NATURAL REMANENT MAGNETIZATION STUDIES OF A LAYERED BRECCIA BOULDER FROM THE LUNAR HIGHLAND REGION

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(Received 8 August, 1975)

Abstract. The average directions of natural remanent magnetization (NRM) of three texturally distinct layers (72215, 72255, and 72275) of a 2 m-sized breccia boulder were found to be the same, while the directions of their stable components of NRM were found to be widely divergent. One clast from 72275 yielded a stable NRM direction which was different from that of the matrix. Approximate paleointensity measurements showed that 72255 and 72275 could have obtained their stable remanence from an ancient magnetic field of the same magnitude. However, 72215 probably was magnetized by a magnetic field of a different intensity. We concluded that the coincident NRM directions owe their origin to a secondary imprint of less stable magnetization imparted during the assembly of the boulder at moderate temperatures (~450 °C) on the South Massif. The stable directions, on the other hand, date from the last, higher-temperature (~770 °C) magnetizing event experienced by the mineral and lithic components while they were part of the immature pre-Serenitatis regolith.

1. Introduction

During Apollo-17 EVA the astronauts observed a boulder-strewn field at Station 2 near the South Massif. The boulders were identified as brecciaboulders, and it was assumed, on the basis of field evidence, that these boulders had rolled off the sloping (20°) wall of the South Massif. The massif itself appears to be composed of layered breccia. The initial interpretation of the origin of these boulders has withstood further analysis; for a detailed field geologic interpretation, the reader is referred to the papers by Schmitt (1975) and Wolfe (1975). One specific boulder (Boulder 1, Station 2, hereafter referred to as Boulder 1) was unique because of its obvious pseudo-stratigraphy. It is about 2 m in size and has five or more layers, each of which ranges in thickness from 10 to 50 cm. It has been clearly determined that Boulder 1 is *not* a soil-breccia; it contains white anorthositic clasts with dark halos. Boulder 1 may represent very early crustal material which was later re-worked, and thus provides an opportunity to study the processes at work in early lunar history and their effects. An interdisciplinary consortium under the leadership of J. A. Wood was formed to study the various physico-chemical and geologic aspects of the above problem. The present contribution represents the results of a magnetic study.

It is perhaps appropriate to mention at the outset the strengths and weaknesses of the magnetic method of studying a complex layered boulder. The natural remanent magnetization (NRM) of a breccia sample is expected to be a combination of at least

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The Moon **14** (1975) 473–481. *All Rights Reserved*

two types of magnetization: (1) a primary thermoremanent magnetization (TRM) imparted during cooling from above 770 °C (the Curie point of iron) in an ambient magnetic field and (2) a secondary shock-induced piezoremanent magnetization (PRM) applied at lower temperatures. Although Fuller (1974) has shown that shock-induced PRM in a lunar soil can, on occasion, have high thermal stability, shocked igneous rocks (Hargraves and Perkins, 1970) usually acquire a 'soft' remanence which can be selectively demagnetized using a low peak value of alternating field (AF) or moderate ($\sim$250 °C) temperature in a field-free environment. Like radiometric ages, the TRM of a rock can be 'set' a number of times when discrete thermal events take place. However, unlike radiometric ages, there is no way to determine the sequence of application of various TRMs to a rock in absolute time. The special strength of the magnetic method lies in the vectorial nature of the data: the directions of remanent magnetization from oriented sub-samples of a large boulder, such as Boulder 1, can yield information about the contemporaneity (or lack of contemporaneity) of the magnetization process. Conversely, if it is established from non-magnetic data that the sub-samples cannot be contemporaneous, the directions can yield important information about time fluctuations in the ambient magnetic field.

Finally, there is a special reason for studying the remanent magnetization of the oriented sub-samples from Boulder 1. This was one of the first occasions when at least roughly oriented sub-samples were available, as a result of the lunar sample analysis program. Until this time it was not possible to make a study of the spatial variations of NRM recorded in lunar rocks. Under suitable conditions such a study can yield valuable information about the origin of the lunar magnetic field. Previously we have published (Banerjee, 1974; Banerjee and Swits, 1974) details of the NRM and other rock magnetic data. In the present paper we have attempted a synthesis of the magnetic data and a discussion of the magnetic data in terms of the formation history of Boulder 1 as determined from other, non-magnetic data.

