ORIGIN OF THE OLYMPUS MONS AUREOLE AND PERIMETER SCARP

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Abstract. The aureole materials that form an annulus of corrugated terrain surrounding Olympus Mons are considered to be the product of mass movement. The scarp at the mountain's foot formed as a result of this massive removal of material from the volcano's outer flanks. This interpretation is supported by a comparison of the amount of material originally available before scarp formation, and the present volume of aureole materials. On the basis of distribution, surface textures and theoretical considerations it is considered that the aureole was produced by a series of megaslides, rather than by a flow mechanism. Production of the megaslides may have been assisted by a period of widespread melting of permafrost.

1. Introduction

Olympus Mons was first recognised as a volcano from Mariner 9 pictures; these showed it to have a basal diameter of about 550 km and a height in excess of 20 km. The summit is capped by an 80 × 60 km diameter complex of at least five coalescing calderas (Figure 1). The base of the volcano is bounded by a well developed scarp rising some 2–6 km above the surrounding plains. Viking pictures show that flows from the summit region extend over the scarp (Figure 2), indicating that the youngest lavas were emplaced after the scarp had formed. These lavas extend well beyond the scarp, which was thought prior to Viking to be the outer boundary of the volcano.

The most enigmatic feature of Olympus Mons is the presence of a surrounding apron of a distinct terrain cut by curvilinear ridges and troughs. This apron extends from near the foot of the scarp outwards. The material making up this terrain has been mapped as aureole material (Carr, 1975) and a number of theories for its origin have been advanced.

From Mariner 9 pictures it was generally accepted that the aureole is genetically related to Olympus Mons. Carr *et al.* (1973) suggest several possibilities, one of which is that the aureole represents the eroded remnant of an originally much larger Olympus Mons, whose outer flanks have been cut back to give the present scarp. King and Riehle (1974) propose a similar hypothesis in which the older material of the volcano consists of ash-flow tuffs, and the less welded zones were differentially eroded, leaving the more resistant tuffs near the volcano centre.

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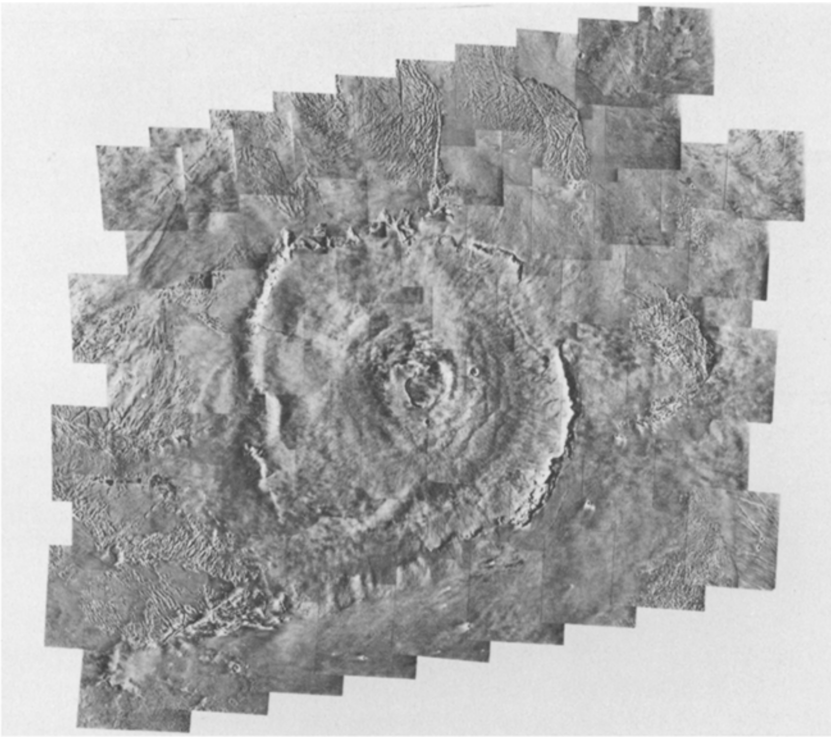

Fig. 1. Viking Photomosaic of Olympus Mons and part of the aureole. North is at the top. The volcano's basal diameter is approximately 550 km. (Mosaic number 211-5360).

