Magnetic Properties of Lunar Sample 10048-22

Abstract. *The natural remanent magnetization (3.7×10^{-4} electromagnetic units per cubic centimeter) and the susceptibility per cubic centimeter (6.3×10^{-13}) of an 18.5-gram breccia specimen were determined with instrumentation and techniques currently used in paleomagnetism. The relatively low magnetic stability of the rock in the earth's field and in alternating demagnetizing fields precludes considering it as a reliable carrier of paleomagnetism. A magnetic balance study yields an unusually high Curie temperature (750°C) which is possibly diagnostic of metallic Fe containing less than 5 percent nickel. The estimated relative abundance of the iron in the sample is about 0.5 percent.*

The identification of a stable component of thermoremanent magnetization in a sample of lunar material could have important implications relative to the past history of the moon's interior. On this basis, an analysis was made of the natural remanent magnetization and of the magnetic properties of sample 10048-22. More specifically, the stability of its natural remanent magnetization was studied and compared with that of an anhysteritic component artificially introduced in the sample. Its magnetic susceptibility and its thermomagnetic properties were also determined in an attempt to identify the ferromagnetic constituents of the sample.

The sample studied consists of an 18.5-g, irregularly shaped portion of the breccia 10048. Because of its irregular shape and of the relatively high friability of its surface, it was necessary to mount the sample in a special lucite container that could be accurately positioned and oriented in some of the apparatus. In order to design the lucite container, to determine the volume of the sample, its centroid and its specific weight, replicas of the sample were cast with various materials. As a by-product of this preparation it was found that the bulk density of the sample is 2.4.

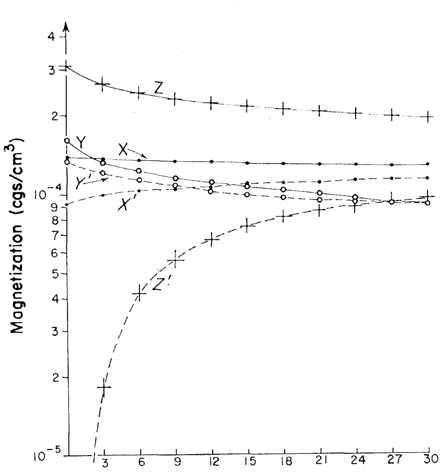

Fig. 1. Decay of viscous magnetization acquired in earth's field in 1 hour with Z axis of sample 10048 pointing upward (solid lines) and downward (dashed line).

The volume susceptibility of the sample was determined with a bridge-type susceptibility meter (*1*) in a field of 0.5 oe and of 1 khz. The value of 6.3×10^{-3} cgs units thus obtained would be considered relatively high for most terrestrial rocks and could be diagnostic of an unusual ferromagnetic mineral.

The remanent magnetization of the sample set in a null-field space was determined with a three-magnet astatic magnetometer (*2*). Prior to the original measurements, the sample was allowed to rest in the earth's magnetic field with its Z axis (the axis of the cylindrical lucite container) pointing upward along the vertical. On account of the relatively high magnetic susceptibility of the sample, its centroid was kept a minimum distance of 7.5 cm from the magnet system during the measurements. The magnetization was then determined ten consecutive times at intervals of 3 minutes. It was noted (Fig. 1) that the intensity of its Z component decreased substantially during the 30 minutes required for the series of measurements. The sample was then replaced in the earth's field with its Z axis pointing downward. This resulted in a reversal of the magnetization along the Z axis, but the soft component of magnetization thus introduced in the sample again gradually decreased during 30 minutes (Fig. 1). This experiment points to the presence of a low-coercivity ferromagnetic mineral in the sample.

The sample was then exposed to a series of alternating field cleaning treatments, a standard procedure in most paleomagnetic laboratories. The apparatus used for these tests has been described (*3*).

The peak intensity of the demagnetizing field was gradually raised to 800 oe in steps of 15, 25, or 50 oe. The net result of this treatment was that the original magnetization of the sample (3.7×10^{-4} emu/cm^3) decreased to 4.5×10^{-5} emu/cm^3 after the treatments in the higher fields. Of particular interest is the variation in the relative orientation of the magnetization in the sample. The inclination changed systematically after the treatments in demagnetizing fields below 250 but very erratically after the treatments in higher fields (Fig. 2). In comparison with the behavior of a typical stable terrestrial rock to which a similar treatment was applied, it is clear that the magnetization of the lunar sample is relatively unstable, either due to the mechanism of its formation or to the nature of its carrier.

A further set of alternating field demagnetization treatments was carried out after the sample was exposed for 5 minutes in a 0.5-oe constant field on which an 880-oe alternating field (60 hz) was superposed. The 3.5×10^{-3} emu/cm^3 magnetization then present in the sample was reduced to 2.5×10^{-5} emu/cm^3 after the cleaning treatment in 700 oe. This experiment suggested

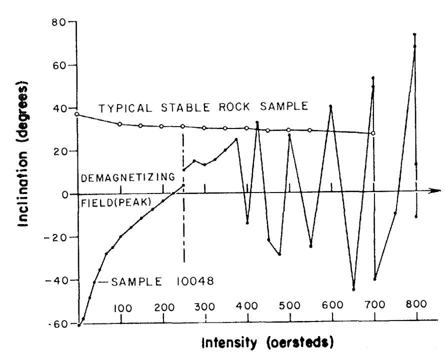

Fig. 2. Variation of magnetic inclination with demagnetization treatment for a typical stable terrestrial rock sample (open dots) and for sample 10048 (filled dots).

