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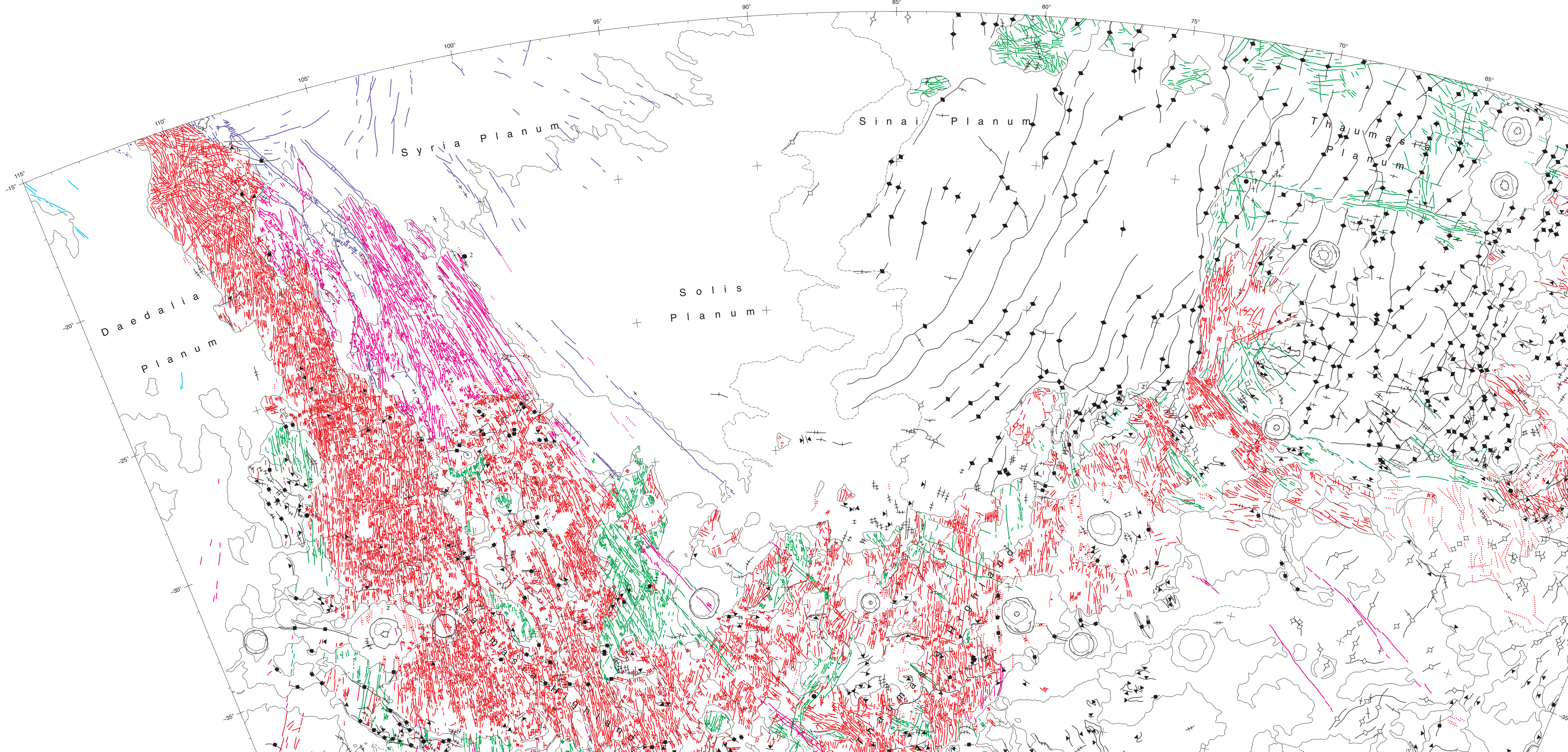
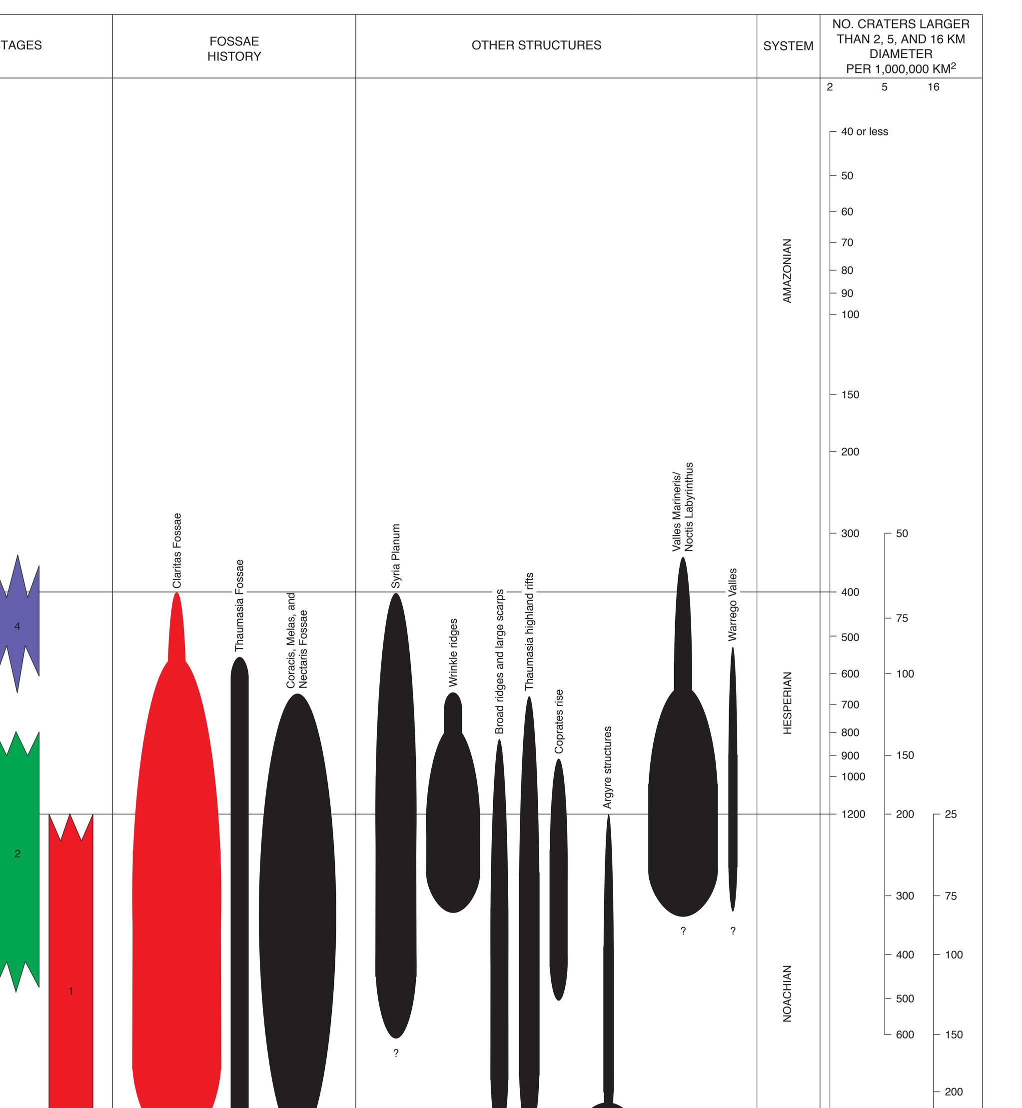
GEOLOGIC INVESTIGATION SERIES I–2650
ATLAS OF MARS: THAUMASIA REGION
SHEET 2 OF 3





