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Magnetic Hysteresis Loops and Magnetization versus Temperature Curves of Some Basalt Samples Containing Titanomagnetite Ore either Single-Phase or with an Intergrowth of Ilmenite Lamellae

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Abstract. Measurements of magnetization versus temperature curves, between −185 and 600 °C, and of hysteresis loops, between −205 °C and room temperature, have been performed on six basalt samples from different localities in fields up to 14.5 kOe. Samples containing homogeneous titanomagnetite ore particles show at room temperature a coercive force $H_c < 100$ Oe which increases to 660 Oe on lowering the temperature to −196 °C. The temperature dependence of the saturation remanent magnetization σ_{r_0} is also pronounced with relatively high values at low temperatures. Basalts with oxidized titanomagnetite grains and ilmenite exsolution lamellae exhibit rather constant values of H_c and σ_{r_0} in the temperature interval mentioned.

The characteristic features of the loops indicate a predominant influence of multi-domain grains, even in the case of oxidized titanomagnetite grains subdivided by ilmenite lamellae down to dimensions of the remaining titanomagnetite that would be expected to show single-domain behaviour. This phenomenon might be interpreted in terms of some kind of cluster effect among these single-domain particles caused by magnetic interaction.

The contribution of the paramagnetic rock matrix to the overall magnetization of the specimens in high magnetic fields is appreciable in most cases. A rough evaluation of the paramagnetic susceptibility deduced at room temperature and at −196 °C gives values consistent with a Curie law for some samples. There are two basalts with hemo-ilmenite grains which contribute presumably to this susceptibility at −196 °C.

Key words: Magnetization of basalts – Hysteresis loops – Paramagnetic susceptibility of the rock matrix.

Introduction

In many investigations on the magnetization of igneous rocks with respect to palaeomagnetism the relationship between the mineralogy of the specimens and their magnetic properties is discussed to a small extent only. On the other hand, attention has been drawn by a growing number of studies to the problem of stability of the natural remanent magnetization in basalts and its correlation with the type and the chemical state of the magnetic ore grains as well as the grain size distribution. This is in particular relevant to measurements of the palaeointensity of the geomagnetic field. Thus, in recent years interest has concentrated e.g. on the early stage of oxidation in titanomagnetite grains. Magnetic data of these particles reflect clearly a chemical process taking place, although any alteration of the titanomagnetite is hardly detectable on polished sections under the ore microscope.

In general investigations of the magnetization in relation to the mineralogy are based on data deduced from magnetization versus temperature T curves ($\sigma - T$), measurements of thermoremanent and induced magnetization and a.c. demagnetization experiments. From the latter the so called coercivity spectrum is derived, representing for the ensemble of magnetic grains in the respective sample the coercive force distribution with regard to the effective particle size. The coercivity spectrum appears to be a good measure for the stability of the natural remanent magnetization (Larson *et al.*, 1969). A classification of $\sigma - T$ curves for basalts according to the shape and the Curie temperatures, related to the degree of oxidation in the ore grains, a primary or secondary one, has been established in the past by various workers (Wilson and Watkins, 1967; Ade-Hall *et al.*, 1968; Creer and Valencio, 1969; Creer *et al.*, 1970).

Relatively few attempts have been made to date to utilize measurements of magnetic hysteresis loops for this purpose (Nagata, 1961; Radhakrishnamurty *et al.*, 1967–1972; Néel, 1970; Wasilewski, 1973). Studies of basalt specimens including measurements of hysteresis loops at low magnetic fields have been done in order to gain information about single- and multi-domain particles (Radhakrishnamurty *et al.*, 1967–1972). As solely minor loops have been measured, it appears that an interpretation of the results requires very careful analysis because the phenomena related with such loops are extremely complex.

In the following, results of an investigation on the magnetization are presented that has been carried out on a selection of basalts from different localities comprising some samples with non-oxidized titanomagnetite grains and others with particles oxidized to various degrees. Measurements of hysteresis loops and $\sigma - T$ curves were combined with a microscope study including the observation of magnetic domain structures of magnetic ore grains on polished sections of basalt specimens at room temperature. The measurements were extended to low temperatures. As in this temperature range characteristic features of the loops may be more pronounced, there is a greater possibility of being able to separate the magnetization into contributions originating from superparamagnetic, single-domain or multi-domain grains.

Experimental

A translation balance of the Weiss-Forrer type was used for measurements of magnetization σ versus temperature T curves in a range of temperatures from −185 °C to above the Curie points of the respective basalts. Heating of the samples, fixed in a sample holder, was done in air. To determine hysteresis loops, two vibrating sample magnetometers were available. One, a commercial instrument (PAR), was employed at room temperature up to 14.5 kOe. The other, somewhat less sensitive, could be operated in the temperature interval of −205 °C to room temperature and a maximum field strength of 13 kOe was attained. The Curie points of the samples were determined from $\sigma - T$ curves in a field of 2.5 kOe.

For the magnetic measurements chips were cut from specimens used for polished sections and ground to spheres of 3–4 mm in diameter. The observation of magnetic domains on polished sections was performed with magnetite colloid (Bitter technique) after ion polishing the sample surface with a method developed by Soffel (1968a, b).

The absolute values of magnetization were determined with the commercial vibrating sample magnetometer. In this way the error of measurement could, also for the results on the balance, be kept $<5\%$. The coercive force H_c and the relative remanent magnetization, quantities derived from the hysteresis loops, are accurate to 5–10%. Values of remanent magnetization have not been corrected for the demagnetizing factor of the ore grains.

The error of the paramagnetic susceptibility deduced from the high field magnetization of the loops may, at −196 °C, amount up to 30% due to possible non saturation of the sample.

Petrographic Data

Six basalt samples were selected for the measurements. In two of them, titanomagnetite grains appear single-phase whereas the remaining four exhibit titanomagnetite oxidized to different extent.

