GEOLOGIC/GEOMORPHOLOGIC MAP OF THE CHRYSE PLANITIA REGION OF MARS

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INTRODUCTION

Since the 1970's, when the Mariner 9 spacecraft revealed the geologic diversity of Mars, the Chryse Planitia region has been noted for its immense outflow channels and chaotic terrain (McCauley and others, 1972; Sharp and Malin, 1975; Baker, 1982, chap. 3; Mars Channel Working Group, 1983). Various proposals for the origin of these features have been offered; most workers have favored a mechanism in which ground water or water-rich debris was expelled from beneath a frozen crust, leading to catastrophic debris flows or floods that may have contained significant amounts of ice (Baker and Milton, 1974; Carr, 1979; Nummedal and Prior, 1981; Lucchitta, 1982; MacKinnon and Tanaka, 1989). The channels originated on or near the flanks of the volcanotectonic rises of Tharsis (whose east margin is the west edge of the map region) and Valles Marineris, which suggests that tectonic and igneous activity led to the conditions for discharge. Estimated discharge rates for some channels exceed those of prehistoric floods on Earth (Carr, 1979; Komar, 1979; Robinson and Tanaka, 1990). Some workers think that the discharges may have led to the development of temporary oceans that filled the northern lowlands (Parker and others, 1989; Baker and others, 1991). The Chryse basin (Chryse and southern Acidalia Planitiae), which is part of those lowlands, apparently has been the site of lava and sediment deposition (Greeley and others, 1977; Scott and Tanaka, 1986).

Earlier geologic mapping of the region based on Mariner 9 images identified chaotic materials, channels, canyons, and other units and features and their sequence of formation (Milton, 1974; Wilhelms, 1976; McCauley, 1978; Saunders, 1979). Further refinements of the ages of the units and their interpretation and global correlation followed, based on the higher quality Viking images (Greeley and others, 1977; Masursky and others, 1977; Neukum and Hiller, 1981; Scott and Tanaka, 1986; Tanaka, 1986). However, these mapping efforts did not reconstruct the detailed geologic history of the region that has significant implications for the planet's hydrologic and climatic histories. For example, one needs to compare the timing of the formation of Valles Marineris with Tharsis volcanism and tectonism; the formation of chaotic materials, channels, and lakes (or ocean); and possible climatic changes interpreted from the geologic record. To help resolve these problems, we have mapped the region on a shaded relief map especially designed for this purpose (U.S. Geological Survey, 1982).

PHYSIOGRAPHIC AND GEOLOGIC SETTING

The Chryse Planitia region includes parts of three major physiographic provinces: the cratered highlands (including chaotic terrain and channels), the Valles Marineris, and the Chryse basin (which is part of Mars' vast northern lowland plains). The topography described here is based mainly on stereophotogrammetry and radar altimetry and has been mapped with a contour interval of 1 km and estimated precision of 1 to 1.5 km (U.S. Geological Survey, 1989). In selected areas, such as parts of Kasei Valles and Valles Marineris, we have more precise topographic information based on higher resolution photogrammetry, photoclinometry, and shadow measurements (Davis and Golombek, 1990; Robinson and Tanaka, 1990).

Highlands, which dominate the map area, can be divided into two terrains: heavily cratered terrain covering the southeast quadrant of the map area and ridged plains covering much of the western part. Heavily cratered terrain is characterized by relatively high densities of craters more than 10 km in diameter. This terrain is about 9 km above datum near Valles Marineris and steadily decreases in elevation to 1 km below datum in the Chryse basin. (In comparison, Arabia Terra to the east has a much lower maximum elevation of about 1 km above datum.) The cratered terrain and relatively smooth intercrater plains contain outflow channels and associated chaotic terrain, as well as narrow, sinuous channels and valley networks (such as Nanedi Valles), wrinkle ridges, troughs, and grabens.

The broad, high, generally smooth plains of Lunae Planum, southern Tempe Terra, Arabia Terra, and southwestern Chryse Planitia are marked by regularly spaced, mostly north-trending wrinkle ridges. Western Lunae Planum is higher than eastern Lunae Planum and has longer and more widely spaced wrinkle ridges. Northeast-trending grabens cut Tempe Terra, and fault-controlled Sacra and Labeatis Fossae form rectilinear and dendritic patterns of troughs cut into ridged plains along Kasei Valles; the fossae are typically about 1 km deep and 5 to 10 km wide.

The Valles Marineris are a system of deep chasmata (canyons) along a topographic high 6 to 9 km in elevation. The canyon system is about as long as the United States is wide (4,000 km); only the northeast half of the system is in the map area. The chasmata are as much as 10 km deep and tens to hundreds of kilometers wide (U.S. Geological Survey, 1989). They appear to be large grabens that have expanded by slope failure and mass wasting, which has resulted in enormous landslides and extensive talus deposits along canyon walls. The large canyons are paralleled by secondary structures that include long, narrow grabens (most less than 5 km wide), pit chains, and linear troughs.

