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Palaeomagnetic and rock-magnetic study of a Pliocene volcanic section in southern Georgia (Caucasus)

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Abstract

Twenty-six basaltic flows were sampled for a paleomagnetic and rock-magnetic study of the Tchuntchka section in the Akhalkalaki volcanic region in southern Georgia (Caucasus). Three to five samples from each flow were subjected to thermal or alternating-field demagnetization. The upper part of the section yields normal (D = 355.5°, I = 54.2°, N = 17, α_{95} = 2.5°, k = 226), and the lower part reversed polarity directions (D = 180.3°, I = – 59.4,° N = 8, α_{95} = 4.8°, k = 135). An anomalous direction was found in one flow in the upper part (D = 118.5°, I = – 77.3°). Rock-magnetic experiments show that the remanence is carried in most cases by magnetite or low-Ti titanomagnetite. The fraction of grains with a multidomain magnetic structure does not seem to be important. The remanence carried by such grains is removed only partly by low-temperature demagnetization. A tentative magnetostratigraphic correlation between the 3.8-Ma-old Thoki and Tchuntchka sites is proposed.

Introduction

Alpine, late Miocene to Holocene, compression is responsible for the formation of mountains and for intensive volcanic activity in southern Georgia (Milanovski 1978). According to geological (Maissuradze 1989) and petrological studies (Skirtladze 1958), three phases of volcanic activity can be distinguished: 1) late Miocene to early Pliocene, 2) middle to late Pliocene or Pleistocene, and 3) Quaternary. In Georgia, late-orogenic subaerial volcanism occurred in four main areas: the south-Georgian volcanic province, the Khrami basin, the Small Caucasus and the Kazbeki region. The Akhalkalaki volcanic area, which is the subject of the present research, is located in the western part of the south-Georgian volcanic province. Its lower units are made up of doleritic-basaltic and, less frequently, of basaltic-andesitic lava flows (Kharadzian 1970). The age of the Akhalkalaki volcanism is still controversial. Mammal fossils found in alluvial deposits covering volcanic series, yield an early Pleistocene age as the younger age limit. At the lower end of the series, late Pliocene faunal fossil deposits have been found in lacustrine sediments interbedded between doleritic flows (Milanowski 1978). On the other hand, Ar-Ar dating of plagioclases from three flows located in the lower part of the Akhalkalaki volcanic area (Thoki section, Figure 1) yielded ages between 3.83 ± 0.09 and 3.69 ± 0.08 Ma (Camps et al. 1996).

Paleomagnetic results from south Georgia are still scarce. A magnetostratigraphic study was carried out by Sologachvili (1986) on more than hundred lava flows from the four main volcanic regions in Georgia. The studied flows are Quaternary or Pliocene in age as could be inferred from geological studies. As only few samples were studied in each flow, this study had, however, only a preliminary character. A detailed paleomagnetic study of a geomagnetic excursion or reversal recorded in a section located near the village

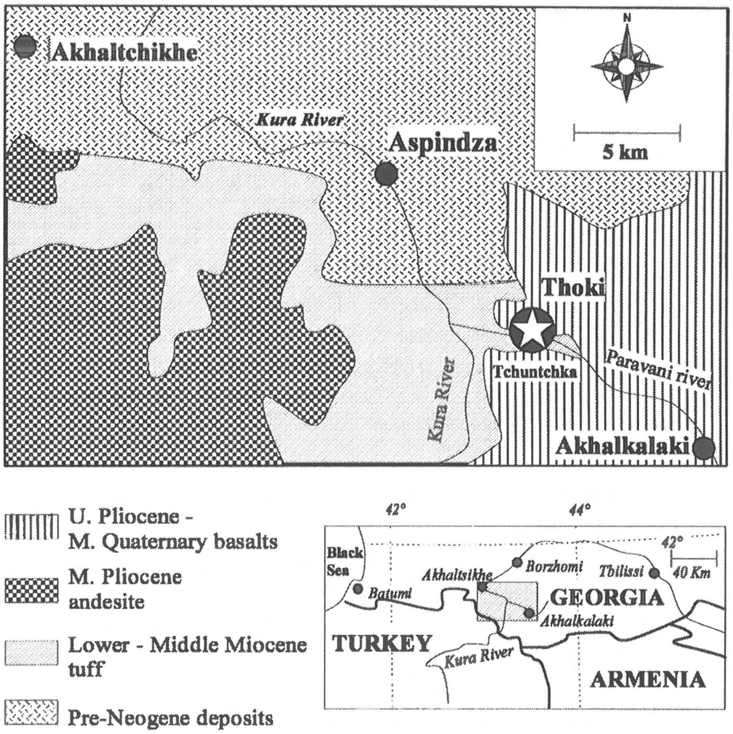

Figure 1. Akhalkalaki volcanic region: geological setting (modified from Camps 1996). ✪ shows location of Tchuntchka and Thoki sampling sites.

of Thoki was carried out by Camps et al. (1996) on 400 cores taken from a sequence of 63 lava flows. Five directional groups were found, dated at 3.8 ± 0.1 Ma. The first three showed intermediate-polarity directions and were followed by two groups of reversed polarity, so that no record of the normal-polarity field existing before the reversal could be obtained. No information about the beginning of the reversal was thus available.

