VARIATIONS IN ANORTHOSITE PURITY AT TSIOLKOVSKY CRATER ON THE MOON. L. C. Cheek,[1] and C. M. Pieters[1], [1] Dept. of Geological Sciences, Brown University, Providence, RI, 02912.

Introduction: Anorthosite is a key rock type in the lunar crust, having formed by the accumulation of buoyant plagioclase crystals during cooling of a global magma ocean early in the Moon's history [e.g. 1-3]. Plagioclase is the dominant mineral in anorthosite (>90% by volume), but variations in the small amounts of pyroxene present in these rocks (always <10% by volume) are related to important aspects of magma ocean crystallization such as melt-solid segregation, cooling rate, and the extent to which these processes were globally homogeneous.

Plagioclase and pyroxene can be distinguished in rocks and soils by characteristic absorptions in the near-infrared (NIR) caused by electronic transitions of Fe^{2+} in specific coordinations. Generally, pyroxene has prominent absorptions at ~1 and ~2 µm due to Fe^{2+} in the M2 octahedral sites, and a weaker band near 1.2 µm due to Fe^{2+} in the M1 site (Fig. 1) [e.g. 4]. The broad plagioclase absorption occurs near 1.25 µm and is likely due to trace amounts of Fe^{2+} in the large, distorted Ca^{2+} site (Fig. 1) [e.g. 5]. Spectral features combine nonlinearly at NIR wavelengths, so that spectra of plagioclase-pyroxene mixtures may not show evidence of plagioclase unless the abundance of pyroxene is <15% [6]. Fortunately, anorthosites are essentially plagioclase-pyroxene mixtures with minimal pyroxene content, such that plagioclase absorptions should be detectable on the lunar surface by NIR spectrometers with appropriate spectral resolution and coverage, such as the MI, SP, and M^3 instruments that flew on the recent Kaguya and Chandrayaan-1 missions [7-9]. These new datasets now permit measurements of small variations in anorthosite "purity", or pyroxene content, across the lunar surface.

This work focuses on anorthosite exposures in Tsiolkovsky crater. The aims include 1) characterizing the spectral variations and their spatial distributions in the central peak, and 2) preliminary estimations of the presence and abundance of pyroxene based on non-linear mixing models applied to laboratory spectra.

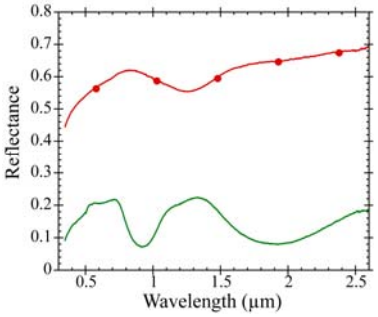

Figure 1 (left): Highland plagioclase with 0.1% FeO (red, circles) and norite orthopyroxene (green, no symbols) spectra from RELAB: LR-CMP-183 and LS-CMP-012.

Tsiolkovsky Crater: Tsiolkovsky is a ~185 km farside crater with steeply sloping central peak ridges exposing fresh material (Fig. 2) that was initially interpreted as olivine-bearing based on 5-band Clementine data with an absorption beyond 1 µm [10]. However, recent SP observations suggest a composition more consistent with a plagioclase-pyroxene mixture [7].

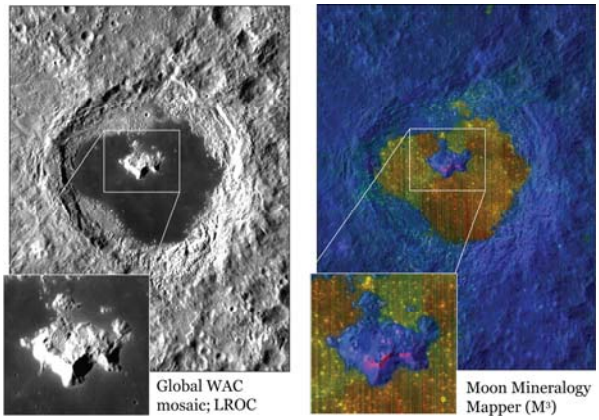

Figure 2. Tsiolkovsky crater shown in LROC WAC (left) and M^3 standard RGB (right). The M^3 image depicts highlands in blue, mare in yellow/orange, and anorthosite in pink.

