SPECTROSCOPIC EVIDENCE OF Mg-RICH LOW-Ca PYROXENES ON THE NEARSIDE OF THE MOON. R. L. Klima[1], C. M. Pieters[2], P. J. Isaacson[2], J. W. Head[2], N. E. Petro[3], M. Staid[4], J. M. Sunshine[5], L. A. Taylor[6], [1]JHU/APL, Laurel MD (Rachel.Klima@jhuapl.edu); [2]Brown University, Providence RI; [3]NASA/GSFC, Greenbelt, MD; [4]PSI, Tucson, AZ; [5]University of Maryland, College Park, MD; [6]University of Tennessee, Knoxville, TN.

Introduction: Pyroxenes provide 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 and extrusive magmatism. Though the lunar samples have enabled detailed petrographic and compositional analyses, the majority of regolith samples are brecciated mixtures of clasts from across the lunar surface. Without remote sensing, there would be no way to put the samples into a global perspective. Fortunately, broad lithologies such as the mare basalts and highland anorthosites are easily identifiable, both telescopically and from orbit. However, more specific geochemical groups, such as the Mg suite highlands rocks or chemical groups within mare basalts, are more difficult to distinguish.

Mg-suite rocks, which have been studied in detail in the lunar samples, are hypothesized to have formed as mafic intrusions into the anorthositic primary crust of the Moon. The complex geochemistry of the Mg-suite rocks has been explained by differing amounts of assimilation and mixing of KREEP and anorthositic crust with a magma derived from either the primitive lunar mantle or the LMO cumulate pile [e.g., 1]. The Mg-suite remains enigmatic, and a better understanding of the geographic distribution and compositions of Mg-rich lithologies on the lunar surface would provide valuable constraints on petrogenetic models for intrusive post-LMO lunar magmatism.

On the basis of Clementine and Lunar Prospector data, Jolliff et al. [2] suggested that the Mg-suite is associated only with the Procellarum KREEP Terrane (PKT), which encompasses most of the nearside maria [3]. More recently, candidate Mg-suite locations were identified using radiative transfer modeling of Clementine data [4,5], including a number of sites outside of the PKT.

Methodology: The Moon Mineralogy Mapper (M^3), a visible-infrared imaging spectrometer flown on Chandrayaan-1, imaged the surface of the Moon at 140 meters/pixel using 85 spectral channels from approximately 400-3000 nm in its low resolution global mode, with selected observations at higher spatial and spectral resolution [e.g., 6, 7]. These data provide an opportunity to examine pyroxene compositions across the lunar surface in detail. In a global study we have identified lithologies dominated by strong low-calcium ($Wo_{<15}$) pyroxene spectral signatures, without a significant spectral contribution from other mafic minerals [8]. The Modified Gaussian Model was used to deconvolve the individual absorption bands in the spectra of 20 of the freshest norite exposures and estimate the Mg-Fe composition of the pyroxenes.

Results: Approximately half of the norites identified in [8] are modeled to have Mg#'s (Mg#=Mg/(Mg+Fe)) in the pyroxene of roughly $Mg\#_{50\text{-}75}$. These include norites within the South Pole-Aitken Basin and in the 'North Imbrium Norites' [9]. Norites containing pyroxenes with $Mg\#_{>75}$ were also detected in several regions. The norites with the highest apparent Mg# occur around the Imbrium basin, in the Montes Alpes near where Vallis Alpes meets Mare Imbrium (Figs. 1,2).