On the other hand, Morris and Dwornik (1978) suggest that the aureole materials are relatively young volcanic flows surrounding Olympus Mons, and that the scarp was formed by a ring fault.

The substantial increase in resolution from Viking pictures greatly assists in interpretation of aureole materials. Improved resolution illustrated that there are mass movement features some tens of kilometres long associated with the perimeter scarp (Carr *et al.*, 1977). These features (Figure 3) have some characteristics in common with the aureole materials, suggesting that the aureole might also be the result of gigantic mass movements. Also, very large mass movement deposits have been recognised on Arsia Mons (Carr *et al.*, 1977).

2. Description of Aureole Materials

The distribution of aureole materials is shown in a geological sketch map (Figure 4). Broadly these materials are disposed around the volcano as a series of overlapping lobes with arcuate outer boundaries. The distribution is asymmetrical, the lobes to the north

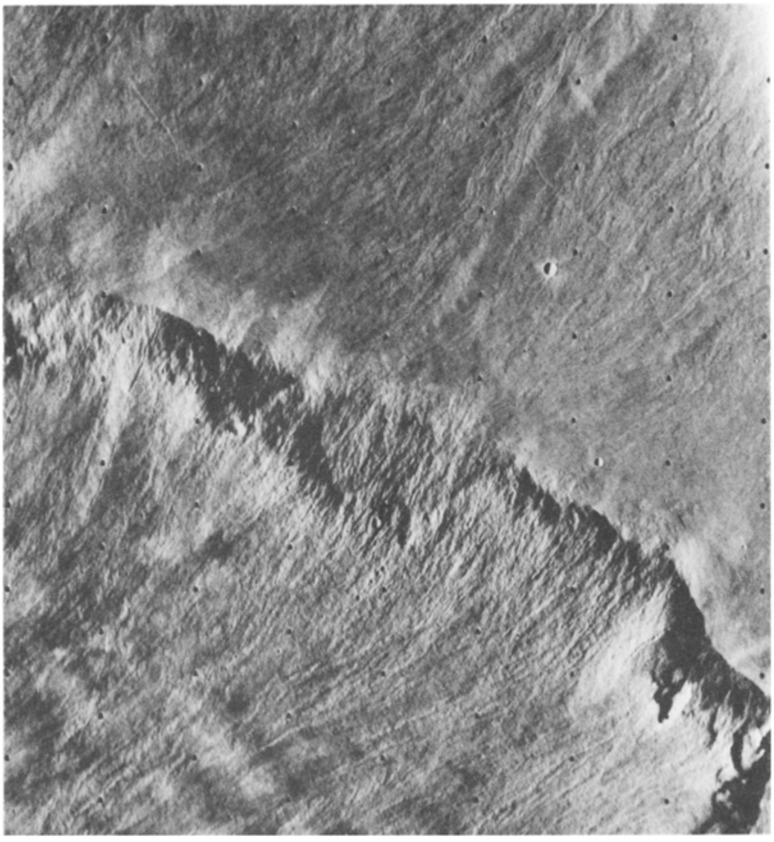

Fig. 2. Part of the northeastern flank and basal scarp of Olympus Mons, showing well-defined lava flows veneering the scarp and extending beyond it. Image height is approximately 80 km (Picno 047 B25).

and northwest extending as much as 750 km from the basal scarp, while those elsewhere extend only for 500 km or less.

Surface characteristics are variable. From Marine 9 pictures, Carr *et al.* (1973) recognised two basic types of aureole materials. Materials closer to Olympus Mons have a coarse surface texture while that further away is finer. These two types of terrain are clearly seen on Viking pictures (Figure 5). The coarser surfaces tend to make up the greater part of individual lobes and consist of arcuate ridges on average 1 km high and spaced at about 1–10 km. Cutting across the ridges are graben-like troughs forming intricate patterns and several radial or sub-radial scarps also occur (Figure 6).

On the finer textured surfaces the ridges again parallel the lobe fronts, but are about $\frac{1}{2}$ km high and spaced at 1–5 km. They also tend to be less continuous than those on the coarse textured surfaces, and graben faults are less common and less pronounced.

