Formation of lobate debris aprons on Mars: Assessment of regional ice sheet collapse and debris-cover armoring

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Article info
Article history:
Received 16 April 2013
Revised 29 August 2013
Accepted 25 September 2013
Available online 5 October 2013

Keywords:
Mars, climate
Mars, surface
Mars, polar geology
Mars, polar caps

Abstract
Lobate debris aprons (LDA) are lobate-shaped aprons surrounding scarps and isolated massifs that are concentrated in the vicinity of the northern Dichotomy Boundary on Mars. LDAs have been interpreted as (1) ice-cemented talus aprons undergoing viscous flow, (2) local debris-covered alpine-like glaciers, or (3) remnants of the collapse of a regional retreating ice sheet. We investigate the plausibility that LDAs are remnants of a more extensive regional ice sheet by modeling this process. We find that as a regional ice sheet collapses, the surface drops below cliff and massif bedrock margins, exposing bedrock and regolith, and initiating debris deposition on the surface of a cold-based glacier. Reduced sublimation due to debris-cover armoring of the proto-LDA surface produces a surface slope and consequent ice flow that carries the armoring debris away from the rock outcrops. As collapse and ice retreat continue the debris train eventually reaches the substrate surface at the front of the glacier, leaving the entire LDA armored by debris cover. Using a simplified ice flow model we are able to characterize the temperature and sublimation rate that would be necessary to produce LDAs with a wide range of specified lateral extents and thicknesses. We then apply this method to a database of documented LDA parameters (height, lateral extent) from the Dichotomy Boundary region, and assess the implications for predicted climate conditions during their formation and the range of formation times implied by the model. We find that for the population examined here, typical temperatures are in the range of −85 to −40 °C and typical sublimation rates lie in the range of 6–14 mm/a. Lobate debris apron formation times (from the point of bedrock exposure to complete debris cover) cluster near 400–500 ka. These results show that LDA length and thickness characteristics are consistent with climate conditions and a formation scenario typical of the collapse of a regional retreating ice sheet and exposure of bedrock cliffs. This scenario helps resolve many of the unusual characteristics of lobate debris aprons (LDA) and lineated valley fill (LVF). For example, the distribution of LVF is very consistent with extensive flow of glacial ice from plateau icefields, and the acquisition of a debris cover in the waning stages of retreat of the regional cover as the bedrock scarps are exposed. The typical concentric development of LDA around massifs is much more consistent with ice sheet retreat than insolation-related local accumulation and flow. We thus conclude that the retreating ice-sheet model is robust and should be investigated and tested in more detail. In addition, these results clearly show that the lobate debris aprons in the vicinity of the Dichotomy Boundary could not have attained temperatures near or above the ice melting point and retained their current shape, a finding that supports subzero temperatures for the last several hundred million years, the age of the LDA surfaces. A further implication is that the LDA ice has been preserved for at least several hundred million years, and could potentially contain the record of the climate of Mars, preserved since that time below a sublimation lag deposit.

1. Introduction

Models of ice sheets on Mars (e.g., Fastook et al., 2008) have helped to identify and interpret glacial deposits observed from orbit (Head and Marchant, 2003), while also testing climate scenarios that may have been responsible for their formation (Forget et al., 2006). In many of these cases it is possible that the ice sheets themselves existed only in the past during periods of different climate dictated primarily by dramatic changes in obliquity (Forget et al., 2006; Madeleine et al., 2009). Here we examine possible formation mechanisms for lobate debris aprons (LDA).
LDAs in the Deuteronilus Mensae region in the fretted terrain along the Dichotomy Boundary (Sharp, 1973) have been thought to involve significant amounts of water ice since the time of Viking observations (Carr and Schaber, 1977; Lucchitta, 1984), but controversy over the amount of water ice involved has ranged from very low (~20–30%), ice assisted talus flow; Squyres, 1978, 1979), to medium (~30–80% rock-glaciers; Li et al., 2005; Mangold et al., 2002), and to high (>80% debris-covered glaciers; Colaprete and Jakosky, 1998; Kargel, 2004; Head et al., 2005, 2006a, 2006b; Parsons et al., 2011). In addition, the low number of craters on the LDA surfaces requires mid-to-late Amazonian ages for formation and movement cessation (e.g., Chuang and Crown, 2005).

