Fluvial morphology of Naktong Vallis, Mars: A late activity with multiple processes

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**A B S T R A C T**

The morphology of fluvial valleys on Mars provides insight into surface and subsurface hydrology, as well as to Mars’ past climate. In this study, Naktong Vallis and its tributaries were examined from high-resolution stereoscopic camera (HRSC) images, thermal emission imaging system (THEMIS) daytime IR images, and mars orbiter laser altimeter (MOLA) data. Naktong Vallis is the southern part of a very large fluvial basin composed by Mammers, Scamander, and Naktong Vallis with a total length of 4700 km, and is one of the largest fluvial system on Mars. Naktong Vallis incised along its path a series of smooth intercrater plains. Naktong's main valley cut smooth plains during the Early Hesperian period, estimated \( \sim 3.6-3.7 \) Gyr, implying a young age for the valley when compared to usual Noachian-aged valley networks. Branching valleys located in degraded terrains south of the main Naktong valley have sources inside a large plateau located at more than 2000 m elevation. Connections between these valleys and Naktong Vallis have been erased by the superimposition of late intercrater plains of Early to Late Hesperian age, but it is likely that this plateau represents the main source of water. Small re-incisions of these late plains show that there was at least one local reactivation. In addition, valley heads are often amphitheatre-shaped. Despite the possibility of subsurface flows, the occurrence of many branching valleys upstream of Naktong’s main valley indicate that runoff may have played an important role in Naktong Vallis network formation. The importance of erosional landforms in the Naktong Vallis network indicates that fluvial activity was important and not necessarily lower in the Early Hesperian epoch than during the Noachian period. The relationships between overland flows and sapping features suggest a strong link between the two processes, rather than a progressive shift from surface to subsurface flow.

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1. Introduction

Since the beginning of Mars orbital explorations, valley networks have been identified in the heavily cratered terrain located in the southern hemisphere of Mars (e.g., Milton, 1973; Schultz and Ingersoll, 1973; Sharp and Malin, 1975; Carr and Clow, 1981; Mars Channel Working Group, 1983; Carr, 1996). Valleys are usually arranged in a branching pattern similar to that of fluvial valley networks on Earth, suggesting that they were formed mainly by liquid water flows when the Martian climate may have been warmer than today (Carr, 1981; Gulick, 2001; Craddock and Howard, 2002). Valley networks were incised into Noachian, \( > 3.7 \) Ga, heavily cratered terrain without affecting younger terrains, suggesting that they were formed at the end of the Noachian period and or at the beginning of the Hesperian (Hr) period (Tanaka, 1986; Scott and Tanaka, 1986; Greeley and Guest, 1987; Carr, 1996; Hartmann and Neukum, 2001; Irwin et al., 2005a; Fassett and Head, 2008). Valley networks have also incised preferentially into large impact crater rims (Craddock and Maxwell, 1993; Craddock et al., 1997; Craddock and Howard, 2002; Forsberg-Taylor et al., 2004) and upland regions where the regional slope is sufficiently high, slope \( > 1 \) (e.g., Baker, 1988; Brakenridge, 1988; Craddock and Howard, 2002; Ansan and Mangold, 2006; Ansan et al., 2008). The presence of valleys on flatter terrains is still debatable, since valley networks often disappear into smooth, ridged, and flat regions located between large degraded impact craters (Baker, 1982). These regions, called ridged intercrater plains, have been mapped as Late Noachian plains (e.g., Nplr) or Early Hesperian plains (Scott and Tanaka, 1986; Greeley and Guest, 1987) depending on crater density. The nature and origin of these plains remains uncertain. Plains may be...
composed of a mixture of impact debris and melt products (Mouginis-Mark et al., 1981); volcanic flows (Greeley and Spudis, 1978; Tanaka, 1986; Brakenridge, 1988; Greeley and Guest, 1987); or sedimentary rocks (Malin, 1976; Scott and Carr, 1978) including aeolian (Moore, 1990), fluvial (Scott and Tanaka, 1986; Greeley and Guest, 1987), and lacustrine deposits (Carr, 1981; Greeley, 1985; Irwin and Howard, 2002).

