UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Preliminary geologic map of the western equatorial region of Mars: Part A

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This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

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NOTE

Full-color copies of plates 1 and 2 are available in the form of 8-in. by 10-in. color film transparencies as Open-File Report 84-659-B. Duplicate color transparencies or enlarged color prints (on paper) can be ordered for the cost of photoreproduction through the U. S. Geological Survey Photo Library, Mail Stop 914, Federal Center, Denver, Colorado 80225 (telephone (303) 236-1010). Prepayment is required.

INTRODUCTION

Viking orbiter images were used to make this preliminary geologic map of the western equatorial region of Mars (Plates 1 and 2). It supersedes previous maps made from Mariner 9 pictures and represents a separate and more advanced geological study of the region based on the higher resolution, better quality and nearly complete coverage of the Viking images. The geology is compiled on a new, 1:15-million-scale base map that also reflects in its physiographic rendition the use of improved imagery and photogrammetry (U. S. Geological Survey, 1982). The geologic map is one of three in a series covering the entire planet. The series portrays the lithology, stratigraphy, and structure of Mars and the major tectonic, volcanic, and fluvial episodes that have contributed to the evolutionary history of the planet. Geologic units are identified and mapped from 1:2-million-scale photomosaics and individual photographs at moderate to high (300-130 m/pixel) resolution. The description and classification of rock-stratigraphic units is based on inferred lithologic characteristics recognized on high- to very high-resolution pictures (130-15 m/pixel). The units are assigned to time-stratigraphic systems previously formulated (Scott and Carr, 1978) from the Mariner 9 mapping. Relative ages of the rock units are established by stratigraphic and structural relations, morphologic appearance, and crater size-frequency distributions. Small craters are better preserved on the relatively smooth surfaces of younger geologic units than on the rough, uneven or highly faulted older materials. For this reason, the graph included on the correlation chart shows the cumulative density of craters >2 km diameter per 10^6 km^2 for rock units in the Amazonian and Hesperian Systems, and for craters >16 km diameter in the Noachian System. Some of the uncertainties inherent in the earlier maps resulting from the modification and obscuration of primary depositional characteristics of rocks caused by erosion and tectonic overprint also occur in the Viking map series. The most notable examples occur in the highly faulted and fractured areas to the north and south of Tharsis Montes and in Tempe Terra plateau. In these places deformation has destroyed all identifying lithologic properties of the rocks; such areas are represented on the correlation chart under "highly deformed terrain" and mapped as fractured materials of different ages.

The map units are broadly subdivided into either lowland or highland categories based on their predominant occurrence. The lowland terrain consists of extensive plains north of the highland-lowland boundary scarp in the northern hemisphere of Mars. Much of the lowland region is densely populated by small knobs and conical hills that may be volcanic in origin (Scott, 1979). No counterpart to this province exists in the southern part of the planet. The highland terrain is comprised of rock and rock-tectonic units having medium to high relief which dominate the southern and equatorial regions of the planet. Rock-stratigraphic classifications of different ranks (formations and members) are employed for the first time in Mars geologic mapping. Their use minimizes the introduction of adjectival descriptions for map units that may be both inadequate and confusing. In the lowland plains as well as the highlands, many units appear to have gradational contacts. Some contacts are drawn where boundaries between units are located primarily on the basis of secondary characteristics such as crater density discontinuities; these should be regarded as "statistical boundaries." In the interest of showing uncluttered relations between geologic units, only those impact craters larger than about 150 km diameter are mapped. No attempt has been made to classify craters as to relative age by their degree of degradation.

More importantly, the stratigraphical position of craters is shown by color code (Sheet 1, Open-File Report 84-659-B) indicating whether they are younger or older than adjacent terrain as determined by superposition and embayment relations.

Among the more significant changes appearing on the new map are: 1) subdivision of lava flows associated with major eruptive episodes at Tharsis Montes and other large volcanic centers, 2) expansion of areas covered by channel and floodplain deposits, especially their greater extension into the northern plains, 3) recognition of possible ignimbrite deposits covering large areas along the western equatorial region, 4) discovery of many small- to moderate-size volcanoes and source vents in the southern highlands and Tempe Terra, 5) a three-fold increase of mappable rock units compared with the Mariner geologic map of Mars (Scott and Carr, 1978), and 6) reassignment of several rock units to different time-stratigraphic systems; for example, mottled plains material, formerly classified as Noachian in age has been placed in the Amazonian System on the basis of crater counts (Plates 2 and 4). It now forms part of the Vastitas Borealis Formation.

PHYSIOGRAPHIC SETTING

The western equatorial region of Mars is dominated by a topographic rise of regional proportions centered around Tharsis Montes-Syria Planum and extending over one-third of the map area. Within this elevated region occur the four largest and youngest volcanoes on Mars: Olympus Mons, Arsia Mons, Pavonis Mons, and Ascraeus Mons; the latter three collectively form the large northeast-trending volcanic mountain chain of the Tharsis Montes. The broad swell forming the Tharsis-Syria rise lies athwart the highland-lowland boundary that transects the western equatorial region in a northeast-southwest direction. The boundary, where not covered by younger lava flows, is marked by a gentle scarp and clusters of low knobby hills. It separates the relatively smooth, flat, and sparsely cratered northern plains from the higher, rougher, and densely cratered terrain of the highlands. Valles Marineris, the major canyon system on Mars, extends several thousand kilometers eastward from Noctis Labyrinthus, located at the central part of the Tharsis-Syria rise. Many of the ancient river channels originate from Valles Marineris and its associated canyons. Argyre Planitia, the largest impact basin in the western hemisphere, is more than 1000 km across. The broad flat floor of the basin lies several kilometers below the rough mountainous rim that encompasses it.

DESCRIPTION OF MAP UNITS

The map units are arranged according to their provincial occurrence and associations as outlined in the correlation chart (Plate 2).

Lowland Terrain

Consists of all plains forming materials north of the highland-lowland scarp, extending to the north map edge.

<u>Northern Plains Assemblage</u>

Materials deposited in widespread sheets that fill the northern plains.

