

ANCIENT MARS CRUST FORMATION: OBSERVATIONS FROM CRATER CENTRAL PEAKS. J.R. Skok¹, J.F. Mustard¹, ¹Brown University, Dept. of Geological Sciences, Providence, RI John_Skok@Brown.edu.

Introduction: The formation and nature of the ancient igneous crust of Mars is poorly understood. Extensive resurfacing, alteration and modification have limited the surface exposures of the ancient crust. Recent high-resolution spectral observations allow the detection and analysis of preserved deep crustal material that have been exposed in excavated crater central peaks. Observations of this ancient crust show Fe-rich dunite and orthopyroxenite cumulates in close proximity. Global occurrences of these units suggest a formational model where early mantle melting created a thick near-surface layered mafic cumulate crust highly enriched in Fe. Extensive brecciation and burial of this crust would explain current observations of the central peak materials.

Methods: We analyzed visible and near infrared (VNIR) observations from the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) instrument [1]. Mafic parameter maps of crater central peaks were used to determine the presence and distribution of olivine and pyroxene mineral deposits [2,3]. High-quality spectra were extracted from these mafic regions for spectral analysis to determine cation composition.

Modified Gaussian Model (MGM). The mafic olivine and pyroxene spectra were quantitatively analyzed with the MGM [4,5,6] that models the crystal field absorptions in the spectra. The modeled bands were compared to laboratory derived relationships to determine cation compositions [5,6].

Olivine's broad 1 μm absorption is due to three overlapping crystal field absorptions, the centers of which vary systematically with Fe-Mg proportions. Modeling the bandcenters allow determination of the mineral Fo# ($\text{Mg}/(\text{Mg}+\text{Fe})$) [6,7]. Pyroxenes have well-characterized crystal field absorptions near 1 and 2 μm that vary with the proportions of Ca, Fe, and Mg in the minerals where the bandcenters are shortest for Mg, increase slightly with Fe and rapidly with Ca. Pyroxenes are modeled in two ways; first with one Gaussian for each the 1 and 2 μm absorption bands and second with a high- (HCP) and low-calcium (LCP) endmember for both the 1 and 2 μm feature. The first method allows comparison to pyroxene band position systematics assuming a single pyroxene is present, and provides a general understanding about cation composition. The second method uses the concept of the normalized band strength ratio (NBSR: $\text{LCP}/(\text{HCP}+\text{LCP})$) providing a value ranging from 0.0 (pure HCP) to 1.0 (pure LCP) [8].

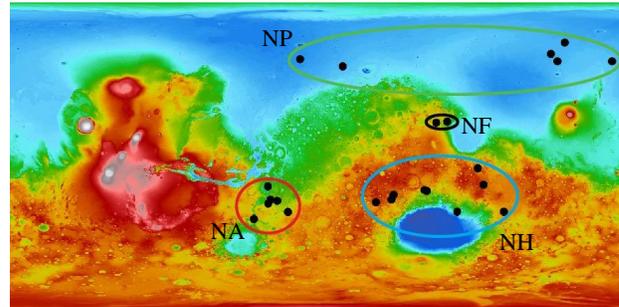


Figure 1: Locations of analyzed unaltered central peaks. Sites are naturally divided into four groupings, North of Argyre (NA), North of Hellas (NH), Nili Fossae (NF), and the Northern Plains (NP).

Results: CRISM observed crater-exposed bedrock exposures were examined for high-quality, unaltered mafic spectra. Out of ~150 possible locations [9], we report on 23 central peaks with well-exposed mafic outcrops. The global distribution of these observations shows concentrations in four general geographic regions that we will separate for regional comparison. We term these regions North Argyre (NA), North Hellas (NH), Nili Fossae (NF) and Northern Plains (NP) (**Figure 1**). As the cratering process is randomly distributed globally, the observation distribution is a function of current CRISM observations, dust cover, alteration, and central peak preservation potential. **Table 1** lists the distribution totals in each region. In each case, the central peak mafic units show deposits of olivine-bearing material or pyroxene-bearing material, with little evidence for mixing between pyroxene and olivine (**Figure 2**). While analysis of the observations cannot rule out significant contributions from minerals that do not have absorptions in this wavelength region (e.g. plagioclase or minor contributions from mafic minerals), the spectra are consistent with mafic purity toward 90% of the spectrally dominant mineral, indicating dunite and pyroxenite lithologies.

Mafic modeling of unit spectra from each central peak shows both local and global trends. Olivine Fo# values range from ~60 (moderately forsteritic) to ~5 (fayalitic) (**Figure 3**). For the NP and NA regions, the modeled compositions span this range, while NF and NH have Fo# concentrated in the fayalitic range. Pyroxene units for all the southern highland sites have a NBSR values focused near 60 (moderately LCP-rich) and range toward more LCP-rich. These values are consistent with values of Noachian pyroxene terrains seen throughout surface deposits [10,11]. The NP sites have pyroxene values that range from NBSR of 60 to

moderately HCP-enriched values of 40. This could be an impact mixing signature from the HCP-rich basaltic resurfacing of the NP. Attempts to correlate composition with depth of excavation and elevation failed to produce discernible relationships.

Table 1: Distribution of sites among regions and presence of Olivine, Pyroxene or both within each site.

