Some Geologic Observations Concerning Lunar Geophysical Models

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The distribution of lunar geologic units in space and time and their mode of origin provide significant data which bear on a number of current problems in lunar geophysics. Observations and problems discussed here deal with the characterization of the upper 25 km of the lunar crust; the tectonic style of the crust; the formation of mascons within major basins; analysis of lunar magnetic anomalies; and the history of the lunar crust.

A number of geological observations provide important insights into, and in some cases constraints on, current problems in lunar geophysics. These observations are predominantly in the form of (1) morphological characterization and classification of lunar surface geologic units and structural features; (2) the areal distribution of these features on the lunar surface; and (3) the distribution of these features in geologic time. The purpose of this paper is to examine relevant geologic observations which bear on a number of specific geophysical problems.

Characterization of the Upper 25 km of the Lunar Crust

APPROACH

A seismic velocity profile for the lunar crust has been constructed by the use of traveltimes and amplitudes of seismic waves generated primarily by artificial impacts (refs. 1–5). The profile is centered on the Fra Mauro-Apollo 12 region in the eastern Oceanus Procellarum-Mare Cognitum area and is summarized in figure 1. The seismic velocities in the upper portion of the crust (upper 25 km) lie within the velocity range of lunar basalts and this upper crustal layer has often been interpreted to be similar in composition to the basaltic rocks found at the surface. Since this profile applies primarily to the geographic area indicated, the geology

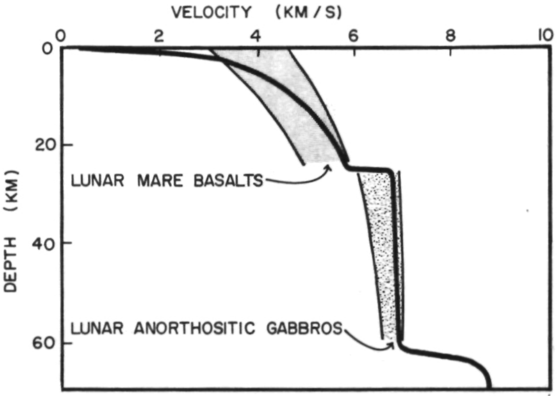

Figure 1.—*Seismic velocity profile for the lunar crust (after Toksöz et al., ref. 48). The velocity model is shown by a heavy line. The lunar basalts for which velocities have been measured include samples from different sites. The anorthositic gabbro region is bounded by Apollo 16 aluminous rocks 68415 at the high-velocity bound and 62295 and 65015 at the low-velocity bound (from Wang et al., ref. 49).*

of that region may provide some evidence for the stratigraphy and structure in the upper 25 km of the lunar crust which would bear on rock composition and physical properties.

OBSERVATIONS

The basaltic mare surface on which the Apollo 12 lunar module landed was deposited subsequent to the deposition of a regional ejecta blanket (Fra Mauro Formation) derived from the Imbrium basin to the north (fig. 2). The Apollo 14 mission explored the surface of this ejecta blanket in an area about 180 km to the east of the Apollo 12 site. There is considerable evidence that the Fra Mauro Formation originally blanketed most of the area around the Imbrium basin at radii from the basin center comparable to that of the Apollo 12 site (ref. 6). Therefore, the Fra Mauro Formation is believed to underlie the mare basalts at the Apollo 12 site. Since the Fra Mauro Formation represents an ejecta blanket deposited on preexisting topography, its regional surface elevation is largely a function of preexisting topography. Since mare lavas tend to pond in low areas, the areas of the Fra Mauro Formation which have been subsequently flooded represent low areas which existed prior to the deposition of the Imbrium ejecta blanket. This is supported by the lack of any deformation in the Fra Mauro Formation that might suggest major post-Imbrium downfaulting or downwarping.

Figure 2.—*Earth-based telescopic view of the Apollo 12–14 region in eastern Oceanus Procellarum-northern Mare Cognitum. Crater in upper left is Lansberg, about 36 km in diameter. See figure 4 for location of Apollo 12 and 14 sites. From Consolidated Lunar Atlas, contributions of the University of Arizona Lunar and Planetary Laboratory No. 4.*

