THERMOREMANENT MAGNETIZATION (TRM) OF LUNAR SAMPLES

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Abstract. The TRM of the lunar breccia 10048–55 and the crystalline rocks 12053–47 and 14053–48 have been investigated. TRM is acquired linearly by 12053–47 and 10048–55 in fields of 100 γ to 1 oe. In contrast, the TRM of 14053–48 departs from linearity in the same range of fields. The AF stability of TRM acquired by the samples varies markedly. 10048–55 and 12053–47 are of intermediate hardness, such as would be expected for a TRM carried at least in part by fine grain particles of iron having high coercivity. 14053–48 has extremely soft TRM which is most probably carried predominantly by multidomain iron. Thermal demagnetization of the TRM of 10048–55 revealed well distributed blocking temperatures, but the TRM of 14053–48 has markedly bimodal blocking temperatures. Comparison of the characteristics of the NRM and the TRM of the three samples suggest that only the NRM of 14053–48 is likely to be primarily thermal in origin.

1. Introduction

Numerous investigators have now reported the occurrence of natural remanent magnetization (NRM) in lunar samples and investigated its stability against AF demagnetization (Doell and Grommé, 1970; Grommé and Doell, 1971; Hargraves and Dorety, 1971; Helsley, 1970, 1971; Nagata *et al.*, 1970, 1971; Nagata and Carleton, 1970; Pearce *et al.*, 1971; Runcorn *et al.*, 1970, 1971; and Strangway *et al.*, 1970, 1971). A variety of stabilities have been found ranging from NRM which is reduced to noise level in a few tens of oersted to that of the microbreccia 10085.13 (Nagata and Carleton, 1970) whose NRM changes very little in demagnetizing fields of up to 500 oe. Strangway *et al.* (1971) suggest that most rocks from the Apollo 11 and 12 collections contain a stable moment which is probably a thermoremanent magnetization.

Thermal demagnetization of NRM has been reported by Grommé and Doell (1971) and Helsley (1970, 1971). The former found that all components of NRM of 12052 and 12063 were destroyed by thermal demagnetization in a vacuum of 5×10^{-6} T to 600 °C and PTRM was not acquired below 200 °C by these rocks after the heat treatment. Helsley (1970, 1971) also noted substantial thermal demagnetization at temperatures considerably lower than the Curie point of iron. Nagata *et al.* (1971) and Pearce *et al.* (1971) have described the acquisition of TRM by Apollo 12 crystalline rocks. Blocking temperatures in excess of 600 °C were found, suggesting that TRM was carried by native iron. Unfortunately, all of these thermal results remain somewhat hard to interpret because of the difficulties associated with the almost inevitable degradation of the specimen during the heat treatment.

While it is not yet clear whether the sole carrier of remanence in lunar rocks is iron, the role of iron alloyed sometimes with small quantities of nickel or cobalt appears to predominate. The occurrence of remanence carried by metallic iron is

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extremely rare in terrestrial rocks, so that the basic data needed for its interpretation are not available from paleomagnetic studies of terrestrial rocks. Nevertheless, the fundamental magnetic properties of iron are well known; in comparison with magnetite, higher coercivities may be expected in single domain particles, but multidomain grains of iron should be markedly softer than those of magnetite.

The NRM of lunar samples was apparently acquired for the most part in fields small compared to the geomagnetic field. Little is known of magnetization processes in such weak fields. In terrestrial rocks, NRM acquired by cooling through the Curie point in the presence of the geomagnetic field has proved to be one of the most valuable forms of NRM for investigating the history of the Earth's magnetic field. Although we do not know that any NRM of lunar rocks has a similar thermal origin, it is probable that thermal remanence does indeed play some role in their NRM. We have therefore investigated the TRM of lunar samples in very weak fields.

The rocks which we have studied are 10048–55, 12053–47 and 14053–48. 10048 is a well-indurated breccia. 12053 and 14053 are igneous rocks. 12053 is a porphyretic basalt. 14053 is a fine grain basalt which is inhomogeneous: olivine and pyroxene concentrations vary on a 1–2 cm scale (NASA sample description). These samples are well characterized magnetically as a result of Nagata's analyses (see Nagata *et al.*, 1971). For convenience, the most relevant results are given in Table I.

