LUNAR MAGNETIC ANOMALIES DETECTED BY THE APOLLO SUBSATELLITE MAGNETOMETERS

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Properties of lunar crustal magnetization thus far deduced from Apollo subsatellite magnetometer data are reviewed using two of the most accurate presently available magnetic anomaly maps – one covering a portion of the lunar near side and the other a part of the far side.

The largest single anomaly found within the region of coverage on the near-side map correlates exactly with a conspicuous, light-colored marking in western Oceanus Procellarum called Reiner Gamma. This feature is interpreted as an unusual deposit of ejecta from secondary craters of the large nearby primary impact crater Cavalerius. An age for Cavalerius (and, by implication, for Reiner Gamma) of 3.2 ± 0.2 × 10⁹ y is estimated. The main (30 × 60 km) Reiner Gamma deposit is nearly uniformly magnetized in a single direction, with a minimum mean magnetization intensity of ~7 × 10⁻² G cm³/g (assuming a density of 3 g/cm³), or about 700 times the stable magnetization component of the most magnetic returned samples. Additional medium-amplitude anomalies exist over the Fra Mauro Formation (Imbrium basin ejecta emplaced ~3.9 × 10⁹ y ago) where it has not been flooded by mare basalt flows, but are nearly absent over the maria and over the craters Copernicus, Kepler, and Reiner and their encircling ejecta mantles.

The mean altitude of the far-side anomaly gap is much higher than that of the near-side map and the surface geology is more complex, so individual anomaly sources have not yet been identified. However, it is clear that a concentration of especially strong sources exists in the vicinity of the craters Van de Graaff and Aitken. Numerical modeling of the associated fields reveals that the source locations do not correspond with the larger primary impact craters of the region and, by analogy with Reiner Gamma, may be less conspicuous secondary crater ejecta deposits. The reason for a special concentration of strong sources in the Van de Graaff–Aitken region is unknown, but may be indirectly related to the existence of strongly modified crustal terrain which also occurs in the same region. The inferred directions of magnetization for the several sources of the largest anomalies are highly inclined with respect to one another, but are generally depleted in the north–south direction. The north–south depletion of magnetization intensity appears to continue across the far-side within the region of coverage.

The mechanism of magnetization and the origin of the magnetizing field remain unresolved, but the uniformity with which the Reiner Gamma deposit is apparently magnetized, and the north–south depletion of magnetization intensity across a substantial portion of the far side, seem to require the existence of an ambient field, perhaps of global or larger extent. The very different inferred directions of magnetization possessed by nearly adjacent sources of the Van de Graaff–Aitken anomalies, and the depletion in their north–south component of magnetization, do not favor an internally generated dipolar field oriented parallel to the present spin axis. A variably oriented interplanetary magnetizing field that was intrinsically strong or locally amplified by unknown surface processes is least inconsistent with the data.

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1. Introduction

During 1971 and 1972, two subsatellites equipped with fluxgate magnetometers were released into low-latitude, retrograde lunar orbits by the Apollo 15 and 16 command modules. A major result of these experiments was the detection of widespread magnetic anomalies (Coleman et al., 1972a), whose invariance on successive closely-spaced orbits, and externally applied field strength and orientation, suggested crustal sources of remanent magnetization.

Subsequent mapping and interpretation of the observed anomalies has allowed the deduction of constraints on the nature and origin of lunar magnetism, which supplement the results obtained from studies of returned samples and surface-site magnetic field observations (see reviews elsewhere in this issue). The purpose of the present paper is to review the evidence for these constraints and to discuss their interpretation in the context of the various proposed theories of lunar magnetism. No attempt will be made to maintain exact chronological order, since several basic results important for the understanding of earlier analyses have only recently become available.

2. Data acquisition and analysis

Detailed descriptions of the Apollo 15 and 16 subsatellites and magnetometers have been given by Coleman et al. (1972b, c). The Apollo 15 subsatellite was placed into lunar orbit on August 4, 1971 and obtained field measurements at altitudes above the surface ranging from 200–40 km for a period of six months until a telemetry system failure prevented further transmission of the magnetometer data. The inclination of the subsatellite orbital plane to the lunar equator was about 28°. The Apollo 16 subsatellite obtained similar measurements at altitudes ranging from 200 km to about 3 km for 34 days during the spring of 1972 before the subsatellite crashed into the moon. Its orbital inclination was only 10.5°.

Figure 1 shows typical field magnitude plots for three Apollo 15 subsatellite orbits, selected at times when the Moon was in each of its three magnetic-plasma environments. These are the solar wind, the magnetosheath, and the geomagnetic tail-lobes. As is apparent in the lower panel, temporal fluctuations in the field magnitude were often minimal in the tail lobes, permitting the direct detection of crustal magnetic fields. The turbulent conditions which characterize the magnetosheath generally precluded the detection of anomalies as is indicated in the center panel. When the Moon was immersed in the free-streaming solar wind, the subsatellite was subjected to two quite different environments as shown in the top panel of the Figure.

