
The determination of the ancient lunar magnetic fields in which the Apollo samples acquired their natural remanent magnetization (NRM) has proved to be an extremely difficult task, and is still not satisfactorily completed. Yet the intensity is an important aspect of these fields and until it is known models of origin of lunar magnetism are not likely to be well founded.

There are obvious difficulties in attempting intensity determinations with the lunar samples and these have been noted elsewhere (1,2,3). Nevertheless, numerous determinations have by now been attempted, both with crystalline rocks and breccias. The NRM of breccias is, however, for the most part, so poorly understood, and their history potentially so complicated, that it is probably wise to exclude them from initial discussions. Even Mare basalts and highland impact melt rocks, which might be expected to have simple histories, tend to give inconsistent intensity results, both for sub-samples from the same rock and for different rocks of the same age. At least part of the problem appears to lie in the nature of the NRM, which is not a simple primary thermal remanent magnetization (TRM). In the light of the complicated NRM of the Mare basalts and the discrepant results from intensity determinations, we have undertaken a re-investigation of the NRM of certain Mare basalts. Previous studies of the NRM of Mare basalts have indicated that some of them carry strong and stable magnetization, suggesting ancient field intensities of as much as several tenths of a gauss (3). These samples were predominantly the finer grain size basalts. In this study we have therefore concentrated upon these fine grain basalts.

From the point of view of magnetic phases, the Mare basalts are a rather homogeneous group of rocks with 0.1% of metallic iron, and lessor nickel and cobalt. The dominant Curie point is that of metallic iron close to 770°C (4). In addition, evidence of NiFe is seen in the lower Curie points of certain Mare basalts (4). Hysteresis studies reveal that the iron in Mare basalts varies from the very fine superparamagnetic state through single domain to multidomain. In fact, it appears that the grain size of the iron can account for much of the variability of magnetic characteristics seen in these rocks (3,5).

Standard methods have been used to discriminate against remanence blocked within the lunar diurnal temperature cycle and acquired by exposure to intermediate DC fields. Alternating field (AF) demagnetization has been used predominantly to characterize the remanence carrying capabilities of the samples because of the difficulty of heating samples without irreversibly changing them. By comparing the AF demagnetization characteristics of NRM with those of laboratory induced remanence such as weak field isothermal remanence (TRM), saturation remanence (TRM_s) and anhysteretic remanence (ARM), one can establish whether the NRM behaves like TRM. Finally, we have used a variety of intensity techniques to get estimates of the fields in which NRM was acquired.

At this point we have partial analyses for 10049.14, 12009.95, 12022.52, 15499.108 and 15597.20. These samples are fine to medium grain size Mare basalts and exhibit a wide range in the amount of mesostasis, that is glassy, poorly crystalline material, which they contain. There is 70% in 12009, 57% in 15499, 40% in 15597, 18% in 10049 and 1.5% in 12022. Thus, 12009 is a vitrophyre dominated by a glassy matrix, while 12022 is a medium grain sized basalt, with a very small amount of residual mesostasis. Of the various magnetic properties observed so far, the coercive force is most clearly related to the variation of the amount of glassy matrix. It is inversely correlated;
being 50 oe in 12009, 60 oe in 15597, 75 oe in 10049 and 85 oe in 12022. Remanent coercivity shows a similar trend, as does the median destructive field (MDF) of the saturation remanence. Given the petrologic information available for these samples, the magnetic results are most readily interpreted as a reflection of the variation in grain size of the ferromagnetic phases. These apparently are dominated by superparamagnetic and single domain iron with only minor truly multidomain material. Additional experiments at low temperature are planned to test the validity of this interpretation.

