

Geochemical anomalies on the eastern limb and farside of the moon

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Abstract—A variety of orbital geochemistry and photogeologic data was used to investigate major geochemical anomalies on the east limb and farside of the Moon and to determine the processes responsible for their formation. These anomalies are located in the following regions: (1) near Lange-mak crater, (2) Mare Marginis, (3) Balmer crater, (4) terrain north of Taruntius crater, and (5) Van de Graaff. It was concluded that these anomalies are related to episodes of extrusive igneous activity which produced deposits with a variety of ages and compositions. Some of the associated volcanic deposits exhibit albedos and surface morphologies similar to those of the nearside maria, while others are now thinly covered by highland debris and are commonly represented by light plains units which exhibit clusters of dark-haloed craters. Little evidence was found for a genuine episode of highland volcanism. (e.g. Apollo 15 KREEP basalt, highland basalt, etc.) The geochemical anomalies appear to be related to basaltic deposits with either mare affinities or that are intermediate in composition between KREEP and mare basalts. The existence of such intermediate basalts on the eastern limb and farside supports previous suggestions that KREEP-like volcanism was not limited to a small area of the lunar nearside. Eastern limb and farside volcanic activity has been more extensive in both space and time and has produced a greater variety of compositions than has previously been thought.

Since thinly covered basaltic units can exert a strong influence on regional surface chemistry as determined from orbit, caution is urged in interpreting the surface compositions of highland terrains which exhibit a high density of dark-haloed impact craters.

INTRODUCTION

Analyses of the orbital geochemistry data have shown that some lunar regions have unusual abundances of certain elements relative to surrounding or adjacent areas, or have a surface chemistry unlike that which would be anticipated from the examination of local geologic relationships. Investigation of the formation of these geochemical anomalies can provide important clues to understanding impact and volcanic processes operative during the early phases of lunar evolution as well as the lateral and vertical composition of the highlands crust. For example, such studies have been of critical importance in outlining the history of KREEP

volcanic activity in the western maria (Haines *et al.*, 1978; Spudis, 1978; Hawke and Head, 1978; Metzger *et al.*, 1979). The purpose of this study was to investigate the geology and geochemistry of selected anomalous highlands regions on the eastern limb and farside and attempt to understand the processes responsible for their formation.

GENERAL CAUSES OF GEOCHEMICAL ANOMALIES

There has been an increasing tendency in recent years to relate geochemical anomalies and other variations in lunar surface chemistry to lateral heterogeneities produced by the chemical differentiation of the global magma ocean. While this explanation is probably valid and may be particularly important in accounting for large-scale variations, it must be recognized that other processes are capable of producing geochemical anomalies in the lunar highlands. These include the following:

Basin-forming impacts

Large objects which impacted near the end of crustal formation may have produced localized melting and lateral chemical heterogeneities. More recent basin-forming impacts created major bodies of impact melt and excavated crustal material from a variety of depths which was deposited in a systematic fashion. Systematic changes in the composition of large basin ejecta deposits may represent changes in the vertical composition of the lunar crust at the target site. The composition of the associated body of impact melt may represent a homogenized section of the upper crust (Ryder and Wood, 1977) or may have differentiated to form a variety of rock types (Head, 1974).

Highland volcanism

Volcanic activity has also been an important process in determining the composition of the lunar surface. Although this is most obvious in the case of mare volcanism, premare or highland volcanism may have been very important. Very early (>4.0–4.1 b.y.) highland volcanic deposits were probably disrupted and largely destroyed during the terminal bombardment of the lunar surface, but may have left geochemical and mineralogic signatures which can be detected with existing remote sensing techniques. The heavily impact reworked KREEP-rich breccias collected at the Apollo 14 site are probably the products of such an episode of early highland volcanism (Hawke and Head, 1977; 1978).

More recent episodes of highland volcanism may have produced deposits which are both compositionally and morphologically distinct. Remote sensing and geologic evidence has recently been presented which strongly suggests that the Apennine Bench Formation is the surface expression of a post-Imbrium highland volcanic unit composed of KREEP basalt (Hawke and Head, 1978; Spudis,

1978; Metzger *et al.*, 1979). In addition, the Gruithuisen and Mairan Domes may represent morphologically and spectrally distinct non-mare extrusive volcanic constructs of Imbrian age (Head and McCord, 1978).

Mare volcanism

Mare volcanic deposits emplaced considerably before the end of the terminal bombardment would have been thoroughly reworked and mixed with highland material (see Ryder and Taylor, 1976). While little morphologic evidence of these very early basalts would remain, they could still exert an influence on the remotely-sensed surface composition of the area in which they were emplaced. Later mare basalts, extruded close to the end of the terminal bombardment, may have been thinly buried by layers of highland debris. These ancient mare basalts are represented on the lunar surface by certain light plains which exhibit dark-haloed craters (see Schultz and Spudis, 1979). These covered basaltic deposits, though present in the subsurface, could still exert a powerful influence on regional chemistry since some mare basalt would have been mixed with the highland material during the emplacement of the debris unit. In addition, variable amounts of vertical mixing of mare basalt with overlying material has occurred during the interval since the emplacement of the highlands debris.

