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Magnetic studies on the remanence carriers in igneous rocks of different ages

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Abstract. A critical study on the type of the magnetic grains, both in composition and domain state, in rocks of different ages has been carried out. One simple, fast and non-destructive test, which can provide useful information on the nature of the magnetic grains in freshly collected samples, seems to be the ratio of susceptibilities at 77 and 300 K. This ratio, termed relative susceptibility, ranges from 0·1, for samples containing 70% ulvospinel bearing titanomagnetite (TM70) to 1·50 for cation deficient magnetite bearing ones. The results indicate that the value of 0·1 for TM70 is not greatly affected even if some amount of TM80, which is nonmagnetic at 300 K, is present in a rock sample. However, the coercive force at 77 K will increase considerably for such a sample. The effects of mixed compositions and domain states of magnetic grains on the overall behaviour of basalts are discussed.

Keywords. Domain states; magnetic parameters; basalts; remanence carriers.

1. Introduction

Only a small fraction of the few percent of the iron oxide grains in an igneous rock is responsible for the remanent magnetization of the sample. The remanence carriers could be of the same composition as the bulk of the iron oxide grains or of a different composition. Similarly, the domain state of the carriers could be the same or different from that of the other magnetic grains in the sample. In an ideal situation when a sample contains magnetic grains of a single composition and of one domain state, the character of the remanence carriers can be understood by any simple magnetic method. But more often than not, rock samples contain both mixed composition and domain states (Radhakrishnamurty *et al* 1982) and the procedure to identify them is yet to be evolved. However, the parameter coercive force (H_c) at 77 K of the rock samples is quite dependable for inferring the composition of the magnetic grains, although the domain state may be somewhat uncertain, as was reported by Radhakrishnamurty and Likhite (1987). It may be pointed out in this context that the measurement of any parameter, especially for a mixture, may be subjected to experimental limitations which could be insurmountable. The measured value of a parameter could be the result of those of the different components of the mixture and it may not be possible to separate the value of each of the component. For example, if a sample contains a mixture of low and high coercive force materials, the measured value of this parameter would be the result of the two individual values and would depend on the relative proportions of the components which might not be easy to estimate from the overall behaviour (Radhakrishnamurty and Sahasrabudhe 1965). At best the parameters for a rock sample could lead to qualitative inferences on the nature of the magnetic grains present. Also, it will be ideal if all the parameters could be measured, preferably by some non-destructive methods, on the same core sample that was used for the natural remanent magnetization (NRM) measurements. In this paper, a brief review of the methods for the study of the magnetic grains in rocks, their usefulness and limitations is presented.

2. Magnetic parameters for basalts

NRM studies are usually carried out on standard core samples of 2·5 cm in diameter and about the same length. The susceptibility of the core samples, both at room and liquid nitrogen temperatures, may be measured by the method suggested by Radhakrishnamurty *et al* (1979), either before or after the NRM studies. However, the Curie temperature, saturation intensity and saturation remanence could be determined only after the completion of NRM studies on the cores. These parameters can be obtained on standard core samples by the procedures described by Radhakrishnamurty and Likhite (1970, 1987), though other methods employing smaller samples are more commonly used. Nevertheless, it is important to get as many parameters as possible on the same core sample, so that they could be inter-related. Even then, these parameters could fail to elucidate the actual situation adequately, if the magnetic grains in a sample are of mixed domain states and compositions. This problem was discussed to some extent earlier (Radhakrishnamurty *et al* 1981). Based on the extensive studies on basalts of different ages ranging from less than a million to more than a billion years, and on the general magnetic behaviour of magnetic materials, the following conclusions could be drawn:

(i) The magnetic susceptibility of a dilute sample will depend on the domain state of the grains, even if all the grains are of one uniform composition, as can be inferred from the hysteresis behaviour of multidomain (MD), optimum single domain (SD) and superparamagnetic (SP) particles described by Beans (1955). Although the actual measurements of susceptibility on samples containing different domain states are very few in the literature, it is common knowledge that SD samples will show a minimum value and SP the maximum with MD between these two extremes.

