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Fluvial geomorphology on Earth-like planetary surfaces: A review

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Abstract

Morphological evidence for ancient channelized flows (fluvial and fluvial-like landforms) exists on the surfaces of all of the inner planets and on some of the satellites of the Solar System. In some cases, the relevant fluid flows are related to a planetary evolution that involves the global cycling of a volatile component (water for Earth and Mars; methane for Saturn's moon Titan). In other cases, as on Mercury, Venus, Earth's moon, and Jupiter's moon Io, the flows were of highly fluid lava. The discovery, in 1972, of what are now known to be fluvial channels and valleys on Mars sparked a major controversy over the role of water in shaping the surface of that planet. The recognition of the fluvial character of these features has opened unresolved fundamental questions about the geological history of water on Mars, including the presence of an ancient ocean and the operation of a hydrological cycle during the earliest phases of planetary history. Other fundamental questions posed by fluvial and fluvial-like features on planetary bodies include the possible erosive action of large-scale outpourings of very fluid lavas, such as those that may have produced the remarkable canali forms on Venus; the ability of exotic fluids, such as methane, to create fluvial-like landforms, as observed on Saturn's moon, Titan; and the nature of sedimentation and erosion under different conditions of planetary surface gravity. Planetary fluvial geomorphology also illustrates fundamental epistemological and methodological issues, including the role of analogy in geomorphological/geological inquiry.

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1. Introduction

Geomorphology, as a science, has achieved its greatest advances through discoveries, notably through encounters with new landscapes, such as those explored on Earth during the nineteenth century (Baker and Twidale, 1991), and most recently those imaged on other planetary surfaces in the Solar System (Baker, 1984, 1985a, 1993, 2008a). The modern era of planetary exploration has revealed fluvial, or fluvial-like, landforms (in this paper the term *fluvial* will be applied to both) on the extraterrestrial surfaces of planets and moons (Table 1). Moreover, these discoveries pose interesting challenges for advancing our fundamental understanding of fluvial processes and their associated landforms (Komatsu and Baker, 1996; Baker and Komatsu, 1999; Komatsu, 2007).

In the study of extraterrestrial planetary surfaces, one must contend with the directionality of space exploration. Extraterrestrial planetary surfaces are first encountered by remote sensing at low resolution. Subsequent, high-resolution imagery then allows focusing on details, but there may be controversy concerning the genesis of various landforms. This controversy commonly arises because multiple processes can be envisioned that are physically capable of producing many aspects of the observed landforms, a problem that has been termed *convergence* and *equifinality*. Schumm (1991) introduced the term “convergence” as applicable to actual landscapes, and the term *equifinality* was introduced by Chorley (1962) in regard to systems theory, which functions to explain landscapes. Thus, convergence is a strong version of the concept, holding that nature in reality does produce similar landforms by different combinations of causative processes. In contrast, equifinality is a weak version, holding that diverse hypotheses or model formulations of a system, as envisioned by scientists, can explain the same landforms. The strong version is ontological, in that it makes a claim about nature, whereas the weak version is epistemological, in that it deals with knowledge or the ability of scientists to understand nature.

A challenge for science is to employ reasoning processes to get past the equifinality issues and to recognize the true cases of convergence. For some problems, the increases in resolution that accompany planetary exploration, both spatial and spectral, can lead to a resolution of formative processes (Zimbelman, 2001). More commonly these advances in data quality must be combined with the study of terrestrial analog landforms with well-understood origins (Mutch, 1979). While explanations for these landforms in terms of physical principles are necessary for full understanding of their development, such explanations will always suffer from the equifinality problem unless the full range of nature’s realities are explored, and analogs can aid with that exploration (Baker, 2014a).

Analogy implies similarity among like features of otherwise different things; and, as with all thinking (Hofstadter and Sander, 2013), science relies upon analogy. Models and computer simulations are actually extremely strong analogies, in which attributes presumed to be fundamental to the two things being compared (attributes such as basic physical or mathematical structure) are incorporated into a necessarily simplified system that can then be compared via testing to the *real world*. Particularly in the study of extraterrestrial planetary surfaces, the complexities of specific phenomena require investigation that begins with weaker forms of analogy, but which takes advantage of natural regularities that allow direct comparisons between real world entities, such that a newly discovered feature can be compared to features that are already known and understood. Insights gained from this comparison then lead to further investigation into the cause(s) of the unknown feature. Geological analogies serve not so much to provide definitive explanations as they do to provide a source for fruitful working hypotheses (Chamberlin, 1890) that move geological investigation into productive lines of inquiry (Gilbert, 1886, 1896).

In contrast to newly discovered fluvial-like landforms on other planets, fluvial and fluvial-like landforms on Earth are much more likely to have their key features and their causative processes understood. Thus, the sharing of key features between terrestrial analogs and extraterrestrial phenomena can suggest possible causes for the latter through the understanding of the terrestrial causes. These possible causes then become hypotheses that require further testing. However, unlike classical physics, geology cannot achieve such testing through controlled experiments on its subject matter. An entire river, volcano, or glacier cannot be isolated from its environment and placed into a completely controlled laboratory setting. Instead, alternative means must be found to test or corroborate the hypotheses that are suggested through analogy. This testing or corroboration can be accomplished by exploring consequences of the working hypotheses for consistency, coherence, and consilience (see Baker, 2014a, for an in-depth discussion of the role of terrestrial analogs in planetary geology and related aspects of geological reasoning).

2. Volcanic channels: moon, Mercury, and Io

2.1. Lunar sinuous rilles

Channels visible by telescopic study of Earth's moon (Fig. 1) initially looked promising as candidates for water flowing on that planetary surface (Pickering, 1904; Firsoff, 1960). The excellent, high-resolution images returned in 1966–1967 from the Lunar Orbiter missions that were designed to prepare for manned landing, provided data for detailed comparisons between sinuous lunar channel ways and terrestrial rivers (Peale et al., 1968; Schubert et al., 1970). Moreover, before the return of rock samples from the Moon, the prevailing theories held that, like Earth itself, Earth's moon had a primordial, water-rich hydrosphere (reviewed by Gilvarry, 1960). These theories even led the famous Nobel laureate chemist, Harold Urey (1967) to conclude that, given the obvious fluvial-like morphology of the sinuous rilles (e.g., their sinuous plan form), special processes must have occurred on the airless Moon to allow water to flow. He even suggested that a large comet impact might have produced a temporary water-rich atmosphere. Lingenfelter et al. (1968) used theoretical modeling to show that the lunar rivers could have been ice-covered and thereby able to flow. Following the consequences of this fluvial hypothesis, Gilvarry (1968) concluded that the lunar maria, instead of being the result of immense outpourings of lava, were actually the surface expressions of sediments and sedimentary rocks.

Geochemical analyses of rock samples returned from the Apollo landing missions showed clearly that the lunar primordial hydrosphere model was wrong and that the maria were the surface expressions of immense outpourings of basaltic lava (Taylor, 1982). The Moon clearly has no water-related context in which to place the sinuous rilles. In the lead up to the Apollo missions, the equifinality problem was encountered because a variety of nonaqueous processes were also hypothesized to be capable of producing sinuous rille morphologies. The hypothesized genetic mechanisms included lava channeling and the collapse of lava tubes (Baldwin, 1963; Oberbeck et al., 1969), pyroclastic flows (Cameron, 1965), and various combinations of structure and subsidence (Quaide, 1965; Schumm, 1970). In 1971, the Hadley Rille was inspected in the field by the Apollo 15 astronauts, and their findings, combined with studies of the regional geology showed that the lava channel and lava tube hypothesis was most consistent with all the available data (Greeley, 1971; Howard et al., 1972). Thus, in this case, the various advances in resolution and measurement during the intensive lunar exploration program of the 1960s eventually resolved the equifinality issue of water-versus-lava as the agent for forming the lunar sinuous rilles.

In retrospect, important morphological differences exist between fluvial channels or valleys and lunar sinuous rilles. Unlike fluvial forms, the latter most commonly have decreasing width and depth along their flow paths (Fig. 1). In a recent study of more than 200 lunar sinuous rilles, Hurwitz et al. (2013a) found that their lengths range from 2 to 566 km, with amedian width of about 500 m and amedian depth of about 50 m. These authors attribute the pervasive downstream decreases in width and depth to turbulent lava flow that facilitates thermal erosion in the proximal portions of the rille and then transitions distally to laminar flow, leading to a progressive decline in thermal erosion efficiency in a down-channel direction.

Hurwitz et al. (2012) used an analytical model to estimate the volume of lava needed to erode the Rima Prinz sinuous rill at ~50 km^3 for a very low viscosity lava and about 250 km^3 for an intermediate viscosity lava. From months to an Earth year would be required to form this feature by lava eroding at up to ameter per day, and the distal accumulation of solidified lava would extend over an area of about 2500 km^2. Thus, what was a highly erosive fluid near its source transitions to a much less erosive fluid, eventually leaving a huge solidified accumulation of all the channel-forming fluid. This is obviously very different than what would occur with water flows, which might leave some volume of sediment related to the amount of material eroded from the channel, but with most of the eroding fluid eventually leaving the depositional area by evaporation, infiltration, or other processes.

2.2. Mercury

The MErcury Surface Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission that reached Mercury in 2008 revealed a dozen or so flat-floored, shallow valleys associated with extensive volcanic plains at high latitudes in Mercury’s northern hemisphere (Head et al., 2011; Byrne et al., 2013). The feature shown in Fig. 2 is about 20 km wide with a smooth, lightly cratered floor that contrasts with the adjacent rough and highly cratered terrain into which it is shallowly incised. It was probably formed by the thermal and mechanical erosive action of high-magnesian, mafic or ultramafic lavas (Hurwitz et al., 2013b). The irregular knobs in the center right portion of the image are remnants of a rim material of the 140-km-diameter Kofi impact basin that was eroded by lavas emanating from vents about 50 km to the northwest of the image.

2.3. Io

Lava channels were observed on the surface of Jupiter's moon, Io, in the course of the 1996–2003 imaging phase of the Galileo space mission (Keszthelyi et al., 2001). Schenk and Williams (2004) documented a particularly large channel, Tawhaki Vallis, that extends for about 200 km and is up to 6 km wide, representing either an ultramafic or a sulfur lava flow. The channel is shallowly incised (about 50 m) into plains that are probably primarily composed of sulfur (Schenk and Williams, 2004). The whole surface of Io must be relatively young, as it lacks impact craters. The young surface age and the lava that generated the channel derive from widespread volcanism that resurfaces Io through the intense tidal interaction of this relatively small moon with the massive planet Jupiter (McEwen et al., 2004).

3. Venusian channels

Channel landforms on Venus were discovered in the early 1990s through studies of images generated by the Synthetic Aperture Radar (SAR) instrument onboard the Magellan spacecraft. More than 200 channels have been identified on the Magellan images of Venus (Baker et al., 1992a, 1997; Komatsu et al., 1993), and they exhibit a wide variety of morphological characteristics (Gulick et al, 1992a, 1992b).

3.1. Simple channels

Simple channels (Baker et al., 1992a; Komatsu et al., 1993) generally consist of a single, sinuous main channel that lacks the complex branching and anastomosing reaches characteristic of other varieties of Venusian channels (Gulick et al., 1992a). Simple channels can be further subdivided into simple channels with flow margins, sinuous rilles, and canali (Fig. 3). Some simple channels are located on well-defined flow deposits or flow fields (Fig. 3A) (Komatsu et al., 1993). These simple channels with flow margins are similar in morphology to channels that form on terrestrial lava flows. Because these channels have formed on lava flows and do not seem to have incised surrounding terrain, they appear to be similar to their terrestrial counterparts in being mostly constructional in origin. In general, these simple channels lack distinctive source regions.

Sinuous rilles emanate from distinct, circular, or elongated regions of collapse (generally several kilometers in diameter), and they form channels up to several kilometers wide and tens to hundreds of kilometers long (Baker et al., 1992a; Komatsu et al., 1993). As in the case of lunar sinuous rilles, these Venus counterparts become narrower and shallower in a downstream direction (Fig. 3B). Most sinuous rilles on Venus are not associated with detectable lava flow margins. The similarities in morphology and size to lunar sinuous rilles may imply that thermomechanical erosion by high-discharge, highly fluid lava was also an important channel-forming process on Venus (Komatsu et al., 1993; Komatsu and Baker, 1994a; Oshigami et al., 2009). Some of the Venusian sinuous rilles are associated with networks of valleys or depressions (Baker et al., 1992a; Gulick et al., 1992a,b; Komatsu et al., 1993, 2001; Oshigami et al., 2009).

Canali are features that are unique to Venus. Unlike other simple channels they have generally constant width and depth over their entire flow path (Fig. 3C) (Baker et al., 1992a, 1997; Komatsu et al., 1992, 1993). These channels generally have widths ranging up to 3 km and lengths exceeding 500 km. However, some canali may be up to 10 km wide; and a few have enormous lengths, up to 6800 km in the case of Baltis Vallis (Baker et al., 1992a; Komatsu et al., 1993). Canali may locally exhibit numerous abandoned channel segments, cutoff meander bends, levees, and radar dark terminal deposits (Baker et al., 1992a, 1997; Komatsu et al., 1993; Kargel et al., 1994). Sources and termini are generally indistinct. Canali are generally located on topographic plains (Komatsu et al., 1993), considered to be volcanic in origin and mafic in composition (Kargel et al., 1993), and they are tectonically deformed along their longitudinal profiles (Komatsu and Baker, 1994b; Langdon et al., 1996). The extraordinary length and a relatively short formation time scale (i.e., geologically speaking) of Baltis Vallis allowed this feature to be used to correlate distant geological units on Venus plains to understand their sequential relationships (Basilevsky and Head, 1996).

The morphology of these channels suggests that they probably formed by continuously conveyed large discharges of low viscosity lava to distant regions over prolonged periods (Baker et al., 1992a, 1997; Komatsu et al., 1992, 1993; Bray et al., 2007). Both erosional and constructional origins have been proposed (Komatsu et al., 1992; Gregg and Greeley, 1993; Bussey et al., 1995; Williams-Jones et al., 1998; Lang and Hansen, 2006; Oshigami and Namiki, 2007). The formative fluids have been hypothesized to be a wide range of silicate lava varieties, as well as low-viscosity flows of sulfur or carbonatite lava (Baker et al., 1992a, 1997; Komatsu et al., 1992, 1993; Gregg and Greeley, 1993; Kargel et al., 1994). More speculative hypotheses invoke the role of non volcanic fluids, including turbidity currents that would have had to occur at a time when an ocean existed on the Venusian surface (Jones and Pickering, 2003). Alternatively, Waltham et al. (2008) envisioned particulate gravity currents resulting from the suspension of fine particulate matter in the dense Venusian atmosphere and moving downslope to travel long distances. The origin of the Venusian canali remains poorly understood.

3.2. Complex and compound channels

Complex channels form anastomosing, braided, or distributary patterns that are generally (but not always) on flow deposits (Gulick et al., 1992a; Komatsu et al., 1993). Individual channel widths range from ~3 km down to the limit of resolution, while the total width of the channel system can range from 20 to 30 km, and up to hundreds of kilometers in length (Gulick et al., 1992a). Most complex channels are located on flow deposits and are classified as complex channels with flow margins (Fig. 4A) (Komatsu et al., 1993). Complex channels are often located along with simple channels on flow deposits, indicating a genetic connection to the lava flows. These channels are commonly separated by radar-bright (or radar-dark in some cases) material that is considered to be lava, and the channels probably formed by a constructional process. Complex channels that are not located on flow deposits appear to have eroded into surrounding terrain. This particular subclass of complex channels is simply known as complex channels without flow margins (Fig. 4B) (Komatsu et al., 1993).

Compound channels contain simple and complex segments (Fig. 4C) (Komatsu et al., 1993). The channels vary greatly in size, with widths ranging between several tens of kilometers in complex regions down to the limit of resolution in simple reaches. Total lengths of compound channels can range from 75 km to thousands of kilometers (Gulick et al., 1992a).

Kallistos Vallis (Fig. 4C) is a particularly interesting compound channel. It emanates from a distinct collapse region (Baker et al., 1992a, 1997; Komatsu et al., 1993). However, instead of becoming distally narrower and shallower like a sinuous rille, the channel displays a great variety of morphologies as it extends about 1200 km. Some morphologic characteristics of Kallistos Vallis, in particular the collapsed source region and anastomosing segment, bear a resemblance to some aspects of what have been termed Martian out flow channels, and the informal name *outflow channel* was given to Kallistos Vallis (Baker et al., 1992a). Leverington (2011) has drawn particular attention to these features of Kallistos Vallis and applied the *outflow* designation much more generally to lunar and Venusian sinuous rills and various other volcanic channel forms sourced at fissures, vents, collapse areas, and other types of depressions, proposing further that these all share a common origin with the Martian channels (see Section 7).

Important differences can be documented between Kallistos Vallis and what are more properly termed *cataclysmic flood channels* on Mars. Of course, the regional geological context is totally different. Venus is a planet dominated by the manifestation of volcanic processes, with the greatest variety of lava-related flow features to have yet been discovered. No regional or temporal context indicates a role of water in forming any of the landscape features on the surface of Venus. Mars is a completely different planet in regard to the role of water, with rich manifestations of relict fluvial forms and other indicators of water and water–ice compositions and processes in shaping the planetary surface (see Sections 5 and 7). Ancient Mars was earthlike in that regard (Carr, 2012); Venus was not.

The main similarities of Kallistos Vallis to an *outflow channel* are its collapsed source region (upper left of Fig. 4C) and the anastomosing segment (lower center of Fig. 4C). However, the collapse region leads not to a fluvial channel but to a linear trough about 400 km long and about 600 km deep. The collapse source pit is connected to the trough by an incised gorge, and a sinuous canali-type channel also emanates from this gorge. The canali channel is about 1.5 km wide and 175 km long. Typical for Venusian canali, it maintains a relatively constant width over its entire length, implying genesis under very poorly understood conditions by a poorly understood fluid process. The linear trough of Kallistos Vallis eventually narrows to only 1.5 km wide and shallows to less than 150 m deep. Beyond this point the channeled fluid seems to have spilled out to create the distinctive anastomosing sub channels that are spread over a width of as much as 18 km (lower center part of Fig. 4C). Deflected eastward, the flows were impounded upstream of a north–south ridge, eroding through that obstacle to create streamlined hills in the divide crossing. Downstream of this divide the system displays a distinctive distributary pattern of radar-bright channels (lower right of Fig. 4C) that feed into an immense area of lobate deposits, the likely solidified flows that traversed the channel, and these cover an area of about 100,000 km^2. The distributary pattern of channels and most of the lava plains are not shown in Leverington's (2014) map of the system.

4. The fluvial dissection of Titan

Titan is the largest satellite of Saturn. Unusual for a moon, it has a thick, N_2-rich atmosphere with ~5% methane (CH_4) (Niemann et al., 2005). The methane cycle on Titan generates clouds, fluvial features, and near-polar lakes (Lunine and Atreya, 2008). These atmospheric and surface features have been observed by instruments on board the Cassini–Huygens mission to the Saturnian (or Kronian) system (Matson et al., 2003). Three instruments on the Cassini spacecraft—the Cassini Titan Radar Mapper (Elachi et al., 2004), the Visual and Infrared Mapping Spectrometer (Brown et al., 2004), and the Imaging Science Subsystem (Porco et al., 2004)—can sense the moon's surface. Of these three surface-imaging data sets, the synthetic aperture radar data from the Titan Radar Mapper instrument (Elachi et al., 2004) provides the highest resolution surface images (~0.3 km/pixel to ~1.7 km/pixel). In addition, a near-visible-wavelength camera, part of the Descent Imager/Spectral Radiometer (DISR) experiment on board the Huygens probe (Tomasko et al., 2002), took images from beneath the obscuring haze at a resolution of ~20–90 m/pixel as the probe fell to the surface (Lebreton et al., 2005; Tomasko et al., 2005).

