

Assessing paleomagnetic shallowing in basalts using magnetic fabrics

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Abstract

Some paleomagnetic works conducted in lava flows retrieve characteristic remanent directions that shows an inclination shallowing relatively to the expected Geocentric Axial Dipole. Contributions of non-dipole components to the resultant Earth magnetic field and/or deficient time covering of the paleosecular variation are the most pointed causes for such shallowing. Another, but often overlooked source of paleomagnetic shallowing, is the anisotropy carried by lava flows. In order to bring more insights about this research topic was conducted on a historical (1761 A.D.) basaltic lava flow from Terceira Island (Azores Archipelago) a detailed paleomagnetic and magnetic fabric study in a well exposed outcrop. The study outcrop of this lava flow shows a linearly positive correlation between the increase of magnetic fabric anisotropy and paleomagnetic shallowing, being verified 20° decrease of the paleomagnetic inclination accompanied by a clockwise shift of paleomagnetic declinations that closely follows the variation of maximum principal axes of magnetic fabrics ellipsoid. These results demonstrates that magnetic fabric analyses should not be overlooked in paleomagnetic studies, as they provide a valuable support for assessing the reliability of paleomagnetic records.

1. Introduction

Owing to its high sensitivity, fast and easy data acquisition, anisotropy of magnetic susceptibility (AMS) has become a powerful and widely used technique since the late 1970's that successfully characterize petrofabrics from a wide range of geological settings, even in the presence of rocks with very low anisotropy or superposition of fabrics that result in a whole-rock AMS fabric that is not representative of the true preferred orientation (e.g., Borradaile and Werner, 1994; Borradaile and Henry, 1997; Borradaile and Jackson, 2010; Chadima et al., 2009; Fanjat et al., 2012; Ferré, 2002; Jelinek, 1981; Hirt and Almqvist, 2012; Henry, 1983, 1997; Hrouda, 1979, 1980, 1982; Hrouda et al., 2016, 2024; Kusbach et al., 2019; Machek et al., 2014; Silva et al., 2006 and 2014; Tarling and Hrouda, 1993).

AMS has also been successfully used to identify and characterize inclination shallowing of paleomagnetic records from sedimentary rocks. It is important to emphasize that our knowledge of the spatial-temporal evolution of the Earth's magnetic field heavily relies on paleomagnetic records obtained from sedimentary rocks, thus making the determination of the intensity of the magnetic fabric anisotropy an important tool to recognize the paleomagnetic inclination shallowing (e.g., Garces et al., 1996; Tauxe et al., 2008; Kodama, 2012; Li and Kodama, 2016).

The difficulty in correcting the inclination shallowing commonly verified in sedimentary rocks has led many researchers to conduct complementary paleomagnetic studies on lava flows as a valuable alternative, despite its temporal discontinuity record which therefore requires laborious analyses on numerous independent lava flows to recover secular variation. The presence of magnetic carriers with strong Thermoremanent Magnetization (TRM) that records the ambient geomagnetic field as lava cools below Curie temperature, the capacity to preserve primary magnetization for millions of years, and typically the presence of low magnetic anisotropy, are some of the main advantages of lava flows for

paleomagnetic records. Moreover, paleomagnetic works conducted in lava flows commonly retrieve characteristic remanent directions (ChRM) that shows an inclination shallowing relatively to the expected Geocentric Axial Dipole that encompass time periods of different scales (e.g., Yukutake 1971; Carlot and Courtillot 1998; Jackson et al. 2000; Van der Voo & Torsvik 2001; Korte and Constable 2005; Biggin et al. 2008; Silva et al., 2012 and 2018; Pavón-Carrasco et al., 2014). Contributions of non-dipole components to the resultant Earth magnetic field and/or deficient time covering of the paleosecular variation due to its discontinuous record, as well as, tectonic and gravitational instability of volcanic buildings promoting considerable tilting's, are the most pointed causes for such shallowing. Another, but often overlooked cause is the anisotropy carried by lava flows petrofabric.

In this work it is presented a paleomagnetic and magnetic fabric study of oriented samples collected from a historical lava flow, 1761 A.D. of Terceira Island, Azores archipelago. Results reveal a considerable high degree of anisotropy of the magnetic susceptibility that imprints accentuated deviations of paleomagnetic directions. Accordingly, it is recommended that paleomagnetic directions be accompanied by magnetic fabric analyses in order to sustain/validate it.

2. Sampling and methods

A series of 16 sun-oriented samples were collected along a profile of 30 m from East to West of a well exposed wall in a local quarry (Fig. 1; Latitude: 38.73785°N; Longitude: 27.24673°W). These samples underwent magnetic fabric, rock magnetic and paleomagnetic analyses.

