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Resolving the Latemar Controversy: a new magnetostratigraphy at the Latemar correlated section of Rio Sacuz

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Abstract

A new magnetostratigraphic study of the Middle Triassic Ambata, Plattenkalke, and Knollenkalke Formations at Rio Sacuz, northern Italy, suggests a depositional duration of ~1 my for the entire Latemar Platform, effectively resolving the debate informally known as "the Latemar Controversy." This debate is framed around an order of magnitude discrepancy in the depositional durations suggested by cyclostratigraphic (~12 my) and geochronologic (~1 my) methods. Since a previous magnetostratigraphic study of the Latemar was inconclusive because of overprinting by lightning strikes, this study determined the magnetostratigraphy of a correlative section unaffected by lightning. A N-R-N-R sequence was observed at Rio Sacuz. With a chron duration of ~0.25-0.5 my for the Middle Triassic, this gives a depositional duration of ~1 my. The magnetic carriers observed in this study were greigite and magnetite. The greigite and magnetite have the same paleomagnetic direction, suggesting a DRM for the magnetite and near-deposition age for the greigite. This study points out the fallibilities of cyclostratigraphic interpretations when calibrations to absolute age are not used to anchor the cyclostratigraphic data.

Introduction

The Middle Triassic Latemar platform in the Dolomites of northern Italy has been the subject of much debate in the recent literature, even earning itself the informal title of "the Latemar controversy." The controversy centers on the order of magnitude differences in estimates of the duration of deposition for the 670 m thick carbonate platform (Preto et al., 2001; Zühlke et al., 2003; Kent et al., 2004). A cyclostratigraphic interpretation suggests that the meter-scale shallowing upward cycles bundled in 5:1 packages are the result of orbital forcing at the precessional scale, giving a depositional duration of ~12 my (Hinnov and Goldhammer, 1991; Preto et al., 2001). U-Pb single zircon dating of tuff layers in the sequence suggest a depositional duration of just ~2 my (Mundil et al., 2003). In addition, the entire sequence is made up of not much more than one ammonite zone, also suggesting a depositional duration on the order of ~1-2 my (Zühlke et al., 2003). A previous magnetostratigraphy also suggested a depositional duration of ~1 my, however it was plagued by poor data (Kent et al., 2004). Resolving this discrepancy has significant implications for our understanding of important paradigms in the Earth sciences. If the ~12 my duration suggested by cyclostratigraphy is correct, then our understanding of U-Pb single zircon dating is not complete. Alternatively, if the ~2 my duration suggested by the U-Pb single zircon dating is correct then we must rethink our understanding of carbonate depositional processes and rates, as well as climate change in the Middle Triassic (Preto et al., 2004). This study resolves this discrepancy by providing an independent estimate of the duration of deposition using magnetostratigraphy.

Previous Work and Geologic Background

The ~600 m thick Latemar Platform in the Middle Triassic Dolomites region of northern Italy was deposited from the Late Anisian through the Early Ladinian at ~240 Ma (Figure 1) (Egenhoff et al., 1999). This region, which formed on the rim of the ancient Tethys ocean, is characterized by large carbonate platforms, such as the Latemar, as well as their surrounding basins. In general, the platforms underwent an initial stage of aggradation followed by a stage of progradation which resulted in ~1000 m of buildup. One of the most striking components of the Latemar section are syn-sedimentary features called tepee structures. Tepees have been interpreted to form diagenetically as a result of the expansion of interstitial cements as well as repeated cracking and expansion of crack-fill cements (Smith, 1974; Burri et al., 1973; Kendall and Warren, 1987) and have been interpreted as supratidal facies. Correlative basinal facies tend to be on the order of ~100m thick and are known as the Buchenstein Beds. These basinal lithologies are comprised of three distinct sections. The basal section, the Lower Plattenkalke, is mainly organic rich laminated limestones and shales. The middle section, the Knollenkalke, consists of muddy pelagic limestone beds containing siliceous nodules. The top section,

Fig. 1 Location map showing the relative positions of the Latemar and Rio Sacuz field sites.

the Banderkalke, is mainly made up of turbiditic calcarenites and breccias. (Brack and Muttoni, 2000)

Arguments for a ~12 my depositional duration: Cyclostratigraphy

The original cyclostratigraphic observation made at the Latemar Platform found that meter scale shallowing upward cycles were bundled in 5:1 packages (Goldhammer et al., 1990). This bundling is widely interpreted as evidence of climatic forced eustatic sea level change due to the precession (~20 ky) and short eccentricity (~100 ky) Milankovitch orbital cycles, and the interpretation was no different here. More recent cyclostratigraphic studies performed on the Latemar platform, however, have been more detailed and nuanced. These studies are based on a depth ranking of subfacies within the platform (Preto et al., 2001; Preto et al., 2004). Both studies focus on a specific 160 m portion of the section and break down the depositional environment into four interpreted depths, in order of increasing depth: carbonate rich soils, supratidal flat, restricted subtidal, and deeper subtidal. The carbonate rich soils are characterized by yellow dolostones with vadose pisoids. Supratidal flats are characterized by weakly laminated limestones with occasional stromatolites and can be distinguished from carbonate rich soils by their lack of pedogenic features. Restricted subtidal facies are characterized by fine-grained wackestones and a lack of biota. Packstones-grainstones with abundant biota characterize the deeper subtidal rank facies. Preto et al. (2004) argues that since these depth ranks combine to form shallowing upward cycles that can be traced for kilometers across the platform through lithofacies boundaries, and thus across depositional environment changes, they likely represent climate forced sea level oscillations.

The varying thickness of these meter scale shallowing upward cycles was interpreted by Preto et al. (2001; 2004) to indicate variations in sediment accumulation rate through time. In order to account for these variations in deposition rate through the section, Preto et al. tuned these shallowing upward cycles to long precession (21.7 ky) based on two key observations. Firstly, the cycles are bundled in 5:1 packages indicating precession bundled in eccentricity. Secondly, in the untuned power spectrum there was a small peak at slightly higher frequency, interpreted as short precession (17.6 ky). After tuning to precession, precession is filtered out to focus on the remaining cyclicities. The resulting power spectrum has remarkably strong correlation to the predicted theoretical orbital variability (used to create a model power spectrum) for the Middle Triassic. All three major peaks in the theoretical power spectrum (400, 125, and 95.8 ky) appear unambiguously in the tuned Latemar power spectrum (390, 125, 97.5 ky, respectively) (Preto et al., 2001). When these cycles are added up a depositional duration of 3.1 my is given for this 160 m of section, which can be extrapolated to ~12 my for the entire ~600 m of section.