Morris and Dwornik (1978) mapped the western side of the volcano recognising lobes

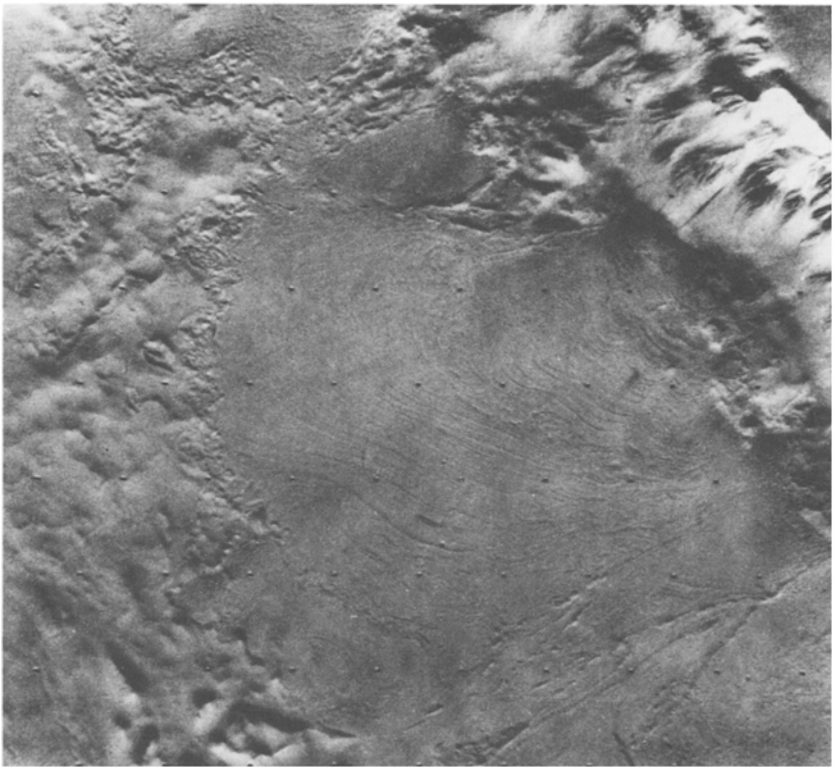

Fig. 3. Relatively small mass movement deposit at the base of the western scarp of Olympus Mons. A pattern of ridges and troughs can be distinguished. Image height is approximately 85 km (Picno 048 B04).

of different ages based on surface textures. Using Viking data at least five major units may be distinguished forming a petal-like distribution around the mountain (Figure 4). However each major unit may, itself, be divided into sub-units based on orientation of the ridge pattern. One difficulty is to determine whether the coarse and fine textured units (Figure 5) represents facies of the same unit, or different overlapping units.

The outcrop of aureole materials is not complete as some areas, particularly near Olympus Mons where they are covered by lava flows and aeolian deposits. Although some of the outer boundaries are buried, in some places the lobe fronts overly the surrounding plains, as illustrated by Figure 7 where the lobe has partly surrounded a pre-existing impact crater on the plains. Also in this area pre-existing graben cutting the surrounding plains appear to have been buried by the lobe front. It is of interest to note that in Figure 7 there is a narrow frontal zone of very finely textured material at the lobe front; this may support the view that each lobe becomes finer textured towards the outer margin and that the coarser and finer surface textures are facies of the same lobes.