Arcadia Formation

Forms low-lying plains in Arcadia, Amazonis, and Acidalia Planitia. Post-dates formation of highland-lowland boundary scarp (Scott, 1979). Largely mapped as cratered plains and smooth plains from Mariner 9 images (Scott and Carr, 1978).

Aa5 — Member 5 - Dark, fresh-appearing lava flows with lobate margins in Acidalia and Arcadia Planitia; several occurrences having relatively small areal extent, few superposed impact craters. Type area: 47° N., 30° W.

Aa4 — Member 4 - Underlies member 5 in Arcadia Planitia and has similar appearance. Type area: 45° N., 175° W.

Aa3 — Member 3 - Forms smooth plains west of Olympus Mons. Lobate lava flow fronts visible in places; embays aureole deposits of Olympus Mons and fractured terra of Acheron Fossae. With members 4 and 5 represents a large part of smooth plains unit previously mapped from Mariner 9 images (Scott and Carr, 1978). Type area: 15° N., 155° W.

Aa2 — Member 2 - Underlies members 3,4, and 5 in Arcadia Planitia. Includes numberous small (<10-km-diameter) volcanoes, cinder cones, and lava tubes. Pressure ridges visible on surfaces of flows. Type area: 45° N., 155° W.

Aal — Member 1 - Occurs throughout Chryse Basin and Amazonis Planitia. Embays highland margins and partly buries outflow channel systems and floodplains of Kasei, Shalbatana, Simud, and Ares Valles. Together with member 2 is equivalent to cratered plains unit of Mariner mapping (Scott and Carr, 1978). Type area: 30° N., 40° W.

Vastitas Borealis Formation

Subpolar plains deposits of northern lowlands. Contrasting albedo patterns probably associated with periglacial and volcanic phenomena.

Avm — Mottled member - Major occurrence in north polar region; extends southward into topographic reentrant in Acidalia Planitia and Chryse Basin. Appears to consist of lava flows extruded from fissures and small central vent volcanoes. Mottled appearance caused by contrast between bright aprons around impact craters and flanks of small (<5-km-diameter) domes and dark summits of domes and generally low albedo of plains background. Crater counts indicate the unit is younger than previously mapped (Scott and Carr, 1978). Type area: 55° N., 40° W.

Avk — Knobby member - Similar in occurrence and appearance to mottled member but has generally higher albedo and abundant small dark knob-like hills with summit craters common. Type area: 55° N., 5° W.

Avr — Ridged member - Small local occurrences of mottled lava plains characterized by concentric pattern of low narrow ridges. Origin unknown, may be river channel meander scars accentuated by differential erosion or periglacial features. Type area: 38° N., 33° W.

Avg — Grooved member - Mottled plains facies in Acidalia Planitia marked by curvilinear and polygonal patterns of grooves and troughs; closed polygons up to 20 km across. Origin unknown, may represent tectonic structures, permafrost features or contraction features. Type area: 45° N., 15° W.

Alluvial and Periglacial Material

Consists of rock units along the highland-lowland boundary that represent transformation of highland material into lowland material by erosion and degradation.

Ach/Achp — Channel and Floodplain Material - Forms broad (100-km) alluvial plain marked by dark sinuous intertwining channels with bars along western margin of map area. Crater counts and superposition relations indicate Amazonian age. Type area: 15° N., 177° W.

Hch/Hchp/Hcht — Channel, Floodplain, and Chaotic Materials - Similar in appearance to younger deposits but channels more deeply incised and floodplains wider and more extensive. Chaotic material occurs at channel source areas and on channel margins. Partly buried in northern lowlands by plains unit (Aal) and by Tharsis Formation (member At5). Channel bars large and well developed. Type area: 20° N., 40° W.

HNk — Knobby Material - Resembles knobby member (unit Avk) of Vastitas Formation but small knobs grade into large (20 km-diameter) rounded hills that in places are remnants of highland terrain isolated by scarp retreat. Type areas: 40° N., 10° W. and 31° N., 176° W.

Highland Terrain

Rock and rock-tectonic units having moderate to high relief; dominates southern and equatorial regions of map area.

Western Volcanic Assemblage

Volcanoes, lava flows, and pyroclastic deposits in the Tharsis region of Mars (Scott and others, 1981; Scott and Tanaka, 1982).

Tharsis Formation

Includes volcanic centers of Arsia Mons, Pavonis Mons, and Ascraeus Mons and associated lava flows; lava flows have similar morphology to terrestrial basalts (Schaber and others, 1978).

At6 — Member 6 - Fresh appearing lava flows form smooth, fan-shaped mantles on northeast and southwest upper slopes of Tharsis Montes volcanoes. Buries concentric grabens that cut the volcanoes' flanks. Originates from fissures along major structural trends.; also form most recent filling within central calderas. Type area: 5° S., 117° W.

At5 — Member 5 - Forms elongate light-colored flow lobes with dark streaks extending outward from upper parts of Tharsis Montes volcanoes. Cut by few faults. Overlies channel and floodplain of Kasei Vallis. Type area: 20° S., 120° W.

At4 — Member 4 - Exposed along northeast and southwest sides of Tharsis Montes; consists of overlapping light and dark flows, elongate on upper slopes, broad on lower. High-resolution images show pressure ridges concentric with lobate flow fronts; minor faulting. Type area: 15° S., 135° W.

At3 Member 3 - Embays highland terrain west of Arsia Mons and along Claritas Fossae. Lobate fronts and ridges less prominent but faults more common than those in member At_4. Central shields of Tharsis volcanoes included in unit. Type area: 27° S., 127° W.

Ht2 Member 2 - Occurs south of Arsia Mons and northeast of Pavonis Mons and Uranius Patera. Composed of dark, relatively smooth flows with broad frontal lobes; embays highland terrain of Tempe Terra; fractures and faults common in places. Type area: 33° S., 135° W.

Ht1 Member 1 - Forms rough, hummocky surface south of Arsia Mons; marelike ridges in places; faults and fractures common. Type area: 30° S., 120° W.

Olympus Mons Formation

Consists of volcanic shield, aureole deposits, and lava plains of Olympus Mons.

