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ATLAS OF MARS
1:5,000,000 GEOLOGIC SERIES
ELYSIUM REGION
25/210 G, 1992
MAP I-2147

GEOLOGIC MAP OF THE ELYSIUM REGION OF MARS

By
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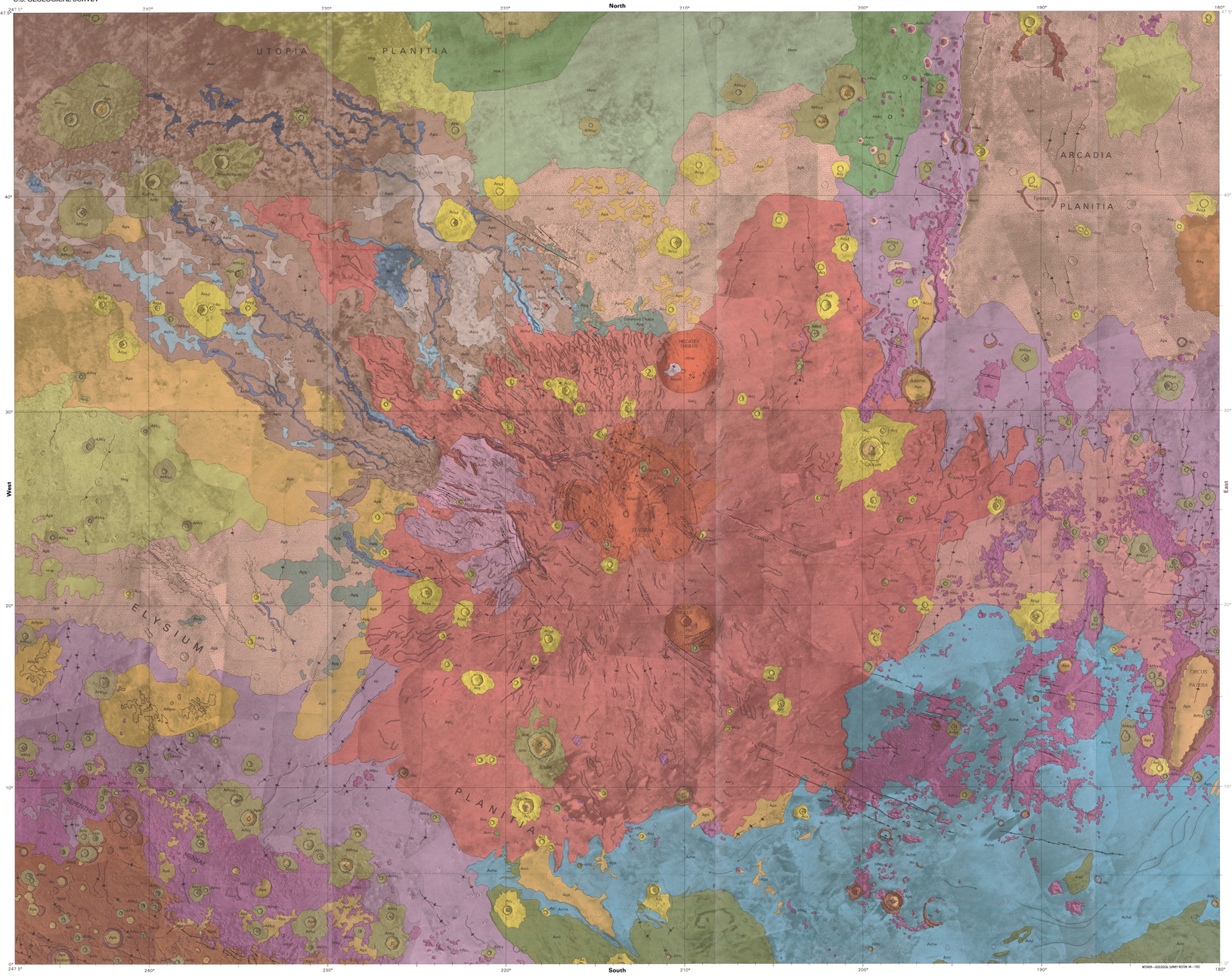
1992



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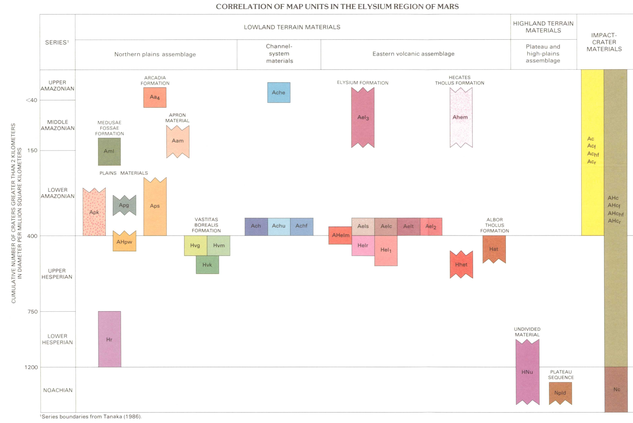
SCALE 1:5 000 000 (1 mm = 5 km) at 0° LATITUDE
MERCATOR PROJECTION