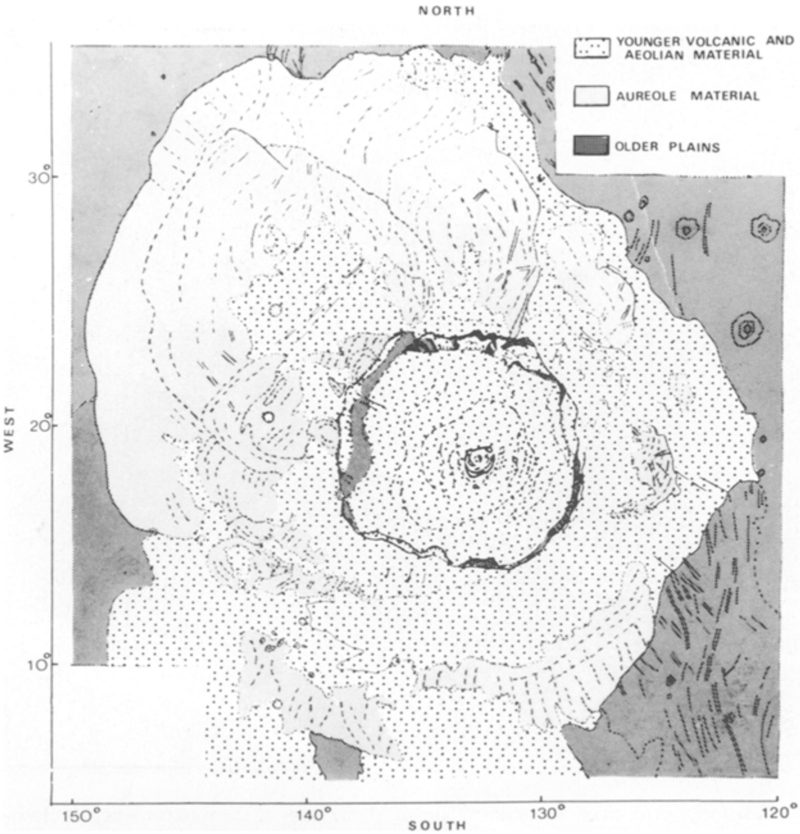

Fig. 4. Geological sketch map of Olympus Mons and the aureole lobes. Older plains material include pedestal material, both of these units being older than the scarp.

3. Origin of Aureole Materials

The surface features on the aureole materials appear much fresher on Viking pictures than was considered from Mariner 9. Thus, it is unlikely that these are eroded lava flows as suggested by Morris and Dwornik (1978). Certainly these materials are younger than would be required for an erosional hypothesis such as that of Carr *et al.* (1973). However, Carr *et al.* (1977) suggest, as an alternative, that aureole materials may have been emplaced by mass movement. Based on the present evidence this interpretation appears most likely. That they were emplaced by outward movement from the volcano is supported by the surface patterns and evidence presented in Figure 7, where the front of the lobe wraps around a small impact crater. Further (Figure 8), there are strong topographic controls, those units that extend towards the Tharsis rise in the southeast being less extensive, while those towards the northwest, where the terrain slopes away from the volcano into the northern plains, are more extensive. A clear gravity control on the surface extent of the units is indicated. Such gravity control would also be expected

Fig. 5. Mosaic of images of the western flanks of Olympus Mons and associated aureole lobes. The coarser surface texture (nearer the Volcano, A) and the finer texture (further away, B) can be clearly distinguished (Mosaic number 211-5722).

Fig. 6. Part of the aureole material to the north of Olympus Mons, showing a radial scarp, associated with a coarse texture ridge pattern. Image height is approximately 95 km (Picno 040 B15).

for lava flows. However, where the aureole materials abut against Tharsis they have clearly travelled uphill; while lavas may travel short distances uphill, it requires a flow of considerable momentum such as a rockslide or debris flow or, possibly, an ash-flow to travel as far as those on Olympus Mons. Clearly an ash-flow origin for the lobes cannot be completely ruled out. Nevertheless, the mass movement hypothesis does also explain the scarp as being the erosional scar left behind the mass movement deposit. The presence of small, but similar, products of mass movement near the scarp adds further support to this idea.

To test the mass movement hypothesis, the volume of individual lobes (Table I) has been estimated using their areal extent and average thickness determined from Viking pictures. These volumes are compared with estimates of material available at the scarp based on height of scarp and slope of the volcano (Figure 9).

The greatest error in estimating the volume of material present in the aureole lobes lies in the estimate of thickness of the lobe. Estimates were made using shadow lengths on the ridges, giving a minimum thickness for the material. The potential volume of material that could have broken from the edge of the volcano in scarp formation was calculated using the average height of scarp adjacent to each lobe unit, based on Blasius

