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Latent outflow activity for western Tharsis, Mars: Significant flood record exposed

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Abstract. Observations permitted by the newly acquired Mars Observer Laser Altimeter data have revealed a system of gigantic valleys northwest of the huge Martian shield volcano, Arsia Mons, in the western hemisphere of Mars (northwestern slope valleys (NSVs)). These features, which generally correspond spatially to gravity lows, are obscured by veneers of materials including volcanic lava flows, air fall deposits, and eolian materials. Geologic investigations of the Tharsis region suggest that the system of gigantic valleys predates the construction of Arsia Mons and its extensive associated lava flows of mainly late Hesperian and Amazonian age and coincides stratigraphically with the early development of the outflow channels that debouch into Chryse Planitia. Similar to the previously identified outflow channels, which issued tremendous volumes of water into topographic lows such as Chryse Planitia, the NSVs potentially represent flooding of immense magnitude and, as such, a source of water for a northern plains ocean.

1. Introduction

The images of Mars acquired by the Mariner 9 and Viking orbiters during the 1970s revealed geologic terrains that display assemblages of geomorphic features characteristic of flood-carved surfaces on Earth such as the Channeled Scabland of the western United States [*Bretz*, 1969; *Baker and Milton*, 1974; *Baker*, 1978, 1982; *Mars Channel Working Group*, 1983]. Assemblages of relict landforms, which include anastomosing channel patterns, streamlined islands, longitudinal grooves, scour depressions, depositional bars, inner channels, and channel sources, strongly indicate ancient catastrophic flood events on Mars. Although smaller outflow channels are recorded elsewhere on Mars including Mangala [*Scott and Tanaka*, 1986; *Chapman and Tanaka*, 1993; *Zimbelman et al*., 1994; *Craddock and Greeley*, 1994], Ma'adim [*Greeley and Guest*, 1987; *Scott et al*., 1993; *Scott and Chapman*, 1995], Dao [*Greeley and Guest*, 1987; *Crown et al*., 1992; *Crown and Greeley*, 1993; *Scott et al*., 1995; *Price*, 1998], Harmakhis [*Greeley and Guest*, 1987; *Crown et al*., 1992; *Crown and Greeley*, 1993; *Scott et al*., 1995; *Price*, 1998], Reull [*Greeley and Guest*, 1987; *Crown et al*., 1992; *Crown and Greeley*, 1993; *Scott et al*., 1995; *Price*, 1998], and Marte [*Plescia*, 1990; *Scott et al*., 1995] Valles, the large outflow channels, which debouch into Chryse Planitia (circum-Chryse outflow channel systems; Figure 1) and generally source near broken surfaces marked by the Valles Marineris canyon system and by fractures, hills, and mesas forming chaotic terrain, have received the greatest attention [e.g., *Milton*, 1974; *Baker and Milton*, 1974; *Scott and Tanaka*, 1986; *Chapman et al*., 1991; *DeHon*, 1992; *DeHon and Pani*, 1992; *Scott*, 1993; *Rotto and Tanaka*, 1995; *Scott et al*., 1995; *Rice and DeHon*, 1996; *Chapman and Tanaka*, 1996; *Nelson and Greeley*, 1999]. Geologic mapping indicates that the outflow systems may have been carved by several flood episodes over protracted time intervals. For example, Kasei Valles is one of the largest previously identified systems of outflow channels on Mars and a major contributor of water to Chryse Planitia. It formed by multiple flood events during the Hesperian and early Amazonian [e.g., *Scott*, 1993]. Another example is Mangala Valles, where at least two episodes of flooding have been recorded [*Chapman and Tanaka*, 1993; *Zimbelman et al*., 1994; *Craddock and Greeley*, 1994].

One commonly held explanation for the origin of the outflow channels involves episodic magmatic-driven processes [e.g., *Baker et al*., 1991; *Dohm et al*., 2000a], perhaps aided by gas hydrate dissociation [*Max and Clifford*, 2000; *Kargel et al*., 2000; *Komatsu et al*., 2000], that explosively expel groundwater and other materials (e.g., water-rich debris) from an ice-enriched crust [e.g., *Baker and Milton*, 1974; *Masursky et al*., 1977; *Carr*, 1979; *Nummedal and Prior*, 1981; *Lucchitta*, 1982; *MacKinnon and Tanaka*, 1989; *Baker et al*., 1991]. The expelled materials are catastrophically discharged down gradient toward the northern plains, sculpting the Martian surface and entraining boulders, rock, and sediment during passage. The sediment-charged water eventually enters the northern plains, contributing to the formation of large bodies of water and sediment, including various hypothesized oceans, seas, lakes, and ice sheets [e.g., *McGill*, 1985; *Jöns*, 1986; *Lucchitta et al*., 1986; *Parker et al*., 1987, 1993; *Baker et al*., 1991; *Scott et al*., 1991a, 1991b, 1995; *Chapman*, 1994; *Scott and Chapman*, 1995; *Kargel et al*., 1995; *Head et al*., 1999]. The "MEGAOUTFLO" hypothesis [*Baker et al*., 2000] first proposed by *Baker et al*. [1991] genetically links such activity to relatively short lived climatic perturbations from a common cold and dry Mars (e.g., short-term hydrological cycles), which include enhanced ero-

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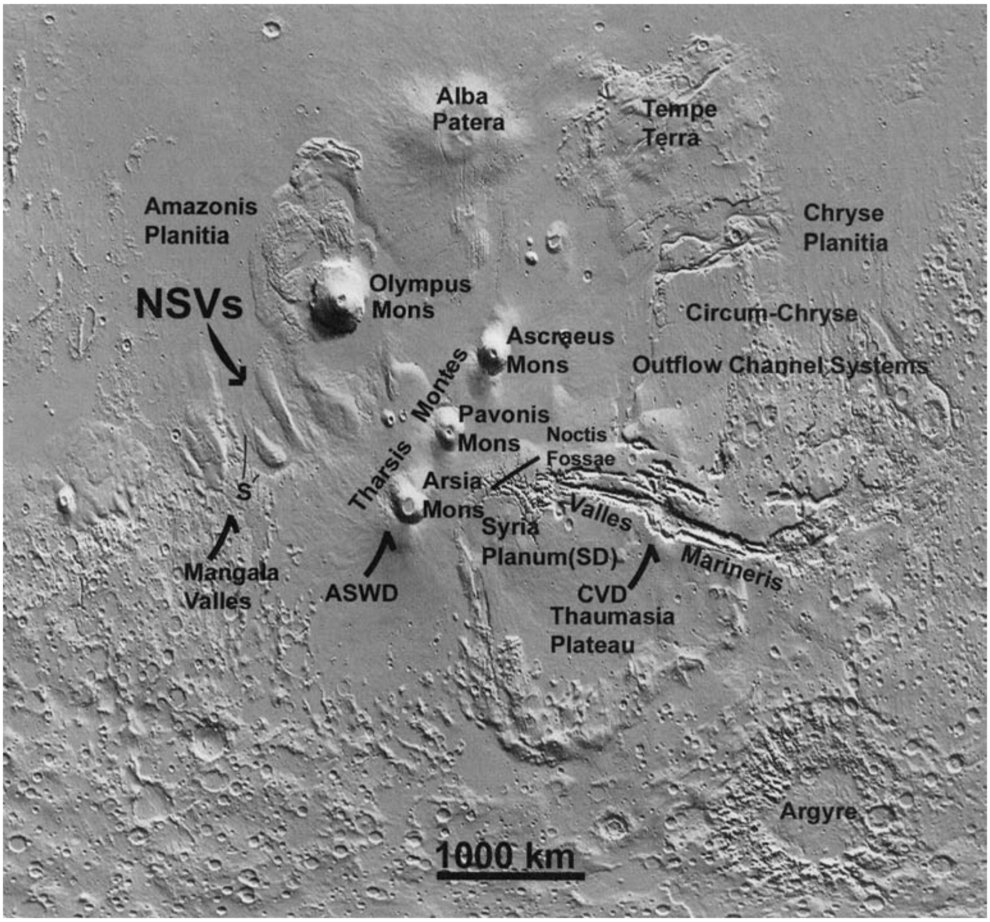


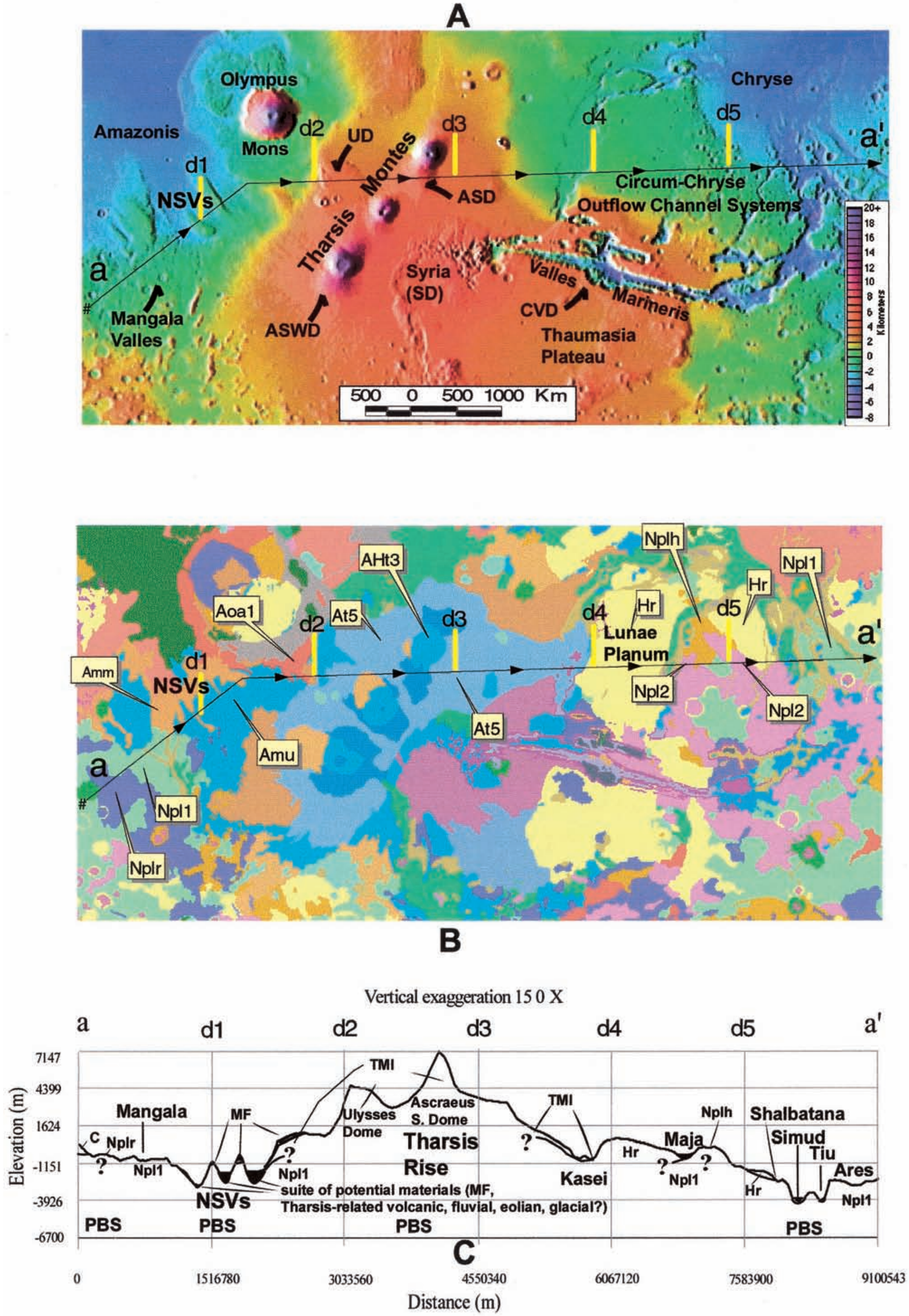
Figure 1. Mars Observer Laser Altimeter (MOLA) shaded relief map of the Tharsis and surrounding regions (courtesy of the MOLA Science Team), which shows the newly identified northwestern slope valleys (NSVs), scarps (s) that may indicate late-stage fluvial activity, and centers of tectonic activity [*Anderson et al*., 1998; *Dohm et al*., 1998] interpreted to represent magmatic-driven doming events (ASWD, Arsia-southwest dome; CVD, central Valles dome; SD, Syria dome).

