Geomagnetic paleosecular variation for the past 1 Ma recorded in lava flows from south Ecuador

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Abstract

Paleosecular variation studies allow observing the most relevant fluctuations related to the Earth's magnetic field. In the southern hemisphere, but especially in southern Ecuador, these data are very scarce. Reconstruction of magnetic field models in the southern hemisphere requires reliable records that can be obtained from volcanic rocks, specifically from lava flows. The geochronology of the volcanic activity in Ecuador during the Quaternary in the involved area was obtained from around twenty-three K-Ar ages reported in previous studies. This study is the first attempt in forming a Quaternary directional paleosecular variation curve for Ecuador. This will help us understand how the magnetic field varied in Ecuador during this time period and allow us to compare how these changes are reflected in global paleosecular variation models.

Introduction

The geocentric axial dipole (GAD) assumption, that states that through time the average geomagnetic field is that close to a GAD, is the basis in paleo and archeomagnetism. (McElhinny & McFadden, (1997); Fisher, (1953); Hospers, (1954); McElhinny & Merrill, (1975); Veikkolainen et al., (2014) and Opdyke & Henry (1969))

McFadden et al., (1988) states that magnetic results from the past at high latitudes have greater angular dispersion related with the Virtual Geomagnetic Pole (VGP) compared with the paleomagnetic results near to Equator, being such dispersion shorter in the Northern Hemisphere than in the Southern Hemisphere (e.g. Johnson et al., 2008). Furthermore, this dispersion will be lower in periods of low frequency of geomagnetic reversals than in high frequency reversals (e.g., Biggin et al., 2008; McFadden et al., 1991).

Specifically, for our purpose we will focus on the Matuyama–Brunhes (M–B) geomagnetic reversal (last polarity reversal, 786 ka) (Harrison 1974; Hartl and Tauxe 1996; Channell et al. 2010) on Southern Ecuador. Brunhes and Matuyama polarity epoch show different geomagnetic field geometries. For example, Brunhes has fewer departures with a strong GAD predominance, while Matuyama shows a significant axial octupole contribution, but also a stronger latitudinal dependence of dispersion on each hemisphere (Northern = primordially negative inclination anomalies; and Southern = zero or positive inclination anomalies) (Johnson et al., 2008; Tauxe et al., 2004).

The nine studied volcanoes (Huisla, Mulmul, Igualata, Carihuairazo, Chimborazo, Sagoatoa, and Licto and Calpi cones) are part of the Ecuadorian Andes (Figure 1), which were active during the Plio-Quaternary (Hall and Wood, 1985; Barberi et al., 1988; Hall and Beate, 1991; Hall et al., 2008; Bablon et al., 2018). Bablon et al. (2018) used geochemical analyzes to show a predominance of medium-K calc-alkaline rocks. Compositionally, the lava flows are predominantly basaltic andesites (e.g. Licto cone, one lava from Calpi cone, Puñalica volcano) to andesites (e.g. two lavas form Calpi cone) (Bablon et al., 2018).

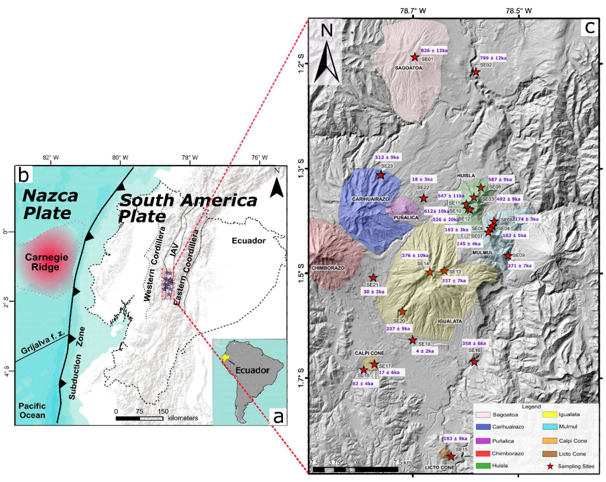

Figure 1. Research area and the sampling site locations. a) South American continent with Ecuador in yellow. B) Geodynamic framework of Ecuador; study zone within the red rectangle; IAV Inter-Andean Valley. c) Study area with the distribution of the different volcanoes and samples sites at the southern end of the Ecuadorian arc.