Understanding hydrologic and chronological relationships, between dissected heavily cratered terrain and non-dissected intercrater plains is important for determining the early Martian water cycle, and many questions remain. For example, we still do not understand when intercrater plains formed relative to fluvial valleys, or how their formation interacted with the presence of liquid water. Questions of this nature were examined in the study area of Terra Sabaea, 30°S–40°N, 10°E–75°E, which contains many highlands, intercrater plains, and large craters, Fig. 1. Terra Sabaea is located south of the Martian dichotomy, dipping ~0.2° northward with a maximum elevation of 5 km, north of the Hellas basin boundary. The largest impact craters of Terra Sabaea are Huaygens, Schiaparelli, and Tikhonrovov, which are characterized by a high degree of degradation. Terra Sabaea has several >300 km valleys (e.g., Indus Vallis, Mamers Vallis, Scamander Vallis, and Naktong Vallis) whose downstream direction is controlled by the regional slope to the northwest, Fig. 1. In this region, Naktong, Scamander, and Mamers form a single-valley system, if we assume that the three valleys were once connected, and that intercrater plains formed later than valleys or were intermediary lakes (Irwin et al., 2005a), Fig. 1. The Naktong, Scamander, and Mamers valley system is the longest organized valley on Mars, with a total length of 4700 km. The valley system, Fig. 1, starts close to the summit of Terra Sabaea, 5°S–40°E, ~3 km in elevation, crosscuts the whole Arabia Terra, and debouches northward into Deuteronilus Colles, 47.6°N–7.2°E, ~4 km in elevation. The valley crosses different geologic units from a Noachian age (Hoke and Hynek, 2008) to an Early Hesperian age (McGill, 2000; Fassett and Head, 2008), that may have involved different formation processes—from predominant runoff in Naktong Vallis (Irwin et al., 2005a) to more sapping controlled valleys in Mamers Vallis (McGill, 2000; Carr, 2001).

Our study focused on the source area of the Naktong Vallis basin, centered at 5.24°N–32.9°E. Questions still remain regarding the origin of the flows that created such a large and long valley system with putative lacustrine systems. The size of the valley system suggests a terrestrial-like hydrologic flow to sustain liquid water. However, the valley network geometry presented in our study indicates a low number of tributaries in the source region that question the role of overland flows in creating Naktong Vallis. When compared to previous studies completed using mars orbiter laser altimeter (MOLA) topographic data (Smith et al., 1999) and thermal emission imaging system (THEMIS) infrared (IR) datasets at 100 m/pixel (Christensen et al., 2003), our study contains improved data from high resolution visible images, 10–20 m/pixel, acquired by the high-resolution stereoscopic camera (HRSC) onboard the Mars Express orbiter (Neukum et al., 2004). Using this data, we focused on relationships between different geologic units, especially, intercrater plains and fluvial landforms inside the Naktong basin, to determine when valley networks formed and which processes controlled their formation.

2. Data

We used nine panchromatic nadir images acquired by the high resolution stereo camera of Mars Express (Neukum et al., 2004; Jaumann et al., 2007) that have a spatial resolution ranging from 10 to 15 m/pixel at the image center (orbits #h1917, h1928, h1950, h1961, h1972, h1994, h2005, h2027, and h3183). We mosaicked images at a spatial resolution of 20 m/pixel to obtain a regional map, Fig. 2.

HRSC images do not cover the whole region of Naktong Vallis. Therefore, we completed the study area with a mosaic of the thermal emission imaging system (Christensen et al., 2003) daytime infrared images, Fig. 2, having a spatial resolution of 230 m/pixel. These datasets allowed us to map the whole Naktong Vallis network and the different geologic/geomorphic terrains with classical photo-interpretation methods.
Additionally, we use altimetry data acquired by the Mars orbiter laser altimeter (Smith et al., 1999). MOLA data are useful for determining the drainage basin of Naktong Vallis, Fig. 3, and for extracting the geometric properties of watersheds and valleys. Utilized data have a spatial resolution of \( \frac{1}{240} \) km/pixel and a vertical accuracy of \( \frac{1}{1} \) m, Fig. 3. The data were ortho-rectified on the Martian ellipsoid with an equatorial axis of 3396.19 km and a polar axis of 3376.20 km as defined by the International Astronomical Union as Mars IAU 2000 (Seidelmann et al., 2002), for a sinusoidal projection centered at the 35° E meridian. Geographic coordinates followed the Martian standard coordinate system with planetocentric latitudes and east longitudes (Duxbury et al., 2002).

3. General context and main geologic units

Before discussing the morphometry and properties of the Naktong drainage basin in detail, here, we define the different units and landforms of interest in the study, as well as the main questions derived from direct observations.

Using MOLA digital elevation data at \( \frac{1}{128} \) resolution, we determined the geometry for the drainage basin of the Mamers/Scamander/Naktong Vallis system with Rivertools software providing automatic delineation of the drainage basin, Fig. 4. Part of the Naktong drainage basin is a sub-basin located in the south of the larger drainage basin of the Mamers/Scamander/Naktong Vallis system. Western and southern boundaries of the Naktong sub-basin correspond to automatic limits of the Mamers/Scamander/Naktong Vallis system. Northern and eastern boundaries were defined manually by locating topographic crests using MOLA data, at \( \frac{1}{64} \) resolution. The Mamers Vallis and its main tributaries incise the northern and western part of this sub-basin, leaving a large undissected fraction.