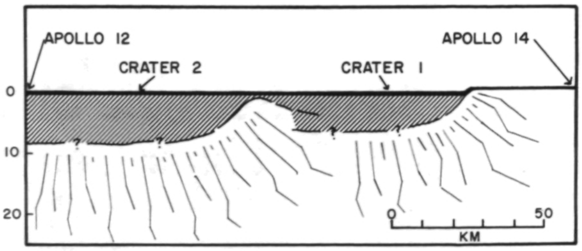

FIGURE 3

Figure 3.—*Schematic cross section of the upper 25 km of the lunar crust in the Apollo 12–14 region, showing dominant effects of large craters 100 to 200 km in diameter. Vertical exaggeration is 2:1. Heavy line at surface is combined thickness of mare and Fra Mauro Formation or Fra Mauro only where appropriate. Slanted lines are deposits related to the major craters including fallback, slump, crater fill, and autochthonous breccias. Exact base of these deposits is uncertain. Radiating lines define region of gradational zone of shock effects in deposits subjacent to the crater.*

Another characteristic of this region is that the small hills which are mapped as part of the Fra Mauro Formation are preserved as small islands in much of the area flooded by mare (ref. 7 and fig. 2). This suggests that the Fra Mauro covers the area under the maria and that the thickness of the maria is generally less than the elevation of these domes (which are up to several hundred meters in height). In mapping the Apollo 12 region, Pohn (ref. 8) assumed that the premare surface dipped away from the exposed highlands to the west at a 1-percent eastward slope, and predicted a thickness of 170 m for the mare material.

Therefore, the youngest regional unit deposited in this area is the mare material, and its thickness does not appear to exceed several hundred meters (fig. 3).

Specific sources for mare lavas are not easily identifiable because of their tendency to pond in low regions and to cover their own sources. Lavas must have reached the surface along some type of conduits. These could form a subsurface network of dikes of unknown density and could affect the seismic velocities in this region.

The next oldest unit in this region is the Fra Mauro Formation and its average thickness at this radial distance from the center of Imbrium is approximately 100–150 meters (refs. 9, 10, and 11). The characteristics of this unit are compatible with its interpretation as a thermally metamorphosed major basin ejecta blanket (refs. 12–15).

Contributions from other multi-ringed basins at the Apollo 12/Apollo 14 sites appear slight (ref. 9) with only Humorum and Nubium approaching 50 m in average thickness of potential contribution. This is beyond the edge of continuous deposition for all the basins considered, so any contribution would lie in the form of secondaries which would be mixed with local material in the manner outlined by Oberbeck et al. (ref. 16).

Because of the erosive and blanketing effects of the deposition of a major multiringed basin ejecta blanket (refs. 9, 16, and 17), pre-ejecta blanket stratigraphy and structure are often difficult to decipher in specific areas. In general, evidence is gained from the detection of "ghost" or buried crater rims and structures (ref. 18). No major pre-Imbrium craters have been described in this area in the mapping of the region between the Apollo 12 and Apollo 14 sites (refs. 7 and 8), although several have been mapped to the south (ref. 7).

Analysis of photography of the region at a variety of scales and lighting angles reveals several possible pre-Imbrium craters between 30 and 200 km in diameter (fig. 4). Crater 1, the oldest of the three described here, is about 125 km in diameter and lies between the Apollo 14 and 12 landing sites. Crater 2, the next youngest of the three, is about 190 km in diameter and underlies the Apollo 12 site. Its ring remnant can be seen within crater 1 (figs. 2 and 4) establishing its younger age. Crater 3, about 30 km in diameter, lies within crater 2 and is therefore younger. These three craters are blanketed by Fra Mauro Formation and are therefore older than the Imbrium event. Three major units should be associated with craters: (1) impact melts and highly metamorphosed breccias concentrated on the crater interiors; (2) less intensely thermally metamorphosed breccias, unconsolidated ejecta, and local material excavated by secondary cratering events (refs. 16, 19, 20, and others), distributed in decreasing thickness outward from the crater rim (ref. 9); and (3) autochthonous breccias underlying the crater floor grading into crustal rocks showing progressively less shock deformation with depth. The pre-Imbrium craters described here would therefore make significant contributions to the outer portion of the lunar crust (fig. 3). Associated rock types would include pure impact melts (perhaps similar to 14310; see reference 21), extremely coherent breccias, weakly coherent breccias, and noncohesive ejecta.

The autochthonous breccias underlying a lens of crater floor fallback breccias and the subjacent gradational zone of shocked material could be several tens of kilometers thick for a crater such as 2.

