

POSSIBLE LUNAR SOURCE AREAS OF METEORITE ALHA81005: GEOCHEMICAL REMOTE SENSING INFORMATION

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Abstract. Antarctic meteorite ALHA81005 is a regolith breccia apparently sent to earth by an impact event in the lunar highlands. Laboratory studies of this sample provide information that is used to understand the source region on the moon using remote sensing data. The meteorites' low Thorium content is inconsistent with Thorium values measured for the central lunar nearside from orbit with Apollo γ -ray spectrometers. Similarly, the mineral assemblages inferred from near infrared spectra of small impact craters on the lunar nearside do not exhibit the significant component of olivine and Fe-bearing feldspar that is observed in the meteorite spectra. The existing remote sensing data suggest the most probable source region for ALHA81005 is the nearside limb or the lunar farside and that the composition of ALHA81005 represents a surface unit that has not previously been extensively sampled.

The unusual Antarctic meteorite ALHA81005, is presumed to have reached the earth through ejection by an impact event that occurred somewhere on the Moon. Reviewed here is evidence that can help locate the source area on the moon for this unique lunar sample. Since there are no global compositional data for the moon, information must be extrapolated from limited amounts of remote sensing data.

Three properties of ALHA81005 provide information relevant to the search for its source area: bulk chemistry, a clast of very low-titanium basalt, and bulk mineralogy. This application of remote sensing data of the lunar surface requires the composition and general character of sample ALHA81005 to be representative of the area from which it originated. The fact that the sample is essentially a regolith breccia (e.g., Warren et al., 1983; Simon et al., 1983) is supportive evidence that this sample does indeed represent a surface unit.

The relevant geochemical data for ALHA81005 are summarized in Table 1 for comparison with similar data derived from the orbital X-ray and γ -ray spectrometers of Apollo 15 and 16. The orbital data were limited to the groundtrack of the Apollo spacecraft (Figure 1). It is particularly significant that the TiO_2 , K_2O , and Th values of the meteorite are markedly lower than both the average and "typical" highlands abundances determined by Taylor (1982) and Korotev et al. (1980) (See Table 1). These low values of the sample indicate that if the composition of ALHA81005 is representative, the source region must be depleted in KREEP-rich lithologies (which contain high abundances of K_2O and Th). Furthermore, MgO values of all measurements for the meteorite are relatively high.

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Both the X-ray and γ -ray results suggest that the entire Apollo groundtrack on the lunar nearside can be ruled out as a likely source region. The Th data alone rule out most regions. The average Th value for the nearside highlands is 1.3 ppm, which reflects the apparent high concentration of KREEP-rich material on the lunar nearside. The Th distribution map prepared by Metzger and co-workers (Plate 2.2, Basaltic Volcanism Study Project, 1981) shows that nearside Th abundances rarely even approach those determined for ALHA81005. On the other hand, Metzger et al. (1977) determined that the average Th values in the farside highland regions range from 0.24-0.84ppm and exhibit an average concentration of 0.5ppm.

Although the Apollo γ -ray experiments provide the only circum-planet data on elemental abundance, a disadvantage of this early data has been its low nominal spatial resolution (~ 200 km mapping resolution). The distribution of Th in certain key highlands regions has thus been subjected to a deconvolution analysis to enhance spatial resolution and contrast. For example while the average Th concentration in the broad central highlands region was determined to be 2.2 ± 0.2 ppm, deconvolution model analysis indicated that Th values in subregions of the central highlands could range from ~ 20 ppm at Davy to <0.2 ppm in an area near Descartes (Metzger et al., 1981). In summary, while areas with the appropriate surface chemistry are extremely limited or non-existent on the nearside, they are much more abundant on the farside at least within the coverage of the Apollo groundtrack.