Demagnetization procedures were conducted by thermic and alternating field techniques after samples rest in zero-field at least one month. Pilot tests, reveal complete demagnetization by both methods and similar paleomagnetic directions. Paleomagnetic directions were determined for each sample through linear segments on the Zijderveld plot (Kirschvink, 1980). The characteristic remanent magnetization for each site (ChRM) was achieved by Fisher (1953) statistics and the respective precision evaluated by the precision parameter (k) and radius of the angular confidence zone at 95% (α_{95}).

In order to evaluate possible paleomagnetic shallowing due to petrofabric anisotropy and/or remanence anisotropy, samples were also submitted to studies of anisotropy of magnetic susceptibility fabric (AMS) and anisotropy of anhysteretic remanence (AARM). For AMS measurements was used kappabridge MFK1-FA (AGICO). In what concerns AARM analyses, the anhysteretic magnetization was imparted through PAM anhysteretic magnetizer (field of 50 μ T) coupled to AF demagnetizer LDA (field of 70mT during each acquisition of anhysteretic remanence and 90 mT before each pair of measurements). The respective magnetization measured with magnetometer JR6 (AGICO). Was used a design of 12 positions, six pairs of symmetrical directions (program AREF designed by Jelinek, 1996).

The identification, characterization and nature of the main magnetic carriers was evaluated by rock magnetic analyses. The thermomagnetic signature was analysed through measurements of magnetic susceptibility $k(T)$ (Hrouda, 1994) until a maximum temperature of 650–700°C under an Argon-controlled atmosphere (MFK1 coupled with CS-4 furnace, AGIGO, Czech Republic). As high-field

analyses, classical hysteresis experiments were conducted until a maximum applied field of 1.0 T using for that Micromag vibrating sample magnetometer (Princeton Measurements Corporation, USA).

3. Rock Magnetism

Rock magnetic experiments sustain the presence of several magnetic phases of the titanomagnetite solid solution as the primary magnetic phases of the lava flow, without evidences of secondary mineralogy.

During the heating run of $k(T)$ analyses it is described an initial hump assigned as a Hopkinson effect with maximum k obtained for 95°C (Fig. 2a). For higher temperatures it is possible to identify up to 600°C three steps with distinct slopes, one between 230°C and 420°C, followed by another observed between 420°C and 540°C, and a final decay between 555°C and 585°C. The cooling run doesn't follow the heating one, revealing a non-reversible character of the $k(T)$ cycle. However, the initial and final steps show similar shapes and the difference between $k(T)$ values isn't so significant, with alteration index A_{40} as proposed by Hrouda (2003) around – 10%. These $k(T)$ experiments suggest the presence of several magnetic phases of the titanomagnetite solid solution with distinct Ti contents and even absence (magnetite), as commonly observed for lava flows. This doesn't mean that locally an oxidation contemporaneous of the lava cooling cannot run (e.g., Wilson et al., 1968; Ade-Hall et al., 1971). In fact, the irreversibility of $k(T)$ analyses agrees with the presence of titanomagnetite partially oxidized (titanomaghemite), as commonly observed for basalt rocks (e.g., Miranda et al., 2002; Moreira et al., 2015).

The presence of magnetite and/or titanomagnetite is also supported by hysteresis and IRM experiments, as attested by the presence of low-coercivity ferromagnetic minerals, with IRM saturating below applied fields of 300mT and hysteresis defining a plateau after paramagnetic correction (Fig. 2b). Day diagram (Day et al., 1977) with limits and mixing curves as proposed by Dunlop (2002), indicates that the grain size of titanomagnetites mostly matches the transition between pseudo-single domain (PSD) and single domain (SD) magnetic states (Fig. 2c).

4. Paleomagnetic data

Paleomagnetic demagnetizations by alternating magnetic field (AF) and thermal treatments mostly show complete demagnetizations until 100 mT and 580°C, respectively (Fig. 3a). During thermal demagnetizations is observed a gentle and gradual decay of the NRM between room temperature and 500°C. The remaining signal, between 50–70%, is cleaned up during a final and more abruptly decay of the magnetization until 580°C. AF demagnetizations show a gradual decrease of the NRM cleaning up 10 to 30% of the initial NRM at 50mT. At 100 mT was possible to demagnetize 90 to 95% of the initial NRM. When compared ChRM directions retrieved by thermal and AF demagnetizations from samples of the same core it is observed a good coherency between each pair, with angular differences limited between 0.2° and 3.0°.