sion by precipitation, landslides/mass wasting (both land and submarine), glacial activity, and the presence of large standing bodies of water such as the Amazonian-aged Oceanus Borealis.

Here, we discuss a system of immense valleys (northwestern slope valleys (NSVs) [*Dohm et al*., 2000b]; Figure 1) as defined using Mars Observer Laser Altimeter (MOLA) data; these valleys have been identified as topographic troughs [*DeHon*, 1996]. The system of valleys has largely gone unnoticed since it was first imaged by the Mariner and Viking orbiters because it is extensively veneered by late Hesperian and younger materials, including lava flows and ash deposits of the Tharsis Montes shield volcanoes and middle Amazonian and younger putative ash flow deposits of the Medusae Fossae Formation [*Malin*, 1979; *Scott and Tanaka*, 1986; *Greeley and Guest*, 1987]. Though several modes of formation cannot be ruled out for the NSVs (see section 4), geologic and paleohydrological investigations and topographic and geophysical analyses using MOLA and gravity data indicate that the NSVs likely represent structurally controlled valleys that routed catastrophic floods. Such potential latent outflow activity of western Tharsis may have contributed tremendous volumes of water to the northern plains, an explanation consistent with the putative existence of large bodies of water in the northern plains and the "MEGAOUTFLO" hypothesis of *Baker et al*. [1991, 2000].

2. Geologic and Physiographic Setting

A conspicuous system of gigantic, northwest trending valleys as much as 200 km wide, referred to as the NSVs, are partly defined by enormous elongated promontories and are located along the margin of the northern lowland plains and the southern highlands, west of the huge northeast trending chain of Tharsis Montes shield volcanoes (Figure 1). The NSVs occur within a large topographic depression (Plate 1) interpreted to be the result of long-term crustal response to loading by Tharsis [*Phillips et al*., 2000] and generally correspond to gravity lows. The northern and southern provinces represent a physiographic and geologic dichotomy of the Martian crust. Several hypotheses have been advanced for the origin of the dichotomy, including mantle convection associated with core formation [*Wise et al*., 1979], a colossal impact that formed a basin in the north polar region [*Wilhelms and Squyres*, 1984], extensive southward erosional retreat of the heavily cratered highland plateau [*Scott*, 1978; *Hiller*, 1979], and plate tectonics [*Sleep*, 1994]. Regardless of origin, the boundary clearly separates relatively young, uncratered materials of the lowlands from the highly cratered, ancient highland rock assemblages. The lowland materials are interpreted to have been emplaced by both subaerial and subaqueous processes, which include eolian, volcanic, fluvial, mass-wasting, lacustrine, and marine processes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suite of potential materials (MF,
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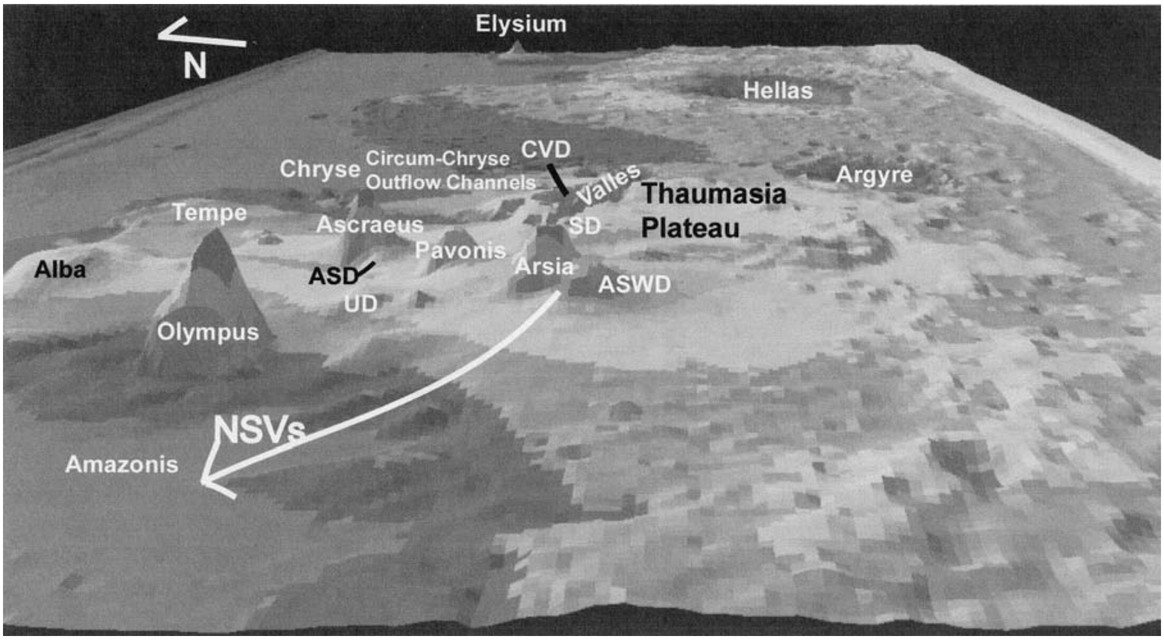

Figure 2. Three-dimensional topographic projection of the NSVs and surrounding region using ARCVIEW (MOLA data courtesy of MOLA Science Team). The white arrow represents potential Noachian/early Hesperian catastrophic flooding from source region (Arsia-SW/Syria dome complex). Also shown are centers of tectonic activity [after *Anderson et al*., 1998; *Dohm et al*., 1998] interpreted to represent magmatic-driven magmatic doming events (UD, Ulysses dome; ASD, Ascaeus-south dome; ASWD, Arsia-southwest dome; CVD, central Valles dome; SD, Syria dome).

[e.g., *Scott and Tanaka*, 1986; *Tanaka*, 1986; *Greeley and Guest*, 1987; *Parker et al*., 1993; *Scott et al*., 1995]. The ancient highlands consist of a mélange of rocks that are interpreted to mainly include lava flows, impact breccias, and eolian, fluvial, and colluvial deposits [e.g., *Scott and Tanaka*, 1986; *Tanaka*, 1986; *Greeley and Guest*, 1987; *Dohm and Tanaka*, 1999], although glacial deposits have also been proposed [e.g., *Kargel et al*., 1995]. Amazonis Planitia, located to the north of and down gradient from the NSVs, is the site of a hypothesized ocean [e.g., *Parker et al*., 1993] and (or) paleolake [e.g., *Scott et al*., 1995]. Heavily cratered plains materials crop out up gradient and to the south of the NSVs [e.g., *Scott and Tanaka*, 1986]. A more abrupt change in slope occurs to the east and northeast of the NSVs as a result of the prominent shield volcanoes and associated lava flows of Tharsis Montes [*Scott and Tanaka*, 1986; *Scott and Zimbelman*, 1995; *Scott et al*., 1998] and Olympus Mons [*Scott and Tanaka*, 1986; *Morris and Tanaka*, 1994], respectively (Figure 1 and Plate 1).

Arsia Mons is the southernmost shield volcano of the northeast trending volcanic chain of Tharsis Montes, located between the NSVs and Syria Planum (Figure 1). Arsia exhibits a summit caldera, reaches a height of greater than 17 km, and displays a basal diameter greater than 300 km. Some of the youngest flows of Arsia overflowed the northeast rim of the caldera while other young flows were extruded from fissures and collapse pits on the northeast and southwest sides of the volcano along the trend of a regional fault zone [*Carr et al*., 1977; *Scott and Tanaka*, 1986; *Scott and Zimbelman*, 1995]. The lower northwestern flank of Arsia Mons is covered by fan-shaped deposits composed of three distinct facies [*Scott and Zimbelman*, 1995] similar to smaller occurrences on the northwest flanks of Pavonis [*Scott et al*., 1998] and Ascraeus [*Scott and Tanaka*, 1986] Montes; the facies may indicate mass movement such as landsliding and debris avalanching, whereas others are characteristic of facies suggesting ash flow or glacial-periglacial processes. Lava flows emanating from Arsia Mons extend to the northwest at least as far as the newly identified NSVs, as evidenced by MOLA data that show lava flows traceable from within the NSVs to near the western base of Arsia Mons [*Zimbelman et al*., 2000].