The existence of a small clast of what seems to be very low-titanium basalt in ALHA81005 (Treiman and Drake, 1983) suggests that the

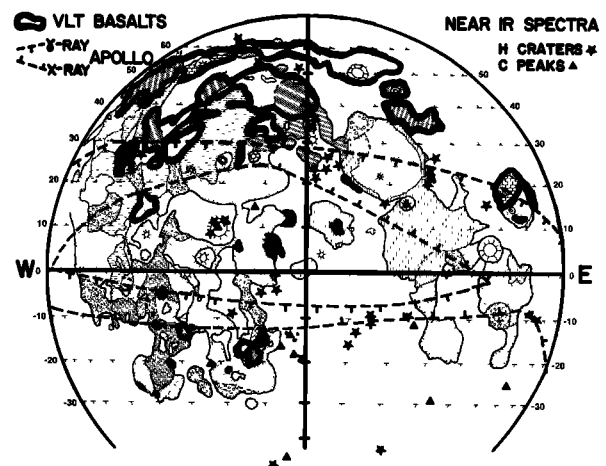


Figure 1. Nearside of the moon showing Apollo orbital groundtrack, distribution of VLT basalts, and general locations of craters studied with near-infrared reflectance spectra.

TABLE 1. Compositional data for ALHA81005 and portions of the lunar surface. All values are weight percent except for Th values, which are ppm. The data in columns A, B, and C are from Lau *et al.* (1983). Column D is from Korotev *et al.* (1983). The Apollo groundtrack average nearside and farside highlands concentrations are from Metzger *et al.* (1977) and Davis (1980). The estimate of the composition of the overall highland crustal surface is by Taylor (1982). The most typical highlands surface composition was determined by Korotev *et al.* (1980).

	ALHA81005				Average Nearside Highlands	Average Farside Highlands	Highland Crustal Composition	Typical Highland
	Bulk A	Matrix B	Clast C	Weighted Mean D				
Al ₂ O ₃	26.3	25.6	25.9	25.1	--	--	24.6	--
MgO	8.0	8.0	9.0	8.8	--	--	6.8	5.4
FeO	5.6	5.6	5.9	5.5	10.0	6.5	6.6	6.2
TiO ₂	0.30	0.30	0.30	0.23	2.1	1.5	0.56	1.5
K ₂ O	0.025	0.025	0.020	<0.04	--	--	0.075	0.076
Th	0.32	0.30	0.25	0.20	1.3	0.54	0.9	0.50

source area of the meteorite should be reasonably close to the source area of the basalt clast since lateral transport of regolith material is relatively inefficient for distances greater than 100 km (summarized by Hörz, 1975). The vast majority of mare basalts occur on the lunar nearside. A wide range of compositions has been observed in lunar basalt samples and a similar range is noted in the remote sensing observations (Basaltic Volcanism, chs. 1 and 2, 1981). The base map for Figure 1 is a summary of basalt types on the lunar nearside (after Pieters, 1978) and the most likely candidates for very low titanium basalts are enclosed with heavy lines (Pieters' units LBSP, LIS-, and LBG-).

This observed distribution of possible VLT basalt units is largely outside of the Apollo groundtrack and is concentrated in the northern hemisphere. It is important to note, however, that small areas of probable VLT basalt occur throughout Oceanus Procellarum and the southwestern maria. These are likely to be earlier basalts that were later covered by basalts of a different composition (e.g., Whitford-Stark and Head, 1980). It is quite possible, if not likely, that a much more extensive area of VLT basalts existed on the lunar surface prior to the late stages of lunar volcanism. The breccia formation age of ALHA81005 will determine the importance of this VLT clast in locating its source.

The detailed petrology of a number of slices through ALHA81005 is described in other manu-

scripts in this issue. Presented here are results of laboratory and telescopic near-infrared spectral reflectance measurements that are used to compare the mineral assemblages observed in the meteorite with those for unsampled areas on the nearside lunar surface.

Cut surface samples of ALHA81005,2 were made available for laboratory reflectance measurements prior to and after thin sections were cut. The exposed surface was relatively flat and contained a random distribution of light clasts in a dark matrix. Bidirectional reflectance spectra were obtained from .4 to 2.6 μ m using the RELAB facility (Pieters, 1983a). Geometry of the measurements was $i = 0^\circ$, $e = 30^\circ$, and effective field of view on the sample was approximately 2 mm. The sample was repositioned frequently to obtain sufficient data to represent the bulk properties of the meteorite. A composite average of the meteorite reflectance relative to the halon standard from .7 to 2.6 μ m (Figure 2) exhibits weak absorption bands near 1 and 2 μ m. Since many key

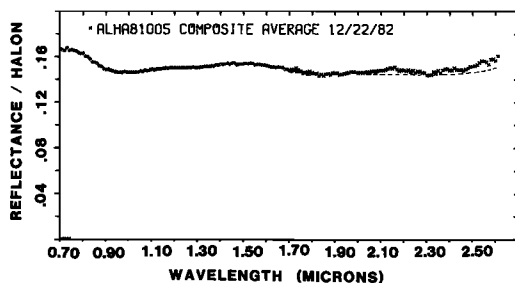


Figure 2. Composite near-infrared reflectance spectrum of meteorite ALHA81005 relative to halon. The dashed line indicates the estimated spectrum after removal of the 2 μ m halon features.

