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Paleomagnetism of the Sierra de Las Animas Complex, southern Uruguay: its implications in the assembly of western Gondwana

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Abstract

Global paleogeographies in the Neoproterozoic are poorly known. In particular, the assembly of Gondwana at the end of the Proterozoic is controversial. In order to constrain the kinematic evolution of the Rio de la Plata craton, a paleomagnetic study was carried out in the Vendian to Cambrian Sierra de Las Animas magmatic Complex, exposed in southeastern Uruguay (34.7°S, 55.3°W). One hundred and forty-seven samples from 23 sites were studied. These included two sites on the Vendian glaciogenic sediments of the Playa Hermosa Formation. After stepwise AF and thermal cleaning a characteristic remanence was isolated at several sites. According to the available isotopic data for the complex and the correlation between remanence directions and lithologic type and age, two paleomagnetic poles were computed for the Sierra de Las Animas complex. SA1 (338.1°E, 5.9°N, dp = 19.6°, dm = 26.7°, $N = 7$ sites, mean declination: 44.5°, mean inclination: 58.0°, α_{95}: 18.1°), with a likely age around 520 Ma, shows a distribution of VGPs that suggests a remanence acquisition that spanned a long time during a period of fast apparent polar wander for Gondwana. SA2 (250.9°E, 16.9°S, dp = 15.9°, dm = 21.5°, $N = 6$ sites, mean declination: 95.3°, mean inclination: −58.5°, α_{95}: 14.5°) corresponds to a likely age around 550 Ma and falls close to a pole of similar age from the Congo craton. This suggests that the Rio de la Plata craton was at that time part of Gondwana and confirms previous postulates that a single APWP can be defined for the supercontinent since 550 Ma. A preliminary mean geomagnetic pole obtained from the Playa Hermosa Formation (PH, 198.4°E, 43.0°S, dp = 8.6°, dm = 16.0°, $n = 6$ samples, mean declination: 226.0°, mean inclination: 24.2°, α_{95}: 15.0°) is consistent with a previous pole of 595 Ma from the Campo Alegre (CA) lavas and may suggest, if confirmed, that the glaciogenic deposits were produced at low to intermediate latitudes. Despite high uncertainties, a new speculative model on the process of assembly of Gondwana is proposed.

Keywords: Paleomagnetism; South America; Neoproterozoic; Gondwana; Paleogeography; Uruguay

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1. Introduction

The global paleogeographic evolution of the Neoproterozoic is loosely bracketed by the break-up of Rodinia (Hoffman, 1991) and the assembly of Gondwana (e.g. Rogers et al., 1995). The exact paleogeographic reconstruction of Rodinia and how the different blocks that integrated it evolved to form Gondwana, as well as the precise time of its assembly, is at present very controversial (see for instance Powell et al., 1993; Weil et al., 1998; D'Agrella et al., 1998; Piper, 2000; Trompette, 2000; Meert, 2001; Powell and Pisarevsky, 2002). In particular, very different models have been proposed for the chronology and sequence of accretions that led to Gondwana assembly (e.g. Trompette, 1997, 2000; Brito Neves and Cordani, 1991; Grunow et al., 1996; Prave, 1996; Brito Neves et al., 1999; Meert, 2001, 2002). The lack of preserved oceanic basins and hotspots and the very limited fossil record in the Neoproterozoic imply that paleogeographic reconstructions for these times must rely heavily on paleomagnetic data. However, the available database is very scarce (see for instance Meert and Powell, 2001) and its reliability is in most cases far from ideal. This indicates that a robust picture of the global paleogeographic evolution in the Neoproterozoic must await acquisition of numerous reliable paleomagnetic data from the major tectonic blocks.

One of the blocks that integrated Western Gondwana is the Rio de la Plata craton (Fig. 1). Its paleogeographic evolution and its relationship to neighboring cratons during Gondwana assembly is controversial and poorly known. In order to reduce the uncertainties on this issue, a paleomagnetic study was carried out in the Vendian to Cambrian Sierra de Las Animas Complex, exposed in southeastern Uruguay.

The Sierra de Las Animas Complex is a bimodal volcanic and subvolcanic suite exposed close to the town of Piriapolis (34.7°S, 55.3°W, Fig. 2). It has been assigned to an extensional event, which marks the end of the Neoproterozoic Brasiliano orogenic cycle (Bossi and Navarro, 1988; Oyhantçabal et al., 1993; Sánchez-Bettucci, 1997). It is represented by syenites, trachytes, rhyolites, ignimbrites, basalts and intercalated sediments. Radiometric dates by different methods on different lithologies range from 615 to 490 Ma (Umpierre, 1965 in Bossi, 1966; Cingolani et al., 1993; Preciozzi et al., 1993; Sánchez-Bettucci and Linares, 1996; Linares and Sánchez-Bettucci, 1997), but precise and systematic geochronologic studies are still lacking.

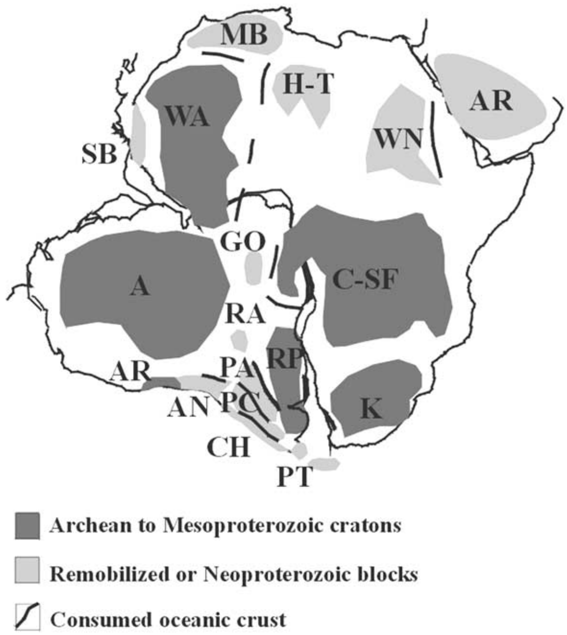

Fig. 1. Main tectonic domains of Western Gondwana in the Neoproterozoic. A, Amazonia; AB, Central Arabia; AN, Antofalla; AR, Arequipa; CH, Chilenia; C-SF, Congo-Sao Francisco; GO, Goias; H-T, Hoggar-Tibesti; K, Kalahari; MB, Moroccan block; PA, Pampia; PC, Precordillera; PT, Patagonian–Malvinas block; RA, Rio Apa; RP, Rio de la Plata; SB, Senegalese block; WA, West Africa; WN, West Nile. Modified from Ramos (1988), Villeneuve and Corneé (1994), Rogers et al. (1995), Unrug (1997), Brito Neves et al. (1999), Rapalini et al. (1999).

The main geological framework of Uruguay shows a great similarity with that observed in southern Brazil. The Paleoproterozoic Rio de la Plata craton (Dalla Salda et al., 1988; Basei et al., 2000 and references therein), makes up most of the Uruguayian territory, and extends to the south into the province of Buenos Aires in Argentina (see Cingolani and Dalla Salda, 2000); and to the north into the Brazilian southern state of Rio Grande do Sur. In Neoproterozoic times, the Rio de la Plata craton integrated a single plate with the

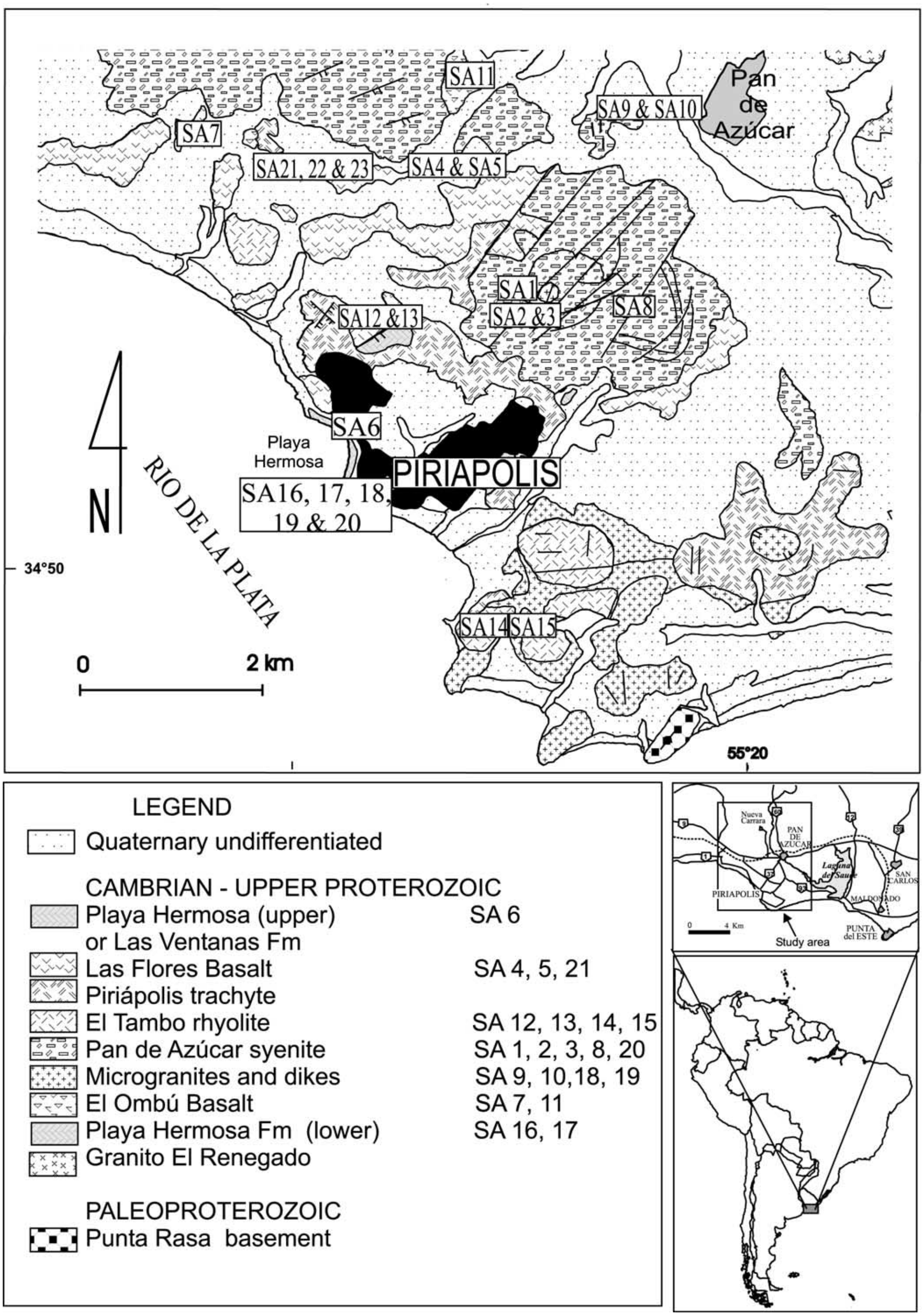

Fig. 2. Geological map of the Piriápolis–Pan de Azucar region in southern Uruguay with location of the paleomagnetic sampling sites.