Methodology / Problem statement

A total of 247 samples were collected from 23 sites throughout the Southern part of Ecuador (Figure 1). The samples were collected with a water-cooled, gasoline-powered drill anda Pomeroy magnetic oriented equipped with a Brunton compass was used for orienting the drill cores. All of the measurements were done in the Laboratory of Paleomagnetism at the University of São Paulo (USPmag).

Susceptibility, anisotropy and temperature dependent susceptibility from selected samples were obtained using a Kappabridge KLY4 coupled with a CS3 furnace, in order to fully characterize magnetic signature and behavior of the main carriers of magnetization in the samples (e.g. Curie temperature, type of magnetic minerology, etc.).

All the hysteresis (magnetic field versus magnetization) analysis, First-Order Reversal Curve (FORC), Isothermal Remanent Magnetization (IRM) and their combinations (Mrs/Ms; Bcr/Bc) were carried out using a Princeton Measurement Corporation Micromag vibrating sample magnetometer (VSM).

A JR6 Dual Speed Spinner Magnetometer was used for all the paleomagnetic measurements from each sample. At around 165 samples from all sites were subjected to stepwise demagnetization using both an AF (altering field) demagnetizer (LDA-5 AGICO) and a thermal demagnetizer TD48SC (ASC Scientific). The paleomagnetic vector directions were retrieved using the principal component analysis (PCA) method (Kirschvink, 1980) and directional statistics (e.g. Fisher et al., 1953).

This project aims to better understand how the paleomagnetic field has been changing on equatorial latitudes. The more specific objectives are:

- Present new rock-magnetic and paleomagnetic results of dated material belonging to past volcanic eruptions in the southern part of the Ecuadorian Andes, which allow us to improve the global paleomagnetic database and the current geomagnetic models with new and modern laboratory techniques.
- Help fill the gap of paleomagnetic data in the southern hemisphere, near equatorial latitudes. Currently two-thirds of all data are from the Northern Hemisphere.

Results

After 100 mT AF-demagnetization, half of samples had lost more than 95% of their Natural Remanent Magnetization (NRM) and the rest after 120 mT. Using thermal demagnetization the samples were completely demagnetized (i.e. more than 98% of NRM lost) between 560 °C and 620 °C.. In particular, more than 80% of all samples lost their NRM at around 580 °C. These results indicate that titanomagnetite with poor content of titanium is the main carrier of the magnetization. However, some minor amounts of Ti-hematite could be the cause for stronger resistance to alternating field demagnetization (>100 mT) and unblocking temperatures above 580 °C. Also, in some cases, a presence of maghemite is observable by the slight inflections at around 350 °C (Figure 2C).

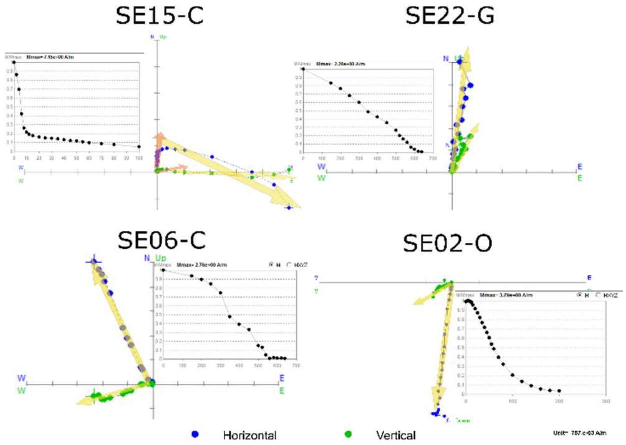

Figure 2. Examples of thermal and alternating field demagnetization diagrams. Zijderveld projections and module plot obtained from SE15, SE22, SE6 and SE2 respectively.

Room-temperature FORC diagrams are shown for two representative samples (Figure 3a, b). They display distinct closed-contour peaks between 0.016 and 0.035 T in the FORC distribution. SE3 (Figure 3a) has a bigger coercivity elongation (from 0.03 to 0.07 T), nearly symmetrical inner contours, and slightly non-symmetrical outer contours. SE20 (Figure 3b) shows smaller coercivity elongation. Both samples shown a PSD-type (Pseudo Single Domain) behavior for a magnetite sample (e.g., Roberts et al., 2000), having a prevalence of low coercivity components and validating a trend from PSD to SD behavior (Figure 3c), which are typical of titano-magnetites. These values indicate a pseudo-single domain (PSD) state for the magnetite grains.

