JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 106, NO. E11, PAGES 27,841–27,852, NOVEMBER 25, 2001

Mapping of crustal magnetic anomalies on the lunar near side by the Lunar Prospector electron reflectometer

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Abstract. Lunar Prospector (LP) electron reflectometer measurements show that surface fields are generally weak in the large mare basalt filled impact basins on the near side but are stronger over highland terranes, especially those lying antipodal to young large impact basins. Between the Imbrium and Nectaris basins, many anomalies correlate with the Cayley and Descartes Formations. Statistical analyses show that the most strongly magnetic nearside terranes are Cayley-type light plains, terra materials, and pre-Imbrian craters. Light plains and terrae include basin impact ejecta as a major component, suggesting that magnetization effects from basin-forming impacts were involved in their formation. The magnetization of pre-Imbrian craters, however, may be evidence of early thermal remanence. Relatively strong, small-scale magnetic anomalies are present over the Reiner Gamma feature on western Oceanus Procellarum and over the Rima Sirsalis rille on the southwestern border of Procellarum. Both Apollo subsatellite and LP data show that the latter anomaly is nearly aligned with the rille, though LP magnetometer and reflectometer data show that the anomaly peak is actually centered over a light plains unit. This anomaly and the Reiner Gamma anomaly are approximately radially aligned with the center of Imbrium, suggesting an association with ejecta from this basin.

1. Introduction

Early measurements showed that the Moon has no global dipole magnetic field (upper limit of ~2×10^{-8} of Earth's [*Russell et al.*, 1978]). However, measurements by magnetometers and electron reflectometers onboard the Apollo subsatellites [*Coleman et al.*, 1972; *Anderson et al.*, 1976; *Lin*, 1979], and sample returns and in situ magnetometer measurements (reviewed by *Fuller and Cisowski* [1987]) showed the surprising existence of extensive crustal magnetism. Hundreds of magnetic anomalies covering the lunar surface were mapped by the Apollo subsatellites; these anomalies range in size from less than ~4 km (the resolution limit of the measurements) to hundreds of kilometers, and range in strength from less than one nanotesla to greater than 100 nT (1 nT = 10^{-5} G). The largest areas of strong crustal magnetism in the area mapped by the subsatellites were located antipodal to the Imbrium, Serenitatis, Crisium, and Orientale impact basins [*Lin et al.*, 1988]. Lunar Prospector data strongly confirm these results and extend them to the entire lunar surface. Lunar Prospector data show that the antipodes of these four young large impact basins, and to a lesser degree that of Nectaris, contain the largest concentrations of strongly magnetized crust on the moon. Conversely, many large impact basins, including Imbrium, Orientale, Nectaris, Humorum, and Hertzsprung, are clearly shown to be demagnetized by new Lunar Prospector electron reflectometer data. D. L. Mitchell et al. (manuscript in preparation, 2000) showed that these effects of antipodal magnetization and impact demagnetization together explain much of the large scale pattern of lunar magnetization.

It should not be surprising that large impacts demagnetize the lunar surface, since it appears that present-day lunar magnetism is confined to the crust, and a large impact will both shock and heat the crust above the Curie point to a significant depth. The basins have not been significantly remagnetized, which shows that either there was not a substantial ambient magnetic field present at the time of the impact, or the magnetic susceptibility of the cooling material was low. The strong magnetization of the antipodal regions is harder to understand. One possible mechanism has been suggested and modeled by *Hood and Huang* [1991]. A hypervelocity (>10 km/s) impact such as those that form large basins will produce a large plasma cloud consisting of partially ionized silicate vapor. Hydrocode simulations show that this cloud will expand around the Moon in a few hundred seconds, compressing and amplifying ambient magnetic fields at the antipode. The compression will last for ~1 day at the most, which is much too short a time for a large body of rock to cool, and thus thermal remanence seems unlikely. However, if large shock pressures could be produced at the antipode during the magnetic field amplification, then shock remanence could occur. *Shultz and Gault* [1975] have observed that grooved and hilly terranes occur at the antipodes of major basins on the Moon and other solar system bodies, suggesting that ejecta and/or seismic waves are focused at the antipodal regions. Thus shock remanence may be a possible mechanism. Whatever the mechanism, however, it seems clear that the large-scale magnetic field on the Moon is dominated by the effects of large basin-forming impacts.

An antipodal magnetization mechanism can explain much, but not all, of lunar crustal magnetism. Many magnetic anomalies do not lie antipodal to any known impact basin, and though they are

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Paper number 2000JE001380.
0148-0227/01/2000JE001380$09.00

smaller and most are not as strong as the antipodal anomalies, we still must explain their formation. A convenient place to investigate these anomalies is on the central near side. There are many magnetic features on the near side that lie outside of the magnetically weak Imbrium, Orientale, Serenitatis, Humorum, and Nectaris impact basins. These include the well-known anomalies associated with Rima Sirsalis and the Reiner Gamma Formation, anomalies associated with the Cayley and Descartes Formations, and other magnetic features which we cannot reliably associate with specific terranes on the lunar surface. Many theories exist for how such magnetic anomalies could have formed (see the review by *Daily and Dyal* [1979]). Two theories seem most plausible, however. One possibility is that the nearside magnetic anomalies were generated by thermal remanence from an early lunar core dynamo. Another is that the nearside anomalies were generated by shock or rapid thermal remanence, associated with ejecta and transient magnetic field amplifications produced by large impacts (such as discussed by *Hood and Vickery* [1984]). The second theory is an extension of the best existing model for the generation of antipodal magnetism. However, a combination of these two theories in which impact plasmas modify and amplify a preexisting dynamo field is also possible.

In this paper we report on new detailed maps of the lunar nearside crustal magnetic fields created using Lunar Prospector electron reflectometry data, and the implications of these maps for theories of near-side magnetic remanence acquisition. We briefly discuss the Lunar Prospector data set and our data reduction and analysis techniques. We then discuss the magnetic properties of the various terranes on the lunar near side. First, we investigate Rima Sirsalis and the nearby magnetic anomaly, which has been interpreted as a gap in a uniformly magnetized crust or a magnetized subsurface dike [*Srnka et al.*, 1979]. Our data show that the anomaly peak is more closely associated with light plains material, which probably includes basin ejecta as a major component, than with the rille itself. An examination of other reflectometry data across the near side further shows that there are no other magnetic anomalies convincingly associated with rilles. We next look at other anomalies in the Rima Sirsalis area, including an anomaly which is closely associated with the Reiner Gamma albedo markings. Both the Reiner Gamma and Rima Sirsalis anomalies are approximately radially aligned with the center of the Imbrium basin, suggesting that they may have formed during the Imbrium impact. We move eastward from here to investigate the magnetic properties of the Cayley, Descartes, and Fra Mauro Formations, all of which have large components of basin ejecta. Statistical results on the magnetic properties of these terranes are also discussed. We find that the Cayley Formation and terra materials of possibly similar origin are relatively strongly magnetic, as is Descartes, while Fra Mauro is only weakly magnetic. Next we discuss statistical results on the magnetism of other lunar terranes, most notably craters of various ages. We find that older craters are moderately magnetic, while younger ones are at best weakly magnetic. Our results show that much of the nearside magnetism, with the possible exception of pre-Imbrian craters, may be associated with basin ejecta terranes. Finally, we discuss these results and their implications for theories of nearside magnetic remanence acquisition.

