The Subglacial Birth of Olympus Mons and Its Aureoles

CARROLL ANN HODGES AND HENRY J. MOORE

U.S. Geological Survey, Menlo Park, California 94025

The vast volcanic plains and shields of Mars, together with the thermal, spectrographic, and morphological evidence for water ice at the poles, for several percent water in Viking soil samples, for ground ice or permafrost over much of the planet, and for the existence of surface water at some time in the past, suggest that magma and water or ice may have interacted during evolution of the planet's landscape. Relatively small mesas and buttes, with and without summit craters, are remarkably similar to the table mountains of Iceland that formed by subglacial eruption during the late Quaternary period. Table mountains typically comprise foundations of pillow lava and palagonitized tuff breccias (móberg), overlain by subaerial lava flows that commonly culminated in a typical shield volcano; some table mountains, however, failed to reach the subaerial stage and thus lack the cap rock. Subglacial fissure eruptions produced ridges composed of pillow lava and móberg. Conical knobs on steep-sided Martian plateaus are reminiscent of the small Icelandic shield volcanoes atop móberg pedestals. Candidate table mountains on Mars are especially numerous in the region between latitude 40°N and the margin of the north polar cap, and interaction of lava with a formerly more extensive ice cap may have occurred. More significant is the possibility that Olympus Mons and the broad lobate aureole deposits around its base may have had similar subglacial beginnings. This hypothesis requires an ice cap several kilometers thick in the vicinity of this enormous shield during its initial stages of eruption. The amounts of water ice required do not appear excessive, given the limits to present knowledge of the water budget throughout the planet's history. A mechanism for localizing such ice, however, is required.

INTRODUCTION

The morphologies of numerous small landforms on Mars are not readily interpretable in terms of conventional impact, volcanic, or erosional processes. Such features include circular to rectangular mesas and buttes, with and without summit craters (Figures 1 and 2), and 'two-story' structures consisting of conical or irregular knobs atop broad, flat, steep-sided pedestals (Figure 2*a*). Some landforms exhibit morphologies consistent with either volcanic or impact origins, so their genetic classification is not obvious. These types of features are especially abundant in the 'northern plains,' between about latitude 40°N and the margin of the polar ice cap. Features that are clearly volcanic also occur in parts of this region, specifically, north of the Tharsis and Elysium volcanic provinces. Well-defined lava flows on the flanks of Alba Patera are intermingled with conical cratered domes a few kilometers across that resemble small volcanic cones; clusters of such features have been noted elsewhere as well (Figure 2*b*).

If terrestrial analogs are to be found for these Martian landforms, they are most profitably sought where geologic and climatic conditions are similar to past or present environments on Mars; Iceland, with its combination of active volcanism and glaciation, is a promising locale to explore [*Allen,* 1977, 1978, 1979; *Hodges,* 1977; *Hodges and Moore,* 1978*a*, *b*; *Williams,* 1978]. The table mountains of Iceland (Figures 3*a* and 3*b*), which formed as a result of subglacial volcanic extrusion, are our major topic of interest here, augmented by reference to oceanic shield volcanoes such as Mauna Loa, which have subaqueous eruptive histories parallel with the subglacial stages of the Icelandic table mountains [*Kjartansson,* 1966*a*; *Moore and Fiske,* 1969].

ICELAND'S TABLE MOUNTAINS

The relatively small, isolated plateaus termed table mountains (Figure 4) have been described in detail by *Van Bemmelen and Rutten* [1955], *Jones* [1966, 1969, 1970], *Kjartansson* [1960, 1966*a*, *b*, 1967], *Sigvaldason* [1968], and *Preusser* [1976]. These distinctive landforms may be roughly circular but more commonly are subrectangular, with abrupt edges and steep flanks that slope as much as 35° or more (Figures 5*a* and 5*b*). The top is flat or gently convex, with or without a crater at the summit, and is composed of aa and pahoehoe flows which in most cases developed into a small subaerial shield volcano [*Kjartansson,* 1960]. Underlying the subaerial flows is a pedestal-like foundation of 'móberg,' the Icelandic term for palagonitized tuffs and breccias [*Kjartansson,* 1960]. The móberg mass in turn overlies and is partly intercalated with a basal core of pillow lava. Some table mountains lack the subaerial basalt cap (Figure 6).

The pillow lava and móberg pedestals indicate that water was abundant at the site of extrusion. The prevailing genetic hypothesis is diagramed in Figure 7 [*Einarsson,* 1968]. Basaltic magma was extruded subglacially into water-filled caverns melted into or through a late Quaternary ice sheet. The initial extrusions of pillow lava were emplaced beneath meltwater and ice. As the pile of pillow lava grew upward, confining pressures of the overlying meltwater and ice decreased, and the consequent increased vesiculation of the magma, augmented by influx of water into the vent, initiated phreatomagmatic explosions [*Jones,* 1970]. Sideromelane tuff breccias, subsequently altered to palagonite, were then deposited atop the pillow lava. If the accumulating pile reached the surface of the meltwater lake, subaerial flows were emplaced, commonly capped by a shield volcano. As the subaerial flows advanced into the meltwater at the margin of the pile, explosive disruption occurred, and tuff breccias were deposited as steeply dipping sediments, much like the foreset beds of a delta, but in this case overridden by topset beds of lava [*Jones,* 1969]. With subsequent withdrawal of the ice, the subaerial flows formed a resistant cap overlying the less resistant móberg foundation. The thickness of the ice sheet, indicated by the height of the móberg pedestals, was apparently 500–1000 m during the Pleistocene stage of table mountain development. Cratered hills or mesas of móberg that are not capped by lava

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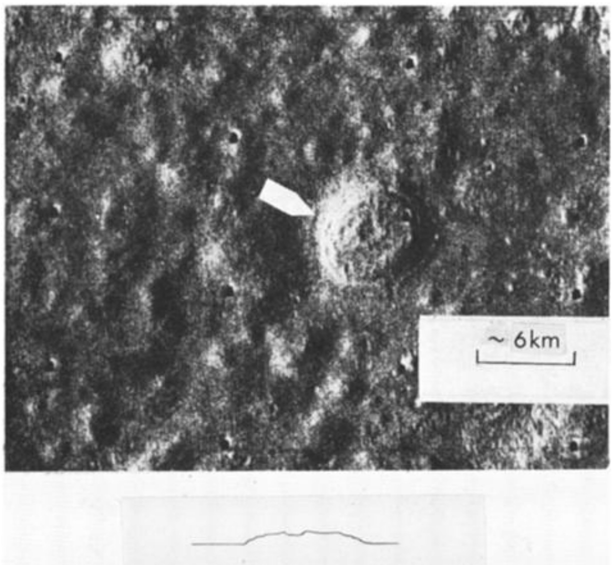


Fig. 1. The small circular plateau with summit crater (arrow) is one of the best candidates for a Martian table mountain. It has a morphology and dimensions that are similar to the table mountains in Iceland which are formed by subglacial volcanic eruption (compare with Figure 3). Terraces and ridges occur near the base. Smaller, similar features are nearby. Horizontal and approximate vertical scales of profile are same scale as photograph. (Height estimated from shadow length.) Sun at left. (Latitude 49°N, longitude 225°; Viking photograph 009B15.)

(Figure 6) and móberg ridges (formed by subglacial fissure eruptions) presumably represent extrusions that did not reach the surface of the ice or meltwater [*Kjartansson,* 1960].

