Rock glaciers and protalus landforms: Analogous forms and ice sources on Earth and Mars

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[1] The basic features and terminology of terrestrial "rock glaciers" are reviewed together with associated forms termed "protalus lobes" and "protalus ramparts." Two basic models of rock glacier formation and flow invoke either the creep of ice derived from permafrost or glacial/former glacial activity; a third possible mechanism invokes landslide emplacement. Observations on terrestrial rock glaciers and similar forms suggest that the ice component can be produced via ground ice or from a glacier system. Finite element modeling of simple slope systems containing (1) a continuous ice layer buried by debris and (2) a mixture of ice and rigid blocks can both show creep but with very low rates, especially at low temperatures. Possible Martian examples of rock glacier and protalus lobe features are identified from Candor Chasma by wide-angle Mars Orbiter Camera (MOC) imagery, although the topography does not allow unambiguous interpretation. Some possible ways in which MOC and Mars Orbiter Laser Altimeter (MOLA) and other Mars orbiter data could help future interpretation of rock glaciers, related protalus landforms, and ice presence are discussed. INDEX TERMS: 5415 Planetology: Solid Surface Planets: Erosion and weathering; 5416 Planetology: Solid Surface Planets: Glaciation; 1823 Hydrology: Frozen ground; 1824 Hydrology: Geomorphology (1625); 1827 Hydrology: Glaciology (1863); KEYWORDS: Rock glacier, glacier, Mars, permafrost, finite element method, creep

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1. Introduction

[2] Although glacial conditions have been proposed for Mars [Kargel and Strom, 1992] some interpretations of landforms as being "glacial" are in doubt [Thomson and Head, 2001]. However, topographic forms, similar to "rock glaciers" on Earth, have been suggested as occurring on Mars. By terrestrial analogy, they are suggestive of buried ice and thus indicative of Martian permafrost or glacial conditions [Baker, 2001]. The extent and form of ice in these features is clearly important in investigating the presence, cycling and age of water on Mars. On Earth, rock glaciers are complex features with a terminology that is by no means settled and a variety of interpretations have been proposed which are still in dispute. Three distinct formation mechanisms have been suggested; for the most part, these cannot be distinguished by visual inspection. For clear interpretation of these features, their implications on Mars and to provide the basis for further investigation, a clear understanding of the Earth-bound features is necessary. This is especially important for interpreting geophysical data as well as topographic imag-

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ing. This paper thus reviews the terrestrial landforms, shows some of their complex topography, discusses the mechanisms of formation and flow, then applies these ideas to previous Martian interpretations and some Mars Global Surveyor (MGS) data: Mars Orbiter Camera (MOC) images, Mars Orbiter Laser Altimeter (MOLA). Suggestions are also made about detection methods and ways in which different types of ice might be detected and their extent determined.

2. Rock Glacier Definitions

[3] Because of the difficulties of applying a unique model for rock glacier formation and flow mechanisms (discussed in the next section) it is desirable that a nongenetic definition and terminology be used. This is helpful on Earth and essential for defining Martian analogs. Some confusion has been, and still is, associated with adherence to a genetic definition for terrestrial rock glaciers. A definition based on morphology, which does not assume a particular formational model, appears to be a reasonable starting point. Genetic findings can then be added to discussions about individual cases. Current generalizations are, unfortunately, likely to mislead as much as clarify.



Figure 1a. Jumbo Rock Glacier, Wrangell Mountains, Alaska. Note the two phases of formation distinguished by shades of gray and also the lack of lobes from the valley sides.

[4] A suitable descriptive definition of a rock glacier [*Potter*, 1972; *Washburn*, 1979] is "a tongue-like or lobate body, usually of angular boulders, that resembles a small glacier, generally occurs in high mountainous terrain and usually has ridges, furrows, and sometimes lobes on its surface, and has a steep front at the angle of repose." Definitions sometimes also include a mention of the low flow rates [*Martin and Whalley*, 1987], which are typically <1 m a⁻¹.

[5] Definition by visual analogy is especially helpful for the interpretation of photographs, especially MOC, so the form itself is best illustrated with a photograph (Figures 1a and 1b). Figure 2 (from *Hamilton and Whalley* [1995] and *Martin and Whalley* [1987], after *Humlum* [1988]) places rock glaciers in the context of mountain landforms. The diagram also shows other debris related forms, discussed below, and provides some of the alternative names found in the literature [*Martin and Whalley*, 1987]. *Capps* [1910] and *Wahrhaftig and Cox* [1959] described the Alaskan landforms seen in Figures 1a, 1b, and 2. We follow Capps' description and term this a rock glacier sensu stricto (but usually dropping this Latin tag).