Contact—Dashed where approximately located or gradational

Fault or graben—Bar and ball on downthrown side of fault; dotted where buried

Scarp—Line marks top of slope; barb points downslope. Forms contact in places

Mare-type (wrinkle) ridge—Symbol on ridge crest; dashed where buried

Subdued mare-type (wrinkle) ridge

Broad (>3 km wide), nearly flat-topped ridge

Narrow (<2 km wide), sharp-crested linear ridge

Narrow (<3 km wide), subdued ridge

Depression or caldera

Crater rim crest

Crater central peak

Crater central pit

Center of figure

PALEOTECTONIC MAP OF THE THAUMASIA REGION, MARS

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INTRODUCTION

The geology of the Thaumasia region (fig. 1) includes a wide array of rock materials, depositional and erosional landforms, and tectonic structures. The region is dominated by the Thaumasia plateau, which includes central high lava plains ringed by highly deformed highlands; the plateau may comprise the ancestral center of Tharsis tectonism (Frey, 1979; Plescia and Saunders, 1982). The extensive structural deformation of the map region, which is without parallel on Mars in both complexity and diversity, occurred largely throughout the Noachian and Hesperian periods (Tanaka and Davis, 1988; Scott and Dohm, 1990a). The deformation produced small and large extensional and contractional structures (fig. 2) that resulted from stresses related to the formation of Tharsis (Frey, 1979; Wise and others, 1979; Plescia and Saunders, 1982; Banerdt and others, 1982, 1992; Watters and Maxwell, 1986; Tanaka and Davis, 1988; Francis, 1988; Watters, 1993; Schultz and Tanaka, 1994), from magmatic-driven uplifts, such as at Syria Planum (Tanaka and Davis, 1988; Dohm and others, 1998; Dohm and Tanaka, 1999) and central Valles Marineris (Dohm and others, 1998, Dohm and Tanaka, 1999), and from the Argyre impact (Wilhelms, 1973; Scott and Tanaka, 1986). In addition, volcanic, eolian, and fluvial processes have highly modified older surfaces in the map region. Local volcanic and tectonic activity often accompanied episodes of valley formation. Our mapping depicts and describes the diverse terrains and complex geologic history of this unique ancient tectonic region of Mars.

The geologic (sheet 1), paleotectonic (sheet 2), and paleoerosional (sheet 3) maps of the Thaumasia region were compiled on a Viking 1:5,000,000-scale digital photomosaic base. The base is a combination of four quadrangles: the southeast part of Phoenicis Lacus (MC–17), most of the southern half of Coprates (MC–18), a large part of Thaumasia (MC–25), and the northwest margin of Argyre (MC–26). The medium-resolution Viking images used for mapping and base preparation also formed the basis of the 1:2,000,000 scale subquadrangle series. Earlier geologic maps of all or parts of the region include: (1) maps of the Phoenicis Lacus, Coprates, Thaumasia, and Argyre quadrangles at 1:5,000,000 scale based mainly on Mariner 9 images (respectively, Masursky and others, 1978; McCauley, 1978; McGill, 1978; and Hodges, 1980), (2) the global map of Mars at 1:25,000,000 (Scott and Carr, 1978) compiled largely from the 1:5,000,000 scale geologic maps, (3) maps showing lava flows in the Tharsis region at 1:2,000,000 scale compiled from Viking and Mariner 9 images (Scott, 1981; Scott and Tanaka, 1981a, b; Scott and others, 1981), (4) the map of the western equatorial region of Mars at 1:15,000,000 scale based on Viking images (Scott and Tanaka, 1986), and (5) the map of the Valles Marineris region at 1:2,000,000 scale compiled from Viking images (Witbeck and others, 1991). The previous maps have described the overall geology and geomorphology of the region but have not unraveled the detailed stratigraphy and complex evolution of this unique and geologically diverse martian province.

The main purpose of this comprehensive mapping project is to reconstruct the stratigraphic, structural, and erosional histories of the Thaumasia region. The region is the last major province of the Tharsis region to undergo detailed structural mapping using Viking images; its history is essential to documenting the overall tectonic history of Tharsis. Other provinces of Tharsis that have been structurally mapped include Syria Planum (Tanaka and Davis, 1988), Tempe Terra and Ulysses Patera (Scott and Dohm, 1990b), and Alba Patera (Tanaka, 1990). Another primary mapping objective is to determine the region's volcanic history and assess the relations among fault systems and volcanoes (Wise and others, 1979; Scott and Tanaka, 1980; Whitford-Stark, 1982; Scott and Dohm, 1990a). A secondary mapping objective is to determine the distribution and ages of valleys. In our study, we incorporated detailed photogeologic mapping, comprehensive crater statistics (table 1), and geologic, paleotectonic, and paleoerosional Geographic Information System (GIS) databases. Sheets 1–3 show geologic units, faults and other significant structures, and valleys, respectively.

To help unravel the complex geologic history of the Thaumasia region, we transferred the highly detailed geologic unit, paleotectonic, and paleoerosional information of sheets 1–3 into a multilayered GIS database for comparative analysis. The geologic information was transferred from hard copy into a digital format by scanning at 25 micron resolution on a drum scanner. The 2-bit scanned image was then converted to an x,y coordinate system using ARC/INFO's vectorization routine. The geologic unit, structural, and erosional data were transformed into the original map projection, Lambert Conformal. The average transformation root mean square error was 0.25 km (acceptable for the Thaumasia map base at 1:5,000,000 scale). After transformation, the features were properly attributed and tediously checked. Once digitized, the map data can be transformed into any map projection depending on the type of data analysis. For example, the equal-area sinusoidal projection was used for determining the precise area of geologic units (table 1).

In addition to the geologic map and its attendant stratigraphic section, correlation chart, and description of map units, we include text sections that clarify the histories and temporal, spatial, and causal relations of the various geologic units and landforms of the Thaumasia region. The geologic summary section defines the sequence of major geologic events.

GEOLOGIC SETTING

The broad Thaumasia plateau, which is about 2,900 km across and rises over 4 km above the surrounding terrain, consists of the high lava plains of Syria, Sinai, Solis, and Thaumasia Plana and surrounding highlands that are fractured by Thaumasia, Claritas, Coracis, Melas, and Nectaris Fossae (fig. 1). The plateau appears to have formed largely by uplift (Dohm and Tanaka, 1999) mainly during the Noachian (initial formation about 4 billion years ago). The structural style especially along its eastern margin (for example, the Coprates rise) appears similar, in part, to that of the younger Rocky Mountains (Laramide orogeny) in the western United States; faulting, valley dissection, and deep crustal roots are characteristic of both the Thaumasia plateau and Rocky Mountains. The ancient Thaumasia plateau has a large crustal thickness estimated at up to 120 km in places (Herb Frey, oral and written commun., 1996).

