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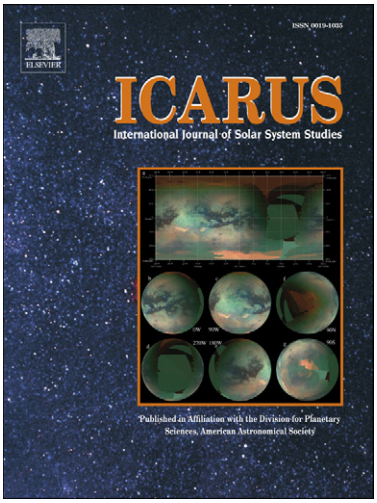

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Abstract

Ares Vallis is one of the greatest outflow channels of Mars. Using high-resolution images of recent missions to Mars (MGS, 2001 Odyssey, and Mars Express), we investigated Ares Vallis and its valley arms, taking advantage of 3-dimensional analysis performed using the high-resolution stereo capability of the Mars Express High Resolution Stereo Camera (HRSC). In our view, Ares Vallis is characterized by catastrophic flood landscapes partially superimposed by ice-related morphologies. Catastrophic flood landforms include erosional terraces, grooved terrains, streamlined uplands, giant bars, pendant bars, and cataract-like features. Ice-related morphologies include probable kame features, thermokarstic depressions, and patterned grounds. Our investigations outline that throughout the Hesperian age, Ares Vallis and its valley arms had been sculpted by several, time-scattered, catastrophic floods, originating from Iani, Hydaspis and Aram Chaos. Geomorphological evidence suggests that catastrophic floods were ice-covered, and that climatic conditions of Mars at this time were similar to those of the present day. At the end of each catastrophic flood, ice masses grounded, forming a thick stagnant dead-ice body. Each catastrophic flood was followed by a relatively brief period of warmer-wetter climatic conditions, originated as a consequence of catastrophic flooding. During such periods thermokarstic depressions originated, liquid water formed meandering channels, and ice-contact deposits were emplaced by ice-walled streams. Finally, the climate turned into cold-dry conditions similar to the present-day ones, and ice masses sublimated.

Keywords: Mars, surface; Mars, climate; Geological processes; Ices.

1 - Introduction

Outflow channels on Mars are large complexes of fluid-eroded troughs up to 100 km wide and 2000 km long. The flows that formed Martian outflow channels appear to have emanated from discrete collapse zones or chaotic terrains (Baker, 1982). Ares Vallis (fig. 1) is one of the greatest among these: it is a trough 1500 km long originating from Iani Chaos, etching Noachian and Early Hesperian cratered plateaus, and debouching in Chryse Planitia.

Ares Vallis has been deeply investigated in the past decades, partially to support landing site analyses of the NASA Pathfinder, which landed near the present termination of Ares Vallis on July 4, 1997. Several geologic interpretations of Ares Vallis have been proposed. Baker and Milton (1974), Baker (1982), Baker et al. (1992), Komatsu and Baker (1997) hypothesize that Ares Vallis was carved by catastrophic floods. Glicken and Schultz (1980) propose that Ares Vallis originated by giant clay-rich volcanic mud flows. Lucchitta et al. (1981) and Lucchitta (1982, 2001) suggest ice-sculpturing processes. Costard (1989) proposes a fluvio-thermal erosion. Robinson et al. (1996) consider that it was formed by glacial processes with some fluvial activity. Marchenko et al. (1998) investigated the mouth of Ares Vallis and interpreted it as shaped by multiple catastrophic flood events. Nelson and Greeley (1999) suggest an initial sheetwash followed by deepening of channels caused by subsequent floodings. Tanaka (1999) propose catastrophic outbreak of water from pressurized aquifers, evolving into debris flows. Furthermore, thermokarstic landforms and processes along Ares Vallis have been reported by some works (Costard and Dollfus, 1986; Costard and Kargel, 1995; Costard and Baker, 2001). Leverington (2004) proposes a volcanic origin. The hypotheses regarding the origin of Martian outflow channels are summarized in Baker et al. (1992) and Carr (1996). Each model of origin and evolution implies different processes of the Ares Vallis formation and different climatic evolutions of Mars. Almost all the proposed models derive from observations carried out using mainly Mariner and Viking data with low-medium spatial resolutions (some tens to few hundreds of meters for each pixel). Aims of this work, therefore, are: i) to investigate Ares Vallis with high-resolution images (HRSC, THEMIS VIS and MOC narrow angle), ii) to describe new observed morphologies, and according to these, iii) to hypothesize new possible scenarios illustrating the geologic history of Ares Vallis. Our observations are based mainly on a detailed geomorphological map of Ares Vallis recently published by Pacifici (2008).

2 – Datasets

The High Resolution Stereo Camera (HRSC), on board the ESA mission Mars Express, provides orthorectified images and stereo-derived Digital Terrain Models (DTMs). The orthorectified images are provided both in gray scale (obtained by nadir channel) and in color (with pan-sharpening of nadir channel). HRSC images fill the gap in cell size between high-resolution small-footprint images (e.g., MGS MOC

narrow angle) and low-resolution large-footprint images (e.g., Viking, Mars Global Surveyor MOC wide angle and Mars Odyssey THEMIS infra-red), over very large areas. Such characteristics of the HRSC images are very helpful in order to observe stratigraphic correlations and wide-ranging, small-scale morphologies. Furthermore, HRSC data allow draping of high-resolution images on stereo-derived DTMs, and their observation in 3-dimensional view.

Twenty-one HRSC orbit datasets covering entire Ares Vallis were processed in order to provide images with resolutions between 12.5 and 50 m/pixel, and derived DTMs with a spatial resolution of about 200 m/pixel. We complemented the HRSC datasets with other mission datasets such as Viking, Mars Global Surveyor MOC wide angle (MOC WA), and Mars Odyssey THEMIS (both Visible and IR). MOC narrow angle (MOC NA) images were used to further characterize the observed morphologies with much more details. The Mars Odyssey THEMIS infra-red (THEMIS IR) data were used in order to characterize also thermal properties of surfaces. Regarding thermal properties, we performed only qualitative and not quantitative observations in this work. Finally, Mars Global Surveyor MOLA-megdr grid data were used to conduct regional topographic analysis.

3 – Physiographic and geological setting of Ares Vallis

Two main reaches characterize Ares Vallis. The upper reach (Narrow Ares Vallis) is about 25 km wide and 1500 m deep. A few erosional terraces characterize its steep walls and broad, shallow, and anastomosing channels occur on the surrounding plateaus. The lower reach (Wide Ares Vallis) is about 100 km wide, and it is shallower and wider and its walls are less steep approaching the valley termination. Widths of both the reaches are generally constant and the transition between them is evident.

Three valley arms tens of kilometers wide merge with Ares Vallis. We appoint these valleys with the informal names of Eastern Valley, Western Valley, and Aram Chaos Channel (fig. 1). Eastern Valley is a trough about 20 km wide and 1 km deep, hanging above Ares Vallis. Similar to Ares Vallis, Eastern Valley originates from Iani Chaos but at a more marginal (eastern) position and higher altitudes. The valley merges into the upper reach of Ares Vallis with a hanging morphology and a difference in altitude of about 600 m. Western Valley is a broad and shallow trough emanating from Hydaspis Chaos and hanging above Ares Vallis. It extends for about 370 km, varies in width from 40 km to 160 km, and terminates with a hanging morphology with a difference in altitude of about 900 m. Western Valley shows gently-sloping walls and lies

about 1000 m below the neighboring plateaus. Aram Chaos Channel is a narrow and deep trough emanating from Aram Chaos and merging with Ares Vallis. Using the term 'the Ares Vallis Complex' we will refer to Ares Vallis and its incoming troughs.

A longitudinal topographic profile of the Ares Vallis floor (fig. 2) shows that the narrower upper reach of Narrow Ares Vallis has a steeper topographic gradient on average. The deepest point of Iani Chaos, which is believed to be one of the main source areas for fluids eroding Ares Vallis (Komatsu and Baker, 1997), lies about 800 m below the beginning of Narrow Ares Vallis. Floors of Wide Ares Vallis lie about 200 m above the lowest floors of Narrow Ares Vallis, and its topographic profile appears to be irregular at the upstream portion and flat on the downstream portion. The present-day termination of Ares Vallis consists of a scarp 50–200 m high, which was formed by Tiu-Simud Valles flows postdating Ares Vallis (Marchenko et al., 1998; Nelson and Greeley, 1999; Costard and Baker, 2001).

Regarding ages of Ares Vallis surfaces, Tanaka et al. (2005) map five units in the area. They vary in ages from Middle Noachian to Late Hesperian. Hartmann (2005) also indicates a Late Hesperian age for the Ares Vallis floor and its surroundings. Pacifici (2008) suggests ages varying from Early to Late Hesperian. Werner (2005) observes that ages of the northern reach of Iani Chaos vary from 3.5 Ga to 50 Ma, while the upper reach of Ares Vallis shows ages varying from 650 to 40 Ma.

4 - Geomorphological analysis

We observe in the Ares Vallis Complex two different typologies of geomorphological features. The first one includes grooved terrains, streamlined uplands, giant bars, pendant bars, cataract-like features and hanging valleys, resembling terrestrial morphologies that are believed to have been shaped by catastrophic floods. The second typology includes ice-contact features, thermokarstic depressions, and patterned grounds. These ice-related features overlap and postdate catastrophic flood morphologies. All these features are described below in detail.

4.1. Catastrophic flood features

4.1.1. Erosional terraces and hanging valleys

Along the upper reach of Ares Vallis, there are terraces (fig. 3) occurring (at least) at five different altitude levels. Each terrace seems to have been sculpted by one (or more) catastrophic flooding, originated

by an enormous release of water emanating from chaotic terrains. A terrace occurring at the highest altitude consists of a very large area extending mainly northeast of Narrow Ares Vallis. This terrace is delineated by the -2000 m contour line, and it is characterized by a smooth-texture on medium-resolution images (15-50 m/pixel). Locally, shallow anastomosing channels occur. This terrace corresponds to the areas produced by the first floods emanating from Iani Chaos. Terraces occurring at lower altitudes mark subsequent floods and illustrate progressive deepening and channelization of Ares Vallis. They develop laterally to the entire widths of Ares Vallis and often show a grooved surface. The grooved surface of the terraces suggests that it was sculpted mainly by erosive processes.

Eastern and Western Valley arms are truncated by the Ares Vallis main channel and hang over its floors. Crosscutting relationships among Eastern Valley and the erosional terraces of Ares Vallis show that Eastern Valley originated during the first four catastrophic flood events (fig. 3), and then became abandoned during the subsequent events.

Western Valley (fig. 4) is a broad and shallow trough characterized by the absence of erosional terraces. This suggests that Western Valley was formed during one single catastrophic flood emanating from Hydaspis Chaos. If multiple floods indeed occurred, they did not leave any observational evidence. Crosscutting relationships between Western Valley and Ares Vallis suggest that such catastrophic flood event occurred between the second and fourth catastrophic flood events of Ares Vallis.

Aram Chaos Channel is a deep and narrow gorge in which erosional terraces are consequently poorly extended. On the base of high-resolution images we hypothesize that Aram Chaos Channel was carved by at least two catastrophic floods (possibly more), which occurred at the same time of last floods emanating from Iani Chaos.

4.1.2. Grooved terrains

Grooved terrains characterize a large part of Ares Vallis Complex. They occur mainly on top of erosional terraces, and on the valley floors as patches. Grooved terrains occur both at the proximal and at the distal portions of Ares Vallis troughs. Grooves appear to consist of equally-spacing furrows or trenches between narrow ridges (fig. 5a and 5c) that extend along the direction of the flow. They are hundreds of meters wide, hundreds of meters spaced, and about a few to tens of kilometers long. Groove depths are not

estimated due to their small scales. The overall morphology of such features resembles those of some terrestrial mega-flutes (fig. 5d and 5e). On the base of relationships among grooves and neighboring morphologies it is possible to assess certain morphological and geological properties of the grooved terrains. The grooved terrains appear to be locally etched and postdated by narrow, meandering channels (fig. 6), which typically emanate from flat-floored impact craters or from shallow, flat-floored irregularly-shaped depressions. Comparison between channels and grooves, and their geometrical relationships, allows hypothesizing that grooves are no more than meters or a few tens of meters deep. In areas where water flowed deeper and longer (i.e. on the main stream of Ares Vallis) grooves appear wider and deeper than in areas where water flowed shallower and for shorter time (i.e. Western Valley). Moreover, relationships among meandering channels and grooves seem to indicate that grooved terrains consist of relatively "soft" highly erodible materials. This inference is consistent with the presence of remnants of ancient impact craters that often characterize grooved terrains (fig. 7). Such remnants, commonly with positive relieves, suggest that they consist of rocks more resistant than the surrounding surfaces to the erosive processes shaping grooves. On the topmost part of remnants, grooves generally are absent or less prominent. Relationships among grooves and impact crater remnants, then, seem to confirm that that grooves formed mainly on relatively "soft" highly erodible materials.

4.1.3. Streamlined uplands

Streamlined uplands occur both at the origin of Ares Vallis Complex troughs (i.e. in the vicinity of chaotic terrains), and at the terminal reach of Ares Vallis. They seem to have been formed by erosion of former Noachian and Early Hesperian plateau materials. Streamlined uplands are teardrop-shaped, and characterized by a whaleback profile. Their topmost part reaches the same altitude of the neighboring plateaus and consists of Noachian and Early Hesperian terrains (Pacifici, 2008). Usually, terrains surrounding streamlined uplands appear to be grooved.

Streamlined uplands located in the vicinity of chaotic terrains (fig. 8) are the most prominent features occurring near (and sometime in connection with) the flood source areas. Arrangement of such streamlined uplands indicates that they were shaped by broad converging floods coming out from the chaos. Cross-cutting relationships among troughs separating streamlined uplands seem to indicate that floods abandoned lateral troughs early with respect to the innermost ones. This setting could be consistent with a progressive

233 decreasing of the fluid level in the reservoirs during discharges, which resulted in a progressive canalization
234 of floods.

235 Streamlined uplands occurring at the terminal reach of Ares Vallis (fig. 9) show a distribution and
236 orientations suggesting a spreading of floods. The upstream portion of streamlined uplands is commonly
237 characterized by an impact crater or a rocky hill, which is believed to have caused the diversion of flow,
238 protecting downstream Noachian and Early Hesperian plateaus from flood erosion (fig. 10).

239

240 *4.1.4 Giant Bars*

241 We observe a few features occurring in alcoves flanking valley floors on the downstream portion of
242 Narrow Ares Vallis (fig. 11). They appear some kilometers long, a few km wide, and rising for about 500 m
243 from the valley floor. We propose two hypotheses for the origin of such features. In the first hypothesis we
244 observe that these features appear strikingly similar to giant eddy bars formed during some known terrestrial
245 catastrophic floods in alcoves flanking flooded valleys (Carling et al., 2002). Thus we suggest that such
246 Martian features could have been formed as giant bars during Ares Vallis catastrophic floods. Their
247 thicknesses suggest that catastrophic flood(s) probably responsible for their emplacement was (were) at least
248 500 m deep in the narrow reach of Ares Vallis. The origin of the alcove features could be related to
249 exhumation and erosion of buried impact craters by catastrophic floods. These features overlie grooved
250 terrains and are separated from the valley wall by a swath of about 1.5 km. Such separation can be
251 interpreted as a non-deposition zone, which occurs between bedforms and valley walls, and which is
252 interpreted to form by flow separation immediately downstream from a flow expansion or channel bend
253 (Burr et al., 2004). The topmost part of the possible bars is almost flat and lacks grooves. It is possible to
254 identify boulders about 5-10 m in diameter on the largest pristine impact crater (1.5 km in diameter)
255 occurring on top of one the possible bar.

256 In the second hypothesis, we suggest that these features could be interpreted as mass wasting
257 deposits originated by collapsing of Ares Vallis walls, and possibly reworked by following catastrophic
258 floods. However, lacking of erosional features, such as grooves, and occurrence of the flat trough, which
259 characteristically separates this feature from the valley wall, lead us to discard this second idea.

260

261 *4.1.5 Pendant bars*

The term pendant bar was introduced to indicate streamlined mounds emplaced by Missoula floods downstream of bedrock projections in the Channeled Scabland of North America (Baker, 1982). Pendant bars form by sediment deposition in flow separations developing downstream from a flow obstacle. Similar features, kilometers long and hundreds of meters high, occur in the Ares Vallis Complex (fig. 12), mostly at the terminal reach of Ares Vallis. Pendant bars distinguish from streamlined uplands: the former, which are essentially depositional features, develop exclusively downstream of a bedrock projection, and appear noticeably thinner with respect to the bedrock; the latter, which are erosional morphologies, typically lack a bedrock projection on the upstream side (fig. 9b) or, if this occurs, both are about the same thickness (fig. 10).