Mineralogic Variation: M^3 spectra of the ridges nearly all exhibit at least a weak plagioclase absorption near 1.25 µm. An additional band at ~0.98 µm is sometimes present with variable strengths, indicating variable proportions of pyroxene. Spatial relations are coherent: materials with a discernable pyroxene absorption are generally confined to the ridge crests (green in Fig. 3) whereas material with only a plagioclase absorption extend farther down all three of the southern-facing slopes (red in Fig. 3).

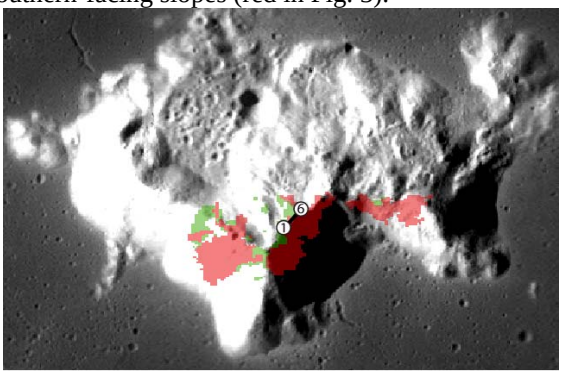

Figure 3. Tsiolkovsky's central peak with different anorthosite mineralogies indicated. Red: no discernable pyroxene absorption, Green: discernable pyroxene. Numbered points correspond to the first and last pixels in Fig. 4 traverse.

Spectra corresponding to a traverse along one of the ridge crests are shown in Fig. 4. Each spectrum represents a single M^3 pixel (~140 m), and they are separated from each other by one pixel. The traverse illustrates that the purest anorthosite occurs in discrete zones, consistent with mineralogical variations on the order of hundreds of meters in the local bedrock. Ongoing analyses will explore the potential contribution of weathering to the observed spectral variations.

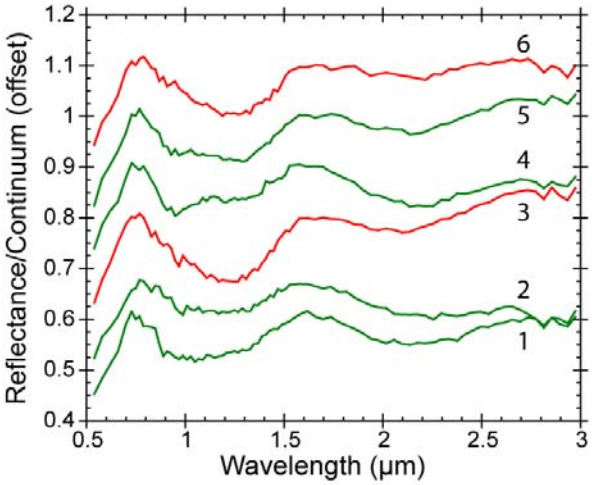

Figure 4. M^3 spectra along the ridge traverse shown in Fig. 3. Spectra for pixels mapped in Fig. 3 as red appear red here. Continuum-removed around 0.75 – 1.6 μm.

Modal abundance calculations: In order to place constraints on the modal abundance of pyroxene in the Tsiolkovsky anorthosites, we have calculated mixtures of laboratory endmember spectra using nonlinear models. Single scattering albedos for the endmember lunar minerals shown in Fig. 1 were calculated from optical constants (*n*, *k*) and combined in various proportions using the equations of [11, 12]. Values of *n* were obtained from [13] for plagioclase and calculated based on [14] for pyroxene. Values of *k* for both minerals were calculated using [15]. The single scattering albedos for the mixtures were converted to reflectance [11] and plotted in Fig. 5.