For that portion of a single orbit when the subsatellite was in the optical shadow or wake region (there is a slight difference between the two due to the average 4.5° aberration of the solar wind velocity vector with respect to the Moon−Sun line), there was a small characteristic rise in the magnetic field strength caused by the greatly decreased plasma density (Colburn et al., 1967) but temporal fluctuations were significantly diminished. The wake intervals are therefore also usable for direct studies of crustal magnetic fields, and provide an important addition to the tail-lobe data as will be seen in Section 3.
For that part of each orbit when the subsatellite was outside the lunar wake, the disturbing influence of the solar wind generally prevented the direct detection of anomalies. However, indirect effects of their existence, the limb compressions, were often present. One example of the latter phenomena may be seen at 2250 on the top panel of Fig. 1 in the form of a sharp rise in the magnetic field strength occurring shortly after the spacecraft re-entered the solar wind. These enhancements are apparently due to the downstream propagation of compressional disturbances of the interplanetary medium, initiated at the lunar surface by fossil magnetic fields (Barnes et al., 1971; Mihalov et al., 1971; Sonett and Mihalov, 1972). The realization of a direct relation between large limb shocks found in Explorer 35 magnetometer data, and specific selenographic source positions, led to the first attempt (Fig. 2) to map the distribution of lunar crustal magnetization (Sonett and Mihalov, 1972). Although this map has only a $15 \times 15^\circ$ resolution, and is in some respects qualitative, the dominance of highland source regions over those occurring in the maria is evident. Also of interest is the region corresponding to the largest number of observed compression maxima. It is centered on the south-central far-side in the Van de Graaff–Aitken region.

A second method for indirectly mapping the distribution of crustal magnetization is the electron-reflectance technique (Howe et al., 1974), which makes use of the energetic particle detector data collected by the Apollo subsatellites. Both indirect techniques are valuable for assessing the global distribution of anomalous magnetization and are complementary to the vector magnetometer data.

2.1. Magnetic anomaly maps from tail lobe data

For the purpose of minimizing possible fluctuations in the background magnetic field, the early mapping of the vector magnetometer data concen-
trated solely on records from times when the Moon was in the geomagnetic tail-lobes. The technique used to map these data will now be described in some detail. As will be seen, the two major shortcomings of the final maps are (1) a restriction in useful (i.e. low-altitude) selenographic coverage and (2) a reduction in absolute accuracy due to altitudinal averaging of the data collected during several different lunations.

A sequence of seven consecutive Apollo 15 subsatellite tail-lobe orbits is shown in Fig. 3. The repeating patterns on successive orbits clearly distinguish crustal magnetic fields from temporal fluctuations (some of which are visible on the Figure). An obvious first step in the mapping procedure therefore consisted of removing periods containing significant temporal changes. Following this operation, it was necessary to attempt to remove the ambient tail-lobe magnetic field, on which the crustal anomaly fields were superposed. Initially, only the average and linear trends in each field component over an orbit were removed. The data were then sorted according to longitude and latitude and smoothed with a two-dimensional Gaussian filter (2 × 2° full width half maximum) (Russell et al., 1974b). However, the resulting maps (Fig. 4) contained elongated contours parallel to the orbit track, indicating that the temporal and spatial variations in the tail-lobe magnetic field amplitude and direction had not been completely removed by the linear detrending procedure. Fortunately, as may be seen from Fig. 3, the maximum repeating wavelength of anomalies discernible in the tail-lobe data is about 10° along the orbit track. It was therefore possible to remove most of the non-linear, low-frequency trend by passing the raw data through a high-pass filter with a corner frequency corresponding to wavelengths of 20° (Russell et al., 1975b). The data were again filtered two-dimensionally as before and maps of the radial, east and north components of the lunar crustal magnetic field were constructed, using all the Apollo 15 (six lunations) and 16 (one lunation) subsatellite data collected within the geomagnetic tail lobes at altitudes ranging from approximately 60–130 km over the far side and from 100 to 170 km over the near side. These maps as well as contour maps of the average altitude, coverage, and the field magnitude were published in the frontispiece of Vol. 1, Proc. Lunar Sci. Conf., 5th (1974).

The largest anomalies to be found on these maps occurred on the lunar far side, in part because of the lower mean altitude of the subsatellite. Figure 5 reproduces a contour plot of the radial magnetic field component for the portion of the map having the lowest-altitude coverage. The largest anomalies are present in the Van de Graaff–Aitken region on the lunar far side. The evolution of the anomaly field pattern from orbit to orbit is due to the rotation of the Moon beneath the subsatellite (Russell et al., 1974).

Fig. 3. Field magnitude plots for seven consecutive orbits of the Apollo 15 subsatellite when the Moon was in a lobe of the geomagnetic tail. The largest anomalies were detected when the subsatellite was near periapsis over the Van de Graaff–Aitken region on the lunar far side. The evolution of the anomaly field pattern from orbit to orbit is due to the rotation of the Moon beneath the subsatellite (Russell et al., 1974).
Fig. 4. Contour maps of the radial, east, and north components of the lunar remanent magnetic field over the Van de Graaff–Aitken region on the lunar far side at the mean subsatellite altitude of about 100 km. The contour interval is 0.4 γ. Before these maps were produced, contributions from the ambient tail-lobe magnetic field were reduced by removing the average and linear trends from individual orbits. The existence of elongated contours paralleling the orbital track indicates that this procedure was not completely successful (Russell et al., 1974a).
higher altitudes over the same selenographic region, which weighted the averages downward. Hood et al. (1978b) have produced limited maps of the Van de Graaff–Aitken region from the same data set, but with the altitude restricted to the range 65–80 km. The maximum radial-component amplitude on these maps is much higher (2.4 γ), as would be expected from the lower mean altitude, but the shapes, positions, and relative amplitudes of the anomalies are very similar to those shown in Fig. 5. This indicates that the lower-altitude contributions to the earlier maps have dominated those at higher altitudes in the averaging process, preserving their relative accuracy. In addition, it should be noted that the method for minimizing low-frequency trends used by Hood et al. (1978b) was also different, and consisted of subtracting simultaneous Apollo 15 lunar surface magnetometer measurements from the subsatellite measurements. The similarity of anomaly shapes, positions and relative amplitudes shown on the resulting maps to those shown on the earlier maps is evidence that both methods for minimizing low-frequency trends were equally successful.