Arguments for a ~2 my depositional duration: Geochronology and Biostratigraphy

The isotope geochronologic constraints on the depositional duration of the Latemar Platform are based on U-Pb single zircon dates from tuff layers within the Latemar

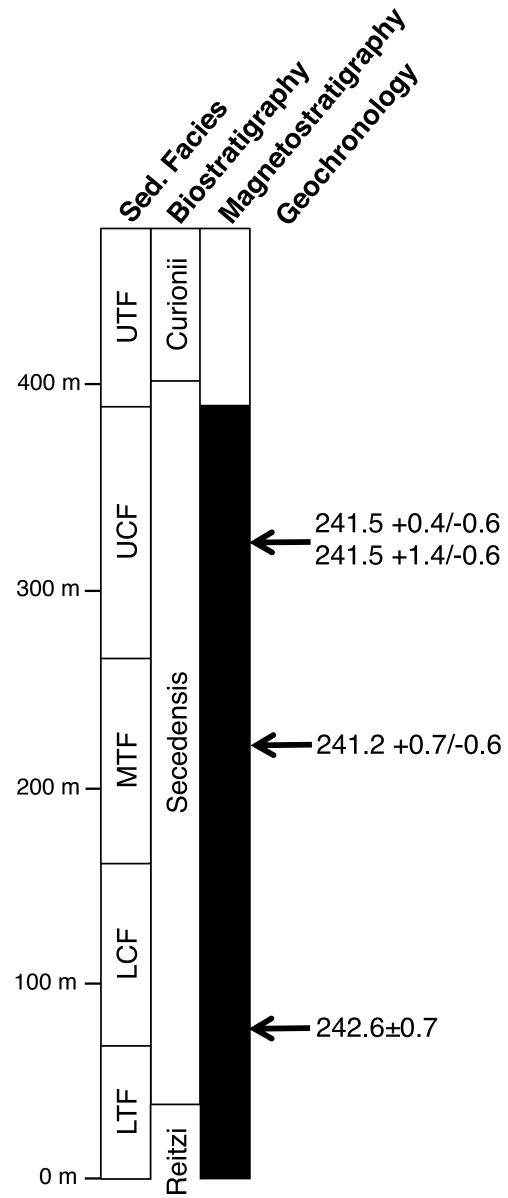


Fig. 2 Correlated dating methods for the Latemar platform. Sedimentary facies (cyclostratigraphy and biostratigraphy (ammonoid zones) are based on Zühlke et al. (2003). Magnetostratigraphy is based on Kent et al. (2004).

sequence as well as correlated outcrops of the same tuffs in the surrounding Buchenstein Basin (Mundil et al., 2003; Muttoni et al., 2004). Mundil et al. (2003) focuses on three tuff layers within the Latemar platform. $^{207}Pb/^{235}U$ and $^{206}Pb/^{238}U$ ages were both calculated and statistically aligned, however the error in the $^{207}Pb/^{235}U$ ages was deemed to be too large, so reported analysis was based on $^{206}Pb/^{238}U$ ages. Mundil et al. made certain attempts in order to achieve the most robust results possible. For instance, crystals were pre-treated in order to minimize the effects of Pb loss, and, upon analysis all ages showing “analytical discordance” and all samples showing Th/U ratios that deviated from the normal distribution were disregarded. This analysis resulted in ages of

242.6±0.7 Ma, 241.2 +0.7/-0.6 Ma, and 241.7 +1.5/-0.7 Ma in order of stratigraphic younging (Figure 2). These ages are strikingly similar to the ages of correlated tuff layers in the region (Mundil et al., 2003). Additionally, the ages of the Latemar tuffs are statistically the same when considering the errors. This indicates that very little time passed between the deposition of these two tuff layers, and implies that the entire platform could not have been deposited in much more than ~2 my.

The biostratigraphic constraints on the depositional duration of the Latemar platform result from the analysis of ammonoid faunas within the platform. Ammonoid biozones are often bracketed by either the initial occurrence or the cessation of certain key ammonoid faunas within a section (Muttoni et al., 2004). The Latemar is bracketed in this way at the top and the bottom of the section (Figure 2). Fauna AF-1 occurs only in the Lower Platform Facies, directly beneath the base of the section that is characterized by shallowing upward cycles (Zühlke et al., 2003). This indicates that the base of the Latemar sequence was deposited at the end of the Reitzi Zone. Fauna AF-8 has only been found in the top ~25 m of the Latemar Platform and is indicative of the lowermost Curionni Zone to the uppermost Secedensis Zone. This indicates that nearly the entire Latemar Platform is made up of a single ammonite zone, the Secedensis Zone, with evidence for bracketing zones occurring in only the lowermost and uppermost portions of the section. These ammonite zones are estimated to last ~ 1 my each, based on biostratigraphic, lithostratigraphic, and magnetostratigraphic correlations to radiometrically dateable tuff layers (Muttoni et al., 2004). The Latemar, thus, being deposited in little more than one ammonite zone, was likely deposited in little more than 1 my. This biostratigraphic evidence, along with the geochronologic evidence, would seem to rule out the order of magnitude faster depositional duration suggested by cyclostratigraphic interpretations.

Reexamining the Data

It is important to consider the possible sources of error that may be present in these seemingly reliable interpretations that lead to such different conclusions about the depositional duration of the Latemar Platform. Preto et al. (2004) makes several arguments in favor of the ~12 my hypothesis. One: the duration of ammonite zones are not precisely known, and there can be some deviation from the average duration. However, it is unlikely that the uncertainties in the ages of the ammonite zones amounts to much more than one or two million years, not nearly enough to account for the order of magnitude difference in depositional duration. Two: the sediment accumulation rates for the Latemar platform predicted by the cyclostratigraphic data match the average sediment accumulation rate for Mesozoic carbonate platforms (~50 m/my). However, the sedimentation rate of ~300 m/my for the platform predicted by the biostratigraphic and geochronologic data is not out of the realm of possibility as some modern platforms are accumulating even faster (e.g. ~2000 m/my accumulation rate suggested for Andros Island, Bahamas) (Maloof et al., 2007). Three: the rates of formation of tepee structures as measured in modern sections is on the order of ~2 m/my, which is more in line with the cyclostratigraphic sediment accumulation rate and much too slow to be accommodated by the geochronologic and biostratigraphic sedimentation rate. Four: Preto et al. (2004) argues that while the single zircon U-Pb dating technique employed by Mundil et al. (2003) is accurate, it may not be precise to a sub million year resolution for two reasons. Some zircons included in the study may not have formed at the time of the eruption of the tuff and rather may have come from recycled parent rock. Additionally, the techniques employed in the winnowing of the zircon data may have lead to inaccurate results. However, even if these objections are taken into account it is unlikely that the zircon ages would shift more than about one million years, again not nearly enough to account for the order of magnitude discrepancy.

The cyclostratigraphic interpretation of directly correlating depositional packaging to orbital cycles while ignoring any absolute age control is inherently flawed. The primary weakness of this technique lies in the circular nature of its argument. While it is interesting that the periodicities observed in the cyclostratigraphic study so closely match the predicted orbital variability, that correlation alone is not enough to prove Milankovitch forcing for the lithologic packaging, as a reexamination of the data will show. Zühlke et al. (2003) reevaluate the cyclostratigraphic data in light of the geochronologic age constraints through the section. Zuhlke et al. (2003) find that the shallowing upward cycle interpreted by Preto et al. (2001, 2004) to be long precession is actually a 4.2 ky sub-Milankovitch cycle. Additional cyclicities were also found: 13.6-16.7 ky, possibly representing short precession or another sub-Milankovitch signal; 18.1-21.5 ky, likely representing a precessional signal; 35.5-48.0 ky, likely representing obliquity; and 95.6-105.9 ky, likely representing eccentricity. While the correlation of these data to the theoretical orbital signal is not as robust as the Preto et al. (2001) correlation, the existence of a correlation is important and means that this cyclostratigraphic interpretation cannot be ruled out.

