The Distribution of Active Glaciers around Olympus Mons, Mars

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ABSTRACT

Glacial landforms have been reported from orbital images of Mars. However, atmospheric conditions on Mars today preclude the precipitation of snow and the accumulation of glacial ice. Global circulation models for Mars suggest that at high obliquity (≈ 45°) water vapor and carbon dioxide will be volatilized from the polar caps, thickening the atmosphere and making glacial accumulation in the low latitudes possible. These models predict that glaciers will preferentially accumulate on the northwestern sides of equatorial highlands. We test the hypothesis that glaciers are preferentially distributed on the northwestern side of Olympus Mons. We divided the circumference of the Olympus Mons escarpment into 10° intervals and used THEMIS visible images to search for signs of glacial features using 14 criteria developed by Head et al. (2010). We identified only two samples—at 310° and 340°—that met some of these criteria. We recognized a significantly smaller area of glacial deposits (≈ 3,614 km^2) than previous workers, possibly because the criteria we used to distinguish glacial deposits from other landforms focused our attention only on active glaciers.

INTRODUCTION

Glacial landforms and possibly active glaciers have been diagnosed 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). Many of the landforms interpreted as active glaciers or glacial remains show structural similarities with cold-based glaciers on Earth (Head et al., 2010, Whalley and Azizi, 2003, Shean et al., 2005). For example, the ridge facies of Pavonis Mons resemble recessional drop moraines associated with cold-based glaciers in the Dry Valleys of Antarctica (Shean et al., 2005). Likewise the hummocky facies mimic sublimation till that develops in the polar deserts of Antarctica (Shean et al., 2005). Low- and mid-latitude glaciers on Mars may form from groundwater outbursts (Head et al., 2004), obliquity-driven global climate change (Head et al., 2005, Head et al., 2006, Madeleine et al., 2009, Milkovich et al., 2006), or in association with volcanic activity (Baker, 2001, Neukum et al., 2004). Except for ice accumulation associated with outpourings of groundwater (e.g., Head et al., 2004), these models of glacier formation require atmospheric conditions different from those present on Mars today. In particular, higher atmospheric pressures and increased levels of atmospheric water vapor would be required to permit precipitation of snow and accumulation of glacial ice in mid- and low-latitudes. As with Milankovitch orbital variation on Earth, variation in Mars' obliquity and eccentricity may be associated with climate variation (Laskar et al., 2004). At high obliquity ($\approx 45°$) global circulation models for Mars show that CO_2 and water ice will sublimate from the poles and be blown to 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). Under these conditions, adiabatic lifting of moist air as it encounters topographic highs could then produce snow on Olympus Mons (Figure 1) and the Tharsis Montes (Madeleine et al., 2009) that could accumulate and persist to form glaciers. Using a global circulation model, Forget and colleagues (2006) predicted glacial accumulation on the flanks of Olympus Mons and the Tharsis Montes. And evidence of glacial deposits has emerged from photogeology surveys of the northwestern flanks of Olympus Mons (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).

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). It also raises the possibility that glaciers may still be active in some regions as suggested by Head and colleagues (2005).

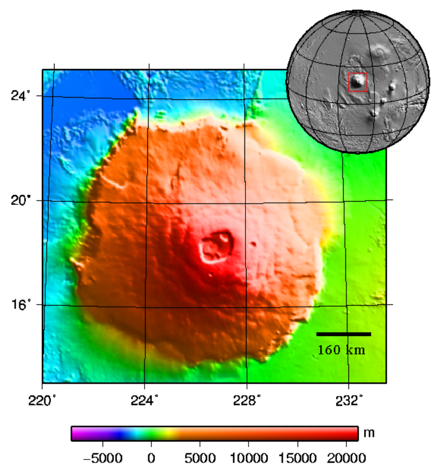


Figure 1. MOLA colorized elevation map of Olympus Mons. Hemispherical geographic context image also shows the three Tharsis Montes: Arsia Mons (southernmost), Pavonis Mons, and Ascraeus Mons (northernmost).

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, Figure 2). 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 km^2 (Milkovich et al., 2006). The conclusion that these deposits are consistent with global circulation models that predict glacial deposits only in the northwestern flanks of the volcano requires that glaciers formed only in these areas. Therefore, we test the null hypothesis that glacial deposits are randomly distributed around the Olympus Mons escarpment with the alternative that they are found only in the northwestern quadrant.