TABLE I

Magnetic properties of lunar samples

	10048–55	12053–47	14053–48
Initial susceptibility (χ_0) emu/g	9.6×10^{-3}	0.26×10^{-3}	2.24×10^{-3}
Saturation magnetization (I_s) emu/g	2.10	0.195	2.20
Saturation isothermal remanence (IRM_s) emu/g	1.3×10^{-1}	8×10^{-4}	0.4×10^{-1}
Coercive force (H_c) Oe	50	8	20
Remanent coercivity (H_{rc}) Oe	520	76	80
Natural remanent magnetization (NRM) emu/g	5.6×10^{-5}	0.23×10^{-5}	203×10^{-5}
AF demagnetization field to reduce NRM to 1/eth ($\tilde{H}$) Oe	400	8	20
Curie point (θ) °C.	765	760	765

The effect of heating upon 10048–55 can be seen by observing hysteresis loops and thermomagnetic curves before and after heating. Heating decreases the very soft component in the hysteresis curves and the superparamagnetic fraction in the thermomagnetic curves (Schwerer, private communication). In addition, we noticed that the viscosity of the samples was much reduced by the heat treatment. These observations are consistent with the elimination of some of the very fine grain iron by heating. We do not have directly comparable results for 12053–47 and 14053–48 at present. However, the initial hysteresis and thermomagnetic curves indicate that these samples do not contain as much very fine grain iron as does 10048–55. It might therefore be expected that changes brought about by heating would be smaller.

2. Field Dependence of TRM in Very Weak Fields

2.1. Introduction

The field dependence of TRM in moderate and strong fields is relatively well known for a variety of materials (e.g., Nagata, 1961). A successful theoretical treatment is available for TRM of single domain particles (Néel, 1949). Recently, Dunlop and West (1970) have modified Néel's model to take account of particle interactions which can explain certain discrepancies between the original theory and observations of the field dependence of TRM. Multidomain TRM is less well understood.

We have investigated the field dependence of the TRM of a variety of terrestrial and lunar samples in fields from 20 γ to 1 oe (10^5 γ). The terrestrial samples were the Monturaqui impactite and the Laurel Hill granodiorite. The lunar samples studied were the breccia 10048–55, the crystalline rocks 12053–48 and 14053–47 and glass from 14047–47.

2.2. Experimental technique

To obtain the necessary low field environment, we used a three-stage μ-metal shield to attenuate the laboratory field and a three-axes set of coils inside the shield to give fine control. To minimize oxidation of the lunar samples, the heating was carried out in a vacuum system which was continuously pumped to between 10^{-6} and 10^{-7} T. Samples were held at high temperature for as short a time as was practicable, which was approximately one minute. The temperature was recorded with a thermocouple alongside the tube in which the sample was placed. To monitor sample degradation, control curves of AF demagnetization of saturation IRM and repeat determinations of TRM were made. In this way we are able to record in some detail the progressive decrease of remanence with successive heatings.

2.3. Results

Results for the terrestrial samples are shown in Figure 1, from which it is clear that the TRM process, in these rocks, in fields between 100 γ and 1 oe is linear. Below 100 γ the Monturaqui impactite curve gives some indication of shallowing, which will be of considerable interest if confirmed by later work.

The results for 10048–55 are presented in Figures 2a and 2b. The former shows multiple determinations of TRM. The numbers by the side of the TRM values refer to the heating during which the TRM was acquired. Again, it is evident that to a good approximation TRM is linear. Repeated determinations of TRM reveal systematic decreases in the magnitude of the TRM. Using the first TRM as a base point, we can calculate the % departure from linearity for each successive TRM. In Figure 2b this quantity (ΔJ) is plotted for the various TRM determinations and a clear trend is apparent. No matter what the strength of the inducing field is the percentage departure from linearity increases with each additional heating. Hence, the departure from linearity is evidently a reflection of the progressive destruction of the sample's capability to carry TRM. The effect of heating is greater upon IRM than it is upon

TRM. The carriers which were destroyed were distributed evenly across the range of microscopic coercivities, except for an anomalously large amount in the very low coercivity region. In the light of the change in the thermomagnetic curves reported by Schwerer, it would seem that the most likely explanation is that very fine particles of iron which were close to their blocking temperature at room temperature were destroyed preferentially.

