# THE ORIGIN OF SELECTED LUNAR GEOCHEMICAL ANOMALIES: IMPLICATIONS FOR EARLY VOLCANISM AND THE FORMATION OF LIGHT PLAINS

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**Abstract.** The Apollo orbital geochemistry, photogeologic, and other remote sensing data sets were used to identify and characterize geochemical anomalies on the eastern limb and farside of the Moon and to investigate the processes responsible for their formation. The anomalies are located in the following regions: (1) Balmer basin, (2) terrain northeast of Mare Smythii, (3) near Langemak crater, (4) Pasteur crater, (5) terrain northwest of Milne basin, (6) northeast of Mendeleev basin, (7) north and northeast of Korolev basin, (8) terrain north of Taruntius crater, and (9) terrain north of Orientale basin. The anomalies are commonly associated with Imbrian- or Nectarian-aged light plains units which exhibit dark-haloed impact craters. The results of recent spectral reflectance studies of dark-haloed impact craters plus consideration of the surface chemistry of the anomalies strongly indicate that those geochemical anomalies associated with light plains deposits which display dark-haloed impact craters result from the presence of basaltic units that are either covered by varying thickness of highland debris or have a surface contaminated with significant amounts of highlands material. The burial or contamination of ancient volcanic surfaces by varying amounts of highland material appears to have been an important (though not the dominant) process in the formation of lunar light plains. Basaltic volcanism on the eastern limb and farside of the Moon was more extensive in both space and time than has been accepted.

## 1. Introduction

The lunar orbital geochemistry data sets 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 expected from the examination of local geological relationships (see Hawke and Spudis, 1980). Investigations into the formation of these geochemical anomalies can provide important clues to understanding the impact and volcanic processes operative during the early phases of lunar evolution as well as the lateral and vertical composition of the highland crust. Such studies have been of critical importance in outlining the history of early volcanic activity in various regions of the Moon (e.g., Haines *et al.*, 1978; Spudis, 1978; Hawke and Head, 1978; Metzger *et al.*, 1979; Hawke *et al.*, 1979; Hawke and Spudis, 1980; Clark and Hawke, 1981, 1984).

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Hawke and Spudis (1980) presented evidence that a number of east limb and farside geochemical 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 have 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 impact craters (Schultz and Spudis, 1979, 1983). More recent work (Hawke and Bell, 1981a, b, 1983; Bell and Hawke, 1984) has provided strong support to the hypothesis that dark-haloed impact craters are formed by the excavation of ancient (> 3.8 Ga), buried basaltic material from beneath light plains deposits. Numerous workers (e.g., Schultz and Spudis, 1979, 1983; Ryder and Spudis, 1980; Hawke and Spudis, 1980; Hawke and Bell, 1981a, b, 1983; Bell and Hawke, 1984) have suggested that the onset of basaltic volcanism may have well pre-dated the last major basin-forming impacts, that early farside volcanism may have been widespread, and that some lunar 'light plains' are early volcanic deposits which were subsequently buried by varying thicknesses of impact ejecta rich in highlands debris. Interest in the possibility of ancient mare volcanism (> 3.8 Ga) has greatly increased in recent months due to the discovery of mare-like basalt fragments in an Apollo 14 breccia (14305), one of which has been conclusively dated at 4.23 ± 0.05 Ga (Taylor *et al.*, 1983; Shervais *et al.*, 1983). Taylor *et al.* (1983) suggested that mare-type volcanism commenced at least as early as 4.2 Ga in the Fra Mauro region and probably across much of the lunar surface.

The purposes of the present study include the following: (1) to locate and determine the extent of geochemical anomalies in selected lunar regions, (2) determine the compositions of anomalous regions, (3) to correlate the anomalies with specific geologic units or surface features, and (4) to determine the origin of the anomalies and associated surface features.

## 2. Method

Digital versions of the various orbital chemistry data sets were obtained and utilized in this study. The newly revised Al/Si and Mg/Si data derived using the technique described by Clark and Hawke (1981) were utilized. The digital iron and titanium data used were those presented by Davis (1980). The thorium abundances are those presented by Metzger *et al.* (1977). In addition, images showing Fe and Ti abundances as determined by Metzger and coworkers (Metzger and Parker, 1979; Haines and Metzger, 1980) were provided by Dr A. E. Metzger.