Syria Planum, including Noctis Fossae, located to the east of Arsia Mons, forms the western margin of a complex system of canyons, Valles Marineris (Figure 1). Syria is a site of long-lived magmatic-tectonic activity including domal uplift and associated radial and concentric faulting and volcanism [*Tanaka and Davis*, 1988; *Anderson et al*., 1997, 1998, 1999; *Anderson and Dohm*, 2000; *Dohm and Tanaka*, 1999]. Valles Marineris appears to have developed, in large part, along fault systems associated with the early development of the Tharsis rise [e.g., *Plescia and Saunders*, 1982]. Additionally, rifting, magma withdrawal, and tension fracturing have been proposed as possible processes involved in the initiation and development of the canyons. *Lucchitta et al*. [1992] noted that the depth of the

Plate 1. (opposite) (a) MOLA shaded relief map showing features of interest, including NSVs, Tharsis rise, circum-Chryse outflow channel systems, and centers of tectonic activity [*Anderson et al*., 1998; *Dohm et al*., 1998] interpreted to represent magmatic-driven doming events (UD, Ulysses dome; ASD, Ascaeus-south dome; ASWD, Arsia-southwest dome; CVD, central Valles dome; SD, Syria dome), (b) part of the geologic map of the western equatorial region of Mars (representative map units are shown [*Scott and Tanaka*, 1986]), and (c) generalized geologic cross section (a-a′, transect of A and B; PBS, potential location of basement structures; TMl, Tharsis Montes lavas; MF, Medusae Fossae materials).

large troughs may have been caused by (1) collapse of near-surface materials due to withdrawal of underlying material or opening of tension fractures at depth, (2) development of keystone grabens at the crest of a bulge, or (3) failure and subsequent drifting of plates. *Lucchitta* [1987] also recognized that many of the valley faults associated with Valles Marineris may have been associated with volcanic activity. Extending from the northern and eastern margins of Valles Marineris into Chryse Planitia are well-documented circum-Chryse outflow channel systems that cut heavily and moderately cratered surfaces of the southern cratered highlands (Figure 1 and Plate 1).

3. Stratigraphy

The stratigraphic positions of rock units in the region of interest (the NSVs, Tharsis, Valles Marineris, and circum-Chryse outflow channel systems; Figure 1) have been established regionally and planet-wide by previous mapping investigations including impact crater counts [e.g., *Scott and Tanaka*, 1986; *Tanaka*, 1986; *Scott and Chapman*, 1991; *Morris et al*., 1991; *Chapman et al*., 1991; *Witbeck et al*., 1991; *DeHon*, 1992; *Scott*, 1993; *Chapman and Tanaka*, 1993; *Craddock and Greeley*, 1994; *Zimbelman et al*., 1994; *Morris and Tanaka*, 1994; *Scott and Zimbelman*, 1995; *Rotto and Tanaka*, 1995; *Scott et al*., 1995; *Chapman and Tanaka*, 1996; *Rice and DeHon*, 1996; *Scott et al*., 1998; *Schultz*, 1998; *Dohm and Tanaka*, 1999; *Nelson and Greeley*, 1999]. The stratigraphic history of the region of interest is summarized in sections 3.1–3.4 and portrayed in cross section (Plate 1c).

3.1. Noachian System

The Noachian System consists of ancient crustal rocks formed during the period of late heavy bombardment that produced a high density of impact craters including enormous basins. Impact cratering, along with water and wind erosion, tectonic deformation, and magmatic-related resurfacing, 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, tectonic, and magmatic-related features that postdate the material. Noachian rocks are interpreted to consist mainly of impact breccias, volcanic materials (shields and flows), and eolian and fluvial sediments that mantle and subdue parts of the heavily cratered terrain. Densely cratered terrain is located to the south and southwest of the system of large valleys. Heavily and moderately cratered terrain also occurs to the north-northeast of Valles Marineris, on the opposite side of the magmatic complex of Tharsis Montes, several thousands of kilometers from the NSVs. Several of the major Noachian rock units, which form the Martian highlands, are observed in the region of interest (Plate 1), including hilly (unit Nplh), cratered (unit Npl_1), ridged (unit Nplr), and subdued cratered (unit Npl_2) materials [e.g., *Scott and Tanaka*, 1986].

The hilly material at the base of the plateau sequence forms heavily cratered terrain of high-standing plateaus, irregular topographic highs, prominent ridges, and highly degraded, ancient crater rims mainly to the south of the NSVs and to the northeast of Valles Marineris in the Xanthe Terra region. Locally, tectonic and impact processes [*Watters*, 1993; *Schultz and Tanaka*, 1994] may have contributed to the prominent relief of the hilly unit. The cratered material, which is the most extensive unit in the western equatorial region [*Scott and Tanaka*, 1986; *Tanaka*, 1986], forms most of the basal rocks to the south of the NSVs and partly embays the hilly material. The cratered material 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] the cratered unit probably consists mostly of impact breccias and volcanic materials. The ridged material outcrops to the south of the NSVs [e.g., *Scott and Tanaka*, 1986] and is generally marked by rough, prominent, sublinear to irregular ridges. Generally, the Noachian ridges are less continuous and less evenly spaced and have more relief than Hesperian ridges, but they follow similar regional trends, forming an arcuate pattern around the southern part of the Tharsis rise [e.g., *Scott and Tanaka*, 1986; *Schultz and Tanaka*, 1994].

Toward the end of the late Noachian many intercrater and intracrater areas of older materials were largely resurfaced by a thin mantle mapped as the subdued cratered material (unit Npl_2) of the plateau sequence of mainly volcanic, eolian, and fluvial origin [e.g., *Scott and Tanaka*, 1986]. The material embays most craters >10 km across and mainly crops out far to the south of the NSVs and to the northeast of Valles Marineris in the Xanthe Terra region. It is marked in a few places by small ridges, channels, and possible flow fronts. Also during this time, centers of tectonic activity, many of which are interpreted to be the sites of magmatic-driven domal uplifts and associated volcanic eruptions, are documented near Arsia Mons (predating the Tharsis Montes volcanoes), Syria Planum, and the central part of Valles Marineris [*Anderson et al*., 1997, 1998, 1999; *Anderson and Dohm*, 2000; *Dohm et al*., 1998; *Dohm and Tanaka*, 1999] (Figures 1 and 2 and Plates 1 and 2). Deep-seated magmatic bodies have been previously inferred for the western equatorial region where fault swarms have been deflected around their central cores such as at the central part of Valles Marineris [*Scott and Dohm*, 1990]. The uplift of the Thaumasia plateau may have also occurred during this time [*Dohm and Tanaka*, 1999] (Figures 1 and 2 and Plates 1 and 2).

Comprehensive geologic investigations of the northeast part of the Thaumasia region indicate that magmatic-tectonic activity occurred at central Valles Marineris as early as the late Noachian and diminished substantially during the early Hesperian, prior to the emplacement of the younger ridged materials (unit Hr) [*Dohm et al*., 1998; *Dohm and Tanaka*, 1999]; such activity may have accompanied substantial volcanism. Similar to the central part of Valles Marineris, Syria Planum is also a site of long-lived magmatic-tectonic activity, which includes domal uplift and associated radial and concentric faulting during the late Noachian–early Hesperian, but at a much larger scale than is observed at the central part of Valles Marineris [*Tanaka and Davis*, 1988; *Anderson et al*., 1998, 1999; *Anderson and Dohm*, 2000; *Dohm and Tanaka*, 1999].

Magmatic-related activity such as doming underlying Arsia Mons and located at Syria Planum and central Valles Marineris during the late Noachian–early Hesperian may be genetically associated with the early development of the circum-Chryse outflow channel systems [e.g., *Dohm et al*., 1998; *McKenzie and Nimmo*, 1999]. Importantly, such activity, which includes volatile and magma interactions, especially underlying Arsia and at Syria, may have also contributed to the formation of the NSVs that occur to the south of Amazonis Planitia

(Figures 1 and 2 and Plates 1 and 2). A proposed Noachian drainage basin/aquifer system may have provided a sufficient source of water necessary to carve the circum-Chryse outflow channel systems and the NSVs [*Dohm et al*., 2000c].

3.2. Hesperian System

The Hesperian System records extensive volcanism including the emplacement of wrinkle-ridged plains materials (unit Hr) [e.g., *Scott and Tanaka*, 1986]. Wrinkle ridge materials dominate the Lunae Planum region located to the north of Valles Marineris (Plate 1b) and outcrop, in places, south of the NSVs. In addition, widespread resurfacing of early Hesperian and older materials, which includes the deposition of colluvial and fluvial deposits and the dissection of rock materials by outflow activity north and northeast of Valles Marineris, is observed during the early Hesperian [e.g., *Rotto and Tanaka*, 1995; *Nelson and Greeley*, 1999]. Incipient Alba Patera [*Scott and Tanaka*, 1986] and other centers of tectonic activity located in the Syria, Pavonis (pre-Tharsis Montes), and Ulysses Fossae regions [*Anderson et al*., 1997, 1998, 1999; *Anderson and Dohm*, 2000; *Dohm and Tanaka*, 1999], which are interpreted to be magmatic-related domal uplifts, are also observed in the geologic record during this time; such activity is indicative of growth of the magmatic complex of Tharsis (Plate 1 and Figure 2).

Also during the early Hesperian period, outflow channel development is recorded at Mangala Valles located to the southwest of the NSVs [*Craddock and Greeley*, 1994; *Zimbelman et al*., 1994] and at the circum-Chryse outflow channel systems located to the north-northeast of Valles Marineris [e.g., *Rotto and Tanaka*, 1995; *Nelson and Greeley*, 1999], on the opposite side of the magmatic complex of Tharsis Montes several thousands of kilometers from the NSVs, although significant outflow channel formation is also recorded during the late Hesperian and into the early Amazonian such as at Kasei [*Chapman et al*., 1991; *Scott*, 1993; *Chapman and Tanaka*, 1996] and Mangala [*Chapman and Tanaka*, 1993; *Craddock and Greeley*, 1994; *Zimbelman et al*., 1994] Valles.

Significant magmatic activity is also recorded during the late Hesperian and early Amazonian including the development of Olympus Mons and the Tharsis Montes shield volcanoes [*Scott and Tanaka*, 1986; *Morris et al*., 1991; *Morris and Tanaka*, 1994; *Scott and Zimbelman*, 1995; *Scott et al*., 1998] and the emplacement of voluminous sheet lavas centered at the large shield volcanoes and at Syria Planum [*Scott and Tanaka*, 1986; *Dohm and Tanaka*, 1999], which include members 1 and 2 of the Olympus Mons Formation, members 1–4 of the Tharsis Montes Formation, and members 1 and 2 of the Syria Planum Formation. Lava flows centered at Arsia Mons, for example, extend at least 1300 km to the northwest [*Zimbelman et al*., 2000], partly embaying the gigantic northwest trending promontories and partly infilling the NSVs (Figure 1 and Plate 1).

