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Paleomagnetic study on mid-Paleoproterozoic rocks from the Rio de la Plata craton: Implications for Atlantica

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ABSTRACT

The first successful paleomagnetic study on middle Paleoproterozoic rocks from the Rio de la Plata craton is reported. Samples collected from the Soca and Isla Mala granitic bodies, located in southern Uruguay, provided characteristic remanences that were used to compute the first paleomagnetic poles for the craton for ca. 2.05–2.02 Ga. The poles were complemented by a virtual geomagnetic pole from the slightly older Marincho and Mahoma complexes. The paleomagnetic results suggest fast apparent polar wander at high paleolatitudes for the Rio de la Plata craton. Comparison with coeval poles from the Guiana, Congo–São Francisco and West African cratons indicates that a configuration of Atlantica that resembles their Western Gondwana fit is not supported by paleomagnetic data. The geologic similarities in these four cratons are supportive of a major crustal forming event between 2.2–2.0 Ga. A modified configuration for Atlantica is proposed that is consistent with our new (and older) paleomagnetic data. Atlantica was assembled at 2.1–2.05 Ga at polar latitudes and drifted towards the equator soon afterwards.

1. Introduction

Scientific interpretation of the Precambrian geological record experienced a major step forward with the hypothesis of the Mesoproterozoic supercontinent of Rodinia proposed over twenty years ago (McMenamin and McMenamin, 1990; Dalziel, 1991; Hoffman, 1991). This generated great interest in paleogeographic reconstructions throughout the Precambrian and fostered the application of several different techniques to unravel the global paleogeographic and tectonic evolution along most of Earth history (Rogers and Santosh, 2002, 2004). Paleogeographic models for the Neoproterozoic have shown significant advances in the last decade (e.g. Meert and Torsvik, 2003; Li et al., 2008; Zhang et al., 2012), although important controversies remain (e.g. Evans, 2009; Meert, 2012; Piper, 2013). Precambrian paleogeographic reconstructions are hindered by several factors (Meert, 2014) including the scarcity and low reliability of paleomagnetic data. In particular, paleogeographic models for the Mesoproterozoic and Paleoproterozoic are still generally sketchy (e.g. Meert, 2002; Pesonen et al., 2003; Li et al., 2008; Meert, 2014). Besides the reliability of paleomagnetic data itself (e.g. Van der Voo, 1990), accurate and precise dating of the rocks is of paramount importance in Proterozoic paleomagnetism applied to paleoreconstructions and has become a pre-requisite for any paleomagnetic data to be considered useful (e.g. Meert, 2003).

Precambrian paleomagnetic data for the Rio de la Plata craton are scarce. Rapalini et al. (2013) presented an updated database for the late Neoproterozoic and Teixeira et al. (2013) published the first pre-Neoproterozoic data from ca. 1.8 Ga tholeiitic dykes in the Piedra Alta terrane of Uruguay.

In order to provide the first paleomagnetic constraints for the paleogeographic position of the Rio de la Plata craton in the middle Paleoproterozoic (2.1–2.0 Ga), a reconnaissance paleomagnetic study was carried out on well-dated undeformed granitoids exposed in the Piedra Alta terrane (Bossi et al., 1993) of the Río de la Plata craton in central southern Uruguay. In this paper, paleomagnetic results obtained from the 2.07 Ga Isla Mala and 2.05 Ga Soca granitic bodies along with preliminary results from the ca. 2.1 Ga Mahoma and Marincho granitoids provide the first paleomagnetic pole positions for Rio de la Plata in the middle Paleoproterozoic. These results are compared with approximately coeval data from other cratons in South America and Africa that have been interpreted as part of the hypothetical landmass called Atlantica (Ledru et al., 1994; Rogers, 1996; Rogers and Santosh, 2004).

2. Geologic background and sampling

The Río de la Plata craton (RPC) is subdivided in Uruguay into two tectonostratigraphic units: the Piedra Alta (PAT) and Nico Pérez (NPT)

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terranes (Fig. 1). The Palaeoproterozoic PAT is constituted (Hasui et al., 1975) of plutonic, granite-gneissic terrains and volcano-sedimentary belts of low to medium metamorphic grade. The basement shows a well-defined E–W structural trend. Bossi et al. (1993) defined the PAT as that part of the RPC located to the west of the Sarandí del Yí shear zone (Fig. 1). Its extension towards the west is unknown where the RPC is covered by the Chaco-Pampean plains in Uruguay and eastern Argentina. Limited geochronologic and isotopic data from oil-well samples suggest that it may extend up to the foothills of the Eastern Pampean ranges in central Argentina (Rapela et al., 2007). Peel and Preciozzi (2006) suggested that the PAT represents a juvenile Palaeoproterozoic unit that was tectonically stable from at least 1.7 Ga (i.e. was not

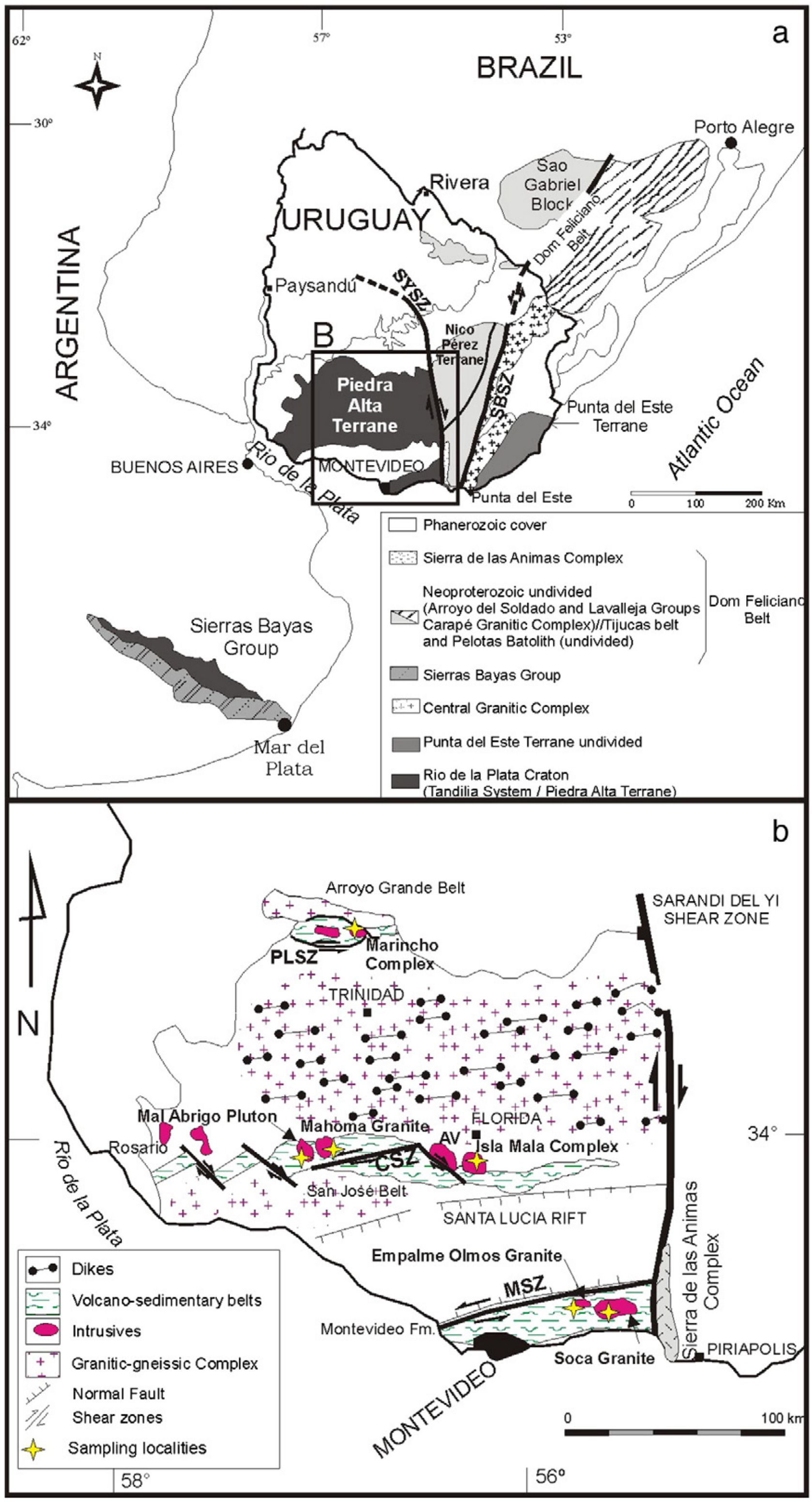

Fig. 1. a) Main morphotectonic units of eastern Argentina, Uruguay and southern Brasil encompassing the Río de la Plata craton. b) Geologic sketch of the Piedra Alta Terrane in western Uruguay with location of the main Paleoproterozoic intrusives. Stars indicate the sampling localities. AV: Arroyo de la Virgen pluton. MSZ: Montevideo shear zone; PLSZ: Paso Lugo shear zone.

affected by the Neoproterozoic Brasiliano cycle, sensu Almeida et al., 1973). It is considered as the best preserved Palaeoproterozoic block of the Río de La Plata craton. Several late to post-orogenic calcalkaline, peraluminous and alkaline granitoids and gabbros are distributed in this block with ages ranging between 1.9 and 2.3 Ga.

A reconnaissance paleomagnetic study was carried out on six independent igneous bodies of middle Paleoproterozoic age, i.e. late Rhyacian to early Orosirian (ca. 2.0–2.1 Ga), well exposed in central and southern western Uruguay. All these granitoids are devoid of any significant tectonic deformation and some of them have high-resolution U–Pb ages. One hundred and fifty five independently oriented cores were collected at nineteen sites located on these bodies (Fig. 1).

2.1. The Soca granite

The Soca granite is exposed 55 km to the East-Northeast of the city of Montevideo (Fig. 1) and consists of an elliptical and undeformed subalkaline, metaluminous or slightly peraluminous A-type rapakivi granite (Oyhantçabal et al., 1998; Sánchez Bettucci et al., 2010). It was described as a lithologically homogeneous porphyritic leucogranite with an exposed area of ~75 km^2 (Oyhantçabal et al., 1998). The eastern boundary of the pluton is positioned alongside the Sarandi del Yi megashear that separates the PAT from the NPT (Fig. 1b). The Soca granite was dated to 2078 ± 8 Ma (conventional U–Pb, Peel and Preciozzi, 2006) and 2056 ± 6 Ma (U–Pb SHRIMP, Santos et al., 2003). Except for solid-state deformation reported on its eastern border, associated to activity of the Sarandí del Yi megashear (Oyhantçabal et al., 1998), no internal deformation was observed. Emplacement of the Soca granite was interpreted as intrusive activity associated with regional extension. Twenty cores were collected from this unit at two different sites (g1 and g2), situated one hundred meters apart. As in the other units, each core was generally drilled between 1 and 5 m apart in order to provide a representative sampling of the unit at each site.