## 3. Selected Geochemical Anomalies

### 3.1. Balmer Basin Region

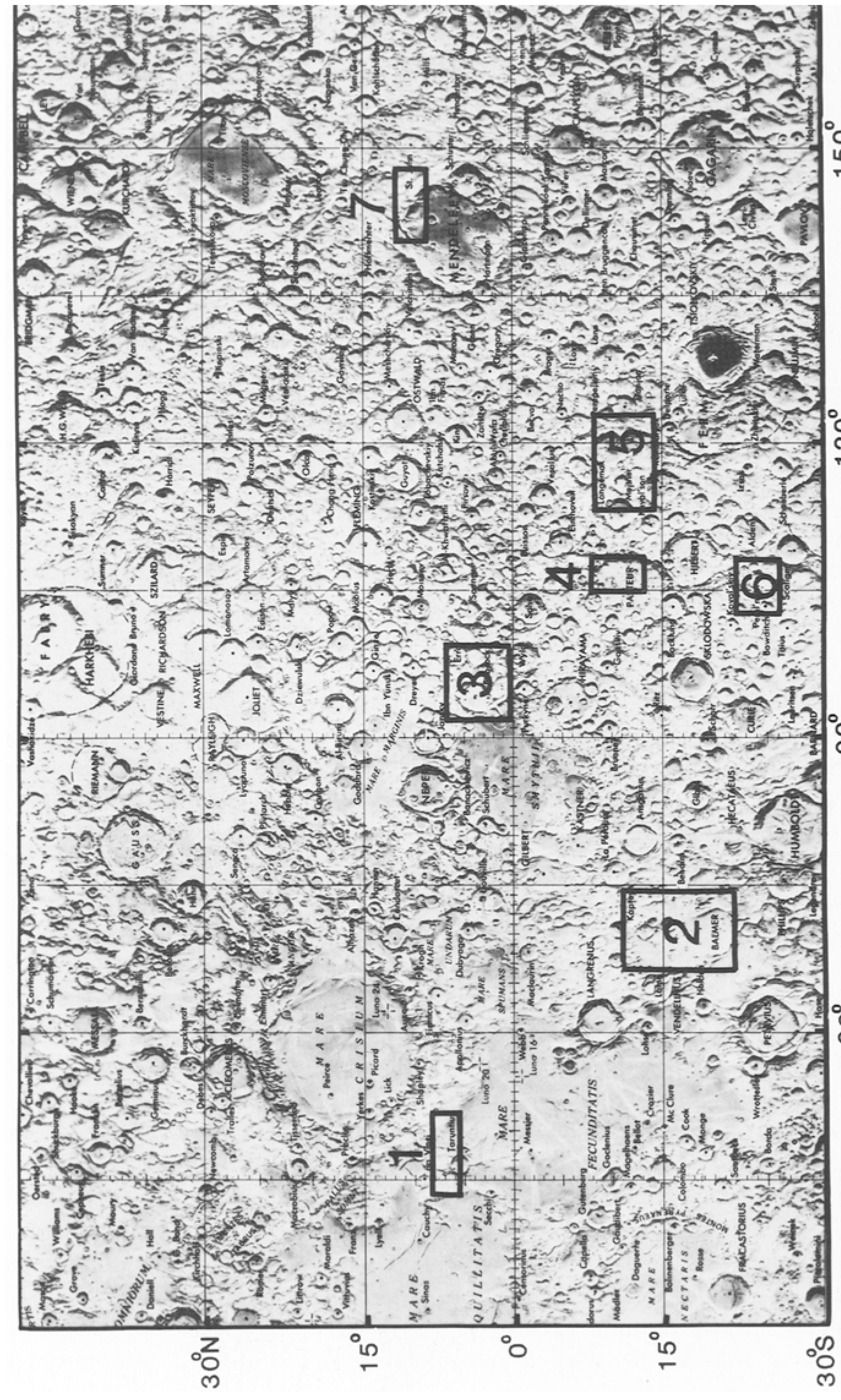
Possibly the best established and most intensively studied geochemical anomaly on the eastern limb is located near Balmer crater. Haines *et al.* (1978) first reported an anomaly in this region. They identified an area with anomalously high Th concentrations (~ 4.0 ppm) just north of Balmer crater (68° E, 15° S; Figures 1, 2, and 3) which correlated with Imbrian plains deposits. Andre *et al.* (1979a) noted that these Imbrian plains have higher Mg/Si intensity values than surrounding units, thus indicating a more mafic composition. Hawke *et al.* (1979) and Hawke and Spudis (1980) pointed out that at least the northern portion of this plains unit exhibits relatively high FeO and $TiO_2$ values ($TiO_2$ = 2.3–3.0%; FeO = 7.2–12.4%). Maxwell and Andre (1981) and Andre and Strain (1982) summarized existing orbital geochemical data for the region and presented Al/Si, Mg/Si and Mg/Al data. The Imbrian plains unit (Ip, Wilhelms and El-Baz, 1977) exhibits Mg/Al concentration ratios greater than 0.58 near the crater Kapteyn C. The older Imbrian- or Nectarian-age plains (INp) unit east of Kapteyn crater is characterized by Mg/Al concentration ratios greater than 0.51. These values are only slightly less than those determined for mare basalts on the lunar nearside (Maxwell and Andre, 1981).

Maxwell and Andre (1981) also noted that the geochemically anomalous light plains deposits were in an ancient multi-ringed impact basin of probable pre-Nectarian age. The inner ring is 225 km in diameter and the outer ring is approximately 450 km in diameter. The Balmer basin is the site of a positive gravity anomaly first noted by Haines *et al.* (1978). This anomaly is centered at 70° E and 10° S and reaches peak values of greater than 40 milligals (Maxwell and Andre, 1981; Frontispiece, Proc. Lunar Sci. Conf. 8th). It can be accounted for by the existence of a large amount of basalt within Balmer basin.

Considerable controversy has arisen concerning the nature and origin of the Balmer light plains units. Wilhelms and El-Baz (1977) generally favored an impact origin for the Ip and INp units on the eastern limb but did not rule out a volcanic origin. Haines *et al.* (1978) proposed that the most likely process for the formation of the Th-rich Imbrian plains unit was highlands volcanism. Schultz and Spudis (1979) and Hawke and Spudis (1980) presented arguments based on the orbital geochemistry data and the distribution of dark-haloed craters that the region was the site of ancient basaltic volcanism and that the resulting deposits were later covered by a *thin* higher albedo surface layer enriched in highland debris contributed by surrounding large craters. This interpretation was challenged by Maxwell and Andre (1981) who claimed that previously identified dark-haloed craters do not exhibit dark haloes in high-sun angle photographs. They proposed that the light plains were composed of mare basalt and exhibited an abnormally high albedo either because of gardening by recent secondaries or because of the composition of the basalt.

Because it is extremely important to establish the origin of the Balmer anomaly and associated plains units, we have reevaluated the available remote sensing and photographic data for this region. The latest generation Al/Si and Mg/Si data sets (Clark and Hawke, 1981) were used to produce images for the region which included the northern portion of Balmer basin. An analysis of these images fully confirms the conclusions of Maxwell and Andre (1981) concerning the mafic composition of the plains units within Balmer basin (Clark and Hawke, 1984).