2. Lunar Prospector Electron Reflectometry Data

We use the electron reflectometry technique to measure lunar crustal magnetic fields [*Anderson et al.*, 1976; *Howe et al.*, 1974]. This method makes use of the fact that electrons behave adiabatically in the lunar environment and reflect from regions of increased magnetic field (the so-called magnetic mirror effect). Thus measurement and comparison of upward going and downward going electron fluxes at the spacecraft location can be used as a remote probe of the surface crustal fields. The onboard magnetometer measurements can be used to approximate the location of the magnetic field line footpoint and thus the location of our measurement on the lunar surface (since electrons follow the magnetic field lines). Using this technique we can map the surface magnetic fields with high sensitivity (~0.2 nT) and spatial resolution (~4 km) [*Lin et al.*, 1998; Mitchell et al., manuscript in preparation, 2000].

We can convert electron reflectometry measurements into estimates of crustal field strength. However, for our purposes it is advantageous to use a simpler measurement, the electron reflection coefficient. This is simply the ratio of electron flux magnetically reflected away from the Moon to that incident upon it. This ratio is extremely easy to measure and provides us with the highest-resolution maps of crustal anomalies. One caveat is necessary in the interpretation of these results, however. Lunar Prospector data have shown that electrons are reflected not only by magnetic fields but also by electric fields. In shadow, where we make most of our measurements, the lunar surface tends to charge up to ~40 V negative because of the difference in thermal flux from electrons and ions (see *Whipple* [1981] for a review of the physics behind surface charging, and *Knott* [1973] and *Horanyi et al.* [1998] for applications of this theory to the Moon). Thus electrons are also reflected from the surface by these fields. However, we have found that there are no discernible systematic regional differences in this electric potential, and thus as long as care is taken, it is possible to get meaningful results using the uncorrected reflection coefficient. By using the uncorrected coefficient we are able to obtain a factor of ~2-3 better data coverage, since to correct for this effect high-quality measurements at multiple energies are necessary. We use the highest-energy channel at which we can measure sufficient electron counts (520 eV), and thus the error is small at moderate crustal field strengths (since the effect is energy dependent). However, it is necessary to remember that the reflection coefficient is overestimated in low field regions (where electrostatic reflection is comparable to magnetic reflection in importance). On some of our maps one can see vertically aligned streaks in the low field regions. These are artifacts of the uncorrected reflection coefficient due to time-varying electric fields. For reference, a reflection coefficient of 0.25 corresponds to a magnetic field of ~1 nT, 0.5 to ~5 nT, and 0.75 to ~20 nT.

We use measurements of uncorrected electron reflection coefficient obtained from all orbits of the 19-month Lunar Prospector mapping mission [*Binder et al.*, 1998] when the Moon is in the solar wind but the spacecraft is on the night side of the Moon and thus shielded from its effects. With these measurements we can map the entire lunar surface (with the exception of the poles) with 0.5° binned resolution (0.5° = ~15 km at the equator). These unsmoothed 0.5° resolution measurements are used for all of our quantitative statistical studies. The data coverage is not complete, but by using boxcar smoothing with a width of 1.5° we can obtain nearly complete coverage for more qualitative studies. These 1.5° resolution maps are the highest resolution and most complete reflectometry maps thus far produced. They should be compared to the ~3.75° resolution maps from Apollo measurements [*Lin et al.*, 1988], which covered ~20% of the lunar surface, and the previously published Lunar Prospector reflectometry maps, which were completely global, but with 5° resolution

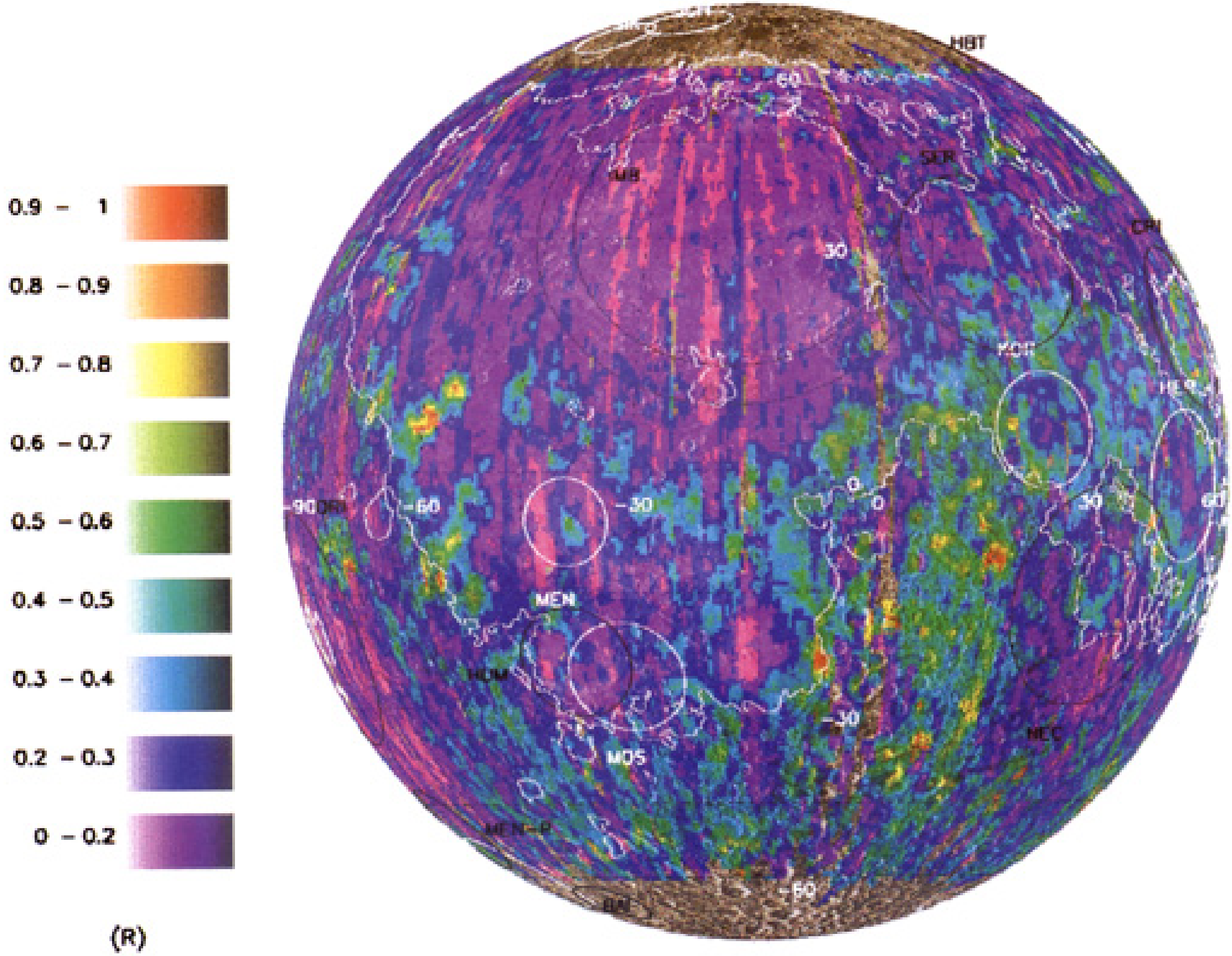

Plate 1. An orthographic view of the lunar near side centered at 15° W longitude. Electron reflection coefficient (smoothed over 1.5°) is shown by colors, as shown by the color bar at left. Each of the nine color bins is further subdivided into 18 shades which serve to show the lunar topography. The white circles show the antipodes of young large impact basins, while the black circles show basins themselves. Finally, a white albedo contour serves to outline the dark mare basalt regions. The electron reflection coefficient is measured at an energy of 520 electron volts, and is uncorrected for electric field effects. There are vertical streaks visible in the low field data. These are artifacts of time-variable electric fields.