2.2. Empalme Olmos granite

The Empalme Olmos granite is a porphyritic biotite granite to granodiorite with large crystals of microcline exposed 24 km to the west of the Soca granite. The granite shows no pervasive deformation (Spoturno et al., 2005). Its proximity to the Soca granite along with petrographical and structural characteristics were used to correlate this granitic body with other late to post-tectonic Paleoproterozoic granites, although reliable geochronology is lacking. Sixteen samples, from two sites (g16, g17) that were situated 1.1 km apart, were collected for paleomagnetic study.

2.3. The Isla Mala pluton

The Isla Mala pluton is part of a larger suite of intrusions exposed to the north of the city of Montevideo and the Santa Lucía rift (Fig. 1). Preciozzi and Bourne (1992) studied this intrusion in detail. According to these authors the Isla Mala forms a composite body with the nearby Arroyo de la Virgen pluton. It is a K-rich granitoid with a dominant facies of hornblende-rich granodiorite. It shows no significant deformation with the exception of localized shear bands near its borders. Preciozzi and Bourne (1992) interpreted a shallow emplacement for these plutons. U–Pb ages on this granitic body were obtained by Hartmann et al. (2000) using SHRIMP analyses on zircons. Two consistent age determinations of 2065 ± 9 and 2074 ± 6 indicate identical ages within error around 2070 Ma. A slightly older conventional U–Pb age on zircon of 2088 ± 12 Ma was interpreted by Preciozzi et al. (1999) as the magmatic age of the Isla Mala granodiorite. Forty-four samples were collected from five sites located about 1 km apart in the Isla Mala pluton (g3, g4, g5, g20 and g21).

2.4. Mahoma granite

The Mahoma granite is a ~20 km^2 discordant biotite leucogranite exposed fifty kilometers to the west of the Isla Mala and Arroyo de la Virgen plutons, along the San José Belt. It is coarse grained and shows no evidence of deformation. The only dating on this granite is a Rb/Sr whole-rock isochron (Umpierre and Halpern, 1971) age of 1998 ± 35 Ma (corrected according to Steiger and Jagër (1977); original data 1930 ± 35 Ma). Oyhantçabal et al. (1990) produced a conventional K–Ar age of 2033 ± 44 Ma for an associated gabbro. Paleomagnetic results suggest that this granite is contemporaneous with the granodiorite of the Marincho complex (see below), with a crystallization age ca. 2100 Ma. Twenty-two independent cores were collected from this pluton at three different sites (g6, g7 and g8) separated between 0.6 and 1.3 km from each other.

2.5. Mal Abrigo pluton

The Mal Abrigo pluton is a large intrusive body of ca. 55 km^2 located 8 km to the west of the Mahoma granite. Similar lithologies and lack of deformation suggest correlation of both intrusive bodies. The Mal Abrigo pluton is a homogeneous coarse grained leucocratic granite to granodiorite with biotite ± hornblende. Nineteen independent cores were drilled in this pluton at two sites (g9 and g10) separated by 750 m.

2.6. Marincho complex

The Marincho complex is a large magmatic complex made up of four different plutons. The main intrusion is a coarse grained hornblende ± biotite granodiorite, with a compositional range between monzogranite and diorite. It contains mafic enclaves and is devoid of any important foliation. Subordinate intrusions include a porphyritic hornblendite and a leucogranite. The Marincho complex was interpreted as late to post-tectonic intrusion due to its lack of internal deformation. U–Pb (SHRIMP) geochronology on zircons of the Marincho complex (s.l.) yielded crystallization ages of 2108 ± 23 and 2076 ± 18 Ma (Ferrando, pers. com. in Maldonado et al., 2003). Older whole rock Rb–Sr age determinations ranged from 2291 to 1969 Ma (Preciozzi and Bourne, 1992). An unpublished conventional K–Ar determination on hornblende from the porphyritic hornblendite yielded an age of 2086 Ma (no errors quoted, Preciozzi and Peel, 2005). Bossi and Ferrando (2001) in the Geologic Map of Uruguay quote U–Pb (conventional) ages of 2139 ± 20 and 2098 ± 22 Ma for the nearby Valenzuela and Andresito granodiorites, respectively. All determinations suggest that the main bodies of the Marincho complex crystallized ca. 2100 Ma. Thirty-four independent cores were collected at five different sampling sites (g11 to g15). Distances between nearby sites ranged from 0.45 to 6 km.

3. Magnetic fabrics

Anisotropy of magnetic susceptibility (AMS) was used to examine the magnetic fabrics of the plutonic bodies (Tarling and Hrouda, 1993). Measurements were done with a MFK1-A kappabridge (AGICO S.A.) at the Daniel A. Valencio Paleomagnetic Laboratory of the IGEBA (Buenos Aires). Jelinek's statistical approach (Jelinek, 1978, 1981) was used to compute site mean AMS parameters and ellipsoids. The main results of the AMS study are reported in Table 1.

Site mean values of bulk susceptibility (k) vs. anisotropy degree (Pj) and anisotropy degree vs. shape parameter (T) are presented in Fig. 2. They show a wide range of susceptibility values for the studied plutons of over three orders of magnitude, from typical paramagnetic bodies (≤500 μSI) to ferromagnetic ones (≥5000 μSI). However, most sites have values within the paramagnetic field (Tarling and Hrouda, 1993). The only exceptions are the Soca granite, three sites on the Isla Mala pluton and a single site on the Marincho complex. Pj values are in most

Table 1
Mean site AMS parameters. *k*1, *k*2 and *k*3 (values in degrees) correspond to the principal maximum, intermediate and minimum axes of the ellipsoid, respectively. Their directions are presented with the respective 95% confidence ovals (maximum and minimum semiaxes are quoted in italics between brackets). Kmean stands for the mean site bulk susceptibility. Pj is the corrected anisotropy factor (Jelinek, 1978). L and F are the magnetic lineation and foliation values, respectively, according to Khan (1962). T is Jelinek's (1981) shape parameter.

Pluton	Site	*k*1 (°)	*k*2 (°)	*k*3 (°)	Kmean μSI	Pj	L	F	T
Soca	g1	017/26 (*38/13*)	108/03 (*38/31*)	204/63 (*31/13*)	6400	1.043	1.017	1.026	0.212
	g2	019/23 (*23/15*)	285/09 (*53/19*)	175/65 (*53/19*)	7140	1.050	1.036	1.011	−0.531
E. Olmos	g16	063/28 (*7/4*)	306/40 (*17/7*)	177/37 (*17/5*)	277	1.057	1.040	1.016	−0.431
	g17	033/08 (*19/12*)	298/33 (*36/16*)	136/55 (*35/12*)	274	1.048	1.025	1.023	−0.034
Isla Mala	g3	083/58 (*21/13*)	300/27 (*27/19*)	202/17 (*25/13*)	3590	1.063	1.043	1.017	−0.426
	g4	022/59 (*48/8*)	222/30 (*48/12*)	127/09 (*12/7*)	20600	1.185	1.018	1.147	0.768
	g5	081/40 (*10/7*)	232/46 (*19/9*)	338/15 (*19/6*)	2940	1.120	1.061	1.055	−0.053
	g20	222/01 (*41/22*)	131/29 (*42/41*)	314/61 (*42/18*)	283	1.021	1.007	1.014	0.363
	g21	005/46 (*52/23*)	246/25 (*44/37*)	138/33 (*51/41*)	55	1.009	1.005	1.004	−0.122
Mahoma	g6	282/66 (*18/6*)	102/24 (*18/7*)	192/00 (*8/5*)	52	1.035	1.008	1.025	0.501
	g7	291/64 (*13/4*)	138/24 (*13/7*)	043/11 (*9/5*)	65	1.016	1.004	1.011	0.411
	g8	269/75 (*17/7*)	140/09 (*31/8*)	049/11 (*29/8*)	59	1.008	1.005	1.002	−0.467
Mal Abrigo	g9	129/78 (*38/5*)	277/10 (*38/7*)	008/06 (*8/4*)	32	1.029	1.004	1.019	0.757
	g10	24/69 (*13/3*)	294/00 (*13/8*)	204/20 (*8/3*)	32	1.031	1.007	1.022	0.540
Marincho	g11	207/69 (*10/9*)	091/10 (*12/7*)	358/18 (*10/9*)	2240	1.103	1.057	1.044	−0.120
	g12	217/59 (*12/2*)	104/13 (*20/5*)	007/27 (*18/3*)	84	1.086	1.035	1.049	0.162
	g13	206/58 (*7/6*)	072/23 (*13/6*)	333/21 (*14/5*)	82	1.048	1.023	1.024	0.014
	g14	200/72 (*22/8*)	075/11 (*26/11*)	342/14 (*18/8*)	89	1.073	1.023	1.060	0.389
	g15	241/61 (*33/15*)	098/24 (*33/14*)	001/15 (*19/10*)	78	1.071	1.017	1.050	0.475

cases under 1.08 (approximate to anisotropy degree of 8%), even in ferromagnetic plutons, which is typical of undeformed granitoids (Lopez de Luchi et al., 2001, 2004; Sen et al., 2005; Lopez de Luchi et al., 2010). A single site (g4) shows anisotropy degree near 20%, consistent with macroscopic evidence of tectonic deformation and cataclasis

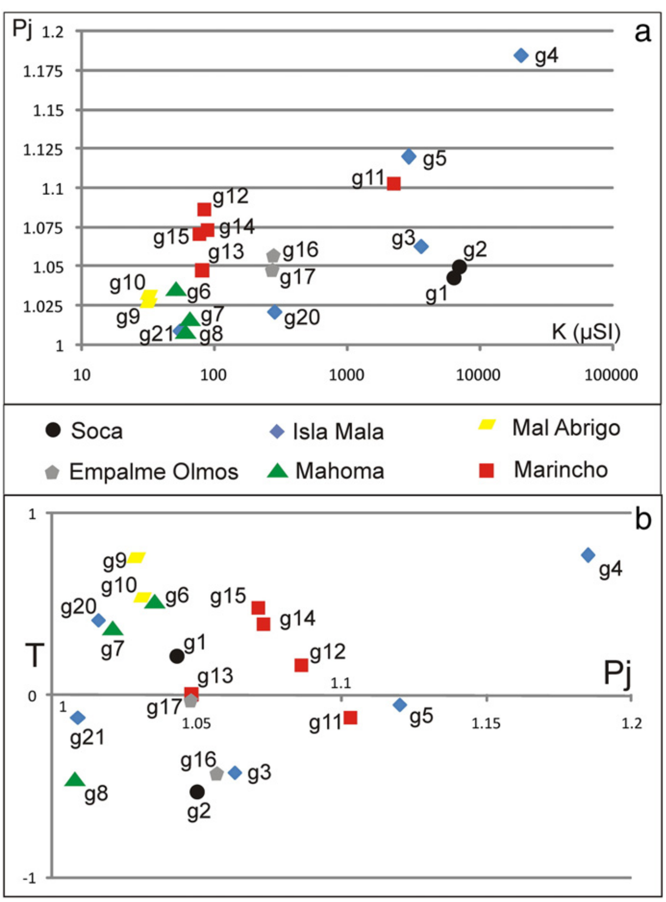

Fig. 2. a) Mean bulk susceptibility (*k*) versus mean anisotropy degree (Pj) for each sampling sit on the Paleoproterozoic granitoids of the Piedra Alta terrane. Different units are shown with different colors and symbols. b) Pj versus Jelinek's shape parameter (T) for each site.

affecting this site. A poorly defined correlation between Pj and *k* is observed (Fig. 2a), that is commonly observed in plutonic complexes (Rochette et al., 1992; Archanjo et al., 1995; Lopez de Luchi et al., 2001, 2004; Ferré et al., 2004). Shape parameter shows a range of values that fall in both the oblate and prolate domains (Fig. 2b). No correlation is seen between Pj and T that is generally the case in bodies with negligible internal deformation. Site g4 is the only exception with T approaching 1, suggesting significant flattening at that site. With the exception of g4, the other sites exhibit AMS characteristics indicating a lack of internal deformation and supporting our conclusion that the fabrics observed in the plutons are related to magmatic processes during intrusion and crystallization.

