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Low-latitude and multiple geomagnetic reversals in the Neoproterozoic Puga cap carbonate, Amazon craton

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ABSTRACT

Palaeomagnetic study of the carbonates that ubiquitously cap glacial deposits may constrain the latitudinal extent of Neoproterozoic glaciations and the duration of the greenhouse recovery. We present the first palaeomagnetic data on the Neoproterozoic cap carbonates covering the Amazon craton, which are folded along the Paraguay Belt. Samples collected at deformed beds along the Paraguay Belt present a single-polarity secondary magnetization acquired by the end of the Brasiliano orogeny (540–520 Ma). In the cratonic area, a dual-polarity component was isolated in dolostones at the base of the sequence. The presence of a stratabound reversal stratigraphy along with high unblocking temperatures strongly suggest that this magnetization is primary. This result implies a low palaeolatitude (22+6/−5°) for the Amazon block just after deposition of Puga diamictites. In addition, the presence of multiple reversals across the first 20 m of the cap carbonate sequence suggests that their sedimentation must have spanned hundreds of thousands of years at least.

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Introduction

The end of the Neoproterozoic is characterized by the occurrence of at least two episodes of widespread glacial deposition at ~740 Ma (Sturtian/Rapitan glaciation) and ~600 Ma (Marinoan/Varanger glaciation). These deposits are commonly capped by carbonate rocks, with strong anomalies in their C isotopic record, marking the sudden end of ice age conditions (Kennedy, 1996). Several models have been developed to explain this peculiar association of ice ages, 'cap carbonates' and isotopic excursions, including the 'snowball Earth' hypothesis (Roberts, 1971; Kirschvink, 1992; Hoffman *et al.*, 1998), which advocates that the planet was entirely covered by ice for millions of years; the rapid unfreezing resulted from ultra-greenhouse events attributed to the build up of volcanic CO_2 during glaciation.

A key aspect of the Neoproterozoic ice ages is the vast extent of their ice caps into tropical latitudes. However, this assumption is based on few reliable palaeomagnetic data, comprising only two well-studied units per glacial interval (Meert and Van der Voo, 1994; Evans, 2000). The best palaeomagnetic evidence for low-latitude glaciation comes from Marinoan deposits in Australia, for which several stability tests, including fold and reversals tests, attest to the primary nature of their remanent magnetization (Schmidt and Williams, 1995; Sohl *et al.*, 1999). Palaeomagnetic data also suggest low-latitude sedimentation for the Rapitan Group in North America (Park, 1997) and the Walsh tillite cap carbonates in Australia (Li, 2000). Moderate latitudes are inferred for the type Varanger sequences of Scandinavia (Torsvik *et al.*, 1995) and for the 'Rapitan/Sturtian' glacial sediments of South China (Zhang and Piper, 1997; Evans *et al.*, 2000).

The palaeogeography at the time of these glaciations is also controversial owing to poor palaeomagnetic coverage (Meert and Powell, 2001), hence preventing global correlations and testing of different geodynamic and palaeoclimatic scenarios. In this respect it is worth mentioning that quantitative models that account for the initiation of such extreme Neoproterozoic ice ages rely on the distribution of most landmasses at low latitudes (Schrag *et al.*, 2002; Godderis *et al.*, 2003).

Another key aspect of the snowball Earth scenario is the rapid carbonate precipitation in the aftermath of periods of glaciation. According to the hypothesis initially forwarded by Hoffman *et al.* (1998) the cap carbonates would precipitate at extremely fast rates of ~40 cm yr^{-1} just after a prolonged glaciation. In this way, a 20-m-thick cap dolostone would precipitate in ~50 years. More recently, Kennedy *et al.* (2001) and Higgins and Schrag (2003) have suggested slower but still rapid depositional rates, implying that the cap dolostones would be deposited in ~10^4 years.

