REVEALING ELYSIUM PLANITIA'S YOUNG GEOLOGIC HISTORY: CONSTRAINING LAVA EMPLACEMENT STYLES, AREAS, AND VOLUMES. J.R.C. Voigt[1,2], C.W. Hamilton[2], G. Steinbrügge[1], M.S. Christoffersen[3], S. Nerozzi[2], L. Kerber[1], J.W. Holt[2], L.M. Carter[2], [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA (voigt@jpl.nasa.gov), [2]Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona, USA, [3]University of Alaska Fairbanks, Geophysical Institute, Fairbanks, AK 99775, USA

Introduction: Elysium Planitia on Mars is a flat-lying plain-forming region located southeast of the Elysium Rise [1, 2]. The surface is dominated by Late Amazonian-aged volcanic units that have been modified by aqueous and tectonic activity [3] as well as aeolian mantling [4]. Elysium Planitia is home to several large, partially buried valley systems [5, 6], including Athabasca Valles, Marte Vallis, Rahway Valles, and Grjótá Valles [7, 8]. All valleys are generally interpreted to have been carved by aqueous erosion that subsequently filled with lava flow-fields. Athabasca Valles is interpreted to be filled by lava within the last few million years, making it the most recent volcanically active region on Mars [7, 9]. Marte Vallis, however, is the largest outflow channel to have been carved within the Late Amazonian epoch on Mars and is now buried by Late Amazonian-aged lavas [5, 10].

Investigating the pre-eruption landscape by analyzing the subsurface is crucial to constrain the geologically recent hydrological and thermal evolution of Mars. This study focuses on the entire Elysium Planitia region to reconstruct the topography prior the volcanic eruption by investigating the lava flow areas using imagery data, thicknesses constrained by Shallow Radar (SHARAD) sounding data [11], and derived estimates of the erupted lava volume by combining these results. Further, we constrain the material properties using SHARAD to better evaluate the nature of the valley infill and plain forming materials (e.g., ice-rich sediment versus basaltic lava).

Data and methods: *Surface:* Geomorphological characteristics for lava flows in Elysium Planitia were mainly determined using Mars Reconnaissance Orbiter (MRO), Context (CTX) camera images [12] with 6 m/pixel resolution. In selected areas, we combined our observations with MRO High Resolution Imaging Science Experiment (HiRISE) images, with a resolution of 0.3 m/pixel [13]. In addition to imagery data, we used a DTM from the Mars Orbiter Laser Altimeter (MOLA) onboard the Mars Global Surveyor (MGS) to obtain topographic information [14].

Two different geomorphological maps were generated: (1) a map that illustrates the spatial distribution of the Late Amazonian volcanic terrains with its major flow units; and (2) the lava flow map that focuses on lava flow margins within the Late Amazonian volcanic terrain in the Cerberus Plains.

Subsurface: To determine the lava flow thicknesses within Elysium Planitia, we analyzed reflectors obtained from the SHARAD sounder [11] onboard MRO. In total, 2100 tracks cross the study area. Reflectors have been picked visually by direct comparison to surface clutter simulations to avoid false picks and special attention has been paid to avoiding sidelobes due to the shallow nature of many reflectors. If a reflector was present, the surface was picked as well to calculate reflector depth. We connected each of the reflectors to their major flow unit seen on the surface, as identified from the surface mapping (Fig. 1) in combination with the sample number (depth) and shape

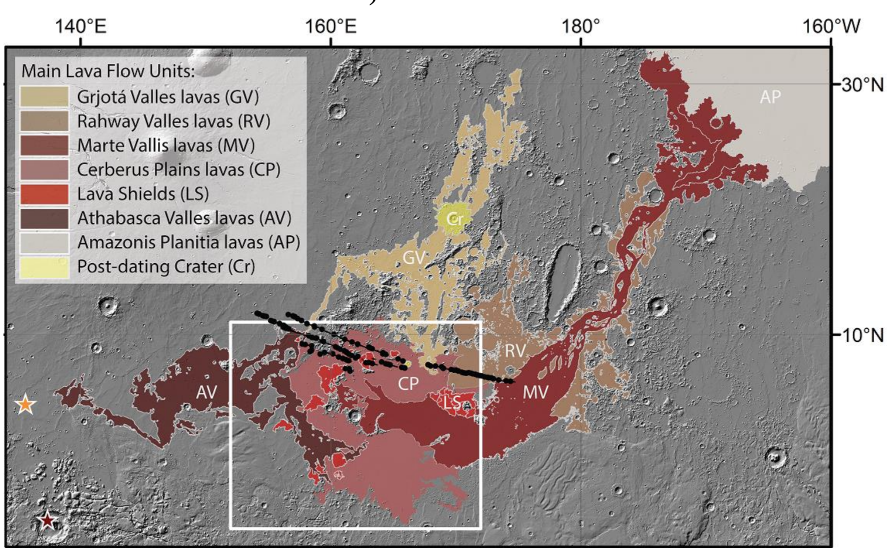

Figure 1. Map showing the main lava flow units in Elysium Planitia namely: Grjótá Valles lavas (GV), Rahway Valles lavas (RV), Marte Vallis lavas (MV), Cerberus Plains lavas (CP), and Athabasca Valles lavas (AV). The map also shows the location of the Lava shields (LS) in Cerberus Plains, Amazonis Planitia lavas (AV), and post-dating impact craters (Cr) Kota and Zuni. Color-coded lava flow units are overlain on a MOLA hillshade and were digitized on a 1:100,000 scale based on CTX images.

of the reflector. Further, to independently assess the permittivity, we studied locations where a lava lobe flowed onto, but did not completely cover, a flat surface. We then assumed that the true elevation of the reflector at the bottom of the lobe is the elevation of the uncovered portion of the flat surface. Under this specific geometric assumption, the radar wave speed, and therefore also the real part of the dielectric permittivity can be estimated. We used Bayesian inference to estimate the speed that minimizes the difference between the depth-converted elevation of the bottom of the lobe and the assumed elevation of the bottom of the lobe at four different locations within the study area.

