VOLCANO-ICE INTERACTIONS AT ARSIA MONS, MARS. K. E. Scanlon and J. W. Head, Department of Geological Sciences, Brown University, Providence, RI, 02912 USA. <kathleen_scanlon@brown.edu>

Introduction. It has been hypothesized that the fan-shaped deposits (FSDs) on the west or northwest flanks of the Tharsis Montes resulted from mass-wasting, volcanic, tectonic, or glacial processes (see review in [1]), but more recent evidence from the Antarctic Dry Valleys [2], climate modeling [3], and glacial flow modeling [4] has strongly validated the glacial hypothesis [5,6]. The evidence for widespread liquid water from volcano-ice interactions in the Amazonian-aged Arsia Mons FSD makes it one of the most recent potentially habitable environments on Mars. We have documented glaciovolcanic landforms in the deposit, using Mars Reconnaissance Orbiter Context Camera images, images from the High Resolution Stereo Camera (HRSC), topographic data from the Mars Orbital Laser Altimeter, and, where available, HRSC-derived [7] Digital Elevation Maps.

Glacial and glaciovolcanic features. Interaction between lava and ice on Earth creates characteristic landforms: tuyas, steep-sided mountains that form when volcanic eruptions occur under ice cover, beginning as mounds of pillow lava and developing flat tops when lava breaches the ice surface [8]; sharp-crested ridges that form when dikes intrude into ice [9]; jokulhlaup plains, which form when glacial melt catastrophically bursts from ice vaults [8]; and steep-sided flows, which form when lava chills against ice [9]. We see evidence for each of these in the Arsia Mons fan-shaped deposit, as well as previously undescribed glacial features.

***1. Northwestern plateau**.* Towards the northwest edge of the deposit (Fig. 1A) lies a steep-sided plateau [10] ~280 km^2 in area and ~140 m high. An elongate mound stands up to 150 m above the plateau's center. Superposed on the plateau are two sinuous ridges, 4 – 20 m high and up to 25 km long, sharply defined atop the plateau and with a more diffuse appearance downslope. The ridges continue downslope to a large moraine, where over a dozen channels coalesce into a braided streambed ~35 km long. Based on morphology and associated landforms, we interpret the plateau as a tuya and the ridges as eskers.

***2. Elongate plateau**.* ~45 km north of the northwestern plateau lies an elongate plateau (Fig. 1B) ~300 km^2 in area and up to 140 m high. The plateau trends approximately north-south and is collinear with a curving graben to the south and a series of pit craters to the north. At its center lies an elongate mound up to 140 m higher than the rest of the plateau. Overlapping, highly sinuous ridges extend ~5 km north and west from the plateau's central mound. A sharply incised channel, surrounded by smooth debris, begins near the northern terminus of the plateau and crosscuts several drop moraines. The channeled debris resembles flows from nearby cones, but for the debris to be part of the flow would require the flows to have breached several moraines, then flowed upslope and under the glacier. We therefore interpret the channels as fluvial and the plateau as a tuya.

***3. L-shaped plateau**.* The largest plateau (Fig. 1C), with an area over 360 km^2 and height up to 400 m, lies near the northern edge of the deposit. The plateau is primarily L-shaped in plan view, with a shorter, less steep-sided, roughly triangular lobe at its upslope extent. Due to its height, steepness, and resemblance to terrestrial analogs [11], we interpret this feature as an ice-confined flow.

4. Buried plateaus. The presence of two mountains buried in the knobby facies has been noted [12], as well as one in a region we have mapped as belonging to the Smooth Lower Western Flank unit. Topographic data has revealed a third, and shows that two of the buried mountains (Fig. 1D) are similar in morphology to the northwestern plateau. Any further distinguishing features are obscured by the knobby facies, but it is probable that they were emplaced by a similar mechanism.