The large Amazon craton stands as one of the units for which no Neoproterozoic palaeomagnetic data are available. Owing to their similar geological evolution, it is typically placed against the south-eastern margin of Laurentia in Neoproterozoic reconstructions (e.g. Weil *et al.*, 1998), from which it is supposed to have rifted away at around 570 Ma (Cawood *et al.*, 2001). Glacial deposits covered by carbonates are mapped along the south-eastern margin of the Amazon craton and inside the 540–520 Ma Paraguay fold belt (Fig. 1A). These deposits comprise a particularly unusual association of stratified Fe–Mn ores at the base and a biota correlative with the Ediacaran fauna in the overlying carbonate rocks (Trompette *et al.*, 1998). In this paper we report the first palaeomagnetic results obtained on the carbonates (Araras Group) that cap the glacial sediments of the Puga Formation. Stability tests were performed to ascertain the

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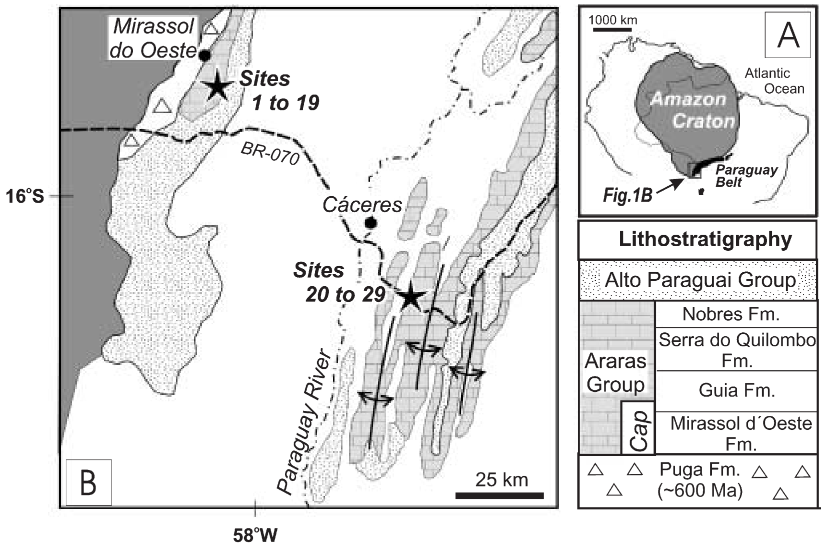

Fig. 1 (A) Amazon craton and Paraguay belt. (B) Location of sampled sites (stars) at undeformed (sites 1–19) and folded (sites 20–29) sectors.

primary nature of the remanence acquired by these rocks. These results, which give the first palaeomagnetic constraints on the position of the Amazon craton by the end of the Neoproterozoic, are used to infer the palaeolatitude of the underlying glacial deposits, and to estimate the duration of cap carbonate sedimentation.

Puga cap carbonate

The Puga Formation is discontinuously exposed at the south-eastern margin of the Amazon Craton. It comprises hundreds of metres of mainly pebbly siltstone and diamictites, with clasts from the gneissic basement, deposited in a glacio-marine environment (Alvarenga and Trompette, 1992). These rocks are overlain by carbonate rocks of the Araras Group. On the craton, the contact between these units crops out at the Mirassol d'Oeste quarry (Fig. 1B), where typical cap carbonates occur as subhorizontal, unmetamorphosed beds, dipping no more than 3° NNW. To the east and south-west, the Araras Group and the Puga Formation are folded within the northern segment of the Paraguay Belt (Fig. 1B). These units are covered by the siliciclastic deposits of the Alto Paraguai Group.