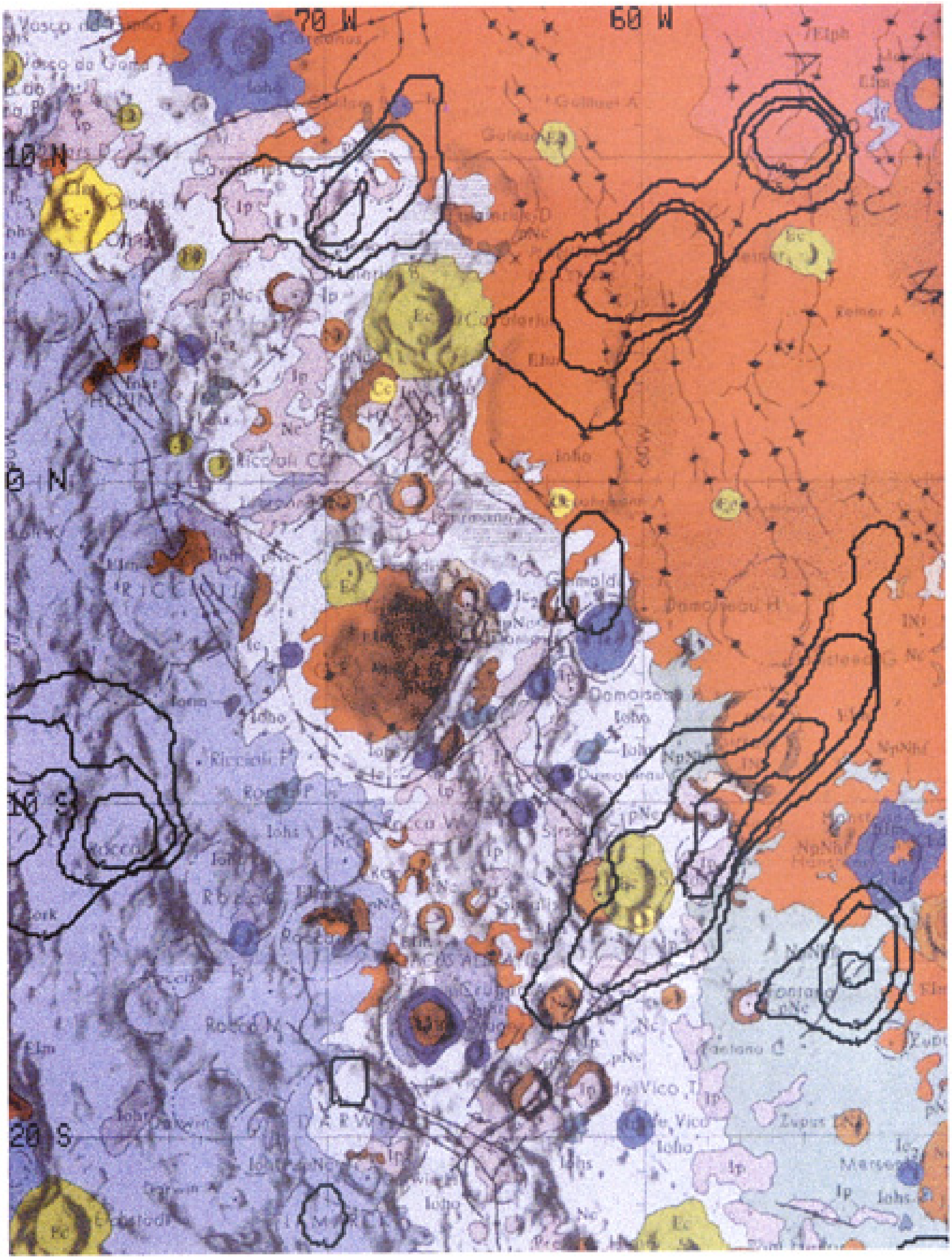

Plate 2. A portion of a geologic map of the west side of the Moon is shown [*Scott et al.*, 1977]. Contours (at levels 0.45, 0.55,and 0.65) of electron reflection coefficient (smoothed over 1.5°) are overlaid on the map. Rima Sirsalis and other rilles are shown as black lines with dots in the center on the map (those with diamonds in the center are wrinkle ridges). The light blue areas of the map are the continuous ejecta blanket from the Orientale impact (the Hevelius Formation), and the red areas are the mare basalts of Oceanus Procellarum. Cayley-type light plains material is shown in pink and denoted Ip. Yellow, green, dark blue, and brown denote crater material of Copernican, Eratosthenian, Imbrian, and pre-Imbrian age.

[Mitchell et al., manuscript in preparation, 2000]. Our maps are complementary to the newest Lunar Prospector magnetometer maps, which are of similar resolution [*Hood et al.*, this issue]. The magnetometer can directly detect polarity information and is better suited to mapping strong field regions, while reflectometry can resolve weaker fields and is thus well suited to mapping moderate field regions. Both results, where overlapping, are thus far in complete agreement.

3. Near Side Crustal Magnetism

Plate 1 shows the electron reflection coefficient mapped over an orthographic projection of the lunar near side. No major basin antipodes lie in this region, and those present show no strong magnetic fields. It seems likely that these basins are not large enough and/or did not form during the right time period for significant antipodal magnetization to have been produced (see Mitchell et al. (manuscript in preparation, 2000) for a discussion). The near side is dominated by the demagnetized Imbrium and Orientale basins and by the partially demagnetized Humorum and Nectaris impact basins. However, outside of these demagnetized regions lie a number of strong magnetic sources. Along the southwestern edge of Oceanus Procellarum lies a group of three strong anomalies. The northern one is Reiner Gamma, the southeastern one is Rima Sirsalis, and the southwestern one is a previously unmapped anomaly. To the southeast of the Imbrium basin lies a large area of relatively strong patchy crustal magnetic fields. There is a good (but not one-to-one) correlation between these anomalies and the Cayley and Descartes Formations. On the very southern part of the near side are more moderate anomalies which lie on mostly pre-Imbrian terrane. Weaker magnetic fields lie in the eastern mare regions and in a concentric partial ring just south of the Imbrium basin. None of these sources lie antipodal to any known basins, and therefore they must have been produced by some mechanism other than that which produced the antipodal anomalies.