[6] Several authors have subsequently modified the terminology and even used "rock glacier" as indicative of a rather different feature (e.g., Figure 3) and illustrated as a "protalus lobe" in Figures 1a and 1b. Thus Outcalt and Benedict [1965] introduced the term "valley-side rock glacier" after a study of features in Colorado. The terms "valley floor rock glacier" or "tongue-shaped rock glacier" [Wahrhaftig and Cox, 1959] were used for the sensu stricto feature. Unfortunately. later discussants have often omitted the "valley side" or "lobate" part and thus "rock glacier" has been used for both features regardless of topographic form. Some authors have indeed suggested differences in origin of these two forms as well as them being in a continuum of landscape elements (see, e.g., Whalley and Martin [1992] and Giardino and Vitek [1988] for discussion). If a genetic connotation is implied in the use of either term, still further confusion arises when discussing genesis. The term "protalus lobe" was introduced as a nongenetic term [Hamilton and Whalley, 1995] acknowledging that there might be differences of ice origin as well as topography. The diagram (Figure 2) summarizes these terms. Figure 3 illustrates distinctive protalus lobes and Figures 4a-4d show possibly related features but which might also be "protalus ramparts" as well as a rock glacier with convoluted transverse ridges. Martin and Whalley [1987] and Hamilton and Whalley [1995] engage in further discussion. The possible origins of these features are reviewed in the next section.

[7] The discussion of possible rock glacier-like features on Mars has been similarly confused, not only because of failure to distinguish between the two types of rock glacier but also because the rock glacier form may be derived in perhaps three possible ways.

3. Terrestrial Models of Rock Glacier and Protalus Lobe Formation

[8] This section briefly reviews the possible formation of the features seen in Figure 2. The word "debris" refers to



Figure 1b. Aerial Photograph showing typical rock glaciers in the Wrangell Mountains, Alaska; **a** has a single lobe, and **b** has a second lobe which appears to have advanced on top of the first as in the case of Jumbo Rock glacier (Image: US Geological Survey).



Figure 2. Debris-ice components in mountainous area with suggested terminology for the main features and alternative terms in parentheses. After *Martin and Whalley* [1987], *Humlum* [1988], and *Hamilton and Whalley* [1995].

material, whether from weathering or the products of rockfall events, for the rock detritus which is involved in the formation of these features, hence the more general term debris-related or debris-derived forms.

3.1. Rock Glaciers

[9] The three main models of rock glacier formation have been proposed and are discussed in detail by *Whalley and Martin* [1992]. These are a permafrost origin, a glacierderived origin, and a mass-wasting (landslide) origin. The first two involve the creep of ice held in the body of the feature whereas the third model may involve, but does not require, the presence of ice. In summary, these models have the following properties.

3.1.1. Permafrost Model

[10] The permafrost model for rock glacier formation follows the ideas of *Wahrhaftig and Cox* [1959] and has been promulgated in particular by *Barsch* [1996] and *Haeberli* [1985]. The "congelation" ice is formed from freezing water, either by ice segregation or water injection under pressure. A pre-requisite is a mean annual air temperature of, at most, -1.5° C. This thermal condition implies a "zonal" occurrence of rock glaciers and this attribute has led to the use of rock glaciers as being indicators of permafrost, both present and relict [*Barsch*, 1996]. The presence of any glacier ice which plays a part in the formation of rock glaciers is generally disputed by adherents to this model. The literature often implies that rock glaciers necessarily have a permafrost origin.

3.1.2. Glacial Model

[11] The glacial model (for a comprehensive review, see *Whalley and Martin* [1992]), relies on the preservation of

a thin (generally <50 m) body of ice by an insulating weathered rock debris layer. The ice is considered to be derived from glacial, i.e., "sedimentary" sources. The thin ice creeps, giving a typically low velocity and the debris preserves this in an otherwise ablation-dominant environment. The controls on maintaining this buried ice are thus related to thickness of debris cover as much as local climate (measured by, e.g., degree-day estimates). As such, they are "azonal" features and cannot be used to delimit temperature regimes such as the presence of permafrost.

3.1.3. Landslide Model

[12] The landslide, or "catastrophic," model [Johnson, 1974, 1984] has used similarity of topographic form to suggest that rock glaciers may be derived from rapid landslides/rock avalanches (Bergsturtz or Sturtzstroms) [Whalley, 1976; Whalley and Martin, 1992]. These will generally be forms which do not flow after emplacement. However, it has been recognized that some Bergsturz have fallen on retreating/down-wasting glaciers and so have produced "instant" rock glaciers. This is a variation of the glacier ice cored model rather than the landslide model [Whalley, 1976]. In the case of fossil rock glaciers, it may not be easy or possible to distinguish between these origins.

3.2. Protalus Lobes and Other Ice/Debris-Derived Features

[13] Two other components of ice plus debris now need to be considered. Some have argued that they are part of a continuum of features, which includes rock glaciers. All of the three possible modes of formation mentioned above



Figure 3. Aerial photograph of protalus lobes, Axel Heiberg Island, Canadian Arctic (Image: Canadian Department of Energy, Mines and Resources; Ottawa).

could be included in this continuum [Shakesby et al., 1987].