The present study was started in order to complete the study carried out by Camps et al. (1996) and to increase and improve the Pliocene to Recent palaeomagnetic record for southern Georgia. We chose for sampling the Tchuntchka volcanic section (Figure 1), which is composed of doleritic flows, and located at a distance of only 800 m from the Thoki volcanics studied by Camps et al. (1996). The Tchuntchka section can be divided into two parts. The lower one (section X) has a thickness of ~200 m and the upper one (Y) of ~100 m. Samples were taken from 26 different flows, 18 belonging to section Y and 8 to section X (Table 1). The thickness of the flows is significantly different between X and Y. In X it varies between 8 and 22 m, while in Y it changes between 4 and 6 m. This difference may be explained by a decrease in eruption intensity at the end of this volcanic episode. The same hypothesis is supported by Skirtladze (1958) and Kharadzian (1970) for other sites in the Akhalkalaki region. No evidence of palaeosol developement or sedimentation has been observed between the X and Y sections and both seem to be petrologically similar, showing a porphyritic-fluidal texture with doleritic tendency. Most flows show evidence of hydrothermal alteration. Olivines are always entirely altered in the X, and only partially in the Y section. The presence of the vacuoles filled with calcite is also observed in both sections. Due to the lack of accessibility to the lowermost 60 m of the Tchuntchka section, only 240 m of a total thickness of 300 m could be sampled. From each flow, three to four oriented blocks with a weight of 1.2 to 2.5 kg were taken and four to seven cubes with edges of 2 cm were cut from each block for laboratory measurements. Blocks were orientated relating their position to the position of the Sun by means of a magnetic theodolite.

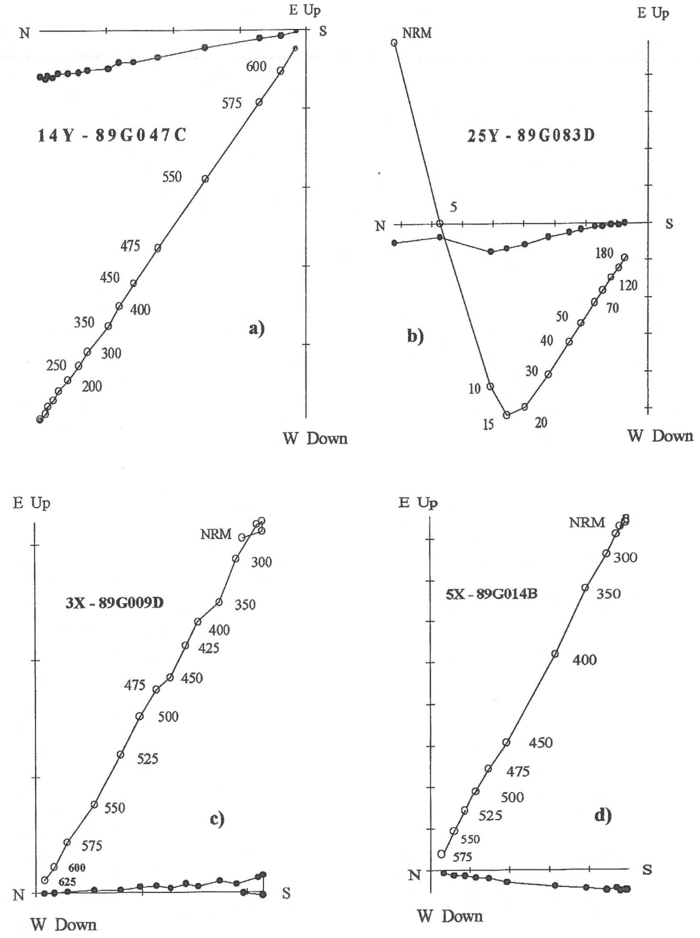

Figure 2. Orthogonal vector plots of stepwise demagnetization of representative samples of the Tchuntchka section (stratigraphic coordinates). a, c, d) Thermal demagnetization, numbers refer to °C. b) Alternating-field demagnetization, numbers refer to peak field in mT. Open (closed) symbols: projection onto the vertical (horizontal) plane.

