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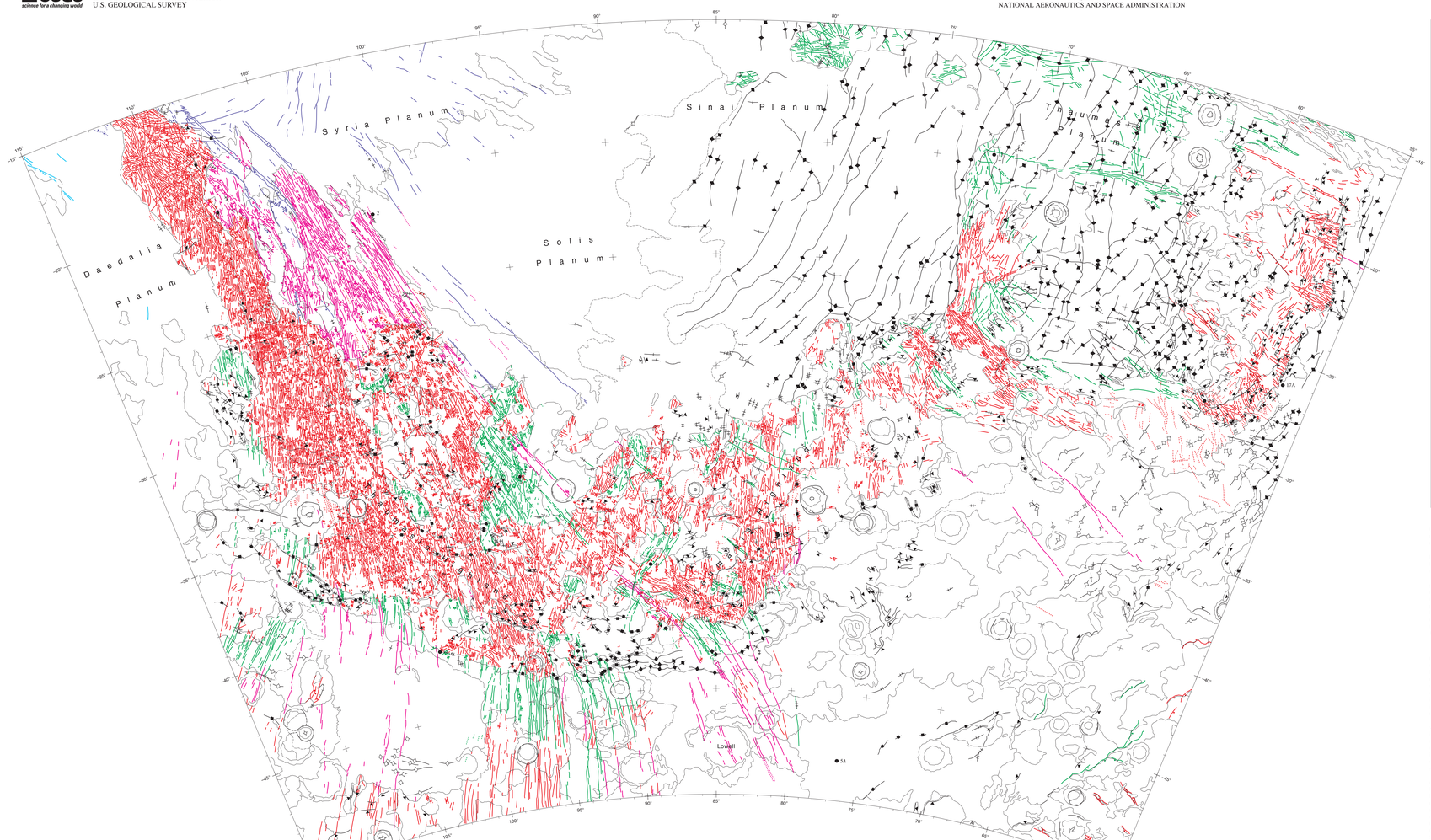
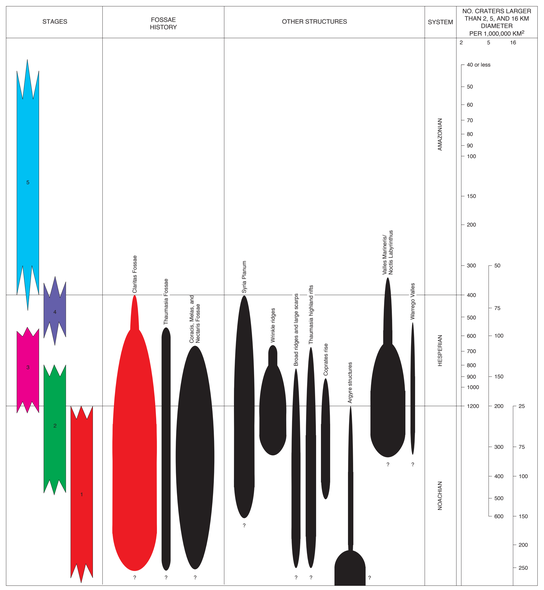
GEOLOGIC INVESTIGATION SERIES I–2650
ATLAS OF MARS: THAUMASIA REGION
SHEET 2 OF 3





