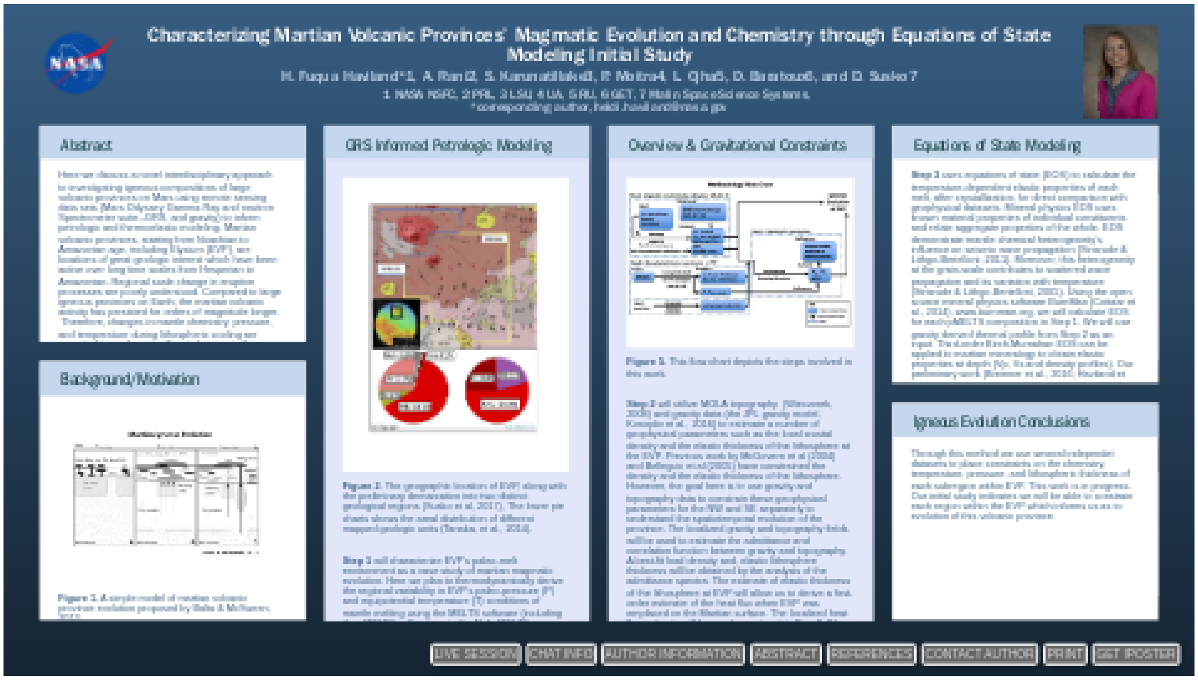
Characterizing Martian Volcanic Provinces' Magmatic Evolution and Chemistry through Equations of State Modeling Initial Study



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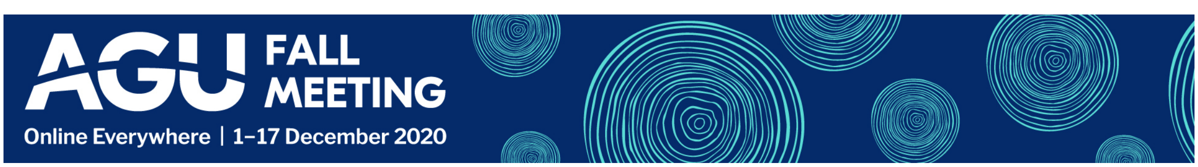

