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Magnetic Properties of Separated Mineral Phases in Unoxidized and Oxidized Icelandic Basalts

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Abstract

Following microscopic study, concentrates of Fe-Ti oxide (predominantly titaniferous magnetite), ferromagnesian silicates (pyroxene plus subsidiary olivine) and plagioclase, were separated from crushed samples of (1) unoxidized and (2) oxidized Icelandic basalt. Saturation and thermal (SRM and TRM) remanent magnetism plus alternating field (AF) demagnetization, magnetic moment (**J**) *vs* magnetic field (**H**), and saturation magnetization ($\mathbf{J}_s$) *vs* temperature (*T*) were measured for these concentrates and for chips of each original rock. The results indicate that although minor amounts of ferrimagnetic oxides of distinctive composition are present in the silicates, the experimental (and presumably natural) RM in both rocks is predominantly associated with the primary oxide grains.

Introduction

It is common experience in paleomagnetic studies that the stability of the natural remanent magnetism (NRM) of basalts with respect to alternating field (AF) demagnetization, increases with increasing high-temperature oxidation (Watkins and Haggerty, 1965; Zijderveld, 1967; Strangway, Larson, and Goldstein, 1968; Ade-Hall, 1969). The increase in stability with oxidation has been demonstrated experimentally, and has been interpreted as resulting from the sub-solidus exsolution of ilmenite lamellae following oxidation in primary ulvöspinel-rich titanomagnetite. Presumably an original homogeneous multidomain grain is partitioned into an aggregate of discrete single-domain or pseudo-single-domain magnetite particles (Strangway *et al*, 1968). This explanation is plausible for samples in intermediate oxidation state, but it presumably cannot be applied to highly oxidized samples in which the primary spinel oxides appear to be completely oxidized to an assemblage of pseudobrookite, hematite, and rutile. Whereas the hematite in such an aggregate may contribute stability to the remanent magnetism, the intensity should be drastically reduced. For this reason, Watkins and Haggerty (1965) suggested that the strong stable remanence may be associated with small magnetite particles produced by oxidation of a ferromagnesian silicate, especially the fayalite molecule in olivine. Because stable remanence has been found to be associated with small particles in the silicates in coarser-grained basic rocks (Evans and McElhinny, 1969; Hargraves and Young, 1969), it was considered worthwhile to compare the magnetic properties of individual mineral phase (Fe-Ti oxides, ferromagnesians, and feldspars) present in samples of both unoxidized and highly oxidized basalt, the commonest material in use in palaeomagnetic studies.

Technique

The samples studied consisted of two 2.5 cm diameter cores, each 2.5 cm long, of Icelandic basalt: one, grey-black, unoxidized (U16-1a) and one reddish, and apparently highly oxidized (U12-2a). Both samples are from a sequence of Pliocene flows in the Noxduradalur area of Eastern Iceland. Locations with respect to flow boundaries are unknown. Magnetic and mineralogical studies indicate that this sequence of flows has never been buried by more than 500 m of younger material. These particular samples were selected to represent the extremes of deuteric oxidation states found in basaltic

TABLE 1. Magnetic Properties of Separated Minerals and of Whole Rock Chips

	Rock Chip U 16-1a (unoxidixed)	Components			Rock Chip U 12-2a (oxidized)	Components		
		Oxide	Pyroxene + Olivine	Plagioclase		Oxide	Pyroxene + Olivine	Plagioclase
Modal Weight Percents	--	8	64	28	--	9	61	30
J_S = Saturation Magnetization*	--	6.8	0.020	0.0025	--	11.0	0.030	0.015
Susceptibility (χ) ($\times 10^{-5}$)**	--	20	1.9	0.3	--	20	1.9	0.70
Curie Point***								
Heating	--	125°	585°	585°	--	580°	625°	630-680°
Cooling	--	280°	580°	580°	--	580°	580°	580°
Increase in J_S†	--	1.25x	1.08x	1.45x	--	1.05x	2.43x	3.6x
MDF ††								
SRM	50	40	140	170	250	200	350	300
TRM	170	120	300	170	330	290	325	350
Remanent Magnetic Moment†††								
J_{SRM} ($\times 10^{-2}$)	4.9	85	0.99	0.22	6.4	250	1.65	0.30
J_{TRM} ($\times 10^{-3}$)	4.3	39	1.4	0.64	3.6	79	1.9	0.11
J_{SRM} / J_{TRM}	10.1	21.8	7.3	3.4	17.8	31.8	8.7	27.1
J_{NRM} ($\times 10^{3}$)	1.1				3.0			
J_{TRM} / J_{NRM}*†	3.9				1.1			