Naktong Vallis is oriented NW–SE, S1 segment AA’ on Fig. 3, and is defined as a continuous sinuous lineament starting from A’, 5°N–38.5°E, south of the Janssen impact crater to the South–East of the Arago impact crater, Fig. 5a, point A, 9.3°N–31.6°E. Point A’ is the main head as mapped by Irwin et al. (2005a) and also appears as the main head from our mapping analysis (the main head is defined as the point that is farthest away from the outlet and continuous to the outlet). The total length of Naktong Vallis is approximately 950 km (Irwin et al., 2005a). The valley belongs to a broad watershed with an extremely low number of tributaries, as also determined by Irwin et al. (2005a). The presence of a small number of tributaries and the presence of large undissected sections of the drainage basin lead to questions regarding the origin of the valley from overland flow. For example, these characteristics could have resulted from a surge channel similar to an outflow channel or from a sapping-dominated valley such as Nirgal Vallis. Irwin et al. (2005b) observed an inner channel inside the valley, 0.26°N and 36.58°E, close to the point A for which they determined a discharge of \( \approx 2700 \) m³/s, suggesting terrestrial-like river flow activity. Our interest is to better understand apparent contradictions by examining the geometry and the lithology. Naktong Vallis incises continuously into smooth and flat terrains.
Fig. 5. (a) A close-up of the northern part of Naktong Vallis determined using a combination of MOLA data (460 m/pixel) and THEMIS daytime IR (230 m/pixel). Naktong Vallis debouches at point A located south-east of the Arago impact crater. Black boxes correspond to the location of Fig. 8a and d, and Fig. 11a and b. (b) A close-up of the southern part of Naktong Vallis determined by using a combination of MOLA data (460 m/pixel) and THEMIS daytime IR (230 m/pixel). Naktong Vallis and its direct tributaries were incised continuously inside smooth plains. A', the main source of Naktong Vallis, is located at the edge of discontinuously and continuously incised plains. Black boxes correspond to the location of Fig. 8b and c, and Fig. 11e. WR corresponds to the locations of wrinkle ridges.
along most sections of its path, Fig. 5b. A close look at these terrains show that they are smooth in images at a HRSC resolution of 20 m/pixel, and flat from the MOLA topography, except for the presence of a few wrinkle ridges, Fig. 5b. The terrains are intercrater plains devoid of large impact craters and hilly topography, characteristics of Martian-dissected highlands. The fact that Naktong Vallis dissects these plains shows a chronological relationship implying a younger age for the valley than for the plains. In the following discussion, we refer to these plains as continuously incised plains (Clpl), because they are cut continuously by Naktong Vallis or one of its tributary. The main head of Naktong Vallis is a single head located in an intercrater plain, Fig. 5b, point A', 5 N–38.5 E. This plain, as well as few others in the basin, are not dissected continuously by valleys despite showing local incision; therefore, they are referred to as discontinuously incised plains (Dipl).

Branching valley networks were observed in the southern part of the drainage basin, sections S2 and S3 in Fig. 3. These valley networks do not connect to the main heads of Naktong Vallis or its tributaries. Despite the fact that no divide separates them from the Naktong valley network, they are separated by discontinuously incised plains. Branching valley networks occur inside terrains that are rougher and steeper than the plains, Fig. 6. Most of these terrains do not look like heavily cratered terrains of typical highlands (no large impact and smoother texture than usual highlands). For this reason, we refer to them as degraded terrains (Dter); those units incised by many valleys in the southern part of the Naktong drainage basin. Irwin et al. (2005a) also observed the existence of branching valley networks and proposed that these valleys are separated from the head of Naktong Vallis by shallow intercrater basins. The outlets of branching valley networks are located at the southern edge of two discontinuously incised plains. Therefore, these valley systems, S2 and S3, are located upstream to the southern part of Naktong Vallis in the same watershed, and in a consistent flow direction from south-east to northwest, only separated from Naktong Vallis by intercrater plains. Many questions remain. Are branching valley networks parts of the same hydrologic system as Naktong Vallis? Did they once connect to Naktong Vallis through the subsurface of intercrater plains? Did they connect to Naktong Vallis before the plains formed? If so, why do valley heads of Naktong Vallis incise these late plains? These questions are important to answer in order to understand the chronology of these valleys relative to the formation of plains, the processes that drained water in the broad Naktong watershed, and types of hydrologic activity.

In summary, Naktong Vallis is a very long valley with few tributaries for which formation through long-term fluvial processes is questionable. The key points of our study show connections of fluvial landforms with the different geologic units. Understanding differences in landforms from one valley system to the others is helpful for understanding the level of activity in different units. In order to establish the relative age of valleys and plains, we focused on the detailed geometry of valley heads and crater counts to distinguish intercrater plain ages, which in turn helped us to constrain the timing of valley formation.