3.2.1. Protalus Lobes

[14] Protalus lobes (Figures 3 and 4a–4d), usually being away located away from glacier ice, are generally accepted to be of nonglacier origin, although the ice could originate as snowbanks and then become buried by debris from cliffs above. They do not then necessarily require permafrost conditions. The preservation of these features may again depend upon azonal conditions such as debris thickness cover, aspect and altitude as well as thermal conditions. However, the large numbers of these features in high latitudes suggests that permafrost may be a sufficient, although not necessary, condition for their formation. Finite element modeling shows the extremely low creep rates of these features and the dependence of surface velocity upon the size of ice bodies contained, their disposition and the depth of burial in the ice-debris mass [*Azizi and Whalley*, 1995, 1996]. This modeling supports the, relatively few, observations on velocities of protalus lobes [e.g., *Sollid and Sørbel*, 1992]. **3.2.2.** Protalus Ramparts

[15] Protalus ramparts (Figures 2 and 4a–4d) are generally attributed to debris accumulating at the front of snow patches or even small "glacierettes." This association with glacial conditions would place them in the glacial, rather than permafrost, realm (i.e., the ground temperature may not necessarily be <c 1.5°C). However, there have been suggestions [*Barsch*, 1996] that they are incipient rock glaciers of permafrost origin. Again, it may be that both could be realistic models, according to local antecedents and contingent factors, and they have been considered as part of a continuum of landforms [*Shakesby et al.*, 1987]. The choice of rock glacier model has an impact on the interpretation of Martian forms. In particular, the possibility of massive ice



Figure 4a. Protalus rampart (a) and poorly-developed protalus lobes (b) (compare to Figure 3) below cliffs (Mynydd Ddu, Wales). The area between the ridges and cliffs would have held a substantial body of ice which, in this case, was probably not supplied with a continuous supply of rock debris.

bodies, derived from glaciers, is fundamentally different from the necessity of permafrost for the formation of rock glaciers [*Barsch*, 1996]. Because of the divergence of opinion about ice presence in terrestrial rock glaciers and protalus lobes, the next section illustrates the diversity of ice locations in ice-debris features.

4. Terrestrial Observations

[16] It is possible that any one of these three models may give rise to the topographic form defined as a rock glacier (or even a protalus lobe); that is, these features show "form convergence" or "equifinality." Thus, if the presence of ice can rarely be determined from remote sensing, or even close surface examination, then a definitive model and its genetic and environmental implications are undetermined. Further, the type of ice, permafrost- or glacier-derived, will not normally be distinguishable. Although it is not accepted by all authorities that rock glaciers can be derived from glacier ice [*Haeberli*, 2000] there is evidence (see below) that such features do exist. That ice may be derived from either of two sources is fundamental to the interpretation of the rock glacier features on Mars.

4.1. Form of Ice in Rock Glaciers: Permafrost Models

[17] Although *Capps* [1910] indicated frozen ground in some of his early observations in Alaska, this is hardly surprising as the Wrangell Mountains are in a discontinuous

permafrost zone. More recently, *Elconin and LaChapelle* [1997] have reported some more massive ice bodies in this area although they attribute this to ice aggradation in permafrost. Aside from direct drilling and observations of a few exposures during engineering projects (see *Haeberli* [1985] and *Whalley and Martin* [1992] for reviews) much of the evidence for permafrost is from geophysical evidence (resistivity, seismic and some gravimetric data). Unfortunately, some of these observations are equivocal (see below) and there are problems of interpreting them [*Whalley and Azizi*, 1994]. However, it is the case that at least *some* rock glaciers contain permafrost-derived ice.

[18] Protalus lobes (Figures 2 and 3) may have, when actively moving, permafrost-derived ice within them. Even so, some protalus lobes could be derived from debris accumulation over perennial snowbanks [*Whalley and Palmer*, 1998; *Azizi and Whalley*, 1995]. These often have a simple, single ridge, form and may be more akin to protalus ramparts than protalus lobes (Figures 4a and 4b). However, the implications of this morphological distinction have yet to be fully explored with respect to their genesis yet shows the problems of associating origin with morphology.

4.2. Form of Ice in Rock Glaciers: Glacier Ice Models

[19] In some terrestrial cases, glacier ice can be traced directly back from a cirque glacier through to the snout [*Whalley et al.*, 1994]. There are now many observations of massive bodies of glacier ice within features which are



Figure 4b. Active production of protalus rampart below small "glacierette" (Pic Campbell, Pyrenees, France). This is similar to the construction of a terminal moraine by a glacier.



Figure 4c. Active glacier with protalus lobe-like feature in front. Note that, although the form is rather different from that in Figures 1a, 1b, and 5a, it is only some 3 km from the feature shown in Figure 5a and is also thought to contain a glacier ice core as seen by the "thermokarst" lakes set in the debris cover.

clearly rock glaciers according to the morphological definition. Most notable of these recent findings are those by Potter et al. [1998], Ackert [1998], and Konrad et al. [1996] in Wyoming and Krainer and Mostler [2000] in the Alps. That these occurrences are not restricted to a few geographical areas or that they are not just "debris covered glaciers" is now clear. Furthermore, some of the topographical features seen allow linkages to be made between the presence of ice and the loss of ice in the relatively recent past (e.g., since the last Little Ice Age maximum, perhaps 200 years ago). These observations show the way in which ice movement has depleted the ice core as the latter has flowed down valley and not been replenished at the upper (cirque) end. These terrestrial observations [e.g., Whalley et al., 1995a; Whalley and Palmer, 1998] suggest that the system once existed as a glacier but the depletion of the ice core now allows the rock glacier to have an independent existence from that of the corrie glacier (Figure 5a). This can be seen too where there is now no visible form of glacier at all (e.g., Figure 4d). It would appear that at least some rock glaciers have glacier ice contained within them (Figures 5a-5d). The duality of origin of ice bodies both confirms the requirement for nongenetic implications when describing the landform and illustrates the difficulty of assessing a single ice mass origin.

