MAGNETIC SUSCEPTIBILITY ANISOTROPY AND PALALEOMAGNETISM OF VOLCANIC ROCKS NEAR SOLEDADE CITY, RS, BRAZIL

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ABSTRACT

The Paraná-Etendeka Igneous Province (PEIP) represents one of the largest volcanic events in Earth's History. In the Lower Cretaceous, about 800,000 km^3 of lava were extruded preceding the fragmentation of southern Gondwana and the opening of the South Atlantic Ocean. Basalts, basaltic andesites (97.5%) and a smaller amount of acid rocks (2.5%) are recorded in PEIP, which make up the Serra Geral Group. This research aims to study basic and acidic rocks of the southern region of PEIP through the methodologies of rock magnetism, low-field magnetic susceptibility anisotropy and paleomagnetism in order to determine the magnetostratigraphy and the emplacement mode of the lava flows. Preliminary rock magnetism data indicate that magnetic mineralogy is mainly composed by magnetites and titanomagnetites with varying degrees of oxidation. The AMS scalar parameters generally show poorly anisotropic rocks with dominantly neutral to oblate ellipsoids, while the magnetic lineation suggests that the lavas were fed by horizontal to sub horizontal flows in two main directions: NNW-SSE and ENE-WSW. Paleomagnetic data show that the sampled section units were placed at different times and that there were at least three geomagnetic field reversions during the emplacement of this rocks from the bottom to the top of the section.

Keywords: AMS, Paleomagnetism, Volcanism, Geophysics, Magnetism, LIP

RESUMEN

La provincia ígnea de Paraná-Etendeka (PEIP) representa uno de los mayores eventos volcánicos en la historia de la Tierra. En el Cretácico Inferior, previo a la fragmentación del sur de Gondwana y a la apertura del Atlántico Sur, alrededor de 800,000 km^3 de lava fueron expulsados. El Grupo Serra Geral, que forma parte de la PEIP, está compuesto principalmente por basaltos y andesitas basálticas (97.5%) y una menor cantidad de rocas ácidas (2.5%). Esta investigación tiene como objetivo estudiar las rocas básicas y ácidas de la región sur de la PEIP a través de las metodologías de magnetismo de roca, anisotropía de susceptibilidad magnética y paleomagnetismo para determinar la magnetoestratigrafía y el modo de emplazamiento de los flujos de lava. Los datos preliminares de propiedades magnéticas indican que la mineralogía magnética está compuesta principalmente por magnetitas y titanomagnetitas con diversos grados de oxidación. Los parámetros escalares de AMS generalmente muestran rocas con baja anisotropía con elipsoides predominantemente neutros a oblatos, mientras que la lineación magnética sugiere que las lavas fueron alimentadas por flujos horizontales a sub horizontales en dos direcciones principales: NNW-SSE y ENE-WSW. Los datos paleomagnéticos muestran que las unidades de las secciónes muestreadas se emplazaron en diferentes momentos y que hubo al menos tres inversiones del campo geomagnético durante el emplazamiento de estas rocas desde el inicio hasta la parte superior de la sección.

Palabras claves*:* AMS, Paleomagnetismo, Volcanismo, Geofísica, Magnetismo, LIP

1. Introduction

The Paraná-Etendeka Igneous Province (PEIP) of Eocretaceous Mesozoic age (~ 145-120 Ma; Renne *et al*., 1996; Janasi *et al*., 2011) represents the second largest continental-type volcanic event present in our Planet, and preceded the South Gondwana fragmentation and the opening of the Atlantic Ocean. The volcanic and subvolcanic rocks generated during this magmatism comprise, in Brazil, the Serra Geral Group and cover a large area of South America and its conjugated units in Africa, for a total length of 1.2 × 106 km^2 (Cordani and Vandoros, 1967; Peate , 1997).