Using HRSC data, three-dimensional analyses were performed for two pendant bars (fig. 12), which are located in the Ares Vallis terminal reach (fig. 9a). Bedrock knobs occurring upstream of the pendant bars are about 3 km wide and 4 km long, and rise for about 500-600 m with respect to the nearest valley floor. Streamlined deposits forming bars are 20-35 km long, and their topmost parts rise for about 300-400 m. The upstream portion of Pb1 (fig. 12a, 12b) is surrounded by a parabolic-shaped scour, and the adjacent valley floor is extensively grooved. Both upstream parabolic scour and grooved terrain are not observed at the Pb2 pendant bar (fig. 12c, 12d); the valley floor surrounding Pb2 consists of a flat deposit characterized by bright, shallow, and elongated hollows observable at the MOC NA resolution.

Our observations suggest that two different phases may have existed during each catastrophic flood event (fig. 12f). In the first phase, flood carved a parabolic scour upstream of bedrock projections and emplaced pendant bars to the downstream. At the same time, flood scoured grooves on the valley floor. The thicknesses of the pendant bars suggest that catastrophic flood in which they formed have a depth of at least about 300 m at the terminal reach of Ares Vallis. In the second phase during waning stage of catastrophic flood, the decreased strength of the flow led to the deposition of a flat sedimentary field in the inner part of channels, burying both parabolic scours and grooved terrains.

Some boulders are visible on the pendant bars as previously observed by Malin and Edgett (2001). However, a majority of boulders should have a smaller size range than can be observed in 1.5 m/pixel MOC NA images (fig. 12e). This boulder size range is similar to that of the largest boulders observed at the Pathfinder Landing site (Golombek et al., 1997), which is located next to the present-day termination of Ares

Vallis (fig. 9a). This fact could indicate that 1.5 m likely represents the upper limit of the dimension of clasts transported by Ares Vallis catastrophic floods at least at the terminal reaches and maybe during last floods.

4.1.6. Cataract-like features

Abandoned cataracts are impressive erosional forms created during the Missoula catastrophic floods in North America. They were shaped by headwall recessional processes when catastrophic floods crossed a sharp scarp of structural or erosional origin (Baker, 1982). A very similar feature occurs at the Ares Vallis Complex near the junction of a shallow trough emanating from Western Valley and the Ares Vallis main trough (fig. 13). The shallow trough is hanging above both Western Valley and Ares Vallis floors: this suggests that it was carved early during the catastrophic flood event originated by fluids emanating from Hydaspis Chaos, and subsequently abandoned.

The cataract-like feature is an arcuate scarp, 500 m high and several kilometers wide. It seems to have originated when a catastrophic flood crossed a sharp scarp, and successively extended 35 km upstream by flood-driven, headwall recessional processes. Unlike terrestrial cataracts, large closed depressions are unobserved at the base of the cataract-like feature of the Ares Vallis Complex. The shallow trough occurring upstream of the cataract-like feature shows an association of grooved terrain, streamlined uplands and pendant bars. In the downstream of the cataract, instead, trough enlarges with a fan-shaped morphology: here grooved terrain and pendant bars are unobserved and only two small streamlined remnants occur.

4.2. Ice-related morphologies

4.2.1 Thermokarstic depressions

Shallow, irregularly-shaped depressions occur in several portions of the Ares Vallis Complex. They occur on erosional terraces, on valleys floors, and on top of ice-contact features (see next section). Several well-developed shallow depressions occur inside a large flat-floored impact crater about 90 km in diameter, which host a portion of Eastern Valley. We gave this impact crater an informal name of Eastern Valley Crater (fig. 14). Irregularly-shaped depressions of Eastern Valley Crater are a few kilometers wide, and typically coalescing. The depressions are 50–150 m deep. The deepest ones are coalescing and larger. The shallowest ones are smaller and isolated. The depression walls show layering (at least four) a few of tens of

meters thick (fig. 18). In its medial portion, the crater floor is incised by Eastern Valley. Nearby impact craters and intra-crater terrains do not exhibit shallow and coalescing depressions similar to those occurring within Eastern Valley Crater. This fact leads us to think that the formation of such features does not depend on regional geological and/or climatic events, but relates exclusively to the geological history of Eastern Valley Crater, and to the geological properties of its floor materials.

The shallow and coalescing depressions observed in the Ares Vallis Complex share several morphological similarities with terrestrial thermokarstic depressions, such as alas valleys. Alas valleys are periglacial morphologies that form in permafrost or ice-rich soils. Thawing of ground-ice leads to the formation of thaw lakes, which could coalesce with others and with a stream (Czudek and Demek 1970). Probable alas valleys and other thermokarstic depressions have been already observed and mapped in circum-Chryse outflow channels by some authors (Carr and Shaber, 1977; Costard and Baker, 2001; Costard and Kargel, 1995). Such morphologies are supposed to form on Mars even by localized enhanced sublimation instead of melting processes (Levy et al., 2005). Carr and Shaber (1977) note that characteristics of alas valley on Mars, with respect to terrestrial ones, may indicate a more uniform distribution of ice within the surface materials. This indicates that the ices were deposited contemporarily with the host material.

We hypothesize the following scenario (fig. 14) about the origin of the thermokarstic depressions in Eastern Valley Crater. Catastrophic flood(s) originated from Iani Chaos, etched the Eastern Valley Crater rim, and infilled it with ice-rich deposits. The layering observed in depression walls seems to indicate multiple occurrences of catastrophic flooding, or at least that variations in the flow regime existed. After the flood(s), an ice-rich deposit occupied the Eastern Valley Crater floor. The ice-rich deposit would have subsequently wasted by melting or sublimating processes, leading to the alas-like landscape. The depths of the thermokarstic depressions suggest a thickness of at least 150 m for the ice-rich deposit.

Eastern Valley incises through the thermokarstic depressions, implying at least two different flood events in the area: the earlier one(s) supplied the stratified ice-rich deposit; the later one(s) eroded it subsequently to the development of the thermokarstic depressions. During the later flood(s), processes of thermal erosion may have played an important role in the reworking of the ice-rich deposit. Thermal erosion causes degradation and removal of ice-rich soils by heat transfer between the water flow and the frozen ground, followed by transport of unfrozen materials (Aguirre-Puente et al., 1994).

The gap in time occurring between the earlier and later flood(s) must have been long enough to allow development of thermokarstic depressions and their coalescence. Brouchkov et al. (2004), based on the study of thermokarstic depressions in Central Yacutia, noted that active phase of a terrestrial thermokarst feature is short, and that its development should be considered a short-term event. Calculations of thermal conditions beneath a thermokarst lake in Central Yacutia show that, if the water level is stable or increasing, thaw may reach 30 m over a period of 200 years. If the ice-wasting processes responsible for the Martian alas-like depressions were dominated by melting rather than sublimation process, development of thermokarstic depressions may have been relatively fast (about some hundreds to a few thousand of years). Harris (2002) observe that a thaw pond, once formed, will go on enlarging in icy materials until it runs out of ground ice or intersect a drainage way. In the same way, it is possible that the last flood(s) through Eastern Valley partially disrupted walls of the alas-like depressions, caused their draining, and then stopped their development.

The overall setting of features observed in Eastern Valley Crater seems to imply alternation of periods characterized by colder-dryer climatic conditions (similar to the present-day Martian climate) in which ice-rich deposits were emplaced, and periods characterized by warmer-wetter climatic conditions in which alas-like features were shaped. The inference about the possible warmer-wetter climatic conditions may be invalid if sublimation rather melting processes dominated the wasting of the ice-rich deposits. Nevertheless, the geomorphological relationship between the alas-like valleys and the present-day Eastern Valley indicates that floods were multiple and well separated in time.

4.2.2. Ice-contact morphologies

Patches of mesa-like features overlie erosional morphologies of the Ares Vallis Complex shaped by catastrophic flood processes. In the narrow upper reach of Ares Vallis, the mesa-like features are flat-topped ridges (fig. 15), a few of kilometers wide, tens of kilometers long, and rising for about 100-200 m. They are slightly sinuous, and elongated parallel to the trough. Locally, the ridges bifurcate and turn around streamlined hills. In the wide lower reach of Ares Vallis (fig. 16), the mesa-like features vary in shape, dimension or orientation. They exhibit forms such as circular, crescent, elongated, reticulated, bifurcating or sinuous. The thickest mesa-like features rise for about 500 m and occur in the upstream portion of Wide Ares Vallis. Toward the downstream direction, the thickness of the mesa-like features progressively decreases, until it reaches a value of about 100 m (fig. 2). The topmost portion of the largest mesa-like feature appears

to be etched by round-shaped, flat-floored depressions, which are consistent with a thermokarstic origin (fig. 16a). At the bottom of such depressions, underlying grooved terrain and streamlined hills formed during catastrophic flood events are observed. Several mesa-like features are characterized by a rising sharp rim (fig. 16d). The mesas-like features lack any erosional marks such as grooves or terraces. Their walls are generally steep and layering is commonly recognizable. Layering is diverse in individual mesa-like feature or even on the different slopes of a mesa-like feature (fig. 16e).

Some morphological characteristics of the mesa-like features appear to be very similar to those of terrestrial kames, and thus they may have formed owing to similar geomorphic processes. Kames are steep-sided, variably shaped mounds, composed mainly of sands and gravels. They form because of emplacement of sediments in ice-walled streams or lakes, in sub-glacial, englacial or supraglacial environments. These features were left as rising morphologies when surrounding ice melted (Benn and Evans, 1998). Commonly shared features characterizing both the mesa-like features of Ares Vallis and terrestrial kames are; steep walls, flat topmost part, irregularly-shaped morphology, layered structure, variations in layering of individual mesa-like features. The rising rim characterizing some mesa-like features of Ares Vallis is somewhat similar to those characterizing terrestrial ice-walled lake plains, which formed by sediments that accumulated near the margin of ice-walled lakes (Johnson and Menzies, 1996). The mesas-like features showing a reticulated pattern can be considered to be a gigantic version of terrestrial disintegration ridges, which formed by infilling of crevasses and other openings in disintegrating ice (Flint, 1971).

Our interpretation of the Martian features as ice-contact deposits mostly agrees with one of those proposed by Costard and Baker (2001), and implies that one or more ice masses filled Ares Vallis. Occurrence of such features requires that ice masses were stagnant at least from the time during which the probable kame features were emplaced until the ice wasted. The varying thickness of the ice-contact features implies i) differences in ice mass thickness along Ares Vallis, ii) variation in the amount of materials emplaced against ice masses, and finally iii) that sediments forming the probable kame features were deposited in different times throughout the wasting of the ice masses.

The materials forming the probable kame features seem to have originated from Ares Vallis walls, and appear to have been emplaced by fluvial-like processes (fig. 17). The bifurcating ridge of fig. 15 shows an olivine-rich composition and thermal inertia values higher than other surfaces occurring in the neighboring areas (Rogers et al., 2005). Thermal inertia values appear to be compatible with gravel and sand

deposits, while the olivine-rich composition could be due to stream sorting processes. Indeed, olivine-rich layers occur on Ares Vallis walls (Rogers et al., 2005) and could represent source areas for sands and gravels forming the ridge.

Russell at al. (2001) describe a giant, supraglacial, ice-walled channel excavated into the snout of Skeiðarárjökull, Iceland, during the November 1996 jökulhlaup. The supraglacial channel was 500 m long, 100 m wide and 40 m deep. Mean flow velocities of the jökulhlaup ranged between 7 and 11 m s^{-1}, which were capable of suspending sediments with grain size up to 20 cm. Deposits occurring at the floor of the channel consist of an 8 meter thick succession of progradational and aggradational gravel macroforms. Russell et al. (2001) observe that, since the November 1996 jökulhlaup, ablation has lowered the surrounding glacier surface by approximately 30 m, and the ice-walled channel has become a prominent flat-topped ridge. This feature could be one of the most interesting terrestrial analogs for the ice-walled stream deposits of Ares Vallis.

Alternative geomorphological processes of landscape evolution seem to be less likely for explaining the mesa-like features. Stream deposits not involving ice-masses can form inverted topography such as those observed in Eberswalde Crater on Mars (Malin and Edget, 2003). However, the patterns of the mesa-like features in Ares Vallis do not present expected fluvial forms such as tributary and distributary patterns. Lava flows could account for the olivine-rich composition of some ridges. Although ice-dammed lavas could form steep-sided lava flows, volcanic features are not observed in this area. The layering observed in Ares Vallis mesa-like features could have resulted from different insolation occurring at different facing slopes, and/or variable climates, leading to dissimilar erosive and/or sedimentary processes, which at places could have masked or enhanced sediment layering.

4.2.3. Patterned terrains

Terrains showing pitted or polygonal patterns appear in various reaches of the Ares Vallis Complex. They occur at the highest stratigraphical level, and thus their emplacement may represent the latest of main geological events shaping the Ares Vallis Complex.

Pitted terrains consist of surfaces dotted by numerous hollows. Larger pits are 100 m wide, whereas the smallest ones distinguishable are 10-20 m wide. Pits have a quasi-circular shape, and sometime tend to aggregate each other. Typically, they exhibit dark floor, and sand dunes are recognizable on the largest ones.

Patches of pitted terrains occupy floors of the Ares Vallis Complex and Eastern Valley Crater (fig. 18). Furthermore, pits characterize mass wasting deposits occurring along Ares Vallis walls (fig. 19). In THEMIS IR nighttime data, pitted terrains show higher emittance values than surrounding surfaces. Association of pitted pattern and thermal properties of such terrains appears remarkable. This association, together with the absence of pits on nearby terrains, leads us to hypothesize that pits formed because of soil properties, rather than alternative causes (e.g. primary or secondary impact craters).

Terrains showing polygonal pattern generally embay the probable kame features occurring on the inner and deeper portions of Ares Vallis (fig. 15 and 16). There polygons appear to be hundreds of meters large and peripheral trenches are tens of meters wide. In THEMIS IR nighttime data, polygonal terrains show emittance values higher than Ares Vallis walls and lower than probable kame features.

Both the pitted and polygonal terrains may have originated because of periglacial processes. On Earth, pitted patterns similar to those observed in the Ares Vallis Complex generally correlate with terrains subject to ground collapses due to thermokarstic processes. Possible terrestrial analogues are kettle-holes and thaw-lakes (Pacifici et al., 2005), which form when buried-ice or permafrost melts, forming pits on the surface. Polygonal terrains could have been formed also by desiccation processes. However, the occurrence of the probable kame features suggests that a periglacial origin is more likely. Melting of buried ice and upward movement of melt water could have originated ice cemented soils and duricrusts on Mars (Landis et al. 2004). Both ice-cemented soils and duricrusts could be responsible for the higher IR emittance values shown by patterned terrains with respect to surrounding surfaces.

The occurrence of geomorphological features related to periglacial processes, such as pitted and polygonal terrains, agrees with the hypothesis that ice masses filled the Ares Vallis Complex in the past. Moreover, periglacial features suggest that portions of the ice masses were buried after their emplacement. Processes responsible for ice burying may have been mass wasting, emplacement of impact crater ejecta, or wind-blown materials, such as dust, sand, and volcanic ash. A sublimation till could have buried ice as well, if the original ice mass contained some amount of debris. Sublimation till of Beacon Valley in Dry Valleys, Antarctica, shows a well-developed polygonal pattern (Marchant et al., 2002). Dry Valleys are known also as one of the best Martian analogues on Earth.

5. Discussion

5.1. Catastrophic floods

Some of the erosional and depositional morphologies occurring in the Ares Vallis Complex, such as streamlined uplands, giant bars, pendant bars, and cataract-like features, suggest that Ares Vallis and its valley arms were shaped by catastrophic floods originating from chaos regions. This idea agrees with the previous hypothesis (Baker and Milton, 1974; Baker, 1982: Baker et al., 1992; Komatsu and Baker, 1997).

Our geomorphological analysis of high-resolution images estimates that flood events were at least six. Reactivation of outflow channel flooding is indicated also at Tiu Vallis west of Ares Vallis (Rodriguez et al., 2005), thus it can be concluded that large circum-Chryse outflow channels were commonly formed by multiple floods. Occurrence of multiple floods is in agreement with numerical model of groundwater flow and surface discharge at the outflow channel sources (Harrison and Grimm, 2008). Topographic analyses of giant and pendant bars indicate that floods were at least 500 m deep in Narrow Ares Vallis, and at least 300 m deep at the Ares Vallis terminal reach. Geomorphological relationships indicate a progressive decreasing of fluid volume in the reservoirs during the discharges, which resulted in a progressive canalization of floods. This is partially in agreement with Nelson and Greeley (1999). Our hypothesis about the geomorphological evolution of Eastern Valley Crater (fig. 14) suggests that the amount of time elapsed between the two different floods in Eastern Valley must have been long enough to have permitted the emplacement of thermokarstic features 150 m deep and a few kilometres large. We do not know how much time was required for their formation. To make a roughly comparison, similar features 20 meters deep could require few hundreds of years to form on Earth (Brouchkov et al., 2004). Occurrence of layering could suggest two hypotheses. On the first one, each layer, a few tens of meters thick, formed during different floods; in the second hypothesis we suggest that layering formed because of variations in the flow regime during a single flood. Both the hypotheses appear to be consistent.