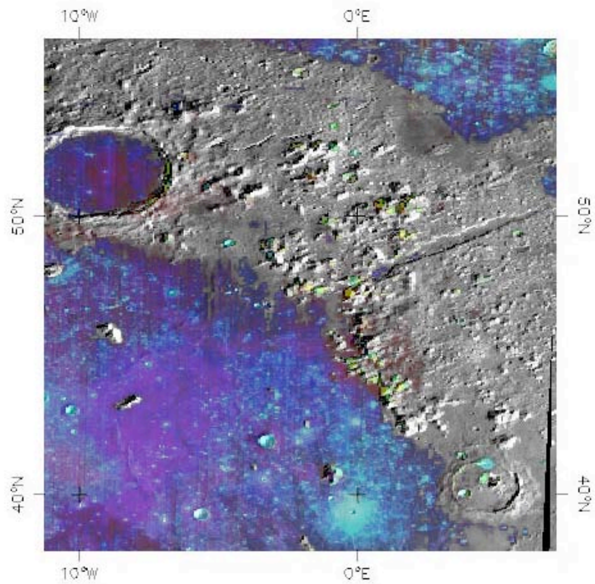

Fig. 1. Context image of the high-Mg, low-Ca pyroxenes near Imbrium. The large crater in the northwest is Plato. A color composite of the mafic mineralogy is overlain on a 2976 nm albedo map to highlight the association of the mafic mineralogies with topography. R=continuum-removed band depth at 1900 nm; G =integrated 2000 nm band depth; B=integrated 1000 nm band depth. Mafic-free feldspathic regions would appear as black in this color scheme, but have been changed to clear. Fresh mare (high-Ca pyroxene-rich) deposits appear as cyan, and norite-rich exposures appear as orange and yellow. The norites are scattered throughout the Montes Alpes and not associated with any small, fresh craters. Image has been binned to 1.4km/pixel spatial resolution.

Shown in Fig. 3 is an example spectrum of the Montes Alpes norites compared with other pyroxenes on the lunar nearside. In general, 1000 and 2000 nm pyroxene absorption bands shift to longer wavelengths with the substitution of Ca and Fe^{2+} for Mg in the pyroxene structure. Orthopyroxenes exhibit bands near 910 nm and 1900 nm, with more Mg-rich pyroxene bands occurring at shorter wavelengths than more Fe-rich pyroxenes. The spectra in Montes Alpes exhibit strong noritic signatures, and the 1000 and 2000 nm bands occur at very short wavelengths bands consistent with high to very high Mg# ($Mg_{>80 \text{ or } 90}$). If olivine were present in these exposures, the 1000 nm band would occur at a significantly longer wavelength, and if more than a small amount (<5-10%) of high-Ca clinopryoxene were present, both the 1000 and 2000 nm bands would also occur at longer wavelengths. The short wavelength positions of these exposures thus suggests that they are both relatively pure norite and high in Mg#.

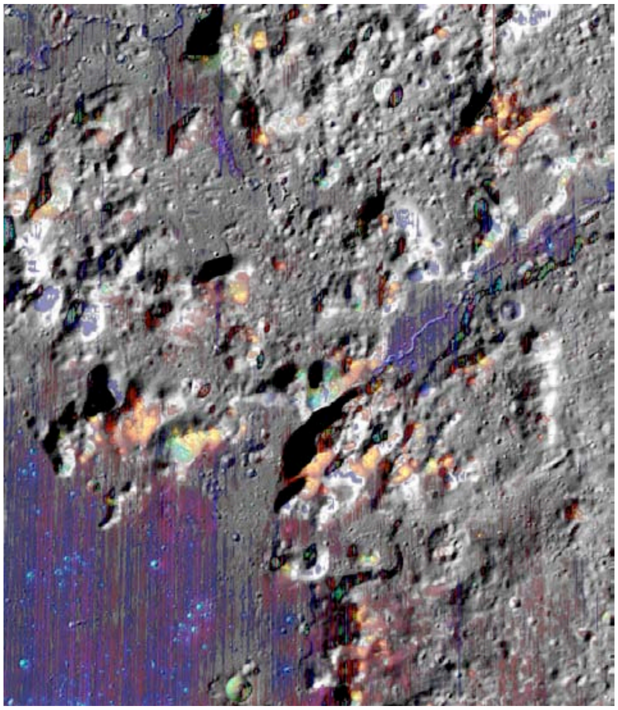

Fig. 2. Higher resolution view of the Mg-rich norites in the Montes Alpes. Colors are the same as as in Fig. 1. Spectrally immature norites (yellow) are concentrated on the sides of the massifs, while basalts extend along the floor of Vallis Alpes. Spatial resolution is 140 m/pixel.