From Zijderveld diagrams and stereographic projections is clear that normal polarity remanence directions are stable during all the demagnetizations procedures (Fig. 3a). After the first demagnetization steps where meaningless viscous component seems to persist, directions follow a linear trend that converges to the origin of Zijderveld diagram. The maximum angular deviation (MAD) is lower than 3° , mostly between 0.5 and 2.5° (Fig. 3b). These results point for the presence primary characteristic remanence directions (ChRM), a result that is also supported by rock magnetic and petrographic observations that indicate Ti-magnetites as the main carriers of remanence. The overall ChRM is defined by Dec/Inc = $347.7^\circ/58.5^\circ$, with $k = 159$ and $\alpha_{95} = 2.0^\circ$ for 32 samples (Fig. 3c).

5. Magnetic fabrics

Bulk magnetic susceptibility values ranging between $7.5\text{--}25 \times 10^{-3}$ (SI) indicate a dominant contribution of ferromagnetic minerals to the total magnetic signature (Fig. 4a; e.g., Tarling and Hrouda, 1993; Borradaile and Henry, 1997). AMS ellipsoid is mostly characterized by a predominant oblate shape (T values mostly ranging between 0.4 and 0.75) and corrected degree of anisotropy that varies from low to high values (Pj) between 1.03 and 1.15, and inversely proportional to the bulk magnetic susceptibility (Fig. 4a). Stereographic projection indicates the presence of a well-defined triaxial without superposition of confidence ellipses.

In what concerns the AARM fabric, despite with distinct values for the parameters Pj, T and k, the main characteristics of AARM fabric mostly mimic the ones achieved for AMS (compare brother graphics of Fig. 4a and 4b). Therefore, ferromagnetic (*s.l.*) phases dominate both types of magnetic fabrics.

6. Discussion

From the paleomagnetic and magnetic fabric analyses there are two results that require particular attention, namely: i) despite mean paleomagnetic direction shows a reasonable overall clustering, $K = 159$ and $\alpha_{95} = 2.0^\circ$ for 32 samples, displays an accentuated variation of ChRMs inclinations, between 47° and 67° (i.e., 20° of amplitude), and in a similar way, also for declinations, between 338° and 359° ; ii) anisotropy of AMS fabric varying from 1.03 to considerable high anisotropy such as 1.145.

In order to verify possible implications of magnetic fabric intensity on paleomagnetic directions, the ChRMs were compared with the corresponding AMS and AARM fabrics, being verified that with the increase of anisotropy (Fig. 5a): i) a gradual linear decrease of ChRM's inclinations; ii) an overall clockwise of declinations towards N (Fig. 5b).

In order to better visualize the implications of magnetic fabric anisotropy on paleomagnetic directions we considered two sub-groups of samples, divided by the limit of $Pj = 1.075$. Samples with values lower than this limit belong to subgroup T13A, while samples with higher values correspond to subgroup T13B. Samples from T13A only display AMS ellipsoids with oblate shape and the highest k values. Subgroup T13B, show some AMS ellipsoids prolate and neutral shapes (despite predominance of oblate shape)

and lowest the k values. According to the increase of anisotropy, the spatial distribution of AMS principal axes (Fig. 5b) defines a clockwise rotation around a sub-vertical axis (from T13A to T13B). Despite the lower spatial resolution, the same is observed for AARM ellipsoid (Fig. 5c).

In what concerns mean paleomagnetic directions for both subgroups (Fig. 5d) it is verified lower inclinations and clockwise deviation towards north for the samples with higher anisotropy (T13B) when compared with samples with lower anisotropy (T13A). Namely: i) T13A defines Dec/Inc = $346.0^\circ/62.2^\circ$, with $k = 564$ and $\alpha_{95} = 1.5^\circ$ for 18 samples; and ii) T13B defines Dec/Inc = $349.4^\circ/53.6^\circ$, with $k = 177$ and $\alpha_{95} = 3.0^\circ$ for 14 samples. Therefore, such results clearly indicate the presence of significant deviations of paleomagnetic directions strictly correlated with the petrofabric acquired during magma flow as inferred from AMS and AARM magnetic fabrics, i.e., anisotropy acquired during magmatic flow have a direct impact on paleomagnetic directions.

Comparing these results with known global geomagnetic field models (Fig. 6), as BIGMUD (Arneitz et al., 2019), SHA.DIF.14k (Pavón-Carrasco et al., 2014) and SHAWQ.2K (Campuzano et al., 2019) it is verified a reasonable agreement in what concerns the declination, but poorly related with expected inclinations. It is also notorious that paleomagnetic results of T13A are in better agreement than results from T13B, in what concerns declination and inclination. Despite mean declination achieved for subgroup T13A is in close agreement with theoretical models it is notorious that mean inclination deviates considerable, suggesting that the magnetic fabric acquisition process is more complex than thought. Moreover, when these results are compared with known paleomagnetic results from Pimentel et al (2016) for the same 1761 A.D. lava flow for samples collected in distinct outcrops (TER05 and TER06), it is verified higher inclination of the mean paleomagnetic inclination (which is in good agreement with theoretical models) and the mean declination points to west of T13 results.