Aop Plains member - Occurs partly around basal scarp of Olympus Mons; surface smooth with many narrow, tongue-shaped to broad and lobate overlapping lava flows extruded from faults and fissures; overlaps youngest shield lava flows from Olympus Mons (unit Ao5). Type area: 20° N., 125° W.

Ao5 Member 5 - Shield lavas that form complex, finely textured, interfingering tongues and lobes with channels and levees extending down flanks of Olympus Mons and across prominent basal scarp on north, east, and south sides of volcano; collapse pits common. Type area: 15° N., 135° W.

Ao4 Member 4 - Uppermost unit of a series of pre-scarp aureoles around Olympus Mons. Forms broad, flat, corrugated, semicircular lobe cut by numerous faults and deep troughs. Origin controversial; may be ash or lava flows extruded from fissures and central vents or nappe-like structures formed by spreading of ice within early shield deposits Type area: 25° N., 145° W.

Ao3 Member 3 - Similar to and underlies member 4. Type area: 28° N., 134° W.

Ao2 Member 2 - Similar to members 3 and 4 but occurs in relatively small area on southwest side of Olympus Mons and as islands surrounded by plains member Aop. Type area: 14° N., 143° W.

Ao1 Member 1 - Basal, widespread aureole; resembles younger members of aureole deposits but more degraded by wind erosion; overlaps fractured terrain units Hf and Nf. Type area: 15° N., 147° W.

Ceraunius Fossae Formation

Acf Occurs as series of relatively smooth, overlapping lava flows having even-toned to mottled and streaked surfaces; extends northeast-southwest across highly faulted and fractured terrain (unit Nf); has channels with levees in places. Lava flows appear to originate from fractures and fissures. Type area: 23° N., 115° W.

Syria Planum Formation

Intermediate-age volcanic flows originating from crestal area and fissures on flanks of topographic high centered in Syria Planum.

Hsu — Upper member - Occurs around crestal area of Syria Planum topographic high; consists of long, narrow lava flows and sheet-type flows with prominent lobes that are mottled light and dark and have pit craters. Partly covers fault systems of Claritas Fossae but cut by troughs of Noctis Labyrinthus; flows extruded from calderas near summit of Syria Planum and from fissures; gradational with lower flow unit Hsl. Type area: 15° S., 100° W.

Hsl — Lower member - Similar to upper member Hsu but more highly cratered and faulted. Exposed beyond the eastern edge of member Hsu. Type area: 25° S., 90° W.

Medusae Fossae Formation

Consists of extensive relatively flat sheets, smooth to grooved or gently undulating; deposits vary in appearance from soft to indurated; albedo moderate

Amu — Upper member - Occurs in large discontinuous deposits extending from Tharsis Montes westward to map boundary. Smooth, flat to rolling light-colored surfaces with broadly curved margins. Wind sculptured into ridges and grooves in places. Postulated to consist of nonwelded ash-flow tuff extruded from fissure vents. Type area: 0° N., 160° W.

Amm — Middle member - Similar to upper member but in places the surface appears rougher, more deeply eroded, and transected by intersecting joint sets. May consist of welded and nonwelded ash flows. Type area: 10° N., 160° W.

Hml — Lower member - Two small occurrences in western map area; smooth to rough and highly eroded dark surfaces. Interpreted as welded and nonwelded ash-flow tuffs and lava flows. Type area: 0° N., 174° W.

Alba Patera Formation

Forms low shield volcano and extensive lava flows of Alba Patera

Aau — Upper member - Covers large central area within and around central caldera of Alba Patera; lava flows bury and partly bury most ring and radial structures; channels with levees common along crests of flows. Type area: 40° N., 110° W.

Aam — Middle member - Encircles crestal region and youngest flow unit (member Aau) of Alba Patera; long, narrow tongue-shaped lava flows having channels with levees; highly faulted but largely buries complex of grabens associated with highly deformed terrain (unit Nf). Type area: 40° N., 118° W.

Hal — Lower member - Covers broad area around north and west flanks of Alba Patera; flow fronts less distinct than in younger members (Aau, Aam); extends into plains region and appears to be overlapped in places by lowermost plains (member Aal), but boundary indistinct. Type area: 35° N., 125° W.

Plateau and High Plains Assemblage

Consists of ancient highland terrain and local tracts of younger, resurfacing deposits.

Surficial Deposits

As — Slide Material - Occurs on northwest flanks of Olympus Mons and volcanoes of Tharsis Montes as moderate to very large-size fan-like sheets. Deposits are thin, ribbed with concentric troughs and ridges, and appears to override topographic obstacles without deflection of internal structure. May consist of material deposited during retreat of ice sheets. Also occurs as numerous relatively small debris flows from local collapse of canyon walls in Valles Marineris. Type areas: 5° S., 125° W. and 9° S., 72° W.

Ae — Eolian Deposits - Forms broad level plains chiefly on aureole deposits of Olympus Mons; in places, surfaces appear rough, striated, and deeply etched in places. Type area: 15° N., 145° W.

AHps — Smooth Plains Material - Occurs characteristically as smooth blankets within impact crater floors where thickness of fill is generally directly proportional to crater age; also covers large low areas in highlands where it is intergradational in places with smooth plateau material (unit Hpls) but is smoother, less cratered, and buries underlying topography more fully. Origin and composition probably varies from place to place, consists of mixtures of eolian and volcanic deposits. Type areas: Argyre Basin (50° S., 40° W.) and many crater floors.

Ridged Plains Material

Hpr — Major occurrence covers an area of about 4 million km^2 extending from Solis Planum to Tempe Terra; consists of lava flows characterized by long, parallel, linear to sinuous ridges resembling those on the lunar maria. Type area: Lunae Planum, 10° N., 65° W.

Plateau Sequence

Forms heavily cratered deposits covering southern and east-central parts of map area.

Hpls — Smooth unit - Forms flat relatively featureless plains throughout southern highland region. Intergradational with smooth plains material (unit AHps) in places but more cratered, thinner, and rougher in texture because of underlying topography. Appears to consist largely of lava flows that have resurfaced other members of the Plateau Sequence to varying degrees. Type area: 28° S., 162° W.