Surrounding the Thaumasia plateau are Valles Marineris, the northwest part of Argyre impact basin (>1,000 km across), Lowell impact crater (> 200 km in diameter), and the center of the northeast-trending Tharsis "bulge" or "rise," which extends for more than 3,000 km across the western equatorial region. This bulge forms a regional slope in the map region that trends southeast from Syria Planum at an elevation greater than 8 km to Argyre Planitia at an elevation less than 4 km (U.S. Geological Survey, 1989). The regional slope is interrupted by rugged highland terrain, which includes rift, fold, and fault systems, mountains, and volcanoes. Differential wind and water erosion has eroded rock materials and structures along parts of the south edge of the Thaumasia plateau, resulting in well-defined valley networks, canyons, troughs, hogbacks, and cuestas. In the southeast part of the map region, irregular topography produced by the colossal Argyre impact event includes relatively small basins and broad, scarp-bounded mesas.

We distinguish eleven geologic provinces within the Thaumasia region based on their structural, topographic, and geomorphic characteristics (fig. 3, table 2). These characteristics include broad canyons, highlands, large mountain ranges, volcanoes (fig. 4), lava and ridged plains, and surfaces that have been modified by tectonic, volcanic, and erosional processes.

STRATIGRAPHY

Geologic units were identified and mapped on individual, digitally enhanced Viking images and 1:2,000,000-scale photomosaic bases and compiled on the 1:5,000,000-scale digital photomosaic map base. Image resolution for the Thaumasia region ranges from 9 to > 500 m/pixel; those in the range of 50 to 300 m/pixel were most commonly used for mapping. The identification and classification of geologic units into groups and assemblages, where applicable, follows that of Scott and Tanaka (1986); in several instances, units are newly identified or renamed.

The materials of the Thaumasia region have been divided into 39 geologic units based on stratigraphic relations and morphologic characteristics. Relative ages were determined from crater densities and stratigraphic and structural relations. Contacts and interpretations of previously mapped units at 1:15,000,000-scale (Scott and Tanaka, 1986) were, in many cases, revised to reflect detailed geologic information mappable at 1:5,000,000-scale; for example, we subdivided the ridged plains material and the lower member of the Syria Planum Formation defined by Scott and Tanaka (1986). The units are assigned to the formal stratigraphic systems (Noachian, Hesperian, and Amazonian) devised by Scott and Carr (1978) and series (upper, middle, and lower divisions of systems) defined by Tanaka (1986). To determine the material and modification ages of the Thaumasia geologic units, we compiled crater statistics for 28 units of significant areal extent, which cover 96.6% of the map region. We measured all crater-rim diameters larger than 2 km using the Mars Digital Image Model (at 231 m/pixel; U.S. Geological Survey, 1991a, b) and calculated unit areas from digitally scanned contacts using GIS (tables 1 and 3). The crater statistics consist of total crater populations (including partly buried, degraded, and pristine impact craters), which may indicate emplacement ages, and superposed craters only, which indicate ages of most recent, major resurfacing (for example, see fig. 5*A*, *B*). We produced hundreds of crater counts that include individual outcrops, groups of outcrops according to local to regional physiographic associations, and all outcrops together for each unit. The crater densities among individual and groups of outcrops vary somewhat; these ranges are largely incorporated in their time-stratigraphic age assignments.

The map units are categorized into channel-system and eolian materials, Valles Marineris interior deposits, western volcanic assemblage (flow and shield materials, Tharsis Montes Formation, Syria Planum Formation), plateau and high-plains assemblage (plateau sequence, fractured materials, dissected and etched materials, high-plains materials, undivided material), circum-Argyre materials, and crater materials. Only materials of impact craters that have rim-crest diameters nearly 50 km and greater are mapped; the materials are assigned relative ages based on age relations with surrounding units and structures. For all units, relative-age assignments represent material emplacement ages; in some cases, erosional and deformational modification of the units occurred during unit formation. For example, dissected and etched materials include the eroded outcrops and superposed sediment deposited by the resurfacing agent because they generally cannot be mapped separately; their relative-age ranges reflect both materials.

Most unit contacts are fairly precise, especially where they are defined by onlap, embayment, and burial relations. Transitional contacts, such as between fractured and dissected materials and adjacent geologic units are also sharp in most places. For example, these contacts commonly form along erosional scarps or partly buried structure. In other cases, because of a paucity of stratigraphic markers or poor image quality, contacts must be considered gradational and appear dashed on the map.

NOACHIAN SYSTEM

The Noachian System consists of ancient crustal materials formed during the period of early bombardment that produced a high density of impact craters including enormous basins. Cratering, along with water and wind erosion and tectonic deformation, have modified or destroyed many of the primary morphologic features of Noachian units, including a substantial part of the ancient crater population. Thus, Noachian surfaces are usually characterized by impact, erosional, and tectonic features that postdate the material. The Noachian materials consist mainly of impact breccia, volcanic materials (volcanoes and lava flows), and eolian and fluvial sediments that mantle and subdue parts of the heavily cratered terrain. Materials of the Noachian System, which include geologic units that straddle the Noachian/Hesperian boundary (fig. 6*A*; table 4), cover over 55% of the Thaumasia region.

The hilly unit (unit Nplh) at the base of the plateau sequence forms heavily cratered terrain consisting of high-standing plateaus, irregular topographic highs, prominent ridges, and highly degraded, ancient crater rims mainly in the Thaumasia highland, Daedalia, and Argyre provinces (fig. 3). Locally, tectonic and impact processes (Watters, 1993; Schultz and Tanaka, 1994; Craddock and others, 1990) may have contributed to the prominent relief of the hilly unit; figure 2 shows scarps and ridges of the hilly unit, which are interpreted to be cuestas and hogbacks resulting from extensional and contractional tectonic warping and differential erosion of the martian crust in the western part of the Thaumasia highland province. In contrast, the basement complex (unit Nb) is cut by numerous faults and forms rugged, highly cratered, locally dissected mountainous terrain of prominent relief mainly in the Thaumasia highland province. Structural uplift along faults produced by local and regional volcanotectonic activity and large impact events probably all contributed to the high relief of the basement outcrops (Scott and Tanaka, 1986).

In the southeast part of the map region, patches of blocky terrain and mountains form erosional remnants of the knobby and basin-rim units of the circum-Argyre materials (units Nak and Nah, respectively). These materials, which partly surround the Argyre basin, formed as a result of the huge impact event and subsequent wind and water erosion.

Degraded, and in places, deformed impact craters (mostly >50 km) occur within Noachian materials mainly in the southern half of the map region. They are mapped as material of degraded craters (unit c_1), which is often embayed by Upper Noachian and younger materials. In highly modified terrains, remnants of large impact crater rims suggest that a substantial part of the ancient crater population has been destroyed in these resurfaced regions.

