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Magnetic properties of some carbonatites from Tanzania, East Africa

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SUMMARY

The magnetization of fresh natrocarbonatite lavas from Oldoinyo Lengai in Tanzania is dominated by small amounts of single- or pseudo-single-domain grains of a spinel in the solid solution series jacobsite ($MnFe_2O_4$)–magnetite (Fe_3O_4). Although this phase may acquire TRM before carbonatite lava crust has ceased being mobile, the Oldoinyo Lengai samples are good palaeomagnetic recorders of the field they cooled in. In comparison, samples from older carbonatites in Tanzania have very different magnetic mineralogies and unstable behaviour of remanent magnetization. There are two possible explanations for the contrast in magnetic properties. Recrystallization of fresh carbonatites during weathering may destroy the original remanence and lead to the production of various authigenic magnetic minerals. Alternatively, the different magnetic mineralogies may derive from distinct types of carbonatite magmas. Some older calcitic carbonatites may have associated magnetic anomalies that could be useful in prospecting for economically valuable minerals often associated with carbonatites.

Key words: carbonatite lava, magnetization, palaeomagnetism, Tanzania, TRM.

INTRODUCTION

Carbonatites are defined as dominately calcitic or dolomitic igneous rocks. Although not nearly as common as silicate igneous rocks, carbonatites representing ages from Precambrian to recent have been identified in many parts of the world and occur most commonly in Neogene volcanos of the African rift valleys (e.g. Von Knorring & Du Bois 1961; Dawson 1962; Le Bas & Dixon 1965; King & Sutherland 1966; Le Bas 1977; Mariano & Roeder 1983). While most carbonatites are calcitic, those from Oldoinyo Lengai in northern Tanzania (Fig. 1), the only active carbonatite volcano in the world, contain a high-alkali carbonate component (Dawson 1962).

The magnetic properties of carbonatites are of interest for economic and palaeomagnetic reasons. The economic interest in carbonatites results from the fact that pyrochlore, columbite and other valuable minerals are common accessory minerals. Magnetite is also a common accessory mineral and therefore some carbonatites may be associated with magnetic anomalies large enough for prospecting purposes. Because of their igneous origin and widespread temporal and spatial occurrences, carbonatites may also be useful rocks for palaeomagnetic investigations.

In this paper we report on the palaeomagnetic and rock magnetic properties of some carbonatites from Tanzania, East Africa. Our main goal in this study was to determine the type, quantity, and magnetic behaviour of magnetic minerals in alkali rich carbonatite (natrocarbonatite) from Oldoinyo Lengai and in some calcitic carbonatites from southern Tanzania.

Magnetic measurements are expressed in SI units. In-keeping with commonly accepted practice (Shive 1986), the magnetic fields referred to in this paper are magnetic inductions. An induction of 1.0 T corresponds to a cgs magnetic field of 10^4 Oe. A volume magnetization of 1.0 A m^{-1} corresponds to a cgs volume magnetization of 10^{-3} emu cc^{-1}. A magnetization of 1.0 A m^2 kg^{-1} corresponds to a cgs magnetization of 1.0 emu g^{-1}, and an SI susceptibility of 1.0 is equivalent to a cgs susceptibility of $1/4\pi$.

PROCEDURE

Carbonatite samples were collected from three localities (Fig. 1) in Tanzania during 1987 and 1988; (1) Oldoinyo Lengai, (2) the Mbeya carbonatite, a Cretaceous intrusion at Panda Hill in southern Tanzania (Fawley & James 1955; Fick & Van Der Heyde 1959), and (3) the Nachendezwaya complex, an intrusive body of unknown age, also located in southern Tanzania (Horne 1959). In November 1987 and June 1988 oriented block samples were collected by Nyblade from fresh flows on the crater floor of Oldoinyo Lengai. The November 1987 samples (#1, 2, 3 and #4, which was not

