The Early Triassic magmatism of the Alto Paraguay Province, Central South America: Paleomagnetic data

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Abstract

A paleomagnetic work was carried out on the Alto Paraguay Province, a series of ring complexes that parallel the Paraguay River (the Brazil-Paraguay border) for more than 40 km. The province is well dated by $^{40}Ar/^{39}Ar$ method giving ages in the range 240-250 Ma with a preferable age of 241Ma. Intrusive to sub-intrusive rocks are predominant, and are usually topped by lava flows and ignimbrites. Paleomagnetic work on these rocks identified normal and reversed magnetic components were identified which are carried mainly by titanomagnetites.The corresponding paleomagnetic pole located at 319°E 78°S (α=6°; k=23) is in good agreement with other South American poles of Permo-Triassic age. Most of the sampling sites showed large variations in the rock magnetization, but displayed similar patterns indicative of geomagnetic polarity transitions. The magnetization data along with the anisotropy of magnetic susceptibility (AMS) determinations showed that the South and North areas of the province have different evolution characteristics.

1. Introduction

The cratonic area of South America experienced an epoch of quiescence since Cambrian times favouring the onset of large intracratonic sedimentary basins as was the case of the Paraná Basin (Fúlfaro, 1996; Zalán et al., 1990). In this basin there is no record of magmatic activity up to the Early Cretaceous when an huge flood magmatism (Piccirillo & Melfi, 1988) covered the entire basin. A subsequent intrusive magmatism of alkaline nature is recognized all around the present limits of the basin. However, on the western border of the basin the alkaline complex named Alto Paraguay Province (APP) shows ages as old as Early Triassic.

The geodynamic context of the APP magmatism has been related either to the Rio Apa Arch (Livieres & Quade, 1987) occurring westwards of the province or to the activation of the Alto Paraguay N-S structures. Comin-Chiaramonti et al. (2005a) proposed a genetic relationship between the APP rocks and the Cabo-La Ventana (Pampean) orogeny following other analogous propositions(Tankard et al., 1995; Milani, 1997; Johnston 2000.). Fisseha et al. (2003) also proposed the continuation of the Pampean belt under the Pantanal sedimentary cover as the Paraguay belt based on magnetotelluric soundings and gravimetric data. According to Kröner and Cordani (2003) and Cordani et al. (2009), small ancient custal blocks at the prest-day Paraguay boundaries were continuosly reworked. In this context, Comin-Chiaramonti et al. (2007)proposes that the APP Na-alkaline magmatism occurred at the boundaries between the Rio Apa and Arequipa-Antofalla blocksas a result ofthe extensional regimes derived from the relative movements of the ancient blocks.

The dynamics of magma pulses and growth of magma bodies has been the focus of an increasing number of studies (recent overviews in Tectonophysics 500, 2011), and new geological, geophysicall and geochronological informations may bring new insights for the pluton build up models. In this paper we present paleomagnetic and anisotropy of magnetic susceptibility investigations aiming to contribute to the understanding the emplacement context of the APP rocks.

2. Geological Background

The Parana basin is a large cratonic basin occupying southern Brazil and adjacent areas in Argentina, Paraguay, and Uruguay. The sedimentary filling of the basin started in the Ordovician and extended until the Early Cretaceous when a huge flood magmatic activity covered the entire basin (Fúlfaro, 1996; Piccirillo & Melfi, 1988). Sills and dykes also of Early Cretaceous age are widespread all over the basin, and cut mainly the upper Paleozoic to Cretaceous sedimentary rocks (*e.g.*Zalán et al., 1990). Dyke swarms also surround the basin, but to the north ages are younger, and Late Cretaceous intrusive alkaline magmatism dominates.

However, in the Brazil-Paraguay border an older alkaline magmatism of Triassic age dominates landscape along nearly 40km of the Paraguay River (Fig. 1). This is known as the Alto Paraguay Province (APP), a series of stocks and ring complexes that parallel the Paraguay river to the north and south of Porto Murtinho locality(geographic limits at 21°00'-23°35'S, 57°10'-58°00'W). These rocks crop out in the Pleistocenic Pantanal Formation which covers the Chaco-Pantanal system (Fúlfaro, 1996). The Pantanal is a N-S elongated basin in central-west Brazil, developed as aconsequence of the Andean orogeny (Almeida, 1945; Ussami et al., 1999). The plain developed over the metamorphic rocks of the Alto Paraguay folded belt; its structural features have been reactivated since the late Pleistocene imprinting NE and NS structural directions in the plain (Paranhos et al., 2013).