0 100 50 0 KILOMETERS 100 200 300 400 500 600 700 800 900 1000

CORRELATION OF MAP UNITS IN THE ELYSIUM REGION OF MARS



*Series boundaries from Tanaka (1986)

DESCRIPTION OF MAP UNITS

[The origin and composition of many units are obscure or controversial, but their interpretations are based on observations of morphologic characteristics and analogies with Earth and Moon. Many of the units were previously described and mapped at 1:15,000,000 scale by Scott and Tanaka (1986) and Greeley and Guest (1987); we adhere to their unit nomenclature and interpretations where possible]

LOWLAND TERRAIN MATERIALS

[Consist of low-lying deposits in plains areas of Elysium region]

Northern plains assemblage

[Widespread materials of northern plains]

Arcadia Formation—Members 1–3 and 5 not present in map area

Member 4—Forms smooth surface; lobate fill of Arcadia basin; sparsely cratered. Forms low-lying plains in Arcadia Planitia in northeastern part of map area. Buries knobby plains material; partly buried by Elysium flood-plain deposits east of map area. *Interpretation:* Lava flows.

Medusae Fossae Formation—Upper and middle members not present in map area

Lower member—Consists of three thick, extensive, relatively flat sheets in southern Elysium Planitia; light colored; highly friable. Sheets characterized by different scarp textures; smooth and gently rolling, rugged and pitted, and ridged. Smooth surface overlies, in part, rugged surface between long 180° and 188° (informally mapped by Scott and Tanaka, 1982, as ignimbrite units 1 and 3, respectively); ridged surface exposed from long 200° to 221° and overlies rugged surface. Ridged plains that parallel outcrop pattern, especially along south-central edge of map area. Overlies ridged plains material and overlain by Elysium flood-plain deposits. *Interpretation:* May be pyroclastic, paleopolar, or aeolian materials; ridges may be yardangs controlled by joints (Ward, 1979)

Aam **Amazonian material**—Smooth, light colored; craters rare; on lower slopes of Pavonis Mons and on slopes of nearby isolated knobs to the northwest. *Interpretation:* Debris aprons formed by mass wasting of scarp-rock materials

Apk **Knobby plains material**—Relatively smooth deposits marked by knobs in Elysium and Utopia Planitiae; materials commonly cut by polygonal, grooved, smooth, warped, and ridged plains materials; with grooved member of Vastitas Borealis Formation; and with member 1 of Elysium Formation. *Interpretation:* Formed by degradation of ice-rich, relatively high standing lowland plains materials (ridged and grooved plains materials and Elysium lava flows)

Apg **Grooved plains material**—Cut by grooves into polygonal shapes that form blocky mesas surrounded mainly by knobby plains material. Recognized north and west of Elysium Mons, adjacent to or near flows of Elysium Formation. *Interpretation:* Distal Elysium lava flows broken by flowage of subsurface material; may be result of ground-ice melting induced by volcanism

Aps **Smooth plains material**—Generally featureless; moderately cratered. Occurs as extensive plains in lowlands west and south of Elysium rise, as smooth areas within knobby plains materials north of Elysium rise and highland scarp, and as crater fill throughout map area. *Interpretation:* Probably various materials having smooth surfaces at image resolution, including lava flows and fluvial, mass-wasted, and eolian deposits

Ahtqse **Warped plains material**—Forms rugged plains marked by irregular depressions and scarps. Gradational with ridged and knobby plains materials. *Interpretation:* Ridged plains material degraded by thermokarst processes

Vastitas Borealis Formation—Widespread, higher latitude plains deposits of northern lowlands. Members distinguished on basis of chief morphologic and albedo characteristics; contacts between members commonly gradational. Superposed craters generally exhibit broad ejecta blankets, indicating high fluidization during emplacement

Grooved member—Marked by curvilinear and polygonal patterns of grooves and troughs; grooves as long as 20 km; contains subtle annular collapse features. Grooves and troughs characterize an eastern extension of Adamas Labyrinthus west of long 241°; also recognized west of Mie crater and near northeast corner of map area where grooves are wide and broadly spaced. Embayed by knobby and smooth plains materials; partly buried by cosme member of Elysium Formation. *Interpretation:* Possibly collapsed and compacted, ice-rich alluvial, eolian, or volcanic materials

Hvm **Mottled member**—Characterized by bright crater ejecta (particularly from Mie crater) and other high albedo areas interspersed with dark plains. Embayed by knobby plains material; partly buried by cosme members of Elysium Formation. *Interpretation:* Ice-rich sediments; may be dominantly fine-grained fluvial or eolian deposits, partly buried by Elysium flood-plain deposits east of map area. *Interpretation:* Lava flows

Hvk **Knobby member**—Consists of plains marked by abundant, low knobs. Embayed plains and highland remnants west of Phlegra Montes; probably surrounds Mie crater. *Interpretation:* Sedimentary plains deposits and remnants of old high plains materials

Hr **Ridged plains material**—Forms smooth plains marked by long, broad wrinkle ridges; moderately cratered. Embays knobs of undivided material; cut by flows of Elysium Formation. Wrinkle ridges trend north in northeastern part of map area, but have various trends in southeastern part. *Interpretation:* Lava plains deformed by surface compression

