GEOLOGICAL AND SPECTRAL ANALYSIS OF LOW-CALCIUM PYROXENES AROUND THE IMBRIUM BASIN ON THE MOON. Rachel L. Klima (Rachel.Klima@jhuapl.edu)[1], Debra L. Buczkowski[1], Carolyn M. Ernst[1], and Benjamin T. Greenhagen[1]. [1]Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA.

Introduction: As an early crystallizing mineral, orthopyroxene provides important clues for understanding the evolution of the lunar surface, from the earliest magma ocean cumulates, through the anorthositic flotation crust, to later stage intrusive magmatism. Using data from the Moon Mineralogy Mapper (M^3) to search for Mg-suite norites, concentrations of low-Ca, high-Mg pyroxene have been located around the Imbrium and Apollo Basins [1]. These deposits may be exposures of Mg-suite plutons, may represent excavated material from deeper within the primary lower crust or mantle, or may be remnants of melt sheets (differentiated or undifferentiated). Iron-rich orthopyroxenes have been identified elsewhere, in smaller craters throughout the highlands crust. To explore the origin of some of the most prominent of these regions, we integrate hyperspectral data from the Moon Mineralogy Mapper, LROC imaging data and Diviner thermal infrared data to thoroughly map and characterize the mineralogy of the orthopyroxene-rich deposits. Ultimately, we aim to address the following questions: (1) What are the compositions of orthopyroxene-rich deposits exposed on the lunar surface and what is the range in their cooling rates? (2) Is there a relationship between orthopyroxene modal abundance, cooling rate, and specific types of terrain? (3) Is there an association between the cooling rate of orthopyroxenes and their depth of origin in the lunar crust? We focus here on deposits located in the Montes Alpes and Montes Apenninus, surrounding the Imbrium Basin.

Imbrium Basin: The Imbrium basin has been extensively studied for many years [e.g., 2-3]. Though the bulk of the basin is flooded by mare basalts, massifs consisting of more generally feldspathic material surround the edges of Mare Imbrium in the northwest, northeast, and southeast (Fig. 1). Telescopic measurements of Apennine mountains revealed regions spectrally dominated by orthopyroxene or pigeonite [3]. Later radiative transfer modeling of Clementine data suggested that Mg-suite-like norites may surround much of the Imbrium basin [4]. In the initial global survey of norites using M^3 data, the norites modeled to have the highest Mg# were found in the Montes Alpes region near Vallis Alpes [1].

The Imbrium basin is large enough to have excavated between 60-85 km into the Moon [3], deep enough to penetrate through the crust and into the mantle. It is also associated with the strongest thorium detections by Lunar Prospector [5], and is likely to be rich in KREEP [6].

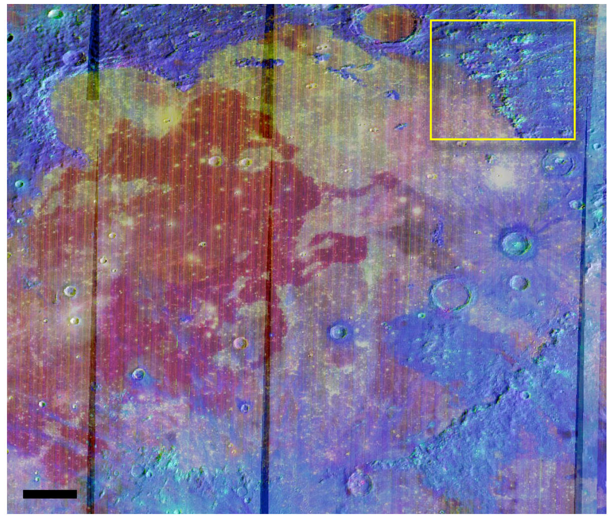

Fig. 1. M3 standard color composite (R=integrated 1 μm band depth, G=integrated 2 μm band depth, B=1.58 μm reflectance). Orthopyroxene-rich regions appear as cyan. The highest concentration of Mg-rich orthopyroxene is in the massifs of Montes Alpes (outlined in yellow). The center of Imbrium basin is located at 32.8°N 15.6°W and the scale bar is 100 km across.

Geological Occurrence of Orthopyroxene-Rich Deposits: Orthopyroxenes around the boundary of the Imbrium basin are primarily associated with material mapped as crater slope material or undifferentiated terra material [eg. 7-8]. This material occurs throughout the Alpes formation, which has been interpreted as deformed pre-Imbrium material, and Fra Mauro formation, which is defined as thick basin ejecta. The massifs in which the orthopyroxenes are found are primarily distinguished from the surrounding formations by their occurrence on steep slopes and their medium to high albedo, and their origin, as currently mapped, may be either uplifted material or crater ejecta. We have identified dozens of LROC narrow-angle camera images covering the most prominent orthopyroxene exposures in the Montes Alpes region. These images are currently being correlated with the M3 data to refine the boundaries of the deposits, and to begin to investigate their specific origin with respect to the impact that formed the Imbrium Basin.

Spectral Properties of Orthopyroxene-Rich Deposits: In parallel with the geological investigation of the orthopyroxene-rich deposits, we are examining the spectral properties of different blocks within the mountains and valley. Shown in Figure 2 are example spectra from outcrops around Vallis Alpes in the Montes Alpes. Compositionally, the orthopyroxenes are generally quite consistent with one another, as evidenced by the positions of the strong absorption bands near 900 and 1900 nm. However, the overall albedo varies among exposures, with the reflectance near 750 nm varying from just below 15% to almost 40%. The observed brightness levels may be due to slight differences in the exposure ages of these deposits, physical mixtures with darker local mare material, or the actual modal mineralogy of the orthopyroxene-bearing (likely noritic) rocks.