2. Directions of Remanent Magnetization

Natural remanent magnetizations (NRMs) from the 'matrix' of three visible layers (72215, 72255, and 72275) of Boulder 1 were measured using a Schonstedt Spinner Magnetometer. The word 'matrix' is used here to denote that the sub-samples did not contain visible mm- to cm-sized clasts. Along with Schmitt (1975) we believe that the three apparent layers are themselves large, flattened-out pods or clasts. The details of the orientation, measurement techniques, and descriptions of the magnetic carriers can be found in Banerjee (1974). All the 72215 sub-samples we studied were lithologically classified as grey competent breccia (GCBx). 72255,23 is also GCBx, while 72255,36 is mostly GCBx, containing a small piece of a coarse norite (CN) clast. All the 72275 sub-samples we studied are classified as light friable breccia (LFBx).

The sub-samples varied in weight from 1 to 3 g. The NRM values of all the 72215 and 72255 sub-samples were of the order of 10^{-5} emu g^{-1}, while the 72275 sub-samples were of the order of 10^{-4} emu g^{-1}. This order of magnitude difference in NRM intensity is due partly to a larger iron content (Table I) and partly to the presence of the more stable carriers of remanence in 72275 (as determined by the saturation magnetization and AF-stability measurements; Banerjee and Swits, 1974). We have pointed out previously (Banerjee and Swits, 1974) that compared to the usually observed inhomogeneity of NRM intensity in sub-samples that may be only 1 cm apart from each other, the present breccia sub-samples are distinguished by their homogeneity. In addition, storage tests in zero field for periods extending to 100 days failed to show the signs of viscous decay of NRM, a characteristic of unstable magnetic carriers. Taken together, the above observations indicate the likelihood of obtaining undisturbed, high-integrity NRM in the sub-samples from Boulder 1.

TABLE I

Fe° content as determined from J_s measurements.
J_s of pure Iron=213 G-cm^3 g^{-1}

Sample No.	J_s (G-cm^3 g^{-1})	Fe° content (wt. %)	Average
72215,26	0.19	0.09	
72215,56	0.51	0.24	0.19
72215,62	0.48	0.22	
72255,33	1.5	0.70	
72255,36	1.79	0.83	0.76
72275,46	3.26	1.52	
72275,47 (1)	4.47	2.08	1.69
72275,47 (2)	2.70	1.26	
72275,56	4.09	1.90	

Figure 1 shows the NRM directions in lunar coordinates obtained from the three rocks mentioned above in equatorial projection. The solid symbols represent NRM vectors pointing down; the open symbols represent vectors pointing up. 95% cones of confidence have been drawn about the mean directions (larger symbols) for each rock (or 'layer' in the composite boulder). Note that all the directions are in the NE quadrant and that the 95% cones of 72275 and 72255 intersect one another. Although the absolute orientations of the individual sub-samples may be in error by ±20° (if not more), it is clear on the basis of Figure 1 that the average NRM directions of the three layers of Boulder 1 are the same. With the single exception of 72255,36, which has part of a CN clast in it, all the sub-samples of Figure 1 represent matrix material; thus the average NRM direction in each layer must be contemporaneous with the time of assembly of that layer. The near-coincidence of the average NRM directions of the three layers, therefore, points unequivocally to a unique time when all three layers of Boulder 1 were magnetized, notwithstanding the fact that the pseudo-stratigraphy may suggest gaps in time. This observation is in excellent agreement with the mineralogy and petrology of the different layers in Boulder 1. Stoeser *et al.* (1974) have pointed out that the similar mineral and lithic composition of different layers in the boulder suggests that the apparent layering and variable porosity could simply be the result of different sintering temperatures for different layers. The nearly-overlapping NRM directions support this hypothesis and in turn suggest that the last magnetizing event, which caused the observed NRM of the matrix, occurred as the boulder was assembled. In the discussion section we shall argue the pros and cons of the site of assembly.

