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New late Proterozoic paleomagnetic pole for the Rio de la Plata craton: Implications for Gondwana

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Abstract

Major uncertainties remain on the precise kinematic and temporal aspects of Gondwana assembly. In order to provide new constraints on them, a paleomagnetic study was carried out on the Ediacaran succession of red claystones exposed in Sierra de los Barrientos (37.8°S, 59.0°W), Buenos Aires province, Argentina. This succesion belongs to the late Proterozoic–early Paleozoic sedimentary cover of the Rio de la Plata craton. Sixty-two oriented samples from 13 sites were submitted to standard stepwise demagnetization procedures yielding a characteristic remanence carried by hematite. A primary origin for the remanence is suggested by the apparent recording of secular variation along the stratigraphic column including a reversal of the earth magnetic field and an improvement in clustering of mean site directions after application of bedding corrections, although the latter is not statistically significant. Since the study samples show a significant anisotropy of magnetic susceptibility (AMS) degree (P up to 1.2) and an ellipsoid shape compatible with significant compaction during diagenesis, remanence inclination shallowing was investigated through oriented isothermal remanent magnetization (IRM) acquisition and demagnetization experiments. These permitted to confirm significant inclination shallowing and to compute a correction factor that was applied to the mean site directions producing a significantly further improvement in the statistical parameters. A paleomagnetic pole was computed for the Los Barrientos claystones at 15.1°S, 252.6°E, dp: 10.9°, dm: 14.2°. When rotated into a Gondwana framework, this new pole agrees with previous poles of ca. 550 Ma from several Gondwanan cratons, allowing the construction of a single APWP for the whole of Gondwana since that time, and suggesting that by ca. 550 Ma Gondwana was already assembled or in the final stages of that process.

Keywords: Paleomagnetism; Gondwana; Precambrian; South America; Rio de la Plata craton

1. Introduction

The global paleogeographic evolution in the latest Proterozoic is dominated by the assembly of the Gondwana supercontinent (e.g. Rogers et al., 1995). Despite significant progress in the last decade, a reliable picture of the whole process of its assembly, including time of accretion and kinematic history of each Gondwana block, is still elusive. One of the main reasons for this is the lack of a robust paleomagnetic database for the large Gondwanan continental blocks (e.g. Meert and Torsvik, 2003).

The Rio de la Plata craton (RP, Fig. 1) is one of the crustal blocks with Archean and/or Paleoproterozoic basement, that integrated Western Gondwana (Dalla Salda et al., 1988; Cingolani and Dalla Salda, 2000). Its paleogeographic evolution and relationships to neighbouring blocks during Gondwana assembly is controversial and very poorly known (for a recent review of geologic evidence see Cordani et al., 2000). Its disputed

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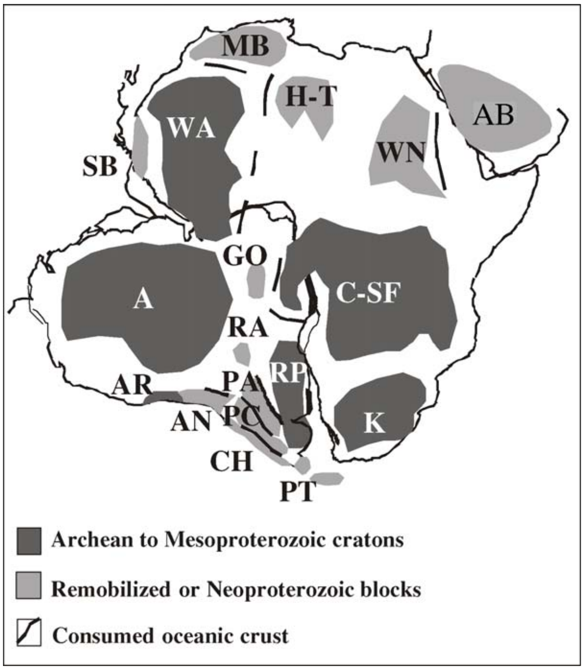

Fig. 1. Main tectonic domains of Western Gondwana in the Neoproterozoic. A: Amazonia, AB: Central Arabia, AN: Antofalla, AR: Arequipa, CH: Chilenia, C–SF: Congo–Sao Francisco, GO: Goias, H–T: Hoggar–Tibesti, K: Kalahari, MB: Moroccan block, PA: Pampia, PC: Precordillera, PT: Patagonian–Malvinas block, RA: Rio Apa, RP: Rio de la Plata, SB: Senegalese block, WA: West Africa, WN: West Nile. Taken from Sánchez Bettucci and Rapalini (2002).

relations with the Kalahari, Congo–Sao Francisco, Amazonia and Pampia blocks make RP a likely key player in unraveling the processes that led to the formation of the Gondwana supercontinent.

Recent paleomagnetic results (Sánchez Bettucci and Rapalini, 2002) started to fill a vacuum of data for RP in the late Proterozoic. These results gave further support to a latest Proterozoic (ca. 550 Ma) age for amalgamation of the major cratonic blocks of Gondwana. The available paleomagnetic poles from some of these blocks were interpreted by Sánchez Bettucci and Rapalini (2002) in terms of a model of assembly of Gondwana that involved the collision of three major continents (western, central and eastern Gondwana) by the end of the Proterozoic. However, several different models have also been postulated recently (e.g. Meert, 2001; Powell and Pisarevsky, 2002). Other authors (e.g. Powell, 1995) proposed that a short-lived supercontinent located in the southern hemisphere, called Pannotia, and involving most land masses of the earth, existed in the latest Proterozoic.

In order to reduce the uncertainties concerning the assembly of Gondwana, a project to obtain reliable paleomagnetic poles for RP in the late Proterozoic is under way by several institutions led by the Instituto de Geofísica Daniel Valencio of the Universidad de Buenos Aires. As part of these studies, a paleomagnetic study was carried out in a succession of red claystones of Ediacaran age exposed in a quarry at the Sierra de los Barrientos (province of Buenos Aires, Argentina, Fig. 2). Results of this study as well as its implications for current models of Gondwana assembly are presented.

