ICARUS 34, 600-613 (1978)

Martian Fretted Terrain: Flow of Erosional Debris

STEVEN W. SQUYRES

Department of Geological Sciences and Laboratory for Planetary Studies, Cornell University, Ithaca, New York 14853

Received November 8, 1977; revised January 9, 1978

Viking orbital photographs of two regions of Martian fretted terrain have revealed a number of landforms which appear to possess distinct flow lineations. These range from valley floors with lineations which parallel the valley walls to debris aprons with distinctly lobate profiles and lineations which radiate outward from the source area. These features are attributed to the deformation and flow of a mass consisting of erosional particles and ice incorporated from the atmosphere. Such a flow should behave much like a terrestrial rock glacier. A plastic deformation model is presented which is consistent with the known mechanical properties of rock glaciers and with the observed features of the landforms. The valley floor lineations are interpreted as being due to compressional forces resulting from debris flowing inward from the valley walls. Climatic implications of the features are discussed.

INTRODUCTION

Fretted terrain was first recognized as a distinct set of landforms in Mariner 9 photographs of the Martian surface. Sharp (1973) described it as being "characterized by smooth, flat, lowland areas separated from a cratered upland by abrupt escarpments of complex planimetric configuration." The intricate patterns traced by the escarpments create a wide variety of landforms. These range from isolated buttes and mesas to large plateau regions divided by narrow, flat-floored, intersecting valleys.

Sharp suggests that the material of the upland plateaus is a thick blanket of regolith containing a substantial amount of frozen water. This view has received considerable support due to the wide variety of Martian landforms which suggest a thick permafrost layer (Malin, 1975; Carr *et al.*, 1976; Carr and Schaber, 1977). Beginning at a break in the upland surface, such as a crater or a structural fracture, he proposes that escarpment recession occurred, leaving behind a smooth lowland floor. He attributes the escarpment recession to undermining by evaporation of exposed ground ice or emergence of groundwater. The debris may have been removed by either eolian or fluvial processes. The former process requires a weathering mechanism, such as the photostimulated oxidation of ferrosilicates suggested by Huguenin (1974), to reduce the particles to transportable size. The latter requires a very different climatic regime, suggested by apparently fluvial features elsewhere on the planet. This issue is currently unresolved.

The study described here was intended to further investigate geomorphic processes operating in areas of fretted terrain, utilizing orbital photographs taken as part of the Viking mission. These photographs provide high-resolution coverage of two limited areas of fretted terrain in the northern hemisphere of Mars. The locations of these regions, Nilosyrtis Mensae and Protonilus Mensae, are indicated in Fig. 1.

0019-1035/78/0343-0600$02.00/0
Copyright © 1978 by Academic Press, Inc.
All rights of reproduction in any form reserved.

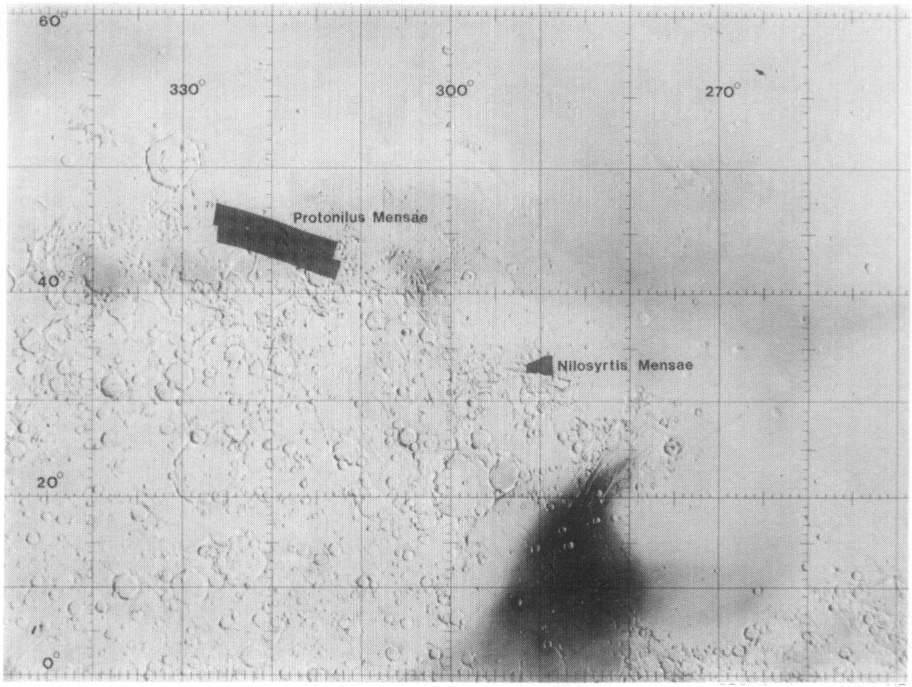

FIG. 1. Location of the study areas.

