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On the possibility of recovering palaeo-diurnal magnetic variations in transitional lava flows 2. An experimental case study

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ABSTRACT

Geomagnetic field variations of external origin may be enhanced during periods of transitional field behaviour, particularly when the dipole moment is low, in which case they are likely to leave a paleomagnetic signature in rapidly cooled lava flows. To test this proposition, we have resampled en bloc and studied in fine detail a thin transitional Aa flow from a mid-Miocene lava sequence on Gran Canaria which was paleomagnetically investigated previously (Leonhardt, R., Soffel, H.-C., 2002. A reversal of the Earth's magnetic field recorded in mid-Miocene lava flows of Gran Canaria, Paleointensities. Journal of Geophysical Research 107, 2299. doi:10.1029/2001JB000949). The flow is characterised by high-unblocking temperatures, an equatorial VGP position and a very low absolute palaeointensity of ~2 μT. Two slabs were cut out of the flow and sampled at 1 cm intervals, along four vertical profiles running parallel to each other. Thermal demagnetisation was performed on two profiles using heating steps as small as 15 °C at elevated temperatures. The high-temperature part of the unblocking spectrum was found to be remarkably constant across the flow, as was the Curie temperature of 540 °C, and the negligible anisotropy of magnetic susceptibility. The exsolution lamallae observed under the microscope point to deuteric (high temperature) oxidation having occurred prior to the acquisition of the primary thermoremanent magnetisation. While the absolute palaeointensity values vary only little with vertical position, the magnetisation directions recovered by thermal demagnetisation vary considerably (on average, by some 20° at 500 °C). These large variations can be attributed to an overprint by secondary minerals, formed by fluid diffusion around vesicles and low-temperature oxidation. Since the secondary magnetisation recorded transitional directions as well, the overprint must have occurred soon after emplacement. The directional variations typically decrease in amplitude with increasing blocking temperature, which is contrary to what would be expected if pronounced diurnal external field variations were trapped in the flow.

1. Introduction

Field variations of external origin have not attracted much attention in palaeomagnetic research so far. Not for the lack of interest, but simply because their relative contribution under normal field conditions is too small to be detected palaeomagnetically. Even during intense magnetic storms, the largest ground field perturbations of external origin do barely exceed 1 μT (at high geomagnetic latitudes) against a background field of 25–60 μT. Besides, such events do not occur frequently enough and it would be coincidence if a lava flow was cooling through the blocking temperature in the very instant of a sudden magnetic storm commencement. However, the situation may be different in times of a diminished main field with transitional geometry (Siscoe and Crooker, 1976; Ultré-Guérard and Achache, 1995). External variations are indeed expected to be significantly reinforced during periods of equatorial dipole fields. Under these circumstances, the magnetosphere reconfigures on diurnal time scales (Saito et al., 1978; Zieger et al., 2004), leading to highly dynamic phenomena such as magnetic storms, which under normal field conditions are only observed during periods of increased solar activity. In our companion paper (Winklhofer et al., this issue), we show that enhanced diurnal external field variations superimposed on a weakened main field would leave a palaeomagnetic signature in a rapidly cooled thin lava flow. Thicker flows, cooling on time scale of months, efficiently smooth

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out diurnal external variations. Furthermore, it is one thing to have such variations recorded in a flow, it is quite another one to extract them palaeomagnetically, which requires a specialised sampling technique and an elaborated measurement protocol.

To begin with, a suitable candidate flow is needed. First, the flow must have been emplaced during low-intensity transitional field conditions. Then it needs to be thin enough (~50 cm thick) to cool off rapidly, as the cooling rate limits the temporal resolution when recording time-dependent signals. Ideally, the thermoremenance carriers should be pristine magnetic single-domain (SD) particles with blocking temperatures starting just below the Curie temperature. The absence of secondary overprint is not strictly required, provided that the overprint has low unblocking temperatures. These requirements reduce the choice of suitable lava flows drastically, and require a great deal of preliminary palaeo- and rock-magnetic reconnaissance studies.

Palaeomagnetic investigations carried out by Leonhardt and Soffel (2002) and Leonhardt et al. (2002) in the Canary Islands covered a composite section of a ~300 m thick lava pile in the mid-Miocene shield basalt of Gran Canaria. The study revealed, in particular, the presence of two excursions and one reversal interpreted to mark the beginning of polarity chron $C5_AC_N$ (*i.e.* 14.1 Ma after Cande and Kent, 1995). For the present study, we selected one particular lava flow of the sequence that meets most of the above conditions besides alteration. Rather than taking oriented cores in the field, we cut out oriented block samples from this specific flow. The two blocks obtained were densely sampled at the laboratory, which allowed us to minimise the directional error between different samples within a block. We conducted detailed palaeo- and rock-magnetic investigations on all samples in an attempt to distinguish between systematic directional variations of external origin and magnetic overprints.