8. Conclusions

The results obtained here show that the magnetic fabric acquired during magmatic flow can significantly deflect paleomagnetic directions, responsible for inclination shallowing and shift of declination according to the direction of the magnetic lineation.

Therefore, magnetic fabric provides a valuable support for assessing the reliability of paleomagnetic records, a method commonly overlooked in paleomagnetic studies.

Declarations

Author Contribution

Single author, responsible for all manuscript.

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Figures

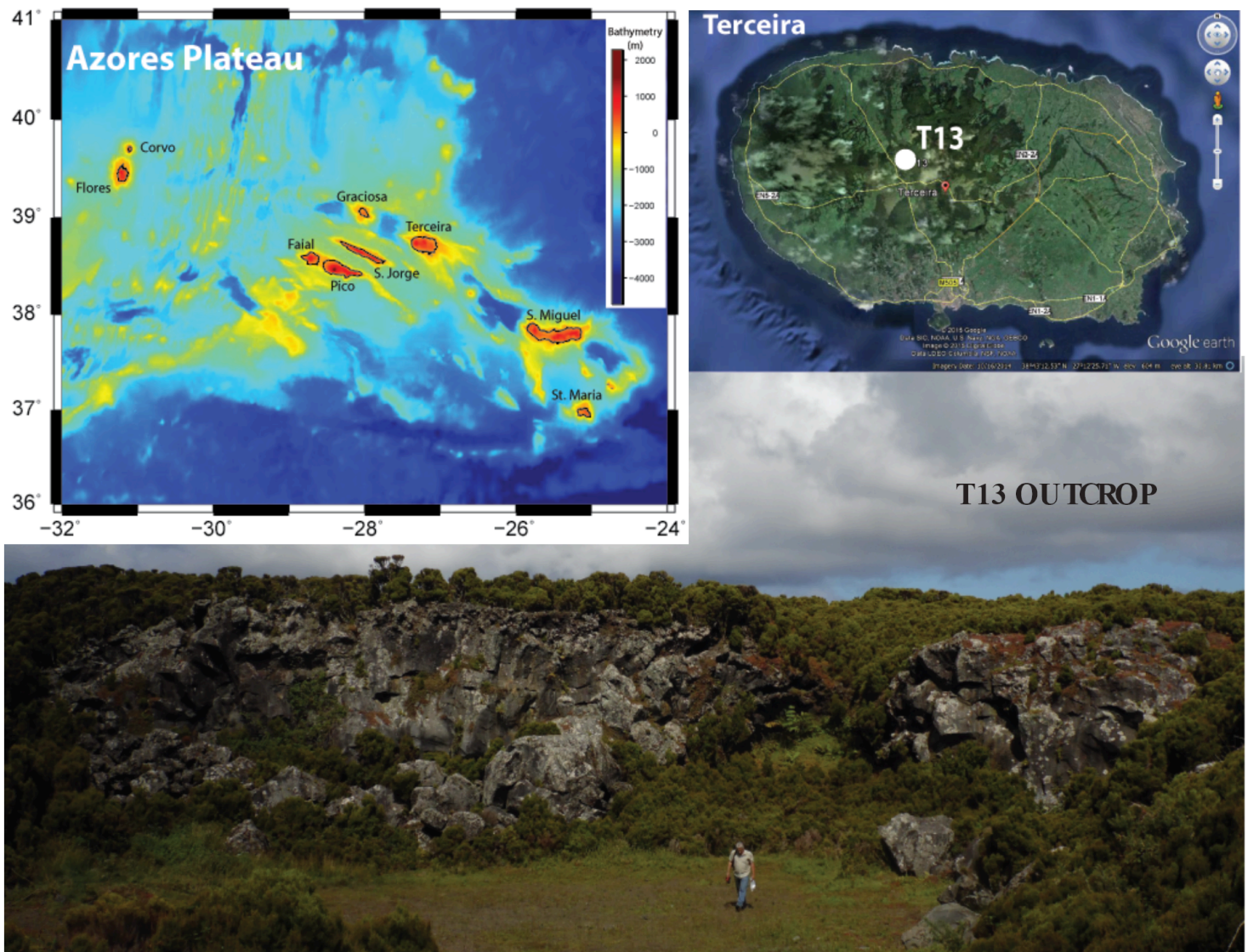


Figure 1

Caption: Shaded relief of the Azores Plateau with indication of the islands. Map of Terceira Island with indication of sampled site T13 of the 1761 A.D. lava flow. Zoom of the sampled outcrop.