These Icelandic features are relatively small, generally a few kilometers across and a few hundred meters high; the highest, Herdubreid (Figure 5), has over 1000 m of total relief [*Van Bemmelen and Rutten,* 1955]. The contrast in morphology between strictly subaerial shields and table mountains in Iceland [*Jones,* 1969] is readily apparent on topographic maps of the two types of structures (Figure 8).

The tuyas of British Columbia also have been interpreted as products of subglacial Pleistocene eruptions [*Mathews,* 1948], as have similar volcanic rock successions in Antarctica [*Le Masurier,* 1972] and Alaska [*Hoare and Coonrad,* 1978]. Analyses of subglacial shield-type eruptions and resulting landforms are applicable to the submarine development of larger oceanic shield volcanoes [*Kjartansson,* 1966*a*, 1967; *Jones,* 1966; *Moore and Fiske,* 1969].

OCEANIC SHIELD VOLCANOES

Moore and Fiske [1969] documented a threefold structure analogous to that of the table mountains in the shield volcanoes on the island of Hawaii (Figure 9): (1) pillow lava and fragments erupted from deepwater vents, overlain by (2) vitric explosion debris, littoral cone ash and breccia erupted from shallow water vents or at the interface of subaerial lava and water, and (3) the subaerial shield that forms the superstructure of the volcano. As in the table mountains, the contact between the subaerial shield and the submarine pedestal is marked by a distinct break in slope (because of the susceptibility to mass wasting and erosion of the breccias and pillow lava), but the lower flank is not as steep as in the subglacial case. *Kjartansson* [1966*a*] inferred that the same stages and products of eruption characterized development of the Surtsey

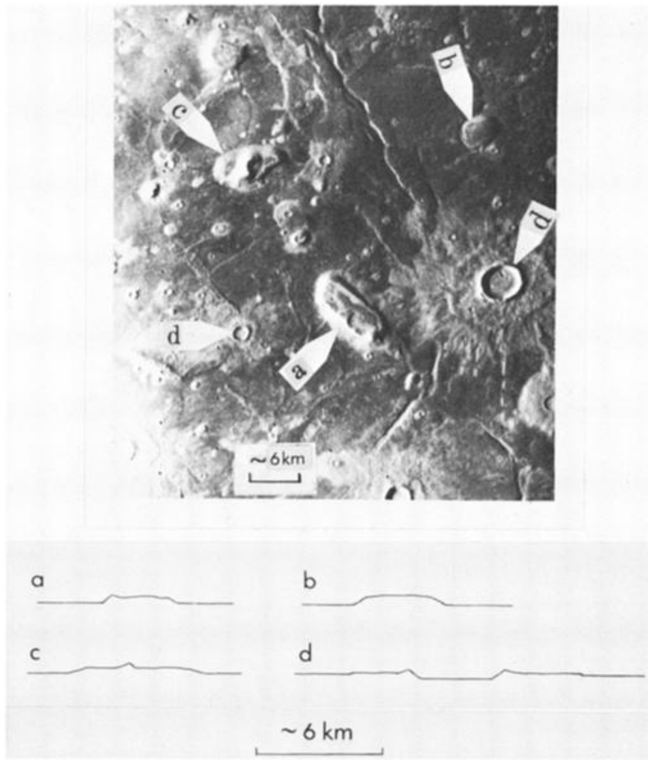


Fig. 2*a*. Rectangular to subcircular Martian mesas that resemble Icelandic table mountains with (arrow *a*) and without (arrow *b*) obvious summit craters. Two-story structure and typical impact craters indicated by arrows *c* and *d*. Diagrammatic profiles drawn at approximately twice the scale of photograph; no vertical exaggeration. (Heights estimated from shadow lengths.) Sun at left. (Latitude 45°N, longitude 20°; Viking photograph 026A30.)

Fig. 2*b*. Small, possibly volcanic, cratered domes (arrow). Diagrammatic profile drawn at scale larger than that of photograph; no vertical exaggeration. (Height estimated from shadow length.) Sun at left. (Latitude 40°N, longitude 15°; Viking photograph 035A62.)

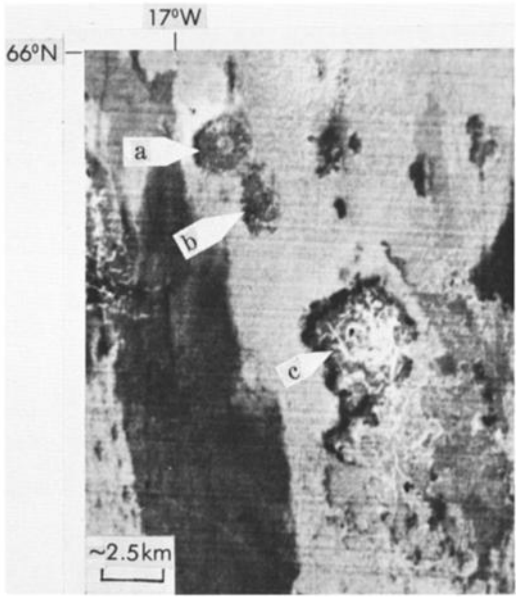


Fig. 3*a*. Landsat view of three table mountains in northern Iceland: (*a*) Baejarfjall; (*b*) Kviholafjöll; (*c*) Gaesafjöll. Gaesafjöll (*c*) has a cap of subaerial lava; the other two tablemountains apparently consist entirely of móberg. All three have summit craters. Compare *a* with probable Martian counterpart in Figure 1. North at top; sun at right. (Landsat image 2094-11403, band 7.)

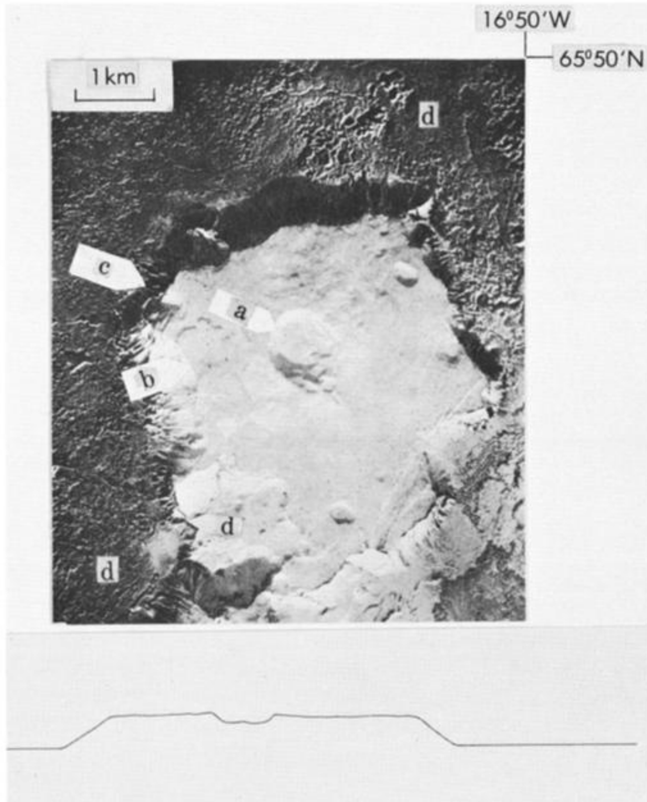


Fig. 4. Aerial photograph of Gaesafjöll with summit crater (arrow *a*) and cap of subaerial flows (*b*) that are superposed on móberg exposed on steep slopes (*c*). Postglacial flows indicated by *d*. North at top; sun at lower right. Profile at approximately same scale as photograph; no vertical exaggeration [*Van Bemmelen and Rutten,* 1955, Plate XIX].

Island shield, off the south coast of Iceland, but recent drilling showed no evidence of pillow lava. The subaqueous section at Surtsey consists entirely of tuffs, down to the preexisting sea floor at about 180 m (J. G. Moore, personal communication, 1979).