Previous Paleomagnetic Work

Since previous studies of the Latemar Platform have yielded such different depositional durations, further study is required to resolve this discrepancy. Magnetostratigraphy has the potential to unambiguously resolve "the Latemar controversy" due to the well-defined magnetic polarity time scale of the Middle Triassic (Hounslow and Muttoni, 2010). Previous magnetostratigraphic studies of Middle Triassic sequences have shown that the field was reversing every ~0.25-0.5 my (Gallet et al., 1992; Kent et al., 1995; Muttoni et al., 1997; Hounslow and Giovanni Muttoni, 2010). Hence, if the Latemar was deposited over ~12 my we would expect to see at least 20 reversals; however, if it was deposited over just ~2 my we would only expect to see on the order of ~2-5 reversals. This is a significant difference and an easily testable hypothesis.

A previous attempt to test this hypothesis using magnetostratigraphy at the Latemar platform was plagued by poor data, yielding ambiguous results (Kent et al., 2004). Upon measurement of NRMs of samples and IRM acquisition experiments it became clear that the specimens could be broken down into two categories based on their NRM intensities and NRM/IRM ratios (Kent et al., 2004). One subset of specimens was found to have relatively high NRM intensities (>0.1x10^{-6} Am^2/kg), high NRM/IRM ratios (>0.02), and univectoral Zjiderveld demagnetograms characterized by component directions of no systematic orientation. The other subset of specimens was found to have relatively lower NRM intensities (<0.1x10^{-6} Am^2/kg) and lower NRM/IRM ratios as well as multi-component remanences. The component interpreted as a primary remanence in this subset displays a statistically sound mean direction. Since high NRM/IRM ratios, as well as high NRM intensities and univectoral demagnetograms with a random distribution of paleomagnetic directions, are characteristic of lightning strikes, all specimens in the group with high NRM intensities were discarded. It is important to note that this set of samples includes all samples that show reversed polarity VGPs. This systematic winnowing of data, while logically sound, is also troubling in the sense that it may have lead to insufficient data resolution, causing Kent et al. (2004) to miss reversed chrons in their reversal stratigraphy.

<u>Methods</u>

Field Work

Since previous magnetostratigraphic results (Kent et al., 2004) were ambiguous, we have studied a section that can be easily correlated to the Latemar that is not likely to be plagued by lightning strikes. Several distinct tuff layers in the Latemar and the surrounding Buchenstein basin and carbonate platform deposits allow straightforward correlations between sections (Figure 3) (Preto et al., 2007). The Rio Sacuz section can be correlated to the main Latemar section in this way. Additionally, its location in a river valley greatly reduced the possibility that our results would be significantly affected by lightning strikes. The Rio Sacuz section is located on the flank of the Cernera platform, mainly in the Lower Plattenkalke and the Knollenkalke. The Cernera platform represents a drowned platform (Blendinger et al. 2004; Brack et al., 2007) and therefore is thought to have a slightly different history than the Latemar rocks.

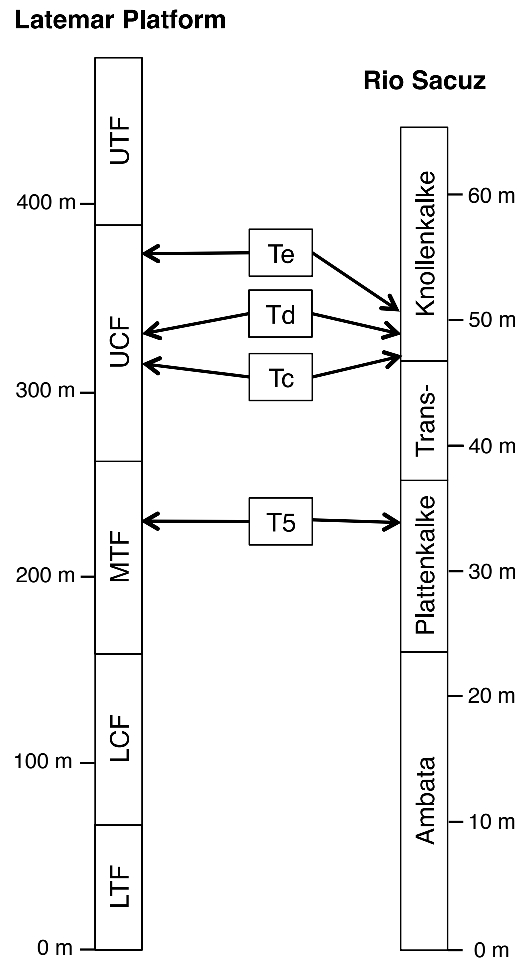


Fig. 3 Tuff correlations between the Latemar and Rio Sacuz. This is based on Preto et al. (2007).

The sampling strategy for this study was devised by assuming the cyclostratigraphic interpretation, which is the limiting scenario for choosing a sampling density sufficient to define chrons. This interpretation would lead to the longest depositional duration, the most geomagnetic field reversals during deposition, and thus the shortest stratigraphic chron thickness and the greatest sampling density required to define a chron. Roughly 20 m of section at Rio Sacuz is bounded by tuff layers that can be directly correlated with the tuff layers in the 160 m section of the Latemar platform studied by Preto et al. (2001). Preto et al.'s cyclostratigraphic study suggested that the tuff layer-bounded 160 m section of the Latemar platform has a depositional duration of 3.1 my, which suggests that the 70 m thick section at Rio Sacuz was deposited over ~10.9 my. Based on this interpretation, at least 20 chrons should be observed in the entire Rio Sacuz section (based on the suggested chron duration of ~0.25-0.5 my), giving a stratigraphic chron thickness of ~3 m. Assuming that at least three horizons are needed to clearly resolve a chron, the Rio Sacuz section was sampled every ~1 m over the ~70 m of section exposed at Rio Sacuz, collecting 65 horizons of at least 3 oriented samples per horizon. Samples were drilled with a Pomeroy core drill and oriented with Pomeroy orienting fixture. A few horizons were not drilled in the field, due to their either being too friable or exposed in a location that was too dangerous to be drilled. Oriented hand samples were collected for these horizons.

Paleomagnetic Measurements

Specimens were treated with stepwise thermal demagnetization starting at 100˚ C, in steps of 25˚ C. Most specimens were fully demagnetized by 400˚ C, however ~10% of the specimens were not fully demagnetized until 500˚ C. Characteristic remanent magnetization (ChRM) directions were determined using principal component analysis (Kirschvink, 1980) with PaleoMag X (Jones, 2002). Virtual Geomagnetic Poles (VGPs) were calculated using L. Tauxe's PmagPy software package. Measurements were made on an SRM-755 2G Enterprises superconducting magnetometer in a magnetically shielded room with a nominal background magnetic field of 350 nT at Lehigh University. Thermal demagnetization was conducted in an TD-48 ASC Thermal Specimen demagnetizer with a field of <10 nT.