Basalt no. 1 (RK) is a tertiary basalt from the Rauher Kulm, Oberpfalz, Germany. It is characterized by homogeneous titanomagnetite particles, embedded in a rock matrix consisting, in order of decreasing concentration, of pyroxenes, olivine, a glassy matrix and to a lesser extent plagioclase as has been established from a large number of specimens (Refai, 1960; Petersen, 1962, 1966; Soffel, 1968; Creer and Perersen, 1969). The titanomagnetite grains are rather uniformly dispersed in the rock matrix and euhedral to anhedral. Their grain size distribution is illustrated in Fig. 1 for the specimen under investigation. The determination of the ore content in a polished section under the microscope with an integration method yielded 3.5% by volume.

Basalt no. 2 (29/1/1) from Jabal Soda, Libya (Schult and Soffel, 1973) is a tertiary alkali basalt. The grain size distribution of the homogeneous titanomagnetite ore is similar to that of no. 1, the dominating percentage by volume being represented by anhedral particles of 3–30 μ in diameter. A minority of grains shows very faint lamellae of incipient ilmenite exsolution. For this reason it is likely that also a large fraction of the particles, although homogeneous in appearance in reflecting light in polished sections, contain submicroscopic alterations possibly in the form of titanomaghemite and exsolved ilmenite.

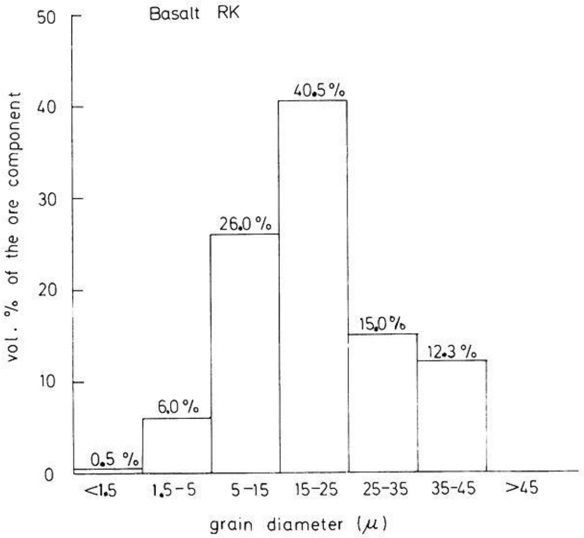


Fig. 1. Grain size distribution of titanomagnetite ore particles in basalt no. 1 (*RK*)

Basalt no. 3 (Fornazzo F4) is from a lava flow of Mount Etna at Fornazzo, Sicily, in 1950/51. The specimen has been drilled from the top of the flow. A detailed description is given by Angenheister *et al.* (1971). The ore grains consist essentially of titanomagnetite grains of 5–80 μ in diameter with clearly developed ilmenite lamellae the amount of the latter being of the order of ≦15 vol.-% of the grains. There occur also some large grains (≦200 μ) with exsolved ilmenite only faintly visible and, hence, the percentage of ilmenite above may not be valid for these particles.

Sample no. 4 (CA-2-AZ,2D) from the Amazon Basin, Brasil, represents a core of a basalt intrusion drilled from a depth of 334 m (Schult, 1970). The ore grains (1.5–100 μ) are on average apparently strongly oxidized titanomagnetite with a dominating intergrowth of ilmenite lamellae the latter representing 60–90 vol.-% of those ore grains. In many of these particles segments of them occur as anisotropic, grey to brownish phase, possibly pseudobrookite. Frequently this phase is also present in the form of well-developed lamellae being occasionally rather broad. The phase is visible also in the form of separate, anhedral grains. By employing the magnetite colloid technique it could be established that this phase is non magnetic whereas a small remainder of original titanomagnetite or titanomaghemite could easily be detected in the grains. The ilmenite lamellae mentioned above are presumably to a large extent decomposed into new, optically not clearly identifiable phases (magnification ×1,000 in oil). Such a situation is frequently observed in strongly oxidized basalts where hematite, rutile or anatase and pseudobrookite are encountered as decomposition products.

Basalt no. 5 (SD-1-MT), from the Parana Basin, Brasil, is a specimen of a basalt intrusion, drilled from a depth of 1,453 m (Schult, 1970). A microscopic inspection reveals a complex structure of the ore grains. In principle, three types of grains can be distinguished.

a) Grains (2–150 μ) of titanomagnetite with ilmenite lamellae, the latter amounting up to $\leqq 50$ vol.-% of these particles. Further, rather large segments which may be pseudobrookite as in sample no. 4 of those grains are grey to brownish in appearance; occasionally some kind of granulation seems to occur in these segments (see c).

b) Relatively large (50–200 μ), discrete, euhedral to anhedral and frequently elongate, primary hemoilmenite grains are found revealing to a more or less extent thin grey, anisotropic veinlets. In small segments a granular structure is present peripherally (see c). No magnetization could be detected with the help of the colloid method.

c) In a number of discrete large grains (up to $\leqq 200$ μ) an intimate mixture of a dominating light grey phase and a darker ore occurs, a texture, that has been denoted in the literature as granulation (Ade-Hall *et al.*, 1968). These grains are probably magnetic.

Sample no. 6 (LS-1-PR, 16D) has been drilled in the Parana Basin Brasil, from a basalt intrusion at a depth of 2,350 m (Schult, 1970). This specimen has been taken for the present study because the ore consists predominantly of primary hemoilmenite. It occurs in the form of large (10–250 μ), homogeneous, frequently elongate, euhedral to anhedral and anisotropic grains. In addition, a highly reflecting, anisotropic phase is contained (particles $\leqq 80$ μ) that is $\leqq 10$ vol.-% of the ore and may be pyrrhotite and pyrite. Using the colloid technique, typical parallel patterns are seen in quite a number of cases which point to a hexagonal structure of this phase as is required for pyrrhotite. The hemoilmenite appears to be non-magnetic at room temperature. Possibly, titanomagnetite is present in the form of very small grains.

Some characteristic features of the samples studied are summarized in Table 1.