Nplc — Cratered unit - Most widespread rock unit in southern highlands. Highly cratered, uneven, moderate relief, fractures, faults, and small channels common. Represents early surface formed during period of rapidly decreasing impact flux and increasing volcanic activity; consists of a mélange of lava flows, pyroclastic material, and impact breccias. Type area: 45° S., 148° W.

Npld Dissected unit - Similar occurrence and appearance to cratered member (Nplc) but highly dissected by small channels of probable alluvial origin. Type area: 45° S., 70° W.

Nple Etched unit - Similar to cratered member (Nplc) but deeply furrowed by sinuous intersecting round to flat bottomed grooves producing an etched or sculptured appearing surface. Type area: 45° N., 55° W.

Nplr Ridged unit - Resembles and intergradational with ridged plains material (unit Hpr) but area between ridges is relatively rough and densely cratered, similar to cratered unit (Nplc). Type area: 15° S., 163° W.

Nplh Hilly unit - Intergradational, hilly facies of cratered unit (Nplc); resembles in part basement rocks (unit Nb) and fractured material (unit Nf) but lacks prominent relief and intense faulting. Type areas: 12° S., 174° W., and 40° S., 65° W.

Valles Marineris Formation

Consists of materials within Valles Marineris and associated canyons.

AHvl Layered member - Deposits having thin multiple layers of dark and light colored material visible on high resolution pictures; occurs on floors of several canyons forming low platforms and hills of moderate relief. Believed to consist of volcanic and lacustrine material deposited during intermediate to late stages of canyon development. Type area: 7° S., 48° W.

HNvw Wall member - Varies from bright, fresh-appearing slopes to more eroded spur-and-gully topography that extend from plateau surface to canyon floor; coarsely layered from place to place in upper part of wall; many reentrants from collapse, landsliding, and sapping. Materials exposed in the top part of the wall range from upper member of Syria Planum Formation (unit Hsu) in west to cratered unit (Nplc) of plateau sequence in the east. No specific type area.

HNvf Floor member - Occurs as hummocky to rugged low-relief surfaces along canyon floors; in places forms inselbergs surrounded by smooth plains (unit AHps). Consists of material exposed in lower parts of canyon walls; in part may be remnants of landslides or debris flows from walls. No specific type area.

Argyre Basin Formation

Consists of fractured bedrock, impact breccias, and perimeter scarp formed by impact event that formed Argyre Basin.

Nam Mountain member - Forms rounded hills and irregular blocky massifs within primary ring wall of basin. Resembles Alpes Formation of Imbrium Basin and knobby facies of Montes Rook Formation on the Moon. Consists of structurally uplifted pre-basin bedrock (unit Nb) and basin ejecta. No specific type area.

Naw Wall member - Similar to wall member (unit HNvw) of Valles

Marineris Formation; consists of ancient crustal rocks exposed in semi-circular fault scarp formed following impact that created basin. No specific type area.

Tempe Terra Formation

Consists of intermediate-age lava flows extruded from small shield volcanoes and fissures within upland area of Tempe Terra.

Htu — Upper member - Smooth, light-colored to partly mottled lava flows that embay hilly, mountainous, and fractured terrain of highlands; small (<10-km-diameter) shield-type volcanoes visible on high-resolution pictures; few faults and fractures; embayed by Tharsis Montes and Alba Patera Formations (units Ht2 and Hal, respectively). Type area: 36° N., 86° W.

Htm — Middle member - Similar to upper member but faults, fractures, and collapse depressions common. Type area: 42° N., 80° W.

Htl — Lower member - Smooth to rough, uneven surfaces, faults and collapse depressions common; overlaps hilly and cratered units (Nplh, Nplc) of plateau sequence but is embayed by upper and middle members (Htu and Htm) of Tempe Terra Formation. Type area: 39° N., 84° W.

Highly Deformed Terrain

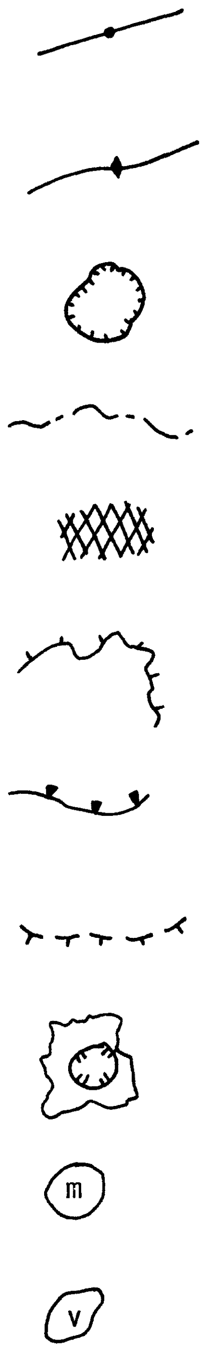
Hf — Fractured Material - Occurs around crestal area of Syria Planum and on lower flanks of Tharsis regional topographic high; relatively smooth, moderate-relief, raised surfaces cut by fractures, grabens, and collapse depressions. Overlies basement (unit Nb) and highly fractured terrain (unit Nf) but is embayed and partly covered by Syria Planum formation (units Hsu, Hsl) and plateau sequence (units Nplc, Hpls). Probably composed of older volcanic materials of Tharsis. Type area: 5° S., 103° W.

Nf — Highly Fractured Material - Similar to fractured material (unit Hf) but higher relief deformation by faulting; impact crater outlines largely destroyed. Type area: 20° S., 109° W.

Nb — Basement Complex - Undifferentiated material having prominent relief and characterized by highly complicated structure; may be composed of diverse rock types including volcanic rocks, impact breccias and possibly intrusive rock bodies. Largest exposures occur in the Claritas Fossae region but numerous smaller bodies project above the surrounding terrain and are interpreted to be erosional remnants of a highly irregular basement topography partly buried by more recent lava flows. Type area: 28° S., 100° W.