Site	OI-Pyx	OI	Pyx	Total
North Argyre (NA)	3	1	2	6
North Hellas (NH)	5	0	4	9
Nili Fossae (NF)	2	0	0	2
Northern Plains (NP)	1	3	2	6

Discussion: Two major observations are evident from spectroscopic analysis of these Martian crater central peaks: that the outcrops tend to be either strongly olivine- or pyroxene-bearing with little evidence of mineral mixing and that compositional analysis shows a wide range of olivine compositions from moderately forsteritic to highly fayalitic while pyroxenes are consistently modeled to be Fe-rich and Ca-poor.

These observed Martian mafic compositions are similar to the well-studied terrestrial values of the Upper unit of the Bushveld layered mafic intrusion [12]. Cumulate segregation and crystallization lead to stratified mineral units, olivine ranging from intermediate (Fo43) to fayalitic (Fo5) and intermediate ferrosilite (Fe-rich orthopyroxene) in the Upper Unit of the Bushveld.

Proposed Crustal Formation Model: Martian planetary formation is modeled to begin with a magma ocean that would crystallize and settle out Mg-rich olivine and pyroxenes. Late stage crystallization of Fe-rich minerals would create a density inversion that would be corrected in an overturn [13]. This overturn would lead to extensive decompression melting from rising diapirs of Mg-rich minerals that would erupt in large igneous provinces or in serial magmatic intrusions [14]. The large volumes of magma would experience crystal settling and segregation into units 1000's of meters thick. High impact fluxes in early Martian history would lead to extensive brecciation and spatial mixing of the segregated lithologies. Later volcanic resurfacing and alteration would create the modern surface where late stage impacts can excavate and expose these ancient crustal breccias in the central peaks.

Conclusions: Observations of Martian crater central peaks reveal deeply excavated materials preserved from the ancient crust. These materials are predominately dunite and orthopyroxenite lithologies with high-Fe compositions. Exposures includes clasts 100's of meters or more, indicating thick cumulate layers and a voluminous magma body. Fractional crystallization and crystal settling are the best explanation for the

range of compositions and globally occurring segregated units.

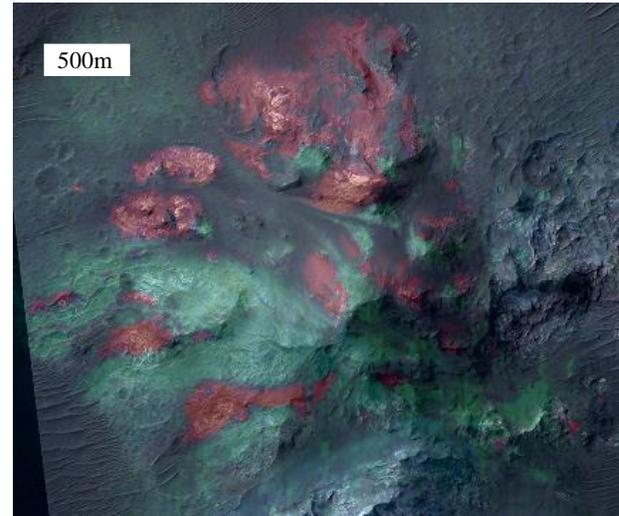


Figure 2: Alga crater central peak (24.3°S, 26.7°W) CRISM mafic parameters on HiRISE. Olivine (red) and Pyroxene (green) units show sharp division between lithologies.

Collected Central Peak Olivine Composition

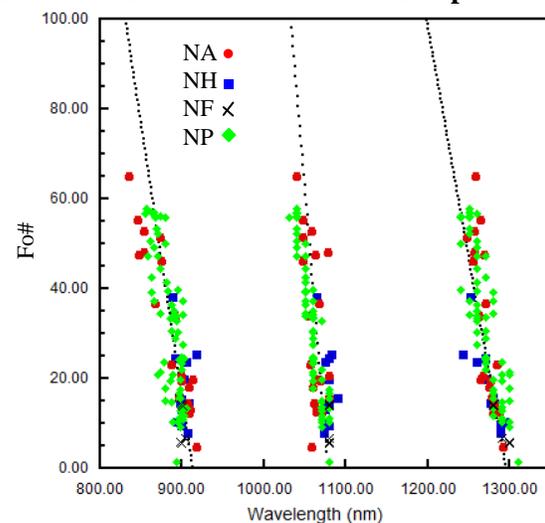


Figure 3: Distribution of olivine compositions show full distribution from intermediate forsteritic to fayalitic. NA:Red circles, NH:Blue squares, NF:Black X, NP:Green diamond.

References: [1] Murchie et al. (2007) *J. Geophys. Res.*, 112 E05S03 [2] Pelkey et al. (2007) *J. Geophys. Res.*, 112, E08S14 [3] Salvatore et al. (2010) *J. Geophys. Res.*, 115, E07005 [4] Sunshine et al. (1990) *J. Geophys. Res.* 95, B5, 6955-6966. [5] Sunshine and Pieters (1993) *J. Geophys. Res.* 98, E5, 9075-9087 [6] Sunshine and Pieters (1998) *J. Geophys. Res.* 103, E6, 13675-13688. [7] Isaacson et al. (2011) *J. Geophys. Res.*, 116, E00G11. [8] Kanner et al. (2007) *Icarus* 187, 442-456 [9] Tornabene et al. (2012) *3rd Early Mars Conf.* [10] Mustard et al. (2009) *J. Geophys. Res.*, 114 E00D12 [11] Poulet et al. (2009) *Icarus*, 201, 84-101 [12] Cawthorn (1996) *Layered Intrusions*. [13] Elkins-Tanton et al., (2005) *J. Geophys. Res.*, 110, E12S01 [14] Longhi (2003) *J. Geophys. Res.*, 108, E8, 5083.