pMELTS MODELING OF THE ELYSIUM VOLCANIC PROVINCE

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Introduction: Vaucher et al. [1] constrained the most recent volcanism in the Central Elysium Planitia south of Elysium Mons to as young as ~2 Ma, superseded by the uncovering from Horvath et al. [2] that the Cerberus Fossae mantling unit in the southern Elysium Planitia may be the youngest volcanic deposit on Mars at a modeled age of 53 to 210 ka. Recent discovery proposed that the Elysium Volcanic Province (EVP) is sitting on top of a ~4,000 km active plume head [3]. Following pilot work [8][10] using pMELTS to model magmatic processes, this work explores the use of pMELTS in younger volcanic regions and regions with a preponderance of sulfur.

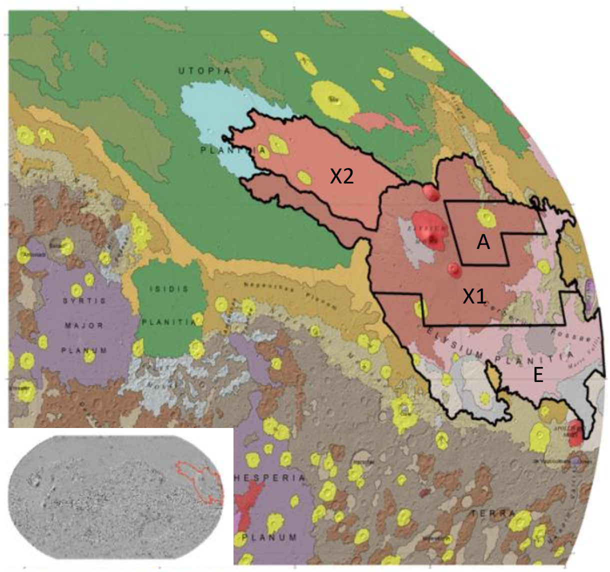

Figure 1: Delineation of key reference regions for the Elysium volcanic province. The inset figure shows where Elysium is situated in a global context, and the perimeter of Elysium is outlined in red compared to Elysium regions outlined in black.

Methods: The boundary of Elysium in its entirety is scrutinized by mapped geology [4]. Subsequently, within the Elysium Volcanic Province, with volcanism as the primary interpretive interest, this work identifies distinct regions informed by synthesizing the statistical chemical province and mapped geology. Chemical provinces adopted here are defined by the results of multivariate analysis, Hierarchical Clustering complement with Principal Component Analysis (HC-PCA), of the Mars Odyssey gamma and neutron spectroscopy (GRS) [5]. pMELTS simulation of an undifferentiated mantle equivalent T13 [6] is performed under pressures ranging from 10 to 30 kbar at an increment of 2 kbar and temperature altering from 1,000 to 2,000 ^{o}C. The iron-rich nature of the Martian mantle is accounted for by applying offsets determined by comparing pMELTS derived and published experimental values for each oxide at 15 kbar [7]. Oxygen fugacity is set to -3 ΔQFM (Quartz-Fayalite-Magnetite buffer).

Results: This delineation results in four distinct regions: A, E, X2, and X1, as shown in Figure 1. Region A and E are delineated by overlapping Intermediate Chemical Provinces 1 and 5 [5] with the boundary of Elysium. Neither X2 nor X1 is defined in the chemical province map produced by the HC-PCA method. Consequently, region X2 is delineated in consonance with mapped geology, namely, a uniformity of Amazonian volcanic unit (Av) across the region. The rest undivided expanse that incorporates the primary volcanic edifices of Elysium is designated to be X1. Although Region X1 encompasses region A, it differs from Region X1 geochemically by observed depletion in the volatiles (H_2O, Cl, S) and Large Ion Lithophile Elements (LILE) K and Th and enrichment in Al mass fractions above the average Martian Crust. Region E features prominent enrichment in volatile (H_2O, Cl, S) concentrations. Region X1 bears moderately depleted Al, and K and Th are moderately depleted in region X1. Region X2 bears the most remarkable depleted Al signature. Its K and Th are slightly and moderately depleted, respectively.

Regions A, E, X1, and X2 are dated to be 3.2 Ga, 1.4 Ga, 3.2, and 2.1 Ga years old using Craterstats2. They are late Hesperian, middle Amazonian, late Hesperian, and early Amazonian in age, respectively.