ABSTRACT

Here we discuss a novel interdisciplinary approach to investigating igneous compositions of large volcanic provinces on Mars using remote sensing data sets (Mars Odyssey Gamma Ray and neutron Spectrometer suite--GRS, and gravity) to inform petrologic and thermoelastic modeling. Martian volcanic provinces, starting from Noachian to Amazonian age, including Elysium (EVP), are locations of great geologic interest which have been active over long time scales from Hesperian to Amazonian. Regional scale change in eruptive processes are poorly understood. Compared to large igneous provinces on Earth, the martian volcanic activity has persisted for orders of magnitude longer. Therefore, changes in mantle chemistry, pressure, and temperature during lithospheric cooling are expected to produce significant changes in the conditions of magma production, storage and ascent, affecting the degree of fractional crystallization and crustal contamination. In this study, we perform a detailed modeling to test the hypothesis that compositional variability within volcanic provinces resulted from spatiotemporal changes in the depth of magma formation and present initial results. Our methods include constraining the pressure and temperature conditions of EVP as a case study of geologically recent magmatic evolution on Mars using GRS informed surface chemistry constraints and pMELTS modeling. Second, we place constraints on the density and seismic velocities of the EVP melt through thermoelastic modeling with a local gravity analysis. This analysis is also extended to Noachian aged volcanic provinces on Mars initial results estimates mantle pressure for each sub-region is 16 kbar pressure, whereas, degree of partial melting is low and varies between 10 to 12. This study aims to validate our theoretical model and develop a perspective view of spatiotemporal changes at the interior of Mars throughout the time.

BACKGROUND/MOTIVATION

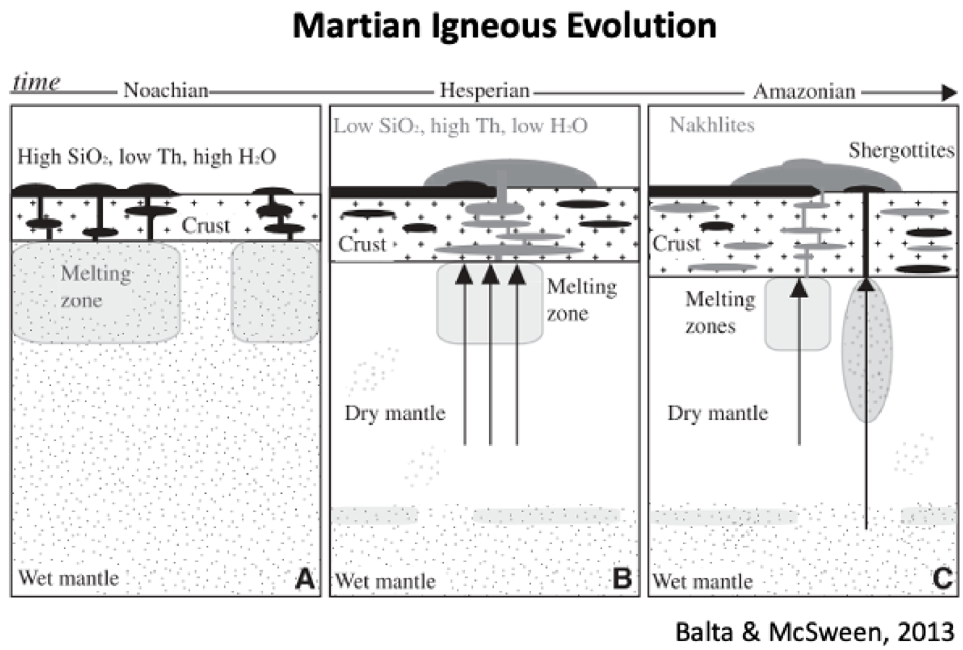

Figure 1. A simple model of martian volcanic province evolution proposed by Balta & McSween, 2013.

The Elysium volcanic province (EVP) is the major isolated volcanic landscape in the martian lowlands. EVP is notable not only for the presence of three shield volcanoes, Elysium, Alber, and Hecates, but also for some of the most recent eruptions on the planet, with some interpretations suggesting activity even in the last few million years (Vaucher et al., 2009). In addition to the striking overlap between southeast (SE) Amazonian lava flows and a chemical province (Karunatillake et al., 2009), we have shown a compositional transition in Elysium's volcanism coupled to differences in geologic age between northwest (NW) and SE regions (Susko et al., 2017) (mapped Geology, Fig.2). The continuity of volcanic activity and the notable spatiotemporal changes in the abundance of heat-producing radioactive elements (K and Th) along with others (Al, Ca, and Fe in particular) make this region an ideal case study for the evolution of individual volcanic provinces on Mars (Karunatillake et al., 2009; Susko et al., 2017). However, even the first-order regional-scale changes in eruptive processes of any given martian volcanic province over geologic time are still poorly understood (Baratoux et al., 2011 (B11); El Maarry et al., 2009 (EM09)). Related first-order investigations are crucial for understanding how the martian interior has evolved in the absence of Earth-like plate tectonics. Consequently, our goal is to advance previous work along with petrological and thermoelastic data analyses to test the emerging hypothesis that regional geochemical trends resulted from spatiotemporal changes in EVP's depth of melt formation.

