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The Balmer Basin: Regional geology and geochemistry of an ancient lunar impact basin

Ted A. Maxwell and Constance G. Andre

Center for Earth and Planetary Studies, National Air and Space Museum, Smithsonian Institution, Washington, D.C. 20560

Abstract—Photogeologic, geochemical and geophysical information supports the existence of an ancient multi-ringed basin in the east limb region of the moon, centered at 15°S and 70°E. The inner ring of the basin, 225 km in diameter, is composed of isolated rugged mountains of pre-Nectarian terra, and the less distinct outer ring, approximately 450 km in diameter, is made up of irregular segments of surrounding large craters. Two units of light plains material occur in this area, and are confined primarily to the region within the proposed outer basin ring. On the basis of orbital geochemical data, the younger unit (Imbrian age plains) consists of a mare basalt not unlike others of the nearside. This unit has high Mg/Al concentration ratios as determined from X-ray fluorescence data, and is also relatively high in Th and Fe when compared to the surrounding highlands. The relatively high albedo of the Balmer plains may be due to either reworking by numerous secondary craters from surrounding impacts, or a basaltic composition with higher albedo and lower Fe than the nearside maria. The positive gravity anomaly associated with this region, and the scarp-like appearance of the inner ring both support a geologic history for the Balmer basin similar to that of other flooded nearside basins.

INTRODUCTION

A variety of remote sensing information has suggested the presence of a mare basalt lithology for the extensive unit of light plains located north of the crater Balmer on the eastern limb region of the moon. Andre *et al.* (1979) noted that the plains in this region exhibit higher Mg/Al ratios than the surrounding highlands, thus suggesting a more mafic composition. Using orbital gamma-ray data, Haines *et al.* (1978) indicated that this area was unusually high in thorium, and Davis (1980) has shown that the Fe content is higher than that of the surrounding highlands. Based on these data, Schultz and Spudis (1979) interpreted the light plains in this region to be underlain by mare material, and noted that this region corresponds to the location of a cluster of dark-haloed craters. Hawke and Spudis (1980) further suggested that the original basalt fill may have been KREEP-rich, and subsequently diluted with highland material ejected from several surrounding basins. However, there is evidence suggesting more than a thin veneer of basalt. A gravity anomaly greater than +40 milligals is associated with the region north of Balmer (Frontispiece, *Proc. Lunar Sci. Conf. 8th*).

These interpretations have led to a reexamination of the Balmer region in order to determine the origin and extent of the chemical anomalies in this area. Of particular importance are: (1) Were these plains units localized by a large crater or basin, or an irregular topographic low that may have been related to some pre-existing basin structure? (2) Was plains formation in this region the result of a high albedo mare fill, or mixing of basalt with surrounding highland material by impact gardening? and (3) Are there any diagnostic features of this particular light plains unit that can be used to distinguish a basaltic composition for plains material where we do not have geochemical information?

BASIN STRUCTURE

Two rings of a degraded basin (here named the Balmer basin) have been identified surrounding the plains deposits in this area (Fig. 1). Although this basin has been omitted from several published tables of lunar basins (Stuart-Alexander and Howard, 1970; Malin,

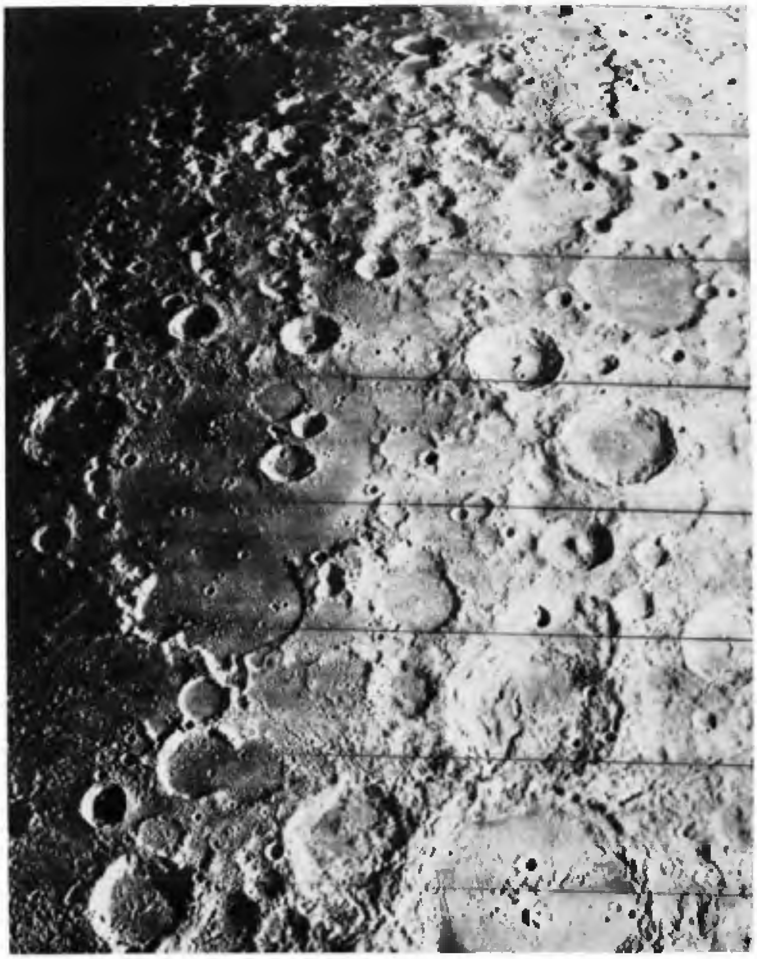

Fig. 1. (a) Lunar Orbiter IV Frame 9M (north-looking oblique) showing location of the Balmer basin. Inner ring (225 km, dia.) is expressed as isolated mountains of highland terra connected by irregular scarps.

