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Millennial-scale climate cycles in Permian–Carboniferous rhythmites: Permanent feature throughout geologic time?

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Notes

Millennial-scale climate cycles in Permian–Carboniferous rhythmites: Permanent feature throughout geologic time?

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ABSTRACT

Two late Paleozoic glacial rhythmite successions from the Itararé Group (Paraná Basin, Brazil) were examined for paleoclimate variations. Paleomagnetic (characteristic remanent magnetization, ChRM) and magnetic susceptibility (K_z) measurements taken from the rhythmites are interpreted as paleoclimatic proxies. Ratios of low-frequency components in the K_z variations suggest Milankovitch periodicities; this leads to recognition of other, millennial-scale variations reminiscent of abrupt climate changes during late Quaternary time, and are suggestive of Bond cycles and the 2.4 k.y. solar cycle. We infer from these patterns that millennial-scale climate change is not restricted to the Quaternary Period, and that millennial forcing mechanisms may have been prevalent throughout geologic time.

INTRODUCTION

An important objective in paleoclimate research is to understand triggering processes of glacial-interglacial cycles and anthropogenic influence on climate thresholds. Studies typically focus on large global changes, especially those occurring at the millennial scale. The best-known examples are the Pleistocene Dansgaard-Oeschger (D-O) warming events, that occur at 1470 yr intervals (Hinnov et al., 2002; Witt and Schumann, 2005). These abrupt events are overprinted by 3.0–8.0 k.y. Heinrich events (Bond et al., 1993, 2001), in a complex interplay known as the Bond cycle (Berger and Loutre, 2004). These stadial-interstadial variations occurred over much of the last glacial cycle (past 100 k.y.) and had a widespread influence on the marine carbon cycle (Bard, 2002).

Hypotheses on the origins of millennial-scale climate change range from internal feedback in the ocean-atmosphere system (e.g., Ganopolski and Rahmstorf, 2002; Timmermann et al., 2003) to external forcing mechanisms (Braun et al., 2005). D-O events have also been linked with recent climate changes, e.g., the Little Ice Age, Medieval Warm Period, and Younger Dryas (Campbell et al., 1998). Modeling (Stocker, 1999) suggests that millennial climate changes were triggered by processes that were not restricted to the last glacial cycle. Therefore, research that focuses on Sun-climate connections in deep time is of considerable importance.

Here we interpret rock magnetic data from two glaciogenic rhythmite sequences in Permian–Carboniferous Gondwana as records of millennial-scale climate variations. Analysis is based on magnetostratigraphic series of characteristic remanent magnetization (ChRM) directions and bulk magnetic susceptibility (K_Z). In both rhythmites, ChRM has a detrital origin; K_Z is a paleoclimate proxy indicating ferromagnetic mineral concentration (Verosub and Roberts, 1995).

DATA AND METHODS

The Itararé Group (IG) in Brazil (Fig. 1) is a record of late Paleozoic glaciation that affected the Gondwana supercontinent. We report on two IG rhythmites exposed near the cities of Itu and Trombudo Central, separated by ~1000 km. Both successions consist of alternating lithological units (couplets) of light, quartz-rich sandstone and/or siltstone (centimeter to decimeter) and dark argillite and/or siltstone (millimeter) layers deposited in a glaciolacustrine setting with an upwardly increasing marine influence (Eyles et al., 1993). The Itu (IT) rhythmites have palynofloras from the late Carboniferous *Crucisaccites monoletus* Interval Zone; the Rio do Sul (RS) rhythmites have palynofloras from the Early Permian *Vittatina costabiliz* Interval Zone (Souza et al., 2010).