3.1. Rima Sirsalis and Other Rilles

One of the most interesting discoveries of the Apollo missions was a very strong magnetic anomaly approximately aligned with the Rima Sirsalis rille [*Anderson et al.*, 1977]. Rima Sirsalis is a nonsinuous rille with a linear extent of more than 300 km. Superposition relations show that the rille was formed after the Orientale impact, but before the emplacement of the Oceanus Procellarum mare basalts. Apollo electron reflectometer and magnetometer measurements showed a magnetic feature with peak fields greater than 100 nT centered over the rille. Within experimental error the magnetic feature appeared to be aligned with the rille.

Plate 2 shows the electron reflection coefficient, measured by Lunar Prospector, contoured over a geologic map of the west side of the Moon [*Scott et al.*, 1977]. The strong magnetic anomaly (bottom right side of the figure) does indeed overlie the rille and is approximately aligned with it (though this alignment is also approximately radial to the center of the Imbrium basin). However, the magnetic anomaly extends ~200 km past the end of the rille into Oceanus Procellarum, while the rille extends ~150 km southwest of the magnetic anomaly. The former can be explained if one assumes that the Procellarum mare basalts have covered the northeastern extension of the rille [*Anderson et al.*, 1977], but the latter is harder to understand. Furthermore, the strongest part of the magnetic anomaly (58° W, 12° S) is not centered directly on the rille. Instead, the southwestern anomaly peak appears to lie over an area of light plains material, interpreted as probable primary and/or secondary basin ejecta [*Scott et al.*, 1977]. Magnetometer data confirm that the strongest anomaly in the group is centered on the light plains material and not on the rille itself [*Hood et al.*, this issue]. The northeastern end of the anomaly, meanwhile, lies in an area covered by mare basalt flows. As *Hood et al.* [this issue] have pointed out, a simple calculation using lunar thermal diffusivities shows that mare basalt flows should not substantially demagnetize the lunar crust beneath them. Thus it is probable that the source of this part of the anomaly (perhaps more magnetized ejecta) lies beneath the visible mare basalt.

Despite such evidence, a case for the association of the anomaly with the rille might be more convincing if more such correlations could be found. However, we have conducted a study of 77 named nearside rilles greater than 50 km in length and have found no other clear associations between rilles and magnetic anomalies. A few small rilles, such as the one just to the southeast of Rima Sirsalis (at 54° W, 15° S), are approximately correlated with anomalies, but the anomalies are not linear and thus cannot be convincingly associated with the rilles. Furthermore, in most cases, there is no association between rilles and magnetic anomalies. We see evidence of this in Plate 1 as well, as there are a number of other rilles to the northwest of Rima Sirsalis which are not associated with any magnetism. Thus, if Rima Sirsalis is truly magnetized, it appears to be the only large magnetized rille on the near side.

3.2. Reiner Gamma and Other Nearby Anomalies

Several other magnetic anomalies (all shown in Plate 2) lie near the Sirsalis anomaly, roughly surrounding the demagnetized Grimaldi impact basin (centered at 68° W, 5° S). To the north of Rima Sirsalis is one of the strongest magnetic anomalies on the Moon (the anomaly peak is located at ~59° W, 7° N and probably has fields of hundreds of nanotesla). As *Hood et al.* [this issue] have shown, this anomaly is very closely associated with the Reiner Gamma Formation, a so-called swirl albedo marking. *Hood et al.* [this issue] have discussed the swirl markings in great detail and concluded that they are most likely a thin surficial marking and are not the source of the magnetic anomaly. It has been proposed that the swirls are instead a result of solar wind deflection away from the anomaly, leading to a reduced rate of surface darkening [*Hood and Schubert*, 1980; *Hood and Williams*, 1989]. An alternate theory is that of *Schultz and Srnka* [1980], which proposes that the swirls and the magnetic anomaly were both produced by the impact of a comet on the lunar surface (see also *Gold and Soter* [1976]). This seems improbable since the swirls have also been found to be associated with all of the large antipodal magnetic anomaly groups [*Lin et al.*, 1988], and it would be very coincidental if comets would preferentially impact the Moon antipodal to large basins. Therefore it appears unlikely that the source of the anomaly is the swirl marking itself. Furthermore, the mare basalts, which are generally very weakly magnetic, are not likely to be the source. Thus it seems probable that the anomaly source is buried beneath the mare surface. The Reiner Gamma anomaly, like the Sirsalis anomaly, is approximately radially aligned with the center of the Imbrium basin, and so it may be suggested that its source is also magnetized Imbrium ejecta buried below the mare basalts.

To the west of Reiner Gamma lies a somewhat weaker anomaly (68° W, 8° N). This anomaly is not clearly associated with any surface feature, though there are several light plains units in the area. We cannot demonstrate a clear match since much of the light plains material is overlain by the Hevelius formation (the continuous ejecta blanket of Orientale). Another anomaly on the very western side of Plate 2 (76° W, 11° S) lies completely on the Hevelius formation and does not correlate with any surficial features. It is possible that both of these anomalies are associated with Imbrium ejecta, but as with Reiner Gamma and part of Sirsalis, the anomaly sources are probably buried beneath overlying terranes. The superposition of many different lunar terranes increases the difficulty of determining the sources of the magnetic anomalies.

3.3. Cayley and Fra Mauro Formations

One region of the Moon not so completely covered by mare flows and other terranes lies south and southeast of the Imbrium basin. As shown in Plates 3a and 3b, a large area of uncovered highlands material lies between the Nubium, Imbrium, Serenitatis, Tranquilitatis, and Nectaris maria. If the source of the nearside magnetism is basin ejecta, then the best possible place to make that association lies in this region. In fact, early work based on Apollo data from these regions led to some of the first suggestions that ejecta materials might be the sources of near-side lunar magnetic anomalies [*Strangway et al.*, 1973a; *Hood et al.*, 1979a, 1979b]. In particular, magnetometer measurements showed that some exposures of the Cayley light plains and Fra Mauro Formations, which are very common in this part of the near side, were associated with moderately strong magnetic anomalies.

The Fra Mauro Formation is interpreted as the ejecta blanket of the Imbrium basin, possibly mixed with secondary impact ejecta [*Wilhelms*, 1984]. The Cayley Formation's origin has been debated, but it seems most likely that it is composed at least partly of Imbrium primary and/or secondary ejecta, mixed with reworked local material [*Wilhelms*, 1984; *Spudis*, 1984]. One possible origin for the Cayley Formation is as partially fluidized Imbrian primary ejecta which ponded in local depressions [*Eggleton and Schaber*, 1972]. Another theory is that the Cayley Formation was emplaced as part of a debris surge induced by secondary cratering from the Imbrium impact and only contains Imbrium ejecta as one component [*Oberbeck et al.*, 1975]. This theory is supported by compositional studies [*Stöffler et al.*, 1985; *Spudis*, 1984]. In situ formation by fallback from crater walls, has also been proposed [*Head*, 1974], but compositional studies do not support this theory. It seems most likely that the Cayley Formation is genetically related to the Imbrium impact and includes both basin ejecta and secondary ejecta as primary components.

