A DETERMINATION OF THE INTENSITY OF THE ANCIENT LUNAR MAGNETIC FIELD*

W. A. GOSE**, D. W. STRANGWAY+, and G. W. PEARCE‡

(Received November 13, 1972)

Abstract. Thermal demagnetization of lunar breccia 15498,36 shows that the natural remanent magnetization is a simple thermoremanence carried by metallic iron. Using the classical Thellier-Thellier method the strength of the magnetizing field at the time of sample formation was found to be 2100 ± 80 gammas.

1. Introduction

All lunar samples which have been studied magnetically contain a remanent magnetization. While part of this magnetization may have been acquired during or after return to Earth (Pearce and Strangway, 1972) most samples possess a stable remanence of lunar origin (c.f., Pearce *et al.*, 1971). But the problem still remains whether this magnetization is a thermoremanent magnetization acquired at the time of the rock formation. This point has particularly been questioned in a recent paper by Helsley (1972). If a thermal origin can be ascertained then the intensity of the magnetizing field is of great interest. Helsley (1970, 1971) and Grommé and Doell (1971) used the classical technique developed by Thellier and Thellier (1959) to obtain a value for the paleointensity but irreversible changes occurred in their samples at fairly low temperatures ($<400°C$). Nagata *et al.* (1970, 1971) used a single heating to 850°C to arrive at an estimate, a procedure which in light of the above results may not be valid. These authors, therefore, warn us not to attach too much significance to their values but generally agree that the magnetization was acquired in a field of a few thousand gammas. We wish to report here on a successful determination of the paleointensity using a modified Thellier-Thellier technique.

2. Experimental Procedure and Sample Description

During the course of this work the sample never left the magnetically shielded chamber with an ambient field below 50 gammas. In addition, the magnetic field at the furnace was controlled by three pairs of Helmholtz coils and a feed-back circuit to ± 1 gamma. The heating experiments were performed in a vacuum furnace in order to prevent oxidation. The continuously pumped vacuum was better than 2×10^{-6} Torr. Since the heating and cooling was performed in a zero field the Thellier-Thellier method can

* Paper dedicated to Professor Harold C. Urey on the occasion of his 80th birthday on 29 April 1973.

** Lunar Science Institute, Houston, Texas, U.S.A.
+ Physics Branch, NASA, Manned Spacecraft Center, Houston, Texas, U.S.A.
‡ Lunar Science Institute and Department of Physics, Univ. of Toronto, Canada.

The Moon 7 (1973) 196–201.

be simplified to one heating for demagnetization and one heating with an applied field as suggested by Thellier and Thellier (1959). Thus after heating to a certain temperature (T_1) and cooling in a zero field to room temperature (T_0) the sample was reheated to the same temperature T_1 and cooled in the presence of a magnetic field H_0. The paleofield is then given by

$$H = \frac{NRM(0, T_1 - T_0)}{PTRM(H_0, T_1 - T_0)} H_0,$$

where $NRM(0, T_1 - T_0)$ is the natural remanent magnetization lost in the temperature interval $T_1 - T_0$ and $PTRM(H_0, T_1 - T_0)$ is the partial thermoremanence acquired in the same temperature interval while applying the field H_0.

The sample used for this experiment is 15498, a low metamorphic grade breccia collected at Dune Crater during the Apollo 15 mission. The enclosed clasts (up to 2 mm) are mainly mare derived material (Butler, 1971). The Curie point is 750 °C indicative of metallic iron containing about 2% nickel or slightly more if the iron is alloyed with small amounts of cobalt as well. From the saturation magnetization the metallic iron concentration was computed to be 0.34 wt%. This value is considerably larger than the metallic iron content in igneous rocks, but it is quite similar to lunar breccias from other missions (Gose *et al.*, 1972a). Much of this iron is in the few hundred angstrom range as evidenced by the time-dependent magnetization of this rock (Gose *et al.*, 1972b). The small grain size and the low nickel content of the iron argues against a meteoritic origin of the additional iron.