Rock Magnetic Experiments

Specimens for rock magnetic study were selected every ~10 meters of section, such that all the lithologies and polarities were studied. The following measurements were made: bulk susceptibility (χ), isothermal remanent magnetization (IRM) acquisition, saturation isothermal remanence (SIRM), anhysteretic remanent magnetization (ARM), AF demagnetization of an SIRM, and coercivity-unblocking temperature spectra (Lowrie, 1990). From these measurements the SIRM/ χ ratio was calculated which can be diagnostic of either sulfides (SIRM/ χ ~70,000) or magnetite (SIRM/ χ ~1) (Roberts, 1995). IRM acquisition results were modeled to determine the coercivity components in the rocks (Kruiver et al., 2001). The coercivity components were used to determine the IRM field levels used for the coercivity-unblocking temperature analysis (Lowrie test; Lowrie, 1990).

In the Lowrie test a specimen is given up to three orthogonal IRMs in different field strengths and then thermally demagnetized (fields of 1 T and 0.16 T were used in this study). While magnetic Fe sulfides and magnetite have similar coercivities, they have very different maximum unblocking temperatures. The unblocking of an IRM at ~250-350˚ C is good evidence of an Fe sulfide (maximum unblocking temperature ~410 ˚C) (Roberts et al., 2011). Unblocking of an IRM at ~< 600˚ C is good evidence of magnetite (maximum unblocking temperature 575˚ C). After thermal demagnetization we re-applied the initial orthogonal IRMs and measured their intensity. This last measurement determines the presence/absence of maghemite, because maghemite will invert to hematite at about 350˚ C, which has a lower spontaneous magnetization than maghemite (Lowrie and Heller, 1982). Much higher intensities after heating could be indicative of an Fe sulfide that has oxidized to magnetite (Turner, 1975).

The final rock magnetic test was designed to determine if biogenic magnetite was present in the rocks (Moskowitz et al., 1993). This test involves IRM acquisition in a direct field and then AF demagnetization of this IRM. The crossover point of the normalized IRM acquisition and AF demagnetization curves is designated Raf and plotted against the ratio of ARM/SIRM. The ARM was applied in a 95 μT DC magnetic field and a 100 mT maximum AF field. Samples with ARM/SIRM ratios of 0.0-0.15 and Raf's from 0.2-0.4 are interpreted to have inorganic magnetite (Moskowitz et al. 1993). Samples with ARM/SIRM ratios of 0.15-0.3 and Raf's from 0.5 to 0.6 contain biogenic magnetosomes in chains.

Results

Paleomagnetic Directions

Based on their paleomagnetic direction, the specimens can be broken down into three different categories (Figure 4). The first category has a low temperature component that is removed by ~200˚ C, followed by a component that has a south and up direction (Figure 4a). The second category is mostly univectoral with a north and down direction

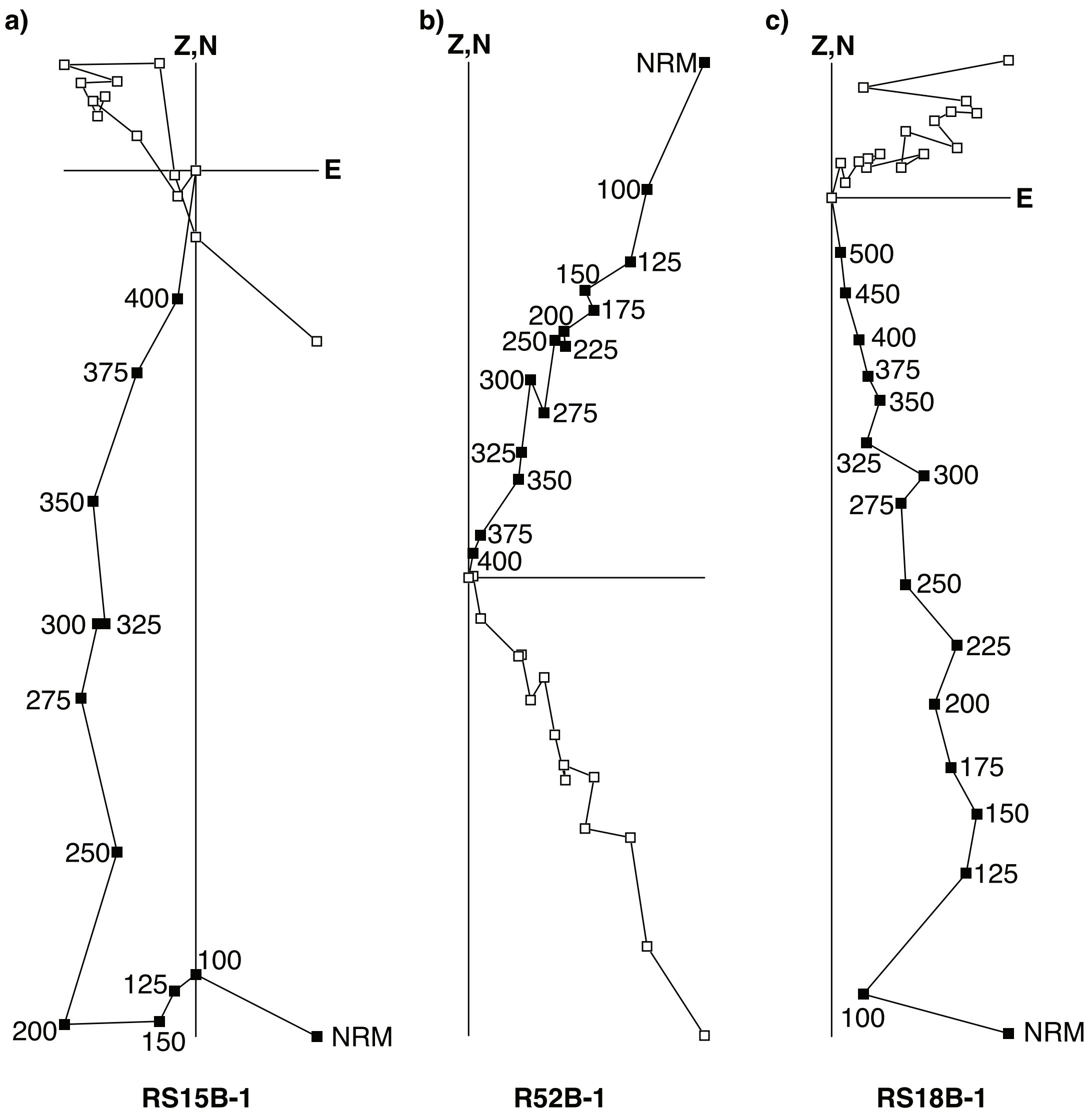


Fig. 4 Representative Zjiderveld demagnetograms for Rio Sacuz. Black squares are the horizontal component and white squares are the vertical component. Demagnetization temperature steps are labeled. A. Shows a representative reversed polarity specimen that has a low temperature component that comes off by 200 C. B. shows a representative normal polarity specimen. C. shows an example of a specimen that has a univectoral demagnetization plot up to 500 C. Plots created with PaleoMag X (Jones, 2002).