OBSERVATIONS

The general surface morphology of Nilosyrtis Mensae is mapped in Fig. 2. The upland plateau surfaces are at roughly the same elevation and appear to be the remains of what was once a continuous, flat, moderately cratered plain. These are separated from the lowlands by abrupt escarpments. Calculations based on sun angle and shadow length indicate that the

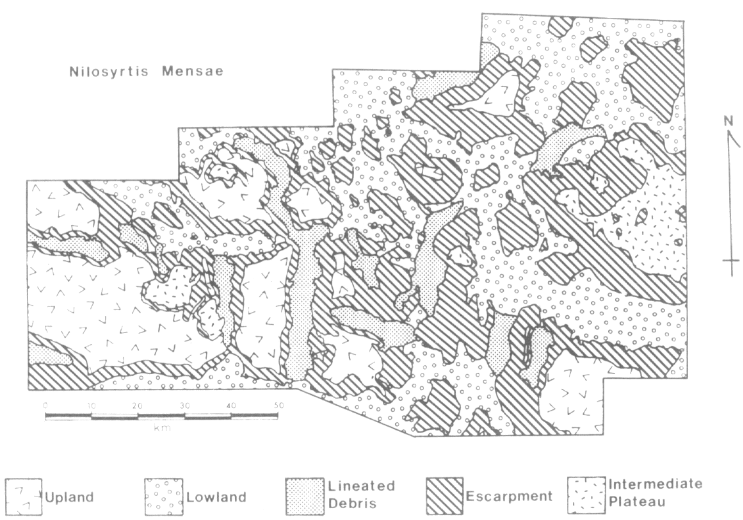

FIG. 2. Geomorphic map of Nilosyrtis Mensae.