2. Geology and sampling

The Rio de la Plata craton extends from the southern states of Brazil (e.g. Rio Grande do Sul) to the south of the province of Buenos Aires, in Argentina (Figs. 1 and 2). Exposures in Argentina are mainly restricted to the Tandilia system (Fig. 2), which constitutes a 300 km long strip of outcrops of Paleoproterozoic

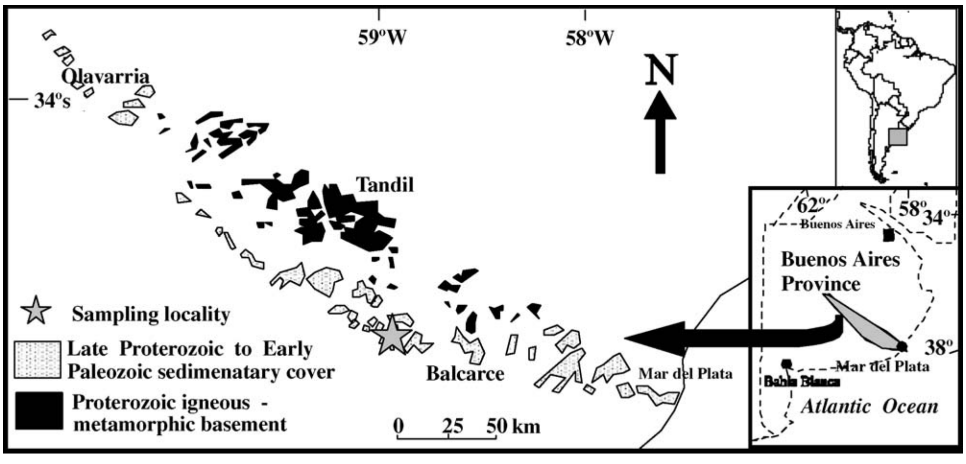

Fig. 2. Geological sketch of the Tandilia system with distribution of the late Proterozoic–early Paleozoic sedimentary cover and location of the sampling locality at Sierra de los Barrientos. Modified from Dalla Salda et al. (1988).

igneous and metamorphic basement rocks (Buenos Aires complex, Cingolani and Dalla Salda, 2000) surrounded to the west, south and east by a thin sedimentary cover of late Proterozoic to early Paleozoic age (the Sierras Bayas Group, the Cerro Negro Fm. and the Balcarce Fm., Cingolani and Dalla Salda, 2000). Some isolated outcrops of late Proterozoic igneous rocks in the Ventana System, 200 km SW from Tandilia, are generally considered as the southernmost exposures of the Rio de la Plata craton basement, although the diagnostic early Proterozoic rocks are not known here.

The study section is exposed in a quarry at Sierra de los Barrientos (37.8°S, 59.0°W, Fig. 2), in the province of Buenos Aires, Argentina. It consists of nearly 20 m of homogeneous, mainly subhorizontal red claystones. This succession lay under several meters of greenish to brownish siltstones and sandstones that mark a transition to the thick beds of coarse quartzite of the Cambrian–Ordovician Balcarce Formation (e.g. Dalla Salda and Iñiguez, 1979; Poiré, 2002). A few hundred meters away from the sampled section a diabasic sill that intrudes the Balcarce Formation crops out. The sill has been dated as early Ordovician (K–Ar whole rock, 498 ± 25, 495 ± 20, 492 ± 20 Ma; Rapela et al., 1974). A precise age for the red claystones at Sierra de los Barrientos is not yet available. However, an Ediacaran age is considered as the most likely. These sediments are generally considered as representative of the Cerro Negro Formation, which has been defined in the northwest extreme of the Tandilia system close to the town of Olavarria. Similar clay composition between these rocks and the red claystones of Los Barrientos, inferred from X-ray analysis (see below) confirms this correlation. The Cerro Negro Formation is composed by more than 100 m of claystones and heterolitic fine-grained sandstones and has been assigned to the Ediacaran (e.g. Cingolani et al., 1991; Poiré, 2002). This age is based on stratigraphic considerations, as this is the top unit of the late Proterozoic succession exposed in the Sierras Bayas area, separated by a marked erosional unconformity from the limestones, claystones and quartzites of the Sierras Bayas Group (Poiré et al., 2001). Ages for this group range from around 900 to 700 Ma based upon Rb/Sr dates on diagenetic minerals in limestones (Cingolani and Bonhommé, 1982), as well as ichnofaunas and stromatolite structures (Poiré, 2002). The Ediacaran age for the studied sediments is confirmed by a radimetric study performed by Bonhomme and Cingolani (1980) on clay minerals from the sequence (also assigned to the Cerro Negro Formation) exposed at the nearby San Manuel locality. These results gave a mean age of 600 Ma for clays which are interpreted as detrital and therefore give a maximum possible age for the succession. The Los Barrientos sediments have also been considered as part of the Las Aguilas Fm (Zalba et al., 1988) exposed in the Barker region and assigned to the Ediacaran. X-ray analysis presented below indicate that illite is the dominant clay fraction in the Sierras de los Barrientos succession, which is identical to the Cerro Negro clays but differ from the Las Aguilas mineralogy in which pyrophyllite has been found in significant proportions. Considering all this, the age of the studied succession can be considered as approximately 550 ± 50 Ma.

