

Mapping Evidence of Glaciation around Olympus Mons, Mars

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ABSTRACT

A variety of purported glacial features have been reported on Mars. Their recognition has led to debate on the origin and age and the glaciers that produced them. We sought to identify a suite of glacial features (lobate structures, lineated valley fill (LVF), ridges, mound and tail structures, knobby facies, and scaly terrain) that have convincing Earth-based analogs, and map these in the vicinity of the Olympus Mons escarpment. Our results showed the predicted relationship of glacial features such as ridges, LVF and knobby facies confined within lobes. We studied one lobe in detail to demonstrate that two prominent ridges, identified with vertical profiles, within the lobe likely constituted recessional moraines. This interpretation was based on relative ages as determined by crater counting and the location of knobby facies proximal to the inner ridge. We did not assess absolute age of these surfaces and some of our crater counting analysis failed due to inconsistent data gathering. Age dating of the glacial terrain around Olympus Mons remains an important area of future research.



(Left) Stewart Draheim and Jeanine Cryan work with Prof. Arens to learn the crater counting function of JMARS. (Right) William Bobbs (foreground l-r), Garrett Crowe and Adele O'Rourke search for glacial features around Olympus Mons.

INTRODUCTION

A variety of glacial landforms have been identified from orbital images of Mars (e.g., Dickson et al., 2008, Dickson et al., 2010, Hauber et al., 2005, Head and Marchant, 2003, Head et al., 2005, Holt et al., 2008, Milkovich et al., 2006, Shean et al., 2007, Choe et al., 2012). Many of these purported glacial landforms show geomorphic similarity in form, scale and

association with similar landforms produced by cold-based glaciers on Earth (Figure 1, Head et al., 2010, Whalley and Azizi, 2003, Shean et al., 2005). Among the most prominent glacial features, lobed facies form in association with rock and piedmont glaciers on Earth (Whalley and Azizi, 2003). These tongue-shaped structures represent the flow lobes of glaciers unconstrained by a confining valley. On Mars, lobed facies are composed of lineated valley fill (Dickson et al., 2012, Pedersen and Head, 2010) and knobby facies (also known as hummocky facies, Shean et al., 2005) that may represent sublimation till on Mars (Head and Marchant, 2003). Ridge facies form within lobe facies (Arfstrom and Hartmann, 2005) and may represent terminal or recessional moraines. Mound and tail facies is characterized by a field of aligned, small (30-50 m long and 10-30 m wide) teardrop shaped hills (Hubbard et al., 2011) that may be analogous to drumlin fields observed on Earth. Scaly terrain consists of a pattern of polygonal cracks in the surface (Hubbard et al., 2011). Polygons may be up to 20 m across and are generally five or six-sided. These may represent frost cracking in periglacial environments based on the occurrence of similar frost polygons on Earth (Hubbard et al., 2011).

Glacial features have been reported from mid- and low-latitude locations across the Martian landscape indicating that glaciation in Mars' past was not restricted to polar latitudes. Lobed facies and associated lineated valley fill have been reported around the Martian Hemispherical Dichotomy (Dickson et al., 2008), within mid-latitude craters (Dickson et al., 2012, Dickson et al., 2010), and on the flanks of volcanoes (Hauber et al., 2005, Head et al., 2005) including those at tropical latitudes in the Tharsis Montes region (Milkovich et al., 2006). Mound and tail facies have been reported from Hellas Planitia in the mid latitudes of the Southern Hemisphere (Hubbard et al., 2011) and Chryse and Acidalia planitiae in the north (Martínez-Alonso et al., 2011). Scaly terrain associated with periglacial environments has been

reported between 10° and 60° north latitude (Martínez-Alonso et al., 2011) and in the mid latitudes of the Southern Hemisphere (Hubbard et al., 2011).

Martian glaciers may form from groundwater outbursts (Head et al., 2004), from the accumulation of interstitial water vapor (Squyres, 1978, Squyres, 1979), as a result of obliquity-driven climate variation (Head et al., 2005, Head et al., 2006, Madeleine et al., 2009, Milkovich et al., 2006, Forget et al., 2006), or in association with volcanic outgassing (Baker, 2001, Neukum et al., 2004). Groundwater outburst and interstitial water vapor hypotheses make no specific predictions about the timing or location of glacial deposits. Choe and colleagues (2012) demonstrated that active glacial deposits are distributed preferentially on the northern and northwestern sides of Olympus Mons (Figure 2) as predicted by global circulation models of glacial development during a climate regime very different from today (Milkovich et al., 2006). This draws attention back to models that call for relatively recent climate change.