AMS ellipsoids for each site are presented in Fig. 3. Most sites show a well-defined magnetic fabric. The Soca and Empalme Olmos bodies (Fig. 3a) show a sub-horizontal foliation plane (plane containing *k*1 and *k*2), with a shallow magnetic lineation (*k*1) trending NNE to ENE. The Isla Mala pluton yielded three (of five) sites with a well-defined magnetic fabric (g3, g4 and g5). Site g4 shows a well-defined linear fabric with a sub-vertical foliation plane trending NE that is interpreted as tectonic in origin. Sites g3 and g5 show a different fabric characterized by a triaxial ellipsoid with a sub-vertical foliation plane trending ENE to ESE and a steep magnetic lineation. The Mahoma, Mal Abrigo and Marincho plutons (Fig. 3b) show similar magnetic fabrics, with triaxial to slightly planar fabrics. Foliation planes are generally sub-vertical, trending SE (Mahoma), ESE (Mal Abrigo) and E–W (Marincho). Since the AMS ellipsoid reflects a magmatic fabric, the consistent results found in the Isla Mala, Mahoma, Mal Abrigo and Marincho plutons suggest that all these bodies were likely intruded under a N–S to NE–SW far-field compressive stress. This is consistent with the well-defined E–W structural grain of the Piedra Alta terrane (see Oyhantçabal et al., 2011 and references therein).

4. Paleomagnetic results

One or two standard-size specimens (2.2 cm high) per core were submitted to stepwise demagnetization (either thermal or by alternating magnetic fields). Specimens were treated at steps of 100, 150, 200, 250, 300, 350, 400, 450, 500, 540 and 580 °C during thermal demagnetization or 3, 6, 9, 12, 15, 20, 25, 30, 35, 40, 50 and 60 mT, during AF cleaning. Occasionally, the AF method required treatment up to 120 mT in steps of 10 mT in samples with high coercivities. Representative magnetic behaviors of the collected samples are illustrated in Fig. 4. Magnetic components were defined by means of principal component

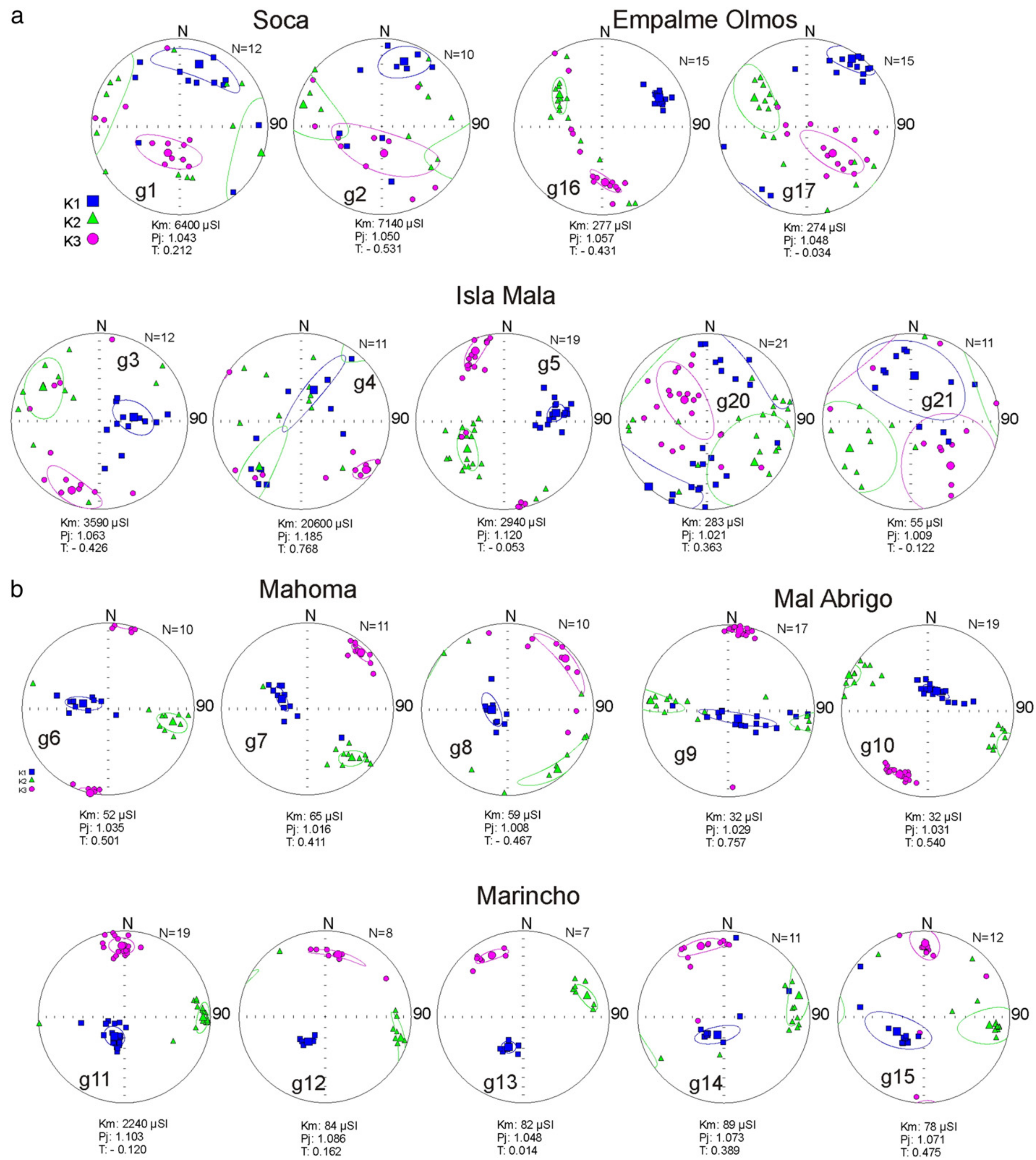

Fig. 3. a) Equal area stereographic projections of main axes of the anisotropy of magnetic susceptibility ellipsoid for all samples of each site of the Soca, Empalme Olmos and Isla Mala plutons. 95% confidence ellipses for each mean axis direction is shown. Squares, triangles and circles represent $k1$, $k2$ and $k3$ axes, respectively. Projections correspond to the lower hemisphere. b) idem a) for sites in the Mahoma, Mal Abrigo and Marincho units. Mean site directions are listed in Table 1.

analysis (Kirschvink, 1980). Characteristic components were defined with a minimum of 5 consecutive steps. Maximum angular deviations (MAD) under 16° were accepted, but over 80% of components were determined with a MAD under 10°.

Samples from sites g1 and g2 (Soca pluton, Fig. 4a and b) showed a coherent magnetic direction that was erased at temperatures of 580 °C or in AF fields in the range 20–30 mT. This magnetic component, that trends towards the origin of coordinates in the Zijderveld diagram with moderate west and downward inclinations, is interpreted as the characteristic remanence (Butler, 1992). A significantly large, but very soft component of likely viscous origin, was erased at 3 mT or 250 °C (Fig. 4a,b).

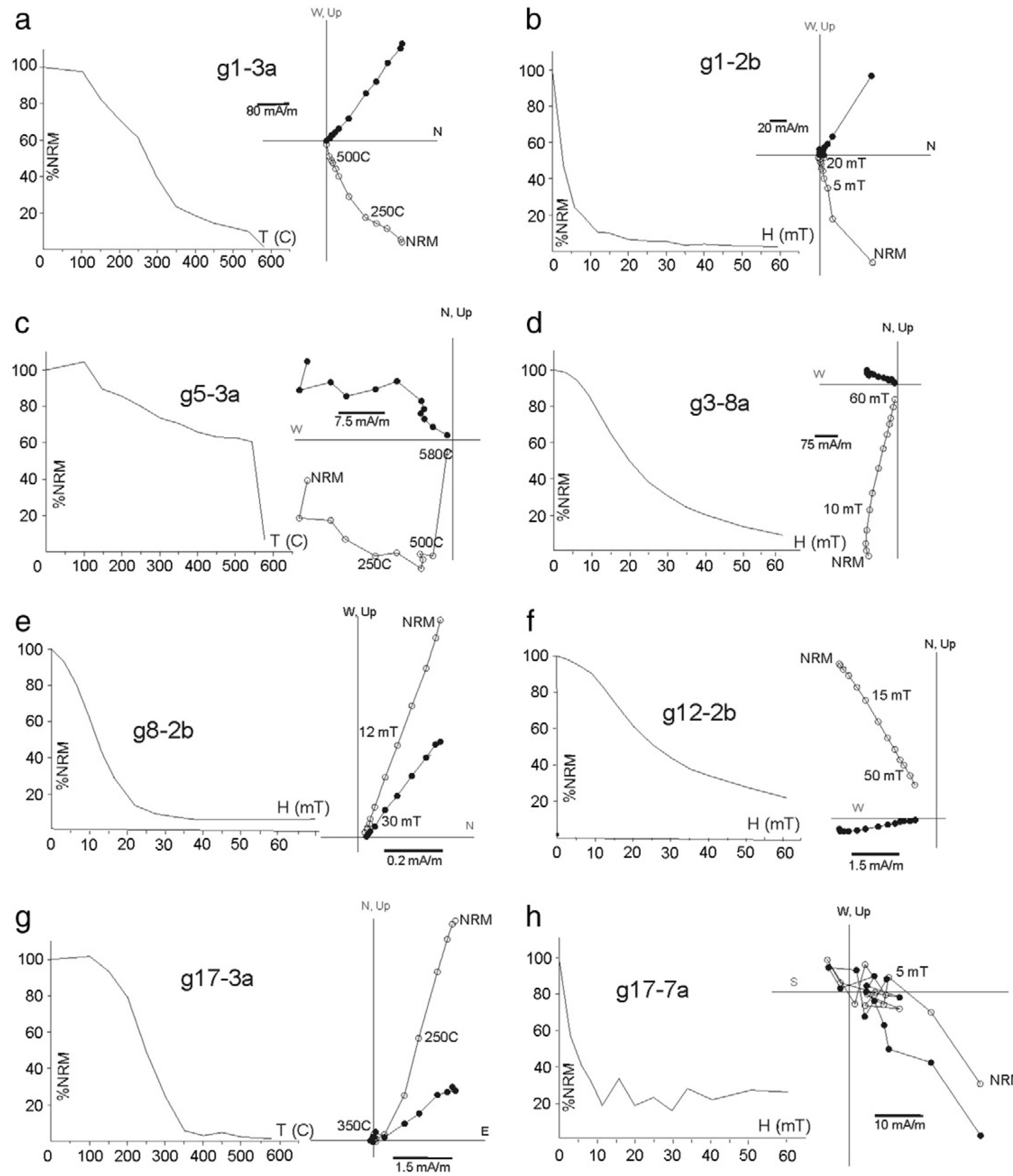

Fig. 4. Representative magnetic behavior of samples of the study collection submitted to alternating field or thermal demagnetization. Open (solid) symbols in the Zijdervled diagrams correspond to projections in the vertical (horizontal plane). a) and b) samples of the Soca granite; c) and d) samples of the Isla Mala complex; e) sample of the Mahoma granite; f) sample of the Marincho complex; g) and h) samples of the Empalme Olmos pluton. More references in the text.