3.3. Amazonian System

Continued development of Tharsis Montes and Olympus Mons is recorded during the Amazonian period including the emplacement of associated lavas and aureole deposits [*Scott and Tanaka*, 1986; *Morris et al*., 1991; *Morris and Tanaka*, 1994; *Scott and Zimbelman*, 1995; *Scott et al*., 1998]. In addition, late-stage outflow channel development is observed at Mangala Valles [*Chapman and Tanaka*, 1993; *Craddock and Greeley*, 1994; *Zimbelman et al*., 1994], Marte Valles, which is interpreted to represent a spillway between the Elysium and Amazonis basins [*Scott et al*., 1995], and the circum-Chryse outflow channel systems [*Scott and Tanaka*, 1986; *Chapman et al*., 1991; *Scott*, 1993; *Rotto and Tanaka*, 1995; *Chapman and Tanaka*, 1996; *Nelson and Greeley*, 1999]. Medusae Formation materials, which partly blanket the NSVs, form a broad but discontinuous band of wind-etched materials that trends east-west along the highland-lowland boundary [e.g., *Scott and Tanaka*, 1986; *Greeley and Guest*, 1987; *Scott and Chapman*, 1991]. On the basis of its morphologic characteristics the Medusae Fossae Formation has been interpreted to consist of ash flow tuffs [*Malin*, 1979; *Scott and Tanaka*, 1982, 1986; *Zimbelman et al*., 1997], ancient polar deposits [*Schultz and Lutz*, 1988], pyroclastic and eolian materials [*Greeley and Guest*, 1987], or a host of additional (but less likely) origins [*Zimbelman et al*., 1997]. Significant to the stratigraphic history of the NSVs region, which has been clouded by late-stage volcanic and other activity, *Sakimoto et al*. [1999] have completed Mars Orbiting Camera (MOC) and MOLA investigations of previously mapped outcrops of Medusae Fossae Formation; they indicate that the outcrops may be comprised of eolian or volcanic deposits that were emplaced on top of existing topography (e.g., older competent materials) and subsequently eroded. Similarly, we interpret the NSVs to be carved Noachian and possibly early Hesperian materials draped by late Hesperian and younger materials (Figure 1 and Plate 1). In addition, relatively small erosional terraces (Figure 1), located at the southwest and western parts of the NSVs, may indicate more recent, local fluvial activity, which is consistent with the recent identification of several small fluvial channels (Figure 3) that intermingle with the Medusae Fossae Formation materials in the region of the NSVs [*Zimbelman et al*., 2000]. Such fluvial activity may be associated with late-stage development of Mangala Valles [*Chapman and Tanaka*, 1993; *Craddock and Greeley*, 1994; *Zimbelman et al*., 1994].

3.4. Stratigraphic Summary of the NSVs

Noachian materials were faulted and carved by the late Noachian–early Hesperian, forming a system of gigantic northwest trending promontories and valleys that are associated stratigraphically with pre-Tharsis Montes magmatic-driven doming events of the Arsia, Syria Planum, and central Valles regions. The geometric shapes and geomorphic character of the gigantic, northwest trending promontories, which include ghost craters, in comparison to other much smaller outcrops of Medusae Fossae located to the west, indicate that the features mostly comprise promontory-forming, older materials. Late Hesperian and younger materials, which may include lavas, air fall deposits from Tharsis Montes, possible ash flow deposits, and eolian materials, appear to blanket and embay the gigantic promontories and partly infill the valleys, subduing the relict landforms, especially when viewed from Mariner and Viking images. Terraces located to the south of the system of valleys and, in places, along the valley floors may have resulted from local, late-stage fluvial activity. In addition, eolian, glacial, and mass-wasting processes may have modified the existing valley morphology.

4. Discussion

In addition to the previously identified outflow channels, observations permitted by MOLA data have highlighted the NSVs located along the highland-lowland dichotomy to the northwest of Arsia Mons and located south of Amazonis Planitia, the site of a postulated ocean [e.g., *Parker et al*., 1993] and

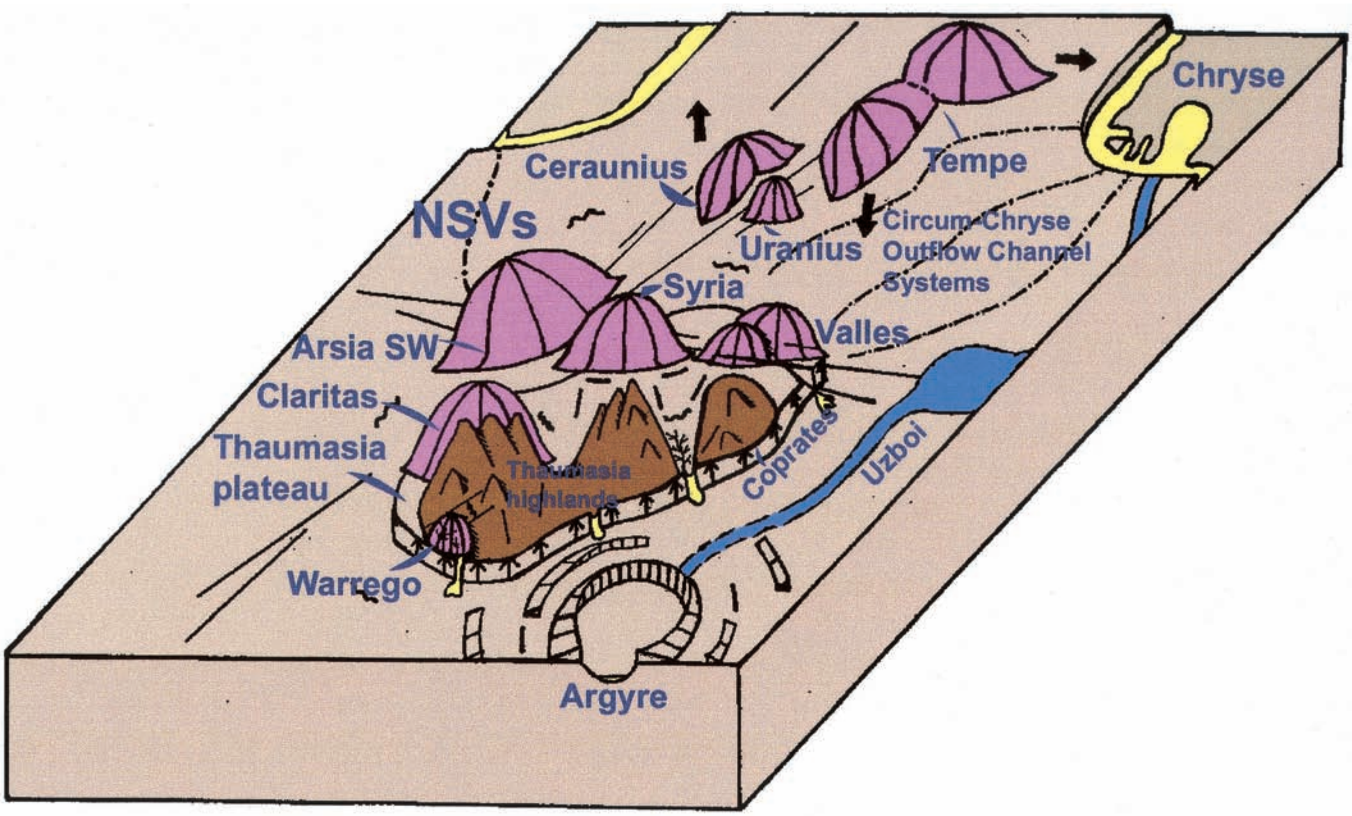

Plate 2. Schematic diagram showing late Noachian–early Hesperian activity. Centers of tectonic activity: Tempe, Uranius, Ceraunius, Arsia-SW, Syria, central Valles, Claritas, and Warrego [*Anderson et al*., 1998; *Dohm et al*., 1998] are interpreted to be magmatic-related doming events and, in many cases, associated volcanic events. The formation of NSVs may be partly related to the development of the Arsia-SW–Syria dome complex. Also shown is modification along the highland-lowland boundary and Thaumasia plateau (uplift shown by narrow arrows), Coprates rise, Thaumasia highlands, early circum-Chryse outflow channel systems, early Valles Marineris canyon system, Uzboi, fault and fracture system (straight lines), and wrinkle ridge development (wavy lines).

(or) a paleolake [*Scott et al*., 1995], in the western hemisphere of Mars (Figures 1 and 2 and Plates 1 and 2). Veneers of lava flows and volcanic air fall deposits and possible ash flow deposits have partly obscured the NSVs. The veneers suppress evidence (e.g., relict features), making it difficult to rule out modes of valley origin. In addition to volcanic modification, local eolian, fluvial, and mass movement processes further obscure clues that would otherwise aid in better understanding the origin of the valleys.

In sections 4.1–4.5, we present several hypotheses that attempt to explain the origin of the NSVs. Following careful consideration of the stratigraphic, geomorphic, paleotectonic, topographic (using MOLA data), and geophysical data, we present these hypotheses, which include catastrophic flooding, tectonism, mass wasting, glaciation, and wind erosion. It is important to keep in mind that combinations of any of the activities listed in sections 4.1–4.5, occurring concurrently or at different times, may have contributed to valley formation.

4.1. Hypothesis 1: Catastrophic Flooding

The premise that the NSVs located near the western slope of Tharsis resulted from one or more catastrophic floods assumes that magmatic-driven processes triggered sudden releases of large volumes of water into Amazonis Planitia (forming a watershed to the northwest of the Arsia-Syria dome complex) (Figures 1 and 2 and Plates 1 and 2), similar to the driving mechanism often envisioned for the formation of the smaller circum-Chryse outflow channel systems that debouch into Chryse Planitia. Spatial and temporal associations of the NSVs with magmatic-driven, late Noachian to early Hesperian doming events located near Arsia (pre-Tharsis Montes) and Syria Planum may corroborate such activity. During the same time, tremendous volumes of water were issued into Chryse Planitia from source areas near Valles Marineris, a region of recorded magmatic and tectonic activity. Similar to circum-Chryse outflow channel systems, the implications of uncovering such a significant flood record of the ancient Martian past are of great significance in that such activity supports northern ocean(s) and (or) large paleolakes in the northern plains.