3. Results

Generally, two components of magnetic remanence are observed in lunar samples. One component is easily demagnetized in alternating fields of a few tens of oersteds and is most likely an isothermal remanent magnetization (*IRM*) of non-lunar origin (Pearce and Strangway, 1972). The second component is usually stable to alternating fields up to at least 400 Oe. This magnetization seems to be of definite lunar origin (Strangway *et al.*, 1971, Pearce *et al.*, 1972). Before a lunar sample can be thermally demagnetized it seems advisable to eliminate the soft magnetization by *AF* demagnetization. Although this component was acquired at room temperature it has some stability towards thermal demagnetization and erroneous results would be obtained (Pearce *et al.*, 1971). Sample 15498,36 is exceptionally stable against *AF* demagnetization both in its direction and intensity (Figure 1). In particular, no soft magnetization is present, possibly because the sample was not given an isothermal remanence like most other samples or more likely because the sample does not contain significant amounts of large multidomain iron grains which can easily acquire an *IRM*.

The sample was then thermally demagnetized by stepwise heating in the vacuum furnace. It was kept at a given temperature for 10 min and then cooled in a zero field. As can be seen in Figure 1 the sample is directionally stable up to 650 °C. The scatter

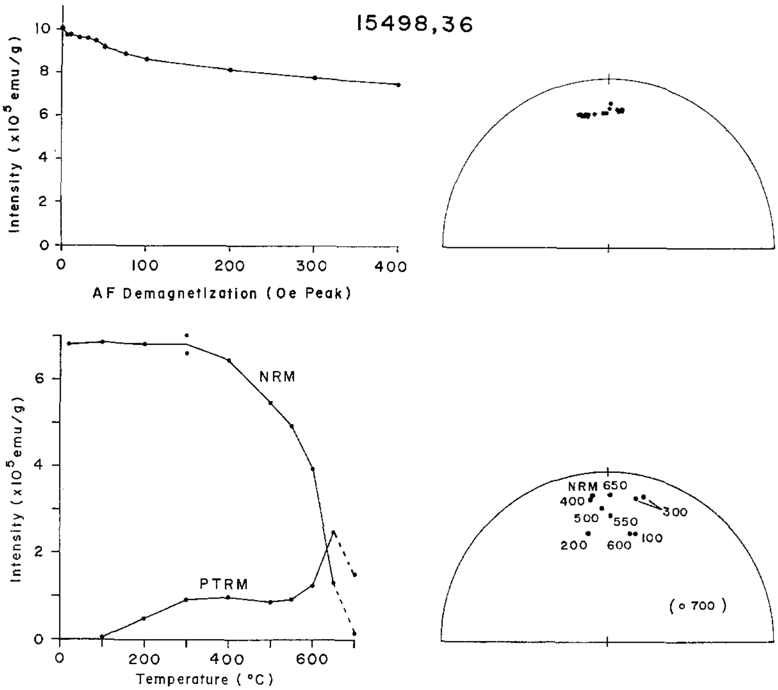

Fig. 1. Alternating field and thermal demagnetization of sample 15498,36. Numbers in the stereographic projection indicate the heating temperature in degrees centigrade.

is somewhat larger than during *AF* demagnetization but this is probably due to the difficulty in reorienting the small, round sample (0.90 gram) in its holder. (During *AF* demagnetization the sample remained in its holder.)

Helsley (1971) reported irreversible changes in a sample at 300 °C. For this reason, sample 15498,36 was reheated to 300 °C after the heating cycle with an applied field was completed. The direction and intensity are very similar to the values after the first heating (Figure 1) i.e., the *PTRM* was totally removed as is expected if no changes occurred in the sample and the magnetization is a thermoremanence.