Figure 3 gives preliminary results on the acquisition of TRM by other lunar samples, namely, 12053–47, 14053–48 and glass from 14047–47. The departures from linearity of 12053 and 14047 like those of 10048–55 are small and are probably related to the heat treatment. However, sample 14053–48 exhibits a strong departure from linearity, which is clearly not due to heat treatment, because repeat determinations demonstrate that there is no progressive destruction of carriers of remanence. The observed field dependence of TRM in 14053–48 is similar to the well known hyperbolic tangent relation exhibited by terrestrial rocks in high fields (see for example Nagata, 1961). Such behaviour has also been reported by Syono *et al.* (1962) in their study of the

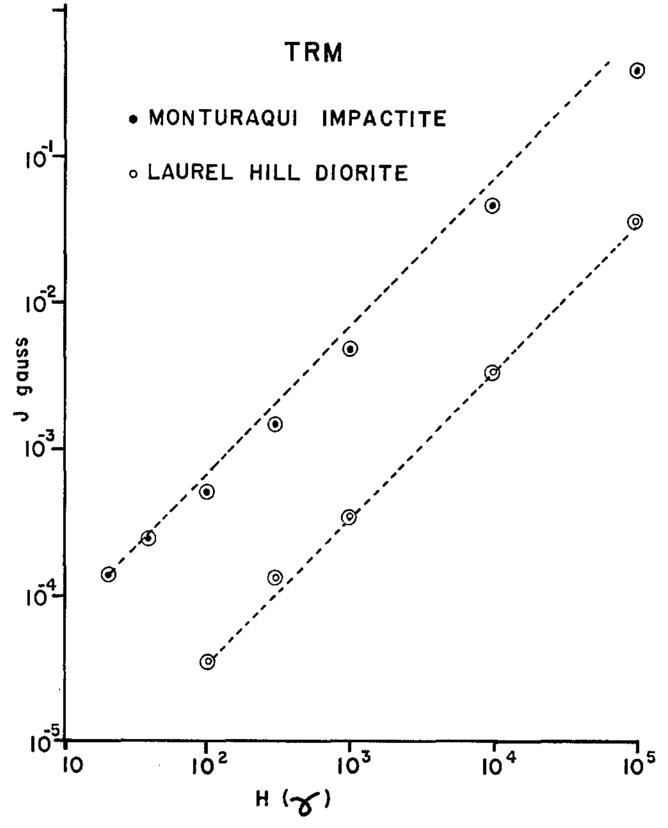

Fig. 1. TRM as a function of field for Monturaqui Impactite and Laurel Hill diorite.

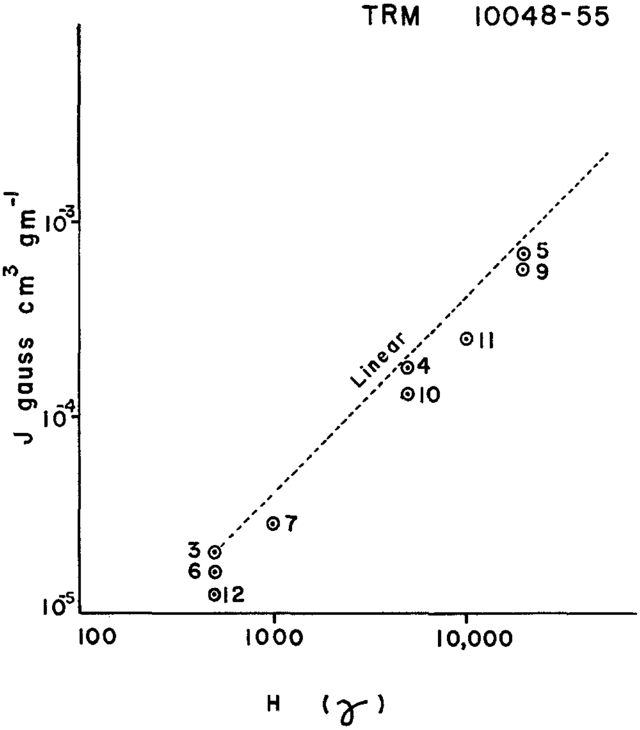

Fig. 2a. Multiple determinations of TRM as a function of field 10048-55.

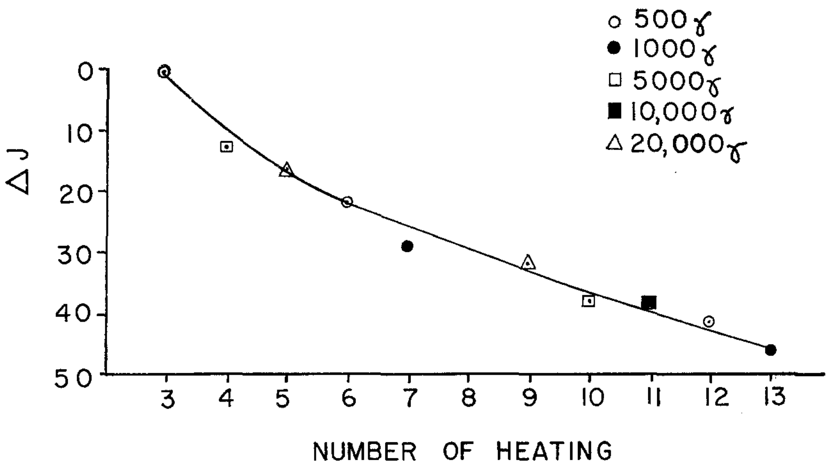

Fig. 2b. Effect of heating upon capability of 10048-55 to carry TRM.