GRS INFORMED PETROLOGIC MODELING

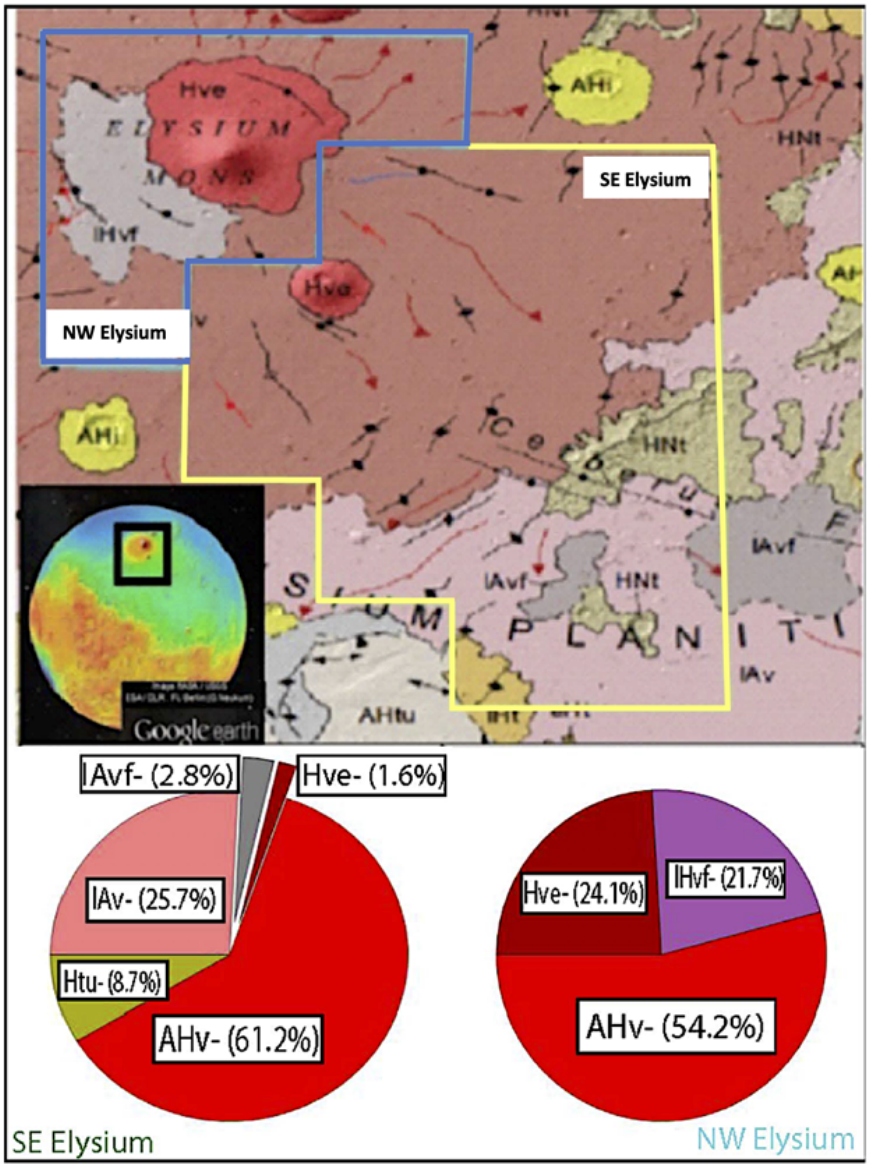

Figure 2. The geographic location of EVP, along with the preliminary demarcation into two distinct geological regions (Susko et al, 2017), The lower pie charts shows the areal distribution of different mapped geologic units (Tanaka, et al., 2014).

