identified for these cycles can serve as a comparative model, it is then likely that the depositional cycles at Mendola Pass and the Latemar, as well as their conspicuous bundled stacking patterns, formed as the result of composite eustatic forcing.

• Resolving the issue of millennial forcing vs composite Milankovitch forcing by comparing the ancient to the modern is difficult because metre-scale carbonate allocycles stacked with millennial periodicities remain undiscovered in modern carbonate sedimentary settings. In addition, a purely sub-Milankovitchian cyclic driver that would act to form bundled carbonate megacycles remains undiscovered in modern settings.

• At the present time, eustatic oscillations involving Milankovitchian composite eustasy are still the most likely explanation for the record of cyclic stratigraphy observed at Mendola Pass and the Latemar—either in the form of pure Milankovitchian forcing (Goldhammer et al., 1987) or mixed Milankovitch-subMilankovitch forcing (Zühlke et al., 2003).
• If one accepts the conclusion that Latemar and Mendola allocycles and allocycle bundles were formed at millennial periodicities, one must accept one of the following conclusions:
  a. That the controls on the sedimentary system, including amplitudes and periodicities of composite eustatic drivers and sustained, very high (0.7 m/kyr+) sedimentation rates in areas of rapid subsidence are unique to mid-Triassic carbonates systems or,
  b. That drivers for Triassic cycles also operate in the Holocene and Pleistocene but do not generate carbonate depositional cycles.

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Appendix 1

Datasets with the original Goldhammer thickness series from Goldhammer (1987) and the Goldhammer+Dunn thickness series published by Preto et al. (2004) (used in this study) may be downloaded from WDC for Paleoclimatology Data Access and Data Contribution: http://www.ncdc.noaa.gov/paleo/data.html

Appendix 2

A MATLAB™ script for Fischer plots, adapted from Read and Sriram (1990), may be downloaded from WDC for Paleoclimatology Free Software: http://www.ncdc.noaa.gov/paleo/softlib/softlib.html

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Figure captions:

Figure 1. Comparison of proposed cyclic driver periodicities for individual cycles and megacycles at the Latemar. Both “Pure Milankovitch” (e.g., Goldhammer et al., 1987; Preto et al., 2004) and “Mixed Milankovitch and sub-Milankovitch” (e.g., Zühlke, 2004) interpret Milankovitchian composite eustasy to have influenced the development of Latemar cycle stacking. The millennial model does not recognize the influence of Milankovitchian forcing on the development of cycles or megacycles at the Latemar. (Note: “Prec” refers to the Precession, and “Ecc.” refers to the Eccentricity.)
Figure 2. A. Location of Ladinian platform carbonate deposits in the Dolomites, N. Italy. B. Paleogeographic and paleotectonic reconstruction of the Dolomites during the Ladinian, after Doglioni (1988) and Bosellini (1991). Note the series of strike-slip faults adjacent to the Latemar buildup. Active sinistral transtension related to the rifting of Pangaea has been recognized in the Dolomites, although quantification of subsidence per locality within the regime has not been established absolutely.

Figure 3. Comparison of ideal shallowing-upward cycles as observed at Mendola Pass (this study) and at the Latemar buildup (Goldhammer et al., 1987; Egenhoff et al., 1999).

Figure 4. Polished hand specimens of cycle tops from Mendola Pass (left) and the Latemar (right). Mendola subfacies include: M1, dasycladacean algal packstone; M2, cryptomicrobial laminitite cap; and M3, mixed skeletal / intraclastic peloidal wackestone. Note flat clasts ripped up from M2 laminitite. Latemar subfacies include: L1, fenestral oncitic / coated grain packstone / grainstone, and L2, dolomitic exposure cap (diagenetically overprinted L1). Direct diagenetic overprinting of L1 subfacies suggests sea-level drop, or “Waltherian skip” between regularly submerged facies and subaerial exposure. Of additional importance is the presence of stylolites, which subtract thickness from the original vertical dimension of the cycles. It is not currently known what percentage of original cycle thickness has been lost through stylolitization of Latemar cycles, but their presence has implications for calculation of sedimentation rates from cycle thicknesses. Mendola facies succession displays a comparably more Waltherian succession from shallow subtidal / intertidal (M1) to intertidal / supratidal facies (M2). Note coin for scale.

Figure 5. Photograph of Mendola road cut section showing cycles 26-31, as well as facies descriptions and megacycle bundling interpretation. Cycles are metre-scale, dolomitized, laminitite-capped peritidal deposits likely formed in environments similar to modern carbonate tidal flats.