In addition, a near-visible-wavelength camera, part of the DISR experiment on board the Huygens probe (Tomasko et al., 2002), took images as the probe fell to the surface, with diminishing amounts of obscuring haze enabling higher resolutions (meters to tens of meters per pixel) than were achievable from the three Cassini instruments (Lebreton et al., 2005; Tomasko et al., 2005). The SAR and DISR data sets form the basis for interpreting the fluvial geomorphology of Titan (Burr et al., 2013b). Although very localized and limited in coverage, the DISR images with their higher resolution reveal drainage networks with valleys on the scale of tens of meters in width (Fig. 5). Although much coarser in resolution, the SAR data provide more global coverage (~50% of the surface for recent analyses conducted to date), which shows a broad distribution of drainage (or fluvial) networks (Fig. 6). Aspects of the drainage networks and the individual fluvial features can be discerned in these complementary data sets.

4.1. Fluvial drainage distribution

Drainages mapped in SAR data (Lorenz et al., 2008; Langhans et al., 2012; Burr et al., 2013a) show a near-global distribution, although their density is not homogeneous. A parameter entitled *delineated fluvial feature density* was calculated for each band of 30° latitude as the total distance along delineated network links ratioed to the area of SAR coverage. The parameter is similar to drainage density but, because the resolution and noise of the SAR data preclude delineation of the low-order links or small networks, it underestimates true drainage density. Comparison of values among latitudinal bands shows that fluvial features are denser, by an order of magnitude, at high northern latitudes (Burr et al., 2013a) where they drain radar-bright, rugged terrain and empty into the numerous north polar lakes (Stofan et al., 2007; Hayes et al., 2008; Cartwright et al., 2011). Like the lakes, the north polar networks are commonly radar-dark, possibly as a result of a drape of fine-grained organic sediments deposited either during back flooding of the river valleys during lake high-stand or during the waning stage of fluvial flow (Lorenz et al., 2008; Burr et al., 2013b).

Fluvial features are also concentrated around the Xanadu province (Burr et al., 2013a), a photometrically and geographically distinct region that stretched over ~100° along the equator (Radebaugh et al., 2011). Standing as high as 2000 m above the surrounding landscape, Xanadu (like the north polar regions) has radar-bright high-relief terrain with irregular or *crenulated* texture, inferred to be mountain ranges (Radebaugh et al., 2011). Radar-bright fluvial valleys with cobble-sized sediments are incised within the crenulated terrain (Fig. 7) (Burr et al., 2013b). The fact that most of these networks within Xanadu are below the resolution of the SAR data suggests that other uplands on Titan that lack discernable networks may nonetheless be fluvially dissected (Burr et al., 2013b). The networks imaged by DISR, although not discernable in overlying SAR data, are evidently heavily incised. Some higher-order links and trunk valleys are visible, as are wide radar-bright extensions that stretch from the Xanadu networks across the surrounding plains (Le Gall et al., 2010). The radar-bright return from these wide fluvial features is interpreted as a result of rounded cobbles greater than a few centimeters in diameter (Le Gall et al., 2010), and the features themselves are inferred to be the deposits of gravel-bed, braided, ephemeral rivers (Burr et al., 2013b).

The remaining fluvial networks visible in SAR data are scattered within the mid-latitudes (Burr et al., 2013a,b); the extensive tropical dunes on Titan apparently either preclude the formation of fluvial flow because of aridity and/or cover over past fluvial flow features at tropical latitudes (Lorenz et al., 2006; Radebaugh et al., 2008; Lorenz and Radebaugh, 2009). In contrast to the polar and Xanadu networks, these scattered mid-latitude networks occur in relatively low-relief settings (the *undifferentiated plains* of Lopes et al., 2010), where they commonly form broad, shallow, radar-dark features, hypothesized to be braided or anabranching channel patterns (Lorenz et al., 2008; Burr et al., 2013b). Often radar-dark, they are interpreted to be braided or anabranching fluvial systems with possible terminal splays of fine-grained sediment (Lorenz et al., 2008; Burr et al., 2013b).

4.2. Fluvial sediments observed on the surface

Although the networks imaged by DISR are below the resolution of the SAR data (Soderblom et al., 2007), their appearance in the DISR images provides some indication of sediment type and size. In these visible-wavelength images from altitude, the DISR networks appear dark and are interpreted as being mantled with fine-grained, likely organic, sediment (Tomasko et al., 2005; Perron et al., 2006). The Huygens probe landed several kilometers from the outlet of the fluvial network on a dark flat surface hypothesized to be a dry lakebed. At the surface, the DISR camera images show rounded cobbles (Fig. 8), inferred to be icy but with significant non-icy material. The relationship between the fluvial networks and the icy cobbles is not clear, but the presence of the cobbles provides plausibility for the interpretation of rounded icy cobbles in the radar-bright fluvial features draining Xanadu (Le Gall et al., 2010).

4.3. Drainage (or fluvial) network morphologies

By virtue of their regional extent and responsiveness to formative conditions, drainage or fluvial networks provide important evidence for surface, and subsurface conditions. Terrestrial drainages have been classified into several basic and modified patterns (e.g., Howard, 1967; although see Drummond, 2012, for a discussion of the slight differences among drainage classification schemes). Each of these drainage patterns carries specific implications regarding landscape slope, substrate erodibility biases, and other conditions at the time of fluvial runoff. Based on a quantitative algorithm for classifying drainages on Earth, an analysis of drainage morphologies visible in SAR and DISR images classified one-half of all the mapped networks as rectangular (Burr et al., 2013a). These rectangular networks are globally distributed in the available SAR data (Burr et al., 2013a), although gaps in the SAR coverage preclude a rigorous statistical analysis of geospatial distribution. As rectangular networks on Earth are commonly the result of control on overland flow by subsurface structures or topography associated with structures, this finding for the Titan networks was interpreted as indicating wide-spread structural control on fluvial flow (Burr et al., 2013a).

5. The fluvial dissection of Mars

As recognized early in the era of spacecraft exploration, channels and valleys extensively dissect the surface of Mars (Fig. 9). Valleys are low-lying, elongate troughs on planetary surfaces that are surrounded by elevated topography. On Earth, fluvial valleys either contain or formerly contained a stream or river with an outlet, but the river or its predecessor is/was confined to the valley floor or, commonly, to just a portion of the valley floor. The stream or river flows or flowed in a channel, which is an elongate depression that conducts or conducted flows of water that wet the channel boundaries. Most commonly such river channels have much smaller cross sections than do the valleys in which they occur.

About 200 years ago a major geomorphological controversy arose concerning the origins of valleys on Earth (Davies, 1969). One view held that valleys in areas such as Scotland were actually former channels that had been filled by the flowing water that had created them relatively rapidly as the result of cataclysmic events. The alternative view held that the prolonged and progressive action of small streams occupying channels on the valley floors was responsible for the valley excavation. Although by the middle nineteenth century this debate was generally resolved in favor of the noncataclysmic, uniformitarian hypothesis, later discoveries revealed that cataclysmic flooding did indeed explain some terrestrial landscapes, notably the Channeled Scabland region of the northwestern United States (Bretz, 1923)—though that insight was resisted by much of the scientific community until the 1960s (Baker, 1981, 2008b). Interestingly the immense cataclysmic flooding channels discovered on Mars are much larger than the many fluvial valleys that dissect portions of that planet (Baker, 1982; Baker et al., 1992b); and unlike those valleys, the Mars channels display clear evidence for large-scale fluid flow across their floors and on their walls or banks, thereby leading to a resurrection of similar methodological issues that played out in regard to the origin of Earth's cataclysmic flooding channels (Baker, 1978a, 1981).

The Mariner 6 and 7 spacecraft first imaged the networks of small valleys dissecting the ancient, heavily cratered terrains of Mars in 1969 (Schultz and Ingerson, 1973). However, these features were not recognized as fluvial until the higher resolution Mariner 9 images were obtained in the early 1970s (McCauley et al., 1972; Masursky, 1973; Milton, 1973). Some confusion was imparted to the early literature by the designation of these small valleys as small and closely spaced channels (Masursky, 1973). Because of their dendritic patterns, Sharp and Malin (1975) referred to the networks of small valleys as runoff channels, leaving open the possibility that the runoff could have been generated by precipitation in a manner familiar for Earth. The original *channel* designation, as opposed to *valley*, can be attributed to the lower resolution of the available Mariner 9 imagery, which did not clearly show the morphology of the valley floors, which the newer high-resolution imagery has shown to be largely obscured by eolian and volcanic deposits.

As noted above, Mariner 9 also revealed other types of fluvial features on Mars. The most spectacular of these were the immense cataclysmic flooding channels, initially termed *broad channels* (Masursky, 1973) because of their size. These were subsequently named *outflow channels* by Sharp and Malin (1975) because the examples first noted on the Mariner 9 images emerged from rubble-filled depressions termed *chaotic terrain* (Sharp, 1973). It is now known that these very large channels have multiple modes of origin, but further discussion of their characteristics will be held until Section 7 below.

5.1. Timing of fluvial activity

The extensive dissection of the heavily cratered terrain on Mars by valley networks (e.g., Fig. 10) was long used to argue that the networks themselves dated to the Noachian epoch (e.g., Carr and Clow, 1981; Carr, 1996). As with other age categories for Mars, the Noachian epoch is defined by the density of impact craters and by comparisons to radiometric dates on lunar cratering (e.g., Hartmann and Neukum, 2001). This procedure defines the Noachian as the portion of Mars geological history prior to 3.7 Ga. Later Mars epochs are then divided into the Hesperian, from about 3.7 to 3.0 Ga, and the Amazonian for surfaces younger than 3.0 Ga.

Recent work has shown that the formation of the well-developed valley networks on Mars is more concentrated in time, with much of the activity occurring close to the Noachian/Hesperian boundary (Howard et al., 2005; Irwin et al., 2005b). Moreover, as was apparent from some of the older Viking imagery of Mars (Baker and Partridge, 1986), fluvial activity in the valley networks continued into the Hesperian (Mangold and Ansan, 2006; Bouley et al., 2009, 2010; Hynek et al., 2010). Also apparent from the earlier Viking images, dense networks of fluvial valleys dissect Amazonian-aged surfaces on some Martian volcanoes, such as Alba Patera and Hecates Tholis (Gulick and Baker, 1989, 1990).

5.2. Valley networks

As noted in Table 2, two major types of Martian valleys can be distinguished. The longitudinal valleys (Baker, 1982) are relatively wide and elongate with few tributaries. They commonly dissect upland plateaus, and their theater-like valley heads suggest an important role of groundwater seepage undermining slopes (i.e., sapping, in their origin; Goldspiel and Squyres, 2000; Harrison and Grimm, 2008). Examples include Nirgal Vallis and Nanedi Vallis. Some of these valleys have small but relatively well-preserved deltas at their termini (Fassett and Head, 2005; Irwin et al., 2005a; Mangold and Ansan, 2006; Di Achille et al., 2007; Mangold et al., 2007; Kraal et al., 2008; Hauber et al., 2009; Dehouck et al., 2010).

Topographic data provided by the Mars Orbiter Laser Altimeter (MOLA) instrument on the Mars Global Surveyor (MGS) orbiter (Smith et al., 1999) show that the orientations of the numerous multi-branched networks of valleys are consistent with gravitational control of fluid flow on the Martian surface. The latter is locally warped by the formation of a trough and bulge that formed around the immense loading of the crust by the Tharsis volcanics (locality TV, Fig. 9) in late Noachian time (Phillips et al., 2001).

The network valleys widen and deepen in the downstream direction (Craddock and Howard, 2002; Howard et al., 2005; Irwin et al., 2008; Hynek et al., 2010). Small channels that are relicts from the rivers that formed the valleys are only rarely discernable because of the relatively young eolian deposits that commonly mantle the valley floors (Irwin et al., 2005a; Jaumann et al., 2005; Kleinhans, 2005). Similarly, deposits at the valley termini, are commonly missing, either because of erosion or mantling by younger lava flows, mostly of Hesperian age (Irwin et al., 2005a; Ansan et al., 2008; Ansan and Mangold, 2013).

The image resolution issue, discussed in Section 1, played an important role for valley network interpretation in that the relatively low-resolution images from the Mariner 9 and Viking Orbiter missions of the 1970s and 1980s seemed to indicate low drainage densities (length of valleys or channels per unit area) for the networks. Based on a global analysis of the relatively low-resolution Viking orbital imagery Carr (1996) and Carr and Chuang (1997) inferred that areas of highly dissected southern highlands on Mars had average drainage densities of only ~0.005 km^{-1}, which is much lower than typical values for fluvial drainage on Earth. These low values suggested that regional rainfall and runoff processes might not be the major cause for valley network formation on Mars (e.g., Squyres and Kasting, 1994; Segura et al., 2002).

The early summaries of drainage densities on Mars did not incorporate some results, also from Viking data (Baker and Partridge, 1986), that showed that local valley networks in the heavily cratered terrain consist of younger (pristine) elements that are portions of much older, though degraded networks. By considering the latter, Baker and Partridge (1986) found that the degraded network densities were as high as 0.1 km^{-1}, which is consistent with some terrestrial data. Using higher-resolution Viking data, Gulick and Baker (1989, 1990) determined that drainage densities were actually an order of magnitude higher for the fluvial valleys that formed on some younger Martian volcanoes (most notably Alba and Hecates) than those in the heavily cratered Noachian terrains. These values were much more similar to their terrestrial counterparts, with the Alba valleys (locality B, Fig. 9) having values between 0.3 and 1.5 km^{-1} compared to 0.2 and 5.0 km^{-1} on the Hawaiian volcanoes (Gulick and Baker, 1989, 1990). These higher values imply at least localized atmospheric precipitation (Gulick et al., 1997), and overland flow developed on a volcanic ash mantle overlying the very porous volcanic lava flows (Gulick and Baker, 1990).

The subsequent recognition of higher drainage densities using MOLA topographic data and higher resolution imagery from the MGS mission of the late 1990s (e.g., Hynek and Phillips, 2003) provided a confirmation of what had been shown in the more localized study of Viking data, and it is now clear that drainage densities average 0.1 to 0.2 km^{-1} over extensive areas of the Martian surface (Ansan and Mangold, 2006, 2013; Luo and Stepinski, 2009; Hynek et al., 2010). The high values of drainage density strengthen the case that prolonged precipitation and runoff processes were necessary for the origin of the valley networks (Ansan and Mangold, 2006; Craddock and Howard, 2002; Mangold et al., 2004; Quantin et al., 2005; Mangold and Ansan, 2006; Ansan et al., 2008; Hynek et al., 2010).

Mangold et al. (2012) relate the evolution of fluvial landscapes in the heavily cratered terrains of Mars to degradation of the highland craters. Craters older than about 3.9 Ga (Middle Noachian) date from the Late Heavy Bombardment, a pulse of very high impact fluxes that occurred throughout the inner solar system for about 100 My around 3.9 Ga. These ancient craters typically have heavily degraded rims, and the older ones are essentially rimless, with their ejecta having been completely eroded away, probably by fluvial processes. The eroded materials fill many of the crater floors and may represent a period of prolonged and effective fluvial planation (Howard et al., 2005; Irwin et al., 2005b). In contrast, the valley networks developed near the time of the Noachian/Hesperian transition (~3.7 Ga) on this planation surface. They dissect areas around craters that are eroded, but much less so than the more ancient rimless forms. In the Hesperian, from about 3.7 to 3.3 Ga, further degradation occurred within craters, leading to alluvial fans on their floors (Moore and Howard, 2005) and local dissection of rims but general preservation of the ejecta. Amazonian craters (younger than ~3.3 Ga) lack fluvial landforms and are relatively fresh in appearance with pristine-looking ejecta blankets and central peaks.

Detailed work in the Libya Montes area, just to the southeast of the Syrtis Major volcanic complex (locality Y, Fig. 9), shows the later evolution of Martian valley networks in relation to standing bodies of water on the planet's surface. The dendritic valley networks in the region were formed in the Noachian between about 4.1 and 3.8 Ga (Jaumann et al., 2010; Erkeling et al., 2012), with some activity continuing into the Hesperian. The fluvial activity was associated with the ponding of water in craters with associated deltas, hydrated minerals, and alluvial fans. At the western end of the Libya Montes, near its margin with the Syrtis Major volcanic complex, a large valley system, Zarga Vallis, has (i) an older, eastern network of dendritic valleys that probably formed by precipitation runoff processes and (ii) a younger, western segment that is a longitudinal valley that probably developed by volcanic melting of ground ice (Jaumann et al., 2010). The transition from runoff valley development to sapping or ground-ice melting seems to have occurred in the middle Hesperian (~3.6 Ga).

5.3. Alluvial rivers, deltas, and sedimentary rocks

On 6 August 2012, the Curiosity Rover of the Mars Science Laboratory Mission successfully landed on the floor of the 150-km-diameter Gale Crater (locality G, Fig. 9). The material on which it landed was a fluvial conglomerate (Fig. 11), deposited near the distal end of an alluvial fan (Fig. 12). As they were reported in the popular media, these features had the appearance of unique discoveries. However, the landing site had actually been carefully chosen to make such observations; the choice was based on the developing understanding of Mars' watery early history. Combined with observations from the Mars Exploration Rover (MER) Opportunity landing site (the *Burns Formation* of Grotzinger et al., 2005, 2006) and the related documentation of sedimentary rocks by various orbiters, the recent lander studies leave no doubt that Mars had a watery ancient past, involving the extensive emplacement of sedimentary rocks (Grotzinger and Milliken, 2012).

Until the later 1990s, channels and valley networks cut into rock had comprised the main evidence that was cited in support of the view that Mars once had conditions that supported an earthlike hydrological cycle. The view of a water-rich planet sharply contrasted with current conditions on the planet and with the then-prevailing views from physics and chemistry that Mars had always been cold and dry (Baker, 2014c). However, starting in the late 1990s, a rapid succession of discoveries added to the list of evidence for more earthlike hydrological conditions on early Mars. Although possible delta and fan-like depositional landforms had been tentatively recognized from the older low-resolution data (e.g., De Hon, 1992; Cabrol and Grin, 1999; Ori et al., 2000), the meter-scale images of the Mars Obiter Camera (MOC) on the MGS spacecraft led to the key discovery of deltaic features very similar in general morphology to what occurs on Earth (Malin and Edgett, 2003). The most impressive of these discoveries is a delta (Fig. 13) in Eberswalde Crater (locality U, Fig. 9). Multiple studies have estimated a dominant, channel-forming discharge for the paleochannels on this delta at a few to several hundred cubic meters per second (Malin and Edgett, 2003; Moore et al., 2003; Jerolmack et al., 2004; Howard et al., 2007; Irwin et al., 2014).

Related to the Eberswalde Delta discovery (Malin and Edgett, 2003) is the recognition of sinuous channels showing meander cutoffs, scroll topography, and related features of alluvial rivers with floodplains. Unlike rivers that are cut into bedrock, alluvial rivers on Earth have channel beds and boundaries composed of the same sediments that they transport. The Mars alluvial channels commonly display an inverted relief, probably because eolian deflation selectively removed the fine-grained sediments of the adjacent floodplains relative to the coarse-grained channel-filling sediments (Williams and Edgett, 2005; Pain et al., 2007). Particularly extensive alluvial river paleomeander belts occur in the Aeolis Dorsa region (Burr et al., 2009a, 2010; Williams et al., 2009a, 2013), which lies a few hundred kilometers east of the Gale Crater region (locality G, Fig. 9). The meandering patterns seem to have formed in alluvial rivers because of the deposition of relatively fine sediments (clay/silt muds) that were flocculated by dissolved salts (Matsubara et al., 2014).

Another interesting Mars delta (Fig. 14) occurs in Jezero Crater in the Nili Fossae region of Mars (locality F, Fig. 9). Hyperspectral data from the Visible and Near Infrared Mineralogical Mapping Spectrometer (OMEGA—Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité) instrument on Mars Express and the Compact Reconnaissance Imaging Spectrometer (CRISM) instrument on the Mars Reconnaissance Orbiter (MRO) revealed that this region has a diverse assemblage of minerals, including phyllosilicates (e.g., clay minerals), consistent with widespread liquid water activity that range from surface weathering to hydrothermal processes (Mangold et al., 2007). A valley network feeds from this altered source terrain to bedded sediments on the floor of Jezero Crater (Fig. 14), and these were probably emplaced in a crater lake near the time of the Noachian/Hesperian boundary (Fassett and Head, 2005). Some of these sediments are rich in iron–magnesium smectite clay (indicated in green on the image shown in Fig. 14) (Ehlmann et al., 2008), and the clay was probably transported as suspended load by a river that drained source areas characterized by clay-rich rocks (Mangold et al., 2007; Ehlmann et al., 2008).

