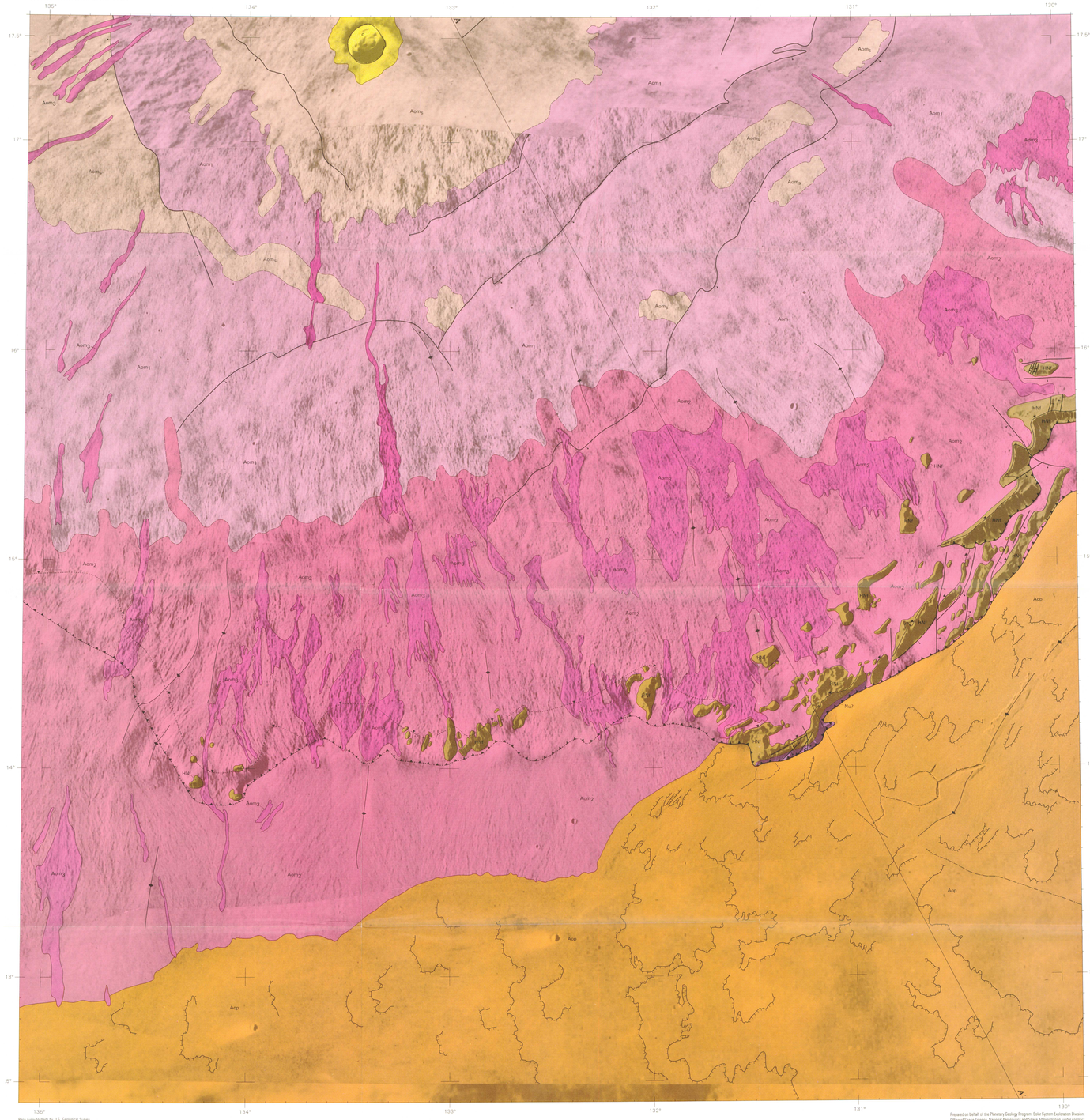
U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Prepared in cooperation with the
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

ATLAS OF MARS
1:500,000 GEOLOGIC SERIES
OLYMPUS RUPES
M 500k 15/132 G, 1991
MAP I-2001 (SHEET 1 OF 2)



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SCALE 1:602 000 (1 mm = 502 m) AT 130° LONGITUDE
TRANSVERSE MERCATOR PROJECTION