5.2. Grooved terrains

Grooved terrains characterize a large portion of the Ares Vallis Complex floors and erosional terraces, and occur also at other Martian outflow channels, such as in Kasei Valles. In earlier works on Martian outflow channels, main interpretations of grooved terrains were: i) features sculpted by high-

492 velocity (catastrophic) flows of water (Baker and Milton, 1974) and ii) features similar to glacial scours and
493 mega-flutes (Lucchitta, 1982; Lucchitta, 2001). In the former hypothesis grooves are considered to have been
494 formed by powerful roller vortices, which developed parallel to the flow direction. In the latter hypothesis
495 grooves are shaped by ice that in place moved through Martian channels. Ices flow similarly in Antarctic ice
496 streams over deformable debris saturated with water under high pore pressure. Other hypotheses about
497 groove origins including formation by roller vortices in fluids such as wind, debris flows and mudflows,
498 were discussed in Baker et al. (1992) and Carr (1996). Origin of grooves could be inferred from geological
499 relationships among grooves and nearby geomorphological features. In the Ares Vallis Complex, occurrence
500 of cataract-like features, streamlined uplands, and pendant bars in association with grooved terrains (fig. 13)
501 seems to support the cataclysmic flood origin.

502 Geomorphological characteristics of the observed grooves, and their relationship with respect to
503 nearby features, such as meandering channels (fig. 6) and impact craters remnants (fig. 7), suggest that the
504 grooves formed mainly on relatively "soft" highly erodible materials.

505 In areas where water flowed deeper and for longer durations (i.e., on the Ares Vallis floor) grooves
506 appear wider and deeper than in the areas where water flowed shallower and for shorter times (i.e., in
507 Western Valley). This appears in agreement with laboratory experiments and field observations. Laboratory
508 experiments on water streams indicate that regular spacing of vortices in flow varies with velocity and depth
509 of the flow (Allen, 1970). Field observations at the base of the Sigsbee Escarpment, in the northwestern Gulf
510 of Mexico (Bean, 2003), show that strong currents formed mega-furrows on fine-grained sediments of
511 seafloor. Higher current velocities and durations lead to form mega-furrow, which are wider, deeper and
512 closer. Furthermore, the stronger sediments determine the maximum depth of erosion and require higher
513 current velocity and duration to be eroded (Bean, 2003). Such seafloor mega-furrows exhibit some
514 similarities with respect to Martian grooves. Therefore, it is possible that similar currents occurred at the
515 bottom of Martian catastrophic floods. At the southern termination of Western Valley (fig. 4), grooves seem
516 to converge and meet to form a deep and narrow canyon-like feature. This appears in agreement with some
517 experimental flow simulations (Shepherd, 1972; Shepher and Schumm, 1974) showing as the longitudinal
518 grooves form early and finally switch to a deep inner channel that progressively extends backward.

519 On the other hand, some variations in trough geometry and consequent fluid properties seem not to
520 have significantly influenced processes sculpting grooves. Several flow properties could have varied along

troughs, such as velocity, bedload quantity, granulometry density, fluid temperature, salt concentration, and amount of gases dissolved in the fluid. Martian grooves occur both in the proximity of the postulated fluid sources (fig. 8) and at the terminal reach of channels (fig. 9). This implies that grooves formed both in areas of convergence and divergence of floods, and in areas characterized by different topographic gradients (fig. 2). Furthermore, the large extension of grooves implies that same flow conditions were sustained for very long distances, such as several hundreds of kilometers. In Western Valley, despite the large variations in width of the trough (fig. 4), grooves do not show significant variations both in morphology and in dimensions along the entire 370 km long valley. A more detailed discussion on the groove formation during flooding requires precise determinations of water depth and flow velocity in various reaches of Ares Vallis, possibly by utilizing numeral modeling (e.g., Miyamoto et al., 2006; 2007).

Lucchitta (2001) shows a remarkable similarity between Martian grooved terrains of Kasei Valles and glacial mega-lineations observed in sonar images of the sea floor in front of the Sea Ross Ice Shelf. Intrigued by this striking similarity, we have compared high-resolution images of grooved terrains of Ares Vallis with sonar images of terrestrial glacial mega-flutes occurring on the floor of the Ontario Lake (fig. 5). Martian grooves consist of narrow and elongated troughs, while terrestrial glacial mega-flutes consist of elongated ridges. However, the overall shapes, the dimensions, and the spatial distributions of terrestrial and Martian features appear to be very similar. Mega-flutes of the Ontario Lake floor consist of compact stony diamict (till) (Lewis et al., 1997). Similar mega-flute observed on seafloors was interpreted as soft, structure-less diamict (Dowdeswell et al., 2004), and subglacial till (Shipp and Anderson, 1997). Diamict and till are non-consolidated, poorly-sorted deposits: clasts vary from clay to boulders. Such kind of deposits could be similar to those forming some of Martian grooved terrains, which we interpret to consist of relatively “soft” highly erodible materials.

5.3. Ice-covered catastrophic floods?

Shaw (1996, 2002) proposed that terrestrial sub-glacial bedforms, such as those observed on the Ontario Lake floor, were shaped during the last ice age by enormous sub-glacial outburst floods. Sub-glacial floods are inferred to have formed meltwater sheets that flowed below ice masses producing mega-flutes, drumlins, tunnel valley and other sub-glacial bedforms. This theory is controversial (Benn and Evans, 1998),

and thus Kargel (2004) suggests that this fact is sufficient to give a pause to any rapid judgment about Martian outflow channels. The catastrophic floods sculpting Ares Vallis could have somehow evolved in conditions similar to those of a sub-glacial outburst floods. In fact, Wallace and Sagan (1979) propose that, under the present climatic condition of Mars, a flowing channel of liquid water would be covered by ice, which evaporates slowly enough to allow the water below to flow for distances up to hundreds of kilometers, even with quite modest discharges. They calculated that thickness of such ice-covers ranging from tens to several hundreds of meters, and that the amount of ice lost by evaporation at the top surface is replaced by freezing at the bottom surface. This implies that the net loss is to the liquid water. Several factors could enhance or reduce the thickness of such ice-covers. These are: i) temperature of water in the reservoirs; ii) amount of possible salts and gases eventually dissolved in water; iii) composition and temperature of Martian atmosphere, and presence of atmospheric clouds or dusts; iv) possible different obliquity of Martian axis (Laskar and Robutel, 1993). Lucchitta (1982) proposed that in the cold Martian climate water coming from chaos regions was supercooled and then acquired rapidly large quantities of frazil ice, which locally may have developed ice caps. Some authors (Harrison and Grimm, 2008 and therein) suggest that in most cases groundwater discharge at chaotic terrain did not provide a direct source of channel flow but ponded locally and produced standing bodies of water; successively, outflow channel floods were triggered by jökulhlaup-type events caused by failure of the lake margins. In this case, if ice masses formed on top of standing bodies of water, they could have been carried by catastrophic floods. Therefore, the formation of ice jams near obstacles and constrictions could have happened, successively followed by consolidation to form ice masses (Lucchitta, 1982). It is possible, then, that floods flowing in the Ares Vallis Complex could have provided enough ice to generate one or more ice masses hundreds of meters thick. Evidence for ice-rich deposits overlying catastrophic flood morphologies was observed in the Mangala Valles outflow channel (Levy et al., 2005). Observation of such deposit draped over grooved terrain suggests to these authors that ice would have formed on top of an outflow flood under cold-dry climatic condition.

If floods were ice-covered, they could evolve into a setting similar to a relatively thin water sheet flooding below an ice-cover, at least during their waning stage. In such condition, water flowing under the ice masses could have shaped grooved terrains, by processes similar to those proposed by Shaw (2002), and/or could have enhanced grooves already carved by roller vortices of catastrophic floods. Furthermore, in such sub-ice circumstances, it is possible that catastrophic floods maintained the same flow condition for

very long distances, both in areas of converging and diverging flow (such as at the beginning and at the termination of Ares Vallis), and regardless of variations in width and depth of troughs. Possibly, small movements of ice cover may have occurred at the end of floods during the grounding of ice masses. This could have both enhanced or smoothed the previously shaped grooves.

5.4. Glacial landscape

Our geomorphological analyses point out that ice masses grounded on the Ares Vallis Complex floors subsequent to multiple catastrophic floods, forming one or more dead-ice bodies, and formed glacial landscapes. It appears very probable that tremendous erosive action of each catastrophic flood should have totally removed ice masses and possible glacial and periglacial features produced after previous flood events. At the present day, a glacial landscape formed following the last catastrophic flood event is still visible. They consist of ice-contact features and thermokarstic depressions. Arrangement of such morphologies allows us to perform a rough estimation of the areas covered by ice-masses. In the case of Wide Ares Vallis where probable kame features appear densely occurring, assuming that these features formed in a single ice mass, the final reach of Ares Vallis was infilled by a dead ice-mass as large as $3x10^4$ km^2. They varied in thickness between 100 to 500 m. For the entire Ares Vallis Complex, the amount of ice infilling troughs should have been much higher than this value.

Evidence for a glacial landscape is absent in Western Valley. This may be due to the fact that Western Valley seems to have been carved by only one catastrophic flood. And the glacial landscape (possibly) emplaced at the end of such flood may have totally sublimate/melted without subsequent reworking. It is also possible that Western Valley was flooded for a brief time, or during warmer-wetter climatic conditions (see below), and then the resulting ice-cover was thinner than in other valleys. Finally, it is possible that fluid emanating from Hydaspis Chaos could have had a different temperature and/or composition in salts with respect to those of Iani and Aram Chaos, and then emplaced a thinner ice mass.

In the current Martian environment, ice once grounded could remain in place for a long time before totally sublimating or melting. Both morphological analyses (Levy et al., 2005) and models (Clifford and Parker, 2001) suggest this situation. In such an environment, ice masses could have preserved underlying grooved terrains from erosion, and could have favored consolidation of loose materials at their base. The pristine appearance of the grooved terrains and probable kame features in the Ares Vallis Complex may

suggest that ice masses disappeared mainly by sublimation processes, not by melting. Regarding the efficiency of sublimation processes on Mars, Clifford and Parker (2001) suggest that at latitudes lower than 40°, which is the case of Ares Vallis, sublimation rates from a bare ice surface could readily exceed 0.1 m yr^{-1}. However, the presence of a debris mantle only 10-20 cm thick could reduce the sublimation rates by more than one order of magnitude. Considering both these end-members, the time required to sublimate a 500 m thick stagnant ice mass varies from 5000 to 50000 years, respectively in cases of bare and mantled ice. Mantling of ice could have been caused by emplacement of wind-blown sand, dust, volcanic ash, slope failure materials and impact crater ejecta. If the dead-ice masses contained some amount of debris, which is possible because of its origin, a sublimation till could have developed as well, lowering ice sublimation rate. Patterned terrains of the Ares Vallis Complex, and their thermal properties, suggest that periglacial processes occurred, and support the idea that ice was mantled or mixed with debris.

Periods of high or low obliquity of Mars, if occurred, could have increased or decreased ice sublimation rate. Observation of thermokarstic features, probable kame features, and relatively small-scale meandering channels, which seem to have been formed subsequent to multiple catastrophic flood events, suggests that relatively brief periods of warmer-wetter climatic conditions took place (see below), which could have favored melting rather than sublimation processes.

5.5. Climatic changes

Some morphological features of the Ares Vallis Complex are interpreted as formed by flowing or standing bodies of water in equilibrium with the Martian atmosphere. Such features are i) narrow, meandering channels, ii) thermokarstic features, and iii) probable kame features. Development of such features requires that periods of warmer-wetter climatic conditions took place. Thermokarstic features (fig. 14) and hanging channels (fig. 13 and fig. 15) formed both on erosional terraces and icy deposits shaped by floods, and were modified by subsequent floods deepening troughs. This suggests that they developed between different catastrophic flood events. We hypothesize that such warmer-wetter climatic conditions were triggered by catastrophic flood events themselves. In fact, water vapor and carbon dioxide/methane gases liberated into the Martian atmosphere by degassing during outflow events could have induced a short-term greenhouse effect (Baker et al., 1991; Gulick et al., 1997; Baker, 2001). Water vapor released by wasting of stagnant ice-masses could have also sustained the greenhouse effect.

637 The pristine morphologies characterizing glacial and periglacial features of the Ares Vallis Complex
638 may suggest that, in spite of the earlier warmer-wetter conditions, the main wasting of ice masses was driven
639 by sublimation processes. This implies that the warmer-wetter climatic conditions occurred for relatively
640 brief spans of time. Subsequently, climatic conditions became similar to those of the present day. Our
641 observations agree with Baker (2001), which proposed that a short-duration, transient, warmer-wetter period
642 followed the activation of catastrophic floods, and that afterward the Martian climate comes back to climatic
643 conditions similar to those of the present day.
644
645 **6 – Conclusion**
646 The Ares Vallis Complex is one of the longest and ancient systems of outflow channels on Mars.
647 Some of its morphological features (i.e. grooved erosional terraces, streamlined uplands, pendant bars, and
648 cataract-like features) appear to have originated by multiple, time-scattered, catastrophic floods. Other
649 morphological features (i.e. probable kame features, thermokarstic depressions, and patterned terrains)
650 indicate that Ares Vallis hosted dead-ice masses in the past. Geological relationships between the
651 catastrophic flood features and the ice-related features depict a possible geological evolution of Ares Vallis,
652 involving a cyclic series of geomorphic processes (fig. 20) consisting of i) multiple, ice-covered catastrophic
653 floods; ii) grounding of ice-masses formed on top of floods; iii) emplacement of ice-contact deposits, and
654 finally iv) ice wasting.
655 A possible geological history of Ares Vallis is here summarized.
656 i) The Ares Vallis Complex originated by enormous floods discharged from chaotic terrains. The
657 floods were responsible for sculpting grooved terrains, erosional terraces, streamlined uplands, and giant
658 cataract-like features. The grooved terrains formed both at the proximal and at the distal reaches of the Ares
659 Vallis Complex, and were originated by powerful vortices at the base of the enormous floods. Grooves
660 formed prevalently on relatively erodible “soft” terrains, and their dimensions seem to vary depending on
661 thickness and duration of the floods. Depositional features emplaced by floods consist of giant bars and
662 pendant bars.
663 ii) Ice-covers formed on top of floods because of low values of temperature and pressure of Martian
664 atmosphere. The amount of ice lost by evaporation at the top surface reformed by freezing at the bottom
665 surface, allowing the ice-cover to thicken up to several tens to few hundreds of meters. As the floods

666 decreased their discharges, this setting evolved into a thick ice mass topping a relatively thin layer of flowing
667 water. In such conditions, subglacial floods contributed to or enhanced sculpting of grooves.

668 iii) At the end of the floods, ice-covers grounded on the valley floor, forming thick, dead-ice masses.
669 The ice masses could have taken a long time to totally waste (about a few thousand to a few tens of thousand
670 of years, respectively in case of bare and debris mantled ice). Warmer-wetter climatic conditions prevailed
671 during the first stage of wasting of the ice, and streams of water etched ice masses forming ice-walled
672 channels and lakes. Origin of such water streams seems to be related to melting of permafrost and/or ice. The
673 warmer-wetter climatic conditions were triggered probably by the greenhouse effect caused by water vapor
674 and carbon dioxide/methane gases released during the catastrophic flood processes. If catastrophic flood
675 events occurred during the warmer-wetter climatic conditions, it is plausible that they were ice free.

676 iv) Finally, ice masses totally wasted. Ice wasting produced a landscape inversion and materials
677 deposited at the floor of ice-walled channels and lakes turn into mesa-like features, similarly to terrestrial
678 kame deposits. Pristine appearance of sub-glacial and supra-glacial features (i.e. grooved terrains and
679 probable kame features, respectively) suggests that colder-dryer conditions prevailed during the second stage
680 of dead-ice mass wasting. This leads us to think that the greenhouse effect persisted no longer than the time
681 required to totally waste the ice masses infilling Ares Vallis.

682 Quantitative geomorphological analysis, realized by using high-resolution images and HRSC stereo-
683 derived DTMs, allowed us to estimate some parameters about catastrophic floods and glacial masses. At
684 least six catastrophic floods originated in Iani Chaos and sculpted Ares Vallis, at least two (probably more)
685 originated in Aram Chaos. Water emanating from Hydaspis Chaos fed the Ares Vallis Complex during one
686 single catastrophic flood event. On the narrow reach of Ares Vallis, floods had a minimum depth of about
687 500 m, estimated on the base of thicknesses of giant bars. In Wide Ares Vallis, instead, thicknesses of
688 pendant bars suggest a minimum depth of about 300 m. Arrangement of ice-related features and their
689 thicknesses allow estimating the minimum aerial extent and thickness of the ice-mass(es) in which they
690 formed. Ice mass(es) was one to five hundreds of meters thick and tens of thousand of square kilometers in
691 area.

692 Throughout the wasting period of dead-ice mass(es), ice were locally buried by mass wasting
693 processes, wind-blown materials, debris flows, and possibly by sublimation till. Periglacial processes acting
694 on the buried ice formed patterned terrains and ice-cemented soils.

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Figure captions

Fig. 1. Location map of Ares Vallis Complex area based on the MOLA grid data. Frames refer to other figures.

Fig. 2. Longitudinal profile of Ares Vallis obtained from MOLA grid data. Notice the lowest portion of the valley resides in the narrow reach. Arrows indicate merging points of main valley arms debouching on Ares Vallis.