All of the hysteresis curves are typical of low coercivity magnetic minerals which suggest the dominance of soft magnetic minerals (magnetite and maghemite) showing a pseudo-single domain state (Figure 3c, d and f). More than 85% of magnetic minerology from samples belonging to Southern Ecuador carrying stable thermal remanent magnetization fall into the field of PSD grains (Dunlop and Özdemir, 1997). Taking account IRM curves, around 80% of samples saturate in fields lower than 0.29mT, showing a low coercivity magnetic minerology and compatible with titanomagnetites magnetization carriers (Figure 3d, e, and f).

In the Day-plot most of the lava flows from southern Ecuador plot in the PSD region, matching the theoretical linear mixing curves SD-MD. Samples belonging to titanium-rich titanomagnetites plot to the right of the SD-MD mixing curves for magnetite (Day et al., 1977; Dunlop 2002). However, in combination, the thermomagnetic curves, hysteresis, FORC and IRM analysis suggest a varying titanomagnetite composition.

Thermomagnetic curves belonging to Southern Ecuador show a representative phase of titanomagnetite with variability amount of titanium, having a Curie temperature ranging from 540°C to 564°C (Figure 3e and f) showing less than 15% mole fraction of ulvöspinel (Nagata, 1961). The samples show a reversible pattern and present a hump between 160-380°C (Figure 3e, and f). In the low temperature analysis (Figure 3e, and f), samples have a Verwey transition (VT) at around -150°C (Verwey, 1939). A VT evidence the transformation of the magnetite from its monoclinic to cubic symmetry (Verwey, 1939).

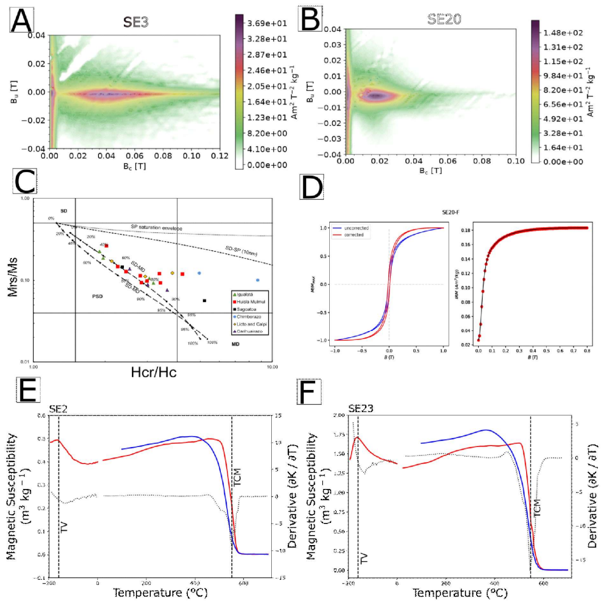

Figura 3. FORC diagrams for (a) SE3, (b) SE20. (c) Day plot (Day et al., 1977) of hysteresis parameters for all samples. Superparamagnetic (SP), Single-Domain (SD), Multi-Domain (MD), and Pseudo-single-domain (PSD). Dashed black lines show SD-MD mixture behaviors according to Dunlop (2002). (d) IRM acquisition and hysteresis curves. Thermomagnetic curves from (e) SE2 and (f) SE23. Dashed black lines are the derivate associated to the heating curve; TV is Transition of Verwey, and TCM: Temperature Curie Magnetite.

The VGP dispersion (Sb) as a function of latitude is shown in Figure 4. Taking into account all non-anomalous data from southern Ecuador, the data show a Sb of 17.07° (Su = 22.54°; Sl = 11.97°, using a Vandamme (1994) cutoff). This Sb value could be a reference for the southern hemisphere, near equatorial latitudes due to the large number of independent well-dated sites. This result is higher than values predicted by the models G (McFadden et al., 1988) and TK03 (Tauxe & Kent, 2004) (Figure 4). The resulting VGP mean from all sites and combining the Brunhes and Matuyama polarities is located at latitude: 84.4º, longitude: 190º, and A95: 8.4° from 23 VGPs.