Channel-system materials

Achv **Elysium flood-plain deposits**—Smooth; dark to mottled with local wispy, light and dark, sinuous, exposed craters rare. Exhibits flow patterns of contrasting albedo. Unit covers lowlands throughout southeastern part of map area. Source channels cut smooth plains material (unit Aps) below west terminations of Cerberus Rupes; outflow channels cut ridged plains material north of Orcus Patera. *Interpretation:* Extensive, thin alluvial deposits consisting of locally ice-rich sandy materials

Achd **Channel deposits**—Materials within channels that originate from troughs and fractures along northwest base of Elysium rise and extend northwestward into Utopia Planitia. Unit embays coarse and smooth members of Elysium Formation; channels cut by knobby plain material. Channel courses may be meandering or braided; channel patterns locally polygonal (fracture controlled). *Interpretation:* River bed material deposited by floods that discharged ground water through fissures

Achu **Utopia flood-plain deposits**—Forms smooth plains along channel courses in Utopia Planitia. *Interpretation:* Distal Elysium lava flows broken by flowage of subsurface material; may be result of ground-ice melting induced by volcanism

Achd? **Channel-lan deposits**—Form broad, fan-shaped deposits; cut by narrow channel distributaries at end of or alongside main channels. Recognized along Apsus Valles (where fans overlap) and along Granicus Valles. *Interpretation:* Alluvial fans formed when stream gradients were lowered

Eastern volcanic assemblage

Elysium Formation—Volcanic materials associated with Elysium Mons; descriptions of members differ from Greeley and Guest (1987)

Axelg **Member 3**—Consists of small, low flows that bury and overlie adjacent shield materials; adjacent to a thermal-inertia anomaly. Occurs on west flank of Elysium Mons. Unit not recognized by Greeley and Guest (1987). *Interpretation:* Lavas and (or) late-stage pyroclastic flows erupted from local fissures or grabens

Axelf **Smooth member**—Forms smooth surfaces, mostly superposed on coarse member; edges either lobate like lava flow fronts or severely degraded into subdued polygonal patterns. Locally cut by channels. Occurs northwest of Elysium rise in Utopia Planitia. Included by Greeley and Guest (1987) in their member 3. *Interpretation:* Friable volcaniclastic flows originating from Elysium Fossae at base of Elysium rise

Axelc **Coarse member**—Flows rugged, heavily pitted, and degraded; edges commonly resemble those of lava flows. Flow sources are long, linear depressions and fractures of member 2 or trough member. Moderately cratered; superposed and partly buried crarters have highly fluidized ejecta blankets. Widespread in map areas near southwest and southeast corners of map area and in Phlegra Montes. Embayed largely by ridged plains material, members of Elysium Mons Formation, and Elysium flood-plain deposits. North of lat 30° N., many high outcrops have produced debris aprons (unit Aam). *Interpretation:* Ancient crustal material comminuted by intense bombardment and degraded by removal of ground-ice cement

Axelj **Trough member**—Consists of wall and floor materials within troughs that cut member 2 and rugged members of formation; troughs associated with fractures, channels, lava flows, and large flows that cover Utopia Planitia (coarse and smooth members of formation). Occurs on steep, lower west flank of Elysium Mons. Mapped by Greeley and Guest (1987) as part of their member 4. *Interpretation:* Lava flows, slope deposits, and fluvial deposits; troughs enlarged from fractures by fluvial and volcanic erosion and mass wasting

Axels **Member 2**—Flows moderately fractured, pitted, and cratered; flow scarps and channels common. Impact-crater blankets commonly have radial or fluidized texture; some craters both overlie and are embayed by unit. Widespread, covering most of Elysium rise and parts of surrounding plains; flows originate from Elysium Mons and associated fissures. Unit embays older flows, Hecates and Albor Tholi, and ridged plains material. Mapped by Greeley and Guest (1987) as main part of their member 1. *Interpretation:* Lava flows of latest widespread volcanic activity in area

Ahelm **Mons member**—Marked by radial flows, rilles, and sinuous ridges; locally cut by concentric grabens and wrinkle ridges. Unit embayed by member 2 flows and includes some flows of member 2 age. Impact-crater blankets are small and fluidized or have radial texture. Covers upper part of Elysium Mons shield; summit caldera cut by small channels. Mapped by Greeley and Guest (1987) as their member 2. *Interpretation:* Lava flows erupted from caldera and upper flanks; radial ridges may indicate tube-fed and leveed flows

Hetf **Rugged member**—Rugged character caused by flow scarps, fractures, channels, small ridges and domes. Recognized along steep west side of Elysium rise. Overlain by member 2 flows. Unit not recognized by Greeley and Guest (1987). *Interpretation:* Complex of lava flows and eruptive vents disrupted by steep topography, ground-water discharge, and fracturing

Hel? **Member 1**—Forms broad, lobate, degraded flows, some warped by wrinkle ridges; included, degraded outcrops along east edge of map area. Superposed impact-craters blankets moderately to highly fluidized, some partly eroded away. Covers ridged plains material in east-central part of map area. Unit not recognized by Greeley and Guest (1987). *Interpretation:* Friable lava or pyroclastic flows; erosion of craters aided by ground-ice interaction

Hecates Tholus Formation

Hetm **Mantle member**—Characterized by subdued, uncratered surface. Forms small patch west of summit caldera of Hecates Tholus. *Interpretation:* Late-stage pyroclastic air-fall deposit from summit caldera