Modeled Elysium magmatic conditions are shown in Figures 2 and 3. Summarily, silica concentrations decrease systematically with increasing pressure, Al_2O_3 abundances decrease with increasing pressure, while FeO and MgO abundances increase with increasing pressure. K_2O concentration variations are relatively agnostic with pressure changes. TiO_2 and CaO abundances have more complicated fluctuations that rely more on the degree of partial melting than pressure. Region E is plotted between 10 kbar and 12 kbar for virtually every oxide pair, except for one exception in which region E is placed almost directly on the 12 kbar isobaric curves. Consequently, region E is modeled to bear the lowest pressure condition among Elysium Regions. However, there are two instances in which region E is plotted outside the isobaric curve cluster defined P-F (pressure-degree of partial melting) space, namely, FeO-SiO_2 and MgO-SiO_2. Region A consistently plots close to 16 kbar and displays the highest-pressure condition in Elysium. Region X1 and X2 are spotted proximal to 14 kbar and 12 kbar through visual approximation, with region X2 being an outlier of the P-F space in the Al_2O_3-SiO_2 plot.

Discussion: Secondary crust was extracted from the mantle via its partial melts. The approach of using pMELTS to calculate the composition of those melts (thus the crust) using T13

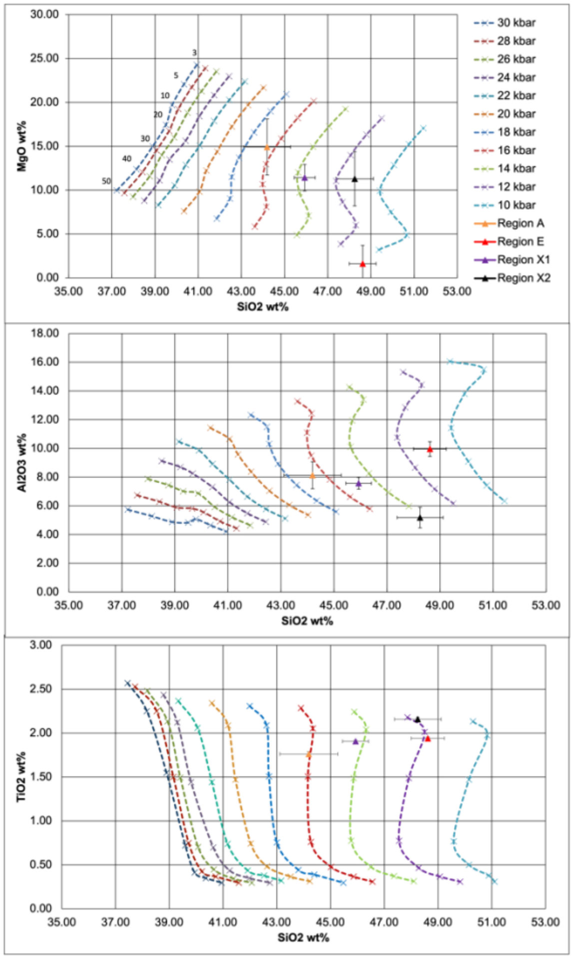

Figure 2: Composition of Elysium regions plotted in the modeled pressure-degree of partial melting space in Harker diagram style (SiO_2 vs MgO, SiO_2 vs Al_2O_3, SiO_2 vs TiO_2). Dashed curves are isobaric lines ranging from 10 to 30 kbar with a 2 kbar increment. Numbers indicate a partial melting fraction from 3 to 50 percent for each isobaric curve.

(primitive mantle equivalent) will become problematic when applied to younger magmatic regions (postdating Hesperian) [9]. The reasoning is that most of the older (Hesperian and earlier) volcanism could have been produced from a primitive mantle. Thus, a primitive mantle composition like T13 for pMELTS modeling is appropriate. However, if the magmatic processes postdate Hesperian, their source would not be considered primitive since the slightest previous melting of the younger lava sources could have depleted themselves significantly with incompatible elements [8]. In this case, the problem of using a primitive mantle composition, T13, to model the melt compositions of younger resurfacing events in regions X2 and E aged at Early Amazonian and Middle Amazonian manifests as plotting themselves outside of the P-F space in the Harker diagrams.

