Origin of natural remanent magnetization of tephra from the 1979 Surtsey drill hole, Iceland

By
SHERMAN GROMME
U.S. Geological Survey
345 Middlefield Road
Menlo Park, California, U.S.A.

ABSTRACT

Magnetic properties of three tephra samples were studied in detail and one dike sample was also examined. The magnetic oxide grains in the dike have a minimum Curie temperature around 80° C. The tephra samples have somewhat higher Curie temperatures, and they have accurately recorded the geomagnetic inclination even though some were deposited below sea level. The mechanism of acquisition of the magnetic remanence in the tephra is probably oxidation of titanomagnetite to titanomaghemite, evidently in a hydrothermal environment. As oxidation and cooling proceed, the net magnetization of Surtsey volcano is expected to increase.

INTRODUCTION

The new volcano Surtsey, located southwest of Vestmannaeyjar (Westman Islands), Iceland, first broke the surface of the sea in late 1963, and eruptive activity ceased in mid-1967. The island is composed mainly of basaltic tephra but is covered by a carapace of lava on the southern and southwestern part (Thorarinsson 1967). In the summer of 1979, a cored hole was drilled on the east margin of the eastern vent and reached a depth of 181 m, which is 123 m below sea level and within a few meters of the pre-eruption sea floor. Almost all of the material penetrated by the hole is vesicular glassy basalt tuff (herein referred to as tephra); a 2-m-thick lava flow was found near the top, and a sub-vertical dike complex was encountered between 72 m and 85 m (Jakobsson & Moore 1980, 1982). Above sea level and below 150 m the tephra is fresh or only slightly altered, but there is a thick altered zone of palagonitized glass between about 80 m and 125 m. The extent of development of palagonite corresponds to a zone of elevated temperature that was measured in the hole after completion of drilling; the maximum temperature was 141° C at a depth of 105 m (Jakobsson & Moore 1982).

The objectives of this study were to estimate the content of magnetic minerals in the tephra (if any), to determine their composition and physical state, and to find out if the Surtsey tephra retained an accurate memory of the geomagnetic field.

EXPERIMENTAL RESULTS

Three core samples of basaltic tephra were analyzed. Recovery depths below ground surface and recovery temperatures are given in Table I. The samples are designated by their recovery depths. Samples 53.3 and 107.5 were well indurated, but sample 150.2 had to be partly impregnated with plastic. One oriented specimen (a core 2.5 cm in diameter) and several very small cores (300 to 400 mg) were cut from each sample. Saturation magnetization and thermomagnetic experiments were done on the small cores. Natural remanent magnetization measurements and conventional alternating-field demagnetizations were done on the oriented specimens.

Thermomagnetic curves for samples 53.3 and 107.5 are shown in Fig. 1. (Because of the plastic impregnation, no thermomagnetic curve could be obtained for sample 150.2.) Most of the iron in these tephra specimens is in paramagnetic form (in glass and silicate minerals), and in order to get