LANDFORMS ON THE NORTHERN PLAINS OF MARS

A preliminary survey of Viking photographs has yielded numerous examples of landforms that resemble rather strikingly the Icelandic table mountains and móberg hills, or possible variants thereof (Figure 10). These structures, like those in Iceland, are a few kilometers across and of the order of a few hundred meters high. (We must emphasize, however, that the heights mentioned here and shown in the illustration profiles were estimated on the basis of shadow lengths and are thus subject to revision; both sun angle and image-processing techniques affect such estimates.) The features are commonly associated with other landforms more convincingly interpreted as volcanic. For example, the isolated flat-topped mesas of Figure 11*a* are adjacent to two cratered cones that resemble terrestrial subaerial volcanoes (Figures 11*b* and 11*c*). In some plains areas (notably, western Elysium Planitia and southeastern Acidalium Planitia), domes and cones with summit craters are numerous; their morphology is different from that of typical impact craters of similar size that appear equally fresh (Figure 2*b*). The configuration of the plains surface in the Elysium area is irregular and pitted (Figure 12), much like the surfaces of terrestrial lava flows.

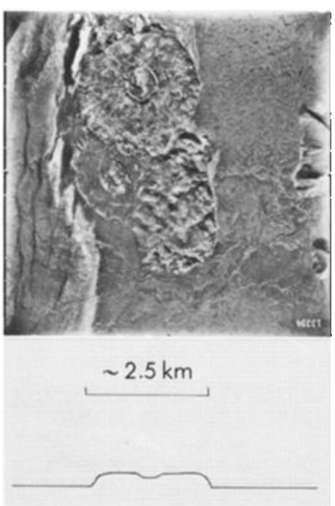


Fig. 3*b*. Vertical aerial photograph of table mountains *a* and *b* shown in Figure 3*a*, with third vent and móberg lobe visible southwest of juncture. North at top; sun at lower left. E-W profile across circular table mountain at approximately same scale as photograph; no vertical exaggeration. (U.S. Air Force photograph AF-55-AM-3, roll 121, frame 13394.)

The geomorphic evidence that volcanism occurred locally in the northern plains is persuasive; we propose that some of the unusual morphologies may have resulted from interaction of magma with ice in a process analogous to that of the subglacial eruptions that formed table mountains in Iceland. This explanation would require surface ice several hundred meters thick to have existed beyond the present north polar cap of Mars, a condition that could perhaps have occurred with relatively slight modifications in temperature or pressure and/or water content of the Martian atmosphere. A comprehensive analysis (in progress) of the spatial distribution of these kinds of features is necessary in order to determine the relation, if any, between their occurrence and latitude on the planet. Our preliminary results are consistent with those of *Allen* [1979].

Fig. 5*a*. Herdubreid, highest of the Icelandic table mountains with over 1000 m of relief, as viewed from the northeast. Snow-covered shield volcano is superposed on subaerial flows at top of steep cliff; intercalated palagonite tuff breccia and columnar basalt form the pedestal foundation. (Photograph by C. A. Wood.)

OLYMPUS MONS AND ASSOCIATED FEATURES

The enormous shield volcano Olympus Mons, 26 km high and 600 km across at its base, may also have had subglacial beginnings. The shield is at an elevation of 2–3 km on the northwest flank of the 'Tharsis bulge,' a northeast trending topographic ridge 10 km above Mars datum [*U.S. Geological Survey*, 1976]. The bulge is surmounted by a chain of three shield volcanoes, each of which is somewhat smaller than Olympus Mons, but like the larger shield, all attain elevations of 26 km. Olympus Mons is distinctive not only for its size but also for the prominent escarpment, up to 6 km high [*Blasius*, 1976], that rings its base. In addition, it is nearly surrounded by peculiar grooved terrain informally termed aureole deposits [*Carr*, 1973], which appear to consist of a sequential series of superposed arcuate lobes, differing in degree of degradation and burial. The distal margin of one of the oldest lobes is about 600–800 km north and west of Olympus Mons; younger lobes are closer to the shield (Figures 13*a* and 13*b*). A gravity anomaly requiring excess mass at depth has been resolved over the northwest lobe of the aureole by line-of-sight tracking of a Viking orbiter [*Phillips and Bills*, 1979; *Sjogren*, 1979]. Smooth plains materials [*Scott and Carr*, 1978] embay and partly bury these deposits in an annular belt at the base of the shield. The exposed area of the aureoles, with some allowance for overlap, is about 1.3×10^6 km^2.

The prominent escarpment encircling the base of Olympus Mons is perhaps its most perplexing feature, for there is no apparent counterpart around subaerial terrestrial volcanoes. The scarp does, however, suggest analogy with the subglacial

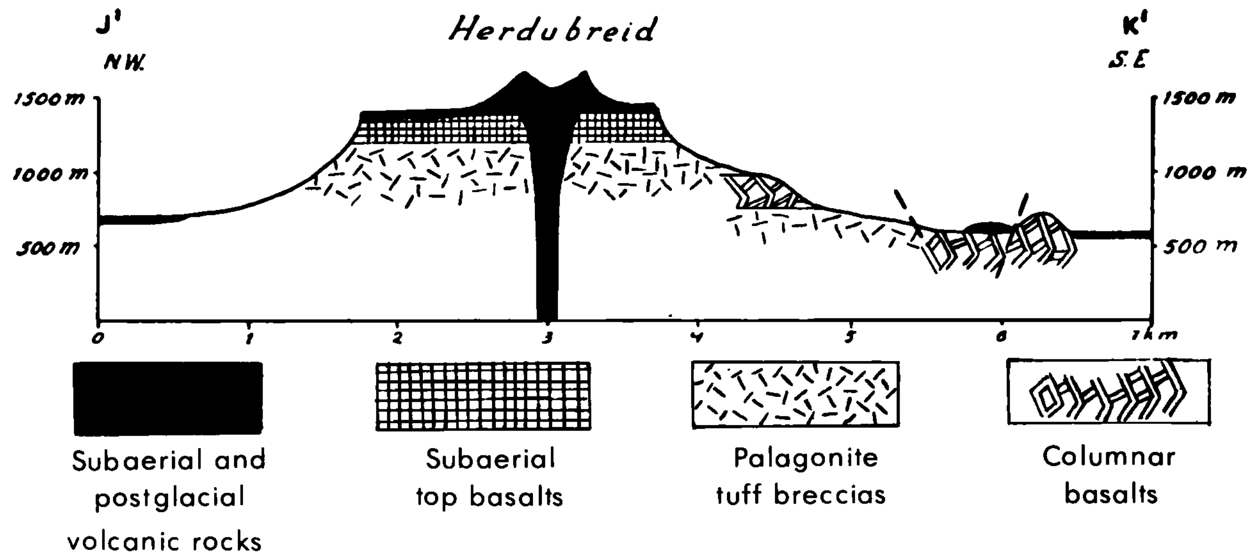


Fig. 5*b*. Diagrammatic cross section through Herdubreid (Figure 5*a*); intercalated columnar basalts and palagonite tuff breccias form the base, overlain by subaerial top basalts and surmounted by shield volcano [*Van Bemmelen and Rutten*, 1955].