The GRS pixel data of Elysium regions were normalized to primary geochemistry by removing SO_3, Cl, and H_2O, contrasting to prior work that disregarded sulfur as a minor constituent of the crustal geochemistry, thus normalization only removed Cl and H_2O [9]. Elysium region E has a categorical high sulfur abundance compared to the rest of Elysium. Sulfur abundance

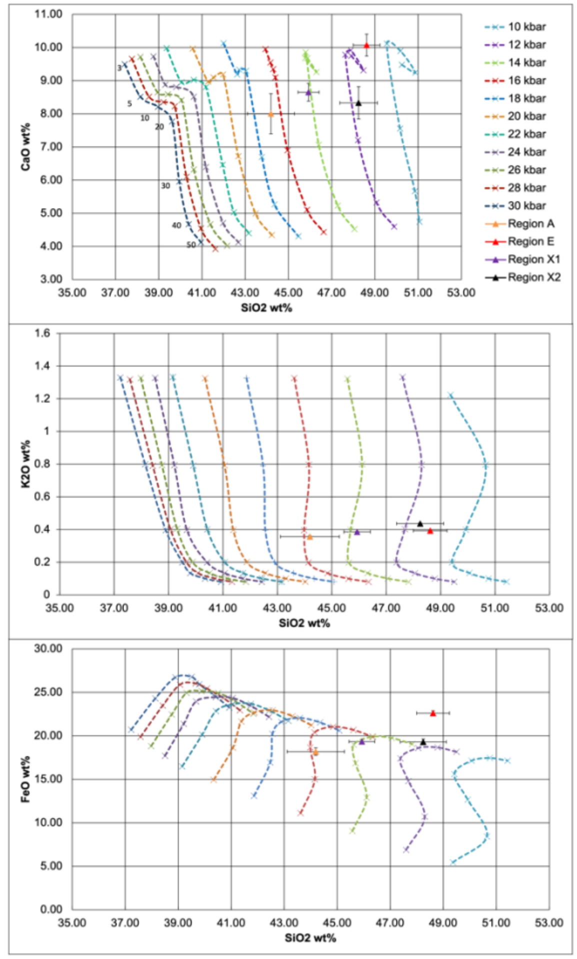

Figure 3: Oxide bivariate plot (SiO_2 vs CaO, SiO_2 vs K_2O, SiO_2 vs FeO) of Elysium regions.

contributes substantively to the bulk chemistry in region E, removing it rendered region E plotting outside pMELTS modeling space in oxide pairs, SiO_2 vs FeO and SiO_2 vs MgO.

The degree of partial melting for Elysium regions varies from oxide to oxide, thus not well constrained by the oxide bivariate plots. Alternatively, we use the ratio of Th_{T13} to $Th_{Elysium\ region}$ as a proxy for the degree of partial melting [8]. The age of Regions of Elysium spans from Middle Amazonian to Late Hesperian. The association of younger volcanism with lowering partial melting degree and increasing pressure condition of the source [8] needs to be revisited in the scale of a single volcanic province since the youngest Volcanism of Elysium has intermediate partial melting degree instead of the lowest and lowest pressure condition instead of the highest.

References: [1] Vaucher, Julien, et al. *Icarus* 204.2 (2009): 418-442. [2] Horvath, David G., et al. Icarus 365 (2021): 114499. [3] Broquet, A., and J. C. Andrews-Hanna. *Nature Astronomy* (2022): 1-10. [4] Tanaka, Kenneth L., et al. Planetary and Space Science 95 (2014): 11-24. [5] Rani, Alka, et al. *Geophysical Research Letters* 49.14 (2022): e2022GL099235. [6] Taylor, G. Jeffrey. *Geochemistry* 73.4 (2013): 401-420. [7] Bertka, Constance M., and John R. Holloway Contributions to Mineralogy and Petrology 115.3 (1994): 323-338. [8] Baratoux, David, et al. Nature 472.7343 (2011): 338-341. [9] Baratoux, David, et al. Journal of Geophysical Research: Planets 119.7 (2014): 1707-1727. [10] El Maarry, Mohamed Ramy, et al. Journal of Volcanology and Geothermal Research 185.1-2 (2009): 116-122.