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# Chemical rings of lunar basins from orbital x-ray data

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**Abstract**—Chemical patterns related to basin structure have been observed in digital maps of Mg/Al, Mg/Si and Al/Si variations on the nearside lunar surface. A large part of the inner topographic ring of the Smythii basin is distinguishable chemically in the orbital X-ray data because it is more anorthositic than the surrounding soil. The aluminum-rich, magnesium-poor units of the ring correlate with material excavated from depth that is exposed on the surface of the rim deposits. The chemical ring created has a composition comparable to that of the geochemical province on the eastern far side. The correlations between the chemistry and morphology of the Smythii basin, supported by X-ray data at Langrenus crater, indicate that: 1) the chemical record of basin-formation in pre-Nectarian times persists in lunar soils despite continuous meteorite bombardment of the Moon; 2) strata of contrasting chemistry were excavated on the western side of the Smythii basin, whereas the lithology east of the basin is homogeneous to the depths sampled; 3) the geochemical boundary between the provinces of the eastern near side and far side may represent only surficial differences; and 4) the extent of primary ejecta from the younger Crisium basin was insufficient to mask the chemical features created by the Smythii impact approximately one Crisium-basin diameter away.

## INTRODUCTION

Orbital X-ray data (Adler *et al.*, 1973) have been successfully used to identify impact craters in the maria that have excavated subsurface basalts of a chemical composition different from that of the mare surface (Andre *et al.*, 1978) and craters that have penetrated through mare basalt layers in lunar basins to expose low Mg/Al terra material of the basin floor (Andre and Adler, 1978). The results of these studies indicate that impacts into multi-layered targets on the moon create the same ejecta patterns that have been observed at nuclear explosion craters, craters produced in laboratory tests and natural terrestrial impact craters. That is, material from the deepest levels of excavation is exposed on the crater floor, on the surface of the rim and extends radially from the rim crest of the transient cavity. The resulting chemical patterns from an orbital view are circular features that grade into the chemistry of the surrounding area. In addition to the information about subsurface composition, the existence of these patterns indicates that the chemical record of some Erastosthenian-age impacts can survive in the top 20 microns of the regolith, the depth to which the X-ray experiment is effective. The extension of these principles of impact mechanics to basins 300 to 600 km in diameter on the moon is the basis for the current study.

Although mare basalts cover the floors of most of the basins within the X-ray coverage, it is possible that a sampling of the deepest strata excavated from the terra crust remains at and beyond the rim crest. If this material exposed in the rim area has the same composition as the adjacent terra surface, the chemical boundary between the mare and terra composition will appear as a *circle* on a digital X-ray image (Andre *et al.*, 1977; Bielefeld *et al.*, 1977). For instance, high Mg/Al ratios of mare basalt will be surrounded by the low Mg/Al values of terra material. However, if the material from depth that is exposed on the rim is chemically different from the mare and the surrounding terra, a *ring* pattern will be created between them. The patterns formed are most obvious in Mg/Al variations because the dynamic range of this ratio is greater than that of the Mg/Si or the Al/Si ratio and because the inverse concentrations of aluminum and magnesium in terra rock types cause the Mg/Al ratio to reflect subtle differences most effectively. The potential of the Mg/Al ratio to distinguish among terra rock types can be seen in an orbital X-ray color image and accompanying key (Andre and Adler, 1979). The geographic distribution of Mg/Al orbital values in terra regions may be compared to their frequency distribution and to the Mg/Al values of lunar rock-types and returned soil samples.

The main objectives of this study are to determine the following:

1. Can the chemical evidence of a pre-Nectarian impact event survive to the present in surface soils?
2. Does the early lunar highland crust have a vertical chemical gradient to the depths of basin excavation?
3. Do highland impact craters indicate a similar chemical gradient at shallower depths?
4. Do boundaries between geochemical provinces on the lunar surface extend to depths of several kilometers?
5. To what extent does primary ejecta from lunar basins blanket the surrounding lithology?

There are numerous advantages to selecting the Smythii Basin as the center of this research. Mainly, it displays a striking chemical ring pattern in the Mg/Al image that correlates with the inner topographic ring of the basin. It has excellent repetitive coverage by the orbiting X-ray spectrometer during the Apollo 15 and 16 mission as well as high-resolution data collected during several low-altitude passes over the area. These low-altitude passes occurred during eliptical orbits early in the Apollo 16 missions when the spacecraft descended to elevations as low as 20 km above the lunar surface in the eastern nearside where the Smythii basin is located. Therefore, the field-of-view for the data points along the orbit paths varies as a function of spacecraft altitude. For instance, the field-of-view at 150E has a radius of 47 km that decreases to a radius of 12 km at 50E. The "effective" field-of-view (that is, 85% of the signal received) is from a surface area with a radius of only 8.7 km at 50E.