Figure 3 is a south-looking oblique Apollo metric photograph of the southern portion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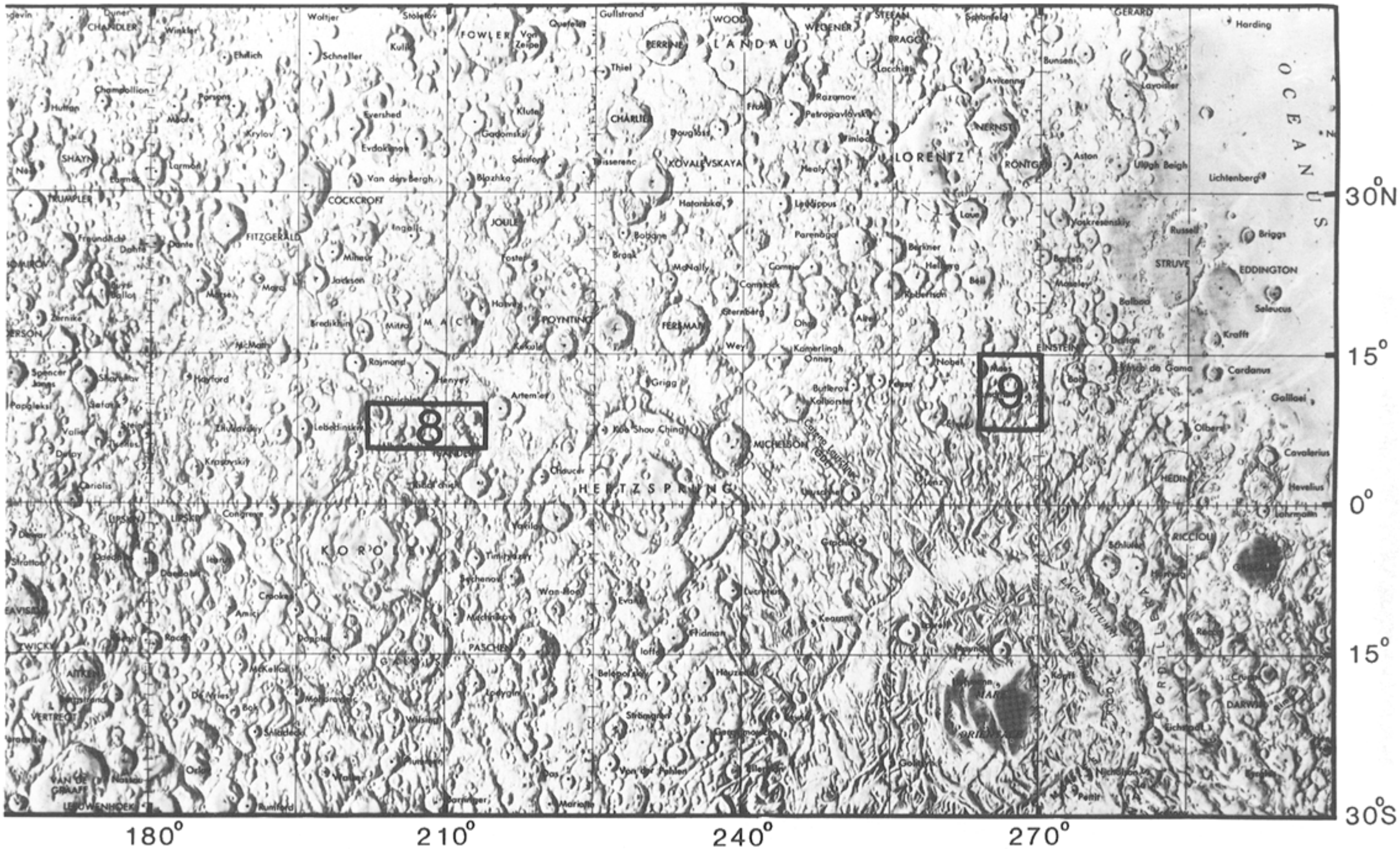


Fig. 1a and b. Maps show the general locations of the anomalous regions discussed in the text. (1) Terrain north of Taruntius crater, (2) Balmer basin region, (3) Terrain northeast of Mare Smythii, (4) The Pasteur crater region, (5) Region near Langemak crater, (6) Region northwest of Milne basin, (7) Northeastern Mendeleev region, (8) Terrain north and northeast of Korolev basin, and (9) Terrain north of Orientale basin.