It is further possible to test the self-consistency of the tail-lobe data maps (such as that in Fig. 5) by applying the condition that the net magnetic flux over the mapping surface should be zero. As noted by Russell et al. (1975b), a qualitative test is to cross-check the component maps of a single area to determine whether the eastward and northward field maxima locations are in agreement with those predicted by the radial component map. For example, if a negative radial-component maximum lies just to the east of a positive radial maximum, then the east component map should show an eastward maximum between them. The field component maps constructed from the tail-lobe data using the methods described above generally appear to satisfy these criteria (see Fig. 13a).

An additional difficulty with the tail-lobe data maps is that low-altitude (<100 km) coverage is restricted mainly to narrow bands across the heavily cratered far-side highlands. No coverage at low altitudes across the geologically better-understood near side was available. The limitation on coverage which resulted from using tail-lobe data only is due to char-

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**Fig. 5.** Contour map of the radial component of the lunar magnetic field detected by the Apollo 15 and 16 subsatellites at altitudes ranging from 65 to 130 km across a section of the lunar far side when the Moon was in a lobe of the geomagnetic tail. The contour interval is 0.1 γ. See the text for a description of the procedures used to construct this map.
acteristics of the subsatellite orbit, as well as to the equality of the lunar orbital and spin periods, which caused the subsatellites to always traverse nearly identical surface locations on successive lunations.

2.2 New mapping program

In preparation for the next phase in the mapping program, some additional constraints were established. In order to reduce the problem of averaging over altitude, only data collected during a single lunation should be allowed to contribute to any given map. An exact contour map of the effective surface of observation and supportive single-orbit plots should be provided with which to evaluate map accuracy. In order to increase useful (i.e. low-altitude)

selenographic coverage using existing data, it is necessary to consider not only those times when the Moon was in the geomagnetic tail lobes, but also those times when the Moon was in the solar wind and the subsatellite was in the lunar wake (Fig. 1).

A new mapping program was embarked upon during 1978 with these principles in mind. To date, only the 425 Apollo 16 subsatellite orbits have been so processed. Nevertheless, because of the low perilunes which characterized the mission, and which invariably occurred within the wake when the Moon was in the solar wind, the resulting maps have been enlightening (Section 3).

The first step in the mapping procedure again consistent of selecting periods when temporal fluctuations were minimal, and then removing the average and low-frequency trends from each component. Several techniques for accomplishing the latter were tried; it was found that a quadratic detrending method was optimal when applied to orbit segments of length ≤100°, but longer than typical anomaly wavelengths (Fig. 6). A similar method has been applied to

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig6a.png}
\caption{Fig. 6a. Radial field component for a series of Apollo 16 subsatellite orbital segments plotted against longitude. The mean for each data segment was removed. Only those times when the Moon was in the solar wind but the subsatellite in the lunar wake were selected. Scale is shown at lower right.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig6b.png}
\caption{Fig. 6b. As Fig. 6a after a quadratic polynomial was least-squares-fitted to the data segments and removed. The repeating patterns on successive orbits identify the dominant remaining field sources as of lunar origin.}
\end{figure}
Fig. 7. Upper three plots: contour maps of the Apollo 16 subsatellite altitude, and the field magnitude and radial field component measured by the subsatellite magnetometer across a section of the lunar near side. Lower three: as upper plots but showing the east and north field components as well as the number of data points per unit area.
large-scale geomagnetic anomaly data by Regan (1979). The field components were then plotted versus longitude, and successive orbits compared, so that true anomalies of crustal origin could be distinguished from transient features. Significant remaining temporal variations identified in this manner were then removed in a second editing phase. The remaining 162 detrended data segments selected from all 425 orbits of the Apollo 16 subsatellite data were sorted according to longitude and latitude, and passed through a specially constructed two-dimensional “low-pass” filtering program, which attenuated features with wavelengths shorter than 2.5°. The resulting vector magnetic anomaly map extends from 5°S to 10°N latitude and encircles the Moon. A map of the effective surface of observation was also produced to allow more exact computer modeling studies than have been possible in the past. Figure 7 reproduces a section of this map having low-altitude coverage across a portion of the lunar near-side.

3. Sources of the near-side anomalies

A preliminary analysis of the magnetic anomalies mapped in Fig. 7 has been given by Hood et al. (1979a). A more detailed discussion of the map itself, the sources of the observed anomalies, and the geologic origin of the sources will be found in Hood et al. (1979b). A brief summary of the main results will be given here.