While observations of the NSVs do not individually confirm hypothesis 1, collectively, they corroborate tremendous flooding. Some of the more significant observations include (1) the tremendous size of the system of valleys and promontories; (2) the unique shape of the gigantic promontories with respect to smaller topographic highs located to the west of the NSVs, including teardrop-shaped ends and tremendously long, relatively straight margins (the shapes indicate that the giant outcrops mostly comprise competent materials similar to the flood-carved mesas north and east of Valles Marineris (Figure 1)); (3) terraces that, in places, mark the margins of the gigan-

Figure 3. Smooth channel floor (black arrows; at 30 m/pixel) exposed among outcrops and boulders of Medusae Fossae Formation (MFF) materials. The smooth floor does not constrain whether the flow preceded or postdated MFF, but the lack of any streamlining on knobs within the channel may argue for an earlier stage of development. The channel gently slopes (0.22°; toward upper left) along the bottom of a broad topographic valley revealed by MOLA data [*Zimbelman et al*., 2000]. Unusual flow-like features (white arrows) crop out from beneath the MFF deposits on both sides of the channel and are visible through the MFF cover (right center); these flows have been interpreted as possible peperites [*Gregg and Schultz*, 1997], implying that the flows may have been emplaced within early MFF materials made wet by flow along the channel. The area shown is 3.0°–4.0°N, 140.0°–141.2°W [*U.S. Geological Survey*, 1995].

tic promontories; (4) a distinctively smooth surface located directly north of the NSVs in Amazonis Planitia, along the western margin of Olympus and associated lava flows (in contrast to the knobby terrain to the west), that closely resembles subaqueous sedimentation in abyssal plains and sedimentary basins [*Aharonson et al*., 1998] or flood-scoured desert terrains on Earth; (5) the system of valleys that generally correspond spatially to gravity lows and occur within a large topographic depression (Plate 1), similar to the eastern Chryse Planitia outflow channels [*Phillips et al*., 2000] (the gravity lows may represent low-density materials that partly infill the valleys and large topographic depression); (6) the late Noachian–early Hesperian age of the NSVs that corresponds stratigraphically with the early outflow development of the circum-Chryse outflow channel systems and with magmatic-driven, pre-Tharsis doming events, which occurred up gradient and to the southeast of the NSVs near Arsia Mons and at Syria Planum (Figures 1 and 2 and Plates 1 and 2); and (7) the trends of the gigantic outcrops, especially the southeast parts in conjunction with linears such as scarps/terraces located to the northeast of the promontories (Figures 1 and 2), which point toward the potential source region, Arsia Mons (pre-Tharsis Montes) and Syria Planum.

Unlike the development of the circum-Chryse outflow channel systems, which may have occurred from the late Noachian to early Amazonian, stratigraphic evidence suggests that potential northwestern slope flooding was limited to the late Noachian–early Hesperian, possibly cut off from a massive water supply by a drainage divide formed by a fully developed Syria-Arsia dome complex and (or) late-stage growth of the Tharsis Montes shield volcanoes, although minor, local fluvial activity occurred later in the southern and western parts of the NSVs. As with the occurrence of mass wasting (see hypothesis 3), it is important to realize that catastrophic flood events are not necessarily limited to streamflow. There is little doubt that the NSVs signify multiple flood events of various magnitudes prior to the late Hesperian. This raises the possibility that phases of hyperconcentrated-flow and debris flow activity may have been associated with the flooding in this area. Such variations in flow behavior would create a unique assemblage of deposits [*Webb et al.*, 1989] that may have at least partly filled these canyons between flood events.

4.2. Hypothesis 2: Tectonism

Tectonic structural control may have played a significant role in channeling catastrophic flood waters from the Arsia-SW–Syria dome complex region (Plate 2) to the Amazonis Planitia region, resulting in significant enhancement of the original valley geometry of the NSVs. For that reason, it is important not to understate the importance of this hypothesis in relation to catastrophic flooding. Large-scale tectonic fabrics, for example, exist within and adjacent to the NSVs. These include (1) ridged material, which crops out to the south of the NSVs and is composed of sublinear to irregular ridges that exhibit trends common to the NSVs, (2) faults that cut Noachian surfaces to the southwest of the special site of interest, and (3) large-scale tectonic fabrics adjacent to and within the NSVs, such as Gordii Dorsum [e.g., *Scott and Tanaka*, 1986]. Although tectonic features may have routed the erosional agent, tectonic activity by itself probably did not result in the gigantic size of the NSVs.

4.3. Hypothesis 3: Mass Wasting

The formation of outflow channels emptying into the Chryse Planitia on Mars has been attributed to debris flow activity [*Tanaka*, 1999]. Mass movements are common in the Valles Marineris canyon system and may be responsible for the development of the aureole deposits on the flanks of Olympus Mons [*Hodges and Moore*, 1994]. Therefore the possibility that mass wasting may have created the NSVs must be thoroughly examined.

Debris flows on Earth are capable of moving huge quantities of material great distances (more than 800 km in the subaqueous Storegga slide) [*Bugge et al.*, 1988]. Most debris flows move in existing topographic depressions, however, and may occur as a brief phase accompanied by subsequent streamflow or hyperconcentrated flow [*Melis et al.*, 1997]. Typically, mass movements will create a scarp or headwall in their source region where the slide material is removed and a lobate zone of deposition where the material stops moving. Erosion is greatest at the source area where debris flow activity has been observed; in some cases, such activity may remove all of the existing unconsolidated material in the source area, leaving exposed bedrock [*Johnson and Rodine*, 1984]. Landslide deposits such as debris flow levees, slump blocks, or a pile of rubble produced by a rock topple are the most typical landforms produced during these mass movements.

No direct evidence of deposits created by mass movement can be found in or around the NSVs. In addition, no scarps or headwalls are visible near Arsia Mons where either mass movements or floodwaters would have originated. Higher-resolution images of the floors of the NSVs and Amazonis Planitia should be examined for deposits typical of mass movements, especially debris flow deposits which would be the most likely subareal mass movements to travel great distances from their source. Subaqueous landslides have the longest recorded runouts of any mass movements on Earth [*Bugge et al.*, 1988]. If the area north of the NSVs was filled with water at any time in the Martian geologic past, subaqueous landslides could have moved through the area, moving large amounts of material out of the channels and into Amazonis Planitia. Such subaqueous slides on Earth have moved huge, intact blocks of material great distances from the slide's source region [*Bugge et al.*, 1988]. Similar activity on Mars could deposit large blocks at great distances out into the smooth plains north of the proposed channels.

It is not likely that mass movement activity alone created the NSVs. Depositional or erosional features typically associated with mass movements are not visible in the region of special interest. In addition, mass movements usually concentrate their erosive activity in their source region and thus would not be likely to create channels a significant distance down slope from their source region. Mass movements are expected as part of the streamflow that may have created these channels. Postflood slumping could have occurred on the sides of the valleys, and some debris flow activity may have occurred in the valleys themselves as a phase in an intermittent streamflow regime.

4.4. Hypothesis 4: Glaciation

Ice streams have been proposed to have carved the circum-Chryse outflow channel systems [e.g., *Lucchitta and Anderson*, 1980]. In order for glaciers to have formed the NSVs the climate had to differ significantly from the present. The "MEGAOUTFLO" hypothesis first demonstrated by *Baker et al.* [1991] genetically links magmatic-triggered activity with relatively short lived climatic perturbations from a common cold and dry Mars (e.g., short-term hydrological cycles), which include enhanced erosion by precipitation, landslides/mass wasting (both land and submarine), glacial activity, and the presence of large standing bodies of water such as the Amazonian-aged Oceanus Borealis. A synthesis of the stratigraphic, erosional, and paleotectonic records indicates that potential pulses of magmatic activity may have triggered climatic perturbations such as those during the late Noachian–early Hesperian [*Dohm et al.*, 2000a] when the NSVs were carved. In addition, in order for glaciers to develop and move down the northwest flank of the pre-Tharsis Montes, magmatic-driven Arsia uplift, a plentiful supply of water must have been present. This water could be provided through an Earth-like hydrologic cycle, which may have existed episodically on Mars [*Baker et al.*, 1991, 2000], or subsurface water that froze upon contact with the surface, creating an ice stream [*Lucchitta et al.*, 1981; *Lucchitta*, 1982].

Glacier formation by accumulation of snow through a hydrologic cycle assumes that precipitation (most likely orographic) would have resulted from prevailing winds rising over the Arsia uplift. Such precipitation would have to continue over a sufficient period of time for the necessary thickness of ice to build up for glacial flow to initiate. Interpretations of striations on the southwestern flank of Arsia Mons as glacial moraines [*Hodges and Moore*, 1994] and fan-shaped deposits on the northwest flanks of the Tharsis Montes volcanoes, which consist of facies that are interpreted to be the result of glacial and volcanic/ice interactions [*Scott and Zimbelman*, 1995; *Scott et al.*, 1998], indicate that variations in climate from the present one have occurred in the recent geologic past. These features, however, are dwarfed by the system of gigantic valleys that formed much earlier in Martian time, during the late Noachian–early Hesperian.

The major drawback to the glacial origin hypothesis is the fact that no characteristic features resulting from glacial erosion or deposition are seen in the region encompassing the NSVs. Depositional features such as eskers, drumlins, or moraines are absent as are erosional features such as cirques at the heads of the valleys or arêtes along the ridgelines between

Table 1. A Comparative Analysis Between Some of the Previously Defined Martian Outflow Valley Systems and the Newly Defined Northwestern Slope Valleys[a]

Reference	Channel	D, m	W, km	S	V, m/s	Q, m^3/s
Komar [1979]	Mangala	100	14	0.003	15	2×10^7
Baker [1982]	Maja	100	80	0.02	38	3×10^8
Komatsu and Baker [1997]	Ares	500–1000	25	0.02–0.0001	25–150	5×10^8
Robinson and Tanaka [1990]	Kasei	400–1300	80	0.009	30–75	$1\text{–}2 \times 10^9$
Dohm et al. [2000b]	NSVs	1200–2400	100–700	0.004–0.005	30–40	$\sim10^9\text{–}10^{10}$

[a] D, depth; W, width; S, slope; V, velocity; Q, discharge.

the valleys. Particularly, there are no moraines or eskers down gradient from the NSVs. An explanation for this is that all evidence of glaciation, except for the gigantic promontories, has been buried and (or) obscured by materials (including volcanic, eolian, colluvial, possible marine, and possible lacustrine) or destroyed by wind and water erosion.

4.5. Hypothesis 5: Wind Erosion

During the absence of an active hydrologic cycle for much of the history of the planet [*Baker et al*., 2000], wind erosion played an important role in the modification of the surface of Mars [*Greeley et al*., 1999]. Thus it is important to consider the possibility that the NSVs are the result of wind erosion. On Earth, winds are efficient at sculpting existing surfaces but not sufficient to carve bedrock canyons of the magnitude observed for the NSVs.