Figure 6. Stratigraphic column of the Latemar platform modified from Egenhoff et al. (1999), Preto et al. (2001) and Manfrin et al. (2005) on the left and proposed correlative stratigraphic chart from Mendola pass to the right. Depth scale applies to both charts. Dasycladacean algae from the Latemar are reported in Gaetani et al. (1981). LTF:
Lower Tepee Facies; LCF: Lower Cyclic Facies; MTF: Middle Facies; UCF: Upper Cyclic Facies; UTF: Upper Tepee Facies. Dasycladacean algae and lithostratigraphy from Mendola Pass are reported in Ogilvie Gordon (1927) and Avanzini (2002). Dasycladacean algae marked with an asterisk (*P. leptotheca, D. annulata, and G. ladinica*) were collected at the Mendola study interval, indicating placement in the “Peritidal Member” of the Mendel Dolomit and providing a zone of possible correlation to the Latemar platform based on the occurrence of *P. leptotheca, D. annulata* there.

Correlation of Mendola study interval to the Latemar (marked by horizontal gray bar) is based on Dasycladacean biostratigraphy and maximum statistical correlation of Mendola and Latemar cycle thickness series.

**Figure 7.** Running cross-correlation analysis of cycle thickness series within the Latemar platform, and between Mendola Pass and the Latemar platform. The 95% confidence limits were estimated by interpolating the "95% Confidence Belt" of Taylor (1990, Table 8.6 on p. 139) to sample sizes (i.e. degrees of freedom) of 180 (for intra-Latemar correlation) and 36 (for Mendola-Latemar correlation). A. Pearson correlation coefficients obtained by progressively shifting the Cimon del Latemar (CDL) cycle thickness series of Preto et al. (2001, 2004) relative to the cycle thickness series at Cima Forcellone of Goldhammer et al. (1987), with 57 additional cycle measurements within the Tepee Facies from Dunn (1991) (see Appendix 1 for details). A singular peak correlation occurs between the CDL series and Cima Forcellone Cycles 356 to 504. B. Pearson correlation coefficients obtained by progressively shifting the Mendola Pass cycle thickness series (this study) against the Cima Forcellone cycle thickness series. Peak correlation occurs at a unique interval of 36 cycles in the Cima Forcellone series, Cycles 351 to 386, which corresponds to the lowermost 30 cycles of the CDL series. In both A and B the 95% confidence limits widen at the top of the section as the shifting shorter series (CDL or Mendola) rolls off the upper end of the longer (Cima Forcellone) series, resulting in ever-decreasing degrees of freedom in the calculated coefficients. C. Detail highlighting the relative positions of the correlated intervals with respect to Cima Forcellone.

**Figure 8.** Accommodation (Fischer) plot scripts were calculated using the Fischer plot script (see Appendix 2 for MATLAB script). Accommodation plots presented here are for
A. the Mendola Pass cycle thickness series (Cycles 1-36) and B. the correlative Latemar cycle thickness series (Cycles 351-386 from the Cima Forcellone section, see Figure 7).

Figure 9. MTM spectral analysis of the Mendola and Latemar cycle thickness series using three $2\pi$ multitapers (orders 0, 1, and 2) with adaptive weighting (Thompson, 1982). Both series have been zero-padded from their initial length of 36 to 500, resulting in interpolated spectra with 250 estimated frequencies, which are dimensionless. However, the elementary sampling frequency remains at $\Delta f=1/36=0.028$, and the $2\pi$ multitapering has the effect of averaging over $\beta=3\Delta f=0.083$ (see horizontal lines).

Harmonic analysis of A. the Mendola series and B. Latemar series. For both A and B, the black curves are the line (or amplitude, or first moment) spectra, and refer to the y-axis to the left; the grey lines are effective degrees of freedom (or adaptive weighted d.o.f.’s), and refer to the y-axis on the right (bottom). The bars descending from the top are F-test results for the lines, reported as significance (50% to 100%), and refer to the y-axis on the right (top). C. Magnitude-squared coherency (MSC) spectrum of the Mendola vs Latemar series. The horizontal dashed lines labeled 90% and 95% indicate significance levels for zero coherence for MSC estimates of normally-distributed variables with 5 degrees of freedom (Carter et al., 1973). The black curve gives the estimated MSC values, corrected for the statistical bias imposed by 5 degrees of freedom (Carter et al., 1973); the grey curves indicate the 95% confidence limits. Labels indicate bundling components at frequencies with lower 95% confidence limits exceeding the 95% level of zero coherence. D. Cross-phase spectrum. The black curve indicates estimated cross phase; the grey curves delineate the 95% confidence limits after Bendat and Piersol (1986). For cross phase values less than 0°, Mendola leads Latemar; for values greater than 0°, Mendola lags Latemar. Labels identify the phase relations associated statistically significant (>95%) peaks in the MSC spectrum depicted in C.

Table 1. Compilation of dated modern and recent cyclic climatic processes and behaviors with millennial periodicities.