Luis Alves block in southern Brasil (Cordani et al., 2000). The Río de la Plata craton is made up of a Paleoproterozoic nucleus with a minor influence of Neoproterozoic orogenic events (Dalla Salda et al., 1988; Cingolani and Dalla Salda, 2000); while on the East this orogenic event is very well exposed along the Don Feliciano belt (Fragoso-Cesar, 1980). Towards the West, it is covered by the very thick Phanerozoic sedimentary deposits of the Chaco-Pampean plains. The western boundary is probably located along a Neoproterozoic-Cambrian suture with the Pampia terrane (Ramos, 1988; Kraemer et al., 1995; Rapela et al., 1998, etc).

2. Geological setting

The Sierra de Las Animas Complex constitutes an association of intrusive, volcanic and sedimentary rocks generated during an extensional stage within the evolution of the Neoproterozoic Brazilian orogeny (Sánchez-Bettucci, 1997). The studied area is situated in southeastern Uruguay (Fig. 2), and presents a complex stratigraphic sequence. It is composed of an igneous association of bimodal character represented by intrusive bodies, subvolcanic, volcanic and pyroclastic rocks. Syenites, microsyenites, and granites represent the intrusive bodies. Trachyte constitutes the more abundant and widely distributed rock. The extrusive units are rhyolites, dacites, basalts and pyroclastic flows. The complex has a subalkaline to alkaline tendency without feldspathoid, but presenting pyroxene and alkaline amphiboles. Lithologically, the volcanic and subvolcanic Sierra de Las Animas Complex is represented (Sánchez-Bettucci, 1997, see also Fig. 3) by.

2.1. Mafic volcanic rocks

2.1.1. El Ombú formation

Massive basalts, dikes and trachybasalts integrate this unit. The massive basalts are cut by trachytes. They show microlitic subfluidal texture, with plagioclase, pyroxene and olivine. The trachybasalt presents intersertal subfluidal porphyritic texture, with phenocryst of plagioclase. There are common titanite patches, iddingsite and great quantity of pyrite. In some places, the basalts are intercalated with rhyodacitic material.

2.1.2. Las Flores formation

Vesicular basalts, amygdaloidal dikes and autoclastic breccias represent the Las Flores Formation. The vesicular basalts present doleritic texture, albitized plagioclase, olivine and scarce pyroxene (augite, augite–aegirite). The amygdaloidal dikes present intersertal subfluidal porphyritic texture, with olivine and augite, plagioclase and alkali feldspar.

2.2. Felsic volcanic and intrusive rocks

2.2.1. Microgranites and granophyric rocks

They present porphyritic texture with granophyric matrix. They consist of alkaline feldspar, quartz, biotite and muscovite.

2.2.2. Pan de Azúcar formation

The Pan de Azúcar hill, located 5 km to the north of Piriápolis City, constitutes a syenitic ovoidal body. It presents uneven-grained to hypidiomorphic texture, with variable grain size, with albite and/or oligoclase, perthitic orthoclase, uralitized pyroxene, alkali amphibole, interstitial quartz and scarce biotite. It is common to find orthoclase surrounding the plagioclase (antirapakivi texture). Arfvedsonite, riebeckite, hornblende, aegirite–augite and brown biotite represent the mafic minerals.

2.2.3. El Tambo formation

Rhyolites, rhyodacites, dacites and pyroclastic flows are well represented. It has microporphyritic texture constituted by phenocrysts of alkali feldspar, plagioclase, quartz and biotite, with felsitic matrix and granophyric texture. The pyroclastic rocks are extremely variable from tuff to breccias. Laminated tuff occurs occasionally. The ignimbrites present a brown color and eutaxitic texture. Spherulitic textures are common.

2.2.4. Piriápolis formation

Trachytic lavas, porphyry trachytes and dikes represent the Piriápolis Formation. These rocks

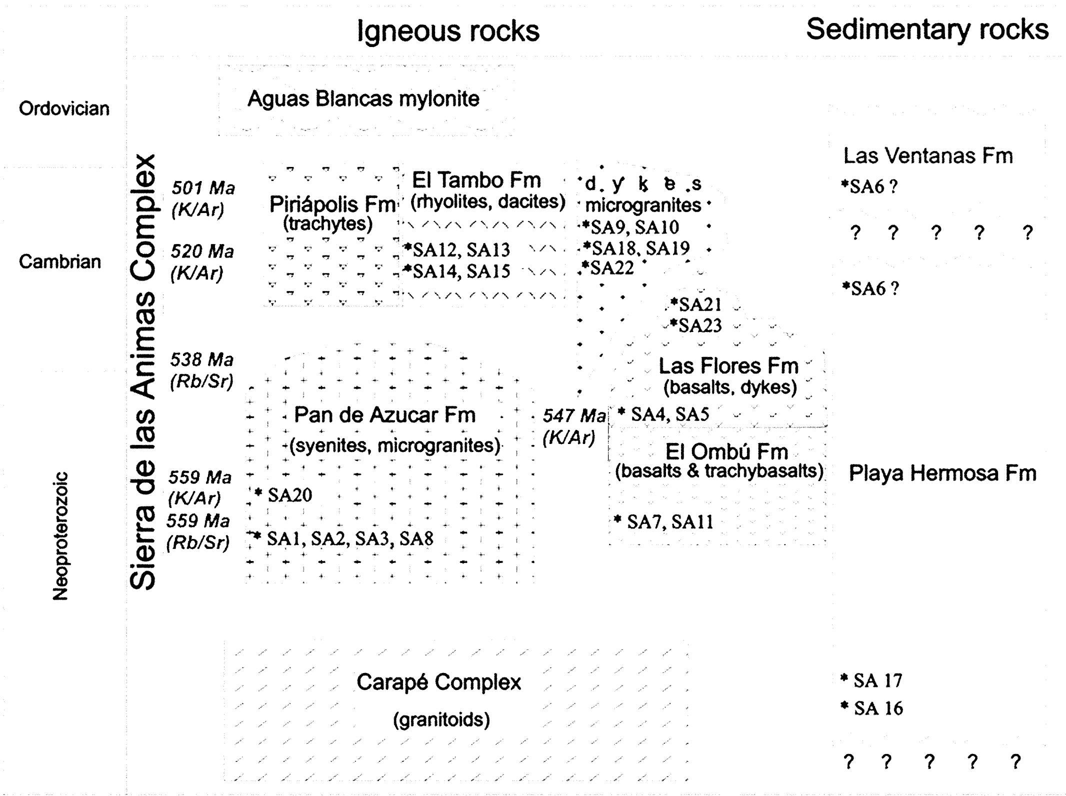

Fig. 3. Simplified stratigraphic scheme of Neoproterozoic–Early Paleozoic rocks in the Piriapolis area. Approximate stratigraphic position of the sampling sites is indicated (based on Sánchez-Bettucci, 1997).

are characterized by a typical trachytic and porphyritic texture, with orthoclase phenocrystals, sanidine, plagioclase, amphibole, biotite and scarce quartz. The matrix present trachytic or bostonitic texture.

The Sierra de las Animas complex was extruded in Late Neoproterozoic and Cambrian times, apparently during a period of around 30–40 million year, according to the available radiometric data (Umpierre, 1965 in Bossi, 1966; Cingolani et al., 1993; Preciozzi et al., 1993; Sánchez-Bettucci and Linares, 1996; Linares and Sánchez-Bettucci, 1997). A simplified stratigraphic scheme of the Sierra de las Animas Complex and related units in the Piriapolis area is presented in Fig. 3. Although a systematic geochronologic study has not been undertaken, and that a recent preliminary attempt to do some Ar/Ar datings of basaltic samples failed (J. Meert, personal communication), the available data suggests the presence of at least two main phases of magmatism (Sánchez-Bettucci and Linares, 1996). The oldest phase produced the intrusion of the syenites of the Pan de Azucar formation and related bodies with an average age of 559 ± 15 Ma as computed from Sánchez-Bettucci and Linares (1996) (see Table 1), and the extrusion of the basaltic flows (computed mean age: 547 ± 12 Ma, from Sánchez-Bettucci and Linares, 1996, Table 1) of the El Ombú and possibly the Las Flores formations. An overall weighted mean age (K/Ar whole rock) for this phase is 551 ± 10 Ma ($N = 6$ determinations, Table 1), although dispersion of individual ages is large. A Rb/Sr errochron based on five samples from the Pan de Azucar formation gives an age of 538 ± 46 Ma (Ro = 0.7043, MSWD = 3.8, Linares and Sánchez-Bettucci, 1997, Table 1), which is compatible considering the large errors with another erro-

Table 1
(A) Available experimental data of K/Ar datings of the Sierra de Animas complex; (B) idem A for Rb/Sr datings