Many of the prominent, isolated mountains within the Coprates, Thaumasia highland, Daedalia, and Sirenum provinces of the map region are located along or near faults and often exhibit summit depressions and highly dissected flanks (fig. 7). They have been interpreted as ancient volcanoes (Saunders and others, 1980; Scott and Tanaka, 1981c, 1986; Witbeck and others, 1991; Hodges and Moore, 1994). Alternative explanations entail impact, erosional, or tectonic processes; for example, Craddock and others (1990) suggest that some of these topographic highs could be massifs associated with ring structures of an ancient impact basin in Daedalia Planum. Although the alternative explanations cannot be ruled out, a volcanic origin for most of the mountains, in our opinion, is more consistent with their morphologies and geologic settings. We have mapped fourteen such features in the map region that we interpret as volcanic constructs including the eight identified by Scott and Tanaka (1981c, 1986). Several smaller, domelike structures in the Coprates and Thaumasia highland provinces may also be volcanoes or outcrops of highly eroded crustal materials; these are mapped as domes on the geologic map (sheet 1). Detailed mapping of the volcanic constructs and their stratigraphic relations with the surrounding materials and structure, which include crater counts of batched outcrops of the construct material, suggest that widespread, construct-forming volcanism was prevalent in the region throughout most of the Noachian Period; two distinct periods of construct-forming activity are shown on the geologic map. The oldest construct-forming activity of the map region produced materials of 11 of the 14 volcanoes, which are mapped as older flow and construct material (unit Nfc).

The cratered unit (unit Npl_1), which is the most extensive unit in the western equatorial region (Scott and Tanaka, 1986; Tanaka, 1986), forms most of the basal materials in the southern part of the map region and partly embays the hilly unit (unit Nplh) of the plateau sequence and basin-rim unit (unit Nah) of the circum-Argyre materials. The cratered unit records a high density of superposed and partly buried and degraded impact craters of all sizes formed during the middle Noachian. Because of continued bombardment and possible early, widespread volcanism (Saunders, 1979; Greeley and Spudis, 1981) and erosion (for example, see Craddock and Maxwell, 1993), the cratered unit probably consists of impact breccia and volcanic and sedimentary materials. Noachian materials in the Coprates, Thaumasia highland, Sirenum, and Argyre provinces, which largely include the cratered unit, are dissected by valleys; the dissected material outcrops and associated valley deposits are mapped as the older dissected material (unit Npld).

The basement complex is embayed by and, in places, partly transitional to other highly faulted Noachian surfaces of lower relief that are mapped as older fractured material (unit Nf). The older fractured material, which is marked by highly eroded and deformed impact craters, is cut by numerous fault systems consisting of complex fractures and graben-bounding faults that record regional Tharsis, Syria Planum, and possible Valles Marineris tectonism and local intrusions and uplifts. Where the older fractured material has been highly dissected, it is mapped as fractured and dissected material (unit Nfd); superposition relations with younger material indicate that many faults and valleys within unit Nfd are Noachian (sheets 2 and 3, respectively).

Along the southeast margin of the Thaumasia plateau, a small isolated patch of etched material (unit Nple) is cut by flat-floored troughs with serrated edges. In this region and in other places along the plateau's edge, a wide variety of geomorphic features occurs, including locally networked trough-and-valley forms, highly eroded impact crater rims, faults, irregular broad ridges, and cuestas. These features may indicate differential wind and water (surface runoff and groundwater flow) erosion and mass-wasting and (or) lateral variations in surficial rock competency.

During the Late Noachian, many areas were largely resurfaced by a thin mantle of probable eolian, fluvial, and volcanic origin mapped as the subdued cratered unit (unit Npl_2) of the plateau sequence (Scott and Tanaka, 1986). This unit embays most craters >10 km across and mainly outcrops in the Coprates, Argyre, Sirenum, and western part of the Thaumasia highland provinces. It is marked in a few places by small ridges, valleys, and possible flow fronts.

The map units whose relative ages straddle the Noachian/Hesperian boundary (sheet 1) show that major resurfacing of the map region continued into the early part of the Hesperian, degrading or burying many Noachian surfaces. The undivided material (unit HNu) forms the cliff faces of elongated depressions and the canyon walls of Valles Marineris in the far northwest part of the map region and probably includes Noachian basal outcrops (Scott and Tanaka, 1986; Witbeck and others, 1991).

Resurfaced Noachian units of the Argyre province include large valley forms, irregular depressions, drainage basins comprising valley networks, furrows, and highly subdued ridges of all shapes and sizes. These highly modified surfaces, which include the materials that partly infill the floors of depressions and assortment of valley forms, are mapped as the dissected and etched unit of the circum-Argyre materials (unit HNade). Crater counts (total crater populations and superposed only crater populations; fig. 5*A*, *B*) clearly indicate that the modified material is Noachian and that the material deposited by resurfacing is Early Hesperian or younger; crater statistics along with stratigraphic and crosscutting relations of the Lowell impact crater materials with the surrounding geologic units and structure indicate that valley systems could have formed locally as a result of the Late Hesperian/Early Amazonian Lowell impact (Lias and others, 1997). Eolian, mass-wasting, fluvial, and (or) possible glacial resurfacing (Baker and others, 1991; Kargel and Strom, 1992) could have formed the dissected and etched terrain.

Pristine to moderately eroded impact craters (mostly >50 km) that have continuous rims and ejecta blankets occur within Noachian and Hesperian materials of the map region. They are mapped as material of fresh to subdued craters (unit c_2), which is mainly superposed on the surrounding rock materials.

Areas of Noachian materials and structure (faults and ridges) along the southern margin of the Thaumasia plateau are highly modified by Late Noachian/Early Hesperian networks of relatively deep and narrow valleys. The dissected outcrops and the younger sediment deposited on their surfaces by the channeling are mapped as intermediate dissected material (unit HNpld). In the Warrego Valles region, several valley segments of Warrego head near a large rift system (fig. 8*A*, *B*).

Intermediate fractured material (unit HNf) in the Claritas, Thaumasia, and Coracis Fossae and in the Sinai, Thaumasia highland, Daedalia southeast, and Sirenum provinces is cut by fewer and less complex faults than the older fractured material (sheet 2). The faults record tectonism of most of the regional centers that contributed to the structure of the older fractured material, but of lesser intensity. The intermediate fractured material is locally buried by younger Hesperian materials, which include member 1 of the Tharsis Montes Formation (unit Ht_1) and lower member of the Syria Planum Formation (unit Hsl_1), younger ridged plains material (unit Hr), and smooth unit of the plateau sequence (unit Hpl_3).

Terraced material (unit HNt) occurs mostly in the southern and northeastern parts of the Thaumasia Planum and Thaumasia highland provinces, respectively, largely bordering topographic highs. It is marked in places by irregular scarps, scarp-bounded mesas, furrows, and subdued wrinkle ridges and faults. The terraced unit is transitional in places with the older ridged plains material (unit HNr) of the Thaumasia Planum province; eolian and fluvial erosion may have formed terraces by exposing older basal materials and (or) by stripping away the upper layers of the older ridged plains material. The older ridged plains material is marked by numerous wrinkle ridges, narrow linear ridges, and faults of varying trends.

The youngest construct-forming activity of the map region produced three of the fourteen prominent volcanoes within highly faulted terrains of the Thaumasia highland province. They are mapped as younger flow and construct material (unit HNfc). One example, along a large rift system (fig. 4), has flanks that are cut by curvilinear faults and well-defined valley networks. Flat-floored troughs and lobate scarps generally similar to those of Apollinaris (Scott and others, 1993) and Hadriaca Paterae (Crown and Greeley, 1993) are present on or near some of the mountain flanks, as at lat 40.5º S., long 101.0º.