A comparison of the altitude map with the radial component map (the strongest and least contaminated by high-frequency external and induced field contributions of the three orthogonal component maps) reveals a strong altitude-dependence of the
lunar crustal magnetic field. This is most evident east of the 0° meridian where a large altitude gradient is present over relatively homogeneous highland terrains. The increase in both amplitude and complexity of anomaly fields with decreasing altitude is indicative of localized, near-surface sources. This property of the orbital anomalies is consistent with the relatively small-scales of surface anomaly sources inferred from Apollo surface magnetometer data by Dyal et al. (1974, 1978).

However, there also appear to be field sources of larger-scale than those which are characteristic of the Apollo landing sites. The two extensive patches of anomalies shown on the right side of the map roughly at 3°W, 7°N and 9°E, 7°N) correspond to two areas peripheral to the Imbrium basin dominated geologically by the Fra Mauro Formation and separated by Sinus Medii. An additional patch of anomalies (35°W, 5°N) may also be associated with an unflooded remnant of the Fra Mauro Formation visible on high-resolution photographs. The Fra Mauro Formation is a roughly textured blanket of basin ejecta debris, deposited at the time of the Imbrium impact 3.9 × 10⁹ y ago.

Figure 8 shows a radial component segment of Apollo 16 subsatellite orbit 220, with the orbital track drawn across the region south of the Imbrium basin. The stronger crustal fields associated with the Fra Mauro and Cayley Formations are evident. In order to further demonstrate the qualitative consistency of the subsatellite measurements with surface magnetic-field investigations, we have summarized the measurements obtained at the Apollo landing sites in Fig. 9. The largest surface fields were detected at the Apollo 14 and 16 sites in areas dominated geologically by the Fra Mauro and Cayley Formations respectively.

The largest single anomaly shown in Fig. 7 has a
smoothed amplitude of 11.0 $\gamma$ at 20 km altitude, and is the largest in apparent magnitude (uncorrected for measurement altitude) found to date in the Apollo 15 and 16 subsatellite data. Its location (58.8°W, 7.6°N) correlates well with that of a conspicuous intermediate albedo marking on western Oceanus Procellarum called Reiner Gamma (Fig. 10). That Reiner Gamma is a deposit of ejecta from secondary craters associated with a nearby large crater is strongly suggested by the existence of a small cluster of craters near the point of the large curved V-pattern in the main deposit (Figs. 10, 11) (Hood et al., 1979b). Experimental work indicates that the V-pattern was most probably produced as a result of interference between rising plumes of ejecta from the fragments which produced the small cluster of craters (Oberbeck and Morrison, 1974). The superposition of

Reiner Gamma on western Oceanus Procellarum mare units requires that the primary impact crater be of post-mare age. There are two possible craters (Schultz, 1976). Öbers A is a very fresh, bright-rayed, late Copernican crater lying 400 km to the west-northwest. Cavalerius, 200 km to the west-southwest, is Eratosthenian (McCauley, 1967). On the basis of various stratigraphic relationships and analyses of mare crater counts and crater degradation measurements, we have estimated that Cavalerius is probably between 3.0 and $3.4 \times 10^3$ y old (Hood et al., 1979b). The long axis of the main deposit is more nearly radial to Cavalerius than to Öbers A. Also the orientation of the large V-pattern in the main deposit, and those of several less conspicuous V-shaped patterns in associated swirls southwest of the main deposit is more toward Cavalerius than Öbers A. In addition, Reiner Gamma and associated markings appear to grade into the Cavalerius ejecta mantle where numerous secondaries with V-shaped ridges occur (Fig. 11). Thus, the morphological evidence favors Cavalerius as the associated large primary-impact crater.

One difficulty with the conclusion that Reiner Gamma is Eratosthenian is the anomalously high albedo of the deposit. More specifically, the reflectance spectrum of Reiner Gamma is very similar to that of Copernican craters and rays. Freshly exposed lunar soils, such as crater ray materials, are initially high in albedo but become darkened to the usual low lunar albedo in a time which appears to be less than $1 \times 10^8$ y (McCord and Adams, 1973). The mechanism by which lunar soils are darkened is not well understood. Suggested processes include solar wind ion sputtering (Gold et al., 1976; Hapke, 1973, Hapke et al., 1975), impact vitrification (Conel and Nash, 1970; Nash and Conel, 1973), and impact vaporization—deposition (Hapke, 1975). In this connection, it is of interest that the Reiner Gamma magnetic anomaly is among the few yet detected whose intensity and scale is sufficient to strongly impede the solar wind ion bombardment of the surface.

Assuming that the Reiner Gamma deposit is the source of the observed anomaly, it is possible to show that the mean level of magnetization is significantly greater than that of any returned lunar sample. The two pertinent quantities are the mean dipole moment per unit area, calculated from the magnetic field mea-

![Fig. 10. The Reiner Gamma anomaly. Top panel: section of Lunar Orbiter IV high resolution frame 157 oriented with respect to a longitude–latitude grid by using McCauley's (1967) map of the region as a guide. The Reiner Gamma feature is at the upper left corner of the photo. Bottom panel: two-dimensional contour map of the total magnetic field intensity using available orbital segments (Hood et al., 1979a).](image-url)
measurements, and the mean deposit thickness, estimated from photogeologic evidence. Using a thirteen-sided polygonal plate with a shape chosen to approximate that of the main deposit, Hood et al. (1979b) have applied a minimum variance criterion to select the bulk direction, and intensity per unit area, of magnetization which gave the best agreement between the model field and the detrended direct measurements. As shown in Fig. 12, the inferred direction of magnetization (r.m.s. 1.8 $\gamma$) has local angular coordinates $\theta = 65^\circ$, $\phi = 115^\circ$, where $\theta$ is measured from the zenith at the position of Reiner Gamma and $\phi$ is measured counterclockwise from east about the zenith. An error cone of angular radius $\sim 25^\circ$ can be estimated from the condition that the r.m.s. deviation of the model field from the data should not exceed the r.m.s. noise level of $\sim 2 \gamma$. The calculated mean dipole moment per unit area is $208 \pm 70$ G-cm.