Fig. 3. Upstream reach of Ares Vallis. Arrangement of erosional terraces and streamlined uplands shows that at least six main catastrophic flood events sculpted Ares Vallis. The terrace formed during the first catastrophic flood event shows relative shallow anastomosing channels. Erosional terraces marking subsequent floods illustrate the progressive deepening and channelization of Ares Vallis. Frames refer to other figures. Mosaic of HRSC h0934_0000, h0923_0000, and h0912_0000 images; topographic profile obtained from HRSC DTM mosaic.

Fig. 4. Western Valley topography from MOLA grid data. Arrows indicate flow directions as suggested from morphological features. Transversal topographic profile (AB) illustrates that Western Valley appears to be characterized by an elevated width-to-depth ratio (vertical exaggeration of profile is four times). Double-arrowed bar indicates lateral extension of grooved terrain. Frames refer to other figures.

Fig. 5. Grooves characterizing floors and erosional terraces of the Ares Vallis Complex consist of equally spacing furrows or trenches between narrow ridges. The most morphologically similar features observed on Earth are the glacial mega-flutes. a) Martian grooves; image MOC R1101630. b) Close up. c) Martian grooves; image THEMIS V12795005. d) Mega-flutes on sonar image of the Ontario Lake floor; reprinted from Quaternary International, Vol. 90, J. Shaw, The meltwater hypothesis for subglacial bedforms, Pages No 5-22, Copyright (2002), with permission from Elsevier. e) Mega-flutes on sonar image of the Ontario Lake floor; modified from Glaciated continental margins: an atlas of acoustic images. Chapman & Hall, London, 1997.

Fig. 6. Three-dimensional view of a portion of Western Valley and Aram Chaos rim; HRSC h1000_0000 image draped on HRSC DTM. See fig. 4 for location. a) The narrow outlet channel emanating from a 50 km wide impact crater located on the extended rim of Aram Chaos meets the central portion of Western Valley. Comparison between the channel 100-250 m deep and the grooves allows hypothesizing that the grooves are no more than some meters or a few tens of meters deep. b) At its downstream portion, the meandering channel etches the grooved floor of Western Valley and appears truncated by a shallow, small, chaotic region. c) The meandering channel does not show variations in proximity of the transition from the grooved to the non-grooved terrain, suggesting that geological properties of grooved and not-grooved terrains are

954 similar. d) HRSC h1000_0000 and MOC E0900989 images mosaic showing a close-up of channel and its
955 abandoned meanders.
956
957 Fig. 7. Impact crater remnants (black arrows) on the erosional terraces of Ares Vallis. Absence of grooves on
958 the topmost part of the remnants suggests that grooves form mainly on relatively "soft" erodible materials.
959 Notice the annular furrows embaying crater remnants. HRSC h1066_0000 image. See figure 16 for a context
960 image.
961
962 Fig. 8. Western Valley proximal reach in the vicinity of Hydaspis Chaos; see fig. 4 for location. This area
963 consists of a fan-shaped system of broad, shallow, and grooved channels, which converge and meet together
964 in the downstream. Higher parts of streamlined uplands appear to be flat and non-grooved. Lower parts
965 appear to be grooved. Arrangement of grooves and streamlined uplands, and crosscutting relationships
966 among channels, indicate an overall converging pattern of floods. HRSC h1022_0000 image.
967
968 Fig. 9. a) Three-dimensional view of terminal reach of Ares Vallis; HRSC h1619_0000 image draped on
969 MOLA grid data. This portion of the valley is characterized by streamlined uplands (Su) and pendant bar
970 (Pb1, Pb2, and Pb3). (P) indicates the Mars Pathfinder landing site. b) Probable kame features (M) clearly
971 overlie a streamlined upland (Su); HRSC h01980_0000 image draped on HRSC DTM.
972
973 Fig. 10. Streamlined uplands at the terminal reach of Ares Vallis. a) In areas of diverging floods, streamlined
974 uplands commonly show an impact crater (C) on their upstream portion. Grooves characterize valley floor
975 surrounding streamlined uplands. Next to the gently raising northeastern wall of Wide Ares Vallis, grooves
976 degrade into transversal, relatively small ridges. Wing-shaped deposits overlie downstream portion of
977 uplands and nearby grooved terrains. Wrinkle ridges (Wr) clearly postdate other features. Mosaic of HRSC
978 h0155_0001 and THEMIS V12795005, V04782003, V10349017, and V14330014 images. b) Three-
979 dimensional view of streamlined uplands; mosaic of HRSC and THEMIS VIS images draped on HRSC
980 DTM. c) Transversal and longitudinal topographic profile of streamlined uplands derived from HRSC DTM.
981 d). Sketch illustrating a possible origin of streamlined uplands.
982

983 Fig. 11. Possible giant bar in an alcove sculpted along the right wall of the narrowest portion of Ares Vallis.
984 Nadir a) and 3D view b) of a portion of HRSC h1022_0000 image. c) Close-up: possible boundary between
985 the giant bar and the grooved terrain is highlighted (MOC Na R0401710). d) Topographic profiles obtained
986 from HRSC DTM.
987
988 Fig. 12. Pendant bars at the terminal reach of Ares Vallis; see fig. 9 for location. a) Parabolic erosional scour
989 (S) forms upstream of the bedrock projection because of acceleration of flow in nearness of a bedrock
990 projection; HRSC h2002_0001 image. b) Three-dimensional view of Pb1; HRSC image draper on HRSC
991 DTM. c) Sediments emplaced on the inner and deeper portion of troughs during the final stage of
992 catastrophic floods overlap parabolic scours and lower portions of pendant bars; HRSC h1154_0001 image.
993 d) Three-dimensional view of Pb2; HRSC image draped on HRSC DTM. e) Close-up of a pendant bar:
994 bedrock projection (Bp) and pendant bar (Pb3) are easily distinguishable. Laterally to the pendant bar, small
995 troughs (solid lines) formed because of enhancement of flow energy: arrows indicate flow direction; wrinkle
996 ridge (Wr) postdates the last depositional event. Portion of MOC E2200200 image. f) Interpretative sketch
997 illustrating development of a pendant bar.
998
999 Fig. 13. a) HRSC mosaic of a cataract-like feature; see fig. 4 for location. Cataract-like feature (C) forms
1000 next to a scarp (F) and successively extends upstream for about 35 kilometers by backward erosion of the
1001 headwall. Grooved terrain (G), pendant bar (Pb) and streamlined upland (Su) occur upstream of the cataract-
1002 like feature. Downstream of the cataract-like feature, all these erosional morphologies disappear; only a few
1003 small streamlined remnants (R) occur. Notice sapping channels (S) emanating from a geological contact
1004 between two different layers forming Noachian plateau, and hanging on Ares Vallis. HRSC h1022_0000 and
1005 h1011_0000 image mosaic. b) Three-dimensional view of the area; HRSC mosaic draped on HRSC DTMs
1006 mosaic; vertical exaggeration = 5.
1007
1008 Fig. 14. a) Several coalescing, flat-floored, depressions (Td), possibly thermokarstic in origin, characterize
1009 materials infilling Eastern Valley Crater. Smaller and shallower depressions (sTd) appear not connected to
1010 others. Eastern Valley incises and postdates the coalescing depressions. Mosaic of HRSC h0912_0000 and
1011 h0901_0000 images; see fig. 1 for location. b) Sketch illustrating a possible geomorphological evolution of

Eastern Valley Crater. Flooding and non-flooding periods alternate. During the flooding period ice-rich deposits were emplaced, while during the non-flooding period ice wasted. The non-flooding period must have been long enough to allow the shaping of thermokarstic depressions.

Fig. 15. a) A bifurcating ridge (Br) outcrops on the valley floor, and possibly represents an ice-walled stream deposit evolved after ice wasting. Black arrows indicate flow directions of the inferred ice-walled stream. A fault (F) truncates the upstream portion of Br. Polygonal terrains (Pt) outcrop at the bottom of closed depressions (which often appear as exhumed impact crater) and postdate Br. Meandering channel (Mc) emanating from the flat-floored impact crater (C) and thermokarstic depressions (Td) etches erosional terraces (t1-t4); Ares Vallis truncates and postdates the meandering channel. HRSC h0945_0000 e h0934_0000 images mosaic; see fig. 1 for location. b) Three-dimensional close-up. Br bifurcates next to a streamlined hill (Sh): the up-convex northern branch of Br suggests that at least this portion of the ice-walled stream flowed in a sub-ice tunnel. Erosional terraces shaped during later catastrophic flood events (t2-t4) are poorly developed with respect to the first one (t1), and then are not easily distinguishable. Notice the meandering channel Mc termination hanging on Ares Vallis. HRSC mosaic draped on HRSC DTMs mosaic. Vertical exaggeration = 3.

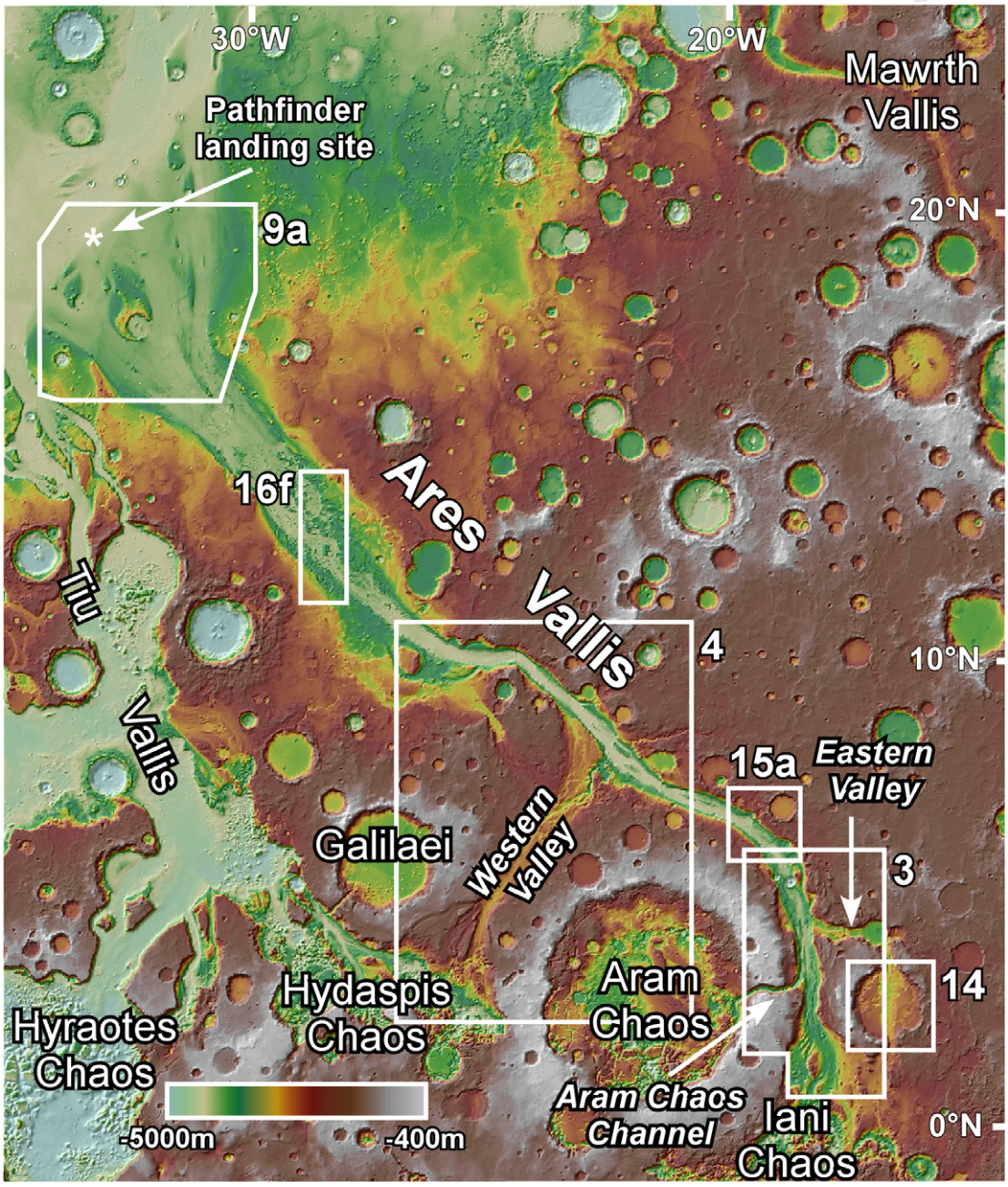
Fig. 16. Close-ups and context image of probable kame features and underlying grooved terrains characterizing Wide Ares Vallis. a) Topmost part of the largest probable kame features appears to be etched by thermokarstic depressions (Td) of which floors streamlined features and patches of underlying grooved terrains (dashed lines) commonly outcrop. b) Polygonal terrains (Pt) surround probable kame features occurring at the inner and deeper portions of the valley. Arrows highlight the layered structures of probable kame features. c) Probable kame features showing reticulated shape (dashed lines). d) Rising rim (Rr) on top of a probable kame feature. Portion of MOC R1800149. e) Individual probable kame features show various layering: a dark layer clearly occurs on the wall of the probable kame K1, while is not observable on the neighboring probable kame K2. Portion of MOC M2001237. f) Context image for image a, b, c, and figure 7. Image HRSC h1066_0000.

Fig. 17. a) Interpretative three-dimensional sketch illustrating relationships among erosional terraces, probable kame features, and the Ares Vallis floor. Sinuous channels partially etch the outermost grooved terraces (t1) and run toward the inner portion of Ares Vallis. Toward downstream, channels turn into elongated, slightly sinuous ridges and mesas (K), which overlie the innermost terraces (t1-2) and extend on valley floor (Vf). THEMIS V12770013, V10012003, and V13394008 mosaic draped on HRSC h0155_0001 stereo-derived DTM; vertical exaggeration = 3. b) Sketch illustrating a possible geological evolution of probable kame features. 1) Subsequent to catastrophic flood processes Ares Vallis was infilled by ice; 2) stream of water carved sinuous channels on both areas uncovered by ice and on the ice mass, emplacing fluvio-glacial deposits; 3) Ice wasting caused the landscape inversion, originating sinuous ridges and mesas consisting of fluvio-glacial deposits. The thickness and spatial distribution of such kame features imply that an ice mass up to hundreds of meters thick infilled Ares Vallis at the time in which fluvio-glacial deposits were emplaced.

Fig. 18. Pitted terrains consist of areas dotted by numerous hollows tens of meters wide. Such terrains show higher radiance values in THEMIS IR nighttime image with respect to nearby areas (see the color-coded bar). Association of such morphological and thermal properties suggests that ground-ice occurred in the past (and possibly at the present day) and that pits originated by ground-ice wasting. a) In the terminal reach of Aram Chaos Channel, pitted terrains occur exclusively at the valley floor (Vf), and they lack on valley walls and terraces (T); data fusion of MOC E0301279 and THEMIS IR Night mosaic; see fig. 3 for location. b) On the floor of Eastern Valley Crater, pitted terrains occur on top of crater floor deposits (Cf), and as patches at the bottom of thermokarstic depressions (Td), where they are less distinguishable. Walls of thermokarstic depressions show layering (at least four) tens of meters thick; arrows indicate boundaries (b1, b2, b3) among different layers. Data fusion of MOC E1700126 and THEMIS IR Night mosaic; see fig. 14 for location.

Fig. 19. Three-dimensional view of a portion of the narrow reach of Ares Vallis. Here valley terrace collapsed as a slump that overlaps and postdates grooved terrains (G) and valley floor. The slump deposit shows a pitted patterned surface (P), suggesting burying of ice and the following activity of periglacial processes. Notice the thermokarstic depressions (Td) etched on the terrace. HRSC h0934_0000 and h0923_0000 images mosaic draped on HRSC DTMs mosaic; vertical exaggeration = 3.

Fig. 20. Sketch (not to scale) illustrating cyclic events responsible for sculpting of Ares Vallis. 1) An enormous flood discharged from chaotic terrains and sculpted Ares Vallis. 2) It shaped grooved terrains and other erosional morphologies at its base, while ice cover formed on its top because of Martian climatic condition. Grooved terrains form by powerful vortices acting at the base of the flood. 3) During the waning stage of flood, a relatively thin sheet of water flowed at the bottom of a thick ice-cover. In this condition, sculpting of grooves was enhanced. 4) At the end of the flood the ice-cover grounded on the valley floor forming a thick mass of dead-ice. Climate started to be warmer and wetter because of greenhouse effect of water vapor and carbon dioxide/methane gas released during catastrophic floods. 5) Such climatic condition favored ice melting and allowed presence of liquid water on the surface, which etched the ice mass forming ice-walled channels and lakes, besides thermokarstic depressions. 6) Greenhouse effect faded and liquid water disappeared from the surface. Climate progressively came back to cold-dry conditions. 7) In such climatic condition ice continued to waste by the prevailing sublimation process. Materials deposited on the floor of ice-walled channels and lakes became kame features, which overlie both grooved terrains and streamlined features. The pristine appearance of grooved terrains and kame features suggests that colder-dryer conditions prevailed during most part of ice-mass wasting. 8) Ice mass totally wasted and it caused the ice-contact features to be overlying erosional features. If some catastrophic floods occurred during wet-warm climatic conditions, they probably were ice-free. In this case floods simply deepened Ares Vallis, removing ice masses and ice-related features occurring on the valley floor.