Implications and Ongoing Work: The exposures modeled in this work are located in or near the regions predicted to be Mg-suite like in bulk-rock composition on the basis of radiative transfer modeling of Clementine data [5]. It is encouraging that modal mineralogy estimated from Clementine is consistent with the pyroxene mineralogy derived using M^3 data. Given the coincidence of these low-Ca, high Mg# pyroxenes with the PKT, they are good candidates for excavated KREEP-related, lower crustal Mg-suite pyroxenes. These pyroxenes also occur in close proximity to the olivine exposures found by the Spectral Profiler on Kaguya around the Imbrium Basin [10]. Detailed mapping is currently underway to examine the stratigraphic relationship between the olivines and these norites and to provide additional constraints on whether these are troctolitic and noritic members Mg-suite intrusions or mantle material.

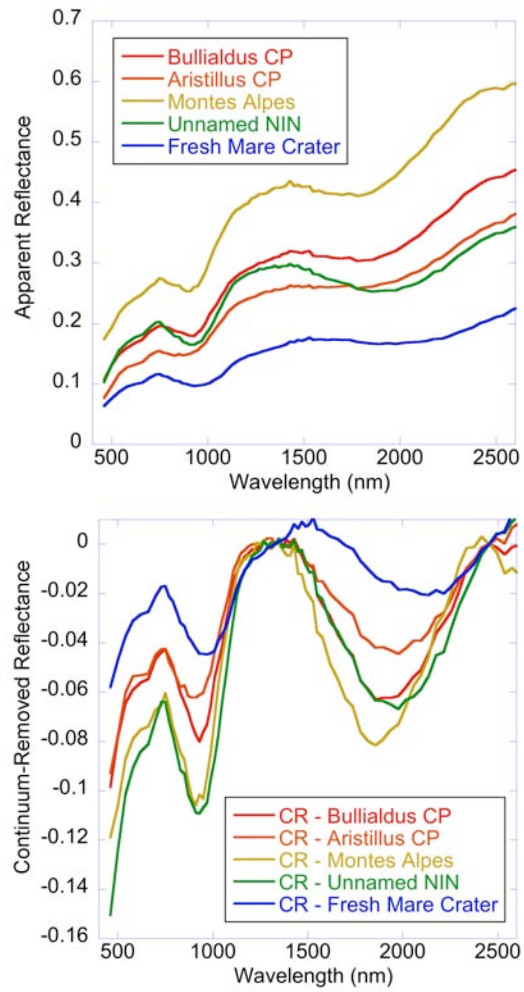

Fig. 3. (A) Examples of pyroxenes from the lunar nearside. The blue spectrum (a mare crater) is shown for comparison to the other four spectra which reflect typical noritic spectral signatures. Among the norites, the Montes Alpes spectra exhibit the shortest wavelength 1000 and 2000 nm absorption band positions. (B) Same spectra with a straight-line continuum removed (line drawn tangent to 1330 and 2460 nm).

References: [1] Shearer et al. (2006) in *New Views of the Moon*. MSA, 365-518. [2] Jolliff et al. (2000) *JGR, 105,* 4197-4216. [3] Wieczorek and Phillips (2000) *JGR, 105,* 20417-20430. [4] Cahill and Lucey (2007) *JGR, 112*, doi 10.1029/2006JE002868. [5] Lucey and Cahill (2009) *LPSC XL*, Abstract# 2424. [6] Pieters et al. (2009) *Science, 326,* 568-572. [7] Green et al. (2011) *JGR, in press*. [8] Klima et al. (2011) *JGR, in press*. [9] Isaacson and Pieters (2009) *JGR, 114*, doi: 10.1029/2008JE003293. [10] Yamamoto et al. (2010) *Nature Geosci. Online,* doi: 10.1038/NGE0897.

Acknowledgements: We are extremely grateful to ISRO for inviting M^3 to travel to the Moon on Chandrayaan-1. This work was partially supported by NASA grants NNX07AP41G and NNM05AB26C.