While most Mars delta landforms are younger than the main phase of valley network development, a striking example of a late Noachian/early Hesperian delta occurs at Terby Crater, a 174-km-diameter feature on the northern edge of Hellas Planitia (locality H, Fig. 9) centered at 28°S, 73°E. At that location a cumulative thickness of 2000 m of sedimentation is inferred (Ansan et al., 2011). Such great accumulations of sediment show that the erosion by the valley networks probably was an important contributor to the filling of craters in the ancient heavily cratered terrain of Mars.

5.4. The early Mars climate conundrum and a northern plains ocean

The spatial distribution of the valley networks is not uniform throughout the heavily cratered terrain (Gulick, 2001), as might be expected if impacts into the southern highlands were responsible for episodic formation of the networks (e.g., Toon et al., 2010). Instead, the densest concentrations of valleys (Fig. 9) follow a swath that circles the planet, extending several hundred kilometers into cratered highlands from the latter’s boundary with the northern plains. Allowance must be made for the great Tharsis volcanic province, which is younger than the valley networks and which imposed itself on this boundary. This pattern is consistent with what would be expected for a precipitation source associated with a hypothetical northern plains ocean (Luo and Stepinski, 2009; Stepinski and Luo, 2010). The relationship of valleys to the northern margins of the heavily cratered terrain of the southern highlands has been confirmed by an independent study that quantified the spatial distribution of drainage densities (Hynek et al., 2010). The distribution also corresponds to the locations of deltas that are graded to the base level of the northern plains ocean (Di Achille and Hynek, 2010), to the concentrations of sedimentary rocks on Mars (Malin and Edgett, 2000a; Delano and Hynek, 2011), and to the presence of high-Al clay minerals in deep weathering profiles (Le Deit et al., 2012; Loizeau et al., 2012). The latter would require intense leaching in a surficial environment for their formation. Moreover, such a leaching episode would occur at the Hesperian/Noachian boundary (Loizeau et al., 2012), corresponding to the same episode of precipitation that is recognized in regard to the valley networks.

An ancient ocean-scale water body, about 3×10^7 km^2 in area, informally named *Oceanus Borealis* (Baker et al., 1991), has long been hypothesized for the northern plains of Mars (Fig. 9). Although it was initially inferred from the mapping of sedimentary landforms (Jons, 1985; Lucchitta et al., 1986), the ancient ocean hypothesis was more controversially tied to the identification of what were interpreted as shoreline landforms by Parker et al. (1989, 1993). However, failure to confirm the latter (Malin and Edgett, 1999, 2001) and variations in the hypothesized shoreline elevations of up to a couple of kilometers (Carr and

Head, 2003) led some to reject the hypothesis. More recent studies, including the explanation of shoreline deformation by true polar wander generated by the formation of the immense Tharsis rise (Perron et al., 2007) and interpretations of compositional data (Dohm et al., 2009), have lent support to the ocean hypothesis. Moreover, recent studies have shown that, unlike Earth's oceans, Mars' *Oceanus Borealis* formed episodically (Baker et al., 1991; Fairén et al., 2003). At least one earlier oceanic phase occurred at a time coincident with the formation valley networks in the Martian highlands (Clifford and Parker, 2001), and later phases were associated with inflows from the immense cataclysmic flood channels that are described in Section 7.

Multiple studies indicate that the formation of the valley networks required prolonged periods of rainfall in amounts comparable to what occurs for Earth's arid or semiarid regions (Howard, 2007; Barnhart et al., 2009; Luo and Stepinski, 2009; Hoke et al., 2011; Irwin et al., 2011; Matsubara et al., 2013). Associated lakes, deltas, and alluvial fans show complex histories of fluctuating water and sediment discharges (Malin and Edgett, 2003; Moore and Howard, 2005; Fassett and Head, 2005, 2008; Di Achille et al., 2006; Pondrelli et al., 2008; Di Achille and Hynek, 2010; Grant et al., 2011; Hoke et al., 2014), and these also imply prolonged periods of precipitation and runoff (Moore et al., 2003; Jerolmack et al., 2004; Matsubara et al., 2011).

This extensive evidence for warm, wet conditions on early Mars climate poses a conundrum because of the inability of current theoretical models to explain all this. In contrast to earlier theory (e.g., Pollack et al., 1987), if one assumes a CO_2–H_2O atmosphere, which involves the most parsimonious extrapolation that can be made from current Mars conditions to those of the ancient past, then brining the global mean surface temperature of Mars to near the freezing point of water would not physically have been possible at or before about 3.8 Ga ago (Kasting, 1991). These same assumptions apply to more complex calculations (Forget et al., 2013; Wordsworth et al., 2013), which also lead to a conclusion that a CO_2–H_2O Martian atmosphere cannot generate the needed warm temperatures.

Another view holds that it may not be necessary to bring global mean temperatures above the freezing point. Gulick et al. (1997) explored the potential climatic effects of instantaneous pulses of CO_2, such as may have been released during outflow channel formation and subsequent *ocean* formation as hypothesized by Baker et al. (1991). They found that a one to two bar pulse is sufficient to raise mean global temperatures above 240 or 250 K for tens to hundreds of millions of years, even when accounting for CO_2 condensation. Such pulses can place the atmosphere into a stable, higher pressure, warmer greenhouse state, where substantial water volumes could be transported from a frozen lake or ocean to higher elevations, despite global temperatures well below freezing. This water, precipitated as snow, could melt, infiltrate, and runoff, ultimately forming fluvial valleys in the southern highlands if associated with localized heat sources and hydrothermal systems, such as magmatic intrusions, volcanoes, or cooling impacts (Gulick, 1998). Thus, if outflow channel discharges were accompanied by a significant release of CO_2, a limited hydrological cycle could result that would be capable of producing fluvial erosion and valley formation. Sources of atmospheric CO_2 during this time could have been provided by venting from associated volcanism, release of gases dissolved in groundwater, de-adsorption of gases from inundated regolith, and vaporization of clathrate in the regolith and ices resident in the polar caps (Baker et al., 1991).

Mischna et al. (2013) recently proposed another scenario. They envision combinations of three driving factors for promoting transient warm/wet conditions on early Mars: (i) an insolation effect, mainly driven by changes in Mars' obliquity; (ii) a trigger effect, mainly as it will subsequently promote a transient water-rich greenhouse effect; and (iii) an albedo effect involving relatively dark portions of the Martian surface. The insolation effect results in periods of increased solar heating at various latitudes. The albedo effect can arise either (i) from dark, dust-free exposures of basalt bedrock or (ii) from the temporary presence of relatively low albedo, ponded water, notably the northern plains ocean inferred for early Mars, acting in the manner hypothesized by Baker et al. (1991) and Baker (2001, 2009a). Finally, a trigger effect can be provided by the massive, short-termvolcanic injection into the atmosphere of particularly potent greenhouse gases, such as sulfur dioxide. Though such gases may be generally short-lived in the atmosphere, their temporary warming effect can provide a trigger to get large quantities of water vapor into the atmosphere and that water will contribute to more prolonged greenhouse warming.

Halevy and Head (2014) also invoke the episodic volcanic release of sulfur dioxide, but in combination with aerosols, as a means of short-term warming of a dusty Martian atmosphere. The combination of mechanisms envisioned by Mischna et al. (2013) might then achieve the necessary warming, especially adjacent to the margins of the northern plains *ocean* that would supply water vapor. The warming could persist long enough to generate the rainfall/runoff conditions needed to produce the valley networks, but ultimately Mars would return to *ice-house* conditions as the obliquity changed on timescales of millennia. These overall interactions are similar to what was hypothesized by Baker (2009a).

5.5. Gullies and other recent flow phenomena

The discovery of gully forms (Malin and Edgett, 2000b) in MGSMOC images sparked a spirited new debate over the history of water on Mars. Although current average temperatures are below 273 K and atmospheric pressures are at or below the triple-point vapor pressure of water at 6.1 mbar, many investigators concluded that the morphology of at least some of the gullies implied a formation mechanism involving the flow of water. Additional studies imply that some gully modification processes may still be ongoing today, including the discovery of gullies on surfaces devoid of craters and gullies with deposits that overlap other modern, possibly active, landforms, such as dunes and polygons.

Although terrestrial gullies are commonly defined simply by the presence of an incised channel segment, Malin and Edgett (2000b) defined the Martian *gullies* as having an alcove in the source region, a defined channel or system of channels in the mid-section and a debris apron in the terminus. The formation and modification of gully systems on Earth involve a variety of fluvial and hillslope processes. These include fluvial (including overland, soil water, and groundwater flow), colluvial, and mass wasting (e.g., debris flows and avalanches) processes. The challenge posed by the Martian gullies is to determine which of these, or other, mechanisms are primarily responsible for gully formation and which are simply modification processes.

5.5.1. Gully distribution and types—Gullies on Mars are concentrated in the mid-latitude regions, primarily in the southern hemisphere, but they are also found in the northern hemisphere (Malin and Edgett, 2000b; Costard et al., 2002; Heldmann and Mellon, 2004; Balme et al., 2006; Dickson et al., 2007; Heldmann et al., 2007). Although the earlier studies concluded that gullies are mostly located on pole-facing slopes in the southern hemisphere, later work points to prominent gully systems formed at various slope orientations in the northern hemisphere and southern latitudes (e.g., Gulick, 2008; Gulick and Davatzes, 2009; Head et al., 2009; Hart et al., 2010). These systems are located on a variety of surfaces, including central peaks and pits of craters, craters, channel and valley walls, polar pits, mounds, mesas, and mid-latitude dune fields.

Imagery from the High Resolution Imaging Science Experiment (HiRISE) camera of the current MRO mission affords a much closer look (~0.3 m/pixel; meter-scale features resolvable) at the gullies than was available in the MOC discovery images (~1.5 to 12 m/pixel; tens of meters-scale features resolvable), and at this higher resolution gullies exhibit a great deal of morphological diversity. While some gullies exhibit the canonical single source alcove, incised middle reach and terminal debris fan deposits, others form tributaries that coalesce into complex networks. Lengths range from several tens of meters to several kilometers; widths range from several tens of meters down to HiRISE's resolvable meter-scale. Some gully sources blend in gradually with the surrounding uplands, while others start full-borne from blunt theater heads. Gully systems displaying different morphologic patterns can be located adjacent to each other, morphologically complex gully systems commonly originate at rocky layers on a cliff face (Fig. 15). Such gullies often undercut walls, erode into the underlying rock and sediment, form point bars and cut banks, exhibit braided and anastomosing reaches, erode multiple terraces along gully margins, and deposit rocks and sediments along the gully and superposed adjacent systems. The resulting complex suite of morphological features is consistent with a fluvial origin (Gulick, 2008).

In contrast, gullies located on mid-latitude dune fields (Mangold et al., 2003; Reiss and Jaumann, 2003) are sourced from alcoves located at dune crests, erode constant-width channels with levees, but generally lack the distal deposits common to the other gullies. Boulders are present at the termini of some dune gullies. Multitemporal imaging (repeat imaging of specific locations taken over multiple seasons and/or years) has documented seasonal changes in the dune gullies (Jouannic et al., 2012; Diniega et al., 2013). Sliding blocks of CO_2 ice down dune slopes (Diniega et al., 2013) and seasonal melting of an upper H_2O ice and brine layer are among several hypotheses that have been proposed for the formation of the linear dune gullies (Kereszturi et al., 2009; Reiss et al., 2010). Recently, long-term observations of crater wall gullies employing HiRISE imagery has documented the role of CO_2 processes on present-day Mars as active processes related to gully morphology (Dundas et al., 2014).

Still other gully types have distinct source regions and debris fans, but lack incised middle reaches. These particular *gully* forms are usually located on steep slopes, such as the inner walls of several volcano calderas, as well as on some crater, valley, and canyon walls; and they may be more akin to debris chutes where material is transported down steep slopes mostly by gravity alone.

HiRISE imaging also shows that gullies in a single locale sometimes emerge at multiple elevations and display a striking variety of morphologies. For example, miniature gully systems, some less than a kilometer long, are located along a crater wall in the Terra Sirenum region (Fig. 16A). These small gullies exhibit typical gully morphologic characteristics. However they emerge much farther downslope than do their nearby full-scale counterparts (Gulick, 2008). Other intriguing gully systems are located on some pristine, mid-sized impact craters (McEwen et al., 2007a; Tornabene et al., 2007). For example, well-developed and integrated *gully* systems heavily dissect the eastern rim region of Mojave Crater (Fig. 16B). In another example, pristine gullies have eroded both sides of the rim of Hale Crater (Figs. 17, 18), flowing in opposite directions. In one location, only a narrow ridge separates eastward- and westward-oriented gullies (Gulick, 2008). Although these gullies display morphological characteristics consistent with a fluvial origin, associations such as these may challenge any single gully formation mechanism applicable to geologically recent times.

5.5.2. Formation processes—Given such diversity in morphology, a continuum of processes is likely involved in the formation and modification of various gully systems. Formation mechanisms may include flows of hyper concentrated fluids, debris flows, dry mass wasting flows and slides, and seasonally active processes involving CO_2 and/or H_2O ice. Proposed sources of water flows include melting snow packs (Christensen, 2003); melting ground ice during periods of high obliquity (Costard et al., 2002; Dickson and Head, 2009); and melting ice-rich, debris-covered, glacial material (Schon and Head, 2012). Other mechanisms involve liquid water from groundwater flow in near-surface aquifers (Malin and Edgett, 2000b), from atmospheric sources (Costard et al., 2002; Hecht, 2002; Christensen, 2003; Dickson et al., 2007; Williams et al., 2009b), or from wet debris flows (Costard et al., 2002; Dickson and Head, 2009; Williams et al., 2009a; Heldmann et al., 2010; Mangold et al., 2010; Schon and Head, 2011). Still other proposed mechanisms include dry mass wasting; granular flows; (Shinbrot et al., 2004) exotic fluids (Musselwhite et al., 2001; Treiman, 2003; Hugenholtz, 2008); seasonal CO_2 frost (Dundas et al., 2014); and, for the linear dune gullies in particular, sliding and sublimation of CO_2 blocks (Hansen et al., 2007; Diniega et al., 2013).

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HiRISE has taken several thousand images of gully forms since 2006, and many of these are repeat, stereo images. Such long-term repeat imaging of specific sites, taken over multiple seasons and years, provides information on seasonal morphologic changes or clues that may lead to detection of processes that are currently active in the gully systems. Additionally, HiRISE digital terrain models (DTMs) can be produced from many of these HiRISE stereo image pairs. Most images are generally ~0.25–0.50 m/pixel, which yields a post-spacing equal to ~1–2 m with vertical precision in the tens of centimeters (McEwen et al., 2007b). In particular, HiRISE DTMs have enabled a new level of gully studies for quantitative detailed longitudinal profile analysis and more accurate volume calculations using slope, distance, and elevation. Several recent studies of Martian gully systems (e.g., Hart et al., 2010; Jouannic et al., 2012; Glines and Gulick, 2014; Hernandez et al, 2014; Hobbs et al., 2014; Narlesky and Gulick, 2014) have incorporated analysis of HiRISE DTMs. These studies have led to estimates of eroded gully volumes and their associated deposits, thus providing a

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measure of the missing water or volatile volumes associated with gully formation. For example, Gulick et al. (2014) determined that the volume of the resulting debris aprons within Kaiser and Corozal craters was ~40% of the eroded gully volumes that resulted in a total water or volatile volume of ~60% of the total gully volume. Such studies provide a better understanding of Mars recent hydrological history and detailed comparisons with terrestrial gully systems.

5.5.3. Recurrent slope lineae (RSL)—A relatively recent discovery on Mars is the identification of what may be the best candidate for modern-day liquid water flow on Mars. The evidence for flow consists of linear patterns, probably of wetting and/or chemical precipitation, that extend and contract seasonally on steep, warm, rocky Martian slopes (McEwen et al., 2011). The phenomenon has been documented on equator-facing slopes of the southern mid-latitudes of Mars, and the transient flow features occur in the local spring and summer seasons (McEwen et al., 2011; Ojha et al., 2014). Termed *recurring slope lineae* (RSL), these features also occur in the Valles Marineris (McEwen et al., 2014). While McEwen et al. (2011) originally proposed that these present day flows would likely need to be briny because of the current surface temperature and pressure conditions, new observations by Stillman et al. (2014) support fresh shallow water flows forming RSL in the southern mid-latitudes. They observed that the vast majority of RSL lengthen only when mid-afternoon surface temperatures are >273 K. Detailed RSL observations over time (Stillman et al., 2014) have been shown by modeling to be consistent with subsurface water flow over a shallow aquitard (Grimm et al., 2014).

6. Lava flow channels on Mars

Mars obviously has a rich fluvial history, particularly in its first billion years. However, this history is also interconnected with a rich history of volcanic phenomena, including interactions of volcanism with water-related processes. These interactions lead to equifinality issues in regard to volcanic versus fluvial channel origins. As an alternative to the fluvial outflow channel hypothesis (see Section 7 below), Leverington (2004, 2006, 2009, 2011) argued that thermal and/or mechanical erosion by lava may have carved the Martian outflow channels. However, discrimination between fluvial and lava channels on Mars is complicated by possible overprinting relationships in which lava flows may have resurfaced fluvial outflow channels. For instance, high-resolution imaging of Amazonian-aged Athabasca Valles shows that this outflow channel is draped in lava (Jaeger et al., 2007, 2008, 2010; Ryan and Christensen, 2012), possibly implying a secondary rather than primary role for lava. Understanding the relative roles of fluvial and volcanic processes in channel formation is therefore vital for understanding the evolution of the Martian surface and climate.

6.1. Channel structures within volcanic plains

On Mars, basaltic provinces divide into three main types (Greeley and Spudis, 1981; Zuber and Mouginis-Mark, 1992): (i) large shield volcanoes fed primarily from centralized sources (e.g., Olympus Mons and the other Tharsis Montes; Bleacher et al., 2007), (ii) regional packages of sheet-like *flood lava* that appear to originate from fissures (e.g., the Cerberus

Fossae Units in Elysium Planitia; Plescia, 1990; Jaeger et al., 2007, 2010), and (iii) vent fields composed of coalesced lava from widely distributed low shields (e.g., Tempe Terra Formation in northeastern Tharsis; Plescia, 1981). Each of these basaltic landscapes includes a diverse range of channels, which may be related to volcanism, bedrock erosion by overland flows of water, or a combination of both processes. However, distinguishing among these hypotheses requires determining if the channels are primarily features associated with lava flow emplacement, or if they are products of subsequent erosional processes. This can be achieved by considering the morphological characteristics and facies relationships associated with lava flows, which generally involve two end-member emplacement mechanisms: channel-fed growth (e.g., Booth and Self, 1973; Baloga et al., 1995; Kilburn, 1996; Harris and Rowland, 2001; Glaze et al., 2009; Harris et al., 2009) and endogenous growth (e.g., Walker, 1991; Hon et al., 1994; Keszthelyi and Denlinger, 1996).

6.2. Channel-fed flows

Channel-fed lavas (Figs. 19, 20) can form within a range of lava flow types including ‘a’ā, pāhoehoe, and transitional lavas (e.g., blocky, rubbly, slabby, and platy flows). Lava channels are commonly associated with high lava-discharge rates, which favor the transport of lava in open ‘a’ā channels caused by shear-induced disruption of the lava surface (Macdonald, 1953; Pinkerton and Sparks, 1976; Rowland and Walker, 1990). Viscous tearing of the lava surface also enhances the cooling of the underlying molten lava, thereby resulting in a thermally inefficient lava transport system, relative to endogenous flows. With distance from the vent ‘a’ā channel geometries tend to evolve from being narrow and leveed in the proximal regions to wide and nonleveed near the flow front (Lipman and Banks, 1987; Kilburn and Guest, 1993; Cashman et al., 1999). However, as the flow front continues to advance, the stagnated lateral margins of the ‘a’ā can develop into stationary levees that help to focus the continued through flux of lava. As the eruption progresses, the levees may continue to grow as lava episodically overtops the channel banks to form a combination of overbank flows and rubble avalanches. However, as lava-discharge rates wane, the ‘a’ā channel may partially drain to produce a deep topographic depression bounded by levees on either side.