## CHEMICAL FEATURES OF THE SMYTHII BASIN

The multi-ring Smythii Basin is of special interest because the impact occurred at the boundary between the nearside and farside highlands. It has long been suspected that this boundary, separating regions of the terra with obvious differences in topography, chemistry (Fe, Ti, Th, Mg, and Al), spectral reflectivity (far ultraviolet) and crustal thickness, marks the dividing line between two different geochemical provinces of the crust (El-Baz and Wilhelms, 1975). The chemical dichotomy is evident in a comparison of the modes produced in separate nearside and farside histograms of Mg/Al orbital X-ray data (Fig. 1). The farside histogram consists of 4,567 data points representing X-ray coverage between 95E and 125E. The nearside set consists of 31,087 data points from 20W to 90E. The modes within the frequency distributions represent rock types, not average Mg/Al values for nearside or farside compositions. For instance, the nearside frequency distribution exhibits a strong, broad mode for mare basalts that peaks at 0.64 and one for terra areas at 0.39 Mg/Al concentration; whereas, the farside distribution lacks a distinct mode for mare basalts and the terra mode is displaced toward lower Mg/Al (more anorthositic) surface compositions. Although the Smythii Basin is classified as one of the oldest lunar basins (Stuart-Alexander and Howard, 1970), its form is clearly distinguishable on the basis of orbital chemistry. The Smythii impact structure has 3 observable topographic rings, as defined by Wilhelms and El-Baz (1977). The innermost, 370 km in diameter, reaches elevations about 4 km above the present basin floor. This topographic ring shows a striking correlation with the inner edge of an annulus of low Mg/Al chemical com-

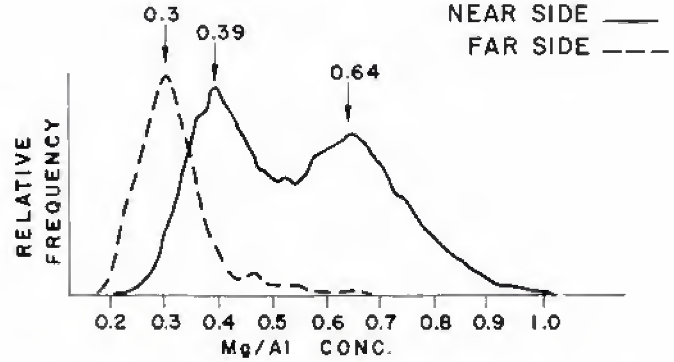

**Fig. 1.** Mg/Al frequency distributions. The farside terra mode is offset toward rock types with lower Mg/Al concentrations than that of the near side. The far side lacks a mode that corresponds to the broad mare feature that peaks at a value of 0.64 in the nearside histogram.

position (Fig. 2). This low Mg/Al annulus is particularly well-defined on the western rim because it contrasts with both the higher Mg/Al soils of the terra to the west of the basin (Andre and Adler, 1979) and the magnesium-rich soils inside the basin (Andre and Adler, 1979; Conca and Hubbard, 1979). The chemical ring cannot be easily distinguished on the east side of the basin because soils of the farside highlands are distinctly more anorthositic, like the ring itself.

The chemical ring observed in the X-ray data implies that the mechanical redistribution of surface soils has not been effective enough to obliterate the evidence of the pre-Nectarian impact that formed the Smythii basin. It also implies a limit to the range of Crisium impact ejecta. The Crisium basin is located immediately northwest of the corner of Fig. 2. It post-dates the Smythii basin (Stuart-Alexander and Howard, 1970) and yet the

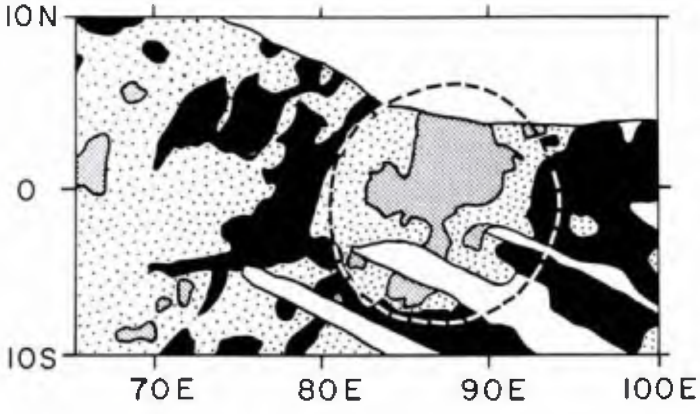

**Fig. 2.** Low Mg/Al concentrations (LT 0.30) of the Smythii Basin rim are comparable to very anorthositic material of the eastern far side (black unit), whereas the nearside terra is more magnesian and less aluminous (lightly dotted). The highest Mg/Al values (heavily dotted), GT 0.53 Mg/Al, are typical of mare basalts like those in the northeast quadrant of the Basin. White areas indicate no data. The dashed line represents the topographic rim of the Smythii basin (Wilhelms and El-Baz, 1977).