Parts of Mars' northern plains occur in the map area as the adjoining Chryse and Acidalia Planitiae. The plains lie north of a distinct highland/lowland boundary scarp that separates the lowland plains from the cratered highlands; the scarp closely follows the elevation datum. The average northern plains elevation is about 1 km below datum. If present topographic mapping is accurate, Chryse basin is enclosed and is about 1,000 km across, centered near lat 25° N., long 39° (Scott and others, 1992). The lowlands are generally smooth; sparsely cratered; and marked by secondary features that include large polygonal cracks, longitudinal grooves, streamlined bars, sinuous depressions (some with central ridges), fields of knobs, and varied albedo.

The circum-Chryse outflow channel system originates from large chasmata and (or) fields of chaotic terrain near northern and eastern Valles Marineris. The channels cut through cratered highlands that cover about 10 percent of Mars' surface. Depth of incision into the highland plateaus commonly exceeds 1 km. All the channels empty into the Chryse basin.

The largest channel system, Kasei Valles, originated in 3- to 4-km-deep Echus Chasma. The Kasei system extends north for 1,500 km, and in this stretch it is partly filled by chaotic material and Tharsis lava flows; near lat 25° N., the system turns east and divides into north and south branches on either side of Sacra Mensa. The branches rejoin and continue farther east for another 900 km, forming a broad, longitudinally grooved plain that extends around large mesas before entering Chryse basin. The mouth of the channel system is about 450 km wide and has 5- to 20-km-wide streamlined bars.

Maja Valles issue from chaotic terrain in 1- to 3-km-deep Juventae Chasma. The Maja channels themselves are shallow; they trend north for 1,300 km and then bend to the east, transecting cratered highlands, and enter Chryse Planitia. The southern reaches are narrow and anastomosing; however, north of lat 9° N., they widen from 100 km to more than 200 km. The system becomes fairly restricted (about 25 km wide) as it crosses the highlands but widens to 175 km where it enters Chryse Planitia.

Shalbatana Vallis is a relatively narrow channel (about 10 km wide), yet in places it is extremely deep (as much as 3 km). The channel begins at a 2- to 3-km-deep circular depression within a large impact crater whose floor is partly covered by chaotic material. It extends north-northeast for 700 km, maintaining a nearly constant width and depth, and terminates in Simud Vallis. The channel floor is generally smooth. At lat 8° N., long 42°, a relatively shallow, anastomosing channel diverges from the main valley, carving a 500-km-long, north-trending segment that leads into Chryse Planitia.

Tiu and Simud Valles consist of a complex of connected channel floors and chaotic terrain. The channels appear to extend as far south as Capri Chasma, which connects with Coprates and Gangis Chasmata (structural troughs of eastern Valles Marineris); the length of the entire channel and canyon system (from east Coprates Chasma to Chryse Planitia) exceeds 2,500 km. The chasmata and the channel floors of Tiu and Simud Valles are typically bounded by scarps 2 to 3 km high. The upper reaches of the channels have generally smooth floors and lack streamlined features; however, some chaotic terrain, knobs, and longitudinal grooves near constricted reaches are observed. Channel branches are separated by highland mesas mostly 50 to 300 km wide and 1 to 2 km high. At the channel mouths, lower streamlined islands are roughly the size of those at the mouth of Kasei Valles.

Ares Vallis originates from discontinuous patches of chaotic terrain within large impact craters. North of lat 5° N., source valleys coalesce into a single northwest-trending channel that is about 75 km wide, 1 km deep, and 2,000 km long. In the Chryse basin the channel forks; one branch continues northwest into central Chryse Planitia and the other extends north into eastern Chryse Planitia.

Mawrth Vallis, in Arabia Terra, emerges from a heavily cratered area that includes crater Trouvelot, and the channel winds through cratered terrain for 700 km before entering the lowlands of eastern Chryse Planitia. Mawrth maintains a relatively uniform width (10 to 25 km) throughout its length and has an average depth of less than 1 km.

STRATIGRAPHY AND STRUCTURE

Many map units and the general stratigraphy of the map region were established by Scott and Tanaka (1986) and refined in the vicinity of Valles Marineris by Witbeck and others (1991). Recent 1:500,000-scale maps show geologic detail of selected areas within the map region, such as Kasei Valles (Chapman and Scott, 1989; Chapman and others, 1991; Scott, 1993; Chapman and Tanaka,1995); Maja Valles (De Hon, 1993; Rice and De Hon, 1995); and the Viking 1 landing-site area of Chryse Planitia (Crumpler and Craddock, written commun., 1991). We have defined new map units and groupings (such as the Chryse assemblage) to bring out the details of the channel and basin history, and we have slightly modified previously mapped units as needed. We obtained relative ages by using the stratigraphic scheme of Tanaka (1986) where reliable determinations of densities of craters greater than 1, 2, and 5 km per 10^6 km^2 are possible (table 1). Some age ranges shown on the correlation chart are slightly modified from previous work due to local stratigraphic relations and the new crater counts.