Sites g3, g5 and g20 from the Isla Mala granitoids were also carriers of a well-defined characteristic remanence. Magnetic behavior of representative samples is presented in Fig. 4c,d. These rocks showed higher coercivity and required alternating fields of up to 60 mT to isolate the characteristic component. Discrete unblocking temperatures close to 580 °C suggest pure magnetite as the magnetic carrier. A low-temperature soft component was erased at around 350 °C. The characteristic remanence is of steep downward inclination and trends towards the origin of coordinates in the Zijderveld diagram.

Site g8 from the Mahoma granite along with a few samples from site g12 (Marincho pluton) also carried a stable characteristic remanence. Samples from these two sites are illustrated in Fig. 4e and f. In both cases a stable magnetic component is erased with medium to high alternating magnetic fields, although in site g12, after 60 mT 20% of the original remanence remains. These two sites show a moderate to steep upwardly directed inclination with a similar declination to the Soca and Isla Mala granites. Two specimens from the Mahoma granite presented downward inclinations and NE-declinations that are ~antipodal to the Marincho pluton.

The remaining sites carried either inconsistent or unstable magnetizations that were not used in this study. An example from the Empalme Olmos plutons is presented in Fig. 4g–h. These rocks are dominated by pyrrhotite or maghemite remanence as suggested by unblocking temperatures between 300 and 350 °C.

Consistent sample and mean site characteristic remanence directions, with the corresponding virtual geomagnetic poles (VGPs) and their means are presented in Table 2 and illustrated in Fig. 5.

Fig. 5a–c shows the distribution of sample characteristic remanence directions for the Soca, Isla Mala and Mahoma–Marincho units. Fig. 5d shows the mean site directions, while Fig. 5f presents the overall mean sample directions for each unit. Fig. 5f shows small but significant differences between the Soca and Isla Mala pluton directions and very large differences between Soca–Isla Mala and Mahoma–Marincho characteristic directions.

Table 2
Sample characteristic remanence directions for the study units and their means. Maximum angular deviation (MAD, Kirschvink, 1980) for each direction and α95 (Fisher, 1953) for their means are presented in italics. Positive (negative) inclinations mean downward (upward) directions. Lat and Long correspond to the latitude and longitude of the virtual geomagnetic pole/paleomagnetic pole. Negative (positive) latitudes correspond to southern (northern) hemisphere. A95 is quoted as the semiaxis of the 95% confidence circle of the paleomagnetic pole or as the minor and major semiaxes of the 95 confidence oval (between brackets).

Unit	Site	Sample	Dec (°)	Inc (°)	MAD a95 (°)	Lat (°)	Long (°)	A95 (°)
Soca	G-1	1-2 a	310.1	56.8	*1.5*	4.3	266.8	
34°42.5′S		1-7 a	293.5	53.7	*12.6*	−2.8	255.0	
55°42.8′W		1-4 a	286.6	68.8	*6.5*	−17.8	266.3	
		1-1 a	303.1	54.4	*15.1*	2.4	260.9	
		1-9 a	331.0	53.6	*16.4*	16.0	279.7	
		1-3 a	318.3	56.9	*2.7*	8.1	272.1	
		1-2 b	304.4	69.6	*2.8*	−10.3	274.3	
		1-5	305.1	61.0	*12.8*	−1.7	266.9	
		All (n: 8)	307.6	60.0	6.6	0.4	267.6	(7.5/10)
34°42.6′S	G-2	2-1 a	296.9	62.3	*13.6*	−7.1	263.8	
55°42.8′W		2-2 b	302.3	72.8	*13.5*	−14.6	277.0	
		2-8 a	323.9	76.5	*6.6*	−13.0	289.2	
		2-5 a	317.9	58.4	*7.2*	6.6	272.8	
		2-3 a	325.0	70.0	*4.5*	−3.6	284.6	
		2-9 b	308.1	52.2	*5.7*	6.8	262.6	
		2-6 a	337.8	75.5	*10.6*	−8.9	294.2	
		2-10	318.6	79.3	*11.0*	−18.3	290.1	
		All (n:8)	313.9	68.8	7.4	−5.7	278.0	(10.6/12.5)
Soca		All (n: 16)	310.3	64.4	5.0	−2.4	272.5	(6.4/8.0)
		All (n:16)				−1.2	273.4	7.2
Isla Mala	G-3	3-5 a	292.7	72.6	*1.2*	−17.8	272.7	
34°11.1′S		3-1 a	24.8	84.9	*2.6*	−24.9	308.3	
56°18.6′W		3-2 a	52.7	85.6	*0.9*	−28.6	311.6	
		3-2 b	313.9	85.5	*0.8*	−27.8	296.4	
		3-4 a	164.9	81.4	*0.9*	−50.3	310.5	
		3-3 a	279.1	78.2	*1.6*	−27.9	278.2	
		3-7 a	317.6	73.4	*1.1*	−9.8	283.2	
		3-9 a	310.3	84.4	*0.6*	−26.6	294.2	
		3-10 a	287.8	77.6	*2.0*	−24.4	278.8	
		3-1 b	178.7	85.3	*1.2*	−43.5	304.0	
		3-4 b	276.0	71.1	*0.7*	−24.5	265.5	
		3-8 a	288.1	75.6	*0.8*	−22.5	275.7	
		3-10 b	254.9	82.9	*1.2*	−36.7	286.8	
		3-6 a	99.5	71.4	*7.8*	−32.8	344.6	
		3-6 b	304.9	83.6	*4.9*	−26.4	292.1	
		All (n:15)	287.7	84.1	5.0	−30.0	290.8	(9.1/9.2)
34°11.3′S	G-5	5-11	328.4	56.5	*9.8*	12.9	278.3	
56°19.3′W		5-1 a	20.7	59.9	*13.4*	12.7	319.6	
		5-7 a	10.8	51.6	*10.8*	22.8	313.6	
		5-9 a	19.5	49.0	*11.7*	23.3	322.0	
		5-3 a	300.6	74.9	*5.2*	−17.1	278.4	
		5-8 b	232.1	83.5	*2.7*	−41.4	290.2	
		5-10 a	326.0	76.0	*4.4*	−11.3	288.9	
		5-2 a	201.8	55.5	*5.1*	−72.1	225.9	
		5-2 b	165.3	65.9	*4.4*	−72.2	337.3	
		5-3 b	301.7	62.3	*5.1*	−4.2	265.5	
		5-4 a	300.6	77.6	*5.8*	−20.2	282.0	
		5-6 a	303.1	74.3	*8.0*	−15.6	278.1	
		5-6 b	291.3	82.7	*4.1*	−28.0	288.5	
		5-10 b	320.2	75.4	*3.7*	−11.8	286.1	
		5-11 b	280.2	75.4	*5.2*	−25.5	273.4	
		5-2 b	171.3	62.4	*6.2*	−78.3	336.3	
		5-7 b	286.1	85.4	*4.0*	−31.2	293.4	
		5-9 b	286.6	80.3	*7.0*	−27.1	283.3	
		All (n:18)	316.1	80.9	9.8	−20.7	290.6	(18.2/18.9)
34°10.8′S	G-20	20-1 b	272.7	71.0	*1.3*	−26.1	264.5	
56°19.2′W		20-3 b	308.0	57.6	*0.8*	3.0	265.4	
		20-4 b	285.4	55.3	*4.5*	−8.7	251.4	
		20-5 b	288.3	81.4	*10.3*	−27.6	285.6	
		20-7 b	284.1	67.9	*4.3*	−18.0	263.7	
		20-9 b	246.8	78.7	*1.9*	−40.0	277.2	
		20-10 b	291.2	69.3	*6.4*	−15.5	268.0	
		20-11 b	291.6	69.4	*1.7*	−15.4	268.3	
		All (n: 8)	287.2	69.5	7.3	−17.7	266.8	(10.7/12.5)
Isla Mala		All (n:41)	298.3	80.1	4.9	−23.7	285.2	(9.0/9.4)
		All (n:41)				−24.6	285.8	8.2
Soca + Isla Mala		All (n:57)	304.3	75.7	4.1	−17.7	281.8	6.8
		All (N: 5)	303.9	73.0	10.0			
Mahoma	G-8	8-1 b	286.4	−68.6	*1.9*	−35.8	349.9	
34°05.3′ S		8-2 a	290.2	−61.9	*3.6*	−36.3	1.3	
56°56.2′W		8-6 a	314.3	−72.9	*4.4*	−51.3	339.9	
		8-3 a[a]	253.8	−38.2	*2.0*	0.6	6.4	

Table 2 (*continued*)

Unit	Site	Sample	Dec (°)	Inc (°)	MAD a95 (°)	Lat (°)	Long (°)	A95 (°)
56°56.2′W		8-2 b	306.6	−58.9	*0.7*	−47.5	9.4	
		8-3 b[a]	253.1	−51.4	*3.2*	−5.4	357.6	
		All (n:6)	277.8	−60.9	15.4	−27.3	359.1	(18.0/23.6)
Marincho	G-12	12-2 a	266.1	−65.8	*1.9*	−21.7	348.7	
33°15.5′S		12-2 b	261.0	−58.1	*1.2*	−14.0	355.4	
57°04.9′W		12-3 a	305.3	−74.7	*9.7*	−45.5	336.8	
		All (n:3)	272.1	−67.2	18.2	−26.1	346.8	(25.1/30.2)
	G8-G12	All (n:9)	276.1	−63.1	10.3			
		All (n:9)				−29.0	354.6	13.8

[a] Antipodal direction has been selected.

5. Rock magnetism

In order to get information on the magnetic carriers of the characteristic remanence isolated in the studied plutons, rock magnetic measurements were carried out on representative samples of each site or geologic unit.

