ON THE INTERPRETATION OF THE NRM OF STABLY MAGNETIZED MARE BASALTS

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1. Introduction.

Attempts to determine the intensity and morphology of ancient lunar fields from the NRM of the returned Apollo samples have so far proved unsatisfying. The principal difficulty has been the inability to establish the origin of the NRM of any of the samples in an entirely convincing way. The most promising samples for this work are the Mare Basalts, for they have the simplest history. Moreover, the NRM of some Mare Basalts is stable against AF demagnetization. The work reported here is a reinvestigation of the magnetic behaviour of certain stably magnetized basalts, to interpret the NRM they carry.

Much of the difficulty of earlier paleomagnetic work with Mare Basalts arose because the NRM proved to be thermally unstable upon heating to temperatures of about 300°C. To understand the thermal instability of the NRM, we have studied synthetic analogues of the magnetic carriers in the basalts. In this way we study simpler systems. Yet these systems can provide adequate analogues of the lunar samples; they reproduce many of the puzzling features of the magnetic behaviour of the lunar samples. The work gives some grounds for optimism that we may eventually be able to interpret the NRM of certain Mare Basalts conclusively and possibly obtain estimates of the fields in which the magnetism was acquired.

2. Characteristics of stably magnetized Mare Basalts.

10017, 10020, 10049 and 12022 are examples of stably magnetized basalts. They are stably magnetized in the sense that the direction of NRM does not change markedly upon demagnetization in fields of a few hundred oersted and the magnitude of remanence decreases in a systematic manner with a median destructive field (MDF) of more than 100 oe. Although such behaviour would hardly be regarded as ideal in terrestrial samples, in lunar paleomagnetism these samples are of uncommon interest.

2.1 Magnetic mineralogy.

Reflected light microscopy has shown that a number of these stably magnetized samples, including all those listed above, contain native iron as blebs in troilite. The samples are in general the finer grain size Mare Basalts and the iron and troilite occur in mesostasis. In some samples, glass occurs. However, the presence of large amounts of glass gives rise to magnetic viscosity due to the superparamagnetic iron in the glass. The occurrence of iron in troilite in other magnetically stable lunar rocks has been reported by Pearce et al. (1). They also reported its occurrence in a synthetic analogue of 10017 prepared by R. M. Housley.

2.2 Magnetic behaviour.

The analysis of the NRM of the stably magnetized Mare Basalts has been reported by Runcorn et al. (2), Hoffman (3) and Fuller et al. (4). The stability against AF demagnetization defines the group. Moreover, different subsamples from a single sample have similar directions of stable magnetization. The intensities tend, however, to vary considerably. Thermal demagnetization brings about a major reduction in NRM at temperatures between 200 and 300°C.

The remanence of the samples is dominantly carried by metallic iron. Its grain size varies within individual samples, so that there is magnetically hard and soft material in a single sample. The ratio of saturation remanence to saturation magnetization (J_{rs}/J_s) is generally close to 0.01, revealing

that the material is not dominantly single domain. Remanent coercivities of as high as 800 oe have been observed but there is much variability in both remanent coercivity and coercive force (4).

A particularly important series of experiments, carried out by Pearce et al. (1), showed that stably magnetized highland samples, containing metallic iron in troilite, had anomalous pTRM acquisition. There were peaks in the cumulative curves between 200 and 300°C and close to 600 and 700°C. The lower temperature peak was interpreted as a negative interaction between the remanence of the iron and a defect ferromagnetism in the antiferromagnetic troilite. The higher peaks were related to the breakdown of troilite and of ilmenite to give additional iron. The lower temperature peak was also reported by Hoffman (3) and by Fuller et al. (4) in stably magnetized basalts. It was also demonstrated (4) that there was no substantial increase in saturation magnetization upon heating to 850°C, so that the high temperature increases in remanent magnetization could not have been simply due to the production of additional iron.

The most puzzling features of the magnetic behaviour of these samples are their responses to heating. Both thermal demagnetization and the acquisition of pTRM are anomalous in ways yet to be interpreted.