4. Morphology of valleys relative to geologic units

4.1. Relationship between intercrater plains and valleys

4.1.1. Morphology of valleys inside intercrater plains

Continuously incised plains mapped in dark green, Fig. 7c, are continuously cut by Naktong Vallis, segment AA, or tributaries. In the upstream area, plain γ, Fig. 7c, close to A', Naktong Vallis has an E–W trending, approximate constant width of ~4 km, and a relatively deep cross-section, ~200 m, with a meander-shape. Naktong Vallis then reaches a chaotic zone, CA, in Figs. 5b and 7c, where the valley is less defined in topography. A close-up on this chaotic zone, Fig. 8b, indicates that the surface is strongly degraded by erosion, implying that this area was filled by weak material later removed by erosion. Due to its circular shape, we interpret this chaotic area as an old impact crater that may have been filled with sediment. Downward from this chaotic area, plain β, Fig. 7c, Naktong Vallis continues its meandering path, but with a more jagged pattern between rimless impact craters. Before joining a ghost crater west of the Arago impact crater, 10.09 N, 29.80 E, Naktong Vallis continues its path inside plain γ, Fig. 7c, with a constant width of around ~4 km. Its outlet, point A in Fig. 5a, vanishes into a smooth floor ghost impact crater located east of the Arago crater, Fig. 8a. Fig. 8a shows that the crater floor is filled by smooth plain material deformed by wrinkle ridges and few local knobs, encircled in Fig. 8a. The knobs may correspond to residual hills of sedimentary deposits, likely corresponding to aeolian or aqueous episodes of deposition. An aqueous origin would be consistent with the presence of a Naktong outlet here and the presence of knobs only in the lower lying area. These deposits cover wrinkle ridges, which suggest that the deposition process occurred after the main filling, and also imply that sedimentary activity occurred after plain formation and its subsequent deformation by wrinkle ridges.

HRSC images enabled us to obtain a closer look at Naktong Vallis and its tributaries. The main valley has a nearly rectangular cross-section with high slope sides and a flat bottom, Fig. 8c. Coupled with MOLA topography, small variations of depth between 200 and 300 m can be seen along the main Naktong Vallis. We observed inner local channels on the valley floor that generally present a simple geometry of one unique channel of ~0.5 km wide, plain γ, 0.26 N, 36.58 E, Fig. 8c. This specific channel was used by Irwin et al. (2005b) to determine a discharge rate of approximately 2700 m³/s, using an empirical relation between discharge and the width of the channel. In addition, a braided geometry with multiple channels of similar width, ~500 m, is observed, plain β, 5°20' N, 32°50'E, Fig. 8d, suggesting high discharge rates locally. At this location the total valley width reaches 10 km.

**Fig. 6.** A close-up of degraded terrain, Dter 2, using a combination of MOLA data (460 m/pixel) and THEMIS daytime IR (230 m/pixel). The black box corresponds to the location of Fig. 15a.
Fig. 7. (a) A MOLA topographic map in the region of Naktong Vallis, with a spatial resolution of 460 m/pixel, (b) a mosaic of THEMIS daytime IR images with a spatial resolution of 230 m/pixel. Black boxes correspond to the locations of images in Figs. 11 and 15, and (c) geomorphic/geologic map of the Naktong valley network. In dark green, continuously incised plains (plains α, β, and γ) incised by Naktong Vallis. In light green, discontinuously incised plains (plains δ and ε) plains which separate valleys in degraded terrains (1 and 2 in orange), and Naktong Vallis and its tributaries. The box corresponds to the location of Fig. 17 and CA—the location of the chaotic zone. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
A few tributaries are directly connected to Naktong Vallis, Fig. 9. We manually mapped all the valleys that we observed, usually with a HRSC mosaic and locally with THEMIS data when HRSC was not available. We concluded that Naktong Vallis and its tributaries represent 3287 km of drainage. In the same region, in a basin 5 times smaller that ours, Hynek and Phillips (2003) mapped 11,161 km of valleys with a MOC wide angle at 256 m/pixel. However, using HRSC 20 m/pixel images and THEMIS daytime IR 230 m/pixel data, we were not able to find the smallest tributaries they mapped.

An order was assigned using the Strahler (1952a) system for each mapped tributary. The lowest order was a segment with no tributary and was designated as a first-order valley. When two segments of same order join together, they form an upper-order segment. The Strahler order was useful to define network size, based on the hierarchy of tributaries. Despite its large basin, Naktong Vallis and direct tributaries only have a Strahler order of five. Even so, 95% of its tributaries have an order of one or two, a ratio consistent with terrestrial systems where percentages such as 93% are reported (Knighton, 1998). Major tributaries form small sub-basins connected to Naktong Vallis. The first- and second-order streams have an average length of 5.2 and 10.6 km, respectively, Table 1. The length ratio, $R_1$, between these two orders is consequently $\sim 2$ (Horton, 1945; Strahler, 1952a,b). In a terrestrial system, the length ratio, $R_1$, between the different orders should be constant (Knighton, 1998) and in the range 1.5–3.5 (Horton, 1945; Strahler, 1968; Ritter et al., 2002). One of the particularities of Naktong Vallis and direct tributaries is the variation of this length ratio $R_1$ between the successive orders. Table 1 shows that $R_1$ between two successive orders is between 1.7 and 3.6. The variation indicates that this fluvial system is unusual when compared to terrestrial systems, and can be explained by an important number of small tributaries directly connected to the main valley of Naktong Vallis, without the presence of wide, order four, sub-basins.