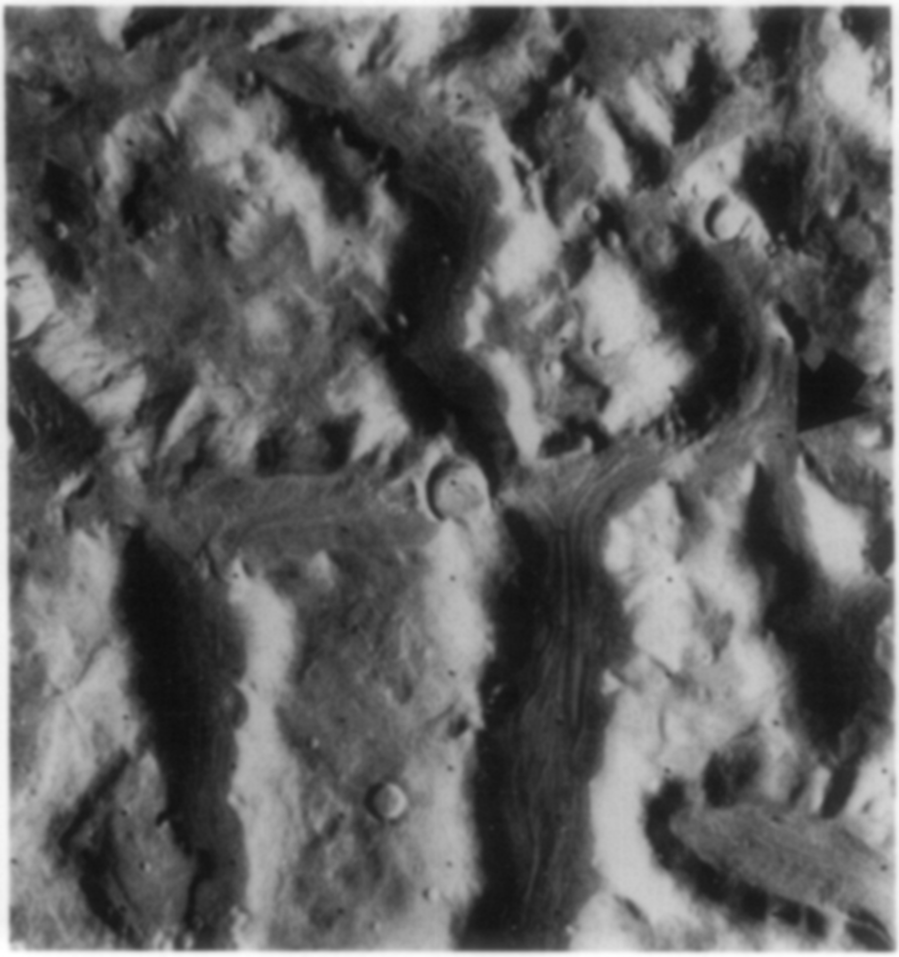

FIG. 3. Nilosyrtis Mensae valley floor lineations. Note lobate front. (Viking frame 84A73.)

escarpments are roughly 1 km high and range in slope from 10 to 40°. Craters on these escarpments are generally more degraded than craters on flat terrain. The lowlands are also moderately cratered and generally flat, although portions appear to be slightly hummocky. There are a few flat areas whose elevations lie between those of the upland plateau and the lowlands. These are designated on the map as intermediate plateaus. The region does not appear to possess a significant debris mantle.

The most noteworthy features of Nilosyrtis Mensae are the distinct lineations found on portions of the lowlands (Fig. 3). They occur primarily where a narrow valley is formed between two adjacent plateau regions. The lineations are restricted to the flat valley floor and are roughly parallel to the two bounding escarpments. They appear to consist of closely spaced linear ridges and depressions, although in one case the depressions are closed and relatively deep, forming aligned, highly elongate pits. Some lineated valleys have a rounded closure at one end resembling a glacial cirque, while others open out onto the lowland plain at both ends. The maximum extent of any set of

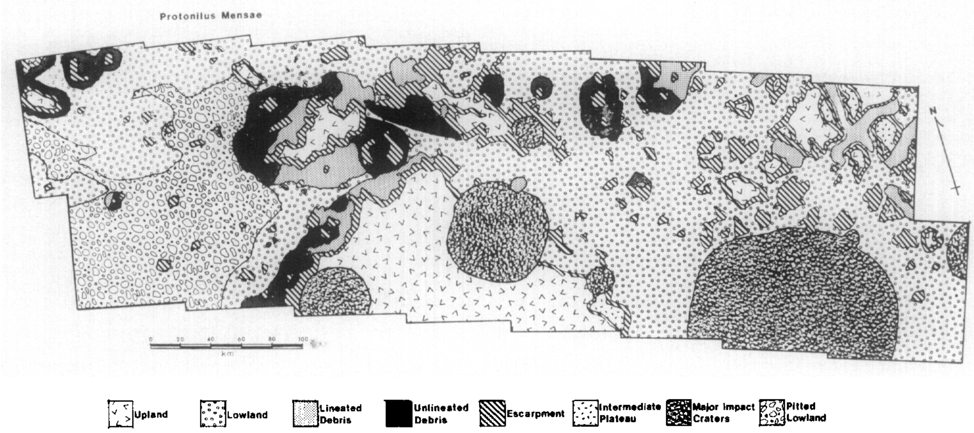

FIG. 4. Geomorphic map of Protonilus Mensae.

FIG. 5. Protonilus Mensae valley floor lineations. (Viking frame 58B65.)

lineations is about 50 km, but most are much shorter, often ending abruptly where the valley widens. The overall appearance of the lineations is very suggestive of flow, either of a fluid through the valley or of the valley floor material itself. In one instance there is a distinct lobate bulge where a valley which is closed at one end opens out onto the lowland plain, implying flow of the lineated material (Fig. 3). However, this is the only case where transport of debris through a valley is clearly indicated. There are no other flow termini or debris deposits at the openings of valleys in the study area.

Figure 4 is a map of Protonilus Mensae. The upland plateau areas, escarpments, and unlineated valley floor are all very similar to those found in Nilosyrtis Mensae. Most of the valley floor lineations, however, are aligned, elongate pits rather than parallel ridges and furrows (Fig. 5). Some areas of unlineated lowland differ from Nilosyrtis Mensae in that they possess a high concentration of irregular pits or depressions. These are generally elongate and roughly aligned, and frequently appear to possess raised rims. Although they superficially resemble some secondary impact craters, no primary crater has been reliably identified, and their origin remains uncertain. Much of the region is characterized by

FIG. 6 Lobate debris aprons. (Viking frame 58B51.)

