moment up to 450°C, as is characteristic of samples with distributed thermal blocking temperatures. Above 450°C, no reliable demagnetization results could be obtained. The cause of this instability is not known, but it may be the result of exceeding the pronounced Curie point at 485°C (Fig. 1). The moment due to the phase with the higher Curie point may be unstable, or it may be that it is completely overridden by the moment acquired during cooling through the 465°C transition in a small residual field (10 to 20 gammas).

After alternating field demagnetization, fragment 3 of the dust sample was heated in vacuum to 450°C and allowed to cool in a field of 500 gammas. No additional detectable moment was acquired during this process. This sample was then heated in vacuum to 750°C and allowed to cool in an applied field of 1000 gammas. Again no detectable moment was acquired, indicating that it acquired its NRM in a field in excess of 20,000 gammas or that it was acquired by some means other than cooling through the Curie point. Alternatively, an irreversible chemical change may have taken place in the sample so that remanence can no longer be acquired in the same way the initial NRM was acquired.

Thus the evidence from fragment 3 of the dust sample allows no estimate of the possible range of values for the moon's field in the past. The partial thermal demagnetization of sample 10022 suggests that the sample may have acquired its initial NRM in a field of 1500 to 2000 gammas. However, the marked instability at higher temperatures leaves this conclusion somewhat in doubt; it is subject to verification by apparently more stable samples such as sample 10069.

Thermomagnetic analysis of the Apollo 11 dust and rock samples studied indicates that the major magnetic minerals are ilmenite, native iron, and possibly pyrrhotite. Of these, the native iron and the pyrrhotite (troilite?) are the dominant carriers of the natural remanence in these rocks. The natural remanences are low in all these samples in comparison with similar rocks from the earth. The stability of the NRM is low in three of the samples studied but is high in the other two. If the NRM of these samples is interpreted as being a TRM acquired by passage through the Curie point in the presence of a magnetic field, a field in excess of 1500 gammas is suggested.

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Magnetic Studies of Lunar Samples

Abstract. *The remanent magnetism of a lunar type C breccia sample includes a large viscous component with a time constant of several hours, and a high coercivity remanence, possibly acquired by impact processes on the lunar surface. Ilmenite(?) and metallic iron in breccias, and ferrous and metallic iron in glass beads separated from lunar fines (type D) were identified by high-field and low-temperature experiments. The iron appears to occur in a wide range of grain sizes including the single domain and multidomain states.*

The purpose of magnetic studies of Apollo 11 lunar materials is to ascertain whether the materials possess a stable remanent magnetization that was originally acquired on the moon, and to compare the magnetic properties of individual glass beads in the lunar fines with those of tektites. These magnetization studies could indicate past lunar magnetic environments and thus be of value in theories concerning the moon's earlier history. Intrinsic bulk and single-particle magnetic properties are also of interest with respect to the magnetic mineralogy of the lunar material.

Magnetization of type C breccia sample number 10059,24 in high applied magnetic fields was measured with a vacuum magnetic balance of the Faraday type (*1*). Results obtained for magnetization versus applied field to 8400 oe and magnetization (in 2000 oe) versus temperature between −180°C and 830°C are given in Fig. 1A. The magnetization curve rises very sharply at low fields and gradually approaches a saturation value near 2.7 emu/g. The thermal curves show a well defined Curie temperature at 775°C, and a suggestion of a second Curie or Néel point slightly below −180°C. These are interpreted as due to reported metallic iron and ilmenite (*2*), with a Curie point of 770°C and a Néel point of −205°C, respectively (*3*). About one-half the original room-temperature magnetization was lost during the heating experiment, but subsequent prolonged heating at 800°C did not further change the shape of the cooling curve, which indicated that the changes took place during the first heating cycle. There is also a small inflection in the cooling curve near 250°C; no interpretation is given for its origin.