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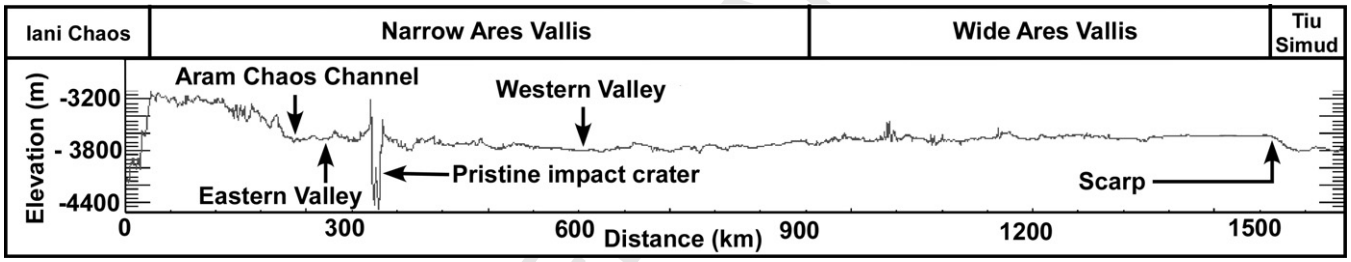

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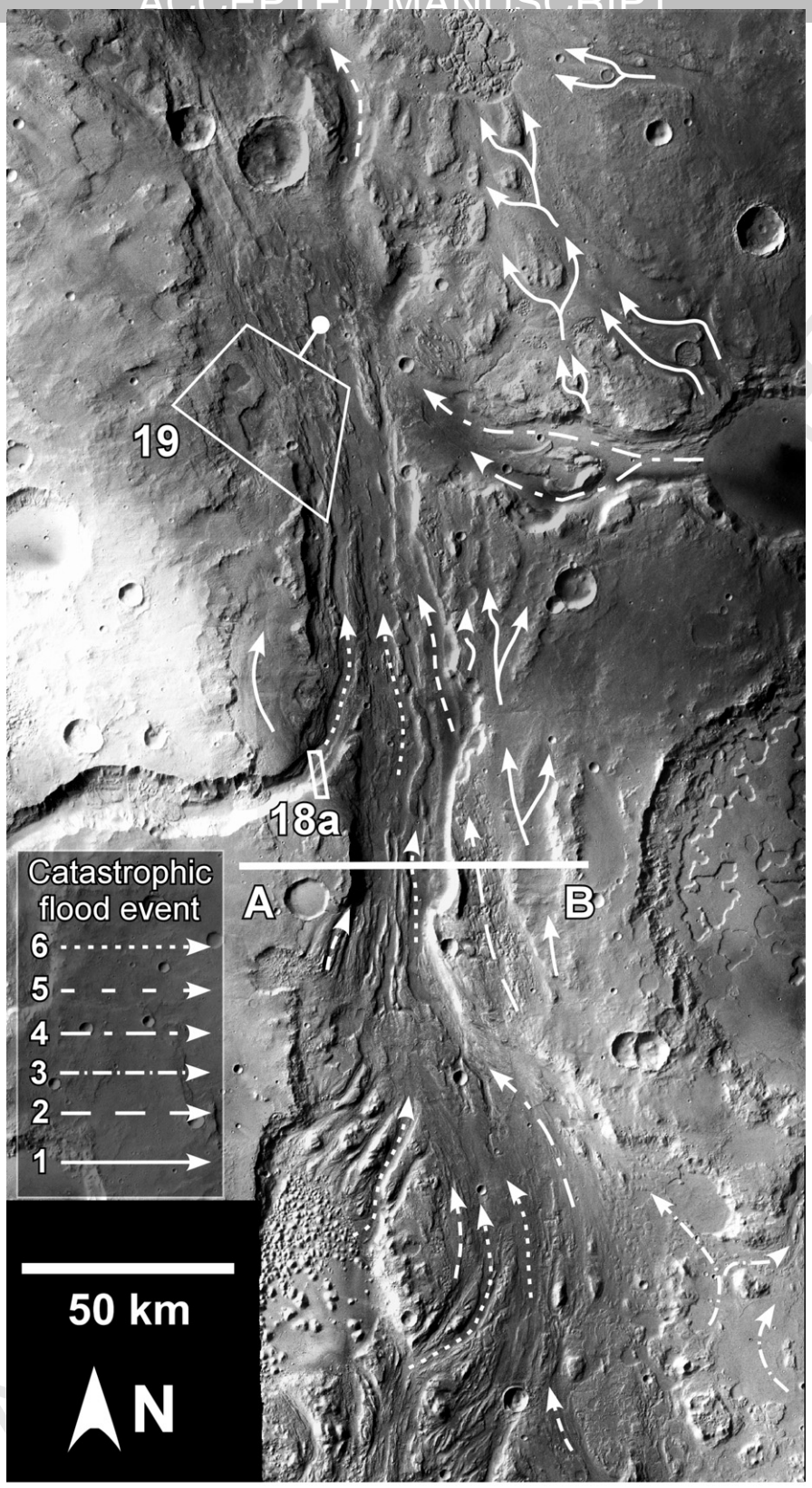

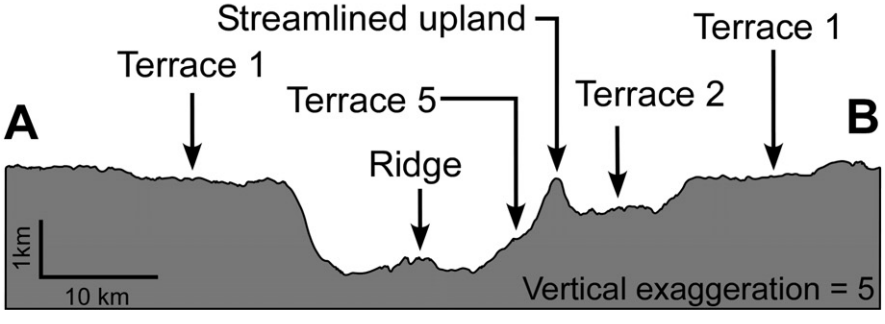

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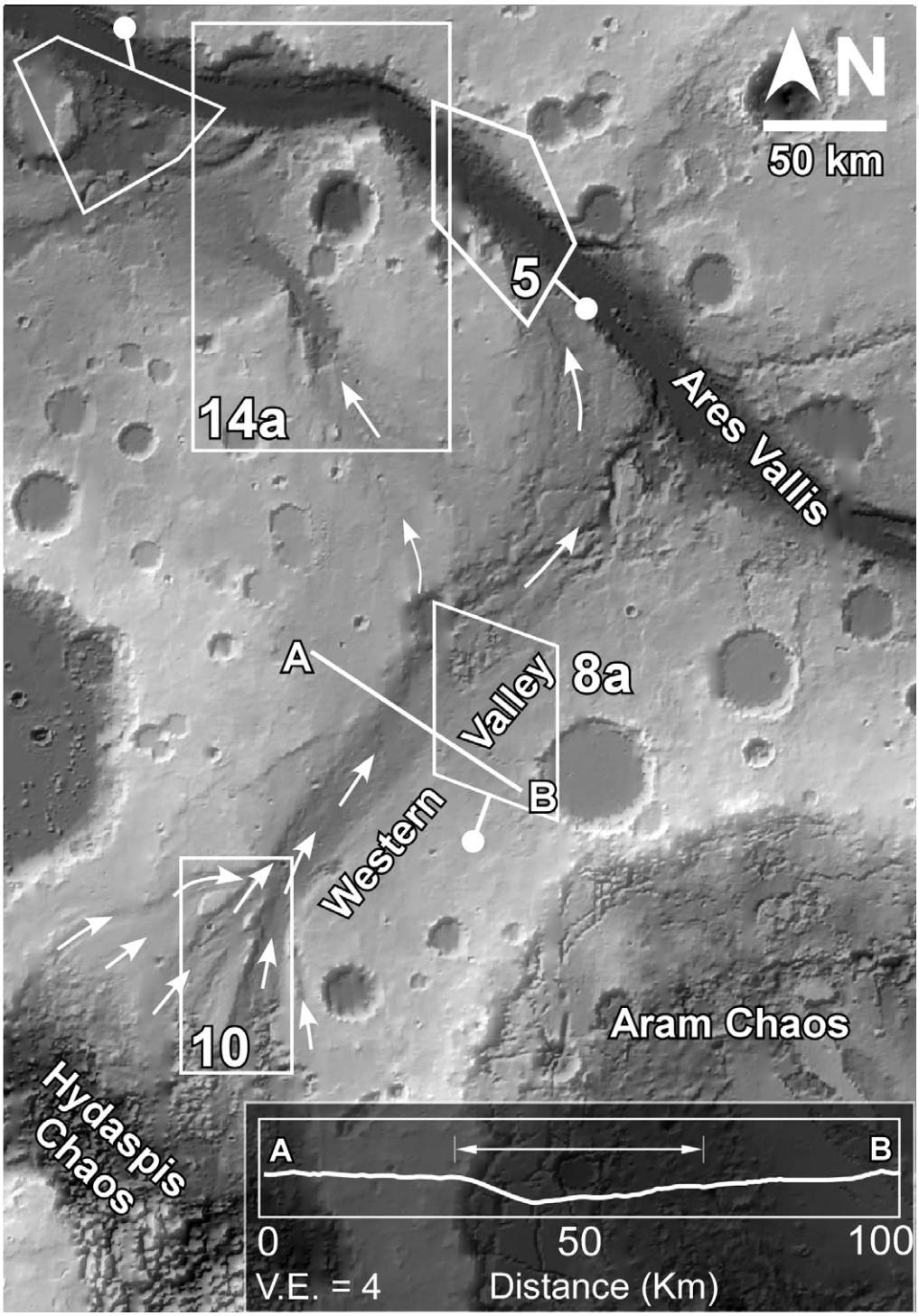

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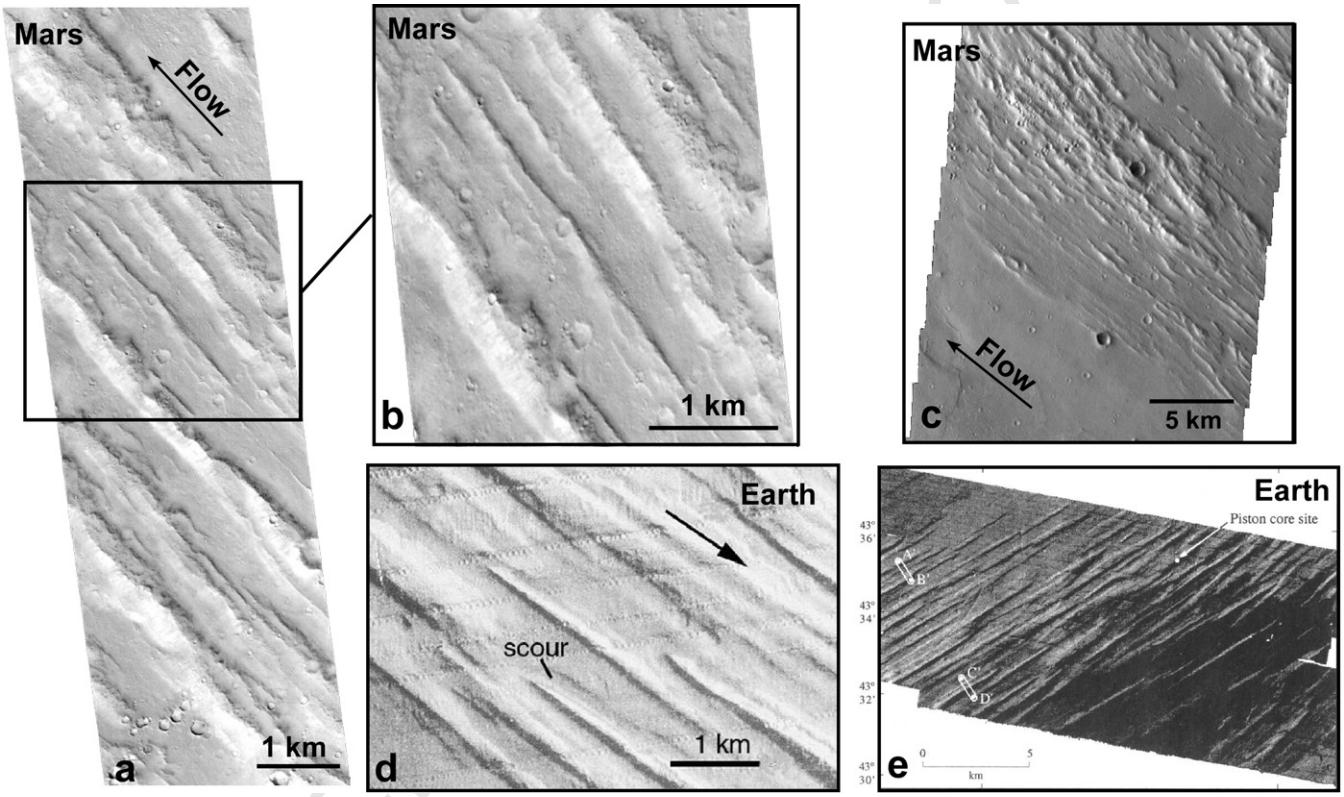

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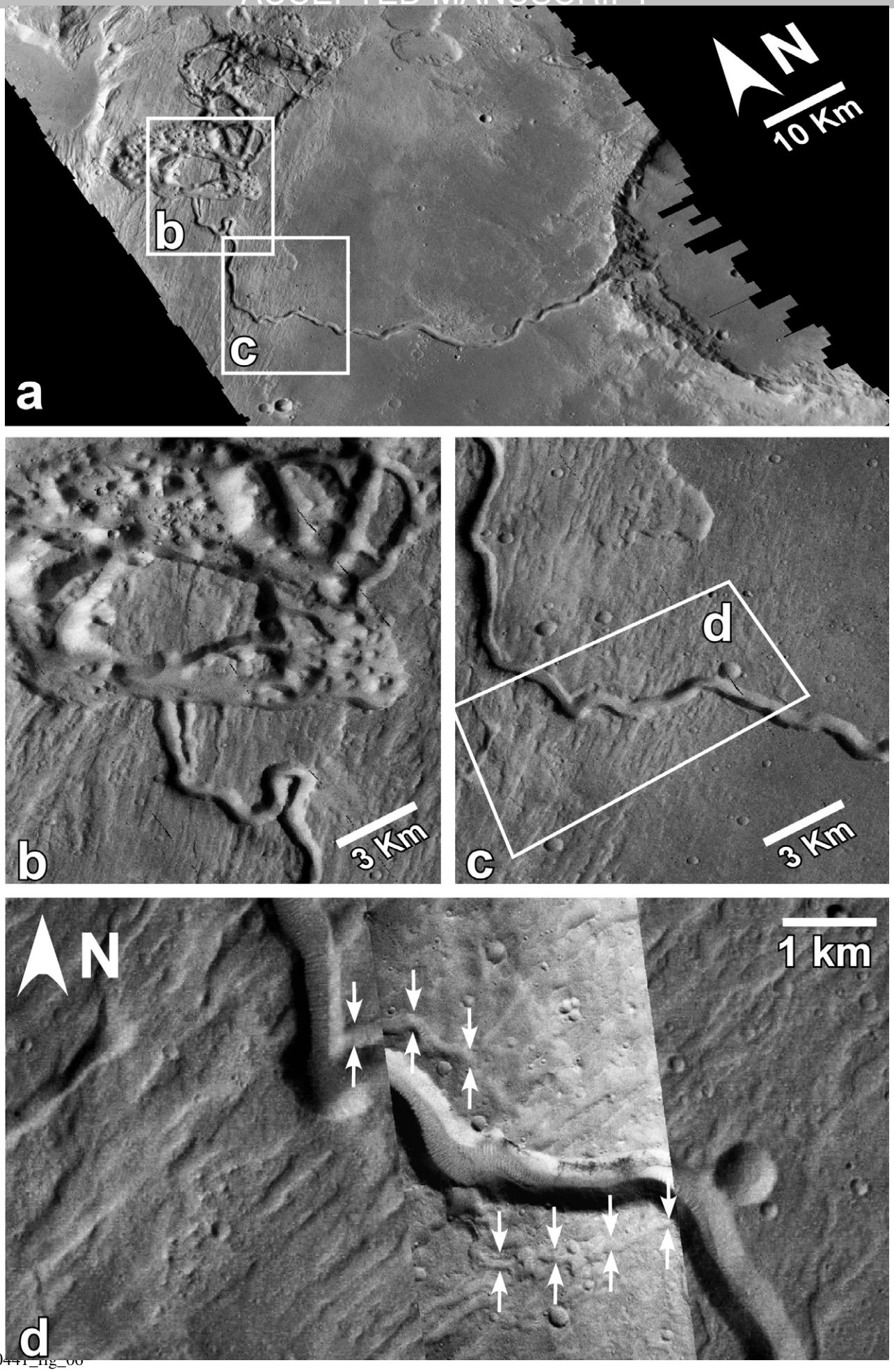