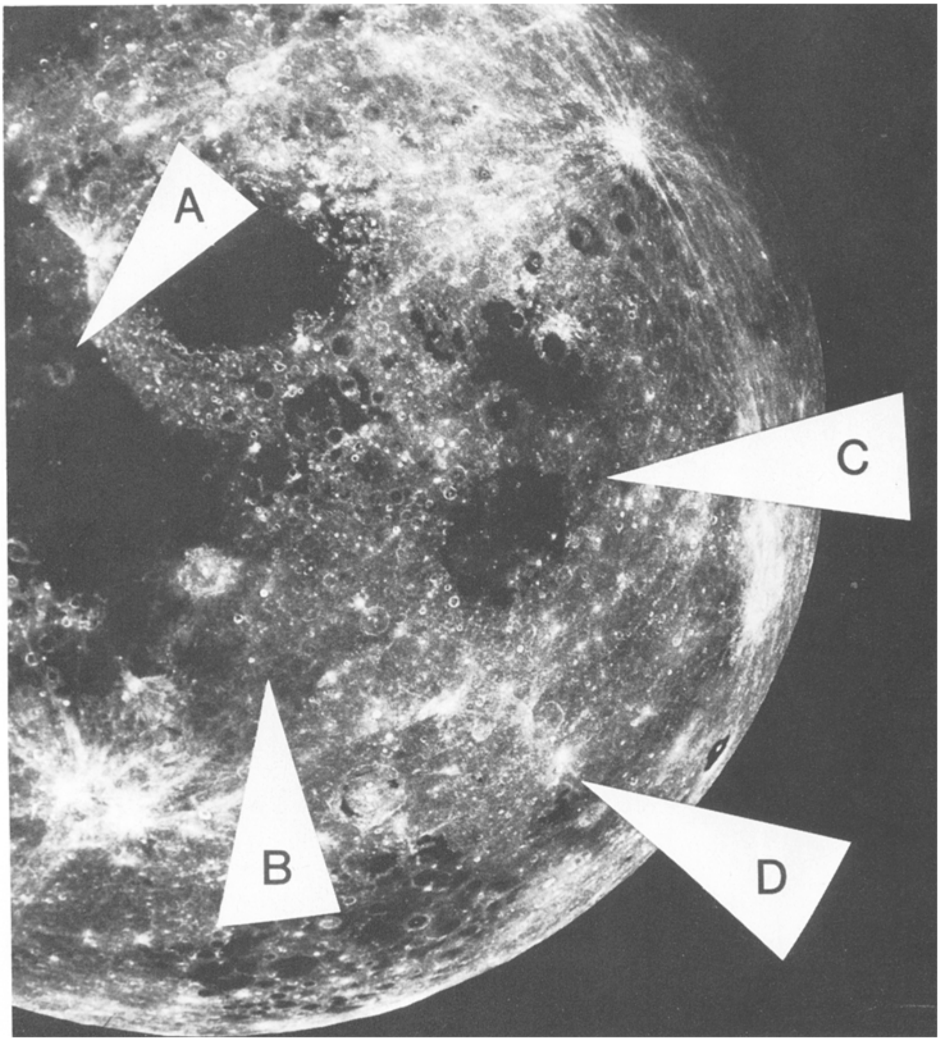


Fig. 2. Apollo 13 photograph (AS 13-8898) of the eastern limb showing the locations of four geochemical anomalies. (A) Terrain north of Taruntius crater, (B) Balmer basin region, (C) Terrain northeast of Mare Smythii, and (D) Region northwest of Milne basin.

of Balmer basin. Arrow A indicates a dark-haloed impact crater (64° E, 20° S) located within the continuous ejecta deposit of Petavius crater which is superposed on the INp plains unit. A high resolution near-infrared reflectance spectrum was obtained for this crater by Bell and Hawke (1984) and an analysis indicated that this crater excavated material with spectral characteristics very similar to those of nearside mare deposits. Therefore it seems likely that the surface of the INp plains unit is underlain by mare-like basalt.

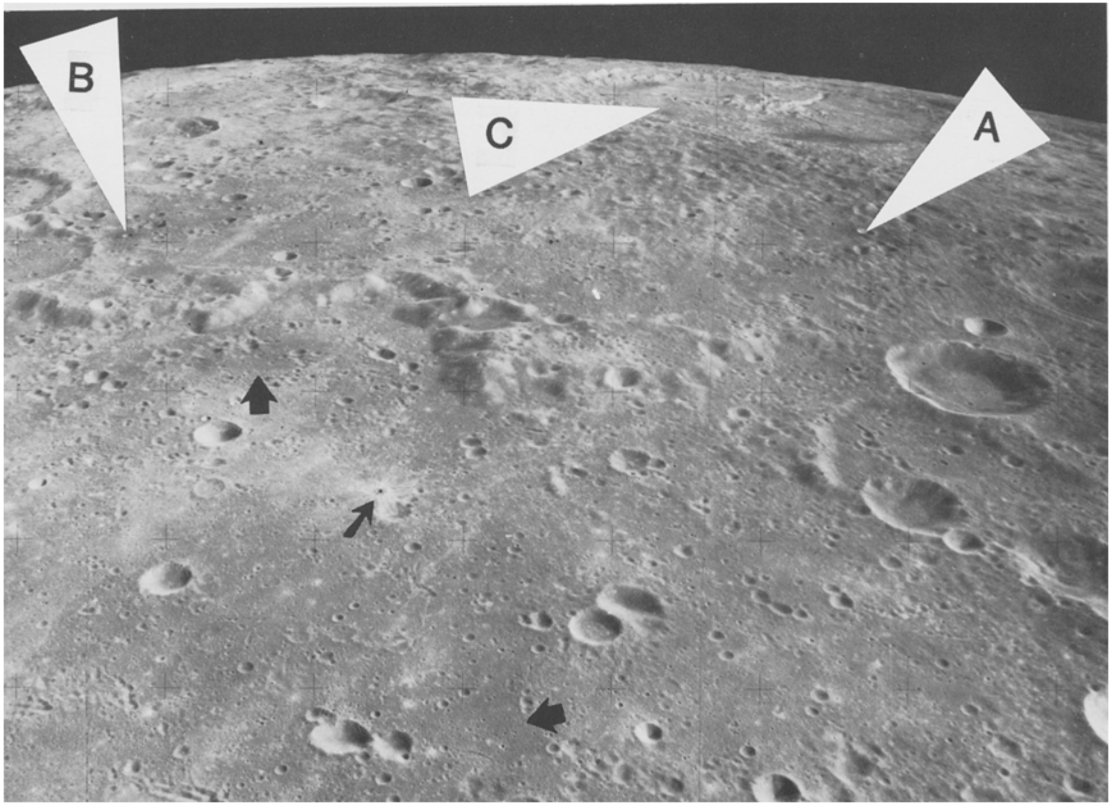


Fig. 3. South-looking oblique Apollo metric photograph (portion of AS 15-2522) of the light plains within the Balmer basin. Arrow A indicates a dark-haloed impact crater (DHC) on the ejecta blanket of Petavius (Diameter ~ 180 km) which is on the top right horizon (arrow C). Spectral studies have shown that this DHC has excavated mare basalt from beneath Petavius ejecta deposits. Arrow B points out a DHC in plains deposits immediately west of Phillips B. The more degraded crater to the SW of this structure also exhibits a dark halo. Both structures display dark-haloes in photographs taken at a wide variety of phase angles and viewing geometries. The rayed crater (thin black arrow) exhibits a dark inner halo that may represent excavated sub-plains basalt. Balmer plains also display low albedo mottling (thick black arrows) that may represent mixing of highlands debris with basaltic substrate.

