A rock- and palaeomagnetic study of geologically recent lavas and 1995 volcanic glass on Fogo (Cape Verde Islands)

MADS FAURSCHOU KNUDSEN, NIELS ABRAHAMSEN & PETER RIISAGER

Knudsen, M.F., Abrahamsen, N. & Riisager, P. 2005–12–15. A rock- and palaeomagnetic study of geologically recent lavas and 1995 volcanic glass on Fogo (Cape Verde Islands). *Bulletin of the Geological Society of Denmark*, Vol. 52, pp. 39–52. © 2005 by *Geological Society of Denmark*. ISSN 0011–6297.

Fogo is the only island in the Cape Verde archipelago with accounts of historical volcanic activity. Here we present palaeomagnetic data from seven geologically recent lava flows on Fogo, including one glassy, volcanic flow from the eruption in 1995. Almost all samples behaved well during alternating-field (AF) and thermal demagnetisation, and the characteristic remanent magnetisations (ChRMs) were generally easily isolated. The dominant magnetic mineral in all flow units, including the glassy flow, is titanomagnetite with a varying titanium content. The non-glassy flow units all display pseudo-single-domain (PSD) behaviour, whereas the hysteresis parameters for the glassy flow unit tend to plot in a region associated with mixtures of superparamagnetic (SP) and single-domain (SD) grains. Despite historical accounts of the eruptive activity on Fogo it was impossible to obtain unique correlations between the historical flow fields and the non-glassy flow units presented in this study. One of six non-glassy flow units yields a direction consistent with existing approximative reference curves for the historical secular variation on Fogo. Consequently, we suspect that some of the non-glassy flow units have been subjected to post-cooling block rotation. The glassy flow from 1995 proved to be a reasonable recorder of the geomagnetic field, yielding a direction (dec = 353.8° and inc = 12.9°), quite similar to the International Geomagnetic Reference Field (1995) for this site location (dec = 346.8° and inc = 14.4°).

Key words: Fogo, Cape Verde Islands, rock magnetism, hysteresis, palaeosecular variation, volcanic glass.

Mads Faurschou Knudsen [*madsk@earth.ox.ac.uk*], *Department of Earth Sciences, University of Aarhus, Finlandsgade 6–8, DK-8200 Aarhus N., Denmark, present address: Department of Earth Sciences, University of Oxford, Parks Road, Oxford OX1 3PR, United Kingdom*; *Niels Abrahamsen* [*abraham@geo.au.dk*], *Department of Earth Sciences, University of Aarhus, Finlandsgade 6–8, DK-8200 Aarhus N., Denmark, Peter Riisager* [*Peter.Riisager@geol.lu.se*], *Geological Museum, University of Copenhagen, Øster Voldgade 5–7, DK-1350 Copenhagen K., Denmark, present address: GeoBiosphere Science Centre, Quaternary Sciences, University of Lund, Sölvegatan 12, S-223 62 Lund, Sweden*.

Reliable records of the geomagnetic secular variation are crucial for construction of magnetic-field models and understanding of core-mantle interactions related to the geodynamo processes generating the Earth's magnetic field (Merrill *et al.* 1998; Jackson *et al.* 2000; Korte & Constable 2003). Compilations of direct magnetic observations have greatly improved the resolution of global secular variation for the period 1590–2000 A.D. (Jackson *et al.* 2000), but only in very limited areas, such as Western Europe (Gallet *et al.* 2002; Le Goff *et al.* 2002), are there sufficient archaeo- and palaeomagnetic data to extend the palaeosecular variation record further back in time. The importance of longer palaeosecular-variation time series, beyond historical observations, is underlined by the suggested existence of 'archaeomagnetic jerks' (Gallet *et al.* 2003), with time characteristics intermediate between geomagnetic jerks and geomagnetic excursions. Hence, detailed palaeomagnetic records of the Holocene secular variation from geographically dispersed locations are in great demand to establish reliable palaeosecular-variation models and confirm the existence and global significance of 'archaeomagnetic jerks'.

Detailed records of palaeosecular-variation from the African region are almost non-existing (Herrero-Bervera *et al.* 2004), despite the abundance of volcanic provinces. Historical accounts of intensive

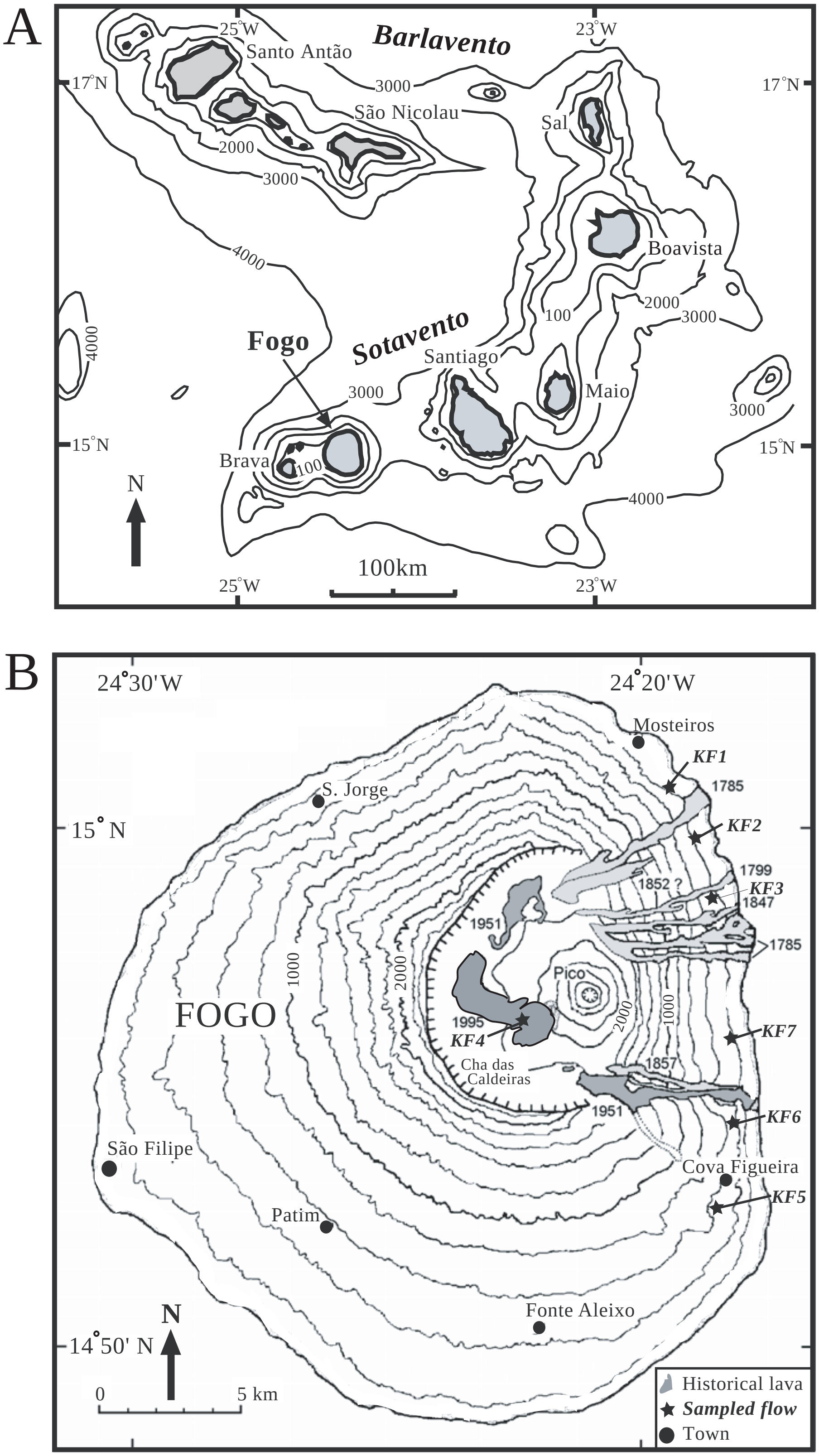

Fig. 1. A) Bathymetric map of the Cape Verde archipelago (modified from Day *et al* .1999, fig. 1).
B) Map of Fogo with the approximate geographical locations of the seven sampled flow units and some of the numerous historical flows summarised by Ribeiro (1960). The glassy flow unit (KF4) was sampled inside the giant collapse structure in the central part of the island. The non-glassy flow units studied here (KF1-3 and KF5-7) cannot be unequivocally correlated with the historical flow fields.