The map units (exclusive of crater materials) are divided into two broad categories: (1) lowland terrain materials and channel units and (2) highland terrain materials. The lowland materials and channel units extend throughout Chryse and Acidalia Planitiae. Channel floors are commonly made up of scoured rocks of varied type and age; we therefore map the channels as *surfaces* rather than *materials* to show the effects of channeling events, as in previous work (for example, Milton, 1974). However, in some places the channel floors are covered by material that is not fluvially derived (for example, eolian deposits), which is mapped as a material unit. Lowland materials that appear on the basis of geomorphologic evidence to have been deposited or modified by outflow channels have been grouped into the new Chryse assemblage and are identified by the letter c following the age designation in the map-unit symbol (for example, unit **Hchl**). The remaining map region consists of various highland materials.

In addition to discussing the stratigraphy and erosional history, we describe tectonic events and their results (for example, tectonism that has triggered discrete flood events) according to the interpretations of previous workers, so that the relation between erosional and tectonic events in the Chryse region can be more fully appreciated.

NOACHIAN SYSTEM

The Noachian System consists of ancient materials formed at the end of heavy bombardment. Noachian materials and structures are commonly degraded because of long exposure time, as well as enhanced erosion rates, during the Noachian Period. Highland rocks are exposed in the eastern and southeastern parts of the map region, on Tempe Terra, and in the walls of Valles Marineris and the outflow channels. At the end of the Noachian, large-scale erosion may have occurred along the highland/lowland boundary, perhaps in response to tectonic lowering of the lowland region by as much as 2 to 3 km in places (McGill and Dimitriou, 1990). Alternatively, the lowlands may have been mainly produced early in the Noachian by huge impacts (Wilhelms and Squyres, 1984; Frey and Schultz, 1988; Schultz and Frey, 1990).

The plateau sequence includes most highland rocks in the map area and on Mars as a whole. High-standing exposures of ancient (Lower Noachian), rugged, densely cratered material are mapped as the *hilly unit* (unit **Nplh**). Schultz and others (1982) noted that some of the rocks in this unit may form part of the rim of an ancient impact basin (Chryse Planitia). More widespread is the somewhat less rugged Middle Noachian *cratered unit* (unit **Npl$_1$**) that is characterized by a high density of large craters (more than 10 km in diameter). Because of the high rates of planetary cooling that may have occurred during the early part of the Noachian (for example, Schubert and Spohn, 1990), considerable volumes of lavas may have been erupted; if so, the hilly and cratered units are made up of lavas brecciated by contemporaneous heavy bombardment. Over much of the highlands, the cratered unit was largely resurfaced during the Late Noachian by relatively smooth plains-forming material that probably consists of fissure-fed lava flows (no associated volcanoes are seen), eolian materials, and perhaps some fluvial deposits in areas where the unit is dissected by valley networks. This resurfacing has resulted in a relatively smooth surface marked by many partly buried large craters—hence the name *subdued cratered unit* (unit **Npl$_2$**). The *dissected unit* (unit **Npld**) consists of cratered material

Table 1. *Crater densities of selected map units of the Chryse region*

Map-unit symbol	Viking image	Area of count (km^2)	Cumulative number of craters per 10^6 km^2		
			>1 km	>2 km[1]	>5 km
Am	897A55–58	26,497	453±130	264±100	75±53
AHcs	668A46–48	23,736	2,149±300	253±104	——
AHchl	44A42–44	11,245	1,690±388	267±154	——
AHcc	595A3,5,6	64,742	1,745±164	371±76	——
AHcg	595A31,32	39,249	1,554±199	382±98	76±44
AHcr	27A34–37	7,490	2,136±534	400±231	——
Hchh		16,900	——	[2]730±220	——
Hchl	4A17–19;6A17,18	21,373	1,965±303	[3]490±75	——
Hck	221S3–5	12,766	2,898±477	548±207	——
HNck	864A07	34,160	1,639±219	878±160	176±72
HNchl	864A43–48	25,170	1,669±258	1,192±218	358±119
HNr	671A7,8	9,363	6,408±827	1,389±385	——

[1]Values used for figure 1.
[2]Value for channeled plains material mapped by Chapman and others (1991).
[3]Value extrapolated from >1-km density on assumption of −2 power-law relation between density and diameter.

that has been modified by valley-forming sapping processes along the south edge of the map region and adjacent to a constricted reach of Maja Valles.

North of Kasei Valles and south of Sharanov crater, highly fractured cratered terrain is mapped as *older fractured material* (unit **Nf**).