Similar high field experiments were made on individual glass beads (0.1 to 1.5 mg) selected from lunar fines type D sample number 10084,86. A quartz-spring balance with the sample in a dry helium atmosphere (*4*) was used for these studies. The low field (< 3000 oe) magnetization at room temperature varied from 10 to 100 × 10^{-4} emu/g, and saturation magnetization varied from nil to 1.2 emu/g. Magnetization (in 3400 oe) versus temperature measurements indicated a Curie point of 770°C, but unlike the breccia, identical heating and cooling curves with a shape resembling the cooling curve of Fig. 1A (without the inflection at 250°C) were obtained. The magnetization versus applied field curve of individual glass beads are very different from those of the breccia: some were linear up to about 5000 to 7000 oe and reached saturation values of about 1 emu/g at 9000 oe. Other individual glass beads did not exhibit saturation magnetization in high fields at room temperature, indicating that essentially all the iron is in the paramagnetic state. Low temperature measurements verified this fact and also showed that in those glass beads that had an appreciable saturation magnetization, only a small part of the iron was in the metallic form with the major part in the paramagnetic state. In some respects these magnetic properties are very similar to those of tektites (*5*); moreover, electron microprobe analysis for total iron detected essentially the same concentrations of ferrous and metallic iron that are indicated magnetically; these concentrations

are also similar to tektites. These similarities therefore suggest that small iron spherules in the beads are the carriers of the magnetization (*5*).

The rapid rise and gradual saturation in the plot of breccia magnetization versus applied field suggests, as in the case of the single-bead experiment, the presence of grains (spherules) of varying size, that range from the multidomain through single domain states. About one-half the magnetization of the breccia is destroyed on heating; in contrast, the beads have reproducible heating-cooling curves, thus implying that up to one-half the iron in the breccia may be within glass beads while the remainder is "unprotected," free to react with other substances. The exact nature of this reaction, which takes place in an atmosphere near 10^{-5} torr, is not known. It is clear, however, that the iron is not being oxidized to a cubic ferrite such as magnetite. The saturation magnetization of iron ferrites is generally about half that of metallic iron, so that their effect should be readily evident in the cooling curve if they were the alteration product.

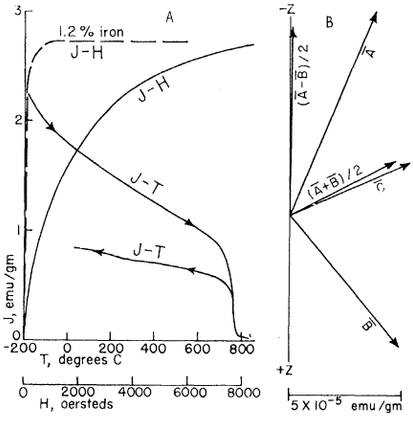

Fig. 1. (A) Magnetization of sample 10059, 24 in high applied fields. The magnetization versus applied field data (J–H) (lower abscissa) were made at 20°C. The magnetization versus temperature (J–T) data were obtained in an applied field of 2000 oe at a pressure of 2 to 3 × 10^{-5} torr (data below 20°C were obtained on a 103-mg sample in dry nitrogen at atmospheric pressure). Heating and cooling rates were 10°C per minute. For comparison, the curve for 1.2 percent iron in large grain sizes is shown by the dashed curve. (B) Results of Traînage experiments; ($\bar{A}$), magnetization vector after alignment for 8 hours with the earth's magnetic field directed parallel to the −Z sample axis; ($\bar{B}$), similarly for 8-hour alignment of earth's field and +Z axis; ($\bar{C}$), remanence vector after tumbling 8 hours in the earth's field. Within a few degrees, all vectors lie in the same plane.

To summarize these intrinsic magnetic studies, it appears that the magnetic mineralogy of the breccia consists mainly of metallic iron (1.2 percent by weight) in a wide range of grain sizes including single and multidomain states, and ilmenite that is antiferromagnetic at room temperature. Probably about half the iron is in the form of spherules within glass beads while the remainder reacts to form nonmagnetic or very weakly magnetic products upon heating to the Curie temperature of iron.

Remanent magnetization measurements of breccia sample 10059,24 (14.25 g) with spinner magnetometers (*6*) suggested that the magnetization may have changed during the experiments or that the measurements were adversely affected by anisotropy of susceptibility (*7*). Additional measurements after the sample rested in the earth's magnetic field for varying lengths of time (Traînage experiments) showed that the remanence did indeed change. Moreover, removal of the earth's field during measurement in the magnetometer improved the internal consistency of the data, which also suggests that the sample is magnetically anisotropic. Thereafter, all measurements were made as quickly as possible in null field without letting the sample come to rest during the measurement sequence.

