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MAGNETIC FABRIC OF A POST-COLLISONAL PLUTON IN THE NEOPROTEROZOIC ARAÇUAÍ HOT OROGEN

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ABSTRACT

Santa Angelica pluton located in the southern sector of the Araçuaí orogen, consists of a NE-SW intrusion of ~200 km². It presents an inverse concentric zoning, with acidic margins grading to gabbroic cores. Anisotropy of magnetic susceptibility (AMS) and anisotropy of anhysteretic remanence magnetization (AARM) were used to determine the pluton internal structure and infer the emplacement mechanisms. Magnetic susceptibility is quite variable but thermomagnetic curves indicate that magnetite is the main carrier of anisotropy. The AMS and AARM magnetic fabric are very similar for all lithotypes, thus attesting the dominant role of the multiple domain magnetite in the definition of the magnetic fabric in these rocks. The central part of the pluton is cut by a linear feature NNW-SSE, where microstructural evidence indicates that there is an inner shear zone in that portion of the body that separates two cores. In both lobs of the pluton, the magnetic foliations show a concentric pattern around the cores. The northeast lobe presents steeply-plunging lineations, while the southwest lobe presents gently-plunging lineations. This suggests that the NE lobe represents a deeper portion of the intrusion, nearest to the source of magma, while in the SW lobe we can observe portions approaching the top of the intrusion. The data suggest that the emplacement was controlled by the buoyancy forces of the magma, (almost) free of tectonic stresses. Therefore, the data indicate that the pluton configures an intrusion associated to the last stage of granitogenesis of the Araçuaí orogen.

Keywords: Anisotropy of magnetic susceptibility, magnetic fabric, hot orogen, emplacement model.

RESUMEN

El plutón de Santa Angélica ubicado en el sector sur del orógeno Araçuaí, consiste en una intrusión NE-SW de ~ 200 km². Presenta una zonificación concéntrica inversa, con márgenes ácidos que se convierten en núcleos gabroicos. La anisotropía de susceptibilidad magnética (AMS) y la anisotropía de magnetización remanente anhisteretica (AARM) se utilizaron para determinar la estructura interna del plutón e inferir los mecanismos de emplazamiento. La susceptibilidad magnética es bastante variable, pero las curvas termomagnéticas indican que la magnetita es el principal portador de la anisotropía. La fábrica magnética del AMS y del AARM es muy similar para todos los litotipos, lo que demuestra el papel dominante de la magnetita de dominio múltiple en la definición de la fábrica magnética en estas rocas. La parte central del plutón está cortada por una estructura lineal NNW-SSE, donde las evidencias micro-estructurals indican que hay una zona de cizalle interna en esa parte del cuerpo que separa dos núcleos. En ambos lóbulos del plutón, las foliaciones magnéticas muestran un patrón concéntrico alrededor de los núcleos. El lóbulo noreste presenta lineaciones que se hunden abruptamente, mientras que el lóbulo suroeste presenta lineaciones que se hunden suavemente. Esto sugiere que el lóbulo NE representa una porción más profunda del intrusivo, la más cercana a la fuente de magma, mientras que en el lóbulo SW podemos observar porciones que se acercan a la parte superior del intrusivo. Los datos sugieren que el emplazamiento fue controlado por las fuerzas de flotación del magma, (casi) libres de tensiones tectónicas. Por lo tanto, los datos indican que el emplazamiento del plutón ocurrió en la última etapa de granitogénesis del orógeno Araçuaí.