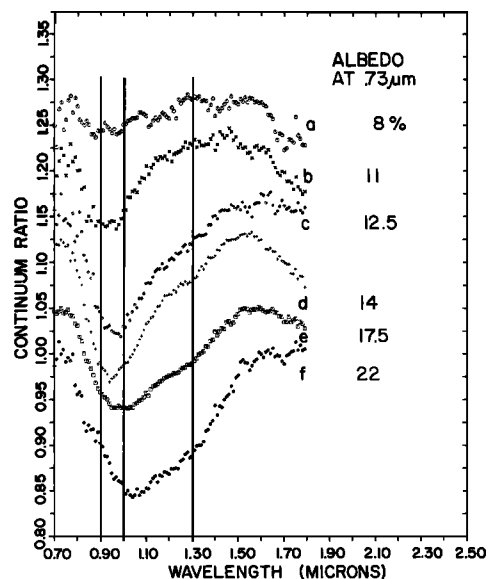


Figure 3. Near-infrared reflectance spectra (after continuum removal) for 2 mm areas of ALHA81005, 2.

Fe^{2+} absorption bands occur near $1\mu\text{m}$, 22 of the 26 data runs obtained were from .7 to $1.7\mu\text{m}$. As is commonly observed for rock or slab spectra, the near-infrared continuum of the meteorite was generally flat or negatively sloped. In order to allow direct comparison of absorption features with telescopic data all spectra were divided by an estimated continuum (straight line tangent at about .73 and $1.6\mu\text{m}$) and the residual absorption features near $1\mu\text{m}$ examined.

Shown in Figure 3 are the range of spectral characteristics for 2 mm areas of ALHA81005 from .7 to $1.7\mu\text{m}$. The spectrum of a clast poor matrix area (3a) is almost featureless and very dark. The absorption bands in all other spectra (3b-3f) arise from the clasts, which also account for the measured higher overall reflectance. These absorption bands can be interpreted directly in terms of the mineralogy of the observed 2 mm area (e.g., see Adams, 1975). The band near $.93\mu\text{m}$ in 2b is indicative of low-Ca pyroxenes. The inflection near $1.3\mu\text{m}$ prominent in spectra 3c and 3d is most likely due to abundant Fe-bearing feldspars. ALHA81005 feldspars are relatively Fe-rich and range from .09 to 0.59 wt% FeO (P. Warren, A. Treiman, pers. comm.). The longer wavelength band center of spectrum 3c indicates a component of more Fe- and Ca-rich pyroxenes. The broad multiple band centered near $1.05\mu\text{m}$ in spectrum 3f is characteristic of olivine. The $1\mu\text{m}$ band distorted toward longer wavelengths of 3e is typical of olivine-pyroxene mixtures with abundant olivine (Singer, 1981).

A single composite spectrum of ALHA81005 was produced by averaging the measured reflectance data of all observed types of material. The continuum removed spectrum shown in Figure 4 is the best estimate of the whole rock near-infrared spectral character for the two sections of meteorite ALHA81005. The effects of individual mineral components are now more subtle, but nevertheless distinct. The observed pair of absorption bands near 1 and $2\mu\text{m}$ in Figure 2 are indicative of the pyroxene component. The band center near $.98\mu\text{m}$ in Figure 4 indicates low Ca pyroxene is not the single mafic component. The distinct asymmetry of the $1\mu\text{m}$ band even near absorption minimum is due to the significant component of olivine in this sample. The strong inflection between 1.1 and $1.5\mu\text{m}$ combines effects of the Fe-bearing feldspar band and the long wavelength

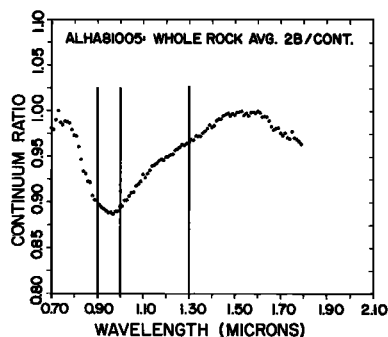


Figure 4. Combined near-infrared spectrum for ALHA81005 (after continuum removal). This spectrum represents the best estimate of properties for the bulk meteorite.