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

By
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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 elsewhere on Mars, has been compared with that of the Colorado plateau, 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) and 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; Phillips, 1990; 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 continued into accessory episodes of valley formation. Our mapping depicts and describes the diverse terrains and complex geologic history of this unique ancient 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 of 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 unpublished series. Earlier geologic maps of all or parts of the region include: (1) maps of the Phoenicis Lacus, Coprates, and Thaumasia quadrangles at 1:5,000,000 scale based mainly on Mariner 9 images (respectively, Masursky and others, 1978; McCauley, 1978; Scott, 1978, and Hodges, 1980), (2) the geologic 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 of lava flows in the Tharsis region at 1:20,000,000 scale based on 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 eastern equatorial region at 1:20,000,000 scale compiled from Viking images (Wilhelms 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 geologic 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 lava plains of different ages and textures (fig. 3) (Scott and Tanaka, 1980; Whitford-Stark, 1982; Scott and Dohm, 1990a). A secondary mapping objective is to determine the distribution and age of valleys in the region using integrated detailed photogeologic mapping, comprehensive crater statistics (table 1), and geologic, paleotectonic, and paleoerosional (geographic location) crater density maps (GIS database, figures 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 computer analysis. 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 vectorization routines. The geologic units, faults, structural, and erosional data were transformed into the original map projection, Lambert Conformal. The average transformation root mean square error was 0.25 km (accuracy better than the original map base at 1:5,000,000 scale). After transformation, the features were properly attributed and tediously checked. Once digitized, the map data were 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 the 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 features 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 Syria, Sinai, and Solis Planums, 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 in response to 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 rugged 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 communs, 1996).

Surrounding the Thaumasia plateau are Valles Marineris, the northwest part of Argyre impact basin (>1,000 km across; Lowell impact crater is 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, mesas, basins, 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, buttes, mesas, and basins. The south edge of the map region, irregular topography produced by the colossal Argyre impact event includes relatively smooth 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 were based on albedo, color, morphologic expression, and relative age relations. Image resolution and topographic contrast were generally sufficient to map the region at 1:2,000,000 scale. Complete coverage of the region was achieved 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 (fig. 5) for significant areas (table 1), 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, 1993a, 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. 5A, *B*). We produced hundreds of crater counts that include only superposed craters, which provide information on local to regional physiographic associations, and all outcrops together for each unit. The crater densities of individual and groups of outcrops vary somewhat; these ranges are largely incorporated in their stratigraphic age assignments.

The map units are categorized into channel-, volcanic-, and plain-forming materials (Noachian and Hesperian volcanic materials, Noachian materials in the Coprates, Thaumasia, Solis, and Syria Planums, and Argyre provinces, which largely include the cratered unit, are dissected by valleys; the dissected material outcropsand associated valley deposits are mapped as the older dissected material, Nplo).

The basement complex is embayed by and, in places, partly transitional to other highly faulted Noachian materials (the cratered unit and the dissected material (undivided) (unit Nt). 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 Periods 2 and 3, respectively.

Along the southeast margin of the Thaumasia plateau, a small isolated patch of etched material (unit Nplm) is cut by flat-floored troughs with serrated edges. In this region and in other places where the plateau edge, a wide zone of highly eroded and fractured rock, including locally networked trough-and-valley forms, highly eroded impact crater rims, faults, irregular mesas, and basins, is present. These features may indicate subsurface and water (surface runoff and groundwater flow) erosion and mass-wasting and (or) lateral variations in surficial material properties.

