

Chemical mixing model studies of lunar orbital geochemical data: Apollo 16 and 17 highlands compositions

Paul D. Spudis¹ and B. Ray Hawke²

¹U.S. Geological Survey, 2255 N. Gemini Drive, Flagstaff, Arizona 86001, ²Hawaii Institute of Geophysics, University of Hawaii, Honolulu, Hawaii 96822

Abstract—Chemical mixing model studies of lunar geochemical data for the central and Taurus-Littrow lunar highlands were performed utilizing pristine highland rock types as end member compositions. The central highlands show considerable diversity in composition; anorthosite is the principal rock type in the Apollo 16/Descartes region while norite predominates in the highlands west of the landing site. This change in crustal composition is coincident with a major color boundary seen in earth-based multispectral data and probably represents the presence of distinct geochemical provinces within the central highlands. The Taurus-Littrow highlands are dominated by norite; anorthosite is far less abundant than in the central highlands. This suggests that the impact target for the Serenitatis basin was different than that of the Nectaris basin and further strengthens the hypothesis that the lunar highlands are petrologically heterogeneous on a regional basis. We suggest that the lunar highlands should be viewed in terms of *geochemical provinces* that have undergone distinct and complex igneous and impact histories. The complexity of the lunar highlands suggests caution should be exercised when attempting to address the concept of average highlands composition based on analysis of returned lunar samples from various landing sites.

INTRODUCTION

Returned lunar samples contain much detailed mineralogical and petrological information for small, select sites on the moon. Many of the highland samples collected on Apollos 14, 15, 16, and 17 are somehow related to lunar multiringed basins, either as direct ejecta or reworked local material. These samples cannot always be related to a basin directly, and it is extremely difficult to characterize the petrologic nature of basin ejecta based on a few returned hand samples. The orbital geochemical instruments carried on Apollo 15 and 16 provide partial major and trace element data for large regions of the lunar surface, including basin ejecta deposits. These data provide a regional framework within which to interpret the significance of the returned lunar samples.

Many methods exist to interpret the orbital geochemical data; we have chosen to perform mixing model calculations on selected regional compositions that appear to be associated with basin deposits. It is important to emphasize that these calculations are *model* results and are dependent both upon assumed end member compositions (selected from the lunar sample data base) and the rather large uncertainty of compositions for the few elements available in a given region. We believe, however, that with suitable caution, these model results can provide significant insight into the petrologic nature of large regions of the lunar surface.

METHOD

Data for this study were provided by the X-ray and gamma-ray spectrometers carried aboard the orbiting Apollo 15 and 16 spacecraft (Adler and Trombka, 1977). The best available reduction of these data were used to derive regional chemical compositions. The X-ray Al/Si and Mg/Si ratio data (La Jolla Consortium, 1977) were converted to oxide weight concentrations by assuming 21 weight percent Si (Bielefeld, 1977); Mg values were corroborated by comparison with the gamma-ray derived values

Table 1. Assumed compositions of pristine rock types used in mixing model calculations (oxides in weight percent; Th in ppm).

Component used	AN	NOR	TROC	MKFM	A11MB	A17MB
TiO ₂	0.02	0.16	0.05	2.2	11.2	12.1
Al ₂ O ₃	35.5	20.9	20.7	14.8	9.6	8.7
FeO	0.23	5.0	4.9	10.6	18.8	21.5
MgO	0.10	11.9	19.1	8.2	7.3	8.2
K ₂ O	0.01	0.06	0.3	0.6	0.19	0.8
Th	0.01	1.7	0.9	10.5	2.2	0.54

AN – anorthosite 15415; NOR – norite 78235; TROC – troctolite 76535; MKFM – Apollo 15 KREEP basalt 15386; A11MB – Apollo 11 mare basalt (average); A17MB – Apollo 17 mare basalt 71055; Highland rock types from Ryder and Norman (1978a; 1978b); Mare basalt compositions from Taylor (1975).