Hetlava **Tholus member**—Lobate flows not apparent but channels common. Forms most of volcano surface of Hecates Tholus; largely surrounded by member 2 of Elysium Formation. *Interpretation:* Pyroclastic flows and air-fall deposits; channels may be carved by running water or ash flows

Hat **Albor Tholus Formation**—Forms rugged surface of Albor Tholus; some flows; channels absent. Tholus has relatively large summit caldera. Surrounded by member 2 of Elysium Formation. *Interpretation:* Lava flows of composite or shield volcano

HIGHLAND TERRAIN MATERIALS

Plateau and high-plains assemblage

Nplf **Undivided material**—Forms knobby remnants of ancient heavily cratered terrain of Noachian age interspersed with mass-wasting products and sediments of Hesperian age. Includes dense population of large, highly degraded craters. Recognized in high areas near southwest and southeast corners of map area and in Phlegra Montes. Embayed largely by ridged plains material, members of Elysium Mons Formation, and Elysium flood-plain deposits. North of lat 30° N., many high outcrops have produced debris aprons (unit Aam). *Interpretation:* Ancient crustal material comminuted by intense bombardment and degraded by removal of ground-ice cement

Nplu **Dissected unit of the plateau sequence**—Highly cratered uneven plateau surface dissected by numerous small channels and marked by grabens and ridges; adjacent to undivided material. Older craters commonly rimless, lack visible ejecta; younger craters have fluidized blankets. Forms plateaus in southwest corner of map area. *Interpretation:* Early bombarded crust eroded by water and wind.

IMPACT-CRATER MATERIALS

[Materials of impact craters whose rim diameters are larger than 10 km. Subscripts of Hesperian and Amazonian craters denote type of ejecta flow, where observable: f, moderately fluidized (lobate, rampart flows extending less than one crater diameter from crater rim); fl, highly fluidized (ejecta blanket extends farther than one crater diameter from crater rim); and r, radial pattern (radial ejecta and secondary craters)]

Aic **Amazonian crater material**—Superposed on Amazonian units. Most craters fresh, bowl shaped; many craters larger than about 30 km diameter have central peaks; ejecta blankets generally well preserved. Some craters degraded where emplaced on easily degraded materials such as lower member of Medusae Fossae Formation and northern part of Utopia Planitia

Hai **Amazonian and Hesperian crater material**—Superposed on Noachian or Hesperian units; similar in appearance to Amazonian crater material

Nc **Noachian crater material**—Recognized on Noachian units; ejecta blankets largely buried or eroded away; crater rims degraded

Contact—Dashed where approximately located or gradational

Fault or narrow graben—Bar and ball on downthrown side

Fracture

Ridge—Symbol on ridge crest

Scarp—Line marks top of slope; barb points downslope

Lobate scarp—Ticks on lower side

Narrow channel or rille

Flow direction

Depression

Rimcrest of impact crater—Well preserved and defined

Rimcrest of inferred impact crater—Highly degraded or buried

Central peak of impact crater

INTRODUCTION

The region centered at Elysium Mons contains the second largest volcanic complex on Mars, surpassed in size by only the Tharsis complex. The Elysium region also has been a center of tectonic, fluvial, and mass-wasting activity. After degradation of ancient cratered terrain within the northern lowlands, volcanic rocks erupted from Elysium Mons, Hecates Tholus, and Albor Tholus in Elysium Planitia. The volcanic activity was associated with episodes of channel formation, faulting, and apparent volcano/ground-ice modifications of some areas. On this map sheet we portray, describe, and interpret the rich geologic history of the region.

This map is the first to show the detailed geology of the Elysium region on a single map base made from Viking images. The base is a combination of three quadrangles: the south half of MC-7, the east half of MC-14, and all of MC-15. Combining the quadrangles required recompilation of MC-7, which was previously produced in the Lambert projection. The medium-resolution Viking images used also formed the basis of the 1:2,000,000 scale subquadrangle series.

Earlier maps of the area at 1:5,000,000 scale based on Mariner 9 data were produced by Scott and Allingham (1976; MC-15), Elston (1979; MC-7), and Hiller (1979; MC-14). However, the low-resolution Mariner 9 frames taken with the A camera, which were the only images then available for most of the map area, are of insufficient resolution and quality to distinguish many important geologic landforms such as flow scarps, crater-ejecta blankets, and channels, as well as contacts and topographic and albedo features. Some landforms were observed on the higher resolution B-camera images (for examples, see Malin, 1977), but these images have small areal coverage. Global-scale maps based on Mariner 9 (Scott and Carr, 1978) and Viking (Greeley and Guest, 1987) data show the region entirely in Mercator projection but at 1:25,000,000 and 1:15,000,000 scales, respectively. At 1:5,000,000 scale, we are able to map more geologic units and structures and to explain the geologic history in greater detail; the present map includes many significant additions and changes in stratigraphy, structure, and the placement of contacts. We also incorporated the results of recent research on geologic and geophysical processes and events in the Elysium region (in particular, Janle and Ropers, 1983; Mougnis-Mark and others, 1982, 1986; Mougnis-Mark, 1985; Hall and others, 1986; Christiansen, 1989). In addition, stereogrammetric topographic mapping of the region has been improved to about 1,000-m precision (U.S. Geological Survey, 1989).