The PEIP rocks were subdivided by Bellieni *et al*. (1984) and Peate (1997) in two main units, in the south, low TiO_2 and in the north, high TiO_2. In southern Brazil, the low TiO_2 sector is composed by a pile of Gramado magma type basalts overlapped by Palmas magma type dacites and rhyolites and, at the top of the sequence, there are Esmeralda magma type basalts (Peate *et al*., 1992; Peate, 1997). This pile was further divided into four formations due to the heterogeneity of their lava packages (Rossetti *et al*., 2017), from bottom to top, the chemically primitive basalts of the Torres Formation, the basaltic andesites of the Vale do Sol Formation, the dacites and rhyolites of the Palmas Formation and the basalts of the Esmeralda Formation.

There are few studies applying magnetic anisotropy techniques in PMPE, considering their full extent and potential applicability. In Brazil, AMS studies in lavas are restricted to those performed by Glen et al. (1997) Tamrat and Ernesto (1999) and more recently by Zaffani (2013), Pescarini and Raposo (2017), Cañon-Tapia and Raposo (2018) and Guimarães *et al.* (2018). These studies show greater coherence between magnetic lineations (K_{max}) at the south and east edges of the PMPE, with essentially NE-SW direction, becoming more diffuse toward the north and west edges possibly due to a change in the flow dynamics of the PMPE magma flows.

Geochemical (Bellieni *et al*., 1986; Mantovani *et al*., 1988; Peate, 1992) and paleomagnetic (Ernesto *et al*., 1988; Ernesto and Pacca, 1990) data were mostly generated in the 1980s and 1990s. The latter in particular, are insuficiente to accurately correlate the stratigraphy of volcanic units in view of their complexity and great extent.

Thus, this research aims to advance the knowledge about the magnetic stratigraphy of volcanic rocks as well as to define the emplacement kinematics and the relationships of these data with other existing data in the region.

2. Methodology

2.1. Localization and sampling

The study area is located in the southern sector of the PEIP and in the southern region of Brazil, in the Rio Grande do Sul state, near the city of Soledade (Fig.1). Samples were collected with the aid of a portable (gasoline-powered) drilling rig where a one-inch diameter diamond drill was attached. The orientation of the samples was done with the magnetic and solar compasses whenever possible. Nine sites (labeled RAs) were sampled where at least five cylinders of each lava flow were collected, obeying whenever possible the base, middle and top of these flows, resulting in a total of 66 samples later cut into 205 specimens. Rock types are basalts, andesites, dacites and rhyolites.

2.2. Experiments

For this research, the following experiments have been performed so far (which will be presented in this article): (1) acquisition of thermomagnetic curves (susceptibility as a function of temperature) using the CS3-CS3L equipment coupled to the MFK-1 (Agico-Czech Republic), (2) low-field magnetic susceptibility anisotropy by Kappabridge equipment (model MFK-1, Agico-Czech Republic) with coupled 3D rotator, (3) AF demagnetization (alternating fields) via demagnetizer AF-D2000T (ASC, Scientific) and termal demagnetization. The remanent magnetizations were measured on a JR6A spinner magnetometer (Agico-Czech Republic). Additional experiments currently being conducted are: isothermal remanent magnetization (IRM) curves, hysteresis cycles and coercivity spectra through partial anisteretic remnant magnetization (pARM).

3. Results

Figura 1. (**A**) Simplified geological map of the Paraná Basin (Modified by Waichel et al, 2012); (**B**) Profiles studied through AMS and paleomagnetism methods in the region; in orange, the profile studied in this work.

3.1. Rock Magnetism

The termomagnetic curves were performed at low (-195° to 0° C) and high (20° to 700° C) temperatures from samples of the nine sites. For the low temperature experiment, the temperature reduction down to -195° C was performed by controlled increase of liquid nitrogen. The experiment at high temperatures was done under argon atmosphere. Figure 2 shows representative examples of the results from the section's sites under study.

The low temperature curves show an inflection at ~ -150° C corresponding to the Verwey transition that is characteristic of magnetites. The corresponding high temperature curve shows an increase in magnetic susceptibility up to 400° C suggesting that a magnetic phase is being generated. On the other hand, there is a complete loss of susceptibility at 580º C (RA-1) and 630º C (RA-3), suggesting that the magnetic minerals present in the samples are oxidized magnetites and titanomagnetites, respectively. The heating and cooling curves are not reversible indicating the destruction of a magnetic phase.