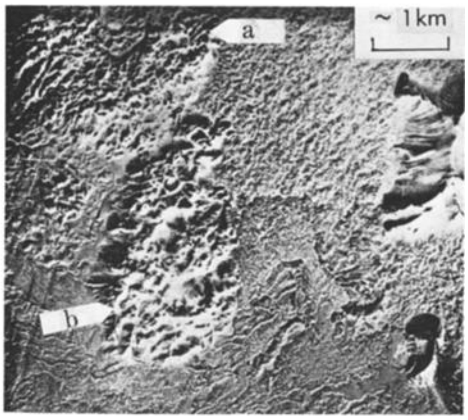


Fig. 6. Aerial photograph of Baejarfjall (arrow *a*) and Kviholafjöll (*b*) (also shown in Figure 3), which are composed almost entirely of móberg. These two table mountains either formed subglacially without subaerial venting and thus were not capped by subaerial flows or were eroded after emplacement so that basaltic cap rocks were removed. Both have summit depressions. Low sun angle enchances topographic irregularities; compare with Figure 3*b*. North at top; sun at lower right [*Van Bemmelen and Rutten,* 1955, Plate XXV].

table mountain pedestals and with the subaqueous flanks of oceanic shields. Such an analogy implies that (1) ice existed in the Olympus Mons vicinity when eruptions began, (2) the vent or vents eventually surfaced above the ice, and (3) the enormous subaerial shield was emplaced atop the subglacially confined platform. Lava flows cascading over the scarp indicate that Olympus Mons continued to grow long after the postulated ice receded; such flows are evidence that the scarp existed during late growth of the shield and is not simply a postvolcanic erosional product. Similar relations occur in Iceland.

The grooved, eroded appearance of the aureole lobes and their specific association with Olympus Mons lead us to suggest further that these deposits also may be products of volcanic eruptions beneath or into an ice cap, but like the móberg ridges in Iceland these extrusions failed to surface above the ice or meltwater lakes. The age of the lobes is uncertain because of the difficulty in recognizing craters within this rugged terrain. In a preliminary effort, however, we classified depressions and circular features (>2.5 km across) as definite craters, probable craters, and possible craters, and our analyses showed that the aureoles appear to have preceded development of Olympus Mons; additionally, they are probably as old as or older than the Chryse area [*Dial,* 1978] and cratered plains [*Scott and Carr,* 1978].

The aureole materials bear some resemblance to the Icelandic móberg hills that are not capped by lava, one of which is portrayed in the low-sun photograph of Figure 6. The móberg deposits of Iceland are highly susceptible to erosion by wind and subsurface water and commonly exhibit irregular grotesque shapes and closed depressions without surficial drainage [*Kjartansson,* 1960, *Preusser,* 1976]. Several ragged mesas that appear to be remnants, or outliers, of the aureole deposits are perhaps the best Martian analogs for table mountains; they are about 250 m high (as inferred from shadow length measurements), with craterlike depressions, and occur 200–300 km south of the base of Olympus Mons (Figure 14).

If the aureole lobes represent sequential volcanic deposits, the eruption centers appear to have migrated within a relatively confined area before eventually being sustained at the

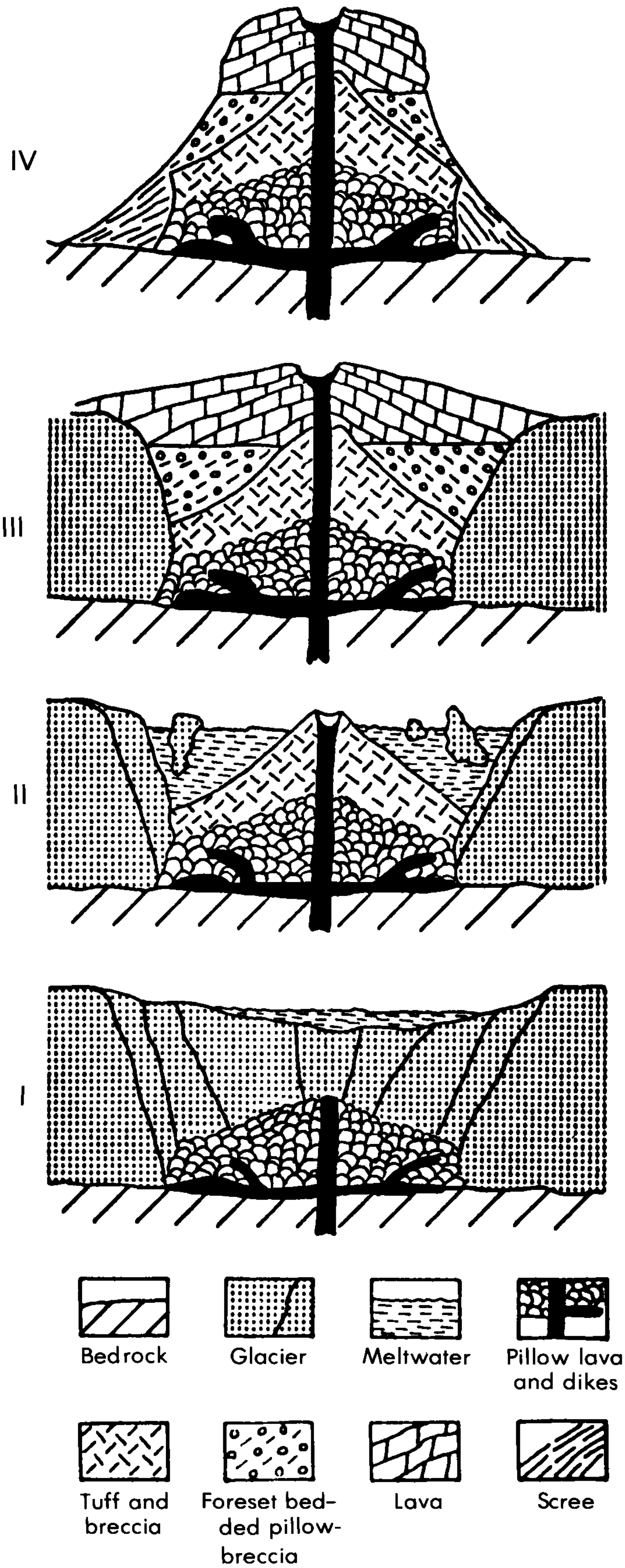


Fig. 7. Development of an Icelandic table mountain from subglacial birth (I, bottom) to subaerial erosion (IV, top). (Modified after *Einarsson* [1968].)

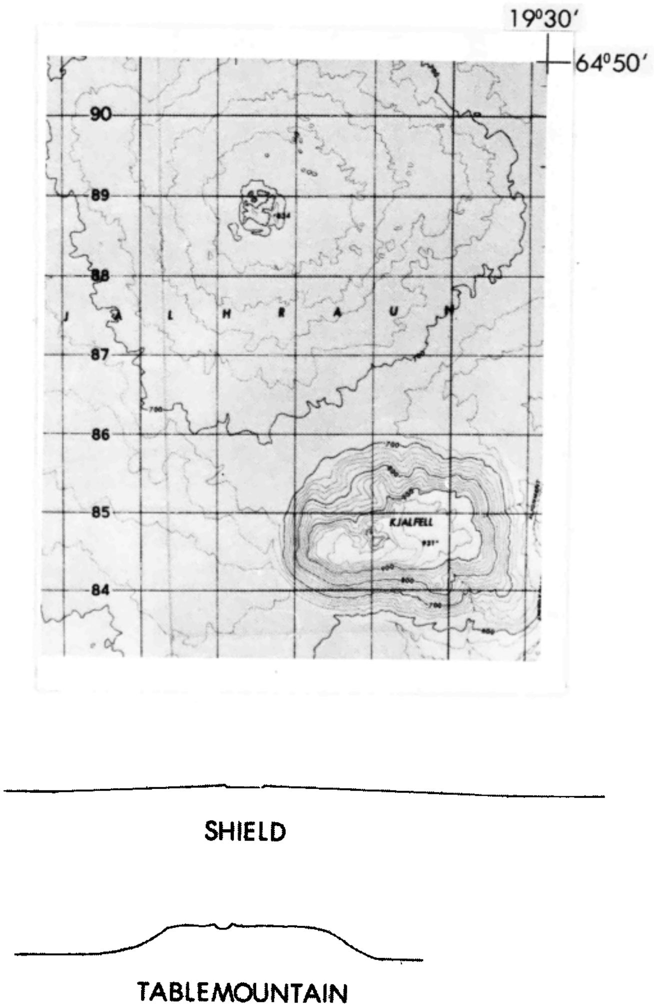


Fig. 8. Contrasting topography of subglacially erupted shield volcano that formed table mountain (bottom) and subaerial shield (top) in Iceland; grid is 1 km, contour interval is 20 m, north at top. Profiles at approximately same scale as map; no vertical exaggeration. (From AMS Series C762, sheet 5721 III, Hrutafell, Iceland, 1:50,000, May 1951.)