(Figure 4b). The third category is mostly univectoral with a south and up direction (Figure 4c). The VGP latitudes calculated from the characteristic magnetizations isolated by principal component analysis of the demagnetization data can be broken down into two distributions, one that has high positive latitudes and another that has mid to high

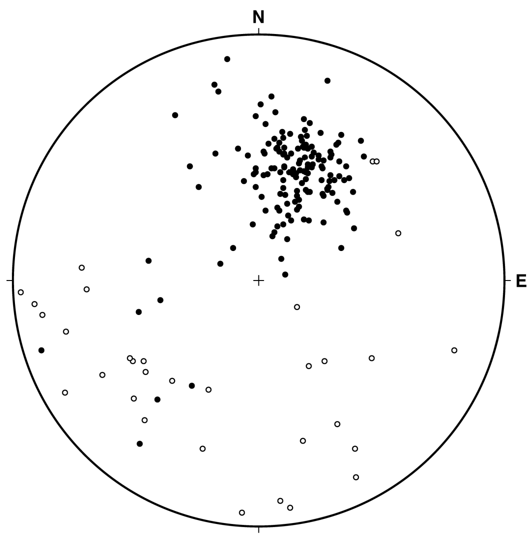


Fig. 5 Characteristic Remanent Magnetization directions from the Rio Sacuz section.

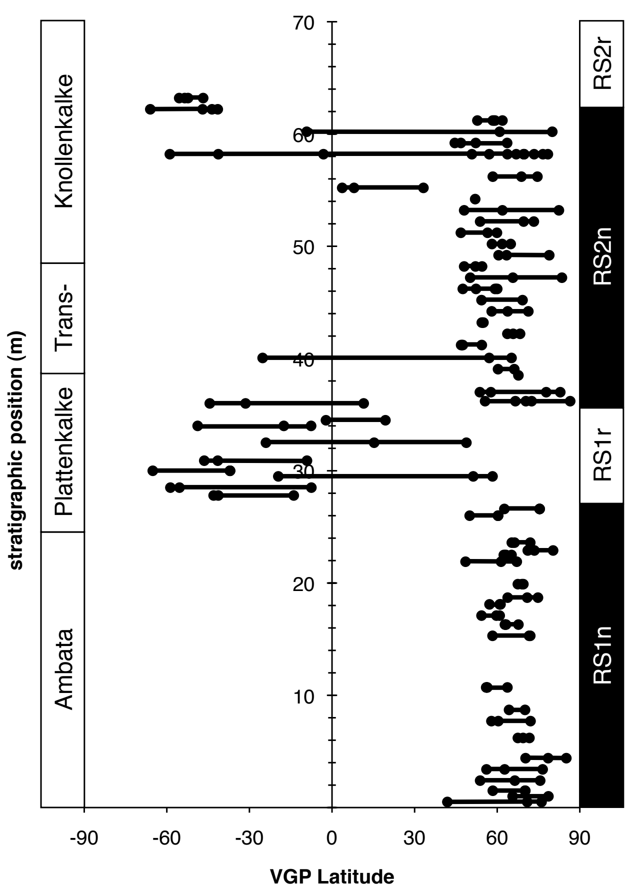


Fig. 6 Reversal stratigraphy for Rio Sacuz

negative latitudes (Figure 5). The reversal stratigraphy of the Rio Sacuz section (Figure 6) shows the latitudes of these VGPs through the stratigraphic section. In general, the trend through the section is as follows: the bottom ~26 m of the section has positive VGP latitudes (normal polarity), the next ~10 m has negative VGP latitudes (reversed polarity), the next ~26 m of section has positive VGP latitudes (normal polarity), and the top ~3 m of section has negative VGP latitudes (reversed polarity). Only ~5% of specimens show the opposite polarity of the polarity zone in which they are located. However, these specimens are always accompanied at a site by at least one specimen that does show the same polarity as the zone in which it is located. Additionally, the sites directly above and below where there is a specimen showing an anomalous polarity contain only specimens that show the same polarity as the zone in which they are located. For example, the site at 40 m is in a portion of the section that shows mostly high positive latitude VGPs, but one specimen at this site shows a low negative latitude VGP. However, two other specimens from that site show high positive latitude VGPs. Additionally, the sites both directly above and below the 40 m site only contain specimens showing high positive latitude VGPs. In total there are 6 sites that contain both positive and negative VGP latitude specimens.

Rock Magnetic Tests

All specimens showed similar rock magnetic characteristics. In IRM acquisition tests, specimens became saturated by ~300 mT (Figure 7). These acquisition curves could be modeled with two coercivity components using the methods of Kruiver et al. (2001). The first component contributes ~95% of the magnetization and has a maximum coercivity of ~0.16 T, with a mean coercivity of 0.05 T. The other component contributes ~5% of the magnetization and has a maximum coercivity of ~1 T, with a mean coercivity of 0.5 T. These maximum coercivity

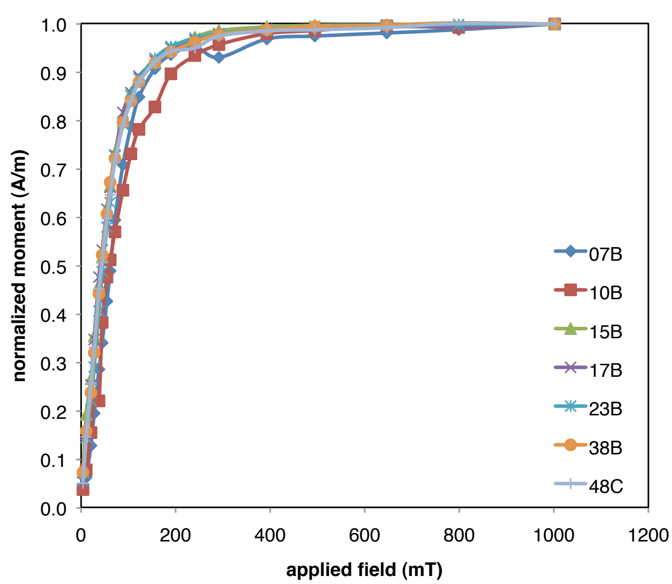
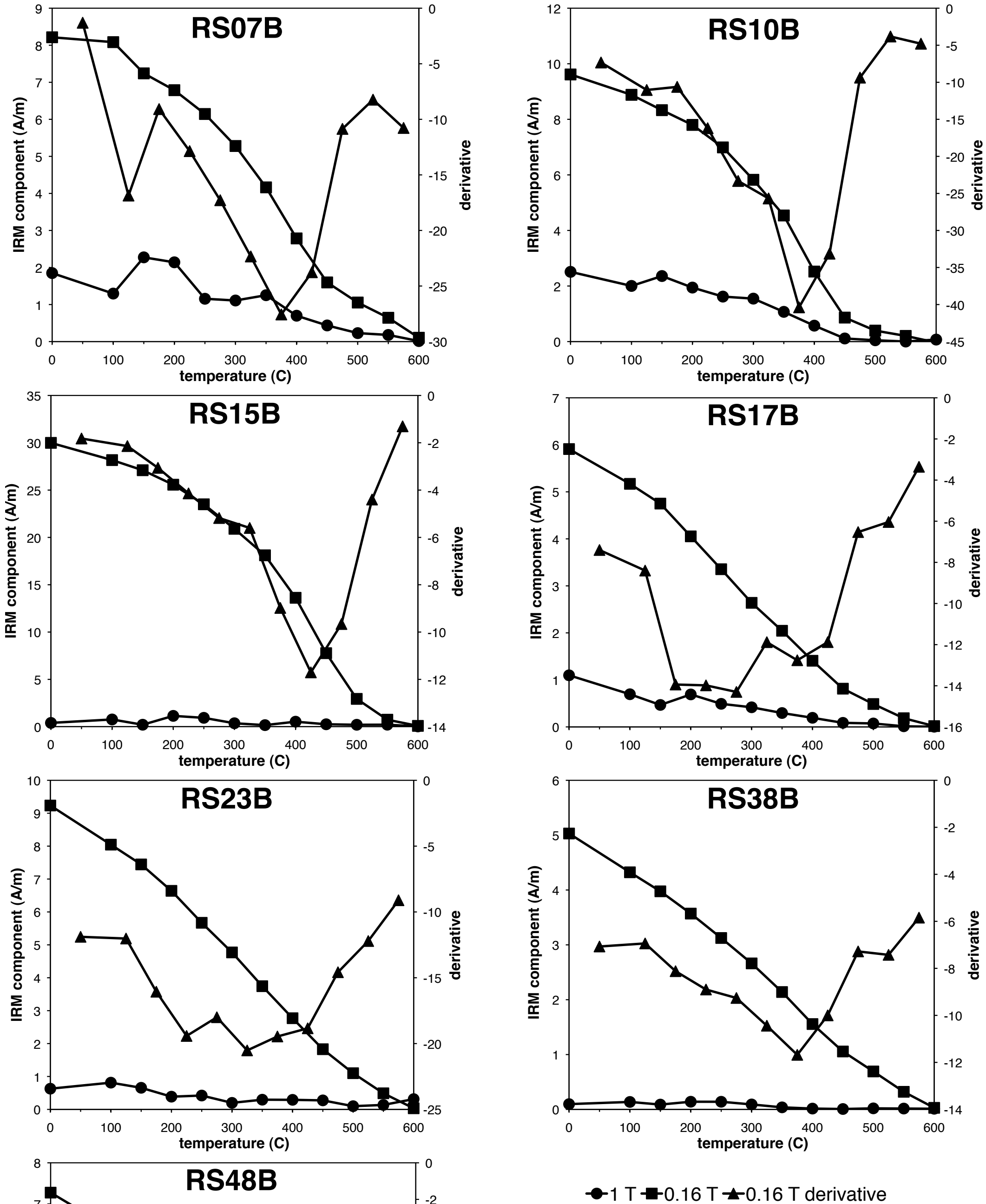