10 0 10 20 30 40 50 60 70 80 90 100
KILOMETERS

CORRELATION OF MAP UNITS

SYSTEM[1]	CRATER DENSITY Cumulative number of craters >1 km in diameter per 10^6 km²	PLAINS AND SHIELD MATERIALS	BASEMENT MATERIALS
AMAZONIAN	100–120	Aop, Aom3, Aom2, Aom1, Aom4	HNf, Nu?
	120–150		
	400–500		
HESPERIAN	1600		
	2200–3200		
NOACHIAN	4800		

[1]System boundaries from Tanaka (1986)

DESCRIPTION OF MAP UNITS

[Crater densities of units given in table 1, sheet 1]

PLAINS MATERIAL

Aop **Olympus plains flows**—Surface appears smooth, level, and featureless at moderate resolution (100 to 150 m/pixel), but abundant tongue-like flows, bounded by lobate scarps, and shallow linear and polygonal depressions visible at high resolution. Unit floods depression surrounding Olympus Mons and embays most adjacent units. *Interpretation*: Youngest basaltic flows of map area. Polygonal fissures may result from cooling; linear depressions may be expression of tensional stresses or result from rejuvenated faulting of basement materials

OLYMPUS MONS SHIELD MATERIALS

Aom_3 **Young flows**—Long, narrow, tongue-like, leveed flows having stubby, lobate terminations; fresh, pristine appearance. Distinct boundaries contrast sharply with those of older flows on which they lie. *Interpretation*: Youngest basaltic lava flows on flanks of Olympus Mons. May have been emplaced subsequent to last activity in summit caldera. May be partly contemporaneous with Olympus plains flows

Aom_2 **Lower-flank light flows**—Form anastomosing networks of distinct, high-albedo, leveed flows several hundred meters to a kilometer across and 10 to 100 km long; many lava fans and smooth radial ridges. *Interpretation*: Basaltic lava flows erupted subsequent to scarp formation. Ridges probably enclose lava tubes that served as distributive centers

Aom_1 **Upper-flank dark flows**—Flows indistinct, generally form rough, hummocky surfaces; some flows broad, sheet-like. Albedo darker than summit and lower-flank light flows. *Interpretation*: Low-viscosity basaltic lava flows; composition possibly different from other flank flows

Aom_4 **Summit flows**—Rough to smooth, hummocky surface with indistinct flow boundaries; some tongue-like flows with vague lobate terminations. Dark and light streaks and patches. Many irregular to round pit craters (<100 m to 1 km in diameter) in chains and clusters. Form summit of Olympus Mons and some terraces near summit. *Interpretation*: Oldest flows on Olympus Mons. Most flows predate formation of summit caldera. Dark and light streaks may be due to thin covering of eolian or pyroclastic material

BASEMENT MATERIALS

[Interpreted as rocks on which Olympus Mons was built. Old volcanic flows, lava plains, and intercalated ejecta material emplaced prior to Tharsis shield building; fractured and faulted during regional doming of Tharsis swell]

HNf **Fractured plains material**—Occurs as blocks of smooth material cut by fractures and graben-bounding faults; forms steep cliffs and ledges of Olympus Mons scarp. Buried by young flows in central and western map area

Nu? **Undivided material(?)**—May occur in lowest part of Olympus Mons scarp

Contact—Long dashed where approximately located; short dashed where inferred; queries on cross section indicates uncertainty

Fault—Bar and ball on downthrown side of fault. Dotted where buried. Some faults may be thrust faults

Fault on cross section—Arrows show relative movement

Ramp thrust fault—Sawteeth on upper plate. Dotted where buried

Linear scarp—Line at crest; arrow points downslope. Dotted where buried

Lobate scarp—Interpreted as volcanic flow front. Ticks in flow direction

Shallow linear or polygonal depression

Ridge

Impact crater material—Rim crest hachured

INTRODUCTION

This map is one in a series of 1:500,000-scale geologic maps initiated by the National Aeronautics and Space Administration to investigate areas of particular scientific interest on Mars. Olympus Mons is the largest known volcanic construct in the Solar System; it is more than 600 km across and more than 27 km above datum (fig. 1, sheet 1). The volcano and the great scarp that bounds it have been the subject of much scientific controversy. Although it has been possible to generate an empirical model that closely resembles Olympus Mons (fig. 2, sheet 1), the dynamics of scarp formation are still unproven. The scarp area is thus a logical selection as a scientific study area. It has also been designated as a candidate site for a proposed lander/rover/sample-return mission to Mars (fig. 1, sheet 2) not only because the site may provide information about the origin of the scarp and the evolution of Olympus Mons, but also because rocks of widely diverse ages may be studied from samples collected from talus at the base of the scarp.