eruptive activity therefore make Fogo, Cape Verde Islands, a suitable location for studies of recent Holocene secular variation in an area largely devoid of such data. However, several secondary factors, such as undetected secondary magnetisations, magnetic-terrain and self-demagnetisation effects, insufficient age constraints, and post-cooling block rotation, often render such studies of palaeosecular variation difficult (Tanguy & Le Goff 2004; Urrutia-Fucugauchi *et al*. 2004). This paper investigates the possibility of improving the existing Holocene secular-variation curve for the Cape Verde archipelago, and the degree to which such secondary factors may influence studies of the secular variation. Here we report palaeomagnetic results from 7 meticulously sampled flow units, including a glassy, volcanic flow from a 1995 eruption. Such a glassy flow unit often contains magnetic microcrysts (Pick & Tauxe 1993; Smirnov & Tarduno 2003), and therefore provides an opportunity to investigate the reliability of palaeomagnetic directions inferred from volcanic glass.

Geological setting and palaeomagnetic sampling

The Cape Verde archipelago, consisting of 10 major and some minor islands (Fig. 1A), is located in the Atlantic ocean some 300–600 km off the coast of Senegal. The rise of the Cape Verde mantle plume resulted in a swell some 500 km across and reaching up to ~2000 m above the adjacent ocean basin, the so-called Cape Verde rise or Cape Verde swell, on which the islands are situated (Gerlach *et al.* 1988). The intense hotspot activity related to the rising mantle plume initiated around 19–20 Ma ago (McNutt 1988; Klerkx & De Paepe 1976) and involved the uplift of deformed Jurassic oceanic crust, plutonic rocks and sediments, which form the geological basement of the islands (Dash *et al.* 1995; Stillman *et al.* 1982; De Paepe *et al.* 1974). The age of the underlying crust, ranging from 122 to 140 Ma, corresponds to Mesozoic marine magnetic anomalies M1-M16 (Hayes & Rabinowitz 1975; Stillman *et al.* 1982). The arrangement of the archipelago in two linear chains (Fig. 1A), the Barlavento (windward) and Sotavento (leeward) islands respectively, is believed to be related to either the geometry of the flow of plume material, as envisaged by Holm *et al.* (2005), or to the structure of the lithosphere (Williams *et al.* 1990). Hotspot volcanics on the islands consist of silica-undersaturated lavas different from MORB, such as nephelinites, basanites and ankaramites, derived from magma formed by low degrees of partial melting of mantle peridotite at considerable depth (Gerlach *et al.* 1988; McNutt 1988).

Fogo and the adjacent island of Brava (Fig. 1A) are the two youngest and seismically and volcanically most active islands in the archipelago. Consequently, Fogo and Brava are believed to be the islands closest to the inferred position of the upwelling Cape Verde mantle plume (Courtney & White 1986). Fogo, however, is the only island in the archipelago with accounts of historical volcanic activity, most recently in 1995 (Fig. 1B).

Morphology and timing of the Fogo volcanics

The shape of Fogo can essentially be described as one large volcanic cone rising out of the ocean from the Cape Verde swell (Fig. 1B). The topography of the relatively small island, covering a sub-aerial area of 472 km^2, is completely dominated by a giant caldera-like collapse structure in the central part of the island, inside which there is a large steep-sided volcanic cone (Pico de Fogo) together with numerous younger scoria cones. The almost circular collapse structure opening eastwards (Fig. 1B) is 9 km wide north to south and bounded by extremely steep, continuous cliffs (the Bordeira) (Day *et al.* 1999). Pico de Fogo is currently the highest point on Fogo, reaching an elevation above sea level of 2829 m. The island is bounded by steep coastal cliffs and steep slopes or flanks (angles generally in excess of 15°) stretch up to the giant central collapse structure (Fig. 1B) (Day *et al.* 1999). Well preserved lava flows and local scoria cones form the outer slopes of the island in several places.

According to the provisional stratigraphic subdivision of Fogo by Day *et al.* (1999), the oldest rocks on the island belong to the poorly exposed basal intrusive complex. This alkali-basic basement complex may be the equivalent of seamount sequences of rocks observed in some of the other islands in the archipelago (Stillman *et al.* 1982). The basement complex is unconformably overlain by the Monte Amarelo Group, denoted the 'pre-collapse sequence' in earlier studies. The Monte Amarelo Group is dominated by highly alkaline basic to intermediate lavas that earlier formed a giant stratovolcano, dissected by numerous dykes. The caldera-like collapse structure is a remnant of this previous giant stratovolcano, which upon collapsing formed the Bordeira cliffs. All rocks postdating the Monte Amarelo collapse belong to the Cha das Caldeiras Group, which is subdivided into the Pico do Fogo Formation and the younger

Monte Orlando Formation. Eruptions postdating the Pico de Fogo Formation have resulted in several scoria cones and lava flows, all belonging to the Monte Orlando Formation, some of which reach the coast from the giant collapse structure in the central part of Fogo (Fig. 1B). Ribeiro (1960) analyzed and summarized the accounts of historical eruptions on Fogo, and more detailed studies have subsequently been published by Torres *et al.* (1997) and Day *et al.* (1999).

Previous palaeomagnetic results from the Cape Verde Islands have been published by Watkins *et al.* (1968), Storetvedt & Løvlie (1983), Abranches *et al.* (1990), Knudsen & Abrahamsen (2000), and Knudsen *et al.* (2003a). Except for the study of Watkins *et al.* (1968), which included the sampling of one flow unit on Fogo, no palaeomagnetic studies have been conducted on Fogo prior to this study.

Palaeomagnetic sampling

Palaeomagnetic samples were collected from seven different flow units, six of which are located along the road parallel to the east coast and one (KF4) inside the central caldera-like collapse structure (Fig. 1B). The six sampled flow units dispersed along the east coast (KF1-KF3 and KF5-KF7) all erupted from fissures and vents inside or close to the central collapse structure and subsequently flowed down the steep slopes towards the coast (Fig. 1B). Palaeomagnetic sampling of these blocky flow units belonging to the Monte Orlando Formation was aimed at studying the secular variation in this area. Flow unit KF4, sampled inside the central collapse structure close to the road through the caldera (altitude: 1900 m; Fig. 1B), is a pahoehoe-type lava flow, which erupted in 1995. This 1995 lava flow is particularly interesting because of its glassy nature, allowing an investigation of volcanic glass, containing magnetic microcrysts, as a carrier of magnetic remanence.

Table 1. Approximate ages, inferred from detailed field observations. (Simon Day, personal communication 2004), of flow units (KF 1-3 and KF5-7) sampled on Fogo. The glassy flow unit KF4 stems from the well-described 1995 eruption. Also listed are the GPS-coordinates of the sampled locations.