A relatively thin, Late Noachian to Early Hesperian and possibly younger plains-forming material blankets valley floors of the Argyre province that trend downslope toward the basin. The material is mapped as the smooth floor unit of the circum-Argyre materials (unit HNafs), which may include deposits of eolian, mass-wasted, fluvial, and (or) possible glacial origin (Baker and others, 1991; Kargel and Strom, 1992).

Chaotic material (unit HNcht) of the channel-system and eolian materials forms several isolated patches of closely spaced knobs mostly near highly faulted and dissected areas in the Thaumasia highland, Sirenum, and Argyre provinces. The knobs are the result of breakup of Noachian/Hesperian rock outcrops, which include older fractured material (unit Nf), fractured and dissected material (unit Nfd), and terraced material (unit HNt). In places, the chaotic material is embayed by the smooth unit of the plateau sequence (unit Hpl_3).

Networks of troughs (fig. 9*A*), which mostly originate from faults and large irregular depressions, dissect surfaces of the southern part of the Coprates rise along the southeast margin of the Thaumasia plateau; these highly modified areas are mapped as troughed material (unit HNplt). The troughs generally resemble those that dissect the flanks of Tyrrhena and Hadriaca Paterae (fig. 9*B*) on Mars (Greeley and Crown, 1990; Gulick and Baker, 1990; Crown and others, 1992; Crown and Greeley, 1993) and ignimbrites on Earth (fig. 9*C*), which may suggest a volcanic origin (possibly pyroclastic) for the eroded rock outcrops although sources (volcanic vents) are not visible. On the other hand, fluvial erosion may have highly modified older rock outcrops of the Thaumasia plateau, which include intermediate dissected material (unit HNpld), fractured and dissected material (unit Nfd), older fractured material (unit Nf), and basement complex (unit Nb) of the plateau and high-plains assemblage. Because many of the troughs head near faults and large depressions, trough development may be explained by a process linkage similar to that proposed for the Elysium and Galaxias regions of Mars where ground-ice melting due to volcanism may have provided the water that formed the valley distributaries (Baker, 1982; Mouginis-Mark and others, 1984; Mouginis-Mark, 1985). Alternatively, the faulting may have produced conduits that tapped confined aquifers (MacKinnon and Tanaka, 1989).

HESPERIAN SYSTEM

The Hesperian System records extensive ridged plains volcanism in the Sinai and Coprates east provinces of the Thaumasia region and widespread resurfacing of older materials (Lower Hesperian Series), which includes the deposition of colluvial and alluvial deposits. Later, sheet lavas were emplaced in the Syria–Solis, Daedalia, and Daedalia southeast provinces from the summit areas and flanks of the large topographic high in Syria Planum and Noctis Labyrinthus region (also referred to as Syria "corona" after Tanaka and others, 1996) and the Tharsis Montes volcanoes (Upper Hesperian Series). Deformation of Upper Hesperian lava flow materials occurs in the northwest part of the region. Materials of the Hesperian System, which include geologic units that straddle the Hesperian/Amazonian boundary (fig. 6*A*; table 4), cover 44% of the Thaumasia region.

Widespread smooth plains-forming material blankets older surfaces and structures in the southern half of the map region; it is mapped as the smooth unit (unit Hpl_3) of the plateau sequence in the plateau and high-plains assemblage. Particularly in the Argyre province, relatively thick deposits of the smooth unit were shed from the Thaumasia plateau's southeast margin by fluvial, eolian, and mass-wasting erosion, burying the lower flanks of crater rims and wrinkle ridges. Here, the smooth unit must be as much as a few hundred meters thick in places because partly buried Noachian crater rims on Mars seldom have heights exceeding 500 m (Roth and others, 1989). In the Thaumasia highland province, materials of the smooth unit fill topographic lows and blanket highly fractured terrains.

Areas of younger dissected material (unit Hpld) occur along the edge of the Thaumasia plateau in the southern and southeastern parts of the Thaumasia highland and the southern part of the Coprates provinces. In places, the younger dissected material partly buries or embays the downslope reaches of older dissected and etched materials (units Nfd, Nple, HNplt, HNpld). Here, the younger dissected material is cut by valleys that could have formed during the later stages of fluvial dissection of the older materials; valley networks of the southeast flank of the Coprates rise (fig. 10) and the eastern reaches of Warrego Valles (fig. 11) transform into single segmented valleys at breaks in slope, similar to valley systems on Earth. The valleys occur downslope from areas interpreted to have been volcanotectonically active (for example, Warrego Valles) and large Hesperian impact craters (for example, valley forms that occur along pre-existing structure near 39.0º S., long 80.5º downslope from a large impact crater near 36.0º S., long 79.5º). Stratigraphic and crosscutting relations among the valleys, materials, and volcanic and tectonic structures may suggest a process linkage between valley formation and volcanic and tectonic activity (see erosional history section for further explanation). A distinct valley along the southwest margin of the Thaumasia plateau northwest of a large shield volcano (fig. 12) heads near a graben. This valley and its associated deposits are mapped as channel and flood-plain material (unit Hch). Because the valley heads near a fracture, release of groundwater may have been related to tectonic and possibly volcanic activity.

Younger ridged plains material (unit Hr) of Sinai province buries the surfaces and associated structures of terraced material (unit HNt) in the northeastern part of the Thaumasia highland province and older ridged plains material (unit HNr) in the western part of the Thaumasia Planum province (fig. 13). Burial of grabens with varying trends between the two ridged materials indicates a termination of extensional tectonism in the Thaumasia Planum and Coprates provinces prior to emplacement of the younger ridged plains material. Although burial relations show that younger ridged plains material embays several wrinkle ridges of the older ridged plains material, ridge development probably was ongoing at least during the emplacement of the younger ridged plains material. Our older and younger ridged materials in the map region are subdivisions of the extensive Hesperian ridged plains unit of Scott and Tanaka (1986) based on stratigraphic relations and crater counts (table 1).

Lava flows of member 1 (unit Ht_1) of the Tharsis Montes Formation in the Daedalia southeast province embay and partly bury wrinkle ridges, older and younger flow and construct materials (units Nfc, HNfc), and older materials of the plateau and high-plains assemblage (units Npl_1, Nfd, Npld, Npl_2, HNf). These lava flows are buried to the northwest by lava flows of member 2 of the Tharsis Montes Formation (unit Ht_2) in the Daedalia province; lava flows of both members are cut by northeast-trending faults of Claritas Fossae.

In the northwestern part of the map region, extensive, moderately faulted lava flows along the northeast margin of the Thaumasia highland province are mapped as younger fractured material (unit Hf). These outcrops, which record continued volcanotectonic activity of Syria Planum and the Tharsis Montes volcanoes, are buried by lava flows of the older flows of lower member, younger flows of lower member, and upper member of the Syria Planum Formation (units Hsl_1, Hsl_2, and Hsu, respectively). The lava flow materials show an age progression from the southeast (older) to the northwest (younger). In the southeast, subdued, individual lava flows and their flow fronts of unit Hsl_1 are scarce, whereas in the northwest, pristine lava flows and flow fronts of the upper member are numerous; an extended period of wind erosion may have contributed to the subdued appearance of the older flows of the lower member.