1976; Wood and Head, 1976; Croft, 1979), it is noteworthy that Hartmann and Wood (1971) included a basin at this location in their list of mascon basins (Table VII of Hartmann and Wood, 1971). Schaber *et al.* (1977) recognized the Balmer basin, and assigned to it a "crater" diameter of 210 km (unnamed no. 9 in Table II of Schaber *et al.*, 1977). D. E. Wilhelms (pers. comm., 1980) also suggested the possibility of a basin in this region, while not specifying its exact location. The inner ring, 225 km in diameter, is centered at 15°S and 70°E. This rim is identified on the basis of isolated rugged mountains of pre-Nectarian terra that occur on the NE and NW rims of Balmer crater, and on the southwest rim of Kapteyn. The western ring segment is severely degraded by a chain of probable secondary craters, but the eastern part of the ring is better preserved. Here, the ring is marked by a wide block of terra material northwest of Balmer, which continues to the north as an apparent fault scarp.

Identification of a possible second ring of the Balmer basin is made on the basis of irregularities in the rim crests of surrounding large craters, and short segments of rugged highlands between these craters. As seen on Lunar Orbiter IV Frame 9M (Fig. 1A), the

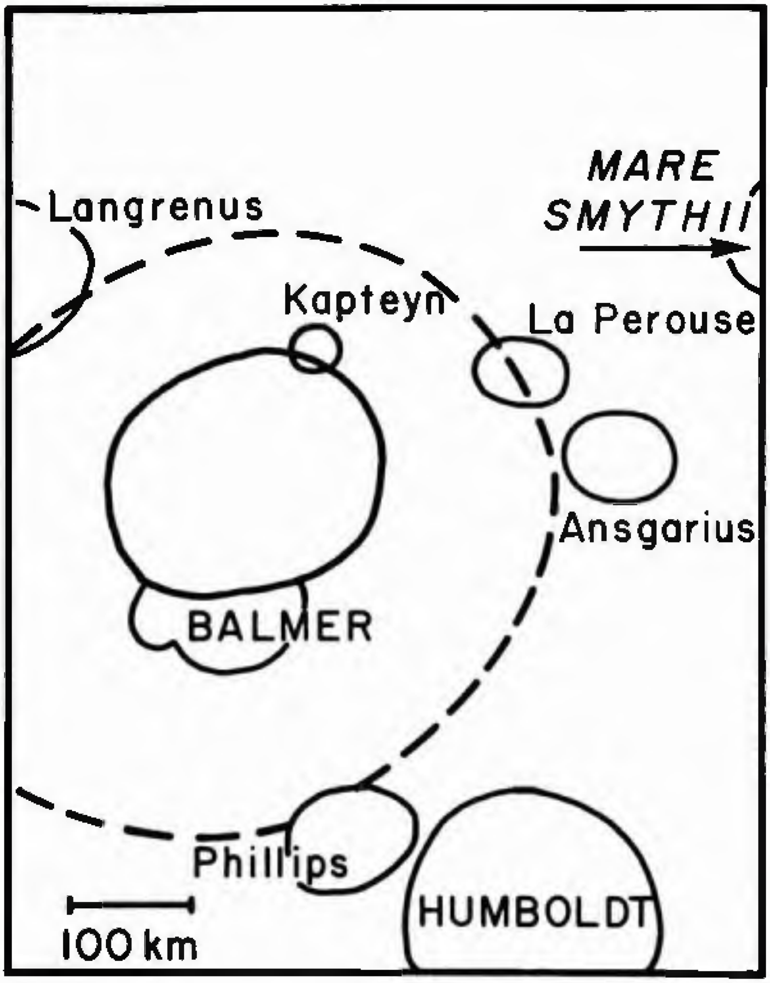

Fig. 1. (b) Sketch map of the region showing location of named craters and Balmer basin rings.

rims of La Pérouse and Ansgarius appear higher and more massive where they coincide with the proposed second ring than on other parts of their rims. However, the rim segments of these two craters also coincide with the third ring of the Smythii basin as mapped by Wilhelms and El-Baz (1977). Nonetheless, additional intercrater segments of rugged terrain south of Langrenus and north of Humboldt (Fig. 2) help to define a second ring that is approximately 450 km in diameter.