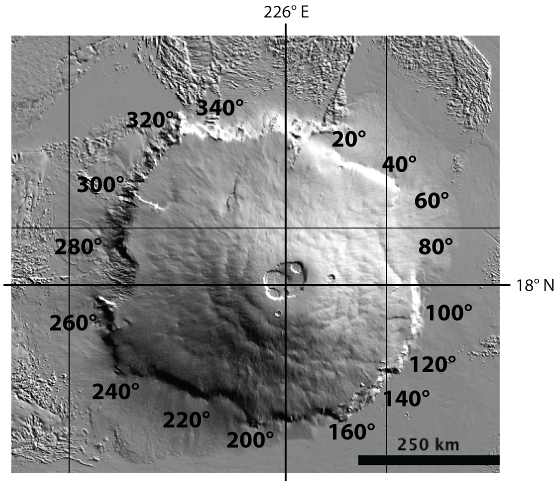


Figure 2. THEMIS visible context image showing Olympus Mons with the circumference of the escarpment divided into degree intervals for sampling.

METHODS

To test this hypothesis, we used THEMIS visible images (spatial resolution = 18 m) captured by the Mars Odyssey spacecraft to conduct a photogeology survey of the region surrounding Olympus Mons. Olympus Mons, a shield volcano, is located at approximately 226.2°E and 18.2°N on the western margin of the Tharsis Platueu (Figure 1). The summit caldera is approximately 22 km in elevation with the basal escarpment rising approximately 6 km above the surrounding plain. Orbital images were accessed and analyzed using 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.

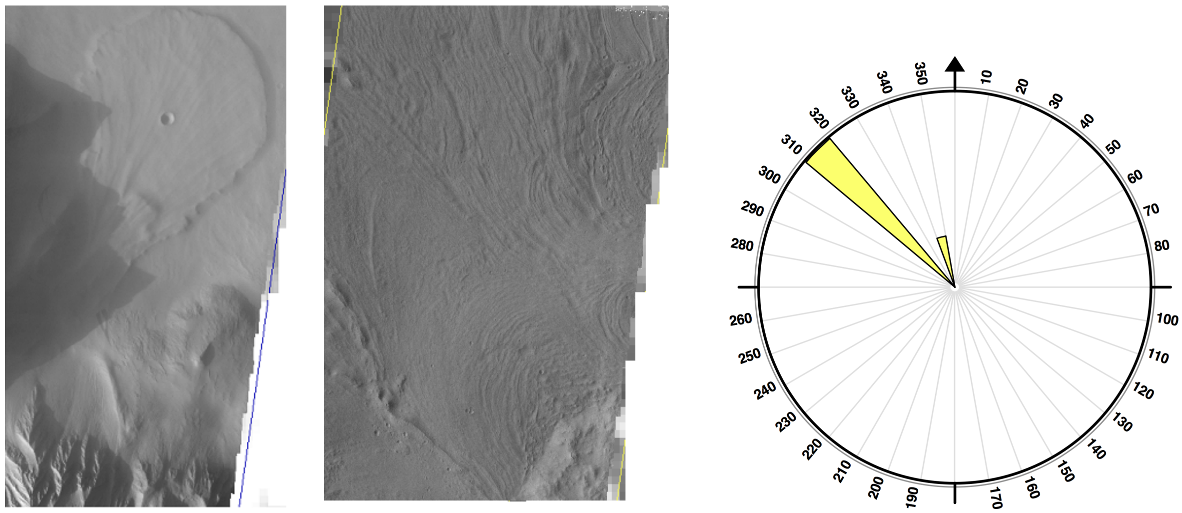
To survey for glacial deposits, we divided the circumference of the Olympus Mons escarpment into 10° increments (Figure 2) and examined images at each increment. The 10˚ interval was selected in order to get a detailed and representative sample around the Olympus Mons escarpment within the time and with the resources available to us. At each sample location, we rendered images that allowed us to examine an area extending approximately 45 kilometers away from the escarpment. This distance represents the average extent of glacial deposits reported by Milkovich and colleagues (2006). To identify glacially derived deposits, we used the 14 criteria developed by Head and colleagues (2010), which are summarized in Figure 3. Each 10° increment was initially studied by an investigator and then verified by a second investigator to assure that the identification criteria were being applied consistently among investigators. A third check was performed by Prof. Arens. When glacial deposits were identified and verified, we measured the area of these deposits using JMARS. Data were assembled in Microsoft Excel and graphs prepared in Aable for Macintosh.

