Magnetic and Dielectric Properties of Lunar Samples

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The dielectric properties of lunar soil and rock samples show a systematic character when careful precautions are taken to ensure there is no moisture present during measurement. The dielectric constant (K) above 10^5 Hz is directly dependent on density according to the formula $K = (1.93 \pm 0.17)^{\rho}$ where ρ is the density in g/cc. The dielectric loss tangent is only slightly dependent on density and has values less than 0.005 for typical soils and 0.005–0.03 for typical rocks. In addition to a density dependence, the loss tangent appears to be directly related to the metallic ilmenite content. These results are in good agreement with the results of the Surface Electrical Properties Experiment carried on Apollo 17. It showed a surface layer of dielectric constant 3.8 and a loss tangent of 0.008. This is presumed to be a layer of compact soil about 7 m thick, overlying a medium with a dielectric constant of roughly 7.5 and a loss tangent interpreted to be 0.035. The medium is presumed to be bedrock. These results are compatible with seismic results.

The magnetic properties of lunar samples can be used to study the distribution of metallic and ferrous iron which shows systematic variations from soil-type to soil-type and a general tendency to increasing Fe°/Fe^{++} distribution in the more highly rewelded breccias. The other magnetic characteristics can also be used to determine the distribution of grain sizes. There are a number of ways of interpreting the origin of the stable remanent magnetization in lunar samples, but several lines of evidence suggest that it is of thermal origin and was acquired at a time when the igneous rocks and breccias cooled from above 800°C in the presence of an ancient field.

In this paper we review the electrical and magnetic properties of lunar samples and discuss the relevance to a number of problems of lunar interest. These problems include determining the history of the lunar magnetic field, studying the distribution of iron (metallic and ferrous) on the lunar surface, and establishing the relevance of magnetic properties to orbital magnetic mapping and surface electromagnetic sounding.

Dielectric Constant and Loss Tangent

Radar sounding of the Moon and planets has been conducted for some years now and provides a part of the basic data for the interpretation of planetary surfaces. A recent review paper (ref. 1) summarizes the results of the large number of measurements made on lunar samples in a number of laboratories. The results measured at frequencies above 10^5 Hz on samples treated with great care with respect to water content are summarized in figures 1 and 2. Samples which have only a small amount of moisture have a dielectric constant that is nearly independent of frequency and which, to a first approximation, is dependent only on the packing fraction. Simple equations relating the bulk density (ρ) and the dielectric constant (K) can be derived as illustrated in figure 1 [$K = (1.93 \pm 0.17)^{\rho}$].

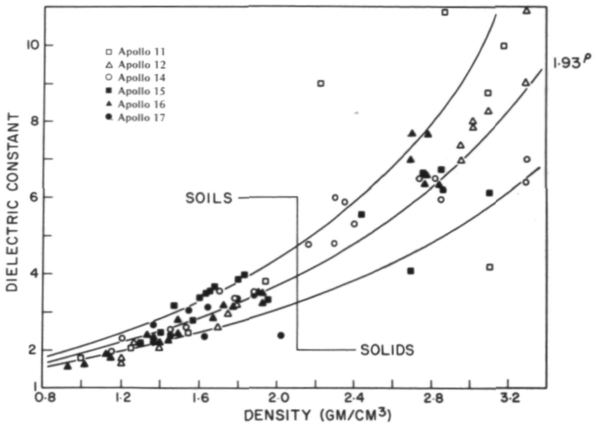

Figure 1.—*Dielectric constant (K) above 10^5 Hz as a function of density for lunar samples. Solid line is a least squares fit to the soil data and is of the form K = $(1.93 \pm 0.17)^{\rho}$, where ρ is the density in g/cm^3. Dashed lines represent the uncertainty limit.*

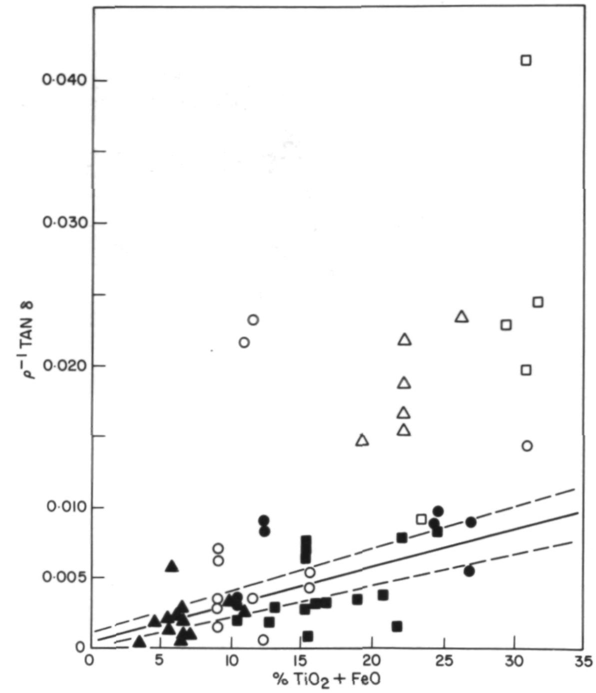

Figure 2a.—*Loss tangent (tan δ) measurements as a function of density for samples which have been extensively vacuum-dried by heating (symbols as in fig. 1). Solid line is a least squares fit to the soil data and is of the form tan δ = (0.00053 ± 0.00056) + (0.00025 ± 0.00009) C ρ, where C is the content of FeO + TiO_2. The loss tangent in all cases represents values above 10^5 Hz. On dry samples the values are nearly frequency-independent at or above this frequency.*

The more difficult measurement is the loss tangent which was found to be extremely sensitive to even minute amounts of moisture. Nevertheless, good results were obtained when careful measurements using high vacuum systems were made, and most results reported in the literature from lunar missions beyond Apollo 14 are considered to be reliable. Again, however, it is possible to fit this to a simple mixing formula that involves the volume fraction of material and that of sample. This given by $\tan\delta = [(0.00053 \pm 0.00056) + (0.00025 \pm 0.00009)\ C]\ \rho$ where C is the content of FeO + TiO_2. The fit is remarkably good and implies that for soils the typical loss tangent (tan δ) is less than 0.005, while solid rocks have somewhat higher loss tangents with values between 0.005 and 0.03. The range of loss tangents is dependent then on the content of ilmenite, a metallic phase, as well as the density.