Both the volcanic and obliquity models of glacier formation in the Martian mid- and low-latitudes require atmospheric/climate conditions different from those present on Mars today. In particular, atmospheric pressure must rise to permit precipitation and water vapor must become a more abundant constituent of the atmosphere. In Baker's (2001) volcanic model, the atmosphere thickens by the addition of volcanogenic CO₂. The added CO₂ increases the global greenhouse and creates a positive feedback that liberates more CO₂ and water vapor from permafrost. When atmospheric pressure rises above a critical point and sufficient water vapor is present, snow may occur and accumulate to form glaciers. In the orbital model (Laskar et al., 2004), high obliquity ($\approx 45^\circ$) increases insolation at the poles causes CO₂ and water ice to sublime. These gasses thicken the atmosphere and make precipitation possible in equatorial regions (Levrard et al., 2004, Mischna et al., 2003, Richardson and Wilson, 2002) where water ice would be most stable

(Jakosky and Carr, 1985, Mellon and Jakosky, 1993). Increased atmospheric dust (atmospheric opacity $\tau = 1.5$ to 2.5) enhances the effect by increasing the capacity of the atmosphere to hold water vapor (Madeleine et al., 2009) at relatively low temperature and pressure. Under these conditions, adiabatic lifting of moist air as it encounters topographic highs could then produce snow on Olympus Mons and the Tharsis Montes (Madeleine et al., 2009) that could accumulate and persist as glaciers. Using a global circulation model, Forget and colleagues (2006) predicted glacial accumulation on the northwestern flanks of Olympus Mons and the Tharsis Montes. And evidence of glacial deposits has emerged from photogeology surveys of the region (Milkovich et al., 2006), Arsia Mons (Dobrea and Bell, 2005, Head and Marchant, 2003, Shean et al., 2007), Pavonis Mons (Shean et al., 2005), and Ascraeus Mons (Kadish et al., 2008). The Fall 2012 class (FSEM 139: Mars!) also recognized evidence for active glaciers persisting in the vicinity of Olympus Mons (Choe et al., 2012).

Most workers agree that there have been several episodes of glacial activity on Mars during the Amazonian (e.g., Hauber et al., 2005, Head et al., 2003, Neukum et al., 2004, Shean et al., 2005). Reconstructions of Martian orbital variation suggests that there have been at least three episodes of mean obliquity of approximately 45° —the range at which glaciers will form in tropical latitudes—within the last 10 Ma (Laskar et al., 2004). This is consistent with crater-count estimates of the age of geologically very young glacial deposits on Hecates Tholus (Hauber et al., 2005), Pavonis Mons (Shean et al., 2005) and Arsia Mons (Shean et al., 2007). Head and colleagues (2005) further suggested that Mars' last ice age may be so recent that some active glaciers remain. Previous work by our group suggests that a few active glaciers remain around Olympus Mons (Choe et al., 2012).