(ii) Saturation intensity of magnetization (J_s) of a sample does not depend on the domain state of the grains provided a sufficiently large field is used for the determination. But the saturation ramanence (J_r) is dependent on the domain state. Thus, the value of the relative remanence (J_r/J_s) will be quite small (0·1) for MD and SP grains, whereas it will be 0·5 for SD grains with uniaxial anisotropy and 0·8 for particles with cubic anisotropy.

(iii) The coercive force (H_c) is highly dependent on the domain state of the grains in the sample; it being very small for MD and SP particles and attaining the optimum value for the SD state for any one magnetic material.

(iv) For determination of the Curie temperature, the two methods generally used are the low-field (susceptibility vs temperature, $\chi - T$) and the high field ($J - T$), whose relative advantages and disadvantages have been discussed by Radhakrishnamurty *et al* (1979). The shape of the $\chi - T$ curve depends considerably on the domain state of the grains in a sample (Radhakrishnamurty *et al* 1982) whereas that of $J - T$ will be less so.

With due consideration of the above points, a procedure to decipher the nature of the magnetic grains in basalts by magnetic methods was proposed (Radhakrishnamurty 1985). Also from the extensive magnetic studies on basalts it has been pointed out (Radhakrishnamurty and Likhite 1987) that the H_c at 77 K could provide dependable information on the nature of the iron oxide grains in the sample concerned. For the present study, all the high field properties were measured in a peak field of 500 mT. This field might not have saturated all types of samples and hence the symbol J_m representing the maximum intensity of magnetization, instead of J_s, has been used in presenting the results.

3. Results and discussion

Table 1 shows some of the parameters for basalts of different ages, obtained by the use of non-destructive magnetic methods. However, the ages of the samples have not been shown as they are not essential for the present discussion. The results have been tabulated on the basis of an increasing value of relative susceptibility (RS) (ratio of susceptibilities at 77 and 300 K, χ_{77}/χ_{300}). The main reasons for this emphasis on the RS value are (i) very low values of RS (0·1) clearly indicate the presence of titanomagnetite grains with 60% to 70% of ulvospinel in solid solution with magnetite, abbreviated as TM60 and TM70 respectively and (ii) any RS value with the association of a susceptibility peak at about 120 K, the isotropic point of magnetite will imply the

Table 1. Some magnetic parameters for selected basalt samples.

Sample	RS	Peak in χ	H_c (mT) at 300 K	H_c (mT) at 77 K	J_r/J_m at 300 K	J_r/J_m at 77 K	% increase in J_m
332	0·06	—	2·3	180·0	0·05	0·67	19
CR23	0·12	—	4·0	222·8	0·12	0·56	50
184	0·12	—	16·1	106·0	0·12	0·63	13
CR5	0·29	—	10·1	153·0	0·27	0·56	56
CR68	0·30	—	4·0	44·4	0·10	0·20	8
262	0·50	—	27·5	95·0	0·25	0·46	2
N'40	0·53	—	9·0	18·5	0·12	0·19	1
R'14	0·68	—	19·6	60·0	0·31	0·29	21
R21	0·70	—	32·4	60·0	0·34	0·23	20
CR51	1·08	—	39·2	51·0	0·29	0·25	17
CR56	1·17	—	16·0	15·9	0·18	0·12	14
M45	1·44	—	23·0	23·0	0·15	0·12	100
E24	1·41	1·52	36·4	27·7	0·43	0·25	17
E26	1·32	1·53	40·9	37·0	0·36	0·46	28
N'19	1·30	1·53	10·8	23·0	0·17	0·16	29
E21	1·19	1·43	36·4	32·3	0·41	0·29	28
E20	0·70	1·44	36·4	64·7	0·36	0·36	14
C39	0·47	1·30	13·9	32·4	0·20	0·30	3
342	0·46	1·36	9·2	36·5	0·08	0·15	28

RS—relative susceptibility χ_{77}/χ_{300}; peak in χ shows the susceptibility peak at around 120K, if any; H_c, J_r and J_m were measured in a peak field of 500 mT; the last column shows the percentage increase in J_m when the sample is cooled from 300 to 77 K.

presence of multidomain magnetite grains in the sample concerned. It may be mentioned in this context that the studies on basalts of different ages have also indicated that the multidomain magnetite can occur together with some SD magnetite and/or cation deficient magnetite only, and rarely with other titanomagnetites.