Pyroclastic deposits in regions of explosive volcanic activity are capable of producing areas of mare-like chemistry in the lunar highlands. A prime example is the Sulpicius Gallus Formation which occurs in a portion of the Haemus Mountains southwest of Mare Serenitatis (see Schonfeld and Bielefeld, 1978). Since pyroclastic activity appears to have been concentrated in the vicinity of basin rims, care must be exercised in interpreting surface compositions in these areas (Hawke *et al.*, 1979; Andre *et al.*, 1979a). Complications arise if the pyroclastics are difficult to detect, as would be the case if the deposits were either very old or originally thin and had been substantially mixed with subjacent material, or if the pyroclastics had a higher albedo than that which generally characterizes such deposits.

GEOLOGIC AND GEOCHEMICAL CHARACTERISTICS OF SPECIFIC EAST LIMB AND FAR SIDE ANOMALIES

Several geochemical anomalies on the east limb and farside were chosen for detailed analysis based on geologic interest, degree and strength of anomaly, and data availability (Fig. 1). While most of the anomalies had been previously identified, some are described here for the first time.

Region near Langemak crater

Hubbard *et al.* (1978) pointed out the rather striking variations in Mg/Si and Al/Si intensity ratios which occur in the vicinity of Langemak crater. The lowest

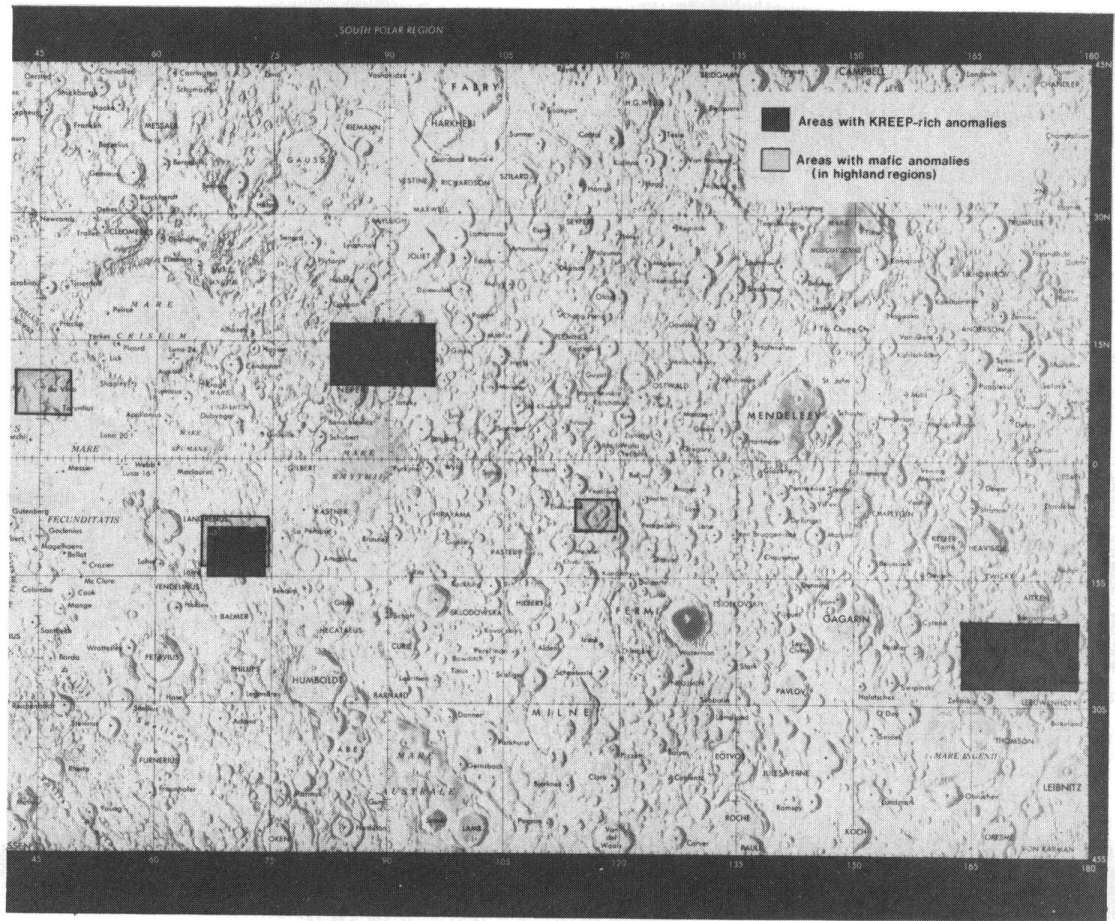


Fig. 1. Location map of geochemically anomalous regions discussed in text.