Palabras claves: Anisotropía de susceptibilidad magnética, fabrica magnética, orógeno caliente, modelo de emplazamiento

1. Introduction

During the Cambro-Ordovician in the Araçuaí-Ribeira Orogen System (AROS), an intense magmatic activity occurred along the Araçuaí belt in southeastern of Brazil. Post-collisional plutons from the Aracuaí belt are reported with an age range of 535 - 480 Ma (De Campos *et al.*, 2016). These plutons of 'I-type' granitoid, usually intruded along high angle ductile shear zones and in the core of antiform structures of the previous deformations (Wiedemann, *et al*., 2002). The presence, or absence, of macroscopically visible planar structures in granitic rocks is the source of the old distinction between oriented or massive granites. Bouchez (1997) suggests that granites, so ever macroscopically massive, are never isotropic. That is, there will always show some degree of fabric anisotropy during the cooling of the magma. A study of anisotropy of magnetic susceptibility (AMS) in several apparently isotropic plutons (Archanjo and Bouchez, 1997; Sant'Ovaia *et al*., 2000; Gleizes *et al*., 2006; Oliveira, *et al*., 2010) indicate patterns of foliation and magnetic lineation that are comparable to magmatic ones and are coherent in every body, among the different facies.

The Santa Angélica pluton covers about 200 km² and is an elliptical-shaped intrusion with a NE-SW trend. The country rocks are high-grade biotite-garnet-sillimanite gneiss and biotite-hornblende granodioritic to tonalitic gneiss. These are locally migmatized, showing sub-vertical concordant foliation toward the borders of the intrusive complex, which dip inwards towards the intrusion. Geochemical data of Santa Angélica pluton were obtained by Horn and Weber-Diefenbach (1987). These data shows a high-K calc-alkaline character, highly enriched in Light Rare Earths Elements. The pluton is inversely zoned with felsic rocks at the margins and mafic rocks towards the nucleus of the intrusion. This compositional variation defines a twin "bull's eye" pattern with two overlapping nodes. The felsic rocks are informally divided into two types, an earlier "Type I" suite of coarse-grained, porphyritic rocks with abundant allanite as a characteristic accessory phase, and a younger "Type II" granitoid that is finer-grained and contains titanite as a prominent accessory phase. Magma mingling between monzogabbros and granites can be observed throughout the intrusion (Schmidt-Thomé and Weber-Diefenbach, 1987; Bayer *et al*., 1987) forming large mingled zones of enclave swarms in different degrees of hybridization with the granite. Type I granite is foliated parallel to the country rock contact on practically all borders of the pluton. A main NNW-SSE intern shear zone separates the two gabbroic cores (Schmidt-Thomé and Weber-Diefenbach, 1987).

U-Pb ages were obtained by Sollner *et al*. (2000) for the granite type I (492 ±15Ma) and for granite type II (513 ±8Ma). In this work, we present the results of an integrated and detailed study of Anisotropy of Magnetic Susceptibility (AMS), anisotropy of anhysteretic remanence magnetization (AARM) and microstructural analysis, performed in order to determine the emplacement mechanisms of the Santa Angélica pluton and its chronology in relation to the collision structure of the Araçuaí-Ribeira Neoproterozoic orogenic system.

2. Sampling and measurements

Oriented samples were extracted from 43 sites separated from each other by 1 to 2 km. At each site, there were collected five to seven cores of approximately 8 cm in length and 2.5 cm in diameter, using a portable gasoline powered drill. The cores were oriented in situ with a magnetic and solar compass. In the laboratory each core was cut in standard specimens of 2.2 cm - length, providing a total of 759 specimens. All measurements were acquired in the Laboratório de Paleomagnetismo of Universidade de São Paulo (USPmag).

To obtain geological significance for AMS and to determine the contribution of specific minerals to the magnetic susceptibility, we performed a detailed magnetic mineralogy investigation. Thermomagnetic experiments were acquired under argon flux using a CS-2 furnace attached to an Agico KLY-4 CS kappabridge (Figure 1). Isothermal remanent magnetisation (IRM) curves, hysteresis curves and first order reversal curves (FORC) were obtained with a vibrating sample magnetometer (VSM) MicroMag 3900 (Princeton Measurements Corp). AMS was investigated using an Agico Kappabridge MFK-1A. For five sites, including all petrographic facies, we have also measured the AARM. The acquisition was achieved with the LDA-3 (AGICO) and remanence was measured with a JR6-A magnetometer (AGICO). The magnitude and orientation of the principal axes of the AARM ellipsoid were determined along fifteen different orientations with a peak field of 50 mT and a biasing field of 100 μT following the procedure described in Trindade et al. (2001). Statistical evaluation of the magnetic anisotropy ellipsoids in individual sites was done using the methods of Jelínek (1978), implemented in the ANISOFT program package (Hrouda *et al*., 1990), defining the $K_1 > K_2 > K_3$ axes of anisotropy ellipsoid.