Results and Interpretations: The main geologic units forming Elysium Planitia divide into five broad groups: Grjótá Valles lavas, Rahway Valles lavas, Marte Vallis lavas, Cerberus Plains lavas, and Athabasca Valles lavas (Fig. 1). All five groups can be associated with the geologic units described by [2], namely the Cerberus Fossae 2 and 3 units (AEc_2 and AEc_3) with most flows belonging to the younger AEc_3 unit. Our mapping results show that the lava flow-fields cover a total spatial area of 1,623,518 km^2, corresponding to 1.12% of Mars's surface area.

Analyzing the SHARAD tracks reveals that 462 tracks in the region contain at least one reflector. However, most of the tracks exhibit several reflectors summing to a total number of 1777 reflectors.

When comparing the reflectors to the geologic units, it becomes evident that the subsurface reflectors are well aligned with the geologic contacts seen on the surface. Within the late Amazonian volcanic unit (lAv) unit, there are topographic steps visible in the subsurface SHARAD map that are well aligned with flow margins. Good examples are located at the Rahway Valles lavas boundary to Marte Vallis lavas at the northern and southern margin.

Permittivity values inferred from the dipping reflectors are consistent with basalt of moderate porosity. The lava flow thicknesses range from a minimum of 4.7 m to a maximum of ~140 m in the Cerberus Plains. The mean thickness of the lavas in the study area is ~40 m, with Athabasca Valles lavas being on the lower end with an average thickness of ~30 m and the Cerberus Plain lavas on the higher end with an average thickness of ~42 m. The radargrams for Amazonis Planitia, Grjótá Valles, and Athabasca Valles lavas typically show one vertical level of reflectors. In contrast, radargrams covering Rahway Valles, Marte Vallis, and Cerberus Plains often show stacked reflectors, which are interpreted to represent the interface of different lava flow-fields. Combining our surface and subsurface results shows that four of the five major groups have one or two major eruptive events and can be classified as flood basalts, namely Grjótá Valles lavas, Rahway Valles lavas, Marte Vallis lavas, and Athabasca Valles lavas. The central part however, Cerberus Plains, is composed of several smaller lava flow-fields (<15 plus <19 lava shields) compared to the other major flow units.

Conclusion: This study reveals the volcanological and aqueous evolution of Elysium Planitia on Mars. By combining detailed geomorphological mapping and the analysis of SHARAD reflectors in Elysium Planitia we reconstructed the subsurface topography and determined individual lava flow thicknesses and volumes. The lava flow fields within Elysium Planitia have been challenging to reconstruct due to the complex surface morphology and the dynamic flow history of typically shallow, overlapping lava flows, ranging from only ~5 m up to ~140 m in thickness. Multiple locations, including the Cerberus Plains, Marte Vallis, and Rahway Valles contain several stacked reflectors, which could indicate compound lava flow-fields or episodic volcanic activity resulting in the emplacement of several lava flow-fields, as seen in large flood basalts on Earth, such as the Columbia River Basalt Group [15]. The pre-eruption DTM exposes a valley centered around 4.0º N and 165.5º E. This valley is likely to represent an aqueous carved channel with increasing depth towards the West, indicating a water flow direction from East to West. This paleo-flow direction is opposite to the flow direction of younger infilling lavas, based on textural kinematic indicators that are exposed on the surface, which implies a complex history of alternating water and lava emplacement.

Acknowledgments: A portion of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. This work was supported by NASA's FINESST program Grant #80NSSC20K1373 and SSW #20-SSW20-0086.

References: [1] Vaucher et al. (2009) Icarus, 2004, 418–442. [2] Tanaka et al. (2014) U.S. Geol. Survey Sci. Inv. Maps. [3] Banerdt et al. (2020) Nat. Geosci, 13(3):183–189. [4] Ojha et al. (2018) Nat. comm., 9(1):1–7. [5] Morgan et al. (2013) Science, 340(6132), 607-610. [6] Xiong et al. (2021) Earth and Space Sci., 8(1), e2019EA000968. [7] Berman and Hartman (2002) Icarus, 159, 1–17. [8] Jaeger et al. (2007) Science, 317(5845):1709–1711. [9] Jaeger et al. (2010) Icarus, 205, 230–243. [10] Voigt and Hamilton (2018) Icarus, 309, 389–410. [11] Seu et al. (2004) Planet. Space Sci., 52, p. 157. [12] Malin et al. (2007) JGR: Planets, 112, E05S04. [13] McEwen et al. (2007) JGR: Planets, 112, E05S02. [14] Smith et al. (2001) JGR: Planets, v. 106, p. 23689–23722. [15] Thordarson et al. (1998) JGR: Solid Earth, 103(B11):27411–27445.