Pāhoehoe flows tend to be associated with lower lava-discharge rates (Rowland and Walker, 1990), which favor the formation of lobes that are bounded by a continuous surface crust (see the discussion of endogenous flows below for more detail). However, in the ventproximal region, or along segments of a lava pathway where local lava-discharge rates are high (e.g., due to topographic constrictions and/or breakouts of stored lava), lava flow velocities may be sufficiently great that a continuous surface is unable to form. At these localities, pāhoehoe and transitional lavas may also form open channels that can subsequently drain to produce topographic depressions.

Channels within ‘a’ā and pāhoehoe lava flows can be expressed as distinctive landforms that are perched above their surroundings by their high-standing margins. However, large eruptions can also produce broad sheet-like flows that inundate the landscape such that they are confined by pre-eruption topography rather than auto-confining by lateral lava levees (Self et al., 1996, 1998; Thordarson and Self, 1998). These *flood lavas* may include one or more preferred pathways that drain as lava-discharge rates wane to produce channel-like depressions that appear to incise into an existing plain. In some cases, lava pathways may carve into the pre-eruption landscape through processes of thermal-mechanical erosion (Baloga et al., 1995; Williams et al., 2000, 2001a,b, 2005), but this process is exceedingly difficult to discern from remote sensing data alone because the apparent *excess depth* of the channel may simply reflect the fact that the preferred pathway formed above the lowest point in the initial landscape.

6.3. Endogenous flows

In contrast to channelized flows, endogenous (e.g., pāhoehoe) lava flows tend to be composed of self-similar lobes (Bruno et al., 1994) that transport lava though thermally insulated internal pathways, which may range from to narrow lava tubes to broad sheet-like regions (Self et al., 1998). Endogenous flows grow as new lobes breakout along existing flow margins (Crown and Baloga, 1999). These breakouts expose fluidal lava that quickly cools to develop a rheological gradient consisting of a brittle outer crust, underlying viscoelastic layer, and inner molten core. Once lobes develop sufficient rigidity to retain incoming lava, they can pressurize and inflate as a network of lobes or coalesce to form a lava-rise plateau (Walker, 1991). Lava-rise plateaus generally have a broad sheet-like geometry, but as they thicken by inflation, they can also generate lava-rise pits above topographic highs in the pre-eruption landscape (Walker, 1991). Lava-rise plateaus and lava-rise pits are important diagnostics of inflation because they are large enough to be observable on high-resolution remote sensing data (e.g., MRO HiRISE and Context Camera (CTX) imagery).

6.4. Facies changes

Distinguishing between channelized and endogenous growth mechanisms is vital for inferring lava emplacement dynamics, modeling flow behavior, and understanding the origin of volcanic plain units on Earth, Mars, and other planetary bodies (Self et al., 1998). However, lava transport mechanisms evolve with distance from source and with time such that structures preserved at the surface of a flow may only represent one part of a complex emplacement history. To address this issue, a facies-based approach can prove fruitful for advancing understanding the formation and characteristics of lava channels.

A facies refers to the suite of characteristics (i.e., appearance, composition, etc.) of a rock unit, or stratified, body that reflects its origin and enables the unit to be distinguished from others around it. In the context of lava facies, Kilburn and Guest (1993) described how lava flows can change continuously from the initial emplacement of isothermal sheets to flows with tubes and channels, which commonly evolve from pāhoehoe to ‘a’ā flows. Kilburn and Guest (1993) also explored how combinations of poorly/well-crusted and sheet/channel zones can be used to establish a continuum of facies. These facies reflect the balance between dynamic processes of lava cooling, crustal growth, and surface stability relative to the mode of lava transport in either thermally insulated internal pathways or open channels. Facies change with distance from the source and at any given location with time, which makes facies relationships a much stronger diagnostic of a unit’s volcanic origin than isolated observations.

In the context of Mars (Fig. 21), small sinuous channel systems in volcanic terrains have been particularly contentious, with proposed origins ranging from fluvial processes and mudflows (e.g., Murray et al., 2010; El Maarry et al., 2012) to lava flow emplacement (e.g., Hamilton et al., 2010, 2011). These channels are hundreds of meters wide, tens of meters deep, and tens to hundreds of kilometers long. Such channels tend to head from fissures, but they are much smaller than outflow channels. These smaller sinuous channel systems are typically located in the Tharsis and Elysium volcanic provinces (localities TV and E, Fig. 9), but they are also distributed in the southern highlands. The channels can have single-stem or multichannel (anabranching) forms with streamlined islands and terraced margins, which are often thought to be diagnostic of bedrock erosion by water. However, examples of similar landforms are also observed within lava flows on Earth (Soule et al., 2004). Unfortunately, in cases where volcanic eruptions have continued for long periods of time, initial lava flow structures, such as anabranching channel morphologies, may be overprinted and erased by subsequent lava flows. For example, as lava-discharge rates wane, endogenous flow units emplaced under lower lava-discharge conditions may overlie channel-fed flows that formed under peak lava-discharge conditions. The time-scales of emplacement for lava flows on Mars are poorly constrained, but Jaeger et al. (2007, 2008, 2010) advocated that some Martian lava flows, such as the Athabasca Valles flood lava (locality I, Fig. 9), may have been emplaced over a relatively short duration, on the order of several weeks. If so, short-lived, but relatively high lava-discharge rate eruptions (e.g., the December 1974 flow on Kīlauea, Hawai'i) may provide valuable insight into the formation of sinuous lava channels on Mars.

7. Martian cataclysmic flooding channels

The largest fluvial channels of the solar system occur on Mars. Their discovery on the Mariner 9 images revealed morphologies that, despite the then-prevailing physical theory of a water-impoverished planet (e.g., Leighton and Murray, 1966), indicated formation by flowing water to the geologists on the Mariner 9 team (McCauley et al., 1972; Masursky, 1973; Milton, 1973). The name *outflow channel* was applied (Sharp and Malin, 1975) because of the immense collapse areas of blocky, fractured terrain at the heads of the largest channels, including Kasei, Maja, Shalbatana, Simud, Tiu, and Ares Valles (Fig. 22). The indicated immense flows of water were attributed to volcanic melting of ground ice (McCauley et al., 1972; Sharp, 1973; Masursky et al., 1977), and various formulations of this mechanism have been dominant in explanations ever since.

In published scientific papers over the seven or eight years following their discovery in 1972, nearly every conceivable fluid was invoked to explain the Martian outflow channels. These included flows of lava (Cutts et al., 1978; Schonfeld, 1979); wind (Whitney, 1979a,b; Cutts and Blasius, 1981), CO_2 (Lambert and Chamberlin, 1978), flows of debris (Thompson, 1979; Nummedal and Prior, 1981), glacial flow (Lucchitta et al., 1981; Lucchitta, 1982), tectonism (Schumm, 1974), and even flows of liquid alkanes (Yung and Pinto, 1978). Motivation for these hypotheses derived from the perceived inconsistency with physical models of the Martian atmosphere (e.g., Leighton and Murray, 1966) and geochemical arguments that purported to indicate a very small planetary water inventory (Anders and Owen, 1977), as well as the lack of deltas at the mouths of various channels (Cutts et al., 1978). However, all the various nonaqueous fluid-flow candidates had consequences for morphology and planetary history that could be evaluated against the facts that were known in regard to those consequences (e.g., Baker, 1982, 1985b). This testing of hypotheses led to a general investigative community consensus in favor of the cataclysmic flooding hypothesis (Mars Channel Working Group, 1983; Baker et al., 1992b) that relied heavily on the analogy drawn to the megaflood landscapes of the Channeled Scabland and Iceland (Baker and Milton, 1974; Baker and Nummedal, 1978; Baker, 1982, 2009b,c; Rice and Edgett, 1997). Relationships for cataclysmic flooding features in Martian channels have since been reviewed in numerous publications (e.g., Nelson and Greeley, 1999; Baker, 2001; Coleman, 2005; Pacifici et al., 2009; Warner et al., 2010a).

After a hiatus of a couple of decades, a new generation of nonaqueous models has been resurrected, including the decompression of solid CO_2 (Hoffman, 2000) and massive eruptions of very fluid lava (Leovy, 2002; Leverington, 2004, 2011; Leone, 2014). The CO_2 hypothesis of Hoffman (2000) predicted that Mars had always been so cold and dry that water never could have been liquid on its surface—a consequence clearly at odds with the immense number and variety of newly discovered features on Mars that are clearly associated with liquid water processes. Urquhart and Gulick (2001) reviewed the plausibility of the *White Mars* hypothesis and concluded that the subsurface of Mars is unlikely to have been as cold as this model suggested and that liquid water would be present much closer to the surface than predicted by this hypothesis. The assumptions of the *White Mars* hypothesis regarding the globally averaged crustal heat flow are below most estimates for the current thermal state of the Martian crust and well below probable values.

Recently the term outflow channel has been applied to many features with very different morphologies than those associated with the original designation. In his model of massive outpourings of very fluid lava on the surface of Mars, Leverington (2011) applied the term not only to features associated with the original definition but to a great variety of large channel forms of volcanic origin, including lunar sinuous rilles (see Section 2.1); channels of more uncertain origin, such as those on Venus (see Section 3); and to Martian channels that do not head at outflow regions, such as Ma'adim Vallis, which has a complex history associated with crater lake spillways (Irwin et al., 2002, 2004). Leone (2014) even applied the term *outflow channel* to the troughs of the Valles Marineris. Carr (2012, pp. 2204–2205) responded to the massive lava hypothesis in his review of the fluvial history of Mars by observing, as follows: "…the consensus is that the channels were cut by water, based on the strong resemblance to terrestrial flood features, on the availability of water as indicated by other indications of hydrological activity such as the valley networks, and on geophysical modeling of channel formation…". Nevertheless, as noted in Section 5, problems remain for relating the aqueous origins of fluvial features on Mars to the general theory of environmental change on the planet, but this poses a challenge to the theory—not to the realities of the fluvial features.

7.1. Cataclysmic megaflooding forms and processes on Earth and Mars

7.1.1. Hierarchy of morphological forms in cataclysmic flooding channels—

The erosional and depositional bedforms of terrestrial catastrophic floods can be described according to a hierarchical classification of macroforms and mesoforms, as originally recognized in the Channeled Scabland (Baker, 1978b, 2009b,c). Macroscale forms (scale controlled by flow width in the channel) develop in cataclysmic flooding channels through the erosion of rock and sediment and/or by deposition (generally as in-channel bars). Some examples of erosionalmacro-scale forms are channel anastomosis, channels with low sinuosity and high channel width–depth ratios, large-scale streamlined residual hills, and scoured surfaces. Examples of depositional macroscale forms include the largest pendant bars, expansion bars, eddy bars, and fan complexes.

Catastrophic floods also produce mesoscale forms, which have their scale controlled by flow depth in the channel. Some examples of erosional mesoscale forms include longitudinal grooves, cataracts, and inner channels. Depositional mesoscale forms include large transverse bedforms (fluvial dunes), smaller pendant bar forms, and slackwater depositional areas. Although the hierarchical arrangement of cataclysmic flooding landforms was originally recognized on Mars at scales considerably larger than what occurs in the Channeled Scabland (e.g., Baker and Milton, 1974; Baker and Kochel, 1979), more recent work with high-resolution imagery has revealed areas where the scales are more comparable (Rodriguez et al., 2014).

In terrestrial catastrophic flooding examples the association of macroforms and superimposed mesoforms result from the nature of the flood hydrograph. For most continuously flowing rivers, flood hydrographs have a long recession phase. The depositional bedforms that are stable at high flow stages (meso-scale forms) get washed out during the prolonged recessional phase, and post-flood surfaces preserve only the more stable macroscale forms, such as alternate bars. However, some catastrophic floods, such as those responsible for the Channeled Scabland (Baker, 1973), undergo an abrupt cessation of flood discharge, and this results in the preservation of many of the mesoscale forms (e.g., fluvial dunes), especially those located on higher elevation bar surfaces. In contrast, other terrestrial catastrophic flood landscapes do not preserve mesoforms because of their more prolonged flow. This was the case for the Bonneville megaflooding (Malde, 1968; O'Connor, 1993), which has no known examples of large-scale transverse bedforms (fluvial dunes). The lack of fluvial dunes in many Mars catastrophic flooding channels may result from similarly prolonged flow phenomena.

Examples of cataclysmic megaflooding landforms on Mars include channel anastomosis (Fig. 23), streamlined hills and longitudinal grooves (Figs. 23 and 24), and expansion bars (Fig. 25). Detailed mapping and analysis of Ares Vallis (locality A, Fig. 22), one of the largest cataclysmic flood channels that was a type example for the designation *outflow channel*, revealed excellent examples of eddy and pendant bars (Pacifici, 2008; Pacifici et al., 2009). These features are characteristic of macro form deposits in the Missoula megaflooding landscapes of the Channeled Scabland (Baker, 1973, 2009b,c). Detailed mapping of upper Ares Vallis using Mars Express HRSC data (Pacifici 2008) showed the association of these depositional landforms with erosional landforms that are also typical of the Channeled Scabland, including longitudinal grooves, streamlined uplands, and cataracts. A spectacular example of the latter is about 500 m high and 15 km wide (Pacifici et al., 2009; Warner et al., 2010a).

The downstream reaches of Ares Vallis are dominated by ice-related landforms that developed after the cataclysmic flooding phase (Costard and Kargel, 1995; Costard and Baker, 2001). These include kame-like features and thermokarst depressions that occur in sediments overlying the cataclysmic flooding landforms (Costard and Baker, 2001; Pacifici et al., 2009; Warner et al., 2010b,c). It is also clear from recent work (Pacifici, 2008; Warner et al., 2009, 2010a, 2013; Roda et al., 2014) that Ares was formed by multiple cataclysmic flooding events/episodes spanning from Early Hesperan (~3.7 Ga) to early Amazonian (~2.7 Ga) time.

7.1.2. Differences in sediment transport and deposition on Mars and Earth— The lack of extensive deposits within the Martian catastrophic flood channels and at their mouths has been noted from the time of their earliest study in the 1970s. Recently resurrected by Leverington (2011), these observations include the supposed lack of fluvial bars within the channels and the lack of deltas at the mouths of many Martian "rivers" where they entered lakes or the ancient ocean that is hypothesized to have episodically occupied the planet's northern plains (see Section 5.4 above). This is an example of a flawed analogy.

The large Martian channels were not formed by the long-term action of Earth-like river flows (hence the need to refer to them as *cataclysmic flooding channels*). Their appropriate terrestrial analogs are not rivers at all, but rather the relatively rare cataclysmic food channels on Earth that are mainly associated with past periods of glaciation in which large ice sheets developed various instabilities because of subglacial volcanism and/or marginal or subglacial lakes. Since the early work in the 1970s on the origin of the Mars cataclysmic flooding channels, many new discoveries have been made of cataclysmic flooding landscapes on Earth (Baker, 1997, 2002a,b, 2009d, 2013), and megaflood-generating processes (e.g., Table 3) are now recognized as being much more important, particularly for the glacial periods of Earth's Pleistocene epoch (e.g., Baker, 1997, 2014b).

High-energy cataclysmic flooding on Earth and Mars occurred when water many tens to hundreds of meters deep flowed with very steep energy slopes, thereby generating velocities of tens of meters per second, which were associated with values of bed shear stress and unit stream power that exceeded by many orders of magnitude those of rivers like the Mississippi (Baker and Costa, 1987; Baker, 2002a). The latter has a very flat gradient, and its channels convey mainly mud and some sand at velocities of no more than about a meter per second and at very low values of bed shear stress and unit stream power. The sand separates out as bedload that is locally deposited as channel or point bars, while the silt and clay move as suspended load that either is conveyed to the river's mouth and delta or is deposited as overbank mud on the floodplains that border the river channel.

As pointed out by Komar (1979, 1980), the combination of extremely high unit stream power and reduced gravity means that the particles in the high-velocity Martian flood flows did not separate out as bedload and suspended bed-material load in a manner typical for a low-energy Earth river like the Mississippi. In cataclysmic megaflooding on Mars, very coarse particles moved as washload, or auto-suspension load, that, instead of being deposited as bars, was mostly flushed through the whole channel system and only was subject to deposition where the high energy levels dropped, as occurred in the huge expanse of a terminal basin, which for Kasei Vallis was the northern plains of Mars (Fig. 26). Fig. 26 shows the immense amount of erosion that occurred along Kasei Vallis and the lack of an obvious delta or fan where the Kasei channels terminated in the northern plains lowlands (blue colors in Fig. 26). The correct analogy here is not to a terrestrial river that would deposit its load at this point, but to terrestrial cataclysmic flood channels entering Earth's oceans. The Columbia River, one of the largest in North America, also has no delta of sediment accumulation at its mouth. Instead, the immense fluxes of sediment generated by the megafloods that occurred in the Columbia River basin are distributed over 2000 km of the abyssal plains of the Pacific Ocean (Normark and Reid, 2003). The bulk of the sediments were carried far out into the terminal basin and spread thinly over immense areas (Baker, 2007). Similarly, sediments moved through the Martian cataclysmic flood channels terminating at the northern plains would have entered the *Oceanus Borealis* (see Section 5.4) as hyperpycnal flows, and the resulting submarine density flows would have been spread out over distances of thousands of kilometers from the channel mouths, constituting deposits that would mantle the entire northern plains of Mars.

While a complete discussion of the hydraulics of the ancient Martian floods and their related erosional/depositional processes is beyond the scope of this review, useful summaries can be found in papers by Baker (1979, 1982), Komar (1979), Baker and Komar (1987), Komatsu and Baker (1997), Burr (2003), Kleinhans (2005), and Wilson et al. (2004, 2009). Advances in computational power now allow the application of two-dimensional hydraulic models to very complex channelized regions like Athabasca Vallis (Keszthelyi et al., 2007; Kim et al., 2014), and it is clear that more work of this type will contribute greatly to our understanding of mechanics of both erosion and deposition for the Martian cataclysmic flooding channels.

7.2. The circum-Chryse outflow channels region

The chaotic source areas and related *outflow channels* surrounding the Chryse region of Mars (locality C, Figs. 9 and 22) have received extensive study for more than 40 years (Sharp, 1973; Baker and Milton, 1974; Carr, 1979; Baker et al., 1991; Clifford and Parker, 2001; Rodriguez et al., 2003, 2005a,b, 2006b, 2007, 2011; Bargery and Wilson, 2011; McIntyre et al., 2012). The upper crustal stratigraphy in this region is thought to consist of interbedded volcanic and sedimentary deposits that were mostly emplaced during the Noachian (Rotto and Tanaka, 1995; Scott and Tanaka, 1986; MacKinnon and Tanaka, 1989). These deposits are hypothesized to contain large populations of buried impact craters (Malin and Edgett, 2001; Frey, 2003; Rodriguez et al., 2005b). Regional investigations indicate that aquifers developed in association with buried craters (Malin and Edgett, 2001; Frey, 2003; Rodriguez et al., 2005b) and tectonic fabrics (Rodriguez et al., 2007). The instabilities within these aquifers probably led to the formation of chaotic terrains. Though not well understood, the instabilities have been linked to conditions such as intrusive magmatism into the hydrosphere/cryosphere (e.g., Rodriguez et al., 2003, 2005b; Harrison and Grimm, 2008), explosive dissociation of upper crustal clathrate deposits (e.g., Komatsu et al., 2000; Rodriguez et al., 2006b; Gainey and Elwood Madden, 2012), and the thermally insolating effect of hydrated salts (Kargel et al., 2007) and porous sediments (Rodriguez et al., 2011).

The regional mapping of Rotto and Tanaka (1995) portrays a generalized history of channel dissection and includes four outflow channel units that distinguish older and younger, higher (shallow) and lower (deep) channel floors. Their mapping suggests that the chaotic terrains and outflow channels mostly developed between the Late Hesperian and the Early Amazonian. However, recent analysis of very high-resolution imagery shows that portions of Simud, Tiu, and Ares Valles experienced major outflow channel flows during the Early and Middle Amazonian, extending to as recent as ~900 Ma (Rodriguez et al., 2015). Other regional hydrogeologic processes, including valley dissection and groundwater upwelling, may have lasted from the Late Noachian until the Amazonian (Andrews-Hanna and Phillips, 2007; Glotch and Rogers, 2007; Fassett and Head, 2008).