3.2. Low-field magnetic susceptibility anisotropy (AMS)

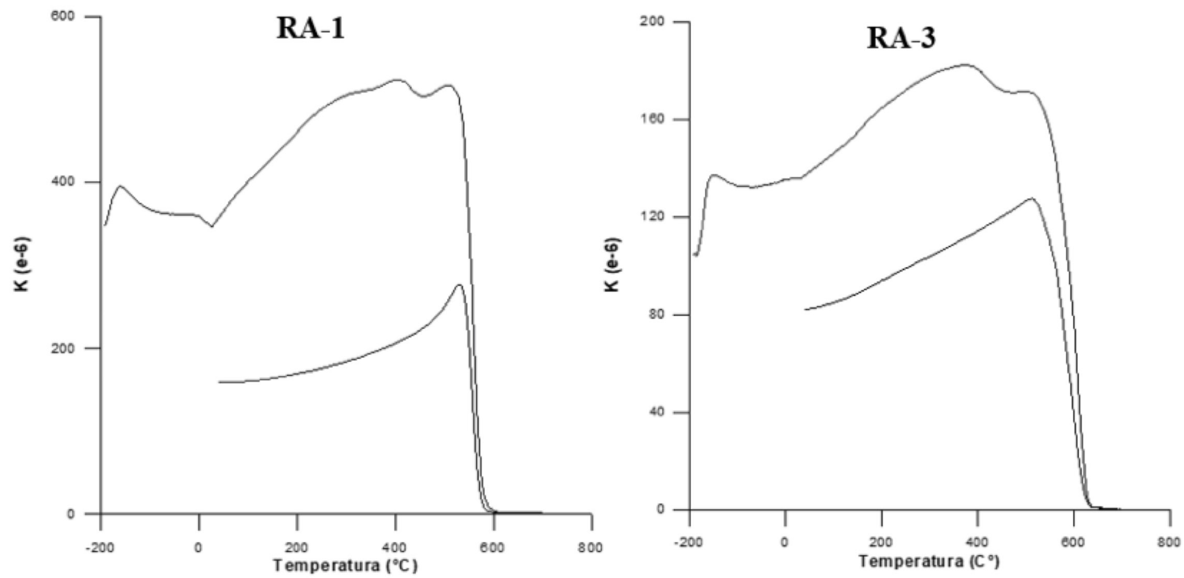

Figura 2. Representative examples of thermomagnetic curves of the profile sites.

The bulk magnetic susceptibility, expressed by the arithmetic mean $K_m = (K_{max}+K_{int}+K_{min}) / 3$ in is generally high, of the order of 10^{-3} (as expected for volcanic rocks). The basalts have a large variation of K_m where the basalts of the lower elevations have the highest susceptibility (> 18.33×10^{-3}) and the highest basalt of the sequence (RA-8) has the lowest bulk susceptibility of the sampled sites in the sampled section (1.75×10^{-3}). All other lithotypes have intermediate bulk susceptibilities ranging from 6.46×10^{-3} (rhyolite) to 20.55×10^{-3} (dacite).

The degree of anisotropy P, given by the ratio P = Kmax/Kmin, is relatively low for dacites and andesites (P < 1.010) and higher for basalts (P > 1.010) and rhyolites, which shows the highest P value (1.057). The relationship between Km and P is not very clear and there is only an indication that P increases exponentially with the value of Km.

In the Jelinek diagram (Fig. 3b), degree of anisotropy (P) × shape parameter (T), we note an interesting result which is the absence of prolate ellipsoids (T < 0) in these rocks. The ellipsoids are neutral (T0) for most sites except the basalts of the base of the profile and rhyolite in the top where the ellipsoids are oblate (T > 0).

The directional data show that the magnetic lineations (Kmax) of all sites are preferably sub-horizontal. It is possible to distinguish two groups of best-marked preferred orientations from magnetic lineation, one ranging from NNW-SSE to NNE-SSW and one from ENE-WSW to WNW-ESE. These directions are consistent with existing South PMPE data.

