CHEMICAL MIXING MODEL STUDIES OF LUNAR ORBITAL GEOCHEMICAL DATA: APOLLO 16 AND 17 HIGHLANDS COMPOSITIONS;

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Introduction and Method. It is important to understand the relation of returned Apollo rock and soil samples to a larger regional context in order to ascertain the relative importance of various chemically and petrologically defined components to the composition of the lunar highlands crust as a whole. Toward this end, we are continuing study of regional geochemical variations within the central lunar highlands (Apollo 16) and the eastern Serenitatis basin rim (Apollo 17). Data for this study were provided by the X-ray and gamma-ray spectrometers carried on the orbiting Apollo 15 and 16 spacecraft [1]; we used the best available reduction of these data [2,3,4] to derive regional chemical compositions. These compositions were interpreted using a least-squares mixing model technique described elsewhere [5,6]. In our previous mixing model studies [6], end members were selected from representative highland hand 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 [7]. 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 [8,9,10]. Consistent use of these end members in the mixing models can test ideas about petrologic heterogeneity within the lunar highland crust.

Central Lunar Highlands: Apollo 16. The Apollo 16 landing site was selected as a region of the lunar highlands thought to be representative of this major geologic province. The X-ray data for this region [2] clearly show that the landing site is within an area of relatively high Al and low Mg; surface chemistry becomes more mafic both east and west of the site. To the east (long. 20-25° E.), the highlands may be veneered by a layer of mafic ejecta from the post-mare crater Theophilus [11], which was formed partly in the basalts of Mare Nectaris. The increasing mafic trend to the west (long. 10°-15° E.) is less readily explained by a single cratering event and may reflect a true geochemical variation within the highlands [12].

Results of mixing model calculations are presented in Table 1. They indicate a substantial enrichment of anorthosite relative to other pristine rock types in the vicinity of the Apollo 16 site, coincident with the high Al mentioned earlier. The increase in the proportion of mare basalt in the Kant region probably reflects contributions by Theophilus to surface soils; this component may be represented in the Apollo 16 soils by rare fragments of high-Ti mare basalt [13]. The highlands west of Descartes (Andel region) show a significant increase in the norite/anorthosite ratio, a reflection of the westerly increase in mafic trend. KREEP (MKFM in Table 1) appears to be relatively constant ($\sim$ 10%) over the entire groundtrack, supporting our earlier conclusion [6] that no systematic KREEP variation relative to the Nectaris basin is observed. It should be stressed, however, that future Th deconvolution of this area, utilizing a technique used elsewhere on the Moon [14], could change these results, as the proportion of MKFM in the mixing model is strongly sensitive to Th content.

These results indicate that the central lunar highlands around the Apollo 16 landing site are geochemically and petrologically heterogeneous. We noted previously [12] that the increase in norite/anorthosite ratio west of the landing site correlates with a distinct color boundary on the multispectral vidicon mosaic of Soderblom ([2] plate 7). We suggest that this boundary defines a distinct geochemical province within the central highlands. Such a province could result from several processes, including: 1) heterogeneities produced by original igneous differentiation associated with crustal formation [15]; 2) ancient volcanism prior to final bombardment [16]; and 3) deposition of chemically distinct basin ejecta. We tend to favor combinations of 1) and 2) above, as the highland color boundary is not obviously related to a major basin [12].

Taurus-Littrow Highlands: Apollo 17. The Apollo 17 highland sampling objective was to obtain pre-Imbrian material, that is most probably Serenitatis basin ejecta. Orbital geochemical studies of this region are complicated by the fact that the highlands are partly embayed by mare basalts; moreover, dark mantling material of probable pyroclastic origin is discontinuously present within the highlands [17]. The two major highland terrain types (massifs and Sculptured Hills [17]) cannot be distinguished with the orbital geochemical data. The mixing model results for this region were normalized to highlands composition only by subtracting the mare component and recalculating to 100 percent (Table 1); this procedure was done with the assumption that mare basalt is absent as a highlands component, so these results should be approached with caution.

The mixing model results for the Taurus-Littrow region are strikingly different from results for the central highlands (Table 1). Norite appears to be the primary component of the Taurus-Littrow highlands with minor amounts of troctolite and KREEP. Of particular interest is the virtual absence of anorthosite; this absence is thought to be real, as examination of individual pixels centered only on highlands material on the La Jolla X-ray image [2] display Al/Si ratios considerably lower than average highland values. As in the case of the central highlands, the low abundance of KREEP should be accepted with caution, as this region has not undergone Th deconvolution.

These results are essentially compatible with studies of returned Apollo 17 highland samples. No pristine anorthosite, sensu stricto, has been found in the Apollo 17 samples; moreover, recent study of "pure" highlands soil from the site [18] demonstrates that anorthosite probably is present in quantities of less than one percent. On the other hand, norite is abundant at the Apollo 17 site, both as numerous clasts in the melt rocks [19] and as large hand and boulder samples (Station 8 norite [20]). The principal disparity seems to be the low abundance of KREEP, as melt rocks of low-K KREEP are abundant in the Apollo 17 collection. However, sample collection at the site concentrated on massif boulders [21]; these melt rocks probably do not make up the bulk of the Taurus-Littrow highlands, because orbital gamma-ray data indicate much lower Th values for the region (1.9 pmm [3]) than would be observed if the melt rocks (Th $\sim$ 6 ppm [22]) 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 [23].

Conclusions. Results of this study suggest the lunar highlands are petrologically heterogeneous on a scale of hundreds of kilometers. This diversity may be produced by plutonic processes associated with original crustal formation, ancient volcanic activity, and impact processes associated with major basin formation. We suggest that the lunar highlands should be viewed in terms of geochemical provinces with distinct, complex, igneous and impact histories. Thus, the concept of "average" highlands composition based on analyses of samples from a single landing site, such as Apollo 16, is probably invalid. The presence of distinct geochemical provinces in the lunar highlands further implies that the impact targets were probably different chemically and petrologically at each lunar multi-ringed basin. Basin ejecta would reflect these differences, complicating attempts to sort out which Apollo samples are from what basin. Continued work is planned to relate these postulated regional geochemical provinces to a variety of other lunar geologic problems.

References

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Table 1. Results of mixing model calculations for the central and Taurus-Littrow lunar highlands. End members used pristine highland rock compositions (9): AN- anorthosite; NOR- norite; TROC- troctolite; MKFM- Apollo 15 KREEP basalt. A11MB- Apollo 11 high-Ti mare basalt (composition from [24]).

Region	Long.	AN	NOR	TROC	MKFM	A11MB
	Apollo 16 groundtrack (latitude 8°-10° S.)					
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 (latitude 18°-22° N.)					
Taurus-Littrow	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	----