1. Deposits have their origin in alcoves where snow and ice accumulate and rock debris is sources from the escarpment surface above.
2. Parallel bow-shaped ridges concave to the alcove and convex in the direction of flow create lobes.
3. Depressions between the ridges and the alcove walls.
4. Progressive compression and distortion of bow-shaped ridges as they interact with topographic features or other lobes.
5. Progressive opening and increasing width of bow-shaped ridges when there are no obstacles.
6. Circular to elongate pits in lobes.
7. Larger tributary valleys composed of lineated valley fill (LVF) form from the amalgamation of individual source alcoves.
8. Trunk valleys of LVF form from convergence of individual tributary valleys.
9. Moving away from the source alcove, a sequential pattern of deformation of bow-shaped ridges from broad lobes to tight folds to chevron folds to lineations oriented parallel to flow.
10. Complex folds where tributaries join trunk valleys.
11. Horseshoe-shaped lineations draped around topographic obstacles and open downstream.
12. Broadly undulating surface texture along valley topography.
13. Loves extend for tens to hundreds of kilometers.
14. Rounded valley wall corners and arête-like plateau remnants.

Figure 3. Criteria for recognizing glacial deposits in high resolution surface images on Mars from Head et al. (2010).

RESULTS

We found evidence of glaciers only at the 310° and 340° samples (Figures 4 and 5). At these locations, we observed alcoves, parallel bow-shaped ridges that face and extend outward and undulating topography in the LVF. We also identified circular to elongate pits in the lobes, folds and chevron folds that form when lobes flow together, and LVF that extend tens to 100s of kilometers from the source alcoves (Figure 6).



A B C

Figure 4. **(A)** THEMIS visible image V26414027 at 340° on the escarpment of Olympus Mons showing a lobe of lineated valley fill that we interpret as an active glacial deposit. **(B)** THEMIS visible image V11139010 at 310° on the escarpment of Olympus Mons showing bow-shaped ridges arising from an alcove, complex folds and distal lineated valley fill with undulating surface texture (Figure 6). **(C)** Rose diagram plotting the position and proportional area of active glaciers around the Olympus Mons escarpment.

DISCUSSION

Our data lead us to reject the null hypothesis that glacial deposits are evenly distributed around the Olympus Mons escarpment in favor of the alternative that glacial deposits are restricted to the northwestern quadrant of the volcanic escarpment. We recognized a much smaller total area of glacial deposits (3,614 km^2, Figure 5) than did Milkovich and colleagues (2006) who identified approximately 15,000 km^2 of glacial debris. We also recognized a smaller region of deposits (310° – 340°) in contrast with Milkovich and colleagues (2006) who recognized deposits between 250° and 330°. A possible explanation for this discrepancy is that we applied the criteria proposed by Head and colleagues (2010) to distinguish glacial deposits from the various other types of deposits (e.g., debris avalanches, lava flows and pyroclastic flows) that might create lobed features around Olympus Mons. The criteria that we used are more restrictive than those used by Milkovich and colleagues (2006) and may have focused our attention on currently active glaciers rather than the more inclusive category of glacial debris documented by Milkovich and colleagues (2006). For example, we used the smooth surface