EXPLANATION OF MAP SYMBOLS

In general, when many features are present, only a few representative or important ones are shown by map symbols. Because of photographic reduction of the geologic map (Figure 1, Plate 1), some of the symbols are difficult to identify.



Graben

Mare ridge

Caldera

Channel

Jount or fracture pattern

Lava flow front

Scarp, arrows on uphill side

Olympus Mons basal scarp

Impact crater; yellow if superposed, blue if partly buried (Plate 1)

Mountain

Volcano

STRATIGRAPHY

Noachian System

Rock units comprising the Noachian System are believed to be correlative in age with those of the Nectarian system on the Moon, based on crater statistics (Tanaka, 1984). The number of small craters (>2 km diameter) recorded on surfaces of Noachian-age materials generally exceed 1000 per 10^6 km^2, and larger sizes (>16 km) exceed 100 per 10^6 km^2.

Basement complex (unit Nb) consists of the oldest identifiable rocks in the western hemisphere of Mars (Scott and King, 1984). These rocks are highly faulted, fractured and cratered and have prominent relief. The largest exposures occur in the Claritas Fossae area (lat 25° S., long 105° W.) and are believed to be of tectonic origin (Masursky and others, 1978). Clues as to their composition are obscured because of their high degree of structural deformation. The rough surfaces and bold relief of the basement, however, suggest that these ancient rocks are formed of highly resistant material. Numerous isolated smaller exposures of the basement project above the surrounding terrain. Though highly faulted in places, these "islands" of basement appear to be nontectonic in origin. They resemble erosional remnants of older topography that has been flooded and partly buried by more recent lava flows. Basement rocks also occur in the Tempe Terra plateau (lat 40° N., long 70° W.), an extension of highland terrain into the northern plains. In this region they are not as densely faulted but have prominent relief and underlie all other units. The main body of this material appears to have been uplifted and tilted by high-angle faulting along its western margin. As in the southern region, small isolated peaks project well above the surface of the plateau on which they are situated. Basement rocks are transitional with other complexly faulted material (unit Nf) whose surfaces are smoother and exhibit less relief. The origin and composition of these rocks are also unknown, except that they predate major tectonic episodes that uplifted and faulted the Tharsis-Syria rise (Scott and Tanaka, 1980). All of these basal rock units of the Noachian Period may consist mostly of impact breccias formed during early stages of high meteorite flux, similar to the lunar highlands.

Hilly plateau material (unit Nplh) and fractured material (unit Nf) are two dissimilar and readily distinguishable rock units. Each of these units, however, resembles in part and appears to be integradational in places with the basement complex. The hilly plateau unit forms the lower part of the plateau sequence and is characterized by rough terrain with irregular peaks, ridges, and ancient crater rims with intervening relatively flat areas. It is not highly structured by faulting as is the basement. Fractured material is almost as complexly faulted as the basement but has broad, gently raised surfaces without prominent local relief. Both hilly plateau and fractured units occur adjacent to and embay basement rocks in places; crater counts also support their relative age relations. The origin of units Nplh and Nf is presumed to be in part volcanic, as small- to moderate-size volcanoes commonly are associated with them.

Cratered plateau material (unit Nplc), the most extensive rock unit in the plateau sequence and the Noachian System, is distinguished by a dense crater population in all size ranges. The craters are partly buried as well as superposed, and intercrater areas are rough but without the prominent relief of the hilly plateau unit. Cratered plateau material represents the basic rock unit of the Martian highlands whose surface has been highly modified by post-accretionary meteorite bombardment. It probably consists of lava flows and interbedded breccias distributed as ejecta blankets around the numerous impact craters. Where the unit has been highly dissected by small channels or etched into irregular grooves and hollows by wind, water, or collapse of ground ice, it has been subdivided into dissected (unit Npld) and etched (unit Nple) plateau materials. Many areas throughout the highland terrain are traversed by rough, prominent ridges or small mountain chains having sublinear to irregular traces (unit Nplr). Generally they are less ordered and have more relief than those of the ridged plains material but follow the same regional trends, forming a great arc around the southern extremity of the Tharsis topographic high.

Argyre Planitia, a large (1500-km-diameter) impact basin, formed early during the period of high meteorite flux that shaped the surface of the cratered plateau material, based on the superposed crater density. The knobby hills and mountainous terrain (unit Nam) within and around the major scarp forming the basin wall (unit Naw), is similar to that of the Alpes and Montes Rook formations around the Imbrium and Orientale basins on the Moon (Wilhelms and McCauley, 1971; Scott and others, 1977). The smaller hills may largely be derived from clumps of ejecta originating deep within the crust. The larger coherent blocks appear to be massifs, uplifted and tilted in places by faulting.

Other mountains, hills, and dome-shaped features occur throughout the highlands. Their age is uncertain as stratigraphic relations with adjacent units are generally not clear and their small size does not permit reliable crater counts. Some may be volcanic, others may be part of the basement complex or remnants of hilly plateau material. Collectively they are designated by the symbol (m) and are not assigned a position in the stratigraphic column, although many may belong to the Noachian.

Hesperian System

Many areas within the highlands have been smoothed and subdued by lava flows and eolian deposits of Hesperian age. Crater rims, ridges, and hills remain visible but smaller irregularities that elsewhere contribute to coarse textured intercrater areas are mostly covered. Where the mantling deposits are not thick enough to completely mask the identity of underlying rock units (mostly cratered plateau material), they are mapped as a smoother and younger facies (unit Hpls) of the plateau sequence; crater counts confirm the younger age.

The most extensive lava flows within the Hesperian System are the ridged plains (unit Hpr). These flows, with long, sinuous wrinkle ridges closely resembling those of the lunar maria, constitute the basal rock-stratigraphic unit of the Hesperian on the Mariner map of Mars (Scott and Carr, 1978); they retain this position on the present map. The greatest concentration of ridged plains is in Lunae Planum, the long broad plateau separating Tharsis lava flows from the lowland plains. From this area the ridged plains extend southward across Valles Marineris into Solis Planum where their western edge is buried by the lower member (unit Hsl) of the Syria Planum Formation. They continue in scattered patches around the southern end of the Tharsis topographic high, forming a broad arc whose western extremity extends into Amazonis Planitia. In the Tempe Terra region, a major disconformity is clearly marked by the overlap and truncation of faults and fractures in the ridged plains by younger flows emanating from the Tharsis volcanoes. This boundary is nearly linear for a distance of about 400 km and may be fault controlled.

