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High paleointensities for the Canary Islands constrain the Levant geomagnetic high

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ABSTRACT

Understanding the behavior of enigmatic geomagnetic traits such as the Levant intensity high is currently challenged by a lack of full vector records of regional variations in the geomagnetic field. Here we apply the recently proposed multi-method paleointensity approach to a suite of 19 lavas from the Canary Islands dating between ∼4000 BC and 1909 AD. Our new record reveals high paleointensities (VADMs >120 ZAm^2) coinciding with and shortly after the peak in geomagnetic intensity in the Levant at ∼1000 BC. Furthermore our data suggests a westward movement of this geomagnetic phenomenon at a rate of 6.7–12° per century. In addition to IZZI-Thellier, microwave-Thellier and the multi-specimen method, the calibrated pseudo-Thellier method is an important part of the multi-method paleointensity approach. The calibration of this relative paleointensity method was derived from a suite of Hawaiian lavas; it is improved with the results of the Canarian cooling units. Pseudo-Thellier results from samples with very low Curie temperature (<150 °C), however, cannot be reliably converted to absolute paleointensity estimates. The multi-method paleointensity approach yielded a reliable estimate for ∼60% of the flows sampled – an unusually high success rate for a paleointensity study involving lavas.

1. Introduction

Obtaining reliable paleointensities from volcanic edifices is notoriously difficult, despite recent methodological developments (e.g. Hill and Shaw, 1999; Riisager and Riisager, 2001; Tauxe and Staudigel, 2004; Dekkers and Böhnel, 2006; Fabian and Leonhardt, 2010; de Groot et al., 2012; Paterson et al., 2014). Yet, such records are indispensible to improve the accuracy of models that describe the behavior of the geomagnetic field during the Holocene, since igneous rocks are the only absolute recorders of the intensity of the geomagnetic field available around the globe and throughout geologic history. Paleointensity results of many flows have to be discarded because they do not satisfy certain quality criteria (Selkin and Tauxe, 2000; Biggin et al., 2007; de Groot et al., 2014; Paterson et al., 2014), often due to thermochemical alteration induced by the laboratory heating of the samples required for paleointensity experiments. It was recently shown that combining different paleointensity methods, including a non-heating calibrated pseudo-Thellier approach, significantly increases the success rate in obtaining reliable paleointensity estimates from lavas (de Groot et al., 2013). This 'multi-method paleointensity approach' consists of the IZZI-Thellier protocol (Tauxe and Staudigel, 2004), microwave Thellier experiments (Hill and Shaw, 1999, 2000), the domain state corrected multi-specimen method (MSP-DSC) (Dekkers and Böhnel, 2006; Fabian and Leonhardt, 2010) and the calibrated pseudo-Thellier technique (de Groot et al., 2013).

The Canarian archipelago (28.1°N, 15.4°W) constitutes a suite of well-dated Holocene volcanic cooling units, but relatively little work has been done in terms of paleointensity on Holocene flows. Recently, Kissel et al. (2015) presented an extensive data set of paleodirections obtained from lavas sampled at Tenerife and Gran Canaria. Here we apply the multi-method paleointensity approach (de Groot et al., 2013) to 19 Holocene lavas from the islands of Tenerife and Gran Canaria (Canary Islands, Spain) to derive their full paleomagnetic vector. We focus particularly on a group of lavas that date between 1250 BC and 250 AD, a period that includes the occurrence of a reported intensity high in the Levant (Gallet et al., 2006; Ben-Yosef et al., 2009; Shaar et al., 2011; Ertepinar et al., 2012). A proper paleointensity record for the

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Canary Islands for the same period may provide important spatial and temporal constraints for this intriguing, yet enigmatic geomagnetic phenomenon.

Our results will also assess the veracity of the multi-method paleointensity approach for a different volcanic edifice beyond the suite of Hawaiian lavas used in de Groot et al. (2013). For Hawaii it yielded reliable paleointensity estimates for 67% of all cooling units sampled, but its performance for other volcanic regions is yet to be tested. An important part of the multi-method paleointensity approach, the calibrated pseudo-Thellier method, is also used in a different region for the first time. By comparing our pseudo-Thellier results to results of other paleointensity techniques from the same flow, we improve the calibration relation for the pseudo-Thellier technique – although the difference with the calibration relation presented in de Groot et al. (2013) is small. By adding results from a different volcanic edifice to the calibration data the general applicability of the pseudo-Thellier technique to obtain absolute paleointensity estimates for samples that fail in classical techniques due to thermally induced alteration is further enhanced.

2. Geological setting & sampling

The geological history of Tenerife (28°16′N, 16°38′W) is mainly dominated by the evolution of two stratovolcanos: Teide and Pico Viejo. The volcanological evolution of the island of Tenerife has been studied in detail (e.g. Carracedo, 1994; Guillou et al., 2004; Carracedo et al., 2007). Numerous Holocene lava flows are present; the most recent volcanic activity is in the Northwest rift zone, in the Chio and Garachico volcanic chains. The island of Gran Canaria (27°58′N, 15°35′W) is approximately 100 kms to the East of Tenerife and is somewhat older in geological terms. Gran Canaria is in its post-erosional stage, and active volcanism is much less prominent than on Tenerife. Holocene volcanic activity is limited to the Northeast part of the island, the most recent eruption occurred 200 yrs ago (Rodriguez-Gonzalez et al., 2009).