Sixty-two oriented samples distributed into 13 sites (4–7 samples per site) were collected with a portable gas-powered drilling machine from the succession of red claystones exposed in the quarry at Los Barrientos. Samples were oriented by means of sun and magnetic compasses and inclinometer. No significant declination magnetic anomaly was observed. Sites were distributed along most of the exposed succession and separation between sites ranged from 0.3 to 4.5 m. Two different types of sites were defined. At some sites samples were all collected at the same stratigraphic level within ±0.02 m. At other sites samples were located in two parallel levels separated by 0.3–0.5 m. These were considered as composite sites and labelled as A and B (see Table 1). The succession investigated is sub-horizontal, with actual dips less than 2° that are interpreted as original paleohorizontal or compaction induced. Sites 18, 19 and 21 were collected from an area tectonically disturbed by an open and local fold with an approximate wave length of 10 m. Age of folding is possibly pre-Ordovician, as the quartzite beds of the Balcarce Fm. are not affected by any tectonic disturbance. Late Proterozoic folding has been reported affecting the Sierras Bayas Group in Olavarría (Massabie and Nestiero, 2005). However, the small scale of folding observed at Sierra de los Barrientos and the rheologic contrast between the sampled claystone and the quartzite do not permit to completely rule out a more recent folding affecting exclusively the studied section.

3. Paleomagnetic study

Samples were sliced into two or three standard paleomagnetic specimens (2.54 cm in diameter, 2.2 cm high). Two to four specimens per site were submitted to a pilot standard stepwise demagnetization procedure. AF demagnetization (applied at least to one specimen per site) was unsuccessful to demagnetize the samples. Therefore, all remaining specimens (at least one per sample) were submitted to stepwise thermal treatment. Typical demagnetization steps were as follows: 100, 150, 200, 250, 300, 350, 400, 450, 500, 550, 590, 620, 645,

Table 1
Mean site characteristic remanence directions for the Los Barrientos claystones

Site	Dec (°)	Inc (°)	α_{95} (°)	κ	n	Bedding		Dec[2] (°)	Inc[2] (°)	F	Dec[3] (°)	Inc[3] (°)
						St.	Dip					
LB13-A	114.8	−21.0	2.8	1059	4	0	0	114.8	−21.0	2.03	114.8	−37.9
LB13-B	93.8	−35.3	2.6	1190	4	0	0	93.8	−35.3	2.03	93.8	−55.2
LB14-A	120.9	−37.8	7.9	92	5	0	0	120.9	−37.8	1.44	120.9	−48.2
LB14-B	106.8	−53.3	14.3	74	3	0	0	106.8	−53.3	1.44	106.8	−62.6
LB15-A	102.9	−46.5	4.4	301	5	0	0	102.9	−46.5	1.44	102.9	−56.6
LB15-B	102.2	−37.9	2.7	1154	4	0	0	102.2	−37.9	1.44	102.2	−48.3
LB16-A	126.4	−70.1	6.3	147	5	0	0	126.4	−70.1	1.72	126.4	−78.1
LB16-B	123.9	−52.2	16.9	53	3	0	0	123.9	−52.2	1.72	123.9	−65.7
LB18	67.4	−41.0	10.1	37	7	23	13.5	56.8	−49.6	1.48	56.8	−60.0
LB19	61.8	−4.9	11.2	30	7	331	33.3	62.0	−38.2	1.93	62.0	−56.6
LB20a*	316.8	4.2	13.2	50	4	0	0	316.8	4.2	1.18	316.8	4.9
LB20b	333.2	54.9	1.9	2252	4	0	0	333.2	54.9	1.18	333.2	59.2
LB21	116.8	−68.4	7.5	67	7	148	15.0	94.5	−58.1	1.94	94.5	−72.2
Mean (1)	103.9	−46.4	14.3	10	12							
Mean (2)	103.5	−49.0	12.0	14	12							
Mean (3)	104.5	−60.8	9.3	23	12							

Dec: declination; Inc: inclination; α_{95} and κ: Fisherian statistical parameters; n: number of samples used to compute mean; St: strike (right-hand rule); Dec^2 and Inc^2: Dec and Inc after bedding correction; Dec^3 and Inc^3: Dec and Inc after correction for compaction. F: mean site remanence correction factor computed from the IRM acquisition and demagnetization experiments. More references in the text. Paleomagnetic pole (LB): 8.4°S, 242.5°E, dp: 11.0°, dm: 16.4° (after correction for bedding). Paleomagnetic Pole (LB): 15.1°S, 252.6°E, dp: 10.9°, dm: 14.2° (after correction for bedding and compaction).

* Site excluded in computing the mean direction.

670, 685, 695 and 700 °C. After each demagnetization step, bulk suceptibility was monitored with an MS-2 Bartington susceptibility meter, in order to check possible mineral changes of the magnetic fraction due to laboratory heating. Samples were measured with either a DC-SQUIDS 2G cryogenic magnetometer or a spinner Schonstedt SSM-2A magnetometer. Thermal demagnetization was performed with a dual chamber oven (ASC TD-48) with internal fields lower than 10 nT. All samples presented high stability of magnetization (Fig. 3) with unblocking temperatures generally over 650 °C indicative of hematite as the single magnetic carrier. This is also consistent with failure of AF demagnetization and is supported by rock magnetic experiments and X-ray mineralogical determinations (see below). Magnetic components were determined by principal component analysis (Kirschvink, 1980). Only MAD <14° were accepted, although 94% of components were determined with MAD <10°.

Within-site consistency of characteristic remanence directions is high for all sites (see Table 1). A primary remanence, probably acquired during first stages of diagenesis, is interpreted for the studied samples, based upon: (i) apparent recording of paleosecular variation along the stratigraphic column, including the recording of a reversal of the earth magnetic field near the top (sites 19, 20A and 20B, Fig. 4), with a transitional direction between both polarity states (site 20A); (ii) an improvement of clustering of directions after application of bedding correction (kappa increases from 10.1 to 13.4, and α_{95} decreases from 14.3° to 12.3°) which suggests that remanence was acquired before folding (pre-Ordovician?), although the fold-test is not significant at a 95% confidence level (McElhinny, 1964; McFadden, 1990) due to the fact that most sites are subhorizontal; (iii) compaction-induced shallowing of remanence inclination as described below, which suggests acquisition of remanence early in the diagenetic process; (iv) lack of resemblance of the isolated site mean direction to any Phanerozoic reference direction for South America (McElhinny and McFadden, 2000). A mean of bedding corrected site remanence directions (excluding site 20A) yields an average direction at Dec: 103.5°, Inc: −49.0°, $N = 12$ sites, $\alpha_{95} = 12°$.