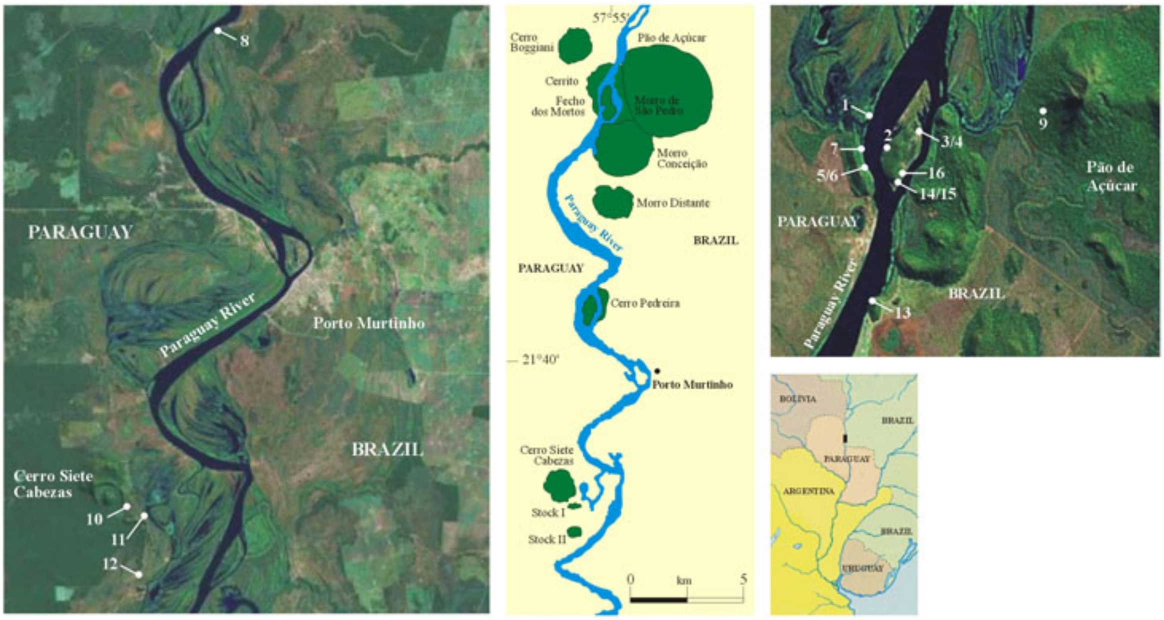

Figure 1. Location maps of the sampling sites. The sketch map shows the location of the complexes, and sampling sites are shown on the left (South area) and the right (North area) images.

Seven major circular complexes are described in the APP (Gomes et al., 1996; Comin-Chiaramonti et al., 2005): Cerro Siete Cabezas, Cerro Pedreira, Morro Distante, Morro Conceição, Fecho dos Morros, Pão de Açúcar and Cerro Boggiani, as well as some minor occurrences and some dykes. Intrusive to sub-intrusive rocks are predominantly sodic-alkaline rocks, i.e. nepheline-syenites, followed by syenites and phonolites. Phonolitic lava flows are eventually found on the top of the hills as in the Pão de Açúcar complex.From a petrochemical point of view, two main suites are apparent in the alkaline rock-types (Comin-Chiaramonti et al., 2005): an agpaitic, strongly undersaturated suite is dominant in the Cerro Boggiani, Pão de Açucar and Cerrito complexes, whereas a suite tendentially miaskitic and oversaturated prevails in the Cerro Siete Cabezas complex.

The APP is well dated by different radiometric methods. K-Ar ages are in the range ~228-255Ma (Comte & Hasui, 1979; Sonoki & Garda, 1988; Velázquez et al., 1996); in the northern APP two Rb-Sr dating gave ages of 255±11Ma (Velazquez et al., 1996),and

Ar^{39}/Ar^{40} ages vary from 236 to 250 Ma obtained from different minerals and whole rock (Velázquez et al., 1996).However, Comin-Chiaramonti et al. (2007) obtained a significant less broad interval of ages (240.6±0.4 to 241.9±0.4 Ma) based on plateau ages for biotite separates from samples representing the entire complex, and authors suggest a mean age of 241.5±1.3Ma as the preferable age to characterize the APP.

Table 1 – Location and description of the sampling sites

Localities	Complex[1]	Lat. (°S)	Long . (°W)	Sampling points	Description
1ª	Cerrito	21°27'06"	57°55'41"	505	
1B	Cerrito	21°27'06"	57°55'41"	506	Dike N276/85; width=10cm
2	Island (western side)	21°27'06"	57°55'33"	507	
3	Island (eastern side)	21°26'55"	57°55'05"	508	
4ª	Island (south of 3)	21°27'17"	57°55'39"	509	
4B	Island (south of 3)			510	Dike (30cm)
5	Fecho dos Morros	21°27'20"	57°55'39"	511	511C - dark fine grain band with phenocrystals
6	Fecho dos Morros	21°27'18"	57°55'43"	512	Dike N98/vertical; fine grained with large alkaline feldspars
7	Fecho dos Morros	21°27'08"	57°55'53"	513	
8ª	Cerro Pedrera	21°36'03"	57°55'04"	514	
8B	Cerro Pedrera	21°36'03"	57°55'11"	515	Dike N303/vertical (25-40cm)
9ª	Pão de Açúcar	21°26'33"	57°55'30"	516	Flow; height=240m
9B	Pão de Açúcar	21°26'33"	57°55'30"	517	Flow; height=250m
10	Stock I	21°47'23"	57°57'09"	518	
11	Cerro Siete Cabezas	21°47'20"	57°57'13"	519	
12	Stock II	21°48'54"	57°57'04"	520/521	521 above 520
13	Fazenda Cerrito	21°28'29"	57°55'41"	522	
14ª	Island (southern area)	21°27'23"	57°55'26"	523	
14B	Island (southern area)	21°27'23"	57°55'26"	524	Dike N280/vertical (30cm)
15	Island 100m northward	21°27'23"	57°55'21"	525	Dike N280/vertical (4m)
16A	Island - 10m north of loc.15	21°27'25"	57°55'26"	526	Dike N310/45NE (1m)
16B	Island –same as 16A	21°27'25"	57°55'26"	527	Dike
16C	Island 10m - same as 16A	21°27'25"	57°55'26"	528	

[1] Named as in Comin-Chiaramonti et al. (2005)

3. Paleomagnetic data

Samples from 22 independent paleomagnetic sites (15 localities, *cf.* Fig. 1) were collected from the river banks where fresh *in situ* rocks were exposed.The sampling sites (Table 1) include the host rock and dikes which were seen mainly in the northern area, and two lava flows (sampling point 9) located on the top of the Pão de Açúcar hill (about 240m high).