From the sample studies alone, therefore, there is an implication that the dielectric properties and loss tangents of a typical lunar regolith are as illustrated in figure 3. The density profile used in this model is reported in detail by Olhoeft and Strangway (ref. 1) and is in general consistent with the results obtained during the lunar program soil experiments. Where the regolith gives way to solid bedrock, the dielectric constant will jump to a value of about 7.7, the intrinsic value of the dielectric constant. The loss tangent will jump to a value ranging between 0.005 to 0.03, depending upon the ilmenite content.

Ilmenite is present in varying amounts and is of course the main metallic conducting mineral present in lunar samples. Although this appears to have very little effect on the dielectric constant, the equation above shows a direct correlation between the ilmenite content and the loss tangent. Thus, the loss tangent can be expected to vary directly with

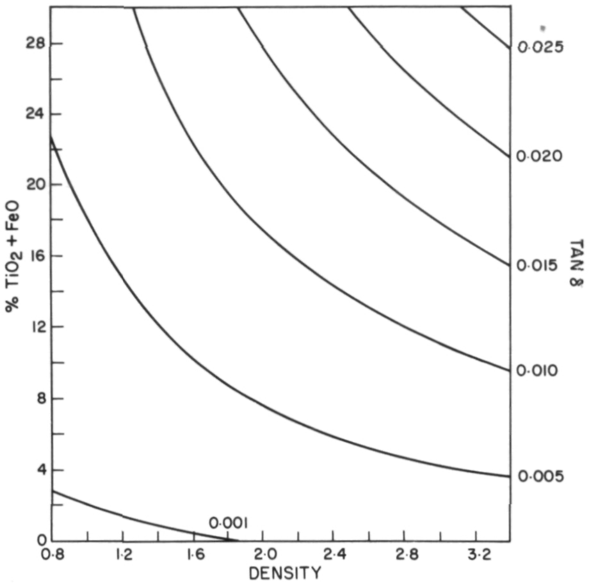

Figure 2b.—*The equation shown plotted as contours of loss tangent in a plane showing density versus FeO + TiO_2. This is roughly equivalent to the ilmenite content.*

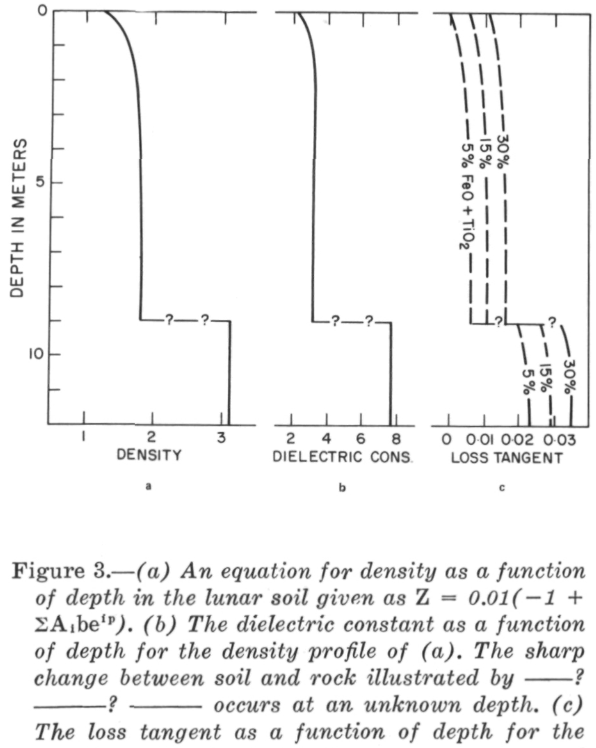

Figure 3.—*(a) An equation for density as a function of depth in the lunar soil given as Z = 0.01(−1 + ΣA*ᵢ*be*^{ip}*). (b) The dielectric constant as a function of depth for the density profile of (a). The sharp change between soil and rock illustrated by ——? ——? —— occurs at an unknown depth. (c) The loss tangent as a function of depth for the density profile of (a). The three curves correspond to 5-, 15-, and 30-percent FeO + TiO_2.*

the amount of metallic mineral present, at least up to the limit of about 25 percent observed in the lunar samples. Figure 3 is a rather generalized profile of the predicted dielectric properties from the surface of the Moon and shows values of the loss tangent that would be predicted for various ilmenite contents. Presumably these results are comparable to those that would be obtained on any planetary body totally free of moisture and having a regolith (ref. 1).

There have been a number of experiments conducted over the years which throw light on this problem. Remote observations of the lunar surface, as recently reviewed by Hagfors (ref. 2), have shown that the surface of the Moon has a dielectric constant in the general range of 1.5 to 3.0. Estimates of the loss tangent are model-dependent, but, choosing reasonable models, values in the range of 0.005 seem to be appropriate. More recently Tyler and Howard (ref. 3) detected Apollo spacecraft communication signals on Earth which had been reflected from the Moon. This permitted them to determine the electrical properties of the surface of the Moon. These observations are also in general agreement with the earlier Earth-based observations, although there is an implication of dielectric layering in the upper few centimeters of the Moon.