2. Sampling and methodology

The lava flow selected for the present investigations corresponds to site C-TP62 of Leonhardt and Soffel (2002). It is characterised by a transitional paleofield direction (declination, D: 072.4°/inclination, I: −04.8°) and a very low palaeointensity value of 1.2 ± 0.5 μT. The virtual geomagnetic pole (VGP) plots near India, and is preceded by 15 flow units, which record a VGP cluster close to South America. The selected flow consists of olivine basalt of 'aa'-type, and is approximately 1-m thick including top and bottom breccias. A portable gasoline-powered diamond saw was used to cut two subvertical blocks, approximately 3 m apart from each other, out of the massive part of the flow. The top and bottom breccias were too friable to be sampled in this way. The blocks were orientated in the field (344.233°E; 27.936°N) using magnetic and sun compasses, and corrected for local declination (−7.1°).

Block.I is ~40 cm high and shows macroscopically four zones from bottom to top (Fig. 1A): a reddish, friable and oxidised zone from 0 to ~5 cm, a lower zone from 5 to ~15 cm showing relatively fine vesicles (millimetric), an upper zone from 15 to ~37 cm with relatively large vesicles (sub-centimetric), and finally a more and more friable but not necessarily oxidised zone up to 40 cm. Note also that the rock is broken at ~22 cm.

Block.II is similar in a height of ~47 cm and composed of similar zones (Fig. 1B). A 6–7 cm oxidised zone is present at the base of the flow, and a friable zone, close to the top breccia between 40–42 and 47 cm. A change in vesicle size is not obvious, but a distinction may be observed at about 20 cm between a lower and an upper zone. A severe break in the rock occurs between 33 and 35 cm, but another exists at 27 cm and some cracks appear at 12–13 cm and perhaps 22 cm.

An ~8 mm thick slice was cut again in each block at the laboratory (University of Munich), hereinafter referred to as slab.I and slab.II, and a 1 cm grid was marked throughout each slab surface. Four columns of cores were drilled every centimetre: one column of ~4 mm diameter cores and three columns of ~8.5 mm diameter cores further referred to as profiles A–C.

The smaller cores (~4 mm) were used for magnetic mineralogy analysis by means of a Petersen's variable frequency translation balance (VFTB) housed at the laboratory of Munich (Germany). The samples were subjected to measurements of hysteresis loops, isothermal remanent magnetisation (IRM) acquisition, backfield and thermomagnetic curves. Data were treated with the RockMagAnalyser 1.0 software (Leonhardt, 2006).

Cores from profiles A and C are used for the determination of the palaeodirections, and palaeointensities were determined from profile B. The anisotropy of magnetic susceptibility (AMS) was measured using a Kappabridge susceptibility-meter (KLY-2; 15 positions) on samples from profile A prior to demagnetisation. The shape of the ellipsoid of magnetic susceptibility (a quasi-sphere at more than 99.5%; Tauxe, 1998) and the degree of anisotropy ($P_J < 1.01$; Jelínek, 1981) indicate that the magnetic fabric of all samples from both blocks is quasi-isotropic. Palaeodirections were defined by thermal demagnetisation (20 steps; rest field in the oven <7 nT) on orthogonal projections using principal component analysis (PCA; Kirschvink, 1980) and on stereographic projections ("Schmidt" equal area). Palaeointensities were estimated using the Modified-Thellier Technique MT4 (Leonhardt et al., 2004a), which includes "pTRM*-tail checks" (Riisager and Riisager, 2001) and "additivity checks" (Krása et al., 2003). By combining these two last checks, it is possible to distinguish whether any significant deviation from the ideal behaviour is caused by multi-domain (MD) bias or by alteration. If no MD bias is detected and the thermoremanence magnetic (TRM) properties are preserved as monitored by "additivity checks", a correction from alteration can be performed following the method proposed by Valet et al. (1996) and Leonhardt et al. (2003). Palaeointensity experiments were carried out with a MMTD-20 thermal demagnetiser and a laboratory-built sample holder for ~8.5 mm cores. For partial thermo-renanent magnetisation acquisition (pTRM/TRM), a magnetic field of 20 μT was applied during heating and cooling. Data analysis was performed with the ThellierTool 4.11 software (Leonhardt et al., 2004a) and its default reliability parameters. All directional and paleointensity measurements were carried out with a 2G-Cryogenic Magnetometer operating in the magnetically shielded room at the Niederlippach laboratory (University of Munich).

In addition to the magnetic measurements, four polished sections per slab (section surfaces of 2.5-cm diameter) have been examined using reflected light microscopy. Porosity and permeability measurements have been carried out on specific samples (2.5 cm in diameter, and 5–7 cm in length) drilled in the two blocks, from which also slabs.I and .II were cut out, respectively. Four samples were taken at about 2, 9, 15, and 30 cm (samples centre) in slab.I, and three at about 11, 33, and 42 cm in slab.II.

Open porosity was measured using a micrometrics AccuPyc 1330 porosimeter. Porosity varies from less than 12% in the lower zone to more than 35% in the upper zone of the two blocks. Note that the open porosity for the sample situated at about 9 cm from the bottom of slab.I was rising from 14% up to 33% after 1 h heating at 300 °C, due to the destruction of zeolite. Without the infill of vesicles, the open porosity appears to correspond, therefore, to approximately a third of the rock throughout the blocks.

Permeability to gas was determined using an autoclave developed by the laboratory of mineralogy (Munich, Germany) and following the measurement techniques of Müller et al. (2005). Only 50% of the gas (argon) at 15 bars went through the most perme-