4.3. Form of Ice in Rock Glaciers: Landslide Models

[20] The existence of purely landslide-derived rock glaciers (i.e., landslides with the topographic form of rock glaciers) is certainly possible, although the number of likely cases is small [*Whalley and Martin*, 1992]. This does not preclude the formation of rock glaciers by the sudden collapse of a rock wall and the burial of a small glacier. The latter has been suggested for the formation of some rock glaciers during deglaciation phases [*Whalley*, 1976]. In mountainous Iceland, because of the large numbers of unstable cliffs, many rockslides do look similar to rock glaciers [*Whalley et al.*, 1983] and some debate still ensues about their relationship to glaciers and rock glacier systems [*Sigur∂sson*, 1990].

5. Development of Ice Masses in Permafrost and Glacier-Derived Systems

5.1. Permafrost Systems

[21] On Earth, glacial/debris systems can renew their ice component from precipitation and add to the debris by discontinuous rockfall. Both are required and the time necessary depends on the type of emplacement. Glacier-derived systems can form an insulating layer rapidly; perhaps within the 200–300 years associated with post Little Ice Age activity. Permafrost systems would seem to require a rather longer period, perhaps several thousand years [*Barsch*, 1996]. *Barsch* [1996] has identified a "rooting zone" below a glacier system (apparently including moraines) which then becomes suffused with congelation ice and interstitial ice under permafrost conditions. *Wayne* [1981] and *Haeberli* [1985] have also



Figure 4d. A probably inactive rock glacier but with features similar to Figure 4c (Olympus Range, New Zealand). A "spoon-shaped depression" occurs between the headwall talus and the main rock glacier (compare Figure 5a, where the glacier still exists).

suggested how ice derived from percolating meltwater may be emplaced to allow ice lenses to grow under permafrost thermal regimes. However, large ice masses are difficult to envisage as the process would seem to be self-limiting. Specifically, in any growth of permafrost from the surface downwards is difficult to envisage unless near a cliff headwall, or bottom-up growth unless artesian water is introduced to give "injection" or "intrusive" ice.

[22] It is relatively easy to see how protalus lobes could form. Ice masses several tens of meters thick could have their origin as large snowbanks. If covered with debris, either catastrophically or occasionally, then the snow will become ice through diagenesis and remain buried if the external thermal conditions are sufficient. A limited amount of ice could be added from water percolation after snowmelt with freezing at the permafrost table. These ice bodies are relatively thin but can still creep at values of several cm a^{-1} [*Sollid and Sørbel*, 1992].

5.2. Glacier-Derived Systems

[23] For a glacier-derived system, the glacier has only to be covered by a sufficiently thick debris load to greatly reduce ablation. If either ice or debris supply is cut off, then modification occurs. With ice depletion, flow still takes place but eventually a rock glacier may form as the ice thins but continues to move. However, the resulting topographic form does depend upon the size of the original feature. Usually, glacier-derived rock glaciers are derived from rather small glacier (corrie or cirque) systems [*Ackert*, 1998] although some may be surprisingly large [*Gorbunov et al.*, 1992; *Krainer and Mostler*, 2000].

[24] One simple view of rock glaciers, that they are "only" debris-covered glaciers, is misleading. Most debris on large glaciers emerges from englacial locations by melting in the ablation area. However, this ablation is self-limiting as the debris thickness increases. Such glaciers usually have enough ice thickness to continue to move at relatively high velocities of $>5 \text{ ma}^{-1}$, such as in some of the rock glaciers of the Altai - Tien Shan [Gorbunov et al., 1992], but these will slow down over time as the ice thins. This thinning need not necessarily be produced by ablation but by the long-term flow of the trapped ice body. The rock glacier shown in Figure 5a, even though it contains glacier ice, appears to flow independently of the glacier system at its head [Whalley et al., 1995b]. Such "trapped ice" systems might also be found on Mars.

[25] It is possible to envisage a combination of ice origins in a rock glacier where a thin glacier with debris cover forms a rock glacier but congelation/segregation ice forms near the surface in the moraine mass ("rooting zone"). In this way, it is possible that both glacial and



Figure 5a. Rock glacier (Nautardalur, Tröllaskagi, North Iceland) showing rock glacier flowing independently from the circue glacier at its head.

permafrost systems may exist in proximity and even form a continuous topographic form with two types of ice. The early finding of Capps [1910], that a trial pit showed permafrost beneath a surface cover of rocks, has done much to influence the development of thought on rock glacier origin [Wahrhaftig and Cox, 1959]. However, this would not be an unexpected finding in a permafrost zone as the ice would have formed in the winter and would, in effect, be the still frozen material of the "active layer." Such ice has been found in debris on a glacier ice cored system in a nonpermafrost area in Iceland shown in Figure 5d. [Whalley et al., 1995a] as well as a permafrost area [Elconin and LaChapelle, 1997]. The trial pit in Figure 5d was dug to 1.3 m in a year with a very late summer. Although this is a small quantity of ice, it does show the complexity of ice-water-rock debris systems on Earth and the difficulty of identifying the origin of ice masses.