Large patches of *older ridged plains material* (unit **HNr**) in Arabia Terra are marked by widely spaced, slightly degraded wrinkle ridges. These patches were mapped by Scott and Tanaka (1986) as Hesperian ridged plains material. However, our count of superposed craters of the ridged material in Arabia Terra (table 1) indicates a Hesperian-Noachian age. Because the ridges are degraded, the plains can be distinguished from the ridged plains of Lunae Planum that are characteristic of those that define the base of the Hesperian System (Scott and Carr, 1978). Also, the unit's wrinkle ridges are lower than those characteristic of the ridged unit of the plateau sequence mapped outside the map area by Scott and Tanaka (1986). Although far removed from the Tharsis rise, the Hesperian-Noachian wrinkle ridges may result from an early phase of development of Tharsis (Scott and Tanaka, 1986), perhaps augmented by global compressional stress due to planetary cooling (Tanaka and others, 1991).

Where plateau rocks are cut deeply by the large canyons of Valles Marineris and the outflow channels, the exposed wall rocks and large, isolated floor remnants are mapped as *undivided material* (unit **HNu**). Much of this unit is made up of various Noachian plateau materials and, in places, of overlying Hesperian rocks. Locally, wall rocks differ in albedo or apparent resistance to erosion and therefore appear layered; layers may include lava flows, sills, and zones of cementation (Soderblom and Wenner, 1978; Lucchitta and others, 1992; Tanaka and Chapman, 1992).

In the Chryse assemblage, the *etched unit of Mawrth Vallis* (unit **HNce**) probably is early flood-plain deposits of the channel that have been eroded by later flooding. The *higher* and *lower floors of Mawrth Vallis* (units **HNchh** and **HNchl**, respectively) cut through mostly Noachian plateau materials and are embayed by Hesperian younger knobby material at the mouth of Mawrth Vallis. Streamlined mesas and distinct terraces are mapped as the higher floor. Mawrth Vallis is perhaps the oldest outflow channel on Mars. Its floor was mapped as Hesperian channel material by Scott and Tanaka (1986) on the basis of the age determined by Masursky and others (1977). Our crater count (table 1) of the lower floor of Mawrth, involving a larger surface area, indicates a greater age. Mawrth Vallis is unusual because its source area contains no chaotic terrain, large fractures or pits, or other distinctive landforms commonly associated with outflow channels. A lava flow partly fills the upper part of the channel; perhaps lava and overlying cratet materials have obscured the source area.

The *older knobby material* (unit **HNck**) of the Chryse assemblage is made up of closely spaced, small knobs surrounded by plains material (locally ridged) along the east and south edges of the Chryse basin. Circular patterns of knobs are the surface expressions of degraded and buried crater rims. The knobs thus are remnants of Noachian plateau materials that resulted from breakup of rocks along the highland/lowland boundary that began at the end of the Noachian. The interknob plains material probably was emplaced during the Hesperian (table 1) and consists of lava flows, mass-wasted deposits, and other materials.

Nanedi and Bahram Valles cut the southwest rim of Chryse basin and are mapped as *valley floors* (unit **HNcv**). The morphology of these valleys suggests that they formed by ground-water sapping; they have theater heads, few tributaries, and constant widths. This unit was grouped by Scott and Tanaka (1986) with Hesperian channel material that includes outflow channels; however, the valley floors are morphologically distinct from the outflow channels. The valleys cut the cratered and subdued cratered materials south and southeast of Chryse Planitia and the ridged plains of Lunae Planum. But where the valleys enter Chryse Planitia, they are buried by ridged plains material. These stratigraphic relations, along with crater counts (Masursky and others, 1977), suggest that development of the valleys began in the Noachian and continued into the Early Hesperian.

HESPERIAN SYSTEM

Although bombardment and erosion rates were lower in the Hesperian Period than in the Noachian, the Hesperian was a time of intense geologic activity throughout the western equatorial region of Mars (Scott and Tanaka, 1986; Scott and Dohm, 1990); outflow channeling and volcanism resurfaced about two-thirds of the map region. Much of the structural development of Valles Marineris occurred during the Early Hesperian in a broad, high area along the southwest border of the map region. Throughout the Hesperian, considerable stresses extending into the Chryse region were produced by growth of the Tharsis rise to the west.

Younger ridged plains material (unit **Hr**) marks the base of the Hesperian System. The unit apparently was emplaced as a sequence of voluminous sheet lava flows thick enough to cover most of the rims of Noachian craters in its areas of outcrop (western part of the map region). The flows apparently were fissure fed; those of Lunae Planum may have erupted from early fractures of Valles Marineris (Witbeck and others, 1991). The ridges typically have an asymmetric profile and are as much as 300 m high (Golombek and others, 1991). Most ridges trend north and have a periodic spacing that may be controlled by the vertical zonation of strength properties of the crust (Watters, 1991). Most workers consider wrinkle ridges to be compressional features (Plescia and Golombek, 1986; Watters, 1988); however, some ridges have geologic associations suggestive of a volcanic origin (Greeley and others, 1977; Scott and Carr, 1978; Scott, 1989).