Palaeomagnetic measurements

The remanent magnetizations of three to five (in one case seven) samples from each flow were measured with a CTF cryogenic magnetometer (sensitivity 10^{-10} to 10^{-11} Am^2) at the palaeomagnetic laboratory of the University of Montpellier (France). Measurements were only recorded after stabilisation of the remanence in this magnetometer, which was made possible with an application code which permitted plotting of magnetization changes in real time (Levêque 1992). Both alternating-field (AF) demagnetization (up to 80 to 200 mT) using a laboratory-made AF-demagnetizer, and stepwise thermal demagnetization (up to 600 to 650 °C) using a non inductive PYROX furnace with a residual magnetic field of 15 to 20 nT were carried out. Fifty-eight samples were subjected to AF, and 41 to thermal demagnetization. During thermal demagnetization, the low-field ($\sim 80 \mu T$) susceptibility at room temperature was measured after each step with a Bartington MS2 susceptibility meter, to check whether chemical or mineralogical changes occurred during the demagnetization.

In most of the flows only one palaeomagnetic component could be recognized (Figures 2a, d). The greater part of remanent magnetization was removed at temperatures between 475 and 600 °C, which points to magnetite as the remanence carrier. Nevertheless, a smaller fraction of higher unblocking temperatures could sometimes be observed, indicating that the samples are not completely demagnetized at 625 °C. As a significant reduction of susceptibility could be recog-

Table 1. Paleomagnetic parameters of the Tchuntchka site. ALT: flow altitude in meters; n/N: number of specimens used for calculation/total number of treated specimens; Inc: magnetic inclination (°); Dec: magnetic declination (°); k and α_{95}: precision parameter and confidence cone of Fisher statistics. PZ-1 and PZ-2 are polarity zones which correspond to sections X and Y, respectively.

Flow	Alt	n\N	Inc	Dec	α_{95}	k
26Y	1667	4\5	49.5	356.2	4.2	578
25Y	1661	3\3	50.8	354.1	1.6	3807
24Y	1658	4\4	47.2	1.4	1.9	405
23Y	1650	3\4	65.3	353.1	2	1956
22Y	1648	3\4	49.9	354.8	1.8	1812
21Y	1636	5\7	−77.3	118.5	2.2	847
20Y	1626	3\3	54.9	359.5	3.6	953
19Y	1618	3\3	51.6	352.9	3.5	950
18Y	1616	4\5	55.7	355.9	2.1	1756
17Y	1609	4\4	52.9	6.2	1.1	1756
16Y	1604	3\3	57.1	355.8	2.5	2505
15Y	1601	3\3	60.3	347.6	2.1	1477
14Y	1592	4\4	51.1	350.8	0.9	4554
13Y	1587	3\3	49.8	352.1	3.1	1464
12Y	1580	4\5	55.8	358	2.2	965
11Y	1576	3\3	56.5	356.7	3.3	1359
10Y	1572	4\4	54.9	359.5	3.6	754
9Y	1568	3\3	56.1	344.3	3.5	613
8X	1550	4\4	−54.5	161.1	4.6	378
7X	1531	4\4	−57.1	187.7	3.8	894
6X	1510	3\3	−57.6	187.9	1.6	3811
5X	1502	4\4	−60.1	183.2	3.3	1287
4X	1484	3\3	−57.2	168.9	2.8	1727
3X	1463	3\3	−56.1	179.8	1.9	2267
2X	1444	4\5	−61.2	185.5	0.5	2419
1X	1422	4\4	−67.7	194.3	1.1	2586
PZ-2			54.2	355.5	2.5	226
PZ-1			−59.4	180.3	4.8	135

nized at temperatures over 500 °C, hematite was probably formed at the expense of magnetite during thermal demagnetization. In some flows, a two-component behaviour could be observed. In some cases a stable component carried by magnetite was found together with a viscous component with a present-day-field direction and maximum unblocking temperatures of 150 to 200 °C (Figure 2c). In other cases, mainly in the six upper flows of section Y, the secondary component was likely produced by lightning strikes, which could be easily recognized by its aberrant directions during AF demagnetization (Figure 2b). Median destructive fields (MDF) of samples struck by lightning were relatively weak (15 to 25 mT), while one-component samples showed higher MDF values (30 to 55 mT). Directions of magnetization components were calculated by means of principal-component analysis (Kirschvink 1980), a minimum of five points being taken for this determination. Mean directions for each flow are shown in Table 1, and it can be easily seen that all flows belonging to section X are reversed (polarity zone 1 in Figure 3), while those which belong to section Y are normal (polarity zone 2). Nevertheless, in section Y an anomalous direction was found in flow 21Y. This direction could be explained by movements after emplacement of this flow which actually consisted of large-size blocks from which the smaller oriented blocks were taken.