TRM of large single crystals. Nevertheless, it is truly remarkable that the departure from linearity of 14053–48 is apparent at so low a field strength.

In summary, we note that the preponderance of our results indicate that TRM is to a good approximation linear in fields of less than 0.1 oe. Yet, 14053–48 departs strongly from linearity throughout the range of fields investigated and departs from a simple power law relation in fields of a few tenths of an oersted.

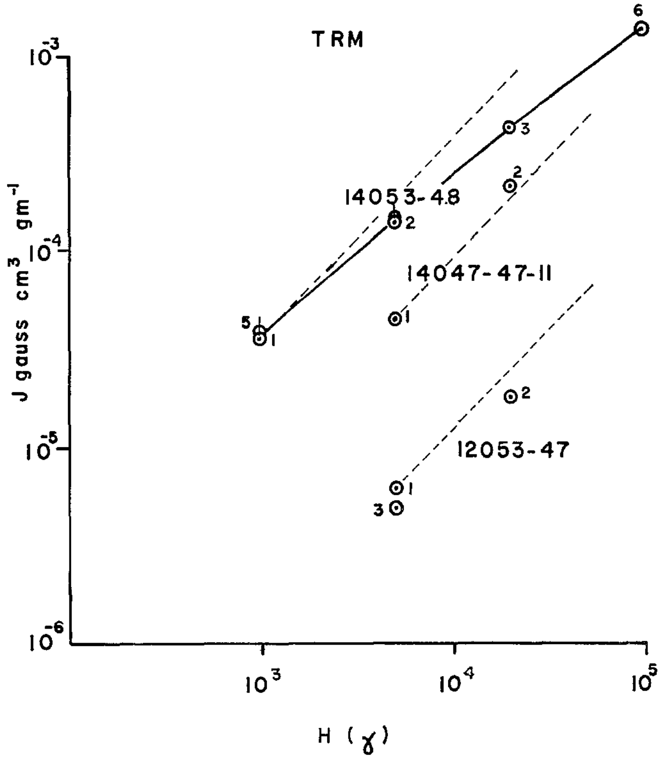

Fig. 3. Preliminary determinations of TRM as a function of field for 12053–47, 14047–47–11 and 14053–48.

3. AF Demagnetization of TRM

3.1. Introduction

AF demagnetization is a common method of analysis of NRM which serves to eliminate undesirable soft contributions to remanence and to discriminate between remanences of different microscopic coercivities. Since the NRM of almost all lunar samples investigated paleomagnetically has been subjected to AF demagnetization, it is important to establish how the TRM of lunar samples demagnetizes so that we may then compare the two forms of remanence. In addition, the dependence of the AF stability of the TRM upon the initial inducing field is a useful characteristic of remanence, which can be used in certain circumstances to distinguish between truly multidomain and fine grain carriers (Rimbert, 1959; Lowrie and Fuller, 1971). We have investigated the stability against AF demagnetization of TRM acquired by the lunar samples in a variety of field strengths.

3.2. EXPERIMENTAL TECHNIQUE

The sample is placed in an alternating field in a region in which steady magnetic fields have been carefully minimized. Meanwhile, it is tumbled in such a way that its orientation changes in a random manner. The magnetization of particles whose coercivity is exceeded by the alternating field follows the field. When the alternating field is decreased the particles acquire remanence controlled by the field as it falls below the coercivity of the particle for the last time. Since the orientation of the sample is changing in a random manner as the field is reduced, these particles give zero net moment. Particles whose coercivities are greater than the maximum peak alternating field unaffected. Hence, the components observed after AF demagnetization have had the soft magnetization preferentially eliminated.

The TRM acquired by 10048–55 and other lunar samples in the experiments described in the previous section were progressively demagnetized by the standard AF method. The demagnetization was carried out in the low field region described previously. A two-axis tumbler was used. Smooth field reduction was achieved with an Inductrol auto transformer.