The IT couplets were originally interpreted as varves (Ernesto and Pacca, 1981), but this interpretation was questioned (e.g., Caetano-Chang and Ferreira, 2006). Silva and Azambuja Filho (2005) investigated IG rhythmites

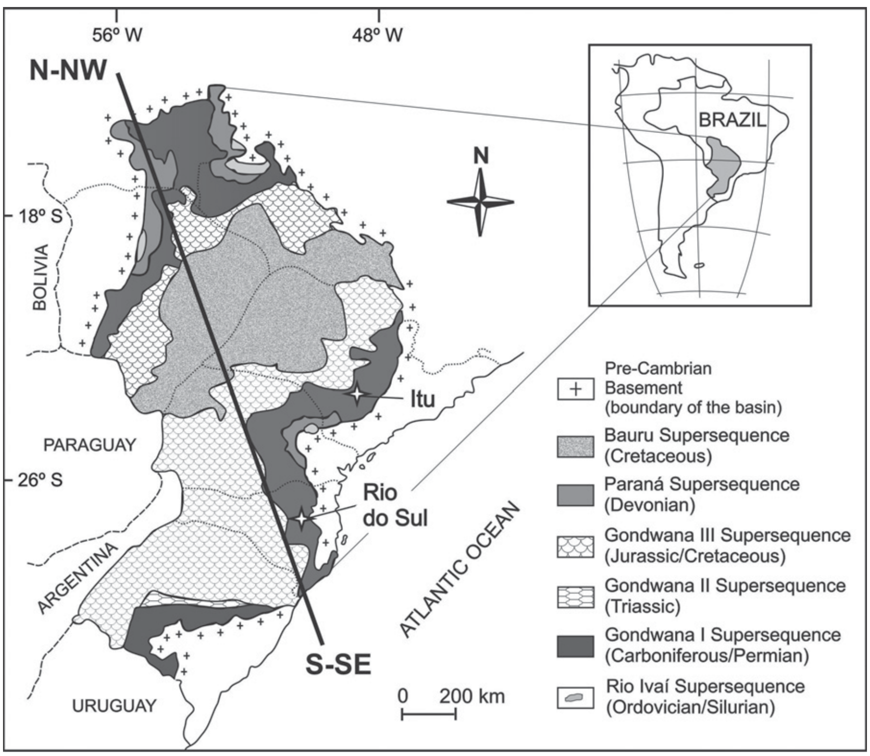

Figure 1. Location and distribution of supersequences, Paraná Basin, southeastern Brazil. Itararé Group is part of Gondwana I supersequence. Itu and Rio do Sul quarries are indicated. Diagonal line south-southeast–north-northwest indicates cross section displayed in Figure DR1 (see footnote 1). From Souza et al. (2010).

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near Anitápolis, Santa Catarina state (~100 km southeast of RS), and concluded that the rhythmites were astronomically forced. They also examined short intervals using grayscale scans, documenting decadal- to millennial-scale variations. Franco et al. (2011) also investigated lamination in IT and RS couplets, as well as ChRM directional changes, that suggest a centennial time scale for the couplets.

Rock magnetism analysis (Fig. 2; see the GSA Data Repository[1]) indicates the following: (1) similar magnetic mineralogy in both couplet lithologies, with higher concentrations in sandstones and siltstones; (2) detrital hematite and titanomagnetite as natural remanent magnetization (NRM) carriers in both rhythmites, with hematite the main carrier of the stronger remanence in the IT rhythmites, and hematite and small-grained magnetite and/or titanomagnetite as NRM carriers for the single, reversed magnetization component in both rhythmites; and (3) a primary ChRM, i.e., a record is retained of the magnetic field at (or soon after) the time of sedimentation.

Spectral analysis was carried out with the Fortran 90 program REDFIT (Schulz and Mudelsee, 2002). In order to interpret the observed harmonic patterns, we converted stratigraphic height to time as follows. The spectra have high-magnitude peaks at low frequencies with ratios comparable to those of theoretical Milankovitch (astronomical) spectra predicted for the Permian (5.7:2.2:1.2:1; Berger et al., 1992). Kruiver et al. (2000) used frequency ratios, reasoning that the frequency spacing of spectral peaks in Milankovitch-forced stratigraphy would reflect that in theoretical spectra.