The Syria Planum Formation and lower members of the Tharsis Montes and Alba Patera formations are closely equivalent in age. Although they all are associated with central volcanic edifices, many of the lava flows consituting these members probably were extruded from fissures in the volcanoes flanks. In particular, some of the older flows from Syria Planum are separated from the main occurrence by a broad expanse of ancient fractured terrain. This part of the Syria Planum Formation, at least, must have originated from some of the numerous faults and fissures whose extensions are largely buried by the lower member which has flooded a wide area centered near lat 45° S., long 105° W. The upper member of the Syria Planum Formation (unit Hsu) appears to have issued from a partly buried caldera-like depression near the crest of the large topographic rise centered at lat 8° S., long 104° W. The older flows (member Hal) from Alba Patera nearly encircle the volcano out to a distance of about 1800 km. They embay the highly fractured terrain around the east edge of Acheron Fossae; elsewhere their outer boundary with plains materials is not clearly defined, except where they are overlapped by the plains member of the Olympus Mons Formation at lat 23° N., long 123° W. The lower, Hesperian age flows of the Tharsis Montes Formation originate from fissures on the lower slopes of Arsia Mons and from around the base of Uranius Patera. They occur as far as 1500-2000 km from the center of the volcanoes and are more subdued by erosion and eolian mantles than the younger and generally higher members.

The Tempe Terra Formation consists of smooth relatively featureless lava flows within a fractured upland region that forms the northern extension of Lunae Planum. It comprises three members that appear to have been erupted from small shield volcanoes, fissures, and collapse depressions. These lava flows blanket cratered plains and highly fractured terrain of Noachian age but are embayed by an older member of the Tharsis Montes Formation and possibly by the lower member of the Alba Patera Formation, although their stratigraphic relations are not very clear.

Materials forming the upper part of the walls (unit HNvw) and parts of the floor of Valles Marineris (unit HNvf) appear competent and form cliffs with light and dark beds. The vast system of channels leading from Valles Marineris and surrounding areas into Chryse Basin are mostly Hesperian in age. The channel and floodplain deposits are overlapped in Kasei Vallis by lava flows from Tharsis Montes and possibly by the upper member of the Syria Planum Formation. As the channels are incised in ridged plains, they are assigned a middle Hesperian age. Crater densities within the channels and floodplains in this region vary from place to place suggesting that water flooding occurred episodically over a considerable period of time. Crescentic depressions that both in size and shape closely resemble meander patterns of terrestrial rivers are recognized within the plains of Acidalia Planitia (Scott, 1982a). They are partly buried by the Arcadia Formation (Amazonian age) but can be identified by narrow central ridges that are characteristic of channel troughs elsewhere in the channel systems. If the inferred association of these features with flooding is correct, then such flooding occurred as far north as lat 45° N. in Acidalia Planitia.

Within Valles Marineris proper, evidence of alluvial processes occur only locally. Small channels, chaotic material, and layered deposits were noted in early investigations of the canyons (Blasius and others, 1977; McCauley, 1978). The layered materials consist of alternating series of light and dark thinly layered material, both horizontal and inclined, that form rounded hills and large flat-topped mesas rising above the canyon floors. The dissimilarity in appearance between canyon wall and layered floor materials, as well as their contrasting patterns of erosion, suggests that their modes of origin were different. One of the hypotheses (McCauley, 1978) advanced to account for the layered floor deposits is that they are waterlaid sediments that accumulated in large lakes within the canyons; their deposition was followed by episodes of catastrophic draining throughout the canyon systems. Materials eroded from canyon walls and eolian material were the source of the sediments. Peterson (1981) has ascribed their occurrence in Hebes Chasma to pyroclastic infilling of the chasma from sources beneath the floor.

Amazonian System

The Amazonian System as originally defined (Scott and Carr, 1978) included relatively young, featureless materials mostly covering the lowland terrain that lies below the 0-km-elevation datum. On the low-resolution Mariner images, the plains appeared flat to gently rolling with few topographic irregularities. They were believed to consist largely of lava flows with variable amounts of eolian cover; on the basis of rather broad morphologic variations, they were classified as smooth plains, cratered plains, and volcanic plains of Tharsis Montes. On the present map, these materials and other young rock units have been further subdivided and, where practicable, assigned formation names.

The northern plains assemblage contains the Arcadia and Vastitas Borealis Formations, the major geologic units of the northern lowlands. They are separated from the more rugged plateau-forming highlands to the south by a highly dissected erosional scarp that is discontinuous and irregular on both local and regional scales. The lava flows of the plains embay the highland frontal scarp and do not represent an older residual surface exposed by erosion and scarp retreat (Scott, 1978). The Arcadia Formation consists of six members, all lava flows, whose age range spans the Amazonian Era; all of the unit members are exposed within Arcadia Planitia. With the exception of the younger flows, their common boundaries are intergradational; in places, they are mapped arbitrarily on the basis of variations in crater density or slight differences in texture and albedo. Lobate flow fronts, pressure ridges, small volcanoes, and collapsed lava tubes or lava channels are commonly visible on high resolution images. The oldest member of the Arcadia Formation is transected by a large channel in the western part of the map area; crater counts indicate that this channel is very young and that flooding occurred during the middle to upper part of the Amazonian Era. Numerous small shield volcanoes and fault fissures are believed to be sources of the Arcadia Formation lava flows.