PHYSIOGRAPHIC SETTING

Elysium Mons, whose summit elevation is 16,000 m above the Martian datum, is at the crest of a regional topographic rise that emerges steeply and abruptly from Elysium and Utopia Planitiae (mostly -2,000- to 0-m elevation) to the west and north; the rise grades gently downward into southern Elysium Planitia to the south and into Amazonis Planitia about 2,000 km to the east (both mostly lower than -1,000-m elevation; fig. 1). The steepest part of the rise is contained within a 1,000-km-diameter circle centered on Zephyria Fossae along the west base of Elysium Mons; the north and west edges of the rise are more sharply defined by a break in slope, as shown on an Earth-based radar profile (Mougnis-Mark and others, 1984). The rise lies north of the circumglobal highland-lowland boundary scarp (Greeley and Guest, 1987), which reaches its southernmost latitude in Elysium Planitia; the scarp cuts across the southwest corner of the map area. Hecates and Albor Tholi both rise to 8,000 m elevation (fig. 1); however, ultraviolet spectrometric altimetry (Hord and others, 1974) indicates an elevation of 6,000 m for Hecates Tholus. The relief of Hecates is about 6,000 m and the relief of Albor is only about 4,000 m, because Hecates is on the edge of the rise whereas Albor is on it. Hecates and Albor Tholi have overall steep flanks, but Elysium Mons steepens near the summit: photogrammetric measurements of Elysium Mons indicate that the average slope is 4.4°, but on the south side near the summit slopes are as steep as 18° (Blasius and Cutts, 1981). Lava flows emanated from Elysium Mons and peripheral fissures, covering the Elysium rise as far as 1,500 km east of the Elysium Mons summit.

Although heavily cratered terrain is generally rare north of the highland-lowland boundary scarp elsewhere on Mars, extensive patches of highly degraded, knobby cratered terrain are recognized in the eastern part of the map area. These patches commonly form broad, north-trending ridges; the most prominent ridge makes up Phlegra Montes, a major topographic and tectonic feature in the northern plains. North and west of the Elysium rise, plains materials consist of degraded knobby and grooved materials.

The long, sinuous outflow channels that make up Granicus, Hrad, and Tinjar Valles in Utopia Planitia emanate from fractures and depressions in the steep northwest flank of the Elysium rise and cut thick, coarsely textured volcaniclastic flow deposits. Shallow channels emerge from Cerberus Rupes on the gently dipping southeast flank of the rise; channel material grades into extensive smooth plains in southeastern Elysium Planitia and was deposited amongst knobs of degraded cratered terrain east of the rise.

STRATIGRAPHY

Geologic units were identified and mapped on individual Viking images as well as 1:500,000- and 1:2,000,000-scale photomosaics; resolutions of most images used range from 50 to 300 m/pixel. Higher resolution images (10 to 50 m/pixel) are available for some locations. The formal terminology of geologic units follows that of Scott and Tanaka (1986) and Greeley and Guest (1987) where applicable; some units are renamed and some new units are introduced. In many places, interpretations and contacts of previously mapped units were revised to reflect information visible on high-resolution images and mappable at 1:5,000,000 scale. In particular, our work resulted in remapping the four members of the Elysium Formation delineated by Greeley and Guest (1987) into 14 units of the eastern volcanic assemblage and channel-system materials.

Relative ages of the units were established by stratigraphic relations and by crater size-frequency distributions. Stratigraphic positions of map units relative to stratigraphic series defined by Tanaka (1986) (subdivisions of the three Martian time-stratigraphic systems of Scott and Carr, 1978) are shown on the correlation chart. Crater-density boundaries for the series, also shown on the correlation chart, were useful in determining stratigraphic positions for several lay units from crater counts (table 1, fig. 2). Some stratigraphic relations noted in our map were previously determined by Greeley and Guest (1987).

The map units are broadly categorized into lowland terrain materials (northern plains assemblage, channel-system materials, eastern volcanic assemblage), highland terrain materials (plateau and high-plains assemblage), and impact-crater materials. Significant geologic features mapped include lobate flow fronts, wrinkle ridges, scarps, grabens, fractures, calderas, channels, and impact-crater rims and central peaks. Only materials of impact craters that have rimcrest diameters larger than 10 km are mapped; the materials are assigned relative ages according to the three time-stratigraphic systems on the basis of overlap relations with strata. Many of the Hesperian and Amazonian crater-ejecta blankets can be observed in sufficient detail to identify blanket morphology; three types of blankets indicating degree of fluidization were mapped according to the scheme of Mougnis-Mark and others (1984).

NOACHIAN SYSTEM

The Noachian System consists of ancient crustal rocks formed during heavy to waning impact flux. Bombardment, combined with intense and pervasive surface erosion, has erased, degraded, or obscured many of the primary morphologic features of Noachian units. Thus Noachian surfaces are generally characterized by impact and erosional features. Lower Noachian rocks, primarily made up of the ancient basement, have not been identified in the Elysium region. However, formation of the northern lowlands possibly occurred during Early Noachian time (Tanaka, 1986).