Because no craters are visibly transected by the ridges, we assume that the ridges probably formed very shortly after emplacement of the plains material, apparently due to Tharsis-centered stresses (Tanaka and others, 1991; Banerdt and others, 1992). Extensive areas of the unit have been eroded away by large outflow channels where they cut through Lunae Planum and the northwestern and southeastern parts of Chryse Planitia. The unit may also be buried beneath Chryse basin deposits and Tharsis flows in the map region.

The *smooth unit of the plateau sequence* (unit **Hpl$_3$**) grades into the younger ridged plains material near several canyons of Valles Marineris. The smooth unit is characterized by smooth intercrater plains and craters that have well-defined, fresh-appearing ejecta; the unit may be made up of undeformed low-viscosity lava flows. In turn, younger ridged plains material and the smooth unit grade into *younger fractured material* (unit **Hf**) on western Ophir Planum and adjacent to Echus Chasma. This unit likely is made up of lava flows and has been cut by many narrow grabens associated with the opening of Valles Marineris.

Somewhat younger lava flows of the *lower* and *upper members of the Syria Planum Formation* (units **Hsl** and **Hsu**, respectively) embay the younger fractured material near Echus Chasma.

Most outflow channels in the map area were carved during the Hesperian. Crater counts (fig. 1) suggest that channel activity in the Chryse region was prolonged. However, because crater ages for channels are somewhat imprecise, the complete, detailed sequence of channel formation could not be determined. Some channel surfaces have crater ages distinct from those of other channel units, whereas others overlap. Additionally, the large channels do not crosscut one another. Thus we cannot prove or reject the idea that some channels were active simultaneously. Available data and known relations suggest that Late Hesperian outflow-channel formation occurred at Kasei, Ares,

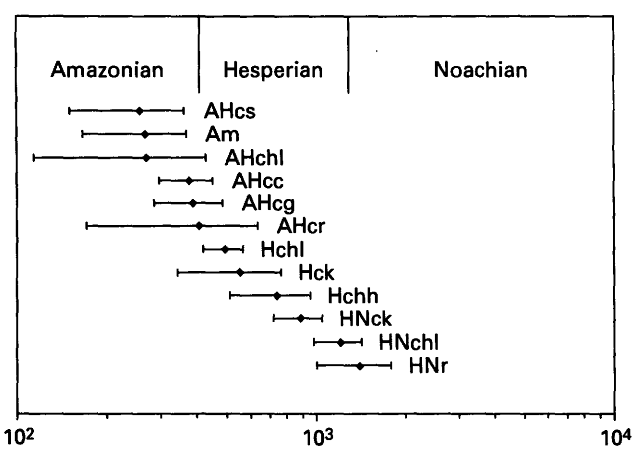

Figure 1. Cumulative densities of craters more than 2 km in diameter per 10^6 km^2 in selected map units of the Chryse region.

Simud, and Tiu Valles; that the younger channeling at Shalbatana and Maja Valles may have been in the Early Amazonian; and that multiple episodes of flooding formed Kasei, Ares, and Maja Valles.

The Kasei Valles system has had at least two episodes of flooding (Neukum and Hiller, 1981; Chapman and Scott, 1989). Floods of the first episode emanated from fractures that were erosionally widened into Sacra and Labeatis Fossae, mapped as *fossae floors* (unit **Hcf**); some fossae may be mantled by younger mass-wasted and eolian materials. The fossae are associated with *degraded ridged plains material* (unit **Hrd**) that may have formed when sapping, by removing ground ice, caused the collapse of ridged plains material. The floods carved much of the surface of Sacra Mensa, which is mapped as *Sacra Mensa channel floor* (unit **Hchs**). Presumably these units formerly extended into the Chryse basin but were removed by later channel erosion.

Some fossae are paralleled by narrow grabens in Tempe Terra, which indicates that both feature types may have formed at about the same time under the same regional stress. Fault-history studies indicate that Tharsis-generated stresses in the map region changed during the Late Hesperian from compressional to extensional (Scott and Dohm, 1990; Tanaka and others, 1991). The resulting east-northeast-trending fractures controlled much of the early erosion of Kasei Valles. Tanaka and Chapman (1992) suggested that such fractures may have guided some flooding from the Tharsis rise into northern Kasei Valles; later flooding apparently originated from Echus Chasma (and perhaps from Hebes Chasma).