The geology of the Amazonis-Tharsis region of Mars, which includes the map area (fig. 1, sheet 1), was first mapped at 1:5,000,000 scale from Mariner 9 data (Carr, 1975; Morris and Dwornik, 1978) and later at 1:2,000,000 scale from Viking data (Tanaka, 1983). Detailed geologic maps of Olympus Mons at 1:2,000,000 and 1:1,000,000 scales, based on Viking data, are being prepared (E.C. Morris and K.L. Tanaka, work in progress). The present map was compiled originally at 1:1,000,000 scale (Morris, 1982); additions and modifications of that map have been made, based on a new 1:500,000-scale photomosaic base map (fig. 2, sheet 2) that includes a computer-generated mosaic of higher resolution images (100 m/pixel; Viking Orbiter images 45B 37–46). Two other computer mosaics of very high resolution images (figs. 3A and 4A, sheet 2) of the general landing-site area were also used to determine stratigraphic relations and morphologic differences of units. A computer-generated, false-color image (Viking Orbiter image 646 A28) that enhances tone and albedo (fig. 3, sheet 1) was used to help discriminate boundaries between flow units. The relative ages of geologic units depicted on the map are determined mainly from their stratigraphic relations (figs. 3B, 4B, and 5, sheet 2); these relations are verified by crater-density statistics, which determine the range of the number of craters equal to and larger than 1 km per 10^6 km² (table 1, sheet 1). Critical stratigraphic relations between the scarp and the flows on the volcano's flanks and at its base are revealed by detailed study of special enhancements of some of Viking's highest resolution images.

PHYSIOGRAPHIC SETTING

The Olympus Rupes area encompasses the southeast flank of Olympus Mons, the basal, circumferential scarp (Olympus Rupes), and part of the surrounding plains. Olympus Mons, one of the most prominent features on Mars, lies on the boundary between the northwest flank of the Tharsis-Syria upland and the sparsely cratered northern lowland region of Amazonis Planitia (fig. 1, sheet 1). Olympus Rupes rises more than 5 km above the Olympus plains in the eastern part of the map area. In the western part, the scarp is almost completely buried by young lava flows emitted from the flanks of Olympus Mons; where buried, relief on the scarp is about 2 km. The proposed landing site for a future rover mission is in the southeastern part of the map area on the flat, almost featureless plains that surround Olympus Mons.

STRATIGRAPHY

NOACHIAN AND HESPERIAN SYSTEMS

The oldest rocks in the Olympus Rupes area are those that formed the surface or platform on which Olympus Mons grew—the basement rocks of this area. They are now exposed in the cliffs and ledges that form the scarp surrounding the volcano and in blocks that project above the lava flows on the raised rim of the scarp. The older of the two basement units is mapped as Noachian undivided material(?) (unit Nu?), which may be exposed in the lower part of the scarp and presumably also may be present as talus at its base. If Noachian rocks are present, they may consist of heavily fractured volcanic deposits from the early period of heavy bombardment (Scott and Carr, 1978). Alternatively, Lopes and others (1982), Francis and Wadge (1983), and Tanaka (1986) consider material in the scarp to be that of an ancestral Olympus Mons and possibly younger than middle Hesperian.

Most of the blocks that project above the lava on the scarp rim, and the rim itself, dip inward toward the center of Olympus Mons (fig. 2, sheet 2). The rough upper surfaces of the blocks are cut by fractures and graben-bounding faults that resemble features commonly seen in older and younger fractured materials (Scott and Tanaka, 1986) exposed in the Ulysses Fossae area 300 km southeast (fig. 1, sheet 1). Material of the blocks and scarp rim is therefore correlated with these units and is mapped as fractured plains material (unit HNf). Its Hesperian and Noachian age is assigned on the basis of crater counts in the Ulysses Fossae area (Scott and Tanaka, 1986, 1986).

AMAZONIAN SYSTEM

The surface of Olympus Mons is made up of many thin lava flows that were very fluid at the time of emplacement. At present resolution, most flows appear intricately intermeshed, and contacts between individual flow units are difficult to distinguish; however, a few of the youngest flows that are distinct enough to map (fig. 3, sheet 2) postdate the formation of the Olympus scarp and overlie all other flows. The complex and intricate boundaries between flow sequences suggest complex distributive systems whose vents were concentric to the volcano. The source vents of most flows cannot be identified, probably because they are buried. Carr and others (1977) suggested that most source vents are on the terraced upper flanks. The lower flanks were probably built primarily by long-ranging distributaries; some are recognized as leveed channels and lava tubes on the crests of ridges radial to the summit. Studies by Blasius (1976), Carr and others (1977), Schaber and others (1978), Scott and Tanaka (1980), and Neal (1981) indicate that the lower flank flows are younger than those near the summit. Carr and others (1977) also noted that flows of the lower flanks are more distinct than those of the upper flanks and summit.