average Al/Si intensity ratios (~ 1.0) and the highest average Mg/Si intensity ratios (~ 0.8) are found around 115°E . In addition, Clark *et al.* (1978) noted that an adjacent highlands area immediately northeast of Pasteur crater was characterized by the unusual combination of high Fe and high Al/Si values. Examination of the most recent versions of the Fe and Ti distribution maps (Davis, 1979) showed that relatively high Fe and Ti values are associated with the Langemak region. The abundance of Ti is quite striking, with Ti content ranging between 2.4% and 3.5% along the northern edge of the ground track between 110°E and 125°E . No apparent radioactivity anomaly has been identified in this general region.

Important clues to understanding the source of geochemical anomalies have come from the work of Schultz and Spudis (1979), who correlated high Mg/Si intensity ratios with the dark-haloed craters in the Langemak region. The existence of these dark-haloed craters with associated high Fe, Ti, and Mg/Si values strongly suggest the presence of a buried ancient basalt layer. The occurrence of other dark-haloed craters in the region demonstrates that this unit is not limited to the immediate vicinity of Langemak and may, in fact, underlie some or most of the Imbrian and Nectarian light plains units located in this area (Wilhelms and El-Baz, 1977). The correspondence of an area of geochemical anomalies with an

area of probable ancient mare volcanic activity suggests that early volcanism may be an important process in the production of regional anomalies elsewhere on the lunar surface.

Additional support for magmatic activity in the region comes from the work of Dvorak and Phillips (1978) concerning the Bouguer gravity anomalies associated with lunar craters. These workers found that in contrast to post-Imbrian craters, which have negative Bouguer anomalies, the Imbrian age craters which display evidence of post-impact magmatic activity (floor fractures, dark floor units, etc.) exhibit no Bouguer gravity anomalies. They suggest that magmatic activity may be responsible for part or all of the net zero mass anomalies associated with Imbrian age craters. It is of interest to note that no Bouguer gravity anomaly is associated with Pasteur which is a pre-Nectarian crater west of Langemak. The absence of a Bouguer gravity anomaly may be due to the presence of either a now covered extrusive unit in the crater floor or an intrusive body beneath the crater, and is consistent with the occurrence of an episode of volcanic activity in the region under study.

Mare Marginis region

The results of Th deconvolution modeling studies by Haines *et al.* (1978) allowed the identification of a region north of Mare Smythii with Th concentrations well above average highland levels. This region is dominated by Mare Marginis and the mare-flooded crater Neper, but also contains highland units including light plains deposits in Babcock crater and just east of Marginis (Fig. 2). While Haines *et al.* (1978) reported a Th concentration of 3.4 ppm for this region as a whole, they also noted that when the model was modified by decoupling the Mare Marginis-Neper and highland portions, the resulting fit was equally good. Using this alternate model, the resulting highland Th concentration was 2.3 ppm and the mare concentration was 5.4 ppm. The high Th concentrations are clearly associated with the mare material and hence there appears to be a mare basalt unit on the eastern limb with a Th concentration of at least 3.4 ppm and perhaps as high as 5.4 ppm; both values are considerably in excess of those associated with typical Apollo mare samples.

The high Th content of the Mare Marginis basalts suggests that they are intermediate in composition between mare and KREEP basalts and may be similar to the Apollo 17 KREEPy basalt described by Ryder *et al.* (1977). Estimates of Apollo 17 KREEPy basalt Th concentrations based on reported K₂O values range from ~4 to 6 ppm and are comparable to those for the Mare Marginis-Neper region. In addition, the MgO values reported by Andre *et al.* (1979a) for Neper (~8–9%) are similar to the average composition of Apollo 17 KREEPy basalt (~8%).

Balmer crater region

Another area with anomalously high Th concentrations (~4.0 ppm) was identified by Haines *et al.* (1978) just north of Balmer crater (68°E, 15°S; see Figs. 3 and



Fig. 2. Region on eastern limb showing Mare Marginis (M), a high Th region with possible KREEPy basalt affinities. Light plains on right contain numerous dark halo craters (arrows) indicating presence of covered ancient mare basalts. Mare Smythii (S) is at 0°N, 80°E. (AS 17-152-23327).