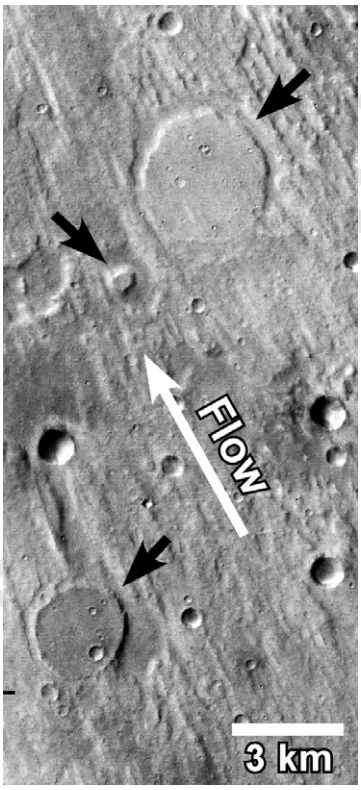

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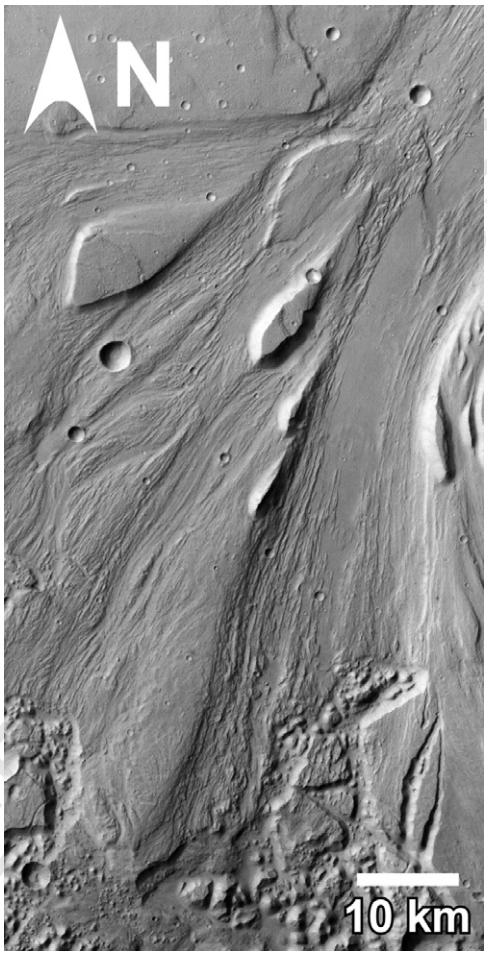

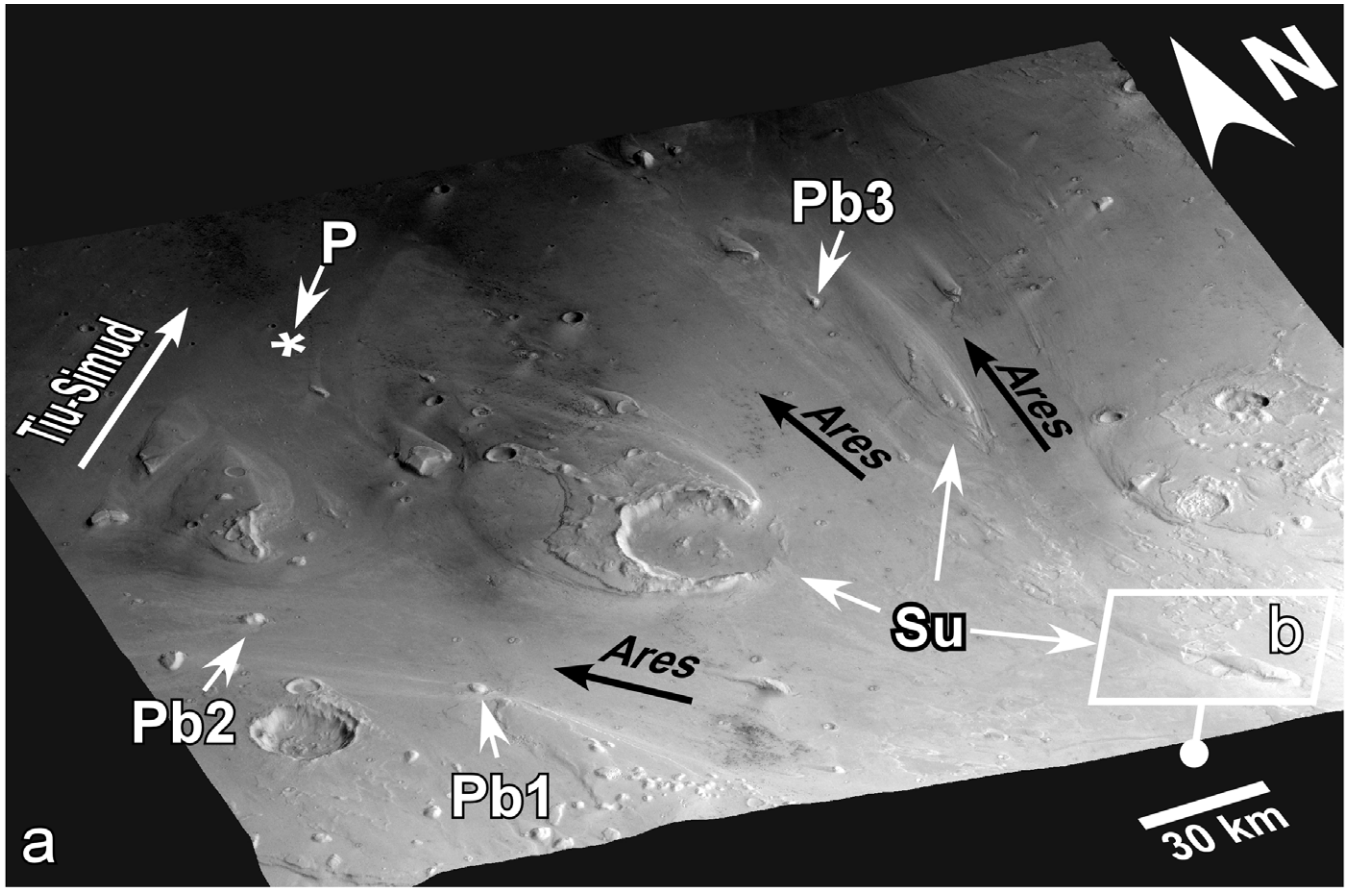

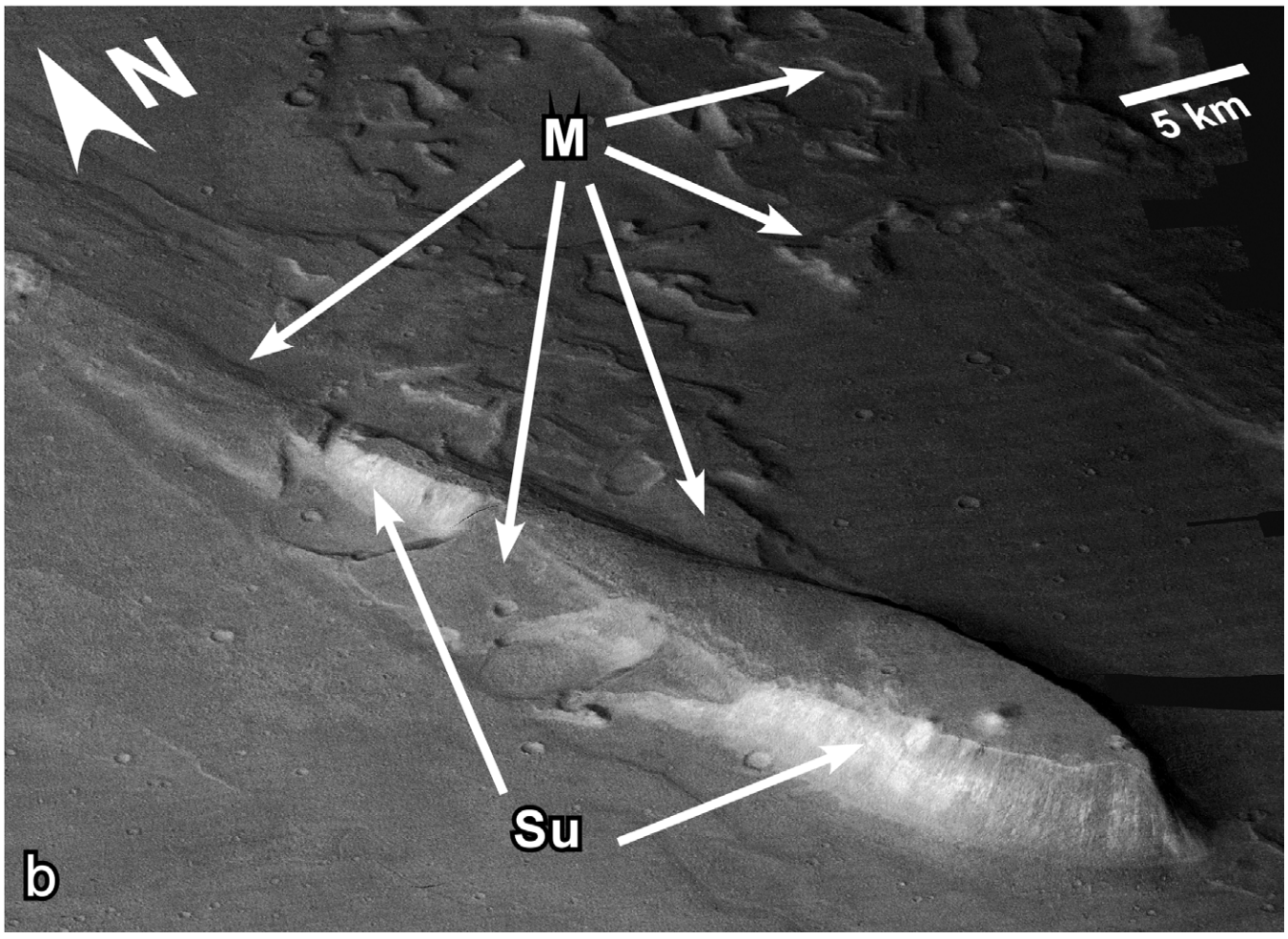

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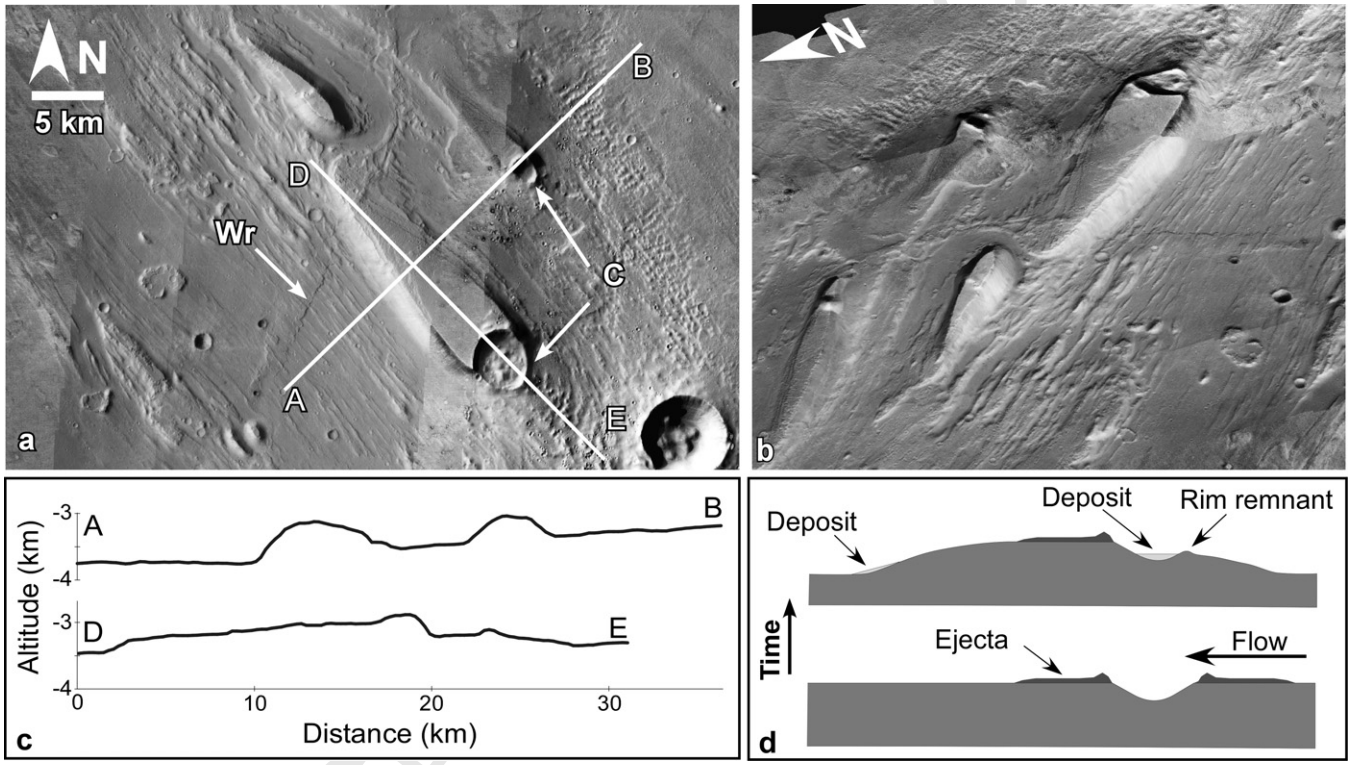