5.3. Finite Element Modeling

[26] Very little modeling has been done on "rock glacier" systems. Some early work has been due to *Olyphant* [1983] although little variation of component (ice/rock debris) parts was allowed and he used only simple flow laws. More recently, *Konrad and Humphrey* [2000] have produced a steady state model of debriscovered glacier and compared this to the behavior of Galena Creek Rock glacier [*Potter et al.*, 1998]. A limited amount of finite element modeling (FEM) has been done

on ice-rock debris systems, mostly on idealized protalus lobes [*Azizi and Whalley*, 1995, 1996] but also on small ice bodies covered with debris. Although the creep parameters used have been for terrestrial systems [*Azizi et al.*, 1994], there is a clear utility of FEM to investigate the possible action and longevity of flow under Martian conditions. A simple model of ice preserved as a wedge (max thickness 20 m, surface slope 40°) in a protalus lobe and covered by debris shows, as expected, a very high dependence on temperature, giving only 0.15 mm a⁻¹ in both vertical and horizontal directions at -25° C [*Azizi and Whalley*, 1994].

[27] Comparison of a layered, two-component system with a mixture of discrete blocks of ice and rock of the same size (Figures 6a-6d) showed rather dissimilar behavior [Azizi and Whalley, 1995]. Figure 6a shows a mesh with debris overlying a layer of ice at the bed. This might be a very small glacier or an accumulation of snow-bank ice subsequently covered by debris. The low flow rate at node 19 is seen in Figure 6b. Figure 6c shows the same size of system but with the ice mixed in with rigid "rock blocks." In this case the flow rate is very much lower (Figure 6d) $(-5^{\circ}C \text{ for all simulations})$. These experiments show not only the expected influence of temperature in the ice/rock debris body but also the significance of the disposition of the ice in a debris-ice system. The component of flow is, in all cases, given by ("Glen's") flow law for ice [Azizi et al., 1994]. Thus, although FEM is useful in helping to explain rock glacier and related features' long profiles, the only



Figure 5b. Ice exposed mid way down the rock glacier (approximately 1m and 3m to the right of the figure).

means of determining the ice component is from direct observation or coring or by geophysical exploration.

5.4. Ice Masses and Mixture Models

[28] The foregoing shows that not only are a number of models of ice disposition possible but that these are found in fact. The disposition of ice volume ranges from no ice (where the forms are relict), a little ice (where stagnant) through to nearly 100% ice (with a thin debris over massive sedimentary ice). Unfortunately, actual identification of the thickness (volume) of the ice is difficult in almost all cases. In particular, ice rock mixture composites can flow relatively easily as long as the ice is continuous and not constrained by rigid rock "blocks" in contact with each other (Figure 6c). Such rigid masses contribute considerable shear strength to the whole of the composite. The only major constraints on surface velocity (assuming constant temperature, no sliding component and, for wide bodies, a form factor of 1) are the total thickness (ice plus debris) and surface slope (i.e., applied shear stress). For very low ice ablation rates the length of a rock glacier and its surface profile will depend upon the length of time available for secondary/tertiary creep to take place. The limiting factor will be ice supply to the system. Some natural systems do seem to show this trait, where the topography indicates ice having flowed down slope but is not replenished upslope [Whalley and Palmer, 1998]. A further complication of the rheological model is where there is a dispersion of smaller clasts within ice rather than large blocks. The creep rate here depends upon the content of fines, decreasing as the percentage of solid inclusions increases (see *Whalley and Azizi* [1994] and *Durham et al.* [1992] for discussions).

5.5. Geophysical Determinations of Ice in Rock Glaciers

[29] Geophysical investigations have been rather scant until the last few years when seismic, resistivity and GPR methods have been used, although some gravimetric measurements have been made by Vonder Mühll and Klingelé [1993]. Contact georesistivity has been used to distinguish between glacier and permafrost ice sources, the actual values of apparent resistivity being used; glacier ice ($\rho_a >$ 1M Ω m) and ground (permafrost) ice ($\rho_a < 1 \ M\Omega$ m). However, impurities in the ice in small glacier systems from dust and salts in precipitation nuclei will greatly reduce the apparent resistivity value found for "glacier" ice and this method may not be as effective as envisaged. This, and the difficulties of actual site measurement, limits the accuracy of this technique to locate or differentiate ice bodies. Furthermore, tying in georesistivity results with an actual mixture model, let alone a determination of ice depths, has not been achieved in most cases although some data are now appearing [Vonder Mühll et al., 2000]. GPR determinations do show some internal structures [e.g., Berthling et al., 2000] although again it is hard to link these structures with the actual ice content let alone a mixture model. It is



Figure 5c. Ice exposed at the snout of the rock glacier. This is typical glacier (or sedimentary) ice.

clear that a great deal more work needs to be done on Earth to determine the range of ice-debris contents of rock glaciers, let alone work on whether there is such a thing as a "typical" value. This of course applies mainly to the permafrost model. The glacier ice core model is much simpler in structure. Yet even here there may be complications due to the accumulation of ground ice lenses in or at the surface of debris accumulations, especially toward the front of rock glaciers in permafrost zones where segregation ice lenses may accumulate.