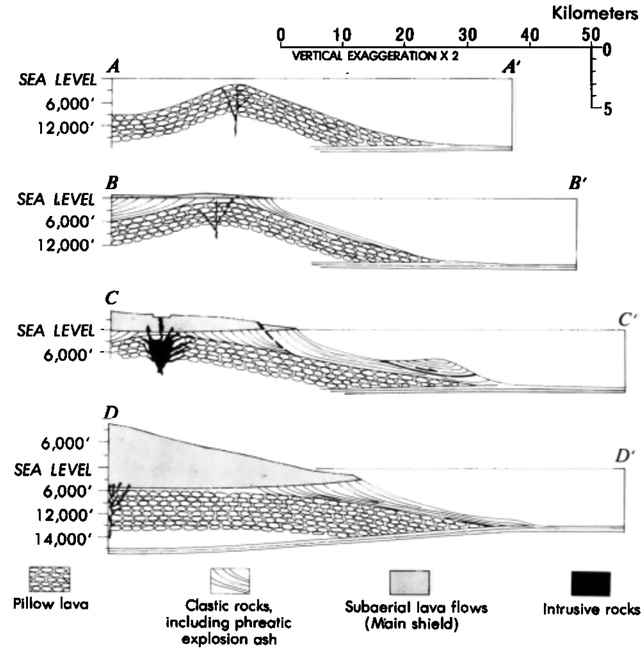


Fig. 9. Geologic sections through Kilauea and Mauna Kea volcanoes, Hawaii, showing sequential stages of development from initial emplacement of pillow lavas (A-A') through construction of subaerial shield (D-D') [*Moore and Fiske,* 1969].

site of Olympus Mons. According to this model the peculiar aureole terrain represents erosional remnants of thick (of the order of a kilometer in places) móberg, which was not capped by subaerial lava. The cratered mesas of Figure 14 appear to be vestiges of the initial móberg surface, vulnerable to erosion by wind and meltwater because of the poorly consolidated, brecciated, and tuffaceous nature of the deposits. In addition to explaining the peculiar dissected fabric of these deposits, which are apparently unique on Mars, this hypothesis also is compatible with the gravity data [*Phillips and Bills,* 1979]; the aureoles represent volcanic centers and, as is characteristic of the table mountains, there should be numerous dikes and sills at depth.

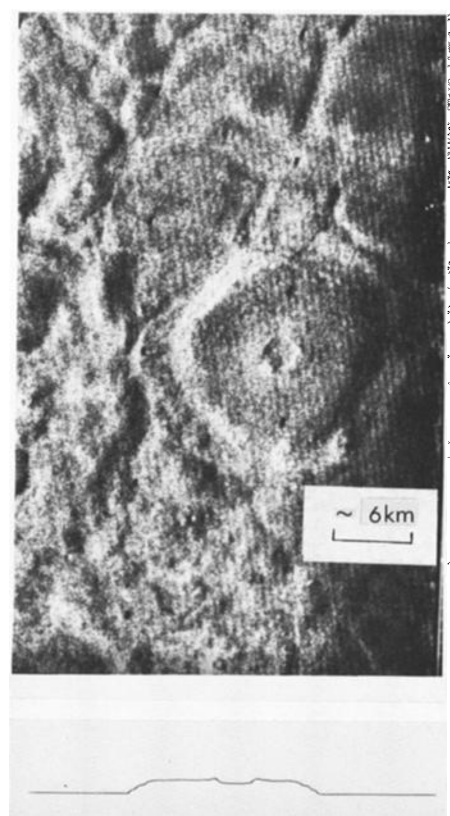
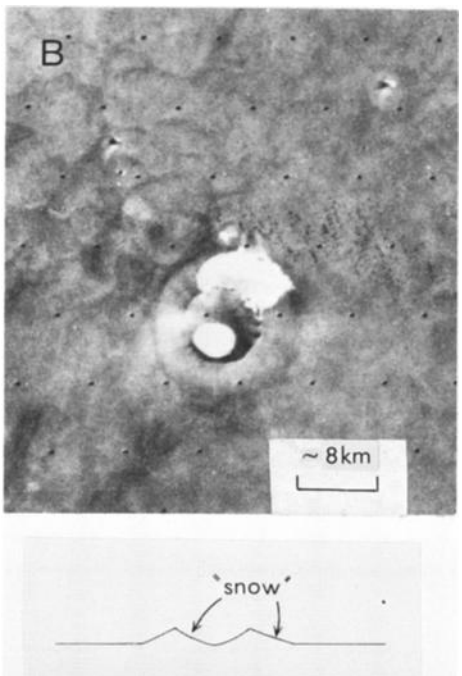


Fig. 10. Martian cratered mesa amid irregular, hummocky patterned ground; narrow terrace occurs near base of flanks. Ratio of crater diameter to mesa diameter is small in comparison to ratios of crater diameter and surrounding ejecta diameters of impact craters (see Figure 2*d*). Diagrammatic profile drawn approximately at scale of photograph, no vertical exaggeration. (Height estimated from shadow length.) Sun at left. (Latitude 47°N, longitude 230°; Viking photograph 009B10.)

Alternative Models for Origin of the Aureoles and Basal Scarp

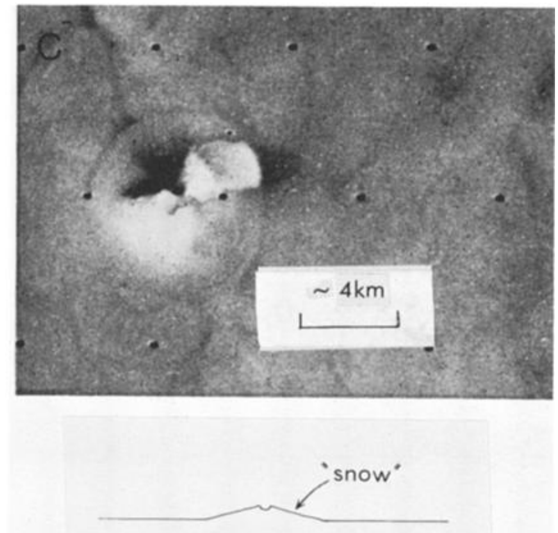
Alternative explanations thus far suggested for either the basal scarp or the aureole deposits of Olympus Mons pose various difficulties. Several hypotheses involve pyroclastic flows, landslides, gravity sliding, gravity thrust faults, debris flows, or lava flows originating from the vicinity of Olympus Mons; some of these address the scarp problem but do not ac-

A



B

Fig. 11. Martian mesas (*a*) that resemble Icelandic table mountains with subaerial lava caps; these features are closely associated with (*b*) a cratered cone and (*c*) a cratered peak that strongly resemble terrestrial volcanic cones. Unlike impact craters, length of slope from center to rim of cratered cone (Figure 11*b*) is equal to the length of slope from rim to edge of flank, and crater flanks appear smooth. If cratered features of Figures 11*b* and 11*c* are volcanic, then mesas (Figure 11*a*) also may be volcanic, possibly originating as subglacial eruptions subsequently capped by subaerial flows. White patches on flanks of all three landforms may be 'snow' localized on north facing slopes. North is approximately at top in all photographs. Diagrammatic profiles not to scale (no shadows from which to estimate heights). (*a*) Latitude 77°N, longitude 68°, sun at lower right, Viking photograph 070B27. (*b*) Latitude 78°N, longitude 66°, sun at bottom, Viking photograph 070B29. (*c*) Latitude 79°N, longitude 75°, sun at lower right, Viking photograph 070B09.