Fig. 6 illustrates the Curie-temperature behavior of selected samples. These were performed with a MFK1-A (Agico SA) susceptibility meter. A few milligrams of crushed sample were heated from room temperature to 700 °C in an inert atmosphere (by continuous pumping of argon). During heating (red curve) and cooling down to room temperature (blue curve), bulk susceptibility was measured as a function of temperature. Fig. 6a and b, corresponding to the Soca and Isla Mala plutons, respectively, show nearly reversible curves, with small Hopkinson peaks and abrupt susceptibility decays between 550 and 580 °C, strongly suggesting that the main magnetic carrier is Ti-poor titanomagnetite. Curves for samples from sites g8 (Marincho) and g16 (Empalme Olmos) are similar. They both show susceptibility magnitudes one order of magnitude smaller and highly irreversible curves. Heating curves do not show a well-defined Curie point, while cooling curves show a relatively broad slope between 400 and 550 °C suggesting the formation of titanomagnetite during heating.

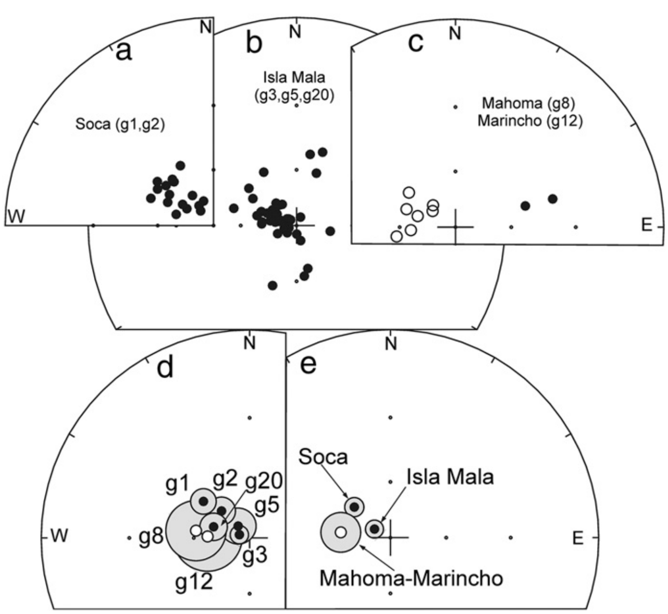

Fig. 5. a) Characteristic remanence directions for samples of the Soca granite; b) idem for samples of the Isla Mala pluton; c) idem for samples of two sites in the Mahoma and Marincho complexes; d) site mean characteristic remanence directions; e) mean sample characteristic remanence directions for the Soca, Isla Mala and Mahoma–Marincho plutons. Open (close) symbols indicate upward (downward) directions. Gray circles indicate mean directions 95% confidence circles. Directions are listed in Table 2. Discussion in the text.

Isothermal remanence (IRM) acquisition curves were also generated for representative specimens from all sites. Results are shown in Fig. 6e. Samples from the Soca and Isla Mala granites (g1, g2, g3, g4, g5) show saturation magnetizations at fields around 200 mT, suggesting ferrimagnetic carriers, consistent with the inference of Ti-poor titanomagnetite from the thermomagnetic curves (Fig. 6a, b). On the other hand, those from the Mahoma, Mal Abrigo and Marincho plutons show more complex acquisition curves that suggest the presence of both ferri and antiferromagnetic phases. Sites g16 and g17 from the Empalme Olmos pluton display widely different behaviors, with (g16) and without (g17) significant contribution of antiferromagnetic carriers.

A few representative samples were analyzed through a vibrating sample magnetometer (Molspin Ltd.). Examples of hysteresis cycles are shown in Fig. 7. In general, a low coercivity phase (Hc < 10 mT) dominates the magnetic signal with variable paramagnetic contribution. Antiferromagnetic contributions are not easily seen in these cycles.

6. Discussion

According to the results presented above, the Soca and Isla Mala plutons, along with isolated sites from the Mahoma and Marincho complexes, carry a well-defined characteristic remanence. Behavior when submitted to AF and thermal demagnetization, as well as rock magnetic investigations, indicates that in the Soca and Isla Mala bodies (Ti-poor) magnetite is the only magnetic carrier. The presence of antiferromagnetic phases in sites g8 (Mahoma) and g12 (Marincho) is likely. AMS results are consistent with macroscopic and microscopic observations of lack of internal deformation in these plutons. Discrete and high unblocking temperatures plus lack of alteration and/or hydrothermal effects on these rocks strongly suggest the magmatic nature of the iron oxides. Based on such considerations, the characteristic remanence is interpreted as a primary magnetization.

Paleomagnetism on plutonic bodies always carries the uncertainty of both paleohorizontal control as well as the possibility for vertical axis rotations that do not internally deform the pluton. In our case, the post-tectonic nature of the magmatism (e.g. Oyhantçabal et al., 2011 and references therein) and the lack of internal deformation suggests that no major post-intrusive deformation has affected the plutons. Late Paleoproterozoic cratonization of the Piedra Alta terrane is widely accepted (e.g. Peel and Preciozzi, 2006; Sánchez Bettucci et al., 2010). Neoproterozoic sedimentary successions in this block are generally flat-lying and the Soca granite is covered by sub-horizontal clastic sedimentary beds of the Neoproterozoic Piedras de Afilar formation (Preciozzi et al., 1985; Gaucher et al., 2008). Consistent directions from the three sites of the Isla Mala body that were separated by distances of ~1 km also support our contention that no major tilting has occurred between the sites. In addition, the Isla Mala body was emplaced at rather shallow depths (around 0.5 kbar according to Preciozzi and Peel, 2005) and therefore major epeirogenic movements also seem unlikely. Finally, since the Soca and Isla Mala mean directions differ mainly

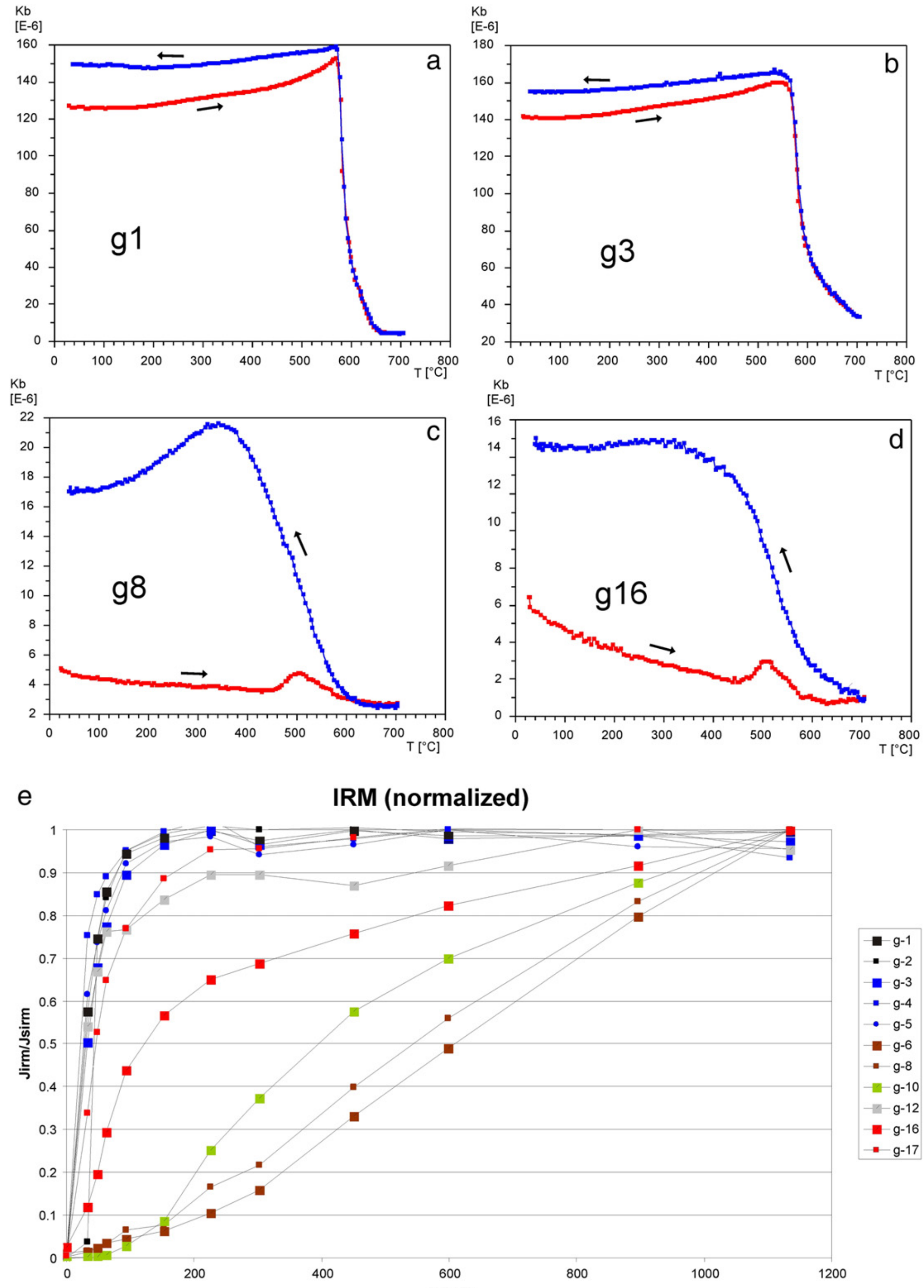

Fig. 6. a) to d) high temperature heating (red) and cooling (blue) thermomagnetic curves (*k* vs. T) for a representative sample of the Soca (a), Isla Mala (b), Mahoma (c) and Empalme Olmos (d) granitoids. e) Normalized isothermal remanent magnetization acquisition curves for representative samples of the study units. Number of sites are indicated. Discussion in the text.

in their inclination values, rotations around vertical axes of the sampling sites do not seem a likely mechanism to explain the discrepancy.

Three different paleomagnetic poles, for the Soca, the Isla Mala and the Mahoma–Marincho plutons, respectively, were obtained in this study. Slow cooling of the intrusive bodies means that there may be slight age differences in remanence acquisition for different samples and therefore we averaged VGP's on a sample basis to calculate individual paleomagnetic poles. Slow-cooling is also supported by opposite polarities directions at the same site (g8) in the Mahoma granite. Although the Soca and Isla Mala plutons carry magnetizations of a single polarity, incomplete averaging of paleosecular variation is considered an unlikely explanation for their different mean directions. Slow cooling of both bodies is strongly suggested by their sizes (Soca: 75 km^2, Isla Mala: over 100 km^2 of exposed outcrops (Oyhantçabal et al., 1998)).