*of saturable ferrimagnetic component (emu/gm)

**of apparent paramagnetic component (χ) emu/gm oe (see Figs. 3a, b, c)

***(T_C) on heating and cooling in vacuum of 2×10^{-5} torr

†after thermal cycle in vacuum

††Median demagnetizing field or alternating field in oersteds needed to reduce by 50% the saturation and the thermal remanent magnetism

†††in emu/gm. Induced isothermally in a 9 kilogauss field ($=J_{SRM}$) and by heating to 650°C and cooling in air in a 1.04 g field ($=J_{TRM}$)

*†The large deviation from unity of the ratio J_{TRM}/J_{NRM} for the unoxidized sample is at least largely the result of changes induced in the sample during laboratory thermal cycling.

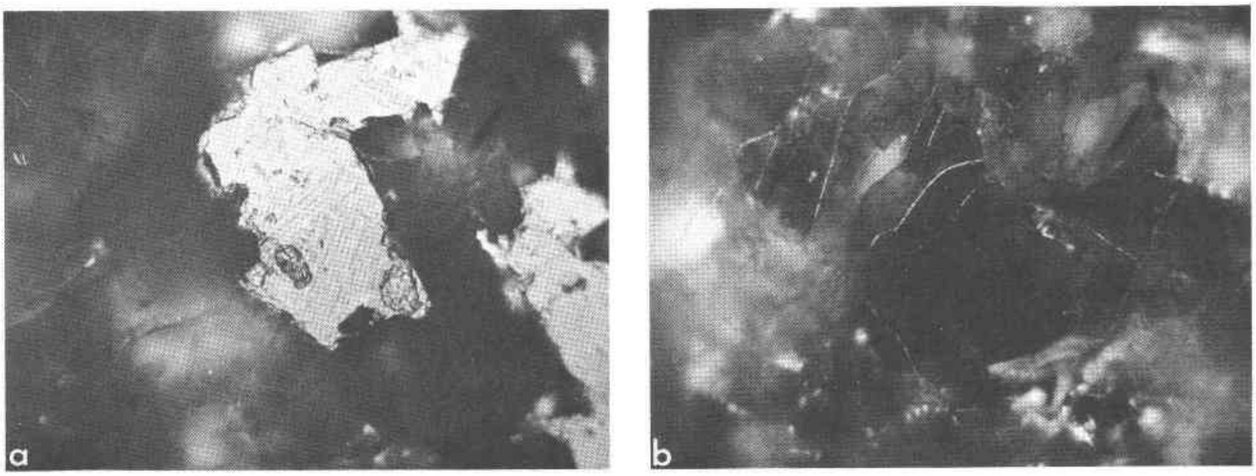

FIG. 1. Photomicrograph of highly oxidized specimen, U12-2a. (a) Deuteric oxidation class 4 grain with small rectilinear islands of magnetite (medium gray) separated by broad off-white lamellae consisting of a fine aggregate of rutile and titanohematite. (b) Partly oxidized olivine grain containing and partly surrounded by thin (white) veins of hematite. Scale: 1½ inches = 50 μ.