4. Magnetic mineralogy, AMS, IRM and remanence correction

As part of studies designed to characterize better the magnetic mineralogy of the Los Barrientos claystones, hysteresis loops were performed at the paleomagnetic laboratory of the Instituto de Geofísica at the Univer-

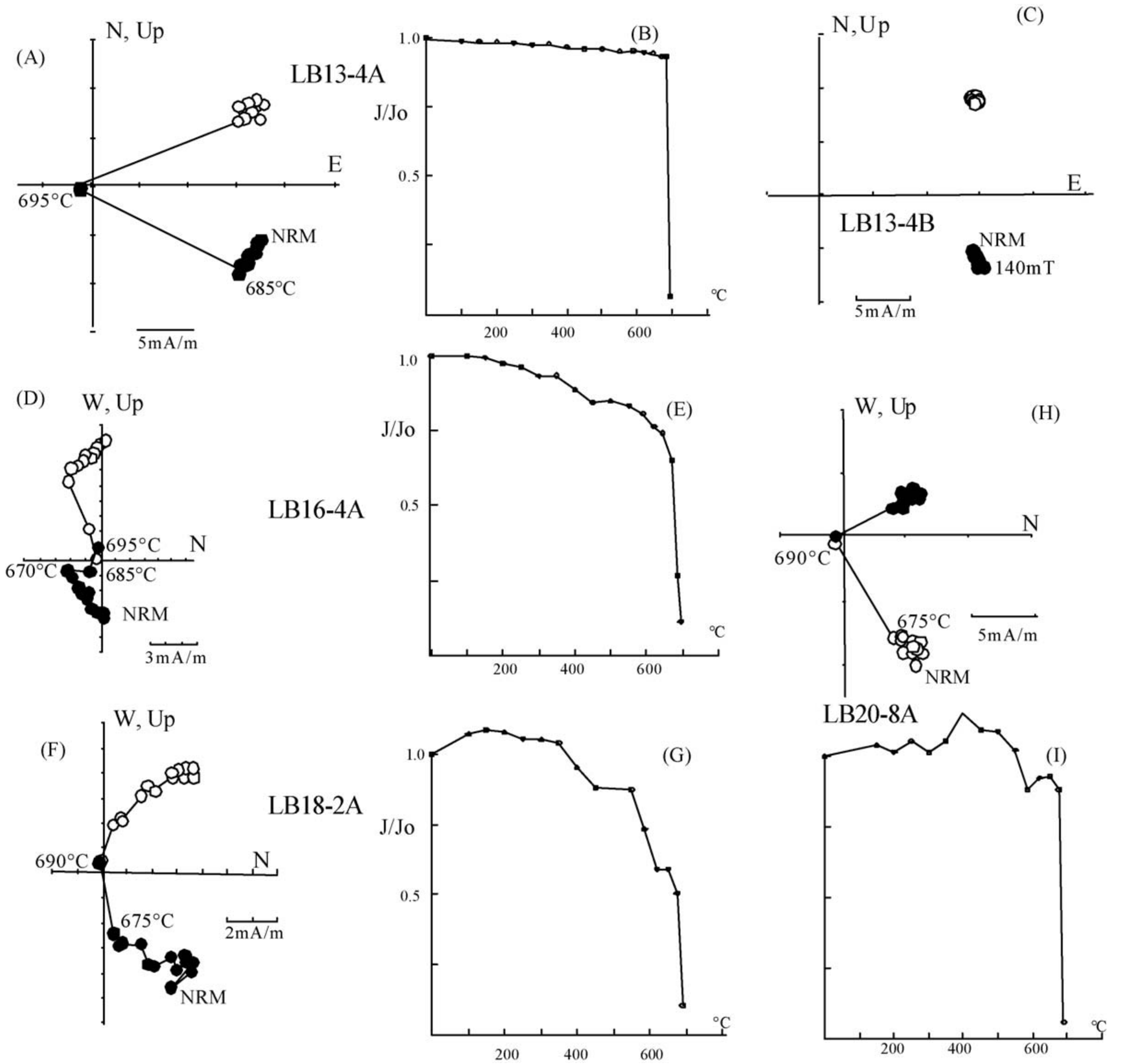

Fig. 3. Typical demagnetization behaviour of samples from the Los Barrientos claystones. Note the high unblocking temperature and coercive forces suggestive of hematite as the remanence carrier. In the Zijderveld diagrams, full (open) symbols correspond to projections on the horizontal (vertical) plane.

sidad Nacional Autónoma de México. A typical loop is presented in Fig. 5A. Lack of saturation at 1 T and the shape of the loop strongly suggest an antiferromagnetic carrier (hematite) with no signs of a ferrimagnetic contribution. This is confirmed by isothermal remanent magnetization acquisition curves (Fig. 5B).

X-ray analyses were performed on two samples from sites LB-14 and LB-18. The study was carried out at the X-ray laboratory of the Department of Geological Sciences of the University of Buenos Aires. Both samples showed nearly identical X-ray diffraction diagrams, confirming the lithological homogeneity of the succession. Difractograms confirmed the widespread presence of hematite plus quartz and subordinate quantities of feldspar. The argillaceous mineral was determined as 100% illite.

