

**LUNAR METEORITE GEOLOGIC CONTEXT: NEW CONSTRAINTS FROM VNIR SPECTROSCOPY AND GEOCHEMISTRY.** P. J. Isaacson<sup>1</sup>, T. Hiroi<sup>2</sup>, B. R. Hawke<sup>1</sup>, P. G. Lucey<sup>1</sup>, C. M. Pieters<sup>2</sup>, Y. Liu<sup>3</sup>, A. Patchen<sup>3</sup>, and L. A. Taylor<sup>3</sup> <sup>1</sup>Hawaii Institute of Geophysics and Planetology, University of Hawaii, Manoa, Honolulu, HI, 96822, <sup>2</sup>Dept. of Geological Sciences, Brown University, Providence, RI, 02912, <sup>3</sup>Planetary Geosciences Institute, Dept. of Earth & Planetary Sciences, University of Tennessee, Knoxville, TN, 37996, [isaacson@higp.hawaii.edu].

**Introduction:** Returned lunar samples from the Apollo and Luna programs are the primary basis of our understanding of the Moon's thermal and chemical evolution [1]. However, manned exploration was limited in coverage of the lunar surface (~6-8 %). But, the discovery of numerous lunar meteorites has provided "new-sample science" and greatly expanded the "sampled" areas of the Moon. Lunar meteorites have inherent limitations in that their provenances have been speculated on but are largely unknown beyond very broad (hemisphere-scale) estimations. Additionally, and most importantly, several of these meteorite samples appear to have originated from outside the anomalous geochemical region from which the returned samples were collected [2-4].

Most lunar meteorite samples are complex polymict breccias made up of a number of different lithologic components (and often abundant lunar regolith). Bulk measurements of such polymict breccias present only crude "averages" of the distinct components that form the rocks. Whereas pristine rocks can provide clear indications to formational processes and petrologic evolution [e.g., 5, 6], bulk measurements of complex breccias cannot provide detailed insights such as those available from study of the individual lithologic components of the breccia.

Visible to near-infrared (VNIR) reflectance spectroscopy is a powerful tool for investigating the mineralogy of planetary materials, because the properties of absorptions in VNIR spectra are diagnostic of mineralogy and mineral composition [7]. With the advent of high-quality orbital VNIR datasets for the Moon, such absorption features can be analyzed globally. Interpretation of such VNIR data relies largely on ground truth from lunar samples and analogues in which information from laboratory investigations is used to interpret remote observations [e.g., 8, 9].

Here, we present results from a study using laboratory VNIR measurements of the individual lithologic components of a suite of lunar meteorite samples combined with various remote sensing datasets. These lithologic components contain signatures of the geologic processes that formed the minerals and rocks from which the clasts were sourced. Indeed, it is these parent rocks and minerals that are observed through orbital remote sensing as distinct "outcrops" or exposures on the lunar surface – the clasts are assumed to

represent small samples of larger outcrop-scale deposits. Comparisons between the laboratory spectra of the clasts and orbital measurements provide constraints on the geologic context of the clasts, particularly when considered in the context of chemical abundance data.

**Methods:** We acquired laboratory reflectance spectra of selected clasts in the samples in the Brown University RELAB following the approach of Hiroi et al. [10]. We also acquired measurements of particulate samples for the unbrecciated samples. Laboratory data were compared to remote VNIR data collected by the M<sup>3</sup> mission [11]. As direct comparisons between laboratory reflectance spectra and remotely-acquired spectra is very challenging and requires a number of assumptions, we employed band-parameter analysis in which the basic properties of the diagnostic 1  $\mu$ m absorption feature (strength, width, and position) were captured by a fitting procedure. The laboratory spectra were analyzed with the Modified Gaussian Model (MGM) [12], and the remote spectra were evaluated with a quadratic polynomial fitting approach [13].