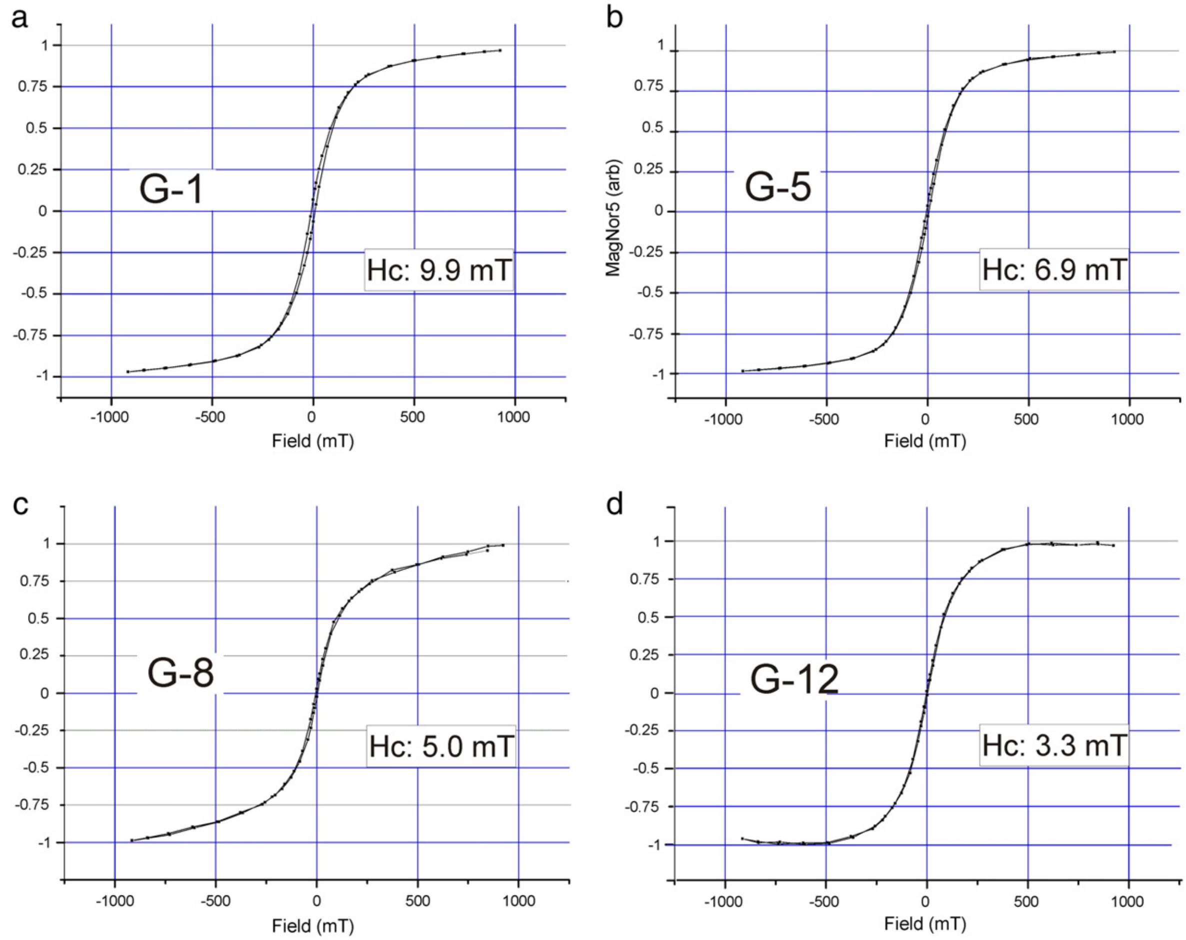

Fig. 7. Representative normalized hysteresis curves for samples of the Soca (a), Isla Mala (b), Mahoma (c) and Marincho (d) plutons. Hc: coercivity values.

Furthermore, in the latter case, the number of samples (41) and distances of around 1 km among sites confirm that enough time elapsed for averaging paleosecular variation during acquisition of magnetization. Therefore, the different mean directions (Fig. 5e) and the corresponding pole positions for the Soca, Isla Mala and Mahoma–Marincho plutons are interpreted as changes in the position of the Piedra Alta terrane during the middle Paleoproterozoic.

Teixeira et al. (2013) recently published a paleomagnetic pole for the Florida dyke swarm of the Piedra Alta terrane, with a well-established age of 1790 Ma. Our poles are distinct from these younger dykes as well as known Phanerozoic pole positions from the Rio de la Plata craton. Although the database is incomplete for the Rio de la Plata, the lack of resemblance to the available younger poles supports our contention that the pole positions obtained in this study represent primary magnetizations. The ages indicated for the paleomagnetic poles on Fig. 8 are those considered most likely for crystallization of the plutons according to U–Pb SHRIMP ages. However, acquisition of magnetization occurs at lower temperatures than closing of the U–Pb isotopic system, so that more likely ages for the paleomagnetic poles obtained may be around 20 to 30 Ma younger (see Discussion below).

The positions of the three paleomagnetic poles in present-day coordinates are shown in Fig. 8. The approximate limits of the Rio de la Plata craton (light pink) and the Piedra Alta terrane (dark pink) are also illustrated. Crystallization ages for the studied plutons range from around 2.1–2.0 Ga. The Mahoma–Marincho preliminary paleomagnetic pole (MM, ca. 2.1 Ga) falls in the South Atlantic and fast apparent polar wander is suggested by the location of the Isla Mala paleomagnetic pole (IM ca. 2.07 Ga) on the Pacific coast of South America near northern Chile. Rapid apparent polar wander, around 25° in latitude, is also implied by the Soca granite pole (S, ~2.06 Ga) that is positioned on the Pacific coast of Ecuador. These are the first paleomagnetic poles of mid-Paleoproterozoic age for the Río de la Plata craton.

Rogers (1996) proposed the existence of a single landmass in the Paleoproterozoic comprising of several South American and African cratons. He called this continent "Atlantica" and proposed that it was made up of the Guiana (or proto-Amazonia), Congo–São Francisco, Río de la

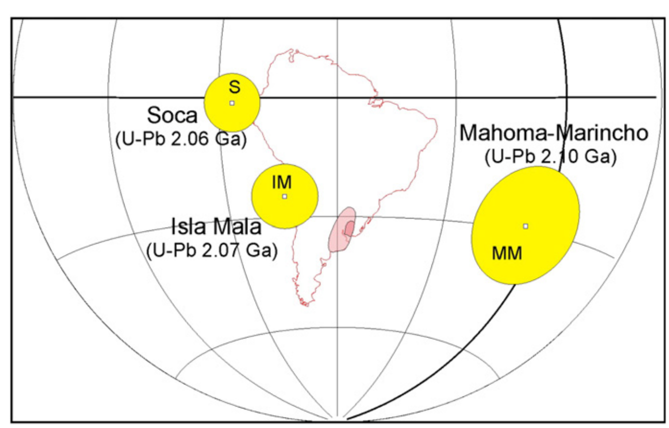

Fig. 8. Paleomagnetic poles for the Soca (S), Isla Mala (IM) and Mahoma–Marincho (MM) units and their respective 95% confidence ovals. Representation in present-day coordinates. The extension of the Rio de la Plata craton (light pink) and the Piedra Alta terrane within it (dark pink) are shown. Ages quoted correspond to the most likely crystallization ages for each unit as inferred from U–Pb datings in zircons.

Plata and West Africa cratons. According to this hypothesis, these blocks remained united from the Paleoproterozoic until the opening of the South Atlantic in the Cretaceous (Rogers and Santosh, 2004). If the Atlantica model is valid, all Proterozoic ophiolitic belts between these cratons (e.g. Fuck et al., 2008) and remains of magmatic arcs (Kröner and Cordani, 2003) reflect subduction and closure of very small oceanic basins. In that light, it is important to test the Atlantica hypothesis in order to understand the geodynamic evolution of South America and Africa. D'Agrella-Filho et al. (2011) provided the first such paleomagnetic test of Atlantica using paleomagnetic poles from the São Francisco, West Africa and Guiana cratons for the interval 2.1–2.0 Ga, approximately (Table 3). They also included a single preliminary paleomagnetic pole for the Soca plus Isla Mala plutons for the Rio de la Plata craton (Badgen et al., 2009). They concluded that the available paleomagnetic data do not support the configuration of Atlantica proposed by Rogers (1996). As shown in Fig. 9, our results do not significantly alter this conclusion as the rudimentary apparent polar wander track obtained for the Rio de la Plata craton in the 2.1–2.0 Ga time span is discordant with coeval paleomagnetic poles from the other cratons.

Our new poles are used to position the Rio de la Plata craton in the Atlantica test. Our new poles along with those used by D'Agrella-Filho et al. (2011) are shown in Fig. 9a. Given the polarity choices made by us (and previous studies), it is difficult to reconcile APWP's for the Atlantica cratons in the 2.1–2.0 Ga interval with the exception of apparent convergence between the Guiana and West Africa poles at around 2.0 Ga (see also Nomade et al., 2003). The overall picture does not support the Atlantica reconstruction proposed by Rogers (1996) and confirms previous conclusions by Badgen et al. (2009) and D'Agrella-Filho et al. (2011). Fig. 9a indicates that the fast polar wander of these blocks is not shared by the Kaapvaal craton (see also Table 3). Most poles from Kaapvaal are distributed in a single group that indicates slow polar wander for this craton, at least for the interval 2.06–2.02 Ga.

Given that the paleomagnetic data do not support an "Atlantica" configuration, is it possible that the blocks were in proximity to one another, but in a different configuration? The idea of Atlantica arose initially from a proposal by Ledru et al. (1994) based on the apparent correlation of Paleoproterozoic fluvio-deltaic sedimentary deposits in the Congo, Guiana and West African cratons. Rogers (1996) and Rogers and Santosh (2004); however, based their hypothesis on similar geologic evolution of these three blocks plus the Rio de la Plata craton in the Paleoproterozoic. A major Paleoproterozoic orogenic cycle, known as "TransAmazonian" (Almeida et al., 1973), with ages of 2.2 to 2.0 Ga is characteristic of these blocks. All these cratons and other smaller crustal blocks (e.g. Borborema province, Nico Perez terrane) share a similar geologic evolution during the Paleoproterozoic (Alkmin and Marshak, 1998; Tassinari and Macambira, 1999; Toteu et al., 2001; Delor et al., 2003; Pacheco Neves, 2003; Barbosa and Sabaté, 2004; Mcreath and Lins Faraco, 2006; De Waele et al., 2008; Oyhantçabal et al., 2011). A brief description of main Paleoproterozoic geologic features of these blocks is presented in Table 4 and illustrates the similarities. They include the existence of large areas of Paleoproterozoic (2.3–2.1 Ga) high grade metamorphic (granulites to gneisses) terrains that correspond to juvenile subduction related magmatism (TTG, e.g. Rio de la Plata, São Francisco, Congo, Guiana) associated with belts of supracrustal rocks composed of metasediments and metavolcanics that were subjected to greenschist to amphibolite facies metamorphism. Protoliths of these metavolcanics generally yield ages around 2.3 to 2.1 Ga. Sm–Nd model ages for the bulk of the metavolcanics fall within the 2.8–2.2 Ga interval with positive ε(Nd)t values and low Sr initial relationships. These data were thought to be indicative of a major crust forming process during the middle Paleoproterozoic.

