The Subglacial Birth of Olympus Mons and Its Aureoles

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The vast volcanic plains and shields of Mars, together with the thermal, spectrographic, and morphologic 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 (möberg), 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 möberg. Conical knobs on steep-sided Martian plateaus are reminiscent of the small Icelandic shield volcanoes atop möberg 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 2a). 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 2b).

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, 1978a, b; Williams, 1978]. The table mountains of Iceland (Figures 3a and 3b), 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, 1966a, 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 Ruten [1955], Jones [1966, 1969, 1970], Kjartansson [1960, 1966a, 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 5a and 5b). 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 'möberg,' the Icelandic term for palagonitized tuffs and breccias [Kjartansson, 1960]. The möberg 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 möberg 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 möberg foundation. The thickness of the ice sheet, indicated by the height of the möberg pedestals, was apparently 500–1000 m during the Pleistocene stage of table mountain development. Cratered hills or mesas of möberg that are not capped by lava
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 möberg 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 Comnrad, 1978]. Analyses of subglacial shield-type eruptions and resulting landforms are applicable to the submarine development of larger oceanic shield volcanoes [Kjartansson, 1966a, 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 [1966a] inferred that the same stages and products of eruption characterized development of the Surtsey...
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 möberg 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 11a are adjacent to two cratered cones that resemble terrestrial subaerial volcanoes (Figures 11b and 11c). In some plains areas (notably, western Elysium Planitia and southeastern Acidalia 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 2b). The configuration of the plains surface in the Elysium area is irregular and pitted (Figure 12), much like the surfaces of terrestrial lava flows.

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. 5a. 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 13a and 13b). 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 \times 10^6 \text{ 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...
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 in-
dicate 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 Ice-
land.

The grooved, eroded appearance of the aureole lobes and
their specific association with Olympus Mons lead us to sug-
gest further that these deposits also may be products of vol-
canic eruptions beneath or into an ice cap, but like the mó-
berg 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 rug-
ged terrain. In a preliminary effort, however, we classified de-
pressions and circular features (>2.5 km across) as definite
craters, probable craters, and possible craters, and our analy-
ses showed that the aureoles appear to have preceded devel-
opment 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 Icelan-
dic móbegr hills that are not capped by lava, one of which is
portrayed in the low-sun photograph of Figure 6. The móbegr
deposits of Iceland are highly susceptible to erosion by wind
and subsurface water and commonly exhibit irregular gro-
esque shapes and closed depressions without surficial drain-
age [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 rela-
tively confined area before eventually being sustained at the

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**Fig. 6.** Aerial photograph of Baejarfjall (arrow a) and Kviholaf-
jöll (b) (also shown in Figure 3), which are composed almost entirely
of móbegr. 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 en-
chances topographic irregularities; compare with Figure 3b. North at
top; sun at lower right [Van Bemmelen and Rutten, 1955, Plate XXV].

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

TABLEMOUNTAIN

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.)

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) möberg, which was not capped by subaerial lava. The cratered mesas of Figure 14 appear to be vestiges of the initial möberg 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.

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-
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. 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 11b) is equal to the length of slope from rim to edge of flank, and crater flanks appear smooth. If cratered features of Figures 11b and 11c are volcanic, then mesas (Figure 11a) 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.

Fig. 12. Complex terrain west of Viking 2 landing site that 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. 13a. Olympus Mons and surrounding lobate aureole deposits. Lobes appear to have been emplaced sequentially (as numbered in figure 13b), 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. 13b. 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 möberg without the pillow lava. A recent investi-
ulated here that their formation was dependent on the pre-
model has not been examined in detail, it evidently would im-
sumed underlying zone with liquid pore water. Although this
lubrication is the interface between permafrost and a pre-
gested as an explanation for the scarp and aureole (M. H.
Carr, oral communication, 1978). In this model the plane of
the main scarp at Olympus Mons (Figure 13b), but it is post-
base of the shield as well as on the break in slope at sea level.

on the existence of the incompetent material in the submarine
volume and location of aureole lobe. None of the above slide
around the entire shield, irrespective of variations in apparent
broadest. The scarp appears to be a nearly constant height
ing the location of the most extensive volume of aureole de-
positions 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 re-
quiring 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 inland from
the main scarp at Olympus Mons (Figure 13b), but it is post-
ulated here that their formation was dependent on the pre-
existing and unrelated basal scarp.

Gravity sliding on a subsurface plane has also been sug-
gested 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 pre-
sumed underlying zone with liquid pore water. Although this
model has not been examined in detail, it evidently would im-
pose 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 em-
placement 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 13a) resembles rather strikingly the map
pattern of the Appalachian Pine Mountain overthrust [Thorn-
berry, 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 13b), the elevated but virtually ac-
cordant surface of the deposits, and, particularly, the develop-
ment of the shield’s basal scarp seem inadequately explained
by this means. Neither of the gravity-induced mechanisms de-
scribed 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 ero-
sonal 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 north-
ern 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 di-
chotomy 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
volcanic ceased. Erosion of domical plutons (K. R. Blasier,
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 au-
reole lobes because an extensive erosion period would plane
such coalescing plutons to a relatively continuous surface, ir-
respective of ages of intrusion. If the aureoles are simply the
deeply eroded remnants of old subaerial lava flows [McCae-
dy 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 re-
semble 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 dis-
tribution as well as with the gravity data is subglacial erup-
tion. The pillow lavas and tufaceous breccias thus accumu-
lated 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 m6berg that has been modified
by erosion. A complex network of intrusions and dikes would
thus be present beneath the aureoles to produce the excess

Fig. 14. Table mountains (a) southwest of Olympus Mons (Fig-
ure 13a), probably remnant outliers of ridged-and-grooved aureole
terrain (b), here interpreted as m6berg deposits (palagonitized tuff
and breccias) and pillow lavas. Texture of aureole terrain (b) resem-
lies that of m6berg 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 10øN, longitude
142ø; Viking photograph 044B13.)
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 x 10^6 km^3, and some individual lobes probably contain as much as 5 x 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 m6berg 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 vent systems (Figure 136).

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, 1976a, 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 Martian 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 northern polar cap appears conclusive, and its present thickness has been estimated at as much as 1 to 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 H2O 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. Toumin 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 pediments described here are generally of the order of a few hundred meters, and therefore 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 m6berg foundation would be perhaps 3-4 km.

The m6berg 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 m6begrlike 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 x 10^6 km^2 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 H2O 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$_2$O 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 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 Arisia 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 Ascaeus Mons, youngest of the large Tharsis shields [Carr, 1976a; Wood, 1976], so that the ‘Ice Age’ may have vanished by the time the Ascaeus Mons eruptions began. Although the present surface of the Olympus Mons shield appears to be younger than Ascaeus 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 thaws 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 initial 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 móbörg. The position, apparent sequence, and grooved, serrate textures of the aureole lobes are compatible with their interpretation as separate subglacial eruptions that did not reach the surface and remained as expanses of móbörg 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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