Discontinuously incised plains mapped in light green, Fig. 7c, show a discontinuous incision between branching valley networks upstream and Naktong Vallis and its tributaries. The two plains $\delta$ and $\zeta$ represent large flat areas with mean slopes $<0.05$, crossed by wrinkle ridges. Fig. 10 shows the plain $\delta$, Fig. 7c, bounded by degraded terrains to the south. Between point B, north of the plain, and B1, southwest of the plain, a valley is visible indicating that a slight incision occurred after plain formation. This valley is identified locally, arrows in Fig. 10, without being clearly marked in topography throughout the whole plain. Additionally, this valley has a width of 1 km and a maximum depth of $\sim 75$ m, and is, therefore, much smaller than the 4 km wide and 200–300 m deep Naktong Vallis. Despite being difficult to follow along the whole $\delta$ plain, this valley may have once connected to a valley from the degraded terrains. In general, however, the degraded terrains, dissected by branching valley networks, stop sharply at the contact of discontinuously incised plains, Fig. 10, suggesting that
these plains embay the degraded terrains. For example, there is no valley joining one valley head, point B2, and the end of the valleys in degraded terrain, point B3. The connection at point B1 should, therefore, being seen as an exception.

The plain e, Fig. 7c, is the largest plain with no continuous incision. Valleys inside degraded terrains always stop sharply at the contact of discontinuously incised plains, Fig. 7c. At this point, no alluvial fan or talus cone is observed that could indicate that valleys were active after plain formation. To the north, the point between Naktong Vallis and plain e is less well-marked. At the edge between plain g and plain e at point A0, Fig. 7c, we observed some incisions which correspond to a few of the heads of Naktong Vallis and its tributaries.

4.1.2. Morphology of valley heads in intercrater plains

Very specific heads of the tributaries of Naktong Vallis were observed inside the continuously dissected plains, plains α, β, and γ. Fig. 11a–c, show valley heads with large amphitheatres. Heads are located at low elevation, <1000 m, compared to the uppermost highlands in the region, >3 km. Valleys are wide, ~1 km, and deep, >100 m, from their heads. Amphitheatres are usually not unique, but they are apparently not connected to any smaller valleys upward on the plateau. The heads are similar to those found in sapping systems, formed by subsurface seepage and further backward incision (e.g., Laity and Malin, 1985). A few studies suggest that overland flows can incise canyons through waterfalls on cliffs and form similar heads (Irwin et al., 2006; Lamb et al., 2006, 2007). In general, the tributaries of Naktong Vallis, including the main valley at point A, extends upward into smooth plains, devoid of visible valleys, suggesting that sapping was a possible process. This does not exclude that fluvial landforms were filled by aeolian processes and contributed to this incision.

Fig. 11d and e shows valley heads inside plains δ and ε, respectively. Amphitheatres also exist for these valley heads, but their geometries are slightly different from those in plains α, β, and γ. Valley width increases with distance from the head, <1 km at the valley head and up to 3 km for example in Fig. 11d. Surface erosion is observed on the plain upstream to the amphitheatres. For example, a narrow and superficial valley is present on plain δ before the amphitheatres, suggesting that overland flows could have occurred there. Therefore, this head could have formed from overland flows rather than from pure sapping processes. For plain ε, small superficial mesas are present on the plateau in the upstream direction of the valley’s head, suggesting erosion of weak shallow deposits. From the current dataset, it is difficult to determine if overland flow, or simply further eolian erosion of superficial material is predominant.

4.1.3. Age of different plains

We resolved craters down to a diameter of 1 km present on the various plains, using HRSC and THEMIS images and extracted the N(1) and N(2) data-cumulative craters down to 1 and 2 km/km². Errors for N(1) and N(2) are represented as the square root of the
number $N$ divided by the study area, Table 2. In spite of the difference in resolution between HRSC and THEMIS images, $N(1)$ and $N(2)$ values are similar for an area dated with the two sets of images. Relative ages for these plains were compared to the main Martian stratigraphic system, Table 3.

Discontinuously incised plains $d$ and $e$ have a similar $N(1)$, approximately $3164 \pm 7213/213/10^{6}$ craters km$^{-2}$; and a similar $N(2)$, approximately $722 \pm 102/10^{6}$ craters km$^{-2}$, see Table 2 for details. Continuously incised plains $a$, $b$, and $g$ are grouped around $N(1)$ values of approximately $4074 \pm 232/10^{6}$ craters km$^{-2}$, so they are relatively older than $d$ and $e$. Large variations of $N(2)$ values may be due to the small sample of craters larger than 2 km. Age can also be determined by the martian impact cratering chronology curve, as determined by Hartmann and Neukum (2001) and shown in Fig. 12 (Hartmann, 2005). For this analysis, we grouped crater counts of continuously incised plains $a$, $b$, and $g$; and discontinuously incised plains, $d$ and $e$, into two different diagrams representing each unit.