Wilhelms and McCauley (ref. 6) have mapped a large multiringed basin in this region centered just east of the crater Copernicus. If this basin exists, then it predates craters 1, 2, and 3, since they are superposed on a ring of this structure. The role of this structure is difficult to assess, but if the ma-

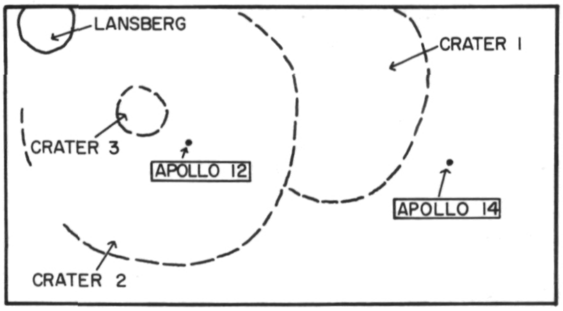

Figure 4.—*Sketch map covering same area pictured in figure 2, and showing location of pre-Imbrian craters 1 (about 125 km), 2 (about 190 km), and 3 (about 30 km). Cross section extends from the Apollo 12 to the Apollo 14 site (depicted in figure 3).*

jor part of the area lies within a multiringed basin, the impact-induced melting characteristic of these deposits (ref. 21) could produce a large volume of rocks with seismic velocities similar to crystalline rocks such as basalts. However, subsequent events (such as the formation of craters 1, 2, and 3) would have obliterated much of these deposits.

MODEL

On the basis of these observations, the most reasonable model for the upper 25 km of the crust in the Apollo 12/14 region (fig. 3) is one characterized by less than a km of basalt and Imbrium basin ejecta underlain by deposits associated with large craters (100 to 200 km in diameter) down to depths probably approaching 25 km. There is little evidence that basalts of the type found at the surface are abundant at depth in the same mode. In addition, lack of abundant typical mare basalt lithologies in highland breccia clasts argues against extensive pre-Imbrium surface volcanism of similar lithology. Finally, the geometry of the large craters seen in the region indicates that they would have destroyed early layered deposits during their formation.

The progressive increase in seismic velocity with depth may be a direct function of the progressive decrease in intensity of shock metamorphic effects, such as microfracturing, in the gradational zone of shock effects typical of subcrater deposits. These gradational zones have been noted in terrestrial craters (refs. 19, 22, 23, 24, and others). In particular, craters in the range of 100 to 200 km in diameter, such as those shown in figure 4, would certainly alter the physical properties of subjacent rocks down to 25 km depth. Abundance of similar large old craters on the lunar surface suggests that the velocity profile may be similar elsewhere.

Thus the seismic velocity profile of the outer portion of the crust probably represents progressive increase in velocities in an anorthositic gabbro crust due to progressive decrease in shock effects, rather than material of basaltic composition.

Todd et al. (ref. 25) and Simmons et al. (ref. 26) have studied the physical properties of terrestrial and lunar rocks. Their results show that shock-induced microcracks are significant in the outer 25 km of the Moon and support the geologic framework presented here for the characteristics of the outer crust.

Tectonic Style of the Lunar Crust

APPROACH

The morphologic characteristics of and distribution of planetary surface topographic features can provide much evidence for the tectonic style of a particular planet in space and time.

OBSERVATIONS

A surprisingly small variety of lunar surface morphologic features have been attributed to lunar tectonism or structural evolution. These include linear rilles, large graben, mare ridges, basin rings, and lineaments (refs. 27–31). Linear rilles generally take the form of flat-floored, steep-walled troughs, ranging up to several kilometers in width, and to tens (and often hundreds) of kilometers in length. The flat floors and linear walls suggest that the rilles are fault-bounded down-dropped blocks or grabens, and their generally constant width over different topographic levels indicates steep dips.

Several large linear graben-like valleys are associated with the major multiringed basins and are oriented in a radial direction. The best known example is the Alpine Valley associated with the Imbrium basin. These structures seem to occur preferentially in quadrants of the basin where they parallel lunar grid directions. They are interpreted to be major graben valleys which develop where radial multiring basin fractures coincide with lunar grid fractures (ref. 32).

Lineaments are abundant on the lunar surface and their distribution and origin have long been a matter of controversy. Structural lineaments are often associated with major multiringed basins in radial and concentric orientations. In many cases, multiring basin-associated lineaments are enhanced in lunar grid directions (ref. 32) suggesting that the lineaments preferentially form along prebasin planes of weakness. Many lineaments may also be related to structural trends from ancient, subsequently obliterated basins. However, the bulk of the lineaments seem more likely to be related to lunar grid patterns. Fielder (ref. 30), Strom (ref. 33), and Elston et al. (ref. 34), have discussed the global lineament systems and have concluded that they represent a stress field with the maximum principal stress axis oriented N–S with strike-slip movement developed 45° to the E and W and tension fractures developed N–S, producing the primary grid patterns.