The highly degraded nature of both the inner and outer ring segments suggests a pre-Nectarian age for the Balmer basin, which is consistent with the mapping of a Nectarian-age terra unit within the second ring. A crater chain on the western inner ring of the Balmer basin is oriented radial to Crisium, and was thus attributed to Crisium basin secondaries by Hodges (1973). This indicates that the basin is "pre-Crisium." However, it does not establish whether the Balmer basin is older or younger than Nectaris, because it is uncertain whether Crisium is pre-Nectarian (Wilhelms and El-Baz, 1977) or Nectarian (Wilhelms, 1976). The presence of pre-Nectarian craters within the basin (as mapped by Wilhelms and El-Baz, 1977), and the degraded nature of the ring segments, however, support a pre-Nectarian age for the Balmer basin.

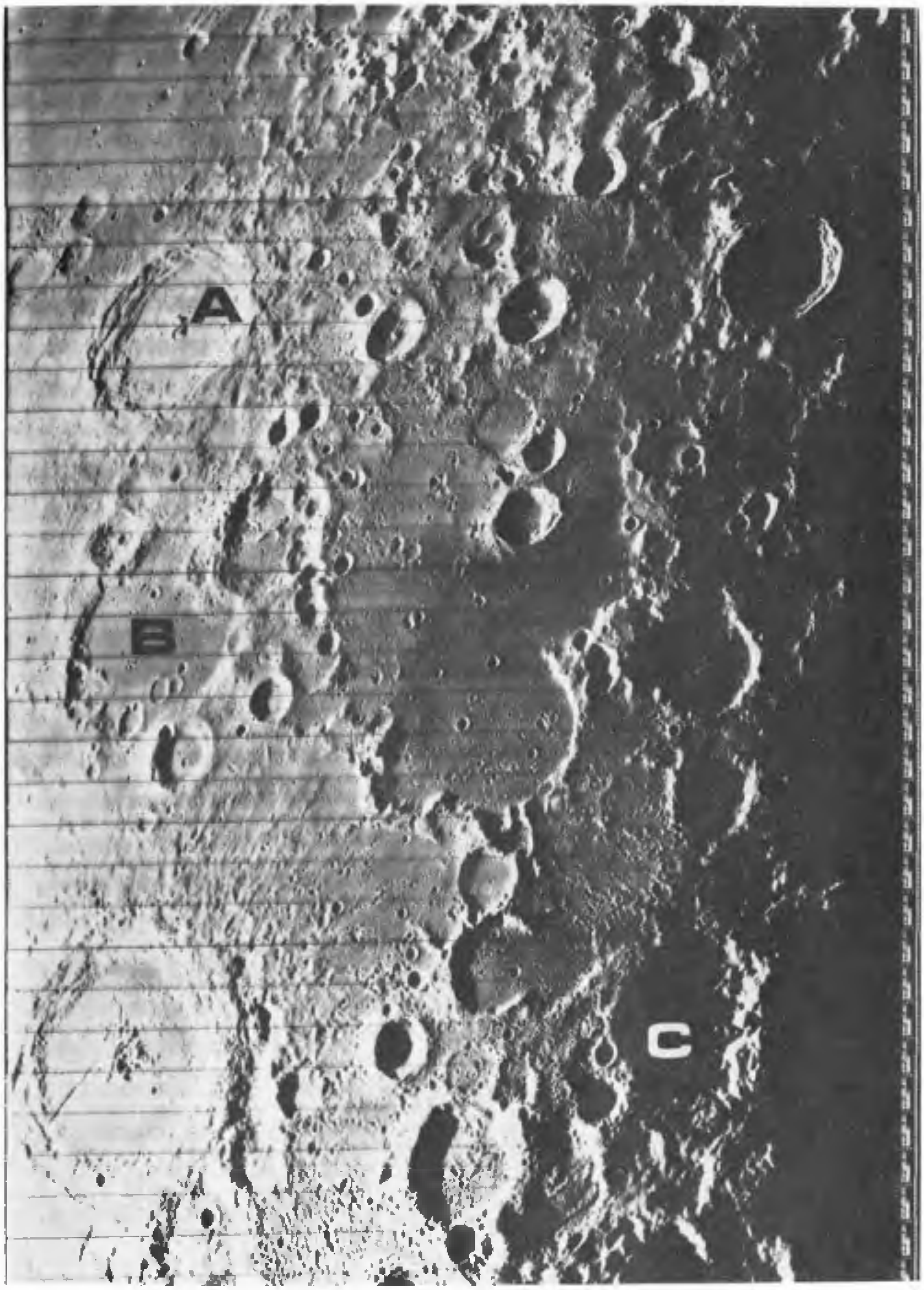

Fig. 2. Western half of the Balmer Basin region showing poorly-defined outer ring structure. Possible ring segments include a ridge of highland terra south of Langrenus (A), and irregularities in the rims of Vendelinus (B) and Phillips (C). (Lunar Orbiter IV Frame 184).