Wind erosion would be most effective in eroding unconsolidated surficial deposits, so the competence of the material in the study area is a major factor to take into account in the assessment of the efficacy of wind erosion. The unique shape of the gigantic promontories with respect to smaller topographic highs mapped as Medusae Fossae Formation materials located to the west of the region of interest, however, indicate that the gigantic landforms comprise competent materials similar to the flood-carved mesas north and east of Valles Marineris (Figure 1). Evidence of recent wind activity exists in and around the special site of interest, especially yardangs and wind streaks that mark the Medusae Fossae Formation surfaces [e.g., *Scott and Chapman*, 1991]; the wind streaks provide evidence of winds originating from several different directions in recent times. Wind erosion is an unlikely sole candidate for the formation of the NSVs for the following reasons: (1) Wind erosion on Earth lacks the power needed to be the sole erosive force for carving gigantic bedrock valleys, (2) wind-formed features of a much smaller scale than the gigantic promontories indicate a variety of wind directions for the special region of interest whereas a single wind direction would have to be maintained for a long period of time for efficient wind erosion to occur, and (3) a well-established, strong wind pattern in this area capable of large-scale erosion would have produced other features of similar size in the area at the same time. No such wind-related features of gigantic proportions can be found elsewhere on Mars.

5. Paleohydrology

After careful consideration of the processes mentioned in section 4, structurally controlled flooding appears to best explain the formation of the NSVs, although the other processes probably further modified the NSVs. Here we attempt to determine the ancient hydrologic conditions on the basis of our knowledge of the geometry of the valleys, as they exist today. This task, however, is daunting because of subsequent volcanic, eolian, fluvial, and gravity-driven modification of the NSVs. Extensive masking of the walls of the NSVs by the Medusae Fossae Formation means that the earlier fluvial erosion of whole channel cross sections must be inferred in order to perform the calculations that follow.

The paleohydrology of the NSVs was estimated from an analysis of the geometry of the valleys (e.g., several MOLA-based valley profiles were generated and analyzed). There are limitations imposed on these calculations. The ancient flow depths, for example, can only be approximated because volcanics as well as other materials of unknown thickness obscure the original valley geometries. Thus we sought to determine the sensitivity of the discharge value by altering the constituent variables of the modified Manning equation [*Sellin*, 1969; *Komar*, 1979]:

$$u = [(g_m hs)/C_f]^{1/2},$$

where u is the average flow velocity, g_m is the Martian gravitational acceleration, h is the hydraulic radius, s is the sine of the channel bed slope, and C_f is a dimensionless drag coefficient approximated by

$$C_f = g_e(n^2/h^{1/3}),$$

where g_e is the gravitational acceleration of Earth and n is the Manning roughness coefficient. Using the method of *Komar* [1979], discharge calculations for the NSVs were made (Table 1).

The greatest source of error in the Manning equation is the value of the Manning roughness coefficient. After careful consideration of hydrologic and geologic factors a value of 0.025 was selected for the Manning roughness coefficient. It is interesting to note that this value, determined independently, agrees with the value used by *Robinson and Tanaka* [1990] in the calculation of flood discharge for Kasei Valles, an outflow channel system that is generally agreed to be the largest currently known on Mars.

A series of calculations were made to determine what effect certain hydrologic variables would have on the discharge values. For example, we performed numerous alterations to the valley geometries, including (1) lowering the valley floors by intervals of 100 m until reaching a depth of 1 km, in order to approximate valley profiles prior to volcanic infilling of the NSV, (2) decreasing the valley widths by 20 and 40%, to account for the possible removal of canyon wall material by wave-cut action, erosion, and (or) mass movements, (3) modifying the valley slopes, in order to accurately gage the sensitivity of the calculations to the shallowing of the regional slope due to infilling volcanic materials, and (4) changing the water

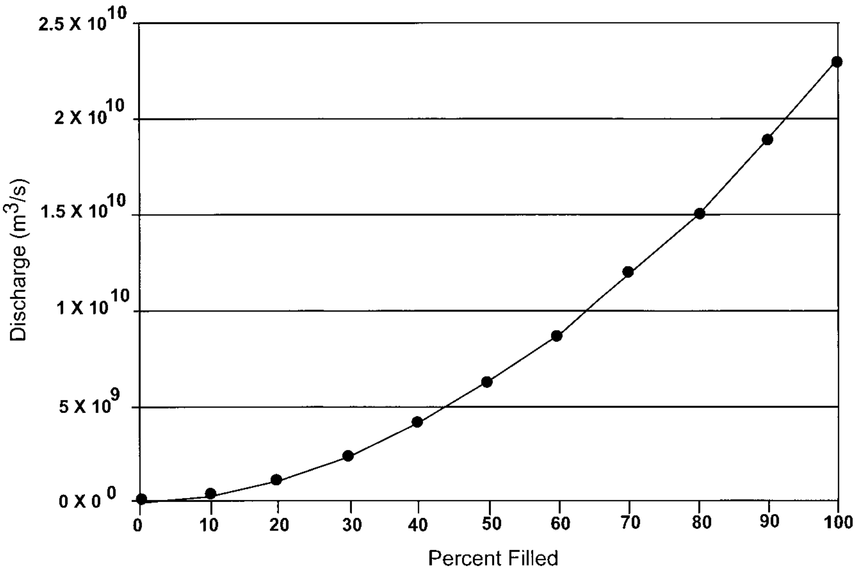

Figure 4. Plot of discharge value for an assumed flow depth.

depth from a bare minimum amount needed to cover the channel floor (roughly 10% maximum capacity), up to 100% of the NSV's maximum capacity. Although the valley geometries were modified in almost every conceivable way possible, because of the immense size of this valley system the discharge values remained consistently large.

More specifically, in the calculation of discharge values the valley profiles were corrected to reflect the infilling of volcanic and other materials since the late Hesperian (e.g., Plate 1c). Progressively away from Arsia Mons, the valley floors were lowered 500 m, 250 m, and 0 m, respectively. The modified geometry of the channel system and a Manning roughness coefficient value of 0.025 yielded a maximum discharge of 2×10^{10} m^3/s. The discharge value for an assumed flow depth is summarized in Figure 4.

The most interesting result of these calculations is that no matter what modifications were made to the observed valley geometries, whether it be the narrowing of the valleys, the lowering of the valley floors, altering the regional slope, or assuming that the NSVs were never filled by more than 10% of their maximum capacity, the resultant discharge values remain large. All other calculated discharge values for the circum-Chryse outflow channel systems of the northeastern watershed of the Tharsis region combined fail to equal many of the maximum discharge estimates for the NSVs.

The NSVs potentially represent catastrophic flooding from an ancient (late Noachian–early Hesperian) watershed located to the northwest of the Arsia-Syria dome complex, perhaps related to the early development of the circum-Chryse outflow channel systems, as well as a potential source of water for a northern plains ocean. Two shorelines have been proposed for the northern plains: an inner, younger one that is close to an equipotential line and an older one that deviates from an equipotential line [*Parker et al.*, 1993; *Head et al.*, 1999]. The inner, younger ocean is estimated to have had a volume of $\sim 1.4 \times 10^7$ km^3, and the larger, older one is estimated to have had a volume of $\sim 9.6 \times 10^7$ km^3 [*Head et al.*, 1999]. The ancient topography, however, most likely varied from the present one. Thus the estimated calculated volume of the putative larger ocean may be considerably different. It is interesting to note that for the maximum discharge rate of 2×10^{10} m^3/s, assuming the flow rate was sustained, the fill time would have been ~8.1 days and ~8 weeks for the smaller and larger oceans, respectively. If the Chryse outflows were occurring at the same time at rates of $\sim 10^9$ m^3/s to 10^{10} m^3/s, then the fill rates would be considerably shorter, from ~7.7 to 5.4 days for the smaller ocean. The discharge rates, however, were most likely not sustained at these peak values, and a greater time period would be required to fill these hypothesized oceans. In addition, other hydrogeologic activities associated with catastrophic flooding and related short-lived ($\sim 10^4$–10^5 years) episodes of quasi-stable climatic conditions [*Baker et al.*, 1991, 2000] may have also contributed water to the hypothesized oceans by mechanisms such as spring-fed activity along areas of the highland-lowland boundary. Another potential contributor to the northern plains ocean is a large quantity of ground ice (e.g., stagnant ice sheets) already in place in the northern plains during this time. This large quantity of ice would be the likely consequence of an earlier warm and wet phase of Mars, possibly induced by catastrophic flooding [*Baker et al.*, 1991, 2000]. As new floodwaters washed over the northern plains, the additional heat would melt the upper layers of ice, and the gradients created would allow the meltwater to cycle into the hydrologic system.

6. Implications

Although several processes were most likely involved with the present-day valley geometries of the NSVs, catastrophic flooding prior to late Hesperian and younger volcanism (including other depositional and erosional modification) contributed significantly to the formation of the NSVs. The implications for flood-carved NSVs are enormous; the NSVs potentially represent (1) previously undocumented Martian catastrophic floods, (2) a watershed to the northwest, perhaps related to the early development of the circum-Chryse systems of outflow channels, and (3) a potential source of water for a northern plains ocean. The discharge rates have been estimated between ~10^9 and 10^{10} m^3/s. Even if maintained for only a short time, these rates would have significantly contributed to the formation of a northern plains ocean.

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References

Aharonson, O., M. T. Zuber, and G. A. Neumann, Mars: Northern hemisphere slopes and slope distributions, *Geophys. Res. Lett.*, *25*, 4413–4416, 1998.

Anderson, R. C., and J. M. Dohm, Magmatic-tectonic evolution of Tharsis, *Lunar Planet. Sci. Conf*. [CD-ROM], *XXXI*, abstract 1607, 2000.

Anderson, R. C., M. P. Golombek, B. J. Franklin, K. L. Tanaka, J. M. Dohm, J. H. Lias, and J. Higdon, A new detailed structural history of the Tharsis region of Mars (abstract), *Lunar Planet. Sci*., *XXVIII*, 39–40, 1997.

Anderson, R. C., M. P. Golombek, B. J. Franklin, K. L. Tanaka, J. M. Dohm, J. H. Lias, and B. Peer, Centers of tectonic activity through time for the western hemisphere of Mars (abstract), *Lunar Planet. Sci*. [CD-ROM], *XXIX*, abstract 1881, 1998.

Anderson, R. C., A. F. C. Halderman, J. M. Dohm, M. P. Golombek, B. J. Franklin, and J. H. Lias, Significant centers of tectonic activity as identified by wrinkle ridges for the western hemisphere of Mars (abstract), *Lunar Planet. Sci*. [CD-ROM], *XXX*, abstract 1972, 1999.