Attempts to date parts or all of the Olympus Mons shield by crater-density statistics have produced varied results, either because workers have used different methods to obtain the data or because impact craters are few and difficult to distinguish from volcanic or secondary impact craters. However, all workers agree that the surface is very young. The complex nature of the flank flows makes it difficult to delineate boundaries between flow sequences and also to date flows on the basis of morphology alone (Neal, 1981). However, differences in albedo, color, or both are recognizable on various parts of the shield. The albedo of summit and lower flank units is lighter than that of the upper middle flanks, and a rough correlation appears to exist between morphology and albedo. Variations are particularly well depicted on the false-color image used to delineate major divisions of the shield (fig. 3, sheet 1). Relative ages of these divisions were determined by counting all craters >1 km across in each (table 1, sheet 1). Although the data are sparse, they agree with observations noted above that the younger flows make up the lower flanks and the older flows are at or near the summit. By using the color/albedo variations confirmed by cratering data, flows on the volcano's flank have been divided into four units: summit flows, upper-flank dark flows, lower-flank light flows, and young flows.

Summit flows

As determined by crater-density statistics, the volcano's oldest flows (unit Aom_4) are those at or near the summit. Flow morphology is indistinct at present resolution; some stubby surface flows are rough and hummocky, while other flows are broad and sheet-like. Dark and light streaks and patches are common and may represent a thin covering of eolian or pyroclastic material (Francis and Wood, 1982). The streaks and patches do not appear to coincide with the boundaries of the few lava flows that can be recognized in high-resolution pictures.

Upper-flank dark flows

Individual flow boundaries on the surface of this material (unit Aom_1) are also indistinct; contacts between this and surrounding units are drawn on the basis of its darker albedo in unenhanced images and on color differences shown in the false-color image (fig. 3, sheet 1). Compositional differences, weathering, mantling, or a combination of these processes may account for the darker appearance of the unit. It probably predates the formation of the basal scarp; it also may have formed contemporaneously with some of the collapse craters of the summit caldera.

Lower-flank light flows

Flows on the lower flanks (Aom_2) appear fresher and are more distinct than those on the upper flanks and summit. They appear to have been fed by long-ranging distributaries, some of which formed long, low ridges radial to the summit. Narrow, leveed channels and some collapsed lava tubes are visible along their crests. In the western part of the map area, these flows partly bury the basal scarp surrounding the volcano and stream outward for almost 50 km onto basal plains. Lava fans are abundant, both on the lower flanks and at the base of the scarp; some fans at the base of the scarp are covered by younger flows.

Young flows

Lobate, stubby terminations and crisp boundaries define the pristine young flows (Aom_3) and separate them from older underlying flows. Most of the unit is on the north flank (outside the map area) and on the south flank of the volcano. The few flows that are mapped (figs. 3B, 4B, sheet 2) probably represent a much larger population; high-resolution images of a more extensive area would enable mapping of the unit in greater detail.

Olympus plains flows

The youngest extensive lava flows of the map area are the plains flows (unit Aop). They probably originated from fissures, rimless craters, and low shields near lat 15.5° N., long 125.5°, east of the map area (Scott and Tanaka, 1981). Lavas from these vents appear to have flowed south and west into a structural depression at the base of the Olympus scarp. In most places, the plains flows appear to embay the lower flank flows of Olympus Mons. Locally, however, young flows (unit Aom_3) appear to overlie the Olympus plains unit (fig. 4A, B, sheet 2). The two units may be contemporaneous, but resolution of the Viking pictures is not sufficient to determine exact stratigraphic relations. High-resolution images show shallow (probably less than 50 m deep) linear and polygonal depressions. Outside the map area, the Olympus plains flows bury all older volcanic material. Within the map area, craters larger than 1 km are too few to allow accurate crater statistics to be determined (table 1, sheet 1); therefore, crater densities for this unit are taken from Scott and Tanaka (1981).