Samples were taken with the aid of a portable gasoline powered drill, and cylinders were oriented by both magnetic and sun compasses. Specimens of one inch in diameter and 2.2 in height were prepared, and submitted to both alternating field and thermal demagnetizations, generally up to 120mT or 600°C (few samples up to 680°C). Normal and reversed magnetic components were identified and calculated by principal component analysis (Kirshvink, 1980).

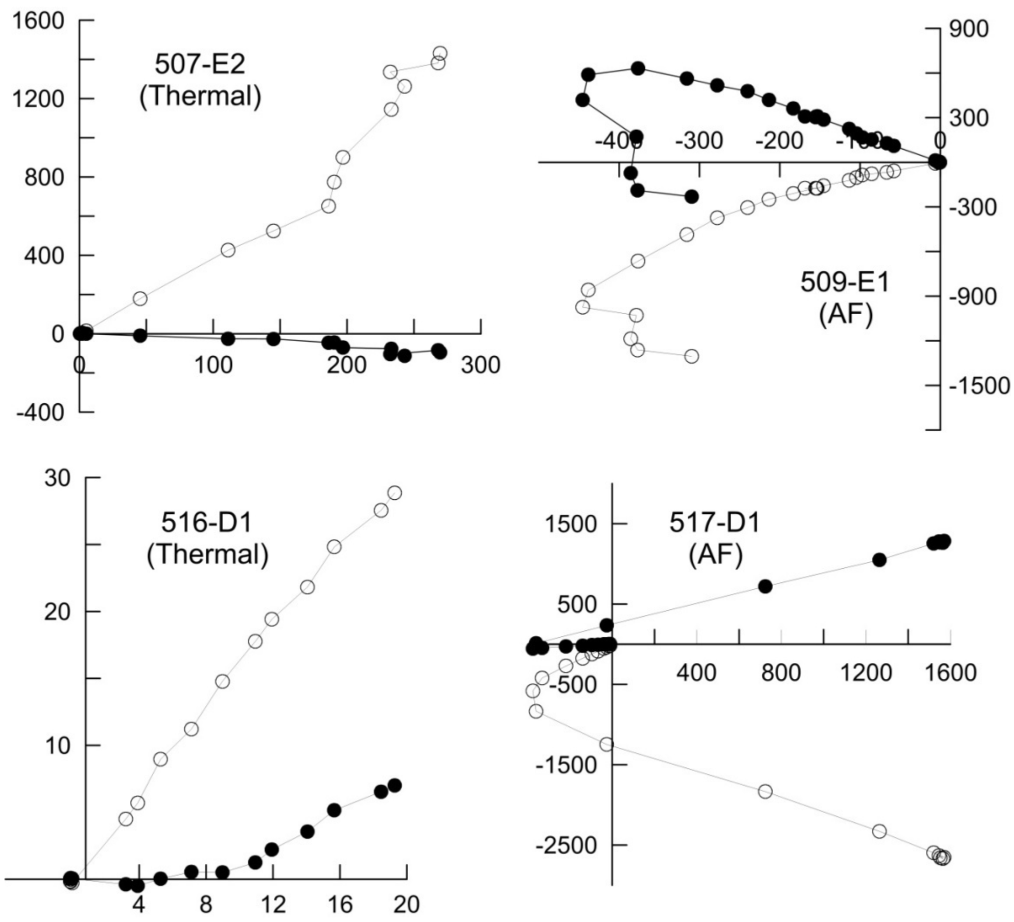

Figure 2. Orthogonal plots fore some samples during thermal and AF demagnetization. Open (full) symbols are vertical and horizontal projections.

In general samples showed high coercivity (Hcr) components which were erased above 80mT (Fig. 2); low coercivity components were isolated at fields lower than 15mT medium; a third component of medium coercivity in the range ~15-30mT was detected in some samples. The Hcr magnetization components were very well defined by the principal component analysis (Kirshvink, 1980); the maximum angular deviation (MAD) is normally less than 4 for 7 to 11 consecutive steps in most cases (Fig.3).

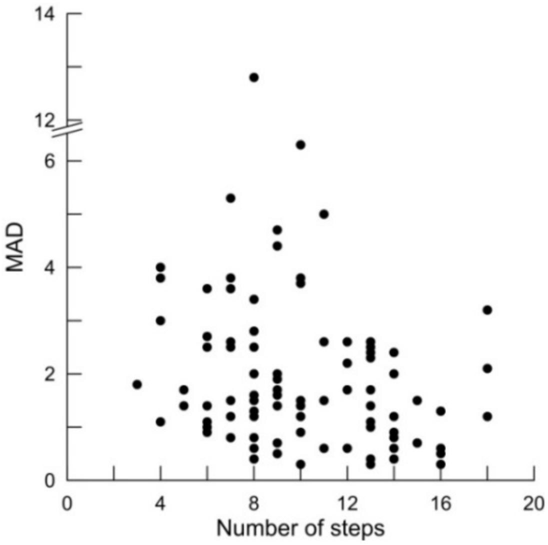

Figure 3. The MAD parameter for the high coercivity components of magnetization as a function of the number of AF demagnetization steps.