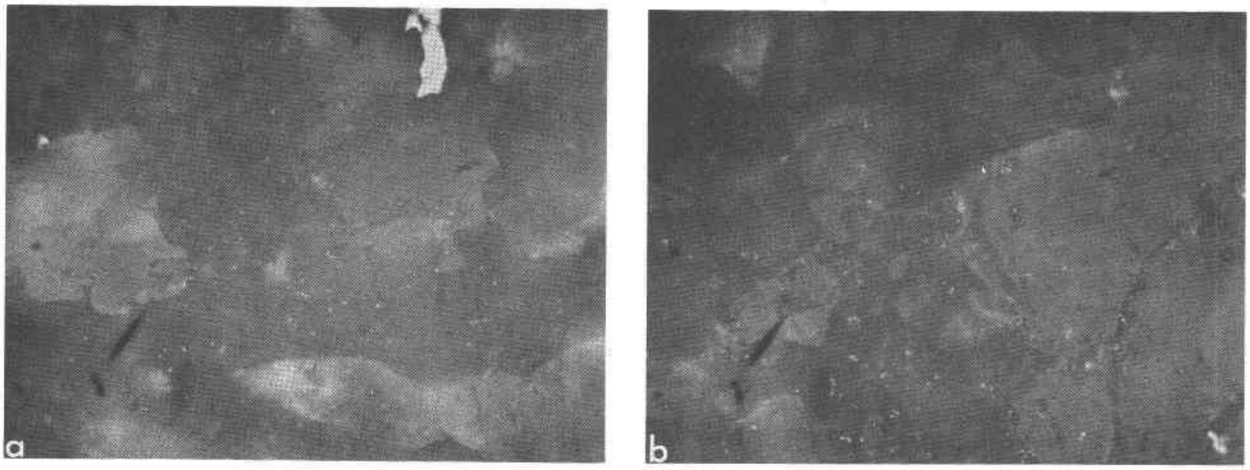

FIG. 2. Photomicrograph of unoxidized specimen, U16-1a. (a) Large primary ulvöspinel-rich titanomagnetite (light grain in upper right) and many examples of the small-sized form of magnetite (light specks). Note the strong partitioning of the small-sized magnetite into the darkest silicate phase, which is plagioclase feldspar. (b) The small-sized magnetite (white specks) is again largely restricted to the plagioclase (dark gray), but also occurs as inclusions within and along the boundaries between the pyroxene grains (medium gray). Scale same as Figure 1.

lavas, and results pertaining to them might be expected to apply equally to intermediate oxidation states. Following preparation and preliminary examination of polished thin-sections, the balance of the cores were crushed to −200 mesh, washed in water and acetone, and the −200 + 325 mesh ($<74\mu$, $>44\mu$) portion recovered. The "oxide" fraction was concentrated by separating with Clerici solution. A specific gravity (SG) of 4.0 was used for the unoxidized sample, but, to recover enough material to work with, was lowered to 3.8 for the oxidized sample. Since the silicates all have densities <3.4, these concentrates consist predominantly of the oxide fraction even though they do contain substantial silicate contaminants. The remaining powder was split using bromoform (SG 2.85), the feldspar being concentrated in the light fraction and ferromagnesian minerals in the heavy fraction.

These concentrates were further purified using a Frantz Isodynamic separator (forward tilt 20°, side tilt 15°), with current brackets of 0.5 to 0.6 amps, and 0.4 to 0.5 amps for the "pyroxene" fraction in unoxidized and oxidized samples respectively; the "feldspar" fraction used was "nonmagnetic" at 1.6 amps in both cases.

Small aliquots of these mineral concentrates were retained for high field magnetic property experiments, the remainder being cast in KBr pellets, using the technique of Evans and McElhinny (1969) for measurement of remanent magnetic (RM) properties.

The RM measurements were made on a Princeton Applied Research SM-1 spinner magnetometer utilizing standard thermal and AF demagnetization equipment and procedures (McElhinny, 1963). High field temperature-dependent properties were measured using a vertical-type magnetic balance (25° to 700°C, up to 9000 gauss) and a horizontal translation balance (−190°C to 25°C, 3500 gauss).

Results

(1) Microscopic Studies

In transmitted light, both basalts are fine grained, with microphenocrysts of plagioclase and olivine set in a groundmass of plagioclase laths, pyroxene, and opaque mineral. The unoxidized basalt also contains some interstitial, greenish, serpentinous material, which may be an alteration product of original glass. The olivine crystals in the oxidized basalt are altered, and a reddish brown stain is present within and around them, and also around the opaque grains. The results of model analyses are given in Table 1.

The reflected light study confirmed the original identification in terms of oxidation state of the specimens and added several significant details:

The high deuteric oxidation state of U12-2a was readily apparent with all original oxide grains now altered to classes 4, 5, or 6 on the Ade-Hall *et al* (1968) scale. These grains frequently contain variable but usually small amounts of magnetite surviving as small islands between the broad lamellae now consisting of fine aggregates of rutile and titanohematite (Fig. 1a). Another quite distinct oxide occurrence in this specimen is the presence of fine veins of probable hematite identified by its high reflectivity, within and along the borders of oxidized olivine grains (Fig. 1b). As noted in transmitted light, these altered olivines are frequently red stained or are surrounded by red stained silicates, indicating the presence of widely disseminated very fine hematite particles. No secondary magnetite was definitely identified within the altered olivine grains.