Image Number	**Position** degrees	**Latitude** north	**Longitude** east	**Number of Glacial Features**	**Area** km^2
V27200028	10	23.155	228.304	0	0
V20224007	20	22.9	228.4	0	0
V14009009	30	19.984	230.406	0	0
V11276008	40	21.965	230.232	0	0
V27724029	50	22.042	230.478	0	0
V27412036	60	21.05	231.535	0	0
V18302013	70	19.672	231.047	0	0
V27125019	80	19.215	231.129	0	0
V27125019	90	19.165	231.073	0	0
V27387037	100	19.305	231.859	0	0
V17366015	110	16.268	231.111	0	0
V18901003	120	16.004	230.805	0	0
V39902018	130	15.177	230.8	0	0
V16655009	140	20.854	221.937	0	0
V27150033	150	13.633	228.978	0	0
V08493012	160	13.275	229.027	0	0
V28348019	170	13.035	227.252	0	0
V05497021	180	13.512	229.75	0	0
V19438015	190	13.809	226.504	0	0
V17541015	200	14.838	222.842E	0	0
V18140008	210	14.365	223.445	0	0
V14783011	220	14.436	222.312	0	0
V15407007	230	15.396	222.589	0	0
V20349006	240	15.2	221.7	0	0
V27899024	250	14.688	224.508	0	0
V19126016	260	16.887	220.917	0	0
V45107012	270	18.545	221.13	0	0
V39241011	280	19.063	220.855	0	0
V13610011	290	21.375	222.461	0	0
V19001007	300	20.803	221.527	0	0
V26776019	310	21.859	222.334	5	3380
V16967013	320	22.855	222.307	0	0
V27150033	330	14.035	229.18	0	0
V26414027	340	23.49	223.872	4	234
V26963025	350	22.953	225.148	0	0
V11638009	360	23.391	226.682	0	0

Figure 5. Data from observations of 10° intervals around the Olympus Mons escarpment. The glacial features identified are those described by Head et al. (2010) and summarized in Figure 3.

texture to distinguish glacial deposits from lava flows, which were abundant all around Olympus Mons. This may have led us to reject some of the ancient glacial deposits documented by

Position	Glacial Features													
degrees	1	2	3	4	5	6	7	8	9	10	11	12	13	14
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0	0	0	0	0	0	0	0
60	0	0	0	0	0	0	0	0	0	0	0	0	0	0
70	0	0	0	0	0	0	0	0	0	0	0	0	0	0
80	0	0	0	0	0	0	0	0	0	0	0	0	0	0
90	0	0	0	0	0	0	0	0	0	0	0	0	0	0
100	0	0	0	0	0	0	0	0	0	0	0	0	0	0
110	0	0	0	0	0	0	0	0	0	0	0	0	0	0
120	0	0	0	0	0	0	0	0	0	0	0	0	0	0
130	0	0	0	0	0	0	0	0	0	0	0	0	0	0
140	0	0	0	0	0	0	0	0	0	0	0	0	0	0
150	0	0	0	0	0	0	0	0	0	0	0	0	0	0
160	0	0	0	0	0	0	0	0	0	0	0	0	0	0
170	0	0	0	0	0	0	0	0	0	0	0	0	0	0
180	0	0	0	0	0	0	0	0	0	0	0	0	0	0
190	0	0	0	0	0	0	0	0	0	0	0	0	0	0
200	0	0	0	0	0	0	0	0	0	0	0	0	0	0
210	0	0	0	0	0	0	0	0	0	0	0	0	0	0
220	0	0	0	0	0	0	0	0	0	0	0	0	0	0
230	0	0	0	0	0	0	0	0	0	0	0	0	0	0
240	0	0	0	0	0	0	0	0	0	0	0	0	0	0
250	0	0	0	0	0	0	0	0	0	0	0	0	0	0
260	0	0	0	0	0	0	0	0	0	0	0	0	0	0
270	0	0	0	0	0	0	0	0	0	0	0	0	0	0
280	0	0	0	0	0	0	0	0	0	0	0	0	0	0
290	0	0	0	0	0	0	0	0	0	0	0	0	0	0
300	0	0	0	0	0	0	0	0	0	0	0	0	0	0
310	1	1	0	0	0	1	0	0	1	0	0	1	0	0
320	0	0	0	0	0	0	0	0	0	0	0	0	0	0
330	0	0	0	0	0	0	0	0	0	0	0	0	0	0
340	1	1	0	0	0	0	0	0	0	0	0	1	1	0
350	0	0	0	0	0	0	0	0	0	0	0	0	0	0
360	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 6. Catalog of glacial features identified at each 10° sampling interval. Features 1-14 correspond to those detailed by Head et al. (2010) and summarized in Figure 3. 0 = feature absent, 1 = feature present.

Milkovich and colleagues (2006) and recognize only currently active glaciers that have a smooth and undulating surface texture. In many of the areas mapped my Milkovich and colleagues (2006) as glacial deposits had a rough, blocky or hummocky surface texture that resembled lava flows. Some of these deposits also seemed to originate from the top of the escarpment rather than alcoves in its sides. The origin of glacial ice in alcoves where snow could accumulate is a key feature in the predominant model of glacier formation (Head et al., 2010).