During the Apollo 17 mission, a specific experiment to measure the dielectric properties of lunar material in place was carried. This experiment has been described in the literature (refs. 4 and 5). The method used is illustrated in figure 4 and consists of the measurement of field strength as a function of distance from a transmitter. The fields transmitted are from two orthogonal dipole antennas laid on the lunar surface and operating at 1, 2, 4, 8, 16, and 32 mHz. These signals were received on the Rover by three orthogonal coils and recorded on tape together with navigation information. It was thus possible to produce plots of field strength versus distance at each of several frequencies. Some of these are shown in figure 5. In general, the information derived from this experiment consists of the interference patterns

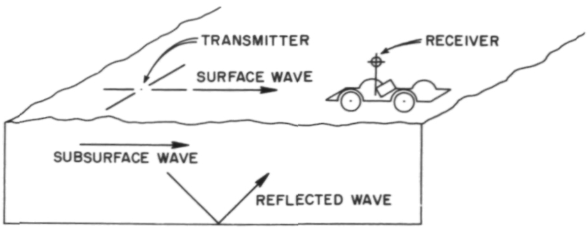

Figure 4.—*Sketch illustrating the principle of the surface electrical properties experiment. Field strengths were measured on the Rover as a function of distance from an electric dipole antenna on the lunar surface. Energy traveling at the speed of light above the interface interferes with the energy traveling below the interface to give a measure of the dielectric constant and loss tangent of the surface layers. Further interferences are generated by reflections from dielectric layering and/or scattering bodies.*

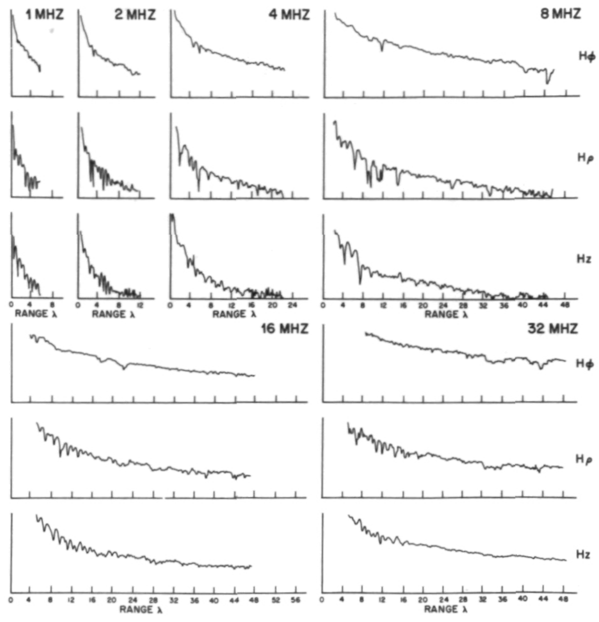

Figure 5.—*Field strength versus distance (in wavelength) plots for data recorded at 1, 2, 4, 8, 16, and 32 mHz. Components shown are the end-fire, maximum-coupled* H_ϕ *component and broadside, maximum-coupled* H_z *and* H_ρ *components where the coordinates are as illustrated in figure 4. The field strength is given in db.*

resulting from one or more of the following waves interfering with the surface wave: (a) subsurface waves, (b) waves reflected from layered electrical property contrasts, and (c) waves reflected from irregular, scattering bodies.

From (a) we can derive the dielectric constant and loss tangent at any frequency not affected by the other interfering effects.

Examining the plots shown in figure 5, a number of conclusions can be drawn. First of all, the $H\phi$ component is maximum-coupled, but the bulk of the energy from the end-fire antenna represented here travels above the surface. The result is that this component is relatively smooth when there is little scattering present either from the surface topography or from the subsurface. It can readily be seen that this component is fairly smooth at all frequencies from 1 to 32 mHz. This clearly implies that there are few scattering bodies in the subsurface. Since the free space wavelength ranges between 300 and 10 m, it is implied that there are not many boulders larger than a few meters present in the soil. Considering the dielectric constant of the medium, this means that there are few scatterers with a scale of 5 m or more. The lack of scattering bodies is in complete contrast to our previous studies on glaciers which we feel are the nearest available terrestrial analogs (refs. 5 and 6). In temperate glaciers the scattering is small at 1, 2, and 4 mHz, but at 8 mHz and above the scattering becomes large and dominates the results. The lack of scattering means that the lunar observations should be interpretable in terms of relatively simple models at all frequencies.

The second observation that can be made by observing figure 5 is that to a rough approximation the data show a rapid falloff relative to wavelength at 1 mHz and a slow falloff relative to wavelength at 32 mHz. This means simply that at 1 mHz the medium behaves much like a dielectric halfspace, and little energy is reflected to the surface, while at 32 mHz the medium is layered, and energy is trapped in the layer and reflected.

The third observation that can be made is that at 1 mHz the frequency of the interference corresponds very closely to the case of a halfspace with a dielectric constant of 7.5 ± 0.5 and a loss tangent of roughly 0.035 ± 0.025. These values are remarkably similar to the values reported on solid lunar samples and imply that at depths below the surface there is relatively solid rock present. The situation is analogous to that at the Apollo 15 landing site where bedrock a few meters below the surface was observed in the walls of Hadley Rille. This layer probably corresponds to the layer characterized by a seismic velocity of about 280 m/s (refs. 7 and 8). This is an extremely low velocity and implies the presence of rock that is strongly dominated by extensive fracturing. In figure 6, a sketch showing the inferred seismic structure at the Taurus-Littrow landing site is given.

At shallow depths (relative to a wavelength in the medium at 1 mHz) there is, however, considerable structure present. We have not yet been able to offer a unique interpretation of these results. It appears, however, that at 16 mHz and 32 mHz the results can be fitted reasonably well with a two-layer case consisting of a layer 7 ± 1 m thick, with a dielectric constant of 3.8 ± 0.2 and a loss tangent of 0.008 ± 0.004 as shown

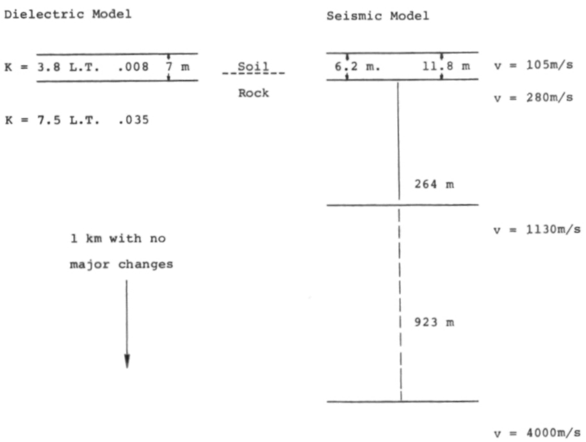

Figure 6.—*Cross section at the Taurus-Littrow landing site determined from the surface electrical properties experiment and from the lunar seismic profiling experiment.*

in figure 6. These dielectric properties are remarkably similar to those reported for dry samples of lunar soil. The dielectric constant is slightly high, which implies that the average density of the top 7 m is about 2.0 g/cc, a value not inconsistent with models of the density of the lunar surface (see fig. 3).