(Bielefeld *et al.*, 1976). Concentrations for other elements were all derived from the gamma-ray data; K from Bielefeld *et al.* (1976), Th from Metzger *et al.* (1977) and Fe and Ti from Davis (1980). The areas resolved by the orbital geochemical data are effectively limited by the resolution of the gamma-ray instrument, i.e., regions about 250 km square. As in previous studies (Hawke and Ehmann, 1976; Hawke and Spudis, 1979), these regional compositions were interpreted using a least-squares mixing model (Bryan *et al.*, 1969). Each element was given equal weight in determining a solution; components were constrained to sum to 100 percent and iterative application of the model was applied within the error uncertainty of the elemental composition to obtain best fits (low standard error, minimal percent difference) for each given region. In our previous mixing model studies (Hawke and Spudis, 1979), end members were selected from representative highland rock samples in the Apollo collections; many of these compositions (e.g., low-K Fra Mauro basalt) probably represent polymict impact products that are themselves mixtures (Schonfeld, 1974; Ryder, 1979). For this study, end members were chosen from an extensively cataloged collection of “pristine” (monomict) highland rock compositions that probably represent the primary components of the highland crust (Warren and Wasson, 1977; Ryder and Norman, 1978a,b; Norman and Ryder, 1979). The selection of these end members is somewhat arbitrary; other workers have attempted to model highland geochemistry utilizing hypothetical end members based on study of lunar soils which are only partly represented by pristine samples (Korotev *et al.*, 1980; Haskin and Korotev, 1981). We believe, however, that the pristine samples better represent the probable true petrologic nature of the highlands crust; we are not concerned here with the ultimate origin and development of these rock types, but only with their relative proportions in observable highland soils. The compositions of the pristine end members used in this study are given in Table 1. These compositions are derived from representative rocks that appear to be typical of a given group, although it is recognized that some elemental variation is present in all categories (Ryder, 1979). Consistent use of these pristine end members can test ideas about petrologic heterogeneity within the lunar highlands crust.

CENTRAL LUNAR HIGHLANDS – APOLLO 16

The Apollo 16 landing site was selected within a region of the lunar central highlands thought to be representative of both the smooth highland plains (Cayley Fm.) and hummocky-textured highlands (Descartes materials; Muehlberger *et al.*, 1980). Analysis of the orbital geochemical data for the central lunar highlands reveals the existence of considerable heterogeneity within this region (Fig. 1; Table 2). X-ray and gamma-ray data (La Jolla Consortium, 1977; Davis, 1980; Andre and El-Baz, 1981) indicate an area of relatively high Al and low Fe situated on the east of the landing site (Descartes, 15–20°E). It should be noted that the very high Al values discussed by Andre and El-Baz (1981) are associated with the Kant plateau, a region that lies mostly in our Descartes region, but also partly in the Kant region (Fig. 1). To the east of the Descartes region (Kant, 20–25°E), the highlands appear to be more mafic. This may reflect partial mantling of highland materials by mafic ejecta from the post-mare crater Theophilus, which was formed partly in the basalts of Mare Nectaris (Milton, 1968). To the west of the Descartes region

Table 2. Regional chemical compositions of the Apollo 16 central lunar highlands and Apollo 17 Taurus-Littrow highlands. Data from Bielefeld *et al.* (1976), La Jolla Consortium (1977), Metzger *et al.* (1977) and Davis (1980). Oxides in weight percent; Th in ppm.

Component	Region ¹			
	Kant	Descartes	Andel	Taurus-Littrow
TiO ₂	1.8	1.2	1.2	2.4
Al ₂ O ₃	21.7	23.2	23.0	21.0
FeO	6.4	4.8	6.4	12.4
MgO	7.6	8.0	8.6	8.7
K ₂ O	0.14	0.14	0.13	0.13
Th	1.9	1.9	2.2	1.9

¹Regions defined in Table 3.

(Andel, 10–15°E), X-ray values again show increasing mafic content, continuing to the western edge of the highlands near Ptolemaeus. This increasing mafic trend to the west is less readily explained by a single cratering event and may reflect a true geochemical variation within the central lunar highlands (Spudis and Hawke, 1981).

Results of mixing model calculations are presented in Table 3. It is noted that anorthosite is substantially enriched in the vicinity of the Apollo 16 landing site (Descartes), coincident with the high Al/low Fe mentioned above. Mare basalt is enriched



Fig. 1. Index map showing locations of lunar highland regions modeled in this study (base map – NASA LMP-1)

Table 3. Mixing model results for the Apollo 16 central lunar highlands and Apollo 17 Taurus-Littrow highlands.