Arrow B points out a dark-haloed impact crater in the plains deposits west of Phillips B. The more degraded crater immediately to the southwest of this structure also exhibits a dark halo. Both craters display dark-haloes in photographs taken at a variety of phase angles and viewing geometries. It is probable that these craters also excavate mare material from beneath the surface of the INp plains Unit. The bright rayed crater (thin black arrow) is located on the Ip units and exhibits a inner dark halo. This dark inner halo cannot be clearly identified in low-resolution, high-sun photography, perhaps because of the small size of the dark halo compared to the surrounding bright ejecta. The dark halo may be due to the presence of sub-plains basalt, or, alternatively, a thin veneer of low-albedo impact melt (see Bell and Hawke, 1984). Other less distinct, dark-haloed craters can be identified in the region. Note that while fresh secondary craters and crater rays are present in the region, they are not sufficiently abundant to account for the albedo of the region.

It is important to note that the Balmer plains are surrounded (within 250 km) by five major impact structures (Langrenus, Petavius, Humboldt, Ansgarius, and La Perouse) which range from Copernican to early Imbrian in age. In fact, portions of the Balmer plains are within one crater diameter of the rim crests of La Perouse, Ansgarius, Petavius, and Humboldt craters. Calculations based on ejecta distribution equations presented by McGetchin *et al.* (1973) as well as the presence of secondary crater chains and clusters and rays, indicate that these impacts contributed significant amounts of highland material to the Balmer plains units. The net result of these nearby impacts would have been the production of a thin surface layer enriched with variable amounts of highland material. Such a surface would exhibit a higher albedo than an uncontaminated regolith developed on mare basalt (see Hartmann and Wood, 1971) and would appear to be a 'light plains' to earth-based observers. Dark-haloed impact craters could be developed on such a surface by the excavation, emplacement, and maturation of pure mare basalt. It should be emphasized that the above situation contrasts with that in the Schiller-Schickard region where mare basalt has been excavated from beneath the major thicknesses (100's of meters) of highland material emplaced as a result of the Orientale impact event (Hawke and Bell, 1981a, b, 1983; Bell and Hawke, 1984).

While it can be demonstrated that the Balmer plains have been contaminated by highlands ejecta from the surrounding craters, it is not clear that this contamination is solely responsible for the high albedo of the Balmer plains units. We do point out that the orbital geochemistry data is consistent with a mare-like basalt contaminated with minor amounts of highlands debris. As noted by Maxwell and Andre (1981), secondaries and rays from Langrenus and other smaller Copernican craters have raised the original albedo of the plains. Since the inter-ray surface of the Balmer plains also exhibits a relatively high albedo, Maxwell and Andre (1981) proposed, as an alternative explanation that the plains may represent a high albedo mare basalt composition. The deconvolved thorium value (4.0 ppm) for the Ip unit is considerably in excess of those of typical Apollo mare samples. The high Th content of the Balmer plains suggests the presence of material intermediate in composition between mare and KREEP basalts, perhaps similar to Apollo 17 $KREEP_y$ basalt (Ryder *et al.* 1977).

In summary, the following points should be emphasized: (1) mare-like basalts exist beneath the surface of the light plains deposits in at least some portions of the Balmer basin, (2) while the presence of secondaries and rays certainly acted to raise the original albedo of the plains, the distribution of *fresh* secondary craters and rays in the region is inadequate to account for the relatively high albedo of the plains units, (3) as noted by Maxwell and Andre (1981), the relatively high albedo of the inter-ray surfaces of the Balmer plains suggests that other processes are operative, (4) the surrounding highlands craters contributed variable amounts of ejecta to the plains surfaces, and (5) the relatively high Th values reported for the Ip unit suggest that the volcanic material is not identical to typical nearside mare basalt deposits.

Perhaps mare-like basalts rich in Th were extruded in this region in early Imbrian or late Nectarian time. These volcanic surfaces, which may have originally exhibited a slightly higher albedo than *typical* mare basalts, were later contaminated with varying amounts of highlands ejecta. Still later, fresh secondary craters and rays helped in a minor way to raise the albedo of the original basaltic surfaces to that which is observed today.

### 3.2. TERRAIN NORTHEAST OF MARE SMYTHII

A number of new geochemical anomalies have been identified in the highlands immediately northeast of Mare Smythii (Figures 1 and 2). Haines *et al.* (1978) had previously identified a thorium anomaly in this region. They noted that the persistence of high Th data values as far east as 5° N, 95° E called for the inclusion of Babcock crater in a region for which deconvolution models indicated an enhanced thorium concentration (3.4 ppm). Elsewhere, the highlands east of Smythii have relatively low Th values (~ 0.5 ppm). The anomalous region has enhanced iron and titanium values in both the Davis and the Metzger versions of the orbital gamma-ray data sets. The Ti image produced by Metzger and Parker (1979) shows high $TiO_2$ values (4.0–5.0%) in a highland region along the Apollo 16 groundtrack between 92° E and 96° E. A similar range of high $TiO_2$ values (4.0–5.8%) can be seen in this region in the Ti data set presented by Davis (1980); although the eastern boundary extends to approximately 102° E. Relatively high FeO abundances (7.2–9.5%) are exhibited by the highlands units along the Apollo 16 groundtrack between 92° E and 95° E.

Anomalies can also be identified in the orbital X-ray data for this region. Schultz and Spudis (1979) and Andre *et al.* (1979b) have previously noted that the region northeast of Smythii in the plains-filled crater Babcock have high Mg/Si intensity ratios, corresponding to approximately 8% MgO. The new Al/Si intensity ratio data show that an area of relatively low Al/Si values (0.70–0.99) extends along the Apollo 16 groundtrack between 92° E and 98° E. Considerably higher Al/Si values predominate in other highland regions east and southeast of Smythii and indicate the presence of abundant anorthositic material.