The complete absence of visible signs of deuteric oxidation in U16-1a was confirmed. The most interesting feature for this specimen was the occurrence of magnetite in two distinct forms. The larger, primary accessory oxide consists of anhedral to ophitic titanomagnetites in the 10μ to 100μ size range. A finer grained form, characteristically associated with plagioclase, consists of material from 0.3μ at least down to the limits of visibility at about 0.1μ (Fig. 2). The nature of such fine, apparently opaque grains cannot be determined wholly satisfactorily at the maximum magnification available of 1350. However, the apparent color and relatively low reflectivity are consistent with magnetite rather than hematite or sulfides. Again the typically equidimensional form of the grains supports their identification as magnetite rather than ilmenite, which frequently crystallizes as elongate grains. It was considered that these tiny grains might consist of fine grains of polishing agents left on the surface of the section. However, they could not be removed by careful cleaning and are not distributed randomly but are strongly associated with the plagioclase feldspar grains; these indicate that they are not extraneous. This fine magnetite probably formed by exsolution from the plagioclase. There is evidence from the Curie point measurements that the two forms of magnetite are of very different compositions, with the plagioclase-associated magnetite being nearly pure magnetite and the larger accessory oxides being ulvöspinel rich (~65% Usp).

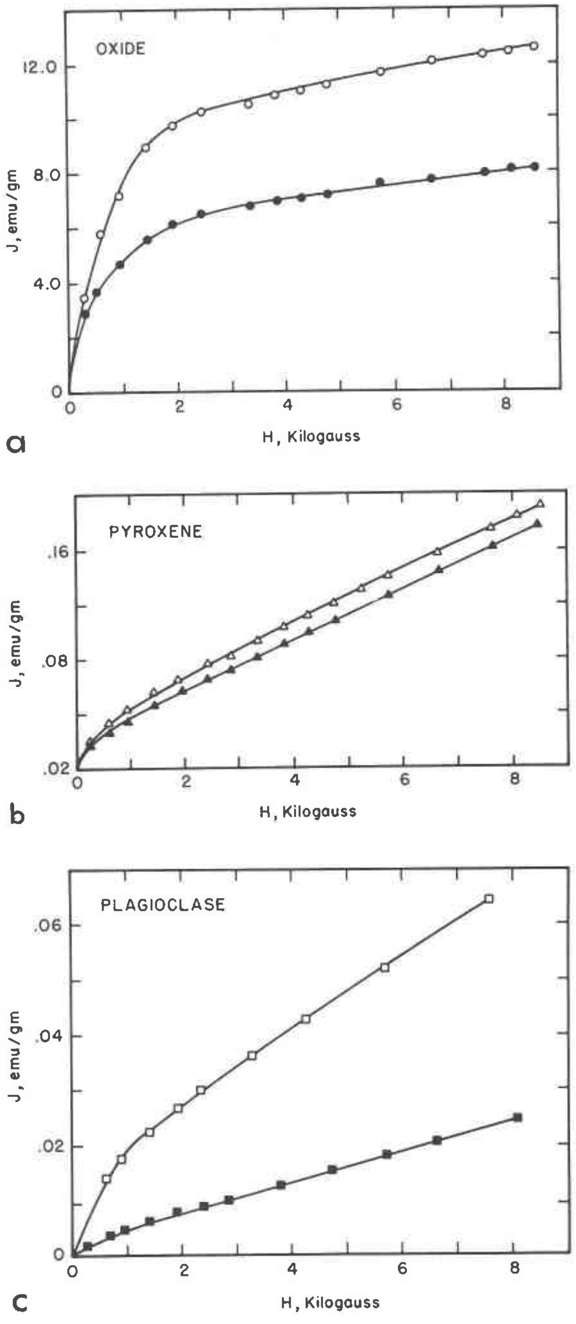

FIG. 3. Specific magnetization (J) *vs* field (H) curves for (a) oxide, (b) pyroxene, and (c) plagioclase concentrates from oxidized basalt (open symbols) and unoxidized basalt (closed symbols).

(2) Magnetic Studies

The magnetic property measurements are summarized in Table 1, and the **J**/**H** and J_s/T runs shown in Figures 3 and 4; the significant points are discussed below:

(a) Comparison of the oxide and whole rock TRM's for both oxidized and unoxidized samples, making allowance for the amount of oxide in the whole rock, indicates that the TRM and presumably the NRM is principally associated with the large-sized primary accessory oxide grains.

(b) The saturation magnetization of the oxide fraction in the oxidized sample is almost twice that for the unoxidized sample. The Curie point of 580° for the oxide in the oxidized sample indicates the presence of pure magnetite, while that in the unoxidized sample has a value of 150°C which indicates the presence of ulvöspinel-rich titanomagnetite. These facts emphasize the important contribution to the magnetic properties of the oxidized sample (U12-2a) by fine-grained near-pure magnetite remaining in the primary oxide fraction even of highly oxidized samples.