Evidence of more than one episode of flooding is also found at the mouth of Maja Valles, where part of the ejecta from a small unmapped crater (lat 19° N., long 50°) is superposed on the channel floor and other parts have been removed by channeling (Baker, 1982). Also, channel sediments deposited on a broad area at the mouth of Maja Valles may have been incised by a second episode of flooding (Theilig and Greeley, 1979).

Most well-preserved outflow channels in the map area were carved in the Late Hesperian, according to crater counts (fig. 1). The counts include only craters that are clearly superposed on the channel floors; however, we cannot in all cases discount possible minor flooding that may have occurred after the latest major erosional event for each channel. This channeling episode produced *older higher* and *older lower channel floors* (units **Hchh** and **Hchl**, respectively). Surfaces mapped as older higher channel floor include (1) the floors of relatively shallow outflow channels (less than 1 km deep) cut into a variety of Noachian and Hesperian plateau materials; (2) distinct terraces in Kasei and Ares Valles, including those in resistant, etched materials in lower Ares Valles; and (3) a lobate deposit that we interpret to be a lava flow in Chryse Planitia below the mouth of Ares Valles (lat 22° N., long 36°) that has been carved by subsequent floods. Some of the higher channel floors are broad (for example, those at Kasei Valles), indicating that stream energy may have been low or diffused or the traversed rock resistant (for example, lava flows or well-cemented material). The deeper parts of the channels south of Chryse Planitia, generally incised into the higher channel floors, are mapped as older lower channel floor.

Areas of chaotic terrain are common sources of the outflow channels. As with the channel floors, Hesperian chaotic material is divided into two units: *higher* and *lower chaotic material* (units **Hcth** and **Hctl**, respectively). The higher unit is higher standing and less broken up than the lower one, but they are genetically similar. The higher material forms mesas and small plateaus at about the same elevation as the cratered plateau material into which it grades. The lower unit forms knoblike hills that have debris aprons at their bases. The chaotic materials apparently formed as a result of the expulsion of underlying ground water and debris and the collapse of plateau rocks. Some lower chaotic material fills sections of Simud and Tiu Valles and may make up large debris flows formed by the collapse of plateau rocks along the channel margins.

The channeling events no doubt resulted in the deposition of sediments in Chryse and Acidalia Planitiae. Two units thought to consist at least partly of such sediments are the *younger knobby material* (unit **Hck**) and the *mottled member of the Vastitas Borealis Formation* (unit **Hvm**), both of which are found in the northeast quadrant of the map region. Younger knobby material consists of scattered small knobs of remnant plateau material that have been embayed by basin deposits. The unit grades with older knobby material (which is dominated by knobs) that was not extensively resurfaced by Chryse flooding. The mottled member is characterized by high-albedo ejecta blankets superposed on lower albedo intercrater plains. The unit's age and location suggest that it may be made up of basin sediments and possibly lava flows. Formation of bright ejecta blankets has been ascribed to the entrapment of high-albedo material by ejecta blocks (Soderblom and others, 1973); excavation of high-albedo material by impacts (Carr, 1981, p. 79); and eolian deflation of a high-albedo debris mantle, which has left high-albedo dust entrapped in crater rims and ejecta blankets (Soderblom and others, 1973). Also, relatively small rampart and pedestal craters are common on the mottled member. If pedestal craters are formed by eolian deflation of unconsolidated material from around a more competent ejecta blanket (Lucchitta and others, 1986), an extensive mantle must have formerly covered the unit. The mottled member has a greater density of impact craters than the grooved and complex units of the Chryse assemblage, which appear to bury rays from a large crater (at lat 42° N., long 30°) that is superposed on the member.

Many of the canyons of Valles Marineris developed primarily through rifting (Blasius and others, 1977; Schultz, 1991; Witbeck and others, 1991; Lucchitta and others, 1992), whereas others appear to have formed by collapse (Tanaka and Golombek, 1989; Spencer and Fanale, 1990). As the canyons developed, various interior deposits were emplaced. *Layered material* (unit **Hvl**), consisting of alternating high- and low-albedo sedimentary or volcanic strata, was deposited throughout Valles Marineris. It forms irregularly shaped, extensive mesas hundreds of meters thick. *High floor material* (unit **Hvf**) forms terraces presumably made up of former floor deposits that were left high by lowering of the canyon floor around them (Witbeck and others, 1991). *Older massive material* (unit **AHvm**) caps a large, irregularly shaped island surrounded by chaotic material between Capri and Eos Chasmata. *Apron material* (unit **AHa**) makes up landslides and slumps along the base of high scarps, particularly within Valles Marineris and Kasei Valles.

According to crater counts (fig. 1), Shalbatana and Maja Valles and the lower floor of Kasei Valles apparently formed a little later than the other outflow channels—at the end of the Hesperian or the beginning of the Amazonian. The channel floors are mapped according to relative depth of incision as *younger higher* and *younger lower channel floors* (units **AHchh** and **AHchl**, respectively). The channels originate from depressions that contain *younger lower chaotic material* (unit **AHctl**); nearby shallow depressions and fractured crater floors that probably formed in association with the lower chaotic material are mapped as *younger higher chaotic material* (unit **AHcth**).