In summary, the measurements of the dielectric constant and loss tangent of lunar soils and rocks give values that can be used to predict the electrical structure of the lunar surface. Soil samples have a dielectric constant which to a first approximation is dependent only on the density. The loss tangent is only weakly dependent on the density, but it is directly proportional to the ilmenite content. Solid rock samples have a higher dielectric constant that is typically around 7.7. The values quoted for the soil are in good agreement with the results of remote radar and of passive thermal observations of the lunar surface from Earth-based observations.

An experiment carried on the Apollo 17 mission to determine the electrical structure shows that the top 7 m are composed of material with a dielectric constant of 3.8, presumably corresponding to fairly compact soil of average density 2.0 g/cc. Beneath this, the dielectric constant jumps to a value of about 7.5, a value which is typical of lunar rock samples. This regolith thickness is in close agreement with the values determined seismically. Low seismic velocities reported for the bedrock are in agreement with the high dielectric constant, provided the low velocity is the result of extensive fracturing of the bedrock.

Magnetic Properties of Lunar Samples

There are now a number of review articles on the subject of lunar magnetism, and no attempt will be made here to review the subject in depth. Rather, the reader is referred to an excellent treatise on the subject by Fuller (ref. 9) and an earlier paper by Strangway et al. (ref. 10). In the present paper, we will discuss the major points of lunar magnetic properties and elaborate on some of the ramifications.

In making measurements on lunar samples, the magnetic hysteresis loop at room temperature is usually measured and can be utilized to determine a number of important parameters. The only ferromagnetic material present in any quantity in lunar materials is metallic iron, sometimes alloyed with nickel and/or cobalt. There have been isolated reports of minute amounts of oxidized phases such as magnetite and goethite, but these are very limited. It is therefore possible to make quite accurate magnetic measurements of the content of metallic iron. A histogram of observations on lunar samples is shown in figure 7. In all cases, the mare basalts have less than 0.1-percent metallic iron by weight and, in general, there is only about 0.05 to 0.06 percent. The few samples of anorthosite that have been measured have even less metallic iron than this. Thus, the major lunar igneous rock types are not highly reduced chemically since they also have considerable amounts of Fe^{++} present in iron silicates.

Soils from the various missions have also been examined, and it is found that the metallic iron content is much higher than that in any of the igneous rocks. This in itself is remarkable since the soil is largely derived from the rocks present. It was thought at one time that this was the result of excess iron added by iron meteorites. It is now known that this is not the case, since most of the metallic iron present is not nickel-rich kamacite.

Breccias which are derived largely as a result of impacts into soils show spreads of values of iron content between those of soils and igneous rocks, and in some cases have contents higher than the soils. We have somewhat arbitrarily used an additional group, here referred to as highland crystalline rocks. These are the highly remelted rocks collected from the Apollo 16 highland landing site. Again the range of metallic iron content is quite large, as with the less severely reworked breccias.

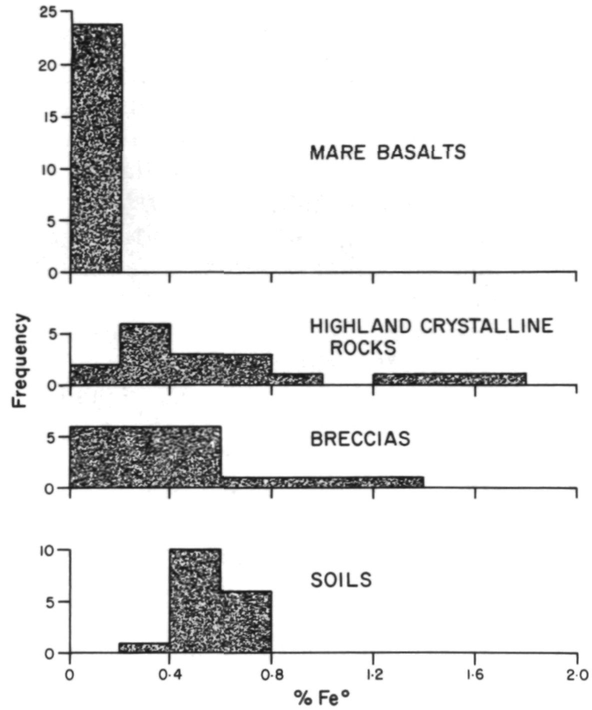

Figure 7.—*Metallic iron content in lunar samples of various types. Data represent a fairly complete compilation up to Apollo 16 from all laboratories as reported in Pearce et al. (ref. 11) and amplified with data from our laboratory on Apollo 17, as reported in Pearce et al. (ref. 12) and from reports in the Proceedings of the fourth Lunar Science Conference and the Lunar Science V abstract.*

It is also possible to determine the ferrous iron content from magnetic hysteresis studies by determining the slope of the paramagnetic portion of the curve. This method gives a good approximation to the true ferrous iron content present in the lunar silicates (refs. 11 and 13) provided there is not a large amount of superparamagnetic iron present. Superparamagnetic iron has grain sizes less than about 150 Å and is sufficiently thermally unstable to be unable to carry a remanence. In general, particles of about 150 to 300 Å are considered to be single domain. These are extremely stable magnetically and are able to carry very stable remanence. In grain sizes over 300 Å, iron is presumably multidomain and can carry a remanence which is often quite soft and easily altered. The lunar soils and the low-grade breccias (refs. 14 and 15) have a significant amount of superparamagnetic iron present (size fractions less than about 160 Å). In such cases the paramagnetic susceptibility systematically overestimates the true iron content by a few percent. This fine-grained iron has led to an interesting study, since the lunar samples are almost unique in their complex range of ferromagnetic grain sizes, permitting the study of the full range of magnetic properties from superparamagnetic to single domain to multidomain in a single suite of samples. In addition to the normal hysteresis loops, it is well known that superparamagnetic particles can acquire a strong Viscous Remanent Magnetization (VRM) simply by being exposed to a field for a period of time. A number of studies of this have been reported (refs. 14, 15, and 16). Multidomain grains can also acquire VRM, but the character is quite different although it has not been studied in detail.