Fig. 7 IRM acquisition experiment results. All specimens show similar results and are saturated by ~300 mT



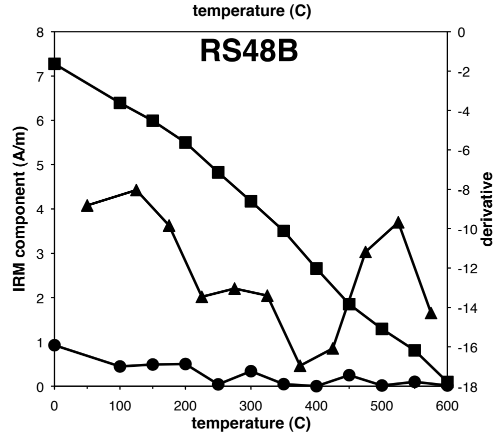


Fig. 8 Lowrie test data. First derivative values are in units of 10^{-8} and IRM Component 10^{-5}. Samples were given a two orthogonal IRM components of 1 T and 0.16 T and then thermally demagnetized from 100 °C to 600 °C in steps of 50 °C. The hard component is weak compared to the soft component. The soft component has two maximum unblocking temperature populations, one ~400 °C, and another ~600 °C.

Sample	SIRM/χ
07B	103.2
10B	317.2
15B	317.4
17B	175.6
23B	71.7
38B	89.4
48C	75.8

Table 1 SIRM/χ ratios. Ratios ~70,000 are indicative of sulfide. Ratios of ~1 are indicative of magnetite

values were used as the orthogonal IRM intensities in our Lowrie test. The results of the Lowrie test show that the magnetic moment of the 0.16 T component generally decreases rapidly through ~300˚-400˚ C, followed by a steady decline to ~0 A/m by 600˚ C (Figure 8). In some specimens the sharp decrease from ~300˚-400˚ C is more pronounced and in other specimens the decay is more linear from 0˚-600˚ C. However, an inflection point is present in this ~300˚-400˚ C range in all specimens, as is clearly shown by the first derivative (Figure 8). SIRM/ χ ratios were not indicative of a single population of either Fe sulfide or magnetite indicating that the magnetization is carried by two populations: an Fe sulfide and magnetite (Table 1). The measurement of the applied orthogonal IRMs showed vales two to four orders of magnitude higher post heating (Table 2). These results rule out maghemite as a potential magnetic carrier, but could be indicative of an Fe sulfide oxidizing to magnetite. The results of the ARM/SIRM vs. Raf experiment were mixed. Raf results were somewhat ambiguous as samples could only be

Specimen	x pre-heating	x post-heating	y pre-heating	y post-heating
RS07B	1.85E-05	1.44E-03	8.22E-05	4.42E-03
RS10B	2.51E-05	5.86E-03	9.62E-05	1.30E-02
RS15B	4.01E-06	6.32E-03	3.00E-04	1.31E-02
RS17B	1.10E-05	1.69E-03	5.91E-05	4.32E-03
RS23B	6.29E-06	2.41E-02	9.23E-05	3.82E-02
RS38B	9.65E-07	2.02E-03	5.03E-05	9.03E-03
RS48B	9.26E-06	2.80E-02	7.28E-05	4.53E-02

Table 2 Measurements of IRM intensity before and after heating during the Lowrie test. Units are in A/m. Significantly higher intensities post-heating could be indicative of an Fe sulfide that has oxidized to magnetite.

Sample	ARM/SIRM	Raf
38C	0.05	0.39
10A	0.02	0.46
35B	0.02	-
24B	0.09	-
47A	0.06	-
53C	0.03	-
04A	0.02	-

Table 3 Results of the test for inorganic or biogenic magnetite after Moskowitz et al., (1993). ARM/SIRM ratios of 0-0.15 are indicative of inorganic magnetite and ratios of 0.15-0.3 are indicative of magnetosomes. Raf vaules of 0.2-0.37 are indicative of inorganic magnetite and values of 0.48-0.55 are indicative of magnetosomes. Note that saturation IRM could not be reached in the Raf experiments so the values reported are anomalously high. ARM/SIRM values, however were diagnostic and fall within the

~90% saturated with the direct field IRM. Because of this, only two specimens were tested for Raf. ARM/SIRM results, however, were successful and gave consistent values diagnostic of inorganic magnetite (Table 3).