Flow	Estimated age (A.D.)	Site Lat.	Site Long.
KF1	1680-1725	15° 00’904 N	24° 18’479 W
KF2	1680-1725	15° 00’145 N	24° 18’125 W
KF3	1852	14° 59’603 N	24° 17’775 W
KF4	1995	14° 57’000 N	24° 22’300 W
KF5	1721-1725	14° 50’782 N	24° 20’753 W
KF6	1721-1725	14° 51’897 N	24° 18’798 W
KF7	1769	14° 52’923 N	24° 17’671 W

An average of 9 cores were drilled from each of the 6 flow units sampled along the road parallel to the east coast (KF1-KF3 and KF5-KF7). The 9 cores from each flow unit were sampled in three clusters several meters apart at various positions within the cross-section of the flow, and at different orientations to the lava flow. The samples were collected from the lower parts of the flow units to avoid the steepest intervals in the vicinity of the central collapse structure. Flows KF1 and KF5-7 appeared very young, with no indications of weathering and no vegetation, whereas flow units KF2-3 appeared slightly older, mostly due to the presence of small trees and plants. 17 cores were drilled from the 1995 glassy flow unit within the central collapse structure (KF4), but the flow was fragile and not all cores remained intact. The altogether 71 cores collected from the seven flow units were oriented by magnetic compass and some additionally by sun compass (all cores in KF4-KF7). When available, the sun compass orientations concurred with the magnetic compass orientations. Because of the low ages of the flow units, no tilt corrections have been made.

The ages of the historical flow fields on Fogo, which reach the east coast from the central collapse structure (Fig. 1), rely on historical accounts summarized by Ribeiro (1960), who carefully examined oral and written descriptions of the eruption history on Fogo. The map in Figure 1B was rendered possible by the early work of Ribeiro (1960). Unfortunately, the *in situ* measured GPS-positions (Table 1) of the flow units in this palaeomagnetic study do not match with the positions of the historical flows (Fig. 1B). Correlation in the field also proved very difficult due to insufficient accuracy of the existing maps (Ribeiro 1960). It is therefore impossible to uniquely correlate the non-glassy flow units sampled in this study with any of the historical flows in the area, and hence obtain unambiguous ages for the 6 flows sampled along the coast. However, approximate ages (Table 1) of flow units KF1-3 and KF5-7 were obtained through tentative correlations based on fleld observations by Simon Day (personal communication 2004), who is currently mapping the historical flow flelds on Fogo in great detail. Note that the locations and inferred ages do not match the flow fields shown on the existing map (Fig. 1B). The age of flow unit KF4 (Table 1) was easily determined, since this glassy lava flow undoubtedly stems from the well-described 1995 eruption.

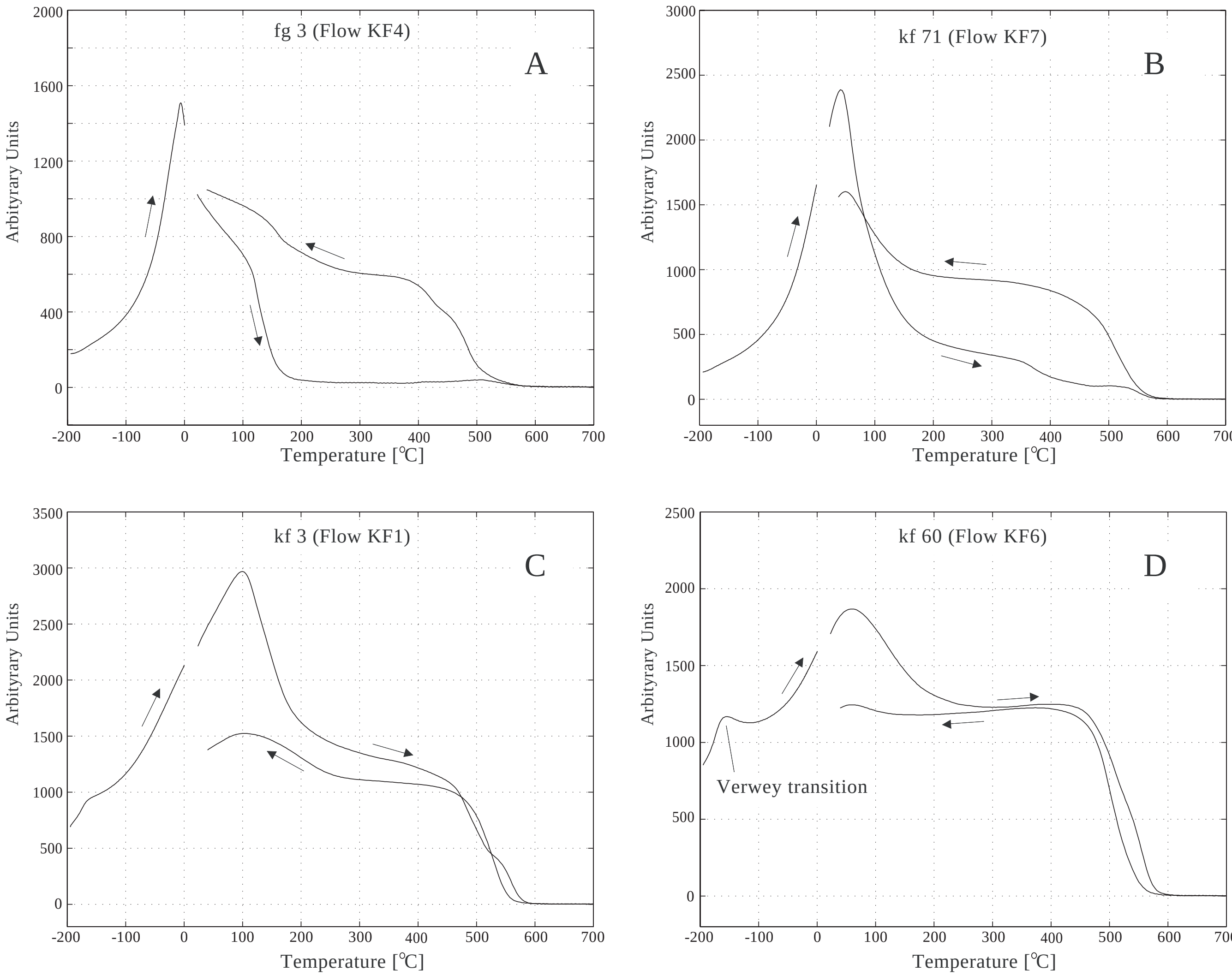

Fig. 2 Weak-fleld magnetic susceptibility as a function of temperature for A) the glassy flow unit (KF4) and B–D the non-glassy flow units (KF1–3 and KF5–7). The glassy flow unit (A) shows irreversible thermomagnetic curves indicating that titanium-rich titanomagnetite is the dominant magnetic mineral, which has partly been oxidized to a titanium-rich and titanium-poor phase of titanomagnetite upon heating. The three thermomagnetic curves in Figure 2B–D reflect the variety of titanium contents in the samples from the other, non-glassy flow units (there is no obvious difference in the compositions of the different flows). B) is a sample from a non-glassy flow similar in composition to A). Both a titanium-poor and a titanium-rich phase of titanomagnetite are present in C), giving rise to a vague Verwey transition. Titanium-poor titanomagnetite, with a conspicuous Verwey transition, is the most dominant magnetic mineral in D.