This geochemically anomalous region closely corresponds to a geologic province (i.e., an area characterized by concentrations of a geologic unit or of units related in age and origin) which contains abundant relatively young light plains deposits (Wilhelms and

El-Baz, 1977). The province is dominated by Imbrian plains (Ip), middle Imbrian to late Nectarian plains (INp), and Imbrian-age terra mantling material (It) (Wilhelms and El-Baz, 1977). It is significant that a highlands region with a chemical composition unlike surrounding highlands can be correlated with a geologic province characterized by light plains and terra mantling material. It is also significant that Schultz and Spudis (1979) as well as Young *et al.* (1972) identified numerous dark-haloed craters in this region. There is clearly an association of geochemical anomalies with a region dominated by light plains deposits which exhibit a concentration of dark-haloed impact craters.

The present surface composition of this anomalous region is intermediate between that of mare basalts and typical lunar highland material. The region probably experienced an episode of volcanism early ($> 3.8$ Ga) in lunar history which produced deposits with both mare and KREEP affinities. The surfaces of these basaltic deposits were subsequently contaminated by highlands material contributed by a number of later impact events. As discussed previously, the addition of highlands material would alter the surface composition and raise the low albedos of the volcanic surfaces. Examination of a variety of Apollo lunar photography (see Figure 2) revealed that the plains units in the anomalous region (and those between the region and the eastern end of Mare Marginis) are darker than the surrounding highlands units. Subsequent small impact events would excavate and deposit basaltic material from beneath the highland material enriched surface layer.

### 3.3. Region near Langemak Crater

Hubbard *et al.* (1978) first pointed out the rather striking variations in Mg/Si and Al/Si intensity ratios which occur near Langemak (Figure 1). Schultz and Spudis (1979) correlated the highest Mg/Si intensity ratios with two dark-haloed impact craters and suggested that the region was the site of an early episode of basaltic volcanism. Relatively high FeO and $TiO_2$ values occur in the same region (Hawke and Spudis, 1980). The abundance of titanium is quite striking, with $TiO_2$ contents ranging between 4.0% and 5.8% along the northern edge of the Apollo 15 ground track between 114° E and 124° E. The high titanium area correlates with an area with relatively enhanced FeO values (7.2–9.5%). No thorium or radioactivity anomaly has been identified in the region.

Examination of the recently revised Al/Si maps (Clark and Hawke, 1981) showed that the lowest Al/Si intensities (0.70–0.99) are also centered on the two dark-haloed impact craters described by Schultz and Spudis (1979). Only slightly higher values are associated with the relatively dark Langemak ejecta blanket and Nectarian plains. Another small Al/Si intensity anomaly (0.70–0.99) is located in the southern part of the Langemak region (15°–16° S, 113°–115° E) and correlates with a small, previously unmapped deposit of light plains material. These latest results support the conclusions of earlier studies (Schultz and Spudis, 1979, 1983; Hawke and Spudis, 1980; Ryder and Spudis, 1980) regarding the importance of early volcanism in this region.

It is important to note that Spudis and Davis (1982) identified a mafic anomaly ($Al_2O_3 < 19.6\%$, $MgO > 8.3\%$) along the Apollo 16 ground track north of the Langemak region. This small mafic region is centered near Firsov crater (4° N, 115° E) and lies well within the Al-Khwarizmi-King basin. They suggested that pre-Nectarian basaltic fill had been gardened into the local megaregolith and pointed out that this concept was supported by anomalously high regional titanium values (Davis, 1980) in the terra within this ancient basin.

### 3.4. THE PASTEUR CRATER REGION

Geochemical anomalies exist in the vicinity of Pasteur crater (Figure 1). Al/Si intensity ratios in portions of the Nectarian plains in the northern floor of Pasteur (10°–12° S, 105°–108° E) range from 0.8 to 1.0. Similar, relatively low Al/Si values occur in the floor of Backlund crater on the south rim of Pasteur and correlate with a light plains unit (INp, Wilhelms and El-Baz, 1977). These anomalies also appear in the Al/Si data presented by Bielefeld *et al.* (1977). No titanium or thorium anomalies were identified but relatively high (up to 9.5%) FeO values occur on the northeast rim of Pasteur and extend into the northeastern portion of the crater floor. Relatively low Al/Si values were also found to be correlated with light plains units northwest of Pasteur (~ 9° S, 98° E). To date, no dark-haloed impact craters have been identified in the Pasteur region. No Bouguer gravity anomaly is associated with the pre-Nectarian crater Pasteur (Dvorak and Phillips, 1978). The absence of a Bouguer gravity anomaly may be due to the presence of a now covered extrusive unit in the crater interior, or of an intrusive body beneath the crater floor.

### 3.5. REGION NORTHWEST OF MILNE BASIN

An area of anomalously high $TiO_2$ values (3.0%–4.0%) occurs northwest of Milne basin (22°–26° S, 102°–109° E, Figures 1 and 2). The high values are seen in the titanium data sets of both Davis (1980) and Metzger. FeO values in the high $TiO_2$ area are variable but increase systematically from the northeast to the southwest. No thorium anomaly has been identified and X-ray data do not exist for this area. The region contains a variety of highland units including furrowed and pitted material, terra mantling material, and Scaliger crater ejecta, as well as a very small amount of mare material in the northernmost extension of Lacus Solitudinis (Wilhelms and El-Baz, 1977). At least four dark-haloed impact craters have been identified around Lacus Solitudinis and their presence suggests that mare volcanism was more widespread in this region than has been recognized. The titanium anomaly may be due in part to the small amount of mare material in the region and to detector response to the larger expanse of mare material to the south in Lacus Solitudinis. Still, the extent and magnitude of the anomaly suggests that the above factors alone cannot account for the feature. The presence of early mare basalts, thinly covered by and mixed with highland material (e.g., Scaliger crater ejecta) may also be partly responsible for the anomaly.

### 3.6. EASTERN MENDELEEV REGION

Relatively high FeO abundances (7.2–9.5%) occur on the northeast rim (Figure 1) of Mendeleev basin. Slightly lower values (5.7–7.2%) occur in the eastern portion of the floor of Mendeleev and extend to the east of the basin. An area of high $TiO_2$ values (5.3–6.8%) can be seen on the northeastern floor and rim of Mendeleev on Metzger's titanium distribution map but not in the data presented by Davis (1980). No thorium or radioactivity anomaly is located in this region and no X-ray data exists. The iron anomaly is centered on a concentration of Imbrian light plains (Stuart-Alexander, 1978). No dark-haloed craters have been identified in the region. It seems unlikely that the high gamma-ray values are caused by detector response of mare material north of the ground track because the nearest significant expanse of basalt occurs over 400 km to the north in the interior of Moscoviense basin.