4). This Th high closely corresponds to an area of Imbrian-age light plains containing a cluster of dark-haloed craters (Schultz and Spudis, 1979) which suggest the presence of a buried basaltic unit. The orbital geochemistry data presented by Davis (1979) show that at least the northern portion of this plains unit exhibits relatively high FeO and TiO₂ values (TiO₂ = 2.3%–3.0%; FeO = 7.2%–12.4%). In addition, Andre *et al.* (1979b) noted that the Imbrian plains southeast of Langrenus exhibit Mg/Si values 16% higher than surrounding units.

While the Imbrian-age plains and the associated geochemical anomalies may be related to a genuine episode of highland volcanism as suggested by Haines *et al.* (1978), the presence of dark-haloed craters on the plains units suggests an alternate explanation. It is possible that the covered basalt is the source of the high Th material. The area is surrounded (within 250 km) by five major impact structures of Imbrian or younger age which could have contributed to the thin cover of highland material. The subjacent basaltic material would have been mixed with crater material during ejecta emplacement and by subsequent vertical mixing by small impacts which penetrated the thin highland debris surface units.

If this explanation is correct, the basaltic unit must have had Th concentrations approaching those found in the Apollo 14 and 15 KREEP basalts. In addition, this KREEP-rich unit have been emplaced by early in the Imbrian Period and may be pre-Imbrian in age.

Terrain north of Taruntius crater

An expanse of low-lying terrain north and northeast of Taruntius crater (Fig. 5) has been mapped as plains and smooth terra material of Imbrian age (Wilhelms, 1972). However, recent remote sensing data presented by Bielefeld *et al.* (1978) suggest that these units have a mare affinity. These workers defined a number of compositional units in the Crisium-Northern Fecunditatis region on the basis of the natural clustering of Al/Si ratios, Mg/Al ratios, and albedo values. The area north of Taruntius is included in a unit which has cluster centroid values of 0.48 and 0.50, respectively, for Al/Si concentration ratio and Mg/Al concentration ratio. Elsewhere in the Crisium region, the same unit generally corresponds to maria surfaces (Mare Undarum, Mare Spumans, and the mare flooded floor of Firmicus crater) or a narrow mare-dominated mixed unit near mare-highland contacts. Hence, mare material might be expected to be associated with the deposits north of Taruntius.

Other geologic and orbital geochemical data support the suggestion that the highland units under consideration have a mare affinity. The Mg/Si intensity ratio variation map presented by Hubbard and co-workers (Frontispiece, 1978) shows that major portions of these units exhibit high values ($\text{Mg/Si} > 0.9$) more commonly associated with mare basalt units. In addition, the normal albedo data of Pohn and Wildey (1970) show that these deposits exhibit albedo values largely between 0.096 and 0.108, a range not typical of the circum-Crisium highlands but only slightly above that which characterizes most of Mare Fecunditatis and Mare Crisium. In Whitaker's $0.61\text{--}0.37\ \mu\text{m}$ color difference photograph (E. A. Whitaker, pers. comm., 1976), the deposits appear slightly less "red" than the adjacent highlands to the north, suggesting a compositional difference. The deposit morphology is also consistent with an extrusive igneous origin. The deposits exhibit a smooth, generally flat surface, embay more rugged highland terrain, and exhibit what appears to be a mare-type ridge (8°N , 48.5°E).

In order to further investigate the composition of the possible volcanic units north of Taruntius, mixing model calculations (see Hawke and Ehmann, 1976) were performed using the geochemical data of Bielefeld *et al.* (1978) and FeO values inferred from Al_2O_3 concentrations using the method described by Miller *et al.* (1974). The results show that the composition of the region can best be modeled as a mixture of 46% highlands material (unit B of Bielefeld *et al.*, 1978) and 54% mare material (unit H of Bielefeld *et al.*, 1978). Models using other endmember compositions yielded fits almost as good, but the results were essentially the same: a major component of mare basalt is required to model the composition of the units north of Taruntius.