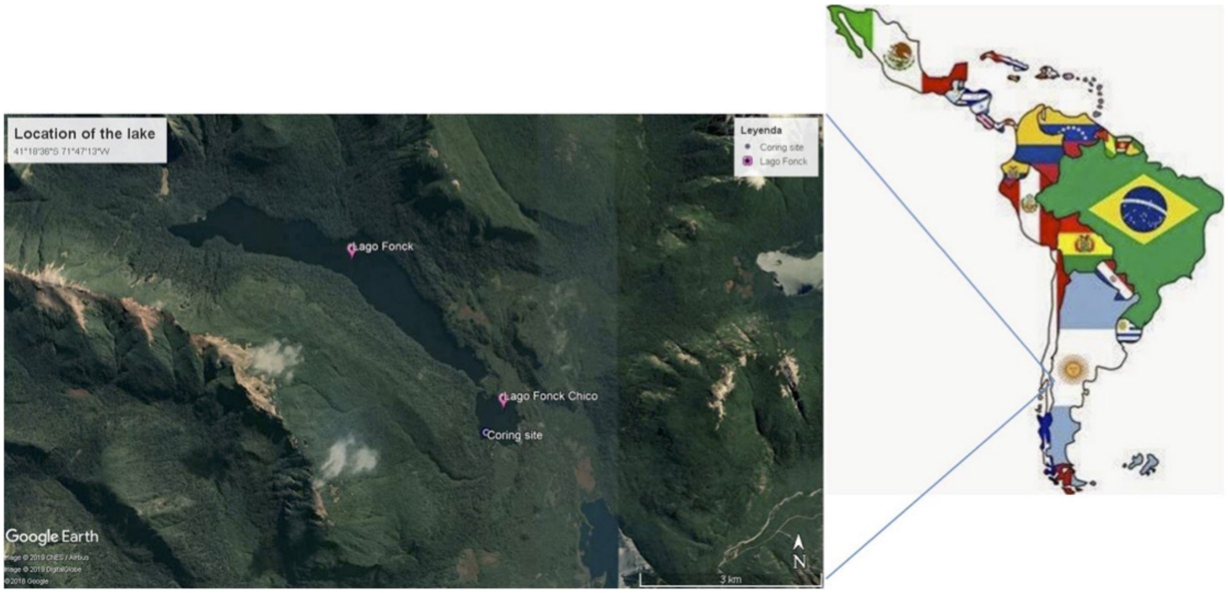

Figure 1. Representative thermomagnetic curves for five samples of the Santa Angélica pluton. The y-axis is the bulk of magnetic susceptibility and the x-axis is the temperature in degrees Celsius. The red lines represent the heating and blue lines represent the cooling.

3. Results

The degree of anisotropy ($P = K_1/K_3$) and the shape of the ellipsoids (T = 2 *In* (k2/k,) / ln(k,/k3) - 1) in the Santa Angélica pluton vary according to the lithology. For the gabbrodiorite, P ranges from 1.102 to 1.464, and all ellipsoids are oblate. The mixing zone has the highest values of P, ranging from 1.245 to 2.049, with prolate ellipsoids slightly more abundant than the oblate ones. For the granite, P ranges from 1.040 to 1.885, and the oblate ellipsoids are slightly more abundant than the prolate ones. Foliated granite at the border has a P value varying from 1.076 to 1.716 and most ellipsoids are prolate.