A maximum value of 10 m for the mean deposit thickness is estimated from the absence of shadows cast by any part of the deposit under low solar illumination (D.W.G. Arthur, personal communication, 1978). The reasoning is as follows. Mare ridges similar to those transecting the Reiner Gamma deposit (see Lunar Orbiter II, frame 215) have slopes 20–50 m high where they have been measured in other areas. The ridges that transect the deposit cast shadows on available telescopic photos taken at low solar illumination angles that show no shadows for the deposit itself. Additional visual searches (which
have a higher resolving power than photographs under good conditions) also found no shadows for the deposit. On this basis, a maximum mean thickness of 10 m was estimated.

Using the inferred dipole moment value of 208 G·cm, and the maximum deposit thickness estimate of 10 m, a density of $\sim 3$ g/cm$^3$ is assumed, giving a minimum mean magnetization level within the deposit of $\sim 7 \times 10^{-2}$ G cm$^3$ g$^{-1}$, or about 700 times the stable magnetization component of the most magnetic sample.

3.1. General comments

The correlations of large total magnetic field maxima found on Fig. 7 with unusual concentrated sur-

ficial deposits of crater and basin ejecta materials leads to the conclusion that these are major sources of the orbital anomalies shown by the Apollo 15 and 16 subsatellites. This possibility was first suggested by Strangway et al. (1973b) following studies of returned samples and surface site magnetic field measurements. Their opinion was based on (a) the high measured levels of magnetization (maximum $\sim 10^{-4}$ G cm$^3$ g$^{-1}$) possessed by certain classes of impact-generated breccias and (b) the large surface magnetic fields, apparently associated with the Cayley plains unit at the Apollo 16 landing site.

Perhaps equally significant is the strong depletion in anomaly intensity shown in Figs. 7 and 8 over mare units and also in the vicinities of the young (<1 × 10⁹ y old) craters Copernicus and Kepler, and their accompanying ejecta mantles and ray materials, despite the extremely low altitudes (minimum 11 km) of the subsatellite over these structures. Also, no detectable anomaly is present near the mare-aged crater Reiner and its ejecta mantle. The relative sparsity of anomalies over the maria is not surprising in view of studies on returned samples which have yielded stable magnetization intensities for the mare basalts that are typically several orders of magnitude less than the most magnetic breccias (Fuller, 1974). The lack of anomalies associated with both young and old crater interiors is consistent with the result obtained by Lin (1978) in his study of electron reflectance maxima across the near-side maria. It is also consistent with the far-side modeling results reported in Section 4.

4. Quantitative interpretation of the Van de Graaff–Aitken anomalies

Hood et al. (1978a, b) have described a computer-assisted method for modeling the complex, large-amplitude anomaly fields found near the craters Van de Graaff and Aitken on the lunar far-side. The data maps used consisted of the radial component map shown in Fig. 5 and similar maps of the eastward and northward components, all of which have been published in the frontispiece of Vol. 1, Proc. Lunar Sci. Conf., 5th (Russell et al., 1975b). The basis for the method is the existence of relatively isolated total-field maxima on these maps which imply the existence of relatively strongly and coherently magnet-
ized source regions. The continuous and constantly changing surface-density of magnetization could thus be approximated by a distribution of uniformly magnetized plates of variable dimensions, separated by unmagnetized material. The choice of model geometry was inspired both by the ejecta deposit hypothesis of Strangway et al. (1973b) and by the possibility that large impact craters in the region could be the sources of the larger anomalies. At the time that the work was carried out, the results described in Section 3 were, of course, unknown.

In contrast to the Reiner Gamma anomaly, the sources of the Van de Graaff–Aitken anomalies have not been identified. Initial estimates for the source positions can only be obtained from the locations of total field maxima. Also, unlike the Reiner Gamma anomaly, the Van de Graaff–Aitken group of anomalies is not dominantly dipolar, and so no single-step programmed procedure could be used to select the directions of magnetization of the several sources. Instead, a less elegant but, we believe, equally effective iterative forward modeling approach was used.

The final result of the calculation, for the Van de Graaff–Aitken region only, is shown in Fig. 13. The inferred source positions, dimensions, and magnetization characteristics are listed in Table 1 of Hood et al. (1978a). Figure 14 illustrates these source characteristics, as refined by Hood et al. (1978b), using more accurate data maps (see Section 2). There is no association of source locations with the several prominent craters shown in the photograph. Additional modeling studies carried out within the boundaries of Fig. 5 confirm that the lack of correlation of visually prominent surface features with major anomalies is characteristic of the lunar far side.

Given the results of the near-side analysis discussed in Section 3, it is very likely that the sources of the Van de Graaff–Aitken anomalies are basin–crater ejecta deposits. Although much less conspicuous than the Reiner Gamma deposits (perhaps because of their greater age, and superposition on highland units of higher albedo than Oceanus Procellarum), at least some of these deposits will probably be identified when more accurate tail-lobe anomaly maps are quantitatively interpreted. The reason for a special concentration of strong sources in the Van de Graaff–Aitken region is unknown, but possible explanations will be discussed in Section 5.