Mean directions were calculated for both sections (Figure 3, Table 1), a value of D = 180.3 °, I = −59.4 °, α_{95} = 4.8 °, k = 135, being obtained for section X (8 flows) and D = 355.5 °, I = 54.2 °, α_{95} = 2.5 °, k = 226, for section Y (17 flows).

Rock-magnetic experiments

In order to identify the magnetic carriers responsible for the remanent magnetization, to obtain information about their palaeomagnetic stability, and to assess the suitability of the studied samples for palaeointensity studies, several rock-magnetic experiments were carried out. These experiments included: a) measurement of the viscosity index, b) measurement of isothermal remanent magnetization (IRM) acquisition curves, c) measurement of thermomagnetic curves (susceptibility, saturation magnetization and saturation remanence versus temperature), d) vibrating-sample-thermomagnetometer (VSTM) experiments, and e) low-temperature experiments.

Viscosity index: Determination of the viscosity index (Thellier & Thellier 1944; Prévot et al. 1983) allows to estimate the capacity of a sample to acquire a viscous remanent magnetization, and is therefore useful to obtain information about the sample's palaeomagnetic stability. For this purpose, we placed the samples during two weeks with one of their axes aligned with the Earth's magnetic field. After measuring their magnetization (M_d), they were placed for another two weeks in a field-free space, and the magnetization (M_o) was measured again. This allows to calculate the viscosity index: $V = [(Z_d - Z_o) : M_{nrm}] \times 100$, where Z_d and Z_o are respectively the magnetization components

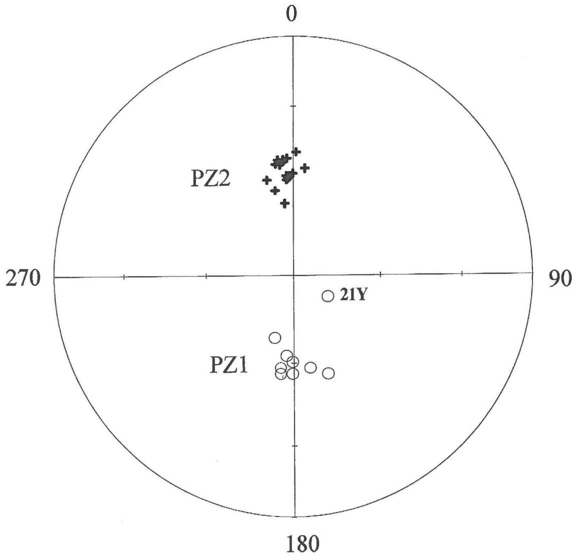

Figure 3. Equal-area projection of mean directions from Tchuntchka. PZ1: polarity zone 1. PZ2: polarity zone 2. (See text).

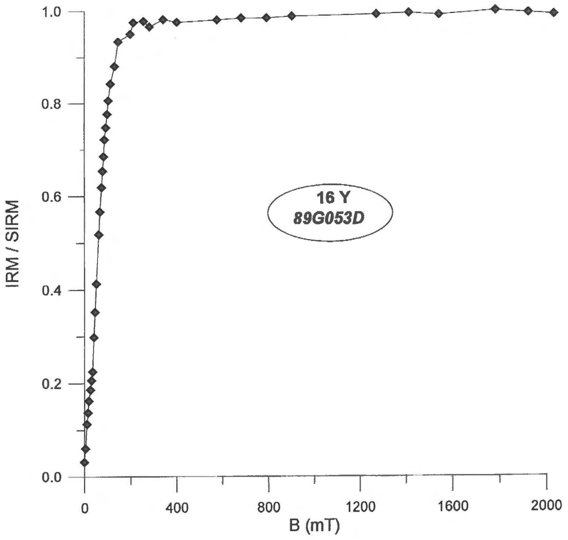

Figure 4. IRM-acquisition curve of a representative sample from Tchuntchka (flow 16Y). Maximum IRM value (SIRM) is $1.08 \cdot 10^{-4}$ Am^2.

of M_d and M_o which are parallel to the magnetizing field. M_{nrm} is the intensity of the natural remanent magnetization. In total 164 samples were subjected to these experiments, and although viscosity indexes varied between 0 and 5.9%, most values were lower than 3%. The Tchuntchka volcanics show therefore a low capacity of acquiring viscous remanent magnetization.