AF demagnetization of the very weak field TRM of lunar rocks is difficult because the TRM is so small compared with the maximum remanence which the sample can carry; for example the ratio between saturation IRM and the 500 γ TRM for 10048 is 10^4. Thus, anhysteretic remanence is very readily acquired during demagnetization. This noise can be partly eliminated by multiple AF demagnetization for each field value, providing it is acquired isotropically.

3.3. RESULTS

The AF demagnetization of the TRM of the lunar samples varies greatly from sample to sample. The crystalline rock 14053–48 is extremely soft, but the other crystalline rock 12053–47 and the breccia 10048–55 and the glass from 14047–47 are all considerably harder.

Preliminary results suggested that the TRM acquired by 10048–55 in very weak fields was distinctly softer than TRM in higher fields and that hence the AF stability of TRM could be used as a diagnostic criteria for the strength of the inducing field. However, by using multiple demagnetization for each field, with up to ten determinations per field value, we have now established that the stability of TRM in the wide range of fields studied is similar (Figure 4). What may be diagnostic of the inducing field is the value of the demagnetizing field at which repeatability breaks down in multiple determinations at each AF field value. The relative stability of saturation IRM was found to be less than that of the weak field TRM acquired in 20000 and 5000 γ (Figure 5). This coupled with the high microscopic coercivity of the magnetization suggest that remanence is for the most part carried by fine grain iron in the sample.

Samples 12053–47 and the glass 14047–47–11 behave similarly to 10048–55 in that they all acquire TRM of considerable stability over a wide range of inducing fields.

The stability of 14053–48 is so low (Figure 6 and 7) that it is reminiscent of the behaviour of soft magnetic materials, rather than that of the hard materials usually encountered in paleomagnetic studies. It is interesting to note from this point of view that the AF stability of saturation IRM is greater than that of weak field TRM and that the stability of the TRM increases with increasing inducing field. These trends are exhibited by multidomain carriers of remanence (Lowrie and Fuller, 1971). This suggestion would account for its extremely soft TRM.

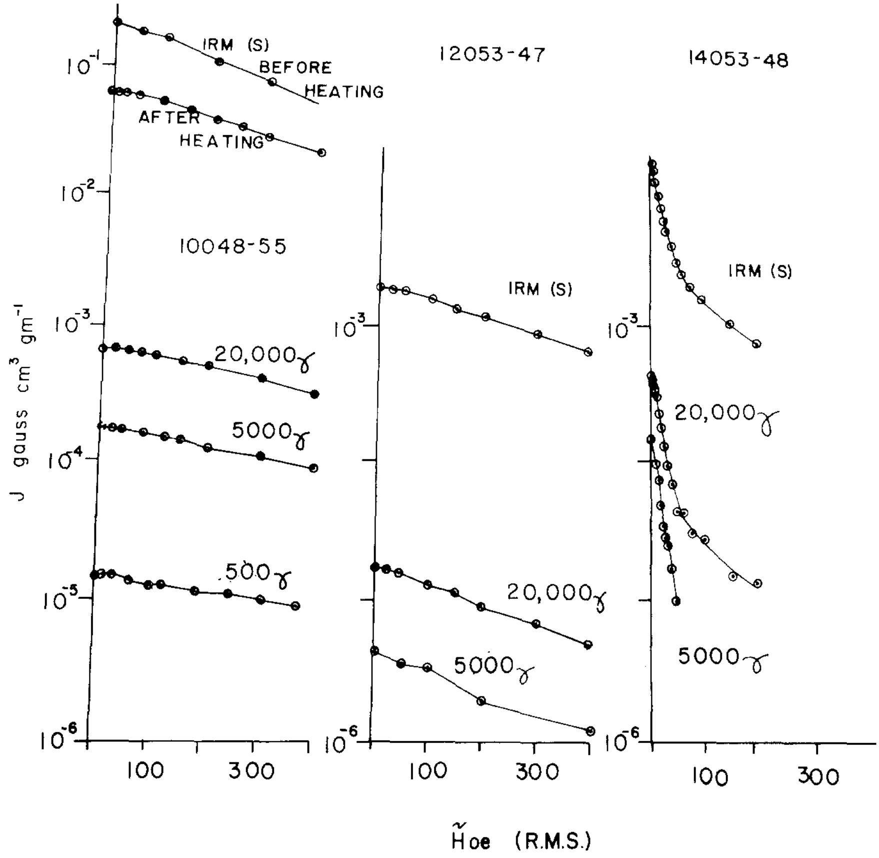

Fig. 4. Alternating field demagnetization of 10048–55, 12053–47 and 14053–48.