STRUCTURAL HISTORY

The tectonic history of the Olympus Rupes area must be considered in the context of the structurally elevated Tharsis-Syria Planum region (fig. 1, sheet 1), on whose flank it lies. Several episodes of intense faulting have occurred in this region. Episodes of faulting affected the older basement rocks during periods of tectonic activity associated with the uplift of the Tharsis-Syria Planum region (Carr, 1981, p. 114–123; Hartmann, 1973), which began early in the planet's history (Wise and others, 1979). This deformation produced fractures radial to the Tharsis-Syria Planum region; the fractures are expressed in the map area by faults and grabens that trend 40° to 60° W. Most of the fractured terrain was subsequently buried by lavas of Hesperian and Early Amazonian age that emanated from Alba Patera, the three large Tharsis volcanoes, and Olympus Mons (Scott and Tanaka, 1981).

In the Olympus Mons area, late tectonic activity included the development of the circumferential basin and the deformation of the flanks of Olympus Mons. This deformation probably resulted from the accumulated mass of the volcano. As the crust sagged beneath the great pile of volcanic rocks, compressional stresses developed. They were relieved by radial and circumferential fracturing around the margins of the volcanic pile and within it. The basal scarp may have formed by reverse or ramp faulting, expressed on the scarp face as a series of imbricate fractures and ledges (fig. 2, sheet 2). Fractured plains material that had been faulted and fractured during the earlier tectonic episodes was uplifted and exposed in the scarp as the edges of the volcano were thrust outward. Relations between flows on the lower flanks and the scarp are complex: some flows appear to have been truncated by the scarp, some were ponded behind the raised rim, and some flowed over the scarp. These relations, together with the low number of craters counted on the flows (table 1, sheet 1) indicate that the scarp formed late in the history of Olympus Mons. Empirical modeling of Olympus Mons and its stress conditions (fig. 2, sheet 1) has produced a pattern of faulting that is strikingly similar to the actual faulting.

Other theories for the formation of the Olympus Mons scarp have been proposed that do not depend on tectonism as the originating force. King and Riehle (1974) considered the scarp to be erosional, formed at the zone of transition between the inner part of the shield, which they proposed to consist dominantly of lava flows, and the outer part of the shield, which they thought to consist of friable ash flows. Head and others (1976) also proposed an erosional origin for the scarp. Hodges and Moore (1979) considered Olympus Mons to be analogous to Icelandic table mountains (volcanoes that form partly under ice); the top of steep cliffs around their outer margins marks the height of the former ice cover. Lopes and others (1982), Francis and Wadge (1983), and Tanaka (1986) proposed that the scarp is a detachment surface formed when part of the flank was removed by landslides or gravity spreading. None of these proposals accounts for the rocks on the rim of the scarp that we infer to be basement material uplifted more than 5 km from its normal stratigraphic position. However, no general agreement exists that the fractured blocks on the rim in the map area are the same as the older and younger fractured materials mapped by Scott and Tanaka (1986).

GEOLOGIC HISTORY

The geologic events recorded in the exposed rocks of the Olympus Rupes area cover more than 3.5 b.y. (Tanaka, 1986). The oldest rocks, designated as basement materials because they make up the surface on which the Olympus Mons volcano was built, may be densely cratered and highly fractured, of Hesperian and Noachian age. These rocks, which are now exposed in the scarp rim and in blocks along it, record a time of extensive volcanism and tectonism associated with the development of the Tharsis swell (Scott and Tanaka, 1986), southeast of the map area.

As Tharsis tectonism diminished during Late Hesperian and Early Amazonian time, the basement rocks were buried under voluminous outpourings of lava that originated from vents associated with other volcanic structures in the Tharsis province (Scott and Tanaka, 1980). Most volcanism was effusive and consisted of broad, flat sheet flows that covered the plains and the lower slopes of the volcanoes, and channel- and tube-fed flows on the steeper slopes (Carr and others, 1977). The oldest flows originated from Alba Patera, northeast of Olympus Mons (Schaber and others, 1978). They were followed by eruptions from the Tharsis area (Scott and Tanaka, 1980); Olympus Mons probably grew during late stages of this volcanic activity. A circumferential basin formed around Olympus Mons as the mass of the great volcano increased, depressing the crust of the planet. During the development of the basin, faulting at the base of the shield formed the scarp. The basin was then filled by young lava flows and the scarp was partly buried by other young flows from the flanks of the volcano. Some of the youngest flows on the flanks of Olympus Mons may have been contemporaneous with flows that filled the basin, which are thought to have been emplaced only a few hundred million years ago and are considered to represent the most recent volcanic activity on Mars (Scott and Tanaka, 1981).