The best preserved Noachian rocks in the Elysium region make up the dissected *unit of the plateau sequence* (unit Npld), which forms highland terrain near the southwest corner of the map area. This unit most likely consists of impact breccias and ancient crustal material largely formed during the Middle Noachian; the unit's surface has been modified by valley dissection and wrinkle ridge formation. These modifications preceded emplacement of ridged plains material and therefore occurred in Middle to Late Noachian time. Similar erosion took place planetwide, resulting in degradation of most poorly consolidated materials (Tanaka, Scott, Frey, and others, 1988; Maxwell and McGill, 1988). *Noachian crater material* (unit Nc) therefore consists of degraded crater rims and adjacent hilly material interpreted to be remnants of ejecta blankets.

Noachian mass wasting, erosion, and scarp retreat were particularly pronounced along the highland scarp and in the northern lowlands. In these areas, ancient cratered terrain was degraded into knobby terrain infilled by mass-wasted debris and other plains materials through Early Hesperian time (Greeley and Guest, 1987; Maxwell and McGill, 1988). The resulting materials have been mapped collectively as undivided material (unit HNu). Decomposition of the cratered terrain may be related to ground-ice removal (Greeley and Guest, 1987) or melting caused by all intrusives and others, 1987; Wilhelms and Baldwin, 1989). East of the Elysium rise, undivided material crops out in areas that have been high standing since the Noachian. Some of these outcrops form broad, north-trending ridges such as Phlegra Montes. Although the knobs are generally rounded, knobs in some areas (for example, those at lat 17° N., long 199°) have flat, angular surfaces and steep flanks apparently produced by faulting (Scott and Allingham, 1976). The undivided material is cut by west-northwest-trending grabens about 5 km wide that postdate most of the mass wasting.

HESPERIAN SYSTEM

The Hesperian System on Mars records extensive ridged plains volcanism (Lower Hesperian Series) followed by more centralized volcanic activity and widespread resurfacing of the northern plains (Upper Hesperian Series). The impact flux declined during the Hesperian, and cumulative erosion of *Amazonian and Hesperian crater material* (unit AHc) has been less than that of Noachian crater material.

Ridged plains material (unit Hr) buries and embays heavily cratered terrains in lowlands southwest of Elysium Mons. The unit's surface is smooth and relatively pristine. Wrinkle ridges typically are tens of kilometers long and several kilometers wide. Stratigraphic relations indicate that the ridges apparently formed soon after the unit was emplaced, and the ridges do not extend into adjacent units. Ridged plains material traditionally has been interpreted as lava flows because of its similarity to known lava flows on the lunar maria (for example, Greeley and Spudis, 1981). Ridged plains material may have been the first volcanic product at the Elysium rise; however, vent features have not been recognized. If so, this relation would be similar to that found at Syrtis Major Planum, about 3,000 km to the west, where ridged plains material was emplaced before lobate lava flows (Schaber, 1982).

Following emplacement of the ridged plains material, plains materials in lower areas in the plains of the Elysium region were degraded and deformed, forming the knobby, *mottled, and grooved members of the Vastitas Borealis Formation* (units Hvk, Hvm, and Hvg, respectively). The origin of these materials is uncertain; one hypothesis is that they are largely sedimentary deposits associated with early floods that originated from the Elysium rise (Lucchitta and others, 1986). Several observations indicate that the materials were (and may still be) ice rich: (1) many impact craters superposed on the formation have extremely wide ejecta blankets, and some have a thick inner ejecta lobe (type 2 craters of Mougnis-Mark, 1979); (2) the formation is in lowlands, where water may have seeped in; and (3) much of the formation is cut by narrow grabens (Pechmann, 1980), which indicates that either the material is fractured and a shallow mechanical discontinuity controls graben width or the material is intact but weak like ice-rich deposits (Tanaka and Golombek, 1989). Grooves (in the grooved member), as well as annular fractures within the formation that may have formed over buried crater rims, indicate compaction and contraction of the formation (McGill, 1986).

The *tholus member of the Hecates Tholus Formation* (unit Hetlava) and the *Albor Tholus Formation* (unit Hat), and the *mons member of the Elysium Formation* (unit Ahelm) compose most of the three large volcanoes of the Elysium rise. These volcanoes are the only known ones in the region and were largely formed by the end of the Hesperian; the time of initiation of their development, however, is uncertain. Formerly, Albor Tholus, in part, and Elysium Mons were mapped as Amazonian in age by Greeley and Guest (1987). However, because these two volcanoes are embayed by lowermost Amazonian flows of the Elysium Formation (unit Aelg), we think they formed during the Hesperian. Crater counts of Elysium Mons (fig. 2A) suggest extensive resurfacing during the Early Amazonian. Crater densities from five different reports all indicate that the Elysium volcanoes are Upper Hesperian to Lower Amazonian (see Tanaka, 1986, table 5)—a position consistent with our findings (fig. 2). Although within the same age range, different workers assign various ages to the volcanoes. Our counts (fig. 2) indicate the oldest volcano is Hecates Tholus (except for its patch of Amazonian mantle member), followed by Albor Tholus and then Elysium Mons.