Despite the relatively small area of glacial deposits that we report, our results conform with current models of glacier formation in association with precipitation during times of high obliquity (Forget et al., 2006, Head et al., 2006, Jakosky and Carr, 1985, Mischna et al., 2003) and previous observations of Olympus Mons (Head et al., 2005, Milkovich et al., 2006, Neukum et al., 2004). Our conclusion that we have focused primarily on active glaciers is also consistent with previous reports of very young or potentially still active glaciers associated with the Olympus Mons escarpment (Neukum et al., 2004). This raises the question: Why are glaciers in these areas still active when all others seem to have sublimated sufficiently that they no longer move?

To address this question, we must first review two features of Martian glaciers. First, Mars' gravity is only about one third that of Earth's. Therefore, three times the ice mass would be required to initiate glacial movement on Mars. On Earth, plastic deformation of basal ice begins only under the weight of approximately 50 m of ice. On Mars, a minimum of 150 m of water ice accumulation would be required to initiate glacial movement. This figure might be somewhat reduced if Martian glaciers incorporated both water and carbon dioxide ice because of the greater molecular weight of CO_2. Second, most of evidence for glaciers on Mars points toward an analogy with cold-based glaciers on Earth (Head and Marchant, 2003, Kadish et al., 2008, Shean et al., 2005). Cold-based glaciers, like those of the Dry Valleys of Antarctica, occur in climates that are so cold that temperatures at the base of the glacier do not exceed the pressure melting point of water. Consequently, these glaciers remain frozen to their beds and move only by plastic deformation of ice within the glacier. Such glaciers move slowly or not at all, and few studies have documented their rates (Waller, 2001). This contrasts with wet-based glaciers where temperatures at the base of the glacier are above the pressure melting point of water and the base of the glacier is lubricated by liquid water. Wet-based glaciers can move at speeds of 20-30 m/day (Joughin et al., 2004) and can surge to rates up to an order of magnitude higher.

Under the prevailing model for tropical glacier formation on Mars (Forget et al., 2006, Levrard et al., 2004, Mischna et al., 2003, Richardson and Wilson, 2002), glaciers are initiated during periods of high obliquity when water sublimated from the polar cap is transferred to low latitudes and precipitates as snow. Snow accumulates on the northwestern flanks of tropical highlands to a critical thickness (> 150 m) and begins to flow, forming a variety of glacial debris features. When obliquity returns to lower levels, accumulation ceases and ablation dominates the glacial environment, first halting glacial advance and eventually eliminating ice within the rock debris. Such ice-cored "rock glaciers" have been reported from Candor Chasma (Whalley and Azizi, 2003) and may constitute some of the glacial deposits from Olympus Mons (Milkovich et al., 2006). Therefore, Mars, with its current obliquity of 25.2° may be in an interglacial (Head et al., 2003) following a geologically very recent glacial advance. If this is correct, the last active glaciers may be in areas where they are 1) thickest and therefore last to sublimate past the point of movement, 2) protected from sublimation by a thick debris blanket, or 3) protected from melting by shadows from Olympus Mons itself.

When the climate regime on Earth transitions from glacial to interglacial, the mass balance of glaciers switches from net accumulation to net ablation. Although net ablation, generally dominated by melting from the distal margin, exceeds accumulation during this time, accumulation still occurs and the glacier will continue to flow. During the transition to an interglacial, the glacier will experience periods when accumulation balances ablation and recessional moraines will develop (Goldsmith, 1982). A series of recessional moraines will develop until the glacier loses sufficient mass to sustain flow. From this point, ice ablates and deposits any debris that it is carrying in place.

The situation may be considerably different on Mars. Since ablation is dominated by sublimation rather than melting, the position of the ice front will not change during the transition to an interglacial because sublimation will happen more-or-less evenly across the glacier surface. Second, because glacial movement is so slow in cold-based glaciers, little or no debris may accumulate in terminal or recessional moraines at the ends of these glaciers. Therefore, a next question to explore will be a comparison of recessional features produced by Earth's cold-based glaciers and a search for those features within the regions mapped as glacial debris on Mars.

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