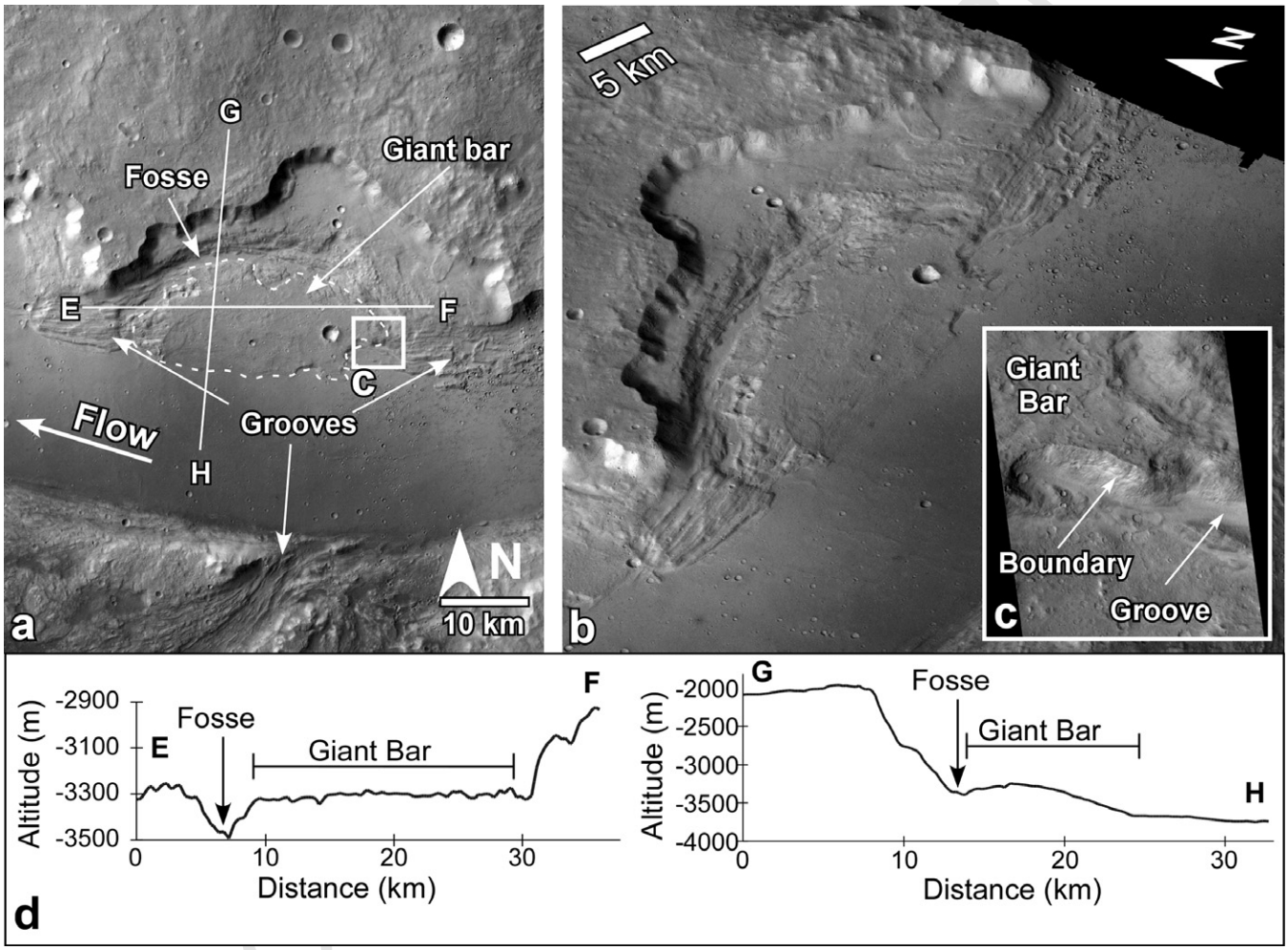

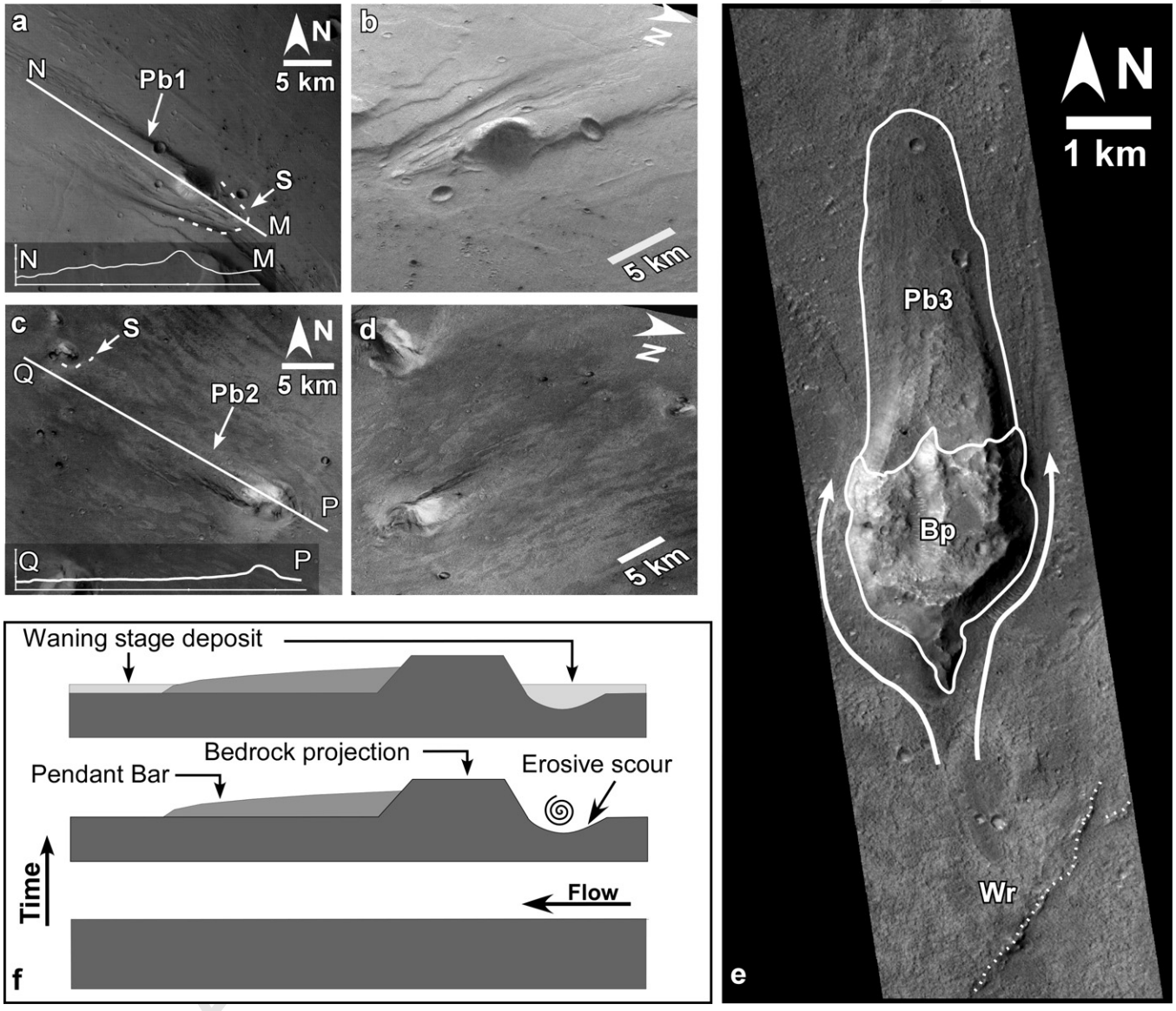
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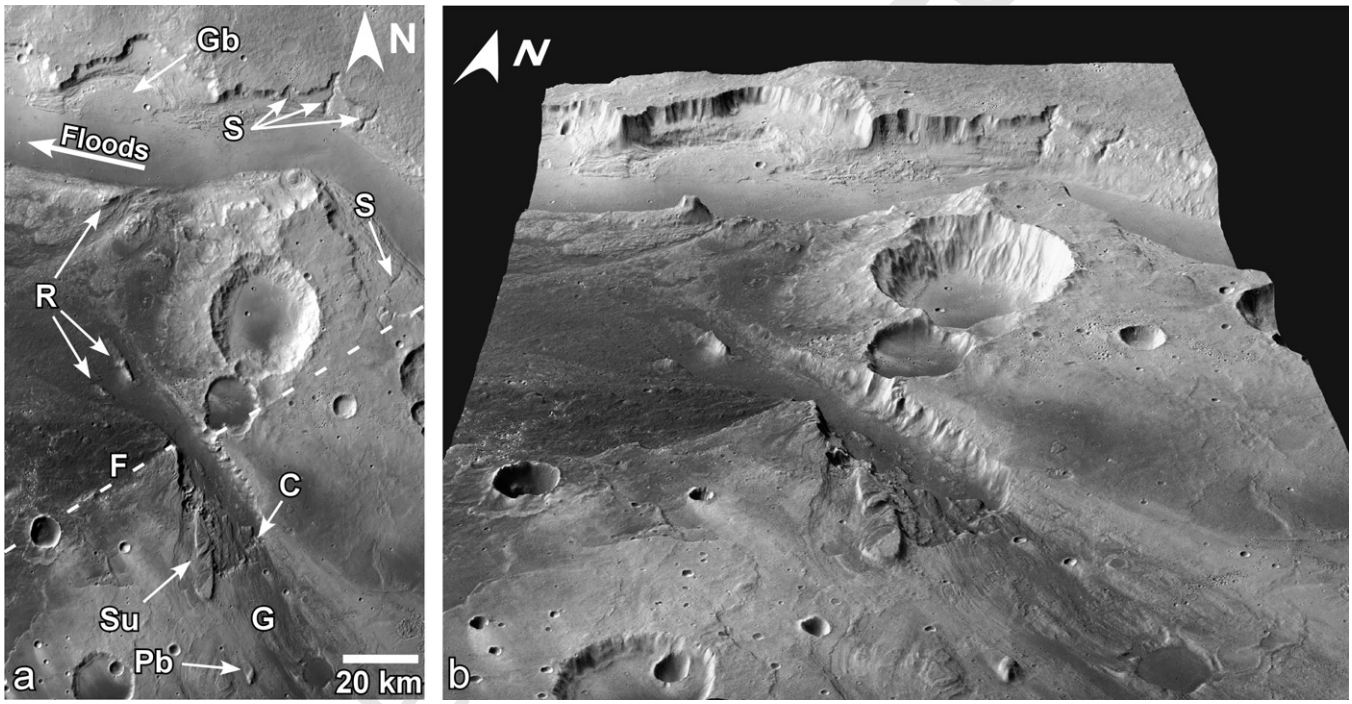

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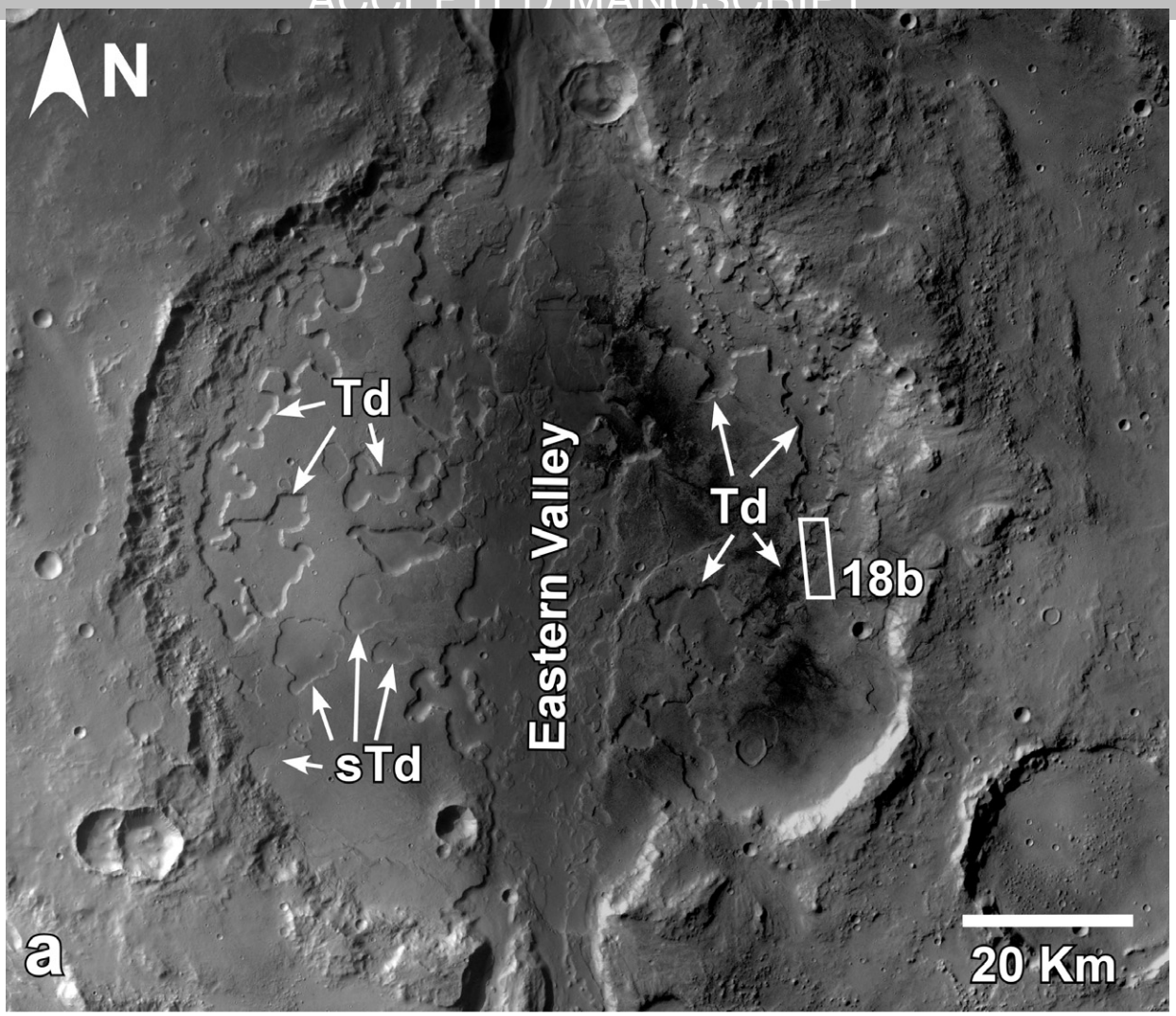