Discussion

Magnetostratigraphy

The general trend of VGP latitudes through the Rio Sacuz section shows a Normal-Reversed-Normal-Reversed (N-R-N-R) reversal stratigraphy in order of stratigraphic younging. These chrons are labeled RS1n, RS1r, RS2n, and RS2r, respectively, in the reversal stratigraphy (Figure 6). RS1n is comprised completely of specimens that show normal polarity VGP latitudes. Within RS1r there are 5 specimens that show normal polarity VGP latitudes. However, there are no sites within this chron that show all normal polarity VGP latitudes and sites that have at least one specimen showing reversed polarity are bounded above and below by sites showing only normal polarity. This suggests that these normal polarity specimens are not evidence for additional chrons, but rather representative of normal overprinting. Within RS2n there are 4 specimens showing reversed polarity VGP latitudes. However, as with RS1r, these outliers are accompanied at the same site by specimens that have normal polarity VGP latitudes. Additionally, the sites within RS2n that contain specimens displaying reversed polarity VGP latitudes are bounded above and below by sites with only normal polarity VGP latitude specimens. These reversed polarity specimens in RS2n are likely showing reversed overprints. RS2r is composed of the top 2 sites in the section and all specimens show reversed polarity. In all, only ~5% of specimens display polarities that disagree with the companion specimens at the site as well as the specimens in adjacent sites. Additionally, if any additional chrons are interpreted the correlation of the Rio Sacuz section no longer aligns with ammonite zone correlations. For these reasons, this small subset of specimens likely displays an overprinting. Additionally, the chron boundaries do not align with sedimentary formation transitions, and there is no correlation between rock magnetic property and paleomagnetic direction (i.e polarity). This lack of correlation between polarity and lithology or rock magnetic properties, as well as a small (~5) percentage of specimens showing evidence for overprinting gives strong evidence that this magnetostratigraphic interpretation is robust.

Because the main goal of this study was to determine a depositional duration for the Latemar platform it is important to compare our results to the previous magnetostratigraphic results of Kent et al. (2004). If the high NRM specimens that Kent et al. discarded are compared to the results of the Rio Sacuz section, the high NRM Latemar platform rocks indicate reversed polarity VGP latitudes in the vicinity of the T5 tuff layer, as well as just above the Te tuff layer where the Rio Sacuz rocks show reversed polarity. This evidence suggests that some of the specimens that Kent et al. discarded may not have been totally overprinted by lightning induced magnetizations and may actually have depositional remanent magnetizations. If the Latemar magnetostratigraphy is reinterpreted in this way the magnetostratigraphies of Rio Sacuz and the Latemar align nicely, both showing a reversal stratigraphy from oldest to youngest of a normal chron followed by a shorter reversed chron just below T5, followed by a normal chron, which is followed by evidence for the beginning of a reversed chron at the top of the sections.

Not only does the Rio Sacuz magnetostratigraphy tie in convincingly to the Latemar magnetostratigraphy, it also ties well to an integrated polarity timescale for the Triassic (Hounslow and Muttoni, 2010) (Figure 9). Ammonite subzones, as well as tuff ages, suggest that the Rio Sacuz/Latemar magnetostratigraphy should correlate to ~the second half of MT7. The chrons match up very convincingly and suggest that we have a robust magnetostratigraphy for Rio Sacuz, and also the Latemar platform. Based on Hounslow and Muttoni's (2010) work a chron duration of ~0.25-0.5

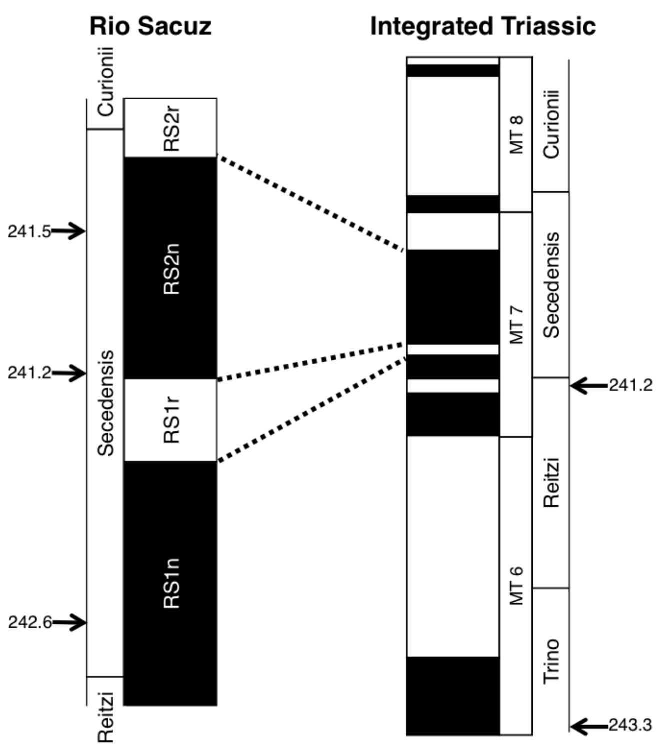


Fig. 9 Correlation of the Rio Sacuz magnetostratigraphy to the integrated magnetostratigraphy of the Triassic in Hounslow and Muttoni (2010). Ammonite zones and Tuff ages at Rio Sacuz and correlated from the Latemar.

my is indicated for this part of the Triassic suggesting a depositional duration of ~1 my for the Rio Sacuz section, and Latemar platform. This duration is supported by the ammonite zone data as well as numerous U/Pb single zircon dates of the Tx tuff layers.

Magnetic Mineralogy

Support for the magnetostratigraphic results must come from evidence that the directions represent the original depositional remanent magnetizations (DRMs). The top ~1-2 m of the sediment column for sediments deposited in carbonate platform settings, like those at Rio Sacuz, often experience early diagenetic reducing environments that result in the pyritization of the iron oxides that carried the original remanence; depositional iron oxides are converted into Fe sulfides (Brack and Muttoni, 2000; Lowrie and Heller, 1982; Roberts et al. 2011; Maloof et al., 2007). This process has the potential to offset the age of magnetization from the depositional age on the order of thousands of years. However, since this study is focused on magnetic chrons that are hundreds of thousands of years in duration, an offset of thousands of years should not appreciably affect the results of this study (i.e. it is unlikely that any whole chrons of a duration of hundreds of thousands of years would have their magnetizations completely reset). For this reason, having a magnetic mineralogy that includes or is even dominated by Fe sulfides would not considerably affect this magnetostratigraphy as long as there is evidence that depositional magnetite and Fe sulfides carry the same paleomagnetic direction.

The results of the rock magnetic tests indicate that the remanence is partially carried by a magnetic Fe sulfide, likely greigite, and also partially carried by magnetite. The results of the IRM acquisition tests (Figure 7) show that the samples become saturated by around 200-300 mT. This can be indicative of either magnetite or greigite. The Lowrie tests show the same general patterns for all samples (Figure 8). The magnetization is carried almost exclusively by grains with coercivities below 160 mT, which could indicate either magnetite or greigite. The decay in magnetization of this coercivity component shows two unblocking temperature components, one with a maximum unblocking temperature of ~450˚ C, and another with a maximum unblocking temperature of ~600˚ C. These multiple unblocking temperature components are also shown by the derivatives of the magnetization peaking in magnitude at temperatures between 275˚C and 425˚ C, while the specimens are not totally unblocked until temperatures of ~600˚ C. These results indicate that the magnetization is likely carried by both magnetite (maximum unblocking temperatures of ~575˚ C) and greigite (maximum unblocking temperatures of ~410˚ C reported by Sagnotti and Winkler (1999)). While there is strong evidence that an Fe sulfide, likely greigite, is an important magnetic carrier in the Rio Sacuz rocks, it is important to note that upon thermal demagnetization of NRMs some samples had maximum unblocking temperatures up to ~500˚C (much too high to be an Fe sulfide), and the decay of that magnetization was univectoral (Figure 4C). This line of evidence indicates that the greigite and the magnetite in the specimens both carry the same paleomagnetic direction. Since these directions are the same, the age of the magnetization cannot be significantly offset from the age of deposition and the results of our magnetostratigraphy are robust.