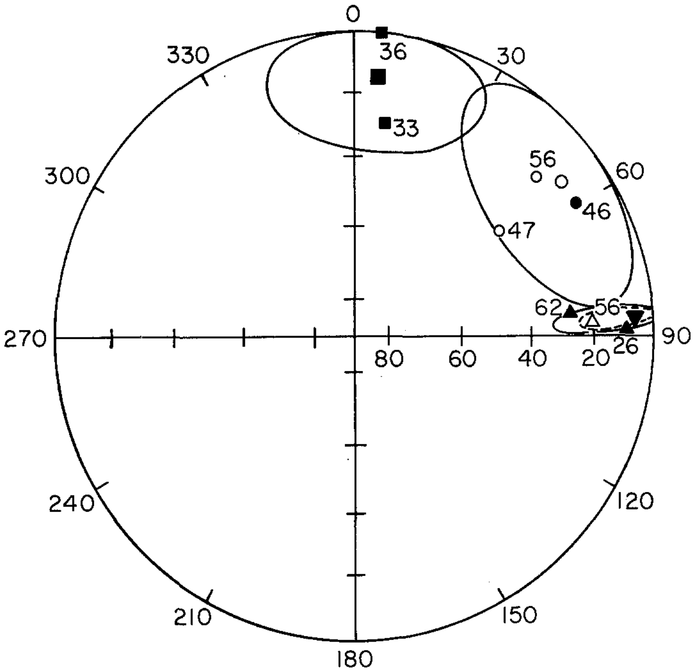

Fig. 1. Equatorial area projections of the 'as-is' NRM vector directions obtained from sub-samples of 72215 (triangles), 72255 (squares), and 72275 (circles). The averages for each rock (or layer) are indicated by the larger symbols. Solid symbols represent vectors pointing down; open symbols represent vectors pointing up. 95% cones of confidence around the average directions are indicated.

Next, we will discuss changes in the NRM directions as selective demagnetization ('cleaning') was carried out to unravel the stable component of the NRM. Thermal demagnetization in zero field is regarded as the best way to remove softer, secondary components of NRM without modifying the stable, primary component (Dunlop and West, 1969). However, thermal demagnetization of the trial samples from Boulder 1 resulted in sintering of the ultrafine iron grains (Banerjee and Swits, 1974), making it impossible to rely on the observed changes in direction of NRM on heating. Stepwise AF demagnetization was employed as a substitute method. Fortunately there was no evidence of any undesirable phenomenon (e.g. a zig-zag increase and decrease of NRM intensity on demagnetization, as seen by Hoffman and Banerjee, 1975). The median destructive field (MDF) necessary to reduce the NRM to half the original value is usually employed as a measure of the softness or stability of the NRM of a rock. In our case the MDFs varied from a few tens of Oe to about 100 Oe, representing the variations in coercivities of the ultrafine iron grains. As a result, the NRM directions after demagnetization to greater than ~100 Oe can be regarded as representing the more stable components of NRM. Figure 2 shows the migration of the NRM vectors of three representative sub-samples to increasing peak values of AF after AF demagnetization. Triangles represent sub-samples 72215,56; squares 72255,33; and circles 72275,56. 72215 has primarily stable NRM (shown by the lack of motion of the NRM vector). 72255 and 72275 have a soft component superimposed on the stable one; however at 100 Oe and above, the vector motion is much smaller, signifying that the more stable components have been separated.