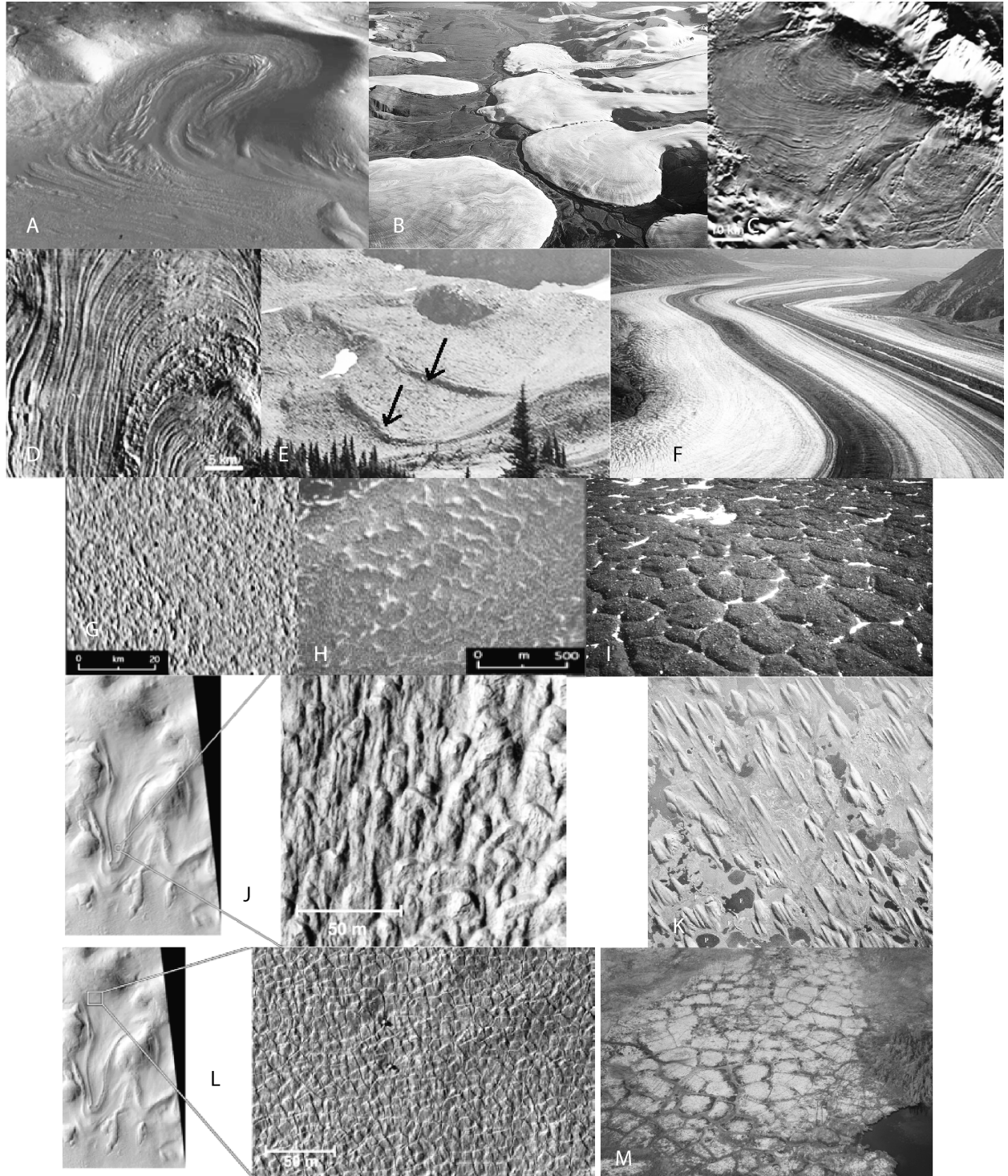


Figure 1: Purported glacial features on Mars and their Earth analogs. A) Lobes and lineated valley fill observed along the Martian Hemispherical Dichotomy boundary (Dickson et al., 2008). B) Glacial lobes near Surprise Fjord on Axel Heiberg Island in the Canadian Arctic (photo by J. Alean). C-D) Lobes with bounding and internal ridges from Olympus Mons (Milkovich et al., 2006). E) Terminal and recessional moraines from Garibaldi Provincial Park, British Columbia, Canada (photo by P. Mleziva). F) Medial and lateral moraines from the St. Elias Mountains, Canada (Photo by O. Carr). These structures resemble Martian lineated valley fill. G) Knobby facies identified from Viking Orbiter imagery (Head and Marchant, 2003). H) Sublimation till from the Antarctic Dry Valleys as imaged from space (Head and Marchant,

2003). I) Sublimation till polygons from the Beacon Valley, Victoria Land, Antarctica (Marchant et al., 2002). J) Mound and tail facies from Hellas Planitia (Hubbard et al., 2011). K) Canadian drumlin field proposed as a glacial analog for mound and tail facies on Mars (photo from Natural Resources Canada). L) Scaly terrain from Hellas Planitia (Hubbard et al., 2011). M) Terrestrial frost polygons.

In a detailed study of Olympus Mons, Milkovich and colleagues (2006) mapped lobate deposits and lineated valley fill (LVF) between 250° and 330° (where the circumference of the Olympus Mons escarpment is viewed as a circle with 0° oriented toward the north). These deposits, which they interpret as the remains of rock-covered piedmont glaciers, extended between 15-140 km (average about 45 km) from the escarpment and covered an area of approximately 15,000 km² (Milkovich et al., 2006). In this study we follow-up on previous research by mapping, in detail, various facies associated with glacial activity and attempt to constrain the ages of some of these surfaces to further understand Martian glacial processes.