chemical ring of the Smythii basin has not been concealed by Crisium ejecta. A conservative maximum limit to the extent of ejecta from Crisium that blankets the surrounding surface would be the diameter of the basin itself. Chemical constraints such as this may assist in calculating estimates of the total displacement of material during basin-sized impacts on the moon.

In order to relate the chemical patterns of the Smythii basin to crustal stratigraphy in the nearside/farside transition zone, some discussion of the surface soils inside the basin is necessary. One would expect from previous X-ray data studies of impact craters that the interior of the basin would have the same subsurface chemistry as the rim, unless the basin floor has been covered by material of a different chemical composition. This is clearly the case for the Imbrian-age mare basalt unit that occupies the northeast quadrant of the basin (Wilhelms and El-Baz, 1977). The remainder of the basin interior, however, has a more complicated history. Numerous investigators have pointed out that the original basin floor is largely buried by material of a different composition. It is not likely that the material superposed on the basin floor is impact ejecta from the Crisium basin or other outside sources (Stewart *et al.*, 1975; Andre *et al.*, 1979) because of the well-defined chemical ring around the Smythii basin in the Mg/Al image (Fig. 2). Sharp chemical boundaries between the Crisium and Smythii basins are also seen in the titanium data (Davis, 1980) and the thorium data (Haines *et al.*, 1978) from the gamma-ray experiments. In other words, ejecta of a common composition cannot be traced between the two basins. Volcanism is an alternate means of "resurfacing" the basin floor. Stewart *et al.* (1975) suggest that early volcanic flows formed the Imbrian plains units (Ip) in the northwest of the basin. Others have shown evidence of pre-mare volcanism in the southern unit in the form of floor-fractured craters and dark haloed craters, and evidence of later volcanism in the form of irregular pits, crater chains, domes and linear and arcuate rilles of "raised rim" morphology that may have served as vents for dark mantle deposits (Wolfe and El-Baz, 1976; Greeley *et al.*, 1977; Schultz and Spudis, 1979).

Previous studies of the Smythii basin using X-ray data (Andre *et al.*, 1977; Conca and Hubbard, 1979) do not include data from several low-altitude orbits directly over the southern unit. These orbits provide the most extensive coverage of the east limb and eastern far side with greatly improved spatial resolution compared to later orbits (Fig. 3). The profile of Mg/Al variations corresponds to the area between the black lines on the map that represent the width of the effective field-of-view. The three low-altitude orbits used to construct this profile measured nearly the same geographic area within these reference lines. Therefore, it was possible to improve statistical reliability by combining co-located points from several orbits to produce the profile shown. For comparison to farside lithology, the upper reference line of the graph represents the nearside mare mode and the lower line shows the nearside terra mode from Fig. 1.

There is a general west to east decrease in Mg/Al values as the lunar far side is approached. This decrease represents a transition from anorthositic gabbro to gabbroic anorthosite. Superposed on this regional trend are local variations that correlate with topographic features. The largest deviations from the nearside terra Mg/Al reference line occur at Langrenus crater, the western rim of the Smythii Basin and the interior of the basin. Al/Si ratios (not shown here) for the interior of the Smythii basin are not substantially different from nearside terra soils. Therefore, the high-resolution Mg/Al data (Fig. 3) may be interpreted to indicate distinctly more mafic soils within the basin than terra soils on either the near side or far side. This implies an endogenic origin. If early and late episodes of volcanism have largely covered the original basin floor, soils extending outward from the crest may be the only visible remains of the material excavated from depth.