Geologic unit	Lithology	Material	K (%)	$K^{40} \times 10^{-8}$	Ar^{40} Rad mol/g $\times 10^{-10}$	Ar^{40} Atm mol/g (%)	Age (Ma)	Reference
(*A*) *K/Ar dates*								
Las Flores Fm	Basaltic dyke	WR	2.80	8.358	27.491	13.30	490 ± 15	1
/ / / / / / / / /	/ / / / / / / / / / /	/ / / / / /	/ / / /	/ / / / /	/ / / / / / /	/ / / / / / /	/ / / / / / /	/ / / / / / /
El Ombú and Las Flores Fms	Basalt	WR	2.00	5.970	20.397	14.90	525 ± 15	1
	Basalt	WR	2.50	7.463	26.730	10.70	565 ± 30	1
	Trachybasalt	WR	3.00	8.955	40.602	4.60	615 ± 30	1
/ / / / / / / / /	/ / / / / / / / / / /	/ / / / / /	/ / / /	/ / / / /	/ / / / / / /	/ / / / / / /	/ / / / / / /	/ / / / / / /
Pan de Azucar Fm	Microsyenite	WR	3.89	11.612	41.932	34.20	533 ± 25	1
	Syenite	WR	3.94	11.761	46.375	19.90	558 ± 25	1
	Syenite	WR	3.22	9.612	39.476	21.30	596 ± 30	1
Geologic unit	**Lithology**	**Material**	**Rb (ppm)**	**Sr (ppm)**	$^{87}Rb/^{86}Sr \pm Er$	$^{87}Sr/^{86}Sr \pm Er$	**Reference**	
(*B*) *Rb/Sr dates*								
El Tambo Fm	Rhyolite	WR	324.0	29.0	33.087 ± 0.660	0.942620 ± 0.000120	2	
" " "	" " "	WR	224.0	36.0	18.256 ± 0.360	0.845410 ± 0.000810	2	
" " "	" " "	WR	222.0	29.0	22.516 ± 0.450	0.871290 ± 0.000210	2	
" " "	" " "	WR	166.0	58.0	8.336 ± 0.166	0.769930 ± 0.000090	2	
Piriapolis Fm	Trachyandesite	WR	53.0	777.0	0.197 ± 0.004	0.708000 ± 0.000090	2	
/ / / / / / /	/ / / / / / / / / / /	/ / / / /	/ / / /	/ / / / /	/ / / / / / / / / / /	/ / / / / / / / / /	/ / / / / / /	
Pan de Azucar Fm	Syenite	WR	95.0	102.0	2.69 ± 0.050	0.726630 ± 0.000130	3	
	" " "	WR	71.0	25.0	8.20 ± 0.170	0.767700 ± 0.000400	3	
	" " "	WR	60.0	12.0	14.45 ± 0.290	0.816100 ± 0.000100	3	
	" " "	WR	62.0	18.0	9.95 ± 0.200	0.779210 ± 0.000230	3	
	" " "	WR	53.0	27.0	5.67 ± 0.110	0.745850 ± 0.000240	3	

(1) Sánchez-Bettucci and Linares (1996), (2) Cingolani et al. (1993), (3) Linares and Sánchez-Bettucci (1997). WR: whole rock.

chron mentioned by Preciozzi et al. (1993) with an age of 559±28 Ma (Ro = 0.7048, MSWD = 12) for the Pan de Azucar syenite. This age range is also consistent with a mentioned age of 552 Ma (no error or analytical values quoted) from a K/Ar dating on amphibol from the Co. Gigante syenite (neighbor to the Pan de Azucar syenite, Bossi and Navarro, 1991). Therefore, and until a systematic geochronologic study is done, it is interpreted that this phase was erupted approximately between 560 and 540 Ma. The younger phase is represented by trachytes, rhyolites and dykes (El Tambo, Piriapolis and perhaps Las Flores formations). A whole rock Rb/Sr isochron on four rhyolitic dykes and one trachyandesite has yielded 520±10 Ma (Ro = 0.7065, MSWD = 2.4, Table 1, Cingolani et al., 1993) and a single K/Ar whole rock age of 490±15 Ma age (Sánchez-Bettucci and Linares, 1996, Table 1) on a basaltic dyke, points to a Cambrian to Early Ordovician age for this phase. This is consistent with ages mentioned by Bossi and Navarro (1991), no error or analytical values quoted) of 487 (K Feld.), 508 (whole rock) and 519 (whole rock) Ma obtained by K/Ar method. An arithmetic average of these four ages yields 501 Ma. It is interpreted that the young phase of the Sierra de Animas magmatism took place at sometime between 520 and 500 Ma. As shown below, the long period spanned by the Sierra de Las Animas complex is supported by the paleomagnetic results.

The Playa Hermosa Formation (Masquelin and Sanchez Bettucci, 1993) consists in an epiclastic succession with volcanosedimentary levels in its upper section, that has been studied by Sánchez-Bettucci and Pazos (1996), Pazos et al. (1998). A minimum thickness of 1500 m has been estimated, being both base and top covered; although recent studies (P. Pazos, personal communication) suggest that these values could be overestimated. The succession is composed of conglomerates, sandstones, diamictites, siltstones of brown to greenish colors and synsedimentary volcanic flows and dykes. It has been subdivided into two sections (Sánchez-Bettucci and Pazos, 1996). The lower section, some 400 m thick, is almost free of volcanic levels. The presence of rhythmites, diamictites and dropstones have been interpreted by Pazos et al. (1998, 2002) as evidence of glaciogenic processes during sedimentation of this section. The exposed succession of the Playa Hermosa formation (Fig. 2) has been affected by tectonic basculation, but internal deformation or metamorphism is generally absent. Although precise dates are lacking, correlation of the upper section volcanic levels with the Sierra de Las Animas complex and the glaciogenic deposits in the lower section suggest that sedimentation took place in Vendian times (Pazos et al., 1998, 2002). Correlation of the glaciogenic deposits of the lower section with the Varanger glacial interval (Knoll and Walter, 1992; Bowring and Erwin, 1998; Sohl et al., 2000; Pazos et al., 2002) suggests that an age around 600 Ma for the initiation of deposition is likely.

As shown below, one paleomagnetic site (SA-6, Fig. 2) was located on clastic sedimentary rocks exposed in an isolated outcrop that have been mapped as the upper section of the Playa Hermosa Formation. However, recent sedimentological studies (P. Pazos, personal communication) indicate that these rocks are unlikely to belong to the same succession and possibly correspond to a younger (Cambrian–Ordovician?) unit (Las Ventanas Fm?, see Fig. 3). Therefore, this site is considered together with those from the Sierra de las Animas complex and it is not grouped with those from the older Playa Hermosa Fm. This is supported by the paleomagnetic results (see below).

3. Paleomagnetic study

One hundred and forty seven samples were collected from 23 sites on different lithologic types, including basalts, rhyolites, syenites, trachytes and sedimentary rocks of the Sierra de Las Animas Complex and Playa Hermosa Formation (Fig. 2). Sampling was done with a portable gasoline-powered drilling machine. Whenever possible samples were oriented with both magnetic and sun compass. Approximate stratigraphic distribution of sampling sites is shown in Fig. 3.

Samples were submitted to standard stepwise alternating field (AF) and thermal demagnetization. Typical demagnetization sequences were 3, 6, 9, 12, 15, 20, 25, 30, 35, 40, 50, 60, 70, 80, 90, 100, 110 and 120 mT or 100, 150, 200, 250, 300, 350, 400, 450, 500, 540, 580, 620, 650, 680 and 700 °C. Paleomagnetic results were analyzed by As-Zijderveld plots (Zijderveld, 1967) and demagnetization curves. Magnetic components were isolated by principal components analysis (Kirschvink, 1980) after visual inspection of each specimen behavior. Mean site directions were computed applying Fisherian statistics (Fisher, 1953).

Some examples of characteristic magnetic behaviors are presented in Fig. 4. The broad lithologic range sampled yielded a variety of magnetic behaviors. A few sites showed highly unstable remanence (i.e. SA-1, 2, 3, 22 and 23). Most other sites presented stable remanent components. In most cases two components were isolated for each sample. A low coercivity—low unblocking temperature component (A) was generally isolated with either scattered directions or consistent with the expected present geocentric axial dipole direction. In site SA-15 only this component was observed. A high coercivity—high unblocking temperature component (B) was found in many samples from different lithologies. In most cases, this component showed medium destructive fields in the range 25–50 mT and unblocking temperatures generally under 600 °C (Fig. 4). This suggests that (Ti?) magnetite is the most frequent magnetic carrier. This seems so even in the clastic sedimentary rocks of the Sierra de Las Animas Complex (SA-6) and the lower section of the Playa Hermosa Formation (SA16, SA17). In the latter case, some B components miss the origin of coordinates (Fig. 4f) which suggests a third non-resolved component. Nevertheless, in these cases the component direction is similar to those trending towards the origin (compare Fig. 4f and g). In any of these cases, AF demagnetization could not proceed over 60 mT due to unstable or viscous behavior. Although in some sites B showed scattered directions, in several others it presented a tolerable to good within site directional consistency. Mean site remanence directions are presented in Table 2, Fig. 5. Distribution of mean site directions can be subdivided into three groups (Fig. 5). A first group is formed by sites SA-6, 9, 12, 14, 18, 19 and 21 with steep to moderate downward E to NE directions (Fig. 5a). Among these sites, SA-6, 9 and 18 are somewhat displaced towards the NE and with lower inclinations. A second group is integrated by sites SA-4, 5, 7, 8, 11 and 20 that show a steep to moderate up and eastward direction or its antipode (Fig. 5b). A third group is composed only by sites SA-16 and SA-17 with a bedding corrected direction trending SSW with low positive inclinations (Fig. 5c).