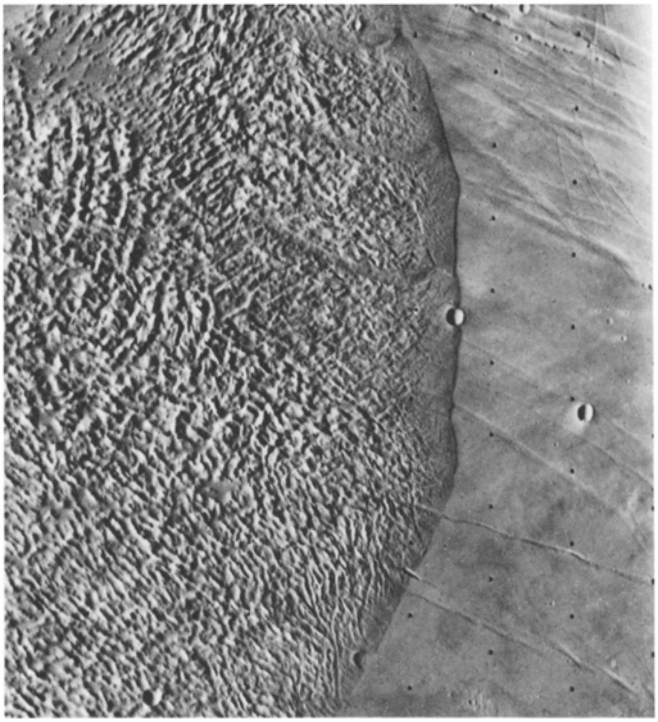

Fig. 7. Part of the lobe to the southeast of Olympus Mons, showing that it overlies the older fractured plains to the left, burying the graben faults. The lobe front surrounds a small pre-existing impact crater, indicating that the lobe was emplaced by flowage. Note the narrow band of very finely textured material at the lobe front. Image height is approximately 164 km. (Picno 044 B27).

et al. (1978) photogrammetic measurements, and an estimate of slope for the flank of the volcano.

The local topography (Figure 8) of the area shows that Olympus Mons sits on a southeast–northwest slope, indicating that the northern to western flanks of the volcano have a shallower average slope than the southern and eastern flanks. The present average slope for the volcano (4° estimated from present values of diameter and height) was used in the calculations of potential volumes from the northeast, east, southeast and southwest flanks. A shallower slope of 2° was taken for the north, northwest and west flanks. Using these slopes a minimum amount of material was calculated as the slopes may well have been shallower at the time of scarp formation.

We assumed that the rockslides removed material up to the present scarp. The scarp face was taken to be vertical since using a reasonable scarp inclination of 34° would only change volumes by about 10%. The comparison between present volume of material in the aureole and volume available in scarp formation is shown in Figure 9 which gives a good correlation between the two and therefore supports the mass movement hypothesis, if we assume an original 4° slope for the NE, SE, E and SW gradients and a 2° slope to