### 3.7. Terrain North and Northeast of Korolev Basin

This region (6°–10° N, 202°–214° E, Figures 1 and 4) is characterized by relatively high FeO (7.2–9.5%) and low $TiO_2$ ($<$ 0.5%) abundances. No thorium anomaly has been identified in the region and no X-ray data exist. The region contains a variety of highland units including Imbrian light plains (Stuart-Alexander, 1978). While light plains are abundant in the anomalous region, they are equally abundant in adjacent areas outside the anomaly. No dark-haloed impact craters have been located in the vicinity; however, no high-resolution, low-phase angle photography exists for the area.

### 3.8. Terrain North of Taruntius Crater

An expanse of low-lying terrain north and northeast of Taruntius crater (Figure 1 and 2) has been mapped as light plains (Ip) and smooth terra material (Its) of Imbrian age by Wilhelms (1972). However, a wide variety of remote sensing data indicate that this terrain does not have a typical highland surface composition (Hawke and Spudis, 1980). The normal albedo data of Pohn and Wildey (1970) show that Ip and Its units in this region exhibit albedo values largely between 0.096 and 0.108. This range is not typical of the circum-Crisium highlands but is only slightly above that which characterizes most of Mare Fecunditatis and Mare Crisium. In the 0.61–0.37 $\mu$m color difference photographs (E. A. Whitaker, pers. comm., 1976), the Imbrian plains and smooth terra material are less 'red' than the adjacent highlands to the north, which suggests a compositional difference. Bielefeld *et al.* (1978) defined a number of compositional units in the Crisium-Northern Fecunditatis region on the basis of natural clusters of Al/Si ratios, Mg/Al ratios, and albedo values. The terrain north of Taruntius is included in a compositional unit which has cluster centroid values 0.48 and 0.50, respectively for the Al/Si and Mg/Al concentration ratios. Elsewhere in the Crisium region the same unit generally corresponds to maria surfaces (i.e., Mare Undarum, Mare Spumans, and the mare-flooded floor of Firmicus crater) or to a narrow mare-dominated mixed unit near mare-highland boundaries (Bielefeld *et al.*, 1978; Hawke and Spudis, 1980). The unit also exhibits enhanced $TiO_2$ and FeO values. Therefore, material with mare affinities might be expected to be present in the deposits north of Taruntius. Chemical mixing model calculations (Hawke and Spudis, 1980) have shown that the terrain south of Taruntius can be modeled as a

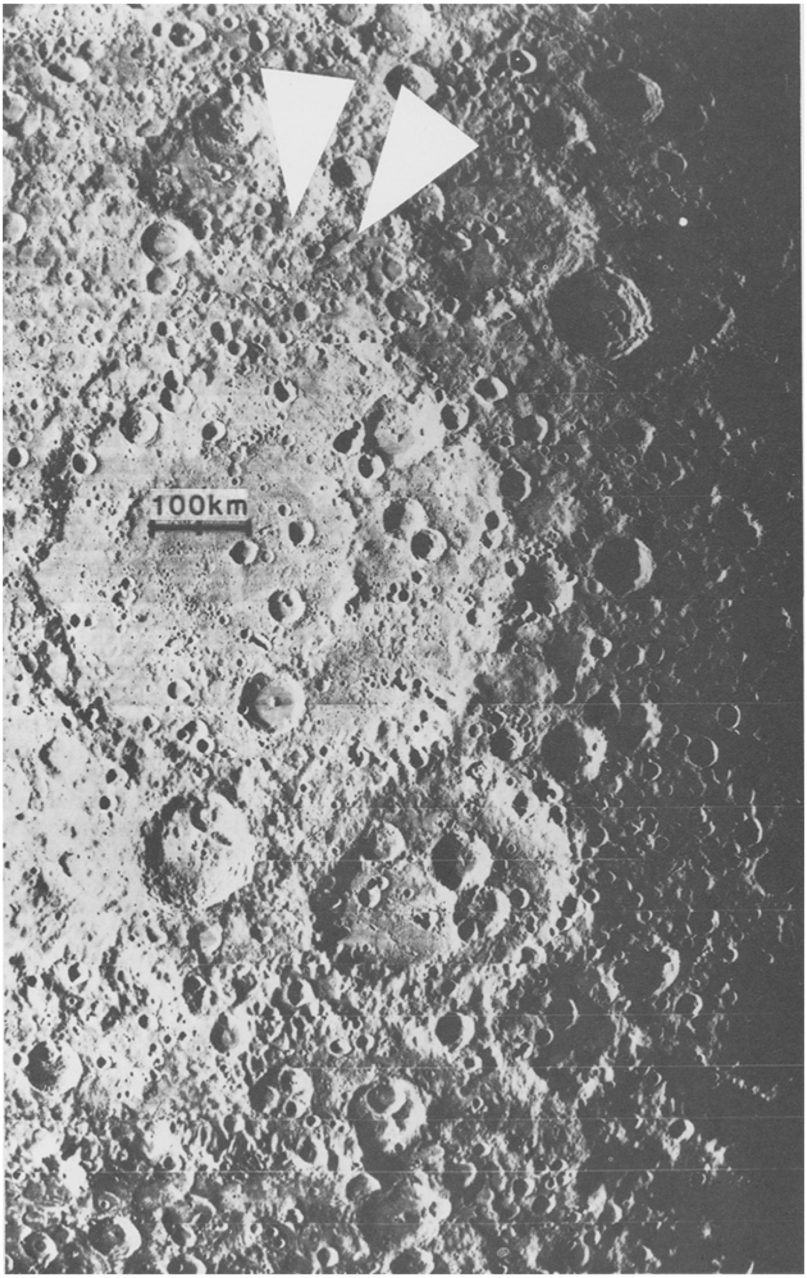


Fig. 4. Lunar orbiter photograph (I-40-M) of the Korolev basin region. The arrows indicate light plains deposits in the area which exhibits relatively high Fe values. North is to the top of the photograph.

mixture of 46% local highlands material (Unit B of Bielefeld *et al.*, 1978) and 54% local mare material (Unit H of Bielefeld *et al.*, 1978).