RESULTS

The spectral analysis of IT and RS magnetostratigraphic series is presented in Figure 3. Depositional conditions of the two rhythmites involved different sedimentation rates, which produced different Milankovitch-scale wavelengths in the stratigraphic domain. For the IT rhythmites, the terms selected as Milankovitch parameters (Fig. 3A, inset) are 4605 mm (eccentricity, E = 100 k.y.), 1320 mm (obliquity, O = 39 k.y.), and 921 mm (major precession, P+ = 20.9 k.y.), corresponding to an average sedimentation rate of 41.4 m/m.y. The 4605 mm term is the length of the series and may not indicate a true cycle. For the RS rhythmites, the interpreted Milankovitch terms (Fig. 3B, inset) are 2220 mm (E = 100 k.y.), 987 mm (O = 39 k.y.), 592 mm (P+ = 20.9 k.y.), and 444 mm (minor precession, P– = 17.5 k.y.), or an average sedimentation rate of 25.3 m/m.y. The absence of a P– term in the IT rhythmites is not surprising, as P– is theoretically much lower magnitude. These rates are somewhat lower than the 75–84 m/m.y. rates estimated by Silva and Azambuja Filho (2005) (also via astronomical calibration) for the Anitápolis rhythmites. The K_Z spectra suggest precession and obliquity forcing of dilution or concentration of magnetic minerals. In the IT spectrum, the peak at 485 mm (11.1 k.y.; Fig. 3A) could be evidence for a slowing of sedimentation upsection, or a half-precession period from tropical insolation (Berger and Loutre, 1997).

The IT ChRM directional spectra (Figs. 3C–3F) have spectral peaks related to precession. IT was relatively close to major glaciers; astronomically forced meltwater inputs may have imposed periodic sediment deposition that generated inclination flattening. The absence of Milankovitch signals in RS ChRM may reflect the low-energy locality far from major input sediment sources.

Both rhythmites have spectral components in millennial-scale bands that are statistically inconsistent with a red noise background. These components are consistent with terms related to millennial climate changes in the late Pleistocene: the 2.4 k.y. harmonic feature, often reported as of heliomagnetic origin (e.g., Clilverd et al., 2003), the ~1.5 k.y. cycle related to D-O events, and 3–8 k.y. Heinrich events. Despite relatively low power, these components are not overtones of low-frequency variations. For example, there is persistent variation through the IT K_z series (Fig. 2A) that completes ~10 cycles/1000 mm; this is a direct observation of the 99 mm component interpreted as a 2.2 k.y. cycle (Fig. 3A).

DISCUSSION

The mechanisms of acquisition of detrital remanent magnetization and postdepositional remanent magnetization are not yet settled (e.g., Shcherbakov and Shcherbakova, 1987; Tauxe et al., 2006). Detrital magnetic minerals tend to align to the geomagnetic field during deposition, and lock in after sediment dewatering and consolidation. Roberts and Winklhofer (2004) suggested postdepositional realignment of magnetic grains, e.g., from meltwater input. Therefore, climatic processes likely influence remanence direction. To search for such an effect in these rhythmites, Franco (2007) compared ChRM series and the maximum axis of anisotropy of magnetic susceptibility ellipsoid tensor (K_1), often considered an important paleocurrent indicator (Liu et al., 2001; Zhu et al., 2006). In the IT rhythmites, superimposition of these records in stereographic and stratigraphic projections reveals a pronounced coherent pattern, suggesting a common environmental control. This supports the idea of ChRM directional data as a paleoclimate proxy.

The spectra are similar for the two rhythmites, despite independent astronomical calibrations, and separation by a distance of ~1000 km and millions of years in time. The results suggest, for both rhythmites, a paleoclimate record with Bond cycles (i.e., D-O and Heinrich events) and an ~2.4 k.y. heliomagnetic signature. Is it possible that Bond cycles and 2.4 k.y. cyclicity are global-scale phenomena that are fixed through geologic time? Eyles et al. (1997) reported ice-rafted layers from the Australian Early Permian analogous to records generated by Heinrich-like events. Milana and Lopez (1998) found 2–3 k.y. cycles in late Paleozoic rhythmites from Río Francia (Argentina) related to rapid glacial advance and retreat processes. Elrick and Hinnov (2007) reported widespread millennial climate variations in North American Paleozoic rhythmites that cannot be explained by thermohaline circulation or restricted to conditions like ice ages.