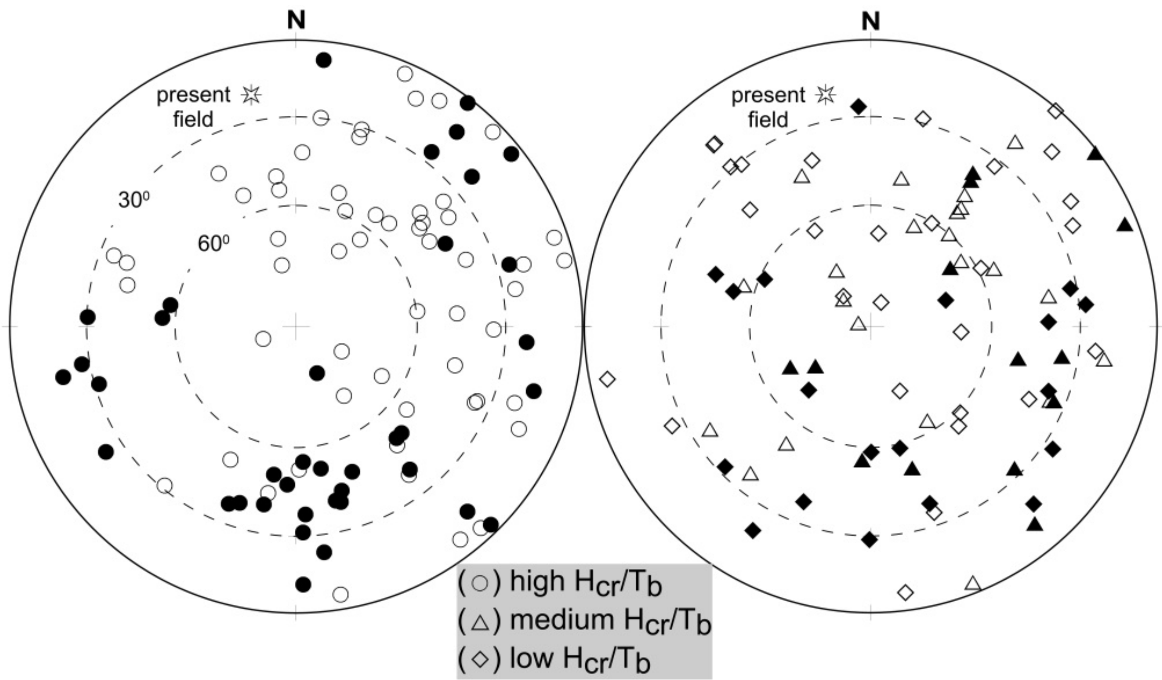

Figure 4. Stereograms displaying all the identified high (left) and medium to low (right) coercivity/unblocking temperature magnetization components. Open (full) symbols represent negative (positive) inclinations.

However, the within-site dispersion of the Hcr components is large, with the Fisher's (1959) α_{95}statistical parameter exceeding 30° for a considerable number of sites. Table 2 displays mean magnetization results for those sites that gaveα_{95}<30°. The distribution of the Hcr components (Fig. 4) show that the characteristic magnetizations of the APP rocks differ from the present geomagnetic field, and were acquired during periods of normal and reversed field polarity. The north-south components with negative and positive inclinations mainly in the range 30°-60° are comparable to the Early Triassic directions already reported for South America (Domeier et al., 2011; Yokoyama et al., 2013).The distribution of the low and medium Hcr components (Fig. 4) is similar to the Hcr component distribution, and very few data plot close to the present field direction, indicating that the magnetization was hard enough to prevent alterations by the present field induction effect.

Table 2. Paleomagnetic results for the APP rocks

	Mean Magnetization Direction					VGPs	
Sampling sites	Dec. (°)	Inc. (°)	N	α_{95} (º)	k	PLong. (°E)	PLat. (°S)
505	171.2	47.8	3	17.4	51	347.3	-79.1
506	29.3	-64.2	3	9.6	17	264.8	-55.8
507	350.2	-65.2	3	20.3	38	316.8	-63.0
508	8.5	-37.2	3	26.0	24	208.8	-82.0
512	152.5	45.1	4	24.5	15	14.9	-64.4
513	58.2	-51.9	3	21.2	35	237.3	-37.6
516	345.5	-50.6	5	11.0	49	351.7	-73.7
518	50.1	-47.5	3	17.6	50	231.4	-44.5
526	182.3	30.8	4	21.7	19	146.6	-84.7
527	109.3	-45.4	4	28.7	11	64.2	-6.3
Mean of sites	183.3	48.9	7	15.8	15	318	-79
						N=7;α_{95}=14.5;k=18	
Mean (cutoff=30°)						319	-78
						N=26;α_{95}=6.0;k=23	
Mean (cutoff=45°)						292	-83
						N=41;α_{95}=6.8;k=12	

(Dec. and Inc., Declination and Inclination; N, number of specimens for mean calculations; $\alpha_{95}$and k, Fisher's (1953) statistical parameters; BP, bedding plane correction.

A closer look to the within-site dispersion allows the conclusion that Hcr components are not random but follow a common pattern identified in some dikes and the host rock. In the dikes 505 and 526 (Fig. 5)the magnetization varies from the border tothe center(faster to slower cooling) tending to shallower positive inclinations. Same vector movement is seen in site 511 where the more mafic band (511C) corresponds to a younger record, and its magnetization may represent a transitional field. Many other sites show the same pattern, and some probably recorded a complete polarity reversal, but unfortunately in these cases there is no time control.