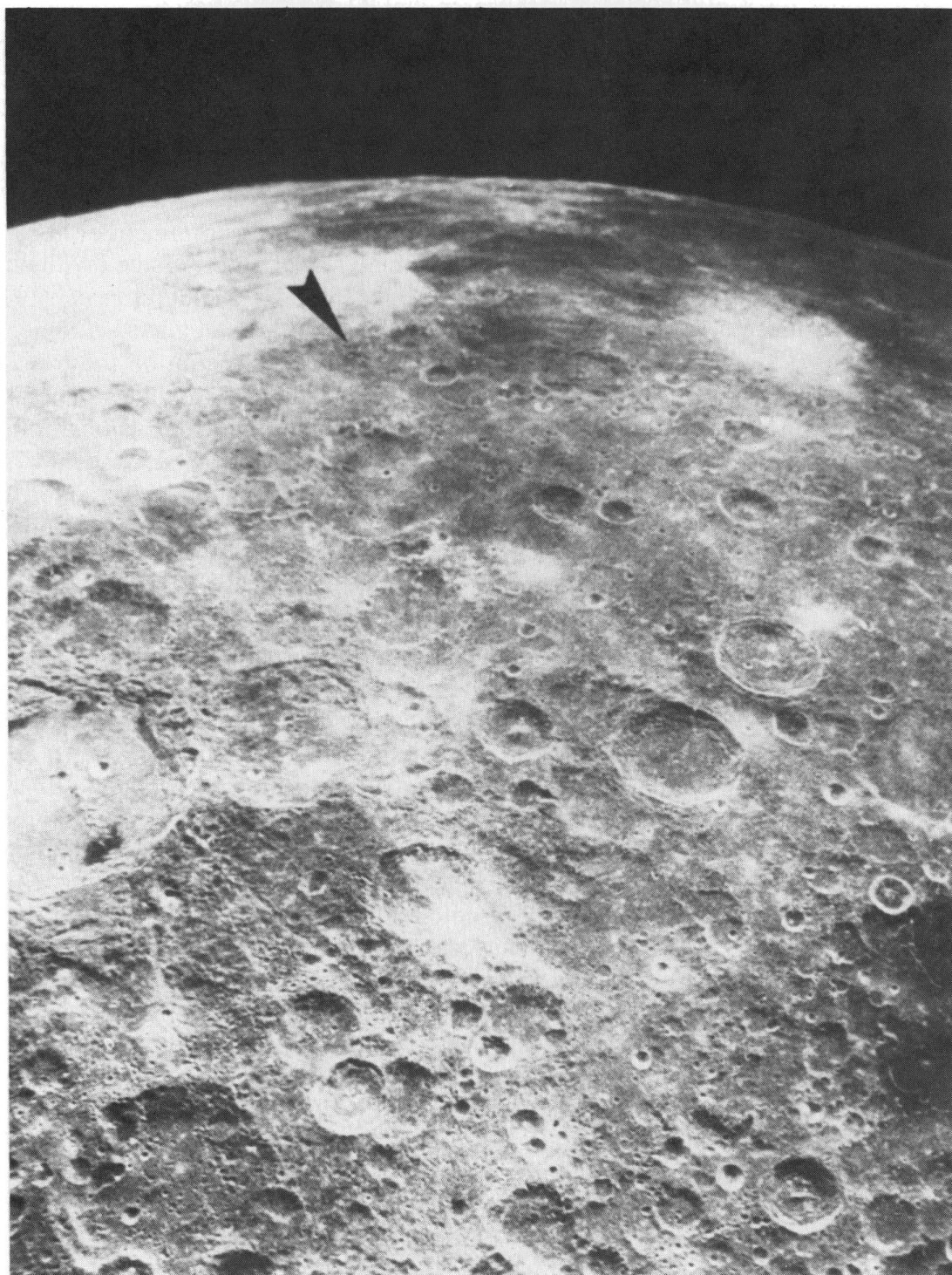


Fig. 3. View looking westward of lunar eastern limb showing regional setting of Balmer light plains (beneath arrow which points to a dark-halved crater). (AS 17-152-23293).



Fig. 4. Light plains region near the crater Balmer (20°S, 70°E) displaying dark halo craters (arrow) indicating the presence of a buried mafic unit. This region also has a high Th content. (AS 17-152-23332).

In summary, the evidence strongly suggests that the plains and smooth terra units north of Taruntius are volcanic units emplaced as fluid flows with some possible pyroclastic activity. The present surface composition is intermediate between mare basalts and highland material. Either the units represent early deposits of mare basalt which have been contaminated by lateral transport of highland material or, if highlands contamination has been minimal, a less mare-like initial composition.

Van de Graaff region

The region near Van de Graaff crater (Fig. 6) has long been noted for its abundance of associated geochemical and geophysical anomalies. The region is just within the proposed outermost rim of the large South Pole-Aitken basin and is also characterized by the occurrence of numerous unusual geologic features including a bright swirl belt and a unique surface unit composed of grooves and mounds (Stuart-Alexander, 1978).

Several major geochemical anomalies have been located in the Van de Graaff region. The region contains relatively high Th, K, and Fe concentrations and low