![Fig. 13. Van de Graaff–Aitken modeling result. (a) Contour maps in gammas of the Van de Graaff–Aitken anomaly field components and the field magnitude as measured by the Apollo 15 subsatellite magnetometer. The radial component map is a section of Fig. 5 (see Fig. 5 caption). (b) Contour maps in gammas of the magnetic field which would be produced at an altitude of 75 km by the surface distribution of magnetization given in Table 1 of Hood et al. (1978a). This source model was slightly refined by Hood et al. (1978b) and is illustrated in Fig. 14 (Hood et al., 1978a).](image)

### 4.1. Magnetization Intensities

Using data maps for which the altitude range of the subsatellite was restricted to 65–80 km, Hood et
al. (1978b) have estimated the scale sizes and dipole moments per unit area of surface plates which are capable of reproducing the Van de Graaff–Aitken anomalies. Although the deposit thickness, and therefore the mean magnetization level, is completely undetermined (unlike Reiner Gamma), it is nevertheless of some interest to consider the magnetization levels required by the inferred dipole moments per unit
area, and by the various assumed thicknesses. Table 2 of Hood et al. (1979b) gives dipole moments per unit area which range from 89 to 338 G-cm. These values are comparable to the 208 G-cm obtained for Reiner Gamma using the visible deposit area, and the minimum-variance analysis described in the previous section. Thus, if the deposits which are likely to be responsible for the Van de Graaff–Aitken anomalies have thicknesses similar to that estimated by lunar geologists for Reiner Gamma (≤10 m), then their mean magnetization levels will be comparable to that inferred for the Reiner Gamma deposit (≥7 × 10^{-2} G cm^{3}/g).

4.2. Directions of magnetization

It seems reasonable to expect that the present bulk directions of magnetization of large-scale magnetic source regions found around the Moon should reflect, in each individual case, the approximate orientation of the applied field at the time of magnetization. The detectability of the associated anomalies at subsatellite altitudes (~100 km) shows that these regions are coherently magnetized, and indicates that subsequent bombardments have not greatly altered the bulk properties of magnetization within given regions. The lack of tectonic overturning and rotation of the lunar crust during the past 4 × 10^9 y must further assist in preserving the original orientations of these features. A method for inferring the global configuration, if any, of the magnetizing field may therefore be available.

Modeling studies of magnetic anomaly maps can be used to infer the bulk directions of magnetization for individual source regions, with an accuracy that is dependent primarily on the accuracy of the data. Hood et al. (1978a) have carried out such an analysis, using the radial magnetic field component map shown in Fig. 5, as well as companion maps of the eastward and northward components. A total of 35 individual source regions were identified and their selenographic locations, sizes and approximate directions of magnetization were estimated and tabulated. Two major characteristics of the directions of magnetization implied by the available far-side anomaly maps were noted. Firstly, nearby sources are generally magnetized in very different directions. This is illustrated for the case of the Van de Graaff–Aitken anomalies in Fig. 14. The indicated directions are estimated to be accurate to within an error cone of angular radius 25° (Hood et al., 1978b), but the directions for these closely adjacent sources differ in some cases by angles exceeding 90°. These results are typical of other modeling results obtained across the far side within usable data swaths from 135° to 235° E longitude and from −30° to 18°N latitude. The variance ellipsoid for the set of 35 inferred directions of magnetization was calculated, and showed no statistically significant preferred direction of magnetization across this rather localized portion of the lunar surface, contrary to the result expected if the magnetizing field was global, and fixed in the Moon over a geologically long period of time. Further, there was no tendency for the directions of magnetization to be preferentially perpendicular to, or parallel to, the lunar surface as might be the case if a local surface process were responsible for the magnetization. If this behavior proves to be typical of other regions of the lunar surface, then it is probable that there is a negligible lunar global dipole moment (<10^{19} G cm^{3}; Russell et al., 1975a) because crustal magnetization vectors cancel one another out on a global scale.

A second characteristic of the directions of magnetization implied by available tail-lobe anomaly maps is a general depletion in the north–south component of magnetization intensity. This is clearly the case for the sources responsible for the Van de Graaff–Aitken anomalies (Fig. 14) and the trend appears to continue across the mapped portion of the far side. The variance ellipsoid for the 35 inferred unit magnetization vectors was disk-like with maximum/minimum and intermediate/minimum axial ratios of 4.3 and 2.7 respectively. The normal to the preferred plane made an angle of only 8° with the selenographic z-axis (the spin axis). This implies a preferred plane of magnetization that was nearly parallel to the lunar equatorial plane. A histogram (Fig. 15) shows the number of unit vectors making angles with the z-axis within specified ranges.

The existence of a preferred plane of magnetization has been criticized as a possible artifact, arising from the small inclination of the subsatellite orbital plane to the lunar equator. The presence of elongated contour lines paralleling the orbit tracks on the early maps of the Van de Graaff–Aitken region (Fig. 4) has prompted these suspicions. As discussed in Sec-
magnetic mare basalt (our interpretation of Reiner Gamma), is the only probable identification of an individual anomaly source body to date. The general correlation of medium-amplitude anomalies with unflooded patches of the Fra Mauro Formation indicates that older basin ejecta debris materials are anomaly sources as well. It appears, therefore, that large meteoroid impacts played an important role in producing the materials that are magnetized on the Moon.