The natural remanent magnetization (NRM) of the samples varies in intensity from 5 x 10^{-5} to 2 x 10^{-6} gauss cm^2 g^{-1}. None of the samples have substantial NRM blocked in the temperature range of the lunar diurnal cycle. The stability against AF demagnetization is very variable. 15499 is strongly demagnetized in weak fields. It, like 12009, also exhibits erratic changes in direction during magnetization. In contrast the NRM of 10049 and 12022 is relatively stable against AF demagnetization. For example, 10049 has a median destructive field (MDF) of about 200 oe. 15597 is remarkable in that while one sub-sample has amongst the strongest and most stable NRM in the entire Apollo collection, others are similar to 12022. Marked instability of NRM in all of these samples correlates with magnetic characteristics indicating magnetic softness and with the presence of plentiful glass. The range of grain size with stable NRM is medium to fine grain with minimal glass. The NRM of 12009, having an MDF of 25 oe, is extremely soft compared with ARM which has an MDF value of greater than 200 oe. Hence, the NRM in this sample is not likely to be a simple thermoremanent magnetization such as might have been acquired by the rock in its initial cooling on the lunar surface. In fact, with the possible exception of 10049, none of these samples have ARM demagnetization characteristics consistent with such an NRM. It is, however, possible that some of the high coercivity fraction of the NRM has a thermal origin, but has been modified by a secondary process. Thermal demagnetization of 12022 revealed the destruction of 50% of the NRM between 150 and 350°C. The result is somewhat complicated by the anomalous pTRM acquisition of the sample. Nevertheless, the AF stability of pTRM in the range of 150 to 350°C is so much greater than the stability of the NRM, that NRM cannot even be a simple pTRM. Thus to explain the bulk of the NRM of 12022 one must find a process, which gives rise to a remanence more stable than weak field ARM, but less stable than ARM or pTRM. An obvious possibility is shock. Yet, since the sample exhibits no petrologic indications of shock, the shock level it experienced cannot have been greater than some tens of Kbars (5). As we noted above, 10049 is the one sample whose NRM may be a relatively pristine primary NRM of thermal origin. Accordingly we have concentrated our efforts to obtain intensity estimates on this sample, with a lesser effort on 12022 and 15597.

If the NRM of a sample is not a primary thermo-remanence, the standard intensity techniques are not applicable. Nevertheless, since there is no known process of magnetization which is more efficient than thermoremanent magnetization, standard intensity estimates should be reliable minimum estimates. Intensity estimates were obtained using the various standard methods reviewed previously (3) and gave the following results: IRM normalization, 0.2 oe; Stephenson-Collinson-Runcorn ARM normalization, 0.28 oe; Banerjee ARM normalization, 0.3 oe; Shaw method, 0.07 oe; modified Shaw method, 0.09 oe; Rigotti method, 0.07 oe; modified Rigotti method, 0.1 oe. If we treat each of these determinations as an independent estimate of equal weight, we obtain a mean of 0.16 oe. This suggests that this sample acquired its NRM in a field of at least 0.1 oe. It remains to be seen whether the NRM of this sample is thermally demagnetized at low temperatures, as is that of 12022.

Intensity estimates for 12022, which are based on the low blocking temperature...
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range, give estimates of the order of one oersted. Similarly, the ARM nor-
malization methods of Stephenson, Collinson and Runcorn and that of Banerjee,
which make use of comparisons of NRM and TRM in different coercivity ranges,
give similar estimates for the low coercivity range. Smaller intensities are
indicated in the higher coercivity ranges. Thus, while the bulk of the NRM
may have been acquired by a secondary process in a field of an order of an
oersted, the field in which the higher coercivity NRM was acquired is at pre-
sent indeterminate. Preliminary intensity estimates for 15597 give a range
from the order of an oersted to $10^{-1}$ oersted.

The intensity estimates obtained from this work conform broadly with
those from earlier studies (3). Thus, some Mare basalts have relatively
strong NRM, which has been acquired in fields of at least several tenths of
an oersted. While 10049 is an older Mare basalt, 12022 is among the youngest,
as is 15597, which also gives high preliminary intensity estimates. It there-
fore appears that at least local transient fields of the order of an oersted
must have been present on the lunar surface throughout the time of extrusion
of the Mare basalts, or at some time since the formation of the youngest of
them. It is not, however, likely that such fields were planetary wide because
we do not see appropriate edge effects associated with the Mare basalts (7).

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