The northern branch of Shalbatana Vallis is cut by its main channel, suggesting that the branch either (1) formed as the result of overflow of the main channel or (2) predates the main channel. Although Shalbatana enters Simud Valles, no crosscutting relations between the two channel systems are seen.

Maja Valles make up what is possibly the youngest outflow channel system in the map area. It is relatively shallow along much of its length. In northern Lunae Planum and Chryse basin, the higher channel floor margin is not well marked and is mapped where wrinkle ridges appear to have been subdued by the channeling event. At Vedra and Maumee Valles (in the lower reaches of Maja), the dissected unit of the plateau sequence was apparently modified as Maja Valles flooding drained an impounded lake in northern Lunae Planum and followed and widened valleys in Noachian rocks (Baker, 1982; De Hon and Pani, 1992; De Hon, 1993).

Detritus eroded from highland areas by these youngest outflow channels, particularly during the floods of Maja Valles, appears to have been deposited throughout Chryse Planitia and in eastern Acidalia Planitia. The deposits are mapped as four basin units of the Chryse assemblage that have similar Amazonian/Hesperian crater densities (fig. 1, table 1) but different morphologies. Scott and Tanaka (1986) also recognized that materials of Chryse Planitia are somewhat younger than surrounding plains materials and most outflow channels. The units are described as they occur in order from southwest (at the mouth of Maja Valles) to northeast.

The larger exposure of the *subdued ridged unit* (unit AHcr) forms a flood plain where Kasei, Maja, and Simud Valles broadly converge. (The Viking 1 landing site is on this flood plain.) The unit contains north-trending subdued or partly eroded ridges, and thus it probably consists of ridged plains material resurfaced by multiple channeling events. Many of the ridges appear to have diverted the floods, particularly at the mouth of Maja Valles (Baker, 1982). Ridges on northern Lunae Planum have an average relief of more than 100 m (Golombek and others, 1991), which suggests that the subdued ridged unit represents a reduction of no more than tens of meters of preflood relief. However, the adjacent *smooth unit* (unit AHcs) is nearly devoid of wrinkle ridges and is therefore interpreted to be overlain by sediments. The plains of the smooth unit are featureless except for superposed craters and a few knobs and degraded ridges. The subdued ridged and smooth units intergrade. Because they show few streamlined features, they are thought to have been deposited in relatively flat areas where stream energy was low.

East of the smooth unit is the *complex unit* (unit AHcc) of the Chryse assemblage. The unit is marked by small hills and mesas and by common northeast-trending grooves and a few streamlined bars. Its western part is cut by sinuous, shallow depressions, some of which have medial ridges. Material in the depressions was mapped as channel material by Scott and Tanaka (1986). Although Scott (1982) proposed that the features are meander scars, their origin remains uncertain because of their unusual morphology (central ridges), discontinuous occurrence, and lack of closely associated streamlined features. Other possible origins include ice-related processes, such as deformation related to floating ice or to convergent ice streams (Lucchitta and others, 1986) or subglacial flow of water and sediment that carved tunnel valleys and deposited eskers as medial ridges (Kargel and others, 1992). Near the boundary of the map region (at lat 44° N., long 41°), the complex unit includes a patch of curved, light-colored streaks that resembles thumbprint terrain. On Earth, thumbprint terrain, eskers, and tunnel valleys can result from the disintegration of ice sheets, which conceivably formed in Chryse basin. Occurrences of thumbprint terrain have been documented elsewhere in the northern lowlands; also, the thumbprint pattern is associated with sinuous depressions elsewhere on Mars (Scott and Underwood, 1991; Kargel and others, 1992). Curvilinear grooves in the unit are tens of kilometers to more than 100 km long; in places they are grouped into disconnected systems several hundred kilometers long. They appear to be fractures that show no indication of later modification; they may be cracks formed by compaction of sediments whose alignments were controlled by Tharsis-centered stress or by pre-existing stream features. Part of the complex unit was mapped by Scott and Tanaka (1986) as the ridged member of the Vastitas Borealis Formation, but the ridges appear subdued in our map region.

The contact between the smooth and complex units is generally a well-defined, sinuous boundary marking changes in albedo (the smooth unit is darker) and in abundance of sinuous depressions. The complex unit partly buries a few large, degraded impact-crater rims (one 125 km in diameter). Degradation of older material, including the large craters, has resulted in small knobs dotting much of the complex unit.