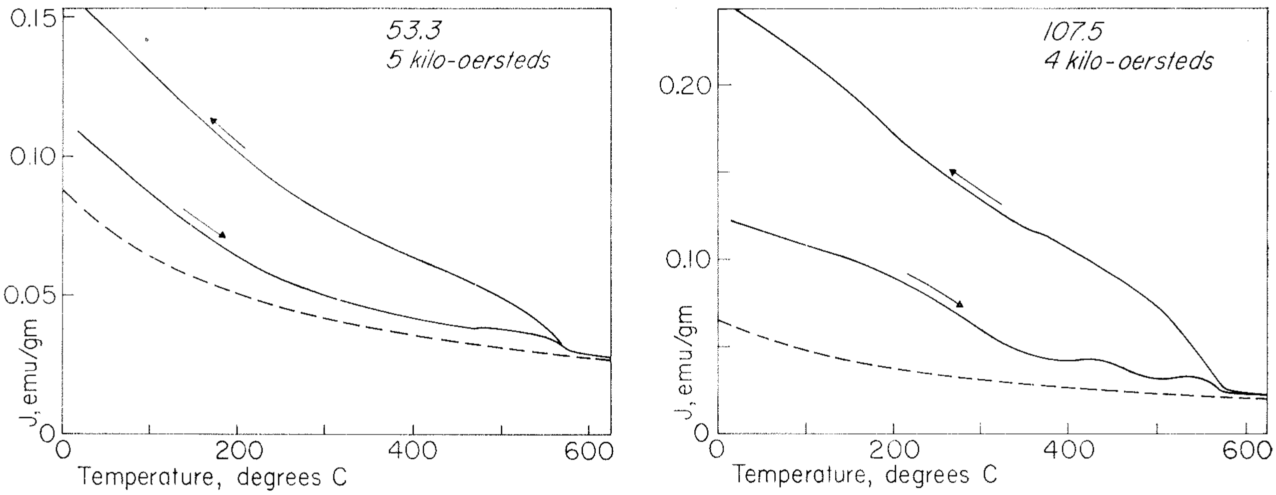

Fig. 1. Strong-field thermomagnetic curves for two tephra samples. Original recovery depths (m) and magnetizing fields are shown; J is specific magnetization. Heating and cooling curves are indicated by arrows. Experiments were done in nitrogen. Each dashed curve is the paramagnetic susceptibility, calculated using the simple Curie law and assuming that at 600°C nearly all the paramagnetism is due to iron in silicates and glass. Thus the ferrimagnetism in oxide minerals below the Curie temperature is the vertical difference between the dashed curve and the observed curve (not dashed).

an adequate signal from the small amounts of ferrimagnetic oxide present, very large inducing fields (5000 and 4000 oersteds) had to be used. The paramagnetic contributions to the thermomagnetic curves are shown in Fig. 1. These are obtained by assuming that the contribution to total magnetization of the iron in oxides at 600° C is very small and by using the simple Curie law to extrapolate the silicate paramagnetism down to room temperature. This extrapolation was confirmed by another experiment described below.

The two tephra specimens show markedly irreversible behavior. Large amounts of pure magnetite were produced during heating, commencing at about 350°—400° C. This irreversibility could arise in two ways: (1) oxidation of titanomagnetite to magnetite during heating, or (2) breakdown of cation-deficient titanomaghemite to magnetite plus other oxides during heating (Ozima and Ozima 1971). Owing to the large amounts of bound water present in the specimens, it was not possible to do the heating experiments in vacuum (which has been shown to supress oxidation effectively); instead, a nitrogen atmosphere was used. Because the tephra samples are so young and because formation of cation-deficient metastable titanomaghemite from stoichiometric titanomagnetite is evidently a process requiring long times and low temperatures (Gromme et al., 1979), oxidation during the experiment might seem to be a sufficient explanation for the irreversibility. Weight loss after heating was 3.2 percent for sample 53.3 and 7.7 percent for sample 107.5, so that oxidation could have been caused by water expelled from the palagonite. The apparent two-stage alteration in specimen 107.5, evinced by the two maxima on the heating curve (430° and 540° C), is quite unusual. The Curie temperatures of the original oxides are difficult to identify because alteration began at lower temperatures, but they are estimated as 250°±50° C for specimen 53.3 and 350°±50° C for specimen 107.5.

If we assume that these oxide minerals are stoichiometric titanomagnetite, then the corresponding mol fractions of ulvospinel in solid solution are roughly 0.45 and 0.35 for specimens 53.3 and 107.5, respectively. These values are significantly lower than the mol fraction 0.76 to 0.8 reported by Steinthórsson (1972) from a microprobe analysis of titanomagnetite in a sample of dolerite from Surtsey. Alternatively, we may assume that the original titanomagnetite in the tephra had the same composition as that in the dolerite. In this case the original Curie temperatures would have been approximately 0° C, and the fact that much higher ones are observed would be the result of natural low-temperature oxidation of titanomagnetite to titanomaghemite (Readman and O'Reilly 1972). Irving (1970) has suggested that such a process may be accelerated by moderate hydrothermal activity. If this interpretation is correct, then the extent of oxidation in specimen 53.3 is 80 percent, and in specimen 107.5 it is almost 100 percent (Gromme et al. 1979).

An attempt to resolve the question was made by examining some of the magnetic properties of a specimen of the dike rock retrieved from a depth of 74.1 m. The rock is well crystallized and contains approximately ten percent opaque minerals, but it is only moderately magnetic, having roughly three times the saturation magnetization (0.18 emu/gm) at room temperature as the average (0.054 emu/gm) of the tephra samples discussed below. The thermomagnetic curve for the dike rock is shown in Fig. 2. The starting temperature was close to that of liquid nitrogen, and the experiment was done in an argon atmosphere. Two magnetic phases are present, and the curve is similar to ones obtained from samples of Hawaiian lava-lake basalt (Gromme et al. 1969). The lower Curie temperature is approximately -140° C and represents a ferrian ilmenite. The higher Curie temperature is difficult to estimate; its minimum value is 80° C on the heating curve and 60° C on the cooling curve. This corresponds to a stoichiometric titanomagnetite containing roughly 70 mol percent of ulvospinel. Hence the unusually low Curie temperatures predicted by the chemical analyses published by Steinthórsson (1972) are partly confirmed, and it seems likely that the magnetic oxide in the tephra samples had the same or nearly the same original composition, but has subsequently been oxidized to titanomaghemite. Carmichael (1974) has reported Curie temperatures of 200° and 500° C for one specimen of Surtsey lava and a single Curie temperature of 550° C for a second, more oxidized specimen. These high Curie temperatures (500° C and above) are the result of high-temperature oxidation (Carmichael 1974, Gromme et al. 1969).