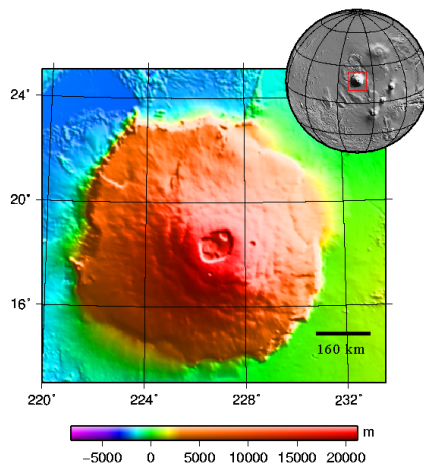


Figure 2: MOLA colorized elevation map of Olympus Mons. Hemispherical geographic context image also shows the three Tharsis Montes: Arsia Mons (southernmost), Pavonis Mons, and Ascraeus Mons (northernmost).

GEOLOGICAL SETTING

Olympus Mons is a basaltic shield volcano with its central crater located at approximately 226.2°E and 18.2°N on the western margin of the Tharsis Plateau (Figure 2). The summit caldera stands approximately 22 km above the Tharsis Plateau and 25 km above Mars mean elevation, making this the tallest mountain in the Solar System. The volcano is approximately 624 km in diameter with the basal escarpment rising approximately 6 km above

the Tharsis Plateau. Milkovich and colleagues (2006) asserted that this escarpment is an important site for low-latitude glacier formation and they reported evidence of lobed deposits with lineated valley fill in the northwestern side of the volcano.

METHODS

To create a detailed map of glacial facies around Olympus Mons, members of our team first researched glacial features that have been described on Mars. They concluded that lobate structures, lineated valley fill (LVF), ridges, mound and tail structures, knobby facies and scaly terrain presented the best candidates for glacial features. Ten members then became experts in the identification of particular glacial terrains. Terrain experts synthesized identification criteria presented in the literature and reviewed proposed Earth analogs, and then explored the area at the base of the Olympus Mons escarpment using THEMIS and CTX orbital images accessed through the Java Mission-planning and Analysis for Remote Sensing (JMARS) geospatial information system software provided by the Mars Student Imaging Project (<http://marsed.mars.asu.edu/msip-home>) in collaboration with Mars Space Flight Facility at the Arizona State University and NASA.

Students identified the following features:

Lobes—Lobes (Figure 1A, C and D) are tongue-shaped protrusions found on the edges of glaciers of several types on Earth (Whalley and Azizi, 2003). Lobes may be composed of lineated valley fill (typical of active or recently active glaciers, Choe et al., 2012), knobby or hummocky facies or ridges (Milkovich et al., 2006). Glacial lobes are distinguished from those formed by lava flows, which tend to be hundreds of times longer than they are wide with complex margins (Milkovich et al., 2006). Glacial lobes tend to be only one to three times as long as they are wide. Glacial lobes can also be distinguished from pyroclastic flows, which tend to fill in low places and thin over topographic highs to create relatively flat topography

(Milkovich et al., 2006). Mass wasting can also produce lobe-like structures but these tend to be less than 100 m in length (Ballantyne and Harris, 1994).

Lineated valley fill—LVF (Figure 1A) is found within lobes and constrained valleys and consists of straight, roughly parallel ridges oriented parallel to the direction of flow. LVF ridges tend to fan out as lobes widen. LVF ridges deflect and part around topographic obstructions. Head and colleagues (Head et al., 2010) tend to restrict LVF to topographically confined ridges and focus on bow-shaped ridges (see below) in unconfined lobes. However, our group has observed LVF in both environments (Choe et al., 2012).

Ridges—Ridges (Figure 1C and D) are found within and around lobes. They are roughly parallel and bow-shaped, with the convex surface perpendicular to and facing the direction of flow (Arfstrom and Hartmann, 2005). Ridges tighten and fold around obstacles including places where lobes interact (Head et al., 2010).

Knobby facies—Knobby facies (Figure 1G) consist of chaotically distributed hills a few kilometers in diameter (Head and Marchant, 2003). Also known as hummocky facies (Shean et al., 2005), individual hills are subround to moderately elongated in the direction of flow (Head and Marchant, 2003). Knobby facies occur within lobes.