Mare ridges and their analogous structures in the highlands have often been related to intrusive and extrusive igneous activity (ref. 35). However, evidence cited by Howard and Muehlberger (ref. 36), Bryan (ref. 37), Head (ref. 32), and Muehlberger (ref. 38) suggests that many of these structures are related to structural deformation which occurred primarily subsequent to the deposition of the main mare sequence. In many cases they appear to be layers of material which have been overthrust onto the surface for short distances.

The stratigraphic distribution of these structural features provides information on the time span of lunar tectonic elements. Major graben valleys appear to be associated with the formation of multiringed basins, smaller linear rilles with the period of mare filling, mare ridges with readjustments during and after mare fill, and lineaments and lunar grid structures with early highland crust formation, perhaps rejuvenated by tidal interaction with the Earth. There is virtually no evidence for extensive tectonic activity in the past 3.0 billion years of lunar history.

MODEL

Immediately obvious in a model of lunar structural deformation is the virtual lack of any evidence of analogs to terrestrial plate tectonics which might indicate major lateral crustal movement on the Moon. Major structural features are related either (1) to a background basement fracture system produced early in lunar history, or (2) to the formation of major multiringed basins or their subsequent filling. For the major part of lunar history, the lunar crust appears to have acted as a prestressed and fractured, but essentially passive and rigid layer, with deformation essentially being localized to the regions of large-scale basin excavation and filling.

Mascon Basins

APPROACH

Observations on the characteristics of Orientale, a young (about 3.85 b.y.; see ref. 39) relatively unflooded basin may provide insight into the cause of gravity anomalies in other older basins.

OBSERVATIONS

The Orientale basin (figs. 5 and 6) formed as a result of impact into lunar highland crustal rocks. In a recent study (ref. 21), the crater rim is shown to be closely represented by the position of the outer Rook Mountain ring, approximately 620 km in diameter. The inner Rook Mountains form a central peak ring within the crater. The Cordillera ring, 900 km in diameter, is a fault scarp which formed in the terminal stages of the cratering event as a large portion of the crust collapsed inward toward the recently excavated crater, forming a megaterrace. This collapse pushed the wall of the Orientale crater inward, distorting it and slightly decreasing its radius. The inward

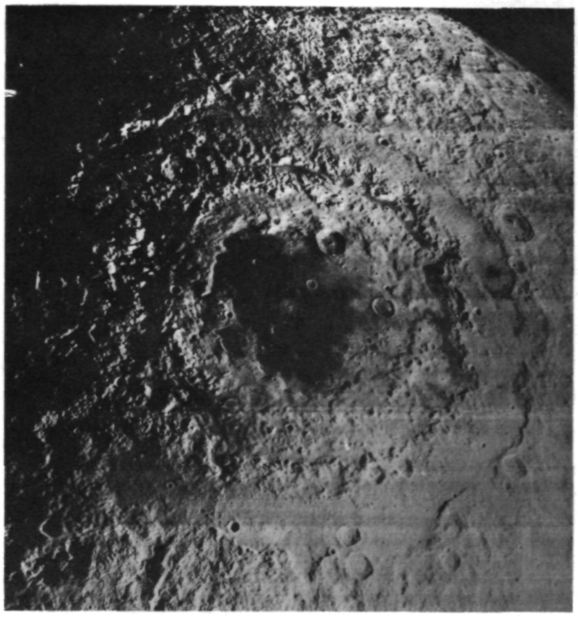

Figure 5.—*Orientale basin, about 900 km in diameter. Portion of Lunar Orbiter IV frame 194M.*

