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Review of Effects of Shock (< 60 kbar; < 6 $\times$ 10^{9} Pa) on Magnetism of Lunar Samples

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Review of effects of shock (< 60 kbar; < 6×10^9 Pa) on magnetism of lunar samples

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Experimental shock studies of highland and mare soils in the range of a few to 50 kbar (5×10^9 Pa) have given the following results:

(1) Shock, if less than 20 kbar, does not change the magnetic characteristics of the soil substantially and only weak and unstable shock remanence is generated in a field of 0.5 Oe.

(2) Shock of between 20 and 50 kbar lithifies the soil and gives rise to stable shock remanence. Acquisition is approximately linear in field for a given shock level. At 30 kbar the acquisition parameter for the highland soil was 10^{-5} G cm^3 g^{-1} Oe^{-1}. In this range of 20–50 kbar the products of shock are petrologically and magnetically similar to certain regolith breccias.

(3) Shock demagnetization preferentially demagnetizes the softer part of thermoremanent magnetization (t.r.m.) and hence makes it relatively harder.

The significance of these results is that shock remanence is likely to be the cause of the natural remanent magnetization (n.r.m.) of certain regolith breccias and shock may modify the primary remanence of other samples.

Introduction

The principal problem in lunar magnetism is to account for the surprisingly large magnitude of the remanent magnetism of lunar surface material, which is far greater than can be explained by acquisition in fields comparable to those presently observed in the vicinity of the Moon. Attempts to resolve this problem have defined three areas of research. First, there is the identification and characterization of the magnetic phases in the samples. Secondly, there is the analysis of their natural remanent magnetization (n.r.m.) and the investigation of possible mechanisms of magnetization. Finally, there is the question of the intensity and origin of the fields in which the n.r.m. was acquired.

It was soon established that the most important magnetic phase in the samples is metallic iron which is sometimes alloyed with up to 10% by mass of nickel (Nagata *et al.* 1970; Strangway, Larson & Pearce 1970). There remains, however, difficulty in explaining the distribution of the magnetic phases in the various types of samples and most particularly in accounting for the excess iron found in mare soils and breccias compared with the mare basalts from which they are derived (e.g. Cisowski, Fuller, Roses & Wasilewski 1973; Cisowski *et al.* 1974; Housley, Grant & Paton 1973; Kieffer 1975; Nagata *et al.* 1974; Pearce, Strangway, & Gose 1972). Hysteresis parameters demonstrate that the recrystallized breccias and the crystalline rocks carry predominantly multidomain and pseudo-single domain magnetic phases. In contrast, in the soils and soil-like breccias, the ferromagnetic material is mostly finer and super-paramagnetic or single domain. Since stable remanence is carried most efficiently by the finer iron, some breccias, which have a relatively high ratio of single domain to super-paramagnetic iron are efficient carriers of stable remanence (Gose, Pearce, Strangway & Larson 1972).

The primary n.r.m. of a sample, acquired at the time of its formation, may be affected by subsequent lunar processes and by magnetic contamination. Nevertheless, the demagnetization characteristics of the samples demonstrate that stable lunar remanent magnetism is carried. Hence, it is likely that in some rocks we do study relatively unperturbed primary n.r.m. In others the subsequent processes may have been sufficiently energetic to modify this stable primary remanence. The most important process of this type appears to be impact-related shock metamorphism.

The problem of inferring the intensity of the inducing field in which n.r.m. is acquired is not simple even in terrestrial samples. In working with lunar samples, two severe difficulties are encountered. First, the mechanism of magnetization is frequently not unequivocably established and, secondly, when the samples are heated it is extremely difficult to avoid irreversible physicochemical effects which invalidate the most important techniques. However, it already appears very likely that there was a wide range of intensity of lunar inducing fields, including fields of up to about one oersted. It has been suggested that the variation is systematically related to the age of the samples (Collinson, Runcorn & Stephenson 1975).

In this paper, attempts to establish the effects of shock upon the magnetic characteristics of lunar samples, and to see what the implications of these effects are for an understanding of lunar magnetism and lunar regolith processes are reviewed.

