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.

RICHARD R. DOELL
C. SHERMAN GROMMÉ
U.S. Geological Survey, Menlo Park, California 94025
A. N. THORPE
F. E. SENFTLE
U.S. Geological Survey, Washington, D.C. 20242

References and Notes

1. R. R. Doell and A. Cox, in *Methods in Palaeomagnetism*, D. W. Collinson, K. M. Creer, S. K. Runcorn, Eds. (Elsevier, Amsterdam, 1967), p. 159.
2. Lunar Sample Preliminary Examination Team, *Science* **165**, 1211 (1969).
3. S. P. Clark, Ed., *Handbook of Physical Constants, Geol. Soc. Amer. Mem. 97*, (1966).
4. F. E. Senftle, M. D. Lee, A. Monkewicz, J. Mayo, T. Pankey, *Rev. Sci. Instr.* **29**, 429 (1958).
5. F. E. Senftle, A. N. Thorpe, R. R. Lewis, *J. Geophys. Res.* **69**, 317 (1964).
6. R. R. Doell and A. Cox, *U.S. Geol. Surv. Bull. 1203-A* (1965).
7. ———, in *Methods in Palaeomagnetism*, D. W. Collinson, K. M. Creer, S. K. Runcorn, Eds. (Elsevier, Amsterdam, 1967) p. 196.
8. ———, *ibid.*, p. 241.
9. We thank E. Mankinen and S. Sullivan for assistance with the laboratory measurements.

4 January 1970

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

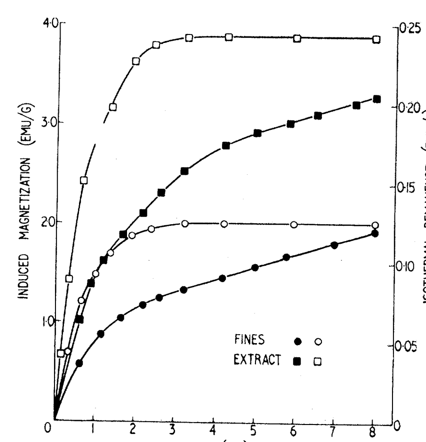


Fig. 1. Curves of J_i–H (left-hand scale, full symbols) and J_r–H (right-hand scale, open symbols) for fines and magnetic separate.

Table 1. Mössbauer data for ^{57}Fe at 78°K. Chemical isomer shift relative to sodium nitroprusside, $Na_2[Fe(CN)_5NO]$; $2H_2O$ taken as zero.

Chemical isomer shift (mm/sec)	Quadrupole split (mm/sec)	Assignment	Resonance (% by area)
0.90	1.0	Fe^{3+}	10
0.26	0	Fe (metal) or Fe/Ni alloy	4
1.45	1.1	Ilmenite	20
1.52	2.0	Tektites, orthopyroxenes, and site 2 of clinopyroxenes	66
1.57	2.9	Olivines and site 1 of clinopyroxenes	

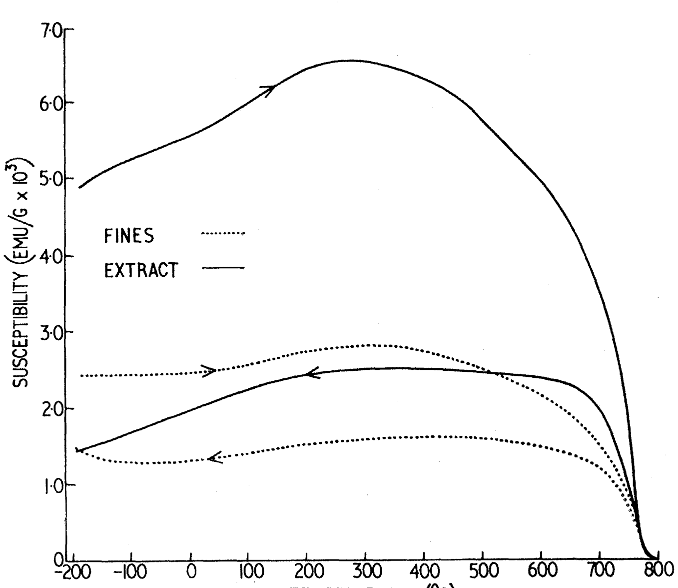
computer-fitted data and assignments are given in Table 1. The presence of ilmenite was confirmed by the disappearance of the paramagnetic quadrupole doublet in the spectrum at 4.2°K (below the Néel temperature).

The Mössbauer spectrum of the magnetic separate was similar to that of the fines except that the percentage of the resonance due to metallic iron increased to ~7. No evidence for iron sulfides or Fe_3O_4 was obtained either from the Mössbauer spectra or from x-ray powder diffraction patterns. This indicates that their concentration, if they were present, was less than 1 percent of the iron in the sample.