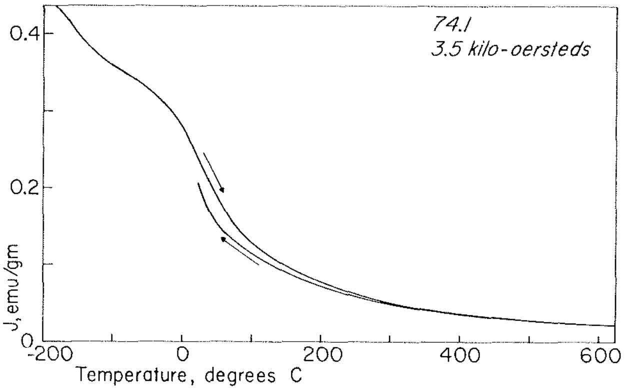

Fig. 2. Strong-field thermomagnetic curves for dike sample. Original recovery depth (m) and magnetizing field are shown; J is specific magnetization. Heating and cooling curves are indicated by arrows. Experiment was done in argon.

Strong-field isothermal magnetization data for all three tephra samples are shown in Fig. 3, representing the sum of both remanent and induced magnetizations. Magnetic saturation occurs at 3000 oersteds for sample 53.3, 4000 oersteds for sample 107.5, and 1500 oersteds for sample 150.2. Straight lines were fitted by least-squares to the collinear points in Fig. 3. The intercepts of the

TABLE I.
Magnetic and other properties

	Surtsey samples			Dredged pillow basalt
Depth, meters	53.3	107.5	150.2	
X_p, gm^{-1}	1.7×10^{-5}	1.7×10^{-5}	1.8×10^{-5}	n.d.
J_s, emu/gm	4.4×10^{-2}	9.2×10^{-2}	2.6×10^{-2}	2.7×10^{-1}
J_{rs}, emu/gm	2.5×10^{-2}	4.7×10^{-2}	1.4×10^{-2}	1.2×10^{-1}
J_{rs}/J_s	0.56	0.51	0.53	0.44
NRM, emu/gm	4.1×10^{-4}	4.1×10^{-4}	6.1×10^{-4}	3.4×10^{-3}
NRM/ J_{rs}	0.02	0.01	0.04	0.03
MDF, oersteds	600	600	530	70—285
Inclination of NRM	81.5°	76.5°	83.0°	n.d.
T_c, degress C	250±50	350±50	n.d.	150—250
T(recovery), degrees C	50	140	65	4
Palagonite thickness, mm	0.06	0.5 (approx.)	<0.01	

Explanation: X_p is paramagnetic susceptibility.
J_s is saturation magnetization at room temperature.
J_{rs} is remanence after magnetization at room temperature in 9 kilo-oersteds.
NRM is natural remanent magnetization.
MDF is median destructive field.
T_c is Curie temperature.
Data for dredged pillow basalt are averages for six L-type fragments obtained near active spreading centers (Gromme et al. 1979), except for MDF which is the range observed in very young pillow basalt obtained from the median valley of the Mid-Atlantic Ridge (Ade-Hall et al. 1973, Johnson and Atwater 1977).
The geomagnetic inclination at Surtsey calculated from the 1965 I.G.R.F. coefficients is 75.5°.

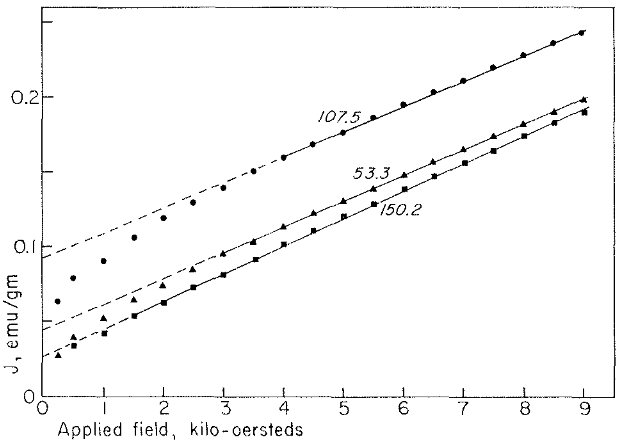

Fig. 3. Strong-field magnetization curves for three tephra samples. Recovery depths (m) of samples are shown; J is specific magnetization (remanent plus induced). The data were taken while reducing the applied field from 9000 oersteds to zero; thus they represent part of a hysteresis loop. Solid lines are least-squares fits to the points they encompass, and dashed lines are extrapolations to the zero-field ordinate.