Shock experiments

Techniques and results

The experimental techniques which have been used to shock the lunar soil have already been described (Cisowski *et al.* 1973, 1974). For the lower pressure range of a few kilobars an air gun has been developed. In these experiments, the modification of the magnetic characteristics of the soil and the acquisition of shock remanence (s.r.m.) have been studied.

The effect of shock is to increase the saturation remanence and the remanent coercivity of both highland and mare soil. The highland soil has a higher initial remanent coercivity than the mare soil and does not change so much upon shocking. The relative changes in saturation remanence are similar in the two samples; the mare soil has a slightly higher initial and final value.

The acquisition of shock remanence (s.r.m.) in the same pressure range is illustrated in figure 1. In the lowest range, the mare soil acquires s.r.m. more efficiently, but from about 30 kbar there is little distinction. Both soils have changes of slope in their s.r.m. acquisition curves at about 20 kbar. The highland soil exhibits a remarkable increase of s.r.m. between 20 and 30 kbar. Considered in conjunction with the earlier experiments (e.g. Cisowski *et al.* 1974), these results define a pronounced knee in the acquisition curve in the region of 50 kbar. It was demonstrated earlier (Cisowski *et al.* 1974) that acquisition of s.r.m. at a particular shock level is approximately linear in field.

The stability against alternating field (a.f.) demagnetization increases with increasing shock pressure from 19 to 50 kbar. If these results are compared with the earlier flying plate results, it then appears that the trend of increasing stability with increasing pressure may reverse at between 50 and 75 kbar.

The stability of shock remanence against thermal demagnetization was investigated for highland soils shocked to 50 kbar in a gun experiment and to 100 kbar in an explosive experiment.

Neither remanence is particularly stable against thermal demagnetization, being comparable to that of a partial thermo-remanence (p.t.r.m.) acquired in the Earth's field, from 350 °C to room temperature.

In addition to its role as a mechanism of magnetization, shock should act as a demagnetization mechanism if a sample carrying remanence is shocked in weak field. To investigate this effect, a highland sample was first given a t.r.m. and then shocked. Even in the Earth's field, demagnetization ensued. To study the nature of the demagnetization a control sample was given a t.r.m. and its a.f. demagnetization characteristics established. It was then apparent (figure 2) that the demagnetization brought about by the shock was primarily of the magnetically soft part of t.r.m. Thus the composite magnetization after shock was relatively harder than the original t.r.m.

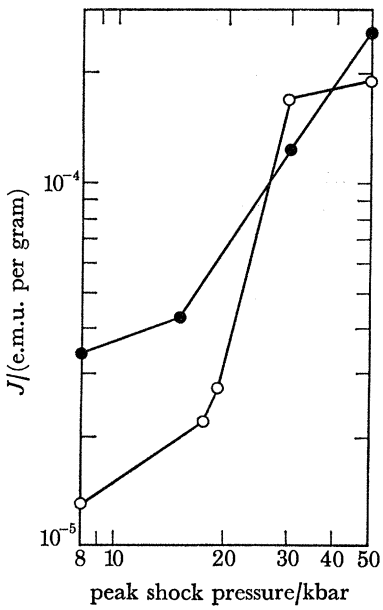

FIGURE 1

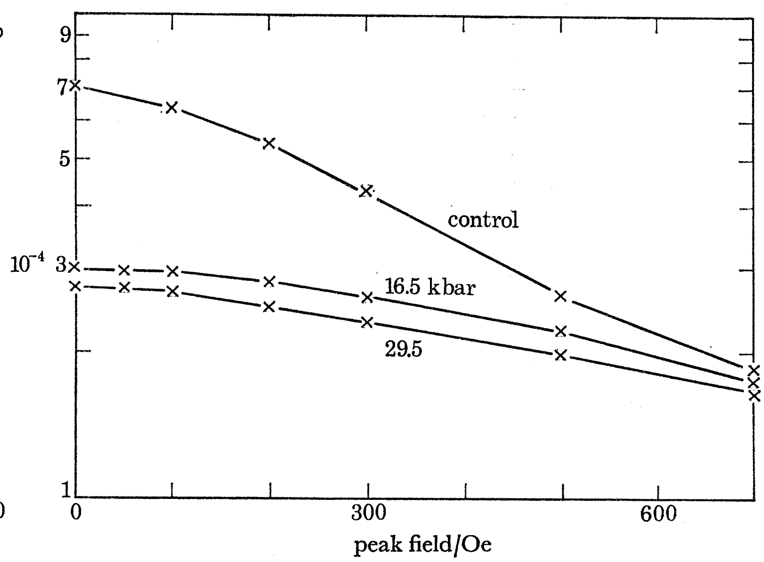

FIGURE 2

FIGURE 1. Acquisition of remanence by soils in shock experiments carried out in 0.5 Oe magnetic field. ●, 75061-10 Mare soil; ○, 65901-10 Highland soil.