The morphology of the Ip and Its units is consistent with a volcanic origin. The deposits exhibit smooth, generally flat surfaces, embay more rugged highland terrain, and exhibit what appears to be a mare-type ridge (8° N, 48.5° E). While no dark-haloed impact craters appear in these units, at least one can be identified near the rim crest of Taruntius, where dark material appears to have been excavated from beneath the Taruntius ejecta deposits.

The available remote sensing and photogeologic evidence strongly suggests that the plains and smooth terra north of Taruntius are volcanic units emplaced as fluid flows. Since the present surface composition is intermediate between mare basalts and highlands materials, the units are either early deposits of mare basalt which have been contaminated by highland material or, if highlands contamination has been minimal, deposits with a less mare-like initial composition. Several factors favor the former interpretation. These include the following: (1) Taruntius crater could have contributed significant amounts of highland material to the nearby surfaces, (2) Schonfeld (1981) demonstrated through the use of high spatial resolution Mg/Al maps that certain Ip and Its deposits north of the area under study exhibit Mg/Al ratios similar to those found in mare regions and some of these anomalous deposits exhibit small dark-haloed impact craters (Schultz and Spudis, 1979), and (3) the existence of a dark-haloed impact crater on the rim of Taruntius.

### 3.9. Terrain North of Orientale Basin

One of the most puzzling geochemical anomalies is located north of the Orientale basin (Figure 1). Both versions of the orbital titanium data show an area of enhanced values ($TiO_2$ = 2.3–3.0%) centered at 12° N, 267° E. Strangely, the same area exhibits anomalously low FeO concentrations (Fe% $\leqslant$ 1.9%). No thorium anomaly has been identified and no X-ray data exist for this region.

The Ti-rich region is located in terrain mapped as both the inner and outer facies of the Hevelius Formation (Scott *et al.*, 1977), which was thought to be a unit emplaced by the Orientale impact event. No mare basalt deposits are located in the anomalous region, although two small ponds were mapped northwest of the anomaly (Scott *et al.*, 1977). Schultz and Spudis (1979) identified at least one dark-haloed impact crater within the anomalous region. Perhaps this area experienced an episode of pre-Orientale basaltic volcanism as did the Schiller-Schickard region (Hawke and Bell, 1981a, b, 1983; Bell and Hawke, 1984). These basalt units could have been obscured by material emplaced as a result of the Orientale event. The relatively high Ti values could then be attributed to the mixing of mare and highland material either by secondary cratering during the emplacement of the Hevelius Formation or by vertical mixing during subsequent impact events.

While the above hypothesis would account for the enhanced Ti abundance, it would not explain the relatively low Fe values exhibited by the same area. Areas with high Ti values due to the presence of a mare component would be expected to exhibit enhanced Fe abundances. The results of simple two-component mixing calculations show that even if the surface material in the anomalous region consisted of high-Ti mare basalt and anorthosite, a rather extreme case, the amounts of basalt necessary to produce the observed Ti values would result in Fe values higher than those determined for this area by a factor of 2.5 to 3. No mixture of known lunar rock types could account for the chemistry of this region. This area of relatively high Ti values and low Fe abundance is not unique (Davis, 1980). Another example is located northwest of Orientale and is centered at 10° S, 243° E. It is clear that additional work will be necessary to understand this type of geochemical anomaly. It should be noted that the uncertainties associated with the Fe and Ti abundances determined for this region are relatively high. Deconvolution studies would help to resolve this problem.

## 4. Conclusions and Implications

(1) Geochemical anomalies are not uncommon on the eastern limb and farside of the Moon.

(2) These anomalies are commonly, though not always, associated with light plains deposits which exhibit dark-haloed impact craters.

(3) The results of recent spectral reflectance studies of dark-haloed impact craters (Hawke and Bell, 1981a, b, 1983; Bell and Hawke, 1984) as well as the surface chemistries of the anomalies strongly suggest that geochemically anomalous areas associated with light plains containing abundant dark-haloed impact craters are due to the presence of basaltic units either covered by highland debris or contaminated with significant amounts of highland material. In the former case, the subjacent basaltic material could have been incorporated into the surface material either by local mixing during the emplacement of the highlands material or by later vertical mixing.

(4) In some instances (e.g., Balmer), the basaltic deposits may have a composition unlike that determined for the common nearside mare basalts.

(5) In those instances where geochemical anomalies correlate with light plains without identified dark-haloed craters, the origin of the anomalies remains uncertain. The thinly buried basalt hypothesis is still viable, but other explanations must be considered. These include highland volcanism as well as the impact excavation of chemically anomalous material.

(6) The burial or contamination of pre-existing ancient volcanic surfaces by varying thicknesses of highland material appears to have been an important (though not dominant) process in the formation of lunar light plains.

(7) Consideration of the ages of the plains units associated with certain geochemical anomalies indicates that *basaltic volcanism was a major lunar process well before* 4.0 Ga.

(8) Basaltic volcanism on the lunar surface was more extensive in both space and time than has previously been thought.

(9) The presence of geochemical anomalies in highlands terrain with abundant dark-haloed impact craters should be taken into account in investigations of crustal inhomogeneity and determinations of the average or 'typical' compositions of the lunar highlands

surface. The inclusion of such regions may account, at least in part, for the relatively high 'typical' highlands concentration of $TiO_2$ (1.5%) reported by Korotev *et al.* (1980) and Haskin and Korotev (1981).

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