Baker, V. R., The Spokane Flood controversy and the Martian outflow channels, *Science*, *202*, 1249–1256, 1978.

Baker, V. R., *The Channels of Mars*, 198 pp., Univ. of Tex. Press, Austin, 1982.

Baker, V. R., and D. J. Milton, Erosion by catastrophic floods on Mars and Earth, *Icarus*, *23*, 27–41, 1974.

Baker, V. R., R. G. Strom, V. C. Gulick, J. S. Kargel, G. Komatsu, and V. S. Kale, Ancient oceans, ice sheets and the hydrological cycle on Mars, *Nature*, *352*, 589–594, 1991.

Baker, V. R., R. G. Strom, J. M. Dohm, V. C. Gulick, J. S. Kargel, G. Komatsu, G. G. Ori, and J. W. Rice Jr., Mars' Oceanus Borealis, ancient glaciers, and the MEGAOUTFLO hypothesis, *Lunar Planet. Sci*. [CD-ROM], *XXXI*, abstract 1863, 2000.

Bretz, J. H., The Lake Missoula floods and the Channeled Scabland, *J. Geol*., *77*, 505–543, 1969.

Bugge, T., R. H. Belderson, and N. H. Kenyon, The Storegga slide, *Philos. Trans. R. Soc. London*, *Ser. A*, *325*, 357–388, 1988.

Carr, M. H., Formation of Martian flood features by release of water from confined aquifer, *J. Geophys. Res*., *84*, 2995–3007, 1979.

Carr, M. H., R. Greeley, K. R. Blasius, J. E. Guest, and J. B. Murray, Some Martian volcanic features are viewed from Viking Orbiters, *J. Geophys. Res*., *82*, 3985–4015, 1977.

Chapman, M. G., Evidence, age, and thickness of a frozen paleolake in Utopia Planitia, Mars, *Icarus*, *109*, 393–406, 1994.

Chapman, M. G., and K. L. Tanaka, Geologic map of the MTM -05152 and -10152 quadrangles, Mangala Valles region of Mars, *U.S. Geol. Surv. Misc. Invest. Map*, *I-2294*, scale 1:500,000, 1993.

Chapman, M. G., and K. L. Tanaka, Geologic maps of the MTM 25062 quadrangle (digital compilation) and the MTM 25067 quadrangle (manual compilation), Kasei Valles region of Mars, *U.S. Geol. Surv. Misc. Invest. Map*, *I-2398*, scale 1:500,000, 1996.

Chapman, M. G., H. Masursky, and D. H. Scott, Geologic map of science study area 2, north Kasei Valles, Mars (MTM 25072 quadrangle), *U.S. Geol. Surv. Misc. Invest. Map*, *I-2107*, scale 1:500,000, 1991.

Craddock, R. A., and R. Greeley, Geologic map of the MTM -20147 quadrangle, Mangala Valles region of Mars, *U.S. Geol. Surv. Misc. Invest. Map*, *I-2310*, scale 1:500,000, 1994.

Crown, D. A., and R. Greeley, Volcanic geology of Hardriaca Patera and the eastern Hellas region of Mars, *J. Geophys. Res*., *98*, 3431–3451, 1993.

Crown, D. A., K. H. Price, and R. Greeley, Geologic evolution of the east rim of the Hellas basin, Mars, *Icarus*, *100*, 1–25, 1992.

DeHon, R. A., Geologic map of the Pompeii quadrangle (MTM 20057), Maja Valles region of Mars, *U.S. Geol. Surv. Misc. Invest. Map*, *I-2203*, scale 1:500,000, 1992.

DeHon, R. A., Martian highland troughs: Regional controls of runoff and sedimentation (abstract), *Lunar Planet. Sci*., *XXVII*, 295–296, 1996.

DeHon, R. A., and E. A. Pani, Duration and rates of discharge through a Martian outflow system: Maja Valles (abstract), *Lunar Planet. Sci. Conf*., *XXIII*, 297–298, 1992.

Dohm, J. M., and K. L. Tanaka, Geology of the Thaumasia region, Mars: Plateau development, valley origins, and magmatic evolution, *Planet. Space Sci*., *47*, 411–431, 1999.

Dohm, J. M., R. C. Anderson, and K. L. Tanaka, Digital structural mapping of Mars, *Astron. Geophys*., *39*, 3.20–3.22, 1998.

Dohm, J. M., R. C. Anderson, V. R. Baker, R. G. Strom, G. Komatsu, and T. M. Hare, Pulses of magmatic activity through time: potential triggers for climatic variations on Mars, *Lunar Planet. Sci*. [CD-ROM], *XXXI*, abstract 1632, 2000a.

Dohm, J. M., R. C. Anderson, V. R. Baker, J. C. Ferris, T. M. Hare, R. G. Strom, L. P. Rudd, J. W. Rice Jr., and D. H. Scott, System of gigantic valleys northwest of Tharsis Montes, Mars: Latent catastrophic flooding, northwest watershed, and implications for northern plains ocean, *Geophys. Res. Lett*., *27*, 3559–3562, 2000b.

Dohm, J. M., et al., The Tharsis basin of Mars: A potential source for the outflow channel systems, layered wall deposits of Valles Marineris, and putative oceans or paleolakes, paper presented at Tharsis Workshop, Planet. Geol. and Geophys. Program, NASA, Keystone, Colo., Oct. 16–18, 2000c.

Greeley, R., and J. E. Guest, Geologic map of the eastern equatorial region of Mars, *U.S. Geol. Surv. Misc. Invest. Map*, *I-1802B*, scale 1:15,000,000, 1987.

Greeley, R., and P. D. Spudis, Volcanism on Mars, *Rev. Geophys*., *19*, 13–41, 1981.

Greeley, R., M. Kraft, R. Sullivan, G. Wilson, N. Bridges, K. Herkenhoff, R. O. Kuzmin, M. Malin, and W. Ward, Aeolian features and processes at the Mars Pathfinder landing site, *J. Geophys. Res*., *104*, 8573–8584, 1999.

Gregg, T. K. P., and P. H. Schultz, Shallow Martian "sills": Intrusions or extrusions? (abstract), *Lunar Planet. Sci*., *XXVIII*, 463–464, 1997.

Head, J. W., III, H. Hiesinger, M. A. Ivanov, M. A. Kreslavsky, S. Pratt, and B. J. Thompson, Possible ancient oceans on Mars: Evidence from Mars Orbiter Laser Altimeter data, *Science*, *286*, 2134–2137, 1999.

Hiller, K., Geologic map of the Amenthes quadrangle of Mars, *U.S. Geol. Surv. Misc. Invest. Map*, *I-1110*, scale 1:5,000,000, 1979.

Hodges, C. A., and H. J. Moore, Atlas of volcanic landforms on Mars, *U.S. Geol. Surv. Prof. Pap*., *1534*, 194 pp., 1994.

Johnson, A. M., and J. R. Rodine, Debris flows, in *Slope Instability*, edited by D. Brunsden and D. B. Prior, pp. 257–361, John Wiley, New York, 1984.

Jöns, H. P., Arcuate ground undulations, gelifluxion-like features and "front tori" in the northern lowlands on Mars, what do they indicate? (abstract), *Lunar Planet. Sci*., *XVII*, 404–405, 1986.

Kargel, J. S., V. R. Baker, J. E. Beget, J. F. Lockwood, T. L. Pewe, J. S. Shaw, and R. G. Strom, Evidence of ancient continental glaciation in the martian northern plains, *J. Geophys. Res*., *100*, 5351–5368, 1995.

Kargel, J. S., K. L. Tanaka, V. R. Baker, G. Komatsu, and D. R. MacAyeal, Formation and dissociation of clathrate hydrates on Mars: Polar caps, northern plains, and highlands, *Lunar Planet. Sci*. [CD-ROM], *XXXI*, abstract 1891, 2000.

Komar, P. D., Comparisons of the hydraulics of water flows in Martian outflow channels with flows of similar scale on Earth, *Icarus*, *37*, 156–181, 1979.

Komatsu, G., and V. R. Baker, Paleohydrology and flood geomorphology of Ares Vallis, *J. Geophys. Res*., *162*, 4151–4160, 1997.

Komatsu, G., J. S. Kargel, V. R. Baker, R. G. Strom, G. G. Ori, C. Mosangini, and K. L. Tanaka, A chaotic terrain formation hypothesis: Explosive outgas and outflow by dissociation of clathrate on Mars, *Lunar Planet. Sci*. [CD-ROM], *XXXI*, abstract 1434, 2000.

Lucchitta, B. K., Ice sculpture in the Martian outflow channels, *J. Geophys. Res*., *87*, 9951–9973, 1982.

Lucchitta, B. K., Recent mafic volcanism on Mars, *Science*, *235*, 565–567, 1987.

Lucchitta, B. K., and D. M. Anderson, Martian outflow channels sculptured by glaciers (abstract), in *Reports of Planetary Geology Program: 1980*, *NASA Tech. Memo*., *TM-81776*, 271–273, 1980.

Lucchitta, B. K., D. M. Anderson, and H. Shoji, Did ice streams carve Martian outflow channels? *Nature*, *290*, 759–763, 1981.