Tan et al. (2002) have demonstrated that hematite-carrying clay-sized sediments are likely to be affected by significant inclination shallowing due to compaction. A first indication of significant compaction-induced inclination error is provided by anisotropy of magnetic susceptibility (AMS). In order to test this, AMS analysis were performed on 14 specimens from several sites (Table 2) with a KLY-3 kappabridge at the Universidad Nacional Autónoma de México and a Minisep kappameter at the Instituto de Astronomía e Geofísica

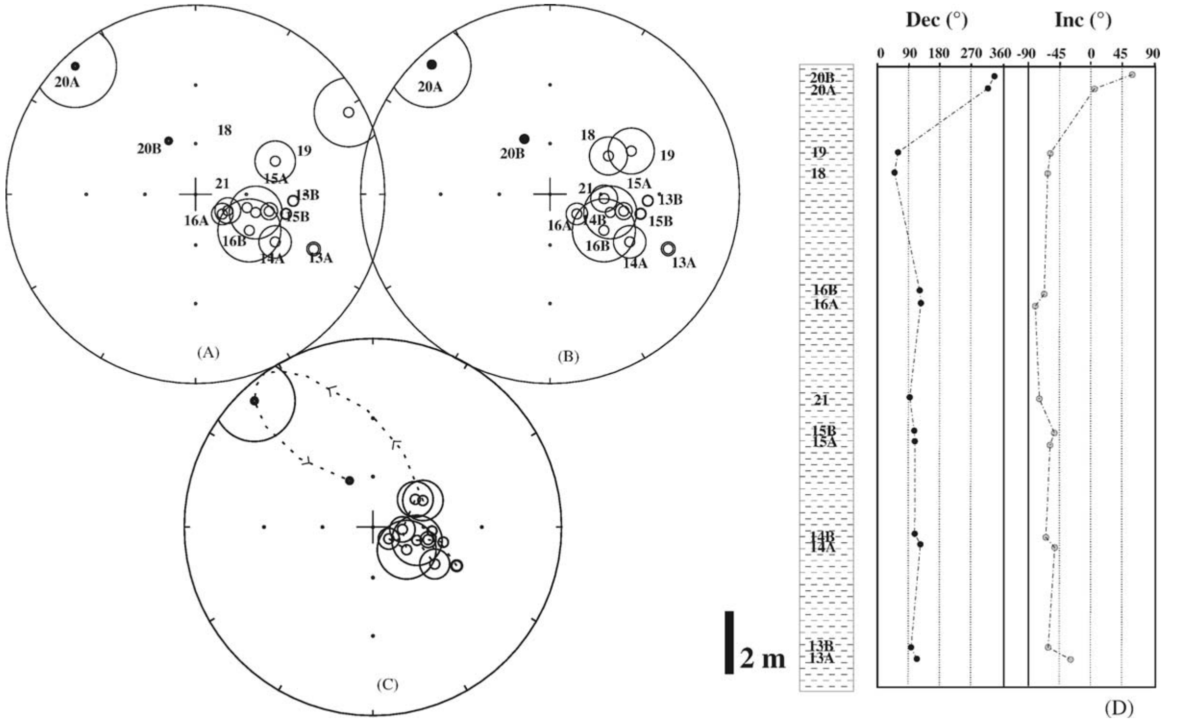

Fig. 4. Distribution of site mean directions of characteristic remanent magnetization (ChRM) from the Sierra de los Barrientos red claystones. (A) in situ, (B) after bedding correction, and (C) after application of remanence correction for compaction. Note the progression of directions and recording of a reversal of the earth magnetic field, between sites 19, 20A and 20B. (D) Stratigraphic position of each site and plot of declination and inclination values vs. stratigraphic position. Note the occurrence of a reversal of the earth magnetic field near the top of the sampled section. For more references see the text.

of the Universidade do Sao Paulo (Brazil). No significant differences were found in measurements with both instruments. The whole collection of samples could not be measured since AMS analysis post-dated the paleomagnetic processing. Therefore, only 14 untreated specimens with suitable sizes and shapes were available for this study. Results are shown in Table 2 and Fig. 6. Magnetic fabric is clearly pre-tectonic as shown by clustering of k_3 axes after bedding correction. Ellipsoid shape is oblate. Vertical k_3 axes and distributed

Table 2
Bedding corrected anisotropy of magnetic susceptibility (AMS) data for the Los Barrientos claystones

Sample	k_1 Dec (°)	k_1 Inc (°)	k_1	k_2 Dec (°)	k_2 Inc (°)	k_2	k_3 Dec (°)	k_3 Inc (°)	k_3	P′
LB13-4A	219.8	0.7	1.0416	83.8	36.3	1.0348	315.9	80.8	0.9199	1.132
LB14-4B	345.7	6.1	1.0428	265.0	6.0	1.0277	143.7	82.8	0.9295	1.122
LB15-1B	146.0	4.0	1.0395	235.8	1.8	1.0288	340.8	85.9	0.9317	1.116
LB16-4B	157.2	2.1	1.0556	247.0	7.6	1.0340	259.6	82.8	0.9104	1.159
LB18-1A	62.0	0.0	1.0507	152.0	2.3	1.0330	332.1	87.8	0.9163	1.147
LB18-3B	62.2	3.4	1.0645	331.9	5.7	1.0309	182.2	83.4	0.9045	1.177
LB19-1B	302.7	0.9	1.0471	23.1	21.5	1.0299	200.2	68.6	0.9229	1.135
LB19-2B	2.4	11.0	1.0560	92.7	1.2	1.0488	189.1	78.9	0.8951	1.180
LB19-4B	84.8	3.1	1.0509	354.1	13.2	1.0456	187.4	76.4	0.9035	1.163
LB19-6B	37.1	6.0	1.0642	306.1	9.7	1.0505	158.2	78.6	0.8852	1.202
LB20-4A[a]	297.3	13.5	1.0094	205.9	5.3	1.0074	94.8	75.5	0.9833	1.026
LB20-5A[a]	259.3	7.7	1.0077	357.4	46.2	1.0009	162.2	42.8	0.9914	1.016
LB21-2A	208.1	16.3	1.0794	117.3	3.0	1.0321	16.7	73.4	0.8885	1.215
LB21-7B	210.4	14.7	1.0879	119.2	4.4	1.0317	13.0	74.6	0.8804	1.236

P': anisotropy degree; values of k_1–k_3 are normalized to mean susceptibility.
[a] Samples not represented in Fig. 6 and not used to compute mean P'.

