SUBSURFACE INTERFACES IN THE ARSIA MONS CALDERA – OBSERVATIONS FROM SHARAD.

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Introduction and previous work: Arsia Mons is considered the oldest and the most structurally evolved volcano among the Tharsis Montes [1]. The caldera floor, dated to be 130 Ma old, is much younger than the main shield (3.54 Ga) [2]. Evidences for both effusive volcanism (lava flows and sinuous rilles) and explosive volcanism (pit craters and mantling ash deposits) have been reported near the shield's summit [3, 4]. A recent study on the magma recurrence rate in Arsia Mons suggests that older flows or ash deposits could be buried beneath the young surface flows in the caldera [5]. Evaluating the subsurface stratigraphy using radar data provides a means for understanding the dielectric properties of volcanic material that accreted over the caldera floor during the final stages of Tharsis eruptions.

The SHAllow RADar (SHARAD) onboard the Mars Reconnaissance Orbiter (MRO) operates at 10 MHz bandwidth centered at 20 MHz, yielding a range resolution of 15 m in free space [6]. This translates to a range resolution of 5 – 10 meters for geologic medium composed of volcanically derived material [7]. The operational wavelength of SHARAD allows for detection of layers caused by dielectric dissimilarities at average depths of 50 meters below the surface [8]. The late time delay echoes from the subsurface contain information about (i) the dielectric properties of the medium and (ii) the distance to the interface. The echo returns observed by SHARAD are processed into radargrams showing power values corresponding to round trip time along the Y-axis and along track ground distance in the X direction. In the presence of vertically stacked media of contrasting dielectric properties, SHARAD records multiple time delay echoes. Subsurface interfaces have been identified in volcanic regions characterized by discrete flows [7] as well as low density porous deposits [9]. The Elysium volcanic province has been noted for the presence of stacked interfaces [10]. We detect similar layered interfaces in Arsia Mons caldera in the Tharsis bulge.

Geology of Arsia Mons: The main shield of Arsia Mons embays a ~ 116 km diameter collapse caldera. The caldera hosts a dozen small shield volcanoes [3] aligned along a NE-SW trending rift that bisects the caldera. Late stage volcanism in Tharsis has been linked with lava flows originating from the rift [1]. 29 vents with accompanying flows have been previously identified within the caldera [5].

SHARAD mapping of Arsia Mons: A total of 29 night side tracks have been acquired that pass through the caldera of Arsia Mons. Apart from subsurface layering, off-nadir surface relief can also result in late time delay echoes. Clutter simulation of the radargrams were examined for all the tracks. Only reflectors not apparent in the clutter simulations were mapped and identified as interfaces caused by subsurface stratigraphic variations (Figure 1). Interfaces were mapped in different regions of the Western and central portion of the caldera, however the radargrams obtained from the Eastern part of the caldera were devoid of subsurface interfaces (Figure 2).

Topographic variations within the caldera do not exceed more than a few tens of meters, hence only the tallest of the intra-caldera shield volcanoes is discernible in SHARAD radargrams (Figure 1). The interfaces found in the vicinity of the identified shield do not show preferential attitude or location with respect to the shield's summit.

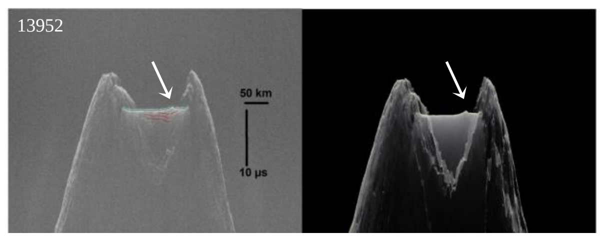

Figure – 1: SHARAD radargram (left) and clutter simulation (right) from track 13952 with the subsurface layers mapped in red. White arrows indicate an intra-caldera shield volcano visible in the radargram.

Interface depths: The depth of the mapped interfaces range from 30 meters to 130 meters below the surface (derived using a permittivity value $\varepsilon' = 7$ typical of basalts). The reflectors closest to the surface are observed at mean round trip delay times of 0.6 μs following the surface echo return and are present close to the caldera walls. The time delays for interfaces farther from the wall range from 1.1 to 1.3 μs following the surface reflection, corresponding to depths of 50 to 70 meters below the surface. A second layer of interface with a mean delay of 1.7 μs after the surface return (80 – 130 meters deep), is seen extending across adjacent radargrams in the Western region of the caldera.

Discussion: The floor of Arsia Mons caldera is smooth at scales of the order of SHARAD's operating wavelength, making it favorable for identification of subsurface layers. The interfaces detected by SHARAD could be caused by a divide between flow units having notable differences in density. It has been noted that stacked lava flows without sufficient density contrasts will not produce time delay echoes at the boundary [10]. If the interfaces indeed are caused by discrete juxtaposed flows, the flows were possibly derived from different melt sources or underwent different alteration histories that produced different dielectric properties. It is also possible that the structure of the flows could include denser cores with less dense upper surfaces or air gaps that could create an interface. Dense basaltic flows with high permittivity and large loss tangent values cause more attenuation in the propagating signal making it harder to record return echo power from the subsurface. Hence, it is more likely that interfaces present at greater depths are overlain by lesser density volcanic flows that allow the radar wave to penetrate through the flow.