C

Fig. 11. (continued)

count for the gravity anomaly. Those involving preexisting volcanoes or domical plutons account for the gravity but are improbable in other respects and have no relation to the scarp. None adequately accounts for both the scarp and the gravity results.

Fig. 12. Complex terrain west of Viking 2 landing site tnat appears to be at least partly volcanic. Dark irregular patch (*a*) is probably a lava flow, and the irregular surrounding surface (*b*) resembles that of many terrestrial flows (see Figure 4, unit *d*). Cratered mesa (*c*) may be a table mountain. Diagrammatic profile drawn approximately at scale of photograph. (Height estimated from shadow length.) (Latitude 44°N, longitude 238°; Viking photograph 009B22.)

Fig. 13*a*. Olympus Mons and surrounding lobate aureole deposits. Lobes appear to have been emplaced sequentially (as numbered in figure 13*b*), and the deposit at the farthest periphery on the northwest (*a*) appears to be among the oldest. Aureole *b* apparently is superposed on aureoles at *a* and *c*. Only arcuate remnants are exposed on the south and east. Cratered plateaus of Figure 14 are at *d*. Base of Olympus Mons at the scarp is about 600 km across. North-south profile along longitude 133.25°W is approximately to scale as shown (larger than that of photograph mosaic); no vertical exaggeration. Composite of Mariner 9 photographs.

Fig. 13*b*. Outlines of Olympus Mons shield and surrounding aureole lobes, indicating a possible nine separate eruptive centers. Numbered from presumed oldest (1) to youngest. Outline of Olympus Mons is about 600 km across.

King and Riehle [1974] proposed that the scarp resulted from extensive wind erosion and slumping of a pyroclastic ash flow or ignimbrite foundation beneath the shield. The foundations of terrestrial shield volcanoes, however, are not known to include substantial pyroclastic phases except during late submarine growth; subaerial pyroclastic activity usually occurs as essentially the last gasp in shield development, as exemplified at Mauna Kea and Haleakala in Hawaii. Extensive ash flows are commonly associated with more silicic stratovolcanoes, not basaltic shields. Also the dependence on wind to erode through lava flows at the base of a shield that initially sloped gradually to the surrounding plains appears to require an intense 'sandblasting' symmetrically on all sides of the shield in order to remove the resistant basalt and expose the ash flows; such a process must have occurred within a relatively restricted time before later lava flows cascaded over the scarp. *King and Riehle* [1974] do not address the origin of the aureoles, but E. C. Morris (oral communication, 1979) has proposed that these deposits also are a series of ash flows.

Carr [1975] suggested that great masses of the volcano could have been dislodged and emplaced as landslide deposits hundreds of kilometers away; but had the shield originally continued its gentle slope outward, merging with the surrounding plain, there is no obvious reason for the accumulated flows to have become uniformly unstable at the low, outermost margin of the flanks. Terrestrial landslides occur on preexisting scarps or steep slopes. Furthermore, present topography would have required uphill sliding on the southeast [*U.S. Geological Survey,* 1976].

An alternative, somewhat similar origin for the aureoles, suggested by J. G. Moore (oral communication, 1978), involves subaqueous debris flows. If the vent were surrounded by a body of meltwater, then subaerial flows from the shield would tend to decrepitate upon entering the water, and, augmented by the aqueous medium, substantial flow breccias could perhaps have moved over the great distances required, more or less as density currents. The resulting deposits might be similar to móberg without the pillow lava. A recent investi-

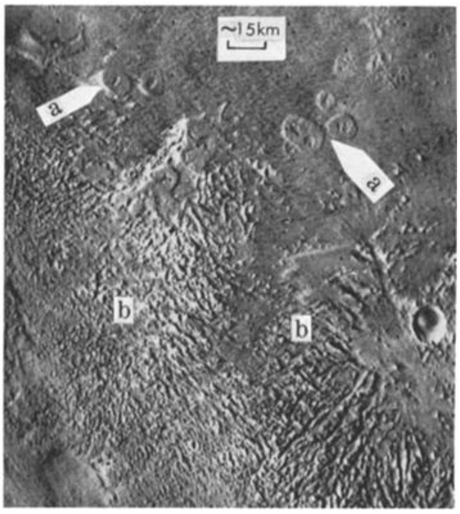


Fig. 14. Table mountains (*a*) southwest of Olympus Mons (Figure 13*a*), probably remnant outliers of ridged-and-grooved aureole terrain (*b*), here interpreted as móberg deposits (palagonitized tuffs and breccias) and pillow lavas. Texture of aureole terrain (*b*) resembles that of móberg hills in Figure 6 (features *a* and *b*). Profile drawn at scale larger than that of photograph; no vertical exaggeration. (Height estimated from shadow length.) (Latitude 10°N, longitude 142°; Viking photograph 044B13.)

gation (J. G. Moore, personal communication, 1978) of a landslide off the island of Hawaii, however, revealed that in a subaqueous environment the coefficient of friction as inferred from the ratio of length of runout to height of fall [*Howard,* 1973] is about 17, essentially equivalent to that of comparable subaerial slides, whereas similar computation for the aureoles suggests that ratios as large as 117 would be required.

All landslide hypotheses present some difficulty in explaining the location of the most extensive volume of aureole deposits on the northwest side, where the volcano's flank is broadest. The scarp appears to be a nearly constant height around the entire shield, irrespective of variations in apparent volume and location of aureole lobes. None of the above slide or debris flow models accounts for the gravity anomaly requiring excess mass beneath the aureole lobes northwest of Olympus Mons.

Steep fault scarps of limited extent occur on the subaerial flanks of Hawaiian volcanoes, exemplified by the Hilina Pali, more than 300 m high, on the southeast flank of Kilauea. Analogy with the continuous scarp at the base of Olympus Mons, however, seems inappropriate because the Hawaiian scarps form in the subaerial shield and possibly are dependent on the existence of the incompetent material in the submarine base of the shield as well as on the break in slope at sea level. Further, the continuity of the Martian scarp is not duplicated by the fault scarps in Hawaii, which have a discontinuous scalloped pattern (J. G. Moore, oral communication, 1978). Similar kinds of slump scars can be identified inboard from the main scarp at Olympus Mons (Figure 13*b*), but it is postulated here that their formation was dependent on the preexisting and unrelated basal scarp.

Gravity sliding on a subsurface plane has also been suggested as an explanation for the scarp and aureole (M. H. Carr, oral communication, 1978). In this model the plane of lubrication is the interface between permafrost and a presumed underlying zone with liquid pore water. Although this model has not been examined in detail, it evidently would impose instability on the crust by loading at the volcanic pile and consequent lifting and sliding of the outermost flanks of the volcano.