Information on other magnetic parameters for a number of samples is illustrated in figures 8 and 9. In figure 8 a plot of the magnetically determined ferrous iron (Fe^{++}) and the metallic iron (Fe^{o}) is illustrated using as an example the Apollo 17 rocks after Pearce et al. (ref. 12). By and large the mare basalts group in a small region with 16 to 18 percent of total iron and about 0.1-percent metallic iron. These samples have been little modified since emplacement, and it is tempting to speculate that this ratio is a norm for igneous processes in the lunar environment. Although the results from other missions are not shown in this figure, the few basalt samples for which these determinations have been made from other missions give comparable results. The dunite clast from 72415 shows a similar ratio, suggesting that it may not have suffered extensive surface modifications after it was formed.

The anorthositic samples are much lower in total iron as expected, but they tend to be enriched in metallic iron. The same is true for the noritic samples from the Apollo 17 mission. It is hard to escape the conclusion that these latter samples, which are in reality chips from the highland breccias of the north massif, have undergone reheating in the lunar vacuum and that chemical reduction of iron from the silicates has been one of the consequences. This process has been demonstrated in the laboratory by Pearce et al. (ref. 17), and Pearce and Simonds (ref. 18) have shown that the

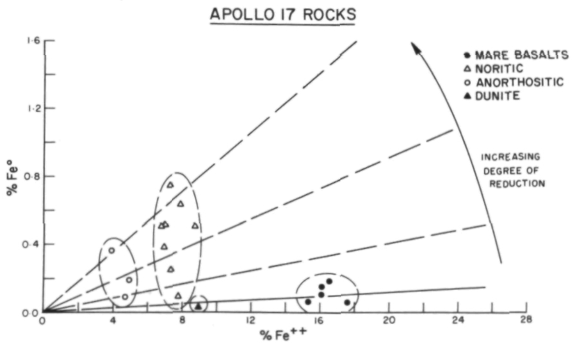

Figure 8.—*Cluster diagram of Fe° versus Fe++ content (both determined magnetically) for rock samples from Apollo 17. Note the distinct groupings by rock type and the spread in the ratio for the anorthositic and noritic breccias. This corresponds to different degrees of chemical reduction.*

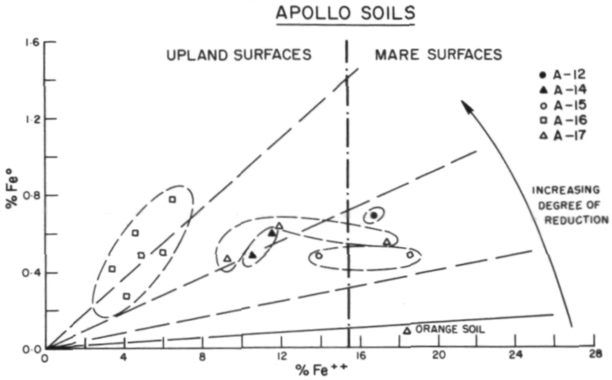

Figure 9.—*Cluster diagram of Fe° versus Fe++ content for soils from all Apollo landing sites. Note distinct groupings for different soils and that the mare soils are generally high in Fe++ and are less reduced than highland soils.*

Apollo 16 rocks are similar to the Apollo 17 rocks in this respect.

The precise cause of the reduction involved remains unclear. Housley et al. (refs. 19 and 20) propose micro-meteorite bombardment that leads to local melting in the presence of samples enriched by reducing solar wind gases. Pearce et al. (ref. 17) and Cisowski et al. (ref. 21) propose that the process takes place as the result of larger impact processes. Pearce et al. suggest that the excess iron is primarily generated in the associated ejecta blanket including gas cloud and regions of local melting. Cisowski et al. (ref. 22) attribute it directly to the effect of shock rather than the associated ejecta blanket heating. In any event, there seems to be little question that surface processes which are the result of impacts generate the excess iron found in the lunar soils and breccias. Housley et al. (ref. 19) have particularly drawn attention to the fact that much of the excess metallic iron in the soils is present in the form of spherules within glass particles and that these spherules are quite accurately spherical.

We illustrate in figure 9 plots of Fe^{++} versus Fe^{o} for soils from the different Apollo missions. It should be noted that the magnetically determined Fe^{++} is the quantity used. As stated earlier, this is a systematic overestimate. The samples plotted are taken from the table given by Pearce et al. (ref. 12) for convenience, but the conclusions are similar when data from other laboratories are examined. The least reduced samples are the young mare soils from Apollo 12, 15, and 17. The number of samples plotted is not large, but the trend is unmistakable. At Apollo 15 and 17 highland samples were also collected. These have much less total iron and are relatively more reduced, probably as a result of the greater age of these surfaces. The proximity of mare surfaces at these two sites suggests that considerable mixing between old highland surfaces and young mare surfaces may have taken place. Samples from Apollo 14 are quite reduced, while the low iron content samples from the oldest site, Apollo 16, are by far the most reduced. Thus, there is a correlation between the amount of reduction and the exposure of the various sites to the continuing bombardment of the lunar surface by impacts of varying sizes during the early active period of lunar history.

The orange soil from the Apollo 17 site is quite anomalous in this sense. In agreement with other studies (ref. 23), it may be concluded that it was formed in a somewhat more oxidizing atmosphere than the bulk of lunar soils. It may well be that this environment was similar to that in which the basalts themselves were formed. Subsequent bombardment then caused chemical reduction of most of the soils. The orange soil, however, has remained relatively untouched by bombardment since its formation and so is not as reduced. There is undoubtedly much yet to be learned about the systematics of iron distribution and the controlling influences. Lunar surface processes will be better understood as we gain this insight.