## CHEMICAL FEATURES OF LANGRENUS CRATER

Langrenus is a Copernican-age impact crater, the floor of which lies below the level of the Smythii basin floor. It is about 600 km west of the Smythii basin and measures about

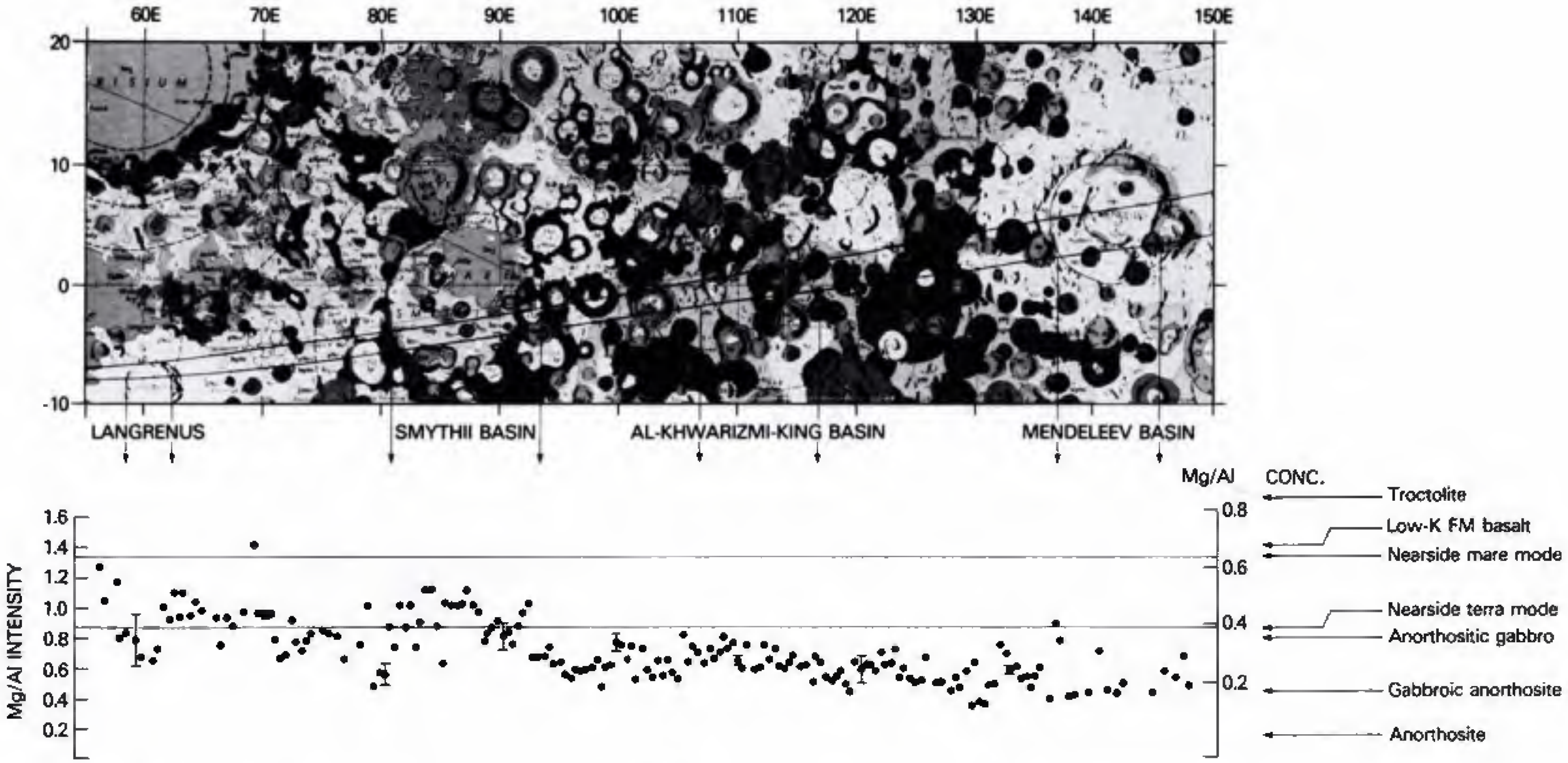

**Fig. 3.** High-resolution Mg/Al profile for the area outlined on the map. Representative error bars are shown every 10 degrees. The data have not been smoothed along orbit paths to retain as much detail as possible. See the text for a fuller explanation.

130 km in diameter. Because of its large size, X-ray data from a number of orbits is available for the crater. During the low-altitude passes, the Apollo 16 spacecraft overflew both Langrenus and the Smythii basin so that these features can be compared in detail (Fig. 3).

Langrenus crater exposes material with unusually low magnesium and unusually high aluminum values on its floor and rim that resembles the Mg/Al concentrations in farside terra soils. The composition of this material, like that of the Smythii basin rim area and the eastern far side, is exceptionally anorthositic compared to nearside terra soils (see nearside terra reference lines on Fig. 3). The same variations in the X-ray data are seen in the titanium variations from the gamma-ray experiment (Davis, 1980). For instance, titanium values at the Langrenus crater are as low as 0.3 to 0.6 wt. %, whereas the terra between Langrenus and the Smythii basin has concentrations of titanium that are as high as 2.5 wt. % near 70E.