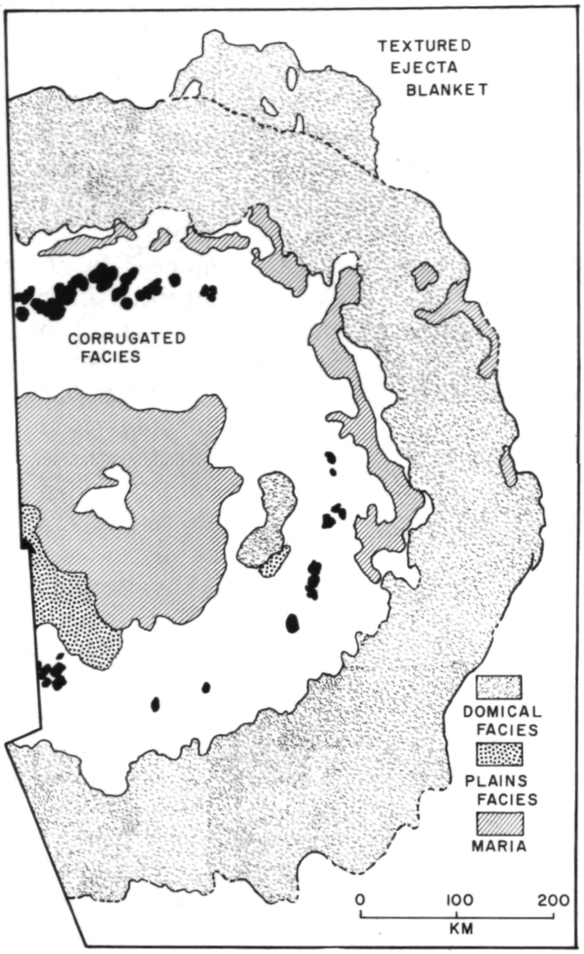

Figure 6.—*Major facies or geologic units in the Orientale basin (from Head, ref. 21).*

collapse was almost certainly aided by the upwelling of subcrater material since the present basin is relatively shallow (maximum height of rings and peaks is about 4.5 km above the surrounding plain; maximum depth must be near this figure).

Analysis of the facies provides evidence for the timing of the upwarping. A domical facies (fig. 6) is almost exclusively developed between the Cordillera and outer Rook rings. The domical facies is interpreted to be radially textured ejecta which was disrupted and modified to a jumbled domical texture by seismic shaking associated with the formation of the mega-terrace. The plains and corrugated facies pre-date the mare fill and lie within the Orientale crater. They are interpreted to have been deposited contemporaneously with the cratering event as partial and total impact melts which collected on the floor of the crater during the terminal stages of the event. The lack of major deformation associated with the crater floor (other than cooling and contraction cracks) strongly suggests that the floor was in its present shallow configuration prior to the final cooling of the corrugated and plains facies. Therefore, rebound and upwelling of the crater floor were coincident with the terminal stages of the cratering event.

Subsequent to the formation of the Orientale crater a small amount of mare material (when compared to other mare basins) was deposited in the central portion of the basin (about 50 000 km^2 in Mare Orientale), around its margin along the base of the outer Rook (Mare Veris, about 12 500 km^2), and along the base of the Cordillera (Mare Autumni, about 5000 km^2).

Sjogren et al. (ref. 40) have mapped a mascon associated with the Orientale basin and concentrated within the inner Rook Mountain ring. Since there is little evidence of subsequent structural modification of the crater or extensive mare fill, this implies that the Orientale mascon formed in relation to the cratering event, rather than at a later time. As pointed out by Phillips et al. (ref. 41), a multiringed basin which was formed in low-density crust (in an area of a crust-mantle configuration of zero anomalous gravity) and which was isostatically compensated by upwelling of a mantle plug (as in the model of Wise and Yates, (ref. 42)), would show a negative gravity anomaly in the analyses of Phillips et al. In this case the gravity effect would be due to the zero density of the unfilled basin. Filling of the basin with material of crustal density tends to produce a positive anomaly due to the mantle plug. Filling of the basin with material of greater than average crustal density (mare basalts) produces a positive anomaly in which mantle plug and basin fill contribute to the effect. The mascon would then be composed of both these elements.

The model for the origin of the Orientale basin (ref. 21) is relevant in differentiating these effects. The model suggests that the present shallow basin configuration is very nearly the same as at its time of origin, and that only a small amount of mare material has flooded the basin. The Orientale mascon cannot be due to the small amount of mare material alone. Therefore, the anomaly may be related to upwelling of a higher density mantle plug and to filling of the topographic depression created by the ejection of material during the cratering event. The Orientale model suggests that these two factors may be dynamically related to the cratering event, rather than separate and occurring at different times. The size of the Orientale crater (620 km in diameter) and its shallowness suggest that it excavated relatively deep in the crust but rebounded in the terminal stages of the event, perhaps *pulling* the mantle plug up with it. Thus, the formation of the mantle plug seems to be related to the process of rebound at the time of the event, rather than to be a simple upwelling to reach isostatic equilibrium. This implies that the Orientale positive anomaly is primarily due to a mantle plug which in excess of equilibrium and which lies above the normal crust-mantle interface. In addition, the topographic depression (basin of excavation) is reduced by movement of material of crustal density into the basin in the terminal stages of the cratering event. This consists of ejecta fallback, upwelling of crater floor crustal material, and inward slumping of the crater walls (which forms a huge megaterrace bounded by the Cordillera Mountains).

