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Paleomagnetic study of juvenile basaltic–andesite clasts from Andean pyroclastic density current deposits

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ABSTRACT

Additional paleomagnetic data are necessary to improve geomagnetic models of secular variation during the Holocene, especially from the southern hemisphere. In most of the Andean volcanoes from Ecuador to the Chilean central volcanic zone, very well dated lava flows are rare. In contrast, andesitic to basaltic pyroclastic density current (PDC) deposits commonly contain charcoal, facilitating their age determination with ^{14}C. In this study we present the magnetic properties and the paleomagnetic results obtained from three PDC deposits of basaltic to andesitic composition. One is the 2006 PDC deposit from the Ecuadorian Tungurahua volcano and the two others are well-dated PDC deposits from Chilean volcanoes Osorno and Villarica. Although most paleomagnetic studies in pyroclastic rocks deal with the estimation of emplacement temperatures from bulk deposits or accessory and accidental (non-juvenile) clasts, we show that juvenile clasts embedded in PDC deposits provide well-grouped paleomagnetic directions indicating post-emplacement in situ cooling below Curie points. Moreover, the rapid cooling of the juvenile clasts yields an abundance of single domain titanomagnetite grains providing low unblocking temperatures and a reliable material for paleointensity determination.

1. Introduction

During the last ten years, there have been several attempts to improve our knowledge of the secular variation of the Earth's magnetic field (Korte and Constable, 2005a,b; Constable, 2011). Although satellite observations provide a detailed spatial understanding of the very recent evolution of the geodynamo, direct field observations complemented by navigational records give a good geographic coverage for the last four centuries (Jackson et al., 2000). Prior to that time, the description of the field variation relies only on paleomagnetic and archeomagnetic data, which are spatially poorly distributed. Archeomagnetic data are mainly obtained from the northern hemisphere and especially Western Europe (Donadini et al., 2009). The data obtained from volcanic rocks are likely to provide a more equitable geographic distribution between the two hemispheres.

Although lava flows are a reliable material for paleosecular variation studies, datable material (e.g. charcoal) below lava flows is not easy to find and many Holocene lava flows cannot be dated precisely by the radiocarbon dating method (^{14}C).

For the last ten thousand year period, the effusive activity of many volcanoes is often determined by the age estimates obtained from charcoal incorporated in pyroclastic deposits from explosive eruptions, marking the eruptive history of the volcano. Few studies of paleosecular variation report results from pyroclastic rocks (for example Hagstrum and Champion, 2002, Genevey et al., 2002) even though Hoblitt et al. (1985) reported on the suitability of non-welded PDC deposits for the record of geomagnetic secular variation. Most paleomagnetic studies of pyroclastic deposits have been used principally to determine the temperature of emplacement (Aramaki and Akimoto, 1957; McClelland and Druitt, 1989; Bardot, 2000) and mostly bulk consolidated deposits or lithic fragments have been studied. Because the emplacement temperatures are in most cases below the Curie point of magnetite, these deposits are not expected to provide high-quality records of the geomagnetic field. Non-juvenile clasts have usually two components and the low-temperature component of magnetization is generally not determined with high precision. Only in very hot pyroclastic deposits, can these clasts be used to determine paleointensities (Paterson et al., 2010).

Juvenile clasts should not record a high temperature component of magnetization during tumbling in the deposit because the total magnetization with blocking temperatures between the temperature of emplacement and the Curie Point should be nearly zero after this randomization process (McClelland and Druitt, 1989). McClelland and Druitt (1989) were, however, surprised that all pumices have a remanent magnetization that has laboratory

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unblocking temperature intervals up to the Curie point of magnetite (580 °C). Zlotnicki et al. (1984) have observed this phenomenon in pumice samples from Guadeloupe, and attributed it to an early-formed chemical remanent magnetization (CRM) with high laboratory unblocking temperatures.

Carracedo et al. (1993) also documented a well-grouped paleomagnetic direction from juvenile clasts, although the results from lithic fragments were highly scattered. In a recent study of PDC from Tungurahua (2006 eruption) and Cotopaxi (1877 eruption) (Ecuador), Rader et al. (2011) indicate that in many cases juveniles clasts were emplaced hot, but lithics were emplaced cold.

In their study of the 79AD PDC from Vesuvius (Italy), Cioni et al. (2004) inferred that the temperature of the coarse juvenile material generally decreased at a slower rate than the mixture of gas and ash. Their thermal modeling indicated that the coarse juvenile fragments act as a heat source for the deposit and that coarse juvenile and lithic fragments completely equilibrate with the rest of the deposit one to several hours after emplacement.

In the course of a detailed study of the geomagnetic secular variation recorded by volcanic rocks in Ecuador and Chile, we have sampled juvenile clasts from several PDC deposits from which we obtained excellent paleomagnetic results. Here we present three typical examples demonstrating their ability to provide high-quality paleomagnetic data and especially a high success rate of paleointensity determinations.

2. Geology and paleomagnetic sampling

We sampled the 2006 AD PDC deposits (Tu-2006) from the Tungurahua volcano (Ecuador), for which we know the direction and intensity of the field to be compared with the paleomagnetic results.