Results

Basalts with Single-Phase Titanomagnetite Grains

The $\sigma - T$ curve of basalt no. 1 (RK) is presented in Fig. 2a. For the sample used it coincides with analogous measurements carried out previously (Petersen, 1962, 1966; Creer and Petersen, 1969). Hysteresis loops of a virgin sample taken from the same hand sample are shown in Fig. 2b at room temperature and -196 °C. At room temperature one can expect saturation of the titanomagnetite grains in a field $\geqq 5$ kOe whereas at low temperatures higher fields are required. A characteristic feature of the loops is the steadily rising σ up to the maximum fields used. The observation of this linear increase in the high field region could be confirmed up to 14.5 kOe. From the graph a slope of $\Delta\sigma/\Delta H = 2.0 \times 10^{-5}$(Gcm^3/g) is evaluated at ambient temperature. The ratio σ_{ro}/σ_o(σ_{ro}= isothermal saturation remanent magnetization, σ_o=saturation magnetization, defined as σ that is obtained by extrapolating σ from high fields to $H \rightarrow 0$) is relatively low at room temperature, however on lowering T, it is raised steadily up to the maximum value attained at -196 °C. A similar behaviour is established for the coercive force H_c which is much higher at low T. Values for σ_{ro}/σ_o and H_c are listed in Table 2.

Table 1

Specimen number	Locality	Sample specification	Grain size (μ)	Curie points	Opaque mineralogy
1	Rauher Kulm Oberpfalz, West-Germany	RK	1.5–45	180 °C	brown, homogeneous titanomagnetite
2	Libya, Jabal Soda	29/1/1	3–30	300 °C 450 °C	brown titanomagnetite, very rarely beginning exsolution of ilmenite
3	Sicily, Aetna	Fornazzo F4	5–200	525 °C	titanomagnetite with an intergrowth of well developed ilmenite lamellae
4	Brasilia, Amazon	CA-2-AZ, 2D	2–100	520 °C	titanomagnetite with dominating ilmenite exsolution lamellae and decomposition products, primary hemoilmenite grains with a faintly visible net of an exsolved light grey phase
5	Brasilia, Parana	SD-1-Mt, 6D	2–200	530 °C 175 °C	titanomagnetite with well-developed lamellae of ilmenite and its decomposition products, primary homogeneous hemo-ilmenite, granular structure
6	Brasilia, Parana	LS-1-PR, 16	2–250	300 °C	primary, homogeneous hemoilmenite, a bright anisotropic phase probably being pyrrhothite

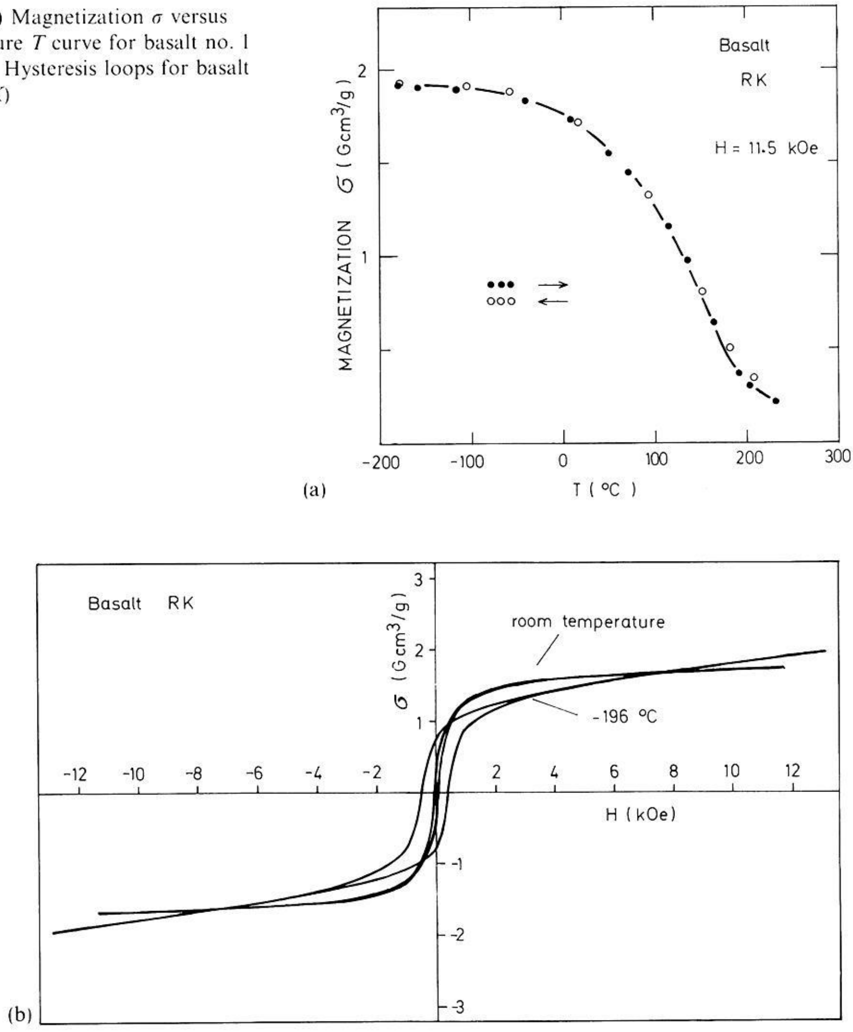
In order to study the behaviour of minor loops on basalt no. 1 at ambient T, a virgin specimen, previously demagnetized in a tumbler applying a starting field of 2 kOe, was subjected to cycles with the maximum field employed during a cycle increasing from 200 to 8,000 Oe. The results for H_c and σ_r thus obtained are plotted in Fig. 3. As can be seen from the graphs, above about 2 kOe differences relative to the high field values are insignificant.

Although basalt no. 2 (29/1/1) appears to contain largely homogeneous titanomagnetite grains, they must be assumed to be in the first step of oxidation, as mentioned. Evidence for this suggestion is seen from the $\sigma - T$ curve of Fig. 4a which shows on heating a tail with a small hump between 300 and 400 °C (see p. 623). The hysteresis loops (Fig. 4b) between ambient temperature and -196 °C resemble those of basalt no. 1 with the exception that H_c is raised much more on lowering T (Table 2). We must bear in mind that the loops are probably due to two phases.