Higher levels within the circum-Chryse outflow channels consist of ~20–50-km-wide canyons, the floors of which are marked by prominent ridges and grooves. Their formation has been attributed to catastrophic floods generated by groundwater eruptions along the flanks of chaotic terrains and plateau zones of subsidence (Rodriguez et al., 2006a). Some of these chaotic terrains are enclosed, while others extend over highlands and modify craters and intercrater plains alike. Associated zones of subsidence consist of complex systems of warped and faulted highlands (Rodriguez et al., 2003, 2005a,b). In addition, a few of these outflow channels extend from structures produced by dilational (Hanna and Phillips, 2006; Coleman et al., 2007) and contractional (Rodriguez et al., 2007) tectonism.

Lower levels within the circum-Chryse outflow channels consist of much broader troughs, generally a few hundred kilometers in width. Their floors are marked by faint ridges and include widespread knobs, which may consist of large blocks likely transported by debris flows (Tanaka, 1997, 1999; Rodriguez et al., 2006b). The debris flow hypothesis is consistent with the finding of rounded, submeter size clasts and imbricated boulders at the Mars Pathfinder landing site (Golombek et al., 1997; Tanaka, 1997, 1999). These debris flows might have been triggered during episodes of large-scale collapse within the Ganges Chasma (Rodriguez et al., 2006a) or by discharges from vast paleolakes within Valles Marineris (locality VM, Fig. 22) (Rotto and Tanaka, 1995; Lucchitta et al., 1994; Warner et al., 2013). In addition, glaciers appear to have significantly contributed to the formational history of the circum-Chryse outflow channels (Lucchitta, 1982, 2001), and immense amounts of glacial ice may have occupied the Valles Marineris (Mege and Bourgeois, 2011; Gourronc et al., 2014).

7.3. Megaflood generation processes

7.3.1. Pressurized outbursts from confined aquifers—The classic morphology of *outflow channels* involves a headward source area of chaotic terrain. This has long been inferred to imply a morphogenetic relationship between chaotic terrains/zones of subsidence in the ice-rich Martian subsurface and the outflow channels (McCauley et al., 1972; Sharp, 1973; Baker and Milton, 1974; Sharp and Malin, 1975; Scott and Carr, 1978; Carr, 1979, 1996; Scott and Tanaka, 1986; Baker et al., 1991; Clifford, 1993; Clifford and Parker, 2001; Rodriguez et al., 2003, 2005b, 2006a, 2007). One of many models for megaflood generation from this association (see Table 4) invokes pressurized water emerging from a confined aquifer (Carr, 1979). A transition from the hypothesized warm wet conditions of the late

Noachian (see Section 5) to dominantly frigid climatic conditions during the Early Hesperian was proposed by Carr (1979) to have led to the formation of vast aquifers (hydrosphere) trapped underneath thick ice-rich permafrost (cryosphere) (Clifford, 1993). These aquifers might have been globally connected (Clifford and Parker, 2001) or regionally compartmentalized (Harrison and Grimm, 2008). This particular hypothesis has many difficulties, some of which have been summarized by Leverington (2011), who claims that the falsification of this particular mechanism, which he claims to be the generally accepted mechanism for the formation of all the Martian *outflow channels*, achieves a kind of blanket falsification of aqueous origins for cataclysmic flooding channels on Mars and therefore results in a need to explain these features by volcanic processes.

Ground-water flow through porousmedia is inadequate to generate the huge discharges evident from the size of the largest cataclysmic flood channels, including Ares, Kasei, Simud-Tiu, and Maja (Fig. 22). Closed basins at the head of these channels and the immense canyon system of Valles Marineris were more likely to have filled relatively slowly with any water provided by groundwater flow. However, the ponding of this water would have led to opportunities to release immense outbursts through the breaching of divides (Coleman and Baker, 2009; Irwin and Grant, 2009; Warner et al., 2010a). Alternatively or in combination, volcanism may have contributed, either by impacting the cryosphere (Chapman and Tanaka, 2002) or by interaction with glacial ice, such as might have occupied the Valles Marineris (Gourronc et al., 2014).

Ravi Vallis (Fig. 27) (locality R, Fig. 22) shows the typical headward chaos zones of an *outflow channel*. However, it can also be seen that chaos areas are also developed along lower reaches of the channel. Moreover, these have been eroded by flows coming from the upstream portions of the channel (Coleman and Baker, 2009). This relationship is one of secondary chaotic terrains (Coleman, 2005; Rodriguez et al., 2005a,b, 2011), which form within the floors of outflow channels, and therefore post-date the outflow channel formational events. Their origin has been attributed to gradual volatile-driven resurfacing by intra-cryospheric fluid lenses exhumed by catastrophic flood erosion (Rodriguez et al., 2011), devolatilization of water-rich sediments (Rodriguez et al., 2005a,b), and exposure of the hydrosphere's upper boundary (Coleman, 2005). Whatever process was releasing fluid from the subsurface, it was clearly acting in a complex manner.

A number of cataclysmic flooding channels also terminate in sites where the fluid flows disappear into subsurface fractures of crevices, as in the case of Hrad Vallis (Rodriguez et al., 2012) and Osuga Vallis (Fig. 28) (locality O, Fig. 22). This suggests that huge subsurface cavities are present. Acting as conduits, such cavities would also have been capable of conveying immense discharges of water to channel source areas, as has been argued for Shalbatana Vallis (Rodriguez et al., 2005b). Water flow through large subsurface conduits, perhaps formed within buried ice zones, would have resulted in the capability to produce much greater subsurface flow than would be possible through the porous media that was envisioned by the confined aquifer hypothesis.

7.3.2. Fissure eruption channels: water and lava—Some cataclysmic flood channels are associated with fissures that evidently erupted lava and pressurized water. The presence of a thick, ice-rich cryosphere seems to be an important factor for this mode of sourcing cataclysmic flows. Magma rising along fractures (dikes) may have risen to just below this thick cryosphere, promoting its wide spread melting and emergence on the surface as erosive megafloods of water. The magma accumulations at depth would also have sourced effusive lavas, which would then run down the preexisting channel ways created by the flood erosion. This sequence of processes seems reasonable as an explanation for relationships observed at Mangala Vallis (locality L, Fig. 9) (Tanaka and Chapman, 1990; Wilson and Head, 2004; Basilevsky et al., 2009) and Athabasca Vallis (Burr et al., 2002, 2009b). The flooding episodes at Mangala Valles spanned much of Mars history with phases dated to 3.5, 1, 0.5, and 0.2 Ga (Basilevsky et al., 2009). The Athabasca flooding was much younger, perhaps as recent as 10 Ma (Berman and Hartmann, 2002).

7.3.3. Spillway cataclysmic flooding channels—Ma'adim Vallis (locality M, Fig. 9) extends for about 900 km from a large enclosed basin in the heavily cratered southern highlands northward to Gusev Crater at the junction of the highlands with the northern plains (Irwin and Grant, 2009). The source basin is interpreted as filling and overflowing in Late Noachian time, releasing as much as 250,000 km^3 of water (Irwin et al., 2002, 2004). A series of breached basins occur along its length, as well as local anastomosis, longitudinal grooves, and at least one large sedimentary bar (Irwin and Grant, 2009). Gusev Crater was the landing site for the Spirit Mars Exploration Rover, which found that floor of the crater was resurfaced by basaltic lava flows of Early Hesperian age (Greeley et al., 2005). This precluded access by the lander to any direct evidence of the earlier breaching of the crater by the Late Noachian megaflooding that formed Ma'adim Vallis.

Another example of a spillway system of cataclysmic flood channels is Okavango Vallis (locality D, Fig. 9) (Mangold and Howard, 2013). This system extends for about 400 km flowing northward toward the northern plains from the cratered southern highlands, at around Lat. 40° N, Long. 10° E. Okavango Vallis displays erosional scour/groove morphologies, fluvial bars, and anastomosing channels, where cataclysmic floods of water spilled through crater rims. Multiple delta fans are developed where the floods entered ponded water on the floors of the depressions. As noted by Mangold and Howard (2013), these relationships are in conflict with the model of Leverington (2011), who considers all *outflow channels* of planetary surfaces to be of volcanic origin.

7.3.4. The greatest fluvial system—An especially remarkable fluvial phenomenon on Mars is the connection of several of the cataclysmic flood channels and related paleofluvial and paleolacustrine features into a great 8000-km-long chain (Fig. 29). As recognized by Parker (1985), this system of channels fed through various breached impact basins to eventually connect up to channels leading to the northern plains of Mars (Clifford and Parker, 2001). As noted in Section 5.4, the latter region has been inferred to have been periodically occupied by the temporary water informally named Oceanus Borealis by Baker et al. (1991).

What is now termed the Uzboi–Ladon–Morava (ULM) (near locality U, Fig. 9) channel system (Irwin and Grant, 2009) heads at the Argyre impact basin (locality A, Fig. 9) and trends northward along a broad, elongate topographic depression, the Chryse Trough

(Saunders, 1979; Baker, 1982). The Argyre Basin is connected to the south polar region of Mars by longitudinal valleys that head in areas underlain by the Dorsa Argentea Formation (Head and Pratt, 2001). Fastook et al. (2012) considered portions of the Dorsa Argentea Formation to be evidence of south polar ice sheet activity that extends back to the late Noachian. This would have been the ultimate source of the great system of channels that spilled into multiple impact basins (Fig. 30) before reaching the northern plains.

Baker (2007) pointed out that the great Mars fluvial system would be comparable in length to the interconnected paleolakes and spillways that developed in Asia at the end of the last ice age. These two systems would have temporarily constituted the largest river systems for their respective planets, and it is interesting that they shared many morphological similarities, including spillways between basins, ice-rich source areas, termination in their respective world oceans, and perhaps even influences on global climates (Baker, 2009a).

8. Discussion

In studying newly discovered fluvial phenomena on planetary surfaces, one needs to rely upon analogy (Baker, 2014a). As pointed out by Gilbert (1886), analogical reasoning does not work by comparing a phenomenon that is not fully understood, like the Kallistos Vallis compound channel (Section 3.2) on Venus, to a newly discovered phenomenon that one is trying to understand, like the cataclysmic flood channels on Mars. In planetary science one employs terrestrial analogs precisely because they are understood (Baker, 2014a), though one must also make allowances for physical realities, as in the case of how the relatively low Martian gravity affects fluid flow and sediment transport. Analogical reasoning in geology cannot be verified by controlled experimentation, but must rather rely upon consistency, coherence, and consilience (Baker, 2014a). The fluvial-like channels of Mercury, Venus, the Moon, and Io all occur in volcanic contexts and completely lack any aqueous context. The valley networks and cataclysmic flood channels of Mars and Earth all have extensive aqueous contexts. Some very interesting Mars and Earth channels have contexts involving interactions among both volcanism and water.

In addition to the similarities of landform assemblages between the Martian cataclysmic flood channels and the Channeled Scabland, interesting similarities can be found in the history of finding the source for the megaflooding. In both cases it is the landforms indicative of aqueous flooding that were first discovered. Various perceived problems with the cataclysmic explanation were then noted, and this led to controversy concerning the mechanism for explaining those landforms and identifying the source of the immense fluid flows. In the case of the Channeled Scabland controversy, glaciation, normal river flow, and collapsed lava tubes were all invoked to explain the landforms (Baker, 1978a, 1981, 2008b). In the initial stages of the debate, J Harlen Bretz, the advocate of the cataclysmic flooding hypothesis, posed a number of problematic source mechanisms. These included the rapid melting of ice sheets and the effects of subglacial volcanism. Neither of these hypotheses proved viable and that recognition was used as an argument against Bretz's cataclysmic flooding hypothesis, with some claiming that failure of Bretz's generative mechanisms made alternatives to cataclysmic flooding more likely. The problem with this type of argument is that rejection of imperfect hypotheses for generating scabland flooding does not constitute a falsification of all the possible ways that nature could generate such flooding. It is nature that has the answer to this problem, not the scientists. Ultimately a very complete case was developed for a cataclysmic flooding origin for the assemblages of Channeled Scabland landforms and for their relationship to the geological context. That context included effects beyond the Channeled Scabland region that could clearly be related in time and genesis to the megaflooding.

The study of extraterrestrial fluvial and fluvial-like features raises many questions, and the foregoing review has introduced some of these. The surface of Venus (see Section 3 above) is particularly puzzling in regard to the indicated scale and erosive capability of lava flows, especially those that formed the canali. Moreover, this puzzle illustrates the general need to advance understanding of the flow mechanics and physical conditions that occur for various lava compositions, water–sediment mixtures, and more exotic fluids, such as liquid sulfur and methane (see Section 4 above). Much more can be gleaned from terrestrial analogs (see Section 6 above), but a challenge remains for explaining those phenomena that differ greatly in their causal associations from what can be accessibly inferred from Earth analogs.

The surface of Mars is particularly interesting with regard to understanding fluvial phenomena on Earth. The very early geological history of Mars probably involved conditions that were able to generate the Earthlike valley networks (see Sections 5.2 and 5.3 above). Unresolved, however, is the role of the hypothesized northern plains ocean in facilitating an Earthlike global hydrological cycle on Mars. Moreover, there is a climate conundrum in that physical models do not seem to be able to produce the climatic conditions that would be consistent with the fluvial evidence (see Section 5.4 above). Equally puzzling is the intriguing evidence for very recent, even current, water-related activity on Mars (see Section 5.5 above).

Another first-order unresolved problem involves the cataclysmic flooding channels that formed on early Mars, with some activity even extending to relatively recent geological history. Those channels emanating from subsurface sources are still not well understood. How can the indicated immense flows be generated? How many flow events are required to produce the resulting channel morphologies? How do some source areas, such as those for Athabasca and Mangala Valles, apparently produce alternating outbursts of both lava and water? Clearly then, plenty of unanswered fluvial geomorphological questions remain for future scientific inquiry.

9. Conclusions

This review has highlighted the very rapid progress in discovery and explanation concerning the great variety of fluvial and fluvial-like landforms on extraterrestrial planetary surfaces. Unlike Earth and Mars, the Moon, Io, and Mercury do not have geological contexts that include water-related landforms and a history of water-related processes on their surfaces. Earth and Mars have such a history, and their surfaces display an immense abundance and variety of fluvial landforms, though, in the case of Mars, these are generally related to the planet's ancient geological history and are not forming today.

After decades of arguing whether Mars was water-rich or not, discoveries of the last decade or so have completely eliminated the *not* (Baker, 2014c). It is no longer necessary or even reasonable to invoke nonaqueous mechanisms for explaining fluvial features on Mars because of physical and chemical models that purport to demonstrate the *not* (e.g., Hoffman, 2000). The inconsistency of the geomorphological interpretations of water-related processes with physical and chemical arguments for Mars being water-poor, summarized by Carr (1996), has now been replaced by the conundrum of reconciling the geochemical and physical understanding of Mars with the fact of its watery past. Moreover, no longer does the geomorphological interpretation of imagery provide the main evidence for that aqueous history. The abundance of Mars water, mostly ice today, but liquid in the ancient past, is now supported by the physical measurements of gamma ray spectrometry (Boynton et al., 2002), neutron measurements (Feldman et al., 2002), and radar penetration of the subsurface (Holt et al., 2008; Plaut et al., 2009), as well as by chemical signatures obtained from orbital spectrometers (Bibring et al., 2006) and in situ measurements made from multiple lander missions (Grotzinger et al., 2006, 2014; Smith et al., 2009; Arvidson et al., 2014). These new data confirm the geomorphological inference (e.g., Baker, 1982) that Mars, like Earth, has a geological history as a water planet. The problem today is reconciling this abundant evidence with a physical understanding of environmental change on the planet.

Early in the modern era of exploring planetary surfaces with spacecraft observations, the geomophologist Robert Sharp (1980) recognized that planetary geomorphology is not confined to the understanding of alien landscapes. What is learned from such study is that other planetary surfaces can also be used to advance terrestrial geomorphology (Baker, 1985a, 1993, 2008a). However, one must exert care in that application. As noted in regard to cataclysmic flood sedimentation on Mars, the controls on processes can be different, and this will result in differences of response. Today with growing prospects for exciting discoveries of extra-solar, water-rich Earthlike planets (Heller, 2015), Sharp's broad vision can be seen to apply particularly well to fluvial geomorphology and that many new discoveries from Earth-like planets will greatly enhance what has already been learned from the familiar fluvial forms that have been studied on Earth.

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Fig. 1.

Apollo 15 image AS15-93-12628 showing Vallis Schröteri (Schröter's Valley) on the Moon. Typical for lunar sinuous rilles, the valley's maximum width (11 km) and depth (about 500 m) occur near its source. It narrows distally over about 160 km to less than a kilometer wide near its terminus, where it grades into volcanic plains that resulted from the immense amounts of lava that coursed through the channel. This is one of the largest sinuous rilles on the Moon. The astronomer Johann Hieronymus Schröter first observed it with a telescope in 1797. The sun direction for the image is from the upper left.

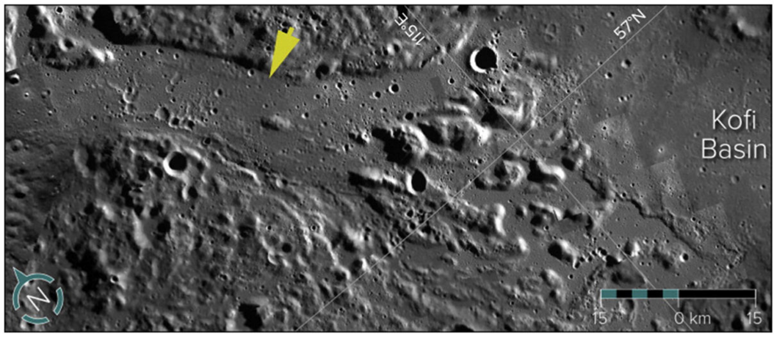

Fig. 2.

Portion of the Mercury lava channel Angkor Vallis at 57° N latitude, 115° E longitude. The image is from the Mercury Dual Imaging System (MDIS) of the MESSENGER spacecraft and has a resolution of 250 m per pixel.

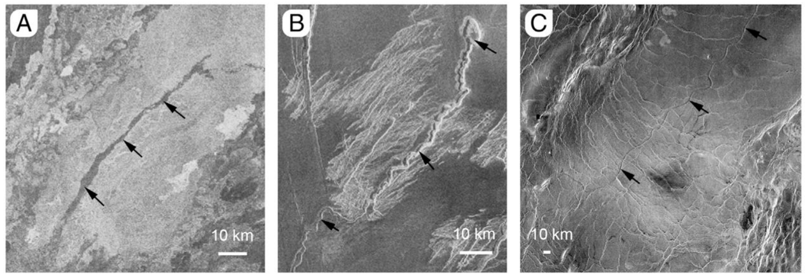

Fig. 3.

Examples of simple channels on Venus (all examples are Magellan left-looking SAR images): (A) simple channel with flow margin; (B) sinuous rille; and (C) a canali-type channel (Baltis Vallis). Arrows show the channel locations, and north is up in this figure.

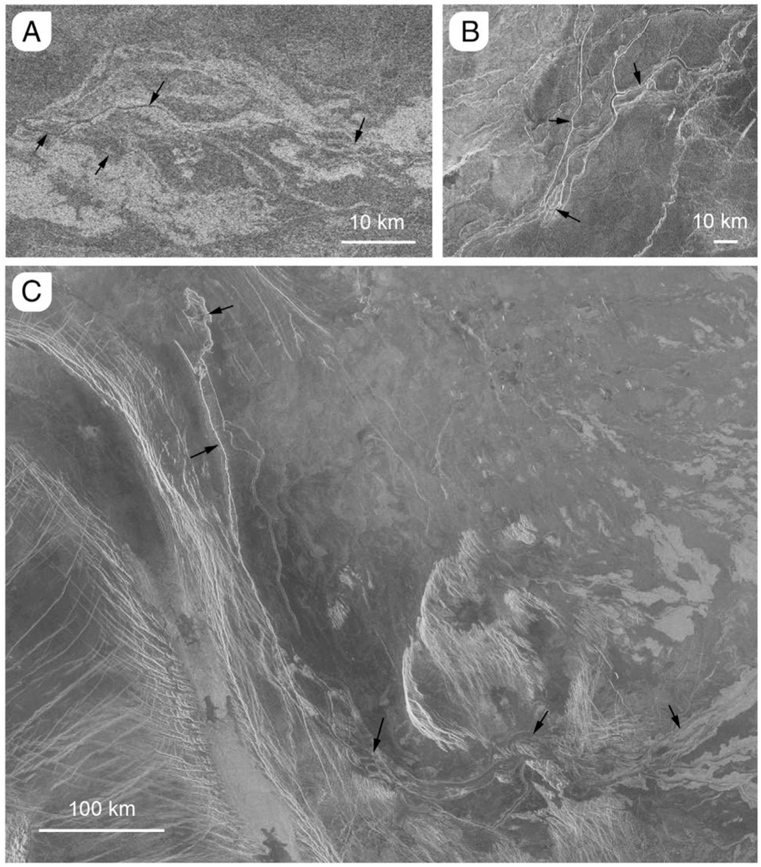

Fig. 4.