In addition to the distribution of metallic iron, it is possible to determine a great deal about the grain sizes from a study of the magnetic hysteresis loop properties. Two such parametric representations are illustrated in figures 10 and 11. In figure 10, the saturation remanence (J_{rs}), which is a measure of the capacity of a sample to retain a memory, is normalized against the saturation magnetization (J_s), which is a direct measure of the total metallic iron. This plot is a histogram of results previously tabulated by Pearce et al. (ref. 11), and data from Apollo 17 (ref. 12) has been added. Most notable in this plot is the fact that the crystalline rocks are invariably the least able to carry a strong memory. This is due simply to the presence of multidomain iron (> 300 Å) and very little single-domain iron (150–300 Å). The crystalline rocks can be used for ancient field studies, but they have a large proportion of magnetically soft iron and are therefore extremely difficult to work with. Soils have distinct higher values of the ratio J_r/J_s and a greater spread. The mare soils tend to have the greatest ability to carry a memory, with values of J_r/J_s approaching 0.1. The breccias, as in previous indicators, tend to be

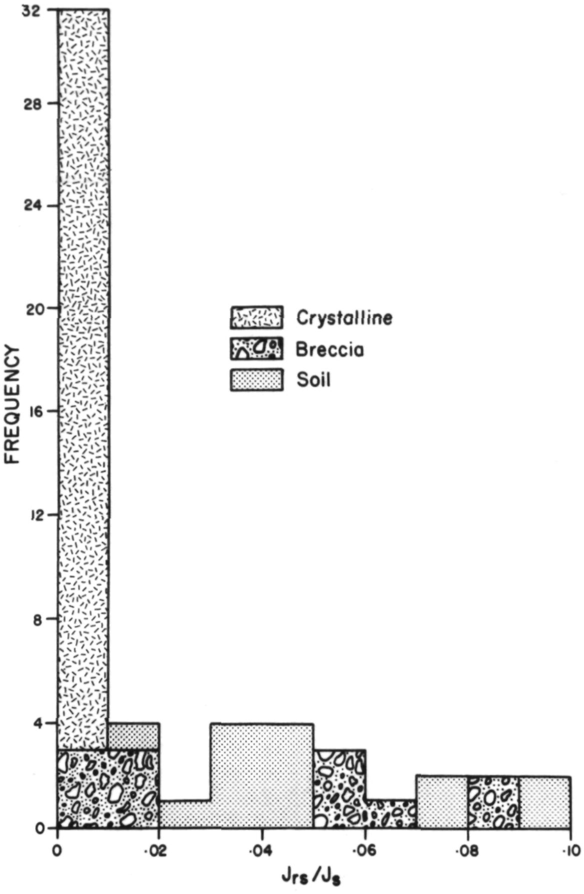

Figure 10.—*Histogram of values of* J_{rs}/J_s *for different types of lunar samples. Small values of this quantity imply multidomain materials which are magnetically soft.* (J_{rs} = *saturation remanence;* J_s = *saturation magnetization.)*

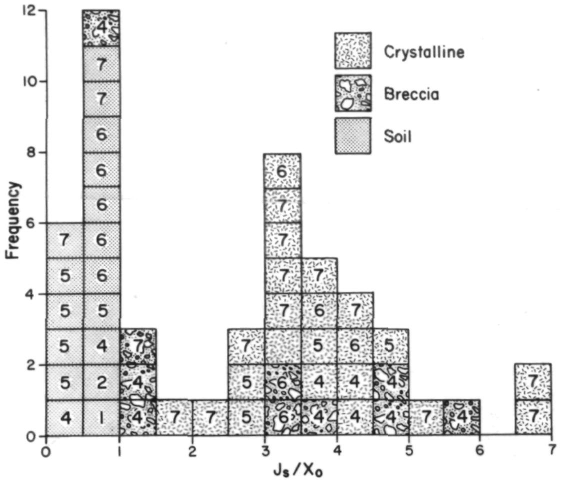

Figure 11.—*Histogram of values of* J_s/X_o *for different types of lunar samples. Small values of* X_o *(the initial susceptibility) imply the presence of multidomain material, while larger values imply single-domain materials. This grades into the largest values for superparamagnetic materials.*

mixed with values ranging from those for the true igneous rocks to those for the least developed soils.

A second parameter, the ratio of the saturation magnetization (J_s) to the initial susceptibility (X_o), is shown in figure 11. The initial susceptibility is a measure of the shape of the hysteresis loop. When the value of J_s/X_o is small, the material tends to have a high proportion of superparamagnetic and single-domain material; when it is large, it implies the presence of multidomain materials. Even though any one sample undoubtedly contains volume fractions of all these, it is interesting to examine the systematics. The soils are almost invariably characterized by low values, implying thereby that they are rich in superparamagnetic or single-domain material. The crystalline rocks tend to have high values, thereby implying that they are rich in multidomain materials. Again the breccias are spread between these and represent intermediate distributions of grain sizes.

It is therefore abundantly clear that not only is the iron content and oxidation state highly variable on the lunar surface, but there are systematic variations in the grain sizes. Mechanisms considered for generating the excess iron appear to create excess fine-grained material which is dominant in the glasses (refs. 19 and 20). Subsequent processes appear to lead to the coarsening of grain sizes as the samples are lithified into breccias and heated to temperatures often approaching the melting temperature (ref. 24).