The values for the *PTRM* acquired in a 925 gamma field are also shown in Figure 1. The *PTRM* acquired at 700 °C is smaller than that acquired at 650 °C signifying that the sample had undergone some changes. To check on this the sample was given a new *PTRM* at 650 °C. It acquired only about half the intensity of the first run implying that it had changed irreversibly. Thus no meaningful value for the *PTRM* at 700 °C could be obtained.

In order to determine the nature of this change a small piece of this sample which had been broken off prior to any test was measured with a vibrating magnetometer. It was progressively heated to temperatures similar to those used for the paleointensity determination in about the same vacuum. After each heating the sample was cooled to room temperature and various magnetic parameters were measured. No significant change in any parameter was observed up to 610 °C while heating to 800 °C drastically changed the coercivity, H_C, the initial susceptibility, X_0, and the saturation remanence, J_{RS}. These changes are interpreted as being due to the loss of very small iron grains (superparamagnetic and single domain particles).

5. Summary

Several conclusions can be drawn from these data.

(1) A portion of the natural remanent magnetization of this sample is stable during a 10 min heating to 650 °C. If the remanence is carried by single domain particles one can use Neél's (1949) theory to compute its stability at different temperature. Thus at 120 °C, the temperature of the lunar day, the magnetization would be stable for times well exceeding the age of the Moon.

(2) The *NRM* is carried by metallic iron and is a thermoremanence, i.e., it was acquired by cooling from above at least 650 °C in the presence of a magnetic field. Lunar breccias can, therfore, be used for paleomagnetic studies in the same way as igneous rocks in agreement with our earlier statement (Gose *et al.*, 1972a).

(3) The *PTRM* spectrum reveals a second component capable of carrying a thermoremanence. The Curie temperature of this phase is about 300 °C which suggests that it is either taenite or troilite. This component does not contribute to the *NRM* although the original cooling process should have given it a remanence. It is possible that this

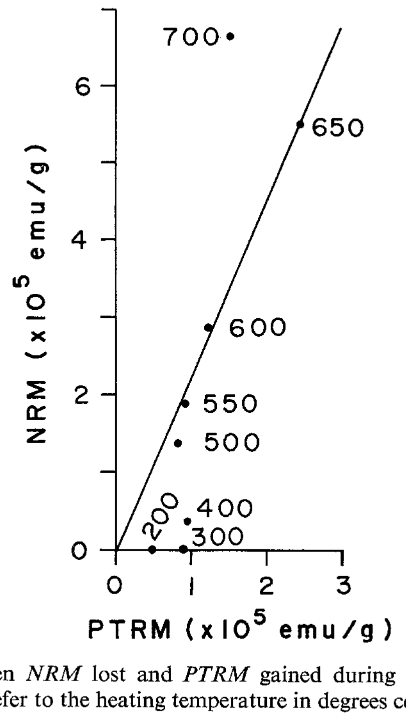

Fig. 2. Relationship between *NRM* lost and *PTRM* gained during the Thellier-Thellier test on sample 15498,36. Numbers refer to the heating temperature in degrees centigrade. The absolute error in the readings is about $\pm 0.2 \times 10^{-5}$ emu/g.

phase occurs in large multidomain grains and is therefore of limited stability. Alternatively, the thermal cycling on the lunar surface may act as an effective demagnetizer for the low Curie point phases. Further tests are necessary to clarify this point.

(4) The results of the determination of the ancient magnetic field are shown in Figure 2. If a sample is well behaved, i.e., if no physical or chemical change takes place, the values of the *PTRM* plotted against *NRM* should fall on a straight line whose slope is the ratio of the paleofield to the applied field. The values below 500 °C are not very indicative, in part because the sample has a narrow blocking temperature range so that very little magnetization was lost below 500 °C, and in part because of the additional phase appearing in the *PTRM* spectrum. The occurrence of this magnetization does not, however, invalidate the experiment since the paleofield is determined by the slope of the line. The measurement at 700 °C has to be discarded because irreversible changes occurred in the sample. The points at 550°, 600° and 650° define a straight line with a slope of 2.27 ± 0.086. Since the applied field was controlled to better than 1%, all major sources of inaccuracy (such as sample orientation, magnetometer accuracy, and temperature control) are contained in the uncertainty of the slope. The applied field was 925 gamma and thus the intensity of the paleofield is $(2.27 \pm \pm 0.086) \times 925$ gamma $= 2100 \pm 80$ gamma. This value lies in the range of previous estimates although this experiment is the first complete determination of the paleointensity.