FIGURE 2. Shock demagnetization and shock hardening of t.r.m. in powdered mare basalt (12053)

DISCUSSION

It is evident from our work, that of Christie *et al.* (1973), and that of Ahrens & Cole (1974) that the process of breccia formation can take place at relatively low shock pressures of some tens of kilobars. Ahrens & Cole (1974) suggest that the shock compression of the soil is completed by 20 kbar. The change in the curves of acquisition of s.r.m. at about 20 kbar may be related to this effect. The change in slope should signal the onset of a different process, which is likely to be shock welding. In the higher shock range of about 50 kbar, shock welding modifies the magnetic characteristics of the sample significantly. In this range, the s.r.m. which is acquired is stronger and more stable than that in the range of less than 20 kbar. The petrologic similarities between the experimentally shocked soils and certain of the lunar breccias has already been established by Christie *et al.* (1973), who showed that the 'unmetamorphosed' or weakly 'metamorphosed' regolith breccias (Chao, Minkin & Best 1972; Chao 1973) are simulated well by the shocked soil.

In plots of n.r.m. against saturation isothermal remanence (s.i.r.m.) the regolith breccias fall in the region of high s.i.r.m. with variable n.r.m. (figure 3). They have somewhat comparable s.i.r.m., which distinguishes them from the recrystallized breccias whose systematically lower values of s.i.r.m. are no doubt in part due to the coarser grain size of their ferromagnetic

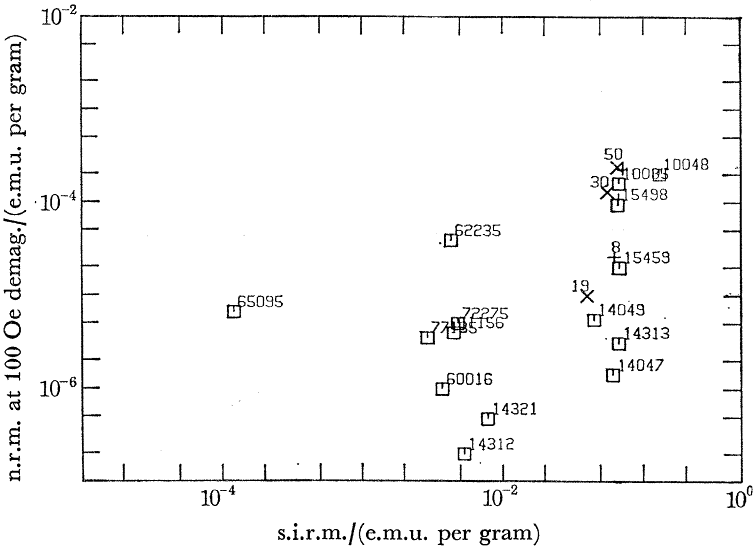

FIGURE 3. Natural remanent magnetization of breccia versus saturation isothermal remanent magnetization for breccias (⊡), experimentally shocked soil (×, highland; +, mare).