Tungurahua, a steep-sided andesitic–dacitic edifice, is one of Ecuador's most active volcanoes. All past-millennium eruptions have originated from the summit crater at an elevation of about 5000 m (Hall et al., 1999; Le Pennec et al., 2008). In August 2006, a violent eruption deposited a major tephra fall layer west of the volcano, and many andesitic scoria flows descended the northern, western and southern flanks of the edifice (Eychenne et al., 2013). The paleomagnetic sampling site is located at ~200 m above the base of the volcano at an elevation of about 2300 m and about 6 km northwest of the crater. At this site the PDC deposit contains juvenile scoria bombs with sizes up to 1 m in diameter (Fig. 1a).

We also present the results obtained from two PDC deposits in Chile, one from the Osorno volcano and the other from Villarrica volcano. The 2652-m-high, dominantly basaltic to andesite Osorno is also one very active volcano of the southern Chilean Andes (Fig. 1c). The sampled site at Osorno is at an elevation of 1080 m and at about 3.5 km of the Osorno summit. The PDC deposit contains numerous dark to brown-tinted vesicular scoria bombs. Two uncalibrated ^{14}C ages of 1250 ± 40 BP and 1180 ± 30 BP) were obtained from the numerous charcoal pieces providing a combined calibrated age range of 782–966 cal AD at a 95% confidence level (median age of 890 cal AD).

Villarrica is one of Chile's most active volcanoes, with a 6-km-wide late Pleistocene caldera. The Pucón PDC deposit, also called "Pucón ignimbrite" (Clavero, 1996), is the largest Holocene eruption of Volcán Villarrica and is associated with the formation of a 2-km-wide caldera located at the base of the basaltic to andesitic, active cone at the NW margin of the Pleistocene caldera. The Pucón PDC deposit has been extensively described by Clavero (1996) and Silva Parejas et al. (2010), who reported several uncalibrated ^{14}C ages (3660 ± 91 years BP, mean of 7 uncalibrated ^{14}C ages). Using the Southern hemisphere ^{14}C calibration curve (Shcal04) and Bayesian statistics, the most likely age range at 95% confidence level for this eruption is in the range of 2030–1910 cal BC (median age of 1972 cal BC). However, Silva Parejas et al. (2010) argued that the spread in ^{14}C ages may be due to an "old wood" problem and that the two youngest ages should be regarded as closer to the true age of the volcanic event. Thus, the two youngest ages (3650 ± 30 and 3580 ± 70 BP) were calibrated and combined to yield a median age of 1810 cal BC within the range at 95% confidence level 1920–1690 cal BC. The deposits are up to 70 m thick at some locations and are preserved as far as 21 km from the present-day summit. The sampling site is located at an elevation of 520 m, about 12 km to the north of the summit crater (2700 m above sea level). We sampled mainly spheroidal, vesicular bombs with diameter from 5 to 20 cm (Fig. 1b).

Standard paleomagnetic core samples (25 mm in diameter) were taken with a gasoline powered drill (Fig. 1c). Although it was easy to drill and orient with great accuracy samples from the large bombs of the 2006 Tungurahua PDC deposits, sampling of the small and fragile juvenile clasts from the two other sites (Pucón and Osorno) was more difficult and probably resulted in slightly lower accuracy in the orientation of short, often broken paleomagnetic cores. To obtain a more precise direction, 21 samples were drilled at both sites.

Petrographic observations of thin sections indicate that the size of the opaque minerals is too small (<1 μm) for clear observation under an optical microscope. We do not observe the micron size dendritic magnetites found in the upper part of rapidly cooled basaltic-andesitic lava flows of the same volcanoes. In a study of strongly vesiculated basaltic scoria clasts from the sub-Plinian April 1999 eruption of Shishaldin volcano, Alaska, Szramek et al. (2010) described dendritic magnetite in the core of the largests clasts. Szramek et al. (2010) estimated that rims of the pumice clasts cool to their glass-transition temperature in ~100–200 s, while their cores take ~500–2000 s to cool, which translates into cooling rates of ~0.2–2.5 °K/s. Magnetite grew only at the slowest cooling rates.

3. Magnetic properties

The intensity of the natural remanent magnetization (NRM) of the three PDC deposits is typically high. Samples with total NRM moments above 10^{-4} Am^2 were measured with either a JR5 magnetometer or a Molspin magnetometer (for the most fragile ones) and were AF demagnetized with a Schonstedt GSD1 degausser up to 100 mT. Samples, whose moment was lower than 10^{-4} Am^2, were measured with a 2G Enterprise magnetometer and further AF demagnetized with an on-line 2G AF degausser up to 160 mT. Magnetic susceptibility was measured with a Bartington MS2 probe.

Samples from the 2006 PDC deposits from Tungurahua have a within-site homogeneous magnetization with intensity of 15 Am^{-1}, a magnetic susceptibility of 0.015 SI and mean Koenigsberger ratio of 25 ± 7 calculated with an inducing field of 50 μT. Samples from the juvenile clasts of the Pucón PDC deposits have an even higher NRM of 20 Am^{-1} but a significantly lower magnetic susceptibility of 0.003 SI. This translates into high Koenigsberger ratios of 163 ± 37. Samples from the Osorno PDC deposits present a higher scatter in their intensity of remanent magnetization from 2 to 42 Am^{-1} and a magnetic susceptibility from 0.002 to 0.01 SI. The Koenigsberger values are high 67 ± 27.

Measurements of bulk susceptibility versus temperature with the Agico KLY3 kappabridge indicate that Ti-rich titanomagnetites are the principal magnetic carriers at site Tu-2006, while two magnetic phases with different Curie points are clearly present in the samples from Pucón and Osorno sites (Supplementary Fig. 1).