For mixtures with highland plagioclase (low FeO content), a 1 μm pyroxene band is discernable even at the 2% level, in agreement with estimations by [5]. Spectra obtained remotely from a planetary surface cannot be quantitatively compared with the calculated reflectances of laboratory spectra unless additional simplifying assumptions are incorporated into the equations of [9, 10]. However, a qualitative assessment of the spectral shapes in Fig. 5 suggests that the anorthosite exposed along the traverse in Fig. 3 varies in pyroxene content by several percent over a few hundred meters.

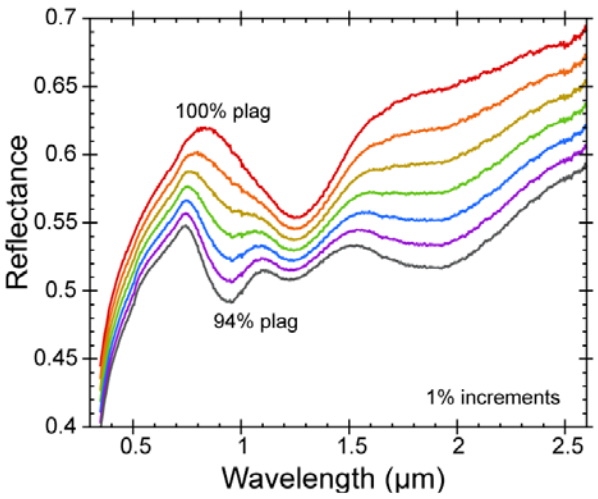

Figure 5. Calculated plagioclase-pyroxene mixture spectra of lunar minerals in Fig. 1 with intervals of 1% pyroxene.

Conclusions: M^3 spectra with detectable plagioclase and pyroxene absorptions confirm that the central peak of Tsiolkovsky exposes anorthosite. The data indicate that regions with the highest plagioclase content are spatially distinct from the more pyroxene-rich compositions, possibly suggesting hundred-meter scale variation in the mineralogy of the anorthositic bedrock sampled by the Tsiolkovsky impact. Comparison with calculated mixtures of sampled lunar minerals indicates that the Tsiolkovsky exposures may vary in pyroxene content on the order of ~5% percent, and confirms that NIR observations can measure percent-level variations in pyroxene content over the range expected for lunar anorthosite.

References: [1] Wood J. A. et al. (1970) *PLPSC 11th*, 965–988. [2] Dowty E. M. et al. (1974) *EPSL, 24*, 15-25. [3] Warren P. H. (1990) *AM, 75*, 46-58. [4] Hazen R. M. et al. (1978) *PLPSC 9th*, 2919-2934. [5] Bell P. M. and Mao H. K. (1973) *GCA, 37*, 755-759. [6] Crown D. A. and C. M. Pieters (1987) *Icarus, 72*, 492-506. [7] Matsunaga T. et sl. (2008) *GRL, 35*, L23201 [8] Ohtake M., et al. (2009) *Nature, 461*, 236-240. [9] Pieters C. M., et al. (2009) *LPS XXXL*, Abstract #2052. [10] Pieters, C. M. and S. Tompkins. (1999) *JGR, 104*, 21935-21949. [11] Hapke, B. (1981) *Bidirectional Reflectance Spectroscopy, 1*. [12] Hapke, B. (1993) *Theory of Reflectance and Emittance Spectroscopy*. [13] Egan W. G. and T. Hilgeman (1973) *Astr. J., 78*, 799-804. [14] Lucey P. G. (1998) *JGR, 105*, 1703-1713. [15] Shkuratov, Y. L., et al. (1999) *Icarus, 137*, 235-246.

Acknowledgements: The M^3 team is grateful for the opportunity to participate in the Chandrayaan-1 mission. This work has been supported by NASA grants NNX07AP41G and NNM05AB26C.