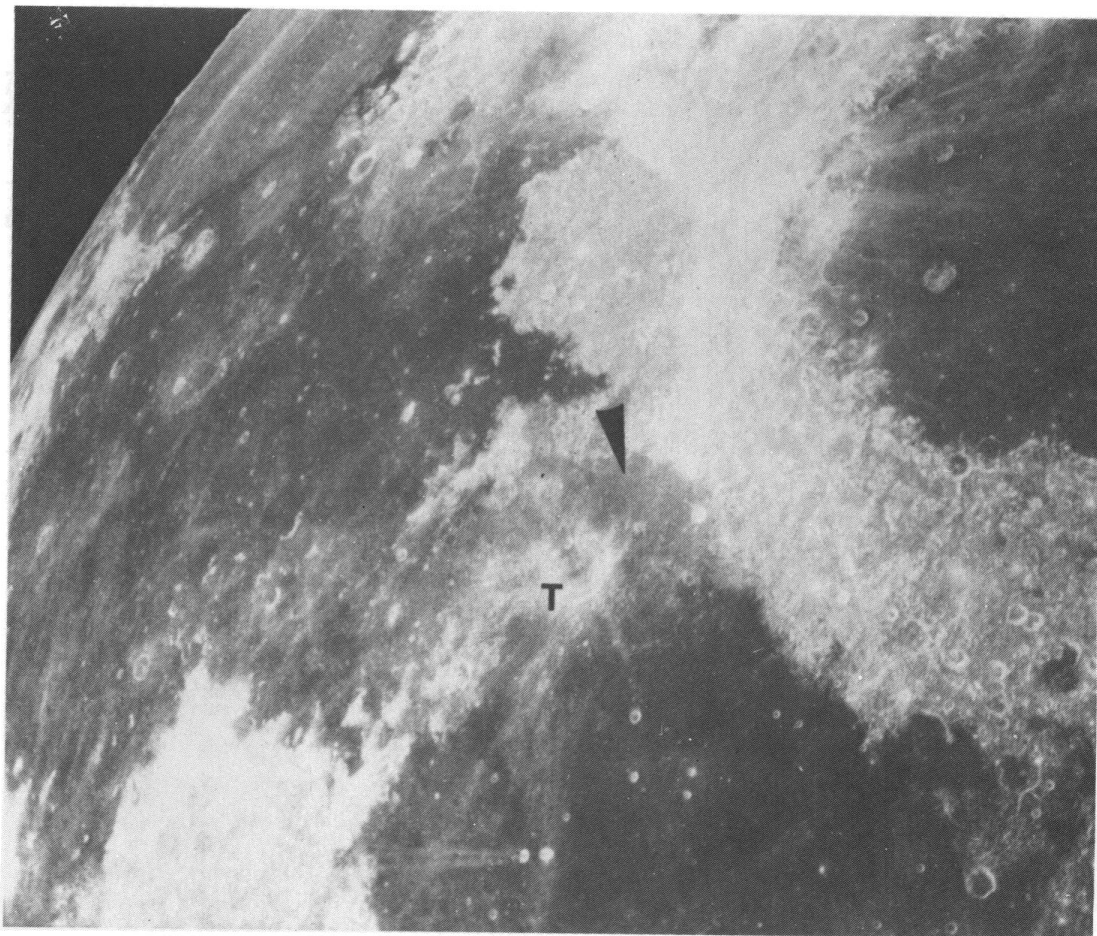


Fig. 5. Regional view of Crisium—Fecunditatis area showing moderate albedo plains (arrow) north of the crater Taruntius (T). (AS 17-152-23329).

Ti abundances (Metzger *et al.*, 1977; Bielefeld *et al.*, 1976; Davis, 1979). Attempts have been made to relate the unusual abundances of certain elements to the presence of specific deposits and rock types (e.g., low-K Fra Mauro basalt, granitic material, mare basalt). A basic question is whether the chemical anomalies are related (1) to material excavated from some depth in the farside crust by the South Pole-Aitken basin or other basins in the vicinity (Schonfeld, 1977; Davis, 1979), (2) to a local episode of extrusive igneous activity, or (3) to exotic material transported from some distant source with Imbrium basin being most often suggested (e.g., Stuart-Alexander, 1978).

Several major objections can be raised to the hypothesis that the geochemical anomalies are related to material transported from the Imbrium basin target site. This hypothesis rests on the interpretation of the grooved terrain (unit Ig, Stuart-Alexander, 1978) as Imbrium basin material concentrated in this region resulting from convergence of Imbrium ejecta at the antipodal point (Moore *et al.*, 1974; Stuart-Alexander, 1978). This interpretation is by no means generally accepted, and Schultz and Gault (1975) have proposed that this terrain was formed as a

result of extensive mass wasting caused by the convergence of Imbrium seismic waves beneath the antipodal point. The observations that the Van de Graaff region exhibits high radioactivity and that the Imbrium event ejected KREEP-rich material enriched in radioactive elements have been used to support the Imbrium ejecta hypothesis. However, recent studies have shown that earlier ideas concerning the amount and extent of KREEP distribution by Imbrium basin were overestimates (Hawke and Head, 1978; Metzger *et al.*, 1979). Finally, as pointed out by Stuart-Alexander (1978), the grooved terrain does not extend under the easternmost 10° of the radioactivity anomaly. This observation makes any direct correlation between the grooved terrain and high radioactivity values highly suspect.