Mound and tail facies—Individual mound and tail structures (Figure 1J) occur in large aggregations to form the characteristic facies. Individual mound and tail structures are teardrop shaped in plan view, 30-50 m long, 10-30 m wide and oriented parallel to one another with the wide ends facing in the same direction (Hubbard et al., 2011). Their small size necessitated searching high-resolution CTX images at high magnification.

Scaly terrain—Scaly terrain (Figure 1L) consists of irregular five- and six-sided polygonal shapes that are 10-20 m in diameter (Hubbard et al., 2011). Individual scales have 1-3 upslope

facing edges that are slightly raised and dip down slope creating a crack that forms the margin with adjacent scales. These features also required searching high-resolution CTX images at high magnification.

When a region of a specific terrain was identified, students mapped this in color onto a THEMIS reference mosaic image of the Olympus Mons region (Figure 3).

One lobe (Figure 4), located in the southwestern part of the region, displayed several prominent internal ridges and was studied in more detail. MOLA elevation data were used to create a vertical profile of the structure to assess the possible origin of the ridges as constructional features that could be interpreted as recessional moraines. Under this hypothesis, the most proximal part of the lobe should be youngest, with successively more distal portions older and the surface outside of the lobe oldest. This hypothesis was tested by using crater counting to determine relative ages for various regions within the lobe. In this method, the diameters of all craters within a defined area were measured using the JMARS crater counting tool. From these data, the log of the cumulative crater count was calculated and plotted against log of binned crater diameter. The CraterStats program for comparing relative age curves against standardized curves was not available to us so we were not able to estimate absolute ages as part of this project.

RESULTS

Figure 3 presents our map of glacial terrains surrounding Olympus Mons. As documented by Milkovich and colleagues (2006), glacial deposits are restricted to the western side of the volcano with larger deposits in the northwest. Scaly terrain, possibly associated with periglacial climatic conditions (Hubbard et al., 2011) but not representing deposits produced by glaciers themselves, is present to the north and southeast of Olympus Mons. Lobes interpreted

as of glacial origin range in size from about 30 km long and 20 km wide to about 80 km by 80 km. Both LVF and knobby facies were present within lobes, with knobby facies dominant. Ridges are present within most lobes and are parallel to the general outline of the lobe. Mound and tail structures were rare and generally found very close to the escarpment.