From these results, it appears that the breccia 10048–55 and the igneous rock 12053–47 can acquire a stable TRM and that the carriers of this remanence are for the most part fine grain particles with high coercivities. In contrast, the TRM of 14053–48 is extremely soft and is most probably carried predominantly by multidomain iron.

4. Thermal Demagnetization of TRM

4.1. INTRODUCTION

Thermal demagnetization like AF demagnetization of NRM, serves to eliminate noise and to give information concerning the nature of remanence. It discriminates between components of remanence on the basis of their blocking temperature, that is the temperature at which the relaxation time of the remanence of a particle, or of a region in a multidomain sample, becomes long compared with the experiment time.

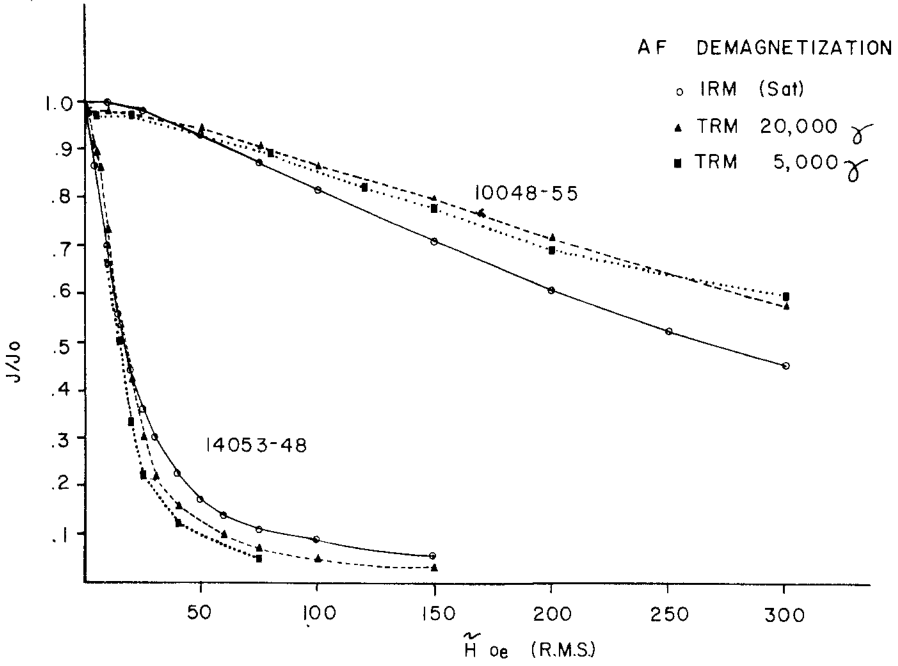

Fig. 5. Normalized alternating field demagnetization curves for 10048–55.

As we noted above, thermal demagnetization of the NRM of lunar samples has proved difficult because of the destruction of the carriers of remanence. However, eventually thermal demagnetization of the NRM of lunar samples will become available and in conjunction with thermal demagnetization of TRM could play an important part in our understanding of the origin of NRM.

4.2. EXPERIMENTAL TECHNIQUE

The sample is demagnetized by thermal cycling in field free space. Components of remanence due to particles whose blocking temperature is exceeded relax at high temperature and give zero net moment on cooling. Remanence carried by particles with higher blocking temperatures is unaffected.

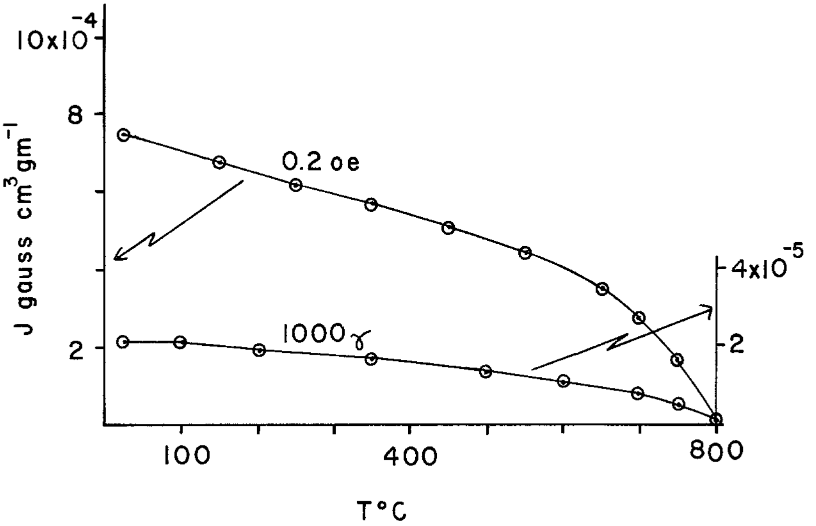

Fig. 6. Thermal demagnetization of TRM of 10048–55.