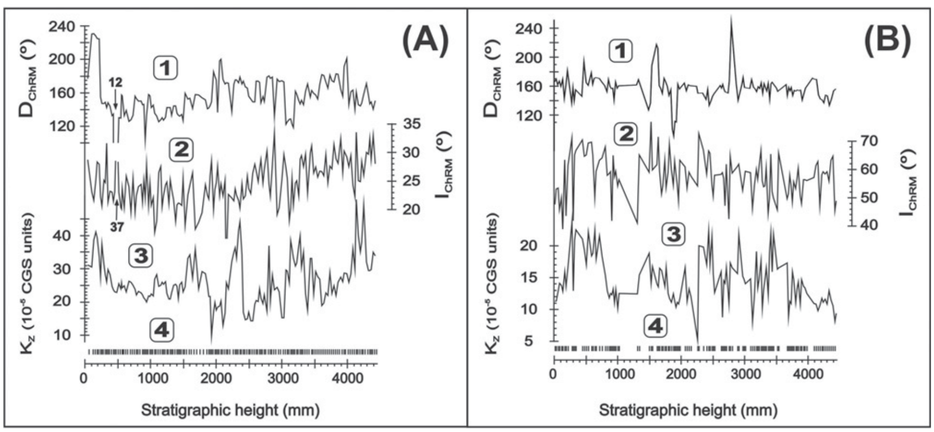

Figure 2. Magnetostratigraphic data series. A: Itu rhythmites. B: Rio do Sul rhythmites. Curves 1, 2, and 3 depict declination (D), inclination (I) of characteristic remanent magnetization (ChRM), and bulk susceptibility (K_z) (CGS—centimeter-gram-second). Curve 4 indicates sample positions of data, and average sample rate of 2.5–3.5 cm.

[1]GSA Data Repository item 2012009, geological setting, methodology for high-resolution magnetostratigraphic investigation, and paleomagnetic and bulk susceptibility (Kz) data sets related to both successions, is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