Traînage experiments showed that viscous remanent magnetization (VRM) was acquired rather quickly in the earth's field but became essentially "saturated" after 4 to 5 hours. Moreover, this VRM could be removed by tumbling the sample in the earth's field for similar lengths of time. These results are summarized in Fig. 1B. The vector $(\bar{A} - \bar{B})/2$ is the VRM acquired in the earth's field and has a value of 8.3 × 10^{-5} emu/g. The "stable" remanence, $(\bar{A} + \bar{B})/2$, is 5.3 × 10^{-5} emu/g and is close in direction and intensity to the remanent vector measured directly by removal of VRM by tumbling in the earth's field.

Partial alternating field (AF) demagnetization experiments (Fig. 2) were all repeated at each step to ascertain the amounts of "anomalous" magnetization added by the process (*8*), and the samples were left tumbling in the earth's field for several hours between AF treatment and measurement of remanence. Progressively larger amounts of anomalous magnetization forced termination of the experiments at a peak AF of 400 oe.

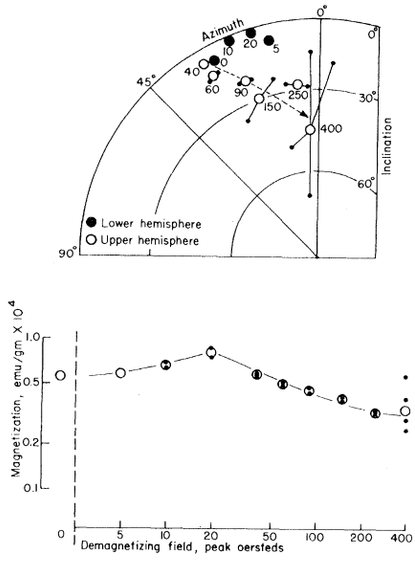

Fig. 2. Partial demagnetization experiments. The upper diagram shows changes in direction of the remanence during demagnetization as points on a Lambert equal-area projection, and the lower diagram shows the corresponding changes in intensity. Large symbols are mean values and lines connect individual values with their mean.

Within the experimental accuracy, these partial AF demagnetization data suggest the presence of three components of remanent magnetization with different coercivities in addition to the large VRM, which was removed by tumbling after each AF treatment. The first component has maximum coercivities of the order of 20 to 40 oe with irregular directions. It is probably an isothermal remanent magnetization (IRM) acquired during sample processing. The second component has high coercivities ranging up to at least 400 oe since the resultant vector was still moving after demagnetization at this peak field strength. The third apparent component—the one the resultant was approaching as the second component was erased—may be interpreted in two ways. It may be a very high coercivity remanence, or it may be an apparent remanent component generated by large susceptibility anisotropy. The measurement data after the 400-oe AF treatments are only consistent within about 10 percent so that the remaining remanence is very likely in part due to anisotropy. Such an argument cannot be invoked for the component with coercivities to 400 oe, however, since it responds linearly to the AF treatment. Its minimum strength—the vector difference of the resultant after 40-oe AF

treatment and that after 250 to 400 oe —is about 3.5×10^{-5} emu/g.

In summary, the breccia contains a rather complicated remanence. It acquires a VRM of about 8×10^{-5} emu/g if left in the earth's field for a few hours. There is a probable IRM component of about 2×10^{-5} emu/g intensity with coercivities to 40 oe. Another component, with coercivities ranging over 400 oe, has a minimum intensity of 3.5×10^{-5} emu/g, and there also possibly exists a very high coercivity remanence with a maximum intensity of 3×10^{-5} emu/g. However, this last component is at least in part only an artifact of susceptibility anisotropy. The wide range of remanence coercivity is consistent with the previous inference of a wide range of iron grain sizes including single and multidomain magnetic states.