Several of these "Atlantica" blocks contain Archean nuclei (i.e. Congo–São Francisco, Guiana and West Africa) suggesting some reworking of more ancient crustal fragments. The Congo and West Africa cratons show the largest Archean nuclei (Doumbia et al., 1998; Beziat et al., 2000; Toteu et al., 2001; De Waele et al., 2008), while those from the Guiana (proto-Amazonia) and São Francisco are considerably smaller (Alkmin and Marshak, 1998; Tassinari and Macambira, 1999; Barbosa and Sabaté, 2004; McReath and Lins Faraco, 2006). Only a small scattering of Archean rocks are found in the Rio de la

Table 3
Selected paleomagnetic poles between ca. 2.1 and 2.0 Ga for the Río de la Plata, Congo–São Francisco, Guiana, West Africa and Kaapval craton. Selection follows that of D'Agrella-Filho et al. (2011). Poles presented in present-day coordinates.

Craton	Pole	Geologic unit	Pole Position			Rock age (Ma) and method	Magnetic age (Ma)	Ref
			Lat (°)	Long (°)	A95 (°)			
Guiana (G)	GF1	Mean granitoids GF1	1.8	292.5	11.8	2115–2089 (U–Pb)	2075	1
	AT	Armontabo tonalite	−2.7	346.3	*15.5*	2080 (U–Pb)	*2040*	2
	OY	Oyapok granitoids	−28.0	346.0	13.8	2020 (Ar–Ar A) 1973 (Ar–Ar B)	2036	2, 3
	GF2	Mean granitoids GF2	−58.5	30.2	5.8	2069–2061 (U–Pb)	*2000*	1
Rio de la Plata (R)	MM	Mahoma and Marincho granites	−34.1	355.8	16.4	2108 (U–Pb) 2067 (Rb–Sr wr)	*2075*	4
	IM	Isla Mala granite	−24.6	285.8	8.2	2074–2065 (U–Pb)	*2040*	4
	S	Soca granite	−1.2	273.4	7.2	2056 (U–Pb)	*2020*	4
São Francisco (S)	J	Jequié formation	−0.5	342.1	9.6	2061–2047 (U—Pb) 2035 (Ar–Ar A) 1876–1766 (Ar–Ar B)	2020	1
	U	Uauá dykes	23.8	331.4	6.5	2003–1975 (K–Ar A)	*2000*	5
West Africa (W)	IC	Ivory Coast granite	−82.0	292.0	13.0	2123–2108 (U–Pb)	2085?	6
	F	Ferke granite	−25.0	83.0	16.0	2094 (Pb–Pb)	2000	6
	L	Liberia granulite	−18.0	89.0	13.0	2044 (Rb–Sr wr)	*2000*	7
	A	Aftout granite	−6.0	90.0	8.0	*1982–1950*	*1980*	8
	H	Harper amphibolite	−10.0	73.0	7.0	1900–2000 (Ar–Ar)	*2000*	9
Kaapvaal (K)	BC	Bushveld complex mean	19.2	30.8	5.8	2056 (U–Pb)		10
	PC	Phalaborwa complex	35.9	44.8	9.0	2060 (U–Pb)		11, 12
	LS	Lower Swaershoek	36.5	51.3	10.9	2054 (U–Pb)		13
	V	Vredefort mean	22.8	41.6	10.6	2023 (U–Pb)		14
	USA	Upper Swaershoek–Alma Fms	−10.5	330.4	9.8	*2054–1930*		13
	LM	Limpopo metamorphics A	26.1	22.3	9.1	1980–1950 (Rb–Sr)		15
	W	Witwatersrand overprint	19.1	45.6	7.8	1945 (K–Ar I)	1945	16

1. D'Agrella-Filho et al. (2011); 2. Théveniaut et al. (2006); 3. Nomade et al. (2001); 4. This paper; 5. D'Agrella-Filho and Pacca (1998), Nomade et al. (2003); 7. Onstott and Dorbor (1987); 8. Lomax (1975); 9. Onstott et al. (1984); 10. Letts et al. (2009); 11. Morgan and Briden (1981); 12. Reischmann (1995); 13. de Kock et al. (2006); 14. Salminen et al. (2009); 15. Morgan (1985); 16. Layer et al. (1988).

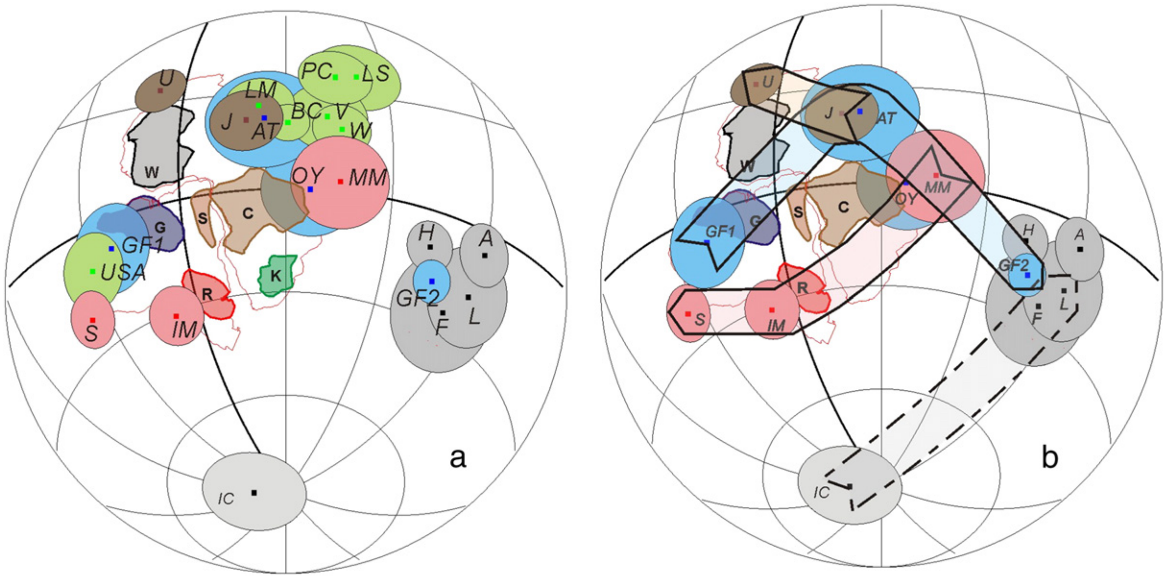

Fig. 9. a) Distribution of selected paleomagnetic poles of ca. 2.1–2.0 Ga from the Río de la Plata, Congo–São Francisco, Guiana, West Africa and Kaapval cratons in south African coordinates within a Gondwana reconstruction according to Lawver and Scotese (1987). b) idem a) with apparent polar wander tracks for each craton (Kaapval poles have been excluded). Discussion in the text.

Plata craton (e.g., the Nico Perez terrane). It is uncertain whether or not these Archean outcrops were part of the Rio de la Plata block in the Paleoproterozoic (e.g. Gaucher et al., 2011; Oyhantçabal et al., 2011; Rapela et al., 2011). Other Archean remnants are found in the Borborema province located between the São Francisco and the Amazonia cratons. The Borborema terrane underwent major crustal remobilization in the Neoproterozoic. Archean nuclei are now surrounded by Paleoproterozoic belts of metamorphosed supracrustal rocks (2.24–

Table 4
Main Paleoproterozoic geologic features of cratons proposed to have integrated Atlantica.

Craton	Main geologic features	References
Río de la Plata (Piedra Alta)	Vast granitic–gneissic areas separated by supracrustal metamorphic belts (basalts, turbidites, iron formations) assigned to intra-oceanic or back-arc environments. Dominant Sm–Nd model ages (2.6–2.2 Ga). Granitic–gneissic terranes are juvenile products of subduction related magmatism (TTG). Crustal stabilization at ca. 2.0 Ga. 2.1–2.0 undeformed granites. Late Paleoproterozoic mafic dykes (1.79 and 1.59 Ga).	Oyhantçabal et al. (2011), Sánchez Bettucci et al. (2010)
São Francisco (mainly northern areas)	Several fragments of Archean basement (ca. 3.4 Ga), e.g. Gaviao, Jequié, Serrinha Blocks. Contendas–Jacobina lineament: structural evidence of 2.1Ga continental collisions of Archean blocks. Deformation, metamorphism and crustal thickening (TransAmazonian Orogeny). Magmatism of 2.1–2.0 Ga in the Archean blocks. Granites, tonalities, gabbros (2.6–2.9 Ga Sm/Nd model ages). Mainly undeformed. Collision of magmatic arcs against continental margin (to the west of São Francisco, present-day coordinates).	Barbosa and Sabaté (2004), Alkmin and Marshak (1998)
Congo	Several Archean blocks: Gabon, Angola, Kazai and Tanzania. Granulite, granite and gneisses. Greenstone Belts. Juvenile crust (2.8–2.7 Ga). Superimposed magmatic activity (2.2–2.0 Ga). Paleoproterozoic belts surround the Angola, Tanzania and Kazai blocks: amalgamation of independent blocks into the proto-Congo craton in the Paleoproterozoic (Eburnean = TransAmazonian Orogeny). Further tectonic and magmatic activity continued in the Paleoproterozoic to Mesoproterozoic. Similar evolution to São Francisco.	De Waele et al. (2008); Toteu et al., 2001
Guiana	Juvenile oceanic crust at 2.26–2.20 Ga, (gabbroic rocks from "Île de Cayenne Complex"). TTG magmatism (2.18 to 2.13 Ga) and regionally associated coeval greenstone belts (multi-pulse island-arc subduction related plutono-volcanism). Post-tectonic granitic magmatism and minor gabbroic intrusions at ca. 2.11–2.08 Ga. No preserved remnants of the Archean continents in French Guiana. Undeformed Archean blocks in the central Amazonian Province. Late Paleoproterozoic mafic dykes (1.79 Ga).	Delor et al. (2003), Tassinari and Macambira (1999), Mcreath and Lins Faraco (2006).
West Africa	Two large Archean cratons. In between very large Paleoproterozoic greenstone belts (2.15–2.10 Ga): intraoceanic volcanic arcs. Juvenile granites intrude the greenstone belts (2.12–2.09 Ga). São Luis craton (Brazil): metavolcanics and metasediments (2240 Ma) intruded by undeformed granitic suites (batholiths) of 2.15 Ga. Sm/Nd ages of 2.22–2.26 Ga. Very juvenile crust. Part of NW Africa.	Doumbia et al. (1998), Beziat et al. (2000), Klein et al. (2005), Klein and Moura (2008).

2.1 Ga). In addition, both reworked Archean crust and juvenile magmatism is present (Pacheco Neves, 2003).

In the largest cratons, Congo–São Francisco, proto-Amazonia and West Africa, the distribution of Paleoproterozoic orogenic belts between Archean blocks indicate that the TransAmazonian cycle was characterized by collision and accretion of Archean and early Paleoproterozoic microcontinents along with the development and accretion of intra-oceanic magmatic arcs.