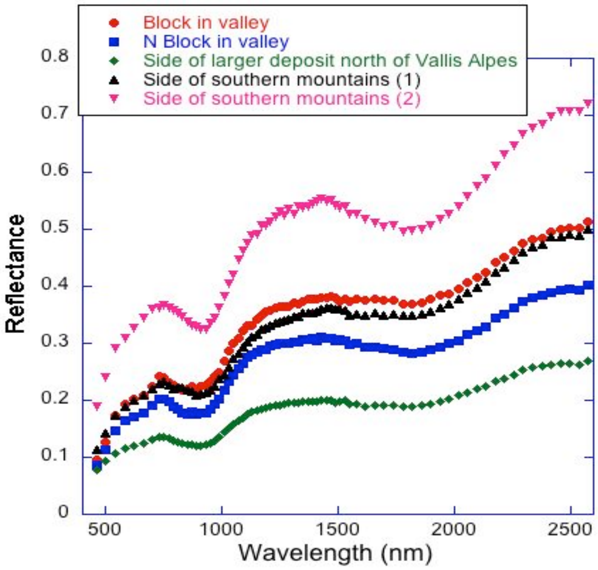

Fig. 2. Example spectra from different geological environments in the Vallis Alpes focus region.

The specific mineralogy and exposure age of the deposits is being investigated by a combination of spectral modeling and by incorporating measurements taken by the Diviner thermal infrared spectrometer. Building on the laboratory work described in [9], we are performing spectral modeling of high-quality orthopyroxene-dominated spectra using the Modified Gaussian Model (MGM) to try to assess the cooling history of the orthopyroxene-rich deposits. The MGM is used to deconvolve a spectrum into a continuum slope and a series of bands that can be directly linked to the crystal field absorptions that produce them [10-11]. The MGM also outputs a wavelength-dependent RMS error, allowing the user to analyze whether additional absorptions are not being accounted for in a given fit. The relationship between the continuum-removed intensity of the absorption band near 1200 nm and that near 2000 nm has been shown to relate to the site occupancy, and thereby the cooling rate, of pyroxenes. An example MGM fit to a laboratory pyroxene is shown in Fig. 3.

To complement our NIR analysis, we will present an initial analysis using Diviner data to analyze the position of the Christiansen feature (CF). The CF shifts in wavelength depending on the silicate polymerization of the bulk rock being measured, and is thus extremely effective at distinguishing relative proportions of minerals in a two-component mixture of a highly polymerized silicate such as anorthite and a less polymerized silicate such as pyroxene. Though fine-grained materials in the NIR and in the vibrational Reststrahlen bands are non-linear, mixing at the CF have been shown to be essentially linear [12]. The assumption of linear mixing of endmember CFs may cause uncertainties in absolute mineral abundances of up to ~10% but will not affect relative abundances between sites [e.g. 13].

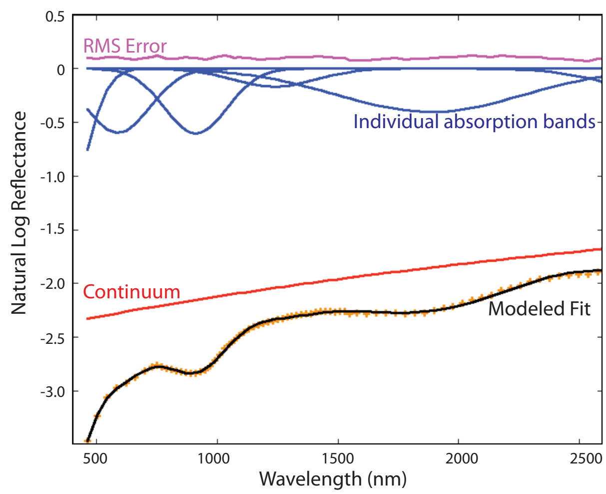

Fig. 3. Example of model fit for M^3 spectrum extracted from Vallis Alpes.

References: [1] Klima, R. L., et al. (2011), J. Geophys. Res., doi:10.1029/2010JE003719. [2] Wilhelms D. E. et al. (1987), The geologic history of the moon, USGS, Washington, D.C.. [3] Spudis, P., et al., (1988), LPSC XVIII, 155-168. [4] Lucey, P. G. and J. T. S. Cahill (2009), LPSC XL, Abstract #2424. [5] Lawrence, D. J. et al. (1998), Science, 281, 1484-1489. [6] Jolliff et al. (2000), J. Geophys. Res., 105, 4197-4216 [7] Page, N. J. (1970) *U.S. Geol. Survey* Map I-666. [8] M'Gonigle, J. W. and Schleicher, D. (1972) *U.S. Geol. Survey* Map I-701. [9] Klima, R. L. et al. (2008), MAPS, 43, 1591-1604. [10] Sunshine, J. M. et al. (1990), J. Geophys. Res., 95, 6955–6966. [11] Sunshine, J. M. et al. (1999), LPSC XXX, Abstract #1306. [12] Arnold, J.A. and Glotch, T.D. (2014), LPSC XLV, Abstract #2470. [13] Greenhagen, B. T. et al. (2014), LPSC XLV, Abstract #2641.

Acknowledgements: We are grateful to the NASA LDAP program for supporting this work under grant # NNX16AN50G.