Figure 2 shows the magmatic foliation and lineation maps. Magnetic foliation and lineation of all lithotypes show a clear concentric pattern in the map around the two gabbro-diortic cores. The foliated granite facies, presents foliation that contours the pluton shape with high dip angle (Figure 2C). As well as the magnetic lineation, which in this same facies has high plunge angle. There is an internal shear zone separating the two mafic cores, dividing the pluton into a northeastern and southwestern lobe (Figure 2). This linear feature was well characterized by AMS data. The sites along this linear feature have magnetic foliation with high dip angle that follow the same NNW-SSE orientation and magnetic lineation with a high-angle NE vergence.

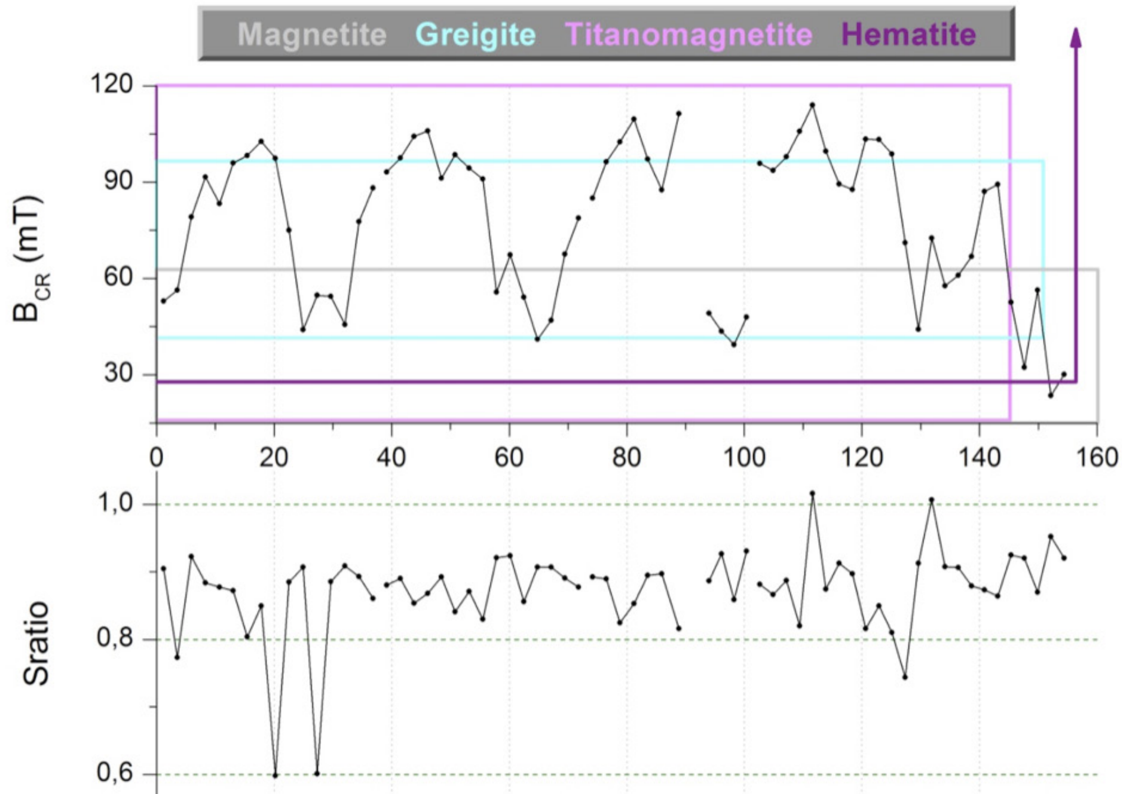

Figure 2. AMS directional data after elimination of scattered sites (for error ellipses above 26°). (A) Magnetic foliations (K_3); (B) Magnetic lineations (K_1); (C) Contour plot of the *Kmax* and *Kmin* of all sites on the border of the pluton; (D) Contour plot of the *Kmax* and *Kmin* of all sites on the northeast lobe of the pluton; (E) Contour plot of the *Kmax* and *Kmin* of all sites on the south-west lobe of the pluton.