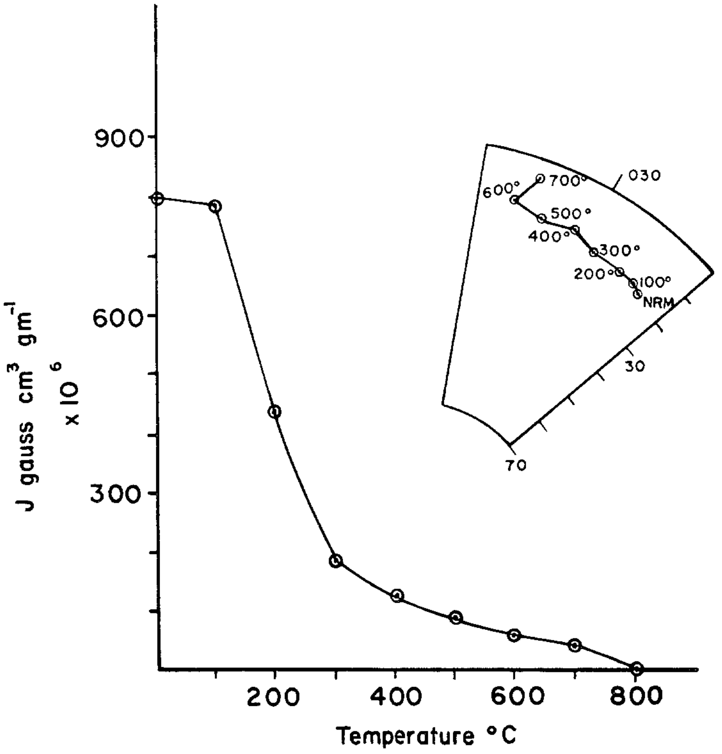

Fig. 7. Thermal demagnetization of NRM of 14053–48.

In thermal demagnetization, one makes use of essentially the same technique utilized in the investigation of field dependence of TRM. It is extremely important to achieve good field cancellation because the TRM process is so efficient. We heated the specimen in the field-free space to avoid the effect of an equilibrium nonzero magnetization at high temperature. The samples were heated in the hard vacuum of 10^{-6} to 10^{-7} T to minimize oxidation.

4.3. RESULTS

Thermal demagnetization of TRM like AF demagnetization has revealed considerable variation in the lunar samples which we have studied. The results of thermal demagnetization of TRM in 10048–55 are shown in Figure 5. The TRM acquired in 0.2 Oe and 1000 γ fields are evenly distributed across the whole range of blocking temperatures from room temperature to the Curie point. In contrast, the TRM acquired by 14053–48 in 1000 γ and 1 Oe fields was carried bimodally in high and low blocking temperatures. This occurrence of low blocking temperature magnetic phases is so marked that the possibility of some low Curie point material is suggested. However, the sample contains plentiful iron and there is no obvious indication of a second magnetic phase. It therefore seems probable that the low blocking temperature TRM is indeed carried by iron. The question which then arises is, why is the blocking temperature so low, if TRM is carried by iron which is multidomain. A possible answer, which we are investigating at present, is that the iron is so soft magnetically that substantial thermal demagnetization can take place hundreds of degrees below the Curie point. Preliminary experiments with high purity iron wire have revealed that multidomain TRM is indeed carried by iron with extremely low blocking temperatures. Hence, we conclude that thermal demagnetization of multidomain iron takes place at low temperatures in 14053–48. However, we have observed unexplained recovery of remanence in high temperature demagnetization so that further work is required before a satisfactory interpretation of the remanence of 14053–48 can be given.

5. Comparison of NRM and TRM of Lunar Samples

In comparing the characteristics of the NRM and TRM of the samples with which we have worked, it is clear that the NRM of 10048–55 and of 12053–47 is quite different from TRM, while the NRM and TRM of 14053–48 are similar.