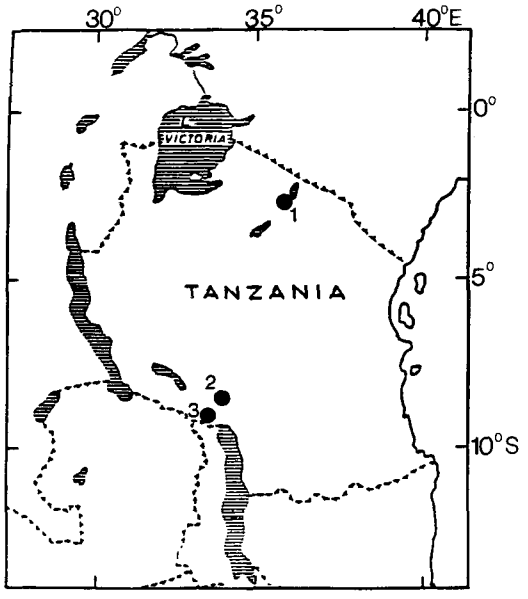

Figure 1. Index map showing the three carbonatites studied in this paper. (1) Oldoinyo Lengai (2°45'S, 36°00'E); (2) Mbeya Carbonatite (Panda Hills) (9°00'S, 33°14'E); (3) Nachendezwaya (9°29'S, 33°11'E).

oriented), collected along the SE side of the crater floor, were probably several days old. The June 1988 samples (#8803, 8804) were extruded about 12 hr prior to sampling from a vent in the northern part of the crater. The crater floor was roughly circular with an approximate diameter of 250 m.

Unoriented block samples from the Mbeya (Panda) and Nachendezwaya (Nach) carbonatites were collected by M. M. Mbasha from the Tanzania Geological Survey. The Mbeya carbonatite consists of a central carbonatite plug about 600 m in diameter surrounded and intersected by numerous dolomitic and calcitic dikes. Our samples come from the carbonatite plug. The Nachendezwaya carbonatite, a 900 m long by 500 m wide body, is centrally located in a larger nepheline syenite complex which intrudes the surrounding Precambrian gneisses.

Standard palaeomagnetic cores were cut from the block samples in the laboratory. Remanence measurements were made with a digitized (Isbell & Shive 1989) Schonstedt SSM-1 spinner magnetometer before and after stepwise alternating field demagnetization in peak fields up to 80 mT. Susceptibilities were measured using a Bison MS-3 susceptibility bridge. Partial and saturation isothermal remanent magnetizations (IRM's) were applied with an electromagnet capable of generating magnetic fields as high as 1.0 T.

Thermomagnetic behaviour of 200 mg chip samples was studied on a Curie balance similar to that described by Doell & Cox (1967). This balance is capable of resolving a magnetization of about 2.5×10^{-2} A m^2 kg^{-1}. Samples were cycled to and from 600 °C at heating and cooling rates of about 10 °C per minute in magnetic fields between 0.3 and 0.5 T in a vacuum of 2.0×10^{-2} Pa or better.

We also performed supporting chemical and petrologic analysis of some samples. Major and minor element analyses were made for samples 8804, 2 and Panda. Optical petrography was done for polished thin sections from samples 8803, 8804, 2, 4, Nach and Panda. Electron probe microanalysis was performed on some opaque phases from these sections. Finally, X-ray diffraction, bulk chemical analysis and thermomagnetic analysis were performed on concentrated samples prepared by dissolving 8804 in water to remove the soluble matrix and further separating the magnetic fraction with a hand magnet.

RESULTS

Chemical and petrologic analyses

The major and minor element chemistry for samples 8804, 2 and Panda are shown in Table 1. The bulk chemistry of the 1987 and 1988 flows (2, 8804) is quite similar to that for the 1960 alkali carbonatite laval from Oldoinyo Lengai reported by Dawson, Garson & Roberts (1987). These samples have very high contents of Na_2O (about 33 per cent) and K_2O (about 8.5 per cent), but their CaO content (about 16 per cent) is quite low relative to values commonly reported for carbonatites (e.g., the Panda sample). Our samples total to slightly less than 80 per cent. This is because we did not analyse for sulphur, carbon, and chlorine, substances that constitute significant portions of fresh alkali carbonatites (Dawson *et al.* 1987).

Minor element analysis (Table 1) shows that the Panda sample is significantly depleted in Ba, Zn, U, and Sr, and enriched in Zr and V with respect to the fresh lavas from Oldoinyo Lengai. As the emphasis of this study is on the magnetic properties, it is important to note that none of the samples contains significant amounts of magnetic cations. The fresh lavas contain about 0.03 per cent Fe_2O_3 and MnO, with slightly greater amounts in the Panda sample. None of the samples contains more than about 10 ppm Ni and Cr. Also, Ti was at or below the limits of detectability, which means that titanomagnetite with compositions very different from magnetite are not likely to be present in magnetically important amounts.