Basalts with Ilmenite Lamellae in Titanomagnetite Grains

The $\sigma - T$ curves and hysteresis loops for several basalts with an ore mineral composition as described above (see Table 1) are presented in Figs. 5 to 8.

Fig. 2. (a) Magnetization σ versus temperature T curve for basalt no. 1 (*RK*). (b) Hysteresis loops for basalt no. 1 (*RK*)



Basalt no. 3 (Fornazzo F4) is an example of a basalt containing a rather uniform ore grain composition of a small number of ilmenite lamellae in titanomagnetite grains, exhibiting a Curie point of about 525 °C (Fig. 5a). In contrast to the loops of samples no. 1 and 2, H_c remains fairly constant between ambient T and -196 °C. It is also relatively high. σ_{r0}/σ_0 does not differ much in the temperature range mentioned. The field strength required to saturate the specimen does not appear to depend appreciably on temperature either. As for the samples presented above, there is an increase in σ with H in a field range where the ore grains can be assumed to be magnetized to saturation. From the form of the low temperature loop in Fig. 5b no indication of an ilmenite contribution can be inferred. For this reason we conclude that the ilmenite, visible under the microscope as lamellae may be paramagnetic down to -196 °C.

Table 2. Basalt

No.		1	2	3	4	5	6
H_c(Oe)	20 °C	52	65	145	115	160	185
	−196 °C	370	660	190	125	280	290
σ_{ro}/σ_o	20 °C	0.17	0.13	0.17	0.13	0.11	0.58
	−196 °C	0.60	0.63	0.20	0.17	0.16	~1.0
$\Delta\sigma/\Delta H \cdot 10^5$ (Gcm^3/g)	20 °C	2.0	2.0	1.9	1.9	2.3	2.3
	−196 °C	7.0	7.9	7.4	6.7	9.7	16.2

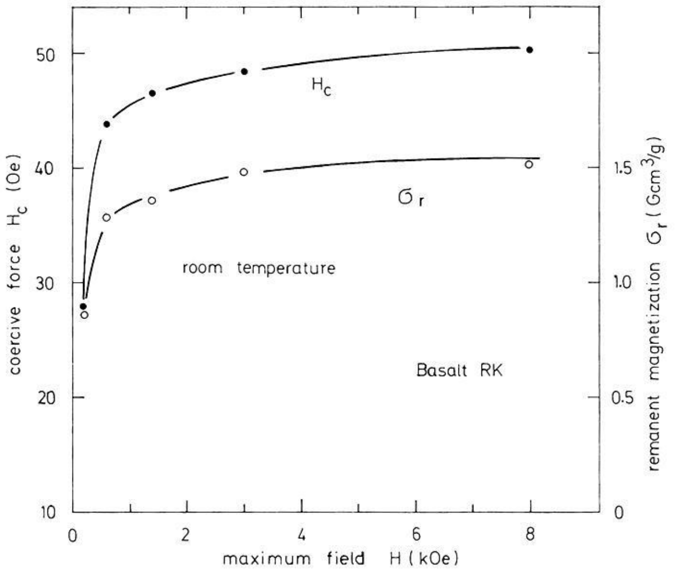


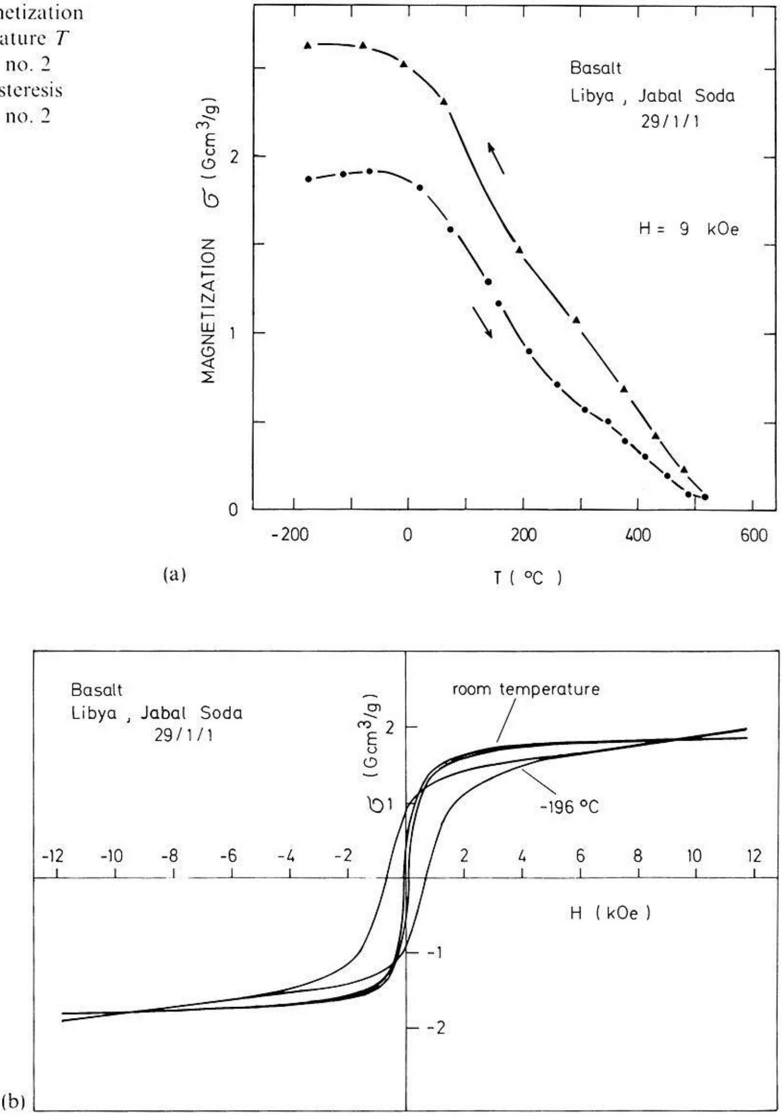
Fig. 3. Dependence of coercive force H_c and isothermal remanent magnetization σ_r on the maximum field strength H, applied during a hysteresis cycle, for basalt no. 1 (*RK*)

We expect the more complex mineralogy of the magnetic ore grains of basalts nos. 4–6 to be reflected in the magnetization data.