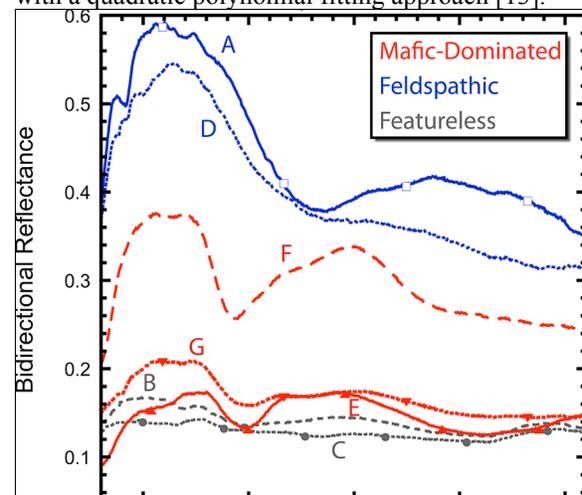


Figure 1: Laboratory VNIR spectra of individual lithologic components (clasts) from ALHA81005. The spectra with clear absorption features (blue, red; A, D, F, G, E) were analyzed with the MGM, and the resulting band parameters were used for comparisons with remote VNIR analyses. "Featureless" spectra (B, C) were not analyzed quantitatively.

In addition to the VNIR analyses, we employed bulk chemical abundance data for additional constraints on the these samples' geologic context. Spe-

cifically, we utilized 0.5°/pixel global maps of Th and FeO abundance produced from Lunar Prospector Gamma Ray Spectroscopy data [14-16]. This approach is hindered by the relatively low spatial resolution of these datasets and the lack of geochemical data for the specific clasts analyzed. This necessitates the use of bulk sample (“whole rock” measurements).

“Matches” were obtained between: 1) regional remote (remote analyses conducted across a series of regions centered on large craters and 2) laboratory values defined by similarity in band position ( $\pm 10$  nm), bulk Th ( $\pm 1$  ppm), and bulk FeO ( $\pm 1$  wt.%). The spatial density of these matches was taken as a proxy for likely geologic context (i.e., more matches in a region indicates a greater consistency between that region and the sample). The constraints were applied sequentially, for each laboratory VNIR spectrum, to arrive at the most constrained case (matches in all three criteria). Finally, matches for all laboratory spectra for a sample (e.g., A, D, E, F, G for ALH) were combined into a composite density/geologic context analysis.

**Results:** Laboratory VNIR spectra for lithologic components for one sample, Allan Hills A81005 (ALH), are shown in Figure 1. There is substantial diversity in these spectra, including pyroxene-rich lithologies (E, F), clear evidence of crystalline plagioclase (A, D), and possible olivine-rich signatures (G). However, several of these spectra exhibit little more than a pronounced negative (“blue”) continuum slope (B, C). These are very challenging laboratory measurements to make, due both to: a) our measurement strategy (spectra were collected from chip surfaces rather than from crushed particulates); and b) the nature of the samples (highly complex and fragmented, with relatively small clasts and abundant glassy, absorbing matrix material). Spectra without diagnostic absorption features (e.g., B, C) were not evaluated with the band fitting procedure and thus were not used in comparisons to the remote analyses. A preliminary density/geologic context analysis for ALH, based on all three constraints and all laboratory spectra, is shown in Figure 2. Note that the results shown here are likely to evolve as the remote analyses are refined.

**Discussion:** Previous analyses of lunar meteorites have attempted to pair laboratory analyses with remote sensing observations to constrain the source region/geologic context of the samples [e.g., 18, 19, 20]. These studies relied primarily on geochemical data such as the Lunar Prospector datasets we employed in our analyses. However, our analyses add the additional element of VNIR spectroscopy. The addition of VNIR spectroscopy offers great potential advances because it provides considerably higher spatial resolution than geochemical remote sensing techniques such as