Table 3
Results from the oriented isothermal remanent magnetization (IRM) experiment

Sample	Applied field Inc (°)	IRM Inc (°)	Steps (mT)	n	α_{95} (°)	F'	IRM 640/675 °C (°)	F
LB13-7c	48.0	33.0	29–600	6	5.8	1.71	28.6	2.03
LB14-6c	45.0	28.0	62–600	5	2.2	1.88	33.4	1.52
LB14-7c	47.0	40.3	90–600	4	1.5	1.26	38.3	1.36
LB15-3c	44.7	36.7	62–600	5	2.5	1.33	34.5	1.44
LB15-8c	51.0	45.0	62–600	5	3.2	1.23	40.7	1.44
LB16-6c	49.0	32.4	62–600	5	1.8	1.81	33.4	1.74
LB16-7c	44.9	27.3	62–600	5	1.1	1.93	30.4	1.70
LB18-1A	45.5	32.2	62–600	5	2.9	1.61	34.5	1.48
LB19-2B	45.2	32.1	29–600	6	3.2	1.60	27.5	1.93
LB20-5A	51.0	43.4	62–600	5	2.7	1.30	48.2	1.10
LB20-5c	39.0	35.0	62–600	5	1.9	1.16	33.0	1.25
LB20-7c	43.0	38.0	90–600	4	2.2	1.19	37.9	1.20
LB21-7B	33.3	13.4	29–600	6	3.5	2.75	18.7	1.94

Inc: inclination in stratigraphic coordinates (respect to the bedding plane). IRM was applied in succesive steps of 29, 62, 90, 150, 300 and 600 mT (see also Fig. 5B). Steps indicate the range of steps used to compute mean inclination values for the IRM, n: number of steps, α_{95}: Fisherian statistical parameter for the IRM mean direction. The IRM inclination value used to compute the remanence correction factor (F, Table 1) is that measured after thermal demagnetization at 675 °C or 640 °C. F' and F correspond to the computed correction factor for inclination shallowing per sample before and after thermal demagnetization, respectively. More references in the text.

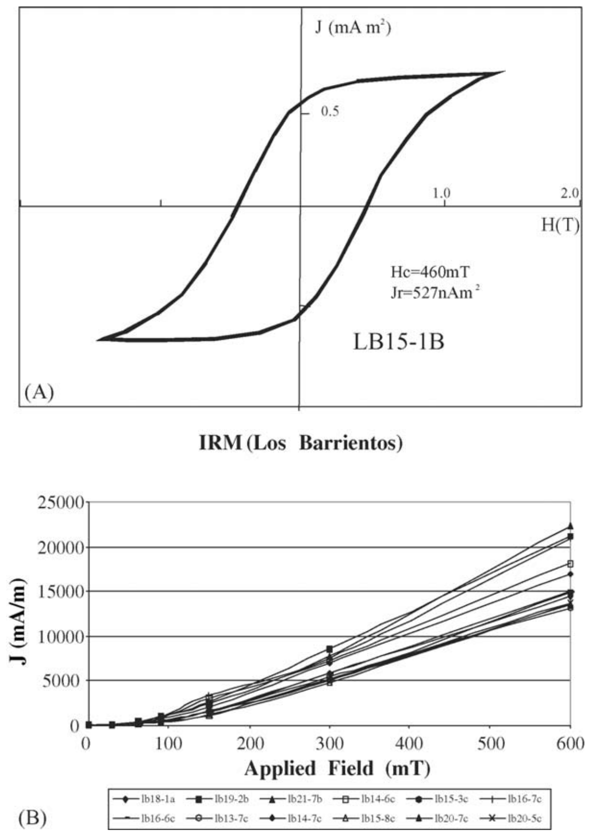

Fig. 5. (A) Hysteresis loop for a representative sample of the Los Barrientos claystone. Note the dominance of an antiferromagnetic signal and lack of ferrimagnetic contribution. (B) Isothermal remanent magnetization (IRM) acquisition curves for a set of samples of Los Barrientos claystone. Note the lack of low coercivity fractions.

k_1 and k_2 on the horizontal (bedding) plane after bedding correction suggests a compactional fabric. Degree of anisotropy (P') is relatively high in all samples (from 1.10 to 1.20), except in those from site LB-20 which shows a slightly coarser grain size (siltstone to fine grain sandstone). These results suggest that significant compaction affected the claystones of Los Barrientos, with the probable exception of site LB-20. It is therefore expected that remanence directions have been affected by post-depositional compaction. Remanence correction for compaction-induced inclination anomaly has been successfully applied in several previous studies (e.g. Jackson et al., 1991; Kodama, 1997; Tan et al., 2002; Raposo et al., 2003; references therein). AMS is potentially a good indicator of compaction-induced shallowing of remanence inclination. However, AMS tensor is the product of the different contributions of the individual susceptibilities and anisotropies of the minerals composing the sample. In general, AMS tend to underestimate the remanence inclination shallowing (Tan and Kodama, 2002). This may also apply to this case, despite the simple mineralogy (illite + hematite + quartz) of the studied samples. Therefore, anisotropy of isothermal remanent magnetization (IRM) was investigated. Since lineation ($L = k_1/k_2$) is very low, remanence correction assumes that the remanence vector rotated due to compaction along the great circle defined by the pole to bedding and the magnetic field (original remanence) direction, towards the bedding plane. Therefore, no declination change should be expected. Tauxe et al. (1990) and Hodych and Buchan (1994) have pointed out the dif-