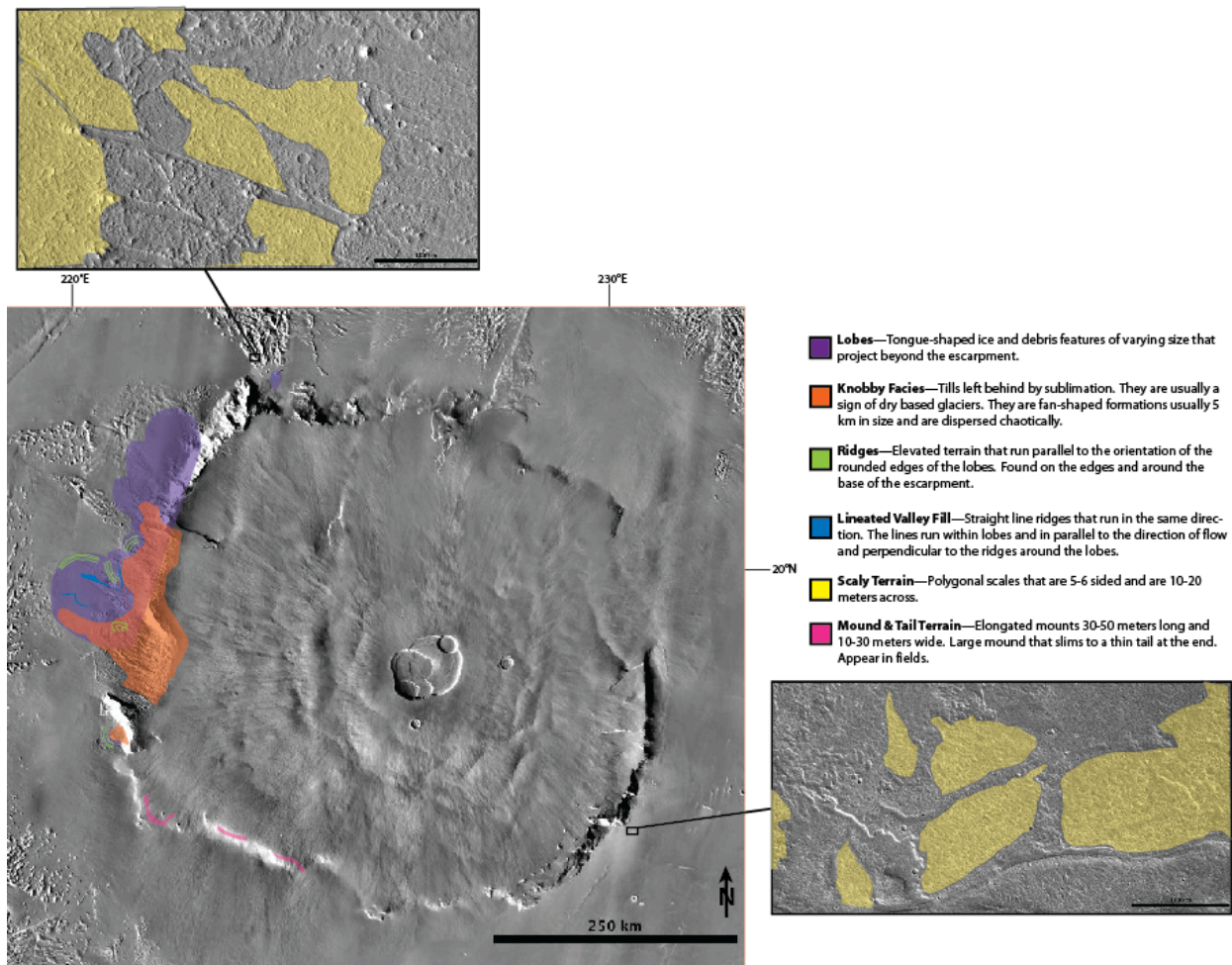


Figure 3: Map of Olympus Mons showing the distribution of various facies types associated with glaciation.

One lobe in the southwestern region of the volcano (Figure 4) showed two prominent ridges that, in one case, defined the boundary between knobby and ridge facies. Vertical profiles of this lobe (Figure 4) indicate that these are raised features that are elevated between 70 m and 100 m above the surrounding lobe surface. The more proximal ridge has the highest elevation

and bounds the knobby facies in this lobe. No ridges are observed proximal to the knobby-facies bounding ridge. The vertical profiles in Figure 4 also show a general slope to the lobe material away from the escarpment and the irregular surface of the knobby facies that compose the proximal half of the lobe.