Basalt no. 4 (CA-2-AZ) shows a $\sigma-T$ curve with a high temperature Curie point of ~520 °C (Fig. 6a). The course of $\sigma-T$ at low temperatures may be interpreted as the onset of a superposed thermomagnetic curve. However, this point can only be decided by measurements down to 4.2 °K. The hysteresis loops exhibit features similar to those of sample no. 3 (Fig. 6b). H_c and σ_{ro}/σ_o reveal only a slight temperature dependence (Table 2). Although it seems that $\Delta\sigma/\Delta H$ may distinctly differ at −196 °c from that of specimen no. 3, the values listed in Table 2 indicate that there is close conformity; the impression arises merely because of the reduced absolute magnitude of σ for sample no. 4.

For basalt no. 5, however, from the shape of the $\sigma-T$ curve in Fig. 7a, the presence of a second magnetic phase can be inferred with a Curie point at low temperature, besides a phase with a high Curie point. This suggestion is supported by the increase in H_c from ~200 Oe to ~300 Oe at T ~ −170 °C

Fig. 4. (a) Magnetization σ versus temperature T curve for basalt no. 2 (29/1/1). (b) Hysteresis loops for basalt no. 2 (29/1/1)



that goes hand in hand with the rise in σ. Also the larger size of the loop in the relevant temperature interval must be attributed to some kind of new phase (Fig. 7b). From Table 2 we see that $\Delta\sigma/\Delta H$ is at -196 °C much higher than for all the basalts so far.

From the ore microscopic results (see p. 619) it is clear that for basalt no. 6 the Curie point at ~ 300 °C as deduced from the σ (T) curve in Fig. 8a originates probably from pyrrhothite. In addition, at low temperatures, a second phase might contribute to σ. The fact that σ_{r0}/σ_0 is very high shows that the carrier of σ with T_c ~ 300 °C cannot be titanomagnetite or titanomaghemite

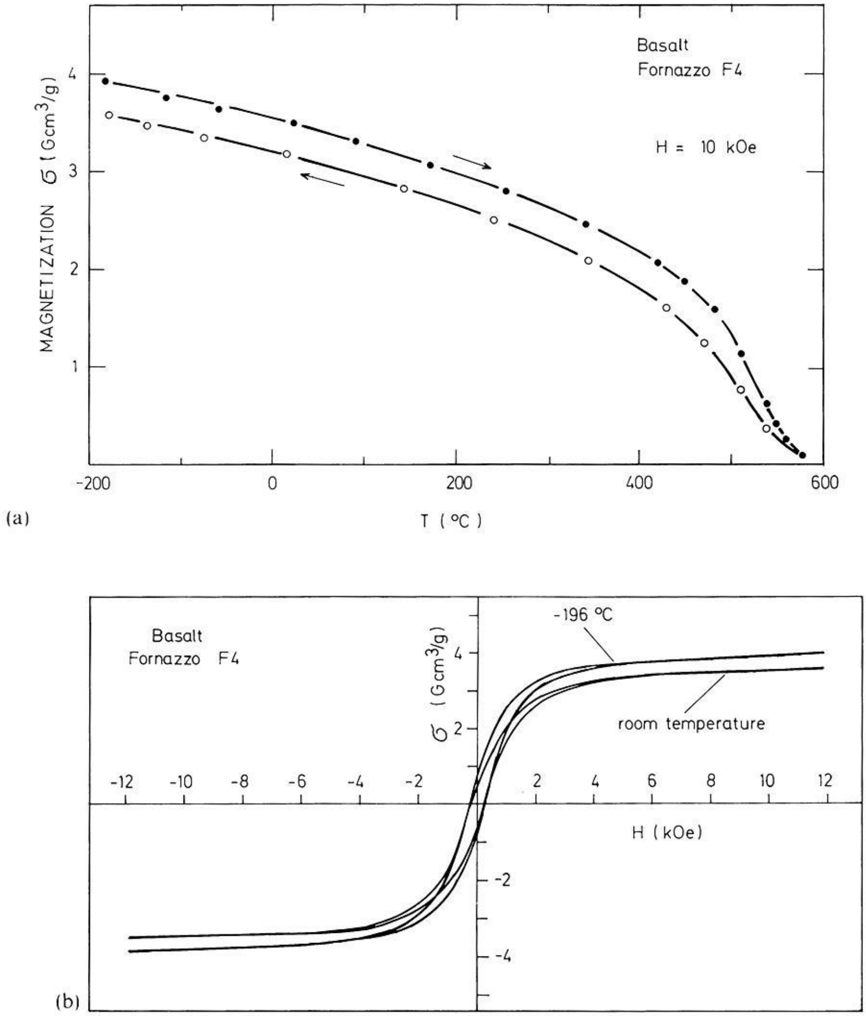


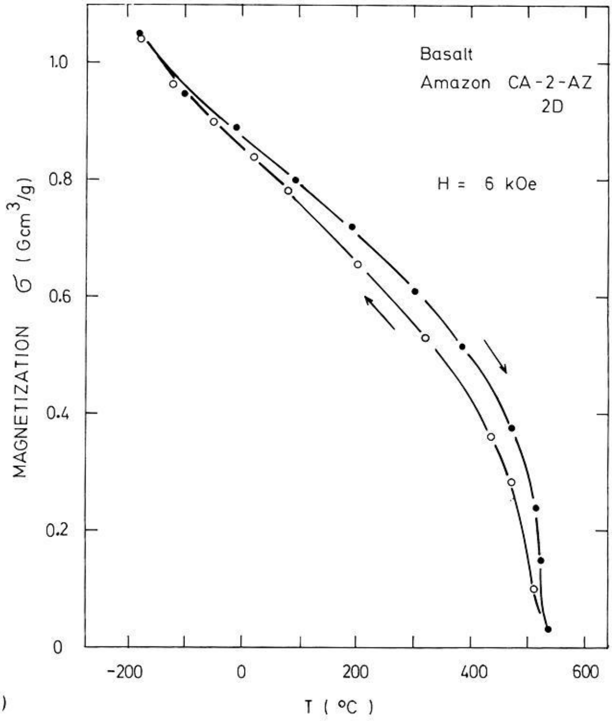
Fig. 5. (a) Magnetization σ versus temperature T curve for basalt no. 3 (Fornazzo F4). (b) Hysteresis loops for basalt no. 3 (Fornazzo F4)

whereas H_c is in the normal order of magnitude (Fig. 8b). Finally, the high magnitude of $\Delta\sigma/\Delta H$ is obviously associated with the low temperature phase (Table 2).