Recently, the SHARAD subsurface radar sounding experiment on the Mars Reconnaissance Orbiter (MRO) (Seu et al., 2007) has confirmed that many, if not most, of the LDAs contain relatively pure water ice covered only by a thin layer of debris shed from adjacent scarps (Holt et al., 2008a, 2008b; Pfaut et al., 2008, 2009). The requirement that the valley floor extend undistorted beneath the observed LDAs dictates a dielectric constant consistent with pure (<10% contaminant) water ice. In addition, the surface debris layer can be constrained to be less than ~10 m due to the lack of a shallow soil–ice interface in the radar data, but must be greater than 0.5 m to explain the lack of a hydrogen signal in gamma ray/neutron data (Boynton et al., 2007; Feldman et al., 2004; Mitrofanov et al., 2002).

Fig. 1 shows a radargram and ground track from Pfaut et al. (2009) for a LDA at 39.1N, 24.2E in the Deuteronilus Mensae region (see Head et al., 2006b). Focusing on the feature in the left-hand side of the track where it crosses between two mesas, one observes a profile showing a classic convex shape often indicative of viscous flow (Fig. 1b). Li et al. (2005) demonstrated that LDA profiles could be reasonably approximated with a plastic rheology defined by a yield stress with resulting parabolic profiles, and used this to categorized them into Types I, II, and III (convex and close to the plastic profile, convex but below the plastic profile, and convex but with much more deviation from the plastic parabolic profile) that reflected their degree of post-formation modification. Parsons et al. (2011) and Parsons and Holt (2013) proposed a formation mechanism whereby the current profiles evolved through viscous flow of predominantly pure ice from a shorter and much thicker deposit, and then used the estimated age of the LDAs to constrain the temperature, the grain size, and dust fraction manifest in their defined ice rheology. We choose a very different approach, with the assumption that the LDAs are remnant features of a larger, regional ice sheet.

2. Formation hypothesis

Of the three major interpretative frameworks for LDAs, (1) ice-cemented debris aprons undergoing viscous flow, (2) local debris-covered alpine-like glaciers, or (3) remnants of the collapse of a regional retreating ice sheet, significant evidence has recently accumulated that supports the regional ice sheet model. This evidence includes (1) the existence of glacial highstands that suggest that many of these features are part of a larger glacial land system with ice being several km thick regionally (Dickson et al., 2008, 2010), (2) the presence of distal ice-rich deposits well beyond the distal margins of lobate debris aprons (Baker et al., 2010), (3) an integrated pattern of exposures that suggest regional glacial land systems (Head et al., 2010), (4) global climate models that support regional snow and ice accumulation rather than local accumulation that would favor alpine-type valley glaciers (Madeleine et al., 2009), and (5) glacial flow models that are consistent with both the climate models and the geological evidence (Fastook et al., 2010). On the basis of this evidence, we investigate the plausibility that LDAs are remnants of a more-extensive regional ice sheet by modeling this process.

In our scenario, as the regional ice sheet collapses, the surface drops below cliff and massif bedrock margins, exposing bedrock and regolith, and initiating debris deposition. Reduced sublimation due to debris-cover armoring of the LDA, which initially is focused near exposed bedrock cliffs, produces a relative increase in the slope of distal (exposed) ice that with consequent ice flow along the entire glacier, carries the armoring debris further away from the base of the cliff. As collapse continues, the debris train eventually reaches the glacier snout, leaving the entire LDA armored by debris cover. This armored LDA, with its considerably reduced sublimation rate, could persist for a long period of time. Indeed, even here on Earth, the oldest known ice may be preserved beneath an analogous armored layer in the Dry Valleys of Antarctica, where preserved ice is known to be several million years old (Marchant et al., 2007; Kowalewski et al., 2011). Ice, being a non-Newtonian fluid, exhibits behavior where for low stresses, deformation, and hence flow, is reduced by orders of magnitude from that which would be produced by a linear flow law. We would expect these armored LDAs to continue to deflate, albeit much more slowly with the reduced sublimation rate, until their surface profile reaches a
configuration where the slope and thickness product provide such a low driving stress that movement, for all intents and purposes, would cease. As this configuration might be attained at different times and places along the profile, one might expect differential movement resulting in longitudinal compression of the debris layer that might appear as ridges transverse to the down-slope direction.