Lucchitta, B. K., H. M. Ferguson, and C. Summers, Sedimentary de-

posits in the northern lowland plains, Mars, *J. Geophys. Res.*, *91*, 166–174, 1986.
Lucchitta, B. K., A. S. McEwen, G. D. Clow, P. E. Geissler, R. B. Singer, R. A. Schultz, and S. W. Squyres, The canyon system on Mars, in *Mars*, pp. 453–492, Univ. of Ariz. Press, Tucson, 1992.
MacKinnon, D. J., and K. L. Tanaka, The impacted Martian crust: Structure, hydrology, and some geologic implications, *J. Geophys. Res.*, *94*, 17,359–17,370, 1989.
Malin, M. C., Mars: Evidence of indurated deposits of fine materials (abstract), *NASA Conf. Publ.*, *2072*, 54, 1979.
Mars Channel Working Group, Channels and valleys on Mars, *Geol. Soc. Am. Bull.*, *94*, 1035–1054, 1983.
Masursky, H., J. M. Boyce, A. J. Dial, G. G. Schaber, and M. E. Strobell, Formation of Martian channels, *J. Geophys. Res.*, *82*, 4016–4038, 1977.
Max, M. D., and S. M. Clifford, The identification of Martian outflow channels through the catastrophic decomposition of methane hydrate, *Lunar Planet. Sci.* [CD-ROM], *XXXI*, abstract 2094, 2000.
McGill, G. E., Age and origin of large martian polygons (abstract), *Lunar Planet. Sci.*, *XVI*, 534–535, 1985.
McKenzie, D., and F. Nimmo, The generation of Martian floods by the melting of ground ice above dykes, *Nature*, *397*, 231–233, 1999.
Melis, T. S., R. H. Webb, and P. G. Griffiths, Debris flows in Grand Canyon National Park: Peak discharges, flow transformations, and hydrographs, in *Debris-Flow Hazards Mitigation: Mechanics, Prediction and Assessment*, edited by C.-L. Chen, 817 pp., Am. Soc. of Civ. Eng., New York, 1997.
Milton, D. J., Geologic map of the Lunae Palus quadrangle of Mars, *U.S. Geol. Surv. Misc. Invest. Map*, *I-894*, scale 1:5,000,000, 1974.
Morris, E. C., and K. L. Tanaka, Geologic map of the Olympus Mons region of Mars, *U.S. Geol. Surv. Misc. Invest. Map*, *I-2327*, 1994.
Morris, E. C., H. Masursky, D. J. Applebee, and M. E. Strobell, Geologic map of science study area 3, Olympus Rupes, Mars (special MTM 15132 quadrangle), *U.S. Geol. Surv. Misc. Invest. Map*, *I-2001*, 1991.
Nelson, D. M., and R. Greeley, Geology of Xanthe Terra outflow channels and the Mars Pathfinder landing site, *J. Geophys. Res.*, *104*, 8653–8669, 1999.
Nummedal, D., and D. B. Prior, Generation of Martian chaos and channels by debris flows, *Icarus*, *45*, 77–86, 1981.
Parker, T. J., D. M. Schneeberger, D. C. Pieri, and R. S. Saunders, Geomorphic evidence for ancient seas on Mars, in *Symposium on Mars: Evolution of its Climate and Atmosphere*, *LPI Tech. Rep. 87-01*, pp. 96–98, Lunar and Planet. Inst., Houston, Tex., 1987.
Parker, T. J., D. S. Gorsline, R. S. Saunders, D. C. Pieri, and D. M. Schneeberger, Coastal geomorphology of the martian northern plains, *J. Geophys. Res.*, *98*, 11,061–11,078, 1993.
Phillips, R. J., M. T. Zuber, S. A. Hauck II, R. M. Williams, and K. B. Portle, Why is there a negative gravity ring around Tharsis on Mars? *Lunar Planet. Sci.* [CD-ROM], *XXXI*, abstract 1303, 2000.
Plescia, J. B., Recent flood lavas in the Elysium region of Mars, *Icarus*, *88*, 465–490, 1990.
Plescia, J. B., and R. S. Saunders, Tectonic history of the Tharsis region, Mars, *J. Geophys. Res.*, *87*, 9775–9791, 1982.
Price, K. H., Geologic map of the Dao, Harmakhis, and Reull Valles region of Mars, *U.S. Geol. Surv. Misc. Invest. Map*, *I-2557*, scale 1:1,000,000, 1998.
Rice, J. R., Jr., and R. A. DeHon, Geologic map of the Darvel Quadrangle (MTM 20052), Maja Valles region of Mars, *U.S. Geol. Surv. Misc. Invest. Map*, *I-2432*, scale 1:500,000, 1996.
Robinson, M. S., and K. L. Tanaka, Magnitude of a catastrophic flood event at Kasei Valles, Mars, *Geology*, *18*, 902–905, 1990.
Rotto, S. L., and K. L. Tanaka, Geologic/geomorphologic map of the Chryse Planitia region of Mars, *U.S. Geol. Surv. Misc. Invest. Map*, *I-2441*, 1995.
Sakimoto, S. E. H., H. V. Frey, J. B. Garvin, and J. H. Roark, Topography, roughness, layering, and slope properties of the Medusae Fossae Formation from Mars Orbiter Laser Altimeter (MOLA) and Mars Orbiter Camera (MOC) data, *J. Geophys. Res.*, *104*, 24,141–24,154, 1999.
Saunders, R. S., Geologic map of the Margaritifer Sinus quadrangle of Mars, *U.S. Geol. Surv. Misc. Invest. Map*, *I-1144*, scale 1:5,000,000, 1979.
Schultz, P. H., and A. B. Lutz, Polar wandering on Mars, *Icarus*, *73*, 91–141, 1988.
Schultz, R. A., Geologic map of the western Ophir Planum region (MTM-10067) of Mars, *U.S. Geol. Surv. Misc. Invest. Map*, *I-2588*, scale 1:500,000, 1998.
Schultz, R. A., and K. L. Tanaka, Lithospheric-scale buckling and thrust structures on Mars: The Coprates rise and south Tharsis ridge belt, *J. Geophys. Res.*, *99*, 8371–8385, 1994.
Scott, D. H., Mars, highlands-lowlands: Viking contribution to Mariner relative age studies, *Icarus*, *34*, 479–485, 1978.
Scott, D. H., Geologic map of the MTM 25057 and 25052 quadrangles, Kasei Valles region of Mars, *U.S. Geol. Surv. Misc. Invest. Map*, *I-2208*, scale 1:500,000, 1993.
Scott, D. H., and M. G. Chapman, Geologic map of science study area 6, Memnonia region of Mars (MTM -10172), *U.S. Geol. Surv. Misc. Invest. Map*, *I-2084*, scale 1:500,000, 1991.
Scott, D. H., and M. G. Chapman, Geologic and topographic maps of the Elysium Paleolake Basin, Mars, *U.S. Geol. Surv. Misc. Invest. Map*, *I-2397*, scale 1:5,000,000, 1995.
Scott, D. H., and J. M. Dohm, Tectonic setting of Martian volcanoes and deep-seated intrusives, paper presented at MEVTV Workshop "Evolution on Magma Bodies on Mars", Lunar and Planet. Inst., Houston, Tex., 1990.
Scott, D. H., and K. L. Tanaka, Ignimbrites of the Amazonis Planitia region of Mars, *J. Geophys. Res.*, *87*, 1179–1190, 1982.
Scott, D. H., and K. L. Tanaka, Geologic map of the western equatorial region of Mars, *U.S. Geol. Surv. Misc. Invest. Map*, *I-1802-A*, scale 1:15,000,000, 1986.
Scott, D. H., and J. R. Zimbelman, Geologic map of Arsia Mons volcano, Mars, *U.S. Geol. Surv. Misc. Invest. Map*, *I-2480*, scale 1:1,000,000, 1995.
Scott, D. H., M. G. Chapman, J. W. Rice Jr., and J. M. Dohm, New evidence of lacustrine basins on Mars: Amazonis and Utopia Planitiae, *Lunar. Planet. Sci.*, *XXII*, 53–62, 1991a.
Scott, D. H., J. W. Rice Jr., and J. M. Dohm, Martian paleolakes and waterways: Exobiological implications, in *Origin Life Evol. Biosphere*, *21*, 189–198, 1991b.
Scott, D. H., J. M. Dohm, and D. J. Applebee, Geologic map of science study area 8, Apollinaris Patera region of Mars, *U.S. Geol. Surv. Misc. Invest. Map*, *I-2351*, scale 1:500,000, 1993.
Scott, D. H., J. M. Dohm, and J. W. Rice Jr., Map of Mars showing channels and possible paleolake basins, *U.S. Geol. Surv. Misc. Invest. Map*, *I-2461*, scale 1:30,000,000, 1995.
Scott, D. H., J. M. Dohm, and J. R. Zimbelman, Geologic map of Pavonis Mons volcano, Mars, *U.S. Geol. Surv. Misc. Invest. Map*, *I-2561*, scale 1:1,000,000, 1998.
Sellin, R. H. J., *Flow in Channels*, 149 pp., Macmillan, Old Tappan, N. J., 1969.
Sleep, N. H., Martian plate tectonics, *J. Geophys. Res.*, *99*, 5639–5655, 1994.
Tanaka, K. L., The stratigraphy of Mars, *Proc. Lunar Planet. Sci. Conf.*, *17th*, Part I, *J. Geophys. Res.*, *91*, suppl., E139–E158, 1986.
Tanaka, K. L., Debris-flow origin for the Simud/Tiu deposit on Mars, *J. Geophys. Res.*, *104*, 8637–8652, 1999.
Tanaka, K. L., and P. A. Davis, Tectonic history of the Syria Planum province of Mars, *J. Geophys. Res.*, *93*, 14,893–14,917, 1988.
U.S. Geological Survey, Controlled photomosaic of the MTM 05142 quadrangle, Gordii Dorsum region of Mars, *U.S. Geol. Surv. Misc. Invest. Map*, *I-2425*, scale 1:500,000, 1995.
Watters, T. R., Compressional tectonism on Mars, *J. Geophys. Res.*, *98*, 17,049–17,060, 1993.
Webb, R. H., P. T. Pringle, and G. R. Rink, Debris flows in tributaries of the Colorado River in Grand Canyon National Park, Arizona, *U.S. Geol. Surv. Prof. Pap.*, *1492*, 39 pp., 1989.
Wilhelms, D. E., and S. W. Squyres, The Martian hemispheric dichotomy may be due to a giant impact, *Nature*, *309*, 138–140, 1984.
Wise, D. U., M. P. Golombek, and G. E. McGill, Tharsis province of Mars: Geologic sequence, geometry, and a deformation mechanism, *Icarus*, *38*, 456–472, 1979.
Witbeck, N. E., K. L. Tanaka, and D. H. Scott, Geologic map of the Valles Marineris region, Mars (east half and west half), *U.S. Geol. Surv. Misc. Invest. Map*, *I-2010*, scale 1:2,000,000, 1991.
Zimbelman, J. R., R. A. Craddock, and R. Greeley, Geologic map of the MTM -15147 quadrangle, Mangala Valles region of Mars, *U.S. Geol. Surv. Misc. Invest. Map*, *I-2402*, scale 1:500,000, 1994.
Zimbelman, J. R., D. A. Crown, J. A. Grant, and D. M. Hooper, The Medusae Fossae Formation, Amazonis Planitia, Mars: Evaluation of proposed hypotheses of origin (abstract), *Lunar. Planet. Sci.*, *XXVIII*, 1623–1624, 1997.

Zimbelman, J. R., S. E. H. Sakimoto, and H. Frey, Evidence for a fluvial contribution to the complex story of the Medusae Fossae Formation on Mars (abstract), *Geol. Soc. Am. Abstr. Programs*, *32*(7), A303, 2000.

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