The results of the Moskowitz et al. (1993) test to determine the nature of the magnetite, biogenic magnetosomes or inorganic, were somewhat mixed but provide strong evidence for an inorganic source for the magnetite (Table 3). The results of the Raf experiments were not diagnostic as specimens were only able to reach ~90% saturation with the magnet applying the direct field IRM. Raf is the crossover of the normalized direct field IRM acquisition curve and the AF demagnetization of that IRM, so if saturation is not being reached these curves would extend to higher relative strengths of magnetizations, thus placing our Raf point at a lower relative normalized magnetization. Shifting the Raf values lower would provide strong evidence for inorganic magnetite. While there were problems with the Raf experiments the ARM/SIRM experiment was successful. All ARM/SIRM vales fell between 0 and 0.15, which is diagnostic of inorganic magnetite. This diagnostic ARM/SIRM experiment, along with an Raf experiment indicative of inorganic magnetite, provides strong evidence that the magnetite in the Rio Sacuz rocks is inorganic in nature.

Reinterpreting the Cyclostratigraphic Data

Kent et al. (2004) reexamined the cyclostratigraphic data from Preto et al. (2001) without tuning the data based on the assumption that the 5:1 bundling of the meter scale shallowing upward cycles is representative of precession and eccentricity. Their reexamination assumed a linear relationship between depth and age allowing a straightforward interpretation with the absolute age control provided by the combination of the U/Pb single zircon tuff dates, ammonite zone data, and magnetostratigraphic data.

Without tuning the meter scale shallowing upward cycles to precession, the peak at one meter is insignificant and indistinguishable from the background noise. The prominent peaks here occur at 0.1 cycles/meter and 0.02 cycles/meter. Interestingly, the ratio of these frequencies is 5:1, possibly suggestive of short eccentricity and precession. If these cycles are precession and eccentricity, then 10 meters of section represents ~21 ky. This assumption would give a depositional duration of ~1.4 my for the entire 670 m Latemar platform, a figure that can be easily reconciled with the zircon dates, the ammonite zones, and the magnetostratigraphic results of this study.

Hinnov (2006) also reexamines the cyclostratigraphic depth rank series of Preto et al. (2001) using an untuned linear relationship between age and depth. Hinnov found that a ~1 m peak was significant at the 95% confidence level, however this was achieved by splitting the 160 m section into two 80 m subsections. In the bottom 80 m subsection statistically significant peaks are at 1.1 and 5.7 m cycles. In the top subsection the statistically significant peaks are at 0.9 and 10 m cycles. These peaks in the top subsection show a 10:1 bundling, not the 5:1 bundling that is the basis of the argument for a tuned model where there is a ~1 m cycle that represents precession and varies in thickness as sediment accumulation rates vary through the section. If the 5:1 bundling of this cycle is representative of precession and eccentricity we would expect to see this ratio throughout the entire section, and not just in a small subset of the section. Additionally, this variation in the bundling ratio would seem to suggest that the bundling is not, in fact, evidence of Milankovitch forcing, but rather caused by some other process.

Geochronologic, biostratigraphic, and magnetostratigraphic data, along with a reinterpretation of the cyclostratigraphic data, provide strong evidence that the meter scale shallowing upward cycles at the Latemar were not forced by precession. Given this overwhelming evidence, there are two possible explanations to explain these cycles and their regular bundling. One explanation is that these cycles are evidence for Holocene-like sub-Milankovitch climate variability, such as Dansgaard-Oeschger cycles (Broecker and Denton, 1989), Heinrich events (Heinrich, 1988), and Bond cycles (Bond et al., 1992), in the Middle Triassic. Another explanation is that the cycles are not allocycles caused by the outside forcing of climate variability, but in fact, are simply autocycles that are controlled by the carbonate system itself (Drummond and Wilkinson, 1993; Beerbower, 1964; Schwarzacher, 2000). In this interpretation the cycles are simply the result of varying accommodation space due to the rate of platform buildup on top of the background rate of tectonic subsidence. Carbonate accumulation rates greatly increase when a certain optimum water depth is reached and the platform builds up to fill the accommodation space. Once this space is filled, accumulation rates are greatly reduced until the platform subsides and the carbonate production zone is in that optimal water depth again and the platform begins to build up rapidly, thus starting a new cycle. Given the autocyclic interpretation, subsidence rates would have been relatively constant during the buildup of the platform, and that bundling is simply a stochastic response, contradicting the interpretation that 5:1 bundling is strong evidence for precession and eccentricity (Schwarzacher, 2000). If this is true and the 5:1 bundling at the Latemar is simply a stochastic response of the system, then previous and future studies that interpret the 5:1 bundling as evidence of Milankovitch cycles without any absolute age control should be questioned.

Conclusions

The new magnetostratigraphic results presented in this study show a N-R-N-R reversal stratigraphy. Based on a Middle Triassic chron duration of ~0.25-0.5 my (Hounslow and Muttoni, 2010), this gives a depositional duration of ~1 my for the the Rio Sacuz section and hence the entire Latemar platform. This duration agrees with the duration suggested by U-Pb single zircon dating of tuff layers within the platform (Mundil et al., 2003), as well as the ammonite zones within and bounding the platform (Zuhlke et al., 2003). However, this duration cannot be reconciled with the ~12 my depositional duration suggested by cyclostratigraphic interpretations that focus on facies depth rank examinations (Preto et al., 2001, 2004). Furthermore, when this facies depth rank series is reexamined without tuning the meter scale cycles to precession, the meter scale cycle does not form a prominent spectrographic peak (Kent et al., 2004). The dominant peaks, rather, are at lower frequencies, which are at a 5:1 ratio to each other: good evidence for precession and eccentricity. If these lower frequency cycles are in fact precession and eccentricity, they would suggest a depositional duration of ~1.4 my, easily reconcilable with the duration suggested by all other dating techniques. This strong evidence for Milankovitch cycles at very different frequencies points out the potential fallibilities in making orbital assumptions without any tie points to absolute ages. The meter scale shallowing upward cycles, which are bundled in 5:1 packages and interpreted as evidence of the orbital forcing of precession and eccentricity could be explained as an autocyclic stochastic response to the varying available accommodation space due to the balance between carbonate bank buildup and tectonic subsidence. Alternatively, these cycles could be evidence for sub-Milankovitch climatically driven eustaic sea level change on the order of ~2ky.

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•Exploring Earth (Fall 2010): introductory laboratory course

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Head TA: oversaw the lab for this course, organized resources

Lehigh University Kravis Scholar: August 2009-August 2010

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Occidental College Science Scholar: January 2008-May 2009

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Skills:

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