The Puga cap carbonate shows depleted $\delta^{13}C$ values, anomalous facies and a subwavebase depositional setting (Nogueira *et al.*, 2003). It consists of two units (Fig. 2): (i) a cap dolomite, composed of pinkish dolomudstone with fenestral microbialite laminites with tubes, planar lamination with fenestral porosity disrupted and up-thrust in the form of tepees; and (ii) a cap limestone cementstone, composed of bituminous lime mudstones with terrigenous grains, and subordinate shales, with crust and aragonite pseudomorphic crystal fans. Four discontinuity surfaces (DS) are recognized at the Mirassol d'Oeste section (Fig. 2). DS1 corresponds to the basal contact of the cap dolostone, with soft-deformed sediments. DS2 marks the contact between fenestral microbialite laminites and laminated dolostone with tepees. DS3 is the contact between the cap dolomite and the cap limestone cementstone. DS4 separates the sediments affected by synsedimentary deformation from the undeformed overlying beds.

Direct radiometric ages for Puga and Araras units are not available. K–Ar and Rb–Sr dating of a post-tectonic granite that intrudes the sediments of the Paraguay Belt gives a minimum depositional age of 504 Ma (Almeida and Mantovani, 1975). In addition, the presence of *Cloudina* and other metazoans contemporaneous with the Ediacaran fauna in the upper carbonates (Gaucher *et al.*, 2003) suggests a depositional age probably older than 560 Ma (Narbonne and Gehling, 2003). The sedimentation age for the basal carbonates is constrained by the comparison of their isotopic values to reference curves. Most $\delta^{13}C$ values are around $-5‰$, approaching $-9‰$ at key surfaces DS1, DS2 and DS3 (Fig. 2). These values are typical of Neoproterozoic post-glacial deposits (Jacobsen and Kaufman, 1999). The $^{87}Sr/^{86}Sr$ ratios are above 0.7074, and strong shifts up to 0.7113 are observed close to the mudstone-capped key surface DS3 that separates dolostones and limestones (Fig. 2). The presence of $^{87}Sr/^{86}Sr$ values up to 0.7081 at undisturbed beds allows us to correlate the Puga cap carbonates with the post-Marinoan/Varanger units, with ages around 600–580 Ma (Jacobsen and Kaufman, 1999).

Our palaeomagnetic sampling covered the lower ~250 m of the Araras Group, comprising the subhorizontal beds covering the craton and the folded strata at the Paraguay Belt (Fig. 1B). Sampling spacing varied from tens of centimetres to metres across the succession at the Mirassol d'Oeste quarry (sites 1–19). Discontinuity surfaces and beds with synsedimentary deformation were avoided (Fig. 2). At the Cáceres outcrops (sites 20–29), sampling sites are metres to tens of metres apart. Sites 20–26 are subvertical beds, and sites 27–29 correspond to inclined beds, dipping to the north (site 27) or to the east (sites 28 and 29).

Palaeomagnetism

The samples carry a weak natural remanent magnetization (NRM) of about 10^{-4} A m^{-1} S.I. In order to reduce viscous overprints on the characteristic magnetization, samples were first stored in a low-field chamber for 3 months. We then proceeded with alternating field (AF) and thermal treatments using 16–20 progressive steps. Measurements were performed in a three-axis 2G-cryogenic magnetometer, housed in a magnetically shielded room (ambient field < 1000 nT). Magnetic susceptibility was measured after each step to control mineralogical changes. Magnetic components were identified in orthogonal plots, and calculated by least-squares fitting. Vector mean directions and palaeomagnetic poles