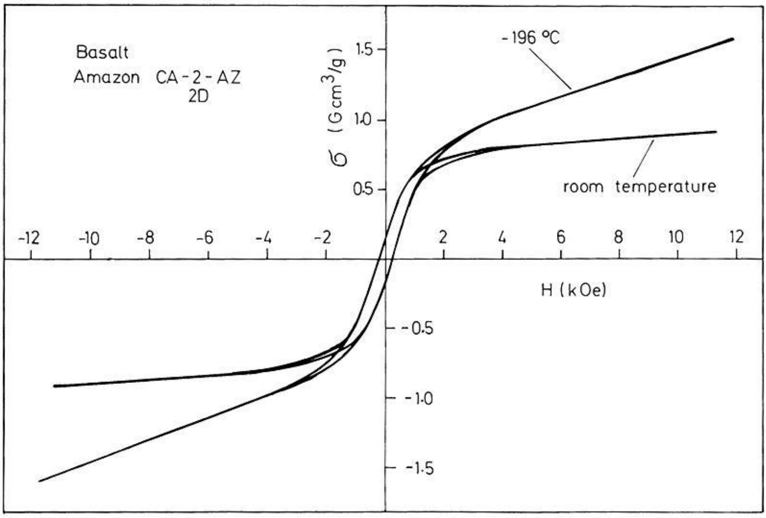
Discussion of Results

Basalts with Single-Phase Titanomagnetite Grains

For basalt no. 1 (RK), an examination of the titanomagnetite ore grains with the microprobe (Creer and Ibbetson, 1970) showed that the titanomagnetite



(a)



(b)

Fig. 6. (a) Magnetization σ versus temperature T curve for basalt no. 4 (CA-2-AZ, 2D). (b) Hysteresis loops for basalt no. 4 (CA-2-AZ, 2D)

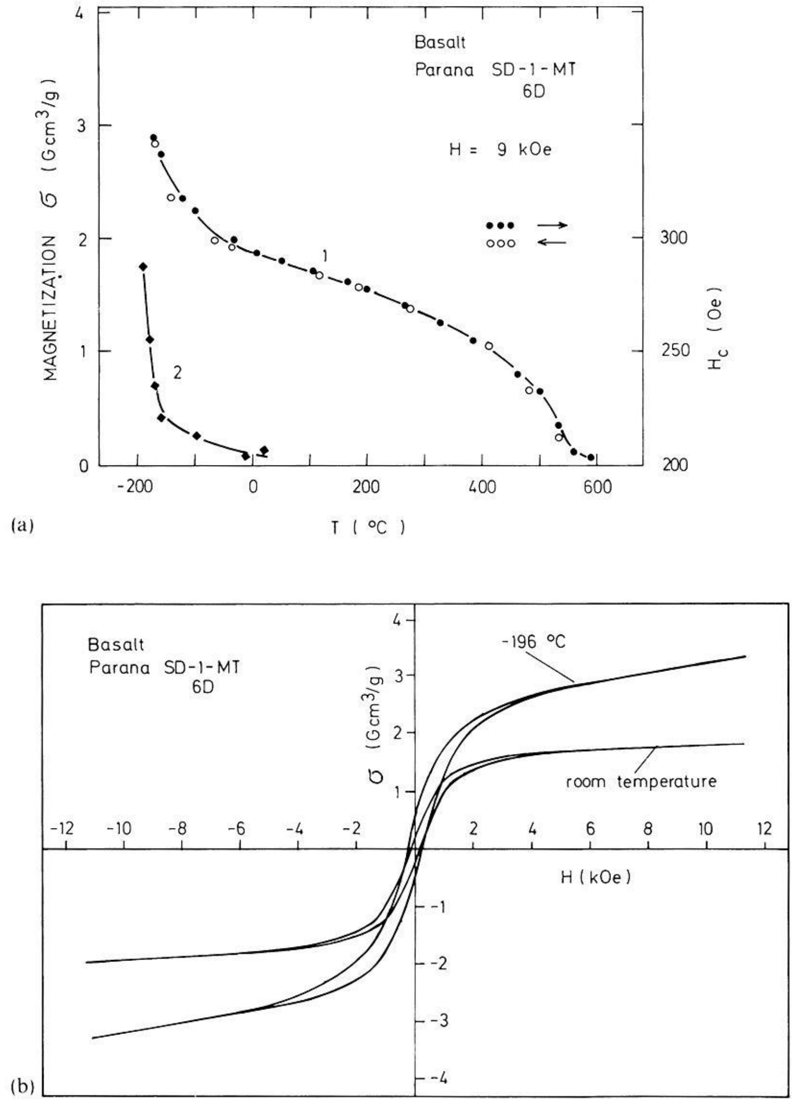


Fig. 7. (a) Magnetization σ versus temperature T curves (*1*) and coercive force H_c (*2*) for basalt no. 5 (SD-1-MT, 6D). (b) Hysteresis loops for basalt no. 5 (SD-1-MT, 6D)

particles may, to a small extent, contain magnesium and aluminum as impurities. Therefore, the salient features of hysteresis loops may not compare completely with those known from the literature for pure, synthetic titanomagnetites, the members of the spinel series Fe_3O_4-Fe_2TiO_4 ($Fe_{3-x}Ti_xO_4$; $0 \leqq x \leqq 1$). On the other hand, the composition of the basalt appears to be notably constant (Refai, 1960; Petersen, 1962, 1966).