Examination of Plates 3a and 3b shows that many exposures of the Cayley Formation are strongly magnetic. In several places, there is nearly a one-to-one correlation between magnetic anomalies and the Cayley Formation. Most notably, the Cayley units overlying the pre-Imbrian craters Albategnius (5° E, 12° S), Alphonsus (3° W, 14° S), Hipparchus (5° E, 6° S), and Ptolemaeus (2° W, 9° S) and some of those to the north of these craters (at 6° E, 7° N and 16° E, 7° N) are clearly associated with moderate magnetic anomalies. Other Cayley units are not as strikingly correlated with magnetic anomalies, but there does seem to be a general association. Interestingly, the Fra Mauro Formation, which is also at least partially composed of Imbrian ejecta, does not show such clear correlations with magnetic anomalies, with the exception of the anomaly at 5° W, 3° N. Instead, Fra Mauro units are in general weakly magnetic at best. This result contrasts with a correlation of magnetic anomalies with the Fra Mauro Formation south of the crater Kepler reported by *Hood et al.* [1979a, 1979b] based on Apollo 16 subsatellite magnetometer data.

3.4. Cayley and Fra Mauro Statistical Results

The data shown in Plates 2, 3a, and 3b clearly indicate the difficulty of determining the sources of lunar crustal magnetic anomalies. We can seldom conclusively associate a magnetic anomaly with a source region on the lunar surface. We therefore try a statistical approach for determining an association of magnetic properties with lunar terranes. To this end we have used 44 1:100,000 scale geologic maps of the lunar near side [*U.S. Geological Survey*, 1962-1971] to build up a database of the lunar nearside terranes at 0.5 deg resolution. Each 0.5x0.5 deg pixel is classified according to the terrane which occupies the majority of that pixel on the lunar surface. This data set currently comprises all of the near-side geologic maps and covers an irregularly shaped region extending from 70° W to 70° E, 64° S to 64° N. Combining this data set with our electron reflection data allows us to classify each pixel in this area according to both its magnetic and geologic properties.

To facilitate the analysis, we first separated the hundreds of different lunar terranes identified on the geologic maps into a smaller number of general categories. Then we calculated the average reflection coefficient for each of these terrane types. A summary of the results from this study, showing the magnetic properties of the most extensive terranes, is shown in Table 1, and the distributions are shown in Figure 1. Orbital photographs and geologic maps only show the surficial terranes. In most cases, many different lunar terranes are superposed, and magnetic sources may be buried below the surface. Our results show that there are significant differences in the magnetic properties of different surficial terranes, but buried terranes probably also contribute to the observed magnetic fields. Also, we must recall that we slightly overestimate the average reflection coefficient (especially for low fields) since we use an uncorrected reflection coefficient.

In keeping with the results of more qualitative studies, we find that the Cayley Formation (lunar light plains in the area south and southeast of the Imbrium basin) is the most strongly magnetic formation on the lunar near side. The so-called terra mantling materials in the same area are also strongly magnetic. These terra mantling materials are probably similar in composition to the Cayley Formation, consisting of primary and/or secondary ejecta from large basins mixed with local materials [*Wilhelms and McCauley*, 1971]. They tend to overlie topographically higher terrane than the depressions which Cayley-type light plains lie in and they are often thin enough to leave some underlying relief visible. The Cayley Formation and the terra materials from this area both have average reflection coefficients between 0.4 and 0.45, which corresponds to an average magnetic field of several nanoteslas.

Light plains similar to the Cayley Formation and terra materials from the whole near side are moderately magnetic, though not as strongly as those in the Cayley/Descartes area. Some basin ejecta materials, though, do not show as strong a magnetic field. Fra Mauro (Imbrium ejecta) is not in general strongly magnetic, nor are the ejecta blankets of Nectaris, Orientale, or Humorum. It is possible that these differences are due to different ages or compositions.

An important question is: are these results statistically significant? As a representative test case, we choose the Cayley and Fra Mauro Formations. Both of these formations probably include Imbrium ejecta as a major component, and thus one might expect their magnetic properties to be similar. However, we found that

Table 1. Magnetic Properties of Lunar Near-Side Terrains

Terrain	Reflection Points	Average Reflection Coefficient
Cayley Formation	837	0.431
Cayley-Area Terra Material	652	0.407
All Near Side Light Plains	3484	0.341
Pre-Imbrian Crater Material	2364	0.330
All Near Side Terra Material	6953	0.321
Entire Near Side	41322	0.275
Ejecta Blankets of Imbrium, Nectaris, Humorum, and Orientale	2687	0.266
Copernican Crater Material	2425	0.266
Fra Mauro Formation	1151	0.259
Imbrian Crater Material	3112	0.256
Eratosthenian Crater Material	1607	0.256
Maria	16836	0.242

Cayley units were much more strongly magnetized than Fra Mauro. We wish to determine if these differences are truly statistically significant. We use for our test case a region from 10° W to 20° E, 20° S to 20° N (part of that shown in Plates 3a and 3b). In this area, the average reflection coefficient for the Cayley Formation (837 points) is 0.431. The average reflection coefficient for the Fra Mauro Formation in this area (371 points) is 0.296. Figure 2 shows the actual distributions of reflection coefficients for Cayley and Fra Mauro in the test region. Using the Kolmogorov-Smirnov test [*Chakravarti et al.*, 1967], we find a lambda value of 5.65, showing that the distributions are different to a significance of 3.83×10^{-28} (this is the probability that these two distributions are actually drawn from the same parent distribution). Distributions are not always different to this level of significance. However, in general, we have found that the magnetic properties of different terranes are statistically quite significantly different.

3.5. Descartes Formation

A strong and previously unmapped anomaly lies in the Descartes mountains (centered at 16° E, 11° S on Plate 3b). This anomaly is very close to the Apollo 16 landing site (15.3° E, 8.6° S) where the strongest surface fields measured by in situ magnetometers were found (fields up to 313 nT were measured) [*Dyal et al.*, 1974]. The Descartes mountains are probably Nectaris ejecta, possibly mixed with Imbrian-aged and/or pre-Nectarian material [*Spudis,* 1984; *Stöffler et al.*, 1985; *Wilhelms*, 1984]. This suggests that ejecta from other basin-forming events, such as the Nectaris impact, may also be magnetized. Since the antipode of Nectaris contains a moderate concentration of crustal magnetic field, it should perhaps not be a surprise to also find magnetized Nectarian ejecta. The relatively strong ring of magnetism extending out from the Descartes anomaly (covering the area from 7° – 19° E, 0° – 13° S in Plate 3b) may also be associated with Nectaris ejecta, which has been subsequently buried (or possibly with the abundant Cayley units on the surface). An interesting aside is that the Descartes anomaly, like the Reiner Gamma anomaly and many of the antipodal anomalies, is associated with an albedo marking. This marking was originally interpreted as a Copernican or Eratosthenian age deposit because of its brightness, but its close association with the magnetic anomaly may show that its origin is similar to that of the swirl markings.

3.6. Craters and Basins

The near side is dominated by the low fields of the maria (their average reflection coefficient of 0.242 corresponds nominally to a magnetic field of about a nanotesla, but this is low enough that the reflection may be mostly electrostatic, and thus the crustal magnetic fields may be as low as a few tenths of a nanotesla or less). As discussed previously, mare lava flows should not demagnetize the crust beneath them significantly, and thus we are actually seeing the weak magnetic fields of the terranes predating and underlying the mare basalts. In fact, the mare basalts mostly overlie large impact basins, which will have demagnetized the lunar crust completely. Thus it is to be expected that the mare regions should have low magnetic fields unless they have been remagnetized subsequent to the demagnetization by basin-forming impacts.