IRM acquisition curves: To determine the isothermal remanent magnetization (IRM) acquisition curves, previously AF-demagnetized samples from almost all flows were subjected to magnetic fields along one of their cube edges. The magnetic fields were steadily increased in 4 to 200 mT steps up to peak values of 1 to 2 T, their remanence being measured after each step. Saturation is reached at relatively weak fields (~200 mT; Figure 4), which points to the presence of (titano)magnetite or (titano)maghemite as a remanence carrier.

Thermal behaviour of low-field susceptibility, saturation magnetization and saturation remanence: To study the thermal evolution of susceptibility χ in a ~80 μT magnetic field, one sample from each flow was progressively heated up to temperatures of 650 to 700 °C and subsequently cooled down. All experiments were carried out under vacuum. Curie temperatures were determined following the method described by Grommé et al. (1969). Representative curves are shown in Figure 5. Some of these curves show a simple behaviour, with the presence of only one ferromagnetic phase and a Curie temperature near that of magnetite (Figures 5a, b). Some curves are almost reversible (Figure 5a). In other cases, two (Figure 5c) or even three (Figure 5d) different magnetic phases could be recognized. It cannot be ascertained however, whether these phases are distinct phases in the samples or whether they have been formed during thermal treatment. The lower Curie temperatures do not exceed 300 °C while the upper ones lie between 525 and 600 °C. Almost all cooling curves recorded in the present study show only a single ferromagnetic phase, with a Curie temperature close to that of magnetite. As experiments were carried out in vacuum, the lower Curie points which are found in irreversible χ(T) curves could be due to the presence of titanomaghemites, which during heating are probably transformed into magnetite and other phases. Magnetite could already be present in the studied samples.

In addition to χ(T) experiments, induced magnetization in a strong field (B = 0.7 T) as a function of temperature, M_S(T), was recorded for a few samples with a Curie balance at the palaeomagnetic laboratory of the University of Münster (Germany). These experiments were also carried out under vacuum. Curie temperatures were determined following the method of Grommé et al. (1969). Representative curves are shown in Figure 6. In one case a single phase (Figure 6a) could

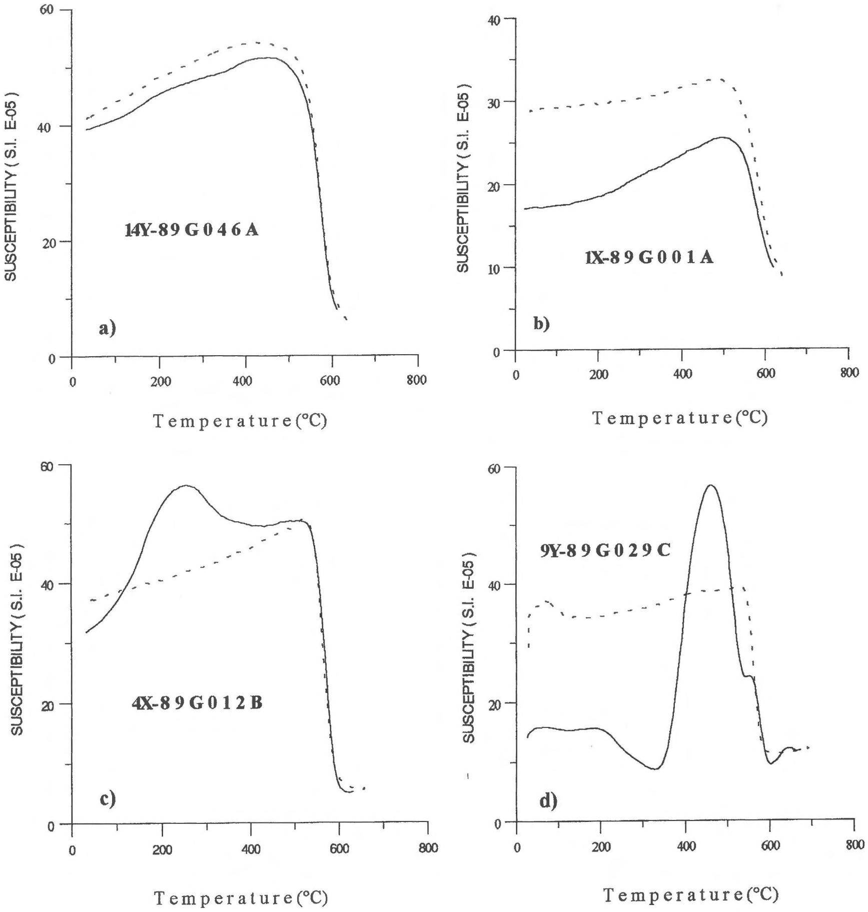

Figure 5. Susceptibility versus temperature curves (a–d) of four representative samples from Tchuntchka. Continuous lines refer to heating, dashed lines to cooling curves.

be recognized which probably corresponds to the intermediate member of the titanomagnetite solid solution. In the other cases, two phases could be distinguished in the heating curves, one characterized by a strong reduction of magnetization at ∼300 °C (Curie point?) and another one corresponding to a phase with a composition close to that of magnetite (Figure 6b). These curves were irreversible, as the cooling curves only showed the presence of magnetite. This behaviour is not very different from that observed on samples belonging to the same flow during χ(T) experiments, although the values of the 'lower Curie points' are not exactly the same in both cases.