Alternately, the interfaces could be caused by a layer of fine ash, porous tephra or pyroclastic material trapped in between layers of basaltic flow. Pit craters and fine mantling deposits have been reported in the summit and flanks of Arsia Mons suggesting that the region witnessed volatile rich explosive volcanism in the past [4]. The mapped interfaces could represent evidences of explosive volcanism amidst episodes of effusive volcanism typical on Mars.

The shallow units close to the caldera wall preferentially occur near the Southern and Western walls where well developed grabens concentric to the summit collapse are present [1]. The possibility that the interfaces close to caldera walls could be associated with tectonic summit collapse events cannot be disregarded.

Interfaces away from the caldera walls lie stratigraphically below the intra-caldera shields and denote volcanic episodes older than the caldera floor unit. The absence of time delay echoes in the Eastern region could imply the lack of stratigraphic variations in the subsurface. Lesser orbital coverage in the East also makes identification of reflectors harder.

Future Work: We are currently in the process of obtaining additional data over these reflectors to better map their locations and properties. In the presence of a structural feature like a trough or a crevice that exposes the bedrock / medium below the surface, precise determination of the dielectric properties and composition of the subsurface is possible [7, 10]. The Arsia Mons caldera does not exhibit such features thereby making precise determination of dielectric properties, layer depths and thicknesses difficult. Additional data and daytime crossing tracks may help to constrain the dielectric properties, including the loss tangents of these layers.

We are also comparing the SHARAD subsurface reflector mapping with high resolution images from HiRISE, thermal inertia values and albedo values to produce a more comprehensive analysis of the characteristics and extent of the layers constituting the present-day caldera floor. Subsequent studies can assist in elucidating the type and relative timeline of late-stage summit volcanism in Tharsis.

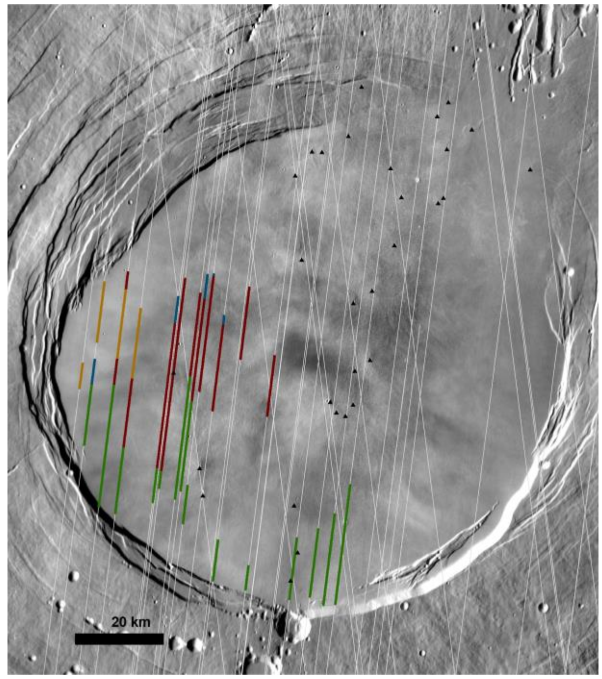

Figure – 2: THEMIS daytime IR image showing the locations of subsurface interfaces: green - shallow interfaces that occur close to the South and West walls of the caldera; yellow - dipping interfaces close to the surface; maroon – flat interfaces underlying those shown in yellow; blue – a second layer of flat interfaces directly beneath the first layer. SHARAD tracks are shown in white. Black triangles mark the locations of surface vents and summit craters in the caldera.

References: [1] Crumpler and Aubele (1978), Icarus 34, 496-511, doi: 10.1016/0019-1035(78)90041-6. [2] Werner (2009), Icarus 201, 44-68, doi: 10.1016/j.icarus.2008.12.019. [3] Mouginis-Mark, P. J. (2003), 6th ICM, Abstract #3001. [4] Mouginis-Mark, P. J. (2002), GRL 29, doi:10.1029/ 2002GL015296. [5] Richardson et. al. (2017), EPSL: 14145, 458, doi: 10.1016/j.epsl.2016.10.040. [6] Seu, R. et al. (2007), JGR, 112, doi:10.1029/2006JE002745, E05S05. [7] L. Carter et al. (2009), GRL 36, doi:10.1029/2009GL041234, L23204. [8] Heggy et al. (2006), JGR, 111, doi:10.1029/2005JE002589, E06S04. [9] Watters et. al. (2007), Science, 318, 1125 – 1128, doi: 10.1126/science.1148112. [10] Simon et. al. (2014), JGR 119, doi:10.1002/2014JE004666.