Recent crater material (the craters themselves and the ejecta surrounding them) also has very weak or no magnetic fields. Imbrian, Eratosthenian, and Copernican-aged crater materials all have average reflection coefficients of around 0.25 (corresponding nominally to about a nanotesla average magnetic field). One would expect all lunar craters to be similarly demagnetized, since any crater greater than ~50 km in diameter will demagnetize the crust to a depth of tens of kilometers. Instead, our statistical results show that pre-Imbrian craters are about as magnetic as the lunar light plains and terra materials (see Figure 1 and Table 1). Unlike the Cayley Formation anomalies, it is not in general possible to find good one-to-one correlations between anomalies and ancient crater materials, but statistical results nonetheless show that these materials are more magnetic than the rest of the near side.

It is conceivable that our crater results are biased because we have included the ejecta blanket (and whatever lies underneath it, which may not be demagnetized) in the calculations, and we have not included portions of craters covered by other terranes (since the geologic maps only show the surficial terranes). Therefore we have also conducted a study of just the lunar craters themselves, excluding all surrounding and overlying materials. The results are shown in Table 2 and the distributions are shown in Plate 4. We find that the pertinent results are not significantly changed from those obtained previously. By leaving out the surrounding area covered by ejecta materials we can see the demagnetization of younger craters even more clearly than before, though for unknown reasons Imbrian craters are more completely demagnetized than Eratosthenian or Copernican craters. In any case, though, pre-Imbrian craters are still shown to be moderately magnetic. This magnetic field is not significantly higher than the pre-Imbrian crater ejecta and terra materials surrounding these craters. However, one might expect these craters, like younger craters, to be demagnetized relative to their surroundings, if no global-scale lunar field was present at the time of their formation.

4. Conclusions and Implications

Extensive crustal magnetism exists on the lunar near side. Very little of it lies antipodal to any known lunar impact basin. Therefore some remanence acquisition mechanism(s) other than that responsible for the large groups of strong magnetic anomalies antipodal to young large impact basins must have generated the nearside magnetism. The most likely candidates are shock or rapid thermal remanence associated with basin-forming impacts, or thermal remanence in the presence of a lunar dynamo field. Sample returns have shown that microscopic metallic iron grains, which are most common in impact breccias, are the main ferromagnetic carriers on the Moon [*Strangway et al.*, 1973b; *Fuller*,

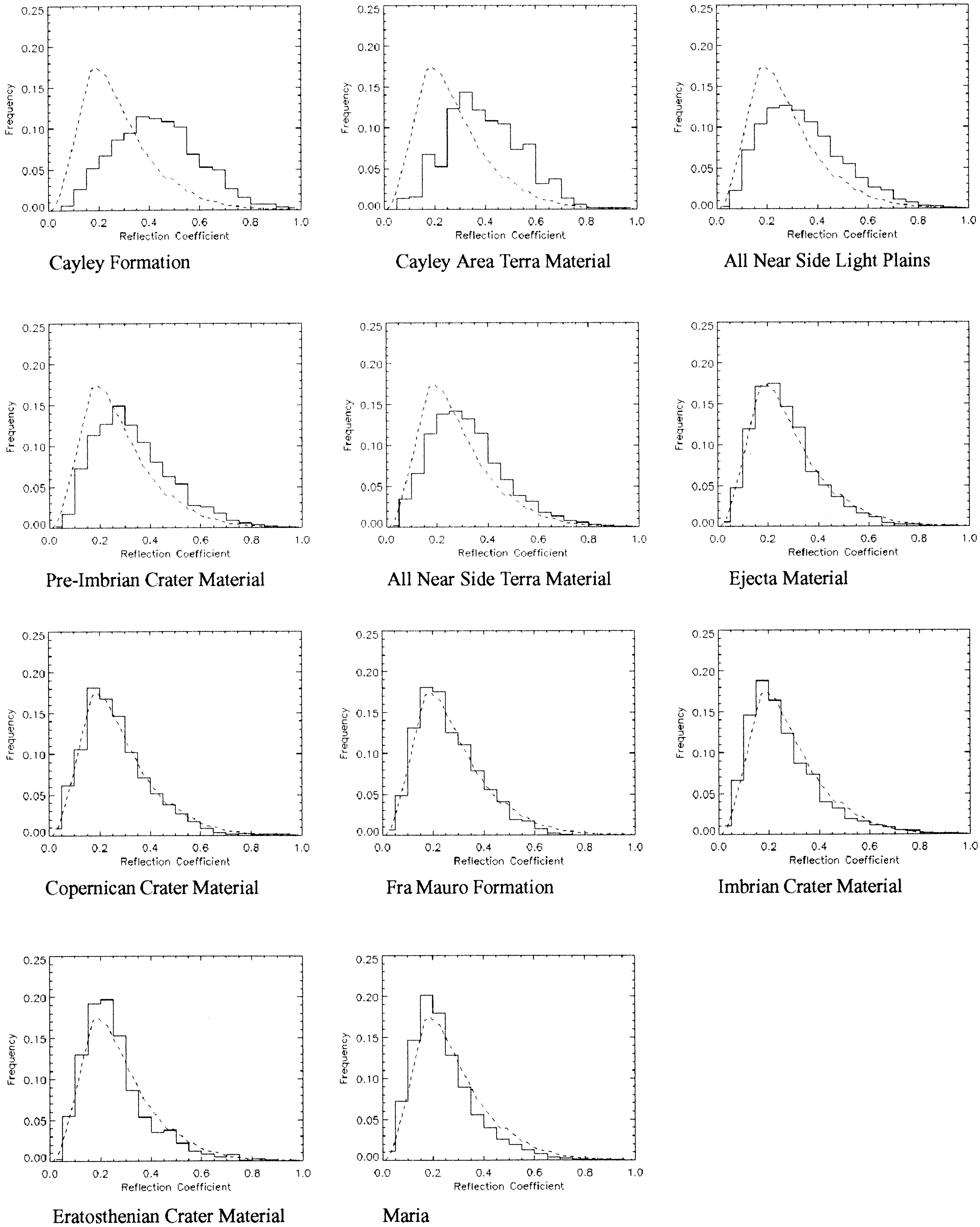

Figure 1. Reflection coefficient histograms for a variety of lunar terranes are shown, ordered from highest to lowest average reflection coefficient. Each histogram is shown along with a dashed curve showing the distribution for the entire near side. The sample sizes and averages of each of these distributions are listed in Table 1.