(c) As indicated by the Curie point measurements, the magnetic phase in the plagioclase and pyroxene fractions of the unoxidized basalt is pure magnetite, but the large, primary oxide phase is ~65 percent Usp. In contrast, whereas the Curie point of the oxide fraction in the oxidized basalt indicates pure magnetite, a hematite- or titanohematite-rich phase is indicated for the plagioclase and pyroxene fraction (in keeping with the red staining and the decomposition products of olivine actually observed). Hematite is present in the oxide fraction, but the surviving magnetite is sufficient to dominate its high-field magnetic properties; oxida-

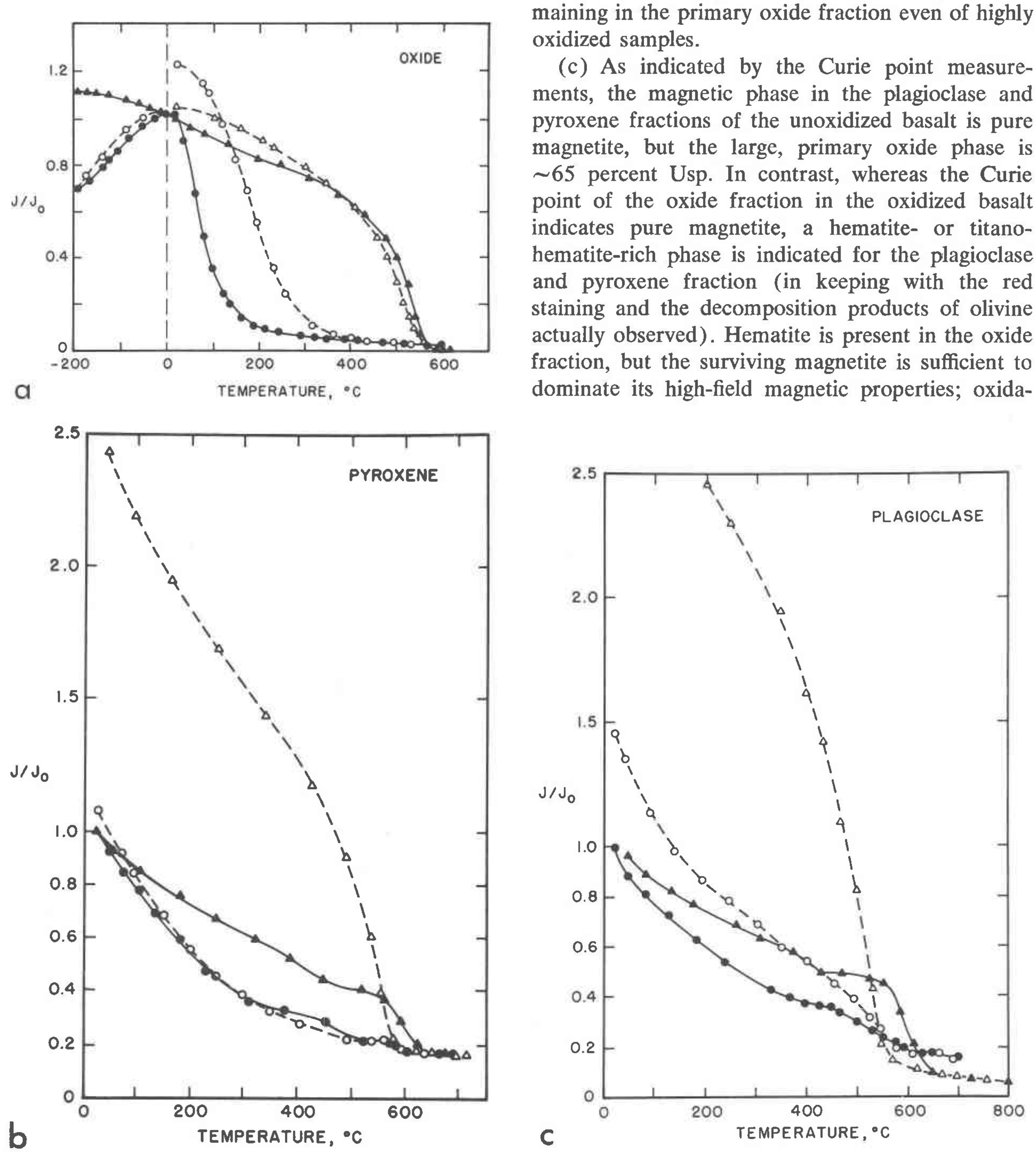

FIG. 4. Magnetization (J) *vs* temperature curves for (a) oxide, (b) pyroxene, and (c) plagioclase concentrates. Magnetizing field = 3000 gauss; initial vacuum = 2 × 10^{-5} torr. Curves normalized to value at room temperature. Circles and triangles pertain to unoxidized and oxidized samples, respectively; solid symbols for heating and open symbols for cooling cycles.

tion of any magnetite originally present in the silicates has been more complete.