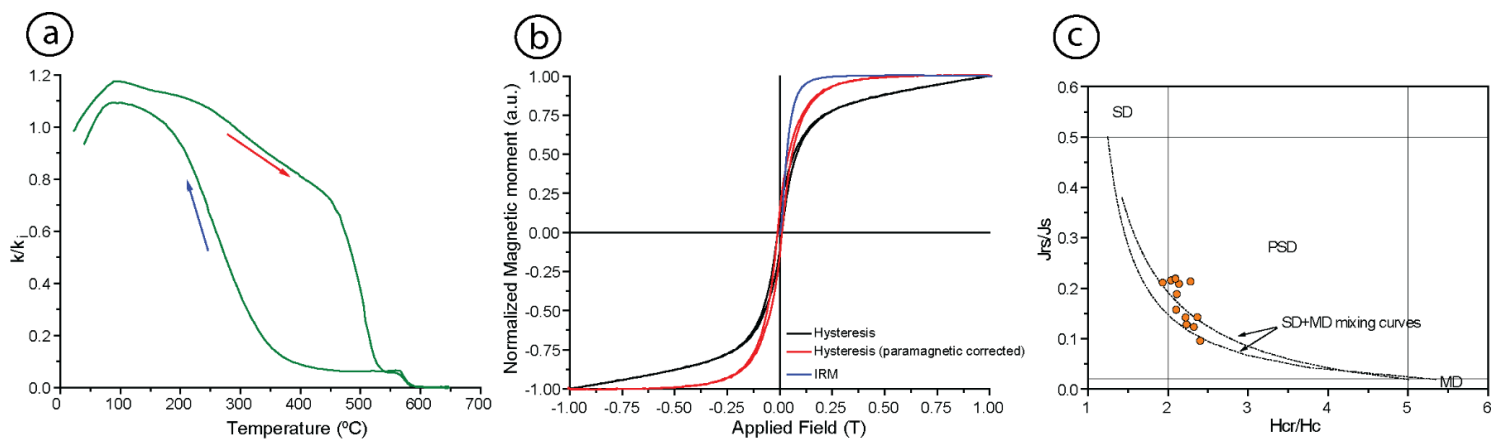


Figure 2

Caption: Rock magnetic properties of historical lava flow 1761 A.D. sampled at site T13. (a) Thermomagnetic experiments performed under Argon controlled atmosphere. (b) Representative examples of hysteresis loops. (c) Day et al. (1977) diagram with limits and mixing curves proposed by Dunlop (2002) for titanomagnetites.