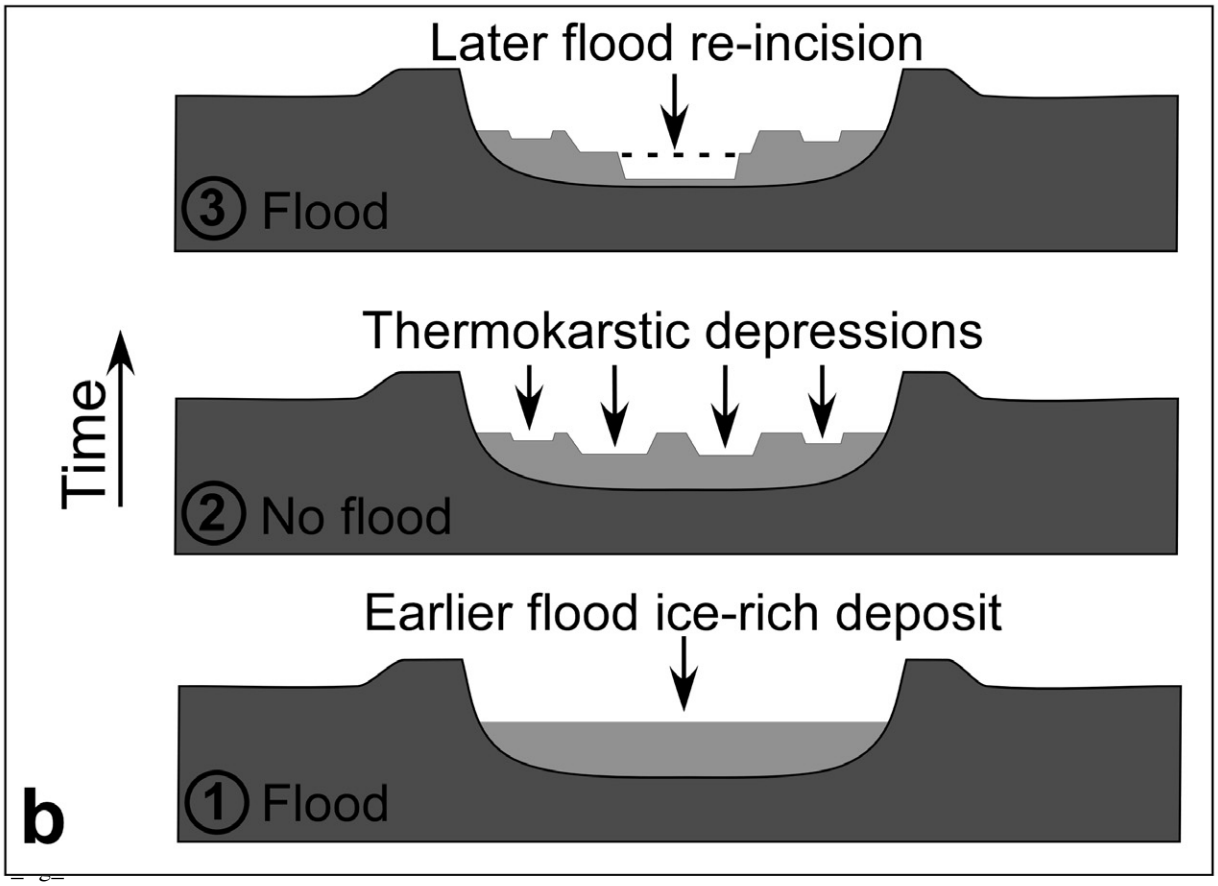

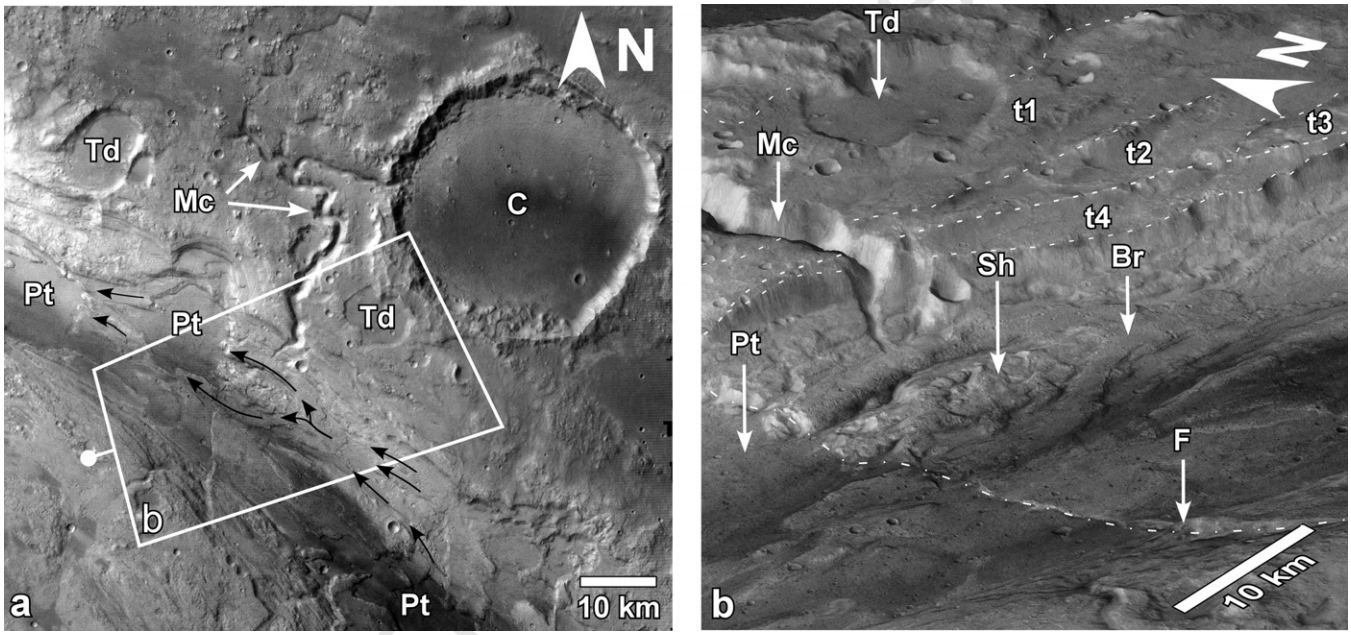

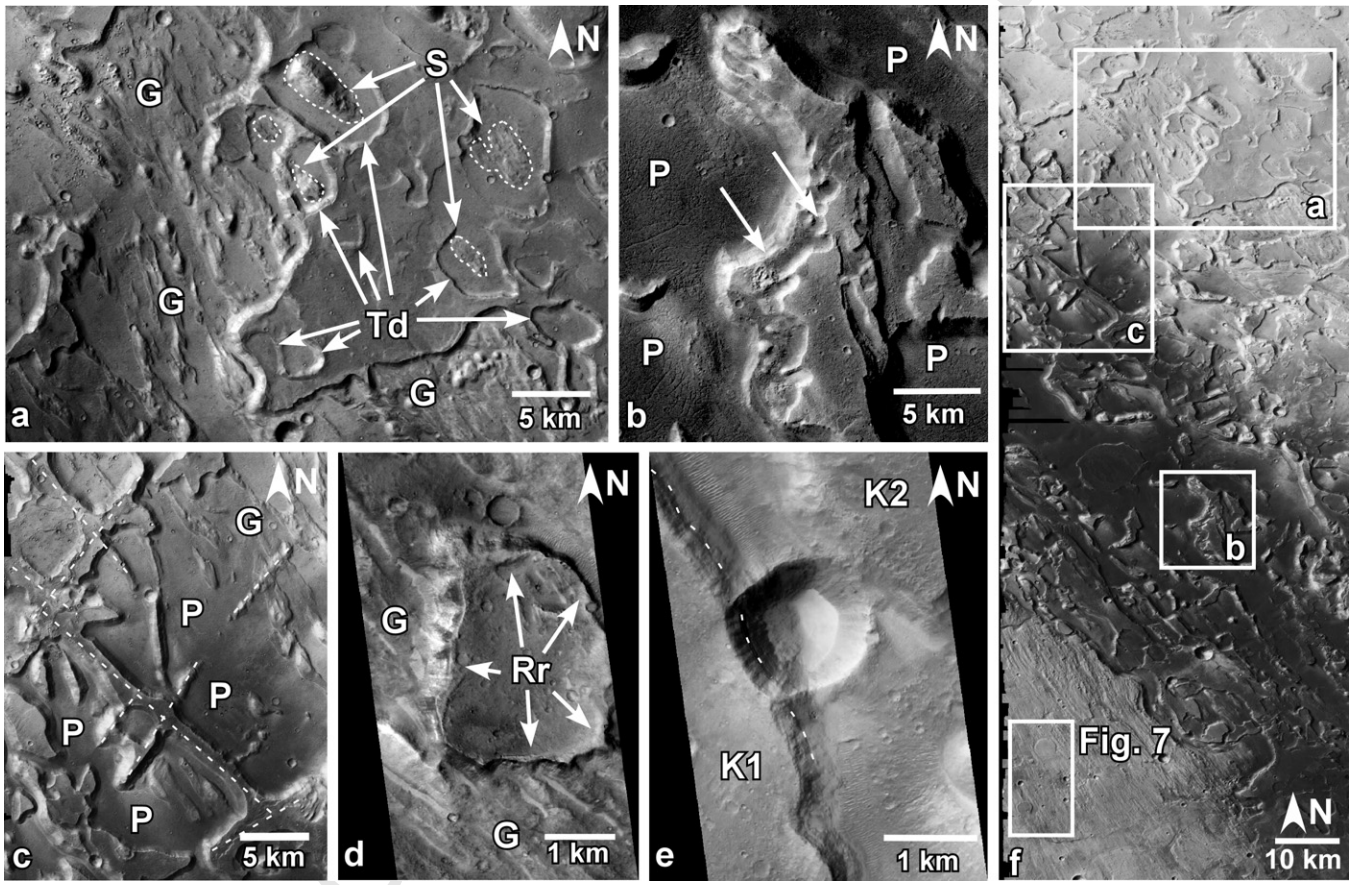

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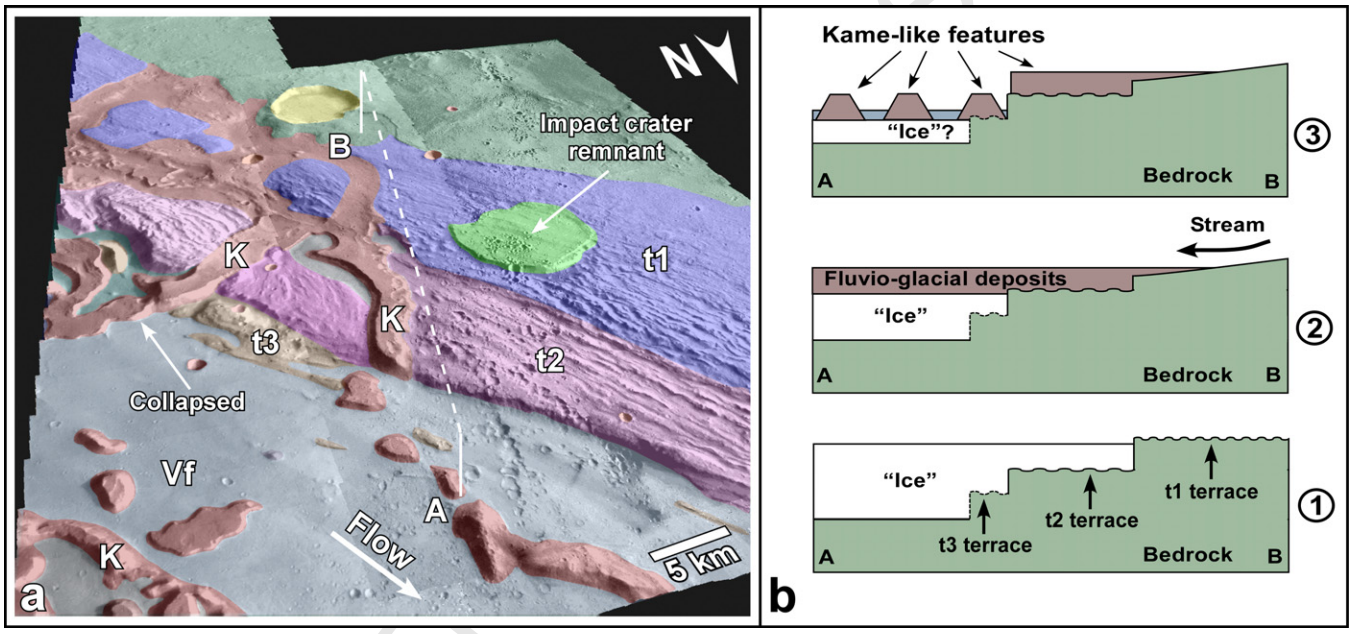

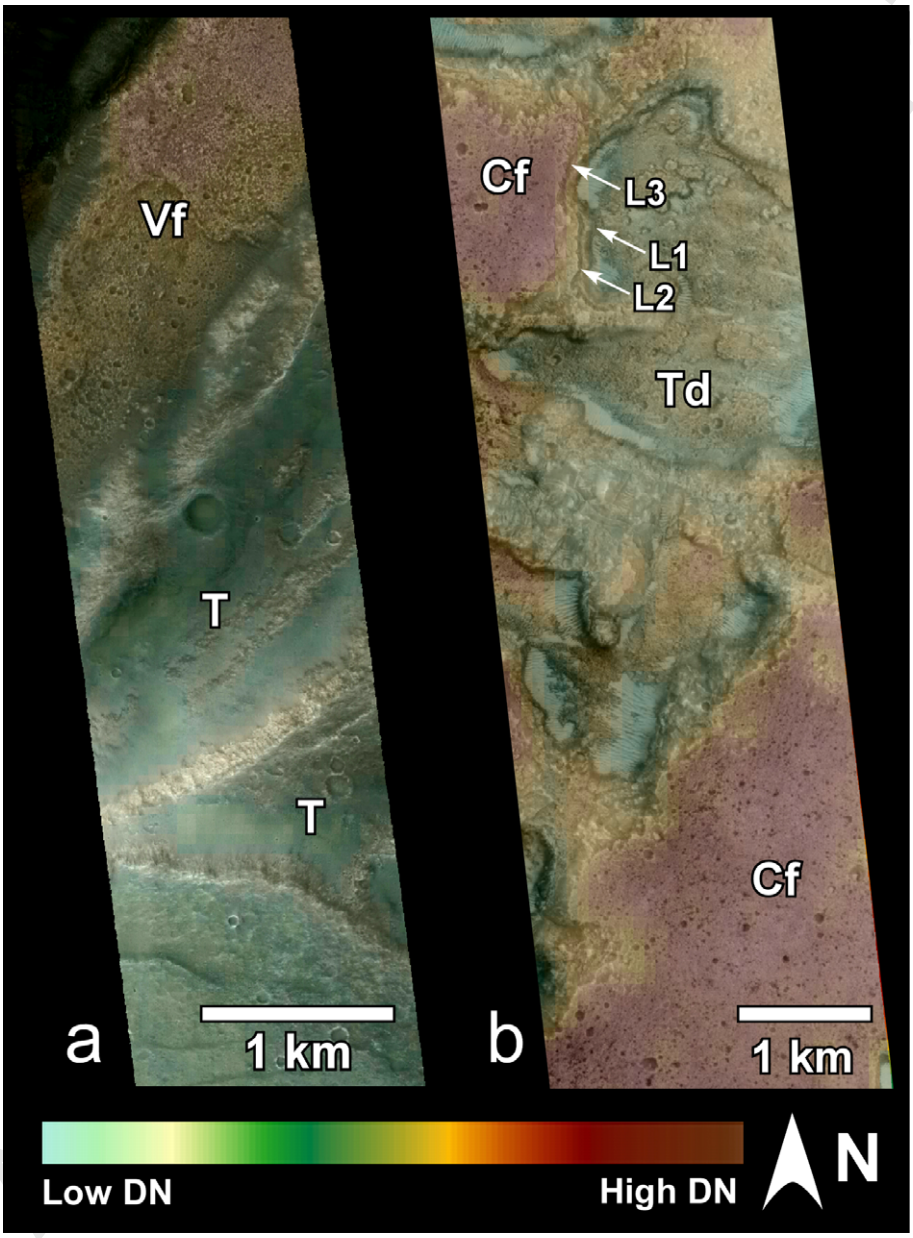

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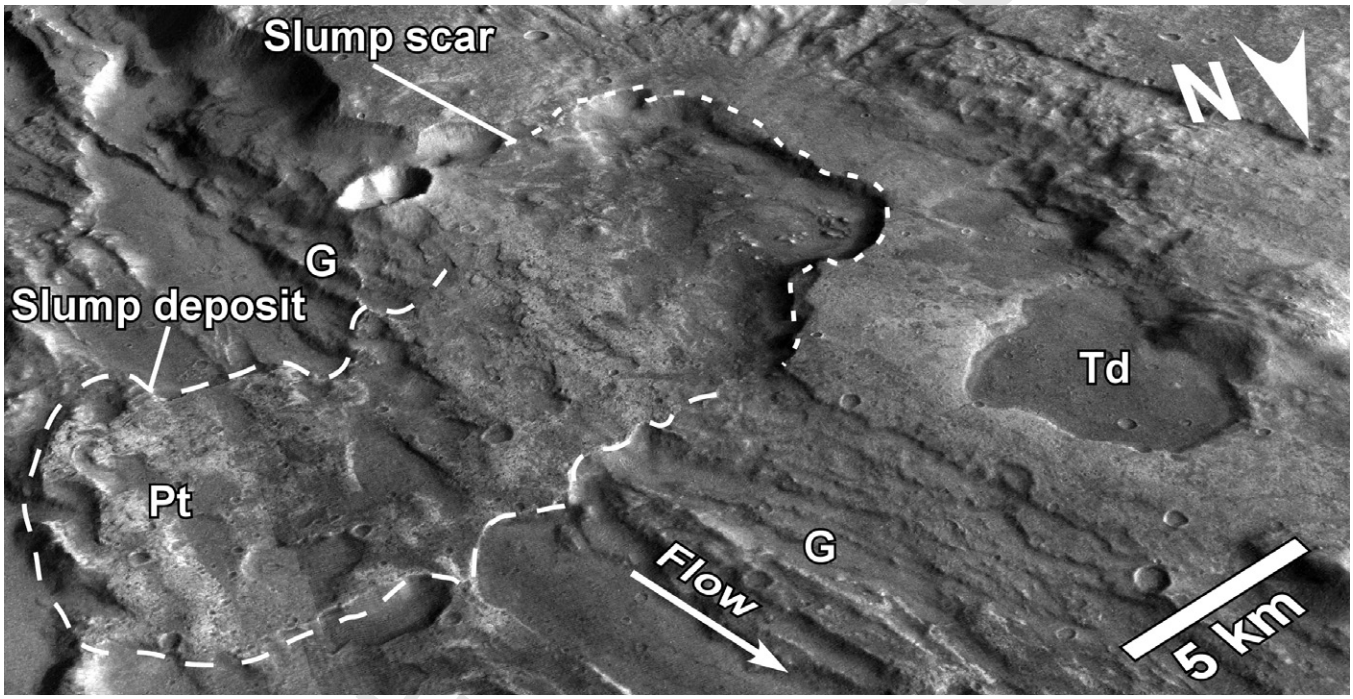

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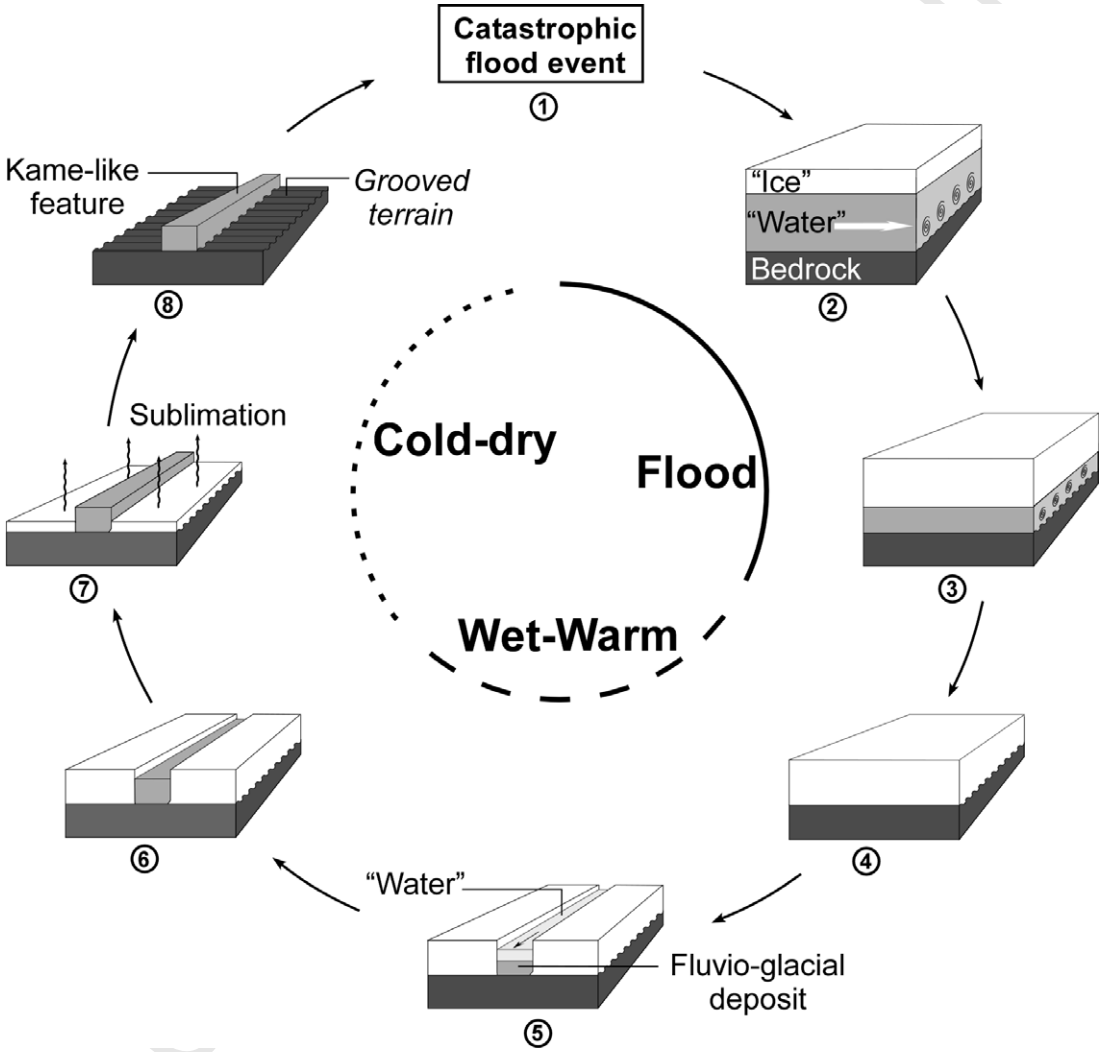

I10441_fig_20