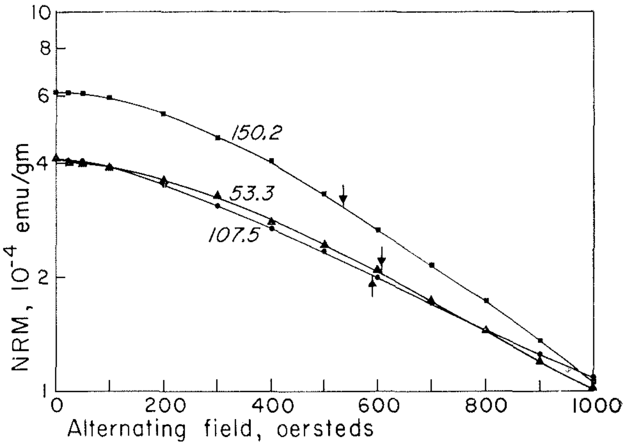

Fig. 4. Alternating-field demagnetization of natural remanent magnetization (NRM) in three tephra samples. Original recovery depths (m) are shown, and median destructive field (MDF) values are indicated by short arrows. Note the logarithmic scale used for NRM.

extrapolated least-squares lines on the magnetization axis are the values of saturation magnetization (J_s) of the ferrimagnetic oxide minerals in the samples (Table 1). The slope of the straight line at fields above saturation is the paramagnetic susceptibility of the iron-bearing silicate minerals and glass. The values of paramagnetic susceptibility (X_p) are essentially the same for all three samples (Table 1), and they are identical to the values obtained by extrapolating the Curie function from 600° C down to room temperature on the thermomagnetic diagram.

After the specimens were magnetized in 9000 oersteds, their saturation remanences were measured, and the values are given as J_{rs} in Table I. The ratio J_{rs}/J_s is a good indicator of the magnetic domain state of the oxides. For titanomagnetite, ratios below about 0.1 indicate multi-domain grains. For single-domain grains whose coercivities are controlled by uniaxial magnetostatic anisotropy (i.e., shape anisotropy of a randomly oriented assemblage of elongate grains), the ideal ratio is 0.50. For single-domain grains of magnetite or titanomagnetite whose coercivities are controlled by magnetocrystalline anisotropy (i.e., magnetization along [111] easy directions of a randomly oriented assemblage of equant grains), the ideal ratio is 0.87. Values between 0.1 and 0.5 represent either mixtures or pseudosingle-domain grains. For all three of the Surtsey samples the ratios are between 0.51 and 0.56. Such values are unusually high for basalts (except for some submarine pillows) and demonstrate that all of the titanomagnetite in the samples is within the single-domain size range. Depending on exact composition, this size range in titanomagnetite is certainly less than 1.0 micron and probably is between 0.6 and 0.1 microns (Dunlop 1981). Hence the oxide particle are probably virtually unobservable using a visible-light microscope.

The natural remanent magnetization (NRM) values and alternating field demagnetization curves of the oriented specimens are shown in Fig. 4. The specimens are magnetically hard, unusually so for basaltic rocks; the median destructive field (MDF) values are approximately 500 to 600 oersteds, and 10 percent of the NRM survives demagnetization at 1000 oersteds. These high values are in keeping with the observation that all the magnetic grains are single-domain. The specific intensities of NRM range from approximately $4x10^{-4}$ to $6x10^{-4}$ emu/gm. Considering the nature and mode of emplacement of these rocks, they carry an unexpectedly large NRM.

Table I is a summary of the magnetic properties of these specimens. For comparison, averages for selected dredged fragments of submarine basalt (L-type, most representative of new seafloor) are also given. J_s in the Surtsey specimens is much more variable than the paramagnetic susceptibility discussed above, and this reflects variations in both amount and composition of titanomagnetite or titanomaghemite. The uniformity of the paramagnetic susceptibility means that nearly all the iron is in paramagnetic form and that total iron content and its oxidation state are essentially the same in all three samples. There is roughly from one-third to one-tenth as much ferrimagnetic oxide in the Surtsey tephra as there is in unweathered dredged pillow basalt, and the amount in each tephra sample is definitely related to the extent of formation of palagonite (Table I).