Magnetic mineralogy and grain sizes

All flow units were subjected to thermomagnetic experiments (weak-fleld magnetic susceptibility measured as a function of temperature in an Ar-atmosphere), which generally indicated that titanomagnetite in varying oxidation states is the dominant magnetic mineral in the Fogo flow units. Largely identical, irreversible thermomagnetic curves were obtained for 5 samples from the glassy flow unit (KF4), one of which is shown in Figure 2A. The curves suggest that the glassy, volcanic flow contains microcrysts of reasonably homogeneous titanium-rich titanomagnetite (~TM60-70) in a low oxidation state, which upon heating partly oxidize to a titanium-rich and titanium-poor titanomagnetite phase (Fig. 2A). Thermomagnetic curves from the six other flow units (KF1-3 and KF5-7) may roughly be subdivided into

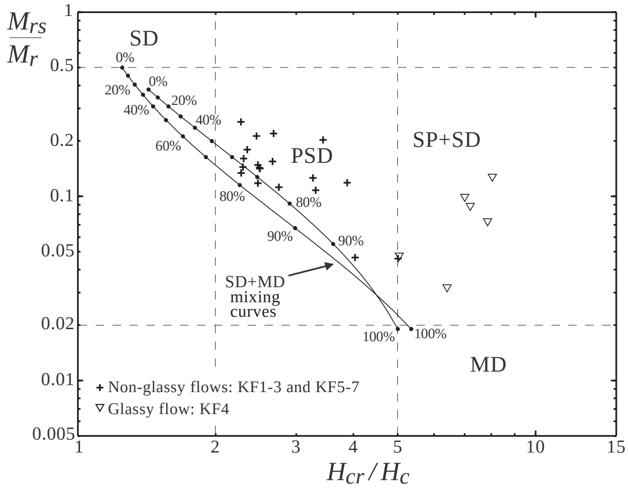

Fig. 3. Day plot (Day *et al* . 1977) of hysteresis parameters for samples from the seven flow units, with the magnetite PSD-range boundary values of Dunlop (2002). Also shown are the theoretical linear mixing curves for mixtures of SD and MD-pure magnetite grains (Dunlop 2002) with two different sets of SD and MD end-members (numbers denote percentage MD grains). The non-glassy flow units KF1-3 and KF5-7 (+) all plot in the PSD-region, with compositions ranging from 20% to 50% SD-domain (50–80% MD) according to the linear mixing curves of Dunlop (2002). An increase in the titanium content may explain why some of these samples plot to the right of the linear mixing curves. Samples from the glassy flow unit KF4 (Δ) tend to plot in a region associated with mixtures of superparamagnetic (SP) and stable SD grains (Dunlop, 2002).

three groups, without systematic variations in composition between the different flow units. The first group displays irreversible thermomagnetic behaviour similar to KF4, i.e. rapid cooling has presumably prevented oxidation of the primary titanium-rich titanomagnetite, which upon heating partly oxidizes to a titanium-rich and a titanium-poor phase of titanomagnetite (Fig. 2B). The second group is characterized by thermomagnetic curves with a vague Verwey transition (at approximately –160°C) and notable presence of both a titanium-rich and titanium-poor titanomagnetite (Fig. 2C), whereas the third group is characterized by a pronounced Verwey transition (at approximately –160°C) and dominance of titanium-poor titanomagnetite (TM0-5; Fig. 2D). Judging from the thermomagnetic curves, the low-temperature oxidation product of titanomagnetite, titanomaghemite, may be present in some of the samples (e.g. Fig. 2B).

Hysteresis parameters, M_{rs}/M_s *versus* H_{cr}/H_c, of samples from all flow units are shown in a Day plot (Day *et al*. 1977; Fig. 3), with the pseudo-single-domain (PSD) boundary values of Dunlop (2002) applied. Most of the non-glassy flows, which all plot in the PSD region, match the theoretical linear mixing curves of Dunlop (2002) for mixtures of SD and multi-domain (MD) magnetite grains. Earlier data (Day *et al.* 1977; Dunlop 2002) suggest that titanomagnetites with an increasing titanium content will tend to plot to the right of the SD-MD mixing curves for magnetite. The fact that the hysteresis parameters from the non-glassy flows scatter around and to the right of the linear mixing curves could thus reflect variable contents of titanium (TM0-70), consistent with the varying titanomagnetite composition observed in the thermomagnetic curves for flow units KF1-3 and KF5-7. Following the linear mixing theory for SD and MD magnetite grains (Dunlop 2002), the samples in the present study range from 20-50% SD (50-80% MD). Hysteresis parameters of samples from KF4 (the glassy flow), with typical wasp-waisted hysteresis loops, plot outside the PSD region. According to the theoretical definitions of Dunlop (2002), samples from KF4 tend to plot in a region associated with mixtures of superparamagnetic (SP) and stable SD grains (approximate limits: $0.1 \leq M_{rs}M_s \leq 0.5$ and $H_{cr}/H_c \leq 100$). This, in turn, indicates that the magnetic microcrysts in the volcanic glass are very small, most likely due to rapid cooling. Bimodal mixtures of grains with different sizes and hysteresis parameters may account for the hysteresis behaviour of the glassy flow unit (KF4), which plots in between the SD+SP and SD+MD regions (Dunlop 2002). Hysteresis parameters associated with flow unit KF4 in this study are largely similar to what is observed for much older submarine basaltic glass (SBG) used extensively in palaeointensity experiments (e.g. Riisager *et al.* 2003; Smirnov & Tarduno 2003; Pick & Tauxe 1993).

Palaeomagnetic procedures and results

All samples from the seven flow units in this study were subjected to step-wise alternating fleld (AF) demagnetisation with the purpose of identifying the characteristic remanent magnetisations (ChRMs). Particularly detailed AF demagnetisations with small incremental steps were performed for samples from the glassy flow unit (KF4) (Fig. 4A, B). Thermal and AF demagnetisation of companion samples from the same cores yielded consistency between directions obtained by the two different demagnetisation methods (Fig. 4C, D). None of the samples from KF4, however, were thermally demagnetized. The ChRM components were in almost all cases easily defined by principal component analysis (PCA) (Kirschvink 1980), as all demagnetisation curves decay towards