Step 1 will characterize EVP's paleo-melt environment as a case study of martian magmatic evolution. Here we plan to thermodynamically derive the regional variability in EVP's paleo-pressure (P) and equipotential temperature (T) conditions of mantle melting using the MELTS software (including the pMELTS calibration via the AlphaMELTS interface, https://magmasource.caltech.edu/alphamelts/) (Balta and McSween, 2013; Smith and Asimov 2005) to determine P and T of EVP's mantle melts. For the required initial parameter space, we will use a range of H2O mass fractions, 39 ppm, 185 ppm, 1800 ppm, for mantle hydration (c.f., McCubbin et al., 2016; Filiberto et al., 2016), and the latest bulk silicate compositional model (Taylor, 2013). pMELTS compositional output for single step melt and eruption can then be compared with the regional chemistry as represented by seven oxides (SiO_2, FeO, Al_2O_3, CaO, K_2O, TiO_2, and MgO) mass fractions derived from GRS data.

The plots below are from previous work demonstrating the steps and outputs from Step 1 which is being updated by this project.

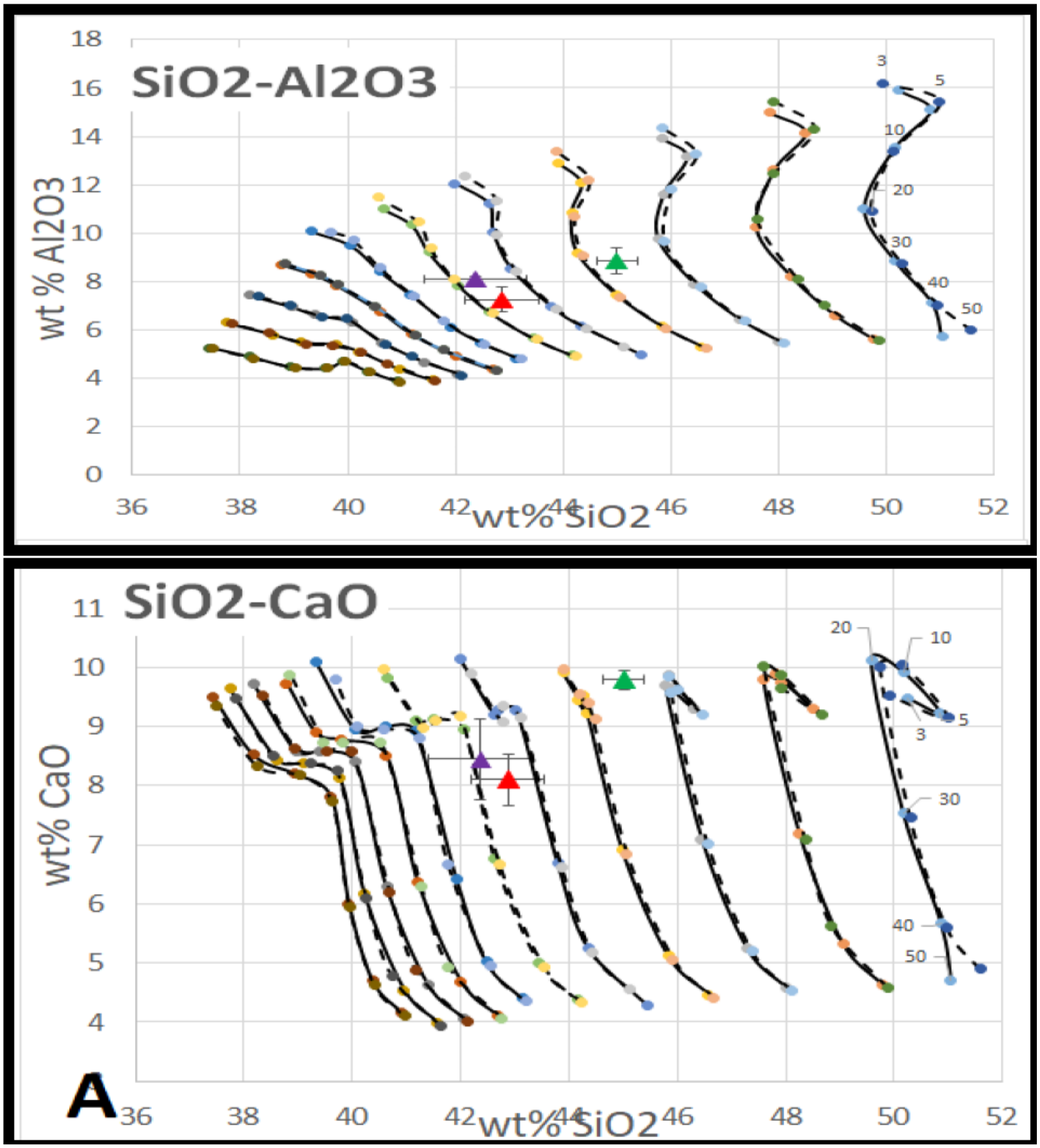

Figure 3. Oxide compositions of the liquids in terms of degree of partial melting, using H_2O wt% of 39 ppm (solid lines) and 185 ppm (dashed lines). Each curve represents a specific pressure. The 10 kbar is the curve furthest to the right and progress to the left by 2 kbar increments (up to 30 kbar). Melt % indicated as a number (3, 5, 10, 20, 30, 40, 50). Triangles represent the average oxide compositions in three preliminary EVP regions. More information is needed to discriminate between plausible melt compositions which is where steps 2 and 3 are able to contribute to, (Susko et al, 2018).

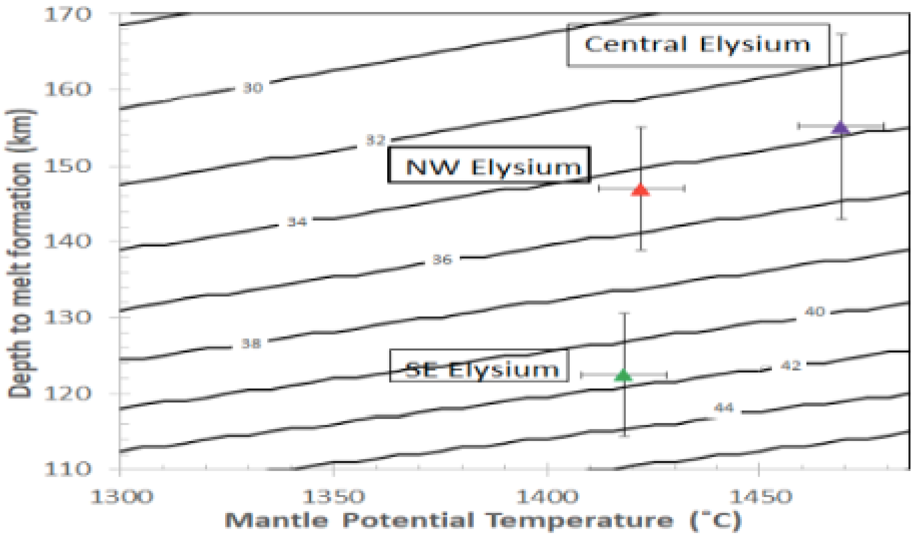

Figure 4. Depth to melting (km) vs. mantle potential temperature (˚C). Heat flow contour lines in mW/m^2 are shown beginning at 28 (top left), through 46 mW/m^2 (bottom right) at increments of 2 mW/m^2 (Susko et al., 2018).