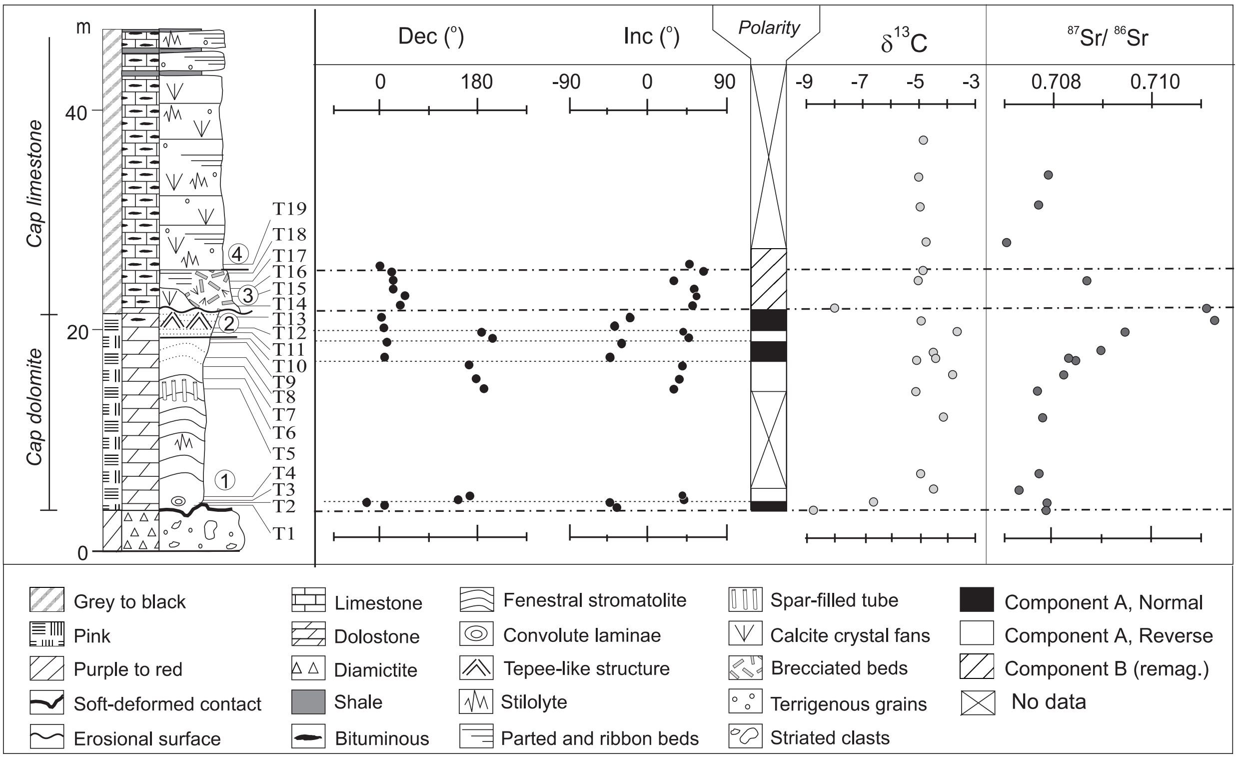

Fig. 2 Stratigraphy at the Mirassol d'Oeste quarry and measured section variation of magnetic and isotopic data. T1–T19 indicate the palaeomagnetic sampling sites. Dashed lines and encircled numbers correspond to discontinuity surfaces DS1 to DS4. Dotted lines delimit the polarity intervals. Isotopic data after Nogueira *et al.* (2003).

were obtained by Fisherian statistics for both individual samples and sites.

Thermal demagnetization was more effective in isolating the characteristic magnetizations. From the 254 analysed samples, 134 presented reliable demagnetization patterns; the remaining 129 samples did not give coherent demagnetization patterns and yielded no useful information. The high-temperature components cluster into groups A and B (Figs 3 and 4).

Group A directions were identified for 13 sites of dolostones from the Mirassol d'Oeste quarry (sites 1–13), starting from the contact with the Puga diamictites (DS1; Fig. 2). Orthogonal plots for samples with component A show very stable demagnetization patterns in spite of their weak NRM. For most samples, remanence progressively decreases down to values at the noise level of our cryogenic magnetometer after heating at 520 °C (Fig. 3A). The resulting directions are either negative/northward directed or positive/southward directed. They correspond, respectively, to normal (AN) and reverse (AR) polarities, and pass a reversals test (McFadden and McElhinny, 1990) at 95% of confidence for both sample-based and site-based means (Table 1). The presence of five