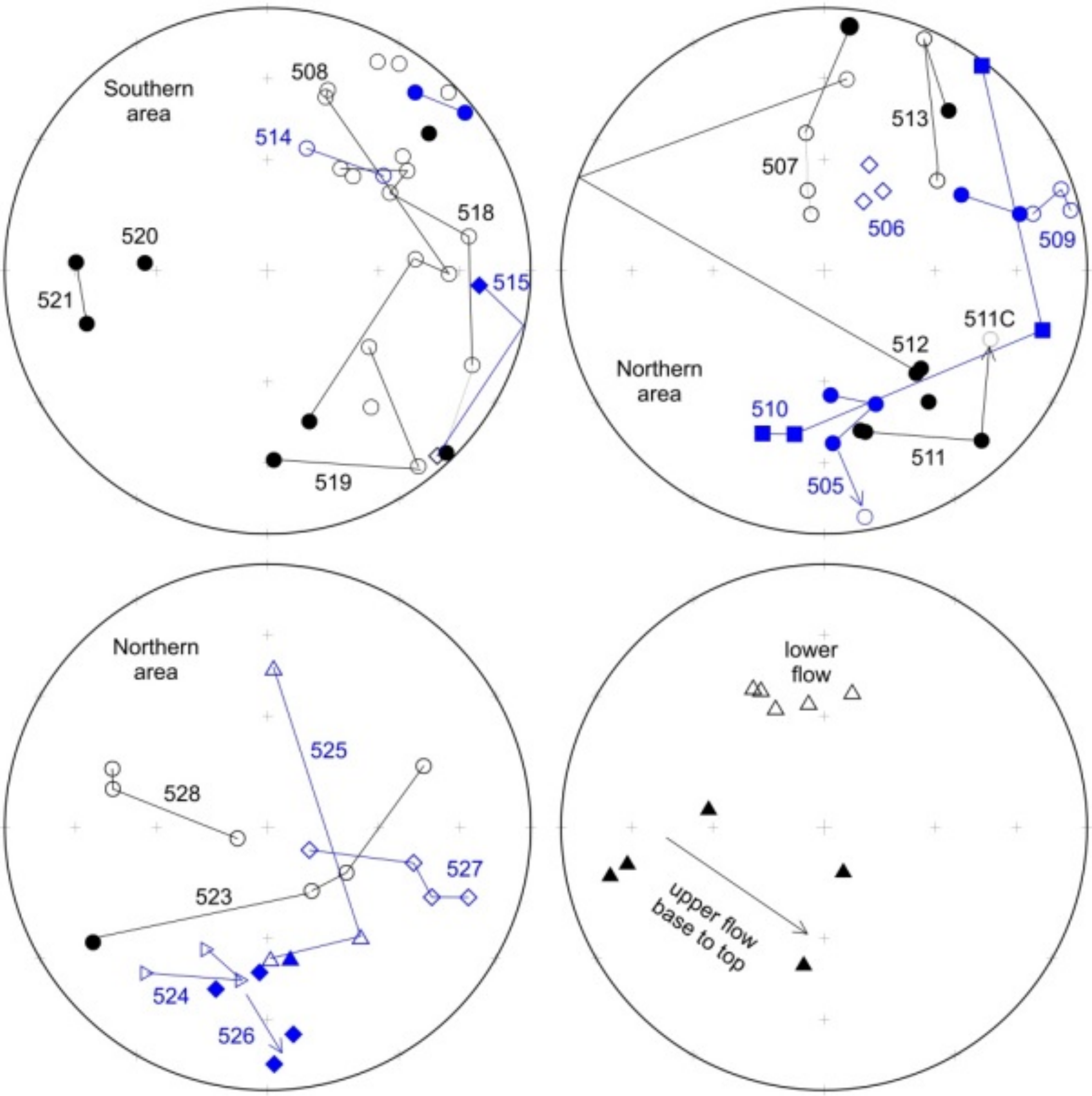

Figure 5. Within-site dispersion of the Hcr remanent magnetization of sites from Southern and Northern areas. Circles indicate host-rock samples, and the other symbols refer to dikes and flows. Blue color identifies sites belonging from the same sampling points. Results are linked by lines for facility of identification but they do not necessarily indicate any chronological order except when an arrow points to the younger magnetization.

The virtual geomagnetic poles (VGP) calculated for each specimen are mainly concentrated within the 30-90º longitude band, and distributed from south to north geographic pole; this distribution may represent the path of the geomagnetic field during a reversed to normal polarity, as indicated by the above analysis of the remanent magnetizations. It is important to note that the magnetization of the two investigated flows also indicate a transition from normal to reversed polarity as the upper and lower flowsrecorded normal and reversed polarities respectively.

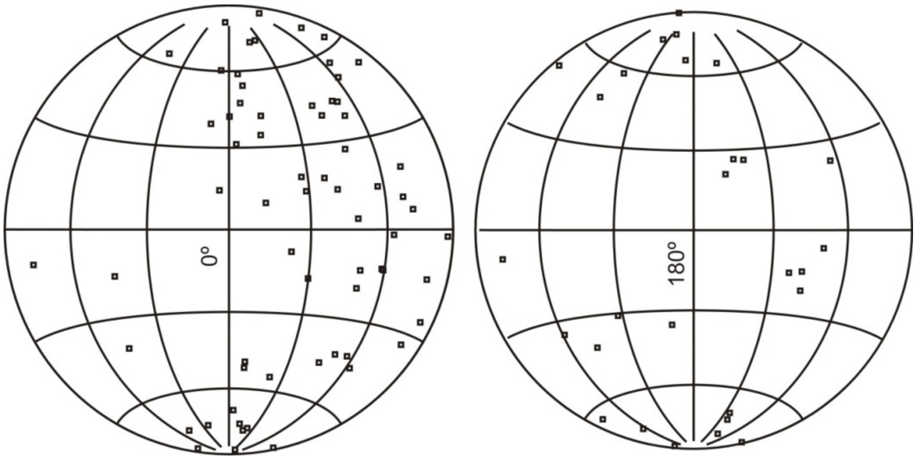

Fig.6. Virtual geomagnetic poles corresponding to the Hcr component of all specimens.