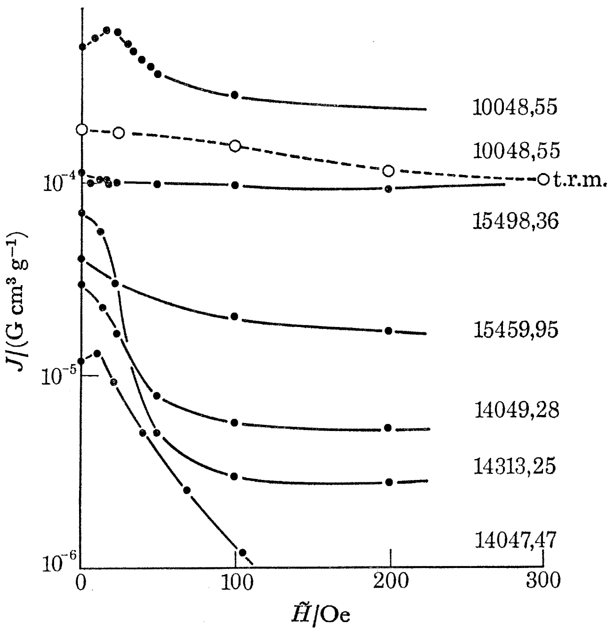

FIGURE 4. Stability of n.r.m. of regolith breccias against a.f. demagnetization, --○--, t.r.m. of 10048,55.

phases. According to magnetic hysteresis criteria, the regolith breccias are very similar to the soils, although some have higher remanent coercivity (see Nagata *et al.* 1972*a*, Fuller, Wu & Wasilewski 1975). In figure 3, we have also plotted the s.r.m. acquired by the soils in the shock experiments which were carried out in fields of 0.5 Oe. In figure 4 the a.f. demagnetization characteristics of the n.r.m. of the samples in the group defined by their high s.i.r.m. are shown and we see that the samples such as 14047, which have the least indication of shock metamorphism, have the weakest and least stable n.r.m. Unfortunately, there is little documentation of the stability of the n.r.m. against thermal demagnetization. However, it appears that the stability of 15498 (Gose, Strangway & Pearce 1973) is greater than would be predicted from the analogy of the s.r.m. obtained in the shock experiments. It does, however, appear that some of the range of observed n.r.m. in these regolith breccias may well be due to the different degree of shock metamorphism involved in their formation.

The n.r.m. and the magnetic characteristics of regolith breccias are consistent with the suggestion that they represent a sequence of samples in which progressively increasing shock of some tens of kilobars has given a correlated progressive increase in n.r.m. and in its stability. Unfortunately, the mechanism of shock remanence is not yet understood, and one therefore does not know what role is played in this magnetization by heating associated with shock. Nevertheless, it does seem possible that the n.r.m. of these samples may have been caused by the process of breccia formation by shock welding.

Natural remanent magnetism and the intensity of the ancient lunar fields

In order to recover the intensity of the fields in which the lunar samples acquired their n.r.m., one must first calibrate the n.r.m. in terms of the amount and nature of the ferromagnetic carriers present in the samples and in terms of the magnetization process by which n.r.m. was acquired. The documentation of the magnetic characteristics of the lunar samples gives some indication of what may be involved in the calibration for material. In some lunar samples, n.r.m. may not be a reliable indicator of the ancient fields because of peculiar magnetic effects (Wasilewski 1973). In particular, one should be somewhat suspicious of the n.r.m. of the samples, which show the anomalous low temperature effects (Nagata *et al.* 1973), since they point to some poorly understood behaviour of the magnetic material in the samples. Nevertheless, there are other samples, such as some of the mare basalts and recrystallized breccias, whose magnetic carriers appear to be relatively pure iron and whose history since cooling through their Curie point at the time of formation may have been straightforward. It seems very likely that they initially carried a primary thermo-remanent magnetization which may have been preserved relatively unperturbed subsequently. Other samples such as the regolith breccias, which we interpret to be shock lithified, must be calibrated in accordance with the magnetization process involved in their formation, which was almost certainly not a pure thermo-remanence.

Calibration for both material and process is carried out in terrestrial paleomagnetism by the Koenigsberger-Thellier-Thellier experiment (KTT: Koenigsberger 1938; Thellier & Thellier 1959). The n.r.m. is compared with a laboratory thermo-remanence acquired in a known field. Two lunar KTT experiments have been reported. One by Gose *et al.* (1972) gave a field of 2100 ± 80 nT, which was later reinterpreted by Collinson *et al.* (1975) to give 7000 nT.

The other determination which was by Collinson, Runcorn & Stephenson (1974) gave 1.2 Oe for the crystalline or recrystallized breccia sample 62235,35.