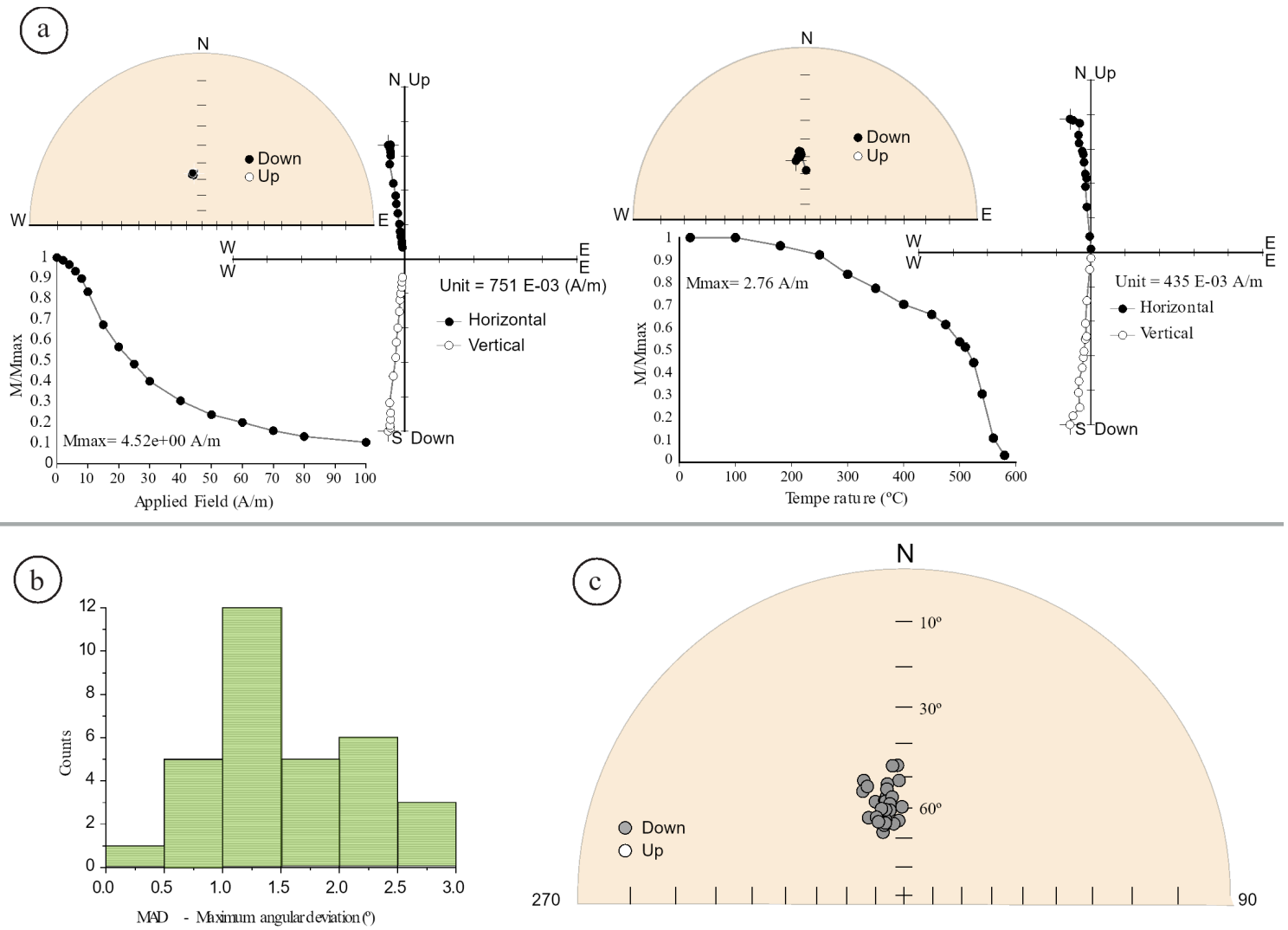


Figure 3

Caption: (a) Examples of the direction and intensity evolution of the remanent magnetization during alternating field (AF) and thermal demagnetization procedures, and stereographic projections and remanence decay curves. (b) Maximum angular deviations obtained during ChRM determinations. (c) Stereographic projection of the obtained paleomagnetic directions.