During the Late Noachian, many areas were largely resurfaced by a thin mantle of probable eolian, fluvial, and volcanic origin mapped as the subducted cratered unit (unit Npkp) of the plateau sequence (Scott and Tanaka, 1986). This unit embays most craters >10 km across and mainly occupies 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 (table 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, Kaiparowits and the canyon walls of Valles Marineris in highly degraded, ancient crater rims mainly in the Thaumasia highland, Dadalia, and Argyre provinces (fig. 3). Locally, tectonic and impact processes (Watters, 1993; Schultz and Tanaka, 1994; Chadwick and others, 1990) may have contributed to the prominent relief of the hilly and rugged terrain. Younger scarps and ridges of the Tharsis bulge 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 southern part of the map region, remnants of blocky terrain and mountains from erosional remnants of the knobby and basin-rim units of the circum-Argyre materials (units Nsk and Nab, 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 cs), which is often embayed by Upper Noachian and younger materials. In highly modified craters, 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, Dadalia, and Sirenum provinces of the map region are located along or near faults and often exhibit rounded topographic profiles and steep slopes. These features have been interpreted as ancient volcanoes (Saunders and others, 1980; Scott and Tanaka, 1981a; 1986; Wilhelms 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 Thaumasia highland. Our geologic interpretations cannot be ruled out, a volcanic origin for most of the mountains, in our opinion, is more consistent with their morphologic and topographic relations. Some of the mountainous features in the map region that we interpret as volcanic constructs including the eight identified by Scott and Tanaka (1986), Tanaka (1990), and Wilhelms and others (1991) in 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 these 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 material of 11 of the 14 volcanoes, which are mapped as older flow and construct material (unit NHc). The cratered unit (unit Npl_2), 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 Npht) of the plateau sequence and the older material (unit Nplr) of the plateau sequence. These units record major episodes of superposed and partly buried and degraded impact craters of all sizes formed during the middle Noachian. Because of continued bombardment and possibly erosion and (or) volcanism, the cratered unit (unit Npl_2) of the Tharsis Montes Formation (see map, sheet 1, and Scott and Tanaka, 1986), the cratered unit probably consists of ejecta material from vulcanic 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 outcropsand associated valley deposits are mapped as the older dissected material, Npldi.

Younger ridged plains material (unit Hr_2) forms prominent, large wrinkle ridges and smaller, more numerous, narrow linear ridges, and faults of varying trends. The younger construct-forming activity of the map region produced three of the four volcanoes within the Tharsis Montes Formation (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 Npht) of the plateau sequence and the older material (unit Nplr) of the plateau sequence. This unit records major episodes of superposed and partly buried and degraded impact craters of all sizes formed during the middle Noachian. Because of continued bombardment and possibly erosion and volcanism, the cratered unit (unit Npl_2) of the Tharsis Montes Formation (see map, sheet 1, and Scott and Tanaka, 1986), the cratered unit probably consists of ejecta material from vulcanic 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 outcropsand associated valley deposits are mapped as the older dissected material, Npldi.

Chaotic material (unit HNch) of the channel-system and eolian materials forms several isolated knobs and irregular patches in the Coprates and Thaumasia highland provinces (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 Periods 2 and 3, respectively.

Along the southeast margin of the Thaumasia plateau, a small isolated patch of etched material (unit Nplm) is cut by flat-floored troughs with serrated edges. In this region and in other places where the plateau edge, a wide zone of highly eroded and fractured rock, including locally networked trough-and-valley forms, highly eroded impact crater rims, faults, irregular mesas, and basins, is present. These features may indicate subsurface and water (surface runoff and groundwater flow) erosion and mass-wasting and (or) lateral variations in surficial material properties.

During the Late Noachian, many areas were largely resurfaced by a thin mantle of probable eolian, fluvial, and volcanic origin mapped as the subducted cratered unit (unit Npkp) of the plateau sequence (Scott and Tanaka, 1986). This unit embays most craters >10 km across and mainly occupies 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.