FIG. 7. Lobate debris aprons. Note lineations and embayment of upland. (Viking frame 58B55.)

partially buried and filled small craters, suggesting the presence of a thin debris mantle.

Of all the features of Protonilus Mensae, the most interesting are the striking debris aprons which have developed at the bases of many of the escarpments. These are often lobate and distinctly convex in profile, giving the impression of outward flow of a viscous mass (Figs. 6 and 7). Many of the debris aprons possess ridge-and-furrow lineations in varying patterns. Most of these lineations are perpendicular to escarpment faces, radiating outward from the bases of mesas and buttes. Where the plateau surface is deeply embayed by the lowland plain, the lineations may be subparallel to escarpments along the sides of the embayment. The resultant landforms are intermediate in morphology between a lineated debris apron and a lineated valley floor, suggesting a similar origin for these features. There are a few exceptions to the general radial pattern of lineations, one of which is shown in Fig. 8. In this case, there is a very well-developed set of lineations on the escarpment-facing side of a residual knob which lies in a debris apron, the lineations being adjacent to the base of the knob and parallel to it. In another instance, a crater on the lowland plain seems to have been overtopped and partially

FIG. 8. Lineations parallel to the base of an escarpment rather than perpendicular. (Viking frame 58B56.)

buried by a debris apron (Fig. 9). All of these features appear to be the results of flow of a highly viscous material.

CRATER DISTRIBUTION

In both regions crater counts were performed for each of the following morphologic units: upland plateau, escarpment, unlineated lowland, and lineated and unlineated debris. Graphs of normalized crater frequency versus crater diameter are shown in Fig. 10. The abundance of fine relief in the flows made it necessary to exclude any small depressions near the resolution limit of the photographs.

The crater frequency curves make it possible to determine the relative ages of the units. Nilosyrtis Mensae as a whole appears to be older than Protonilus Mensae, but this may be due simply to the thin debris mantle found in the latter region covering some of the more degraded craters. In both areas the upland plateau regions are older than the unlineated lowlands. This is consistent with the escarpment recession model suggested by Sharp. In both areas also there is a sharp break in the curve for craters lying on escarpments. This unexpectedly low concentration of small craters, as well as the highly degraded nature of those craters which are visible,

FIG. 9. Crater partially buried by a debris apron. (Viking frame 58B61.)

indicates that some process has eroded escarpment surfaces. Because pronounced crater degradation seems to be prevalent only in sloping regions, and because debris is observed at the bases of many escarpments, it is clear that debris has been transported downslope. The lineated valley floors and debris aprons are essentially uncratered and are thus very young features, having either been deposited recently, or eroded recently, or, considering their morphology, flowed recently. In summary then, it seems that material has been loosened from the escarpments, transported downslope, accumulated on the lowlands, and undergone some type of further movement or flow. These processes have operated recently in Martian history and perhaps may be currently active. It is particularly important to note that they are quite distinct from the processes which originally formed the fretted terrain and that this fact may imply a significant environmental change.

NATURE OF THE FLOWS

These flows have been tentatively described by Carr and Schaber (1977) as frost creep or gelifluction features. Two important points suggest that this may not be the case. First, the thick lobate

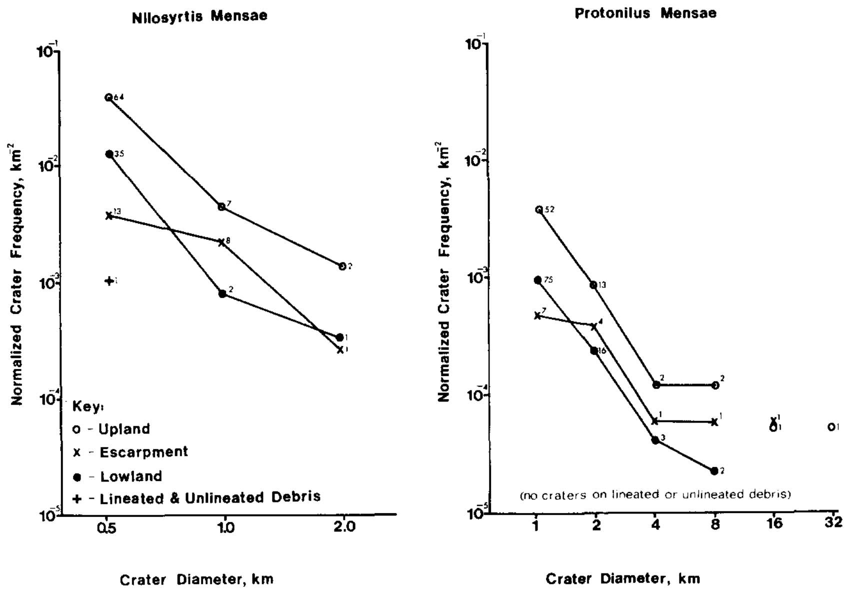

FIG. 10. Crater distribution. (Numbers next to data points indicate number of craters.)