The difficulties of carrying out the KTT experiment with lunar samples, due to oxidation of the metallic iron in the heating involved in the experiment, have led to attempts to simulate thermo-remanence used in the KTT experiment with anhysteretic remanence (a.r.m.). The main justification of this procedure is that the a.r.m. and t.r.m. are somewhat similar types of magnetization. Both are readily acquired in weak d.c. fields. The efficiency of the magnetization process is enhanced compared with an isothermal remanence, in the one instance by heating the sample, and in the other by the applied alternating field. Two different approaches have been used (Banerjee & Mellema 1974; Collinson *et al.* 1974). A number of samples have now been analysed in this way and Collinson *et al.* (1975) have presented data showing a gradual decay of the field from 4.2 to 3.3 Ga. Comparisons between the a.r.m. and KTT experiments for 62235,35 give 1.4 and 1.2 Oe respectively, so that there is good agreement for the two methods using this sample. The chief uncertainty in the method lies in the factor f' defined as

$$\partial \text{t.r.m.}/\partial H = f' \, \partial \text{a.r.m.}/\partial H.$$

Values of 1.28 and 1.40 were obtained experimentally and a value of 1.34 used.

Only two KTT experiments have been completed and even the number of a.r.m. simulations of the experiment remains small. In light of this situation, which is likely to persist for a while, it seems sensible to see if some calibration can be achieved for the many samples for which analyses of n.r.m. and of magnetic characteristics are available. Such a method would have to be very simple and rely on the somewhat minimal studies completed on some samples. A possibility which has been used (Cisowski *et al.* 1975) is to normalize with the saturation i.r.m., which is given by most experimenters and is a measure of the amount of remanence a sample can carry. This is likely to be a crude analogue of low field remanence, but it can be improved by utilizing our understanding of the magnetic characteristics of the samples so that only the most favourable samples are used.

Before applying this method of calibration to estimate lunar field strengths, it is necessary to establish the nature of the n.r.m. analysed. The n.r.m. of the mare basalts and the recrystallized breccias should be thermo-remanent, with possible subsequent shock demagnetization. Using the calibration discussed above, one would estimate a range of inducing fields of the order of 10^2–10^3 nT for the mare basalts with 15597 indicating an anomalously large field of 10^4 nT. The highland crystalline rocks give lower fields and a range of 500–5000 nT. Preliminary results for individual orange soil particles are also shown and give a somewhat consistent value of a few tenths of an oersted. The breccias are distinctly grouped by their s.i.r.m. For both of the two predominant values of s.i.r.m., there are considerable ranges of n.r.m. which, if interpreted as of thermo-remanent origin, imply ranges of fields from tens to 10^4 nT. It is likely that at least some of the range of n.r.m. in the regolith breccias is due to the variation in the process of their formation and the associated primary magnetizations.

In attempting to interpret the inducing fields in which the regolith breccias were magnetized, one can make use of the shock experiments to give a calibration similar to the t.r.m. calibration. However, the shock level experienced by the samples is now known precisely, so that there are two unknown parameters, the field and the intensity of shock. Some indication of shock range does come from the magnetic characteristics of the samples. Thus a sample such as 14047 is unlikely to have experienced a shock of several tens of kilobars by analogy

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with our experimental results. Its acquisition parameter for n.r.m. should therefore be similar to those observed in the range of less than 20 kbar, i.e. between 2 and 5×10^{-5} G cm^3 g^{-1} Oe^{-1}. Its n.r.m. would then imply an inducing field of the order of 10^3 nT. Thus, the lower end of the field range is increased by the interpretation of the n.r.m. as a shock remanence. 15498, which is interpreted by Christie *et al.* (1973) as a shock-lithified sample, has been used by Gose *et al.* (1973) for a KTT analysis which implies a thermo-remanent magnetization. It is still not clear to what temperature this sample was heated by the shock. Indeed, Gose *et al.* (1972) suggested such samples were formed by heating in thermal blankets so that shock is not involved. We prefer the interpretation that 15498 was formed from local soil by shock event. This leads to the suggestion that the n.r.m. is not a true t.r.m., but a mixture of s.r.m. and partial t.r.m. acquired somewhat inhomogeneously throughout the sample. It appears that a p.t.r.m. acquired from about 600 °C is consistent with the data from the KTT experiment. This would imply a field of the order of 10^3 nT. If the n.r.m. is entirely shocked without any significant thermal contribution, then the field estimate would increase somewhat but not by as much as an order of magnitude. In interpreting this n.r.m. we clearly encounter the difficulty that the thermal regime and the simulation of the lunar shock by our experiment is not understood in detail. It is our interpretation that the n.r.m. of the regolith breccias could have been acquired in fields of the order of 10^3 nT and that the large range in n.r.m. is due to variations in degree of shock, including associated heating experienced in formation.