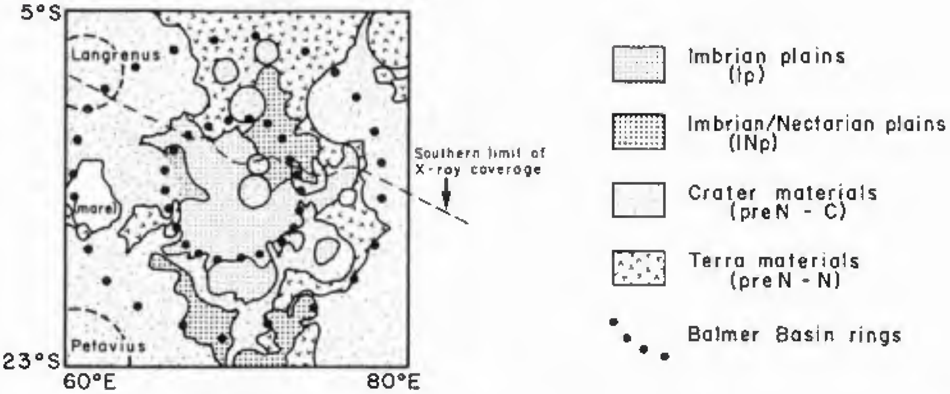

Fig. 3. Map of geologic units in the Balmer region, simplified from Wilhelms and El-Baz (1977). Crater and terra materials are not subdivided.

BASIN FILL

Geologic units within the proposed second ring of the Balmer basin consist of pre-Nectarian to Nectarian terra, crater materials of various ages, and extensive plains materials (Wilhelms and El-Baz, 1977). An older Imbrian- or Nectarian-age plains unit (INp) occurs predominantly between the inner and outer rings in the northern third of the basin, and a younger, Imbrian-age plains unit (Ip) is present within the inner ring of the basin (Fig. 3). In the southern part of the Balmer basin, especially within the crater Balmer, the relatively high crater density of the old plains unit (INp) is created at least in part by secondaries from Humboldt. In addition, lineated ejecta and chains of secondary craters from Petavius that are superposed on unit INp indicate that the plains here were emplaced prior to the Imbrian-age impact of Petavius. Thus, the distinction between younger and older plains units in the southern Balmer basin may be artificial, created by small secondary craters originating from Humboldt and Petavius.

In the northern half of the basin, stratigraphic relations are similarly obscured by fresh secondaries from the Copernican crater Langrenus, and by more subdued secondaries from the Imbrian crater La Pérouse. Nonetheless, the older plains unit in this region has a greater crater density and a rougher surface texture than the young plains to the south, which supports the previous distinction between plains units of two ages (Wilhelms and El-Baz, 1977), indicating at least a two-stage filling history for the Balmer basin.

ORBITAL CHEMISTRY OF THE BALMER REGION

In addition to studies of the iron and titanium content of materials in the Balmer region based on gamma-ray data (Haines *et al.*, 1978; Davis, 1980), orbital X-ray fluorescence coverage exists for the northern part of the basin. Regional X-ray coverage of the east limb region has suggested that a major geochemical boundary exists between the lower Mg/Al farside terra units and the higher Mg/Al values associated with nearside terra soils (Frontispiece, *Proc. Conf. Lunar Highlands Crust*). Low Mg/Al material excavated at Langrenus and exposed along the inner ring of the Smythii basin indicates that farside anorthosites extend into the nearside below the surface (Andre, 1981). Thus, the impact that created the Balmer basin may have occurred in a layered target, with highly anorthositic farside crust overlain by typically higher Mg/Al soils of the nearside terra.

The extremely degraded nature of the basin rings, and consequent lack of any extensive, basin-excavated unit make it impossible to recognize a chemically discrete, highland unit associated with rings of the basin. The regional setting of the Balmer basin between low Mg/Al material of Smythii basin rings and Langrenus crater ejecta (Andre,