Specifically, the formation mechanism, shown schematically in Fig. 2, begins with a larger regional ice sheet that completely buries the underlying terrain (Fig. 2a) (Fastook et al., 2010; Head et al., 2010; Madeleine et al., 2009). As this ice sheet collapses in an ablation environment, its surface drops below the level of the scarps where current LDAs are found (Fig. 2b). At this point debris from the scarps begins to accumulate on the ice sheet surface. As with our terrestrial analog, the Mullins Glacier in the Dry Valleys of Antarctica (Marchant and Head, 2005, 2007; Marchant et al., 2007; Shean et al., 2007), this debris cover armors the surface (Fig. 2c) and reduces ablation by orders of magnitude (Kowalewski et al., 2006, 2011). As the initial armoring begins at the base of the scarps, the ice sheet will begin to evolve a surface slope down away from the scarp (Fig. 2d). This surface slope will continue to carry surface debris away from the scarp, expanding the armored area. As the sheet continues its collapse, at some point the surface debris will reach the glacier snout and the entire profile will be completely armored by debris (Fig. 2d), leaving behind a LDA with a particular thickness and lateral extent that depends on the choice of certain parameters within the model. We now take this conceptual model and explore a quantitative formulation.

3. Modeling

The model is a 1D flowband shallow-ice formulation simplified by assuming isothermal conditions, i.e., a specified uniform temperature in the flowband interior equal to the mean annual surface temperature (Fastook, 1987; Millour et al., 2011). This simplification is reasonable given that the low flow velocities will produce little shear heating and the typical thicknesses of LDAs of a few hundred meters will provide little insulation of the already low geothermal flux (for reference see treatments in Fastook et al., 2008, 2011; Fastook and Head, 2012). The model uses Glen’s Flow Law (Glen, 1955; Paterson, 1994), and while newer rheologies exist (e.g., Goldsby et al., 2013), these defining properties are poorly constrained in the current LDAs. Future analysis of LDA radar properties (e.g., Holt et al., 2008b; Plaut et al., 2009) might provide minimum estimates of dust/debris content, and analysis of terrestrial cold-base glacier flow textures could provide additional clues (e.g., Marchant et al., 2010). Other parameters in the model besides temperature, which determines flow rates in the evolving LDA, include the debris-free sublimation rate, the limiting debris-covered sublimation rate, the debris accumulation rate at the base of the scarp, a factor relating the depth of debris cover to the reduction in sublimation rate, and the height of the scarp at which debris begins to accumulate. Using this model, we now explore the parameter space to assess the model predictions and to identify the most sensitive parameters.

4. Experiments

Extensive model runs with randomly chosen values for the various input parameters yield a suite of final configurations, each with a resulting thicknesses and lateral extent. After extensive examination of the parameter space we find that the most sensitive parameters are temperature, debris-free sublimation rate, and scarp height. Since scarp height is well constrained by MOLA topography, we examine in detail the effects of temperature and debris-free sublimation rates. Fig. 3 shows plots of margin distance and thickness as functions of temperature (horizontal axis, °C) and debris-free sublimation rates (vertical axis, mm/a). Each colored dot (they appear as irregular clusters due to the very large number of randomly-generated simulations) represents one of the 50,000 model runs generated with temperature and debris-free sublimation rates provided by a range-constrained pseudo-random number generator. One can clearly see that warmer temperatures and lower sublimation rates lead to greater margin extent, while warmer temperatures and larger sublimation rates lead to thinner LDAs. This is to be expected since warmer ice is softer and supports faster flow for a given surface slope, allowing the armoring debris to be carried further before reaching the glacier snout, resulting in a completely armored LDA. On the other hand, higher sublimation rates reduce the overall thickness faster, typically leaving much thinner LDA for the same lateral extent.