5. Steep-sided flows in the Smooth Lower Western Flank unit. Throughout the Smooth Lower Western Flank unit are steep-sided flows (Fig. 1E) with morphologies not seen elsewhere in the deposit. These include an exceptionally smooth-topped plateau, potentially representing an englacial eruption that breached the ice surface and became subaerial; several flows resembling the plateaus in planform and steepness, but with sunken centers suggesting a single eruptive episode and subsequent lava retreat into the vent; and irregular, comparatively thin flows resembling terrestrial pillow sheets.

***6. Steep-sided flows in the lobate facies**.* Pit crater chains and lava channels obscure many features in this unit, but several flows (Fig. 1F) resemble the plateaus discussed above. Isolated ridges may be englacial dike intrusions.

***7. Steep-sided flows in the accumulation zone**.* The upslope edge of the FSD is marked by numerous digitate, flat-topped, steep-sided protrusions (Fig. 1G). A typical lobe is a few kilometers wide and tens of kilometers long. Similar digitate features appear near the summits of Pavonis Mons and Ascraeus Mons, but only on the sides of their summits covered by their FSDs. On the basis of their steepness relative to nearby flows and their exclusive association with the upslope edge of the glacial deposit, we interpret the lobes as ice-chilled lava flows.

***8. Hollowed ridges**.* Two landforms dispersed throughout the deposit share the morphology of an elongate ridge with a trough along its axis. Near the western edge of the fan, several of the drop moraines in the ridged facies appear to degrade into this morphology. Elsewhere, some moraines have small hollows along their crests. We interpret this morphology to result from sublimation of a remnant ice core: when some initial disturbance causes local removal of the moraine's debris armor, sublimation continues until no more ice is exposed. A class of smaller

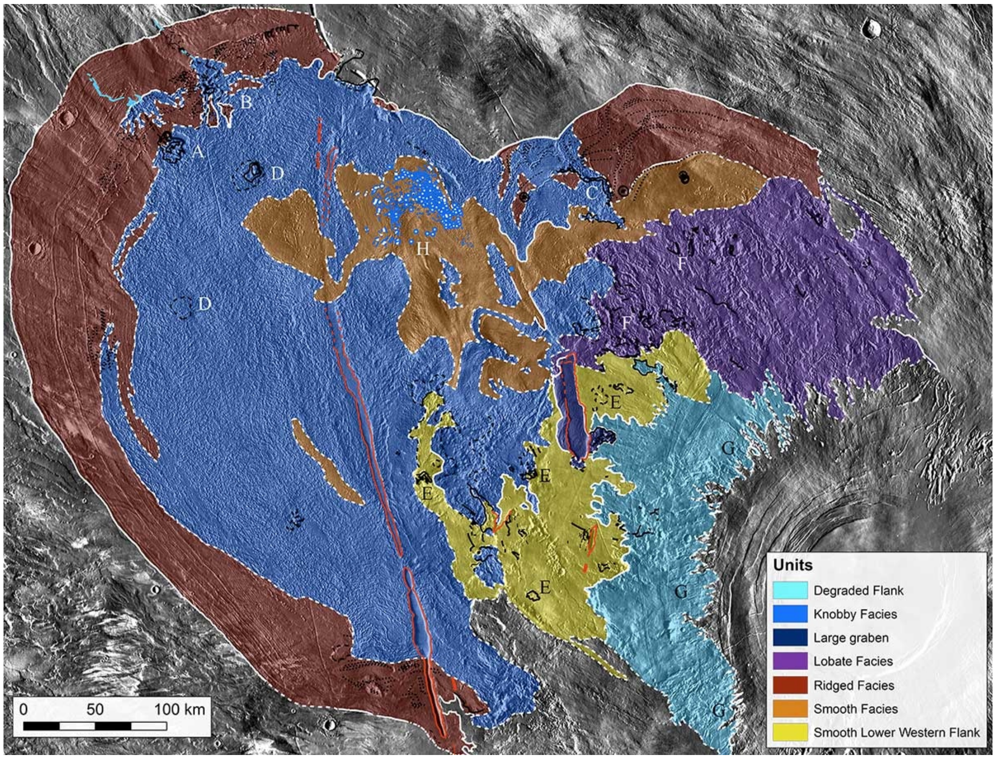

Figure 1. *Geologic map of Arsia Mons, after* [12, 13]*, showing (A) the northwest plateau, (B), the elongate plateau, (C) the L-shaped plateau, (D) buried plateaus, (E) Smooth Lower Western Flank steep-sided flows, (F) Lobate Facies steep-sided flows, (G) accumulation zone steep-sided flows, and (H) pit and knob terrain. The hollowed ridges are not visible at this scale.*