Figure 1 shows the dependence of induced (J_i) and isothermal remanent (J_r) magnetization on the applied field, H. The J_i–H curve may be interpreted as a constituent saturating at about 3000 oersteds, together with a nearly paramagnetic constituent apparent above 4000 oersteds, with susceptibility about 0.12×10^{-3} emu g^{-1} oersted^{-1}. The susceptibility value is too large to be accounted for by the iron present, even if all the iron is in paramagnetic form; thus superparamagnetic material may be present. However, there is some suggestion of slight curvature in the upper part of the curve, and the whole curve may also be explained by superparamagnetism (*1*). The evidence suggests that native iron is the important magnetic constituent ($J_s \sim 220$ emu g^{-1}) in the fines and separate, and the J_i–H curves indicate the presence of the order of 1 and 2 percent of iron, respectively. Saturation remanence is reached in a field of about 3000 oersteds (0.13 and 0.24 emu g^{-1}, respectively), and the coercivity of remanence in the fines is 400 oersteds.

Figure 2 shows the reversible susceptibility (χ_r) of the fines and the separate in the temperature range −196° to 800°C; the samples were contained in an evacuated quartz tube and χ_r was measured in an a-c field (1500 hz) of 2.5 oersteds r.m.s. The variation of χ_r at low temperature is small and no discontinuities occur, so the existence of large-grained magnetite is ruled out. Above room temperature no discontinuities indicative of titanomagnetites or magnetite are present, and the Curie points of both the fines (778° ± 3°C) and the separate (775° ± 3°C) correspond closely to that of pure iron (782° ± 3°C) measured on the same instrument. The curve for iron falls much more steeply toward the Curie point than do those of the fines and the separate; this steepness is explained by the demagnetizing effects in isolated grains of high intrinsic susceptibility (*1*), and these effects seem to be less important in the lunar material. This is confirmed by the large amount of iron (~8 percent) required to be present on the basis of the observed χ_r of the fines (2.4×10^{-3} emu g^{-1} oersted^{-1}). The lower susceptibility after heating may be ascribed either to oxidation of iron particles or to growth of particles (by coalescence) above the critical size for superparamagnetism.

The thermomagnetic curve in a high field (10,000 oersteds) again shows a high Curie point of about 775°C, with a shape more similar to that expected from a paramagnetic or superparamagnetic component—that is, a slow decrease toward the Curie point without marked discontinuities; there is evidence that physical or chemical changes commence at about 500°C. This is confirmed in the course of



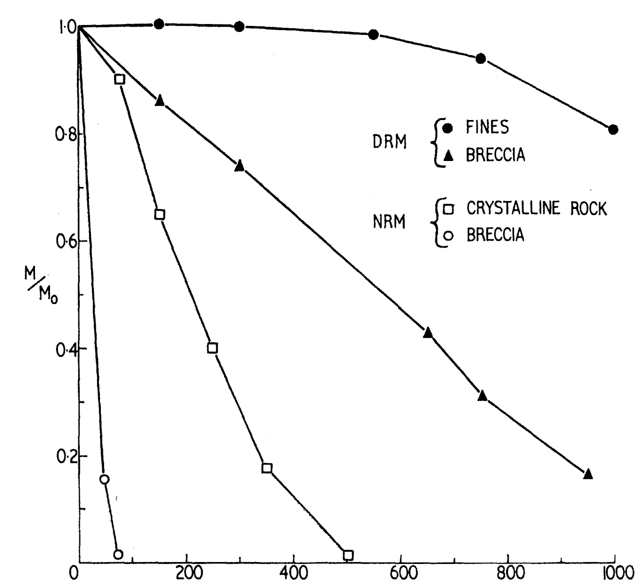


Fig. 2 (left). Reversible susceptibility of fines and magnetic separate plotted against temperature. Fig. 3 (right). Stability of NRM in breccia and crystalline rock, and of artificial DRM in fines and crushed breccia.

partial thermoremanent magnetization (PTRM) experiments (*1*), in which the TRM acquired in 100°C intervals up to 800°C in a field of 0.42 oersted was measured. The importance of iron is again indicated by the fact that the maximum PTRM was acquired between 800°C and 700°C, and measurement of susceptibility after each temperature interval shows that changes occur in the material after 500°C. Smaller PTRM's are acquired in all temperature intervals; these may be due to blocking temperature effects or small amounts of iron-titanium oxides.

Measurement of high field anisotropy (rotational hysteresis) of the fines on the torque magnetometer (*2*) shows a curve of which part is characteristic of iron, together with a peak at about 2500 oersteds, similar to that found in measurements on titanomagnetites in terrestrial rocks; this peak is absent in the separate, but appears after heating in vacuum to 800°C. These results suggest the presence of titanomagnetites with spinel structure in the fines, but the absence of such titanomagnetites in the separate is puzzling; there is as yet no evidence of significant quantities of iron-titanium oxides, other than ilmenite, under the microscope.