Besides χ(T) and M_S(T) curves, the behaviour of the saturation remanence (M_{RS}) as a function of temperature was also recorded. Although no Curie temperatures can be determined directly with this kind of experiment, the trend of unblocking temperatures may be used to estimate this parameter. Continuous thermal demagnetization up to 650 °C along one axis was performed with a VSTM. In all curves magnetite could be recognized.

VSTM and low-temperature experiments: As blocking and unblocking temperatures of multidomain grains are not equal, the presence of such grains can be detected by means of partial thermoremanence (PTRM) acquisition and demagnetization experiments. A PTRM acquired, for example, between 300 °C and room temperature, would not be completely demagnetized below Curie temperature (Bol'shakov & Shcherbakova 1979; Worm et al. 1988). For these kinds of experiments, a VSTM is a useful tool, as it allows the acquisition and demagnetization of TRM or PTRM, and the measuring of remanence during thermal demagnetization in a continuous way along one

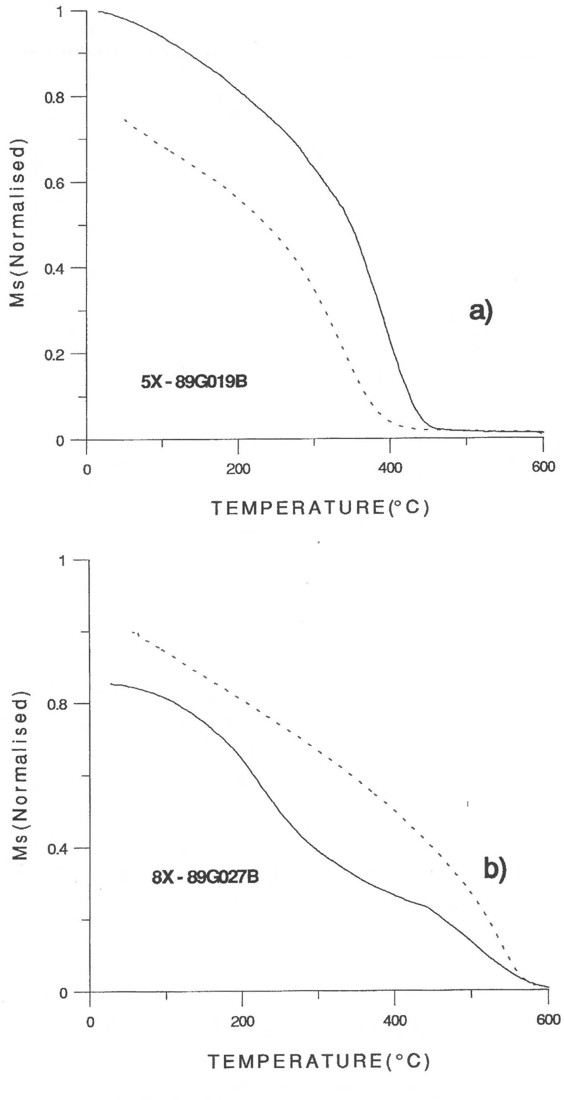

Figure 6. High-field (B = 0.7 T) induced magnetization versus temperature curves (a, b) of two samples from Tchuntchka. Continuous lines refer to heating, dashed lines to cooling curves.