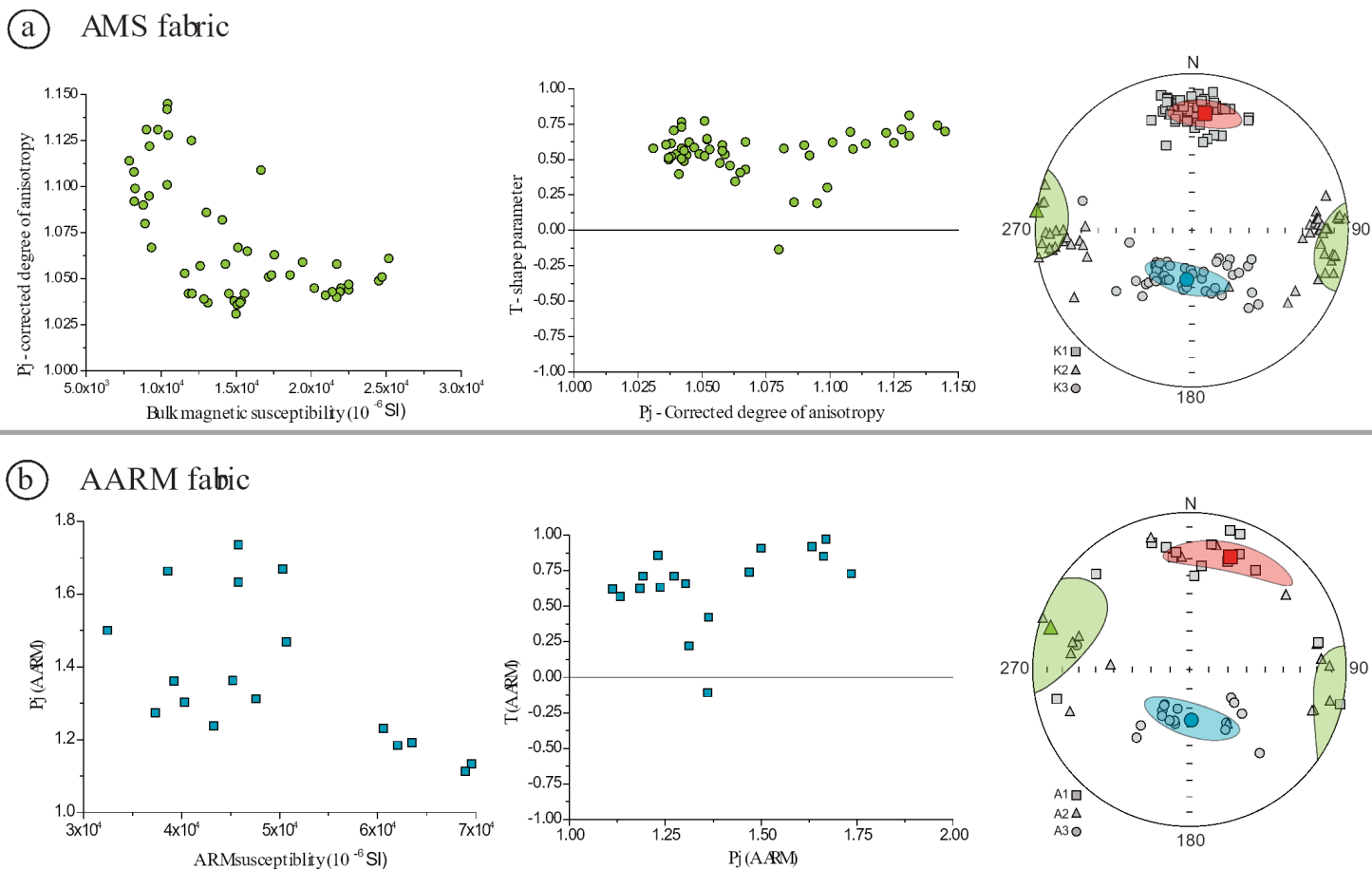


Figure 4

Caption: Corrected degree of anisotropy P_j versus Bulk magnetic susceptibility and the shape parameter T (Jelinek 1981), and lower hemisphere Schmidt stereographic projections with squares corresponding to maximum, triangles corresponding to intermediate and circles corresponding to minimum principal axes of the AMS (a) and AARM (b) ellipsoids.

