

**PETROLOGIC IMPLICATIONS OF MARTIAN IGNEOUS CRUSTAL FORMATION BASED ON REMOTE OBSERVATIONS.** J. R. Skok<sup>1</sup>, J. F. Mustard<sup>2</sup>, L.L. Tornabene,<sup>3</sup> S. Karunatillake<sup>1</sup>, <sup>1</sup>Department of Geology and Geophysics, Louisiana State University, Baton Rouge, LA 70803 <sup>2</sup>Department of Geological Sciences, Brown University, Providence, RI 02912, <sup>3</sup> Department of Earth Sciences, Western University, London, Ontario. (jskok@lsu.edu).

**Introduction:** On a single-plate planet, such as Mars, the early igneous crust should be preserved beneath its modified, altered and brecciated surface. Well-preserved impact craters have the potential to excavate and exposed this buried material for remote observation and analysis. We present here the synthesis of the analyses of 23 crater central peaks [1] with the Modified Gaussian Method (MGM) [2,3,4] on hyperspectral observations from the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) [5]. MGM modeling allows major element cation ratios to be determined for the primary mafic minerals of olivine (Mg-Fe) and pyroxene (Ca-Mg-Fe). These specific cation values provide insight into the petrogenesis of the primary crust, as well as providing a starting point (i.e., parent composition) towards determining the alteration history of this crust.

**Remote Observations of the Ancient Martian Crust:** Observations from crater central peaks show excavated blocks with strong mafic spectral signatures that are either olivine or pyroxene dominated with no significant spectral mixing [1]. These minerals are detailed below.

**Olivine.** Outcrops dominated by olivine-bearing spectra were detecting in 17 of the examined central peaks with 126 isolated exposures modeled for composition (Table 1) [1]. Olivine-dominated central peaks show a distribution from strongly fayalitic to moderately forsteritic with most examples strongly enriched in Fe. Strong olivine signatures are typically seen in relatively light-tone outcrops of bedrock and in some cases deposit (impact melt or talus) that have abundant light-toned clasts (Figure 1).

	# Regions	Fo# Range	Fo# Mean	Fo# SD
North Of Argyre	18	7-70	34	23
North Of Hellas	15	8-38	18	7
Nili Fossae	6	5-14	10	4
Northern Plains	87	7-58	32	15

Table 1: Summary table of observed olivine units. For each region we list the number of regions examined, the full range of Fo#, the mean Fo# and the standard deviation of the Fo# values.

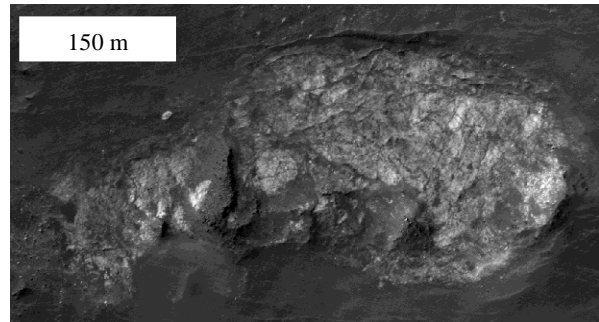


Figure 1: Light-toned olivine deposits near the central peak of Alga Crater (24.34°S, 26.65°W), North of the Argyre region. The light-toned and fractured nature of this crater exposed deposit is the most common expression of the olivine-bearing units. North is up (HiRISE: PSP\_007573\_1555)

**Pyroxene.** Outcrops dominated by pyroxene-bearing spectra are observed in 19 of the central peaks with 120 exposures modeled for composition (Table 2) [1]. The modeled results indicate that the samples from the heavily-cratered Southern Highlands are enriched with low-calcium pyroxene (LCP), with a slight enrichment in high-calcium pyroxene (HCP) in the Northern Lowlands that may be due to mechanical mixing with the wide spread surface basalts during impact excavation. The pyroxene-bearing deposits are commonly associated with fractured, blocky (Figure 2) or tabular surface expressions.

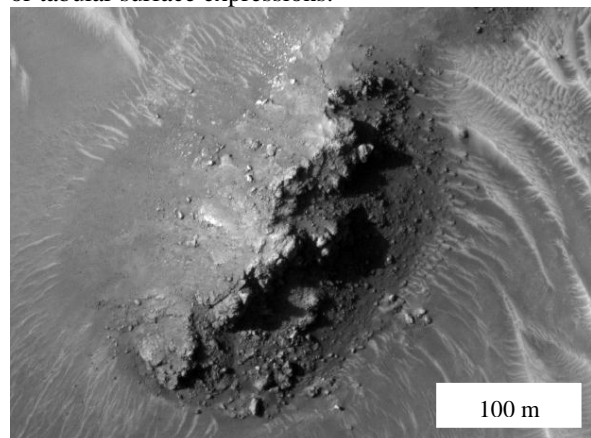


Figure 2: Pyroxene-bearing deposit from the central peak of Hargraves Crater (20.76°N, 75.81°E) in the Nili Fossae Region. Pyroxene deposit typically have fractured, blocky textures with no discernible albedo differences. North is up. (HiRISE: PSP\_009639\_2010)