The similar geologic evolution reveals a major episode of crustal formation and continental assembly at roughly 2.3–2.0 Ga that would seem to support the conclusion that they were assembled into an Atlantica configuration (as originally proposed by Rogers, 1996). Paleomagnetic data, on the other hand, do not support the Rogers (1996) proposed configuration of Atlantica. Below we illustrate that the paleomagnetic data can be reconciled into a modified version of Atlantica.

Since many of the paleomagnetic results used in the following analysis are derived from plutonic igneous rocks that are dated with high precision U–Pb techniques that give crystallization ages, we note that the ages may be older than the age of magnetization. The availability of Ar–Ar ages, whether in hornblende or biotite, allows for the calculation of approximate cooling ages and rates, and therefore more realistic ages for primary magnetizations in plutons. In some cases that age determination is available. For instance, the more likely magnetization age for the Oyapok granitoids in Guyana (Nomade et al., 2001) is around 2036 Ma (see Table 3), although Théveniaut et al. (2006) have argued for a slightly younger age of ca. 2020 Ma. The most likely magnetization age for the Armontabo Tonalite, also in Guiana (with an U–Pb crystallization age of 2080 Ma, Théveniaut et al., 2006), is considered as 2040 Ma, slightly older than the 2030 Ma proposed by Bispo-Santos et al. (in press) or 2020 Ma by Théveniaut et al. (2006). The Jequié Complex from the São Francisco craton (D'Agrella-Filho et al., 2011) has been assigned a likely age of magnetization of ca. 2020 Ma (U–Pb age 2061–2047), and the Ferke Granite, in Ivory Coast (West Africa craton, Nomade et al., 2003) a likely one of just 2000 Ma, with a crystallization age of 2094 Ma. Other plutonic bodies, such as the Ivory Coast Granites could be estimated from the age (ca. 2085 Ma) of a major hydrothermal event affecting these rocks (Nomade et al., 2003). In most cases inferred magnetization ages are 20–40 Ma younger than crystallization ages (Table 3). From their respective position on the proposed track, the most likely magnetization ages are suggested for the remaining paleomagnetic poles (in italics in Table 3). Our best estimate for the ages of the Mahoma–Marincho, Isla Mala and Soca poles are 2075, 2040 and 2020 Ma, respectively.

Fig. 10 shows that a single, lengthy APWP can be constructed for the Rio de la Plata, Congo–São Francisco and Guiana cratons for the interval from 2075 to 2000 Ma. West Africa can be positioned within this larger landmass at around 2000 Ma based on the merging of several poles from West Africa with coeval poles from Congo–São Francisco and Guiana.

A single track for the Rio de la Plata, Guiana and West Africa cratons from around 2.075 to 2.0 Ga described above, requires drastic paleogeographic positioning of the constituent cratons (as compared to Atlantica sensu Rogers, 1996). In the alternative reconstruction, Rio de la Plata and Congo–São Francisco are inverted as shown in Fig. 10. The position of West Africa with Guiana (as constrained by significant geologic evidence and the West African affinity of the small São Luis craton in NE Brazil, Klein et al., 2005) does not match the position required by the 2.085 Ga paleomagnetic pole of West Africa and the approximately coeval poles of Rio de la Plata and Guiana, suggesting that assembly of West Africa into Rio de la Plata/Guiana postdates that age. Coincidence of poles of around 2.0 Ga from Guiana and São Francisco with those from West Africa, on the other hand, suggests that the latter had already accreted by that time.

Taking into account the striking mid-Paleoproterozoic geologic similarities in all four cratons, it is a reasonable conclusion to propose an Atlantica landmass with a modified configuration. In our hypothetical

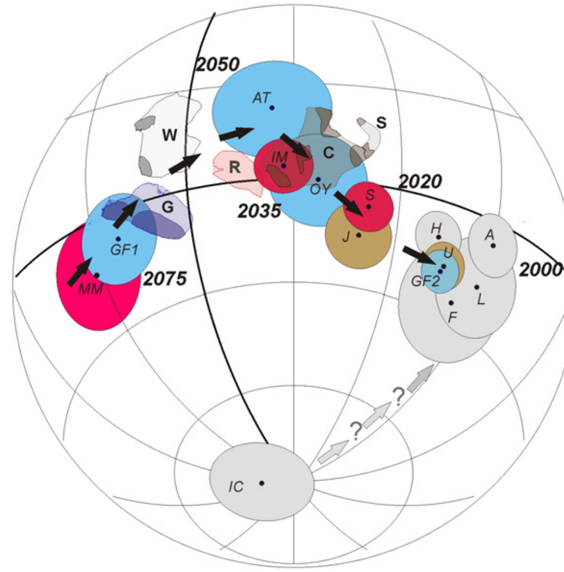

Fig. 10. A single apparent polar wander path can be defined for the Atlantica forming cratons (Río de la Plata, Congo–São Francisco, Guiana and West Africa) accepting a different configuration. Numbers indicate most likely magnetization ages (Ma) along the track. Note that West African poles only coincide for ages of 2.0 Ga., while the single older pole (ca. 2.085 Ga — IC) is not consistent with poles of similar ages, suggesting accretion at some time in between. Darker areas correspond to approximate extension of Archean nuclei. More discussion in the text. The proposed reconstruction was obtained by the following rotations relative to West Africa: Congo (0°S, 30°E, 155°ccw); Rio de la Plata (12°S, 8°E, 165°ccw). All South American blocks were previously rotated into African coordinates following Lawver and Scotese (1987; 45.5°N, 32.2°W, 58.8°ccw).

reconstruction, a relatively large gap is found between the eastern (present day coordinates) margin of the Rio de la Plata craton and the Guiana block. Smaller crustal fragments like the Nico Perez (Oyhantçabal et al., 2011) and the Borborema province (Pacheco Neves, 2003) may account, at least partially, for that missing part of Atlantica. Both terranes have significant evidence of mid-Paleoproterozoic magmatic and tectonic activity, coeval with that of the major cratons. The Congo craton is presented in the figure as an already formed single tectonic unit. This is likely a simplification, as this large craton is made of several large Archean nuclei, like the Gabon, Angola, Kasai and Tanzania blocks. Further tectonic and magmatic activity continued in the Congo craton in late Paleoproterozoic and Mesoproterozoic times (Toteu et al., 2001; De Waele et al., 2008; Tack et al., 2010), indicating major tectonic activity within the Congo craton. Nevertheless, correlation of eastern Tanzania and western Río de la Plata is suggested by our reconstruction. Since several poles show uncertainties of 10° or more and cooling rates for most units are not known, the proposed configuration of Atlantica that permits a single apparent polar wander path for this continent is not unique. Further paleomagnetic results and new precise cooling ages are needed for a refinement of the model (see also discussion by Meert, 2014).

Paleogeographic relations between Atlantica-forming blocks and Columbia (Rogers and Santosh, 2002; Hou et al., 2008; D'Agrella-Filho et al., 2011; Meert, 2012) are not well constrained. Separation of both blocks and/or disintegration within Atlantica may have occurred in the late Paleoproterozoic to early Mesoproterozoic (i.e. 1.8–1.5 Ga), an interval in which large tholeiitic dyke swarms intruded the Rio de La Plata, São Francisco and Amazonian crusts (Choudhuri et al., 1990; Teixeira, 1990; Bellieni et al., 1995; Silveira et al., 2013). Teixeira et al. (2013) have recently presented a paleomagnetic pole from the 1.79 Ga basic Florida dykes from the Piedra Alta terrane. When compared with the coeval poles from the Amazon (Guiana) craton, no matter whether the 1.78 Ga, Avanavero Sills pole (Reis et al., 2013) or the 1.79 Ga Colider complex pole (Bispo-Santos et al., 2008) is selected (see Reis et al., 2013 for discussion on both poles), no consistency is found with that from the Florida dykes that can support the alternative

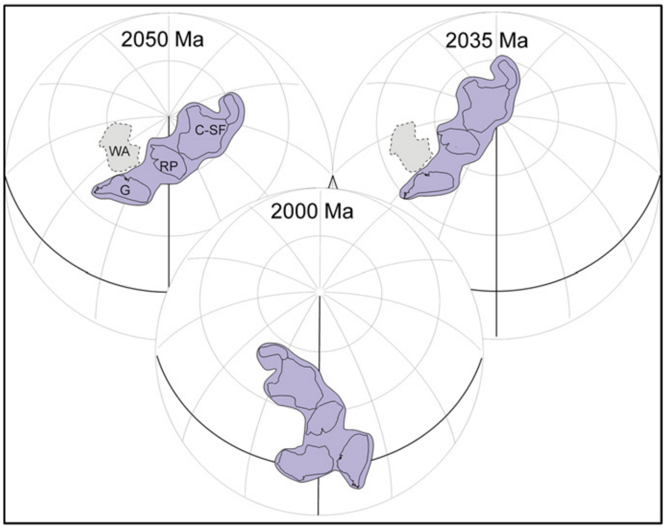

Fig. 11. Paleomagnetically controlled paleogeographic reconstruction of the proposed Atlantica continent at 2.05, 2.035 and 2.0 Ga. West Africa is presented with a different color in the former two reconstructions since no paleomagnetic constrain on its position is available. Note fast displacement towards lower latitudes between 2.035 and 2.0 Ga. Polarity indetermination precludes defining to which hemisphere corresponds. More discussion in the text.

paleogeographic reconstruction of Atlantica presented here. This would mean that by ~1.8 Ga, the Atlantica continent was no longer a single entity. However, the characteristic remanence directions for the Florida dykes (Teixeira et al., 2013) are similar to the present-day Earth's magnetic field direction in Uruguay, as already found by Halls et al. (2001), whose component “B”, considered as a recent overprint, corresponds to that interpreted by the former authors as a primary remanence but with no field test that confirms the nature of the remanence. This suggests that no unambiguous paleomagnetic test of the Atlantica configuration is yet possible after 2.0 Ga.

Fig. 11 shows sketches on the paleogeographic configuration and evolution of Atlantica between 2.05 and 2.0 Ga, as determined by paleomagnetic data. The motions implied by our reconstruction indicate both rapid rotation and latitudinal shifts of Atlantica in that interval.

7. Conclusions

A paleomagnetic study on mid-Paleoproterozoic undeformed plutons in the Piedra Alta terrane of the Río de la Plata craton produced three paleomagnetic poles. They correspond to the Soca, Isla Mala and Mahoma–Marincho granites, with crystallization ages of ca. 2.06, 2.07 and 2.10 Ga, respectively. These poles suggest fast apparent polar wander at high latitudes for Rio de la Plata. A comparison with coeval poles from the Guiana, Congo–São Francisco and West African cratons indicates that the previously proposed configuration of Atlantica as a landmass nearly identical to Western Gondwana is unlikely. The paleomagnetic data permits the existence of a single landmass comprising the four above mentioned cratons if a radically different configuration is accepted. This new paleogeographic reconstruction of Atlantica allows a single apparent polar wander track for Rio de la Plata, Congo–São Francisco, Western Africa and Guiana from ~2.1 to 2.0 Ga. According to the available data Atlantica may have originated at high (polar) latitudes and migrated towards the equator by 2.0 Ga.

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