The AF demagnetization of the NRM of 10048–55 (Nagata *et al.*, 1970) revealed a component which was demagnetized within a few tens of oersted. Associated changes in direction took place in low fields and in higher fields no consistent direction was observed. In contrast the AF demagnetization of TRM revealed a hard magnetization. It therefore seems unlikely that the NRM of 10048–55 is predominantly due to TRM although the possibility of a weak stable moment due to TRM cannot be discounted. Unfortunately, no thermal demagnetization of NRM is as yet available.

The AF demagnetization of 12053–47 is similar to that of 10048–55 except that the NRM is still softer than that of the breccia. Again the possibility of a weak stable moment occurs but we have no evidence of it at present (Nagata *et al.*, 1971). No thermal demagnetization of NRM is available.

The AF demagnetization curves of TRM and NRM of 14053–48 are similar. Both are extremely soft. Moreover the thermal demagnetization of NRM is also similar to that of the 1000 γ and 1 oe TRM, although the TRM is blocked at slightly higher temperatures than is the NRM. There was only a relatively small change indirection during the thermal demagnetization of NRM, which suggests that magnetization blocked at high and low temperature was acquired in similar fields and probably by the same process at approximately the same time. It is curious that there is no NRM blocked between room temperature and 100 °C. If subsequent thermal demagnetizations of NRM show this to be a general feature of lunar samples, it will be convincing evidence of demagnetization by thermal cycling in the present weak fields on the lunar surface. Provisionally, we interpret the NRM of this sample to be thermal in origin.

It is possible to extend the comparison of TRM and NRM of the lunar samples by using results reported by other workers. Thus the AF stabilities of TRM of 12063–55 and 12021–106 are given by Pearce *et al.* (1971) and Strangway *et al.* (1971), respectively. The stabilities are comparable to those of 10048–55 and 12053–47. Thus, in these samples demagnetization in fields of 200 or 300 oe brings about substantial decreases in remanence. We therefore now know that variation in stability of TRM extends at least from the intermediate hardness of 10048–55, 12053–47, 12021–106 and 12063–55 to the extremely soft TRM of 14053–48.

In turning to the AF demagnetization curves of the NRM which have been reported, we see that although most of the curves lie within the broad range of stability defined by observations of the stability of TRM, others do not. In particular, the AF demagnetization curves of NRM of 10047, 12063 and 12065 reported by Hargraves and Dorety (1971) and those of 12002, 12017, 12021, 12038, 12051 and 12063 reported by Strangway *et al.* (1971) reveals NRM which is more stable than any TRM which we have observed.

6. Field Test of Stability of NRM

In the face of the obvious difficulties in interpreting the NRM of lunar samples and the importance of establishing whether the NRM represents magnetization acquired at the time of origin of the rocks, field tests of the stability of NRM such as those introduced into paleomagnetism by Graham (1949) are highly desirable. Strangway *et al.* (1971) have tried to apply a test, which is somewhat analogous to the Graham conglomerate test. They refer the NRM of lunar samples (when possible) to a lunar coordinate system and test for random orientation. Preliminary analysis of the inclination of NRM reveals substantial scatter between samples. This suggests that magnetization was not acquired by the rocks on the surface in their observed orientation, but rather that the samples acquired a stable magnetization before coming to their present positions.

A second test is made possible by the occurrence of glass spatter on certain rocks, because there is a great difference in age between the glass and rock. If one compares the NRM of the glass with that of the rock on which it is found, two distinct magnetic events should be recorded, if the rock acquired stable NRM at its time of origin. Glass on 14047–47 is capable of carrying IRM and TRM. Unfortunately, we have not yet been able to prepare a large enough sample of the glass to measure its NRM so we can only set a crude upper limit of 10^3 γ on the field in which NRM was acquired.

7. Conclusions

It is clear that at this early stage of our investigations conclusions must be limited. At present, we have good evidence that the NRM of 10048–55 and 12053–47 is not predominantly thermal in origin. In contrast, the NRM of 14053–48 may be essentially thermal. If this interpretation is correct then a field of several tenths of an oersted existed in the immediate vicinity of this rock as it cooled. On the other hand, since this rock has revealed anomalous thermal demagnetization, its NRM may include a component of unknown origin which has been misidentified as TRM. Neither of these possibilities give one much confidence in inferring the magnitude of a planetary wide lunar field from the NRM of this sample. The origin of the soft magnetization in the NRM of 12053–47 and 10048–55 is not at present clear. It may be due to processes taking place relatively recently on the lunar surface, yet such a process would be remarkable in that it must generate or harden remanence (Helsley, 1971; Butler and Cox, 1971) in fields which are at present less than are frequently used in laboratory demagnetization experiments.

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