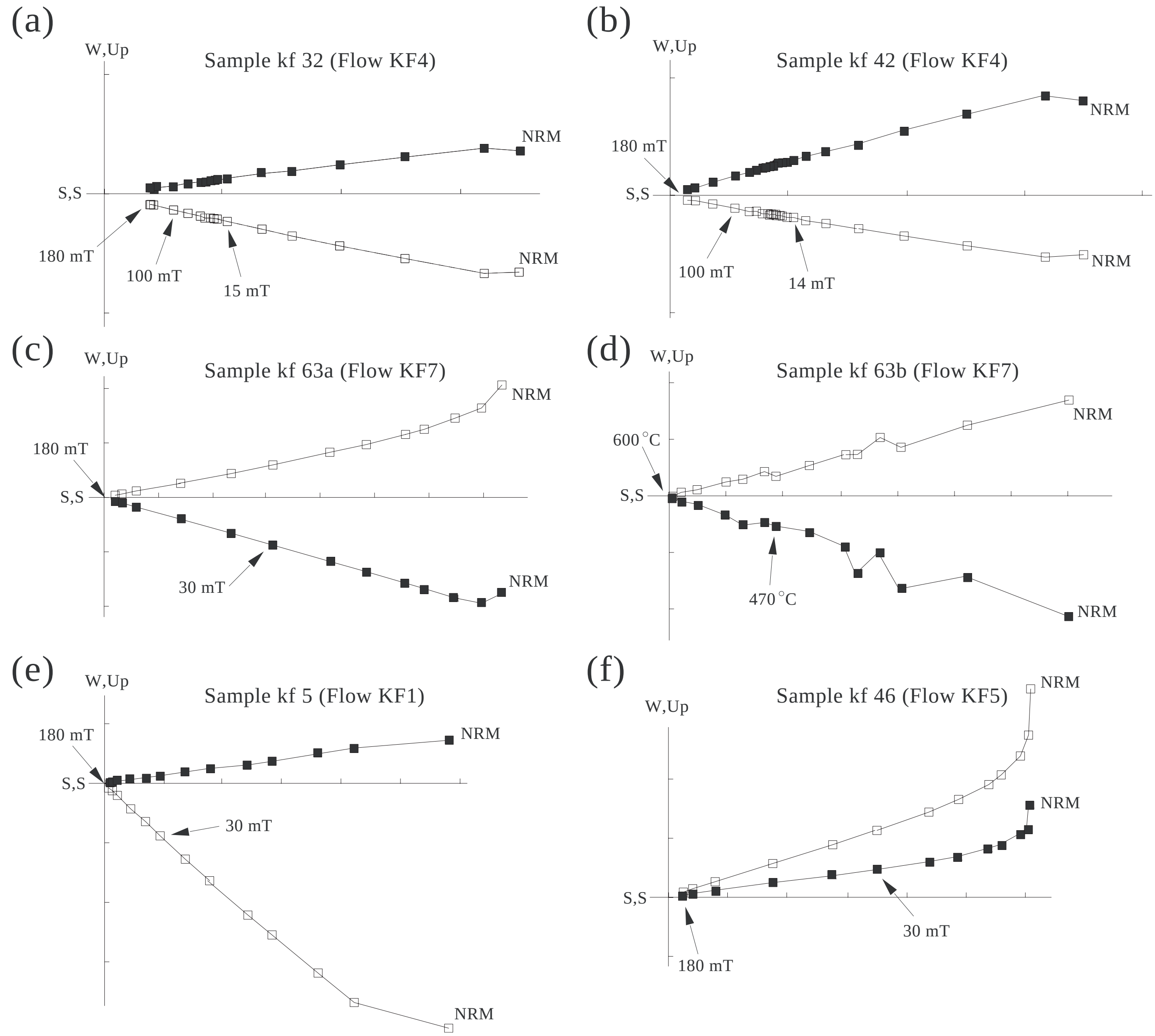

Fig. 4. Orthogonal vector plots of stepwise demagnetisation of representative samples. A) and B) illustrate typical AF demagnetisation of two samples from the glassy flow unit (KF4). C) and D) illustrate the consistency between AF and thermal demagnetisation of companion specimens from the same core, but also the poorer quality of thermal-demagnetisation data. E) shows a typical example of single-component magnetisation, whereas F) illustrates the secondary overprint present in some samples.

the origin with typically no (Fig. 4E) or little (Fig. 4F) evidence of secondary magnetic overprints. One sample (kf 20 from flow KF3) was rejected because it yielded a declination deviating 180° from the mean declination of the other samples from the same flow, most likely caused by misorientation in the fleld.

The mean directions of the ChRMs for the different flows are shown in a stereogram (Fig. 5) and furthermore listed in Table 2, together with the common parameters from Fisher-statistics. The within-flow dispersion varies, but the ChRM-directions generally cluster reasonably well with α_{95} confidence limits close to 5°, the exceptions being flow units KF3 and KF7 (Table 2).

Discussion

Unlike some areas in Europe and North America, such as e.g. France (Gallet *et al.* 2002; Le Goff *et al.* 2002), no archaeomagnetic reference curves exist for

Table 2. Results of the seven sampled flow units.

Flow	Dec*m* N1	Dec_m (°)$_2$	Inc_m (°)$_3$	α_{954}	κ_5	Plat(°)6	Plong(°)6	dp	dm
KF1	9	358.8	43.1	4.3	144.68	79.9	329.8	3.3	5.3
KF2	9	20.6	–4.2	5.7	82.4	–63.4	284.3	2.9	5.7
KF3	8	5.2	17.9	7.5	55.36	82.3	114.3	4.0	7.8
KF4	8	353.8	12.9	5.0	124.5	79.6	192.2	2.6	5.1
KF5	9	5.0	–18.8	4.1	159.0	–65.0	323.9	2.2	4.3
KF6	8	0.0	–16.4	5.1	120.4	–66.8	335.7	2.7	5.3
KF7	8	18.4	–12.1	8.1	47.4	–62.2	293.4	4.2	8.2

The latitude (Plat) and longitude (Plong) of the corresponding virtual geomagnetic poles (VGPs) were computed by using Dec*m* and Inc*m* in combination with the position coordinates of the observation sites (see Table 1).
The ovals of 95% confldence about the VGP positions are deflned by dp and dm.
N = number of samples - Dec*m* = mean declination - Inc*m* = (º) inclination - α_{95} = circles of confidence - *K* = precision parameters Plat (º) = latitude - Plon (º) = longitude

the geomagnetic secular variation in the Cape Verde archipelago. Moreover, no detailed records of palaeosecular variation are available from Africa, despite the abundance of volcanic provinces (Herrero-Bervera *et al.* 2004). Numerous historical observations of the Earth's magnetic fleld recorded by ancient mariners were compiled by Jackson *et al.* (2000), which resulted in a continuous model (*gufm1-model*) of the magnetic field at the core-mantle boundary (CMB) for the interval 1590–1990 A.D. The continuous spherical harmonic model of Korte & Constable (2003), based on available archaeomagnetic, lake sediment, and palaeomagnetic data, provides an estimate of the secular variation at the CMB in the time-span 1000 B.C. to 1800 A.D. Since the data coverage used to compute the magnetic fleld at the CMB is significantly sparser in the model of Korte & Constable (2003) than in that of Jackson *et al.* (2000), the model of Korte & Constable (2003) is less accurate, but it offers a longer palaeosecular-variation time series. Both models provide an approximative reference curve for the directional variations at the Fogo location, but cannot be regarded as representing the true geomagnetic secular variation.

Flow unit KF1 yields a direction consistent with the geomagnetic direction in 1690 A.D. (Fig. 5), according to the reference curve of Jackson *et al.* (2000), which is in agreement with the approximated eruption interval of flow unit KF1, 1680–1725 (Table 1). The ChRM direction of flow unit KF1 is likewise reasonably consistent with the palaeosecular-variation curve of Korte & Constable (2003) around 1700 A.D. Flow unit KF4 displays a direction similar to that predicted by the model of Korte & Constable (2003) in ~1300 A.D. (Fig. 5), but this must be a coincidence since flow unit KF4 stems from the 1995 eruption. The directions of the remaining non-glassy flow units deviate considerably from those expected from the reference curves (Fig. 5), and some flow units (KF2 and KF5-7), quite surprisingly, yield negative inclinations.

Several factors may potentially account for the observed discrepancies between the palaeomagnetic mean directions and those derived from the secular variation models of Jackson *et al.* (2000) and Korte & Constable (2003). These factors include: (1) undetected secondary magnetisations, (2) magnetic-terrain and self-demagnetisation effects, (3) imprecise secular-variation curves, (4) misidentification of the ages, and (5) post-cooling block rotation. We will discuss each of these factors in the following. The sampling procedures applied along with the behaviour of the demagnetisation curves indicate that the discrepancy between palaeomagnetic directions and the reference curves are not caused by lightning-induced magnetisations or other secondary magnetisations (Tanguy & Le Goff 2004). The directions obtained from samples taken at different sub-sites and at different angles to the flow unit in question are consistent. Furthermore, the discrepancy between palaeomagnetic directions and the reference curves appear to be independent of whether the thermomagnetic remanent magnetisation (TRM) is weak (Fig. 2A, B) or strong (Fig. 2D) with respect to AF demagnetisation. We therefore reject possibility (1). Magnetic-terrain effects (MTE) (Baag *et al*. 1995; Valet & Soler 1999; Tanguy & Le Goff 2004) and self-demagnetisation effects (Vogt 1969; Coe 1979; Knudsen *et al*. 2003b), grouped under factor (2), may introduce significant inclination anomalies in the palaeomagnetic record. Inclination shallowing often occurs inside strongly magnetised rocks, such as volcanic lava flows, due to shape-anisotropy effects influencing the acquisition of magnetic remanence. However, the MTE and