The results of our analysis suggest that the geochemical anomalies in the Van de Graaff region are due to volcanic activity. A major objection to the volcanic hypothesis has been the limited areal extent of mare-like basalt deposits in the region for which the geochemical data were obtained. There are four deposits of

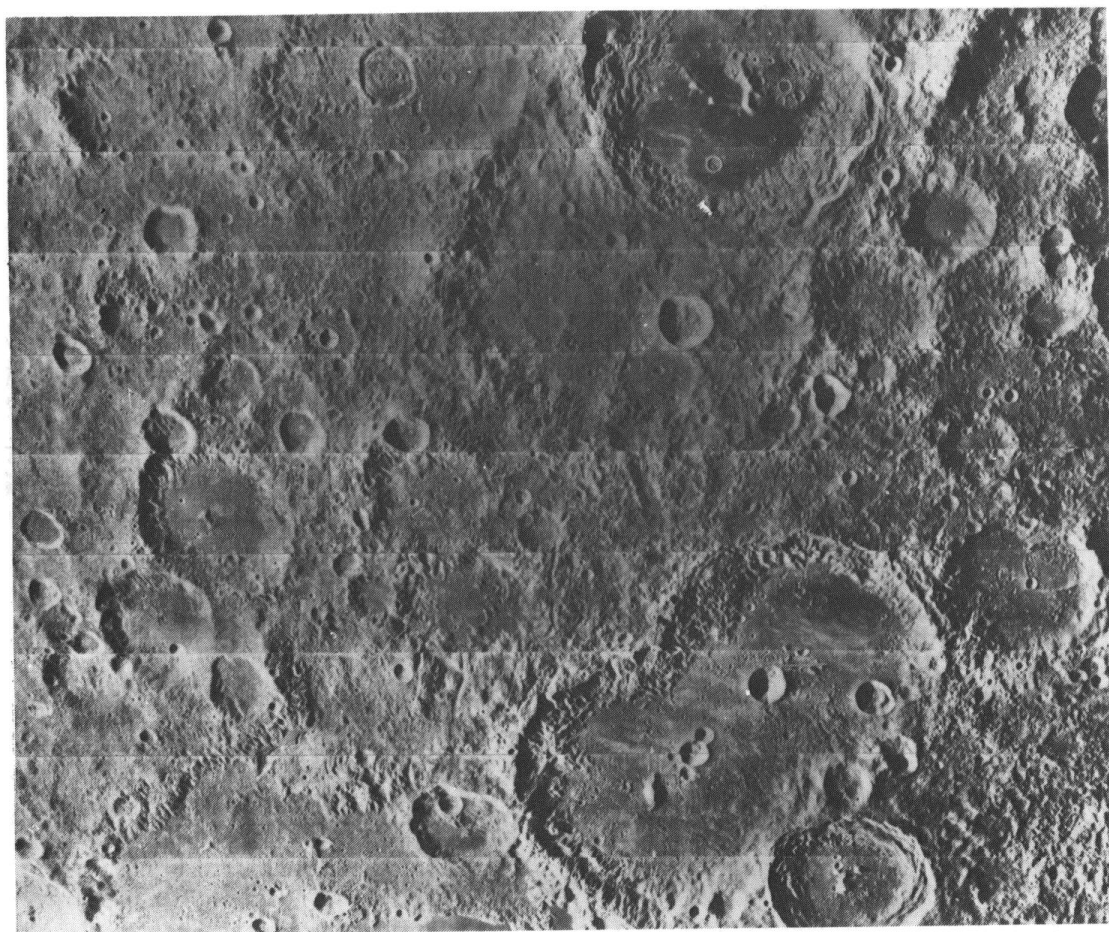


Fig. 6. Area near the crater Van de Graaff (25°S, 170°E), a radioactivity anomaly on the lunar farside. (portion of LO II-33M).

mare basalt directly under the ground track but these make up less than 20 percent of the region (Stuart-Alexander, 1978). A partial explanation for this problem comes from consideration of the response characteristics of the Apollo gamma-ray spectrometer. Because the directional response of the spectrometer was essentially isotropic, the elemental concentrations observed from any given position were a composite of all concentrations within its field of view, which extended from horizon to horizon (Haines *et al.*, 1978; Metzger *et al.*, 1979). Although the instrument responded most efficiently to elements at the nadir and less efficiently the elements at greater distances, the spectrometer did respond to elements off the ground track (see Fig. 2 of Haines *et al.*, 1978). We suggest that at least some of the geochemical anomalies in the Van de Graaff region are due to the influence of major deposits of mare basalt just south of the ground track. For example, the highest Fe values (9%) in the region as determined by Davis (1979) are just north of Mare Ingenii.