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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, Dadalia, 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 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, irregular mesas, and smooth, plateau-forming units that are highly subdivided 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 HNdec). 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 the modified material is Early Hesperian. The Argyre impact event, which formed Amazonian Lowell impact (Lias and others, 1997), Eridan, mass-wasting, fluvial, and (or) possible glacial resurfacing (Baker and others, 1992; Kargel and Strom, 1992) could have formed the dissected and etched terrain.

Pristine to moderately eroded 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 cs), which is often embayed by Upper Noachian and younger materials. In highly modified craters, 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, Dadalia, and Sirenum provinces of the map region are located along or near faults and often exhibit rounded topographic profiles and steep slopes. These features have been interpreted as ancient volcanoes (Saunders and others, 1980; Scott and Tanaka, 1981a; 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 Thaumasia highland. Our geologic interpretations cannot be ruled out, a volcanic origin for most of the mountains, in our opinion, is more consistent with their morphologic and topographic relations. Some of the mountainous features in the map region that we interpret as volcanic constructs including the eight identified by Scott and Tanaka (1986), Tanaka (1990), and Wilhelms and others (1991) in 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 these 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 material of 11 of the 14 volcanoes, which are mapped as older flow and construct material (unit NHc).

The younger construct-forming activity of the map region produced three of the four volcanoes within the Tharsis Montes Formation (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 Npht) of the plateau sequence and the older material (unit Nplr) of the plateau sequence. This unit records major episodes of superposed and partly buried and degraded impact craters of all sizes formed during the middle Noachian. Because of continued bombardment and possibly erosion and volcanism, the cratered unit (Npl_2) of the Tharsis Montes Formation (see map, sheet 1, and Scott and Tanaka, 1986), the cratered unit probably consists of ejecta material from vulcanic 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 outcropsand associated valley deposits are mapped as the older dissected material, Npldi.

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The younger construct-forming activity of the map region produced three of the four volcanoes within the Tharsis Montes Formation (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 Npht) of the plateau sequence and the older material (unit Nplr) of the plateau sequence. This unit records major episodes of superposed and partly buried and degraded impact craters of all sizes formed during the middle Noachian. Because of continued bombardment and possibly erosion and volcanism, the cratered unit (Npl_2) of the Tharsis Montes Formation (see map, sheet 1, and Scott and Tanaka, 1986), the cratered unit probably consists of ejecta material from vulcanic 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 outcropsand associated valley deposits are mapped as the older dissected material, Npldi.

The basement complex is embayed by and, in places, partly transitional to other highly faulted Noachian materials (the cratered unit and the dissected material (undivided) (unit Nt). 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 Periods 2 and 3, respectively.

Along the southeast margin of the Thaumasia plateau, a small isolated patch of etched material (unit Nplm) is cut by flat-floored troughs with serrated edges. In this region and in other places where the plateau edge, a wide zone of highly eroded and fractured rock, including locally networked trough-and-valley forms, highly eroded impact crater rims, faults, irregular mesas, and basins, is present. These features may indicate subsurface and water (surface runoff and groundwater flow) erosion and mass-wasting and (or) lateral variations in surficial material properties.

During the Late Noachian, many areas were largely resurfaced by a thin mantle of probable eolian, fluvial, and volcanic origin mapped as the subducted cratered unit (Npl_2) of the plateau sequence (Scott and Tanaka, 1986). This unit embays most craters >10 km across and mainly occupies 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 (table 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, Kaiparowits and the canyon walls of Valles Marineris in highly degraded, ancient crater rims mainly in the Thaumasia highland, Dadalia, and Argyre provinces (fig. 3). Locally, tectonic and impact processes (Watters, 1993; Schultz and Tanaka, 1994; Chadwick and others, 1990) may have contributed to the prominent relief of the hilly and rugged terrain. Younger scarps and ridges of the Tharsis bulge 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).

Resurfaced Noachian units of the Argyre province include large valley forms, irregular depressions, irregular mesas, and smooth, plateau-forming units that are highly subdivided 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 HNdec). 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 the modified material is Early Hesperian. The Argyre impact event, which formed Amazonian Lowell impact (Lias and others, 1997), Eridan, mass-wasting, fluvial, and (or) possible glacial resurfacing (Baker and others, 1992; Kargel and Strom, 1992) could have formed the dissected and etched terrain.

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