4. Rockmagnetism and AMS

Reversible thermomagnetic curves (Fig. 7) are typical for almost all sampling sites, and suggestlow Ti-content titanomagnetite as the main magnetic carrier. In flow samples theseminerals show structures related to high temperature oxidation, and ilmenite exsolution. In the majority of the sampling sites fine grains of titanomagnetite are spread in the matrix.Eventually some hematite is present, as well as small quantities of titanomaghemite as seen in the curve of site 506.The isothermal remanent magnetization (IRM) acquisition curves indicate high coercivity minerals normally saturating at fields of at least 100mT. This behavior is indicative of fine magnetite grains of high coercivities.

In general the APP rocks have a low degree of anisotropy of magnetic susceptibility (AMS) with values concentrated in the range 1.02-1.06 (Fig. 8). Bulk susceptibilities concentrate over a narrow range, but some higher values are noticed in the northern area. The magnetic fabric is either of lineated and foliated character, howeverfoliation prevails in the flows. These characteristics are indicative that the rocks have not been subject to important stresses.

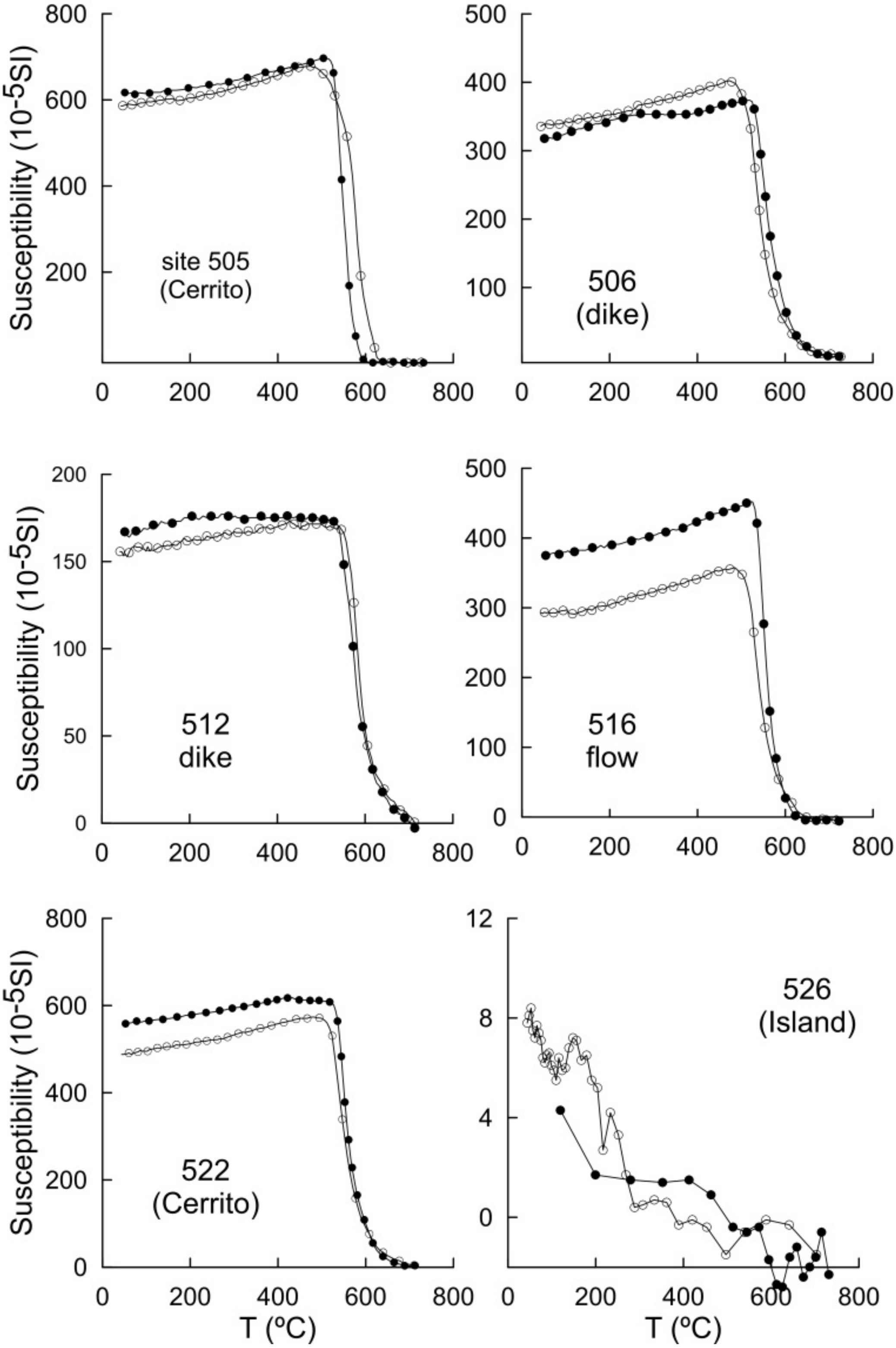

Fig. 7. Thermomagnetic curves (k versus T) for samples from different sampling sites during heating (full symbols) and cooling (open symbols). The curves indicate titano-magnetite as the main magnetic carrier.

AMS determinations were performed before submitting the specimens to magnetic cleaning. The three mainanisotropy axes (k_1, k_2 and k_3) determined for flows, dykes and the host rocks are displayed in the stereograms of Fig. 9.The two flows show the major axes k_1 and k_2 distributed in a sub-horizontal plane (k1 inclinations ≤ 30º). The mean direction of the k_3 axes correspond to the pole of the foliation plane defined by the major axes.The dykes show mainly sub-vertical k_1 axes in accordance to the measured dip of the filled fractures (Table 1), and indicating steep magma fluxes admitting that $k_1$marks the magma flux (*e.g*. Cañon-Tapia & Pinkerton, 2000; Bascou et al., 2005).The other sites tend also to give steep k_1 axes mainly in the outcrops of the North area. In the South area data is more variable and k_1 describes a N-S plane.