In all petrographic facies, the northeast lobe presents magnetic lineation with high-angle (Figure 2D), while the southwest lobe presents magnetic lineation with low-angle (Figure 2E).

Figure 3 shows the AMS and AARM results for five sampling sites, distributed in all lithotypes of the Santa Angélica pluton. The AMS and AARM magnetic fabric are very similar for all lithotypes, thus attesting the dominant role of the multiple domain magnetite in the definition of the magnetic fabric in these rocks. This indicates that the dispersion in the AMS fabric of these sites is not related to the influence of other magnetic phases, but mainly reflects the dispersion in the orientation of the MD magnetite grains in the rock.

4. Discussion

Magnetic fabric in Santa Angélica pluton is controlled mostly by coarse-grained magnetite. The presence of magnetite is attested by the dependence of susceptibility with temperature (k-T) (Figure 1). The shape anisotropy control of the magnetic fabric is attested by the AARM measurements that have principal axes coaxial similar to the AMS ellipsoids for all the analysed samples. These AARM ellipsoids correspond to the low-coercivity window of 0 to 50 mT, being controlled only by the coarse-grained multidomain magnetite grains (Figure 3).

Through microstructural analysis, a predominance of solid-state deformations along the entire border of the pluton is evidenced. There is also solid-state deformation at the contact between the NE and SW lobes. Such deformation is related to a shear zone that affected the pluton during its emplacement. These regions with deformation in solid state present high values of P (up to 1.7) and commonly linear fabric. In the shear