In the Daedalia province, lava flows of member 3 of the Tharsis Montes Formation (unit AHt_3) overlap flows of member 2 (unit Ht_2) and embay highly faulted material (unit Nf) of the northwest margin of the Thaumasia highland province. An increase in lava flow fronts of member 3 compared with member 2 may be due to a smaller time of eolian deposition and erosion or thicker flows. Minor faulting of the lava flows of member 3 indicate a significant waning of Tharsis-centered tectonic activity during the Late Hesperian/Early Amazonian.

AMAZONIAN SYSTEM

Amazonian rocks form the youngest materials on Mars, and thus they are superposed by relatively few impact craters. A major decline in martian tectonism (Scott and Dohm, 1990a) and highland valley formation (Craddock and Maxwell, 1993; Scott and others, 1995; Carr and Chuang, 1997) is recorded during this period. In the region, wind erosion appears to be the dominant resurfacing agent. The Amazonian System materials consist of less than 1% (fig. 6*A*; table 4) of the total geologic units in the Thaumasia region. Amazonian materials consist of widespread smooth floor crater material (unit cs), Valles Marineris interior deposits mapped as rough and smooth floor materials (units Avfr and Avfs, respectively, of Witbeck and others, 1991), lava flows of member 5 (unit At_5) of the Tharsis Montes Formation, which occur as a small outcrop along the northwest edge of the map, and linear material (unit Al), which forms a small, putative dune field along the southeast edge of the map region.

STRUCTURAL HISTORY

The history of tectonic events in the Thaumasia region is recorded by the distribution and ages of fault and ridge systems mapped from Viking orbiter images (sheet 2). We have mapped thousands of tectonic structures, which include faults and grabens, mare-type wrinkle ridges, and broad and narrow ridges (for example, see fig. 14). Stratigraphic and crosscutting relations among the geologic units permitted us to construct a map of the faults and grabens as they prevailed during five successive stages. The five stages are defined by major periods of geologic activity, which are recorded in sets of geologic units of the Thaumasia region (each unit was assigned a stage based on crater densities and stratigraphic and structural relations; see table 3), and their stratigraphic positions are correlative with the stratigraphic series defined by Tanaka (1986). Based on uncertainties in the unit age ranges, we conservatively show slight overlaps between the stages (see correlation chart on sheet 2).

The stage assignments of structures on the maps adhere to the following guidelines: (1) structures of younger age may extend across boundaries of older geologic units, (2) structures of intermediate age may extend into older units but not into younger materials, and (3) stage 1 structures occur only in Noachian materials. However, some structures, which are wholly confined to their host materials and not in contact with younger units, are indeterminate in age; they are assigned the age of the host material. The large rift system of Claritas Fossae (fig. 2), for example, consists of a complex system of graben and fault segments, some of which are wholly confined to Noachian host materials; these segments are assigned a Noachian age (stage 1) though they may have been formed or reactivated concurrently with similar-trending faults and grabens that cut younger materials. The much greater density of these faults in stage 1 rocks versus younger materials suggests that the majority did form during stage 1.

In addition to incorporating similar mapping methods that were used for determining the stratigraphic and structural histories of the Syria Planum (Tanaka and Davis, 1988), Tempe Terra and Ulysses Patera (Scott and Dohm, 1990b), and Alba Patera (Tanaka, 1990) regions of Mars, we have transferred the Thaumasia region's highly detailed geological unit, paleotectonic, and paleoerosional information into a multilayered GIS database for comparative analysis to help unravel its geologic history (Dohm and others, 1996; Dohm and others, 1997a, b).

Our analysis of faults, grabens, and wrinkle ridges in the entire Thaumasia region using GIS indicates that tectonic activity, which includes Tharsis-centered volcanic and (or) tectonic activity, began and reached its peak during the Noachian and declined substantially during the Late Hesperian and Amazonian periods (stages 4–5; fig. 15*A*, *B*; table 5). These results are in general agreement with previous work (Scott and Dohm, 1990a) but provide more temporal, spatial, and geologic detail. At Claritas Fossae, for example, Tharsis-centered faulting probably commenced in the Early to Middle Noachian (stage 1), declined during Late Noachian and Early Hesperian (stages 2 and 3), and waned substantially during Late Hesperian/Amazonian (Dohm and others, 1997a). The waning of Tharsis-centered tectonism is coeval with the emplacement of large volumes of Tharsis- and Syria-related lava flows; thus, a significant change from tectonic to volcanic Tharsis-dominated activity occurred during the Late Hesperian (stage 4) in the Thaumasia region. The decline in Tharsis-radial normal faulting may correspond with a decline in intrusive thickening of the crust at Tharsis (Tanaka and others, 1991).

Other significant Tharsis-centered structures occur in Thaumasia Planum (south of Coprates Chasma) and elsewhere, including radial faults and grabens that parallel Valles Marineris and wrinkle ridges that are mainly concentric to Syria Planum. In Sinai Planum, undeformed, stage 4, older flows of the lower member of the Syria Planum Formation (unit Hsl_1) bury stage 3 younger ridged plains material (unit Hr) that in turn buries stage 2 rock surfaces and associated structures of older ridged plains material (unit HNr) in the western part of the Thaumasia Planum province (fig. 13). These relations indicate a sharp decline of Tharsis-centered normal faulting and compressional deformation during the Early Hesperian for the northeastern part of the Thaumasia region. Below, we discuss the history of major tectonic features and structure sets represented in figure 16.

Claritas Fossae (stages 1–4). Prolonged Tharsis-centered extensional tectonism resulted in the formation and subsequent reactivation of narrow (<5 km across) and wide (>5 km across) grabens. These form the densest and most numerous and long-lived system of grabens in the region. Faulting decreased over successive periods, especially during stages 4–5 (Dohm and others, 1997a); a large percentage of northwest-trending faults and grabens of Claritas Fossae in the northwest part of the map region are buried by stage 4 lavas of the Syria Planum Formation.

Thaumasia Fossae (stages 1–3). Narrow to broad grabens apparently formed a southern extension of Claritas Fossae.

Coracis, Melas, and Nectaris Fossae (stages 1–2). Grabens and rifts radiate from possible centers at Syria and Sinai Plana and (or) Valles Marineris and from local volcanotectonic centers; some also parallel Valles Marineris. Faulting waned during stage 2 tectonism, and materials of stages 3 and 4 buried the fossae.

Syria Planum (stages 1–4). This long-lived volcanotectonic center, which we interpret to be a coronalike feature (Tanaka and others, 1996), was the site of (1) the development of a raised north rim, (2) the formation of numerous concentric and radial grabens (including Noctis and some of Claritas Fossae) and collapse troughs (Noctis Labyrinthus), and (3) the emplacement of lavas of stage 4 that buried the feature's southeast rim and lavas (possibly of stages 3 and 4) that infill the feature's interior (Tanaka and others, 1996). Tectonism largely waned after the emplacement of stage 4 lavas.

Wrinkle ridges (stages 1–3). Mainly Syria-centered tectonism produced wrinkle ridges in the Sinai, Thaumasia Planum, and East of Coprates provinces of the Thaumasia region. Wrinkle ridges developed before and after the emplacement of the stage 3 younger ridged plains material (unit Hr), suggesting a long time period of wrinkle ridge formation.