3.3 Paleomagnetism

To isolate the direction of the characteristic remanent magnetization (ChRM) of these rocks, it was performed a demagnetization test by the AF and thermal method in one specimen of the nine sites. The results were compared by the Zijderveld diagram (1967) and by plotting the magnetization directions in stereographic projection. Comparison between the two demagnetization methods showed that both thermal and AF demagnetization were efficient in isolating the direction of ChRM. Thus, considering that the demagnetization process by AF is much faster than the thermal, it was decided to use the AF process to

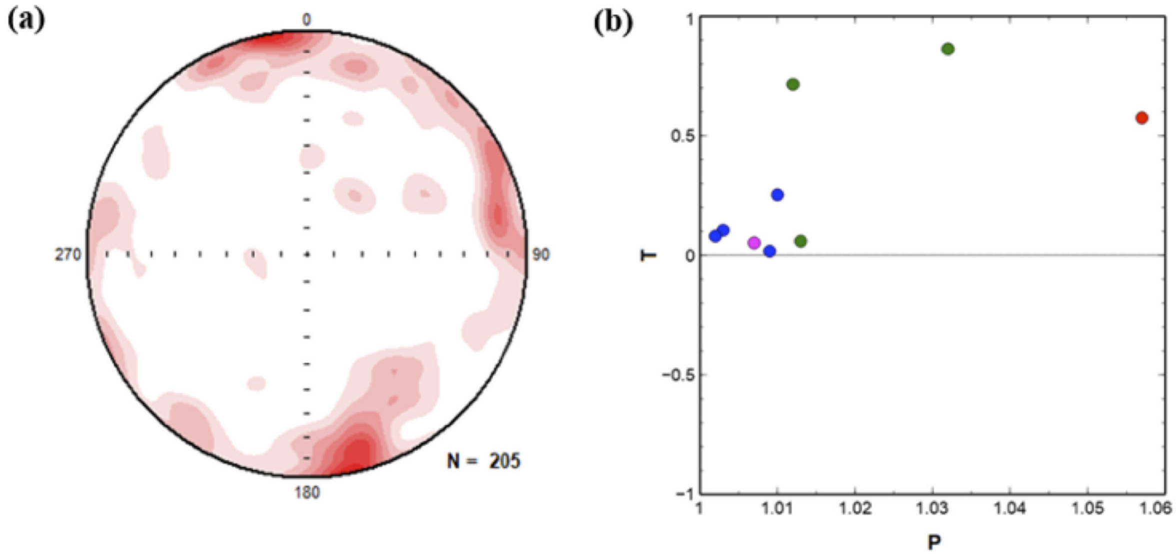

Figura 3. (**a**) Contour diagram for the magnetic lineations (K_{max}) of all specimens. (**b**) P x T diagram, green circles represent basalts, dacites blue, andesite pink and rhyolite red.

obtain the ChRM of the other specimens. For these specimens, demagnetization was performed at an initial peak field of 10 mT to at least 150 mT in 10 mT steps.

Nine more specimens were then demagnetized from each site for a total of 11 specimens per site, except for the RA-5 site where 15 specimens were demagnetized. These specimens (RA-5) exhibit very low coercivity retaining only secondary magnetization components, thus, no results were obtained for this site.

The results obtained by the demagnetization processes were inserted in a program (home-made of the Magnetic Anisotropy Laboratory of the Institute of Geosciences of the University of São Paulo (LAMs, IGc-USP)) that allows to calculate the average magnetization direction for each specimen and consequently for the site. The average direction of each specimen was calculated by principal component analysis (Kirshivink, 1980), always respecting the statistical criterion of a maximum angular deviation (MAD) less than 10º. The magnetization direction of each site was then determined by the vector mean of the directions of the analyzed specimens. Fisher's (1953) statistical parameters were also determined. All sites (except RA-5 site as already mentioned) showed satisfactory results (Fig. 4a). With the magnetization directions obtained, the virtual geomagnetic poles (PGVs) shown in figure 4b were determined. The magnetization directions indicate normal polarity for the RA-1,3,4,6 and 7 sites and reverse for the RA-2,8 and 9 sites, showing that the profile units were placed at different times and that there were at least three geomagnetic field inversions during the placement of the rocks from the bottom to the top. The statistical parameters are still being worked on at this research stage and will be presented in the future.