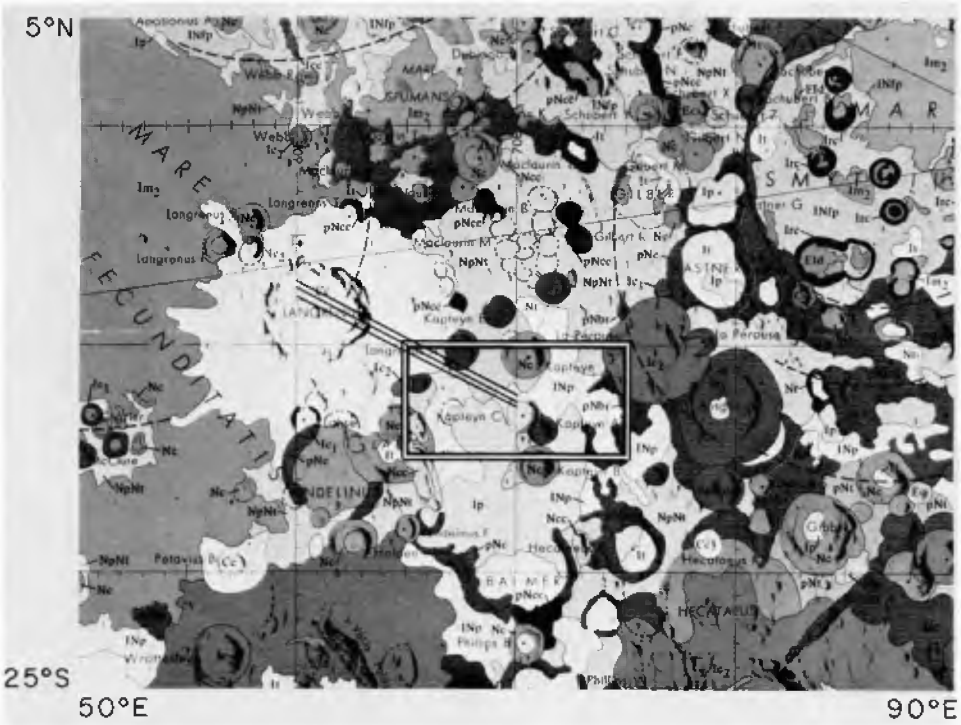

Fig. 4. (A) Segment of the Geologic Map of the East Side of the Moon (Wilhelms and El-Baz, 1977) showing location of X-ray fluorescence coverage for the northern part of the Balmer basin. Diagonal lines indicate ground tracks for profiles shown in Fig. 5.

1981), further complicates any possible identification, as does the limited extent of X-ray coverage (Fig. 3). Isolated patches of low Mg/Al material do, however, coincide with the proposed ring structures on the east and northeast sides of the basin, although the data are by no means as convincing as the ring of low Mg/Al values surrounding Smythii. On the northeastern edge of the basin, low Mg/Al ratios (Mg/Al concentration =0.30) correspond to the region between La Pérouse and just to the north of Kapteyn, on the second ring of the Balmer basin. To the east, similar low concentration values are present on the southern edge of Ansgarius on the second ring, and centered on a degraded crater at 14°S 74°E, on the inner ring of the basin. These scattered remnants of low Mg/Al terra provide further support for the survival of anorthositic crustal material at basin rings.

Unfortunately, only a small tongue of the old plains unit (INp) is covered by repetitive orbits from the Apollo 15 experiment, and the young plains (Ip) within the inner ring were measured only at the beginning of an orbit, near the terminator where statistical errors are high. Mg/Al ratios in this region are clearly higher over the younger plains (Fig. 4). This unit (Ip) has greater concentrations of Mg/Al (>0.58) near the rimless crater Kapteyn C. East of Kapteyn, however, unit INp is characterized by Mg/Al concentration ratios greater than 0.51, values slightly less than mare basalts on the near side of the moon. For comparison, the peak in the histogram of Mg/Al values for nearside mare units occurs at a concentration value of 0.64. However, the broad arch rising steeply from 0.57 Mg/Al indicates a wide range in chemical compositions for mare basalts as detected from orbit. Consequently, it is likely that the younger plains unit in the Balmer basin is composed of mare basalt.

The Mg/Al digital image (Fig. 4B) can be interpreted to a fuller extent by referring to

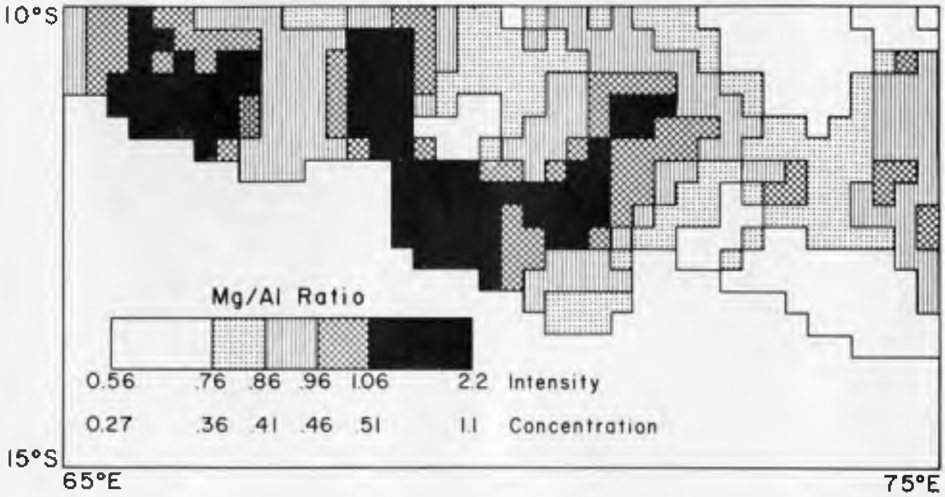

Fig. 4. (B) Mg/Al intensity and concentration values for the northern Balmer plains; highest values of Mg/Al are located just west of Kapteyn C and west of Kapteyn in the central part of the basin, and at the outer edge of Langrenus ejecta in the northwest part of the basin. Conversion of X-ray intensity to concentration is from data presented in Bielefeld (1977).

the aluminum and magnesium values that can vary independently in rock types other than the anorthositic suite. The Mg/Si and Al/Si profiles indicate a sharp inverse trend toward mare basalt values at 70°E (Fig. 5). This location represents the northernmost extension of the Imbrian plains unit that is contained within the inner ring of the Balmer basin. The composition of this material is comparable to that of basalts in Mare Nectaris, although between the two mare units, Langrenus crater has exposed very anorthositic material resembling that of the eastern farside terra.