These volcanoes show a variety of styles of volcanism. Hecates Tholus displays no lava flows but is dissected by channels. Reimers and Komar (1979) suggested that the channels were carved by volcanic density currents (pyroclastic flows); however, Mougnis-Mark and others (1982) thought that the channels formed mainly by fluvial action in easily eroded material. Both hypotheses imply that Hecates is constructed largely of pyroclastic material. In addition, the Amazonian mantle member near the summit of Hecates may be pyroclastic air-fall material (Mougnis-Mark and others, 1982). A large rille, Buvinda Valles, cuts flows that embay the northeast edge of Hecates; the rille may indicate late evacuation of Hecates-area volcanism. In addition, large craters of possible volcanic origin are on the west side of Hecates Tholus. Much of the surface of Elysium Mons is rugged, but only a few lava flows are recognized; therefore the volcano may consist partly of pyroclastic material. Also, because of its steep upper flanks, Scott and Allingham (1976) and Malin (1977) suggested that Elysium Mons is a stratovolcano (or composite volcano). Several ridges on its north flank are similar to crested ridges northwest of Alba Patera (at 40° N., long 110°) that were interpreted to be tube-fed flows (Carr and others, 1977). Albor Tholus also has a rugged surface, and relatively small lava flows are visible on its flanks. It has the largest summit caldera of all the Elysium volcanoes.

In eastern Elysium Planitia, moderately to highly degraded flows of *member 1 of the Elysium Formation* (unit Hel) cover ridged plains material. Parts of this unit have been eroded, leaving some remnant outcrops and knobs. Arriving at a consistent relative morphology around sections of a few impact craters (for example, at lat 29° N., long 187.5°). Degradation of the flows may be due to inherent material weakness, indicating either a pyroclastic composition or volcano/ground-ice interactions that led to their disintegration.

West of Elysium Mons is a complex volcanic area mapped as the *ragged member of the Elysium Formation* (unit Hetr). The unit appears embayed by Lower Amazonian flows of Elysium Mons (unit Aelg), and crater counts (fig. 2B) indicate an Upper Hesperian position. The surface, composed primarily of lava flows, is locally cut by channels, sinuous rilles, and northward-trending grabens. The flows differ in thickness and state of degradation. Small groups of hills, some with summit craters, occur on this unit and may be cinder cones. These features led Mougnis-Mark and others (1984) to label this terrain a "complex area." They proposed that the rilles formed by effusive volcanism on a steep slope. Mougnis-Mark (1985) recognized that the style of volcanism here, including the formation of a caldera, is largely characterized by many vents sugesting a small, near-surface magma chamber or a large, deep-seated one.

AMAZONIAN SYSTEM

Amazonian tectonic, volcanic, and fluvial activity on Mars was largely restricted to the active volcanic centers of Elysium Mons and the Tharsis complex east of the map area. Fluvial activity appears to have been much more important in the Elysium region than at Tharsis. The Early Amazonian was particularly eventful: about half of the map units were emplaced or acquired their present forms during this epoch.

Because much of the map area is covered by Lower Amazonian materials, a relatively large amount of *Amazonian crater material* (unit Aic) formed where large impacts occurred. Moderately fluidized Amazonian crater material mostly occurs south of lat 30° N. in highland and lava-flow materials, whereas highly fluidized crater material is seen mostly north of lat 30° N. and in low-lying plains materials farther south. Radial-patterned crater rimcrest material overlies mainly the Elysium and Medusae Fossae Formations.

In the eastern volcanic assemblage, *member 2 of the Elysium Formation* (unit Aelg) is the dominant lava-flow unit. Its flows were extruded from Elysium Mons and surrounding circumferential and northward-trending fissures and most of the Elysium rise. Most of the fluvial, tectonic, and mass-wasting activity in the region is related in time to the emplacement of this unit. The unit is characterized by lava channels, overlapping lava-flow margins, a few crested flows, and development of rilles (including Buvinda, Ierus, Iruxu, Patapsco, and Stura Valles). East of Elysium Mons, member 2 overlaps a few wrinkle ridges on member 1 flows and on ridged plains material. Member 2 was previously mapped as material of "compound lava plains" and as "flood lava" (west of Elysium Mons) by Mougnis-Mark and others (1984) and as member 1 of the Elysium Formation by Greeley and Guest (1987). Thinner and less lobate flows emanating from the bases of lobate flows of Galaxias Fluctus (north of Elysium Mons) have been interpreted as mell-water deposits (Mougnis-Mark, 1985). In some areas of member 2, images are not of sufficient quality to confirm the presence of lava flows.

West of Elysium Mons, member 2 and the rugged member of the Elysium Formation are cut by troughs and valles mapped as the *trough member of the Elysium Formation* (unit Aelt). These features are as much as 1 km deep (Mougnis-Mark, 1985) and appear to be enlarged from nearby, parallel grabens of Elysium Fossae that trend either northwest or concentric to Elysium Mons. Although most troughs appear to postdate adjacent lava flows, flows appear to emanate from several of the troughs. Elysium and Hyblaeus Chasmata are two large enclosed troughs southwest of Elysium Mons that connect with an irregular, branching system of fractures known as Hyblaeus Fossae. These fractures are mapped as tension fractures because of their irregular, branching pattern (Schumm, 1974) and may have formed by local bulging related to magma intrusion. Some of the troughs that are oriented parallel to slope direction are connected with narrower channels downslope. Width-versus-wavelength (channel sinuosity) plots of the channels indicate that channel reaches in Utopia Planitia (including Tinjar and Granicus Valles) have a fluvial character, whereas those on the Elysium rise near the troughs probably are of volcanic origin (Mougnis-Mark and others, 1984). One suggested origin for the troughs is turbulent erosion caused by low-viscosity magma erupted at high rates on relatively steep slopes, but the lack of associated volcano construction is puzzling (Mougnis-Mark and others, 1984). The trough member probably consists of older lava flows, slope debris, and trough-floor material of volcanic, mass-wasting, and fluvial origins.