The first group (Group 1) corresponds to sites located in rhyolitic bodies, basaltic, trachytic and trachyandesitic dykes and sediments of the Sierra de Las Animas complex (Piriapolis, El Tambo and Las Flores formations). The most likely age for this group should be around 520–500 Ma, according to the scarce datings available for some of these lithologic types, as described above. As explained below, it is likely that these rocks encompass a significant time span (> 20 Ma). Some of the sampled dykes are vertical, while rhyolitic bodies show no evidence of tilting, although paleohorizontal on these bodies is not evident. In these cases, no paleohorizontal correction was applied to the remanence directions (Table 2). Sills intruded in the upper levels of the Playa Hermosa Formation (SA-18 and SA-19, Table 2) were found to be concordant with the sedimentary beds, therefore the bedding correction of these beds was applied. The remanence direction from the only site on sediments (SA-6) was corrected by bedding measured in the field. Both the sills and these rocks are moderately tilted (from 20 to 40° towards the NW, Table 2). After bedding correction of the remanence of these sites a slight improvement in grouping of the directions is observed although this is not statistically significant (Table 2). Excluding SA-14 from the analysis due to its large α_{95} does not change significantly the mean direction (Table 2).

The second group (Group 2) corresponds to sites located on basaltic flows, the Pan de Azucar syenite and a microsyenitic dyke intruded in the upper section of the Playa Hermosa succession. Available datings indicate a more likely age around 560–540 Ma for the rocks of this group. All basaltic flows were observed to be subhorizontal in the field, therefore, their mean site directions need no bedding correction. The syenitic intrusive body of the Pan de Azucar formation is

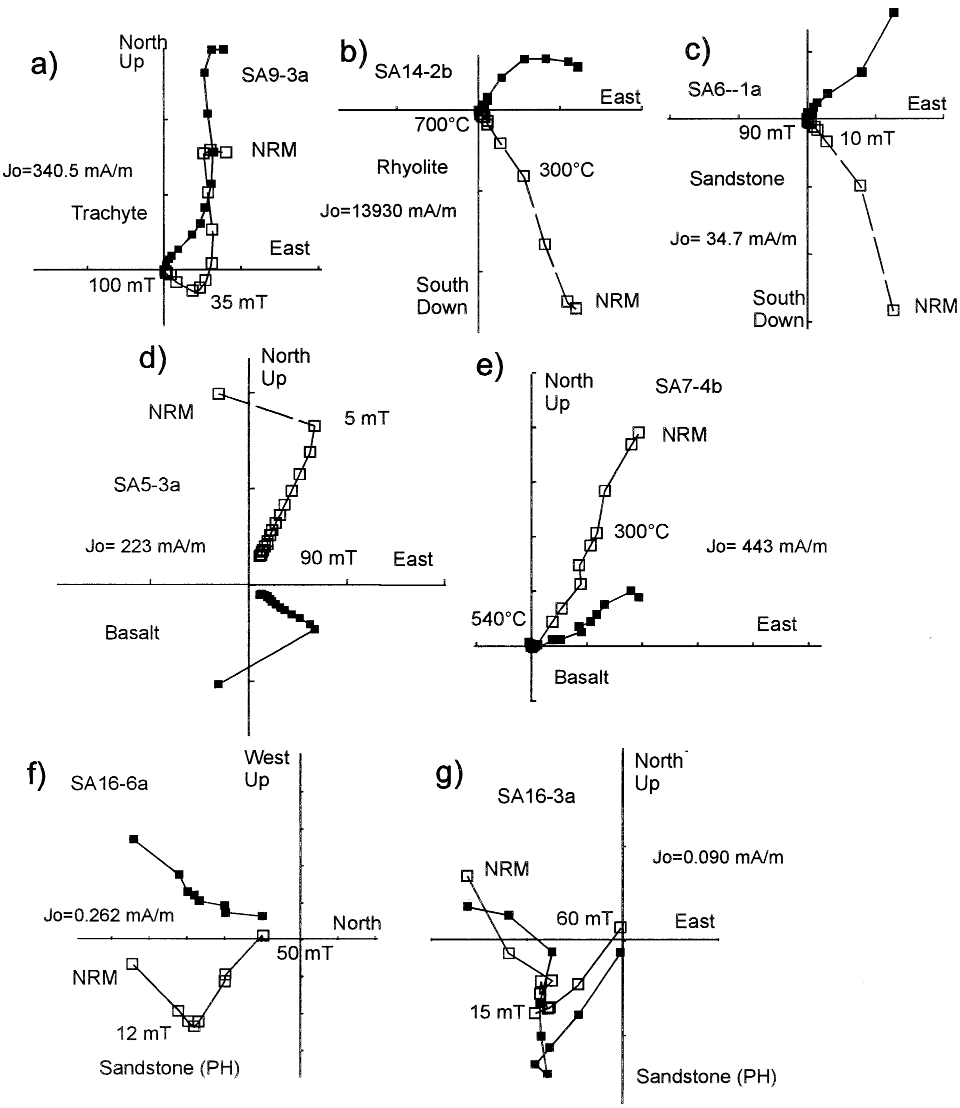

Fig. 4. Representative demagnetization behavior of samples from the Sierra de las Animas Complex: Group 1 (a, b and c) and Group 2 (d and e) and from the Playa Hermosa Formation (f and g). Solid (open) symbols represent projections on the horizontal (vertical) plane.

also considered to have not been tilted, which is likely taking into account its postectonic nature and the lack of major tilting in the region. Only the remanence from a microsyenitic dyke (SA-20) has been corrected for the bedding attitude of the sediments of the Playa Hermosa Formation. When the correction is applied to this direction, the statistical parameters are improved but without reaching statistical significance (Table 2). Excluding sites SA-4 and SA-8 whose mean directions are based on only two samples does not change significantly the overall mean direction, although, the α_{95} obviously increases substantially.

The third group corresponds to sites located on fine grain sandstones of the lower section of the Playa Hermosa Formation. The age of this formation is not accurately determined. At least its lower parts must be older than most or all of the

Table 2
Paleomagnetic data from the Sierra de las Animas Complex and Playa Hermosa Formation

Site	Lithology	*N*	Dec	Inc	α_{95}	*K*	Bed Corr		Dec *	Inc *	α_{95}	K	VGP	
							Strike	Dip					Lat	Long
SA-6	Sandstones	6	48.5°	41.3°	9.2°	54	243°	22°	32.9°	32.8°	9.2°	54	28.8°	340.9°
SA-9	Trachytic dyke	4	29.2°	45.2°	24.0°	16	0°	0°	29.2°	45.2°	24.0°	16	22.6°	332.9°
SA-18	Trachyandesite and dyke	7	73.1°	31.9°	12.7°	24	232°	39°	45.2°	37.1°	12.7°	24	19.9°	349.6°
SA-12	Rhyolite	3	72.1°	72.5°	13.9°	80	0°	0°	72.1°	72.5°	13.9°	80	−20.3°	337.5°
SA-14 #	Rhyolite	3	84.4°	49.9°	34.7°	14	0°	0°	84.4°	49.9°	34.7°	14	−12.8°	6.1°
SA-19	Trachyandesite and dyke	4	133.2°	54.9°	3.5°	687	232°	39°	12.2°	83.4°	3.5°	687	−21.9°	307.6°
SA-21	Basaltic dyke	6	18.2°	71.0°	13.2°	27	0°	0°	18.2°	71.0°	13.2°	27	−1.5°	314.9°
All (SA-1)	**All**	**7**	**65.7°**	**57.1°**	**20.0°**	**10**			**44.5°**	**58.0°**	**18.1°**	**12**	**5.9°**	**338.1°**
All except # (SA-1)	All except #	6	61.6°	58.1°	23.8°	9			36.6°	57.8°	19.5°	13	9.4°	332.9°
SA-4 #	Basaltic flow	2	91.6°	−67.3°	–	249	0°	0°	91.6°	−67.3°	–	249	−25.0°	259.7°
SA-5	Basaltic flow	7	107.6°	−55.2°	7.9°	60	0°	0°	107.6°	−55.2°	7.9°	60	−7.5°	253.4°
SA-7	Basaltic flow	4	48.5°	−60.2°	15.3°	37	0°	0°	48.5°	−60.2°	15.3°	37	−51.7°	239.2°
SA-8 #	Syenite	2	291.8°	60.7°	–	30	0°	0°	291.8°	60.7°	–	30	−8.7°	260.2°
SA-11	Basaltic flow	3	295.4°	36.5°	21.0°	35	0°	0°	295.4°	36.5°	21.0°	35	7.7°	246.0°
SA-20	M-syen dyke	9	16.0°	−54.2°	8.2°	41	232°	39°	79.2°	−57.9°	8.2°	41	−28.4°	243.9°
All (SA-2)	**All**	**6**	**86.1°**	**−61.5°**	**20.7°**	**11**			**95.3°**	**−58.5°**	**14.5°**	**22**	**−17.5°**	**250.7°**
All except #(SA-2)	All except #	4	78.3°	−59.2°	35.9°	8			92.3°	−55.3°	24.1°	16	−17.8°	246.4°
SA-16 and SA-17 (PH)	**Sandst. (Playa Hermosa Fm)**	**6**	**203.6°**	**30.6°**	**14.6°**	**22**	**210°** **203°**	**41°** **42°**	**226.0°**	**24.2°**	**15.0°**	**21**	**−43.0°**	**198.4°**

N, number of samples used to compute the mean site direction; in the cases of All (SA-1) and All (SA-2), N means number of sites. *K* and α_{95} are the statistical parameters of Fisher (1953). Dec* and Inc* correspond to declination and inclination values after application of the respective bedding corrections. Bed Corr: Bedding correction following the right hand rule (dip to the right of the strike). VGP stands for virtual geomagnetic pole. Positive (negative) correspond to northern (southern) latitude. More references in the text.