When first measured, the breccia sample had a natural remanent magnetization (NRM) of 62×10^{-6} emu g^{-1}, which was reduced to about 1.0×10^{-6} emu g^{-1} after demagnetization in a peak field of 75 oersteds (Fig. 3). The initial NRM was clearly a viscous remanent magnetization (VRM) acquired in the earth's field before the sample was received in Newcastle, and further tests showed the rapid growth of VRM in a weak field (0.16 oersted) to be logarithmic with time, with a viscosity coefficient S of 22×10^{-6} emu g^{-1}. The fines gave a similar result with $S = 27 \times 10^{-6}$ emu g^{-1}. The ease with which the breccia sample acquires stray magnetizations made further demagnetization difficult, and consistent results were not obtained. At present it may be stated that any "hard" remanence has intensity less than 1.0×10^{-6} emu g^{-1}, and probably less than 10^{-7} emu g^{-1}. Measurements on the Princeton Applied Research spinner and also on the astatic magnetometer on an approximately equidimensional chip of the breccia showed its susceptibility anisotropy to be less than 0.5 percent; its bulk susceptibility (2.9×10^{-3} emu g^{-1}) is close to that of the fines.

The presence of any grains possessing a hard magnetization was investigated in the fines and in a sample of crushed breccia by allowing a suspension of each in acetone to settle out in a weak field (~1.0 oersted); after the acetone was evaporated off, the resulting depositional remanent magnetization (DRM) was measured and subjected to alternating field demagnetization. The stability of the DRM is shown in Fig. 3. It is seen that there are particles of extremely high stability in the fines and of somewhat less stability in the breccia.

Preliminary measurements on the crystalline rock sample indicate an NRM of intermediate hardness. An initial NRM of 5.6×10^{-6} emu g^{-1} was reduced to 2.0×10^{-7} emu g^{-1} in a demagnetizing field of 500 oersteds (Fig. 3); this is clearly not a VRM acquired in a few weeks or days. The growth of VRM in the rock in a field of 2.4 oersteds over a period of 9 days suggests that the measured NRM could not have been acquired in any reasonable magnetic field or time on the moon, if the growth is logarithmic. The only other measurement made on this rock was of reversible susceptibility; a value of 7.7×10^{-5} emu g^{-1} $oersted^{-1}$ was obtained.

Although so far no native iron has been definitely identified under the microscope, it appears to dominate the magnetic properties of the fines and breccia. However, a range of submicroscopic particle sizes can account for the results described in this report; iron particles less than about 160 Å in diameter will be superparamagnetic, those between about 160 and 320 Å will be single domains, and larger ones will be multidomain grains. Superparamagnetism can account for the anomalously high initial susceptibility and for the shape of the J_i–H curve, single domains are presumably responsible for the stable DRM observed in the fines and breccia, and these and larger grains carry the isothermal remanence. Viscous remanence may be carried by multidomain grains as well as by those on the margin of superparamagnetism. The magnitude of the observed properties is explained by the presence of between 0.1 and 1.0 percent of native iron; this amount is in agreement with the Mössbauer results (~0.5 percent). It is possible that any nickel present is associated with the iron. If all the nickel present in the fines (250 ppm) is assigned to 0.5 percent of nickel-iron, then the latter will contain about 5 percent nickel, a somewhat lower concentration than that usually found in iron meteorites.

The remaining iron is contained in the abundant ilmenite (~15 percent) and in the paramagnetic pyroxenes and olivines, with possibly a small proportion in a spinel phase. Although the paramagnetic forms of iron will contribute to the magnetic properties in an applied field and the spinel phase will contribute to all properties, the native iron is the dominant magnetic constituent.

It is unlikely that the breccia has any stable remanence, and it appears that the "hard" magnetic particles that it and the fines contain are randomly oriented single domains. The NRM of the crystalline rock requires further investigation; it is not a recently acquired VRM, nor does it appear to be a simple VRM acquired logarithmically in any reasonable lunar field. The magnetometer results from Apollo 12 can be interpreted by supposing that the bedrock in the maria is uniformly magnetized to about 10^{-5} emu g^{-1}. (The monthly thermal cycling in the presence of the component of the solar wind field along the moon's rotation axis requires study.) Failing this, the NRM might be a TRM acquired 315×10^{9} years ago; it is possible that the moon has a small iron core in which dynamo action was once more vigorous than it is now.

S. K. Runcorn
D. W. Collinson
W. O'Reilly
A. Stephenson

Department of Geophysics and Planetary Physics, School of Physics,

N. N. Greenwood

Department of Inorganic Chemistry, School of Chemistry,

M. H. Battey

Department of Geology, The University, Newcastle-upon-Tyne, England

References and Notes

1. T. Nagata, *Rock Magnetism* (Maruzen, Tokyo, 1962).
2. D. W. Collinson, K. M. Creer, S. K. Runcorn, Eds., *Methods in Paleomagnetism* (Elsevier, Amsterdam, 1967).
3. We are indebted to the following for valuable discussion and assistance with measurements: K. M. Creer, R. G. J. Strens, D. H. Tarling, A. Manson, and P. Redman, Department of Geophysics and Planetary Physics, School of Physics; J. M. Jones and P. C. Jones, Department of Geology, and A. T. Howe, Department of Inorganic Chemistry, School of Chemistry. Support from the Natural Environment Research Council is acknowledged.

4 January 1970