6. Rock Glaciers and Debris-Derived Forms: An Overview of Observations From Mars

6.1. Observations

[30] Given the difficulties of terrestrial determination of the genesis of rock glaciers and debris-derived forms, there are clearly problems in interpreting Martian topography. Aside from the inability to see the ice, even surface flow rates are lacking from Mars and they will, in any case, be very low [*Colaprete and Jakosky*, 1998]. On Earth, we can at least identify creep flow of active ice and distinguish active from relict features. Recent reviews of water on Mars have been provided by Carr [1996] and Baker [2001], with overviews of glacier and permafrost ice in Martian upland terrain. Examples of "glacial" features are given, e.g., by *Carr* [1996], and moraine like features are shown by *Carr* [1996, Figure 5.12 at 49N 284W (VO 11B05)]. Both Baker and Carr acknowledge the diversity of views on the origin of rock glaciers on Earth but Baker suggests the predominant viewpoint follows the permafrost model. Both rock glaciers sensu stricto and protalus lobes as defined previously are used as analogs for interpretation in several papers interpreting Martian flow features. In this section, "rock glaciers," i.e., in double quotes, indicates the term used in the texts of these papers rather than as an attribution according to the more restricted morphological definitions given above.

[31] Detailed discussion of rock glaciers has been provided in formal papers, presentations at conferences and on websites. The first suggestion that "lobate debris aprons" might be interpreted as rock glaciers was by *Squyres* [1979]



Figure 5d. A trial pit and exposure in the Nautardalur rock glacier showing frozen active layer with ice lenses in debris material (right) with the banded glacier ice core of the main rock glacier (top left).

[see also *Squyres*, 1989]. *Lucchitta* [1979, 1981] interpreted the clear large landslide features and also suggested that some small flow like features could be "rock glaciers". The lobate tongues [*Lucchitta*, 1981, Figure 6A: VO42B39] are somewhat indistinct but appear to be rock glacier forms as well [*Lucchitta*, 1981, Figure 5c: VO512A63].

[32] With the enhanced resolution of the MGS/MOC, more investigations have been made in the last two years. *Rossi et al.* [1999] have identified flow-like features in the Valles Marineris and suggested "ice-assisted creep processes" either as glacier or rock glacier flow and acknowl-



Figure 6a. Mesh for a FEM of a wedge of ice (shaded) overlain by a "rigid" rock debris mantle [after *Azizi and Whalley*, 1995].

edge that amounts and roles of ice genesis are unclear on Mars. In a later paper [*Rossi et al.*, 2000] illustrate a "rock glacier" with the restricted form (i.e., like Figures 1a and 1b of this paper). R. A. Marston (Ridge and furrow morphology of rock glaciers: Implications for water on Mars, available at http://www.uark.edu/misc/csaps/marstonres. html) has suggested that ridges and furrows on rock glaciers represent "buckling" of the material to compensate for decreasing downstream velocity. This leads to a "toe thickening" documented by *Squyres* [1978] and also seen on Earth, although by no means all rock glaciers have this form (Figures 1a and 1b). The terrestrial example shown by Marston is a protalus lobe, and the Martian example in NE Hellas Impact Basin (VO, 585B09) is of a similar morphology. *Mangold et al.* [2000] have linked MOLA data with an



Figure 6b. Response of one node (19) near the foot of the flow. Component **u** (dashed line) is in the horizontal direction, **v** (solid line) the vertical; temperature: -5° C.



Figure 6c. FEM mesh for a system of ice (shaded) mixed with "rigid" rock debris components.

interpretation of a protalus lobe ("rock glacier") and *Mangold* [2001] have suggested GPR sounding might be employed to determine ice quantities.

[33] Other rock-debris-ice systems (apparently not reported previously) can be seen in several MOC (wide-angle camera) images. Figure 7 shows two forms identified here as possible representatives. Using the terminology of this paper, one is a rock glacier the other more akin to a simple protalus lobe or a protalus rampart. This latter feature shows a rather sharp crest, which may be due to lighting conditions. Such sharp ridges are not uncommon in terrestrial protalus ramparts [e.g., *Shakesby et al.*, 1987] (Figures 4a–4d). Neither feature is as complex as some of those reported elsewhere on Mars by *Lucchitta* [1984] and *Squyres* [1978]. Unfortunately, narrow angle camera transects cover only a small portion of the protalus lobe type (Figure 8). Both protalus ramparts and simple protalus lobe forms can be found on Earth (Figures 4a–4d).