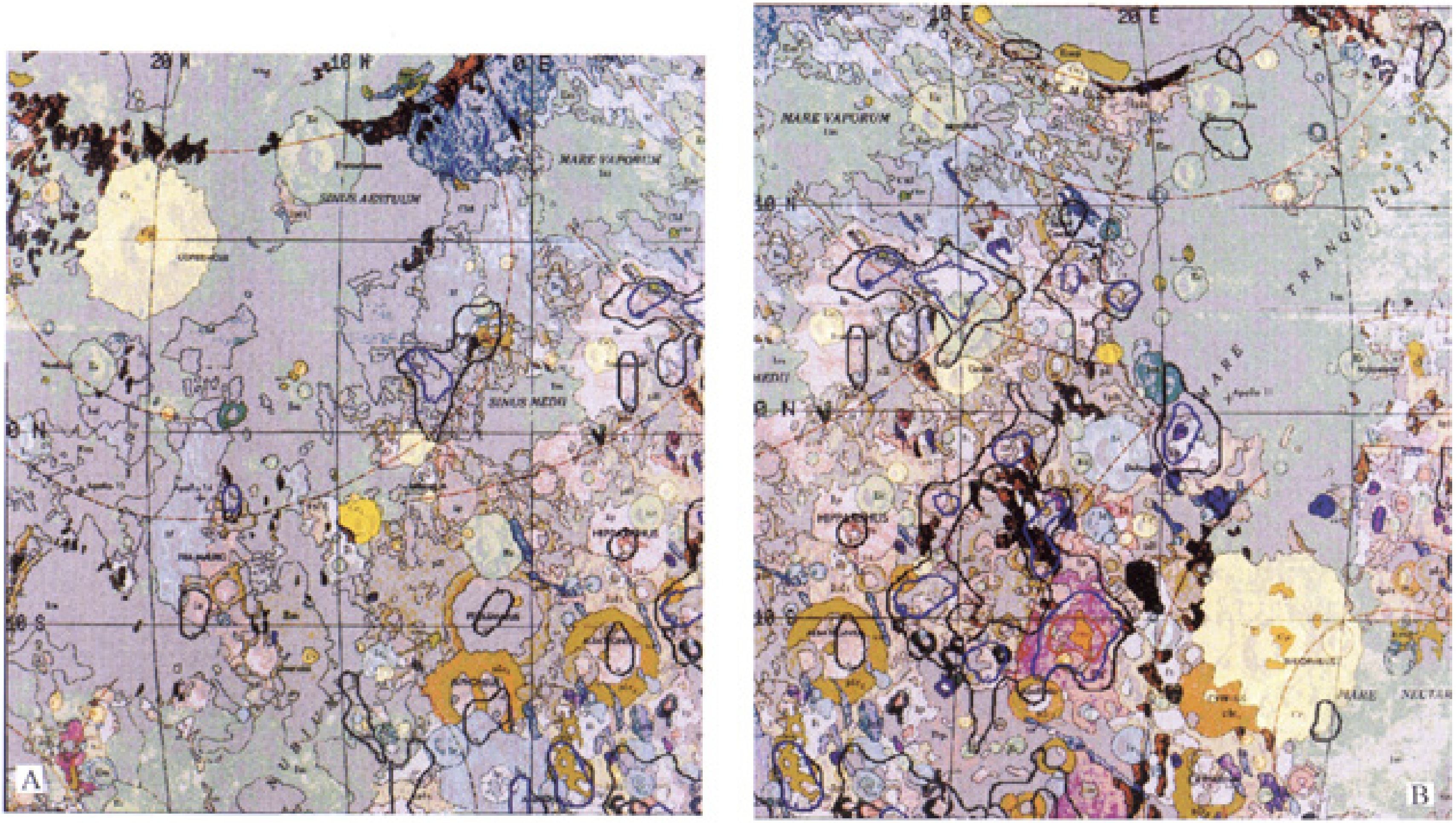

Plate 3. Partially overlapping portions of a geologic map of the central near side of the Moon [*Wilhelms and McCauley*,1977]. Contours (black = 0.55, blue = 0.65, red = 0.75) of electron reflection coefficient (smoothed over 1.5°) are overlaid on the map. The green and brown background are the Imbrian and Eratosthenian age mare basalts. Yellow, green, blue, and brown denote crater material of Copernican, Eratosthenian, Imbrian, and pre-Imbrian ages. The Fra Mauro Formation is shown in light blue and denoted If. The light plains units (locally known as the Cayley Formation) are denoted Ip and are shown in light pink. The Descartes mountains are shown in bright pink on Plate 3b and are denoted Ihf. The orange terrane denoted by CEhf, which lies in the center of Descartes, is a bright albedo marking originally interpreted as Copernican or Eratosthenian age terrane.

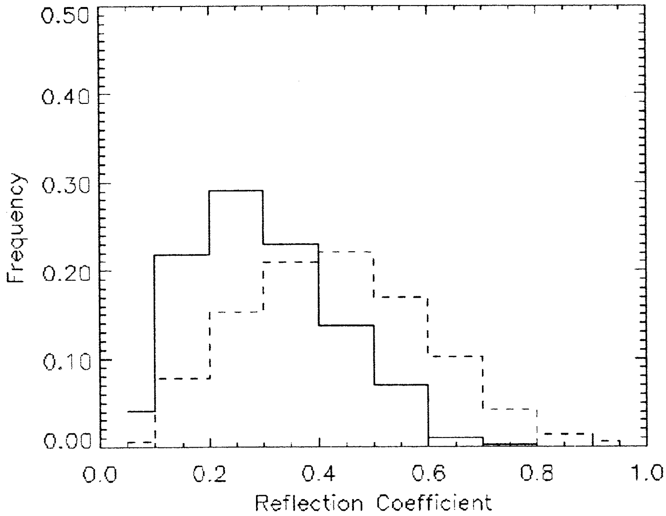

Figure 2. Reflection coefficient histograms are shown for Fra Mauro and Cayley in the test area 10° W to 20° E, 20° S to 20° N. The distribution for Fra Mauro (371 points, average = 0.296) is shown as a solid line and that for Cayley (837 points, average = 0.431) as a dashed line.

1974]. This suggests that an impact-related process may be a more likely candidate. However, the details of such a mechanism remain unclear. An extension of the process proposed to explain antipodal magnetization, involving the interaction of transient magnetic field amplifications and ejecta from basin-forming impacts, is one candidate. This would require shock remanence or rapid thermal remanence of the small metallic iron carriers, since the magnetic field amplifications associated with impacts do not persist for longer than at most ~1 day. This would be more than long enough for micron-sized iron grains to acquire shock or rapid thermal remanence, but not long enough for more than a few hundred cm^3 volume of impact melt to cool and acquire thermal remanence.

One of the strongest nearside anomalies lies nearly on Rima Sirsalis. A magnetic field could be associated with a rille if it were a gap in a uniformly magnetized crust or if it were a magnetized subsurface dike [*Srnka et al.*, 1979]. Each of these explanations would require thermal remanent magnetization and would strongly suggest the presence of a lunar dynamo at some time, since a strong and steady field is required to generate coherent thermal remanence. Lunar Prospector data, however, show that the strongest part of this anomaly is more likely associated with a patch of lunar light plains material, and a large part of the Sirsalis rille is clearly not magnetized. Furthermore, our studies have shown that no other large rilles are magnetized. An alternate hypothesis is that the Sirsalis magnetic anomaly is actually associated with ejecta from Imbrium (or perhaps Orientale). This possibility is more consistent with sample returns, which show that impact breccias are the most strongly magnetized lunar rocks, while igneous rocks are in general only weakly magnetized. Furthermore, the magnetic anomaly is aligned approximately radially with the center of the Imbrium basin, which also suggests an Imbrium origin.

Another strong anomaly near Sirsalis is closely associated with a swirl albedo marking (Reiner Gamma) similar to those associated with all of the strong antipodal anomaly groups and the Descartes anomaly, which may be a result of magnetic deflection of the solar wind away from the anomalies. Whatever the source of this anomaly, it is probably buried below the mare basalts. The anomaly, like Sirsalis, is approximately radially aligned with the center of the Imbrium basin, again suggesting an association with the Imbrium impact.