hollowed-ridge landforms behave more like dunes than moraines; they are oriented southwest-to-northeast throughout the deposit and aggregate in local lows of varying ages rather than being associated with a particular stratigraphic level. We also interpret these as resulting from sublimation of a debris-ice mixture.

9. Pit and knob terrain. Near the northern edge of the deposit (Fig. 1H) is a field of knobs up to 1 km wide and shallow pits similar in size and shape to the knobs. Moats surround many of the knobs, and some pits have what appear to be degraded knobs at their centers, implying a progression from knob to pit. The pits and knobs are aligned, concentric with a young glacier nearby [14]. We interpret the Arsia FSD pit and knob terrain as kettles and kettle blocks left during rapid retreat of the nearby glacier. The ice blocks are likely to have sublimed rather than melted to leave the pits, and they were probably covered by pyroclastic debris or dust settling from a storm rather than by glacial outwash. Since the sediment would have come from above, it could have armored some blocks from sublimation, leaving the knobs.

Evidence of local wet-based glaciation. In addition to the outflow channels near the northwestern plateau, many of the other hypothesized glaciovolcanic features in the deposit are accompanied by evidence of locally wet-based glaciation. Moraines near the plateaus, and downslope of the lobate facies, are bowed outward relative to superposed moraines, and in many of these locations boulders are streamlined or aligned along the direction of the outward glacial flow. Downslope of the lobate facies, and near several of the plateaus, moraines are sharply defined and regularly spaced, and do not gently drape underlying topography; we interpret these as Rogen moraines, which are associated with wet-based glacial flow. Parts of the deposit's large terminal moraine have a ribbed appearance consistent with a push moraine, also a wet-based glacial landform.

Preliminary conclusions. Glaciovolcanic landforms are abundant in Arsia Mons FSD. The emplacement of these features would have melted large volumes of ice [15], potentially creating habitats. Previous work has made a strong case for cold-based glaciation, but new data also show landforms indicative of local, volcanism-induced warm-based glaciation distributed throughout the deposit. The morphology of some landforms suggests a larger extant ice inventory than previously thought.

References. [1] Shean D. E. et al. (2005), *JGR*, 110, E05001. [2] Head J. W. and D. R. Marchant (2003), *Geology*, 31, 641-644 [3] Forget F. et al. (2006), *Science*, 311, 368-371. [4] Fastook J. L. et al. (2008), *Icarus*, 198, 305–317. [5] Williams R. S. (1978), *GSA Abstr. with Programs*, 10, 517. [6] Lucchitta B.K. (1981), *Icarus*, 45, 264–303. [7] Dumke A. et al. (2008), *LPSC* 39, #1910 [8] Smellie J. L. (2009) *GSA Spec. Papers* 453, 55-76 [9] Head J. W. and L. Wilson (2007), *Ann. Glac.* 45, 1-13. [10] Head J. W. and L. Wilson (2007), *2nd Volcano-Ice Interaction on Earth and Mars Conference.* [11] Lescinsky D. T. and T. W. Sisson (1998), *Geology*, 26, 351-354 [12] Scott D. H. and J. R. Zimbelman (1995), *USGS Miscellaneous Geologic Investigation Map I-2480*. [13] Zimbelman J. and K. Edgett (1992), *Proc. of Lun. and Planet. Sci.*, 22, 31–44. [14] Shean D. E. et al. (2007), *JGR*, 112, E03004 [15] Wilson L. and J. W. Head (2007), *Ann. Glac.* 45, 83-86.