Voluminous flows and fluvial channels emanate from the troughs and fractures on the northwest flank of the Elysium rise. More rugged and thicker flows are mapped as the *coarse member of the Elysium Formation* (unit Aelc), whereas smoother and thinner flows are mapped as the *smooth member* (unit Aels) (together mapped as member 3 of the Elysium Formation by Greeley and Guest, 1987). The flows of both these units are generally thicker and rougher than the lava flows characteristic of our member 2 and extend more than 1,000 km out into the plains. They form a sequence of overlapping and abutting flows that are interbedded with flows of member 2. Christiansen and Greeley (1981) and Christiansen (1989) proposed that these flows are huge lahar deposits because of their morphology and association with channels. They surmised that volcanism melted ground ice, leading to liquefaction of subsurface material. However, Mougnis-Mark and others (1984) mapped the units as erosional plains material and suggested that many of the flows may not be lahars. Also, extensive collapse features would be expected from the excavation of such large volumes of near-surface material, which prompted Tanaka and Scott (1987) to postulate that the flows are pyroclastic and originated at depth. Alternatively, the flows may have originated as lava flows that were later modified by ground-ice interaction, as suggested for member 1.

The coarse and smooth members are carved by outflow channels (such as Hrad, Tinjar, and Granicus Valles) whose materials are mapped as *channel deposits* (unit Ach); these channel deposits were mapped as member 4 of the Elysium Formation by Greeley and Guest (1987). Where narrow, the channels are shown by symbol only. Most of the channels form long, sinuous valleys several kilometers across; larger channels may be as much as 1,000 km long and 10 km wide. Hephaestus Fossae (completely shown by symbol), however, have a polygonal pattern, apparently because flooding occurred subterraneously through buried polygonal fractures (which are exposed west of the map area as Adamas Labyrinthus). In eastern Utopia Planitia, smooth channel deposits are not confined within channel banks; these areas are mapped as *Utopia flood-plain deposits* (unit Achu). *Channel-lan deposits* (unit Achf), well developed at Apsus Valles, appear to consist of channel deposits dissected by channel distributaries along the edges of main channels; the deposits reflect sedimentation where stream energy was low. Because many of the channels head from fractures and troughs of Elysium and Galaxias Fossae, release of ground water was likely related to the volcanic and tectonic activity that produced the tissue. Baker (1982, p. 79), Mougnis-Mark and others (1984), and Mougnis-Mark (1985) have suggested that ground-ice melting due to volcanism may have provided the water. Alternatively, the fracturing may have produced conduits that tapped confined aquifers (MacKinnon and Tanaka, 1989).

In the northern plains assemblage along the west edge of the map area, *warped plains material* (unit Ahfqv) continued to form rugged plains, which were probably degraded by thermokarst processes (Carr and Schaber, 1977). In the plains beyond member 2 of the Elysium Formation exposures of Lower Amazonian smooth plains *material* (unit Aps) may include some lava flows west and south of Elysium Mons. However the unit generally lacks distinct forms and may include sedimentary deposits. Smooth plains material also occurs on large crater floors.

This Early Amazonian period of geologic activity also includes degradation of plains units north and west of Elysium Mons. Mougnis-Mark and others (1984) mapped these areas as knobby and chaotic terrain; we have divided the material into grooved plains *material* (unit Apg) and knobby *plains material* (unit Apk). Grooved plains material is mapped north (at Galaxias Chaos) and west of Elysium Mons where member 2 of the Elysium Formation and possibly other high plains material are fractured into polygons. The fractures are similar in pattern and size to those that characterize the knobby member of the Vastitas Borealis Formation. The grooved plains material is found near channel deposits, perhaps because its fracturing was related to melting of ground ice and discharge of the melt water (Carr and Schaber, 1977; Baker, 1982, p. 81; Mougnis-Mark and others, 1984). Knobby plains material is mapped farther from the Elysium rise where Elysium lava flows have developed and only knobs of high plains material remain. At Galaxias Mensae and surrounding Hephaestus Fossae, the knobby plains material is gradational with grooved plains material; although both units were probably formed by ice-related degradational processes, the knobby plains material is more highly degraded and has less relief. Elsewhere, knobby plains material is morphologically similar to the knobby member of the Vastitas Borealis Formation but is less cratered and, in some places, may result from modification of the Vastitas Borealis Formation.

Somewhat later, in southern Elysium Planitia, the *lower member of the Medusae Fossae Formation* (unit Aml) was emplaced. The material is highly friable and superposed impact crater blankets are unusually broad and have a well-developed radial texture. Three sheets of the member are characterized by different surfaces in the map area (see Description of Map Units). Origin of the unit is uncertain; pyroclastic