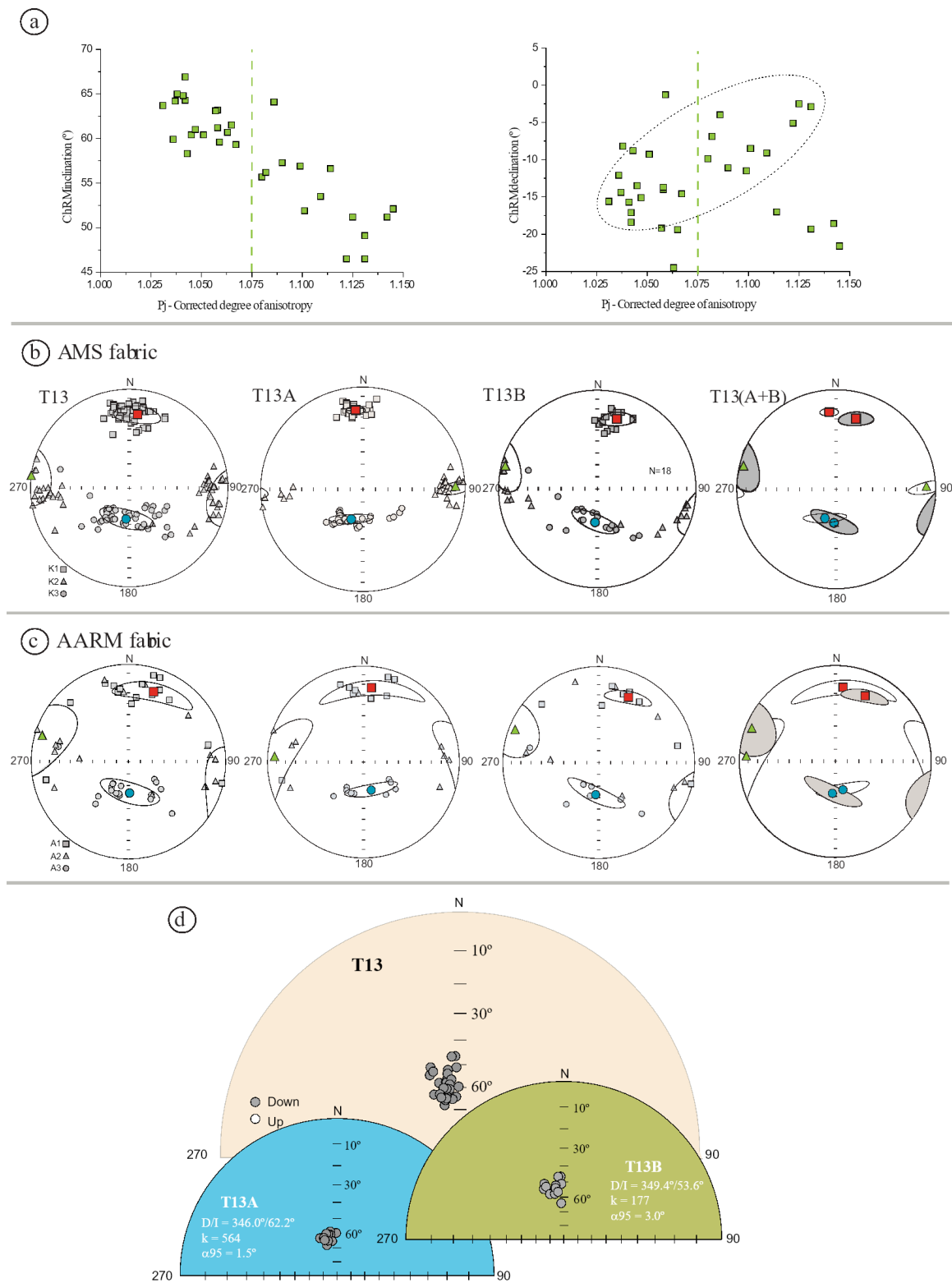


Figure 5

Caption: For historical lava flow sampled at site T13: (a) correlations obtained between ChRMs (inclinations and declinations) and corrected degree of anisotropy P_j of AMS fabric. (b) Decomposition of AMS fabric in subgroups T13A and T13B. (c) Decomposition of AARM fabric in subgroups T13A and T13B. (d) Decomposition of ChRMs in subgroups T13A and T13B.

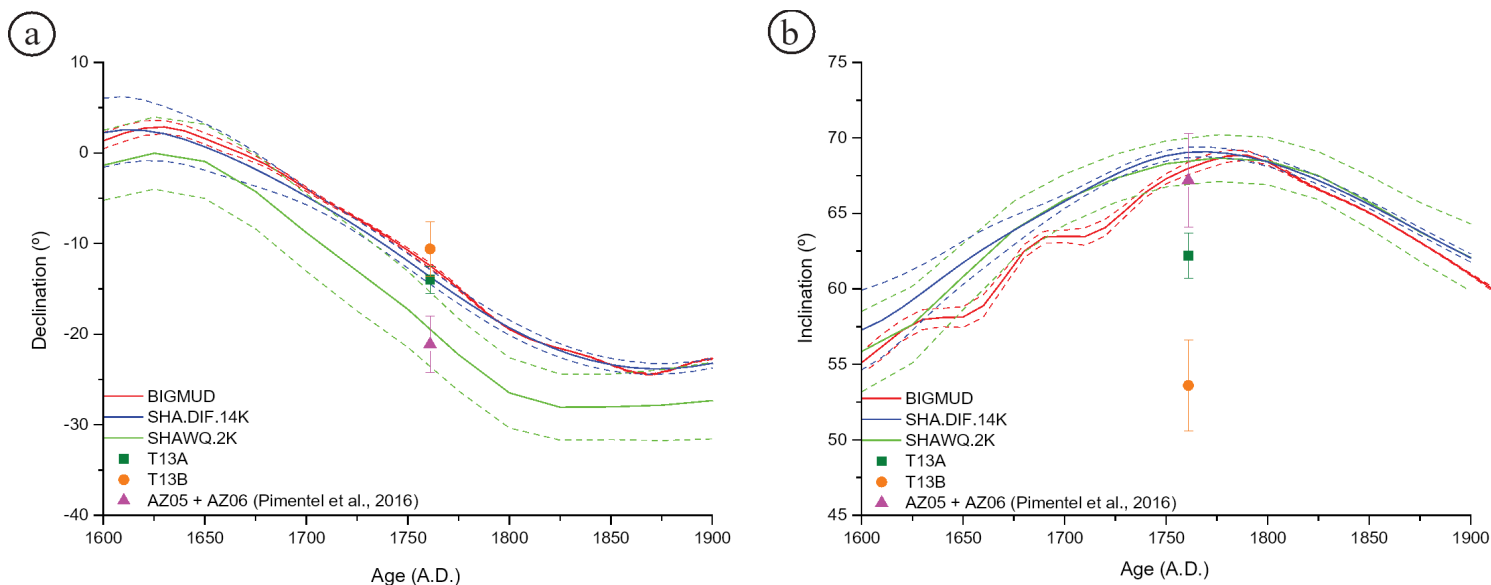


Figure 6

Temporal evolution of declination (a) and inclination (b) of the secular variation according to global geomagnetic field models BIGMUD (Arneitz et al., 2019), SHA.DIF.14k (Pavón-Carrasco et al., 2014) and SHAWQ.2K (Campuzano et al., 2019). Solid symbols and their error bars correspond to paleomagnetic directions and respective a_{95} obtained for historical lava flow 1761 A.D., by this study (T13A and T13B) and by Pimentel et al (2016) for sites AZ05 and AZ06.