3. Synthetic analogues of magnetic carriers in stably magnetized Mare Basalts.

3.1 Preparation of samples.

Synthetic analogues of the lunar iron bearing troilite were prepared by heating mixtures of iron and sulphur for 24 hours in evacuated silica tubes. The tubes containing the mixtures were enclosed in a second tube containing a Titanium getter (5). The iron was electrolytic and had been previously heated to 850°C for 5 hours in hydrogen to reduce oxide coatings. The samples were analyzed by electron microprobe, reflection microscopy, X-ray and thermomagnetic methods, which demonstrated that the product was indeed troilite with varying amounts of metallic iron in it. Some pyrite was also detected, but no magnetite, nor pyrrhotite. Five samples were produced. Sample 1 had an initial Fe:S ratio of 1:1. Samples 2 and 3 had an excess of metallic iron to sulphur of 1.1:1, and Samples 4 and 5 of 1.2:1.

3.2 Magnetic behaviour of synthetics.

The hysteresis properties of the synthetics were similar to those of the lunar samples, although none were as magnetically hard, nor had such low J_{rs}/J_s values, as did the Mare Basalts. Sample 1, which had the 1:1 Fe:S ratio, had the most single domain-like characteristics with a J_{rs}/J_s ratio of 0.14 and H_{rc}/H_c equal to 1.8. The remaining samples had clearly multidomain characteristics, although the remanent coercivity was remarkably high.

The TRM which the samples acquired in their initial cooling after preparation was subjected to AF demagnetization. The demagnetization curves were consistent with the characteristics of the samples established by the hysteresis measurements. Sample 1 exhibited a typical curve for fine grain iron, with very little demagnetization in the weakest fields. The remainder of the samples were typically multidomain with substantial loss of remanence in the weakest fields. AF demagnetization of IRM_s was compared with that of the TRM. In Sample 1, the weak field TRM was harder than IRM_s. In contrast, in the other samples the IRM_s was hardest. This is consistent with all but Sample 1 being multidomain.

Thermal demagnetization of TRM and saturation IRM was carried out using the stepwise technique. Sample 1 behaved normally; both IRM_s and TRM demagnetized monotonically, although both unblocked mainly between 600 and 650°C,

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well below the Curie point of iron. The saturation IRM of the other samples also behaved normally. However, the demagnetization of weak field TRM in Samples 2 and 3 gave rise to a marked increase in magnetization between 550 and 700°C. Continuous thermal demagnetization of Sample 2 eliminated this anomalous behaviour.

The acquisition of pTRM by Sample 1 was anomalously large between 200 and 300°C, but was otherwise normal for fine grain iron. In complete contrast, Samples 2 and 3 exhibit a peak in the cumulative curves between 500 and 700°C. Such peaks in the pTRM acquisition of the lunar samples thwarted attempts to determine intensity using the Thellier-Thellier method.

The acquisition of total TRM was linear over the range 0.034, 0.1, 0.2, 0.34, 0.68 and 0.95 oersted, in all samples.

The magnetic behaviour of the synthetic iron troilite mimics a number of features of the lunar samples. Yet this behaviour can only be due to the Fe-troilite in the synthetics. Moreover, since the synthetics are stable on heating the effects cannot be due to progressive modification of the two phases during experiments.

4. Conclusions.

The synthetic samples are demonstrably adequate analogues of the magnetic phases in Mare Basalts. We may therefore learn about the processes involved in the magnetization of the lunar samples from the behaviour of the synthetics. Remarkably, the synthetics acquire TRM with a linear dependence on field, although they behave anomalously on thermal demagnetization and in their acquisition of pTRM. This suggests that, despite the complexities seen in Thellier-Thellier determinations of field intensity of lunar samples, their TRM could also be acquired with a linear dependence upon field. Moreover, the anomalous behaviour of the synthetics suggests that similar anomalous behaviour exhibited by certain Mare Basalts should not be interpreted as conclusive evidence that the NRM of these samples cannot be a primary TRM.

5. References.

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