OVERVIEW & GRAVITATIONAL CONSTRAINTS

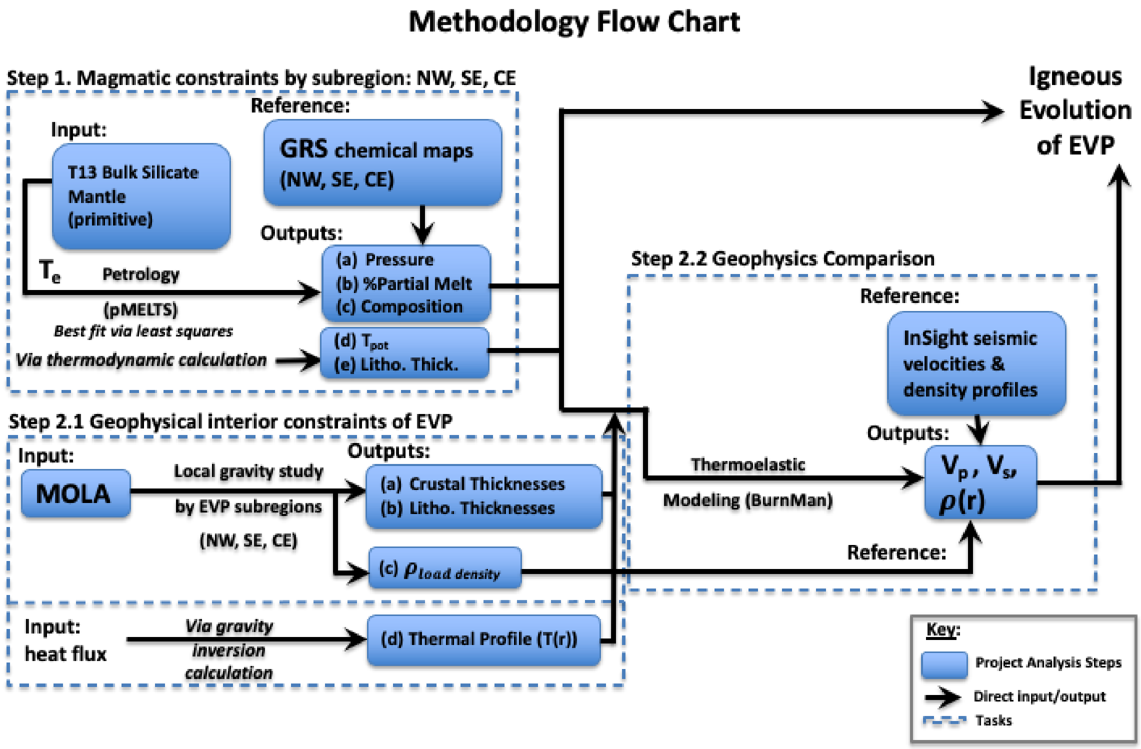

Figure 5. This flow chart depicts the steps involved in this work.

Step 2 will utilize MOLA topography (Wieczorek, 2008) and gravity data (the JPL gravity model, Konopliv et al., 2016) to estimate a number of geophysical parameters such as the local crustal density and the elastic thickness of the lithosphere at the EVP. Previous work by McGovern et al (2004) and Belleguic et al (2005) have constrained the density and the elastic thickness of the lithosphere. However, the goal here is to use gravity and topography data to constrain these geophysical parameters for the NW and SE separately to understand the spatiotemporal evolution of the province. The localized gravity and topography fields will be used to estimate the admittance and correlation function between gravity and topography. A best-fit load density and, elastic lithosphere thickness will be obtained by the analysis of the admittance spectra. The estimate of elastic thickness of the lithosphere at EVP will allow us to derive a first-order estimate of the heat flux when EVP was emplaced on the Martian surface. The localized heat flux estimate will be used as an input in Step 3. We have previously used similar techniques to infer the density and lithospheric thickness at the Medusae Fossae Formation (MFF) and the north polar cap on Mars (Ojha & Lewis, 2018; Ojha et al., 2019).

The plots below are demonstrate the local gravity study being undertaken by Step 2 of this project.

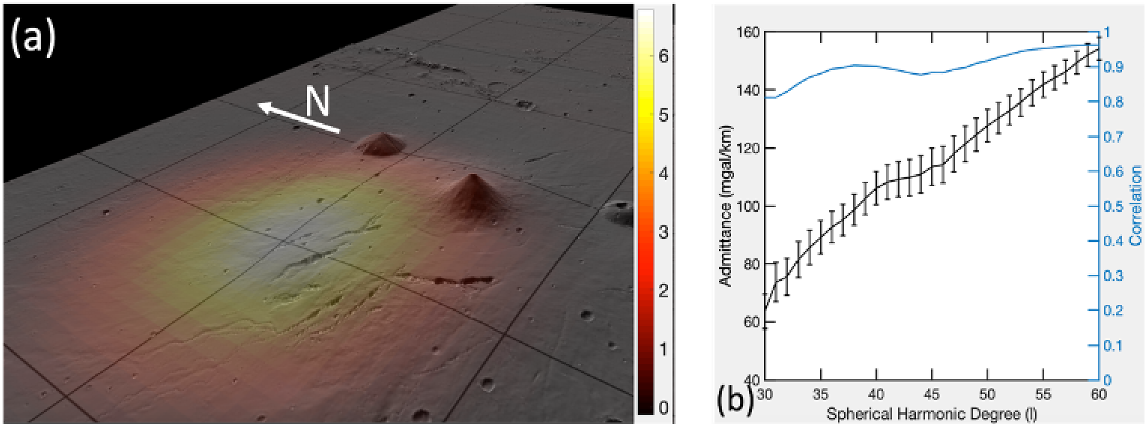

Figure 6. Local gravity study preliminary results. (a) Here a single taper is used to localize the gravity and topography signature of NE. The colors show the magnitude of the taper (unitless) overlaid on a 3D shaded relief of Mars. Vertical lines show regions of 10°10° area. (b) Admittance and correlation spectrum for the localized region left. The vertical bars are admittance uncertainty estimates.