Table 1. Analyses of three carbonatite samples.

	8804	2	Panda
Oxides (wt %)			
SiO_2	.13	.08	.38
TiO_2	--	--	--
Al_2O_3	--	--	.19
Fe_2O_3	.27	.30	.82
MnO	.35	.38	.50
MgO	.28	.37	1.58
CaO	16.18	16.13	57.39
Na_2O	33.20	33.45	.06
K_2O	8.42	8.94	.01
P_2O_5	1.04	1.08	2.86
LOI	19.24	17.81	40.06
TOTAL	79.11	78.54	103.85
Trace Elements (ppm)			
Ba	9206	9339	863
Cr	9	1	8
Mn	3631	2898	4477
Ni	12	--	8
Zn	40	57	18
V	102	131	--
Zr	--	--	46
Sc	--	--	2
Sr	13523	14214	4899
Y	10	6	82
Cu	15	30	8

Petrographic analysis showed that the Oldoinyo Lengai samples are vesicular with fine-grained trachytic groundmasses. Samples 2 and 4 appear to have experienced some flattening as indicated by the shape of the vesicles. Lath-like microphenocrysts of nyerereite (identified by qualitative microprobe analysis) dominate all samples. The groundmass consists of nyerereite, fluorite, gregoryite, apatite, pirssonite (?) and rare opaque minerals. Opaques make up less than 1 per cent of the samples. Microprobe analysis shows that these are dominantly alabandite, $(Mn_{0.80}Fe_{0.18})S$, with subordinate amounts of Mn-rich spinel $(Mn_{0.54}Fe_{2.13}Mg_{0.28}Zn_{0.01}Ti_{0.02})O_4$. The presence of spinel compositions was confirmed by X-ray diffraction of concentrated samples.

The Mbeya sample (Panda) is composed primarily of coarse-grained low-magnesium calcite with apatites and rare subhedral grains of columbite (identified by qualitative microprobe analysis). Columbite is the only opaque phase; the lack of any other opaque is consistent with the low magnetic susceptibility observed for this sample. We found no disseminated magnetite or pyrrhotite in our sample; both minerals were reported to occur throughout this carbonatite by Fick & Van Der Heyde (1959). The Nachendezwaya sample consists of coarse-grained calcite with apatite and rare oxides. This sample was not studied in detail.

Palaeomagnetic analyses

We performed standard palaeomagnetic analysis on cores from the five samples from Oldoinyo Lengai that were oriented (8803, 8804, 1, 2, 3), including stepwise alternating field demagnetization in peak fields between 2.5 and 80 mT. All samples provided at least two cores; seven were drilled from 8804. The mean NRM intensities of these samples ranged from 1.6×10^{-1} to 12.6×10^{-1} A m^{-1}, with an overall mean of 5.76×10^{-1} A m^{-1}. Remanence directions changed negligibly (usually less than 1°) during demagnetization to 40 mT.

Table 2 shows the palaeomagnetic data for the five oriented samples at the 30 mT demagnetization level. The samples show generally stable and well-clustered directions, considering that they were collected as hand samples and redrilled in the laboratory. The palaeoinclination is identical to the present field inclination at Oldoinyo Lengai ($I = -30°$), but the palaeodeclination is almost 10° east of the present field declination ($D = 359°$).

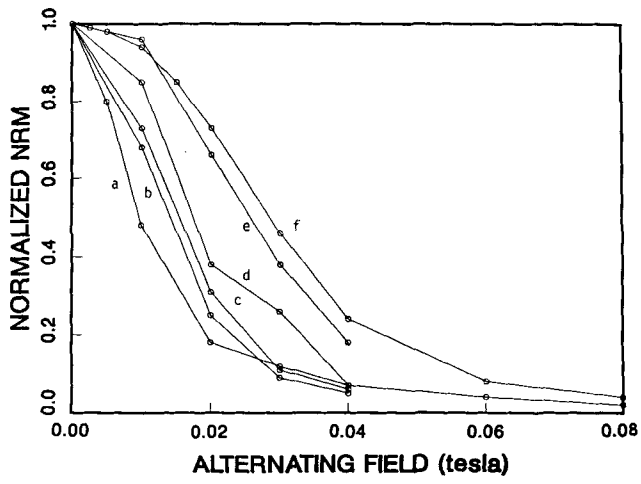

Figure 2. Intensity of remanence versus peak alternating field strength. (a) Panda; (b) 3; (c) 2; (d) 1; (e) 8803; (f) 8804.