The magnitude of H_c and σ_{ro}/σ_o of the RK basalt at −196 °C accords roughly with data measured by O'Reilly (1965) and Banerjee and O'Reilly

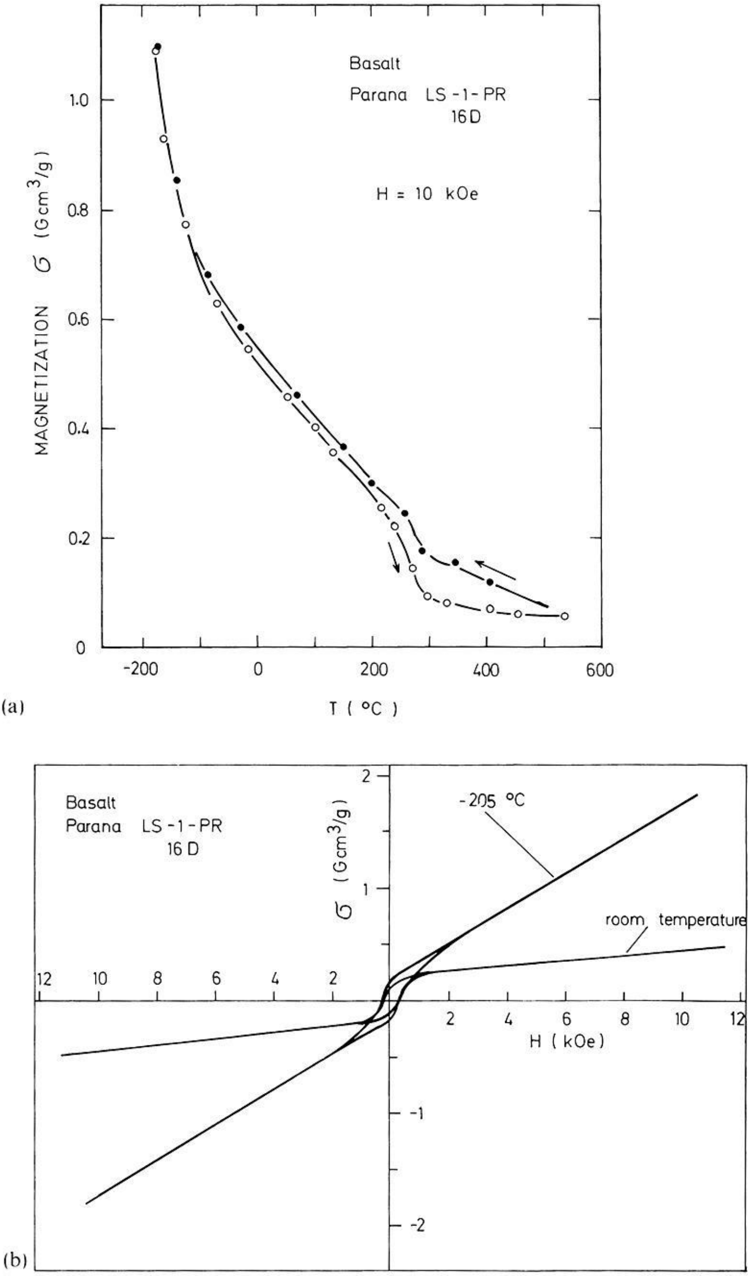


Fig. 8. (a) Magnetization σ versus temperature T curves for basalt no. 6 (LS-1-PR, 16D). (b) Hysteresis loops for basalt no. 6 (LS-1-PR, 16D)

(1966) on polycrystalline titanomagnetite with $T_c \sim 180$ °C ($x \sim 0.65$). Therefore we assume that in both cases similar mechanisms may be operative determining H_c and σ_{ro}/σ_o. If single-domain particle would be responsible for the loop characteristics at $-196\,°\mathrm{C}$, the value $H_c = 370$ Oe found for the RK basalt would be too low. The same applies for the ratio $\sigma_{ro}/\sigma_o = 0.6$ as compared to 0.83 for single-domain particles and $K_1 > 0$. In the synthetic samples the hysteresis loop characteristics at low temperatures are presumably dictated by the high magnetocrystalline anisotropy constant K_1 which is probably due to Fe^{2+} ions on A- and B-sites of the spinel lattice (Syono, 1965). We suppose that also for the RK basalt ore grains K_1 is considerable at low temperatures in spite of the presence of a small amount of Mg and Al in the spinel lattice. Soffel (1971) has demonstrated by observation of domain walls on ore grains of the RK basalt that the critical diameter d_{cr} of the ore grains for the transition from the single-domain to the multi-domain state is $< 1.5\,\mu$ at room temperature. As dimensions $\leqq 1\,\mu$ cannot be studied using the reflecting light microscope, it is likely that the real d_{cr} is still smaller. It is well known that d_{cr} depends on the crystalline anisotropy constant K_1. Making a rough estimation, Readman and O'Reilly (1972) argue that for titanomagnetites of composition x between 0.4 and 0.7 the critical diameter d_{cr} may be between 0.2 and 1.4 μ, respectively, at $T \sim 80\,°\mathrm{K}$ due to the large K_1 value. Taking these values for the RK sample, we conclude that part of the magnetic grains is likely to be single-domain at low T (see Fig. 1). Although this volume fraction may not be sufficient to raise the coercive force H_c of the RK sample to the values expected for pure single-domain grains, the contribution to the saturation remanent magnetization σ_{ro} may be more pronounced. There must also be considered the fact that a certain percentage of grains which are superparamagnetic at room temperature become single-domain particles at low temperatures and, therefore, carry also remanent magnetization as has been pointed out by Markert and Steigenberger (1971).