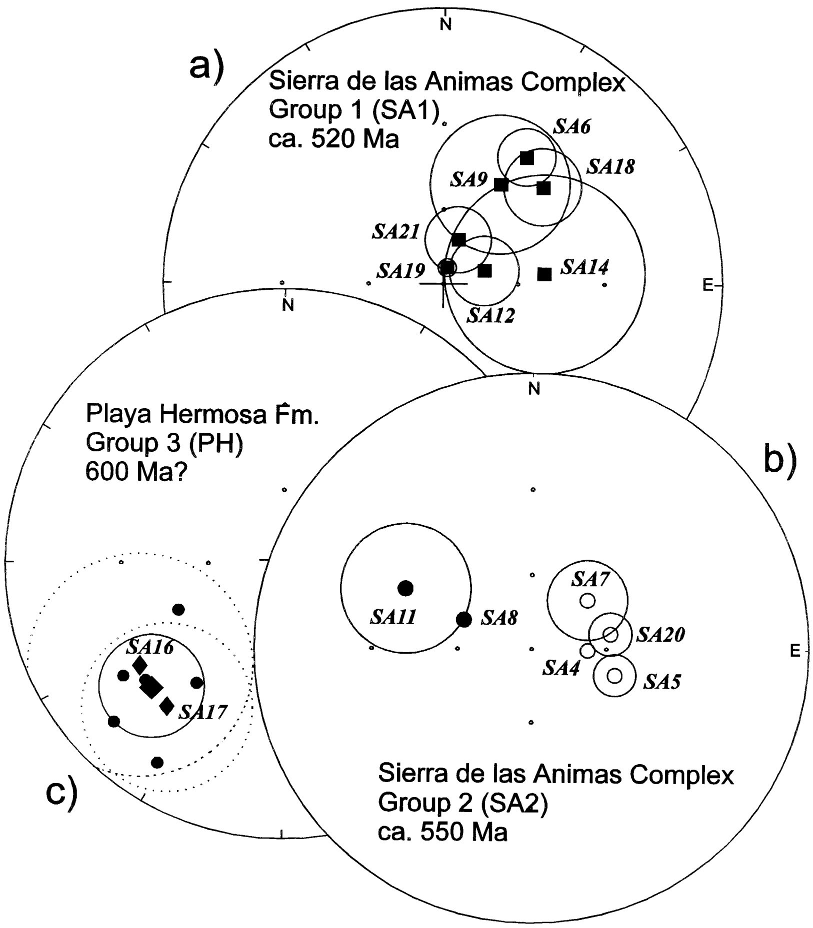

Fig. 5. (a) Mean site characteristic remanence directions from Group 1 of the Sierra de las Animas Complex with their respective α_{95}. (b) Idem (a) from Group 2. (c) Sample characteristic remanence directions (solid circles) from the lower section of the Playa Hermosa Formation. Small diamonds and dotted circles represent mean site directions and their α_{95}. Mean sample direction and its α_{95} are represented by the large diamond and circle. Solid (open) symbols represent directions pointing down (up).

Sierra de Las Animas complex, since the upper section of the sequence is intruded by basaltic to rhyolitic dykes of this complex. In the upper parts, some flows are reported to be interbedded with the sedimentary levels (Sánchez-Bettucci and Pazos, 1996). All of this suggests a Vendian (or older) age for the Playa Hermosa Formation. Pazos et al. (1998, 2002) have interpreted that the lower part of the formation was deposited in a periglacial environment from the presence of dropstones, clast striae and rythmites. It is, therefore, interpreted that the lower section of the Playa Hermosa Formation is older than 560–540 Ma. As shown below, the paleomagnetic results are more consistent with an age of approximately 600 Ma. The mean sample remanence directions were corrected for the bedding attitude (around 40° towards the WNW, see Table 2), which do not produce any significant change in the statistical parameters (Table 2).

Acquisition of isothermal remanence curves (Fig. 6) indicate that low coercivity magnetic phases (Ti? magnetite) tend to be dominant in most cases. This is consistent with the observed demagnetization behavior. However, a high coercivity phase is present in some sites, being more

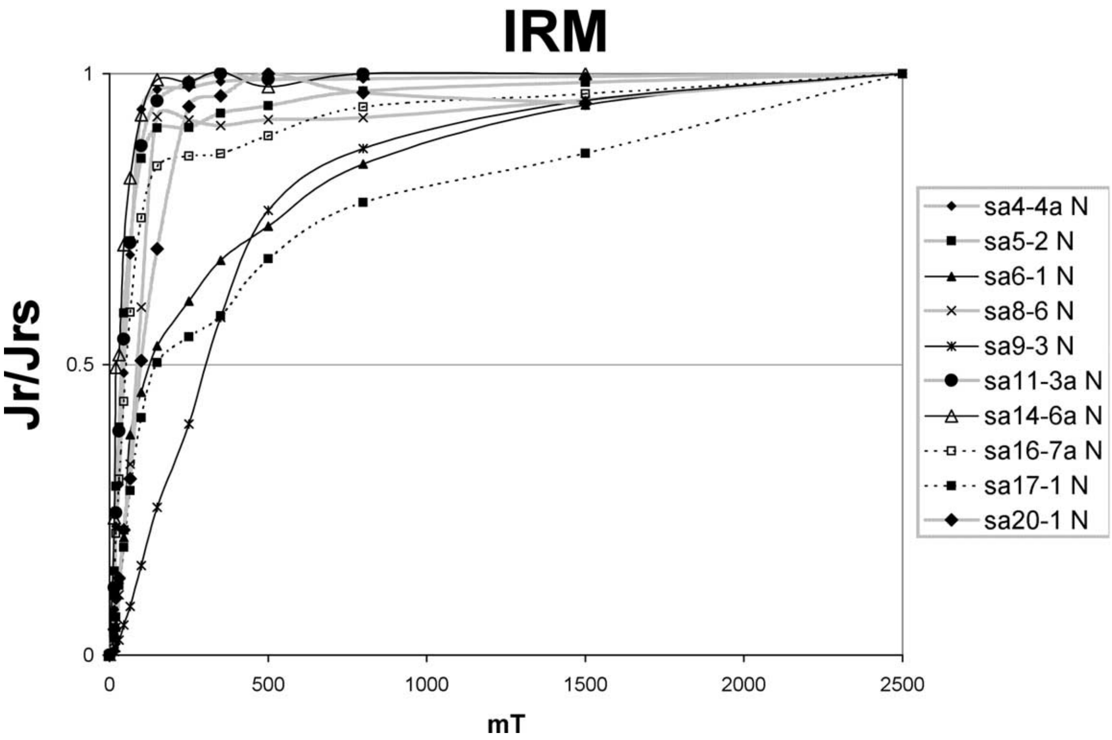

Fig. 6. Representative isothermal remanence acquisition curves from the Sierra de las Animas Complex: Group 1 (narrow black lines), Group 2 (thick grey lines), and the Playa Hermosa Formation (dotted lines). Curves have been normalized to saturation (or maximum) magnetization values.

conspicuous in sedimentary rocks (e.g. SA17-1, SA6-1). This antiferromagnetic phase could account for the third unresolved component seen in some samples of the Playa Hermosa Formation, as mentioned above. Despite this, the characteristic component isolated in these sites showed coercivity and unblocking temperature spectra consistent with a ferrimagnetic carrier (see Fig. 4).

4. Analysis and interpretation

A paleomagnetic pole was computed from the mean remanence direction from each of the three groups. They, as well as the virtual geomagnetic pole for each site, are presented in Table 2. SA1 is based on seven sites and it is interpreted that it corresponds to an age around 520 Ma. The large confidence oval is due to the fact that, as shown in Fig. 5, this group seems to be integrated by two subgroups (sites 6, 9 and 18 and sites 12, 14, 19 and 21, respectively). The angular standard deviation (S.D.) of this small population (28.7°) is much larger than that expected from paleosecular variation at this latitude (Merrill et al., 1996). This can be interpreted as caused by remanence acquisition during a period of fast apparent polar wander, although undetected tectonic tilting of intrusive rocks at some sites may also play a role. Meert and Van der Voo (1996) proposed a Late Vendian—Cambrian APWP for Gondwana that implies a fast period of polar wander. An even faster, global episode of inertial interchange true polar wander, was proposed by Kirschvink et al. (1997), although this is disputed by Torsvik et al. (1998), Meert (1999), Torsvik and Rehnstrom (2001). In any case, a fast Vendian to Cambrian APWP for Gondwana seems well established. Distribution of VGPs from these seven sites is consistent with this path, suggesting that age of remanence for different sites on this group may vary as much as 20 million year or more (Fig. 7).

The second group of mean site characteristic directions shows both polarities and yields a paleomagnetic pole labeled SA2.

The Playa Hermosa Formation is represented by just two mean site directions. Being a sedimentary succession, an average on a sample basis ($n = 6$) was performed (Table 2). However, the number of samples is not enough to average paleosecular variation, therefore the pole position obtained (PH) is considered a mean geomagnetic pole.