The Cayley Formation, which probably contains at least a component of Imbrium ejecta, is strongly correlated with magnetic anomalies. In a few cases, this correlation is nearly one-to-one, but even when it is not, statistical results show that the Cayley Formation and other light plains units are some of the most strongly magnetic terranes on the near side. Terra mantling materials of possibly similar origin to the light plains also show moderate remanent magnetization. The Descartes mountains, likely consisting of ejecta from the older Nectaris basin, are strongly magnetic (and, like Reiner Gamma, are associated with an albedo marking). These results all strengthen the hypothesis that magnetized ejecta is the source of the nearside magnetic anomalies. It would be very difficult to explain the magnetization of these ejecta-related formations as thermal remanence acquired in a dynamo field, since if there were a field capable of magnetizing these formations to the degree that we see today, it would almost certainly have at least weakly remagnetized impact basins and craters of the same age as these ejecta formations. Since we instead see almost complete demagnetization of these impact sites, it seems quite unlikely that there was a strong enough ambient field present to result in thermal remanence of ejecta terranes.

Some of our results raise questions, however. Light plains and terra materials in the Cayley/Descartes area show stronger magnetic fields than those elsewhere. There are several possible explanations for this. One plausible explanation is a compositional

Table 2. Magnetic Properties of Lunar Near-Side Craters

Terrain	Reflection Points	Average Reflection Coefficient
Pre-Imbrian Craters	2518	0.326
Imbrian Craters	553	0.177
Eratosthenian Craters	120	0.206
Copernican Craters	176	0.243

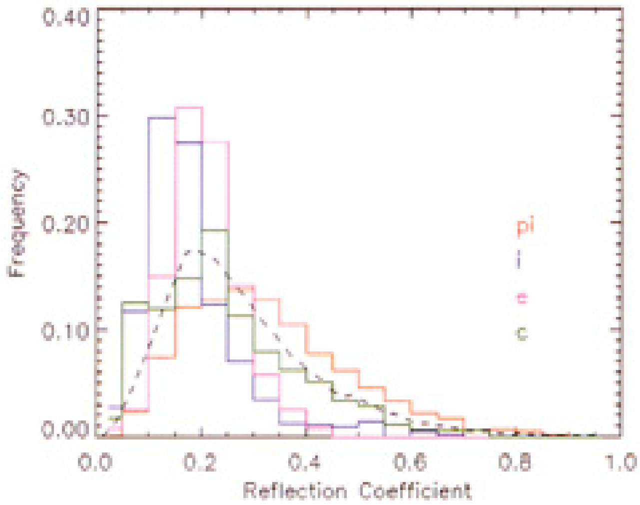

Plate 4. Reflection coefficient histograms for pre-Imbrian (pi), Imbrian (i), Eratosthenian (e), and Copernican (c) craters are shown. Also shown for comparison is a distribution for the entire near side (dashed curve). The sample sizes and averages of each of these distributions are listed in Table 2.

difference between the different ejecta units. Studies have shown that the mafic breccias which are a major component of the Cayley plains (and presumably also the nearby terra materials) have a large concentration of metallic iron compared with melt breccias from other sites [*Korotev*, 1994]. Since metallic iron is a primary carrier of lunar ferromagnetic remanence one would therefore expect that the Cayley Formation could be more strongly magnetized. Lunar plains and terrae in other areas of the near side may not have such a large concentration of ferromagnetic carriers. Also, some of these formations were probably emplaced at different times than the Cayley plains and Cayley-area terrae. This is supported by crater count studies which show that the lunar light plains are not all of the same age [*Neukum*, 1977], and by geologic mapping which shows that light plains and terra materials are not all of the same age [*Wilhelms and McCauley*, 1971].

Another result which raises questions is the relatively low magnetic fields found in ejecta terranes near large basins (such as Fra Mauro). Though there is much more basin ejecta present in these areas, it is more weakly magnetic than terranes such as Cayley and Descartes which are farther from large basins. Also, the most strongly magnetic terranes on the moon are actually antipodal to the basins! Part of the reason for this may again be compositional. Also, since ejecta size and shock levels depend on the distance from the impact site, as do the transient magnetic field amplifications generated by large impacts, so will the details of any impact-related magnetization process. Thus one would expect some dependence on distance from the origin if magnetized ejecta are the sources of the nearside magnetic anomalies. This dependence would be even harder to explain in a thermal remanence model, especially since one must also explain the very strong antipodal anomalies.

Statistical results show that pre-Imbrian aged craters have moderate magnetic fields comparable to the ejecta terranes mentioned previously. Since we expect that impacts should demagnetize the lunar crust (as our results show is true for younger craters and many basins) it follows that either the craters are overlain by magnetized material or that they have been remagnetized. The possibility that the magnetic field is due to edge effects from crater impacts that punctured previously magnetized crustal materials has also been suggested, but the lack of a magnetic signature for younger craters lying in the same area shows that this is not the case. Presumably, there are no strong edge effects because any preexisting magnetization is not of uniform polarity and strength but is instead extremely jumbled.

If the apparent pre-Imbrian crater magnetization is due to overlying materials they must be relatively thin, since the crater relief is still clearly visible and geologic maps do not show a layer covering the craters. It is possible, however, that there are thin overlying layers of magnetized ejecta from other ancient impacts which are not shown on geologic maps. If the craters themselves have been remagnetized, on the other hand, we are forced to consider the possibility of thermal remanence. It appears unlikely that any ambient nonlunar field could be steady over a long enough period for a large mass of molten rock (such as that created by an crater-forming impact) to obtain a coherent thermal remanent magnetization, and thus we are led to consider the possibility of a lunar dynamo field. If a dynamo was active, however, it seems that it must have been only in the earlier history of the moon, before Imbrium and other relatively recent impacts, since Imbrian age and younger craters are not remagnetized and nor are most other young impact basins. Since our results show that ejecta-related terranes, especially those of Imbrian age, are the most strongly magnetic it appears unlikely that a thermal remanence process could be responsible for all the nearside magnetism. Thus, even if a dynamo was active in the early history of the moon and was responsible for pre-Imbrian crater remagnetization, it still seems that we must appeal to an impact-related mechanism to explain most of the more recent nearside magnetic fields that we see.

The superposition of terranes of many different ages on the lunar surface makes the identification of magnetic sources very difficult. However, our data show that many of the lunar nearside magnetic anomalies are apparently associated with terranes which contain basin ejecta and secondary ejecta as a major component. If this correlation is real, we should clearly look more closely at magnetic remanence acquisition mechanisms involving the interaction of transient magnetic fields and ejecta produced by basin-forming impacts. Such mechanisms may explain nearside magnetic remanence as well as the larger areas of strong magnetic fields lying antipodal to young large impact basins. It appears that the magnetism of the Moon, unlike that of Earth or Mars, is dominated by the effects of impact processes rather than thermal processes. Therefore detailed modeling of the plasma physics of basin-forming impacts is clearly necessary to understand the puzzles of lunar magnetism.

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(Received September 11, 2000; revised February 2, 2001;
accepted February 19, 2001.)