For Tenerife, Carracedo et al. (2007) recently presented a suite of both ^{14}C and K/Ar datings from which we selected the nine most recent flows for our study: the oldest flow is ∼6000 yrs old. From the radiocarbon datings for Gran Canaria that were presented by Rodriguez-Gonzalez et al. (2009), we could sample six independent cooling units; some of the dated flows could not be located unambiguously based on the locations provided. A total of 19 independent cooling units were sampled, including four flows dated from historical records (1492, 1706, 1798 and 1909 AD). Some cooling units were sampled at multiple locations (Table 1). Since the laboratory ages are available (Carracedo et al., 2007; Rodriguez-Gonzalez et al., 2009), it was possible to recalibrate the radiocarbon results using the newest INTCAL.13 curve (Reimer et al., 2013) using the Calib 7.0 program (Stuiver and Reimer, 1993). A kml-file with our sampling locations is available in the online Supplementary information.

Samples were usually taken within meters of the given UTM locations (Carracedo et al., 2007; Rodriguez-Gonzalez et al., 2009). Sampling was done using a petrol-powered drill with a bore of 2.5 cm. Taking cores in-situ was not always possible; in those cases (unoriented) hand-samples were taken – paleomagnetic directions are therefore not available for those sites. For each site up to 20 cores were drilled close together to ensure homogeneity between samples since sister specimens are indispensible to compare paleointensity methods. Where possible samples were taken from fresh surfaces (i.e. road cuts) and from solid parts of the flow; sometimes these solid parts were quite vesicular. Two sites, TF-11 and TF-13B, were difficult to drill and appeared to be volcanic glass, implying a rapid natural cooling.

Paleointensity studies on Canary Islands' lavas generally concentrate on pre-Holocene geomagnetic features such as the Matuyama–Brunhes transition; or the Laschamps, Blake, or Mono Lake excursions (e.g. Quidelleur, 1996; Szérémèta et al., 1999; Valet et al., 1999; Leonhardt et al., 2000; Leonhardt, 2002; Ferk et al., 2011; Kissel et al., 2011). Studies on Holocene lavas are sparse (Sherwood, 1991; Tulloch, 1992) and only performed on lavas younger than 1435 AD. Two of the flows presented here were also subject of a study by Valet and Soler (1999), measuring the local field anomalies caused by the morphology of the terrain underneath the cooling lava (Valet and Soler, 1999). Large possible anomalies were reported: the NRM of samples was biased up to 9° in declination, 6.5° in inclination and 20% in intensity, especially near sharp edges in the terrain and close to the underlying flow. The influence of these local field anomalies on the magnetic vector recorded in the flows is reduced by sampling in the upper part of undisturbed large blocks of the cooling units.

3. Rock-magnetic behavior

To optimize the boundary conditions of the paleointensity experiments the rock-magnetic behavior of samples from all sites is characterized first. Both the thermal behavior of the susceptibility and high-field rock-magnetic properties are assessed.

3.1. Susceptibility-versus-temperature (χ–T) analysis

The susceptibility of samples from all sites was measured as function of temperature using an AGICO KLY-3S susceptometer with a CS3 furnace attachment. The temperature was increased in seven cycles with the following approximate peak temperatures: 210, 280, 330, 375, 430, 480 and 580 °C. To check the reversibility of the signal the sample was cooled ∼50 °C after reaching each peak temperature. An irreversible susceptibility segment indicates (chemical) alteration in the sample. The highest peak temperature for which the susceptibility still is reversible is the highest temperature that can safely be used in paleointensity experiments, since alteration prevents a reliable paleointensity estimate. Furthermore, the Curie temperature of the samples is obtained from the χ–T diagrams. The Curie temperature is defined here as the inflection point after a peak in susceptibility. Several samples show two or more inflection points, indicating the presence of at least two magnetic carriers with different mineralogical composition. Since the χ–T behavior is diagnostic concerning the magnetic mineral composition and magnetic properties of the samples, the sites are categorized based on this parameter. The boundary conditions of the paleointensity experiments are chosen accordingly.

3.1.1. Group L

Samples that lose 80% of their susceptibility at room-temperature before reaching 150 °C, are labeled as 'type L' (low temperature). Sites TF-2, TF-5, GC-47A, TF-1909A, and the GC-6-(sub-)sites are in this group (Fig. 1b). These sites with a Curie temperature between 100 and 200 °C are vulnerable to viscous overprints. However, the sample shown here retains half of its NRM at 500 °C. The onset of alteration, indicated by non-reversible behavior in the susceptibility-versus-temperature diagram, is generally at 300–350 °C. Higher temperature steps in the paleointensity experiments may therefore be not reliable.

3.1.2. Group L*

Samples in group L that show a rapid decay in susceptibility already from room-temperature onwards, interpreted to imply a Hopkinson peak with its related Curie temperature below room-temperature, are labeled 'L*'. All TF-1798 and GC-64-(sub-)sites, and sites GC-73, GC-60, GC-47B and TF-1909B form this group