The palaeodirection and the present field direction are about 8.5 great circle degrees apart, which is slightly greater than the α_{95} value of 6.21°. The difference is possibly due to a consistent marking error during redrilling in the lab. Alternatively, it may be due to rotations of portions of the lava crust at temperatures below the Curie temperature of the magnetic minerals. In this connection we note that Krafft & Keller (1989) made thermocouple measurements of lava temperatures in moving flows during the June 1988 eruption, and found them to range from 491° to 519 °C. Portions of the solidified crust could have been considerably cooler than this while still mobile.

Three cores were drilled from both the Nach and Panda samples. The Nach sample had an average NRM intensity of 3.36×10^{-4} A m^{-1}. The average NRM intensity of the Panda sample was 8.35×10^{-1} A m^{-1}, but values for individual cores varied by an order of magnitude or more. This amount of variation was unusual; in other samples the variations were seldom greater than 20 per cent. The Panda and Nach samples were demagnetized more easily than the Oldoinyo Lengai samples (Fig. 2). They showed little internal consistency, and their directions shifted erratically during demagnetization.

Rock magnetic analyses

Table 3 shows the magnetic susceptibility, NRM intensity and Konigsberger ratio for the seven samples. Mean sample

Table 2. Palaeomagnetic data for carbonatites.

Sample	N	D	I	K	α_{95}
8803	2	1.52	-24.03	70.4	30.22
8804	7	7.75	-29.67	881.6	2.03
1	2	7.37	-32.78	669.9	9.66
2	3	11.06	-33.18	949.9	4.00
3	2	17.22	-30.15	430.5	12.07
Total	5	8.89	-30.05	170.0	5.88

N, number of independent measurements included in the calculation of the mean; D, mean declination; I, mean inclination; K, precision parameter of a Fisherian distribution; α_{95}, radius of 95% confidence cone about the mean direction.

Table 3. Susceptibility, NRM intensity and Konigsberger ratio for carbonatite.

Sample	k	NRM	Q	N
8803	3.10×10^{-3}	3.72×10^{-1}	4.51	2
8804	2.40×10^{-3}	1.60×10^{-1}	2.55	7
1	4.50×10^{-3}	12.60×10^{-1}	9.31	2
2	4.90×10^{-3}	4.67×10^{-1}	3.62	3
3	4.50×10^{-3}	6.21×10^{-1}	5.22	2
4	5.20×10^{-3}	3.59×10^{-1}	2.65	1
Nach	a	3.36×10^{-4}	--	3
Panda	14.7×10^{-3}	1.72	4.74	1
	a	7.25×10^{-1}	--	1
	a	6.15×10^{-2}	--	1

k, susceptibility in SI units; NRM, natural remanent magnetization in A/m; Q, Konigsberger ratio = NRM/kH_e where $H_e = 33 \times 10^3$ nT; N = number of individual cores; a, susceptibility is less than 2.3×10^{-4} SI.

values are shown for all samples except Panda. For this sample the values for individual cores are given because of the extreme variability noted above. Table 3 indicates that susceptibilities of fresh carbonatite lavas are generally close to 4×10^{-3} SI, while older carbonatites show much more variation.

The susceptibility value allows us to place an approximate lower limit on the amount of magnetic material present, using the argument that the magnetic phase in pure form is not likely to have a susceptibility greater than that of magnetite, which is about 2.5 SI (Stacey & Banerjee 1974). This suggests that the volume per cent of magnetic material should be greater than 0.15. A more accurate estimation of the amount of magnetic material present in these samples may be made from the thermomagnetic analyses below.

Most of our thermomagnetic analyses were preformed on the samples from Oldoinyo Lengai. Fig. 3 shows runs for 8803, 8804, 2, 4, the concentrate from 8804, and the most strongly magnetic Panda sample. The four Oldoinyo Lengai samples (Fig. 3a–d) show the following similar characteristics: (a) saturation magnetization at room temperature between about 0.2 and $0.3\,A\,m^2\,kg^{-1}$, (b) a low-temperature phase that disappears upon heating, and (c) a dominant magnetic phase with reversible behaviour with a Curie temperature between 400° and 500 °C.