Harris [1977] proposed that the aureoles were a series of gravity thrust faults in the plains materials caused by emplacement of and crustal loading by the huge volcanic shield. Thrusting of surrounding ground may indeed have occurred; in fact, the offset in the outer margin of the northwest segment of lobe *b* (Figure 13*a*) resembles rather strikingly the map pattern of the Appalachian Pine Mountain overthrust [*Thornberry,* 1965]. However, the distinctive outlines of the lobes that define discrete bodies of material and can be traced nearly to the volcano's base (Figure 13*b*), the elevated but virtually accordant surface of the deposits, and, particularly, the development of the shield's basal scarp seem inadequately explained by this means. Neither of the gravity-induced mechanisms described above would account for the gravity anomaly.

If the deposits were the eroded base of a larger Olympus Mons or of similar but separate shields [*Carr,* 1973], the erosional agent or process required to remove successively several structures on the scale of Olympus Mons, with destruction of each before the next is built, is difficult to envision. A similar problem is raised by the hypothesis of *Head et al.* [1976], who attributed the scarp to erosion by unknown agent or process of the prevolcano cratered terrain in virtually the entire northern hemisphere of Mars. The absence of scarps around other older shields is not explained, however, nor is the origin of the aureoles addressed. It would appear that Olympus Mons is considerably younger than development of the hemisphere dichotomy on Mars, inasmuch as the plains at the base of Olympus Mons, now surfaced by young lava flows partly from the shield, are topographically continuous with the older mottled plains to the north [*Scott and Carr,* 1978]. The age of the older plains constrains the time of the northern hemisphere plains development. The lava flows cascading over the basal scarp of the volcano indicate that the scarp existed well before volcanism ceased. Erosion of domical plutons (K. R. Blasius, unpublished manuscript, 1974), although consistent with the gravity data [*Phillips and Bills,* 1979; *Sjogren,* 1979], does not explain apparent age differences and superposition of the aureole lobes because an extensive erosion period would plane such coalescing plutons to a relatively continuous surface, irrespective of ages of intrusion. If the aureoles are simply the deeply eroded remnants of old subaerial lava flows [*McCauley et al.,* 1972; *Morris and Dwornik,* 1978], such lavas must have been entirely different physically and/or chemically from the long, narrow flows that now cover the surrounding plain; these were clearly derived from the shield volcanoes and resemble morphologically typical terrestrial basalt flows from central vents [*Greeley,* 1973; *Carr et al.,* 1977].

The volcanic explanation for the aureoles that at present seems to us most compatible with their configuration and distribution as well as with the gravity data is subglacial eruption. The pillow lavas and tuffaceous breccias thus accumulated would be analogous in origin, though clearly not in scale, to those Icelandic table mountains on which subaerial basalts either were removed by erosion or were not emplaced. The cratered mesas of Figure 14, and the massive aureole lobes as well, probably are not subaerial lavas, nor were they likely capped by such lava, but they may represent instead thick subglacially developed móberg that has been modified by erosion. A complex network of intrusions and dikes would thus be present beneath the aureoles to produce the excess mass at depth required by the gravity data. The gravity high northwest of Olympus Mons is currently interpreted by *Phillips and Bills* [1979] as evidence for magmatic source rocks beneath the aureoles, and this analysis is consistent with the model proposed here.

An obvious difficulty with this explanation for the aureoles is the mechanism that permitted such extensive eruptions beneath ice and meltwater with little or no subaerial venting. Subaqueous pillow lavas generally tend to pile up because of rapid chilling [*Sigvaldason,* 1968]. As in subaerial flows on earth, however, a high rate of effusion [*Shaw and Swanson,* 1969; *Walker,* 1973] apparently permits extensive spreading of submarine extrusions as sheet flows [*Holcomb,* 1978; *Ballard et al.,* 1979]. The total volume of aureole material may be of the order of 1–4 × 10^6 km^3, and some individual lobes probably contain as much as 5 × 10^5 km^3. An ice sheet 1–2 km thick might not have been breached if such volumes were erupted from different vents at different times and at very rapid rates. *Walker and Blake* [1966] described a móberg ridge in Iceland that formed as lava flowed 22–35 km beneath a valley glacier at the relatively low gradient of about 0.018, and they speculated that an enormous 'jökulhlaup' (catastrophic flood), caused by the eruption, must have formed a subglacial conduit down which the lava subsequently flowed. Subaerial Martian lavas have flowed on gradients as low as 0.002 [*Moore et al.,* 1978], so that subglacial flows on similar gradients are possible. Olympus Mons is on the flank of the Tharsis bulge, and a low westward gradient of about 0.002 likely existed when eruptions began; subglacial confinement and the low gradient unrestricted by valley walls may have induced broad lateral spreading or ponding from each of the 8–10 postulated subglacial vents (Figure 13*b*).

Alternatively, if the magma reservoirs were initially shallow within the crust and became progressively deeper as the crust thickened, then low pressure heads may have existed during the initial aureole eruptions, permitting little vertical growth. As the planet cooled and magma reservoirs deepened, sufficient pressure head must have been attained to permit the vertical growth of Olympus Mons [*Carr,* 1976*a*, *b*] and the three large shields near the crest of the Tharsis ridge, each of which also reaches 26 km in elevation.

As magma contacted ice, vast meltwater lakes probably formed, although surfaces could have remained frozen. The existence of liquid water at the surface would of course require atmospheric conditions different from those of the present, a difficulty encountered as well in attempts to explain Martin channel configurations.

The Role of Ice

If the Icelandic analogy is to be drawn, the former presence of more extensive surface ice on Mars must be established. The pervasive evidence for a substantial thickness of ground ice has been described elsewhere [*Carr and Schaber,* 1977; *Masursky et al.,* 1977; *Soderblom and Wenner,* 1978]. A largely water-ice composition of the north polar cap appears conclusive, and its present thickness has been estimated at as much as 1 or 2 km [*Farmer et al.,* 1976; *Kieffer et al.,* 1976]. Water in Viking samples measured about 0.3–2% [*Biemann et al.,* 1977]. Geochemical and spectral data from the Martian surface further indicate that magma may have interacted with H_2O to form sideromelane, the precursor of palagonite. *Soderblom and Wenner* [1978] observed that the 0.3- to 2.5-μm spectrum of antarctic palagonite samples is the closest approximation to the disc-wide spectrum of Mars. Palagonite is also a reasonable petrologic interpretation of samples analyzed by both Viking landers; major constituents of the Martian fines, as of the Icelandic palagonites, are iron-rich clays. *Toulmin et al.* [1977] postulated that explosive interaction of iron-rich basaltic magma and subterranean ice could readily account for the large quantities of clay-rich material apparently present at the Martian surface.

The interaction of magma with water and ground ice or permafrost appears inescapable if the climatic regime of Mars during volcanic epochs was similar to its current state. Landforms similar in size and morphology to the Icelandic table mountains, however, suggest that large expanses of surface ice may have existed over some parts of the planet during various times in the past. On the basis of shadow lengths the heights of the pedestals described here are generally of the order of a few hundred meters, and therfore the requisite thickness of ice, at least in the northern latitudes, could probably have existed in the past with relatively slight modifications in atmospheric temperature of pressure and/or an increase in the amount of water.

A more demanding challenge to current models of volatile budget and planetary history, however, is engendered by our interpretation of Olympus Mons and adjacent features, which calls for extensive ice in the Tharsis region of Mars. Assuming that the top of the talus on the Olympus Mons scarp is approximately at the base of the subaerial flows, the thickness of ice required to form the móberg foundation would be perhaps 3–4 km.