In addition to the orbital X-ray data presented here, several previous studies of other lunar remote sensing data have indicated the presence of a mafic component in the Balmer region. By using a deconvolution technique for orbital gamma ray data, Haines *et al.* (1978) were able to model the best-fit Th values for the region south of Mare Smythii. As shown in Fig. 10 of Haines *et al.* (1978), the plains units within the Balmer basin are characterized by 4.0 ppm Th. It was also found that the best-fit compositional model worsened significantly if these units were deleted from the model. In addition, data from the Fe band of the gamma ray experiment reported by Davis (1980) indicate a value of 7.4–9.6% Fe for this region, although this data set is limited to the same northern part of the basin as that covered by the X-ray data. According to Haines and Metzger (1980), the value for Fe may be too high due to omission of two ground site correlation points, but they also consider these plains to have relatively high Fe after deconvolution of the gamma ray data.

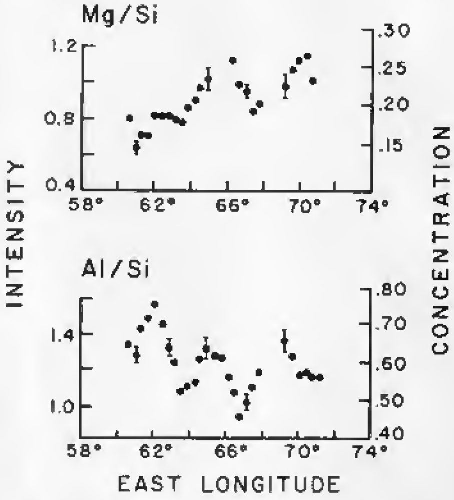

Fig. 5. Al/Si and Mg/Al profiles across the northern part of the Balmer basin; values are the average of the three orbits shown in Fig. 4A.

DISCUSSION

The traditional rationale for the separation of plains from mare materials on the lunar near side depended on the visible albedo of the deposits (Wilhelms, 1970). Light plains are generally intermediate in albedo between mare and highlands, and in some cases exhibit a greater crater density than that of mare surfaces (Wilhelms and McCauley, 1971). Unfortunately, absolute values for albedo are not available for the east limb region, forcing the distinction between plains and mare to be made on the basis of oblique, earth-based photographs and selected Apollo photographs. In addition to the numerous secondary craters that have modified the northern and southern parts of the basin, rays from Langrenus extend across the central portion of the plains, and may substantially contribute to the high albedo. However, as shown in Fig. 6, Langrenus is not completely responsible for the relatively high albedo plains in the Balmer region.

As shown above, there are several geochemical inconsistencies with a predominant anorthositic lunar highland composition for the Balmer region, and several explanations are possible for the mafic composition of the young light plains unit. The most likely of these are: 1) Old basalts excavated from beneath a discrete "light plains" unit, 2) A typical nearside basalt, with an abnormally high albedo created by gardening of the regolith by recent secondaries, or 3) Relatively high albedo basaltic material.

Schultz and Spudis (1979) presented strong evidence for ancient mare volcanism, now identified on the basis of dark-haloed craters that are common on lunar light plains. Although this hypothesis is supported by topographic and remote sensing data for several areas on the moon, we find the evidence less compelling in the central part of the Balmer basin. The presence of a dark halo surrounding the crater cluster at 68°E 15°S (Schultz and Spudis, 1979) is not apparent in high sun angle photographs of the region, despite the fact that other dark-haloed craters are visible in the same photographs (outside the Balmer light plains). In addition, it is doubtful that the limited extent of dark ejecta surrounding this crater cluster could be responsible for the strong mafic signature of the Balmer region. However, as suggested by Schultz and Spudis (1979), the role of dark-haloed craters in locating ancient mare deposits is well-illustrated in the southwestern part of the Balmer basin. Here, a dark-haloed crater is located within the continuous ejecta blanket of Petavius, which is superposed on plains unit INp (Fig. 6). This crater has apparently excavated either a localized deposit of basalt, or a portion of the older plains unit with a much lower albedo than the surrounding plains.

Based on the high Mg/Al ratios seen in the X-ray fluorescence data, the high Fe value from gamma ray data, and the extremely smooth texture and patchy nature of the light coloration, we propose that the younger plains (Ip) within the Balmer basin are composed of mare basalt, and thus feel that hypotheses 2 or 3 are more attractive. It is possible that the relatively high albedo that distinguishes "light" from "mare" plains was caused by reworking of local material by numerous small secondaries. In this respect, the Balmer plains may be analogous to the mare of western Crisium, where numerous rays from Proclus have substantially raised the albedo of the mare (Maxwell and El-Baz, 1978), but have left its chemical signature intact. In the Balmer region, indistinct rays from Langrenus and other small Copernican craters have raised the original albedo of the plains, although the surficial material retains a high proportion of local to exotic material (based on the sampling depth of the X-ray experiment; 10–20 microns). This conclusion is consistent with the work of Oberbeck *et al.* (1975), suggesting the predominance of local material in areas beyond the continuous ejecta deposits of craters.