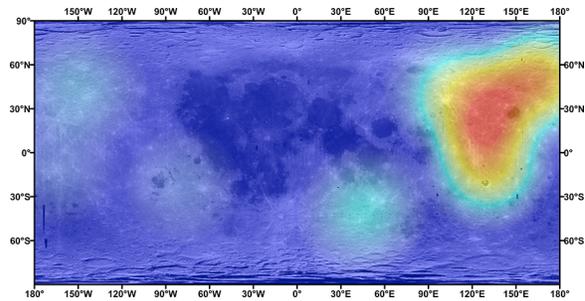


Figure 2: Preliminary density/geologic context analysis for ALH. The map shows the spatial density of matches between laboratory and remote analyses, with greater density in orange-red and low density in blue. Matches for all individual component measurements (A, D, E, F, G in Figure 1) are combined and are defined by all three constraints (band position, bulk Th, bulk FeO) applied sequentially. The map identifies regions most consistent with the sample in these three parameters, and thus regions most likely to provide geologic context for the samples. Note that we do not claim to identify specific source craters.

gamma ray, neutron, and x-ray spectroscopy. There are a variety of limitations to the work presented here; perhaps the most notable is that the remote analyses focus on large craters, whereas lunar meteorites may actually derive from relatively small craters [21]. However, the combined application of diverse remote sensing and laboratory techniques should enable significant new insight into the geologic context and potentially into source regions of these important samples of unexplored regions of the lunar surface. With more refined remote analyses, our approach could potentially constrain the geologic context of these samples at the  $10^2$  km scale.

**Acknowledgments:** The authors acknowledge the support of NNX08AY89G to CMP/PJI. RELAB is a multiuser facility supported by NNG06GJ31G.

**References:** Papike, J.J. et al., in *Planetary Materials*, 5.1-5.234. [2] Korotev, R.L. (2005) *Chemi der Erde*, **65**, 297-346. [3] Warren, P.H. (2005) *MAPS*, **40**, 477, 10.1111/j.1945-5100.2005.tb00395.x. [4] Korotev, R.L. et al. (2003) *GCA*, **67**, 4895-4923, 10.1016/j.gca.2003.08.001. [5] Warren, P.H. (1993) *AM*, **78**, 360-376. [6] Dymek, R.F. et al. (1975) *PLSC*, **6**, 301-341. [7] Burns, R.G. (1993) *Mineralogical applications of crystal field theory*. [8] Isaacson, P.J. et al. (2011) *MAPS*, **46**, 228-251, 10.1111/j.1945-5100.2010.01148.x. [9] Taylor, L.A. et al. (2001) *JGR*, **106**, 27985-28000, 10.1029/2000JE001402. [10] Hiroi, T. et al. (2011) *Pol. Sci.*, **5**, 337-344, 10.1016/j.polar.2011.06.002. [11] Pieters, C.M. et al. (2009) *Current Science*, **96**, 500-505. [12] Sunshine, J.M. et al. (1990) *JGR*, **95**, 6955-6966, 10.1029/JB095iB05p06955. [13] Isaacson, P.J. et al. (2011) *LPSC*, **42**, 2556. [14] Feldman, W.C. et al. (1998) *Science*, **281**, 1489, 10.1126/science.281.5382.1489. [15] Lawrence, D.J. et al. (1998) *Science*, **281**, 1484, 10.1126/science.281.5382.1484. [16] Lawrence, D.J. et al. (2002) *JGR*, **107**, 5130, 10.1029/2001je001530. [17] Isaacson, P.J. et al. (2010) *LPSC*, **41**, 1927. [18] Joy, K.H. et al. (2008) *GCA*, **72**, 3822-3844, 10.1016/j.gca.2008.04.032. [19] Joy, K.H. et al. (2010) *Meteoritics & Planetary Science*, **45**, 917-946, 10.1111/j.1945-5100.2010.01067.x. [20] Arai, T. et al. (2010) *GCA*, **74**, 2231-2248, 10.1016/j.gca.2009.11.019. [21] Warren, P.H. (1994) *Icarus*, **111**, 338-363, 10.1006/icar.1994.1149.