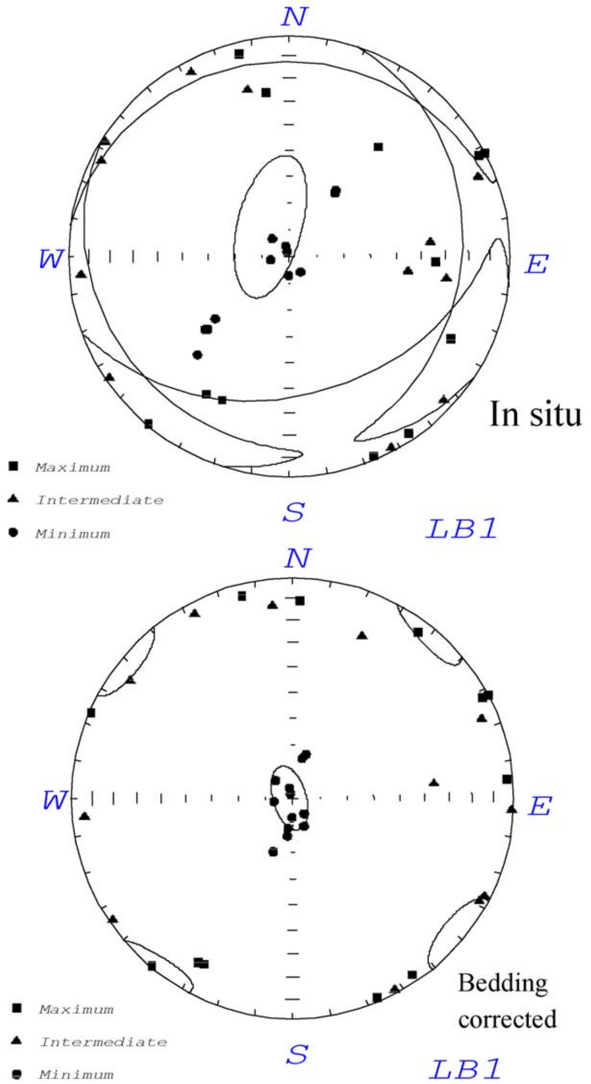

Fig. 6. Distribution of maximum (k_1, squares), intermediate (k_2, triangles) and minimum (k_3, circles) axes of AMS ellipsoid for the Los Barrientos claystone both in situ and after bedding correction. Note the coincidence of k_3 axes with the pole to bedding and the girdle described by k_1 and k_2 on the bedding plane. More details in the text.

ficulties in obtaining a reliable IRM anisotropy tensor. The latter and Tan et al. (2002) have indicated that a single component IRM test may suffice in many cases to reliably determine the compaction induced inclination shallowing. A single component IRM was produced in thirteen samples from all sites with an approximate angle of 45° respect to the bedding plane (exact angle for each sample is presented in Table 3). Successive steps of 29, 62, 90, 150, 300 and 600 mT were applied (Fig. 5B) with a PM-2 (ASC) pulse magnetizer. Table 3 shows that a large flattening of IRM towards the bedding plane occurs. Hodych and Buchan (1994) and Tan et al. (2002) have pointed out the fact that magnetic domains activated by the IRM experiment may not be necessarily the same as those carrying the natural remanence. In order to eliminate this problem thermal demagnetization of IRM was applied at 200, 400, 600, 640 and 675 °C. In all samples 50–60% of the original isothermal remanence remained at 600 °C indicating that a large proportion of the activated domains have unblocking temperatures similar to those of the natural remanent magnetization. Following Tan et al. (2002), the IRM at 675 or 640 °C in the cases in which the remanence was fully unblocked at 675 °C, was considered as the most reliable indicator for computing inclination shallowing. Orientation and other experimental errors are considered low as remanence direction at the last stage was nearly identical (generally within 2°) with those at 640 and 600 °C. A correction factor (F) for the mean site characteristic remanence was obtained considering that

$$F = \tan I_a / \tan I_{irm}$$

I_a being the inclination of the applied field and I_{irm} that of the measured IRM, both respect to the bedding plane.

The correction applied is therefore

$$\tan I_c = F \tan I_o$$

I_c being the corrected mean site remanence inclination and I_o is the measured remanence inclination, both after bedding correction. As shown in Table 3 the use of the thermally demagnetized IRM produces a better agreement of F values for different samples from the same site. F values range from 1.10 to 2.03, the lowest values corresponding to site LB-20 (siltstone to fine grain sandstone), which also yielded a very low degree of AMS. All remaining sites show much larger F values from 1.44 to 2.03 pointing to a very significant inclination error due to compaction. F for sites with more than one sample was computed by averaging sample values. When a single sample was available, that value was taken as representative for the corresponding site. The application of the remanence anisotropy correction produces a much better clustering in the site mean directions (Table 3 and Fig. 4C). The mean inclination for all sites changes from 49.0° to 60.8° after correction. This yields an increase of the computed paleolatitude for the Los Barrientos claystones from 29.9° to 41.8°. The pole position for the Los Barrientos claystones after correction for compaction is 15.1°S, 252.6°E, dp: 10.9°, dm: 14.2°.

5. Interpretation and conclusions

Fig. 7 shows the location of the Los Barrientos claystones paleomagnetic pole (LB), and its 95% con-