nature of the flows implies that movement has occurred throughout a substantial thickness of the body rather than being limited to a thin surface layer. Second, there is no evidence to support the idea that thawing has occurred to any significant depth. The features seem to be relatively recent, and thawing of no more than a superficial outer layer could be expected under the current climatic regime. While geothermal warming is a possibility, no volcanic landforms are seen in the area. These considerations indicate that near-surface, thaw-dependent processes are probably not responsible for the movement.

An interpretation that is consistent with the requirement that movement occurs at depth but is not the result of thawing is that the flows behave in a manner similar to that of rock glaciers. Rock glaciers are found in many terrestrial arctic and alpine environments and consist of erosional particles ranging from angular blocks to sand and silt-sized grains cemented by interstitial ice. It is now agreed by most authors that rock glaciers deform and flow due to creep of the ice, and that thawing is not involved in the motion (Ives, 1940; Wahrhaftig and Cox, 1959; Thompson, 1962; White, 1976).

The source of the ice in terrestrial rock glaciers is snowfall. Clearly, another means of ice formation is necessary for similar features to have been recently active on Mars. The most reasonable possibilities are direct condensation of ice from the atmosphere or outgassing and freezing. While it is difficult to make quantitative estimates of the amounts of near surface ice these two processes could produce, it is reasonable to assume that the former would be predominant on a regional scale.

Earth-based spectrographic analysis has shown strong seasonal variations in atmospheric water content, implying a sink in the winter hemisphere (Barker, 1976). While the polar caps could perhaps provide such a sink, there is a pronounced phase lag between observable cap recession and growth of atmospheric water vapor in each hemisphere (see, for example, Farmer, 1976). This is interpreted by Leovy (1973) as evidence that the seasonal water vapor fluctuation is due instead to exchange between the atmosphere and subtropical permafrost, since he shows that any seasonal ice which forms at a polar cap should be highly concentrated around the outer edge of the cap. This possibility of a seasonal water sink in the middle latitudes was recognized earlier by Barker *et al.* (1970). It is likely, then, that a small but significant quantity of near surface ice condenses during the winter at the latitude of the study areas.

In order for ice to survive the summer, it must be buried by debris which has moved downslope. The occurrence of downslope transport is indicated by the crater count data, the degraded nature of escarpment craters, and the accumulation of debris at the bottom of slopes. The transport mechanism, however, is difficult to establish with any certainty. Thaw-dependent processes such as frost creep and gelifluction are very unlikely for climatic reasons. While thawing of a thin surface layer may be possible on south-facing slopes during the summer, there is no evidence of preferential debris accumulation at the bases of such slopes. Further, transport must occur in the winter as well to bury ice formed then.

Because the escarpments are often steep and probably composed of loose debris, it is possible that they lie near an angle of repose. Downslope transport could then be accomplished by any process which disturbs the surface material or removes debris from the bottom of the slope. It appears that material is in fact removed from the bottom of the slope by flow. If it is assumed that a significant part of the debris is fine-grained, wind could loosen and redistribute slope material, with the steepness of the escarpment causing a net downslope transport. The only thing which may be postulated with any real confidence concerning downslope transport, however, is that it does occur.

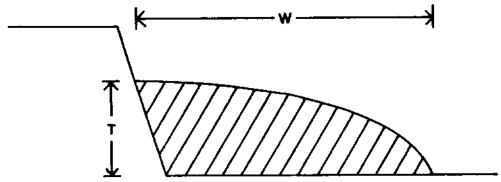

FIG. 11. Schematic cross section of a lobate debris apron.