This result is both consistent with, and predictable from, studies of the returned samples (Strangway et al., 1973b). The main ferromagnetic carriers in lunar rocks are free iron grains. Although mare basalts contain abundant iron oxides, the percent by weight of Fe is <0.1, and the stable magnetic remanence associated with these rocks is typically $2 \times 10^{-6}$ G cm$^3$/g. The breccias and soils, however, contain 0.3—1.0% Fe, and the stable remanent intensity of some returned breccias has ranged up to $10^{-4}$ G cm$^3$/g (Strangway et al., 1973a; Fuller, 1974). The mechanism for the concentration of free-iron grains within the breccias and soils is reduction of iron oxides by impact-associated shock (Cisowski et al., 1974) or heat (Pearce et al., 1972), or both. In addition to the percentage of Fe, the measured stable magnetization levels of breccias and soils is strongly dependent on the Fe grain-size, which is in turn a strong function of the metamorphic grade or degree of welding (Gose et al., 1972). In particular, the lightly welded or intermediate breccias are dominated by single-domain iron grains (diameter 150—300 Å), and are capable of retaining a magnetic remanence that is some orders of magnitude higher than breccias of other metamorphic grades.

In view of the observed sensitive functional relationship between magnetic properties and the shock/thermal history of the breccias, it is less surprising that not all crater and basin ejecta materials are equally magnetic. Evidently, only a relatively small number of ejected fragments had the proper combination of high Fe content and a shock/thermal history conducive to the formation of a strongly magnetic deposit.

In an attempt to explain the unusual magnetization level of Reiner Gamma, a special concentration of meteoritic material (Fe) in the secondary fragments which appear to be responsible for the depos-
it could be suggested. However, there is some evidence that the distribution of magnetic sources around the Moon is not random, as would be expected from unusual additions of meteoritic material. Although large orbital anomalies are generally prevalent across the lunar highlands, particularly large groups of anomalies occur in the Van de Graaff–Aitken region on the central far-side and north of Mare Marginis on the eastern limb (electron reflectance maps, frontispiece, Proc. Lunar Sci. Conf., 8th, Vol. 1). These two areas are nearly antipodal to the Imbrium and Orientale basins, respectively, and are marked also by the occurrence of unusual hilly and lineated terrain (Stuart-Alexander, 1978; Wilhelms and El-Baz, 1977). The latter terrain has been explained as due to compression by seismic waves generated by the basin impact (Schultz and Gaut, 1975), or alternatively as due to convergence of basin ejecta at the antipode (Moore et al., 1974). It is significant that swirl-like deposits of similar albedo and morphology to Reiner Gamma occur at or near the same two areas — within a broad band north of Mare Marginis, and within southern Mare Ingenii on the far-side (El–Baz, 1972; Schultz, 1976). It is possible, therefore that the generation of highly magnetic ejecta materials is indirectly related to special properties of the crust at the primary impact point (Hood et al., 1979a, b).

5.2. Mechanism of magnetization and origin of the magnetizing field

One possible explanation for the existence of magnetized materials on the Moon which should be considered first is that there was no strong, large-scale magnetizing field in the lunar vicinity 3 to $4 \times 10^9$ y ago, but that local surface processes somehow produced short-lived magnetic fields which caused the observed magnetization. A leading contender in this category is usually referred to as impact magnetization. This process is known, from experiment, to occur only when large ambient magnetic fields are present (Martelli and Newton, 1977). There have been theoretical suggestions that impact magnetization could also occur without an ambient field, if strong magnetic fields are generated spontaneously within a hypothetical plasma cloud associated with the impact event (Srnka, 1977). However, the lack of association of mapped anomalies with impact craters is a major difficulty with this possibility. Also, the apparently uniform magnetization of the Reiner Gamma deposit over a $30 \times 60$ km area located some $200$ km from the primary impact crater Cavalerius is difficult to explain without an ambient magnetic field. The present solar wind field ($5–10 \gamma$) is too weak to have served the purpose, since the self-field of the deposit is at least of the order $10^2–10^3 \gamma$ near the surface.

There are two means of checking for the existence of an early magnetizing field of global or larger extent using existing data. The first method consists of determining the bulk directions of magnetization for individual sources about the Moon, and then combining these to look for evidence of non-randomness. The results of the first attempt to apply this approach to the subsatellite magnetometer data were described in Section 4, and their implications will be further discussed below. The second method amounts to obtaining evidence that the magnetizing field varied with time. Although paleointensity determinations using the lunar samples have proved to be more difficult than for terrestrial rocks, it remains significant that the available measurements show a general increase in intensity with sample age (Stephenson et al., 1974). Attempts to use the orbital magnetometer and electron reflectance data to infer a variation with time of the magnetizing field intensity (Lin et al., 1977; Russell et al., 1977) suffer from an ambiguity problem (because the intensity of magnetization depends strongly on compositional characteristics, as well as on the strength of the magnetizing field) but may yet yield important results. For example, if a late Copernican ($<<1 \times 10^9$ y old) deposit is found to be associated with a strong magnetic anomaly, then no strong magnetizing field of global extent is likely to have been responsible for the magnetization of that deposit. By implication, the necessary existence of a large-scale magnetizing field for other older anomaly sources would be in doubt. In this context, it may be significant that no large anomalies were detected by the Apollo 16 subsatellite magnetometer at altitudes ranging from 40 to 11 km over the craters Copernicus and Kepler, and their associated ejecta mantles and ray materials (Fig. 7).