Armed with our database of results from particular input parameters, we can specify a “target” configuration (i.e. thickness
and margin extent), and ask what climatic conditions (i.e. temperature and debris-free sublimation rate) could have produced that configuration. We define a “distance” metric that is a measure of the goodness of the result to the desired target, where \( T_0 \) and \( M_0 \) are the target thickness and the margin extent respectively.

\[
D = \sqrt{\left( \frac{T - T_0}{T_0} \right)^2 + \left( \frac{M - M_0}{M_0} \right)^2}
\]

Fig. 4 shows envelopes of candidate temperatures and debris-free sublimation rates that would produce specific target configurations. Shown here are solutions whose “distance” metric is less than 0.32 \((10^{-0.5})\), indicated by color in the figure by its base-10 logarithm and chosen arbitrarily to show the envelope of “nearby” conditions that yield solutions close to the target margin extent and thickness). Fig. 4a targets a configuration with a margin extent of 13 km and a thickness of 370 m, the mean values of the catalogued LDAs considered here (Chuang and Crown, 2005; Ostrach, 2007). For this target configuration, the best fit at the center of the “bullseye” is obtained for a temperature of \(-64.2\) °C and a debris-free sublimation rate of 8.9 mm/a. A thinner and smaller target configuration, 10 km in extent and 200 m thick is shown in Fig. 4b. The best fit now requires a slightly warmer temperature of \(-58.2\) °C but a larger sublimation rate of 10.2 mm/a. Fig. 4c and d are for target configurations one standard deviation larger in extent (20 km) and one standard deviation thinner (4c at 200 m) and thicker (4d at 550 m). The larger but thinner configuration of Fig. 4c requires much warmer temperatures, \(-36.4\) °C, but a considerably reduced sublimation rate, 7.1 mm/a. The larger but thicker configuration of Fig. 4d is obtained with virtually the same sublimation rate, 7.1 mm/a, but much colder temperatures, \(-54.5\) °C.

As we repeat the procedure for different target margin extents and thicknesses, we find the following behavior shown in Fig. 5. Lines of constant thickness trend from lower left to upper right (200 along the lower right to 900 along the top at 50 m intervals shown with colors from the left-hand vertical scale bar). Lines of constant margin extent display an “L-shaped” pattern (with 5 km on the left and 50 on the upper right at 5 km intervals shown with colors from the right-hand vertical scale bar). Also shown in Fig. 5 are the resulting temperatures and debris-free sublimation rates for the LDAs listed in Appendix A of Ostrach (2007) where here the absolute “distance” metric (not \(\log_{10}\) as in Fig. 4) for the closest fit is shown by colors from the horizontal scale bar along the top of the figure. Most achieved reasonable fits with the conspicuous exception of the LDAs thinner than 200 m, all of which, regardless of extent, had unreasonably large “distance” metrics. A possible explanation for this is that the thinner LDAs have undergone continued deflation subsequent to the complete arming, a process not included here. For the rest, with the exception of a few very thick outliers, most of the LDAs lie along a curved line trending from low temperature, high sublimation rates (\(-90\) °C and 15 mm/a) for those with the smallest lateral extent (5 km) to warmer, lower sublimation rates (\(-25\) °C and 5 mm/a) for those with larger lateral extents (30 km). Given our proposed formation mechanism, this makes sense in that cold ice flows less readily, so debris is not carried as far during the time interval in which the higher sublimation rate is deflating the ice. Conversely, warmer more easily deformed ice will carry the debris much farther during the longer time interval provided by the lower sublimation rate. This observation has implications for the relative humidity during the formation episodes, since normally warmer temperatures at the same pressure and humidity would be expected to produce higher sublimation rates. The results in Fig. 5 provide us with a “mapping,” or transformation, that we can use to convert any measured LDA’s thickness and extent into a climatic record of the temperature and debris-free sublimation rate present at the time the LDA formed.