This is characterized by the plots of figure 12 that use a scheme like the one developed by Wasilewski (ref. 25) for classification of the magnetic properties of basalts and used by Fuller (ref. 9) for lunar samples. Here it

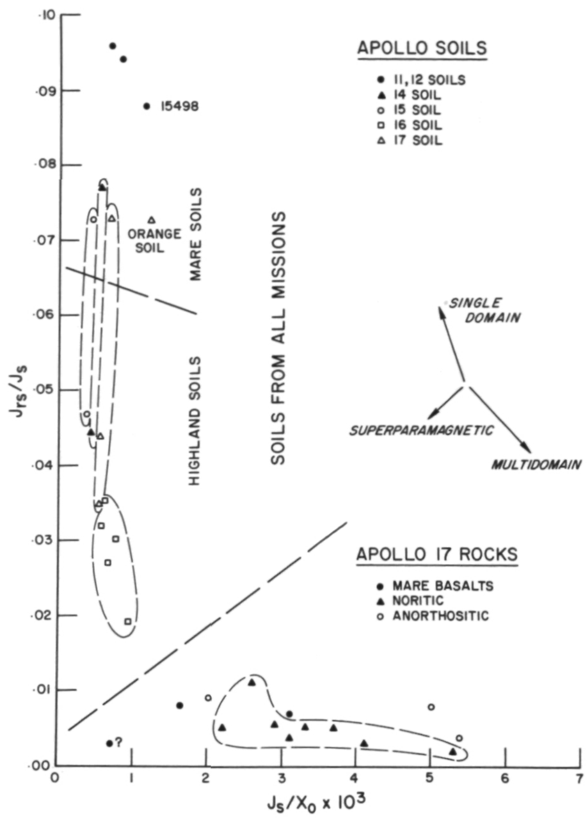

Figure 12.—*Cluster diagram of data from figures 10 and 11 showing character of soils from all missions and character of rocks from Apollo 17. Note that the mare soils tend to be rich in superparamagnetic and single-domain materials (high* J_r/J_s *and low* J_s/X_0*). Highland soils tend to be lower in single-domain materials and have more multidomain grains. Mare basalts and the high-grade noritic and anorthositic breccias tend to be low in single-domain materials and rich in multidomain materials.*

is shown that the basalts fall into a characteristic region of the plot just as the soils do. There are characteristic variations in the soil properties depending especially on whether they are of mare or of highland origin. The anorthosites and noritic rocks from Apollo 17 tend to show the coarsening of grain size and are intermediate between soils and mare.

Added to figure 12 are the data for sample 15498 which led to a useful paleointensity determination (ref. 26). Notice that this sample is rich in single-domain iron.

Natural Remanent Magnetization (NRM)

The intensity of remanent magnetization in lunar samples covers a wide range of values. Tabulated data for a large number of samples are shown in figure 13 (ref. 11). These data include most observations up to the time of the Apollo 16 mission.

A distinct peak for mare basalts occurs at

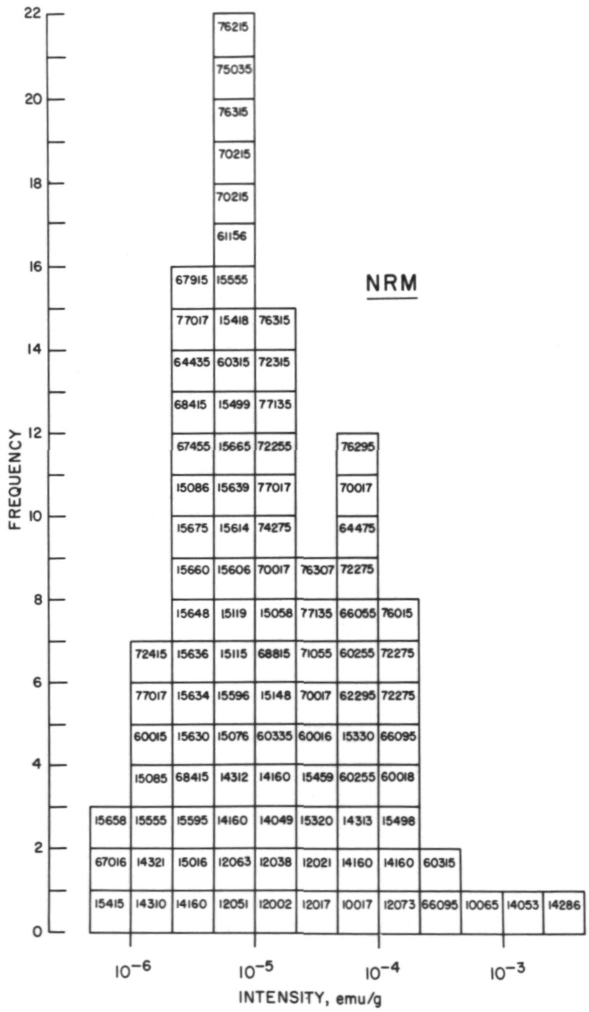

Figure 13a.—*Natural remanent magnetization (NRM) as measured on returned lunar samples. Figure from reference 11, with new data from references 13 and 27 through 32.*

about 10^{-5} emu/g. When the samples are demagnetized at 100 Oe as shown in figure 13, a large soft component is removed from most of the mare basalts and some of the breccias. This gives a peak of stable NRM at about 10^{-6} emu/g. A limited number of samples, however, retain their strong magnetization and form a small group at about 10^{-4} emu/g. Most of these samples are breccias. It seems likely that only this type of material can give the magnetic fields detected on the lunar surface.

One of the most important observations that must be the focus of more studies is the determination of the ancient lunar field intensity. To date only a few generally unsatisfactory observations have been made. The full Thellier-Thellier technique has proven to be difficult to apply since the samples change character on heating. One observation by Gose et al. (ref. 26) on a sample rich in single-domain particles gave a value of 2100 gammas. Heating in vacuum to 650°C showed no mineralogic changes, but at 700°C the sample changed irreversibly. Watson et al. (ref. 33) have reported measurements on breccias and basalts that gave intensity values of about 1100 gammas. Their heating was done in a controlled oxygen fugacity system. They were able to heat a basalt to 700°C with no apparent changes, although heating to 800°C caused generation of excess iron. A breccia sample started to alter even at temperatures less than 550°C. They attribute this to the presence of very fine-grained iron with a large ratio of surface area to volume.