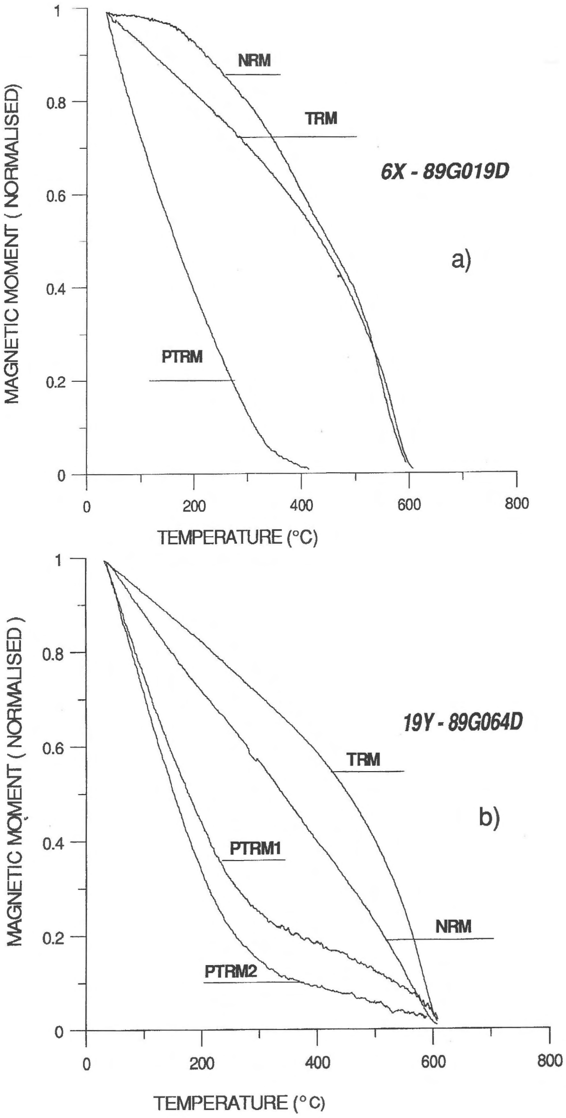

Figure 7. Continuous thermal demagnetization of natural remanent magnetization (NRM), thermoremanence (TRM) acquired in a field of 50μT, and partial thermoremanence (PTRM) acquired in a field of 50 μT, cooling down from 300 °C to room temperature (PTRM1 before, PTRM2 after treatment with liquid nitrogen). The absolute values of the magnetic moments at room temperature are: sample 6X-89G019D (a) NRM = $4.86 \cdot 10^{-7}$ Am^2, TRM = $2.78 \cdot 10^{-6}$ Am^2, PTRM = $4.09 \cdot 10^{-7}$ Am^2; sample 19Y-89G064D (b) NRM = $3.49 \cdot 10^{-7}$ Am^2, TRM = $1.57 \cdot 10^{-6}$ Am^2, PTRM1 = $2.89 \cdot 10^{-7}$ Am^2, PTRM2 = $2.17 \cdot 10^{-7}$ Am^2.

axis. The sensitivity of the magnetometer is $5 * 10^{-10}$ Am^2, the maximum field H which can be applied is $4 * 10^3$ Am^{-1} and the residual field after turning off the magnet is < 0.1 Am^{-1}. For our experiments, small cylindrical specimens were cut. Their magnetization was measured and fields were applied along their axis of maximum magnetization. For these experiments we chose nine representative samples which show reversible behaviour during continuous χ(T) measurements with a Curie point near that of magnetite. First their natural remanent magnetization (NRM) was demagnetized (Figure 7a, curve ‘NRM’) and then they were cooled down to room temperature in a 50 μT field, so that a TRM was acquired. Afterwards, this TRM was demagnetized (curve ‘TRM’). Subsequently, a PTRM was given to each of the samples between 300 and 25 °C, which was subsequently thermally demagne-

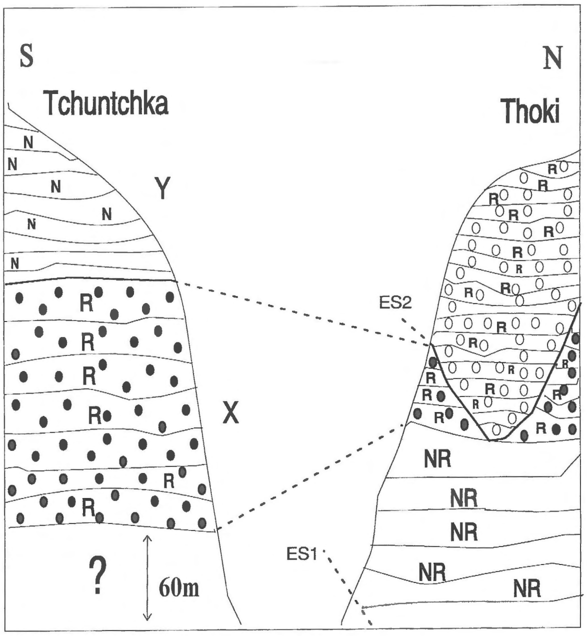

Figure 8. Possible magnetostratigraphic correlation between the Tchuntchka (this study) and Thoki (Camps et al. 1996) sites. Distance between sites is ~800 m. N: normal, R: reversed, NR: intermediate polarity; ES1: first, ES2: second erosion surface; ○: reversed polarity zone above ES2; ●: reversed polarity zone below ES2.