Broad ridges and large scarps (stages 1–2). These large structures, interpreted to have been formed chiefly by compressional tectonism (Schultz and Tanaka, 1994), occur mainly along the edge of the Thaumasia plateau within the Thaumasia highland and Coprates provinces. Most of the broad ridges follow an immense, arcuate swath centered at Syria Planum, which has been called the Thaumasia fold belt (Schultz and Tanaka, 1994). The formation of these structures largely ceased during the latter part of stage 2. In addition to large scarps, highly resurfaced smaller scarps that are scattered throughout the map region may be the result of extensional or contractional tectonism, erosion, or deposition.

Thaumasia highland rifts (stages 1–3). Rift systems in the Thaumasia highland province are defined by long, broad grabens (tens of kilometers wide) and associated narrow fractures (<5 km wide) and commonly include probable volcanic constructs (for example, see fig. 4). Tectonism from regional and local volcanotectonic centers and vertical plateau uplift (Dohm and Tanaka, 1999) contributed to the development of the rift systems during stages 1 and 2; locally, the rift structures were reactivated during stage 3. The close association of fault systems with volcanoes on Mars (Wise and others, 1979; Scott and Tanaka, 1980; Whitford-Stark, 1982; Scott and Dohm, 1990a; Banerdt and others, 1992), which is similar to strong correlations between volcanic constructs and fault systems of several volcanic fields on Earth (for example, see Scott and Trask, 1971; Shoemaker and others, 1978; Crumpler, 1982; Holm and others, 1991; Dohm, 1995), suggests that magma used deep-seated basement structures as conduits to reach the martian surface during periods of volcanic activity.

Coprates rise (stages 1–2). Contractional tectonism, which may be related to vertical plateau uplift related to magmatism and thermal rise (Dohm and Tanaka, 1999), mainly during stage 2 resulted in the formation of a large (900 km long and 2 to 4 km high) asymmetric ridge (higher on the east); the ridge is the largest of several in the Thaumasia fold belt (Schultz and Tanaka, 1994) and has morphologic features (fig. 17*A*) similar to those of the narrower (<50% of Coprates) Wind River Mountain Range of Wyoming (fig. 17*B*). Both mountain ranges exhibit faults, cuestas, hogbacks, and valleys.

Argyre structure (stages 1–2). During stage 1, a large impact event produced the Argyre basin and associated fault-controlled radial valleys and concentric mountain ranges, large fault scarps, and broad ridges. Normal offset of some of the concentric faults may have occurred during stages 1 and 2 because of isostatic adjustment of the basin.

Valles Marineris/Noctis Labyrinthus (stages 2–5). Numerous narrow (<5 km) and broad grabens (>5 km), which are radial to and parallel with Valles Marineris, cut stage 1 and 2 materials in the Sinai, Thaumasia Planum, Coprates, and Thaumasia highland provinces but are buried by stage 3 younger ridged plains material (for example, see fig. 13) of the Sinai province and stage 4 lava flows of the Syria Planum Formation of Syria–Solis province. Faults and grabens cut stage 4 and 5 materials of the Noctis Labyrinthus region outside the map region near Syria Planum. The south-central part of Valles Marineris has been identified as a possible center of stage 2 magmatic-driven tectonic activity (Anderson and others, 1998; Dohm and others, 1998).

VOLCANIC HISTORY

Detailed mapping of volcanic constructs and determination of their stratigraphic relations with surrounding materials and structures suggest that construct-forming volcanism occurred in the region throughout most of the Noachian Period and continued into the Early Hesperian; two distinct periods of construct-forming activity are shown on the geologic map. The older construct-forming activity produced 11 volcanoes in the Coprates, Thaumasia highland, Daedalia, and Sirenum provinces; several smaller domelike structures, which occur in the Coprates and Thaumasia highland provinces, also may represent volcanic activity during this time. Many of the volcanoes formed along extensional fault systems, suggesting a correlation between tectonism (development of deep-seated basement structures) and magmatic intrusions.

Late Noachian and Early Hesperian, younger construct-forming activity produced 3 volcanoes in the Thaumasia highlands province. Also during this time, widespread volcanism resulted in the emplacement of older ridged plains material (unit HNr; interpreted to consist of lava plains) in the Thaumasia Planum and northwestern part of the Argyre provinces and troughed material (unit HNplt; interpreted to consist mainly of pyroclastic material) in the southern part of Coprates province. Younger rocks probably obscure a more widespread distribution of older ridged plains material; for example, subdued ridges of Daedalia southeast province may represent buried older ridged plains material.

The Hesperian system records younger ridged plains volcanism in the Sinai and Coprates east provinces followed by the emplacement of extensive sheet lava in the Syria–Solis, Daedalia, and Daedalia southeast provinces from the summit areas and flanks of the corona-like feature of Syria Planum and the Tharsis Montes volcanoes. The emplacement of voluminous sheet lava is coeval with waning Syria- and Tharsis-centered tectonism; thus, a significant change from tectonic to volcanic Syria- and Tharsis-dominated activity occurred during the Late Hesperian (stage 4) in the Thaumasia region. Similar to the Tharsis activity, the corona-like feature of Syria Planum may have developed over a long period of time (Middle Noachian to Late Hesperian). Evidence for long-lived volcanotectonic activity at Syria Planum is the wide age range of Syria-centered faults especially in the Syria–Solis and Thaumasia highland provinces coupled with the large age progression of lava flow material from the east-southeast to the northwest in the north-central part of the map region. If the older and younger ridged plains materials (units HNr and Hr) of the Thaumasia Planum and Sinai provinces, respectively, originated from the Syria Planum region, the age progression would be Late Noachian from the east-southeast (deformed and subdued lava flows with scarce flow fronts of the older ridged plains material) to Late Hesperian in the northeast (younger, pristine lava flows with numerous distinct lobe fronts of the upper member of the Syria Planum Formation). Thus, tectonism associated with magmatic intrusions of the Syria Planum region probably extended from the Noachian to Late Hesperian. Continued Tharsis volcanic activity during the Amazonian Period resulted in the emplacement of lava flows in the northwest corner of the map region.

EROSIONAL HISTORY

In conjunction with identifying and analyzing tectonic structures, we have also mapped and determined relative ages for thousands of valleys (sheet 3) in order to unravel the erosional history of the Thaumasia region. The same basic geologic principles and methods used for mapping and relative-age dating tectonic structures were used for this comprehensive valley study; for example, each valley form in the region was assigned a maximum age based on the age of the youngest material cut. Networking valley forms, which indicate fluvial and (or) ground-water erosion, are mapped as channels. On the other hand, individual valley forms (many are degraded), which may have been formed by erosional, tectonic, and (or) volcanic processes, were identified as furrows.

The objective of this detailed channel and furrow GIS mapping is to determine their temporal and spatial relations with the surrounding geology and whether rainfall, volcanotectonic activity, and (or) impact events influenced their formation (Dohm and others, 1997b; Tanaka and others, 1999).

Our data (fig. 18*A*, *B*; table 5) indicate that the formation of channels and furrows in the map region peaked during the Noachian (stages 1–2) and declined substantially during the Hesperian and Amazonian Periods (stages 3–5), which corresponds to the results of Scott and others (1995). Additionally, patches of Noachian channels and furrows of stage 1 are distributed widely, whereas the majority of Late Noachian and Hesperian channels and furrows of stages 2 and 3 are mainly near volcanoes and highly faulted areas (Dohm and others, 1997b). In many areas, resurfacing and intense faulting may have obscured older channels.