If Orientale were flooded by mare material (denser than surrounding crust) to the same extent as that in the Imbrium basin (virtually covering the crater interior with additional shallower flooding out to the Apennine fault scarp), an additional contribution to the anomaly would be made. The thicker mare plate within the crater would also tend to broaden the positive anomaly so that it more closely corresponded to the crater rim, as is the case with the Imbrium anomaly (see Sjogren et al., ref. 43).

MODEL

On the basis of a model of the origin of the young multiringed Orientale basin (ref. 21), the Orientale mascon is thought to be due primarily to a mantle plug pulled up to form a positive anomaly during rebound associated with the cratering event. The Orientale gravity effect is enhanced by filling of the excavated crater during the impact event largely by material of density similar to the surrounding crust. Subsequent mare filling of the crater, such as has occurred in the Imbrium basin, tends to add to the mascon and broaden its distribution.

The gravitational history of mare basins therefore includes the following elements: (1) an initial crater of excavation, with circumferential ejecta deposition, causing a mass deficiency; (2) upward displacement of denser mantle material which brings the crater up to or above an equilibrium state in the terminal stages of the cratering event; (3) fallback of ejecta, inward slumping of multiple rings, and upwarping of the crater floor due to rarefaction, which contribute to a super-isostatic configuration; and (4) in the case of the Imbrium basin, later extrusion and deposition of higher density mare flows, which cause a further increase in the mass excess, broadening the mascon distribution by laterally extending the high-gravity region.

Lunar Magnetic Anomalies

APPROACH

Numerous magnetic anomalies have been noted at Apollo sites (Dyal et al., ref. 44, and from lunar orbit (Russell et al., ref. 45) (reviewed by Fuller, ref. 46). Their correlation with geologic surface units may provide important information on their origin.

OBSERVATIONS

The remanent magnetic fields measured in the Descartes region (Apollo 16 landing site) are the largest extraterrestrial fields yet measured in situ (ref. 44). Four magnetic readings (generally large with downward components) were taken on the regionally flat Cayley plains surface. An additional reading (large and upward) was obtained on the slopes of Stone Mountain, which is a portion of low mountains bounding the Cayley plains in an arc-like manner. Thus, the plains and surrounding mountains appear to have differing characteristics. Strangway et al. (ref. 47) have suggested that the differences may be due to edge effects and consider that the Cayley plains represent breccia blankets which were deposited at temperatures above 770°C by a mechanism such as volcanic or impact base surge. An alternative model for the history of the site (ref. 18) supports the concept of an edge effect but attributes the formation of the Cayley plains and surrounding mountains to floor material and wall material, respectively, of an old 60-km diameter crater centered about 25 km west of the Apollo 16 site. In this model, the magnetism associated with the Cayley plains is believed to have been caused by cooling of impact melts concentrated on the crater floor of the 60-km diameter crater in the presence of a magnetic field. The crater wall (Stone Mountain) bears less intensely shocked ejecta and pre-crater material.

MODEL

The association of the strong magnetic field at the Apollo 16 site with the floor of an old large crater suggests that many localized anomalies may be caused by cooling of impact melts on crater floors in the presence of a magnetic field.

History of the Lunar Crust

A summary of the structural history of the lunar crust as inferred from photogeologic evidence is as follows: (1) formation of lunar crustal rocks and formation of lunar grid patterns; no apparent lateral offset associated with grid patterns (their origin is unknown); (2) formation of large multiringed basins (undoubtedly coincident with (1) in part, but youngest basins formed in crust which contained grid); (3) initial filling of many multiringed basins with mare material; tensional deformation of this material as many basin interiors subside to form linear and arcuate rilles; (4) continued filling of major basin interiors; little tensional deformation; and (5) compressional deformation associated primarily with mare basins and basin margins, and evidenced by mare ridges and associated structures. This latter phase may be associated with final mare subsidence or shrinking of crustal regions due to cooling of mare source areas. Except for mare ridges, there appears to be virtually no evidence for extensive tectonic activity in the past three billion years of lunar history.

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