A MECHANICAL MODEL

Further insight into the nature of these flows may be gained by considering their mechanical properties. Studies of the flow of active terrestrial rock glaciers have indicated that their behavior is similar to that of a very high viscosity fluid. Representative calculations of their apparent viscosities are 2 to 9×10^{14} P (Wahrhaftig and Cox, 1959) and 5 to 9×10^{15} P (White, 1971). Wahrhaftig and Cox also noted that the minimum basal shear stress for active rock glaciers is approximately 1 bar. Those with basal shear stresses below this value are not observed to flow. Thus the mechanical behavior of a mixture of debris and ice may be roughly that of a plastic with a yield stress of 1 bar and a viscosity above yield stress in the range 10^{14} to 10^{16} P. This is not meant to imply that the situation is truly this simple, but merely that the crudity of the existing measurements does not justify a more elaborate model.

The primary reason for this behavior is that the interstitial ice has an extremely low strain rate for stresses below about 1 bar, and that this figure is thus effectively the yield stress of the rock glacier material as a whole. Glen (1953, 1975) has more precisely described the deformational behavior of polycrystalline ice as

$$\dot{\epsilon} = A\sigma^n, \tag{1}$$

where $\dot{\epsilon}$ is strain rate, σ is stress, and A and n are constants. He suggests that for low values of σ, n is roughly 3.5, but that it decreases toward unity for stresses above

TABLE I

APPROXIMATE DIMENSIONS OF THREE REPRESENTATIVE LOBATE DEBRIS APRONS

T (km)	W (km)
0.8	18
0.9	25
0.5	15

1 bar. The value of A is also not truly constant, but decreases with decreasing absolute temperature. Although the effects of inclusion of a large amount of erosional debris are not at all clear, this relationship nevertheless has an important implication for the flow model used here. Because the linear factor (A) is temperature dependent and the exponential (n) is not, the apparent viscosity of such a mass under colder Martian conditions should be somewhat higher than that observed for most terrestrial rock glaciers, but the effective yield stress should be significantly affected.

Of the features studied, the lobate debris aprons are the simplest from a mechanical standpoint. It is assumed here that they are composed of a mixture of rock and ice which behaves as a plastic and that they lie on a flat base, deforming under their own weight and flowing outward. A schematic cross section of one of these features is shown in Fig. 11. Because of the low sun angle in the photographs it is possible to make fairly accurate estimates of their dimensions. Figures for three representative debris aprons are given in Table I.

Using a reasonable estimate of the viscosity, it is easy to demonstrate that the basal shear stress of these forms does not exceed the yield stress of the material, that is, that viscous flow is not occurring. The shear stress due to overlying load for any point at the base of such a mass is given by

$$\tau = -\rho g t(dt/dw), \qquad (2)$$

where τ is basal shear stress, ρ is the density of the material, g is the gravitational acceleration, t is the thickness of the material perpendicular to the base, and w is the horizontal distance from a hypothetical vertical escarpment (Paterson, 1969) (see Fig. 12). If the basal shear stress is greater than the yield stress viscous flow occurs at the base with rate of shear $\dot{\gamma}$ given by

$$\dot{\gamma} = \tau/\eta = -\rho g t(dt/dw)/\eta,$$

where η is the viscosity. The rate of advance of the flow terminus is thus

$$-\int_0^W [\rho g t(dt/dw)/\eta]dw = \rho g T^2/2\eta. \qquad (3)$$

Using the terrestrial upper limit of 10^{16} P for η, 0.7 km for T, and 2.0 g cm^{-3} for ρ yields a rate of advance of 60 m per year, clearly an unreasonable figure. If the surface at the base of the debris apron were sloping outward rather than flat as assumed here, basal shear stress would be increased, and this viscous flow rate would be still higher. Even if the value used for η here is several orders of magnitude too low, there is no conceivable method of downslope transport that could produce the amount of material needed to maintain viscous flow. It must be assumed then that the debris is in equilibrium, with the basal shear stress equal to the yield stress. Addition of debris at the head of the apron causes a gradual advance of the terminus, with the profile of the mass shifting to maintain internal equilibrium.

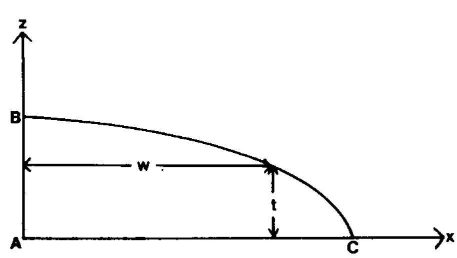

FIG. 12. Dimensions discussed in the text.