Perhaps the simplest theory of lunar magnetism which makes use of a large-scale magnetizing field
supposes that the Moon once possessed an intrinsic magnetic field generated by dynamo action within a small iron core. The early interpretation of the magnetization of lunar rocks as thermoremanent in origin (Collinson et al., 1973; Strangway et al., 1973a) and the concurrent detection of large surface magnetic fields (~300 γ at the Apollo 16 landing site; Dyal et al., 1974), as well as the orbital anomalies, seemed, by analogy with the terrestrial case, to require lengthy intervals during which massive beds of rock cooled slowly through the Curie point. A large-scale field, fixed in the Moon and steady in amplitude and direction over these intervals was indicated. Further support for the hypothesis of an ancient lunar dynamo came when Runcorn (1975) showed that the present negligible lunar global dipole moment (≤10^{19} G cm^3; Russell et al., 1975a) could be consistent with a lunar crust magnetized along dipolar field lines in the non-permeable limit.

However, the great disparity in adjacent, roughly inferred magnetization directions (Fig. 14), and the general depletion in the north–south component of magnetization intensity across part of the far side, are not consistent with an internally generated dipolar field oriented mainly parallel to the present lunar spin axis. If such a field behaved in the same way as presently observable planetary fields, then polar wandering and secular variation on an impossibly large scale must have occurred.

Runcorn (1978) has calculated the pole positions of an assumed internal dipole field which correspond to the directions of magnetization given by Hood et al. (1978a). He finds a slight clustering of these pole positions in the east–west direction (i.e., along the selenographic y-axis, which is perpendicular to both the Moon–Earth line and the lunar spin axis). However, as Runcorn (1978) notes, such a clustering in the east–west direction would also have occurred for a group of randomly oriented magnetization vectors located on the central far side of the Moon. This pole-position artifact effect is well known, and is due to the variation with latitude of the directional gradient of a dipole field. As long as the inferred internal dipole has the same orientation as that expected for a random distribution of magnetization vectors on the central far side, it is not wise to attach great physical significance to the result.

In addition to observational difficulties, there are several theoretical arguments against an ancient lunar dynamo which should be noted. Firstly, moment of inertia measurements (Blackshear and Gapcynski, 1977), deep magnetic sounding studies (Goldstein et al., 1976; Wiskerchen and Sonett, 1977) and seismic evidence (e.g., Nakamura et al., 1974) restrict the present lunar metallic core radius to a maximum of about 400 km. Paleointensity estimates of ~1 Oe at 4 × 10^9 y ago would therefore require an assumed dipolar paleofield at the lunar core–mantle boundary of ~82 Oe, far larger than the present ~5 Oe field at the terrestrial core–mantle boundary. Thus, an inordinately efficient ancient lunar dynamo is required. Secondly, classical thermal evolution models predict the formation of a metallic core within a body as small as the Moon at a relatively late stage (after 3.5 × 10^9 y ago), well after magnetization of some lunar materials is known to have occurred. Only the introduction of special early heating mechanisms (Runcorn et al., 1977) seems capable of producing the thermal conditions necessary for convective dynamo action in the lunar interior at a sufficiently early stage in lunar history. However, surface geological features are indicators of the amount of thermal stress and expansion experienced by a planet during its history, and interpretation of these features for the case of the Moon (Solomon and Chaiken, 1976) support the contention of an initially cold lunar interior.

Finally, it is possible that an external magnetic field was responsible for the magnetization of lunar crustal materials. Banerjee and Mellema (1976a, b) have suggested that lunar and meteoritic paleomagnetism (see reviews in this issue) may have a common origin due to the similarity in magnitudes of paleointensity estimates for both lunar rocks and meteorite samples. Although Brecher (1977) has correctly pointed out the difficulties inherent in comparing meteoritic paleointensity determinations to those of the lunar samples, the major theoretical problem is that of maintaining a solar nebula magnetic field over a period of at least 1.5 × 10^9 y (see Levy and Sonett, 1978, for a recent review of possible models for the origin of the magnetic field responsible for meteorite magnetism).

But from an observational point of view, it must be admitted that an external, variably oriented, interplanetary magnetizing field (whether intrinsically strong or locally amplified by unknown surface pro-
cesses) could explain several characteristics of the data. Firstly, the very different directions of magnetization inferred for nearly adjacent anomaly sources could have occurred either by means of external fluctuations in the field orientation as individual sources formed, or as a consequence of the rotation of the Moon on its spin axis (or both). If the rotation has remained approximately constant during the past $4 \times 10^9$ y, then the north–south depletions in the magnetic field across the far side could reflect a tendency for the magnetizing field to have been mainly parallel to the ecliptic plane — as might be expected for an interplanetary field embedded in a differentially rotating, electrically conducting medium. Further work to corroborate the existence of the north–south depletions of the magnetization intensity across the far side and in other selenographic areas is needed. The angle of only $30^\circ$ made by the Reiner Gamma bulk magnetization vector with the lunar spin axis dictates caution until this work is complete.

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References