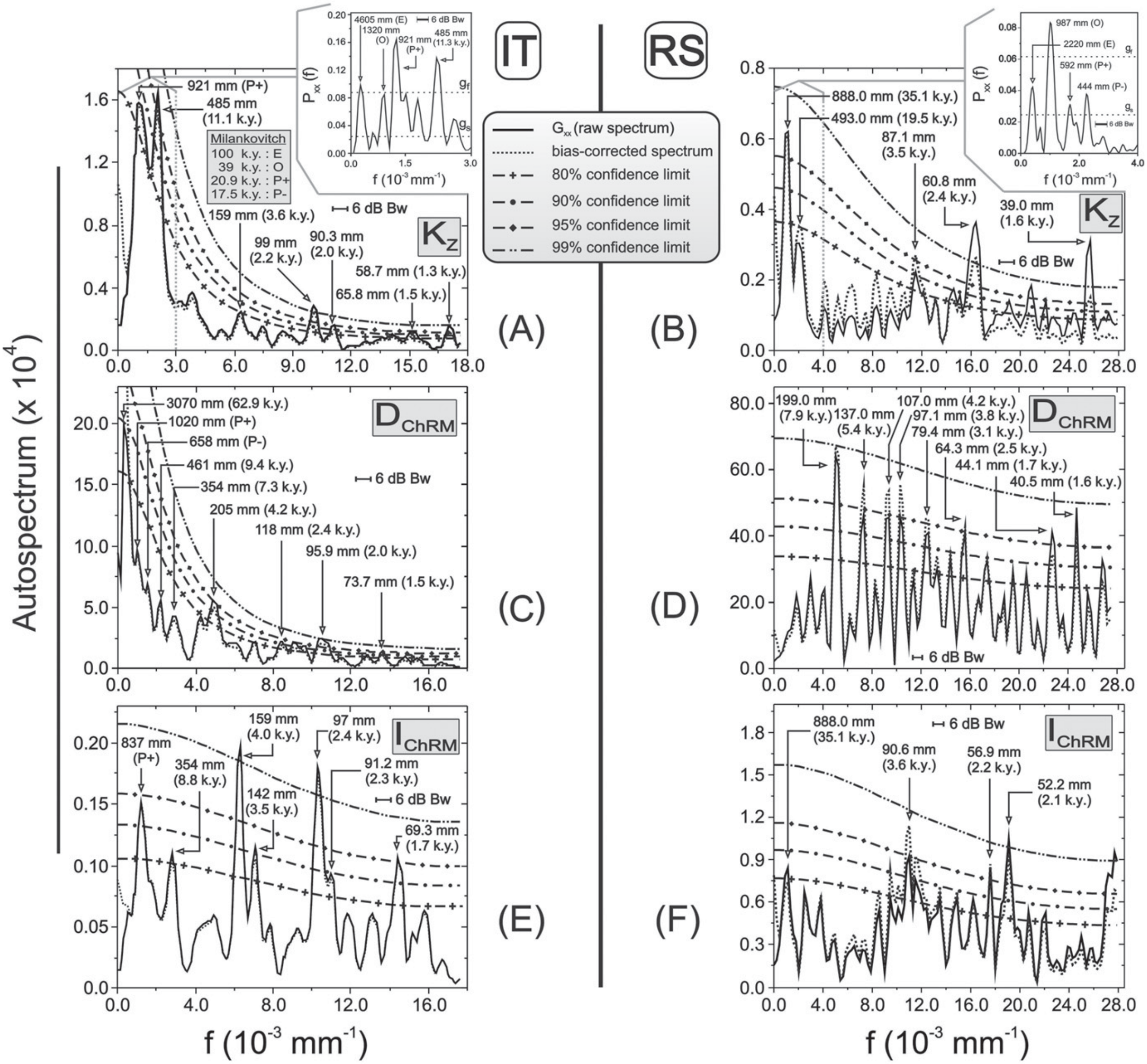

Figure 3. Spectral analysis of bulk susceptibility (K_Z) data series. A: Itu (IT) rhythmites. B: Rio do Sul (RS) rhythmites. Peaks exceeding confidence limits are labeled; period (in k.y.) is also given. In gray legend, Milankovitch components are represented by E (eccentricity), O (obliquity), P+ and P– (major and minor precession); periods are as predicted for Permian (Berger et al., 1992). Insets in A and B are harmonic line spectra of Milankovitch band; dashed lines g_f and g_s are, respectively, 95% significance levels for null hypothesis tests for one (Fisher) or more (Siegel) harmonic components (Schulz and Stattegger, 1997). For alternative red noise test, see footnote 1. C–F: Spectra of magnetic declination (D) and inclination (I) of characteristic remanent magnetization (ChRM) for Itu and Rio do Sul.

These data indicate that millennial-scale climate changes were prevalent during the Permian–Carboniferous ice age, and reinforce hypotheses of a complex interplay among external sources involving solar activity. The Holocene ~2.4 k.y. radiocarbon cycle is linked to solar activity (Clilverd et al., 2003); the origin may be from solar inertial motion (Charvátová, 2000). There is evidence linking ~1.5 k.y. periodicity to solar variability in ^{14}C and ^{10}Be records (van Geel et al., 1999; Vasiliev and Dergachev, 2002; see Muscheler and Beer, 2006, for a counter view); superposition of decadal to centennial solar cycles has also been suggested (Clemens, 2005). Braun et al. (2005) proposed that the regular timing of D-O events could arise from a beating of ~87 yr DeVries and ~210 yr Gleissberg solar cycles, although D-O cycling regularity has now been questioned (Ditlevsen et al., 2007). Milankovitch forcing was shown to generate D-O cycles in a glacial climate system undergoing logistic-delay dynamics (Rial, 2004).

CONCLUSIONS

Two glaciogenic rhythmite sections have been interpreted as records of millennial-scale climate change with spectral components that are remarkably similar to those observed in the last glacial cycle, but from the Permian–Carboniferous glacial age, hundreds of millions of years ago. Our main results are the following.

Rock magnetism analysis indicates that late Permian and early Carboniferous glaciogenic rhythmites from two locations in the IG, southern Brazil, retain primary ChRM and K_Z records, enabling paleoclimate interpretation.

Spectral analysis of ChRM and K_Z series measured along the rhythmites reveals components with frequency ratios suggestive of

Milankovitch (astronomical) forcing in the depositional process.

Time calibration based on the astronomical forcing shows that weaker, but statistically significant, spectral components are present at the millennial scale.

The millennial-scale variations include a 2.4 k.y. cycle reminiscent of the Holocene solar cycle, an ~1.5 k.y. cycling similar to D-O events in the last glacial cycle, and 3–8 k.y. variations that occurred during the last glacial cycle as Heinrich events.

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