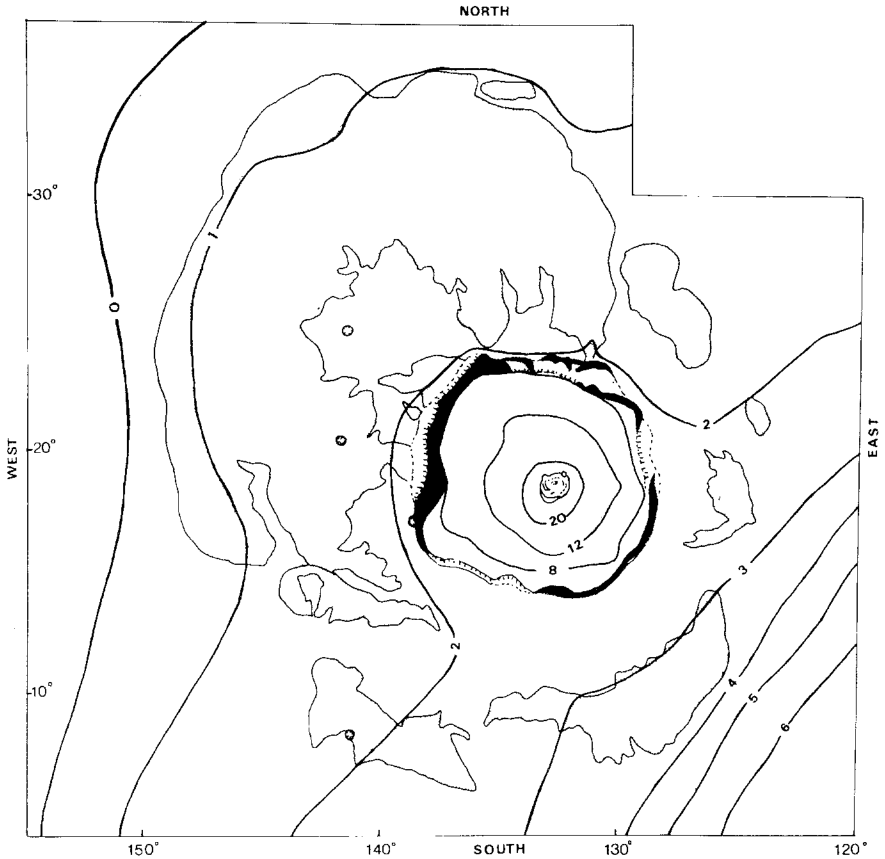

Fig. 8. Topographic sketch map of Olympus Mons, aureole lobes (light stipple) and surrounding plains, showing the variable reach of the aureole lobes around the volcano. The scarp is indicated by heavy stipple.

the N and NW. The 4° slope is the maximum slope possible and at the time the aureole was formed it may have been less. If a shallower slope is taken we get an excess of material available still demonstrating that sufficient was available to produce the aureole material by mass movement.

4. Discussion

The evidence in favour of aureole materials being of mass movement origin is as follows:

(1) Surface features indicate emplacement by flowage away from the volcano.

(2) Comparison with small mass movement features at base of scarp.

(3) Control of local topography on length of lobes.

(4) Highest scarps are adjacent to largest volume lobes.

(5) Volumes of lobes are consistent with their having been derived from scarp formation.

LOBE UNIT	MEASURED VOLUME ($\times 10^3$ km^3)	MAXIMUM HORIZONTAL DISTANCE (km)	AVERAGE HEIGHT OF SCARP (km)	MAXIMUM VERTICAL DROP (km)	POTENTIAL ENERGY ($\times 10^{26}$ ergs)	Max Horiz Dist / Max Vert Drop
NORTH EAST	12	370	3.0	4.0	13	93
EAST	10	300	2.0	2.0	5.5	150
SOUTH EAST	17	425	2.5	3.0	13	140
SOUTH WEST	30	510	4.0	5.0	37	100
NORTH / NORTH-WEST	340	750	4.5	6.0	480	125

The strongest impediment to a mass movement hypothesis is the large size of the features. Large mass movement features on Earth are only a few kilometres in length. For example, the Saidmarreh landslide travelled some 12 km, covering an area 166 km^2 (Voight and Pariseau, 1978). However, giant submarine landslides have been described on the Hawaiian ridge (Moore, 1964), one extending for more than 150 km.

Assuming the features around Olympus Mons were produced by rapid mass movement of material from the scarp, how were they emplaced? Two possibilities are:

(a) Catastrophic flows (*Sturzstroms*, Hsü, 1975) of fragmental material falling from the scarp and behaving as a material akin to a complex fluid capable of deforming internally to a greater or lesser extent, and producing thin units some tens of metres thick.

(b) Rockslides moving as relatively rigid non-deforming blocks along a surface of low coefficient of friction, the material breaking up and fracturing in the last stages of movement and producing a unit some hundreds of metres thick.

The physical processes involved in mass movement and the relation of these processes to surface features is not clearly understood. Thus, although there is a strong case for the materials of the Olympus Mons aureole having been formed by mass movement, it is difficult to determine which of the possible processes was involved. Nevertheless, there is evidence that the Olympus Mons examples were emplaced mainly by the rockslide mechanism and at a relatively low velocity compared with catastrophic flows or Sturzstroms.