We are uncertain about the identification of the low-temperature phase. We suspect that this is an iron sulphide. Sulphides were common among the opaque minerals of 8804. None of these phases persists above about 300 °C, which is close to the 320 °C Curie temperature of pyrrhotite. The irreversible behaviour of this phase reminds us of the thermomagnetic behaviour of pyrrhotite in vacuum (e.g. Williams *et al.* 1985–86). Perhaps this phase is the alabandite detected by the microprobe.

The dominant high-temperature phase is probably a manganous spinel, a member of the solid solution series between jacobsite (Fe_2MnO_4) and magnetite (Fe_3O_4). This is consistent with the microprobe analyses of an Fe–Mn spinel in 8804 and subsequent XRD confirmation of spinel structure in the concentrate from 8804. Furthermore, bulk chemical analysis of that concentrate shows that Fe_2O_3 (9.16 wt per cent) and MnO (9.93 wt per cent) are very strongly enriched compared to the parent sample (Table 1). Pure jacobsite has a Curie temperature of 300 °C (Kneller 1962). The microprobe analysis indicated a composition about halfway between jacobsite and magnetite. Assuming that Curie temperature varies in a roughly linear manner with composition, which is typical for spinels, the Curie temperature of that phase should be about 450 °C, which is in good agreement with our observations.

The room-temperature saturation magnetization of jacobsite is $4.3 \times 10^5\,A\,m^{-1}$ (Kneller 1962). The saturation magnetization of a Mn-spinel halfway between magnetite and jacobsite should be about $4.7 \times 10^5\,A\,m^{-1}$. Our samples would need about 0.30 wt per cent Mn-spinel to produce observed values of room-temperature saturation magnetization of about $0.25\,A\,m^2\,kg^{-1}$. This is consistent with the lower limit of 0.15 (volume per cent) magnetic material suggested by the susceptibility values.

The Curie run for the 8804 concentrate (Fig. 3e) does not show the low-temperature phase. Perhaps the low-temperature phase was dissolved during the concentration process, or is not as effectively concentrated with a hand magnet as the spinel. The Curie temperature of the main phase (500 °C) is the same as that in the unconcentrated sample (Fig. 3b), but much intensity is lost during the run. We cannot explain this behaviour.

The Panda sample (Fig. 3f) did not yield reliable low-temperature data, but the portion of the curve above 100 °C shows clearly that magnetite is present on cooling. The heating curve is more difficult to interpret. The magnetite may be created during the run, perhaps by chemical alteration of pyrrhotite (or alabandite?). Alternately, at least some magnetite may be initially present.

Figure 4 shows the results of partial IRM acquisition for five samples, and Fig. 5 shows the alternating field demagnetization of saturation IRM for those same five samples. IRM is more than 80 per cent saturated at 0.1 T for all samples except Nach, indicating that the dominant magnetic contribution probably resides in the spinel phase in these samples. Nach is distinctly more resistent to IRM acquisition than the others, and is also distinctly more resistent to the demagnetization of IRM. Although this sample was too weakly magnetic to respond to other types of magnetic analyses, these tests suggest that its magnetic mineralogy may be different from the other samples. Its behaviour in Figs 4 and 5 suggests that it contains haematite.

Comparison of Figs 2 and 4 show that the NRMs of fresh lava samples have somewhat greater resistence to demagnetization than their saturation IRMs. Assuming that the NRM is a TRM, this observation suggests that the carriers of the remanence are single-domain (Lowrie &