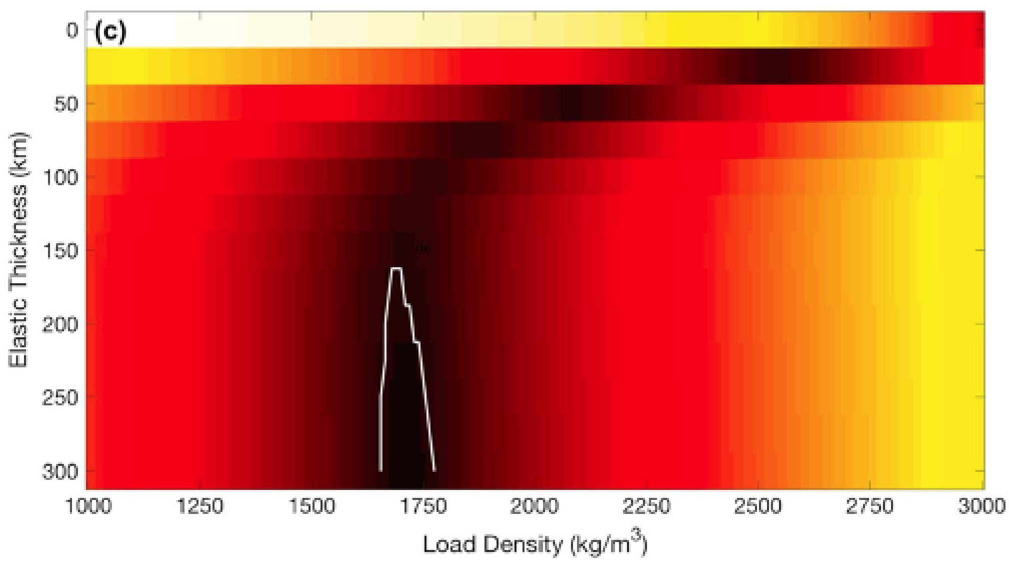

Figure 7. RMS difference between observed and modeled admittances for the MFF (Ojha & Lewis, 2018) as a function of Te and load density. The solutions within 1-σ of the observed admittance are denoted with white contours. Here, 'load-density' refers to the density of the topography that is above the planetary radius.

EQUATIONS OF STATE MODELING

Step 3 uses equations of state (EOS) to calculate the temperature-dependent elastic properties of each melt, after crystallization, for direct comparison with geophysical datasets. Mineral physics EOS uses known material properties of individual constituents and relate aggregate properties of the whole. EOS demonstrate mantle chemical heterogeneity's influence on seismic wave propagation (Strixrude & Lithgo-Bertelloni, 2011). Moreover, this heterogeneity at the grain-scale contributes to scattered wave propagation and its variation with temperature (Strixrude & Lithgo-Bertelloni, 2005). Using the open source mineral physics software BurnMan (Cottaar et al., 2014, 2016), www.burnman.org, we will calculate EOS for each pMELTS composition in Step 1. We will use gravity derived thermal profile from Step 2 as an input. Third-order Birch-Murnahan EOS can be applied to martian mineralogy to obtain elastic properties at depth (Vp, Vs and density profiles). Our preliminary work (Bremner et al., 2016; Haviland et al., 2018; Mallik et al., 2015; Panovska et al., 2017) successfully used this method to place constraints on the lunar interior chemistry at depth. Other groups have successfully applied these methods to the martian context (Zeff & Williams, 2019).

The plots below are demonstrate the EOS modeing work previously performed by the author and demonstrate the work being undertaken by Step 3 of this project.