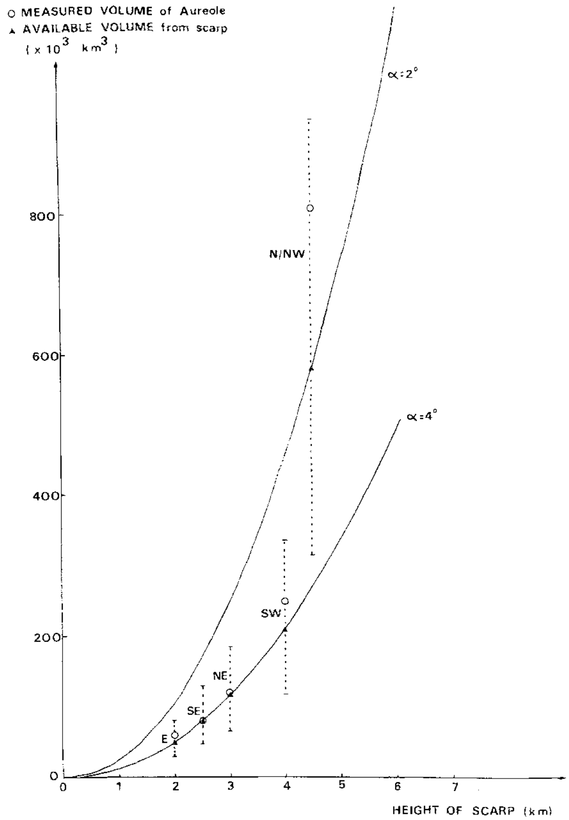

Fig. 9. Comparison between volume of material present in aureole lobes and volume of material available from scarp formation. The curves show how the latter varies with height of scarp for a given value of slope, following the relation:

$$\frac{V}{F} = \frac{\pi h^2}{3 \tan^2\alpha} (h + 3r \tan \alpha)$$

where V = volume available from scarp, F = part of volcano's circumference adjacent to each lobe unit, h = height of scarp, α = slope of volcano, r = present radius of volcano (275 km).

The points marked on the curve represent the available volume from the scarp adjacent to each lobe unit, using the local average scrap height. The error bars represent an error in volume equivalent to a 25% error on the estimation of the scarp height.

The volumes of each aureole lobe are plotted as circles for comparison and fall within the error bars of the available volumes from scarp.

Firstly, the Olympus Mons examples are relatively thick. Also they lack the longitudinal grooves and digitate flow lobes more commonly found with the Sturzstrom type units, as illustrated by the Sherman glacier slide (Shreve, 1966; McSaveney, 1978). As has been noted earlier, some of the aureole units travelled uphill by as much as 1 km in 200 km; if these materials had been flowing as Sturzstroms they would require a considerable velocity to carry them uphill. Because the slopes on which the aureole materials travelled initially are only one or two degrees, it is unlikely that Sturzstrom type velocities would have been achieved; with relatively low velocities the moving material would most likely have been diverted by topographic highs rather than being carried uphill. However, if the material had been non-fragmented and was emplaced as a slide, then it would have been able to transmit a high stress, and therefore assuming that there was a low friction coefficient at the base, the slide would have been capable of transmitting the stress required for movement up the slope.

Secondly, the surface textures are not inconsistent with the slide mechanism. The arcuate ridges can be interpreted as having been formed by the fragmentation of the sheet into a series of mega-blocks and thrust slices as the slide came to rest. Such a mechanism appears to be appropriate for explaining the blocky relief found on the Hawaiian submarine megaslides (Moore, 1964).

The two different facies occurring on the aureole units may be explained by differences in thickness of the unit or, indeed, in terms of the degree of fragmentation. Nevertheless, it is probably too simplistic to consider that these enormous units were formed by one process and the possibility that parts of the unit, such as the distal margins, may have been produced by a Sturzstrom type mechanism cannot be overlooked.

There are some ways that we can compare these Martian features with those on Earth and on the Moon. In Figure 10 we plot the potential energy of the aureole units against the ratio of maximum horizontal distance (L) to the maximum height of fall (H), following Howard (1973). Clearly, compared with terrestrial examples, the Martian ones travelled great distances relative to the height of fall and can be considered as highly 'efficient'. To get a far travelling unit, an adequate supply of material is needed together with a mechanism to reduce the overall 'friction factor' to levels adequate to explain known terrestrial examples. A low 'friction factor' requires the material to have a low permeability. In the case of a Sturztrom flow, grain dispersive forces interacting in the flow reduce the internal friction (Hsü, 1975); this is achieved by having debris with a high proportion of fine grained material. In the case of a slide, the friction is reduced by high pore-fluid pressures acting along the sliding surface, similar to the effect in the thrust fault tectonics as described by Hubbert and Rubey (1959), and requiring a low permeability material such as an unfractured sliding mass.