4. Discussion

This experiment verifies in a definite way that the stable natural magnetization of lunar samples is carried by metallic iron. It substantiates our previous contention that the lunar breccias are usable for paleomagnetic interpretations. Most important, a reliable value of 2100 gammas has been obtained for the magnetic field at the time breccia 15498,36 formed. No age date is available for this sample. Since this breccia contains mare derived material it may be as young as or younger than the Apollo 15 mare basalts which are dated at about 3.3×10^9 yr (Compston *et al.*, 1972). The origin of the magnetizing field is, of course, of fundamental importance. The relatively large value of 2100 gammas seems to favor an internal rather than external origin.

Acknowledgements

We wish to thank Mr J. A. Love of Lockheed Electronics Company for his patience in measuring the sample. Portions of this work were supported by the Lunar Science Institute which is operated by the Universities Space Research Association under Contract No. NSR-09-051-001 with the National Aeronautics and Space Administration. This paper constitutes the Lunar Science Institute contribution number 127.

References

Butler, P. (compiler): 1971, *Lunar Sample Information Catalog, Apollo 15*, National Aeronautics and Space Administration, MSC 03209.

Compston, W., deLaeter, J. R., and Vernon, M. J.: 1972, in J. W. Chamberlain and C. Watkins (eds.), *The Apollo 15 Lunar Samples,* The Lunar Science Institute, Houston, 347–357.
Gose, W. A., Strangway, D. W., and Larson, E. E.: 1972a, *The Moon* **1**, 106–120.
Gose, W. A., Pearce, G. W., Strangway, D. W., and Carnes, J.: 1972b, in J. W. Chamberlain and C. Watkins (eds.), *The Apollo 15 Lunar Samples,* The Lunar Science Institute, Houston, 430–434.
Grommé, C. S. and Doell, R. R.: 1971, *Proc. Sec. Lunar Sci. Conf.* **3**, 2491–2499.
Helsley, C. E.: 1970, *Proc. Apollo 11 Lunar Sci.* Conf. *3*, 2213–2219.
Helsley, C. E.: 1971, *Proc. Second Lunar Sci. Conf.* **3**, 2485–2490.
Helsley, C. E.: 1972, *The Moon* **5**, 158–160.
Nagata, T., Ishikawa, Y., Kinoshita, H., Kono, M., Syono, Y., and Fisher, R. M.: 1970, *Proc. Apollo 11 Lunar Sci. Conf.* **3**, 2325–2340.
Nagata, T., Fisher, R. M., Schwerer, F. C., Fuller, M. D., and Dunn, J. R.: 1971, *Proc. Second Lunar Sci. Conf.* **3**, 2461–2476.
Néel, L.: 1949, *Am. Geophys.* **5**, 99–136.
Pearce, G. W., Strangway, D. W., and Larson, E. E.: 1971, *Proc. Second Lunar Sci. Conf.* **3**, 2451–2460.
Pearce, G. W. and Strangway, D. W., 1972, Apollo 16 Preliminary Science Report, NASA SP315.
Pearce, G. W., Strangway, D. W., and Gose, W. A.: 1972, *Proc. Third Lunar Sci. Conf.* **3**.
Strangway, D. W., Pearce, G. W., Gose, W. A., and Timme, R. W.: 1971, *Earth Planet. Sci. Let.* **13**, 43–52.
Thellier, E. and Thellier, O.: 1959, *Ann. Geophys.* **15**, 285–376.