Examples of complex channels and compound channels on Venus (all are Magellan left-looking SAR images: A) complex channel with flow margin; B) complex channel without flow margin; C) compound channel (Kallistos Vallis). Arrows show the channel locations, and north is up in this figure.

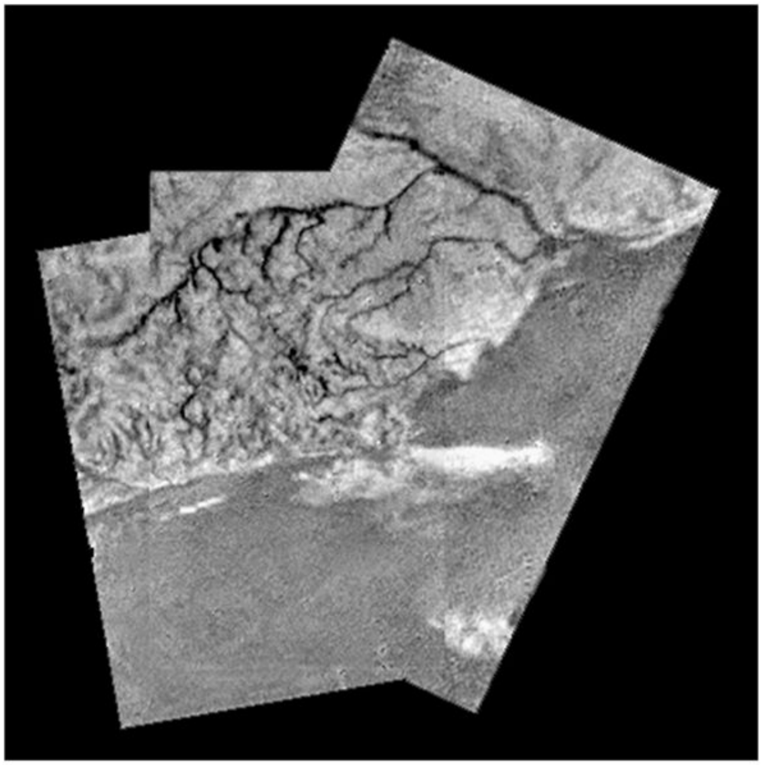

Fig. 5.
Mosaic of images taken by the Descent Imager/Spectral Radiometer (DISR) on the Huygens probe during descent to the surface of Titan showing fluvial networks. Image quality varies across the mosaic as a function of the amount of haze between the camera and the surface. North is up, and the mage is ~6 km wide, so that the most prominent network in the center of the mosaic is ~4 km from west to east.
Image courtesy of National Aeronautics and Space Administration (NASA)/Jet Propulsion Laboratory (JPL)/European Space Agency (ESA)/U. Arizona.

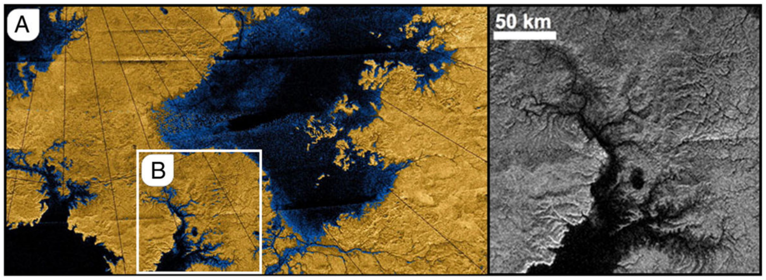

Fig. 6.

(A) Colorizedmosaic of Titan Radar Mapper synthetic aperture radar (SAR) images of the *northern lakes* region of Titan. The scene shows a large dark region, Ligeia Mare, interpreted to be a shallow lake of liquid methane. An example of a narrow, elongate valley can be seen in the lower right of the image, feeding into a drowned network. Other drowned valleys are visible along the lake margins to the west and east. Ligeia Mare is ~400 km in maximum north–south extent (along longitude lines). The North Pole is off the image to the upper left. SAR image quality varies across the mosaic. The inset (B) shows the location of the image on the right. Right: Another drowned network near the lower center of the image is shown in more detail in the black-and-white SAR image.

Images courtesy of National Aeronautics and Space Administration (NASA)/Jet Propulsion Laboratory (JPL)/European Space Agency (ESA)/U. Arizona.

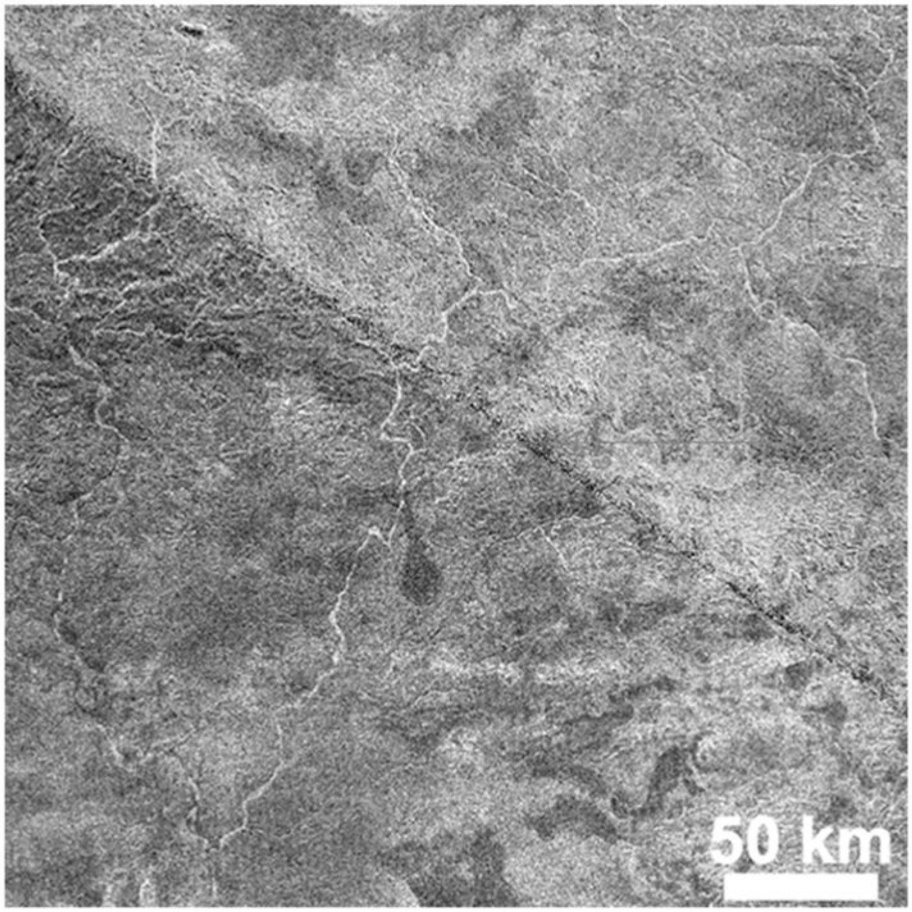

Fig. 7.

Mosaic of synthetic aperture radar (SAR) images from the Titan Radar Mapper of the Cassini Mission, showing narrow, elongate fluvial valleys in the Xanadu region, approximately 100° S, 1370° Won Titan. On this image, fluvial feature are bright, which is hypothesized for other radar-bright fluvial features to result from internal reflections from cobble-sized debris. SAR image quality varies across the mosaic. North is up in this figure. Image courtesy of National Aeronautics and Space Administration (NASA)/Jet Propulsion Laboratory (JPL)/European Space Agency (ESA)/U. Arizona.

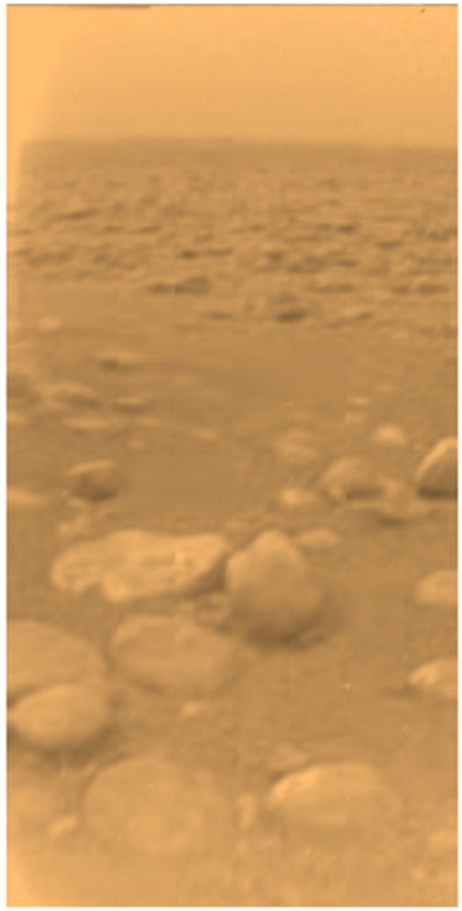

Fig. 8.

Rounded cobbles imaged by the Huygens probe at its landing site. The largest clast in the image is about 15 cm in diameter.

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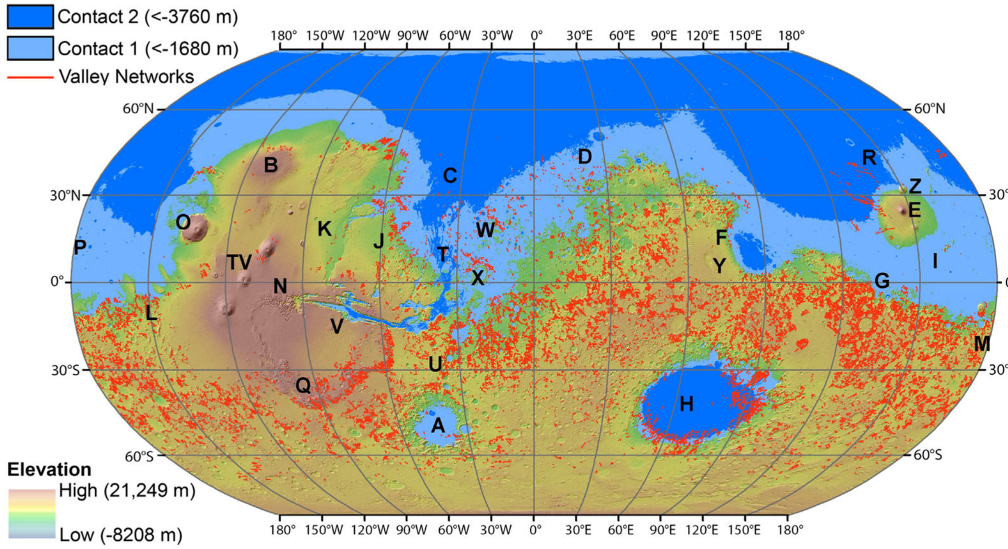

Fig. 9.

Map of Mars showing the distribution of small valleys in red and possible extents of ancient inundation to up to topographic level of–3780 m (dark blue) and–1680 m (light blue). The possible inundation levels correspond to the Contact 2 (lower level) and Contact 1 (higher level) shorelines defined by Parker et al. (1989, 1993), which were renamed respectively the Deuternolilus and Arabia Shorelines by Clifford and Parker (2001). Other features indicated by letters are volcanoes, B—Alba Patera, E—Elysium Mons, O—Olympus Mons, TV—Tharsis volcanoes, Y—Syrtis Major Planitia, and Z—Hecates Tholis; impact basins and craters, A—Argyre, C—Chryse, F—Jezero Crater, G—Gale Crater, H—Hellas; deltas-F—Jezero, U—Eberswalde; tectonic features, N—Noctis Labyrinthus, V—Valles Marineris; channels and valleys, D—Okavango Vallis, I—Athabasca Vallis, J—Maja Vallis, K—Kasei Vallis, L—Mangala Vallis, M—Ma'adim Vallis, P—Marte Vallis, Q—Warrego Vallis, R—Hrad Vallis, S—Shalbatana Vallis, T—Tiu and Simud Valles, U—Uzboi Vallis, W—Mawth Vallis, X—Aram Chaos and channel. The valleys were extracted from Mars Orbiter Laser Altimeter (MOLA) digital elevation model (DEM) data using a computer algorithm that recognizes valleys by their concave upward morphologic signature, aided by visual inspection against Thermal Emission Imaging System (THEMIS) imagery to remove any false positive identifications by the algorithm (see Luo and Stepinski, 2009).

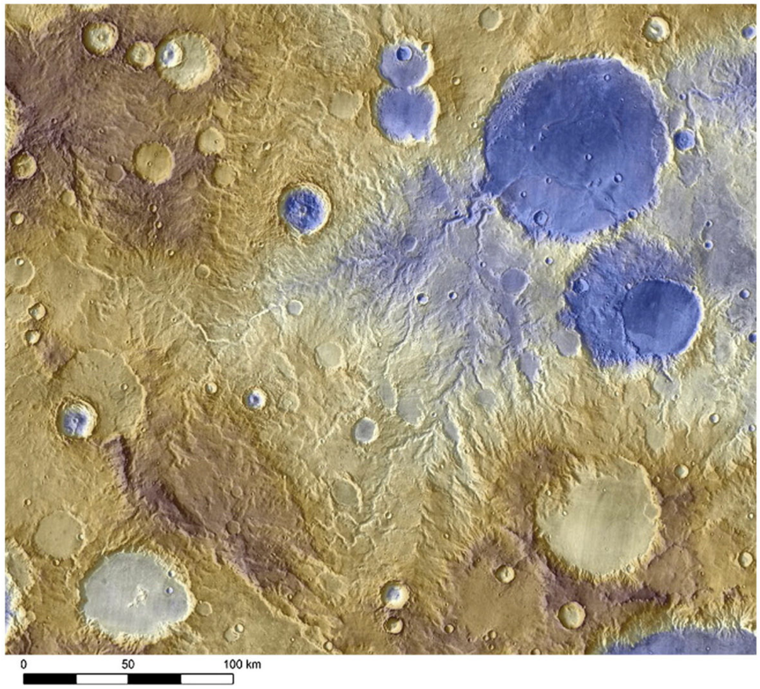

Fig. 10.

Fluvial network dissection of the heavily cratered highlands of Mars. Elevation data from the Mars Observer Laser Altimeter was combined with imagery so that low-lying areas are indicated in darker shades of blue and higher areas in darker shades of brown. North is up in this figure.

Fig. 11.
Fluvial conglomerate imaged by the Curiosity Lander of the Mars Science Laboratory Mission.

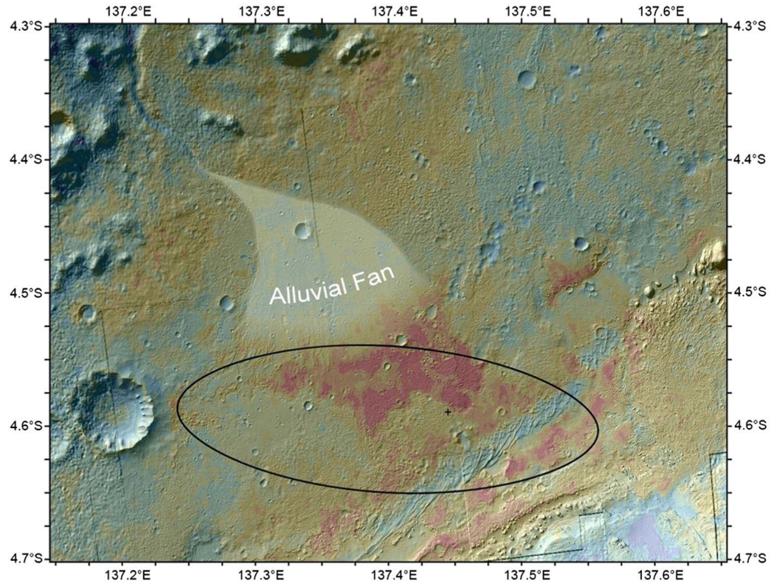

Fig. 12.

Peace alluvial fan, the site of the Curiosity landing in Gale Crater, Mars. The small cross shows that actual landing site, and the dark ellipse outlines the planned landing zone. Note the red colors indicating high thermal inertia measured with the Thermal Emission Imaging System (THEMIS) on the Mars Odyssey spacecraft. These are areas of finer-grained sediments at the distal end of the alluvial fan.

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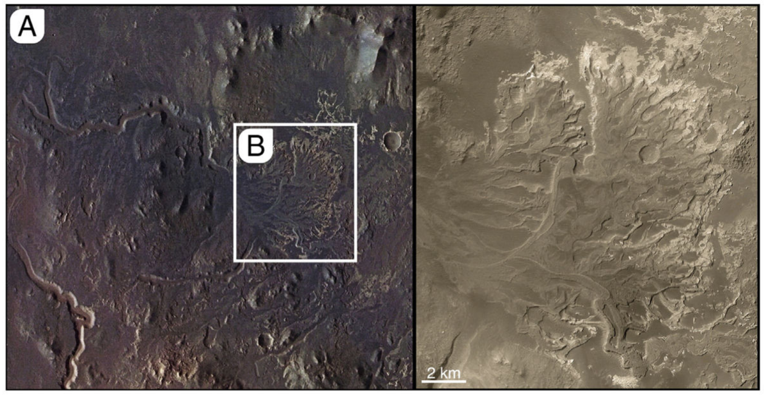

Fig. 13.

(A) Image of Eberswalde delta taken by the High-Resolution Stereo Camera (HRSC) of the Mars Express spacecraft. The delta surface is marked by alluvial paleochannels that fed into a lake that occupied the Eberswalde crater. The inset (B) shows the location of the figure on the right. Right: Detail of the distributary complex of alluvial channels imaged by the Mars Orbiter Camera (MOC). The channel sediments, presumably sand and/or gravel, are etched into positive relief because of the erosional removal of adjacent materials, presumably overbank silt and/or clay. Note the prominent scroll bar topography associated with the meander bend near the center of the image. North is up in each figure.

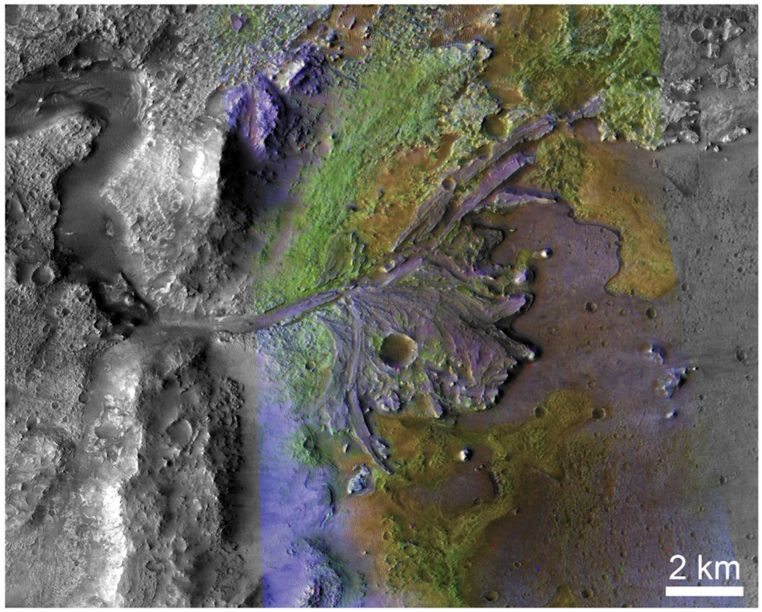

Fig. 14.