	# of Regions	1 $\mu$ m NBSR	1 $\mu$ m NBSR SD	2 $\mu$ m NBSR	2 $\mu$ m NBSR SD
North Of Argyre	32	0.65	0.14	0.62	0.09
North Of Hellas	46	0.56	0.09	0.60	0.07
Nili Fossae	12	0.55	0.08	0.59	0.02
Northern Plains	30	0.46	0.07	0.54	0.09

Table 2: Pyroxene compositions from impact excavated crust in terms of Normalized Band Strength Ratio (NBSR) is the modeled cation ratio given in terms of (LCP/LCP+HCP) [4], ranging from all LCP at 1.0 to all HCP at 0.0 with 0.50 indicating an even mix.. The columns list the number of exposures sampled in each region, the mean NBSR of the 1  $\mu$ m band, the 1  $\mu$ m NBSR standard deviation, the mean NBSR of the 2  $\mu$ m band, and the 2  $\mu$ m NBSR standard deviation.

The absence of mafic spectral mixing and the observed compositions indicate that the crustal formation process that created the early crust underwent significant mineral segregation to create spatially separate iron-rich dunite and low calcium pyroxenite material. Compositional segregation is best explained with wide scale differentiation from adiabatic melting in a rising mantle diapir driven by mantle overturn [1].

**Petrographic Interpretation:** Once the mafic cation composition has been determined with spectral modeling, the results are applied to petrologic understanding based on terrestrial experiments. This step is complicated by the systematic differences between the Earth and Mars. For example, all observations of Martian olivine (remote spectral, in-situ, and samples) have indicated minerals ranging from fayalite to only moderately forsteritic [6]. On earth, mantle and basaltic olivine are strongly forsteritic with fayalite being relatively rare. This discrepancy could be caused by sampling bias, lower temperatures of crystallization or a Fe-enrichment throughout Mars. Despite this, a terrestrially derived petrologic understanding, modified with the planetary caveats, is used to interpret the Martian crustal observations.

**Olivine:** The typical crystallization pathway for a mafic magma would cool to the compositionally dependent olivine liquidus (up to 1890°C for Mg-rich magmas) and produce olivine crystals enriched in Mg compared to the melt. This would lower the Fo# of the remaining melt, which produces increasingly Fe-rich olivine crystals [7]. However, experimental work has shown that the precise cation ratio is also a function of related variables of pressure and temperature of crystallization [8]. Primary olivine of a generally low Fo# [6] would suggest crystallization from a magma enriched in Fe at relatively moderate temperatures (e.g., ~1500-1600°C). The effects of pressure and the planet-wide spatial properties on the crystallization of olivine is currently under further investigation.

**Pyroxene:** Pyroxene crystallization typically begins at lower temperatures than olivine (~1400°C) with initial crystal formation favoring Ca-poor, Mg-rich enstatite. Continued crystallization and cooler temperatures will then allow additional Fe and eventually Ca into the pyroxene structure [7]. Pyroxene compositions may be used as a geothermometer due to the well-constrained temperature dependency [10]. Generally, the higher the proportion of LCP observed, the higher the temperature of crystallization [11]. The effects of pressure are again a complicating variable for the compositional results. The composition differences of observations based on location will produce a global map of melt composition and inferred crystallization history.

**Conclusions:** The determination of mafic mineral cation ratios from remote sensing observations of crater central uplifts is the first step toward applying experimentally derived mineralogical understanding the formation of the Martian crust. To these observations, we seek to apply an experimentally-derived understanding of mafic mineral crystallization.

From this work we report the following initial results: 1) The observation that crater-exposed crustal blocks are either dominated by olivine or pyroxene. 2) these samples of the deeply-seated crust do not show evidence of significant spectral mixing, and indicate that the Martian crust contains large regions of highly differentiated units of dunite and pyroxenite. 3) The dunite compositions range from low to moderate Fo#. This may be due to high melt Fe content, low crystallization temperatures or high crystallization pressures [8], with melt composition and temperature having the greatest effect. 4) The crater-exposed pyroxene is dominated by a low-calcium endmember throughout the Southern Highlands and is the expected result from a relatively hot magma and the early instance of crystallization. Enrichment in high-calcium pyroxenes in the Northern Lowlands could be due to cooler crystallization temperatures or a consequence of surficial mixing with a basaltic upper crust.

Additional interpretations based on the spatial distribution of the observed crustal compositions will be presented along with a detailed analysis for each of the spectrally model crustal observation.

**References:** [1] Skok J.R. et al. (2012) *JGR*, 117, E00J18. [2] Sunshine, J.M and C.M. Pieters (1993) *JGR*, 98, 9075-9087. [3] Sunshine, J.M and C.M. Pieters (1998) *JGR*, 103, 13,675-16,688. [4] Kanner et al., (2007) *Icarus*, 187, 442-456. [5] Murchie et al., (2007) *JGR*, 112 E05S03 [7] Winter, J.D. (2001) *Prentice Hall*. [8] Ulmer, P. (1989) *Contrib Mineral Petrol Sci.*, 32, A74. [6] McSween et al., (2006) *JGR*, 111. [10] Lindsley D. H. (1983) *Am Min*, 68, 477-493. [11] Baratoux et al., (2011) *Nature*, 472, 338-341.