The *grooved unit* (unit AHcg) of the Chryse assemblage is marked by a polygonal pattern of narrow (hundreds of meters wide) grooves and dispersed knobs. Lucchitta and others (1986) noted that grooved terrain here and elsewhere on Mars occurs where basin sedimentation likely took place. Also, McGill and Hills (1992) interpreted the grooves to result from the differential compaction of about 600 m of water-laden sediments over buried topography (McGill, 1986). Although the unit was formerly mapped as part of the Vastitas Borealis Formation (Scott and Tanaka, 1986), we have placed it in the Chryse assemblage because of the association of the unit with the Chryse basin and because of the unit's Amazonian-Hesperian crater age (fig. 1).

AMAZONIAN SYSTEM

Following extensive outflow channeling during the Hesperian and perhaps the Early Amazonian, geologic activity in the map area was greatly reduced. Some parts of Kasei and Shalbatana Valles and Echus Chasma were covered by thin deposits of smooth *mantle material* (unit Am) that may have eolian or alluvial origins. In Valles Marineris, a variety of deposits were emplaced. Floor materials include *rough floor material* (unit Avfr) that probably includes landslide blocks locally mantled by eolian material and *grooved floor material* (unit Avfg) of Candor Chaos, formed by compaction of water-laden sediment (Witbeck and others, 1991). *Etched massive material* (unit Avme) and *dark surficial material* (unit Avsd) are probably volcanic materials etched and partly redistributed by wind.

Two sequences of lava flows of the Tharsis Montes Formation, *members 4* and *5* (units At_4 and At_5), originated west of the map region on the flanks of Ascraeus Mons (lat 12° N., long 104°). Member 4 covers part of the broad flood plain of Kasei Valles along the south edge of Tempe Terra, whereas member 5 buries southern Kasei Valles, obliterating part of its west edge. Some flows cover the floor of Echus Chasma and a deeper channel within Kasei Valles as far as the west edge of Sacra Mensa. Both members, together with other units on the Kasei floor, are deformed by several north-trending wrinkle ridges. The ridges may have formed as a result of compressional stresses developed through the deep erosion of Kasei Valles (Tanaka and others, 1991).

GEOLOGIC SUMMARY

Early and Middle Noachian—Intense impact cratering produced heavily cratered materials that make up much of the highlands and presumably form a basement underlying younger units in the northern plains. Runoff from ground-water sapping or precipitation, perhaps suggestive of a warmer and wetter climate than that at present, degraded crater rims and dissected highland rocks.

Late Noachian—Local volcanism and fluvial sedimentation formed the smooth intercrater plains of the highlands. Wrinkle ridges in Arabia Terra developed due to Tharsis-centered tectonism. Possible tectonic lowering of the Chryse basin and upwarp at Valles Marineris induced ground-water sapping, producing knobby terrain within the Chryse basin and in sloping highland material along the basin's east side, as well as local catastrophic outbreak of water that carved Mawrth Vallis and sapping that formed Nanedi and Bahram Valles.

Early Hesperian—Broad, fissure-fed lava flows blanketed the cratered terrain in Lunae Planum, the Valles Marineris region, and much of Chryse Planitia. The flows were compressed by Tharsis stresses, resulting in north-trending wrinkle ridges (concentric to Tharsis). Extensive rifting produced much of Valles Marineris.

Late Hesperian—Extensive sapping and mass wasting along scarps and in canyons broke up receding plateaus bordering Kasei Valles. Tharsis-generated stress had become extensional, producing some northeast-trending grabens at Tempe Terra and similar-trending fractures in part of Chryse basin. Floods and debris flows originated from canyons, local fractures, and impact craters of the Valles Marineris region and traveled for thousands of kilometers to the Chryse basin, carving broad, deep outflow channels in the highland rocks along the way. The floods were the result of outbreaks that, in part, may have been due to liquefaction of water-saturated material below the permafrost zone, perhaps instigated by tectonic and volcanic activity at Tharsis and Valles Marineris. Removal of subsurface material led to broad collapse of some areas, producing chaotic terrain. Kasei, Ares, and Maja Valles appear to have had more than one episode of erosion. The channel erosion was accompanied by sedimentation in the Chryse basin. In the basin, fluvial and glacial processes locally formed streamlined islands and discontinuous depressions and ridges, and sediment compaction resulted in the formation of curvilinear and polygonal grooves. Possible volcanic activity and sedimentation formed layered deposits in Valles Marineris.

Amazonian—Outflow channel activity ceased by the end of the Early Amazonian. Although tectonism waned in Valles Marineris, volcanic, fluvial, mass-wasting, and eolian activity produced pyroclastic deposits, alluvium, eolium, talus, and huge landslides. Extensive lava flows erupted from the Ascraeus Mons area and covered the floors of Echus Chasma and the upper reaches of Kasei Valles. A few wrinkle ridges formed in northern Kasei Valles. The lower parts of some channels and canyons bounded by high scarps were filled by mass-wasted and eolian deposits.

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