Region	Long.	AN	NOR	TROC	MKFM	A11MB	A17MB
Apollo 16 groundtrack (8°–10°S lat.)							
Kant	20°–25°E	29.3	33.0	12.3	9.9	15.5	—
Descartes	15°–20°E	33.9	30.7	16.5	10.7	8.1	—
Andel	10°–15°E	22.8	54.2	4.2	10.5	8.4	—
Apollo 15 groundtrack (18°–22°N lat.)							
Taurus-Littrow (best fit)	30°–35°E	1.2	67.7	2.2	2.4	26.5	—
(normalized highlands)	30°–35°E	1.6	92.1	3.0	3.3	—	—
Taurus-Littrow (alternative fit)	30°–35°E	15.3	48.4	7.6	6.4	—	22.2
(normalized highlands)	30°–35°E	19.7	62.3	9.8	8.2	—	—

in the Kant region and probably reflects contributions by Theophilus to surface soils. This component also exists, although in reduced amounts, within the Apollo 16 landing site region and may be represented in Apollo 16 soils by rare fragments of high-Ti mare basalt (Delano, 1975) and by glass particles with mafic affinities (Wood, 1975; Butler, 1978). The concentration of mare basalt in the Descartes region (8.1%; Table 3) is in general agreement with values obtained from mixing model studies of Apollo 16 lunar soils, which range from 7.5 to 13.9 percent (Duncan *et al.*, 1973). The highlands west of the Descartes region (Andel) display a significant increase in norite/anorthosite ratio, a reflection of the westerly increase primarily in Mg and Fe.

The KREEP component appears relatively constant (~10%) across the three regions in our results. This effect was produced primarily as a result of use of the regional Th value of Metzger *et al.* (1977) that indicates little Th variation across the central highlands. However, recent deconvolution modeling of this region by Etchegaray-Ramirez *et al.* (1981) shows a considerable variation in Th across this region; notably, Th lows (0.1–0.7 ppm) in the vicinity of Descartes crater and Kant Plateau and a Th high (~5 ppm) associated with Ptolemaeus. These new results predict higher KREEP contents for the Andel and western Descartes regions and a lower KREEP component in the eastern Descartes/Kant plateau region. Further work utilizing these new Th values is planned for the near future.

Spudis and Hawke (1981) previously noted that the clear change in norite/anorthosite ratio around Andel correlated with a major color boundary within the central highlands on the multispectral vidicon mosaic of Soderblom (La Jolla Consortium, 1977; plate 7). Based on this correlation, we believe this color boundary has true petrologic significance, indicating a distinct geochemical province within the central highlands. The concept of a *geochemical province*, defined herein, is discussed more fully in a subsequent section.

TAURUS-LITTROW HIGHLANDS – APOLLO 17

The Apollo 17 highland sampling objective was to obtain pre-Imbrian terra materials that comprise two major morphologic units in this region; massifs and the “sculptured hills”, a widespread knobby textured highland unit on the lunar eastern limb. It was assumed on the basis of pre-mission mapping (Scott and Carr, 1972; Lucchitta, 1972) that these highland units would be composed primarily of ejecta from the Serenitatis basin, with the possible presence of a thin and/or discontinuous quantity of Imbrium basin ejecta. These highland units occur on the topographic rim of the Serenitatis basin and it was hoped that deeply derived material would be accessible for sampling within the ejecta sequence (Hinnert, 1973).

Studies of the orbital geochemical data for this region are complicated by the fact that Taurus-Littrow highlands are partly embayed by mare basalts; moreover, dark mantling material of probable pyroclastic origin is discontinuously present within the highlands (Scott and Carr, 1972; Lucchitta, 1972). Furthermore, the two major terrain types, massifs and sculptured hills, are relatively small units and cannot be distinguished in the orbital geochemical data due to the large (~ 250 km square) resolution of the gamma-ray spectrometer. The mixing model results for this region were normalized to highlands composition only by subtracting the mare component and recalculating to 100% (Table 3). This procedure was done under the assumption that mare basalt is absent as a highlands component; studies of highland soils from the site suggest mare basalt is present in the terra component, but total abundance of less than one percent is likely (Ryder, 1981). However, these results are less certain than the model results for the central highlands and should be used with caution. Two alternative models are presented, one utilizing Apollo 11 high-Ti basalt as the mare basalt end member, the other using Apollo 17 high-Ti basalt for which poorer, but still acceptable, fits were obtained.

The mixing model results for the Taurus-Littrow highlands are strikingly different from results for the central highlands (Table 3). In both alternative fits, norite is the primary component in the Taurus-Littrow highlands, with minor amounts of troctolite and KREEP. Of particular interest is the low abundance of anorthosite; it is virtually absent in the best fit model (Apollo 11 mare basalt end member) and subordinate to norite in the alternative fit. This difference is thought to be real, as examination of individual pixels centered on relatively unmantled highlands material on the La Jolla X-ray image display Al/Si ratios considerably lower than typical highland values. The low abundance of KREEP in the best fit model should be accepted with caution, as the Th deconvolution technique has not been applied to this region; slightly higher KREEP abundance is suggested by the alternative fit model.