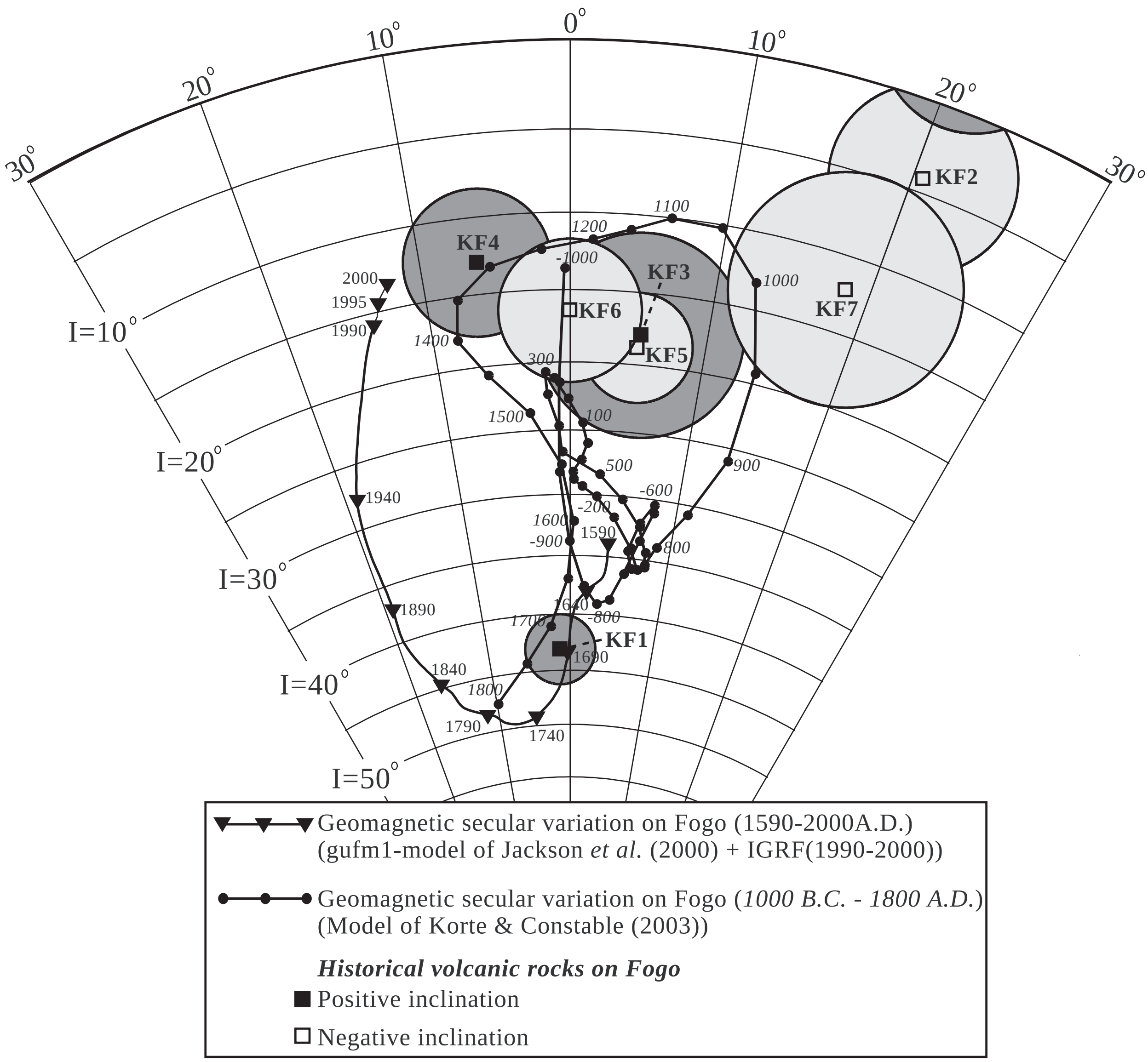

Fig. 5. Geomagnetic directions and their associated confidence limits (α_{95}) from historical flow units on Fogo, including the glassy flow unit (KF4) from the 1995 eruption. Also shown are reference curves for the palaeosecular variation of the Earth's magnetic field at the Fogo site location. The reference curve generated by the *gufm-1-model* (1590-1990 A.D.) of Jackson *et al.* (2000) is based on historical observations, whereas the reference curve generated by the *CALS3K.1-model* of Korte & Constable (2003) relies on archaeomagnetic, lake sediment, and palaeomagnetic data.

shape-anisotropy effect (self-demagnetisation effect) cannot account for the large discrepancies between the approximative reference curve (Jackson *et al*. 2000) and the directions obtained from some of the non-glassy flow units in this study (KF2-3 and KF5-7), simply because the maximum realistic anomaly introduced by these effects amounts to ~10°. Factor (3), imprecise secular-variation curves, is rather difficult to assess as a possible explanation for the observed discrepancies. Although the existing reference curves for the Fogo location are approximative due to lack of data from the area, it seems highly unlikely that the palaeosecular-variation curve of Jackson *et al.* (2000) deviates more than 40° from the true direction. Hence, we consider factor (3) an unlikely explanation for the observed discrepancies.

The poor age constraints imply that the approximate ages of the non-glassy flow units may have been misidentified, as suggested by factor (4), and consequently that these coastal flow units may be considerably older than assumed. Tanguy *et al.* (1985, 2003) showed that records of Mount Etna eruptions were often misinterpreted and that the lava flows were in fact several centuries older than previously believed. Comparison of the palaeomagnetic data from Fogo with directions at this location from the palaeosecular-variation model of Korte & Constable (2003) shows that none of the flows in question (KF2–3 and KF5-7) display a palaeomagnetic mean direction matching their palaeosecular-variation curve for the Fogo location (Fig. 5). Moreover, none of the directions derived from the model of Korte & Constable (2003) show negative inclinations, and thus differ significantly from the Fogo flows that display negative inclinations (KF2 and KF5-7). Although the model of Korte & Constable (2003) cannot be regarded as a highly accurate representation of the geomagnetic field, especially in areas with poor data coverage such as the Cape Verde archipelago, it indicates that either these flows erupted before 1000 B.C., or we have to seek another explanation for the discrepancies observed. Judging from the morphology of the flows displaying anomalous directions, it seems highly unlikely that these largely unvegetated flows erupted before 1000 B.C. This judgment is supported by a detailed geological study of Fogo by S. Day, who, based on the tracing of an ash marker horizon across the island, concludes that it is very unlikely that these flows erupted before 1680 A.D. (S. Day, personal communication 2004).

Alternatively, the unexpected directions could be caused by flow displacement after the flow unit cooled below the blocking temperature, factor (5), hereby distorting the original directions by several degrees. Such post-cooling block rotation, most likely roll-over effects, can explain the palaeomagnetic mean directions observed in the flows displaying negative inclinations. Considering that the sampled lavas flowed down the steep slopes of the central caldera-like collapse structure, together with the blocky appearance of the sampled units, we believe that factor (5), post-cooling block rotation, is responsible for the anomalous directions. Similarly, Urrutia-Fucugauchi *et al.* (2004) observed abnormal shallow inclinations in a study of historical lava flows of the Paricutin volcano (Mexico), which they also ascribe to post-cooling block rotation during emplacement.