Using $N(1)$ value, we concluded that discontinuously incised plains, plains $d$ and $e$, formed in a distinct episode after continuously incised plains, plains $a$, $b$, and $g$. As reported in Table 3, Continuously incised plains date strictly to the Early Hesperian, and discontinuously incised plains to the Early to Late Hesperian. This finding is confirmed by the second method, in Fig. 12, for craters between 1 and 4 km in diameter. Crater retention ages are assumed to be close to the formation ages, since these plains are not strongly affected by later degradation, except for local fluvial erosion. If erosion removed $4 \pm 1$ km craters, continuously incised plains should have had an age younger than the two discontinuously incised plains, since they are more eroded and craters could have been more degraded. The older age of continuously incised plains indicates that the crater retention ages are relevant to their formation, rather than to their erosion.

In summary, the older ages of the three continuously incised plains suggest that they formed first and dissected later, before a second episode of plain formation occurred for discontinuously

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**Table 1**

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<td>2</td>
<td>7</td>
<td>75.07</td>
<td>465</td>
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<td>Average</td>
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incised plains. Fluvial erosion mainly dissects the Early Hesperian plains in the downward part of Naktong valleys. The erosion of these Early Hesperian plains may correspond to the late-stage incision reported by Howard et al. (2005). Local incisions in discontinuously incised plains observed in the northern part of plains δ with narrow valley located up to the heads, and ε 1° 48' N and 35° E; heads located at the edge between plains γ and ε.

4.2. Degraded terrains

4.2.1. Morphology and morphometry of valleys inside degraded terrains

We mapped degraded terrains which contain many valleys, orange in Fig. 7c., and focused on the observations for degraded terrains, Dter 1 and 2, which are located in the south of plains δ and ε.

![Fig. 11.](image-url)
Divides of 17 different small drainage sub-basins containing valleys in Dter 1 and 2 were mapped using MOLA data, Fig. 13. All are contained in the Naktong basin and represent < 15% of this basin area. We considered them as individual basins, since they do not connect to downward valleys. All drainage basins were elongated with a predominant north–south (N–S) direction except for basins 5, 6, 7, and 12 which were west–east (W–E) oriented. Drainage areas range between 465 and 41,563 km². The heads for basins 5, 6, 7, and 12 which were west–east (W–E) oriented. Drainage areas range between 465 and 41,563 km². The heads for all of these valley networks are located at 2000 m or higher. We mapped valley networks 1 through 4 with HRSC images, 20 m/pixel, and valley networks 5 through 17 with THEMIS images. The extra resolution of HRSC images did not allow us to map more valleys for network 1 through 4. Results in Table 1 can be compared despite the difference of resolution. We assigned a Strahler order to each mapped valley segment. Using the Strahler segmentation system, there were four second order networks (B6,7,13,17), eight third-order networks (B2,3,5,9,10,14,15,16,17), three fourth-order networks (B4,11,12) and one, the most developed, fifth-order network (B4). First- and second-order valleys had an average length of 13.2 and 26.9 km, respectively. The length ratio, R_l, between these two orders was approximately two. Drainage densities for each drainage basin varied from 0.02 to 0.20 km−1. The mean drainage density of all valley networks was 0.08 km−1. Seven times higher than the mean drainage density of Naktong Vallis, Table 1. Three longitudinal profiles of the three main valleys are shown in Fig. 14 (basin 1: BB’, basin 8: CC’, and basin 11: DD’). The mean slopes along valleys are around 0.15–0.20° for the main segments, Fig. 14, which is generally higher than the one observed for Naktong Vallis, 0.06°. Higher slopes in degraded terrains than in intercrater plains create higher erosional capacity that may have contributed to an increased number of valleys.

The valley networks observed in degraded terrains present a much more branching organization than in the main Naktong Vallis, but their general morphology is different from usual highlands which are much hillier and more cratered. Some smooth terrains were observed in several places between different valleys dissecting this unit, suggesting that they correspond to a residual horizon of the surface before erosion, Fig. 15. This suggests that the valleys were incised in a terrain which was initially smoother.

Degraded terrains also show a large number of valleys heads, sometimes difficult to characterize, especially due to the dust cover that is important in this region (e.g., Ruff and Christensen, 2002), Fig. 15. Nevertheless, when visible, valley heads present locally amphitheatre shapes, with shallower initial depths than those in the plains. The major part of valleys heads are located inside, or just below, the southern plateaus, which contain the highest part of the basin and form a large plateau.