It is possible to determine the yield stress of such a mass of material if the parameters T and W are known. For a lobate debris apron at the base of a long escarpment, the outward force on the plane AB per unit of length normal to the paper is

$$\int_0^T \rho g(T - z)dz = \rho g T^2/2.$$

The inward force due to the shear stress along the base AC is just τW. At equilibrium these forces are of equal magnitude, and the basal shear stress is equal to the yield stress of the material τ_0. Thus (Orowan, 1949),

$$\tau_0 = \rho g T^2/2W. \tag{4}$$

Using the data from Table I, equation (4) yields values for τ_0 of 1.3, 1.2, and 0.6 bars. These are in good agreement with the 1.0-bar yield stress figure found by Wahrhaftig and Cox.

By a similar argument, the equation which describes the profile of the debris apron is the parabola (Paterson, 1969)

$$(t/T)^2 = 1 - (w/W). \tag{5}$$

Allowing for an ice content of 30%, the volumes calculated for typical debris aprons indicate that up to 5 km of escarpment recession has been accomplished by the downslope transport and flow of debris.

ORIGIN OF LINEATIONS

The surface lineations may also be helpful in determining the formation and behavior of these features. Wahrhaftig and Cox found two types of lineations on terrestrial rock glaciers, both consisting of parallel ridges and furrows. Longitudinal lineations are formed parallel to flow direction and are believed to be due to inhomogeneities in the supply of debris. They may also be formed by uneven distribution of ice throughout the mass, causing unequal rates of flow and producing internal shear. Transverse lineations are perpendicular to flow direction and are caused by compressional forces generated by a decrease in flow velocity "downstream" from the lineations.

Most of the lineations on the debris aprons are longitudinal and are probably accurate indicators of flow direction. One case where lineations have formed transverse to flow direction is the small set of ridges and furrows indicated in Fig. 8. The obstruction has apparently blocked advance of the flow at this point, causing compression and formation of transverse lineations perpendicular to the compressional force.

Lineations on the floors of narrow valleys present a more complicated situation. If the lineations are assumed to be aligned with the principal flow direction, immediate problems arise. While they often extend for considerable distances, there is rarely any evidence that material has been transported a substantial distance—there are no large accumulations of debris at one open end of any valley except for the one small flow terminus already mentioned. Another important point is that longitudinal lineations must arise from the base of the escarpment which is the debris source. In valleys which open at both ends this condition is not met. Many sets of lineations do not have a source area at either end. It can only be assumed that the primary sources of the debris are the escarpments which form the sides of the valley rather than material at one end of the valley. The valley floor lineations are then simply explained as compressional features. The hypothetical formation of such a set of lineations is illustrated in Fig. 13. After the valley floor has filled with debris, flow would be diverted toward the open end or ends of the valley (Fig. 13C). In this sense the lineations are aligned with the flow of the material, although they probably originally formed by compression. The origin of the elongate pits found in some lineated valley floor debris is uncertain but

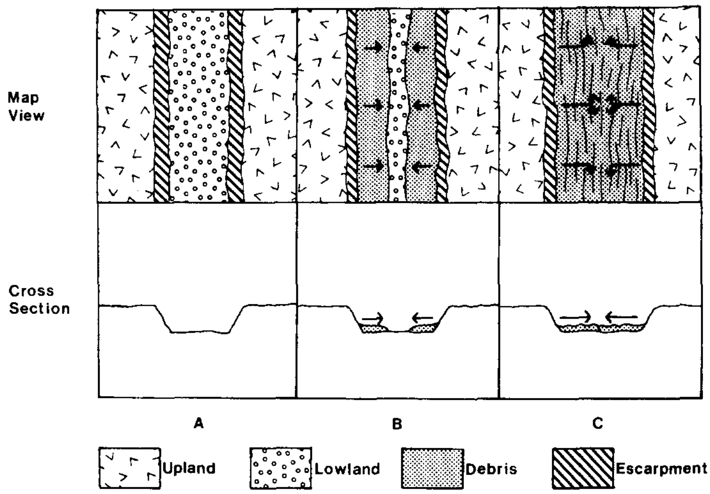

FIG. 13. Formation of valley floor lineations.

may involve collapse due to evaporation of ice, perhaps accompanied by eolian deflation of fine debris.