The chemical contrast seen at Langrenus on the low-altitude profile is enhanced by the high Mg/Al soils east of Langrenus and the magnesium-rich border units of the mare basalts that fill the Fecunditatis basin (Andre *et al.*, 1979). The border units have been interpreted as the remains of early magnesium-rich basalt flows that were subsequently covered by less-magnesium flows in the central part of the basin. High-Mg basalts characterize border units of several maria and often extend into highland regions (Andre *et al.*, 1979). Therefore, the magnesium-rich soils east of Langrenus may be an extension of this unit. Or they may be an extension of early volcanism southeast of Langrenus. The topographic boundaries of an ancient basin north of the crater Balmer have recently been identified (Maxwell and Andre, 1981). The northern limits of the outer of two topographic rings of the Balmer Basin are immediately south of the X-ray data coverage shown in Fig. 3. Geochemical and geophysical data indicate that volcanic flows filled some of the low-lying areas. Regardless of the reason for the mafic terra soils between Langrenus and the Smythii basin, the fact remains that the anorthositic chemical ring around the Smythii basin and the anorthositic material exposed inside and of the rim of Langrenus are distinctly more anorthositic than the nearside terra reference line (Fig. 3).

## STRATIGRAPHIC IMPLICATIONS OF CHEMICAL RINGS AROUND LUNAR BASINS

Terra craters or basins that sample subsurface compositions distinct from the surrounding terra soils indicate a vertical chemical gradient in the crust or a layered target. A uniform chemistry between the material excavated from depth and the surrounding surface suggests a homogeneous rock type to the depths sampled. Thus, the semi-circular low Mg/Al annulus on the near side of the Smythii Basin (Fig. 2) implies a layered target, whereas, lack of chemical contrast between rim deposits east of the basin and farside soils implies a homogeneous, anorthositic (low magnesium, high aluminum), rock type to the sampling depth of the basin. Laboratory experiments, explosion tests and natural terrestrial craters demonstrate that chemical rings, such as the one observed at the Smythii Basin, are created in the form of "overturned flaps" that encircle transient cavities in multi-layered targets (Shoemaker, 1960; Roddy, 1973; Gault, 1974). The continuous ejecta displays the inverted order of the strata excavated so that material from the deepest layers samples are exposed on the surface and extend radially from the crater rim. Although the ejecta from the greatest depths thins with distance from the rim, the strata retain their relative pre-impact positions. Thus, a stratified target may be identified by chemistry if the continuous ejecta has a different composition from the surrounding surface soils.

The orbital X-ray data imply that rock types like those found on the surface of the farside province are rare on the surface of the near side and yet they are visible in two places on the eastern near side where material from depth has been exposed. Based on the X-ray data the following stratigraphic model is proposed. The eastern farside geochemical province dips toward the west at a low angle. It extends into the lunar near

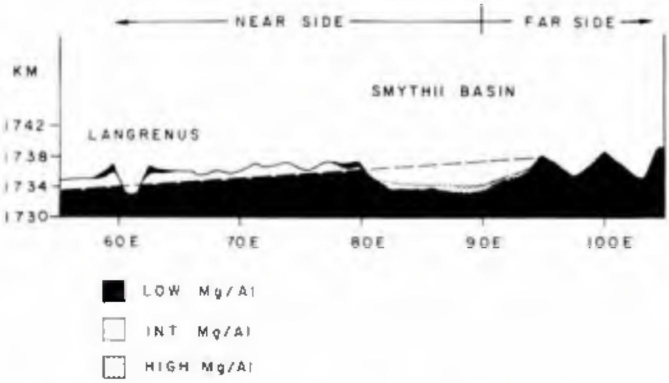

**Fig. 4.** Hypothetical subsurface contact between the nearside and farside geochemical provinces shown in cross-section. The depth of the nearside surface layer (INT Mg/Al) cannot be determined from the data.

side as a subsurface layer on the west side of the Smythii Basin and extends at least as far as Langrenus at 60E. This highly anorthositic material was excavated from depth at the Smythii Basin and the crater, Langrenus. This stratigraphic model would be impossible if it were not for the fact that the floor of Langrenus lies below that of the Smythii Basin. The topographic cross-section in Fig. 4 shows the hypothetical subsurface contact between the nearside and farside "geochemical provinces." The dip of the contact, however, may be at an angle much less than that shown.

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