Another perhaps more important factor may involve thinly covered basaltic units. As discussed above, the region is antipodal to Imbrium basin and any pre-Imbrian volcanic deposits could easily have been covered by the extensive mass-wasting caused by seismic waves associated with Imbrium (Schultz and Gault, 1979). Dark-haloed craters have been identified in the region and suggest the presence of buried basaltic units (Schultz and Spudis, 1979). At least some of the light plains deposits along the ground track may consist of thinly covered basalts buried either at the time of the Imbrium event or later in the Imbrian period. The presence of major magnetic anomalies in the region which do not correlate with maria (Hood *et al.*, 1978) strongly suggests that igneous activity was not strictly limited to areas where mare basalt is seen on the surface.

In order to further investigate the possibility that the occurrence of basalt is responsible at least in part for the geochemical anomalies in the Van de Graaff region, chemical mixing model calculations were performed on the composition of the total region as determined by the Apollo gamma-ray spectrometer. The latest values for TiO_2 , FeO, MgO, K_2O , and Th concentrations were used (Bielefeld *et al.*, 1976; Metzger *et al.*, 1977; Davis, 1979). A wide variety of lunar rock type compositions was employed in the effort to model the composition of the region. The best fit obtained to date was for a mixture of anorthositic gabbro (61%), low-K Fra Mauro basalt (5%), and a basaltic component (34%), similar in composition to the Apollo 17 KREEPy basalt described by Ryder *et al.* (1977) as being intermediate in composition between mare and KREEP basalts. Attempts to model the regional composition with mixtures of KREEP, mare basalts, granites, and felsites with typical highland components (anorthositic gabbro, etc.) were either unsuccessful or yielded unsatisfactory standard errors.

In summary, the results of these mixing calculations together with the evidence discussed above, suggest that the geochemical anomalies in the Van de Graaff region are related to episodes of extrusive igneous activity. These basalts are unlike the typical mare basalts returned by the Apollo missions but appear similar to the igneous-textured Apollo 17 KREEPy basalts. Most are of Imbrian age but some may have been emplaced in pre-Imbrian time.

CONCLUSIONS AND IMPLICATIONS

We conclude that the east limb and farside geochemical anomalies discussed in this paper are related to episodes of extrusive igneous activity which produced deposits with a variety of ages and compositions. Some of the associated volcanic deposits (e.g., Mare Marginis) exhibit albedos and surface morphologies similar to those of the nearside maria and are post-Imbrian in age. Others are now thinly covered by highland debris and are commonly represented by light plains units which exhibit clusters of dark-haloed craters. These deposits are thought to be the products of an early phase of volcanic activity and were largely emplaced in pre-Imbrian time (Schultz and Spudis, 1979). The volcanic deposits associated with the geochemical anomalies discussed above generally correlate with regional topographic lows, areas of relatively thin crust, and structural features such as basin rings (Spudis, 1979). These associations are consistent with an extrusive igneous origin. Apparently, eastern limb and farside volcanism have been more extensive both in space and in time than has previously been thought.

The compositions of these volcanic deposits have important implications for the petrologic, geochemical, and thermal evolution of the lunar interior. Little evidence was found for a genuine episode of highland volcanism. The geochemical anomalies appear to be related to basaltic deposits with either mare affinities (e.g., terrain north of Taruntius) or that are intermediate in composition between KREEP and mare basalts (e.g., Mare Marginis, Van de Graaff). These basalts of intermediate composition may be similar to the Apollo 17 KREEPy basalts (Ryder *et al.*, 1977), which have been dated as 4.01 b.y. (Compston *et al.*, 1975). If the basalts in Mare Marginis are chemically similar to these Apollo 17 KREEPy basalts, it is significant that the Marginis deposits were emplaced at much later time (age <3.65 b.y.), (Boyce and Johnson, 1978; Boyce, 1979). In addition, the age data presented by Boyce and Johnson (1978) indicate that the mare units within Marginis were emplaced over an interval of 1.15 b.y. (3.65 b.y. to 2.5 b.y.). This evidence argues against the hypothesis that an early (~4.0 b.y.) moonwide episode of volcanism produced all deposits intermediate in composition between KREEP and mare basalt. The existence of such intermediate basalts on the eastern limb and farside supports previous suggestions that KREEP-like volcanism was not limited to a small area of the lunar nearside (Haines *et al.*, 1978; Spudis, 1979).

Finally, the results of this study strongly suggest that thinly buried volcanic deposits are the source of certain geochemical anomalies on the eastern limb and farside and apparently can exert a strong influence on regional surface chemistry. Caution should be exercised in interpreting the surface compositions of what appear to be highland terrains which exhibit a high concentration of dark-haloed impact craters (see Fig. 6 of Schultz and Spudis, 1979). Inclusion of such terrains in attempts to establish average global and regional highlands compositions could lead to serious errors.

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