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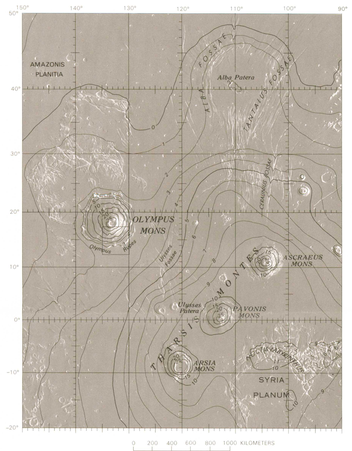
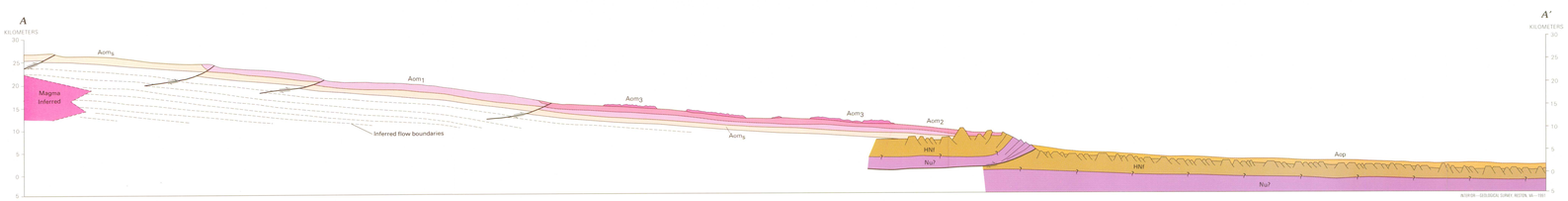


Figure 1. Index map showing location of Olympus Rupes map area; from topographic map of Mars (U.S. Geological Survey, 1976). Contours in kilometers; original scale 1:25,000,000.

Figure 2. Photograph of an empirical model of Olympus Mons constructed of very fine (<120 μ) sand grains on an elastic surface. Compressional stresses developed in model when support under material was removed and modeled structure was allowed to sag into depressed surface. Stresses were relieved by faulting so that a boundary scarp and "petal" (semicircular) faults formed; configuration of faults in model is strikingly similar to that of Olympus Mons (fig. 2, sheet 2). Mathematical modeling that would describe stress relations and sequence of faulting that would generate this morphologic configuration has not been attempted.



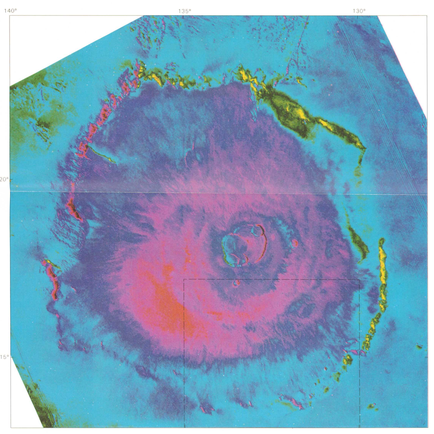


Figure 3. False-color computer enhancement of Viking Orbiter image 646 A28 used to discriminate major flow divisions on flanks of Olympus Mons. Blue tone of flows near summit and on lower flanks indicates lighter color or albedo than reddish-lavender tone of darker upper-flank flows. Dashed line indicates map area.

Table 1. *Crater densities of geologic units in Olympus Rupes area of Mars.*
[Dashes (—) indicate insufficient data; 1:1M, scale 1:1 million]

Unit	Source of crater counts	Area counted (km^2)	No. craters >1 km diam. per $10^6 km^2$	Crater density N=no. craters >1 km
Aop	(1)	143,200[1]	13	90 ± 25
Aom_3	—	no data	—	—
Aom_2	1:1M mosaic, Olympus Mons	221,590	25	112 ± 23
Aom_1	1:1M mosaic	105,110	14	133 ± 36
Aom_4	1:1M mosaic	16,180	8	494 ± 175
HNf	VO 41B 14, 17	18,357	43	2342 ± 360
Nu?	—	—	—	—

[1]Scott and Tanaka, 1981

GEOLOGIC MAP

GEOLOGIC MAPS OF SCIENCE STUDY AREA 3, OLYMPUS RUPES, MARS

(SPECIAL MTM 15132 QUADRANGLE)

By

E.C. Morris, D.J. Applebee, and M.E. Strobell

1991

For sale by U.S. Geological Survey, Map Distribution, Box 25286, Federal Center, Denver, CO 80225