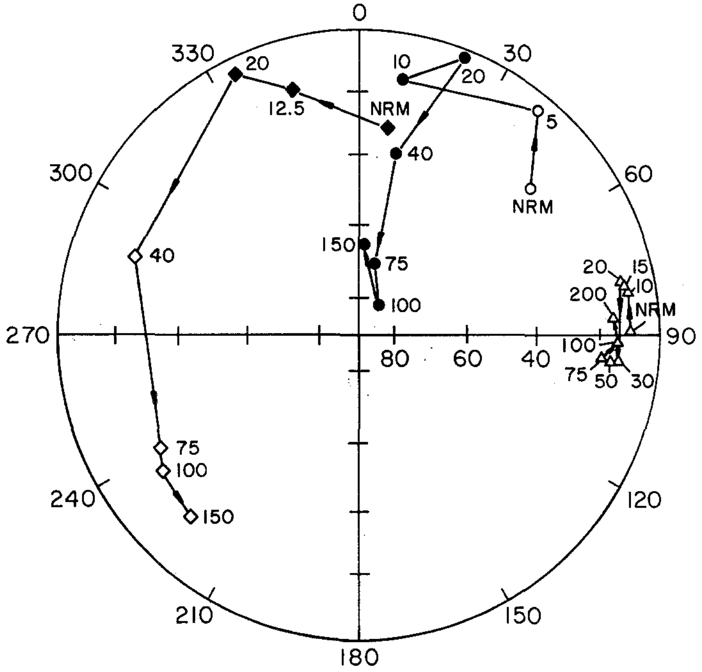

Fig. 2. Migrations of the NRM vector directions upon AF demagnetization. The numbers represent increasing peak values of AF. The last points for each sample represent the most stable directions. Triangle: 72215,56; Square: 72255,33; Circle: 72275,56.

The most obvious conclusion to draw from Figure 2 is that the stable components of NRM for the three representative sub-samples are quite different from one another. This is to be contrasted with the fact that the as-is NRM directions shown in Figure 1, on average, suggested a unique direction. It is to be recalled that we are still dealing with samples that represent the individual layers; hence we must conclude that the more stable, and usually higher-temperature, magnetizing event seen by the three layers resulted in three widely separated NRM vectors. Alternatively, it could be argued that the three layers are *not* recording the same event but different events, during which the ambient field changed its direction twice.

One small oriented clast composed of three types of breccia, black competent, anorthositic, and light friable materials, was made available to us for magnetic measurements. This was sample 72275,158. It has an extremely stable NRM. However, the stable component of this clast had an NRM direction in the SW quadrant of Figure 2 far from the stable direction of the 72275 matrix, which lay in the NE quadrant. This information helps us to conclude that the assembly of the 72275 layer (at least) did not take place at a high enough temperature (close to 770 °C) to 'reset' and homogenize the stable NRM directions of both the clast and the individual components in the layer.

Direct measurements of thermal stability of NRM can, of course, be made, but the results can be slightly misleading because of the previously mentioned sintering problem encountered when heating the more porous rocks (e.g., 72275). However, such measurements were attempted, and it was observed that the stable NRM of clast 72275,158 was blocked close to 770 °C, with a secondary component blocked at about 450 °C. 72275 showed one blocking temperature of 200 °C and one around 400 °C.

3. Paleointensity Measurements

Another indirect way of determining the contemporaneity of different magnetizing events is to measure the paleointensity values (i.e. magnitudes of the ancient magnetic fields necessary to produce the observed remanent magnetizations) of the rocks in question. Unlike the NRM direction measurements however, correct paleointensity measurements are very difficult to make for lunar samples. The basic technique is to compare the observed NRM with TRM applied in the laboratory using a known magnetic field. The imparting of TRM requires repeated heatings, which results im deleterious changes in chemistry and microstructure in lunar rocks. We have therefore developed a method which requires measurements of anhysteretic remanent magnetization (ARM) at room temperature, plus one heating to determine the blocking temperature. The details of the method and theories for ultrafine single-domain grains (Banerjee and Mellema, 1974) and the larger, multi-domain grains (Stacey and Banerjee, 1974) have already been published. The samples from Boulder 1 were determined to be multi-domain, and the latter theory was applied to determine paleointensity values for three representative samples from the three layers of the boulder. The data for 72255,36 and 72275,36 have already been presented (Banerjee and Swits, 1974). In Table II we produce a revised version that includes new data from 72215,26. As we have previously pointed out, 72255 and 72275 seem to have the same average paleointensity (0.27 Oe), within one standard deviation. However it now appears that 72215 has a paleointensity of 0.62 Oe. This is clearly a different value, in spite of the observed standard deviation of ±0.17 Oe. In addition to concluding, as we did in Section 2, that the stable components of the three layers have different directions, we now have to add that ancient magnetic fields of different magnitudes were responsible for the stable components of the NRM of these three layers of Boulder 1.