The móberg pedestal on which Olympus Mons rests, according to this hypothesis, would, like the scarps of terrestrial table mountains, readily retreat by mass wasting and wind erosion, but the initial relief of the scarp could be explained as a primary feature, an inherent consequence of the volcano's subglacial beginnings. Furthermore, like the Pacific guyots and shields [*Moore and Fiske,* 1969], the huge Olympus Mons edifice probably subsided somewhat, causing the annular depression around its base. Subsequent deposition of lava, eolian debris, and mass-wasted materials in this circumferential depression obscured aureole deposits that probably existed at the base of the scarp, as suggested by the outcrop pattern. If the broad aureoles do consist of móberglike materials, they would supply an extensive source for the palagonitic debris that appears to be widely distributed over the planet.

Ice Volume and the Volatile Budget

The morphology of the Olympus Mons complex seems rather well explained by the table mountain analogy, but accounting for an ice accumulation of perhaps 7–10 × 10^6 km^3 poses some difficulty. Some current estimates of the volatile budget, based on argon isotope ratios, permit a maximum amount of water-outgassed equivalent to a planet-wide thickness of only about 9.5 m [*Anders and Owen,* 1977]. However, the amount of H_2O intrinsic to Mars is a matter of some dispute, and it appears that the total volatile inventory of the planet is not yet well defined. *Bogard and Gibson* [1978] enumerated the difficulties of using noble gas ratios and comparisons with chondrites and stated that present data are inadequate for determining the relative abundances of volatile elements originally supplied to Mars. *Lewis* [1974] proposed that Mars had an initial water content 6 times (per unit mass) that of earth, based on an equilibrium condensation model of solar system formation. *McElroy et al.* [1977], using a nitrogen isotope analysis, suggested that H_2O could have been abundant enough to form a planet-wide surface ice layer 200 m thick. If this last amount were concentrated in a 30° spherical cap of ice centered on Olympus Mons, a 6-km-thick ice sheet could result. Assuming adequate amounts of water, the temperature of the planetary surface would dictate that ice be the dominant phase, unless atmospheric pressure increased, as may have occurred during times of extensive volcanism.

The ice coverage called for here is probably best derived as a localized cap. The possibility that the rotational axis may have wandered during the course of the planet's history has been proposed by *Murray and Malin* [1973] and by *Ward et al.* [1979], who cite as evidence the position of the Tharsis bulge with its excess mass essentially at the equator. They consider it more probable that the bulge and volcanic shields grew elsewhere (i.e., when the rotational axis was differently located) and caused a shift of the poles, such that the excess mass would be repositioned nearer the equator. This postulate is further supported by the large basin (~800 km across) and resulting mass deficiency near the present south pole. Conceivably, the hypothesized glacial stage occurred if and when the Tharsis region was nearer the pole before adjustment of the planet to the excess mass.

An alternative and perhaps more appealing cause of a localized ice cap is the relief of the Tharsis bulge itself, regardless of its latitudinal position. Under favorable atmospheric conditions, ice may have accumulated at high altitude and been sustained below 10 km, even at equatorial latitudes. Thus both ice and volcanism would have followed the deformation that produced the bulge and, presumably, the extensive fracturing of the old cratered plains. Stratigraphic difficulties (M. H. Carr, oral communication, 1978) that arise with the polar wander hypothesis are thereby eliminated.

The means by which such ice could be preferentially concentrated as a result of altitude changes depends on atmospheric conditions in addition to water concentration. The present atmosphere decreases in temperature with altitude from about 240°K at the surface to about 100°K at 200 km, with about a 50° decrease in the first 20 km. Higher temperatures must have occurred at the surface when and if fluvial action occurred to form or modify channels. According to *Masursky et al.* [1977] fluvial channel ages vary from 3.5 to 0.5 b.y. During periods when liquid water existed at low altitude, ice may have accumulated contemporaneously at higher altitudes on the flanks of the Tharsis ridge.

An ice cap could have been sustained throughout intermittent volcanism, as is the case in Iceland today. *Williams* [1978] has suggested that the blocky, conspicuously ridged terrain at the northwest base of Arsia Mons is best explained as a sequence of recessional moraines from a glacier that developed on the volcano or existed prior to eruption and was maintained as the volcano grew. Similar deposits occur in an apronlike lobe at the northwest base of Pavonis Mons. However, there are no such deposits around Ascraeus Mons, youngest of the large Tharsis shields [*Carr,* 1976*a*; *Wood,* 1976], so that the 'Ice Age' may have vanished by the time the Ascraeus Mons eruptions began. Although the present surface of the Olympus Mons shield appears to be younger than Ascraeus Mons [*Wise et al.,* 1979], eruptions could have begun at the larger volcano during an earlier glacial stage. If a thick ice cap existed on the Tharsis bulge, it probably was in a dynamic state, with ice accumulating rapidly at highest elevations as the mass flowed outward and downward into regions of thaw at lower elevations. The maximum thickness of the ice cap on Greenland is currently 3.4 km [*Flint,* 1971]; even thicker sheets may have existed on earth during the Pleistocene.

A possible alternative to the extensive coverage by glacial ice is the interaction of magma with more readily explicable ground ice. If such interaction occurred, tuffaceous flows and breccias may have erupted until the conduit was insulated from further entry by meltwater. But under approximately these conditions on earth, small maars and tuff cones are the predictable landforms. On the Seward Peninsula (Alaska), angular blocks of loess are incorporated in the ejecta around several maars, indicating (along with other evidence) that the sediments were frozen at time of eruption (D. M. Hopkins, oral communication, 1979). Only the subglacial and submarine eruption style appears to produce morphologies comparable to those of the table mountains and the Olympus Mons shield and associated features on Mars.

SUMMARY

The morphologies of small Martian buttes and mesas, especially concentrated in latitudes north of 40°, are similar to those of Icelandic table mountains that are presumed to have formed by subglacial eruption. The geologic and climatic regimes of Mars may be or have been analogous to the environment of Iceland, where volcanism and glaciation have interacted throughout much of recent geologic history. In the northern latitudes of Mars the candidate table mountain structures are associated with landforms and terrains that appear more obviously volcanic, and thus it seems a reasonable postulate that a relatively slight modification in position or extent of the polar cap could have allowed volcanic extrusion into or through ice.

More problematical is the localization of a sufficient thickness of ice in the Tharsis region to account for our interpretation of Olympus Mons and its surrounding aureoles by initially subglacial eruptions. The basal scarp around the enormous shield is readily explained if the shield were built atop a pedestal of pillow lava and palagonitized tuff breccias, or móberg. The position, apparent sequence, and grooved, serrate textures of the aureole lobes are compatible with their interpretation as separate subglacial eruptives that did not reach the surface and remained as expanses of móberg uncapped by subaerial lava flows. Massive palagonite would thus have been subjected to wind erosion and transport, partly accounting for the widespread distribution of such material implied by spectral and Viking geochemical data. Initial localization of the ice could perhaps be attributed to the 10-km elevation of the Tharsis bulge.

The total water budget may indeed be an obstacle to this hypothesis, but there appears to be at present a broad range of volume estimates, dependent on analytical technique, and little knowledge of the possible variations of near-surface volatile concentrations throughout Martian history. Photogeologic interpretations presented here suggest the former existence of more extensive glacial ice than is currently measured or inferred; the feasibility of such an ice age depends ultimately on development of a compatible and defensible model for atmospheric evolution, and further geologic investigations of Mars may require such a model.

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