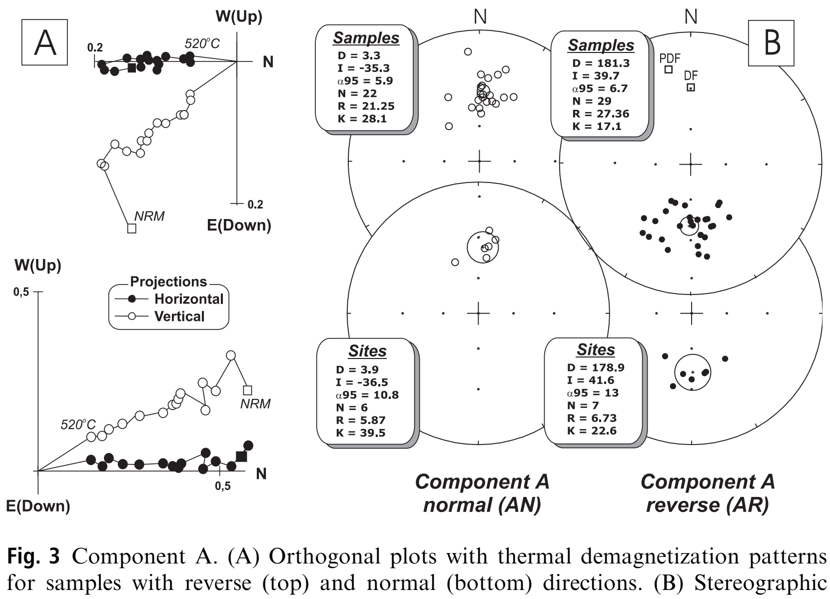

Fig. 3 Component A. (A) Orthogonal plots with thermal demagnetization patterns for samples with reverse (top) and normal (bottom) directions. (B) Stereographic projections of sample-based and site-based means; closed (open) symbols indicate downward (upward) directions. Boxes show mean directions and Fisherian statistical parameters. PDF indicates the present-day field and DF the dipolar field.