5. LDA inventory

With this mapping from LDA extent and height to temperature and debris-free sublimation rate provided by our database of 50,000 model runs and illustrated in Fig. 5, we can now apply this transformation to specific measurements of LDA extent and height in order to assess what climatic conditions might have been present at the time of formation of specific LDAs. An inventory of LDAs (Ostrach, 2007) for a region near the Dichotomy Boundary provided tabulated locations, thicknesses, and lateral extents for over 200 LDAs, some 80 of which are in the region shown in Fig. 6. The distribution of tabulated LDA thicknesses and margin extents is shown in Fig. 6a and b respectively. Thicknesses range from 42 to 890 m, with a mean and standard
deviation of 372 and 179 m respectively. Margin extents range from 2 to 47 km, with a mean and standard deviation of 13 and 9 km. Our mapping predicts a temperature of $-64.2^\circ C$ and a sublimation rate of 8.9 mm/a for the mean thickness and extent. Reducing thickness by one standard deviation requires 13 $-58.2^\circ C$ but a larger sublimation rate of 10.2 mm/a. (c) Targets one standard deviation larger in extent (20 km) and one standard deviation thinner (200 m). The larger but thinner configuration of (c) requires much warmer temperatures, $-36.4^\circ C$, but considerably reduced sublimation rate, 7.1 mm/a. The larger but thicker configuration of (d) is obtained with virtually the same sublimation rate, 7.1 mm/a, but much colder temperatures, $-54.5^\circ C$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

![Fig. 4. Envelopes of candidate temperatures and sublimation rates that would produce specific target configurations for solutions whose “distance” metric is less than 0.32 (10–0.5, indicated by color in the figure by its base-10 logarithm). (a) Targets a margin extent of 13 km and a thickness of 370 m, the mean values of the catalogued LDAs, with best fit for a temperature of $-64.2^\circ C$ and a sublimation rate of 8.9 mm/a. (b) Targets a thinner and smaller target configuration (10 km in extent and 200 m thick) and requires a slightly warmer temperature of $-58.2^\circ C$ but a larger sublimation rate of 10.2 mm/a. (c) Targets one standard deviation larger in extent (20 km) and one standard deviation thinner (200 m). (d) Targets one standard deviation larger in extent (20 km) and one standard deviation thicker (550 m). The larger but thinner configuration of (c) requires much warmer temperatures, $-36.4^\circ C$, but considerably reduced sublimation rate, 7.1 mm/a. The larger but thicker configuration of (d) is obtained with virtually the same sublimation rate, 7.1 mm/a, but much colder temperatures, $-54.5^\circ C$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)](image)

An example profile detailed in Ostrach (2007) from orbit 12123.2, located at 29.43E, 41.27N is shown in Fig. 7. The lateral extent and thickness is listed at 26 km and 636 m. For comparison, also shown is the model-generated profile identified from our mapping of Fig. 5 for its tabulated extent and thickness. The best match to extent and thickness is for a temperature of $-50.2^\circ C$ and debris-free sublimation rate of 6.4 mm/a. Given the simplifications in the ice sheet model, the match between the observed and modeled profile is reasonable. Since the model profile is for the instant the debris train reaches the glacier snout and the whole LDA is armored, it is not unexpected that the measured profile would fall below the modeled profile. Even at this temperature there would be some continued movement subsequent to the entrained debris reaching the glacier snout that would lower the profile. The presence of a slightly concave profile at the toe of the LDA is perhaps indicative of continued sublimation, even beneath the debris armoring.

With the tabulated distribution of LDA characteristics and our mapping of LDA thickness and extent into climatic information, we can ask the question: What is the distribution of derived climatic conditions predicted by the distribution of LDA characteristics? Fig. 8 shows the properties derived from the LDAs of Ostrach (2007). Fig. 8a and b show temperatures and debris-free sublimation rates respectively. While we are aware of the dangers of interpolation (and more so extrapolation) of unevenly spaced data, it is
still worthwhile to visualize the spatial distribution. Contours in Fig. 8c and d are cubic-spline fits to the LDA results for temperature and debris-free sublimation, generated using Generic Mapping Tool (GMT). While there are clear north–south and topographic trends in the temperature results, with temperatures colder at higher latitudes and warmer at higher elevations, the debris-free sublimation rates do not display similar simple trends. For sublimation, a saddle of medium rates separates two eastern and western patches of high sublimation and two northern and southern patches of low sublimation, with no clear association with either latitude or elevation. These preliminary results are meant to show broad candidate trends. When more LDA and LVF data are collected and ages for the various occurrences are determined this approach can become a potentially robust description of the climate during formation.