4. Conclusion

In conclusion, the thermomagnetic curves indicate that the rocks of the profile contain, as ferromagnetic minerals, magnetites and titanomagnetites of low to high oxidation. AMS scalar parameters generally show poorly anisotropic rocks with dominantly neutral to oblate ellipsoids (Fig. 3b) while bulk susceptibility is relatively high, as expected for volcanic rocks. The magnetic lineation (Fig. 3a) suggests that the lavas were fed by horizontal to sub horizontal flows, in two main directions: NNW-SSE and ENE-WSW. Paleomagnetic data (Fig. 4) show that the profile units were placed at different times and that there were at least three geomagnetic field reversions during the emplacement of these rocks from the bottom to the top.

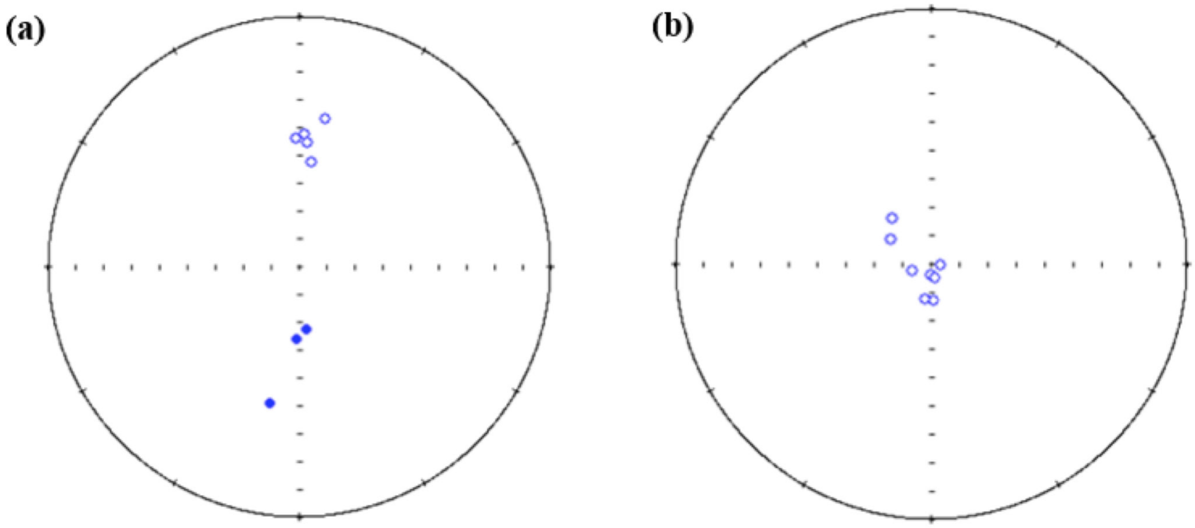

Figura 4. Preliminary results of (**a**) site magnetization directions and (**b**) virtual geomagnetic poles (PGVs) in equal-area projection.

References

Bellieni, G., Brotzu, P., Comin-Chiaramonti, P., Ernesto, M., Melfi, A., Pacca, I.G., Piccirillo, E.M., 1984. Flood Basalt to Rhyolite Suites in the Southern Paraná Plateau (Brazil): Palaeomagnetism, Petrogenesis and Geodynamic Implications. *J. Petrology 25(3),* 579-618.

Cordani, U.G., Vandros, P., 1997. Basaltic rocks of the Parana Basin. In: Bigarella, J.J, Becker, R.D., Pinto, J.D., (Eds) Problems in Brazilian Gondwana Geology, pp. 207-231.

Ernesto, M., Pacca, I.G., 1988. Paleomagnetism of The Paraná Basin Flood Volcanism, Southern Brazil. In: Melfi, A.J. (Ed) Piccirillo, E.M., The Mesozoic Flood Volcanism of The Paraná Basin, São Paulo, pp. 229-255.

Ernesto, M., Pacca, I.G., Hiodo, F.Y., Nardy, A.J.R, 1990. Paleomagnetism of The Mesozoic Serra Geral Formation, southern Brazil. *Phys. Earth Planet. Inter. 64,* 153-175.