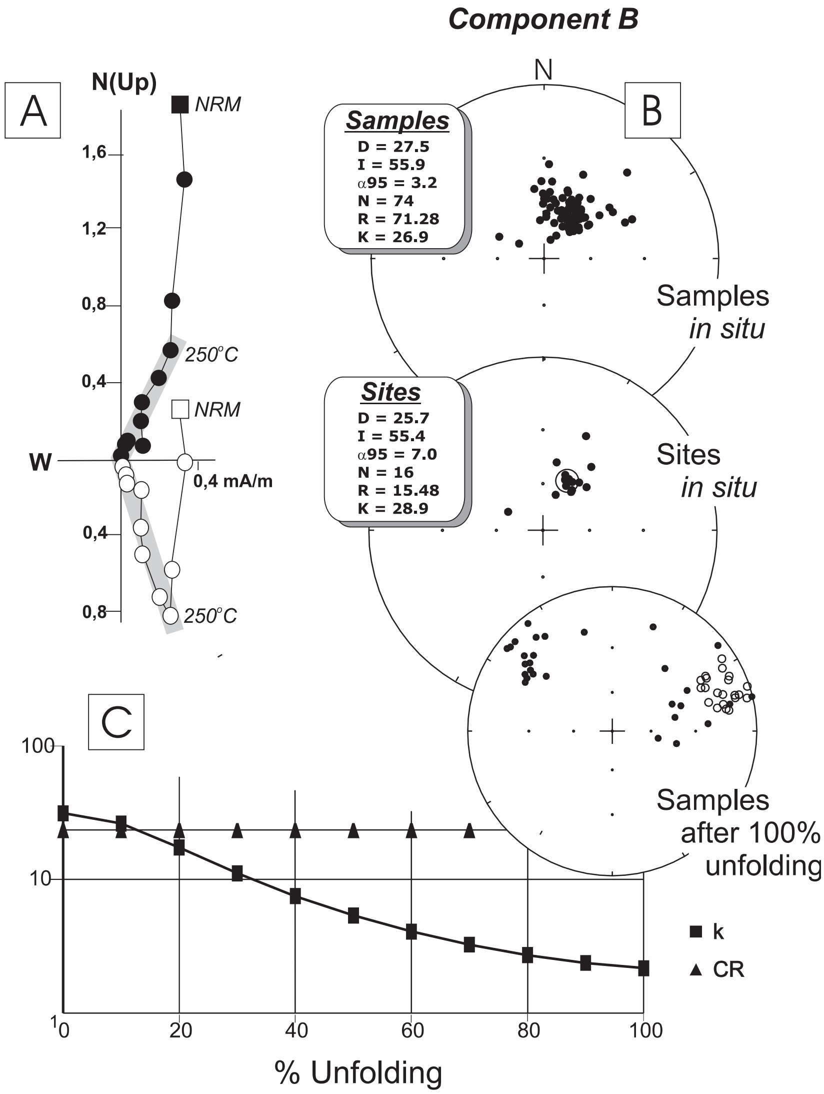

Fig. 4 Component B. (A) Orthogonal plots with thermal demagnetization pattern; component B is highlighted in grey. (B) Stereographic projections of sample-based and site-based means, *in situ* and after 100% unfolding. (C) A continuous decrease in *k*-values with percentage unfolding gives a negative fold test (McElhinny, 1964).

distinct polarity intervals (Fig. 2), and the high unblocking temperatures, strongly suggests an early magnetization acquisition by these rocks, even if it lies close to the present-day dipolar field.

Group B directions were found at six sites from the Mirassol d'Oeste quarry (sites 14–19). The transition between group A and group B directions in the Mirassol d'Oeste quarry is sharp and coincides with the DS3 (Fig. 2). Component B directions are positive, and plunge steeply to the north-east (Fig. 4A,B). Similar directions were found upsection along the limbs of folds at the Cáceres region within the Paraguay Belt (sites 20–29; Fig. 1). Before tilt correction, results from folded and undeformed sectors show a strong cluster in the stereographic projections (Fig. 4B). Accordingly, they fail a fold test (Fig. 4C), indicating that the component B is an overprint younger than the regional folding of the Paraguay Belt. The corresponding pole overlaps the palaeomagnetic poles obtained for remagnetized carbonates from the São Francisco basin of eastern Brazil (see D'Agrella-Filho *et al*., 2000). After rotation of South America toward Africa, these poles lie close to the ~520 Ma sector of the apparent polar wander path for Gondwana (Meert, 2003). Thus, a Cambrian age is inferred for the palaeomagnetic reset, also giving an upper age limit of ~520 Ma for the deformation within the Paraguay Belt.

Discussion

As carbonate rocks conformably overlie the Puga diamictites, with no significant hiatus between glacial sedimentation and precipitation of the basal dolostones (Nogueira *et al*., 2003), our palaeomagnetic results from the cap carbonates can reasonably be used to constrain the palaeolatitude of Puga glaciation. Palaeolatitudes derived from the component A are within $22+6/-5°$ (Table 1). Hence, sedimentation of Puga glacial rocks must have occurred at low latitudes. In addition, if we assume that the age of the B component is ~520 Ma (see above), we can track the position of the Amazon plate between the end of the Neoproterozoic and the beginning of the Cambrian. According to these results (Table 1), Amazonia has drifted to the south between 580 and 520 Ma, moving with a latitudinal speed of ~0.2° Ma^{-1}. At ~520 Ma it would be placed at latitudes within $36+7/-6°$.

Additional constraints on the drift history are derived from the sedimentary record. The Araras Group is a more than 700-m-thick platform carbonate deposit, thus requiring a long-standing regime of warm temperatures at the south-west margin of the Amazon craton. The presence of aragonite-pseudomorph crystal fans and crusts directly precipitated on the seafloor is striking evidence for the anomalously high temperatures at the end of the Neoproterozoic ice ages (Sumner, 2002). In the Puga cap carbonates these typical associations are replaced upsection by other strata with structures that also indicate warm conditions (Nogueira and Riccomini, 2001). Metre-scale shallowing/brining-up cycles of arid tidal flat and sabkha occur at the top of the sequence, presenting fenestral and birdseye laminations, desiccation cracks, rip-up clasts, pseudomorphs of nodular gypsum and tepee structures (e.g.