In all cases, the characteristic remanence directions are considered primary. This is based on the demagnetization behavior of the samples and the lack of resemblance of these directions with any expected post-Ordovician direction for South America. Given the lack of structural complexities

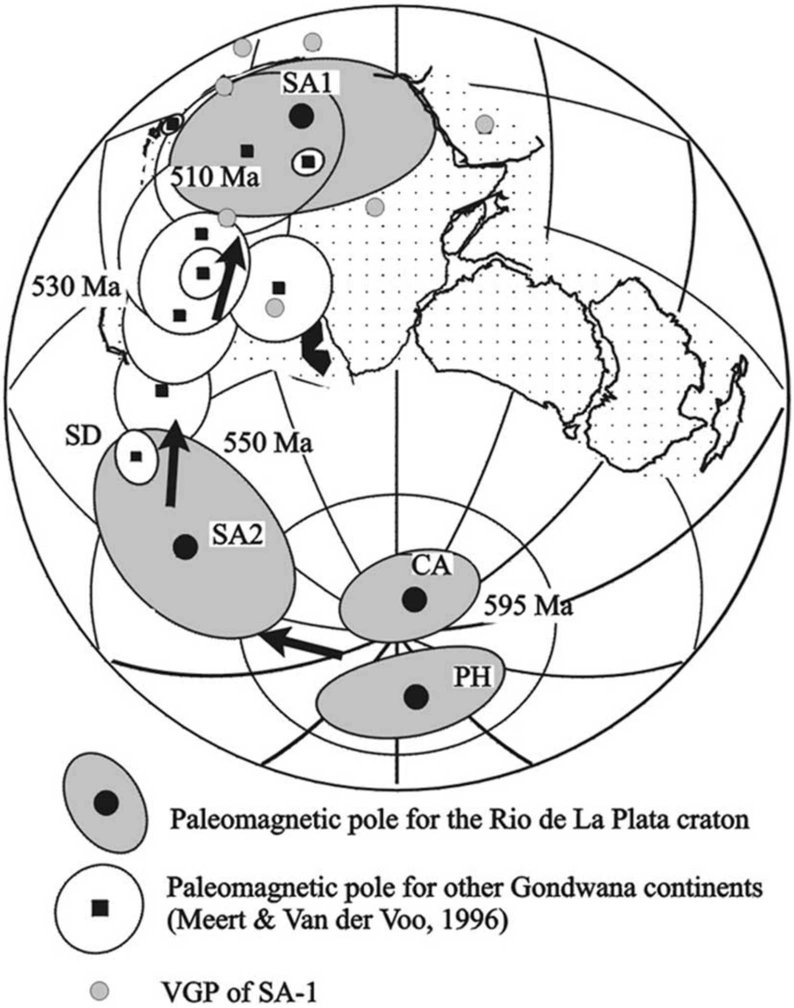

Fig. 7. Paleomagnetic poles for the Rio de la Plata craton and other Gondwanan continents (Meert and Van der Voo, 1996). SA1, paleomagnetic pole for Group 1 of the Sierra de las Animas Complex (around 520 Ma); SA2, idem for Group 2 (around 550 Ma); PH, mean geomagnetic pole for the Playa Hermosa Formation (circa 600 Ma); CA, paleomagnetic pole for the Campo Alegre lavas (595 Ma). The approximate ages along the Gondwana path are indicated. See discussion in the text.

in the region a remagnetization yielding a direction not consistent with the South American polar wander path would be difficult to justify.

The positions of SA1, SA2 and PH are shown in Fig. 7 after rotation into African coordinates following Lottes and Rowley (1990). Meert and Van der Voo (1996) obtained a approximately 547 Ma paleomagnetic pole from the Sinyai Dolerite, which has become a reference pole for the Congo craton (SD). On the basis of this and previous results from other Gondwana blocks they proposed a single APWP for the whole of Gondwana since around 550 Ma. This implies that the major Gondwana blocks were already assembled (within the paleomagnetic error) by that time. The single APWP for Gondwana indicates a fast displacement of the pole from a position off southwestern South America in the late Vendian to central Africa in the Early Cambrian and northern Africa in the Late Cambrian (see also Meert, 2001). SA1 and SA2 are consistent with the Gondwana path of Meert and Van der Voo (1996) both in position and age. In particular, SA2 falls close to the Sinyai dolerite pole. On the basis of the available radiometric datings, we have assigned an age of around 550 Ma to this pole, which is coeval with the Sinyai dolerite pole. SA2, thus, confirms that the Rio de la Plata craton was part of Gondwana by 550 Ma and suggests that most Gondwana blocks were about to be or already assembled by those times. Other recent results, yet unpublished in detail, from the Rio de la Plata (Rapalini and Rapela, 1999) and Congo cratons (Ponte Neto, 2001) are consistent with SA2 and SD. Kempf et al. (2000) has recently published a mean geomagnetic pole from the Arabian Shield of around 550 Ma also consistent with these poles.

PH lies close to the 595 Ma pole of the Campo Alegre (CA) lavas (D'Agrella and Pacca, 1988). These rocks have been dated accurately recently as 595 ± 5 Ma (U/Pb, Citroni et al., 1999) and are exposed in the Luis Alves craton. However, they can be considered representative of the Rio de la Plata craton or La Plata plate (Rio de la Plata plus Luis Alves cratons), considering the strong geological evidence in favor of a previous amalgamation of both blocks (Campos Neto, 2000). The similar positions of PH and CA may be taken as further evidence of a approximately 600 Ma for the remanence acquisition (and deposition?) of the Playa Hermosa sediments. This would imply that the glaciogenic deposits of this unit can be correlated with the Varanger glacial episode that occurred around 600 Ma (Hambrey and Harland, 1985; Knoll and Walter, 1992; Bowring and Erwin, 1998; Pazos et al., 2002). Using PH as a reliable paleomagnetic pole would imply deposition of the glaciogenic parts of the Playa Hermosa Formation at low paleolatitudes ($12.7° +9.5°/-8.1°$). Therefore, more robust paleomagnetic results on this unit will be of special interest to determine if this is a new case of Neoproterozoic low latitude glaciation. In the mean time, however, if the more reliable CA pole is used, a paleolatitude of $33.3 \pm 9.5°$ is obtained, still moderately low but compatible within the confidence limits with a paleoclimatic scenario similar to the Quaternary glaciation.

The respective positions of CA, SA2 and SA1 are interpreted as a preliminary APWP for the Rio de la Plata craton in the approximately 600–500 Ma interval. It suggests a fast displacement of the plate during the amalgamation of Gondwana.

Paleomagnetic poles of approximately 600 Ma from other Western Gondwana blocks are also plotted in Fig. 8. A significant coincidence between CA (and PH) with the Bir Safsaf (BS) and Nabati Complex (NB) poles from the West Nile craton (Saradeth et al., 1989) is observed. This suggests that Rio de la Plata and West Nile cratons integrated a larger land-mass by approximately 600 Ma, which would imply that part of Western Gondwana was already assembled at that time. A coincident pole of the same age has been obtained by Kellogg and Beckmann (1983) for the Arabian shield, although the position of this block is controversial as the Dokhan volcanics pole (Davies et al., 1980) recently dated at 595 Ma (Wilde and Youseff, 2000) does not agree with it, suggesting that one of these two poles was remagnetized. On the other hand, the approximately 610 Ma pole from the Adma diorite (AD, Morel, 1981; Fig. 8), in the West African craton, does not agree with CA, PH, BS and NB. Its position is close to Late Cambrian–Ordovician poles from Gondwana (compare AD with NR, Ntonya Ring structure,

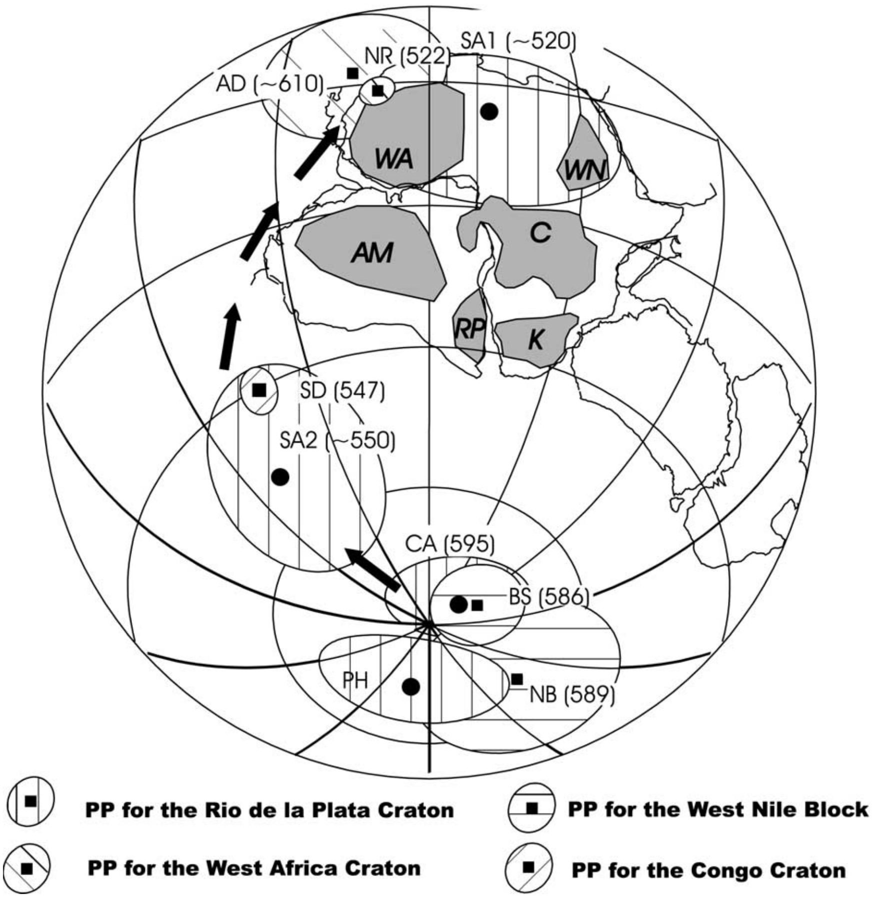

Fig. 8. Vendian to Cambrian paleomagnetic poles from the Rio de la Plata, Congo, West Nile and West Africa blocks in a Gondwana reconstruction (Lottes and Rowley, 1990). Note the coincidence of poles of ca. 600 Ma for the Rio de la Plata and West Nile blocks and their disagreement with a pole of similar age from the West African craton. See discussion in the text.