Fisher, R.A., 1953. Dispersion on a sphere. *Proc. R. SOC., Ser. A217*, 295-305

Glen, J.M.G., Renne, P.R., Milner, S.C., Coe, R.S., 1997. Magma flow inferred from anisotropy of magnetic suscepitibility in the coastal Paraná-Etendeka igneous province: Evidence for rifiting before flood volcanism. *Geology 25* (12), 1131-1134.

Guimarães, L.F., Raposo, M.I.B., Janasi, V.A., Cañón-Tapia, E., Polo, L. 2018. An AMS study of different silicic units from the southern Paraná-Etendeka Magmatic Province in Brazil: implications for the identification of flow directions and local feeding. *Jour. Volc. Geot. Res. 355*, 304–318.

Janasi, V.A., de Freitas, V.A., Heaman, L.H., 2011. The onset of flood basalt volcanism, Northern Paraná Basin, Brazil: A precise U-Pb baddeleyite/zircon age for a Chapecó-type dacite. *Earth and Planetary Science Letters 302 (1-2),* 147-153.

Mantovani, S.M., Peate. D.W., Hawkesworth, C.J., 1988. Geochemical stratigraphy of Parana continental flood basalts: a contribution from boreholes samples. In: Melfi, A.J. (Ed) Piccirillo, E.M., The Mesozoic Flood Volcanism of The Paraná Basin, São Paulo, pp. 15-24.

Peate, D.W., 1997. The Paraná Etendeka Province. Large Igneous Prov. Cont. Ocean. Planet. Flood Volcanism, American Geophysical Union, Washington, pp 217-245.

Peate, D.W., Hawkesworth, C., Mantovani, M., 1992. Chemical stratigraphy of the Paraná lavas (South

America): classification of magmas types and their spatial distribution. *Bull. Volcanol. 55,* 119-139.

Pescarini, T.; Raposo, M.I.B. 2017. Estudos magnéticos da Formação Serra Geral (Bacia do Paraná) na região de Santa Cruz do Sul-Herveira, RS, Brasil: resultados preliminares. *Latinmag Letters 7*, PM16, 1-5.

Raposo, M.I.B. 2017. Magnetic Fabrics of the Cretaceous dike swarms from São Paulo coastline (SE Brazil): Its relationship with South Atlantic Ocean opening. *Tectonophysics 721,* 395-414.

Renne, P.R., Deckart, K., Ernesto, M., Féraud, G. e Piccirillo, E.M., 1996. Age of the Ponta Grossa dike swarm (Brazil), and implications to Parana flood volcanism. *Earth and Planetary Science Letters, 144* (1-2)*,* 199-211.

Rosseti, L., Lima, E.V., Waichel, B. L., Hole, M.J., Simões, M.S., Scherer, C.M.S., 2017. Lithostratigraphy and volcanology, of the Serra Geral Group, Paraná-Etendeka Igneous Province in Southern Brazil: Towards a formal stratigraphic framework. *Jour. Volc. Geot. Res.355,* 98-114.

Tamrat, E., Ernesto, M., 1999. Magnetic fabric and rock-magnetic character of the Mesozoic flood basalts of the Paraná Basin, Brazil. *Jour. Geodynamics 28.* 419-437.

Waichel, B.L., Lima, E.F., Viana, A.R., Scherer, C.M., Bueno, G.V., Dutra, G. 2012. Stratigraphy and volcanic facies architecture of the Torres Syncline, Southern Brazil, and its role in understanding the Parana–Etendeka Continental Flood Basalt Province. *Journal of Volcanology and Geothermal Research*. 215–216, 74–82.

Zaffani, L.A., 2013. Paleomagntetismo e Anisotropia Magnética de derrames e sills da região Norte da Província Magmática do Paraná. Masters dissertation, IAG-USP, 70pp.

Zijderveld, J.D.A., 1967. Demagnetization of rocks: analysis of results. In: Collinson, D.W., Creer, K.M., Runcorn, S.K., (Eds.), Methods in paleomagnetism, Elsevier, Amsterdam, 254-286.