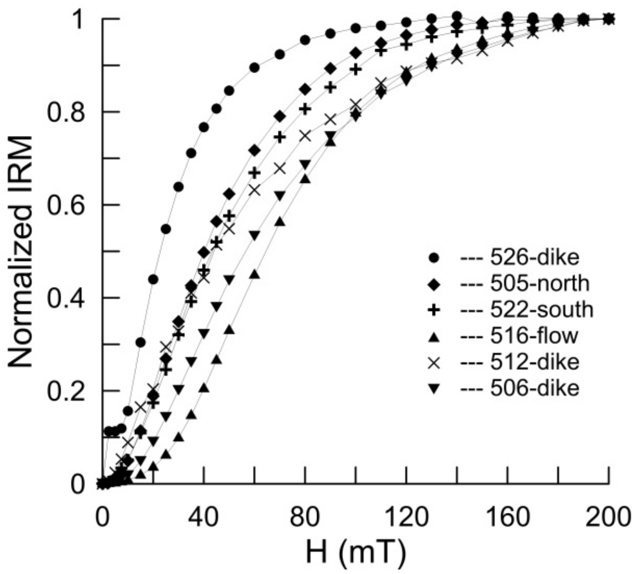

Fig. 8. Isothermal remanent magnetization curves for samples of different sites.

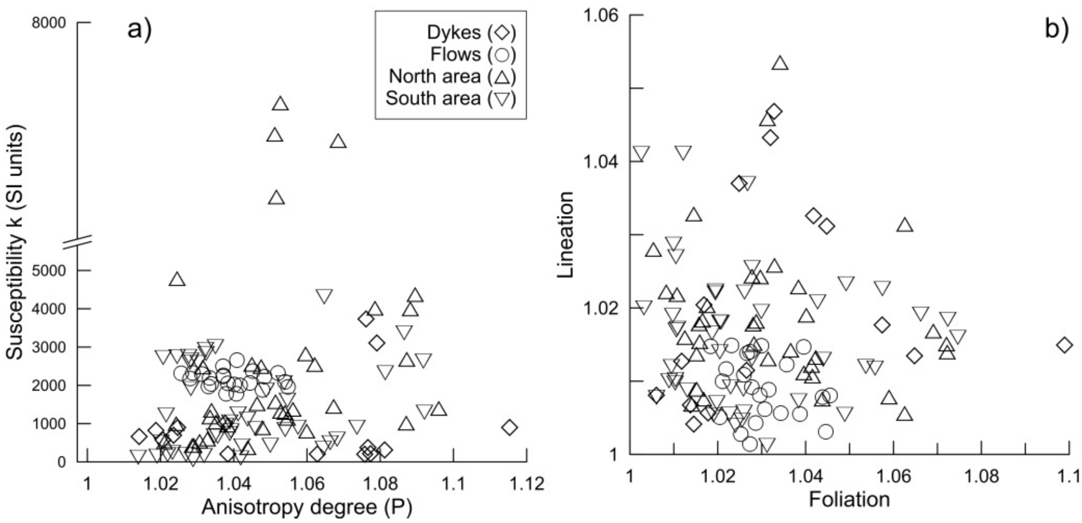

Fig. 9. a) Variation of magnetic susceptibility as a function of the anisotropy degree, and b) the magnetic lineation (k1/k2) versus the magnetic foliation (k2/k3).

5. Discussion and Conclusions

The characteristic components of magnetization in the APP include both normal and reversed polarities, but also a large number of transitional directions which can be related to a reversing ambient field. A paleomagnetic calculated as the mean of the virtual poles related to the mean magnetization of the more stable sites (Table 2) is located at 318°E 79°S (N=7;α_{95}=14.5°;k=18) which is in accordance to other Late-Permian to Triassic poles for South America.However, this pole is based mainly on the results of theflows and dikes; if we give unit weight to specimens we can calculate a paleomagnetic pole wich includes information from other sites. In Table 2 calculations using different cut offs are displayed, and they do not differ significantly; the preferred pole is at 319°E 78°S (N=26;α_{95}=6.0°;k=23) which does not differ significantly from the othe poles but shows better statistical parameters.The mean pole for South America for the interval 250-200Ma compiled by Domeier et al. (2011) is at 295°E 79°S(N=3;α_{95}=9.5°) matches well the APP pole.

One problem in calculating a paleomagnetic pole from the APP rocks is the lack of reference planes to estimate possible tilting. The subhorizontal foliation planes given by the AMS measurements of the flows may give an indication of the paleohorizontal. The mean of the minimum axes k_3 (the pole to the foliation plane) directions suggest a dip of 24° to N205°, and such a bedding correction would displace the APP paleomagnetic pole to a position (157°E 80°S), if taken as representative of the entire igneous province. This pole position is close to the Late Jurassic segment of the apparent polar wander path for South America (Tamrat & Ernesto, 2006), and would imply in a remagnetization of the entire province, for which there are no evidences from the paleomagnetic and the rockmagnetic data described above.Therefore, if the maximum axes k_1 are really parallel to the flow direction it is possible that the foliation plane refers only to the Pão de Açúcar complex or it means that the emplacement surface was not horizontal. Strong evidence against the hypothesis of remagnetization is given by sampling points 1A and 1B where the host rock (sample 505)has a reversed magnetization (and probably recording a transitional field as well; sample 505F) whereas the cutting dike (sample 506) is of normal polarity (Table 2 and Fig. 4). The dike is only 10cm thick and is about 20m from sample 505F, but closer to the reversed polarity samples. Therefore, an influence of the intrusion to the magnetization of the host rock must be discarded. These results can also be seen as a contact test.