The alternative explanation, that the Balmer light plains may represent a relatively high albedo mare basalt, is supported to some extent by the high albedo inter-ray surface of the Balmer plains. As pointed out by E. A. Whitaker (pers. comm., 1981), the Balmer plains are not as dark as the surface of Mare Fecunditatis at equivalent radial distances from Langrenus, suggesting that the pre-Langrenus plains surface was intermediate in albedo between average mare and average highlands. Thus, the presence of an intermediate albedo basalt composition remains a possibility. In either case, the degradation of

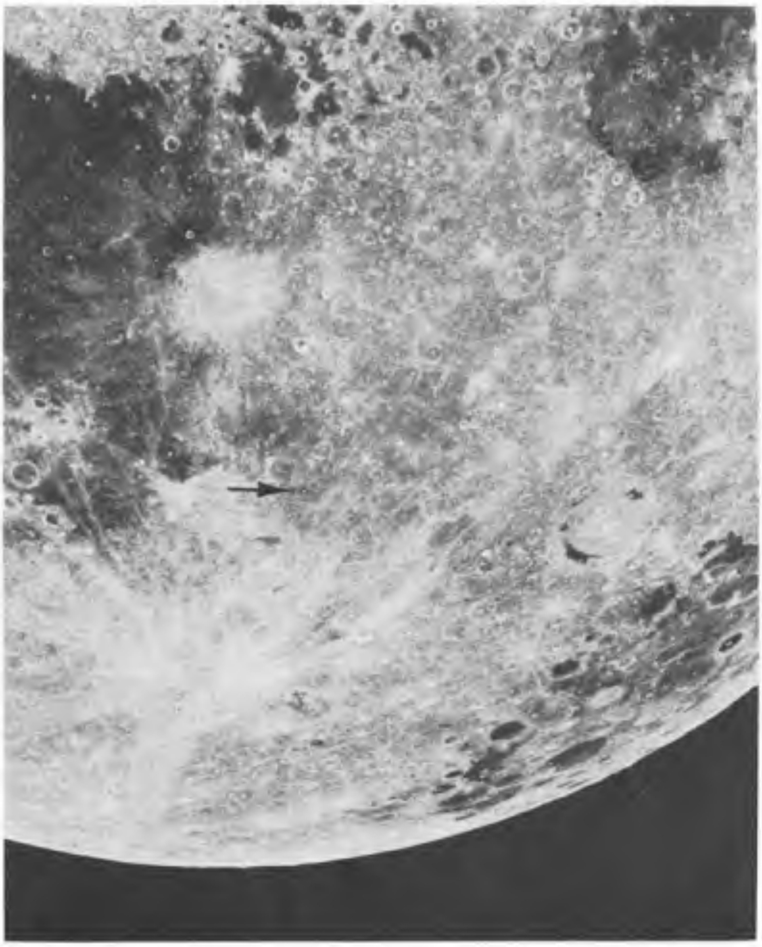

Fig. 6. High sun-angle photograph of the Balmer basin region showing albedo variations between east limb highlands, basin fill, and Mare Fecunditatis. Arrow points to dark-haloed crater located on ejecta of Petavius (AS11-6664).

the Balmer plains surface by rays and secondary craters (from Imbrian through Copernican time) has effectively removed any features diagnostic of the mode of basalt emplacement. The smooth surface of the inner basin and presence of small rimless craters, however, suggest a volcanic emplacement for the central "plains" unit, similar to that of other nearside maria.

Geophysical data also support the geochemical evidence of a basaltic composition for the Balmer basin fill. A positive gravity anomaly (noted by Haines *et al.*, 1978), centered at 70°E and 10°S. It extends southward as far as the second ring of the basin (25°S), and northward to 5°S (slightly north of the outer ring). The anomaly reaches peak values of greater than 40 milligals (Frontispiece, *Proc. Lunar Sci. Conf. 8th*), although more refined gravity models of this region may be expected to show higher values within the inner ring, where the fill is thickest. Such modeling would be useful for more accurately depicting the higher order lunar harmonics, and for placing further constraints on the thickness and composition of the basin fill.

The identification of a basaltic composition for the Balmer light plains provides additional support for different modes of origin for separate light plains units (Andre *et al.*, 1979). Geophysical and geochemical data for the Balmer region support an endogenic origin for at least this patch of "light plains." Thus, those plains units that can be chemically distinguished from the adjacent highlands contradict a derivation from the surrounding terrain.

CONCLUSIONS

Photogeologic investigation of the Balmer crater region on the southeast limb region of the moon has led to the delineation of a multi-ring impact structure, here designated as the Balmer basin. The inner ring of the Balmer basin is 225 km in diameter, and is formed of isolated large blocks of pre-Nectarian terra, and an apparent fault scarp marking the eastern edge of the ring. A possible second ring, 450 km in diameter, is recognized on the basis of irregularities in the rim crests of surrounding craters, and the localization of plains material within the proposed second ring. Geochemical and geophysical data indicate a predominant basaltic composition for the light-colored plains in the Balmer basin, with the relatively high albedo attributed to either (1) reworking of local material by secondary craters, or (2) emplacement of intermediate albedo material of basaltic composition, with a lower Fe content than typical nearside mare units.