When did the rockslides occur in the history of Olympus Mons? The first phase in the construction of the mountain was the formation of the pedestal now exposed in the scarp. Apart from in the scarp face, little of this is now exposed. Where it is exposed above the scarp it appears to be smooth-surfaced at the scale of the pictures and cut by faults which may themselves be related to break-up that produced the scarp. Scarp formation and production of aureole materials then occurred, followed by volcanic activity which built the upper part of the present mountain and veneered the scarp with thin lavas that extend out over parts of the aureole. These flows have characteristics typical of basaltic flows on Earth (Carr *et al.*, 1977). Caldera collapse was associated with this volcanism.

In terms of the broader history of Mars the rockslides occurred after the rise of the Tharsis region and associated faulting. It is tempting to consider that permafrost developed

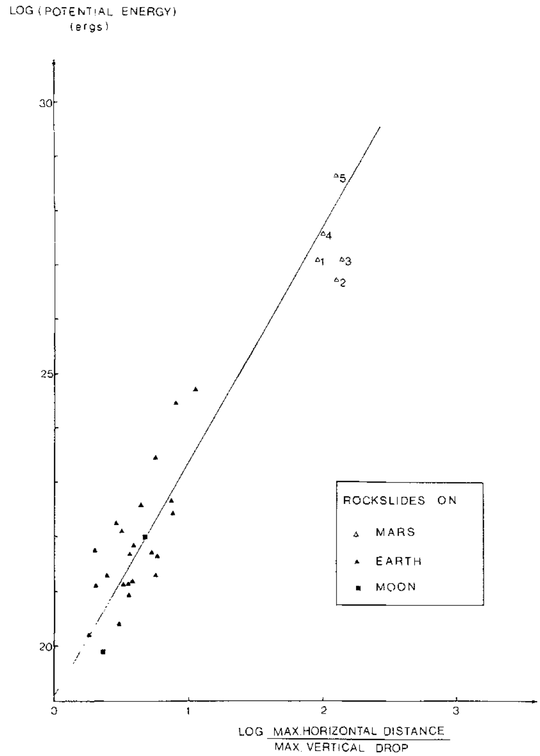

Fig. 10. Gravitational potential energy of rockslide material plotted against the ratio of the maximum total horizontal distance travelled to the maximum total height of fall. The data for the terrestrial and lunar examples was taken from Howard (1973). A simple least squares fit was performed to all data points, and the density of the material was taken as 2.5×10^3 kg m^{-3}. The data for the martian rockslides is shown on Table I.

in the rocks of the pedestal material and played a part in the emplacement of these rockslides. The presence of permafrost in other places on Mars is supported by Viking evidence (Carr and Schaber, 1977). Renewal of volcanic activity to produce the present summit cone may well have been accompanied by a general increase in heat flow. If permafrost was present in the pedestal rocks, which are perhaps early formed unconsolidated and welded tuffs as suggested by King and Riehle (1974), an increase in temperature near the surface could have caused melting of permafrost and general slope instability of the mountain, leading to breaking up of large quantities of material from scarp. This break up may have been assisted by the existence of unconsolidated tuffs underlying dense lavas.

It is interesting to note that the surface of Mars is cut by channels, some of which must have been produced by evolution of ground water at a rapid rate, causing catastrophic flash floods across the surface. It is considered by many workers that some of these features were produced by an increase in the thermal gradient, melting permafrost. It could be that a general increase in the surface temperature on Mars, accompanied by the onset of volcanic activity giving off large volumes of volcanic gases led to an amelioration in climatic conditions. Such relatively sudden changes could have been responsible not only for the Olympus Mons megaslides, but the flooding episodes observed. Certainly for the Chryse Basin, Greeley *et al.* (1977) suggest that there were alternating episodes of extensive volcanism and flash floods. Our present knowledge of the timescale of these various events on Mars is not adequate to determine whether the Olympus Mons rockslides occurred at the same time as these other events.

On the basis of the present information the mass movement hypothesis appears to be the best explanation for the Olympus Mons aureole. For future investigations, detailed topographic maps of the Olympus Mons region would be of great value, as would be a detailed relative time scale of the volcanic, landsliding and flooding events in the Olympus Mons/Tharsis Ridge area.

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