TABLE II

Paleointensities (H_{paleo}) by ARM-method for Boulder 1 samples

Sample	H_{CR} (Oe)	H_{paleo} (Oe)	Mean	S.D.
72215,26	25	0.57		
	50	0.57		
	50	0.57		
	75	0.51	0.62	0.17
	100	0.44		
	150	0.64		
	200	0.97		
72255,36B	25	0.55		
	50	0.50		
	75	0.32	0.35	0.13
	100	0.24		
	150	0.28		
	200	0.20		
72275,56	25	0.40		
	50	0.23		
	75	0.12	0.19	0.10
	100	0.13		
	150	0.14		
	200	0.12		

4. Discussion

In the two previous sections we have presented raw magnetic data in terms of the directions of stable and unstable components of the NRM vector, and the magnitudes of the paleointensities which were responsible for the stable components of the NRM. The constraints on the formation of Boulder 1 that emerge from the raw data are the following:

(1) All three layers studied (and perhaps the whole boulder) carry differing amounts of soft secondary component of NRM whose direction, however, is the same for all three.

(2) The stable components of NRM for the three layers have widely different directions in space.

(3) In one case, rock 72275, the stable direction of NRM for a small clast does not agree with the rest of the rock as a whole. Subsequent thermal demagnetization of the NRM of the clast showed that the stable component was highly stable, imprinted at a temperature close to 770 °C (the Curie point of iron).

(4) The thermal stability of the NRM of the clast-free regions of the three rocks is lower than the small dark clasts, and a blocking temperature in the region of 450 °C is indicated.

(5) The paleointensity of the field responsible for the stable component of the magnetization of 72215 is distinctly higher than that responsible for both 72255 and 72275.

Let us now discuss alternative scenarios for boulder formation, keeping in mind the above constraints.

(A) The boulder was assembled in pre-Serenitatis regolith. It was then excavated by the Serenitatis event and placed on the South Massif, whence it later rolled down. If this was so, the stable components of NRM for the three layers should have been the same. Then additional secondary components of lower stability could have been added, resulting in divergent total NRM directions. Since this is not what we observe in the magnetic data we have to discard this model.

(B) The assembly on the South Massif was made when the ambient temperature was in excess of 770 °C, perhaps as high as 1000 °C, as Stoeser *et al.* (1974) have suggested. In this model the primary stable component would be acquired on the Massif and the secondary component while rolling off the Massif (for example). In that case there would have been no memory of an earlier magnetization left in the clasts and other finer components of the layers. Thus the stable components should have been convergent and not divergent. Secondly, rolling or mild shocks could give rise to low-stability NRM but would not make the final directions convergent, as we see them.

(C) The boulder was assembled in a debris pile on the South Massif from primary materials excavated by the Serenitatis event. In this case the stable primary NRM directions for the constituent lithic and mineral fragments would have survived if the temperature in the debris blanket did not exceed 770 °C. A large, secondary NRM could be superimposed on all the layers to provide a unique direction for the total NRM. In so far as we do observe a convergent NRM direction of low AF stability (as well as a suspected moderate thermal stability of about 450 °C), this model for assembly on the South Massif may be acceptable. Furthermore, it enables us to say that the assembly temperature was low, perhaps only 450 °C, and this is the reason for the retention of the volatile halogens (Jovanovic and Reed, 1975). There is a problem with this scenario, however. The paleointensity for 72215 is not the same as that for 72255 and 72275. If the three layers were imparted a stable magnetization in a given field, why are the intensities different? The answer could be that the stable magnetization of 72215 dates from a distinctly different time, and perhaps space as well, when the ambient field was different. In this connection it is worthwhile to mention that 72215 is also distinct from both 72255 and 72275 in terms of its Ge/(Au + Ir) ratio (Morgan *et al.*, 1975).

5. Conclusion

Our best hypothesis is that the stable primary components of the NRM of the matrix and the clasts of 72215, 72255, and 72275 date from the time spent in the immature pre-Serenitatis regolith. A basin-forming event transported the breccia components to the South Massif, where a secondary magnetization was imparted to the boulder during its assembly at a temperature of perhaps 450 °C. This is responsible for the convergent NRM direction and the divergent directions of the stable components of the NRM.

Acknowledgment

This work was supported by NASA Grant NGR24-005-248.

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