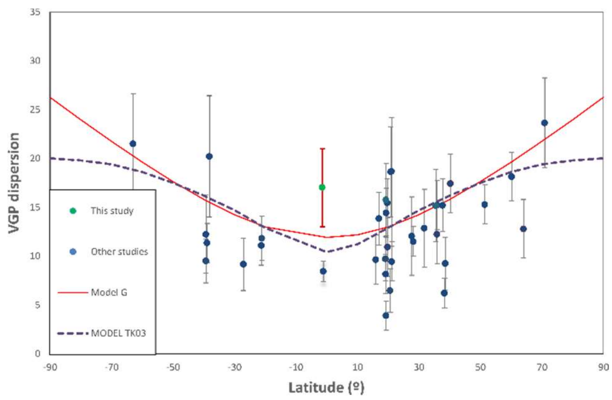

Figure 4. VGP angular dispersion (S_b) for Southern Ecuador compared to other estimates VGPs from the last 1 Ma.

Discussion and conclusion

A hump between 160 to 380°C related with the thermomagnetic behavior is interpreted by 1) the maghemite inversion occurring between ~150 to -350°C (Johnson and Merrill, 1972) or 2) small amounts of pyrrhotite (Tc: ~325°C; Sagnotti, 2007). Furthermore, demagnetization analysis, FORC curves, Day plot, hysteresis and thermomagnetic curves shows consistently that the main magnetization carrier is titanomagnetite, being mostly in Pseudo Single Domain state. Some samples show the presence also of Ti-hematite as secondary component.

This study comprised a directional paleomagnetic analysis from Southern Ecuador from 23 distinct lava flows that are well dated with K-Ar method and covering in time the last million year. The mean direction from all sites is (D = 354.6°, I = -1.8° and α95=11.6). This result is near different from the prevalent GAD field (D = 0°; I = -2.95°). However, it is consistent with earlier data published by Opdyke et al., (2006) (declination = 359.9°, inclination = −5.4°, and α95 = 4.2°), which means that this data agrees with a GAD field plus 5% quadrupole. For the Brunhes chron the mean direction is (D = 355.6°, I = 0.6° and α95=11.2) (Figure 5). On the other hand, for the Matuyama chron the mean direction is (D = 185.5°, I = 8.8° and α95=7), both directions being consistent with past works (Opdyke et al., 2006; Kent et al., 2010).

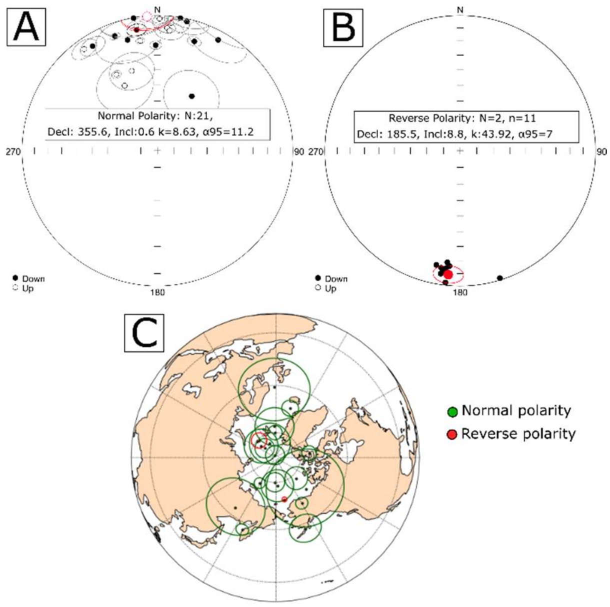

Figure 5. Stereographic projection of (a) normal and (b) reverse polarity for all sampling sites. (c) VGPs from lava flows belonging to Southern Ecuador. Green and red circles are the errors associates with the poles.

The Sb value from this study is 17.07°, which is higher than PSV models proposed in past works (McFadden et al., 1988; Tauxe and Kent 2004) and higher than past works carry out on the Continental Ecuador and Galápagos (Opdyke et al., 2006; Kent et al., 2010). However, the well-dated lava flows, especially for Brunhes chron (equal to 21) infer that this new value could be a good reference for Southern Equator.

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