The remanent component with coercivities up to at least 400 oe is quite interesting in that no process is known by which the sample could have acquired this remanence after it left the lunar surface. The relatively slow decrease of remanence with increasing AF treatment is not characteristic of an IRM acquired in a large magnetic field. Thus, it is likely that this remanence is of a kind that results from the presence of a magnetic field plus some energy change such as cooling from high temperatures, chemical change, shock, and so on. Which process is most likely depends, of course, upon the mode of genesis of the breccia itself. If the rock acquired its magnetization by cooling from high temperatures (or by chemical action), then a relatively permanent field in the lunar vicinity at some time in the past might be postulated. On the other hand, shock induced magnetization by lunar impact could take place essentially instantaneously, and ionization processes at the time of impact might provide the necessary magnetic field. It would be desirable to study artificial magnetizations of these types in the breccia; unfortunately the large VRM, anisotropic properties, and anomalous magnetization acquired during AF treatment in sample 10059,24 preclude useful studies of this type.

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Magnetic Properties of Lunar Samples

Abstract. *The magnetic properties of samples of rock, fines, and magnetic separate from the fines from Apollo 11 have been measured. Native iron, or possibly nickel-iron, of submicroscopic particle size is the most important constituent, with minor contributions from ilmenite, paramagnetic iron minerals, and other iron-titanium oxides. The remanent magnetization of a sample of the microbreccia rapidly acquires a viscous magnetization and does not appear to have a significant stable remanence. The crystalline sample has a weak natural remanence showing some stability.*

The samples we investigated were fines (10084,13), a magnetic separate from fines (10084,135), a 17-g sample of the microbreccia rock (10046,46), and an 11-g sample of crystalline rock (10017,64).

Washing followed by sorting of the fines under the microscope showed (i) glass, including spheres, dumbbell shapes, and broken fragments, of brown, green, and colorless hue with the rare brown fragments containing opaque cruciform and square-section crystallites 10 μm across; (ii) purplish pyroxene with refractive index β 1.698 and $2V = 44°$, suggesting $Ca_{37}Mg_{38}Fe_{25}$ (atomic percent); and (iii) opaque grains.

The salient feature in the microbreccia is the variability of texture in different parts of the sample. Combined study of thin and polished sections showed: (i) Ilmenite in a wide variety of forms, from crystals 50 by 20 μm through laths and patterned growths to tiny interphase rods. It makes up about 16 percent by volume. One crystal of ilmenite showed a core of lower reflectivity than the bulk of this mineral, and investigation with the electron-probe microanalyzer showed the presence of titanium-rich pseudobrookite. (ii) Two types of sulfide, making up about 2 percent volume. One of the types is probably troilite or pyrrhotite. (iii) Pyroxene, the chief translucent phase. (iv) A few grains of olivine ($2V = 90°$, suggesting $Mg_{86}Fe_{14}$). (v) An intergrowth of unknown nature, making up about 38 percent by volume of the section studied, opaque and yet of low reflectivity. Ilmenite and sulfide occur as tiny interphase rods and granules within the intergrowth.

The identity of the pyroxene has been confirmed by x-ray powder diffraction. No iron particles have been definitely identified microscopically in any of the material.

The ^{57}Fe Mössbauer spectra of samples of the fines were obtained at 290°, 78°, and 4.2°K. The predominant feature of all spectra was a series of overlapping quadrupole-split doublets centered at the Fe^{2+} chemical-isomer-shift position of typical silicate minerals. In addition, about 3 to 5 percent of the total resonance appeared as a magnetically split six-line spectrum with a hyperfine field of 330 ± 5000 oersteds attributable to free iron or a dilute alloy of nickel in iron. It is also probable that ~10 percent of the iron in the sample is present as Fe^{3+}. Typical

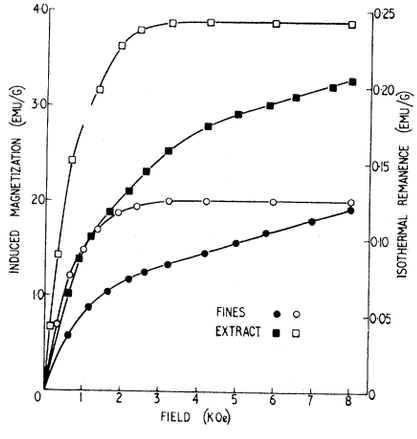

Fig. 1. Curves of J_i–H (left-hand scale, full symbols) and J_r–H (right-hand scale, open symbols) for fines and magnetic separate.