In Fig. 9 we examine the duration of the formation process, specifically the time from the moment the surface drops to the level of the cliff top and armoring debris begins to accumulate on the ice surface until the transported debris train reaches the glacier snout and the LDA is completely armored (between Fig. 2b and d). Fig. 9a shows the formation time as a function of temperature and debris-free sublimation rate and includes the LDAs of Ostrach (2007). For cold temperatures we observe a monotonically decreasing formation time for increasing debris-free sublimation rate, as would be expected since with cold, and therefore very hard ice, the rate at which the surface lowers depends primarily on this sublimation rate. As we move to warmer temperatures, an inversion occurs, where for sublimation rates between 5 and 6 mm/a we observe a secondary maximum in formation times exceeding 700 ka. This occurs because the faster flow of the warmer, and hence softer ice is able to carry the debris farther from the base of the cliff retarding ultimate formation time. From Fig. 3 it is clear that this occurs for LDAs with thickness of ~100–250 m and margin extent of ~20–30 km. The only LDA that falls into this category is one at 29.89E, 45.56N with a thickness of 154 m, an extent of 20.1 km, and a formation time of 745 ka. Excluding this and the two with formation times greater than 1 Ma (both anomalously thick and large, requiring very low sublimation rates), the mean formation time is 422 ka

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<tr>
<th>Thickness (m)</th>
<th>Extent (km)</th>
<th>Temperature (°C)</th>
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Fig. 5. Best fit contours for thickness and margin extent with LDAs from Ostrach (2007). Lines of constant thickness trend from 200 m at the lower left to 900 m at the upper right at 50 m intervals with colors from the left-hand vertical scale bar. Lines of constant margin extent display an L-shaped pattern with 5 km on the left and 50 on the upper right at 5 km intervals with colors from the right-hand vertical scale bar. The absolute “distance” metric for the best-fit temperatures and debris-free sublimation rates for the LDAs listed in Appendix A of Ostrach (2007) are shown by stars with colors from the horizontal scale bar along the top of the figure. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1

Predicted temperature and debris-free sublimation rate for the mean LDA thickness and lateral extent with the range in response for a range of plus or minus one standard deviation from the means.

<table>
<thead>
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Fig. 6. Location maps for Dichotomy Boundary LDAs from Ostrach (2007) (a) Thickness (m), ranging from 42 to 890 m, with a mean and standard deviation of 372 and 179 m respectively. (b) Margin extent (km), ranging from 2 to 47 km, with a mean and standard deviation of 13 and 9 km.
with a standard deviation of 88 ka. Clearly, flow due to the softening temperature effect in the ice is insignificant below −80°C and becomes progressively more important only as one approaches the melting point.

Fig. 9b shows the distribution of LDA formation times in the Dichotomy Boundary region. The two white stars correspond to the outliers in Fig. 9a at −100°C, −0.24 mm/a and −55°C, −0.8 mm/a. These are the only two with formation times greater than 1 Ma and correspond to very thick (>800 m) and relatively large extents (16.5 and 47 km). With the exception of the orange star that corresponds to the LDA described above that lie in the inversion, the rest all have formation times close to 400 ka.

Finally, Fig. 10 summarizes the frequency distributions of the LDA configurations used as input to our analysis: (Fig. 10a) LDA thickness and (Fig. 10b) LDA extent. Also shown are frequency distribution histograms for the properties derived by our modeling exercise: (Fig. 10c) predicted temperatures, (Fig. 10d) predicted debris-free sublimation rates, and (Fig. 10e) formation times. In each of these, a red bar with a width of one standard deviation is centered on the mean value. LDA thickness shows two clusters around 100–150 and around 300–450 m. LDA extent is clustered towards smallest sizes declining rapidly in frequency as one moves to larger extents. The temperature frequency distribution resembles LDA extents, whereas formation time resembles LDA thickness. The sublimation rate frequency distribution, with the exception of a cluster around 8 mm/a, appears to be more of a normal distribution about the mean.
Given the generally cold temperatures predicted by the model and shown in Fig. 10c, we would expect little supraglacial melting to have taken place, with the dominant ablation mechanism in the form of direct sublimation. There is evidence, however, for at least some limited melting that was capable of producing small glaciofluvial valley systems outside the current limits of some LDAs. These systems, as described by Fassett et al. (2010), are small and indicative of cold-based glaciers, and what melting did occur resulted from "preferred insolation geometries" such as cliff faces and solar-heated surface debris alongside exposed glacier ice.