Orbital X-ray data and the regional setting of the Balmer plains suggest that the younger light plains unit (Ip) is not the result of thinly covered mare basalt fill exposed by dark-haloed craters. Thus, a simple surface veneer of highland "plains" seems unlikely. Further mixing model studies based on both X-ray and gamma ray data will help to constrain the possible compositions in this region. The relative age and location of the basin fill, as well as the scarp-like appearance of the inner ring and positive gravity anomaly all support a predominant basaltic composition for the central basin, and suggest a tectonic history not unlike that of the lunar nearside multi-ring basins.

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REFERENCES

Andre C. G. (1981) Chemical rings of lunar basins from orbital X-ray data. In *Multi-ring Basins, Proc. Lunar Planet. Sci.*, 12A (P. H. Schultz and R. B. Merrill, eds.), p. 125–131. Pergamon, N.Y.

Andre C. G., Maxwell T. A., El-Baz F., and Adler I. (1979) Chemical diversity of lunar light plains from orbital X-ray data (abstract). In *Papers Presented to the Conference on the Lunar Highlands Crust*, p. 1–2. Lunar and Planetary Institute, Houston.

Bielefeld M. J. (1977) Lunar surface chemistry of regions common to the orbital X-ray and gamma-ray experiments. *Proc. Lunar Sci. Conf. 8th*, p. 1131–1147.

Croft S. K. (1979) Impact craters from centimeters to megameters. Ph.D. Thesis, Univ. Calif., Los Angeles. 264 pp.

Davis P. A. (1980) Iron and titanium distribution on the moon from orbital gamma ray spectrometry with implications for crustal evolutionary models. *J. Geophys. Res.* **85**, 3209–3224.

Haines E. L. and Metzger A. E. (1980) Lunar highland crustal models based on iron concentrations: Isostasy and center-of-mass displacement. *Proc. Lunar Planet. Sci. Conf. 11th*, p. 689–718.

Haines E. L., Etchegaray-Ramirez M. I., and Metzger A. E. (1978) Thorium concentrations in the lunar surface. II: Deconvolution modeling and its application to the regions of Aristarchus and Mare Smythii. *Proc. Lunar Planet. Sci. Conf. 9th*, p. 2985–3013.

Hartmann W. K. and Wood C. A. (1971) Moon: Origin and evolution of multi-ring basins. *The Moon* **3**, 3–78.

Hawke B. R. and Spudis P. D. (1980) Geochemical anomalies on the eastern limb and farside of the moon. In *Proc. Conf. Lunar Highlands Crust* (J. J. Papike and R. B. Merrill, eds.), p. 467–481. Pergamon, N.Y.

Hodges C. A. (1973) Geologic map of the Langrenus quadrangle of the Moon. U.S. Geol. Survey Misc. Geol. Inv. Map I-739.

Malin M. C. (1976) Comparison of large crater and multiringed basin populations on Mars, Mercury, and the Moon. *Proc. Lunar Sci. Conf. 7th*, p. 3589–3602.

Maxwell T. A. and El-Baz F. (1978) The nature of rays and sources of highland material in Mare Crisium. In *Mare Crisium: The View from Luna 24* (R. B. Merrill and J. J. Papike, eds.), p. 89–103. Pergamon, N.Y.

Oberbeck V. R., Horz F., Morrison R. H., Quaide W. L., and Gault D. E. (1975) On the origin of the lunar smooth plains. *The Moon* **12**, 19–54.

Schaber G. G., Boyce J. M., and Trask N. J. (1977) Moon-Mercury: Large impact structures, isostasy and average crustal viscosity. *Phys. Earth Planet. Inter.* **15**, 189–201.

Schultz P. H. and Spudis P. D. (1979) Evidence for ancient mare volcanism. *Proc. Lunar Planet. Sci. Conf. 10th*, p. 2899–2918.

Stuart-Alexander D. E. and Howard K. A. (1970) Lunar maria and circular basins – A review. *Icarus* **12**, 440–456.

Wilhelms D. E. (1970) Summary of lunar stratigraphy – Telescopic observations. *U.S. Geol. Survey Prof. Paper 599-F*, p. F1-F47.

Wilhelms D. E. (1976) Secondary impact craters of lunar basins. *Proc. Lunar Sci. Conf. 7th*, p. 2883–2901.

Wilhelms D. E. and El-Baz F. (1977) Geologic map of the east side of the Moon. *U.S. Geol. Survey Misc. Geol. Inv. Map I-948.*

Wilhelms D. E. and McCauley J. F. (1971) Geologic map of the near side of Moon. *U.S. Geol. Survey Misc. Geol. Inv. Map I-703.*

Wood C. A. and Head J. W. (1976) Comparison of impact basins on Mercury, Mars and the moon. *Proc. Lunar Sci. Conf. 7th*, p. 3629–3651.