Finally, this palaeomagnetic study of Fogo shows how volcanic glass containing fine-grained magnetic inclusions may be a potential recorder of the geomagnetic field. Flow unit KF4 from the 1995 eruption yields a mean declination and inclination of 353.8° and 12.9°, respectively, which is reasonably consistent with the International Geomagnetic Reference Field (IGRF) for this site location at the time of eruption (dec = 346.8° and inc = 14.4°) (Fig. 5). Nevertheless, the relatively small within-site scatter results in reasonably narrow confidence limits (α_{95} = ~5°), which exclude the IGRF(1995)-direction, hereby implying that the two directions are statistically different at the 95% confidence level (the angle between the two directions is 6.97°). This directional discrepancy, which is close to the uncertainty of palaeomagnetic sampling, is unlikely to be a failure of the recording mechanism in volcanic glass (i.e. the magnetic microcrysts), to correctly record the ambient field direction. It is most likely caused by MTE and self-demagnetisation effects, or alternatively by a small degree of post-cooling block rotation.

Conclusions

Rock magnetic analyses, performed on one glassy and six non-glassy volcanic flow units from Fogo, Cape Verde Islands, show that titanomagnetite, with a varying titanium content (TM0–70), is the dominant magnetic mineral in all flow units. All non-glassy flow units (KF1–3 and KF5–7) display PSD behaviour, and, according to the mixing theory of Dunlop (2002), the mineral grains carrying the magnetic remanence in the non-glassy flows are mixtures of 20–50% SD and 50–80% MD magnetite grains. The magnetic microcrysts in the glassy flow unit (KF4) are a mixture of SP and SD magnetite grains, indicating that the microcrysts in the volcanic glass indeed are very small.

Flow unit KF1 (which probably erupted in the interval 1680–1725 A.D.) yields a direction consistent with that at ~1690 A.D. in the approximative reference curve for the geomagnetic secular variation on Fogo (Jackson *et al.* 2000), while the directions of the other non-glassy flow units (KF2–3 and KF5–7) deviate considerably from the existing reference curves for Fogo (Jackson *et al.* 2000; Korte & Constable 2003). These directional discrepancies most likely arise from post-cooling block rotation of the flows in question (KF2–3 and KF5–7), which makes these flows unsuitable for accurate assessment of the palaeofield. The glassy flow unit (KF4) from the 1995 eruption proved to be a reasonable recorder of the geomagnetic field, yielding a direction (dec = 353.8° and inc = 12.9°), quite similar to the International Geomagnetic Reference Field (1995) for this site location (dec = 346.8° and inc = 14.4°). This result supports the notion that volcanic glass may be a suitable archive for palaeomagnetic studies.

Acknowledgements

This work was supported by the Danish National Science Foundation. We are indebted to our colleagues in the Danish Working Group on the Geology of the Cape Verde Islands for collaboration and help during field work, and to Xixi Zhao, University of California, Santa Cruz, USA, for offering free laboratory facilities. We thank Simon Day, Benfield Greig Hazard Research Centre, UK, for valuable comments and suggestions, and the two referees Sten-Åke Elming and Richard Wilson for constructive criticism. Andrew Jackson, University of Leeds, UK, kindly generated the approximative reference curve for the Fogo location.

Dansk Sammendrag

Fogo er den eneste ø i Kap Verde Øgruppen med beretninger om vulkansk aktivitet inden for den historiske tidsramme. Dette studium omhandler bjergarts- og palæomagnetiske undersøgelser af de historiske vulkanitter på Fogo, heriblandt en lavastrøm af vulkansk glas hidrørende fra det seneste udbrud i 1995.

De magnetiske mineraler og deres egenskaber

Prøver indsamlet fra 7 forskellige lavastrømme blev underkastet detaljerede afmagnetiseringsforsøg (vekselfelt og termiske), hvorefter prøvernes oprindelige magnetisering, der blev fastlåst under den pågældende lavastrøms dannelse, let lod sig bestemme. Termo-magnetiske kurver, hvor den magnetiske susceptibilitet måles som funktion af temperatur, indikerer at det dominerende magnetiske mineral i lavaerne fra Fogo er titanomagnetit med en varierende sammensætning. Sammensætningen varierer fra titaniumrig titano-magnetit til magnetit med et ringe indhold af titanium, i hvilket tilfælde den diagnostiske Verwey-transition kan observeres. De varierende sammensætninger afspejler forskellige grader af deuterisk oxidation af den primære titanomagnetit.

En bjergsarts hystereseparametre er diagnostiske for den dominerende domænestruktur, der indirekte afspejler stabiliteten af bjergartens remanente magnetisering. Laboratorieforsøg viser at pseudo-single-domænet (PSD) er den dominerende magnetiske struktur i de mineralkorn der bærer den remanente magnetisering i lavaerne på Fogo. Den remanente magnetisering i det vulkanske glas består af en blanding af magnetiske mineralkorn med superparamagnetiske (SP) og single-domæne (SD) egenskaber.

Magnetfeltets sekularvariation på Fogo

Variationer af Jordens magnetfelt i tid og sted indeholder vigtig information om magnetfeltets dannelse i Jordens kerne. Detaljerede optegnelser over magnetfeltets palæosekularvariation findes ikke fra Kap Verde Øgruppen, hvilket også i vid udstrækning gælder hele det afrikanske kontinent. De historiske lavastrømme fra Fogo levererede derfor en unik mulighed for at studere sekularvariationen i dette område.

På trods af de historiske beretninger viste det sig imidlertid vanskeligt, at etablere en entydig korrelation mellem 6 af lavastrømmene indsamlet i dette studium og de, der er beskrevet i litteraturen. Retningen af magnetfeltet bestemt ud fra en af disse seks regulære lavastrømme var konsistent med, og leverer følgelig støtte til, de approksimative kurver for palæosekularvariationen på Fogo. Disse kurver beror på teoretiske modelberegninger, baseret på historiske og arkæomagnetiske observationer af Jordens magnetfelt, fortrinsvist i Europa, og kan derfor ikke betragtes som repræsentanter for feltets sande sekularvariation i området omkring Kap Verde. Retningerne fra de fem resterende, regulære lavastrømme afviger i varierende grad fra de approksimative kurver for sekularvariationen. Den mest sandsynlige forklaring på de største afvigelser er, at de pågældende lavastrømme har været udsat for blokrotation efter at den remanente magnetisering blev fastlåst under lavastrømmenes dannelse.

Det vulkanske glas fra 1995 gav en palæomagnetisk retning, der stemmer nogenlunde overens med det Internationale Geomagnetiske Referencefelt (IGRF) for Fogo, hvilket vidner om, at vulkansk glas kan være en brugbar kilde i palæomagnetiske studier.

References

Abranches, M., Storetvedt, K., Serralheiro, A. & Løvlie, R. 1990: The palaeomagnetic record of the Santiago volcanics (Republic of Cape Verde); multiphase magnetization and age consideration. Physics of the Earth and Planetary Interiors 64, 290–302.

Baag, C., Helsley, C., Xu, S. & Lienert, B. 1995: Deflection of paleomagnetic directions due to magnetization of the underlying terrain. Journal of Geophysical Research 100(B7), 10013–10027.

Coe, R. 1979: The effect of shape anisotropy on trm direction.