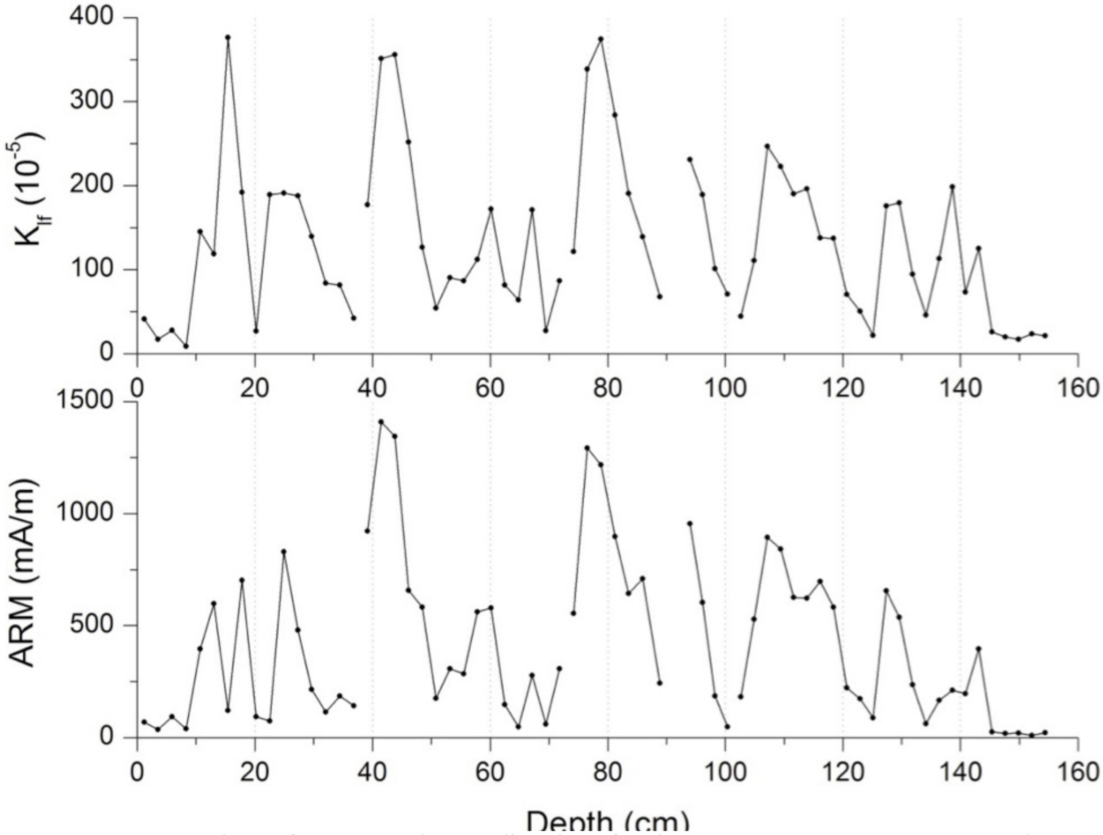

Figure 3. Comparison of AARM and AMS directions for sites SA27, SA28, SA31, SA43 and SA68. While AMS is related to all minerals, AARM is exclusively controlled by magnetite. Their agreement indicates the large, multi-domain magnetite control the fabric.

zone, all sites have magnetic lineation with vergence to NE. At site SA28, affected by this deformation and located at the center of the pluton, kinematic indicators were found. An AMS-oriented sample was carefully sawed parallel to the magnetic lineation and perpendicular to the magnetic foliation. In this plane, kinematic ductile indicators were identified that indicate vertical-sinistral movement between the lobes.

Magnetic foliation and lineation of all lithotypes inside the pluton show a clear concentric pattern in the map around gabbro-dioritic cores. These two lobes are separated by the NW-SE trending shear zone, well defined by the AMS data in the contact of the both lobes. In the inner part of the lobes (core and mingling zone) sub-magmatic deformation was identified. Therefore, AMS scalar parameters can be interpreted in terms of deformation recorded by magmas during their emplacement until they crystallized completely. The mingling zone of magma presents in its majority, planar fabric with high values of P (up to 2.04). Both cores present similar behaviours in relation to the AMS parameters. Both have high values of P (up to 1.4) and planar fabric. But their directional data shows different behaviours (Fig. 2). The NE lobe presents vertical lineations, with high dip angles (61-90°), whereas in the SW lobe the lineations are horizontal-tending (0-29°). Such observation suggests that the NE lobe is closer to the feeder source of the pluton, while the SW lobe represents a topmost sector of the intrusion.

Through the AMS data, we hypothesize that the northeast lobe represents the first pulse of magma to be emplaced, being soon followed by the southwest lobe (Fig. 4A). Mafic magma in both plutons are transferred into the lower crust and emplacement as gabbro during the cooling of the orogen along an early NE-SW-trending discontinuity. According to the model of Schmidt-Thomi and Weber-Diefenbach (1987), it induced anatexis of crustal rocks and production of granitic magmas,. The observed mingling texture of basic and acidic magmas may be produced by three different mechanisms envisaged by Whalen & Currie (1984): buoyant convection, forced convection, and tectonic shearing. However, buoyant convection is considered the most effective driving mechanism, causing commingling of magmas in the Santa Angélica pluton.

The emplacement of the Santa Angélica pluton corresponds to a coupled pluton complex. Profile A-B (Fig. 4 B) shows the structural relationship of the country rocks with the pluton that are locally migmatized, showing sub-vertical concordant foliation to the border of the intrusive complex, which dip inwards towards the intrusion (Fig. 2). This relationship evidences the vertical rise of the pluton during its emplacement (Fig. 4 B). The profile A-B also shows the internal shear zone that affected the pluton, precisely at the contact between the two plutons during final stage of the emplacement. At the final stages of body emplacement, upward transport of the NE lobe relative to the SW lobe was accommodated along a shear zone between the two lobes (see in profile A-B, Fig. 4 B). Through the AMS data, we hypothesize that the two lobes represent different levels of erosion, where the northeast lobe represents the deepest sectors of the intrusion (Fig. 4 A). Such exposure difference of erosion levels occurred due to the upward transport previously mentioned. Both, U-Pb and AMS data suggest the magma buoyancy forces, (almost) free of stress tectonic, were those that controlled the magma emplacement.