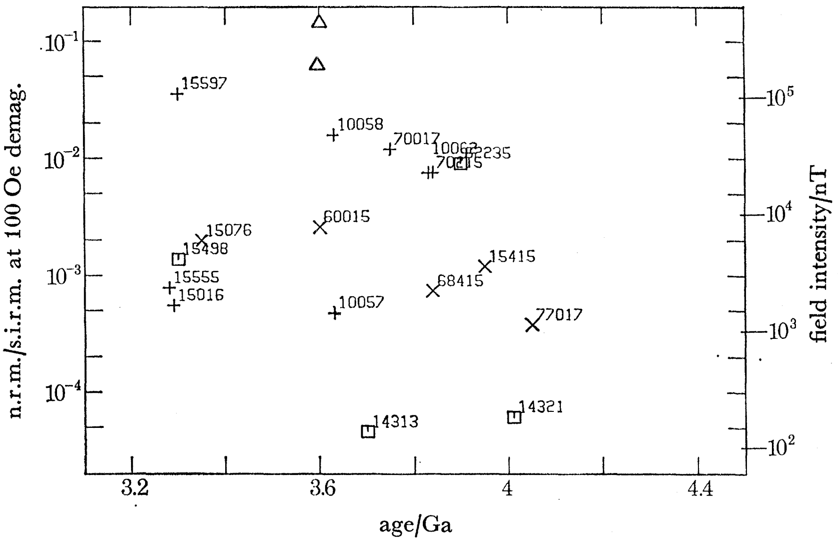

FIGURE 5. N.r.m. calibrated by the s.i.r.m. method to give estimates of ancient field intensity against age. Mare basalts (+), highland crystalline rocks (×), breccias (□), orange soil spherules (△).

The main conclusion to be drawn from these attempts to calibrate n.r.m. in terms of ancient lunar field is that a considerable variety of inducing fields is implied. It is natural to attempt to correlate this variability with the age of the sample. It was noted earlier that there does not appear to be any marked correlation with age (e.g. Fuller 1974). However, recently Collinson *et al.* (1975) have strongly canvassed the view that from 4.2 to 3.3 Ga the intensity of the lunar field gradually decreased. Their suggestion is based upon the ARM calibration method. We have therefore looked again at the more extensive data set obtained from an s.i.r.m.

normalization method (Cisowski *et al.* 1975) to see if there is evidence of such behaviour of the ancient lunar field.

The results of s.i.r.m. normalization are plotted against the age of the rocks in figure 5. The results can be calibrated in terms of ancient lunar field intensity, by independent t.r.m. experiments with rocks which are the most suitable for such an experiment (Fuller 1974). However even the most suitable lunar rocks exhibit irreversible changes of their magnetic phases on heating and therefore this calibration cannot give an accuracy of better than about a factor of five. Since it is unclear that the n.r.m. of breccias is a simple t.r.m., these samples should be excluded from the field estimates for the present. Even after exclusion of the breccia samples, it is clear that there are still young rocks (15597) which imply high lunar intensities and old rocks which imply low field intensities, in contradiction to the trend proposed by Collinson, Runcorn & Stephenson (1975). Nevertheless, there is some tendency for the older mare basalts, which are from the Apollo 11 and 17 sites, to give higher field intensities than the younger Apollo 15 basalts. However, there is such a large range of field intensity implied by rocks of the same age, that the next important step is to understand the cause of this variability. Some of it is presumably due to shock demagnetization of primary n.r.m. If it were possible to make allowance for such effects, the estimates of field intensity might be refined. At present it is simply clear that many lunar rocks acquired n.r.m. in fields of between 10^3 nT and 1 Oe.

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