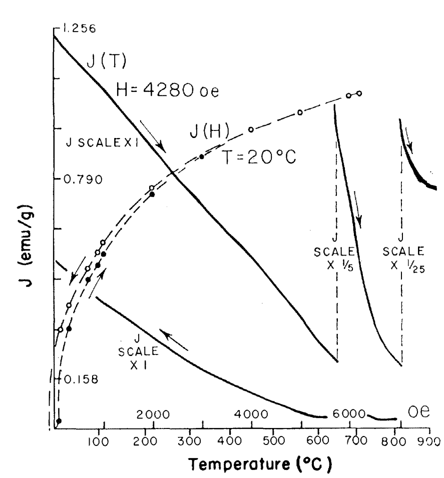

Fig. 3. Part of hysteresis curve (dashed line) and thermomagnetic record (solid line) obtained for grains from sample 10048.

that the instability of the sample magnetization should be attributed to the nature of its carrier rather than to the mechanism of its formation.

To investigate the nature of the carrier(s) of remanent magnetization in the sample, small grains detached from its surface were examined with a recording magnetic balance (*4*). The investigation was carried out with a sample weighing approximately 20 mg and under an air pressure of 3×10^{-3} mm-Hg.

Figure 3 shows the dependence of the magnetization (J) on the applied field (H) at 20°C and the change in J (H = 4280 oe) during heating to 900°C and subsequent cooling. The J(H) curve shows that the original sample approached magnetic saturation at about 4000 oe and that its coercive force was approximately 70 oe. Such a low coercive force is in accord with the previously noted tendency of the sample to acquire a large component of viscous magnetization when exposed for a few minutes in a field as low as the earth's magnetic field (Fig. 1). Moreover, it suggests that there is no major component of high micro-coercivity in the sample.

The J(T) curve shows a monotonic decrease in magnetization from −180°C to the Curie temperature at 750° ± 8°C (only partly shown on Fig. 3). The high Curie temperature is diagnostic of a mineral that is uncommon in terrestrial rocks. The cooling part of the J(T) curve suggests that a substantial transformation of the original mineral took place at high temperature.

The Curie temperature of the original ferromagnetic constituent at 750° ± 8°C and the transformation of this constituent into one with a Curie point of 580°C and with lower saturation magnetization were interpreted as follows: (i) the original ferromagnetic constituent was relatively pure metallic Fe with perhaps as much as 5 percent Ni, this estimate being based on standards given by Kneller (*5*). In this context, it is noteworthy that the Fe in meteorites normally contains more than 5 percent Ni; (ii) the estimated abundance of fine-grained Fe in the sample is about 0.5 percent; (iii) it is possible that virtually all the metallic Fe was oxidized to Fe_3O_4 at higher temperatures. This is in keeping with the Curie temperature of the new mineral and with the halved saturation moment of the sample at 20°C after heating.

In the light of the above magnetic data it is not possible to state conclusively whether a substantial magnetic field witnessed the last cooling of sample 10048 on the lunar surface. It would thus be presumptuous to speculate further on the original configuration of the moon's interior along this avenue on the basis of this sample.

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6. We thank K. W. Christie and G. N. Freda for assistance in the preparation of the sample and in making some of the measurements.

5 January 1970

Search for Magnetic Monopoles in the Lunar Sample

Abstract. *An electromagnetic search for magnetic monopoles of the minimum size predicted by Dirac, or of any larger magnitude, has been performed on 8.37 kilograms of lunar surface material. No monopole was found. This experiment sets new limits on the production cross section for monopoles and on their occurrence in cosmic radiation.*

For several years now, the hunt has been on for particles that would interact with the magnetic field just as electric charges interact with the electric field, acting as a source for the field and being accelerated by it. These particles, called monopoles, would be stable. They would have a magnetic charge measured by an integer ν, the Dirac charge 3×10^{-8} emu being used as a unit (*1*). Their existence would give credence to the only known explanation for the extraordinarily accurate phenomenon of charge quantization (*2*). According to a recent theory (*3*), they would be the most fundamental particles, the building blocks of the universe. However, no such particle or combination with a net nonzero magnetic charge has ever been found (*4–6*).

In view of the negative results of these experiments (*4–6*), the lunar surface is considered to be the most likely hiding place for monopoles, whether they belonged to the primary cosmic rays or were produced in the collision of a high-energy cosmic ray particle with a nucleon of the lunar surface. In either case, the lunar material would slow the monopole down and trap it. The reasoning that favors the lunar sample involves its great age, 3 to 4×10^9 years, and the small depth to which the surface has been churned during the long period of time. These two factors give the lunar surface the longest known exposure to cosmic rays. Furthermore, the absence of both an atmosphere and a magnetic field on the moon allows the fate of a monopole after it has been slowed down to be assessed with more certainty than it could be on the earth.

Our detection technique relies on the electromotive force induced in a coil by a moving monopole. As in previous work (*7*), the sample was transported along a continuous path threading the windings of a coil. In this experiment the coil was made of superconducting material and was short-circuited by a superconducting switch. A small current was stored in the superconducting loop before a sample was run. If a sample containing a monopole had been run, the induced electromotive force would have modified this current. After each sample had been circulated 400 times, the superconducting switch was opened and a signal proportional to the current in the loop was transferred electrically out of the cryostat, amplified, and finally recorded on an oscilloscope. A real magnetic charge would have been detected as a difference between the signal obtained when the switch was opened and the one normally observed when the opening of the switch interrupted the "standard current" that had been introduced as an overall check on the apparatus. A zero magnetic charge therefore corresponded to a nonzero standard signal. This technique assured us that the equipment was working at all times.

An overall calibration was obtained from a long solenoid in which a known change of current simulated the "missing term" in Maxwell's equations—the one describing the contribution of a "magnetic current density." A statistical study of our signals shows that the measurement of the magnetic charge was affected by a 1 standard deviation error of about ⅛ of a Dirac unit, when