A crude measure of the relative efficiency of acquisition of NRM is the ratio NRM/J_{rs} (assuming that the intensity of the geomagnetic field that produced the NRM was the same for all samples being compared). For the Surtsey samples this ratio ranges from 0.01 to 0.04, and for comparison the average value for the submarine pillows is 0.03. In other words, the mechanism of production of NRM in the Surtsey tephra was nearly as efficient, on the average, as the acquisition of thermoremanent magnetization (TRM) in submarine pillow basalt. The Surtsey tephra apparently recorded the geomagnetic field direction accurately as well. When probable orientation errors are considered, the measured inclinations (Table I) do not differ significantly from the present geomagnetic inclination at Surtsey. Moreover, the NRM directions did not change during demagnetization. The NRM of the tephra is sufficiently strong for a magnetic anomaly to be visible in a low altitude aeromagnetic survey, although magnetic effects of the overlying and underlying lavas would make such an anomaly difficult to distinguish.

DISCUSSION

The origin of the NRM in the tephra is something of a puzzle, in part because the thermal history of the samples is incompletely known. For example, dikes were encountered in the interval 72 to 85 m, and it is not known how close these or other dikes may be to other parts of the drill hole. We might suppose that both the maximum in the temperature profile at 105 m and the greater degree of induration of the upper two samples result from proximity of the dikes. Then if the NRM were TRM we would expect the lowest sample to be the least efficiently magnetized, but the opposite is true. Except in the immediate vicinity of dikes, the maximum temperature that any sample could have reached in situ is shown by the sea-water boiling curve (Jakobsson and Moore 1982). The measured Curie temperatures of the tephra samples are well above this curve, so that only a small fraction of the NRM in the tephra can be partial TRM. Depositional remanent magnetization (DRM) can be ruled out as well for several reasons. Many of the clasts are too large to have been oriented by the geomagnetic field as they settled through the sea water (or through air only in the case of sample 53.3). Even under optimal conditions of particle size, DRM is a very inefficient process compared to TRM. Finally, considering the turbulent state of an ash or tephra cloud during an eruption, it is improbable that the particles could have acquired coherent TRM's between the moment of eruption and the moment of deposition.

The NRM must have originated through an isothermal low-temperature processs, at least in the part of the volcano that is below sea level. The deepest specimen (150.2) has the most intense NRM and also shows the highest efficiency of NRM acquisition (Table I). Moreover, this specimen is virtually unaltered; the palagonite rinds are barely resolvable in an optical microscope (J.G. Moore, oral communication, 1982). It follows that the titanomagnetite responsible for the NRM must have formed in situ, evidently by precipitation from the basaltic glass (partial devitrification). The observation that the grain size of the titanomagnetite is less than 1 micron is supporting evidence for the plausibility of such a process. Under the circumstances the NRM would be a chemical or crystallization remanent magnetization (CRM). Although CRM has never been produced in titanomagnetite at low temperature in the laboratory, at higher temperatures (300° C—400° C) the efficiency of the mechanism of acquisition of CRM has been shown to be comparable to that of ordinary TRM under some circumstances (Kellogg et al. 1970).

Acquisition of NRM must have preceded the onset of the hydrothermal activity that caused extensive palagonitization higher in the tephra cone. The process of hydration of glass seems to have produced additional magnetic material, but it did not change the NRM appreciably. Note that sample 107.5 is almost completely altered whereas sample 53.3 is only moderately altered, yet they have identical NRM's. Low-temperature oxidation of titanomagnetite to titanomaghemite accompained the palagonitization of the glass, and the Curie temperature increased concomitantly. Arguing from the evidence of the dike sample, the Curie temperature of the original unoxidized titanomagnetite would have been high enough for the CRM to exist, and therefore the low-temperature oxidation would not have produced additional NRM, but would rather have diminished it somewhat (Gromme et al. 1979).

It is interesting that the Curie temperature of the dike sample (at 74.1 m) is lower than the temperature measured in the drill hole at that depth in late 1979. Hence at that time the dikes were essentially nonmagnetic. The abrupt increase that was observed in the magnetic field intensity just south of the summit (station Surtsey III) between 1968 and 1970 (Sigurgeirsson 1974) was probably due to cooling of the lava quite close beneath the observation station. The implication is that the net magnetization of Surtsey volcano has increased since that time owing to slow cooling of dikes, and it may still be increasing. The amount of increase would depend on the relative volume of such dikes.

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