These results are compatible with studies of returned Apollo 17 highland samples. No pristine anorthosite, *sensu stricto*, has been found to date in the Apollo 17 samples; moreover, a recent study of "pure" highlands soil from the site suggests that anorthosite probably is present in quantities of less than one percent (Ryder, 1981). On the other hand, norite is abundant at the Apollo 17 site, both as numerous clasts in the melt rocks (e.g., Ryder *et al.*, 1975) and as large hand and boulder samples (e.g., Station 8 norite; Jackson *et al.*, 1975). The principal disparity seems to be the low abundance of KREEP in both fits, as melt rocks of low-K KREEP are abundant in the Apollo 17 collection. However, sample collection at the site concentrated on massif bounders (AFGIT, 1973); these melt rocks are probably over-represented in the returned samples. The melt rocks probably do not make up the bulk of the Taurus-Littrow highlands because orbital gamma-ray indicate much lower Th values for the region (1.9 ppm; Metzger *et al.*, 1977) than would be observed if the melt rocks (Th ~ 6 ppm; Simonds (1975) were a major component. The majority of the low-K KREEP melt rocks are probably present as a thin, discontinuous "melt sheet", related to the Serenitatis basin event (Winzer *et al.*, 1977).

COMPARISON WITH PREVIOUS RESULTS AND OTHER BASINS

A summary of chemical mixing model studies for several lunar basin ejecta deposits was given by Hawke and Spudis (1979) and Hawke *et al.* (1980). As mentioned previously, these mixing model calculations utilized end member compositions found to be representative of lunar highland rock samples; many are likely to be polymict (e.g., "anorthositic gabbro"; see Norman and Ryder, 1979). Moreover, these earlier mixing model studies utilized orbital geochemical data that has since been refined and improved, correcting for solar variations in the X-ray flux (e.g., Clark and Adler, 1978) as well as new regression curves for the gamma-ray data (e.g., Davis, 1980). It is interesting to compare these previous results with the new calculations and to attempt to assess their relative merit. An abridged summary of these previous results is presented in Table 4.

The selection of different end members has significantly affected the mixing model

Table 4. Mixing model results for selected regions around the Nectaris, Crisium and Orientale basins as presented in Hawke and Spudis (1979). Representative region "A" around Crisium is defined in Bielefeld *et al.* (1978).

Region	Long.	AN	GABAN	ANGAB	LKFM	MKFM	A12MB	A11MB
		Apollo 15 groundtrack (3°–10°N latitude)						
Crisium A	50–65°E	—	—	75.5	22.7	—	1.8	—
		Apollo 16 groundtrack (8°–10°S latitude)						
Kant	20.5°–26°E	—	—	65.5	16.1	—	—	18.4
Descartes	14°–20.5°E	21.1	—	47.4	27.7	—	—	3.7
Andel	5°–14°E	9.2	—	63.6	—	14.7	—	12.5
		Apollo 15 and 16 groundtrack (5°S–20°N latitude)						
Orientale	76°–110°W	—	40.1	59.9	—	—	—	—

GABAN – gabbroic anorthosite; ANGAB – anorthositic gabbro; LKFM – low-K Fra Mauro basalt; A12MB – Apollo 12 mare basalt; see Hawke and Spudis (1979).

results for Nectaris basin deposits (central highlands; Tables 3 and 4). Both models show the enrichment of anorthosite in the Descartes region. A significant difference between the two is the incorporation of KREEP in the low-K Fra Mauro component (possibly polymict; see Reid *et al.*, 1977). This is probably a more realistic interpretation of these chemical data since poikilitic melt rocks collected at the Apollo 16 site are of LKFM composition (Simonds *et al.*, 1973). However, pristine anorthosite is found in quantity at the Apollo 16 site, as well as minor amounts of norite and troctolite. It would thus seem that a realistic estimate of the petrologic composition of the highland crust would incorporate the best of both modeling techniques.