CONCLUSIONS

The process by which debris is thought to flow in Nilosyrtis Mensae and Protonilus Mensae may be summarized as follows: Material is loosened from escarpment surfaces and transported slowly downslope by some type of mass-wasting process. Upon reaching the base of the escarpment it incorporates seasonal ice from the atmosphere. The resultant mixture of debris and ice behaves in a manner similar to that of a terrestrial rock glacier. The mass deforms in response to continual loading of fresh debris, flowing away from the escarpment in order to maintain equilibrium between basal shear stress and the yield stress of the material. Where a flow encounters an obstruction or another flow, lineations form which are perpendicular to the compressional forces generated. Other lineations may form which parallel the direction of flow. The process is an extremely gradual one, owing to the lack of an efficient downslope transport mechanism. It has operated recently in Martian history, and may be currently active.

If this interpretation and Sharp's hypothesis of fretted terrain formation are correct, there are important climatic implications. In the climatic regime existing during the original formation of fretted terrain, debris which moved downslope was carried away by either water or wind. The climate existing during the formation of the features studied here allowed the accumulation of considerable thicknesses of debris and the incorporation of ice into this debris. This marked change in processes suggests either a general cooling of climate or a major decrease in eolian activity. The appearance of massive fluvial features in many other regions of the planet provides strong evidence for the first view.

ACKNOWLEDGMENTS

The author would like to thank Joe Veverka, Peter Thomas, Peter Gierasch, A. L. Bloom, and Bev Henderson for their helpful discussion and suggestions during the course of this work. Ron Greeley and Paul Spudis provided useful comments on an early draft of the paper. Preparation of the final manuscript was supported by the Cornell University Department of Geological Sciences.

REFERENCES

BARKER, E. S., SCHORN, R. A., WOSZCYK, A., TULL, R. G., AND LITTLE, S. J. (1970). Mars: Detection of water vapor during southern hemisphere spring and summer season. *Science* **170**, 1308–1310.

BARKER, E. S. (1976). Martin atmospheric water vapor observations: 1972–74 apparition. *Icarus* **28**, 247–268.

CARR, M. H., MASURSKY, H., BAUM, W. A., BLASIUS, K. K., BRIGGS, G. A., CUTTS, J. A., DUXBURY, T., GREELY, R., GUEST, J. E., SMITH, B. A., SODERBLOM, L. A., VEVERKA, J., AND WELLMAN, J. B. (1976). Preliminary results from the Viking orbiter imaging experiment. *Science* **193**, 766–776.

CARR, M. H., AND SCHABER, G. G. (1977). Martian permafrost features. *J. Geophys. Res.* **82**, 4039–4054.

FARMER, C. B. (1976). Liquid water on Mars. *Icarus* **28**, 279–289.

GLEN, J. W. (1953). The creep of polycrystalline ice. *Proc. Roy. Soc.* **A228**, 1175, 519–538.

GLEN, J. W. (1975). The Mechanics of Ice. USA CRREL CRSE Monograph II-C2b. AD778009.

HUGUENIN, R. L. (1974). Formation of goethite and hydrated clay materials on Mars. *J. Geophys. Res.* **79**, 3895–3905.

IVES, R. L. (1940). Rock glaciers in the Colorado Front Range. *Bull. Geol. Soc. Amer.* **51**, 1271–1294.

LEOVY, C. B. (1973). Exchange of water vapor between the atmosphere and surface of Mars. *Icarus* **18**, 120–125.

MALIN, M. (1975). Ancient massive blankets and the surface of Mars. *Bull. Amer. Astron. Soc.* **7**, 369 (abst.).

OROWAN, E. (1949). Remarks from Joint Meeting of the British Glaciological Society, the British Rheologist's Club, and the Institute of Metals. *J. Glaciol.* **1**, 231.

PATERSON, W. S. B. (1969). *The Physics of Glaciers.* Pergamon, Oxford.

SHARP, R. P. (1973). Mars: Fretted and chaotic terrains. *J. Geophys. Res.* **78**, 4073–4083.

THOMPSON, W. F. (1962). Preliminary notes on the nature and distribution of rock glaciers relative to true glaciers and other effects of the climate on the ground in North America. In *Symposium at Obergurgl*, pp. 212–219. Internat. Assoc. Scientific Hydrology Publ. No. 58, Obergurgl, Austria.

WAHRHAFTIG, C., AND COX, A. (1959). Rock glaciers in the Alaska Range. *Bull. Geol. Soc. Amer.* **70**, 383–436.

WHITE, S. E. (1971). Rock glacier studies in the Colorado Front Range, 1961 to 1968. *Arctic and Alpine Res.* **3**, 43–64.

WHITE, S. E. (1976). Rock glaciers and block fields, review and new data. *Quat. Res.* **6**, 77–97.