Briden, 1968) which may suggest a remagnetization of that age. However, the primary nature of this pole seems to be supported by a similar direction (with antipodal polarities) presented by volcanics of a slightly younger age in the same region (Morel, 1981). If a primary origin for AD is accepted, it would indicate that the West African craton was at very high latitudes at those times and was not part of the same plate of the Rio de la Plata and West Nile (and Arabian?) blocks by around 600 Ma. This may lead to further speculation on the sequence of assembly of the Western Gondwana blocks. If West Africa was a separate block, then the only possible link between the Rio de la Plata and the West Nile blocks is the Congo–Sao Francisco craton, for which there is no paleomagnetic pole of that age. This would imply that by around 600 Ma a single plate composed by at least these three cratonic blocks may have existed (Central Gondwana). Brito Neves et al. (1999), Campos Neto (2000) have proposed that collision of the Rio de La Plata and Sao Francisco cratons occurred around 620 Ma with closure of the Tocantins ocean. On the other hand, it is generally accepted (Trompette, 1997, 2000; Villeneuve and Corneé, 1994) that West Africa and Amazonia were a single plate since Rodinia breakup. This has not been tested by paleomagnetism, but if accepted, it would imply that collision of a smaller Western Gondwana (West Africa–Amazonia) and Central Gondwana (West Nile–Congo–Sao Francisco–Rio de la Plata–Arabia?) was a major event in the assembly of Gondwana. The smaller Western Gondwana plate proposed here will be called proto-Western Gondwana to avoid confusion with the already established meaning of Western Gondwana. This hypothesis is not very different from that by Trompette (2000), who proposed a subdivision of Gondwana prior to its assembly into three blocks: Western, Central and Eastern Gondwana, not exactly coincident to those proposed here. However, the age of assembly proposed by this author is mainly around 600 Ma. In our case this should occur somewhat later. Our speculation is not so different either from the model proposed by Meert (2001). However, in our model, the Rio de la Plata craton would be part of Central Gondwana, while proto-Western Gondwana would be constituted only by Western Africa and Amazonia. It is however possible that the smaller Pampia terrane (Ramos et al. 1993), located to the west of Rio de la Plata, was also part of proto-Western Gondwana (Brito Neves et al., 1999). Collision of Amazonia with Rio de la Plata–Sao Francisco as one of the latest events in Western Gondwana amalgamation has been recently proposed by Alkmim et al. (2001) on geological grounds. Final assembly of Gondwana, however, did not happen until Early Cambrian (ca. 530 Ma) when the South American Pampia block (Rapela et al., 1998) collided with the Rio de la Plata craton. Later on, in the Paleozoic, several other terranes were accreted to the southwestern Gondwana (southern South America) margin (Ramos, 1988; Astini et al., 1995; Rapalini et al., 1999).

It is generally accepted to place western Amazonia as the conjugate margin of eastern Laurentia in a Rodinia configuration, although its precise position is disputed (see for instance Hoffman, 1991; Dalziel et al., 1994; D'Agrella et al., 1998). Therefore, consistency of coeval paleomagnetic poles from Laurentia and proto-Western Gondwana blocks would suggest no separation between both continental masses. On the other hand, assuming such crustal continuity, reliable paleomagnetic poles from one continent could also be used to reconstruct the paleogeographic position of others. Geological evidence strongly suggest that proto-Western Gondwana was still attached to Laurentia by approximately 610 Ma (see Cawood et al., 2001 and references therein). However, and despite its larger paleomagnetic database, the paleogeographic evolution of Laurentia in the latest Neoproterozoic is controversial (Pisarevsky et al., 2000, 2001; Meert and Van der Voo, 2001). Meert et al. (1994) re-interpreted the Long Range dykes paleomagnetic data (Murthy et

Fig. 9. (A) Laurentia (LAU), Western Africa (WA), Amazonia (AM) and Pampia (PA) in a Rodinia reconstruction similar to those by Hoffman (1991), Weil et al. (1998), and paleomagnetic pole positions for ca. 615 Ma poles for Laurentia (Long Range dykes, Murthy et al., 1992) and for Western Africa (AD, Adma Diorite, Morel, 1981). Mean paleomagnetic pole for Laurentia for ca. 580 Ma (580, Meert et al., 1994) is also shown. Poles are presented with their respective α95 North American coordinates. (B) Speculative paleogeographic reconstruction of Gondwana forming blocks, Laurentia and Baltica for ca. 600 Ma. WA, AM and PA (proto Western Gondwana) and Laurentia are positioned by interpolation of LR and 580 poles (Fig. 9A). Baltica is positioned according to Meert et al. (1998). Central Gondwana is reconstructed according to the CA pole (D'Agrella and Pacca, 1988). Kalahari as part of Central Gondwana by 600 Ma is not constrained by paleomagnetic data. Eastern Gondwana is positioned according to the Elatina and Yaltipena formations poles (Sohl et al., 2000), although recent studies suggest that it might not be completely assembled by those times (Meert, 2002). (C) Idem (B) but for ca. 575 Ma. Laurentia and proto-Western Gondwana are positioned according to the ca. 580 Ma mean Laurentian pole of Meert et al. (1994). Central Gondwana position is not constrained by paleomagnetism but is compatible with the paleomagnetically based reconstructions at 600 and 550 Ma (Fig. 9B and D). The position of Eastern Gondwana is compatible within the paleomagnetic error with the 570–590 Ma Bunyeroo Formation pole (Schmidt and Williams, 1996). Baltica is positioned according to Meert et al. (1998). (D) Reconstruction for ca. 550 Ma: Gondwana already assembled and Laurentia and Baltica drifted apart. Reconstruction of Gondwana is based upon the Sinyai Dolerite pole (Meert and Van der Voo, 1996); Baltica is based on the 550 Ma pole position from Smethurst et al. (1998); Laurentia is based on the 550 Ma reference pole of Meert et al. (1994). Note that amalgamation of proto Western Gondwana by 550 Ma is not constrained paleomagnetically. Lau, Laurentia; Bal, Baltica; IN, India; AU, Australia; M, Madagascar; EA, Eastern Australia. For references of other blocks see caption of Fig. 1. Western Gondwana cratonic blocks in grey. More details and discussion in the text.

al., 1992) as indicative of a very high southerly latitude for Laurentia at around 615 Ma. This interpretation assumed that the dykes studied by Murthy et al. (1992) comprised two separate sets with ages around 615 and 550 Ma approximately. However, Kamo and Gower (1994) subsequently demonstrated that all dykes have similar ages around 615 Ma. Therefore, the case for a high latitude at that age is substantially weakened (as explicitly recognized by Meert and Van der Voo,