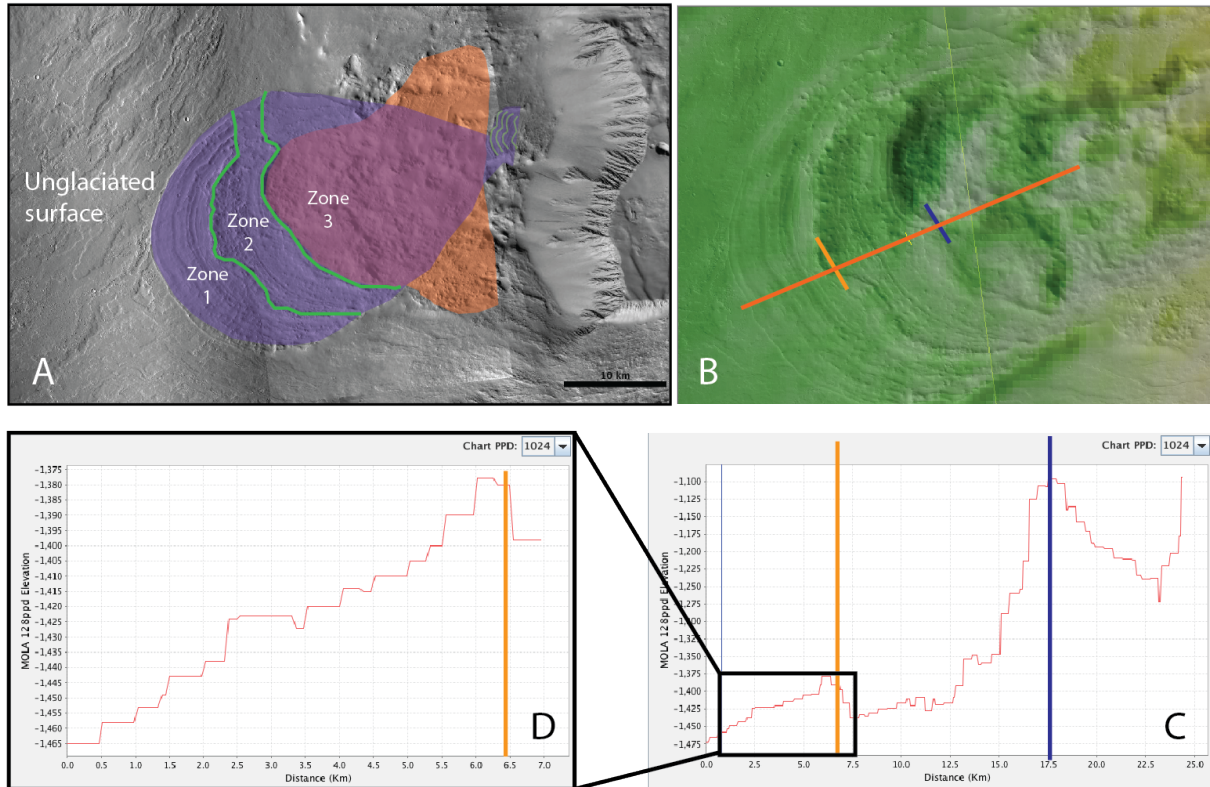


Figure 4: A glacial lobe in the southwestern region of Olympus Mons that we investigated in more detail. A) Geological map of the glacial facies identified. Legend is the same as that for Figure 3. Raised ridges identified in THEMIS imagery are indicated in green. Crater counting zones are marked. B) Image of the lobe in which the line of profile is drawn and the position of the two elevated features are noted. C) Vertical profile of the entire lobe. High points in the profile at the 6 km and 17.5 km positions are interpreted as moraines. The lobe also increases in height proximal to the escarpment suggesting that as a source of the debris.

Crater count data were gathered to assess the relative ages of different surfaces within this lobe. Unglaciated surface (Figure 4A) was assumed to represent the pre-glacial age of the surface surrounding Olympus Mons. If the interpretation that the edge of the lobe represents the maximum extent of the glacier and the two internal ridges represent recessional moraines is

correct, we expect that the unglaciated surface will yield the oldest age with zone 1, zone 2, and zone 3 being successively younger. Crater count data are presented in Figure 5.

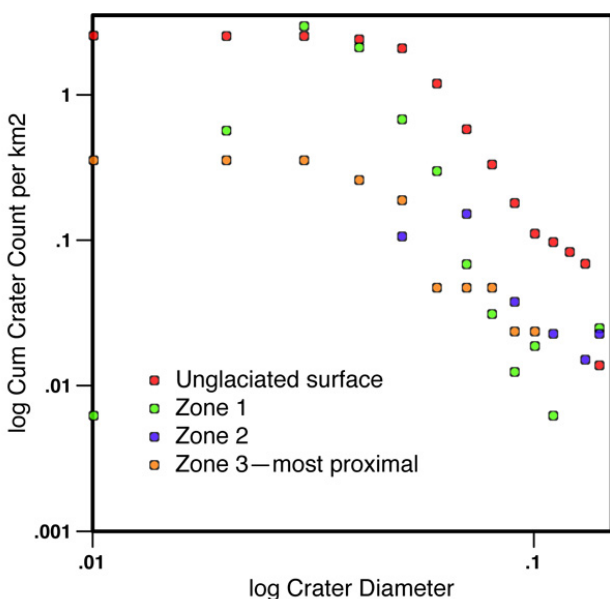


Figure 5: Log of crater diameter plotted against the log of the cumulative crater count normalized by area. The unglaciated surface shows the expected shape of distribution and plots in the position expected of the oldest surface in this analysis. Data from zone 1 and zone 2 fails to show the expected curve shape, suggesting poor data quality. Data from zone 3, the most proximal zone shows a somewhat better data distribution and the youngest age, as predicted by the recessional moraine hypothesis.