6. Conclusions

LDAs have been interpreted as (1) ice-cemented talus aprons undergoing viscous flow, (2) local debris-covered alpine-like glaciers, or (3) remnants of the collapse of a regional retreating ice sheet. We investigated the plausibility that LDAs are remnants of a more extensive regional ice sheet by modeling this process. The model is a 1D flowband shallow-ice formulation simplified by assuming isothermal conditions, i.e., a specified uniform temperature in the flowband interior equal to the mean annual surface temperature (Fastook, 1987; Millour et al., 2011). Other parameters in the model besides temperature, which determines flow rates in the evolving LDA, include the debris-free sublimation rate, the limiting debris-covered sublimation rate, the debris accumulation rate at the base of the scarp, a factor relating the depth of debris cover to the reduction in sublimation rate, and the height of the scarp at which debris begins to accumulate.

Our model results suggest a clear relationship between temperature and debris-free sublimation rates at the time of ice formation and the resulting thickness and lateral extent of LDA’s. We found
that warmer temperatures and lower sublimation rates led to a greater margin extent (Fig. 3b), while warmer temperatures and larger sublimation rates led to thinner LDAs (Fig. 3a). With the definition of a “distance” metric that allows us to assess the goodness of our fit to the desired target LDA’s thickness and lateral extent, we observed an envelope of temperatures and debris-free sublimation rates that could have produced the target LDA configuration (Fig. 4).

We then compared model results to observations and found that: (a) modeled profiles compare well with observed LDA profiles (Fig. 7); (b) an inventory of LDAs along the Dichotomy Boundary observed and characterized by thickness and lateral extent (Ostroch, 2007) yielded a map of temperatures and debris-free sublimation rates showing geographic and topographic trends in our results (Fig. 8); (c) a typical formation time from when the ice surface drops below the cliff top to when the LDA is completely armored for the cataloged LDAs of 400–500 ka is observed (Fig. 9), suggesting that these LDAs could have formed relatively rapidly during the collapse of the ice sheet. These results show that observed LDA length and thickness characteristics are consistent with climate conditions and a formation scenario typical of the collapse of a regional retreating ice sheet and exposure of bedrock cliffs.

The collapse of a regional retreating ice sheet helps resolve many of the unusual characteristics of lobate debris aprons (LDA) and lineated valley fill (LVF). For example, the distribution of LVF is very consistent with extensive flow of glacial ice from plateau icefields (e.g., Head et al., 2006a, 2006b; Head et al., 2010; Fastook et al., 2010), and the acquisition of a debris cover in the waning stages of retreat of the regional cover (Dickson et al., 2008, 2010) as the bedrock scars and regoliths are exposed. The typical concentric development of LDA around massifs is much more consistent with ice sheet retreat than insolation-related local accumulation and flow of alpine-type glaciers. In addition, results from GCMs (Forget et al., 2006; Madeleine et al., 2009) that predict widespread areas of positive accumulation rates are consistent with the formation of regional ice sheets whose collapse would leave these features as remnants.

Martian ice sheets, in their colder and drier environment, might never attain full equilibrium configurations as ice sheets do on the warmer and wetter Earth. However, our LDA formation mechanism indicates that regional ice sheets that completely bury the terrain are very likely to form. During collapse in response to changing climate, this ice sheet is controlled by the basic conservation of mass and momentum framework on which the ice sheet model is based. Given our results, we thus conclude that the retreating ice-sheet model is a reasonable LDA formation scenario and should be investigated and tested in more detail.

Further, we conclude that LDAs in the along the Dichotomy Boundary could never have experienced temperatures near or above the ice melting point and still retain their current shape, a finding that supports subzero temperatures for the last several hundred million years. One might then expect to potentially find preserved below the sublimation lag deposit, ancient ice that contains a record of the climate of Mars when the LDAs formed.

Acknowledgments

We thank the National Aeronautics and Space Administration (NASA) for financial assistance to support this work through a Mars Data Analysis Program Grant (NNX11AI81G) to J.W.H.

References