4.2.2. Age of degraded terrains

Craters down to 1 km were counted using HRSC and THEMIS images. As referenced in Table 2, degraded terrains (1 and 2) have N(1) values of approximately 3484 ± 176 x 10⁶ craters km⁻². This value is intermediate between discontinuously and continuously incised plains in the Early Hesperian, Fig. 16. Erosion has strongly affected these terrains, so parts of craters larger than 1 km may have been degraded if not deleted by erosion. Ages for the degraded terrain formation may be older than measured. Valleys on degraded terrains stop at the contact with discontinuously incised plains; the younger age of these plains is consistent with stratigraphic superposition, showing the occurrence of a main fluvial erosion before the discontinuously plains formation.

4.3. Southern plateaus

4.3.1. Morphology of southern plateaus

Southern plateaus are located at the highest elevation of the Naktong region reaching 2700 m, and consist of three plateaus at different elevations (~2700, ~2000, and ~1600 m) with a low slope around 0.1° towards north. Most of the surface of these plateaus is smooth, flat with some wrinkle ridges, and locally incised by a few valleys. This texture is very close to that of intercrater plains, dissected by Naktong Vallis to the north.
We mapped the three different plateaus from HRSC images, 20 m/pixel, with the aid of MOLA topography, Fig. 17. Plateau H is the highest and southernmost plateau and displays a low degradation level on the surface, but many valley heads around 2600 m elevation which incise the east of this plateau. These valley heads have frequent amphitheatre shapes with an initial width of >3 km. Other heads have a smaller width, <1 km, and

Fig. 13. (a) The Naktong basin with THEMIS daytime IR (230 m/pixel) images. Colors of different observed valleys indicate Strahler order (1952a). (b) MOLA topographic map in southern Naktong basin with a spatial resolution of 460 m/pixel, (c) THEMIS daytime IR (230 m/pixel) images in southern Naktong basin and (d) close-ups of southern of Naktong basin with Strahler order. Black lines represent the drainage basin mapped manually with MOLA data. BB’, CC’ and DD’ correspond to the location of longitudinal topographic profiles of valleys shown on Fig. 14. White numbers correspond to numbers of basins in Table 1. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 14. Three longitudinal topographic profiles of the main valleys BB’, CC’ and DD’, represented on Fig. 13d with the mean slope of each observed segment.

We mapped the three different plateaus from HRSC images, 20 m/pixel, with the aid of MOLA topography, Fig. 17. Plateau H is the highest and southernmost plateau and displays a low degradation level on the surface, but many valley heads around 2600 m elevation which incise the east of this plateau. These valley heads have frequent amphitheatre shapes with an initial width of >3 km. Other heads have a smaller width, <1 km, and

Fig. 15. (a) THEMIS daytime IR (230 m/pixel) image, located on Fig. 6, showing valleys inside degraded terrains, Dter 2. We note the presence of residual smooth plains between valleys and (b) HRSC image, 20 m/pixel, located on Fig. 7, showing blunted valley heads inside degraded terrains, Dter 1.
form small branching networks, Fig. 18c. Plateau I is an intermediary plateau at approximately 2000 m elevation. Plateau L is the lowest plateau at approximately 1600 m elevation. Narrow valleys developed in poorly branched patterns are observed in the east of this lower plateau, Fig. 18d. Small mesas are observed around the principal valley in this region, which could indicate residues of plateau I, Fig. 18e.

Erosional landforms were observed at the transition between plateaus L and I, and plateaus I and H, Fig. 18a and b. The 100–200 m scarps at plateau edges display ancient slightly visible gullyng. These erosional landforms incise the middle and the highest plateaus and indicate that plateau L and I may be intermediary to the thicker plateau H which has been partially eroded. Two topographic profiles of the three plateaus indicate a 200 m escarpment between the highest and the intermediary plateaus; and an escarpment between 100 m, profile aa′, Fig. 19, and 200 m, profile bb′, Fig. 19, between the intermediary and lowest plateaus. This variation of escarpment heights observed for both profiles can be explained by the fact that bb′ crosses the valley, and consequently shows the effect of erosion posterior to the formation of plateau L.