The Vastitas Borealis Formation consists of four members: mottled plains, knobby plains, ridged plains, and grooved plains. The mottled plains form an extensive zone that nearly encircles the planet between about lat 50°-70° N. Mariner pictures were degraded in this region by atmospheric haze and high-sun angles that combined to produce a blurred appearing surface with high albedo contrast. Viking images show that contrasting light and dark patches are due chiefly to relatively small- to moderate-size impact craters whose ejecta blankets are much brighter than intercrater areas. The ejecta blankets are of various ages, but even the older ones are lighter than the background surface. Intercrater areas have numerous conical hills whose crests are darker than their flanks; some hills have summit craters and may be of volcanic origin. Where the hills are very closely spaced and have higher albedo, they are mapped as a separate, knobby member (Avk) of the formation. The ridged and grooved members are characterized respectively by whorl-like patterns of ridges resembling fingerprints, and irregular to polygonal-shaped troughs as much as 20 km across. It is difficult to tell whether the ridge textures reflect primary or secondary surface forms; the grooves and troughs were probably produced by tectonic, contraction, or periglacial processes (Carr and Schaber, 1977; Pechmann, 1980) and have been enhanced by erosion. Stratigraphic relations between the Arcadia and Vastitas Borealis Formations are unclear except in Acidalia Planitia where the lower member of the Arcadia Formation overlies the grooved and ridged members of the Vastitas Borealis Formation.

The origin of the Western Volcanic Assemblage is clearly evident from its geologic setting and the morphologic similarity of its mountains to terrestrial volcanoes. Identifying features include prominent relief, circular form, presence of summit calderas, encircling grabens and faults, pit craters, flow fronts, lava channels and tubes. The Western Volcanic Assemblage consists of six formations shown on the correlation chart (Plate 2). With the exception of Syria Planum and lower part of Alba Patera, Tharsis, and Medusae Fossae Formations, they are Amazonian in age. The areal distribution of these lava flows and volcanoes greatly exceeds the original conception of the limits of the Tharsis volcanic region (Scott, 1982b).

The Tharsis Montes Formation and its giant volcanoes form the best known volcanic sequence on Mars. These shield volcanoes and their associated lava flows cover about 18 million km^2, more than twice the area of the conterminous United States. The formation has been subdivided into six members that were extruded from the summits and flanks of the volcanoes. The lava flows spread across a broad, gently arched plateau and appear to have had low viscosities, allowing individual flows to extend far from their sources. Their relative ages were determined mainly by their stratigraphic relations and by morphology of the flows. Crater counts on the various members were made to verify these age relations and to obtain some degrees of correlation between flows in widely separated areas where overlap relations could not be established. The eruptive sequence of members of the Tharsis Montes Formation appears to have been nearly continuous throughout the volcanic history of the region. Textural details associated with even some older flows retain morphologic features characteristic of the younger members, including tongue-shaped individual flow units with lobate fronts. These observations, together with the relative absence of faults and fractures transecting the flows and low crater densities indicate that Tharsis volcanism mostly occurred late in Martian history.

The oldest members of the Olympus Mons Formation are the aureoles of grooved and ridged terrain surrounding the volcano. Their origin and composition are controversial. Such features as light color, wind-scoured surfaces, broad areal extent, and distribution patterns suggest that they may consist of welded and non-welded ash-flow tuffs (Morris, 1982). However, they exhibit other features not generally associated with pyroclastic material on earth and may be caused by gravity spreading (Francis and Wadge, 1983), perhaps with the aid of ground ice (Tanaka, 1983). The relative ages of the aureoles with respect to most other lava flows in the Tharsis region can be only broadly determined. Stratigraphic relations show that the aureoles are overlapped by the postscarp extrusives of Olympus Mons (member Ao5) which, in turn, are buried in places by flows of Olympus plains (member Aop). The lowermost aureole unit (member Ao1) clearly overlaps fractured terrain of Hesperian age (unit Hf). Crater counts are of little value in relative age determinations of the aureole deposits because their rough and apparently soft surfaces promote rapid deterioration of crater forms by mass wasting; thus their crater densities are abnormally low compared with younger plains that embay the aureoles in places (Morris, 1982). Their position in the stratigraphic column is provisional. The two youngest members of the Olympus Mons Formation consist of lava flows originating from the flanks and summit of Olympus Mons and from fissures in the plains east of the volcano. The plains member partly encircles Olympus Mons on the east within a topographically low area between the volcano and its aureole deposits. Both of the members postdate formation of the basal scarp surrounding the volcano. Prescarp lava flows from Olympus Mons, though not mapped, may exist; in places, flow lines appear to be sharply truncated at the scarp and exposures of more mature surfaces occur in windows along its raised edge.

The younger flow member (Aau) of the Alba Patera Formation fills a large circular area (600 km diameter) around the partly buried caldera at the crest of the volcano. It covers radial and concentric faults that transect middle (Aam) and lower (Hal) members of the formation. Lava flows of the Ceraunius Fossae Formation originate from a complex of fracture systems associated with highly faulted terrain between Ascraeus Mons and Alba Patera volcanoes; they extend northeast-southwest across a broad saddle between these two volcanoes. The flows bury most of the fissures from which they were extruded and cover the lower member of the Alba Patera Formation. They are overlapped by the plains member of the Olympus Mons Formation and by some members of the Tharsis Montes Formation.

The Medusae Formation consists of a series of rock units that are believed to represent ignimbrites (Scott and Tanaka, 1982). They are distributed along an east-west border zone between the highland plateau and lowland plains of Amazonis Planitia. The materials interpreted to be ignimbrites are massive deposits without visible bedding on high-resolution Viking images. They have smooth, flat to gently rolling surfaces and closely resemble welded and nonwelded ash-flow tuffs within the Basin and Range Province of the western United States. In places where the softer, possibly nonwelded, upper parts of the deposits have been stripped by wind erosion, the underlying material shows fracture patterns resembling complementary joint sets in terrestrial welded tuffs. Surfaces of the deposits are less hilly and cratered than those of the highlands, but have more relief and are lighter colored than lavas forming the plains. The postulated ignimbrites lack the lobate, tongue-shaped fronts and pressure ridges on many Martian lava flows. The formation was originally subdivided into seven units (Scott and Tanaka, 1982) which have been combined into three members on this map.