The remanent magnetizations suggest that at least three polarity intervals were recorded by the complexes. Kent & Olsen (1999) estimated a mean duration of 0.53 m.y. and a corresponding reversal rate of 1.88/m.y. for the Late Triassic. Therefore, a few million years may be estimated to accomplish for the magnetic records of the investigated rocks if that estimate is also valid for the Early Triassic.

The distributions of the VGPs for the North and South areas (Fig. 10) have the same NE-SW tendency but for the South area they concentrate in the 180°-270° quadrant, and at latitudes lower than 60°S. This distribution contrasts to the one for the North area which includes the flows and the dikes, except one. The AMS also show different patterns in the two areas (Fig. 11): k1 axes are steeper and trend NW-SE in the North area; in the South area they trend N-S. These differences are related to distinct modes of construction of the plugs, and/or indicate that the two areas have been submitted to different stress fields.

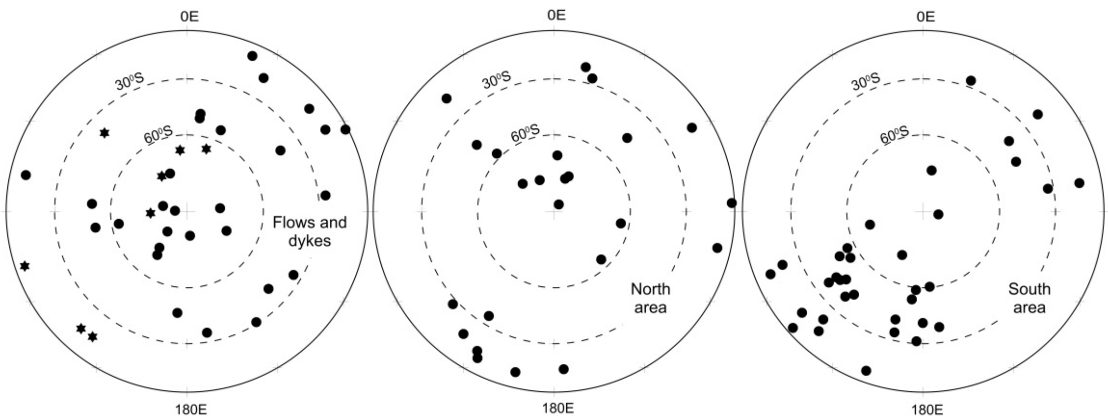

Fig. 10. Comparison of the VGPs as seen from the South geographic pole. Left plot shows results for dikes (circles) and flows (stars); the other two plots show results for the other rocks from North and South areas.

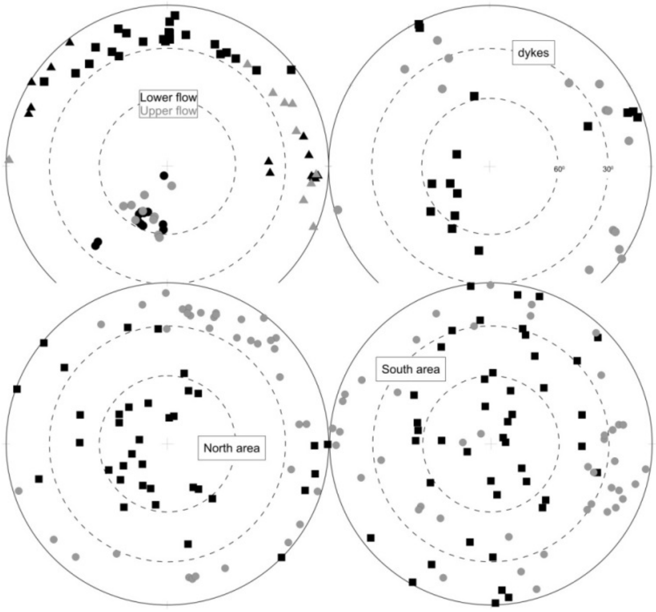

Fig. 11. Distribution of the AMS main axes (k_1, k_2 and k_3) for the flows and dykes (top plots); k_1 and k_2 axes the other samples of the complexes are shown in the bottom plots corresponding to the north and south areas.

6. Concluding remarks

The Alto Paraguay Province consists of a series of ring complexes that parallel the Paraguay river (the border between Brazil and Paraguay) for more than 40 km along a narrow N-S band. Intrusive and subintrusive rocks are predominant, except for the Pão de Açúcar complex which corresponds to a volcanic field. The province is well dated by Ar/Ar method with preferable age of 241 Ma.

The remanent magnetization of the APP rocks is mainly carried by high coercive magnetite. Characteristic components of magnetization include both normal and reversed polarities, but also an abnormally large number of anomalous directions which can be related to polarity transitions. The calculated paleomagnetic pole along other Late-Permian to Early Triassic poles places South America in a position that favors the A-type reconstruction of Pangea (*cf.* Brandt et al., 2009; Domeier et al., 2012). Magnetic anisotropy indicate subhorizontal foliated fabric for lava flows which may be related to original magma fluxes or to tilting. For the intrusive complexes the main susceptibility k_1 axes delineate planes in approximately N-S (South area)and NW (North area) directions; however, in the North area steep inclinations are predominant.

Acknkowledgments. Thanks are due to Daniele Brandt for her help in various laboratory routines. This work was funded by the Brazilian agencies FAPESP and CNPq.

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