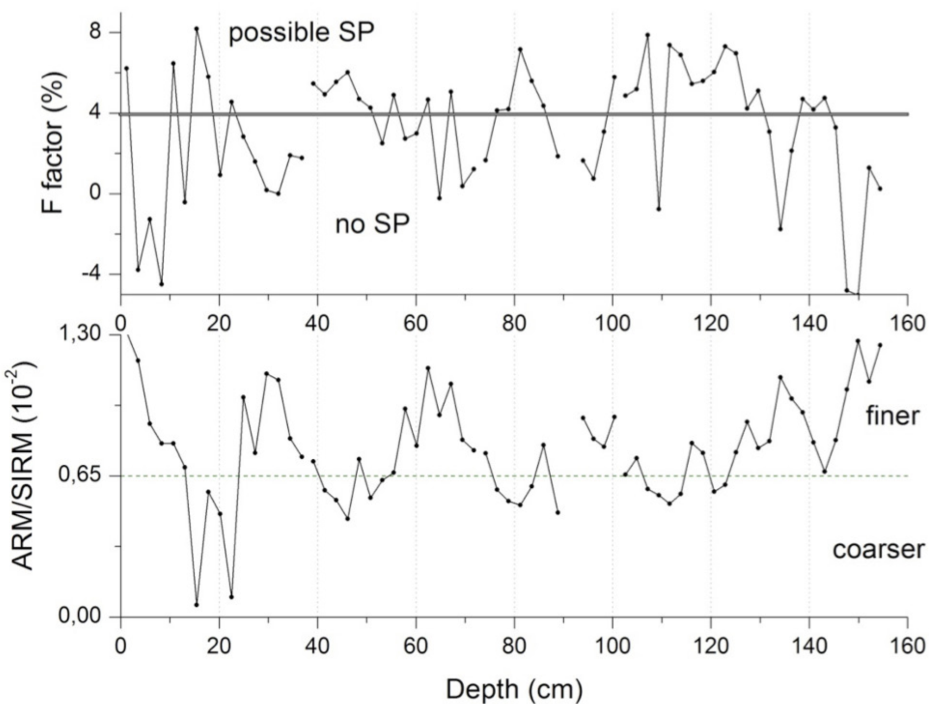

Figure 4. Emplacement model for the Santa Angélica pluton (right panel: map view, left panel: vertical sections). (A) Emplacement of two coupled plutons. Through the AMS data, we hypothesize that the northeast lobe was the first to be formed and soon after the southwest lobe joined it. As a result, the current level of erosion can be seen to be deeper in the northeast to the southwest. (B) Profile A-B (see in Fig. 2) shows the structural relationship of the country rocks with the pluton and the shear zone that affected the pluton during the emplacement, precisely at the contact between the two plutons.

5. Conclusion

The magnetic susceptibility is a feature quite variable in the Santa Angélica pluton and the thermomagnetic curves indicate that magnetite is the main carrier of magnetic anisotropy. Measurements of hysteresis and FORC loops indicate that such magnetite is multi-domain. In both lobes of the pluton, magnetic foliations show a concentric pattern around the cores. The northeast core show high angles lineation, while the southwest core presents lines with low angles of slope. This suggests that NE represents deeper portions of the intrusion near the source of magma, while in the SW we can observe portions approaching the top of the intrusion. The data suggest that the emplacement was mainly controlled by the buoyancy forces of the magma, free of tectonic stresses. Therefore, the data indicate that the pluton configures a late intrusion associated to the last stage of granitogenesis of the Araçuaí orogen.

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