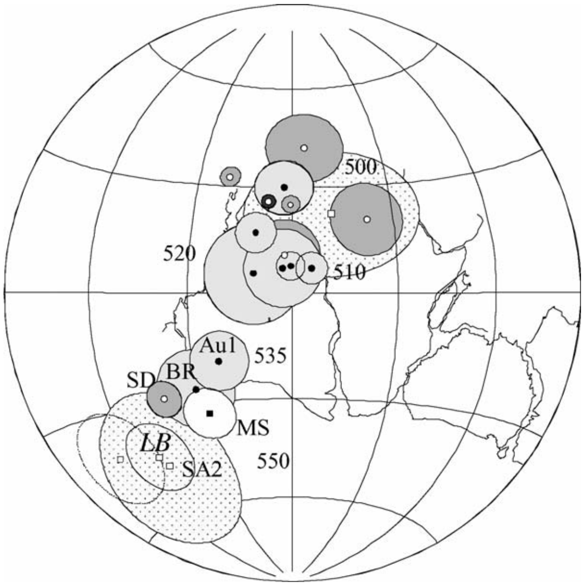

Fig. 7. Paleomagnetic pole for Sierra de los Barrientos claystones (LB, dashed line, before and solid line, after correction for compaction) plus other poles for the Rio de la Plata craton and other Gondwanan continents. Note that since 550 Ma all poles tend to form a single apparent polar wander path. SA2: Sierra de las Animas 2 (Rio de la Plata craton, ca. 550 Ma), SD: Sinyai dolerite (Congo–Sao Francisco, 547 Ma), MS: Mirbat sandstone (Arabia, ca. 550 Ma), BR: Bhander–Rewa Mean (India, ca. 550 Ma), Au1: Australia mean 1 (ca. 535 Ma; Trindade et al., 2004). Poles from Rio de la Plata craton: white squares with dotted confidence ovals; poles from Congo–Sao Francisco: white circles with dark grey confidence ovals; pole from Western Africa: white circle with black confidence oval; pole from Arabia: black square with white confidence oval; poles from Australia, India, Madagascar and Antarctica: black circles with light grey confidence ovals. Numbers indicate approximate age in Ma for the apparent polar wander path of Gondwana. Poles have been rotated into Southern Africa coordinates according to Lottes and Rowley (1990). For references see Sánchez Bettucci and Rapalini (2002), Meert (2003), Meert et al. (2003) and Trindade et al. (2004).

fidence oval, in a Gondwana reference frame following the rotations parameters of Lottes and Rowley (1990), computed both before (dashed oval) and after the application of the correction for inclination shallowing due to compaction as reported above. The latter is considered the best estimate of the Los Barrientos pole. Its better agreement with coeval poles from the Rio de la Plata craton and other Gondwanan continents also argues in favor of the correction applied, and it is considered as the best estimate for the Los Barrientos pole. Latest Proterozoic to Cambrian paleomagnetic poles for other Gondwanan cratonic blocks are also shown in the figure. LB, particularly after correction, is consistent with the SA2 pole recently obtained from the Sierra de Animas complex (Sánchez Bettucci and Rapalini, 2002), the Sinyai dolerite pole (SD, Meert and Van der Voo, 1996) and the Mirbat sandstone pole from Arabia (MS, Kempf et al., 2000). SA2 is approximately dated in 550 Ma, SD is more accurately determined as 547 Ma. A similar age for LB can be inferred, although a slightly older age cannot be ruled out on the basis of the available paleomagnetic data. In any case an age younger than 600 Ma is implied from geologic considerations already exposed and from the far located paleomagnetic pole of that age from RP (Sánchez Bettucci and Rapalini, 2002). LB position confirms the conclusions obtained by Meert and Van der Voo (1996) and Sánchez Bettucci and Rapalini (2002) that Gondwana was likely already assembled or nearly so by 550 Ma. However, it must be kept in mind that coeval paleomagnetic poles are lacking from some other western Gondwana forming blocks, such as Amazonia, Western Africa, Kalahari and Pampia (Fig. 7). This is significant considering the geologic evidence pointing to an early Cambrian (ca. 530 Ma) age for final closure of oceanic basins among some western Gondwana forming blocks. These events are recorded as the Pampean orogeny in western Argentina (Rapela et al., 1998), the Rio Doce and Buzios orogenies in southeastern Brazil (Campos Neto and Figueredo, 1995; Heilbron and Machado, 2003; Schmitt et al., 2004) and deformation of the Kaoko and Gariep belts in western South Africa and Namibia (Prave, 1996; Passchier et al., 2002), which collectively indicate that the Gondwana assembly process continued after 550 Ma. Whether these events are related to closure of small or large oceanic basins is scarcely known (e.g. Rapela et al., 1998; Kroner and Cordani, 2003). Paleomagnetic poles of 600–530 Ma are therefore necessary from all the crustal blocks involved to determine the time and kinematics of final Gondwana assembly.

The new paleomagnetic pole reported in this study reinforces previous interpretation that suggested a single APWP for most Gondwana blocks since ca. 550 Ma. However, the uncertainty in its age permits further considerations. An age much younger than 550 Ma looks unlikely considering the fast APWP track of the Rio de la Plata craton and other Gondwana blocks from the latest Neoproterozoic to the middle Cambrian. However, an older age, up to 580–590 Ma cannot be ruled out on the basis of its pole position due to the lack of reliable paleomagnetic poles from RP or even other Gondwana blocks for that age. This awaits either an independent determination of the age of Los Barrientos claystones or new paleomagnetic poles for the interval 550–590 Ma for RP.

Powell (1995) proposed the existence of a short-lived supercontinent named Pannotia in Ediacaran times. Briefly, this proposal suggests that Gondwana was formed before western Gondwana (interpreted here mainly as Amazonia and RP) drifted apart from Eastern Laurentia. Confirmation of the ca. 550 Ma paleomagnetic pole position for RP attained in this study supports ruling out the possibility of such supercontinent on paleomagnetic grounds, as previously proposed by Meert (2001). Available, albeit weak, paleomagnetic data suggest that RP, Congo–Sao Francisco and West Nile blocks formed a single continent by ca. 600 Ma, separate from Amazonia and West Africa that were still attached to Eastern Laurentia by that time (Sánchez Bettucci and Rapalini, 2002). This implies that a supercontinent like the hypothetical Pannotia did not exist at 600 Ma either.

Q&A Section

Pares: Since the mean direction could be secondary (there are no solid or conclusive field tests), what age could it be?

Rapalini: The computed direction does not agree with any Phanerozoic expected direction for the study area, according to the South American reference poles. Furthermore, the computed pole position can only be reconciled with previous poles from the Rio de la Plata craton and other Gondwanan continents if the age of magnetization is older than 530 Ma. This points to an age of magnetization very close to depositional age, consistent with deflection of remanence due to compaction and recording of a reversal of the earth magnetic field.

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