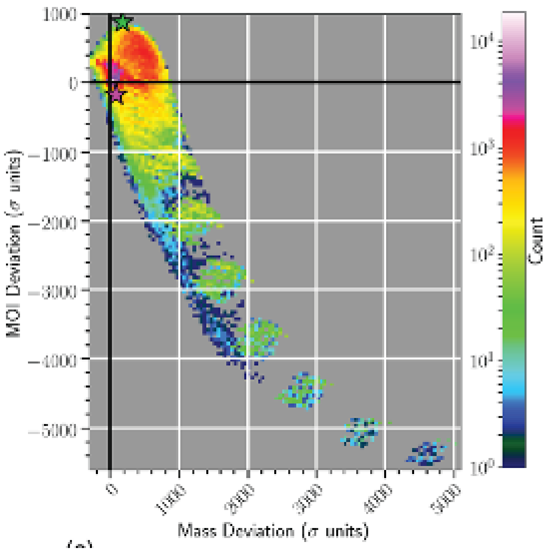

Figure 9. EOS modeling results for ~400,000 moon compositional models (Bremner et al., 2016; Haviland et al., 2018; Mallik et al., 2015; Panovska et al., 2017).

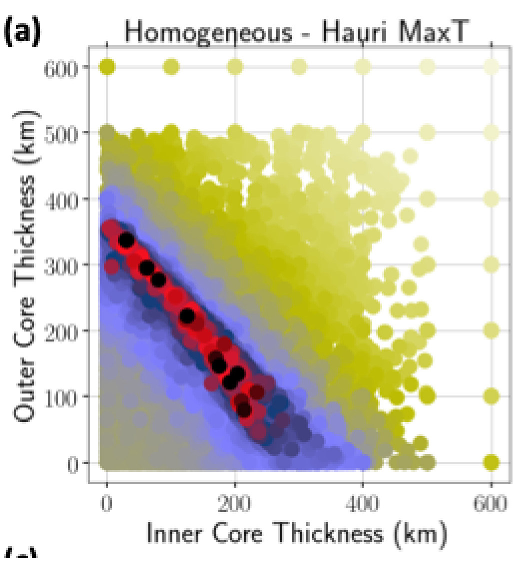

Figure 10. The relationship between compositional layers, inner and outer core, is shown for a single type of compositional models (Hauri et al 2014 using the maximum temperature profile) (Bremner et al., 2016; Haviland et al., 2018; Mallik et al., 2015; Panovska et al., 2017).

IGNEOUS EVOLUTION CONCLUSIONS

Through this method we use several independet datasets to place constraints on the chemistry, temperature, pressure, and lithospheric thickness of each subregion within EVP. This work is in progress. Our initial study indicates we will be able to constrain each region within the EVP which informs us as to evolution of this volcanic province.

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ABSTRACT

Here we investigate igneous compositions of several large volcanic provinces on Mars using remote sensing data sets (Mars Odyssey Gamma Ray and neutron Spectrometer suite--GRS, and gravity) to inform petrologic and thermoelastic modeling. Martian volcanic provinces, starting from Noachian to Amazonian age, including Elysium (EVP), are locations of great geologic interest which have been active over long time scales from Hesperian to Amazonian. Regional scale change in eruptive processes are poorly understood. Compared to large igneous provinces on Earth, the martian volcanic activity has persisted for orders of magnitude longer. Therefore, changes in mantle chemistry, pressure, and temperature during lithospheric cooling are expected to produce significant changes in the conditions of magma production, storage and ascent, affecting the degree of fractional crystallization and crustal contamination. In this study, we perform a detailed modeling to test the hypothesis that compositional variability within volcanic provinces resulted from spatiotemporal changes in the depth of magma formation and present initial results. Our methods include constraining the pressure and temperature conditions of EVP as a case study of geologically recent magmatic evolution on Mars using GRS informed surface chemistry constraints and pMELTS modeling. Second, we place constraints on the density and seismic velocities of the EVP melt through thermoelastic modeling with a local gravity analysis. This analysis is also extended to Noachian aged volcanic provinces on Mars initial results estimates mantle pressure for each sub-region is 16 kbar pressure, whereas, degree of partial melting is low and varies between 10 to 12. This study aims to validate our theoretical model and develop a perspective view of spatiotemporal changes at the interior of Mars throughout the time.

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