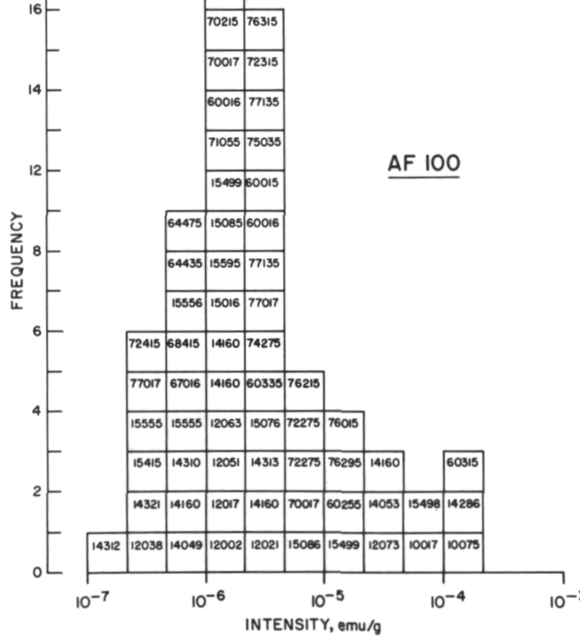

Figure 13b.—*Natural remanent magnetization after cleaning samples in alternating fields of 100 oe.*

The heating question is the central dilemma for paleointensity studies, and other workers have tried other approaches, including measurements of anhysteretic remanent magnetization. Stephenson and Collinson (ref. 34) report on a number of samples measured in this way which give apparent paleointensities of around 10 000 to 120 000 gammas. Heating to 500°C was reported (ref. 28). Above this, changes again took place. The subject requires much more careful study because, as pointed out by Dunlop et al. (ref. 35), the viscous effects in some samples can probably only be removed by heating to above about 300°C. Any information acquired without thermal demagnetization is likely to have a strong VRM effect. This means that the most important temperaature range to study (300°C to the Curie point) is only barely accessible to us. It is also worth noting that lunar samples are especially difficult to work with because, in general, they have a large soft component of magnetization which can introduce spurious effects unless extreme precautions are exercised. The presence of large soft components of NRM in lunar samples is one of the unsolved problems. At least some of this component may be of nonlunar origin, as shown by Pearce and Strangway (ref. 36). They returned an Apollo 12 sample to the Moon on Apollo 16. This sample had the soft component removed before flight, but it had acquired a large, soft component on return, presumably from spacecraft fields of a few oersteds. However, some of the soft component may be of lunar origin.

History of the Magnetic Field of the Moon

There is of course a high degree of importance to study of ancient lunar magnetic fields in view of the importance this has in determining something about the history and evolution of the Moon. The impact of magnetic studies on terrestrial studies is well known since it ushered in the new generation of the Earth sciences. While it may play the same role in lunar studies, it is important to understand the origin of the fields which magnetized the lunar samples. This same magnetization has been dramatically confirmed by the study of lunar surface fields (ref. 37) at a few places and by lunar orbital fields (ref. 38). There seems to be little question that large volumes of lunar material are present on the Moon, magnetized in a sufficiently coherent manner that they can give rise to detectable anomalies even at orbital heights. One model for this has been proposed by Strangway et al. (ref. 39) who call on the deposition of Cayley-type breccias in a coherent manner. Although only a small portion of the Moon has been studied by orbital mapping, there are several genuine anomalies and several inferred ones. This type of anomaly was also detected by the Apollo 16 subsatellite when it was at low altitude (ref. 38) and by the study of electron mirroring from the Moon (refs. 20 and 40). The Russians have reported on the presence of fields observed on the Lunokhod. By comparison with terrestrial studies, it is interesting to note that at comparable altitudes detectable crustal features are very weak (refs. 41, 42, and 43) relatively speaking, when the large magnetic field of the Earth is considered.

There are many unknowns about the nature and origin of lunar fields, but with the presence of lunar magnetic anomalies there can be no doubt that portions of the crust carry a memory of some early field. The geometry and the time duration of this field are unknown, and many speculations have been put forward as reviewed by Fuller (ref. 9). As we have already indicated, there are some highly magnetic samples on the Moon, and these are the most likely cause of the field observed from orbit. Since these samples are generally breccias, it has been considered that the magnetization they carry is somehow related to the impact that created them. These samples appear to carry a stable remanence, and there are many indications that they were heated well above the Curie point of iron. Many lines of evidence support this view as reviewed by Williams (ref. 44). The remanence in these samples would therefore be a Thermoremanence Magnetization (TRM) acquired on cooling in the presence of a field. As reviewed by Wasilewski (ref. 45), those regions around an impact not heated above the Curie temperature could acquire a Partial Thermoremanence Magnetization (PTRM).

Because of the similarity of this process to the comparable terrestrial process, we briefly review here the observation made on terrestrial impact structures and their related melts. Studies of the remanent magnetism of a number of terrestrial craters have been made. These include the Ries crater (ref. 46), the Rochechouart structure (ref. 47), the Mistastin Lake structure (ref. 48), the Manicouagan structure (refs. 49 and 50), the Charlevoix structure (ref. 51) and Meteor Crater (ref. 52). The findings can be very simply summarized. Wherever impactites containing glass are found so that the temperature clearly approached the melting temperatures, there is a consistent report of unusually strong, unusually stable, and unusually well-grouped paleomagnetic results. There seems to be no question that the materials cooled slowly enough that any transient magnetic fields associated with the impact had no influence on the resulting magnetization. Rather, the materials acquired a TRM which is considered to be an unusually accurate record of the ambient Earth's field. It seems likely that a similar mechanism operated on the Moon. The larger impacts caused heating to above the Curie temperature; in many cases the temperature approached melting. On cooling, the transient field effects of the impact were gone, and portions of the lunar crust acquired a coherent remanence governed by the ambient lunar field. Where heating does not reach the Curie point it is likely that scatter will be introduced just as is found in the low-temperature portions of terrestrial ash flows (ref. 53). In most cases, the softer portions of any preexisting remanence can, of course, be modified by shock, as at Meteor Crater.

If this explanation is correct and the terrestrial analog is relevant, we have yet to account for the origin of the original field controlling the process. Many models have been proposed, and we select no favorites in this paper. However, the discovery of a significant field on Mercury (ref. 54) and the strong indication of a field on Mars (ref. 55) suggest that these bodies also retain a memory of something that happened early in the history of the solar system. It seems to us that it is necessary to create models of the Moon and other nondynamo planets that have the ability to acquire a coherent magnetization at some time in the past.

Future mapping of the intrinsic magnetic field of planets and asteroids continues to be an important goal in understanding the early solar system.

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