Composite imager generated from data from the Mars Reconnaissance Orbiter(MRO) Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) and Context (CTX) Imager data. The background is composed on a CTX image with a resolution of 6 m per pixel resolution, and the spectrometer data are show for the following wavelengths: 2.38 µm(red), 1.80 µm (green), and 1.15 µm (blue), which were acquired at 35 m/pixel resolution from CRISM image HRL000040FF. North is up in this figure.

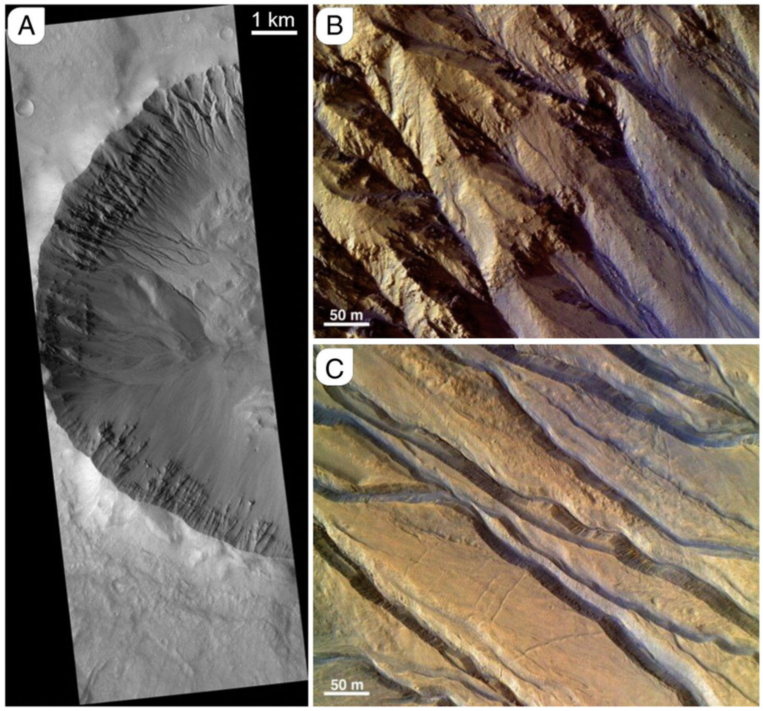

Fig. 15.

(A) Crater gullies southeast of Gorgonium Chaos. Note the detail of gullies that have eroded into bedrock of the proximal source regions shown in (B) and into distal surfaces shown in (C) of drainages off the inner rim of an impact crater shown in (A). North is up in each figure.

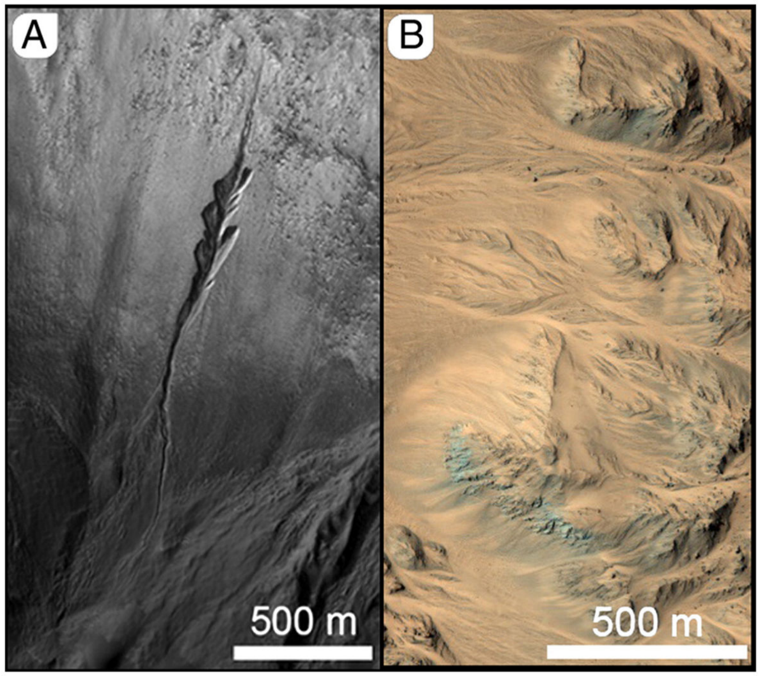

Fig. 16.

(A) A portion of Mars Reconnaissance Orbiter (MRO)High Resolution Imaging Science Experiment (HiRISE) image PSP_1712_1405 (0.3 m/pixel resolution) showing theater headed gully tributaries with inner channels (left). Sun direction is from the left, and north is up. (B) Portion of HiRISE image PSP_001415_1877 (0.3 m/pixel resolution). The image shows the eastern rim region of Mojave crater, which is extensively dissected by integrated *gully* systems. North is up in the figure, and the sun is illuminating from the left.

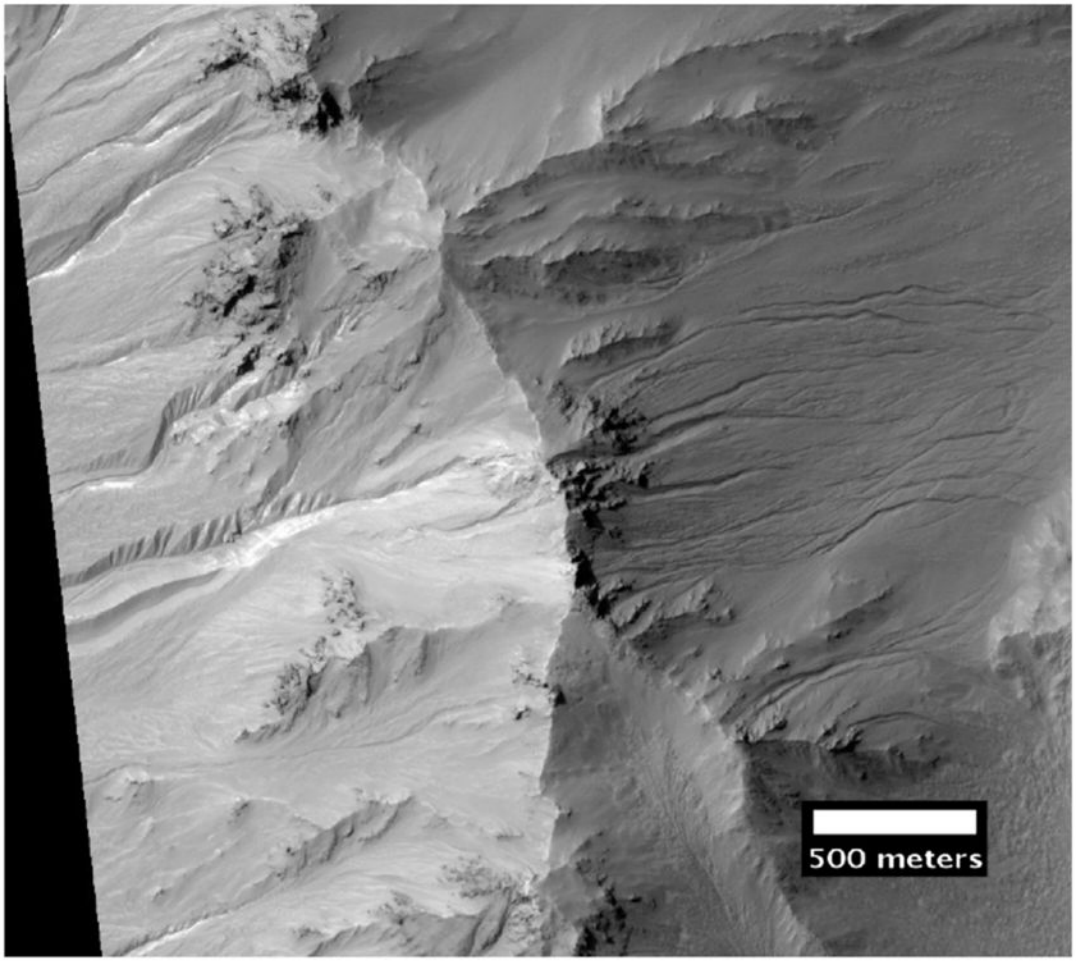

Fig. 17.

Portion of High Resolution Imaging Science Experiment (HiRISE) image ESP_011753_1445 (0.3 m/pixel resolution), showing gullies along the eastern rim of Hale Crater. Gullies with different orientations are developed on both sides of the ridge running through the center of the image. Note bright deposits along some gullies. North is up in the figure, and the sun is illuminating from the left.

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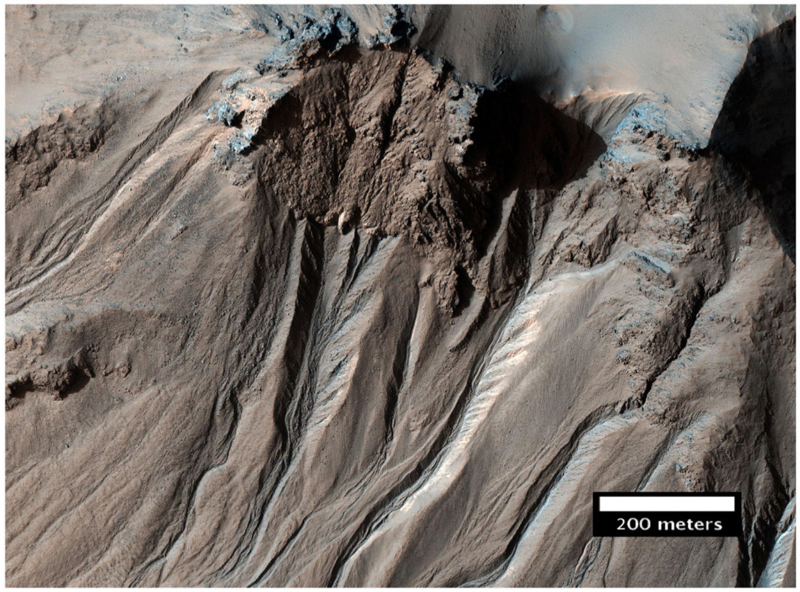

Fig. 18.
Portion of High Resolution Imaging Science Experiment (HiRISE) color image PSP_002932_1445 (0.3 m/pixel resolution) showing greater detail of the Hale Crater gullies. North is up in the image, and the sun is illuminating from the left.

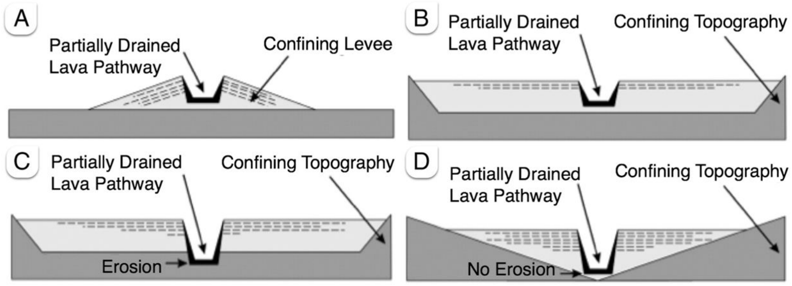

Fig. 19.

Lava channel formation scenarios: (A) partially drained channel bounded by confining levees; (B) broad sheet-like lava lobe bounded by the initial topography; (C) deep channel formed by thermal-mechanical erosion into the substrate followed by partial drainage of the preferred lava pathway; (D) deep channel formed by constructional processes followed by lava drainage without substrate erosion.

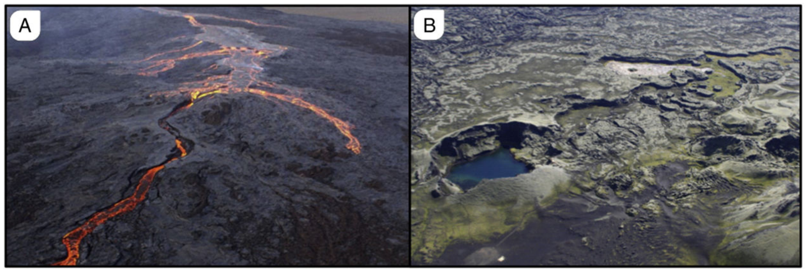

Fig. 20.

Examples of terrestrial lava channels: (Left) example of an active lava channel forming on Kīlauea, Hawaii, during the 2007–2008 phase of the Pu'u 'Ō'ō eruption; (Right) example of a 5-m-deep channel formed within the 1783–1784 A.D. Laki eruption in Iceland.

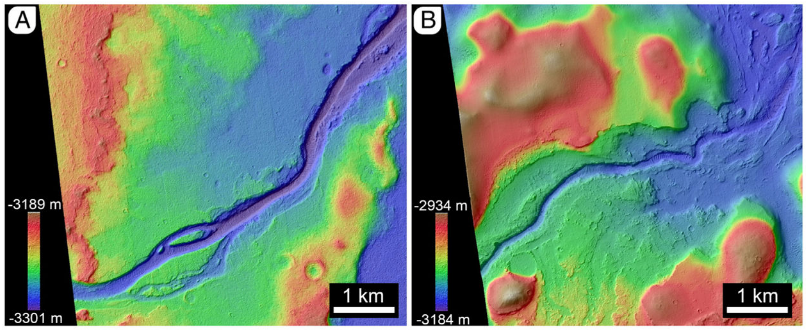

Fig. 21.

Examples of partially drained lava channels on Mars: (A) digital terra in model (DTM) (1 m/pixel) derived from High Resolution Imaging Science Experiment (HiRISE) stereo-images ESP 012444 2065 and ESP_014000_2065; and (B) DTM (1 m/pixel) derived from HiRISE stereo-images ESP_019235_2050 and ESP_018945_2050. North is up in each figure.

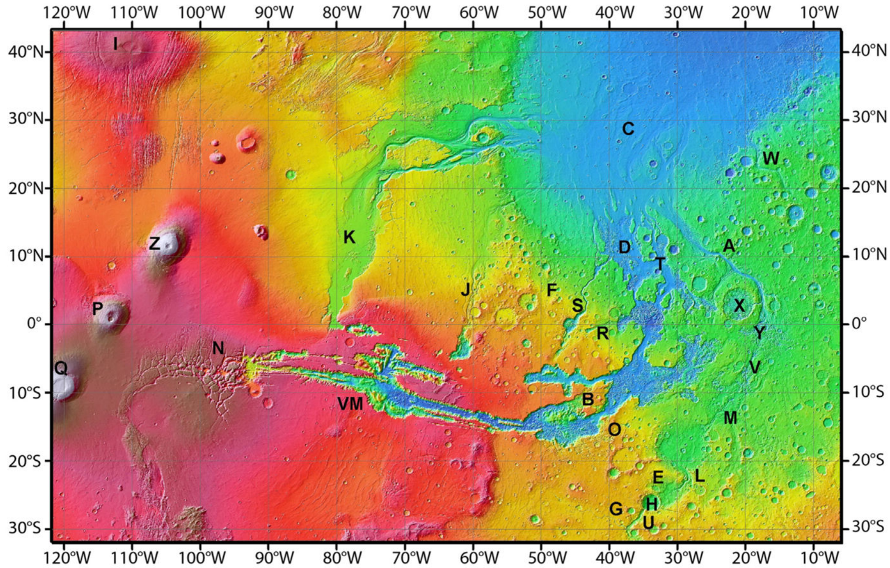

Fig. 22.

Map of eastern Tharsis and circum-Chryse areas of Mars on MOLA topographic base (low areas in blue, high areas in red and brown). Features indicated by letters include volcanoes, I —Alba Patera, P—Pavonis Mons, Q—Arsia Mons, Z—Ascraeus Mons; impact basins and craters, C—Chryse, H—Holden; delta—Eberswalde; tectonic features, N—Noctis Labyrinthus, VM—Valles Marineris; channels and valleys, A—Ares, B—Columbia and Daga Valles, D—Simud Vallis, F—Nanedi Vallis, G—Nirgal Vallis, J—Maja Vallis, K—Kasei Vallis, L—Ladon Vallis, M—Morava Vallis, O—Osuga Vallis, R—Ravi Vallis, S—Shalbatana Vallis, T—Tiu Vallis, U—Uzboi Vallis, W—Mawth Vallis, X—Aran Chaos and channel, Y—Iani Chaos.

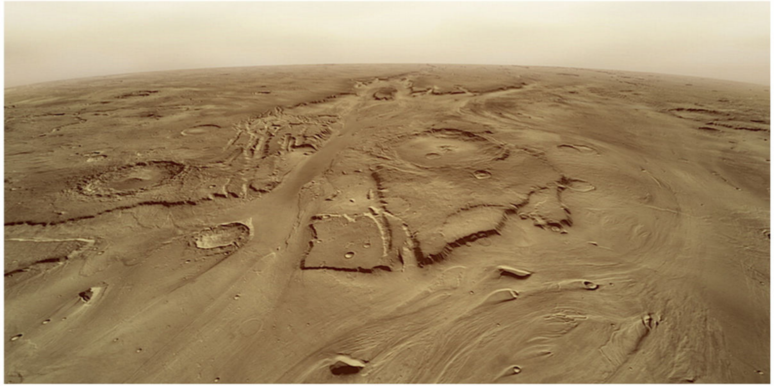

Fig. 23.
Mouth of Kasei, the largest and longest (2400 km) “outflow channel” on Mars. This oblique view was generated at 2× vertical exaggeration from the THEMIS data acquired by the Mars Odyssey spacecraft. The view is upstream, and the large crater in the center is Sharonov, which is 100 km in diameter. Note the splitting and convergence of channels (anastomosis).

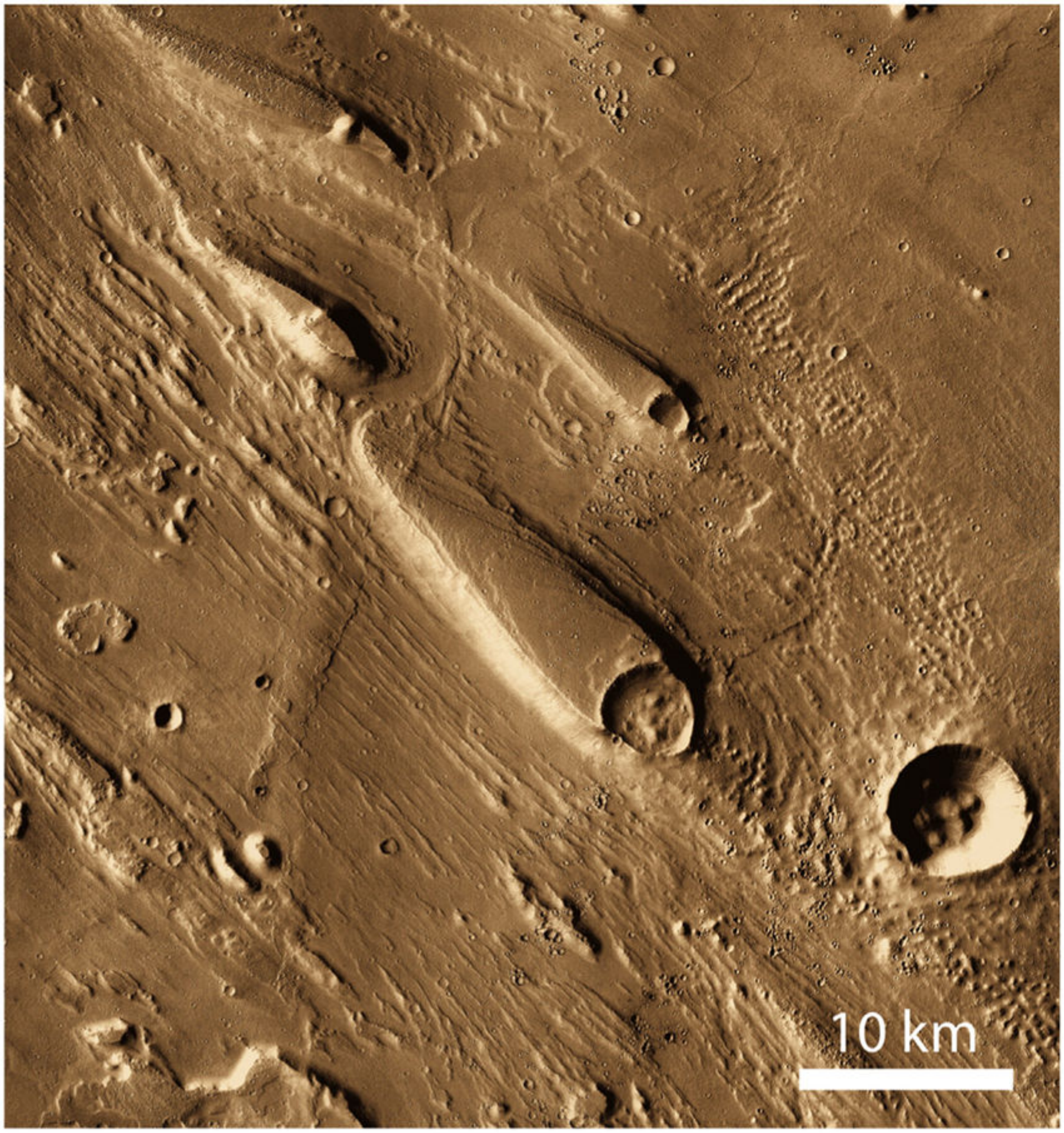

Fig. 24.