(d) The vacuum employed in the J_s/T runs ($\sim 2 \times 10^{-5}$ torr) preserved the pure magnetite of the silicates in the unoxidized specimen, and the oxide fraction of the oxidized specimen, but otherwise was unable to prevent significant changes in the ferromagnetic phases. In the pyroxene and plagioclase fractions of the oxidized sample Curie points were reduced to about 580°C, and the room temperature saturation moments increased two to three times. (Note: a J_s/T run on this pyroxene *in air* showed no such increase.) These changes are consistent with the reduction of hematite to magnetite. In contrast the Curie point and saturation magnetization of the oxide phase of the unoxidized basalt both increase as the result of thermal cycling. Presumably the vacuum employed was inadequate to prevent some oxidation of the ulvöspinel component, or the original titaniferous magnetite was somewhat cation deficient (titanomaghemite), and heating caused its inversion to a less titanium-rich spinel, plus ilmenite.

(e) The Curie point of the unoxidized plagioclase indicates magnetite, in keeping with the identification of the fine grains observed microscopically. The Curie point of the oxidized plagioclase suggests hematite; yet, other than the reddish staining, no discrete opaque grains could be resolved. It is a surprise therefore that the original saturation moment of the oxidized plagioclase should be more than five times stronger than that of the unoxidized feldspar. This suggests that the oxidized plagioclase must contain a considerable amount of submicroscopic superparamagnetic hematite of which the reddish brown pigmentation is one manifestation. The white unoxidized feldspar, on the other hand, contains far fewer, but relatively larger grains of exsolved magnetite.

(f) Oxidation respectively increases and improves the overall specific remanence and microcoercivity of all major mineral phases in basalt.

Conclusions

We conclude that, for these two specimens, the natural remanence is associated with original Fe-Ti oxide grains, and not, in the case of the highly oxidized specimen, with the breakdown products of ferromagnesian silicates. Minor amounts of oxide phases are associated with the silicates and have interesting compositions, but contribute little to natural remanences. Since TRM and saturation moments per unit oxide content are similar in the two specimens, the great reduction in spinel oxide content in the highly oxidized specimen must be largely compensated by the reduction in effective grain size and increase in saturation magnetization of the surviving magnetite that result when titanium is expelled from the structure of the original titanomagnetite.

References

ADE-HALL, J. M. (1969) Opaque petrology and the stability of natural remanent magnetism in basaltic rocks. *Geophys. J. R. Astron. Soc.* **18,** 93–107.

———, M. A., KHAN, P. D. DAGLEY, AND R. L. WILSON (1968) A detailed opaque petrological and magnetic investigation of a single Tertiary lava from Skye, Scotland, I. *Geophys. J. R. Astron. Soc.* **16,** 375.

EVANS, M. E., AND M. W. MCELHINNY (1969) An investigation of the origin of stable remanence in magnetite bearing igneous rocks. *J. Geomag. Geo-Elec.* **21,** 757–773.

HARGRAVES, R. B., AND W. M. YOUNG (1969) Source of stable remanent magnetism in Lambertville diabase. *Am. J. Sci.* **267,** 1161–1177.

MCELHINNY, M. W. (1963) Theory and operating procedures: rock magnetism instruments at Princeton University. *Princeton Univ. Geol. Eng. Rep. No.* **63-1,** 24 pp.

STRANGWAY, D. W., E. E. LARSON, AND M. GOLDSTEIN (1968) A possible cause of high magnetic stability in volcanic rocks. *J. Geoph. Res.* **73,** 3787–3796.

WATKINS, N. D., AND S. E. HAGGERTY (1965) Some magnetic properties and the petrogenic significance of oxidized zones in an Icelandic olivine basalt. *Nature (London)*, **206,** 797–800.

ZIJDERVELD, J. D. A. (1967) A. C. demagnetization of rocks: analyses of results. In, *Methods in Paleomagnetism,* Ed. D. W. Collinson, K. M. Creer, and S. K. Runcorn, Elsevier, New York.

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