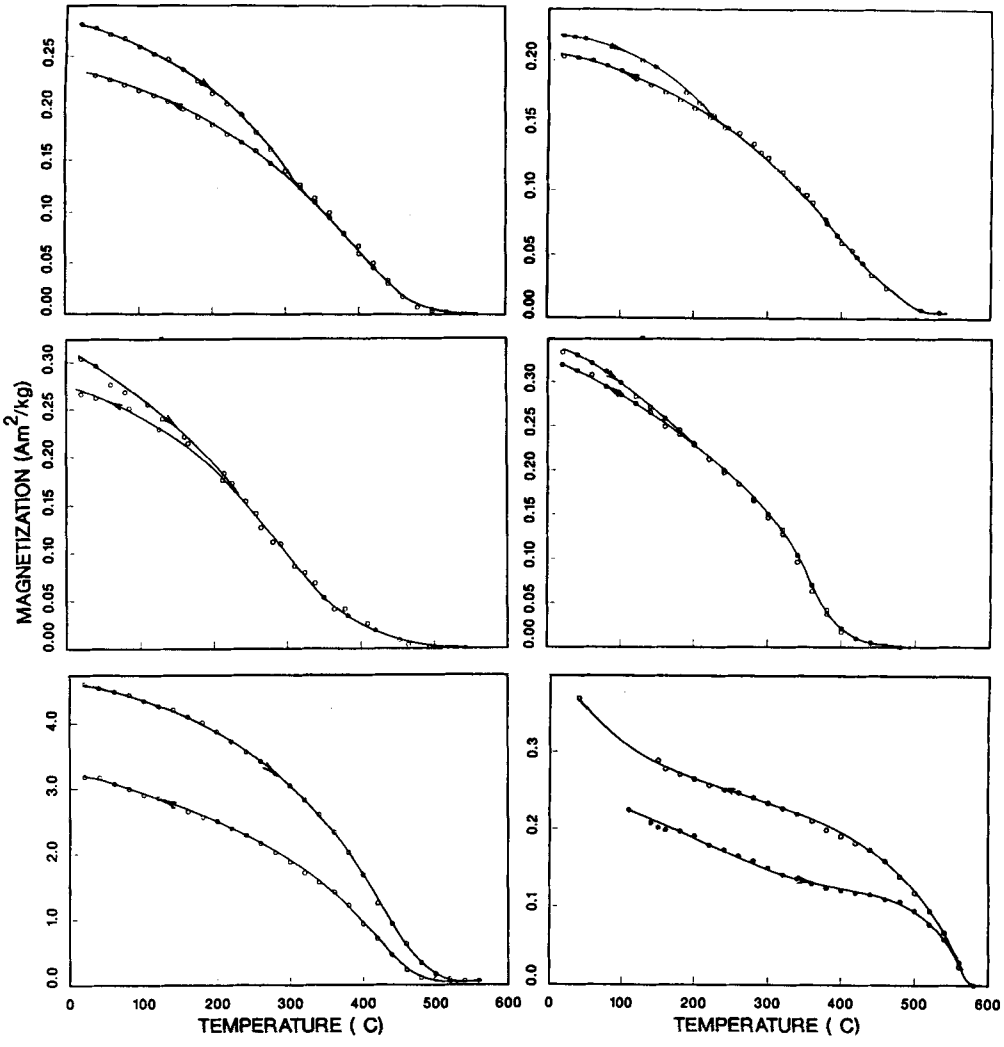

Figure 3. Saturation magnetization versus temperature for six carbonatite samples. (a) 8803; (b) 8804; (c) 2; (d) 4; (e) concentrate from 8804; (f) strongly magnetic Panda sample. All runs were made in fields between 0.3 and 0.5 T.

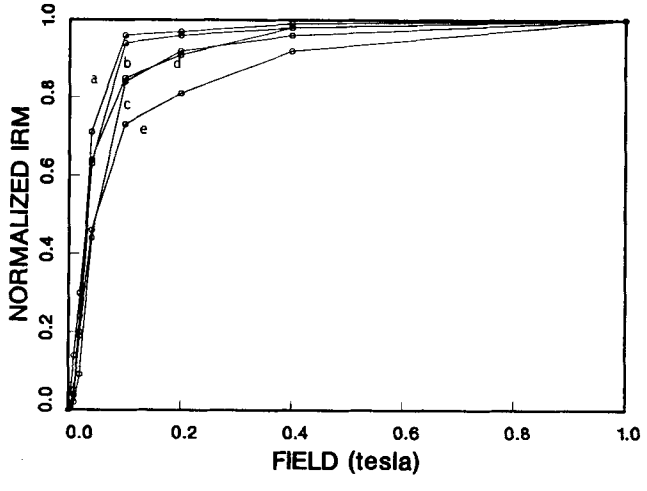

Figure 4. Acquisition of isothermal remanent magnetization as a function of applied field strength for five carbonatite samples. (a) 1; (b) 2; (c) 8804; (d) Panda; (e) Nach.