[34] It appears to be unusual to find both rock glaciers and protalus lobes active in the same region on Earth. In a survey of the >100 rock glaciers in the Wrangell mountains (W. B. Whalley, unpublished data), no examples of protalus lobes were identified, despite this being a permafrost area (*Capps* [1910] locus typicus). However, in the high arctic, both forms may be found together [*Evans*, 1993], so this Martian example may not be unusual. In France, an active rock glacier has been found in the vicinity of protalus lobes [*Whalley and Palmer*, 1998]. The latter are presumed to be inactive and were perhaps last moving about 4ka ago. Thus, although topographic forms may be seen, they do not necessarily represent currently active features. Protalus ramparts are more commonly seen in the same area.

6.2. Discussion on Ice Content and Flow in Martian "Rock Glacier" Features

[35] *Mangold and Allemand* [2001] and *Mangold et al.* [2000] have provided analyses of profiles by comparing lobate debris apron profiles with models using ice as the rheological component. They conclude that lobate debris aprons are due to the deformation of ice-rock debris mixtures but point out that the mechanism(s) which initiates formation is still unknown, as is the origin of the ice. Both terrestrial rock glacier forming processes invoking an ice origin are plausible as sections 4 and 5 indicate. On Earth, identification of topographic forms - rock glacier, protalus lobes and protalus ramparts - need not necessarily confirm the presence of ice today and thus care needs to be taken about using topographic forms to identify either the type or the size of any ice body. The presence of ice below Martian rockslide material [*Lucchitta*, 1981] is again difficult to interpret without detailed surface exploration.

[36] Evans [1993] provides a discussion of the ways in which permafrost-derived and glacier-derived rock glaciers can be found over long time periods. In both, debris supply from cliff talus is an important factor in burying ice. Evans suggests that permafrost development in fine-grained silts may be a major component in nonglacial rock glaciers (protalus lobes of this paper). The long time period of time for deglaciation of the high arctic area (Ellesmere Island) examined by Evans may make this a useful analogous area for Martian rock glacier features. On Mars, the identification of rock glaciers and protalus lobes does not mean both are currently active. Ice could have been removed from the system according to: past Martian climatic conditions, location of ice in the system (e.g., buried below debris, or interspersed with debris) as well as thermal and permeability properties of any rock debris mass associated with the ice.

[37] It is perhaps important to note that the term "permafrost," in a terrestrial setting, denotes a thermal regime. There are genetic implications for the formation of geomorphological features (not just protalus lobes and rock glaciers). *Colaprete and Jakosky* [1998] have discussed the processes of water emplacement on Mars; apart from thermal and atmospheric conditions, these processes are similar to those suggested for terrestrial analogs. The emplacement of ice in Martian "rock glacier" systems could be envisaged as being similar to any one, or



Figure 6d. Response of the same node (19) in the mesh of Figure 6c; temperature: -5° C.





Figure 7. Two possible rock-ice systems from the Candor Chasma area, Mars. Image FHA01275 [*Malin et al.*, 2000]. Feature A has the basic forms of a rock glacier sensu stricto; feature B has similarities to both a simple ridge form (protalus rampart) and a more complex set of ridges similar to a protalus lobe.

several, of their terrestrial counterparts. Seepage of water from buried aquifers has been suggested as an explanation for water flow on valley slopes on Mars [Lee et al., 2001] and this is also a terrestrial possibility for emplacement of ice at some rock glacier headwalls to produce segregation ice. It is not clear if such a mechanism could produce the large quantities of water required for movement of a large rock glacier or protalus lobe, although terrestrial ice lenses may be found up to 10 m thick. The FEM results show that creep may occur in only a thin ice layer but that is covered by a thick debris cover [Azizi and Whalley, 1995]. The mass of the latter provides the normal stress on the ice which, when preserved, will flow. With limited ice ablation flow could continue for very long periods (Figures 6a-6d). Such modeling however does not tell us what the quantity of ice may be in Martian environments, where it exists or what the ice-rock percentage of a



Figure 8. Detail from Narrow Angle Camera of a section of feature B in Figure 7. Image M2101824 [*Malin et al.*, 2001]. Although there is the possibility that the "ridge" is structural, the irregular cropping out along the length of the cliff seen in the wide-angle view is reminiscent of the debris constructed ridges seen terrestrial environments, e.g., in Figures 4a–4d.

flowing body may be. More precise determinants of ice volume may need to be used.

7. **Detection Methods**

[38] The identification of rock glacier and protalus lobe systems from morphological surface topography (via MOC) offers a preliminary assessment of genesis and ice origin. However, just as on Earth, exact determination of the ice may depend upon examination of the ice, hardly possible on Mars with present-day technology. There are however, surface features which might give more precise clues. Colaprete and Jakosky [1998] have used profiles to suggest lobate debris aprons, concentric crater fill and lineated valley fills are "rock glacier" (i.e., both "protalus lobe" sensu stricto and rock glacier ss) forms. Similarly, Mangold and Allemand [2001] have compared MOLA profiles with theoretical profiles for ice rock mixtures. However, examination of the long-profile form may not be entirely helpful in determination of origin. First, the various surface wrinkles and furrows may be quite different from one rock glacier to the next. It is probable that transverse furrows, especially near the snout, are the result of a compressing flow regime (ice body flowing but being restricted by debris piling up and restricting flow in the lower reaches). It would appear that this applies to both glacigenic rock glaciers and protalus lobes. Secondly, these ridges should not be confused with those produced by large rockslide (Sturzstrom or Bergsturz) deposits as these and other large rockfall-derived features may be very similar [Lucchitta, 1979].