DISCUSSION

In addition to lobes, lineated valley fill, knobby facies, ridges, mound and tail structures and scaly terrain, we also explored alcoves (Head et al., 2010), talus cones and troughs (Milkovich et al., 2006) as possible indicators of glaciated terrain. Alcoves have been interpreted as zones of ice accumulation—cirque-like structures (Arfstrom and Hartmann, 2005)—associated with the birth of Olympus Mons’ escarpment glaciers (Head et al., 2010). Troughs have been likened to the U-shaped valleys that characterize glaciated landscapes. Talus cones have been reported in association with some mountain glaciers, but have also been linked to post-glacial mass wastage (Milkovich et al., 2006). Ultimately, troughs proved too small and difficult to identify to be useful for our research. Alcoves that were zones of ice accumulation and talus associated specifically with glacial movement proved too difficult to distinguish and were not mapped in this project. The exercise of identifying, searching for and eventually

abandoning possible glacial indicators proved useful as students learned that the process of science sometimes leads down blind alleys.

Our data confirm the observations of Milkovich and colleagues (2006), who documented extensive glacial deposits on the western side of the Olympus Mons escarpment. Our data provide convincing support for the interpretation of these features as evidence of recent or still active glaciers because they show the predicted association of features that were identified independently. In isolation, lobate structures or ridges might be interpreted as resulting from other processes such as volcanism or mass wastage, however, when found together in the predicted pattern, these features provide strong evidence of glaciation. For example, knobby facies (hummocky terrain, Shean et al., 2005) has been interpreted as sublimation till based on similarity in form and scale with similar material on Earth (Head and Marchant, 2003). The presence of this facies only within lobes supports this interpretation. Processes that produced lobate structures can be distinguished by the size and dimensions of the debris flows. Volcanic lobes tend to be much longer than they are wide, commonly extending for tens to hundreds of kilometers (Milkovich et al., 2006). In fact, volcanic flow terrain is visible surrounding Olympus Mons and extending much farther than any of the mapped glacial deposits (unmapped but visible on Figure 3). In contrast, debris flow or landslide deposits tend to be only as wide as the scarp from which they failed, they do not spread laterally. Most mass-wastage talus will spread less than 100 m from its source (Ballantyne and Harris, 1994). When unconfined by topography, glacial lobes tend to spread in a fan-shape away from their source. Glacial lobes are roughly equidimensional and generally less than 100 km in length. The dimensions of the lobes identified on the western side of Olympus Mons satisfy all of these criteria for interpretation as glacial structures.

Knobby facies was more common than lineated valley fill within Olympus Mons lobes. Choe and colleagues (2012) suggested that LVF represented active glaciers where lineations represent lateral and medial moraines within actively flowing ice. Once ice ceases to flow and ablation dominates, sublimation transforms the glacier into a mass of rock that is gradually let down onto the surface to form knobby facies (Head and Marchant, 2003). Using this criterion, Choe and colleagues (2012) identified two regions of active glaciation in the north and northwestern regions of Olympus Mons. The present study reconfirms this result and further notes that in the case of the northwestern region, the areas of LVF are embedded within a larger lobe of glacial debris, suggesting that these may be the last flowing remnants of a once larger glacier. The presence of small regions of active glaciers under atmospheric conditions where ice accumulation is no longer possible further suggests that the Olympus Mons glaciers are relatively young.

Crater count data for the small southwestern lobe analyzed in this study were largely inconclusive, due to inconsistencies in how completely craters of a given size class were sampled and how precisely the diameter of craters were measured. This inter-researcher variability should be reevaluated in future studies. However, despite the poor data quality, surfaces outside of the lobe were clearly older than the glaciated surfaces as would be predicted (Figure 5). Furthermore, zone 3—the most proximal to the escarpment—appears to be youngest, as would be predicted if glacial movement ceased from distal to proximal. This provisional conclusion also supports the conclusion that the two most prominent ridges can be interpreted as recessional moraines, with the most proximal representing the point at which glacial movement ceased and sublimation created knobby facies. This interpretation suggests that during ablation phases, Martian glaciers behave much as Earth-based glacier in ceasing activity over a stretch of several

kilometers and then continuing flow at a new active margin. A primary difference between Martian and mid- to low-latitude Earth glaciers is that melt water is not an important agent in reworking the remaining glacial debris. Ablation of Martian glaciers appears to be dominated by sublimation so glacial debris distal to the recessional moraine is not disturbed as the glacier retreats. Future work will repeat the crater counting test for this hypothesis and attempt to provide absolute age dates for the glacial interval.

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