Table 1 Mean directions and palaeomagnetic poles

Magnetic components	Mean directions						Palaeomagnetic Poles					
	n	D (°)	I (°)	α_{95} (°)	R	k	Long. (°)	Lat. (°)	dp	dm	Plat. (°)	Error(+/−)
Sample-mean directions												
AN	22	3.3	−35.3	5.9	21.3	28.1	267.4	−84.5	3.9	6.8	−19.5	3.8/4.1
AR	29	181.3	39.7	6.7	27.4	17.1	292.9	−82.4	4.8	8.0	22.5	5.2/4.5
A (N + R)	51	182.2	37.8	4.5	48.6	20.6	283.7	−83.5	3.1	5.3	21.2	3.3/3.0
B	74	27.5	55.9	3.2	71.3	26.9	326.6	33.1	3.3	4.6	36.4	3.5/3.1
Site-mean directions												
AN	6	3.9	−36.5	10.8	5.9	39.5	267.6	−83.5	7.4	12.6	−20.3	6.8/8.2
AR	7	178.9	41.6	13.0	6.7	22.6	308.4	−81.0	9.7	15.9	23.9	11.2/8.7
A (N + R)	13	181.3	39.3	7.8	12.6	29.1	292.6	−82.6	5.6	9.3	22.3	6.0/5.3
B	16	25.7	55.4	7.0	15.5	28.9	326.9	33.6	7.1	10.0	35.9	7.8/6.5

n is the number of sites. Mean directions are given by their declination (D) and inclination (I), and palaeomagnetic poles by their latitude (Lat.) and longitude (Long.). R, α_{95} and k are Fisherian statistical parameters. Plat. is the palaeolatitude of the studied region by the time of remanence acquisition.
The pole A (N + R) satisfies five out of the seven reliability criteria defined by Van der Voo (1990), including criteria: (2) sufficient number of samples and adequate statistical precision, (3) adequate demagnetization, (5) structural control and tectonic coherence with the craton, (6) the presence of reversals and (7) no resemblance to younger palaeopoles.

Kendall and Warren, 1987). Just below, hummocky cross-stratification is common at the dolostones of the upper Serra do Quilombo Formation, implying that the area was affected by tropical storms (Duke *et al.*, 1991). All these facies associations are accompanied by the recovery of $\delta^{13}C$ to positive values (Nogueira, 2003), suggesting that the Amazon craton did not attain high latitudes during sedimentation of the Araras carbonates even after the proposed post-glacial ultra-greenhouse conditions.

Finally, it is worth noting that five polarity reversals were identified in the first 20 m of the Puga cap carbonate succession (Fig. 2). The presence of several polarities along Marinoan glacial successions of Australia, considered to be correlatives of the Puga deposits, has been used to infer a time-span of hundreds of thousands to millions of years for glacial deposition (Sohl *et al.*, 1999). The same reasoning would lead us to suggest that deposition of Puga cap carbonates spanned an interval much larger than the hypothesized rapid carbonate deposition after Neoproterozoic glaciations (e.g. Hoffman *et al.*, 1998). Even if the magnetic field has experienced a high frequency of reversals by the end of the Neoproterozoic, similar to the Middle Cambrian mode described by Pavlov and Gallet (2001), the sedimentation of the first 20 m of the Araras cap carbonate sequence would span hundreds of thousands of years at least. The record of a strat-abound reversals stratigraphy opens the possibility for fine correlations between cap carbonate sequences through magnetostratigraphy, and as a consequence the possibility of testing the contemporaneity of these successions predicted by the snowball Earth hypothesis. Much additional work is required to define a detailed reversals chart for this time period.

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