The decline of valley systems is commonly viewed as indicative of a change from a warm, wet climate to a colder, drier one (Masursky, 1973; Sagan and others, 1973; Pollack, 1979; Carr, 1989). A large number of channels and furrows of stage 1 dissect many Noachian surfaces in the southern part of the Thaumasia region (sheet 3), which include those along the southwest edge of the Thaumasia plateau, along the east margin of the Coprates rise, and near large rift systems and impact craters. The widespread distribution of Noachian valley forms may be attributed to rainfall or sapping processes during a warm, wet climate and high geothermal gradient early in martian history, or widespread impact bombardment and heating (Masursky, 1973; Sharp and Malin, 1975; Pieri, 1976; Carr and Clow, 1981; Brakenridge and others, 1985; Pollack and others, 1987; Squyres, 1989; Craddock and Maxwell, 1993; Dohm and Scott, 1993; Carr, 1995; Tanaka and others, 1999). In comparison to terrestrial drainage densities, martian drainage densities are typically much lower, indicating that periods of valley formation on Mars were short-lived or had very low rates of erosion (Carr and Chuang, 1997).

In addition, the distribution of stage 1 valleys in the Thaumasia region (sheet 3) may also indicate that several different processes may have contributed to channel formation (Scott and others, 1995), including (1) local hydrothermal activity due to heating by intrusions (Mouginis-Mark and others, 1984; Mouginis-Mark, 1985; Squyres and others, 1987; Gulick and others, 1988; Wilhelms and Baldwin, 1989; Mouginis-Mark, 1990; Clifford, 1993; Cabrol and others, 1997) and impacts (Newsom, 1980; Brakenridge and others, 1985; Clifford, 1993); (2) increased hydrologic activity due to tectonic deformation and seismic pumping (Mouginis-Mark, 1990; Tanaka, 1991; Tanaka and Schultz, 1991; Clifford, 1993; Leyva and Clifford, 1993); and (3) local condensation and precipitation of water vapor from volcanoes (Gulick and Baker, 1990).

Stage 1 valleys in the Thaumasia region tend to originate near volcanoes, rift structures, and impact craters of similar age (sheets 1–3). A similar association of stages 2–3 valleys with volcanoes and highly faulted terrains also occurs in the region. For example, several channel segments of a well-developed channel system, Warrego Valles (Dohm and others, 1998; Dohm and Tanaka, 1999), head near a large rift system that consists of stages 1 and 2 and possibly 3 faults (figs. 8*A*, *B*, 11, and 16). The Late Noachian/Early Hesperian (stages 2–3) channel system dissects Noachian and Early Hesperian rock materials and modifies and destroys older fault systems mainly of stage 1. Also, the development of networks of troughs in the southern part of the Coprates rise corresponds to faults and depressions of similar age (sheets 2 and 3; fig. 9*A*). Areas where valleys occur near impact craters of similar age include: (1) stage 3 valley forms (fig. 19) mapped as furrows (near 39.0º S., long 80.5º) that occur along preexisting structure downslope of a large Hesperian impact crater (near 36.0º S., long 79.5º), and (2) a well-defined channel system (fig. 5*A*) that is upslope and to the northeast of Late Hesperian/Early Amazonian Lowell impact crater (Lias and others, 1997). Although the channels northeast of the Lowell impact crater are shown as stage 2 channels, they may have formed as a result of the Lowell impact event.

In most of the map region, the temporal and spatial associations of valleys with volcanoes, rift structures, and impact craters may suggest that local hydrothermal activity due to intrusions and tectonic deformation largely resulted in channel development. Although greater incisement would tend to be more obvious near such features because of their greater slopes, other steep terrains such as that of the hilly unit (unit Nplh) have a relative paucity of valleys. This observation indicates that widespread precipitation was not likely a major factor in valley formation in most of the Thaumasia region, except perhaps during the Early Noachian, for which much of the geologic record has been destroyed. Origin of valleys in the Argyre province, however, is highly uncertain because of the great variability in valley development and erosion there (at lower elevations with respect to the Thaumasia plateau; fig. 1). Here, Early Hesperian resurfacing of Noachian units resulted in large valley forms, irregular depressions, drainage basins comprising valley networks, furrows, and highly subdued ridges of all shapes and sizes of the dissected and etched material (unit HNade) that are not evidently associated with volcanoes and highly faulted terrains. The variety of landforms may largely be due to the complex, irregular topography generated by the impact. Additionally, a variety of processes including eolian, mass-wasting, sapping, fluvial, glacial processes (Baker and others, 1991; Kargel and Strom, 1992) and (or) hydrothermal activity related to basin-controlled intrusions (Schultz and others, 1982) may have resulted in the diversity of landforms.

GEOLOGIC SUMMARY

1. Early–Middle Noachian (part of stage 1)—Ancient crustal rocks were emplaced during a period of high meteorite flux and intense bombardment that produced enormous impact basins, including Argyre, and a high density of impact craters; rugged basement rocks formed; Thaumasia plateau, mountains including the Coprates rise, volcanoes, broad ridges and scarps, and Thaumasia highland rifts began to form; faulting radial to Tharsis, Syria Planum, Valles Marineris, and local intrusions resulted in incipient Claritas, Thaumasia, Coracis, Melas, and Nectaris Fossae; widespread valley development occurred.

2. Late Noachian (stages 1–2)—Decreasing impact rate; widespread aggradational and degradational modification that partly subdued older surfaces; ridged plains volcanism in the Thaumasia Planum province; continued development of Claritas, Thaumasia, Coracis, Melas, and Nectaris Fossae, volcanotectonic centers of Tharsis and Syria Planum, Coprates rise, volcanoes, broad ridges and large scarps, and Thaumasia highland rifts; wrinkle ridge formation and the production of faults and grabens associated with local magmatic-driven centers of tectonic activity near central Valles Marineris and the source region of Warrego Valles; possible reactivation of Argyre impact-related, concentric faults; formation of local valley systems and isolated valleys, which include Warrego Valles.

3. Early Hesperian (stages 2–3)—Extensive ridged plains volcanism in the Sinai and east Coprates provinces; widespread resurfacing of older Noachian rock; ending production of Coracis, Melas, and Nectaris Fossae, wrinkle ridges, broad ridges and large scarps, volcanoes, Thaumasia highland rifts, Coprates rise, and faults and grabens of the Thaumasia Planum province; continued development of Claritas and Thaumasia Fossae, Valles Marineris/Noctis Labyrinthus faults and grabens, volcanotectonic centers of Tharsis and Syria Planum, and local valley systems and isolated valleys.

4. Late Hesperian (stage 4)—Emplacement of extensive sheet flows in the Syria–Solis and Daedalia provinces from the summit areas and flanks of Tharsis Montes volcanoes and Syria Planum; faulting of lava flow materials in the northwest part of the map region; significant waning of tectonic deformation, which includes faults and grabens of Claritas Fossae, Syria Planum, and Valles Marineris/Noctis Labyrinthus, and waning development of valley systems and isolated valleys.

5. Amazonian (stage 5)—Continued emplacement of Tharsis-related lavas in Daedalia province; deposition of smooth crater material, Valles interior deposits, and dune material; minor Tharsis-related faulting in the northwest corner of map region; wind erosion and deposition becomes the dominate resurfacing agent.

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