[39] As well as transverse ridges near snouts, some rock glaciers have a series of longitudinal ridges, mainly toward the sides. These are probably due to extensive flow where the ice core movement has been rapid (they are seen especially in glacier ice cored rock glaciers). As a consequence, ice below a surface cover of debris has become depleted. This cross-sectional concavity is indicative of a glacier ice core that has since down-wasted, leaving the ridges as essentially stable, and not flowing [Whalley et al., 1995a; Whalley and Palmer, 1998]. Determination of cross profiles also suggests the possibility that the ice core no longer is maintained by ice from the upstream (uncovered) glacier. On Mars, the same would hold true. A MOLA profiled cross section may be helpful to determine the internal structure and provide a means of distinguishing ice body origin as well as some flow characteristics. As well as MOLA profiling, orbiter geophysical soundings could provide a sufficient indication of debris thickness over ice. However, basal topography, and therefore overall feature thickness, is not yet known. We do know that ice can be preserved under thin debris mantles for Ma in Antarctica [Sugden et al., 1995] so that the same would probably apply on Mars, whether as discrete (glacier) bodies or ice rock mixtures of congelation ice lenses in permafrost.

[40] Sequential/differential mapping is unlikely to be useful to detect movement on Martian rock glacier or protalus lobe systems because of the extremely low creep rates. For systems even at -5° C on Earth, movements are very small (Figures 6a-6d). Additionally, the disposition of debris in ice also makes a noticeable effect on the flow. First, ice must be present in continuously thick bodies to produce a flow effect and secondly, the shear stresses (slope

and normal load) must be sufficient to allow creep. We thus return to the problem of the ice disposition. The FEM suggests (Figures 6a-6d) that widely different flow rates can result from different locations of ice but the Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS) could certainly be helpful in suggesting "mixture models" of ice and debris.

8. Summary of Discussion

[41] Interpretation of many Martian surface forms has, currently, to be done by comparison with terrestrial landforms. For "rock glaciers" this seems to be particularly troublesome. Unfortunately, not only is there a lack of agreement on the terrestrial forms and their significance but there is also little about the nature or volume of any ice bodies found. For example, a glacial model for a rock glacier (ss) implies that it is likely to contain much more ice than if a permafrost model was applicable. Conversely, creep of a deforming body containing little ice may take place over many thousands of years. That ice is a major, probably the only, reason for flow in these debris masses seems to be clear but the identification of the volumes and their location is difficult on Earth and Mars.

[42] Modeling of ice bodies under Martian temperatures [Colaprete and Jakosky, 1998] and FE modeling, of rock glaciers and protalus lobes with variations of the component mixtures [Azizi and Whalley, 1995] shows a way forward. It is probably necessary to combine the flow model with suppositions of where the ice may be located. Not only would this apply to various forms of ice-rock debris composite but might also be used to test the origin of the water source. However, there are still difficulties in knowing which constitutive equations to use (ice-rock mixture ratios as much as temperature) let alone the actual thickness of the body and ice location. Effective shear stresses acting on deforming ice requires knowledge of both the thickness of material, deforming and rigid, at any location. There is still a paucity of information in terrestrial rock glacier systems which relates topographic features to rheology.

9. Conclusions and Future Possibilities

[43] Determining the origin of ice in extant, active, rock glaciers on Earth is difficult. Topography, because of equifinality of form, will not uniquely distinguish between ice of glacier or permafrost origin. This means that analogue identification of features on Mars cannot be used to determine ice presence. A further complication arises where large landslides (Bergsturz, Sturzstroms) also give topography which may be similar to rock glacier forms. It should be possible to use MOLA altimetry to identify some detailed features which may be helpful to provide more critical criteria. These are, by analogy with terrestrial features: lateral ridges, "spoon-shaped hollows" in the corrie head (Figures 4a-4d and 5a-5d) and concavities between stable lateral ridges as well as the detailed ridges and furrows of protalus lobes.

[44] Protalus lobes, or similar forms, appear to be found on Mars. Terrestrial protalus lobes do suggest a possible permafrost origin. However, it is possible that snowbank accumulation below cliffs, when covered with debris falls

from cliffs above can give rise to these ridge systems. A unique indicator cannot be used here either. Using terrestrial analogues for features on Mars has considerable difficulties, accentuated when the Earth-bound features are themselves both difficult to interpret and indeed, sometimes in dispute. MOLA data from a variety of identified rock glacier and protalus lobe types may help to discriminate between landforms as well as provide test sites for future investigations.

[45] The advent of new orbital sensors using a variety of investigative techniques may help to determine and distinguish ice origins. In particular, MARSIS could be particularly helpful in determining the presence and location of ice bodies, although interpretation of terrestrial GPR data shows that appropriate models of ice location need to be devised to analyze the imagery. One way to progress would be with careful mapping on digital terrain models and map the features using Geographical Information Systems methodologies to look for patterns in location and type of feature. This approach may give a better overall understanding of the distributions of these complex features as thermally zoned or age differentiated.

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