Geophysical Journal of the Royal Astronomical Society 56, 369–383.
Courtney, R. & White, R. 1986: Anomalous heat flow and geoid across the Cape Verde Rise: Evidence for dynamic support from a thermal plume in the mantle. Geophysical Journal of the Royal Astronomical Society 87, 815–868.
Dash, B., Ball, M., King, G., Butler, L. & Rona, P. 1995: Geophysical Investigation of the Cape Verde Archipelago. Journal of Geophysical Research 100 (B7), 10013–10027.
Day, R., Fuller, M. & Schmidt, V. 1977: Hysteresis properties of titanomagnetites: Grain-size and compositional depence. Physics of the Earth and Planetary Interiors 13, 260–267.
Day, S., Heleno da Silva, S. & Fonseca, J. 1999: A past giant lateral collapse and present-day flank instability of Fogo, Cape Verde Islands. Journal of Volcanology and Geothermal Research 94, 191–218.
De Paepe, P., Klerkx, J. & Plinke, P. 1974: Oceanic tholeiites on the Cape Verde Islands: Petrochemical & geochemical evidence. Earth and Planetary Science Letters 22, 347–354.
Dunlop, D. 2002: Theory and application of the Day plot (M_{rs}/M_s versus H_{cr}/H_c) 1.
Theoretical curves and tests using titanomagnetite data. Journal of Geophysical
Research 107 (B3), doi: 10.1029/ 2001JB000486.
Gallet, Y., Genevey, A. & Le Goff, M. 2002: Three millinnea of directional variation of the Earth's magnetic fleld in Western Europe as revealed by archeological artefacts. Physics of the Earth and Planetary Interiors 131, 81–89.
Gallet, Y., Genevey, A. & Courtillot, V. 2003: On the possible occurrence of archaeomagnetic jerks in the geomagnetic fleld over the past three millennia. Earth and planetary Science Letters 214, 237–242.
Gerlach, D., Cliff, R., Davies, G., Norry, M. & Hodgson, N. 1988: Magma sources of the Cape Verdes archipelago: Isotropic and trace element constraints. Geochimica et Cosmochimica Acta 52, 2979–2992.
Hayes, D. & Rabinowitz, P. 1975: Mesozoic Magnetic Lineations and the Magnetic Quiet Zone off Northwest Africa. Earth and Planetary Science Letters 28, 105–115.
Herrero-Bervera, E., Ubangoh, R., Aka, F. & Valet, J.-P. 2004: Paleomagnetic and paleosecular variation study of the Mt. Cameroon volcanics (0.0-0.25 Ma), Cameroon, West Africa. Physics of the Earth and Planetary Interiors 147, 171–182.
Holm, P., Wilson, J., Christensen, B., Hansen, L., Hansen, S., Hein, K., Mortensen, A., Pedersen, R., Plesner, S. & Runge, M. 2005: Sampling the Cape Verde Mantle Plume: Evolution of Melt Compositions on Santo Antão, Cape Verde Islands. Journal of Petrology p. doi:10.1093/petrology/egi071.
Jackson, A., Jonkers, A. & Walker, M. 2000: Four centuries of geomagnetic secular variation from historical records. Philosophical Transactions of the Royal Society of London 358, 957–990.
Kirschvink, J. 1980: The least squares line and plane and the analysis of palaeomagnetic data. Geophysical Journal of the Royal Astronomical Society 62, 699–718.
Klerkx, J. & De Paepe, P. 1976: The main characteristics of the magmatism of the Cape Verde Islands. Ann. Soc. Geol. Belg. 99, 347–357.
Knudsen, M. & Abrahamsen, N. 2000: Magnetostratigraphy of young Pliocene volcanics at Santo Antão, Cape Verde Islands: The Escabecada and Chã de Morte Profiles. Physics and Chemistry of the Earth 25, 461–467.
Knudsen, M., Abrahamsen, N. & Riisager, P. 2003a: Palaeomagnetic evidence from Cape Verde Islands basalts for fully-reversed excursions in the Brunhes Chron. Earth and Planetary Science Letters 206 (1–2), 199–214.
Knudsen, M., Jacobsen, B. & Abrahamsen, N. 2003b: Palaeomagnetic distortion modelling and possible recovery by inversion. Physics of The Earth and Planetary Interiors 135, 55–73.
Korte, M. & Constable, C. 2003: Continuous global geomagnetic fleld models for the past 3000 years. Physics of The Earth and Planetary Interiors 140, 73–89.
le Goff, M., Gallet, Y., Genevey, A. & Warmé, N. 2002: On archeomagnetic secular variation curves and archeomagnetic dating. Physics of The Earth and Planetary Interiors 134, 203–211.
McNutt, M. 1988: Thermal and Mechanical Properties of the Cape Verde Rise. Journal of Geophysical Research 93(B4), 2784–2794.
Merrill, R., McElhinny, M. & McFadden, P. 1998: The Magnetic Field of the Earth. 386 pp. Academic Press, San Diego.
Pick, T. & Tauxe, L. 1993: Geomagnetic paleointensities during the Cretaceous Normal Superchron measured using Submarine Basaltic Glass. Nature 366, 238–242.
Ribeiro, O. 1960: A Ilha do Fogo e as suas erupcoes. 2nd ed. Memorias, serie geograflca I. **Publ.** Junta de Investigacoes do Ultramar, Ministerio do Ultramar, Lisbon, Portugal.
Riisager, P., Riisager, J., Zhao, X. & Coe, R. 2003: Cretaceous geomagnetic paleointensities: Thellier experiments on Pillow lavas and Submarine basaltic glass from the Ontong Java Plateau. Geochemistry Geophysics Geosystems 4 (12), doi:10.1029/2003GC000611.
Smirnov, A. & Tarduno, J. 2003: Magnetic hysteresis monitoring of Cretaceous submarine basaltic glass during Thellier paleointensity experiments: evidence for alteration and attendant low fleld bias. Earth and Planetary Science Letters 206, 571–585.
Stillman, C., Furnes, H., LeBas, M., Robertson, A. & Zielonka, J. 1982: The geological history of Maio, Cape Verde Islands. Journal of the Geological Society 139, 347–361.
Storetvedt, K. & Løvlie, R. 1983: Magnetization Properties of Intrusive/Extrusive Rocks from East Maio (Republic of Cape Verde) and their Geological Implications. Geophysical Journal of the Royal Astronomical Society 73, 197–212.
Tanguy, J.-C. & Le Goff, M. 2004: Distortion of the geomagnetic fleld in volcanic terrains: an experimental study of the Mount Etna stratovolcano. Physics of The Earth and Planetary Interiors 141, 59–70.
Tanguy, J.-C., Bucur, I. & Thompson, J. 1985: Geomagnetic secular variation in Sicily and revised ages of historic lavas from Mount Etna. Nature 318, 453–455.
Tanguy, J.-C., Le Goff, M., Principe, C., Arrighi, S., Chillemi, V., Paiotti, A., La Delfa, S. & Patanè, G. 2003: Archeomagnetic dating of Mediterranean volcanics of the last 2100 years: validity and limits. Earth and Planetary Science Letters 211 (1-2), 111–124.
Torres, P., Madeira, J., Silva, L., Brum da Silva, A., Serralheiro, A. & Mota Gomes, A. 1997: Carta geologica das erupcoes historicas da Ilha do Fogo: revisao e actualizacao. A erupcao vulcanica de 1995 na Ilha do Fogo, Cabo Verde. Publ. IICT, Lisboa pp. 119–132.
Urrutia-Fucugauchi, J., Alva-Valdiva, L., Goguitchaichvili, A. & Rivas, M. 2004: Palaeomagnetic, rock-magnetic and mi-

croscopy studies of historic lava flows from the Paricutin volcano, Mexico: implications for the deflection of palaeomagnetic directions. Geophysical Journal International doi: 10.1111/j.1365-246X.2004.02166.x.
Valet, J.-P. & Soler, V. 1999: Magnetic anomalies of lava flelds in the Canary Islands. Possible consequences for palaeomagnetic records. Physics of The Earth and Planetary Interiors 115, 109–118.
Vogt, P. 1969: Can demagnetization explain seamount drift? Nature 224, 574.
Watkins, N., Richardson, A. & Mason, R. 1968: Palaeomagnetism of the Macaronesian Insular Region, The Cape Verde Islands. Geophysical Journal of the Royal Astronomical Society 16, 119–140.
Williams, C., Hill, I., Young, R. & White, R. 1990: Fracture zones across the Cape Verde Rise, N.E. Atlantic. Journal of the Geological Society, London 147, 851–857.