It should be emphasized that the mixing model technique only supplies alternative ways of viewing the geochemical data. In regions dominated by basin ejecta deposits, models utilizing polymict end members can potentially give valid results in the petrologic reconstruction of the upper lunar surface. Use of pristine end members in mixing models tends to define regional petrologic trends, since basin ejecta is ultimately derived from deeper levels in the crust and impact reworking of such material does not change the relative proportions of the pristine components. Thus, use of both techniques is desirable; use of polymict end members to characterize the true petrologic nature of basin ejecta and use of pristine end members to test ideas about lateral heterogeneity in the highland crust. Although both utilize the same regional compositional information, they are alternative means of interpreting these data and complement one another.

REGIONAL GEOCHEMICAL PROVINCES

It will be seen in Table 4 that basin deposits are not only internally heterogeneous, but differ significantly from one another. The same phenomenon is seen in mixing models utilizing pristine end members (Table 3). This strongly suggests that the lunar highland crust is petrologically heterogeneous on a regional basis, an idea supported by numerous other studies (Schonfeld, 1977; Hubbard, 1979). Thus, the concept of "average" highlands composition based on analyses of samples from a single landing site, such as Apollo 16, is probably invalid. We suggest that the lunar highlands should be viewed in terms of *geochemical provinces*, that is, regional volumes of crust that have undergone distinct but complex igneous and impact histories.

Several processes could affect the petrologic and chemical composition of a given geochemical province. Many models of early crustal formation by global melting suggest that this original igneous differentiation would produce heterogeneities, both vertically and laterally (e.g., Hubbard, 1979). In addition to *in situ* heterogeneities in the highland

crust, basin forming impacts of various sizes could mobilize and distribute this material producing the observed geochemical provinces. Another important process that affects regional chemistry on the moon is volcanism. It has recently been shown that volcanism prior to the termination of heavy bombardment has been an important process in early lunar history (Schultz and Spudis, 1979; Ryder and Spudis, 1980). Extensive volcanic resurfacing of large regions of the lunar highlands could contribute to the distinctive signature associated with certain geochemical provinces, and apparently volcanism is the primary cause for some highland geochemical anomalies (Hawke and Spudis, 1980).

The presence of these distinct geochemical provinces in the lunar highlands implies that the impact targets were probably chemically and petrologically different for each lunar multi-ringed basin. Thus, basin ejecta is likely to be heterogeneous, even if ejection and deposition processes are simple, which is not likely. These observations greatly complicate the long sought goal of assigning various returned lunar samples as ejecta of specific lunar basins. In any case, it is clear that much further work is needed both to clarify the existence of regional geochemical provinces and to define their extent and composition. This work will probably be best achieved when complete global geochemical data are available, i.e., when the lunar polar orbiter data are in hand.

SUMMARY AND CONCLUSIONS

Chemical mixing model studies of the central lunar highlands have demonstrated pronounced differences between the Apollo 16 landing site and surrounding highlands. Thus, the samples collected on the Apollo 16 mission may not be representative of the central highlands as a whole. Based both on mixing model results and the earth-based color data, it appears that the central highlands are composed of at least two separate geochemical provinces. In the west, norite (Mg-rich) predominates over anorthosite by more than two to one; east of the crater Andel, anorthosite (Al-rich) is abundant and subequal to norite. This anorthosite-rich zone appears to be primarily associated with Descartes material that overlies the Kant plateau (Milton, 1968). It is still not clear what the ultimate origin of the Descartes material is; both Imbrium and Nectaris basin origins have been proposed (Wilhelms, 1981).

The highlands of the Taurus-Littrow region are chemically distinct from any composition found in the central highlands. In this geochemical province, norite is the dominant rock type (in much greater abundance than in the central highlands; Table 3) and anorthosite appears to be rather scarce. The ultimate cause of this major difference is not immediately apparent. One possibility suggests that the original magma ocean was not global in extent and ferroan anorthosites were never present in the Serenitatis basin target site (Ryder, 1981). Alternatively, the highland crust in this region could have been the site of a post-magma ocean plutonic intrusion (James, 1980). In this event, a large norite batholith could have been the protolith from which most Serenitatis basin ejecta was derived. Continued work is planned to address this interesting and significant problem.

It is clear from this work that the lunar highlands are chemically and petrologically heterogeneous and that the highlands should be viewed in terms of geochemical provinces that have undergone distinct and complex geological histories. This idea has gradually evolved independently by some lunar sample studies and represents an important advance in recognizing that lunar geologic history has been considerably more complex than was thought early in the nascent history of lunar science. Continued work is planned to relate these postulated regional geochemical provinces to a variety of lunar geologic problems.

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