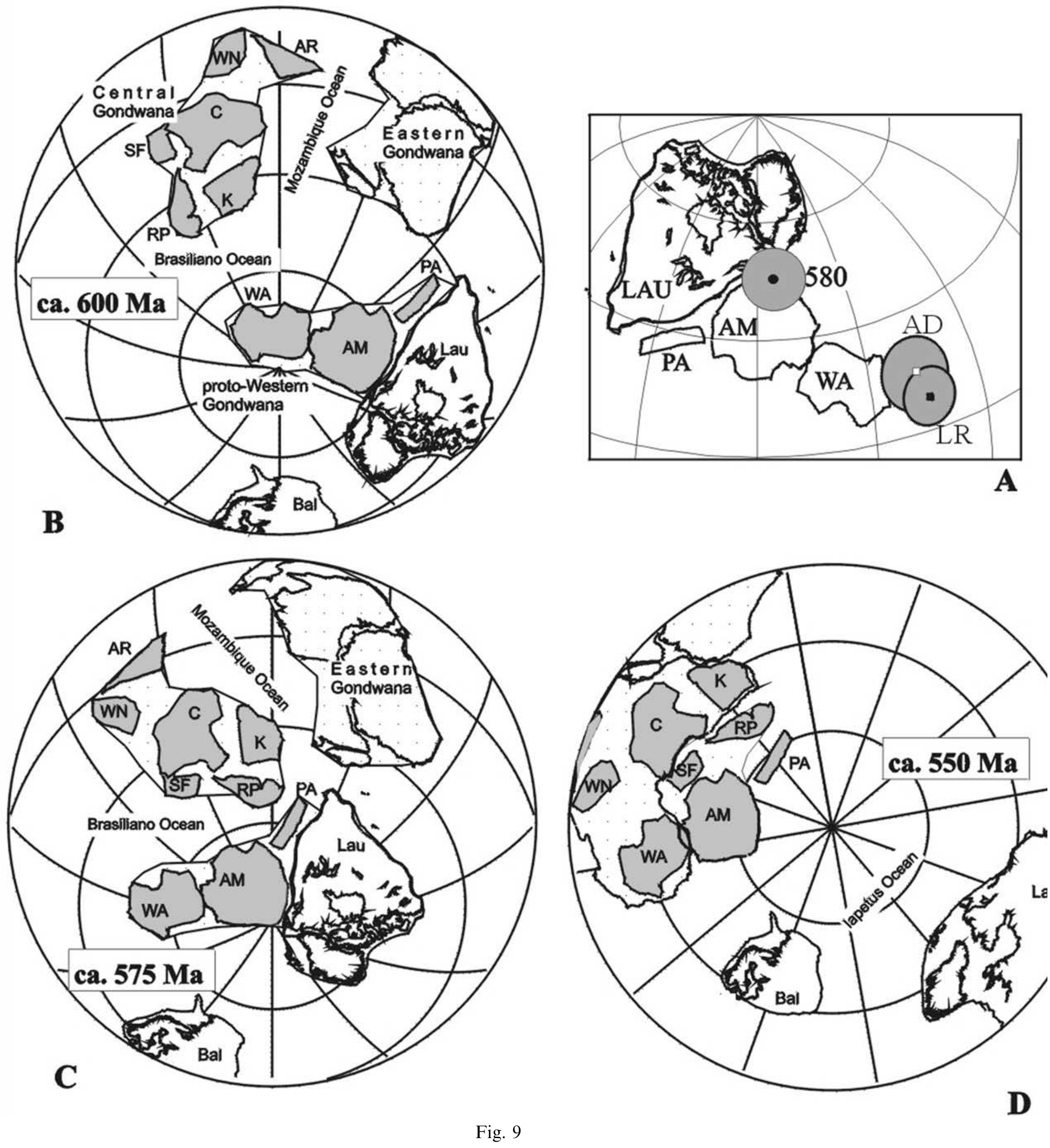

Fig. 9

2001) since the Long Range dykes original pole, that indicates lower latitudes, is to be preferred on paleomagnetic grounds (Murthy et al., 1992; Pisarevsky et al., 2000; Meert and Van der Voo, 2001). This is coincident with the nearly coeval Adma diorite pole (AD) from Western Africa when proto-Western Gondwana (Western Amazonia plus Western Africa) is placed against Eastern Laurentia in a fashion similar to a classic Rodinia reconstruction like those by Hoffman (1991) or Weil et al. (1998) (Fig. 9A). This further supports that both land masses were still attached at those times. Based on these poles and those already discussed for Central Gondwana, we present in Fig. 9B an speculative paleogeographic reconstruction for around 600 Ma. Considering that the paleomagnetic database for that time is still scarce and of variable quality its speculative and sketchy character is stressed. Laurentia + proto Western Gondwana (Rodinia's remains?) have been positioned interpolating between the Long Range dykes original pole (Murthy et al., 1992) and the approximately 580 Ma mean reference pole (Meert et al., 1994, Fig. 9A), Central Gondwana according to the CA pole (D'Agrella and Pacca, 1988), while Eastern Gondwana reconstruction relies on the approximately 600 Ma paleomagnetic poles of the Elatina and Yaltipena Formations (Sohl et al., 2000). However, as proposed recently by Meert (2002), Powell and Pisarevsky (2002), Eastern Gondwana may have not been completely assembled until later, and therefore the picture displayed in Fig. 9 is likely oversimplified. The position of Baltica is taken from the somewhat younger pole of the Fen Complex (Meert et al., 1998), assuming very little polar wander for this interval. According to this, Baltica has already drifted apart from Laurentia. The Kalahari craton is shown as already assembled to Central Gondwana, although this is highly uncertain and unconstrained by paleomagnetism. We also depict a tentative reconstruction for the South American Pampia terrane as an 'appendix' of Amazonia (Brito Neves et al., 1999), and close to the southeastern Laurentian margin, which is consistent with models of evolution of the Puncoviscana basin (e.g. Dalziel et al., 1994). A large Brasiliano Ocean is implied by this reconstruction. Several terranes may lie outboard of proto-Western Gondwana, in this ocean, like the Rio Apa, Goias and Hoggar–Tibesti blocks (not depicted), either already attached to or as separate terranes. The Mozambique Ocean separates Central and Eastern Gondwana.

Despite some recent challenge by Pisarevsky et al. (2000) high southerly latitude for Laurentia around 575 Ma seems well established by reliable paleomagnetic data from the Callander Complex (Symons and Chaisson, 1991), Catoctin volcanics A (Meert et al., 1994) and Sept Iles Intrusion B (Tanczyk et al., 1987) poles (for discussion see Meert and Van der Voo, 2001), which yield the mean reference Laurentia pole of approximately 580 Ma (Fig. 9A). Fig. 9C presents an hypothetical paleoreconstruction for that time, in which Laurentia is now close to the south pole according to this mean paleomagnetic pole, while proto-Western Gondwana has just started rifting apart (see Cawood et al., 2001). No paleomagnetic data from proto -Western Gondwana is available for that age, although a recent high quality paleopole from Avalonia (McNamara et al., 2001) is consistent with it. Central Gondwana is not constrained paleomagnetically either and has been tentatively placed closer to its final amalgamation with West Africa and Amazonia in a fashion compatible with its paleomagnetically controlled position at 550 Ma (Fig. 9D). Eastern Gondwana is placed considering that the Mozambique Ocean must be much reduced and compatible within paleomagnetic error with the 570–590 Ma Bunyeroo Formation pole (Schmidt and Williams, 1996). Baltica has been positioned according to the approximately 583 Ma Fen Central Complex pole (Meert et al., 1998). This paleoreconstruction implies a fast drift of Laurentia-proto Western Gondwana and a ccw.rotation of Central Gondwana which produce closure of the Brasiliano Ocean. Similar movement by Eastern Gondwana leads to closure of the Mozambique Ocean. At the same time an ocean widens between Baltica and Laurentia.

By approximately 550 Ma, however, Laurentia should be again in low latitudes, according to most accepted paleogeographic models (see Meert et al., 1994; Dalziel, 1997; Pisarevsky et al., 2000, etc.) and recently confirmed by new paleomagnetic data by McCausland and Hodych (1998). This means that Laurentia must have drifted from low latitudes approximately 615 Ma to high latitudes approximately 575 Ma, to low latitudes again by approximately 550 Ma. Fig. 9D shows a paleogeographic reconstruction for 550 Ma based on paleomagnetic data. The Gondwana blocks have been positioned on the basis of the SD pole (Meert and Van der Voo, 1996). Laurentia's position is based upon its 550 Ma reference pole (Meert et al., 1994) while Baltica's is based on the 550 Ma pole position presented by Smethurst et al. (1998). The assembly of Gondwana by 550 Ma depicted in Fig. 9D implies break up and fast drift apart of Laurentia and proto-Western Gondwana between 575 and 550 Ma (see Cawood et al., 2001). The displacement of Laurentia to equatorial latitudes produces the opening of the South Iapetus Ocean (see also McCausland and Hodych, 1998). Proto-Western Gondwana also moves to lower latitudes, but in opposite direction, and displays a small clockwise rotation leading to final closure of the Brasiliano Ocean, while the same occurs with the Mozambique Ocean between Central and Eastern Gondwana. According to our sketches, final assembly of Gondwana may have involved substantial transcurrent movements, which is in accordance with geological evidence (see for instance Villeneuve and Corneé, 1994; D'Agrella et al., 1998).

In any case, by 550 Ma the Pampia terrane is approaching, but not yet assembled to, the southern margin of Gondwana, which suggests some relative movement between Pampia and Amazonia. In the Early Paleozoic other blocks would be accreted to this margin (Ramos, 1988; Astini et al., 1995; Rapalini et al., 1999). It is worth noting that there is actually no paleomagnetic constraint for the 550 Ma assembly of proto-Western and Central Gondwana shown in Fig. 9D, since the oldest pole for proto-Western Gondwana consistent with those from other Gondwanan continents is that from the Ntonya ring structure of 522 Ma (Briden et al., 1993). However, significant geological evidence suggests that oceans were already closed by those times between Amazonia-West Africa and the Central Gondwana blocks (e.g. Villeneuve and Corneé, 1994; Brito Neves et al., 1999).

Powell (1995) proposed the hypothetical Pannotia supercontinent, that implies a short lived connection between Laurentia and Baltica and an already assembled Gondwana in Vendian times. Meert et al. (1998) ruled out the inclusion of Baltica into this supercontinent on paleomagnetic grounds; however, Hartz and Torsvik (2002) maintain a loose connection with Laurentia by inverting older (750 Ma) poles from Baltica. Geological evidence of a connection between Eastern Laurentia and western South America, particularly western Amazonia, the Arequipa–Antofalla block and the Pampian Puncoviscana basin (see Dalziel et al., 1994 and references therein) has been taken as evidence in favor of the Pannotia hypothesis. In our hypothesis, this connection may remain in place but will not necessarily mean the existence of any supercontinent, but perhaps the final events of break-up of Rodinia. As mentioned above, ages for separation of proto-Western Gondwana from Laurentia and collision with Central Gondwana are still very loosely constrained by paleomagnetic data.

5. Conclusions

A paleomagnetic study was carried out on the Late Vendian–Cambrian Sierra de Las Animas magmatic complex, in southeastern Uruguay. The rocks studied comprised basaltic and rhyolitic flows, trachyte and basaltic dykes and sills, syenitic intrusions and clastic sedimentary rocks. A small study was also done on the Vendian sedimentary Playa Hermosa formation. Due to the variety of lithologies different magnetic behaviors were observed. Despite this, stepwise AF and thermal cleaning permitted the isolation of the characteristic remanence at several sites. According to the available radiometric datings of the complex and the correlation between remanence directions and lithologic type and age, two paleomagnetic poles were computed for the Sierra de Las Animas complex. SA1 corresponds to rhyolites, trachytic and basaltic dykes and clastic sediments with a likely age around 520 Ma.

Distribution of VGPs suggests that remanence acquisition involved a time span (>20 million year) during an event of fast apparent polar wander path for Gondwana. The position of SA1 over northern Africa (in a Gondwana reconstruction) is consistent with other paleomagnetic poles of Gondwana of that age. SA2 corresponds to basaltic flows and a syenitic intrusion with a likely age between 540 and 560 Ma. SA2 falls close to a 547 Ma pole from the Congo craton suggesting that the Rio de la Plata craton was at that time part of Gondwana and confirming previous postulates that a single APWP can be defined for the supercontinent since 550 Ma. A preliminary mean geomagnetic pole was also obtained from clastic sediments from the lower section of the Playa Hermosa Formation (PH). The age of these rocks is not precisely defined although a Vendian age around 600 Ma is likely. This pole falls consistently close to a 595 Ma pole from the lavas Campo Alegre in the Luis Alves block, part of the same plate as the Rio de la Plata craton for those times. If PH is confirmed in its position, the Playa Hermosa sediments could be another example of Neoproterozoic low or mid latitude glaciation. PH and CA agrees with two coeval poles from the West Nile block and disagree with a pole of similar age from the West African craton. Taking these poles at face value, a possible sequence of events for the assembly of Western Gondwana is presented as a working hypothesis. This involves a final collision between three major land-masses: proto-Western Gondwana (Amazonia and West Africa), Central Gondwana (Rio de la Plata–Congo-Sao Francisco–West Nile–Arabia) and East Gondwana (Australia–East Antarctica–India–Madagascar). The position of the Kalahari craton is not constrained paleomagnetically. The Pampia block in Argentina could have also integrated proto-Western Gondwana. This may have remained attached to Laurentia at least until around 600 Ma, and possibly up to 575 Ma, while Central Gondwana was in low to intermediate latitudes. By 550 Ma, while the latter moved towards the pole and Laurentia drifted away towards the equator, proto-Western Gondwana had drifted away from Laurentia to collide with Central Gondwana. Since paleomagnetic data for the latest Proterozoic is scarce and in cases controversial, the events leading to the assembly of Gondwana still remain highly speculative. New and reliable paleomagnetic data from Gondwana forming blocks and Laurentia will likely modify all present paleogeographic models.

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