Streamlined features in Ares Vallis (15.9° N, 330° E) imaged at visible wavelengths by the Thermal Emission Imaging System (THEMIS) on NASA's Mars Odyssey orbiter. The cataclysmic flooding came from the lower right. Lins is the post-flooding, fresh looking crater in the lower right. It is about 6 km in diameter, and the imaged scene is about 40 × 50 km. The streamlined features probably developed by a combination of deposition and preservation of pre-flood bedrock downstream from obstructions to the cataclysmic flood flows. There are also smaller-scaled lineated forms that may have developed as grooves or as depositional accumulations behind small obstructions. They are oriented longitudinally relative to the cataclysmic flood flows. Some intriguing transverse bedforms occur in the upper left quadrant of the image. These have orientations similar to what would be expected for subfluvial dunes, but at a spacing of about 500 m they are even larger that would occurs in terrestrial cataclysmic flooding channels. North is up in the figure.

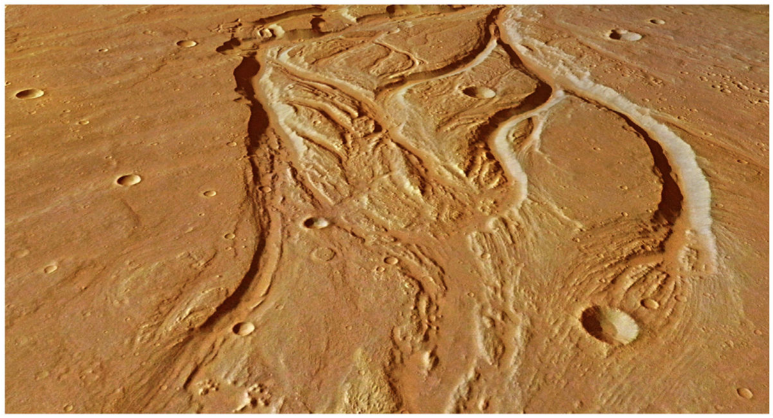

Fig. 25.

Expansion bar complex in Osuga Vallis. This is an oblique view generated data provided by the High Resolution Stereo Camera (HRSC) on the Mars Express spacecraft. The view is downstream, and the channel width is about 20 km. The regional context for this image is shown in Fig. 29.

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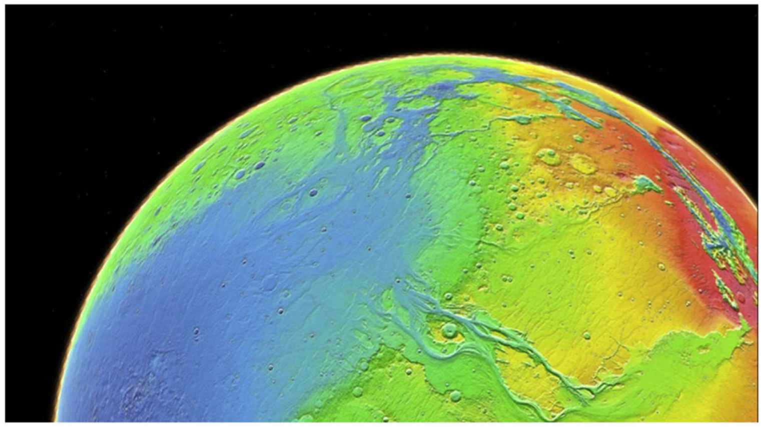

Fig. 26.
Kasei Vallis (bottom right quadrant) entering the northern plains of Mars as shown on a topographic base provided by the MOLA instrument on Mars Global Surveyor. Note the transitions from the cataclysmic flooding channels directly into the northern plains without extensive sediment accumulation. The mouth of Kasei in the lower center of the image is also shown in Fig. 23.

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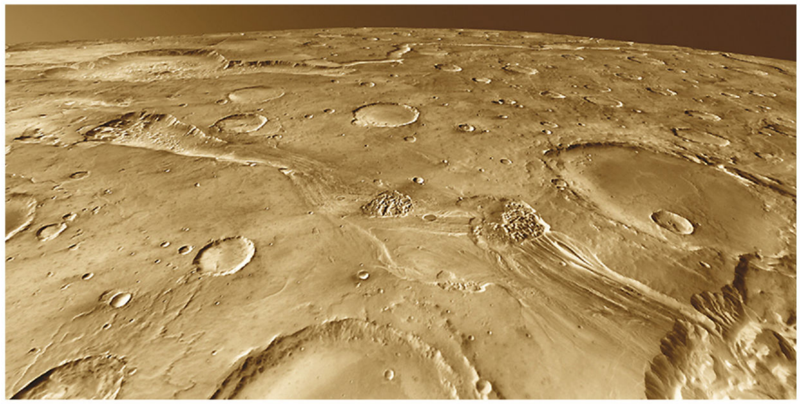

Fig. 27.

Ravi Vallis. A 200-km long catastrophic flooding channel that emanates from Aromatum Chaos (left). Note the erosion of two chaos zones in the channel (center) and distal spilling of the channel-forming fluid over and the plateau edge to disappear into another chaos region (right foreground). This oblique view was generated from the Mars Odyssey spacecraft using the THEMIS instrument with a vertical exaggeration of about 1.5×.

Fig. 28.

High Resolution Stereo Camera (HRSC) image of Osuga Vallis. This relatively short cataclysmic flooding channel has length of ~160 km, but its depth is up to 900 m. The expansion bar complex in the upper center portion of the image is also shown in Fig. 25. The cataclysmic floodwaters flowed toward the northeast (lower right in the image), entering a depression at the lower right of the image. The floodwater entering this depression must have been able to drain away very quickly, probably into the adjacent chasmata canyons of the Valles Marineris (Fig. 22). Otherwise, the water would have ponded, preventing the erosion of the channel. Subterranean conduits would have been necessary to convey the immense flows. North is to the right in this figure.

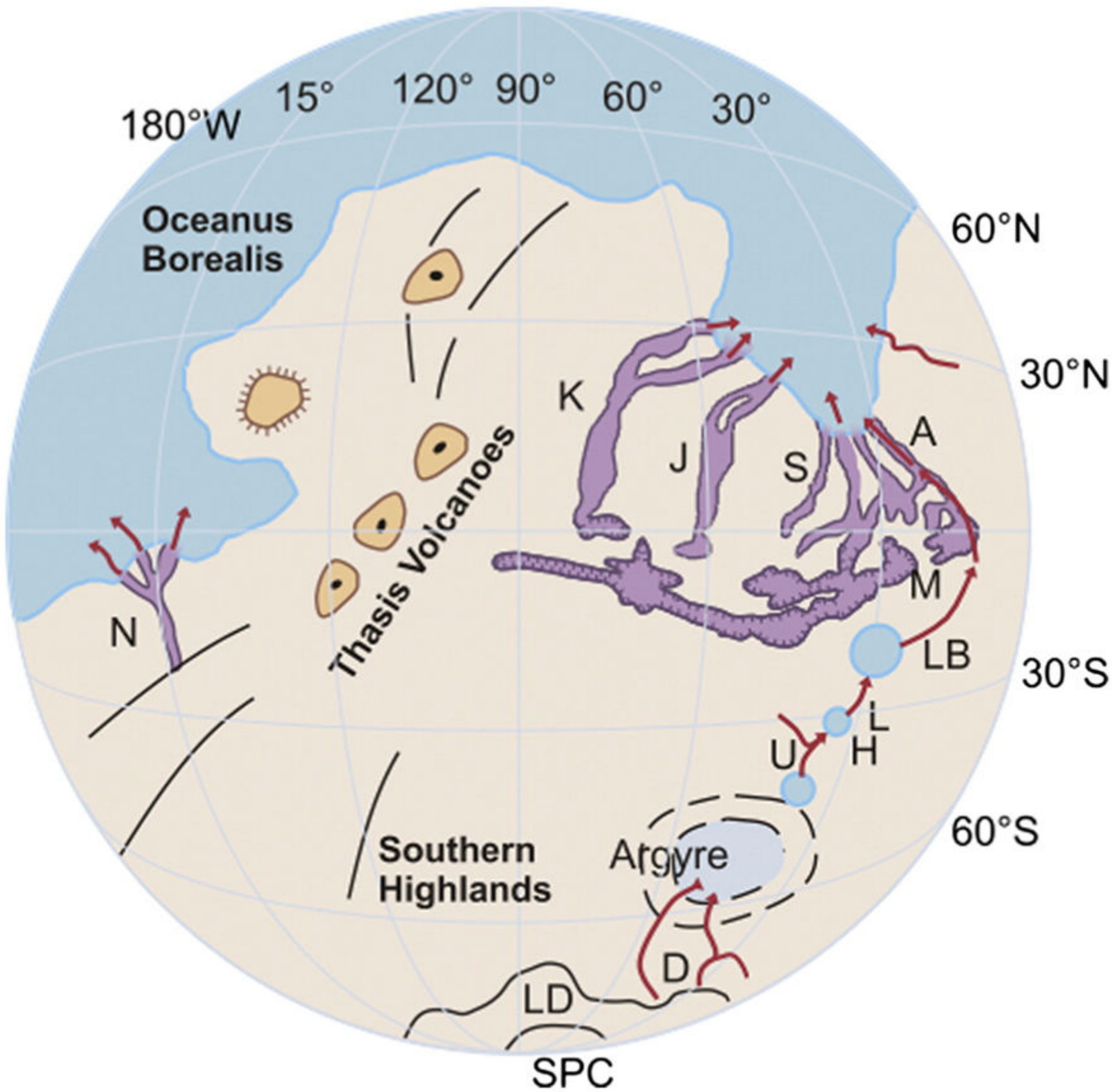

Fig. 29.

Sketch map of the western hemisphere of Mars, showing the 8000 km drainage system, including the Uzboi–Ladon–Margaritifer (ULM) system, that extends to the northern plains (‘Oceanus Borealis’) from the layered deposits (LD) that underlie the South Polar Cap (SPC). Elements of the drainage include (from south to north): Dzigai Vallis (D), the Argyre impact basin, Uzboi Vallis (U), Holden Crater (H), Ladon Vallis (L), Ladon Basin (LB), Margaritifer Vallis (M), and Ares Vallis (A). Other prominent cataclysmic flooding channels include Mangala Vallis (N), Kasei Vallis (K), Maja Valis (J), and Shalbatana Vallis (S).

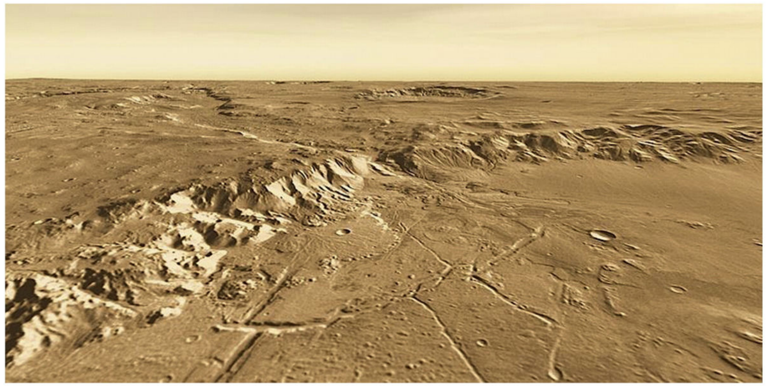

Fig. 30.

Oblique view with a 2× vertical exaggeration of a portion of the Uzboi–Ladon–Margaritifer (ULM) system generated from visible THEMIS data acquired by the Mars Odyssey spacecraft. The view is toward the southwest, showing the mouth of Uzboi Vallis (center) into Holden Crater through its southern rim. There is a fan-like accumulation of layered sediments at this junction, and a possible landing site for the Mars Science Laboratory rover was proposed for the flat, smooth area at right center, close to where the channel cuts through the rim.

Table 1

Fluvial and fluvial-like features on planetary surfaces discussed in this article.

Surface	Feature	Example	Geological context	Origin	References
Moon	Sinuous rilles	Rima Prinz, Schroter's Valley (Fig. 1)	Volcanic and impact (no water-related context)	Lava	Hurwitz et al. (2012)
Mercury	Broad channels	Anghor Vallis, Timgad Vallis (Fig. 2)	Volcanic and impact (no water-related context)	Lava	Hurwitz et al. (2013b)
Io	Channels	Tawhaki Vallis	Volcanic (no water-related context)	Lava	Schenk and Williams (2004)
Venus	Simple channels				
	With flow margins	Fig. 3A	”	Lava	Baker et al., 1992a
	Sinuous rilles	Fig. 3B	”	Lava	”
	Canali	Baltis Vallis (Fig. 3C)	”	Exotic Lava?	Komatsu et al., 1992
	Complex channels				
	With flow margins	Fig. 4A	”	Lava	Komatsu et al, 1993
	No flow margins	Fig. 4B	”	Lava	”
	Compound channel	Kallistos Vallis (Fig. 4C)	Volcanic (no water-related context)	Exotic Lava?	Baker et al., 1997
Titan	Channels/valleys	Fig. 5	N_2, CH_4 atmosphere	Runoff	Burr et al. (2013b)
	Fluvial dissection	Fig. 6	”	”	”
	Xanadu channels	Fig. 7	”	”	”
	Fluvial sediments	Fig. 8	Erosion of water ice	”	”
Mars	Valley networks	Figs. 9, 10	Numerous other aqueous phenomena	Runoff	Luo and Stepinski (2009) Hynek et al. (2010)
	Fluvial sediments	Fig. 11	”	Fluvial	Palucis et al. (2014)
	Alluvial fans	Fig. 12	”	”	Moore and Howard (2005)
	Fluvial deltas	Figs. 13, 14	”	”	DiAchille and Hynek (2010)
	Gullies	Figs. 15, 16, 17, 18	”	Hillslope	Malin and Edgett (2000b)
	Lava channels	Fig. 21	Volcanic and Aqueous	Volcanic	Mouginis-Mark et al. (1992)
	Cataclysmic flooding channels	Figs. 22, 23, 26, 27, 28	”	Cataclysmic flooding	Baker and Milton (1974), Carr (1996)
	Streamlined uplands	Fig. 24	Aqueous	”	Baker (1982)
	Depositional landforms	Figs. 25, 30	”	”	Irwin and Grant (2009)
	Spillway channels	Figs. 29, 30	”	”	Irwin and Grant (2009)

Table 2

Geomorphological aspects of the largest fluvial features on Mars.

Attribute	Valley networks	Longitudinal valleys	Cataclysmic flooding channels
General	Dendritic and quasi-parallel patterns of dissection with multiple low-order tributaries. Locally high densities (0.1 to 1 km^{-1}). Valleys widen and deepen in a downstream direction.	Long, wide main valley with poor tributary development. Sourced at theater-like valley heads. Width relatively constant in downstream direction.	Huge troughs with low sinuosity, local anastomosing reaches, streamlined uplands (“islands”), generally lacking tributaries.
Length	<200–2000 km	Hundreds of km	Few hundred to 3000 km
Width	1–4 km	Several to 20 km	3–400 km
Depth	Tens to 300 m	Hundreds to 500 m	Up to 2.5 km
Age	Mid Noachian to Early Hesperian. Reactivation occurred locally in Late Hesperian. Early Amazonian valleys dissect some volcanoes.	Late Noachian to Hesperian	Mainly Late Hesperian, but extend from late Noachian to late Amazonian
Erosional features	Local inner channels, where not obscured by eolian deposition	Local inner channels, erosional meander bends	Suite of scabland erosional forms: longitudinal grooves, inner channels, Cataracts, scour marks
Depositional features	Some deltas and fans, but termini obscured by later lava flows or eolian deposition	Deltas at channel termini, where flows entered paleolakes	Depositional bars (pendant, eddy, and expansion); fans; northern plains deposits
Origin	Mainly precipitation, rainfall for the older networks, and probably snow for younger ones	Ground-water sapping	Cataclysmic flood generation by a variety of processes (see Tables 3 and 4)
Discharges	300–5000 $m^3\ s^{-1}$	10^4–10^5 $m^3\ s^{-1}$	10^5–10^9 $m^3\ s^{-1}$
Examples	Warrego V.	Nanedi Vallis, Nirgal Vallis, Zarga Vallis	Ares Vallis, Kasei Vallis, Ravi Vallis, Marte Vallis, Nirgal Vallis, Zarga Vallis, Athabasca Vallis, Mangala Vallis, Ma’adim Vallis, Uzboi–Ladon–Morava Vallis, Okavango Vallis

Table 3

Megaflood generation processes for Earth.

Mechanism	Example	References
Subglacial volcanism	Icelandic jokulhlaups	Gudmundsson et al. (1997)
Ice-dammed lake bursts	Missoula	Pardee (1942)
	Altai	Baker et al. (1993)
Lake spillways	Bonneville Man	Malde (1968), O'Connor (1993)
Ocean, sea spillways	English Channel (La Manche)	Smith (1985), Gupta et al. (2007)
	Bosporus	Ryan et al. (2003)
	Strait of Gilbraltar	Baker (2001, 2002); Garcia-Castellanos et al. (2009)
Pressurized subglacial lake outbursts	Laurentide ice sheet Antarctic	Shaw (1996)
	Missoula	Shaw et al. (1999)

Table 4

Various megaflood generation processes hypothesized for Mars.

Mechanism	Example	References
Pressurized flow through permeable media	Circum-Chryse channels	Carr (1979, 2000), Clifford (1993), Andrews-Hanna and Phillips (2007), Harrison and Grimm (2008)
Magmatic intrusion and melting of cryosphere	Circum-Chryse channels	McCauley et al. (1972), Sharp (1973), Masursky et al. (1977), Chapman and Tanaka (2002), Leask et al. (2006), Meresse et al. (2008)
Lake formation by melting of buried ice sheet	Aram Chaos and valley	Zegers et al. (2010), Roda et al. (2014)
Lake Spillways	Ma'adim Vallis	Irwin et al. (2002, 2004), Irwin and Grant (2009)
	Uzboi–Ladon–Moreava	Parker (1985), Grant and Parker (2002)
	Mangala Vallis	Zimbelman et al. (1992)
	Okavango Vallis	Mangold and Howard (2013)
Lake drainage	Circum-Chryse channels	Lucchitta and Ferguson (1983), Warner et al. (2013)
	Columbia and Daga Valles	Coleman and Baker (2009)
Geothermal heating of confined water	General	Clark (1978)
Fissure eruptions of water and lava	Mangala Vallis	Tanaka and Chapman (1990)
	Anthabasca Vallis	Burr et al. (2002)
	Marte and Grjota Valles	Burr et al. (2009a)
Liquefaction of sensitive substrates	Ravi Vallis	Nummedal and Prior (1981)
Catastrophic dissociation of gas hydrates	General	Milton (1974), Komatsu et al. (2000), Max and Clifford (2001), Kargel et al. (2007)
Meteor impacts into ground ice	General	Maxwell et al. (1973)
Catastrophic dewatering of evaporite deposits	Circum-Chryse	Montgomery et al. (2009)
Cavern formation by hydrothermal processes	Shalbatana Vallis	Rodriguez et al. (2003, 2005b)
	Xanthe Terra channels	Rodriguez et al. (2005a,b, 2007)