Table 2. Compilation of dates of modern carbonate shallowing-upward facies successions. Most have not yet filled accommodation, and none of these examples exhibit stacking of shallowing-upward facies successions at millennial periodicities.
All of Cycle & Megacycle Stacking Showing Frequencies Consistent with Milankovitch Forcing

Analyses of Cycle & Megacycle Stacking Showing Frequencies Consistent with Milankovitch Forcing

Milankovitch Forcing not Present in Cycle & Megacycle Stacking

Prec. Ecc. 4.2 ky Prec. 1.7 ky ???

Interpreted Cycle Periodicities
Ideal Mendola Cycle

Unit 2: Dolomitized M/W; mm-scale planar to wavy laminae, cm-scale v-shaped polygons. (Mudcracked cryptomicrobial laminit - Peritidal)

Unit 1: Dolomitized M/W; peloidal, fine-bioclinal debris; mm-scale wispy incipient lamination, rare burrows, rare cm-scale vugs. Basal contact is erosive, consisting of entrained mm-cm scale flat laminit clasts from the underlying laminit. Upper 10 cm consists of coarse skeletal (dasycladacean) grainstone which grades upward into fenestral P/G with discontinuous mm-scale laminations. (Shallow restricted subtidal lagoon; shallowing-upward into intertidal storm-reworked grainstone beneath peritidal cap)

Ideal Latemar Cycle (Goldhammer et al., 1987)

Unit 2: Dolomitized P/G; mm-to-cm-scale coated grains, fenestrae, sheet cracks, cement-filled voids. (Dolomitized vadose diagenetic cap)

Unit 1:
(a) Coarse, sand-to-gravel sized oncitic, lithoclastic grainstone
(b) Medium to very coarse sand-sized skeletal grain packstone to grainstone (Shallow restricted subtidal lagoon; shallowing-upward into shallow, higher-energy lagoon beneath vadose cap)

Ideal Latemar Cycle (Egenhoff et al., 1999)

Microfacies
5: Dolomitic caliche crust or tepee. Diagenetically overprinted coated grain P/G. (Subaerially exposed).
4: Oncoid/bioclinal P/G. (High energy intertidal to supratidal).
3: Fenestral W/P with peloids and lumps. (Transition between shallow subtidal and intertidal).
2: Dasycladacean algae-bearing packstone. (Reworked shallow subtidal)
1: Dasycladacean algae-bearing peloidal W/P. Common erosive bases with flat pebbles. (Transgressive reworking followed by low energy shallow subtidal)

Components
Tepee structure
- Pendant cements
- Dolomitic caliche
- Desiccation crack
- Cryptomicrobial laminit
- Oncoid
- Bioclast
- Dasycladacean algae
- Micritized granis/lumps
- Mixed skeletal allochems
- Firmground / scour
- Peloids / pellets
- Flat intraclasts
<table>
<thead>
<tr>
<th>Study</th>
<th>Cycle Type</th>
<th>Cycle Period</th>
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<tr>
<td>Roth and Reijmer, 2005</td>
<td>Oxygen isotope excursions in a 30 m-long core from the leeward margin of the Great Bahama Bank related to aragonite content</td>
<td>Multi-millennial</td>
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<tr>
<td></td>
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<td>1.725 kyr</td>
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<tr>
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<td></td>
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<td>Niggemann et al., 2003</td>
<td>Oxygen isotope excursions in 61-cm stalagmite</td>
<td>ca. 1.450 kyr</td>
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<td>Bond et al., 1993, 1997, 2001</td>
<td>Oxygen isotope excursions &amp; Ice-rafted sediment cycles</td>
<td>1.5 kyr DO Cycle</td>
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<td>5-6 kyr Bond Cycle</td>
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<td>Munk et al., 2001</td>
<td>Tidal forcing - Millennial Scale</td>
<td>1.795 kyr</td>
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<td>van de Plassche et al., 1998</td>
<td>Mean high water marks from Hammock River marsh, Clinton, Connecticut, USA</td>
<td>Century-scale</td>
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<td>Locality</td>
<td>Depositional Cycle Type</td>
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<td>Strasser and Samankassou, 2003</td>
<td>Florida Bay Bahamas Bermuda</td>
<td>Variable, Shoaling, tidal flat, and subtidal facies successions.</td>
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<tr>
<td>Gischler, 2003</td>
<td>Belize platforms</td>
<td>Variable, Reefal, shoaling, and subtidal facies successions.</td>
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<td>Parkinson 1989</td>
<td>Southwest coast of Florida</td>
<td>T-R cycle, capped by red mangrove peat</td>
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<td>Tudhope 1989</td>
<td>Davies Reef, central Great Barrier Reef complex</td>
<td>Shallowing-up from: gravel lag; bioturbated muddy sand; shoal or exposure cap</td>
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<td>Logan et al., 1969</td>
<td>Shark Bay, Western Australia</td>
<td>Shallowing-up from: grainstone; skel. m/w; laminitie cap</td>
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<tr>
<td>Taft et al., 1968</td>
<td>New Providence Platform, Bahamas</td>
<td>Coarsening-up from mud; Skel. P/G; Grapestone GS</td>
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