Surficial materials of eolian, landslide and debris flow, periglacial, and volcanic origin occur in various localities throughout the western hemisphere of Mars. Eolian deposits are concentrated in low areas where they mantle underlying terrain; on high-resolution pictures, yardangs and dune forms of various types are visible in places. Wind plumes in the lee of surface obstacles form long bright streaks across the lowland plains; in some areas the streaks are dark colored and may represent patches of older rocks laid bare by erosion or consist of dark, relatively fresh volcanic materials. Landslides and debris flows are common in Valles Marineris and may form the large, spatulate, concentrically striated and ribbed patterns on the northwest flanks of the Tharsis volcanoes, and on a smaller scale at Olympus Mons. The largest mantling deposits are the smooth plains which cover the floors of many craters, valleys, and other low areas. The smooth plains materials are more common and thicker in older craters than in younger ones and reflect a wide age range as indicated by crater counts. In some places they may consist of lava flows extruded from fractures in crater floors as on the Moon and Mercury; in other areas they consist of eolian and alluvial deposits.

STRUCTURE

Stratigraphic relations of structurally deformed surfaces have provided new and more complete determinations of the tectonic history for the region. Intermediate- and late-stage tectonism in the map area is mostly related to or associated with the Tharsis uplift. Relations of older, regional structures to Tharsis are unclear. Such structures include: (1) a NE-trending set of grabens in Thaumasia Fossae that appear to radiate from the eastern part of Sinai Planum, (2) NW- to N-trending volcanoes in the Phaethontis and Thaumasia quadrangles and a NW-trending scarp at the south edge of Claritas Fossae

(Scott and Tanaka, 1981), (3) the semicircular, elevated Acheron Fossae arch containing concentric faults and volcanic structures, and (4) possible ancient fractures associated with initial structural development of Valles Marineris (Masson, 1976).

Radar profiles (Downs and others, 1982) and estimated thicknesses of Tharsis lavas (De Hon, 1982) suggest that the ensuing uplift of the NE-trending, elliptically-shaped Tharsis bulge may have been as much as 7 km. The cause of formation of the Tharsis bulge is speculative; proposed models include isostatic uplift followed by flexural loading (Banerdt and others, 1982), crustal thickening by intrusion (Willemann and Turcotte, 1982), and locally thin lithosphere (Solomon and Head, 1982). Our mapping suggests that development of the Tharsis bulge involved a complex history of episodic tectonism and volcanism at local and regional scales. The major fault systems of Tharsis trend northeast to north and radial to a sequence of centers at Syria Planum and Pavonis Mons (Wise and others, 1979; Plescia and Saunders, 1982) and occur in the basement terrain (units Nf and Nb) of Thaumasia Fossae, Claritas Fossae, Ceraunius Fossae, Acheron Fossae and Tempe Terra; the fractured plateau rocks (unit Hf); and the volcanic rocks of the Alba Patera, Syria Planum, and Tempe Terra Formations. The radial trends deviate around local, circular structures that include Alba Patera, localities within Tempe Terra, and Syria Planum-Noctis Labyrinthus.

This period of intense Tharsis faulting was followed by the formation of wrinkle ridges on smooth surfaces of Hesperian-age (unit Hpr) and older plateau sequence rocks. The ridges have trends that broadly arc around the Tharsis uplift at distances of up to 3,000 km from the Tharsis center and are N-S in the eastern part of the map area. Further observations about these ridges include: 1) they mostly predate, although a few postdate, Kasei Vallis (unit Hch); 2) they occur on smooth material that postdates intense faulting in Thaumasia and Tempe Terra; 3) they locally aline with and fill linear depressions (e.g. lat 26° N., long 78°), and 4) they locally grade into large, linear edifices interpreted as volcanoes (e.g., lat 46° S, long 172°). Proposed origins of ridges include: compressional folding associated with Tharsis uplift (Wise and others, 1979; Watters and Maxwell, 1983), compressional folding caused by contraction of the planet's surface (Gifford, 1981), and eruption of volcanic material along structurally controlled, linear trends (Greeley and others, 1977). The occurrence and N-S alinement of wrinkle ridges outside of the Tharsis region indicate that they are related to a global stress pattern. Perturbations of the stress field caused by Tharsis tectonism and other local impact and volcanic structures could account for variations in the N-S trends of the ridges.

Formation of the northern plains apparently followed ridged-plains formation, although relationships are unclear because of probable extensive erosion along the highlands-lowlands boundary. Ridged plains (unit Hpr) are overlain by materials of the northern plains assemblage in Chryse Planitia. Several postulated explanations for the formation of the northern plains are: break-up of the crust due to a volume-expanding phase change in the mantle (Mutch and Saunders, 1976), subcrustal erosion and crustal foundering caused by mantle convection (Wise and others, 1979), and impact by an immense object (Wilhelms and Squyres, 1984).

Following northern plains formation, Tharsis fault activity was revived, but at much lower intensity, causing sporadic faulting in parts of the ridged plains and plateau sequence rocks and the Tharsis Montes, the Medusae Fossae, Alba Patera, Arcadia, Tempe Terra, and Olympus Mons Formations. Late-stage caldera and concentric graben formation has occurred on many of the Tharsis volcanic structures. Gravity studies suggest that the Tharsis bulge is at least partly compensated at present (Phillips and others, 1973). Complete isostatic compensation of Tharsis at great depth has been modeled with variable crustal thickness and mantle density (Sleep and Phillips, 1979).

Other local structural features occur in the western region of Mars. Ancient impact basins are mostly buried and highly degraded but exert structural and topographic control on channels, mare ridges, fretted terrain, and perhaps other features (Schultz and others, 1982). Relatively recent vertical faulting and expansion within the Valles Marineris canyon system has offset canyon wall and floor materials (Blausius and others, 1977). A scarp appears along the north edge of Argyre Basin which probably formed during or soon after the basin-forming impact. Such scarps are commonly found encircling impact basins on the Moon. Origin of the basal scarp of Olympus Mons is controversial; ideas have included deep-seated vertical tectonism (Mutch and others, 1976) and processes occurring at the surface that are related to the formation of the aureole deposits of Olympus Mons (Lopes and other, 1980; Morris, 1981; Tanaka, 1983).

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