Although the RS value between 0·1 and 1·3 seems to have a specific relation with the composition in the case of synthetic titanomagnetites (see Radhakrishnamurty *et al* 1981), it may not often hold good in the case of basalts due to the mixed nature of the iron oxide grains present. As a matter of fact, a mixed domain state and more than one composition of the iron oxide grains in rocks cause non-compatibility among the different magnetic parameters. On the other hand, the very same non-compatibility will indicate the mixed nature of the iron oxide grains. Some of the interesting points that could be visualized from the results presented in table 1 are as follows:

(i) Rock samples showing nearly the same RS value can differ considerably in their H_c values at 77 K (e.g. CR5 and CR68; 262 and M4).
(ii) High values of H_c at 300 K are often associated with high J_r/J_m values (e.g. 21, E24, E21). These features normally indicate the presence of considerable proportion of SD grains in the sample concerned.
(iii) Large increase in the values of H_c and J_r/J_m at 77 K compared to those at 300 K indicates the presence of significant amount of SP fraction in them (e.g. 332, CR23). Such an increase will be limited to a factor of two or less in the case of SD samples (e.g. R21, CR51). Also these large changes pertain to samples containing TM60 to TM70 grains (Radhakrishnamurty *et al* 1981).
(iv) Samples containing MD magnetite (inferred from the presence of a susceptibility peak—E24 downwards in table 1) generally show small changes—increase or decrease—in H_c and J_r/J_m values with temperature.
(v) An increase in J_m for the samples, when cooled from 300 K to 77 K (column 8), will depend on the composition of different TM grains and their relative proportions. The sample CR23 showed the highest H_c (222·8 mT) at 77 K. The coercive force at 77 K for TM68 is 180 mT and for TM80 it is 250 mT and further TM80 is non-magnetic at 300 K (Radhakrishnamurty *et al* 1981). In view of this, a reasonable explanation for the behaviour of CR23 may be that it contains some TM80 grains besides others, whereby the resultant H_c could be as high as 222·8 mT at 77 K. It is interesting to note that this sample, containing even probably some amount of TM80, showed an RS value of 0·12 which is nearly the same as that expected for TM60 and TM70 (Radhakrishnamurty *et al* 1981). An important implication of these observations is that the presence of TM80 grains, in association with TM60 or TM70 in a rock sample, can be deciphered, probably by the measurement of H_c at 77 K only.
(vi) The very large (100%) and quite small (1%) increases in J_m shown by some samples when cooled to 77 K, are somewhat unexpected and difficult to explain and need further investigations for elucidation.

Thus the data presented in table 1 can provide a broad perspective of the limits within which the values of different magnetic parameters of basalts could lie.

In the case of samples from diabase dykes from northwest Greenland, Murthy *et al* (1981) showed that the remanence carriers were essentially SD grains but the overall magnetic behaviour of the samples was soft, probably dominated by other domain states. In another recent study (Smith and Banerjee 1986) of marine basalts wherein both thermoremanent magnetization (TRM) and intrinsic magnetic properties were documented, the complexity of attempting a correlation between them was discussed. The authors stated "it is possible that the TRM-ARM anology is not valid for this minerology, but it seems likely that some, if not all, of the observed behaviour is due to alteration". Alteration could thus produce different compositions and domain states among the mineral grains which in turn could bring about incompatibility amongst otherwise compatible magnetic parameters. The non-destructive methods described above would be useful to identify if a particular rock sample indicates mixed composition and domain states or single uniform composition and one domain state.

4. Conclusions

(i) A high value of coercive force ($>$ 200 mT) at 77 K shown by a basalt may be used for inferring the presence of titanomagnetite grains that are non-magnetic at ambient temperatures.
(ii) Mixed composition and domain states of the magnetic grains commonly present in basalts may cause incompatibility among otherwise compatible magnetic parameters.

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