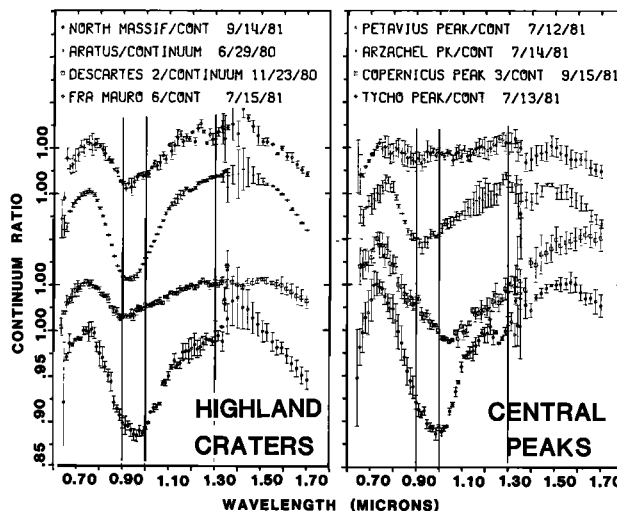


Figure 5. Near-infrared reflectance spectra (after continuum removal) obtained with earth-based telescopes of (left) small fresh highland craters representing four groups of mineral assemblages observed and (right) representative central peaks of large craters.

olivine band edge. Any surface material with mineralogy similar to ALHA81005 would have to exhibit similar spectral characteristics.

Near infrared spectral reflectance measurements have now been obtained for about 150 small lunar areas 3-20 km in diameter, using earthbased telescopes. Initial analyses of these data for highland craters on the lunar nearside have been produced (Pieters, 1983b) and allow direct comparisons with ALHA81005 reflectance measurements. The current distribution of small fresh highland craters whose near-infrared reflectance has been measured is shown in Figure 1 with oversized symbols. Also shown in Figure 1 are the observed large craters with central peaks which contain material uplifted from greater depths.

Examples of four general classes of spectral features for the small impact craters are shown in Figure 5. The first three classes, and the vast majority of nearside highland craters and mountains observed, exhibit an absorption band centered between .90 and $.93\mu\text{m}$, clearly indicating low-Ca pyroxenes as the dominant mafic component. This observation is inconsistent with the properties of ALHA81005. A few small highland craters scattered throughout the lunar nearside exhibit an absorption band longwards of $.95\mu\text{m}$ (Censorinus, Aristarchus- A, Lalande, and a small crater south of Fra Mauro), but none of these craters exhibit all the spectral details of ALHA81005.

Of all the small highland craters studied to date there is no strong candidate for the source area of meteorite ALHA81005. Additional target areas of interest will be included in future studies for the lunar nearside but mineralogical information for the other half of the lunar surface cannot be obtained with earthbased telescopes. Material excavated from depths up to 10 km on the lunar nearside to form the central peaks of large craters (Figure 5) exhibits a somewhat different array of rock types than the

small fresh impact craters, although these large craters are too old (>40 my) to be considered viable sources for the meteorite (e.g., Sutton and Crozaz, 1983).

Summary and Conclusions

The mineral assemblages that can be identified in the near-infrared spectra of ALHA81005 are distinctly different from the bulk mineral character inferred from spectra of small impact craters of the lunar nearside surface. Specifically, no small fresh impact crater observed to date has excavated a mineral assemblage with a component of olivine and Fe-bearing feldspar comparable to that observed for the meteorite. Similarly, the low Th content of ALHA81005 is inconsistent with the measured Th level of almost all the lunar nearside covered by the Apollo groundtrack. The meteorite Th values are more consistent with measured values that occur on the lunar farside. This combined evidence would place the source area of ALHA81005 well away from the nearside central highlands of the moon (which have been sampled by U. S. and Soviet missions). The existence of a basaltic clast in the meteorite, on the other hand, suggests the source area may be close to the lunar nearside. Taken together, the current limited remote sensing information favors a nearside limb or a farside source area for ALHA81005. Stated another way, ALHA81005 is material from a surface unit on the moon that has not previously been extensively sampled by any U.S. or Soviet mission.

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