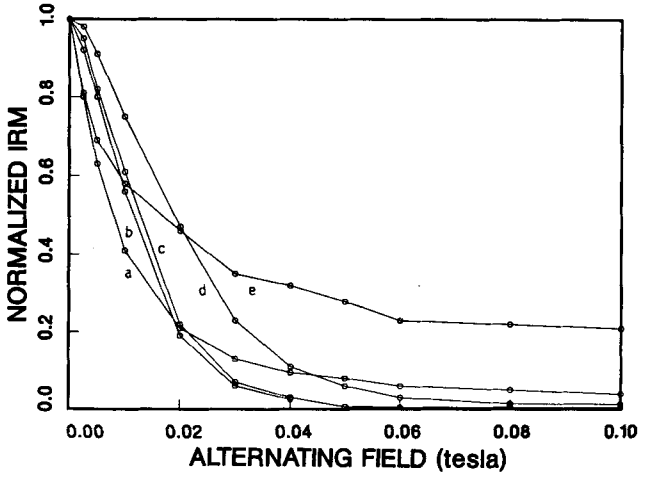

Figure 5. Alternating field demagnetization of saturation IRM for five carbonate samples. (a) Panda; (b) 2; (c) 1; (d) 8804; (e) Nach.

Fuller 1971). In contrast, the IRM and the NRM of the Panda sample are about equally stable to alternating field demagnetization.

DISCUSSION

The magnetic properties of fresh carbonatite lavas are apparently dominated by small amounts (less than 0.5 per cent by weight) of a spinel with composition midway between jacobsite ($MnFe_2O_4$) and magnetite (Fe_3O_4). This is, to our knowledge, the first time this type of spinel has been reported in nature. This phase will have a magnetization intensity about 10 per cent lower and a Curie temperature about 150 °C lower than magnetite. The latter property, together with the observation that molten carbonatite lava can be cooler than 490 °C, means that thermoremanence in carbonatites may be at least partly acquired before solid portions of the lava crust have lost their mobility. Nevertheless, the Oldoinyo Lengai lavas seem to be good palaeomagnetic recorders of the field they cooled in, given the limitations of our sampling procedure.

In comparison, the old calcitic carbonatites have very different magnetic properties; their magnetic mineralogies are different and remanent magnetizations appear to be unstable and uncorrelated even with a single block sample. The Panda sample was magnetically very inhomogeneous. Both the NRM intensity and the magnetic susceptibility varied by more than an order of magnitude over a distance of a few cm. One of the three Panda samples was quite magnetic, having a susceptibility of 2.1×10^{-2} SI and a NRM intensity of 1.72×10^{-1} A m^{-1}. Rocks this magnetic could produce significant magnetic anomalies, which could be useful in prospecting for economically valuable minerals often associated with carbonatites.

Clearly the small number of calcitic carbonatite samples analysed in this study limits the significance of our results in determining the usefulness of calcitic carbonatites for palaeomagnetic investigations. Nevertheless, in the context of recent theoretical and experimental developments on the origin of carbonatites, our results could indicate that calcitic carbonatites may generally be ill-suited for palaeomagnetic studies. Gittins & McKie (1980), Twyman & Gittins (1978) and Dawson *et al.* (1987) suggest that carbonatite lavas are originaly rich in sodium and potassium carbonates (such as nyerereite and gregoryite), and that these water soluble alkali carbonates are converted to calcite during weathering. Thus, if the original carbonate magma is alkali rich, then in the weathering process these rocks apparently lose their primary magnetic minerals while recrystallizing to form calcitic carbonatites. This chemical model, coupled with our results from this study suggest that calcitic carbonatites will not be good candidates for palaeomagnetic study because they are completely recrystallized.

However, the marked contrast in magnetic properties between the fresh and calcitic carbonatites may simply reflect distinct types of carbonate magma. Peterson (1989a,b) cites petrographic and petrogenetic evidence to show that the natrocarbonatite of Oldoinyo Lengai is unique and that calcitic carbonatite cannot form from a natrocarbonatite. Peterson's arguments would deny any generalization about the usefulness of calcitic carbonatites for palaeomagnetic investigations because the occurrence of magnetic minerals in calcitic carbonatites varies widely (Deans 1966; Heinrich 1966; Le Bas 1981). If the carbonatite has not recrystallized, then some, if not all the magnetic minerals could be primary.

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