The slope $\Delta\sigma/\Delta H$ above technical saturation of the basalt specimen at room temperature arises from the so called paraprocess of the single-domain and multi-domain grains, from superparamagnetic particles, and from the paramagnetism of the rock matrix. ($\Delta\sigma/\Delta H = \chi_{as}$ = specific susceptibility above saturation). In general, the contribution of the paraprocess is small for temperatures well below the Curie temperature of the grains. However, it may become noticeable if major contaminations of non-magnetic ions as Mg and Al are incorporated in the spinel lattice of titanomagnetites. In this case a certain percentage of magnetic ions may be surrounded predominantly by Mg and Al ions and, thus, only a weak or negligible interaction to the magnetic sublattices may occur. For superparamagnetic particles, the Langevin curve, describing σ as a function of H may have a very small curvature within the range of H in question and, hence, the field dependence of σ may hardly be distinguished from a straight line. Commonly, a significant portion of the slope originates from the paramagnetism of pyroxene, olivine, iron-bearing glass etc., being the constituents of the basalt. A determination of σ at $-196\,°\mathrm{C}$ from Fig. 2b is possible with a reduced accuracy only, on account of the high fields required to saturate the specimen. Assuming that saturation is accomplished at 8–10 kOe, the order of magnitude of χ_{as} at ambient temperature in relation to that at $-196\,°\mathrm{C}$ is in rough accordance with an assumed Curie law $\chi = C/T$ (C= constant, T= temperature in °K). Therefore the main contribution may arise from rock paramagnetism. For a more detailed investigation into this problem the maximum magnetic field used in this study may not be sufficient and the temperature range has to be extended down to liquid helium temperature.

From Fig. 2b one infers that σ_0 is lower at -196 °C than at room temperature. Thus, there might be a *P*-type of thermomagnetic curve according to Néels notation. A measurement down to 4.2 °K could decide this problem.

Basalt no. 2 with slightly oxidized titanomagnetite grains, as mentioned, reveals at -196 °C a significantly higher H_c that that discussed above. This finding can be a result of submicroscopic alterations of the ore particles bringing possibly a small-particle effect into play. The other quantities measured do not show salient features. As the composition of the ore grains is unknown, contamination of Al, Mg, Cr etc. may have an influence, too.

Basalts Containing Ilmenite Lamellae in Titanomagnetite Grains

The $\sigma - T$ curve of basalt no. 3 shows a sharp Curie point at 525 °C. The shape in the temperature interval studied is largely what one would expect from a spinel phase rich in Fe with a composition close to magnetite ($T_c = 575$ °C). The steady rise at low temperatures may be brought about by rock paramagnetism. For this reason, the contribution of ilmenite can be supposed to be small. This fact implies that ilmenite must be rather pure and cannot contain a significant amount of hematite. Because members of the hematite (Fe_2O_3)$-$ilmenite ($FeTiO_3$) solid solution series are ferrimagnetic already at low hematite content, ilmenite with $\geqq 5\%$ Fe_2O_3 should give a measurable σ at -196 °C in our case whereas pure ilmenite is antiferromagnetic with a Neel point of ~ 60 °K. Of course, ilmenite contributes also to σ by means of its paramagnetism above the Neel point at -196 °C. Though, the magnitude of σ is distinctly reduced in this case.

As H_c and σ_r/σ_0 are not appreciably variable with temperature, the magnetic anisotropy at low temperatures may be relatively small. On account of the subdivision of titanomagnetite grains by ilmenite lamellae one would derive the existence of single domain particles whence characteristic features of the hysteresis loop may emerge. Such an effect is not obviously recognizable from Fig. 5b. The somewhat increased H_c might be interpreted in terms of some kind of small particle effect, however not being typical for single domain grains. The origin of this discrepancy may lie in a cluster effect of the magnetization of single domain particles. Due to the close neighborhood of titanomagnetite single domain grains in basalt ore particles, subdivided by ilmenite lamellae, they can interact by virtue of their magnetic fields with each other, a phenomenon that must be taken into account in this case. A satisfying theoretical treatment of this problem is still missing. The situation is problematic as well if a mixture of single-domain and multi-domain particle is involved.

The magnitude of χ_{as} deduced from the loops above technical saturation at ambient temperature differs only slightly from that of basalt no. 1 within the accuracy of measurements. The value at -196 °C may be compatible with a Curie law (see Table 2).

The $\sigma - T$ curve of basalt no. 4 (Fig. 6a) is similar to that of basalt no. 3

notwithstanding the complex mineralogical composition of the ore grains. Only in the low temperature range might there be an indication of a second magnetic phase. Thus, the characteristics of the hysteresis loops may originate from quite the same phase as in basalt no. 3.

The relatively low absolute value of σ, inspite of the fact that the ore content in the basalt cannot be considered as low, is due to the high percentage of ilmenite lamellae or their decomposition products in the ore grains. H_c and the shape of the loops are comparable with those of basalt no. 3. The ambiguities inherent in the explanation of the loop behaviour of the latter apply also for basalt no. 4.

Basalt no. 5 gives a $\sigma - T$ curve that shows undoubtedly two magnetic phases (Fig. 7a). Primary hemo-ilmenite grains visible under the microscope may contain so much Fe_2O_3 that a contribution to σ of the correct order of magnitude is possible. A separation of σ at low temperatures into contributions of the various phases is difficult as the magnetization of the hemo-ilmenite compositions in question does not exhibit salient features (Ishikawa and Akimoto, 1957).

As in basalt no. 6 only two ore phases can be detected, σ must be due to these plus paramagnetism at low temperatures. The unusual large linear portion of σ at high fields might in part be associated with primary hemoilmenite particles. This may be possible as hemoilmenites close to ilmenite in composition exhibit $\sigma - T$ curves with tails smeared out towards higher temperatures. Thus, an exact definition of T_c is difficult and, in this temperature region, a linear increase in σ with H might take place in high fields (Ishikawa and Akimoto, 1957).

The magnetic properties of the basalts, presented in the foregoing sections show that the connection between magnetization and the mineralogy is fairly complex, even for basalt no. 1 (RK) the ore grains of which are optically homogeneous. In principle, a more detailed knowledge of this relationship appears to be possible. One of the presuppositions is a careful analysis of the natural specimens with the microprobe and also a chemical analysis in particular of the Fe content would be very useful. On the other hand, a serious barrier that is hindering the aim is a certain lack of data concerning the magnetization of the minerals. A thorough investigation on synthetic single crystal and polycrystalline specimens including the influence of grain dimensions would provide us with data which would assist the study of natural rock samples.

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