tized (curve 'PTRM'). The amount of remanent magnetization still present after heating above the highest PTRM acquisition temperature can provide information about the fraction of multidomain grains in a sample (Shcherbakova et al. 1996). It should nevertheless be borne in mind that the previous heatings may have changed the grain structure of the ferromagnetic minerals contained in the sample. In a final step, the same PTRM was given again to the samples where a significant multidomain-grain fraction seemed to be present, and they were then placed into liquid nitrogen and left in a field-free space for approximately two hours. Subsequently, they were again thermally demagnetized (Figure 7b, curve 'PTRM2'). The low-temperature demagnetization (LTD) should destroy the remanence carried by multidomain grains of magnetite (Markov et al. 1983). At the isotropic point of magnetite (T ~130 K), the magnetocristalline anisotropy constant K_1 changes its sign and the easy magnetization axis its orientation (Bickford et al. 1957). This transition is accompanied by abrupt changes in coercivity, remanence and susceptibility (Aragon 1985, 1992). The magnetic memory (the fraction of TRM surviving after LTD) is much more resistant to AF demagnetization than the original TRM before LTD (Heider et al. 1992). This hypothesis is supported by McClelland & Shcherbakov (1995), who indicate that LTD could destroy the component of multidomain remanence.

In all cases, demagnetization of NRM and TRM showed a similar behaviour. In four of nine curves, pTRM unblocking temperatures were quite similar to their blocking temperatures (Figure 7a), so that the pTRM was completely demagnetized at 380 °C. This result probably indicates the presence of grains with a pseudo-single-domain structure. In five other cases, samples had to be heated to 600 °C to completely demagnetize the PTRM. At 300 °C, still 20 to 30% of the PTRM remained undestroyed (Figure 7b). In those cases, a significant fraction of grains seems to have a multidomain structure. Nevertheless, low-temperature treatment reduces the PTRM only partly (Figure 7b). In those cases where no significant reduction was observed, the remanence is probably not carried by magnetite but by titanomagnetite with a higher titanium content. In such oxides, no Verwey transition is observed, and no low-temperature demagnetization of multidomain grains will occur. Indeed, small deviations from stoichiometry in magnetite have an important effect on the Verwey transition and the magnetic memory is controlled in part by the internal stresses developed during oxidation (Özdemir et al. 1993).

Results and conclusions

In 25 of the 26 studied flows of the Tchuntchka site, stable palaeomagnetic directions could be determined. Only in flow 21Y an anomalous direction was found. With this one exception, all other flows from section Y yielded normal, and all flows from section X reversed polarity directions (Figure 3, Table 1). We consider these directions to be stable and of primary origin because the remanence is carried in most cases by magnetite which could have been created by deuteric oxidation while the flows were still hot. In addition, VSTM experiments show that in many samples almost no multidomain grains can be found, and in others only a small fraction of the remanence is carried by such grains.

As detailed geological studies and geochronological data are scarce, a stratigraphic correlation of lava flows from different sites in the Akhalkalaki volcanic region is very difficult. This difficulty is increased by the presence of a great number of faults. On the other hand, no evidence of faults was found between the

Tchuntchka section and the Thoki section studied by Camps et al. (1996), the latter being located at a distance of only 800 m of the former. A petrographic study of thin sections has shown, that while the uppermost flows of the Thoki section contain non-altered olivines, those from section X in Tchuntchka show clear signs of alteration, which is probably due to hydrothermalism. Thus, these two groups of flows probably correspond to different volcanic emissions. Nevertheless, some lower flows of the Thoki section are petrologically similar to the flows from section X in Tchuntchka, and also show the same palaeomagnetic directions and polarities. As these lower Thoki flows and those in section X at Tchuntchka belong to the same volcanic episode, and Ar-Ar dating of three flows with reversed polarities located in the lower sequence of the Thoki section yields ages of 3.7 to 3.8 Ma (Camps et al. 1996), this age can be tentatively assigned to the reversed section X at Tchuntchka. This is schematically shown in Figure 8. In this case, the remanent magnetization of the Tchuntchka section would have been acquired during the Gilbert reversed polarity chron.

The mean direction for all studied flows yields values of $D = 356.8\,°$, $I = 55.3\,°$, $k = 159$, $N = 25$, and $\alpha_{95} = 2.3\,°$. As the expected Pliocene direction for south Georgia is $D = 4.9\,°$, $I = 59.8\,°$ (Sologachvili 1986), no major tectonic rotations seem to have occurred in this region from the late Pliocene to the present.

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