In the northern section, we observed a possible connection between the intermediary plateau I and the degraded terrains north of plateau L. We note that the slope is not the same on plateau I, ~0.06°, and on the degraded terrain, 0.15–0.20°. A possible explanation is the presence of a possible blind fault, between plateau L and degraded terrains visible here from the straight shape. Fig. 17 also shows several heads of valleys in the degraded terrains located at more than 2500 m elevation, very close to the blind fault and plateau L. Therefore, we interpret that these valleys have progressively eroded back into the southern
plateaus, but stopped their erosion due to the topographic divide formed by the uplift on the fault, Fig. 19. Observation for these valleys suggests that the degraded unit is the result of an enhanced dissection of the southern plateaus that were tilted at this location. As a result, the degraded unit is rougher and less flat than plateaus, but may correspond to a similar geologic unit, tilted to a higher slope and clearly dissected by fluvial landforms for this reason, Fig. 19.
the highest plateau, H, is older with a thick plateau, and plateaus I and L stratigraphically below H, Fig. 20. The incremental crater densities of plateaus L, I, and H are plotted. The $-2$ power laws (Hartmann, 2005), dashed lines, mark the boundaries between (from lower to upper) the Late Hesperian–Amazonian (LN–LA), Early Hesperian–Late Hesperian (EH/LH), Late Noachian–Early Hesperian (LN–EH), Middle Noachian–Late Noachian (MN–LN). Error bars represent a one-$\sigma$ interval of $\sqrt{n}/A_j$. ($n_j$: number of crater for one interval; $A_j$: studied area in km$^2$). For each terrain $N(1)$ and $N(2)$ is given—number of craters larger than 1 and 2 km per million square kilometre—with an error of $\pm \sqrt{n}/A_j$.

4.3.2. Crater counts of the three southern plateaus

Craters greater than 1 km were compared for the three different plateaus, Table 2. The youngest aged plateau is the lowest plateau L with a $N(1)$ of approximately $2087 \pm 420 \times 10^{-6}$ craters km$^{-2}$. Relative counts show that the intermediary plateau I has a $N(1)$ of approximately $3184 \pm 657 \times 10^{-6}$ craters km$^{-2}$, and the highest plateau, H, is older with a $N(1)$ of approximately $3869 \pm 221 \times 10^{-6}$ craters km$^{-2}$. Crater retention ages given by Hartmann curves, Fig. 20, show that plateau L has a Late Hesperian age, plateau I an age of Early to Late Hesperian, and plateau H an Early Hesperian age. Assuming that these retention ages are formation ages would suggest that the plateaus are younger when going down in topography. However, these ages are modified by erosion on plateaus, and are, therefore, not formation ages. For example, crater counts for plateau L give an age younger than discontinuously incised plains. If this age corresponded to the formation of the plateau, the age relationship with Dipl plains would not be possible. Indeed, the network incising plateau L crosses degraded terrains down to the discontinuously incised plain i, and is apparently buried by these plains. Therefore, these valleys formed before plain i, and plateau L must be older than plain i to contain these valleys.

The following hypothesis for the origin of plateaus L and I can be proposed, since it takes into account the contribution of erosion: plateaus L and I resulted from the progressive erosion of a thick unique plateau sequence, with plateau H at the top of this thick plateau, and plateaus L and I stratigraphically below H, Fig. 19. Ages for eroded plateaus L and I corresponded to retention ages after strong erosion occurred, which does not mean that the terrains are younger than plateau H, but rather than that they were later exposed at the surface. Since, the uppermost plateau H is the one the least affected by the erosion, the crater count for plateau H gives the oldest surface and is close to a formation age. An Early Hesperian age for plateau H is still a minimum; the plateau could be of Noachian age and could have mainly been eroded during this Noachian period, with the last period of erosion taking place in the Early Hesperian. Such an erosional scheme would indicate that the Martian landscape was substantially denuded by hundreds of meters in the Late Noachian to Early Hesperian that leave geomorphic surfaces at significantly different levels.

5. Discussion

5.1. Formation of the fluvial landforms observed

The interest in the Naktong basin for understanding Martian fluvial erosion is as follows: (1) the main valley, Naktong Vallis, crosses intercrater plains that formed late in early Martian history; (2) the main valley is long and deep, being a major fluvial valley on Mars; and (3) the basin contains a few isolated heads in plains, but not directly connected branching organization. Compared with the mapping of Hynek and Phillips (2003), the geometry in our study is much less organized despite better image resolution. Poor branching geometry is not typical of terrestrial-like valley networks. Nevertheless, branching valley networks, of similar organization to terrestrial watersheds, exist at higher elevations in the same basin, sections S2 and S3. Naktong Vallis and S2/S3 valleys display a flow direction from south to north consistent with the feeding of the Naktong by S2 and S3 drainage systems, but the two systems are separated by two plains. Was Naktong Vallis once connected to these valleys previous to the formation of these plains? Was this connection active through overland or subsurface flows? Or, did their respective activity occurs at different periods and timescales? The problem in answering these questions lies in the origin of the water that carved Naktong Vallis. A 950 km main valley, likely connected to a huge 4700 km system of valleys, would require a large amount of water flow that is difficult to reconcile with the observed geometry of Naktong Vallis and its main tributaries.

Valleys incised smooth intercrater plains, plains $\alpha, \beta,$ and $\gamma$, in continuity, but they are discontinuous inside two other discontinuously incised plains, plains $\delta$ and $\epsilon$. Assuming that overland flows connected both the Naktong and S2/S3 systems, formation in a single stage after the formation of the observed DI plains $\delta$ and $\epsilon$ would require that these plains were incised continuously, contrary to the observations. Irwin et al. (2005a) proposed that
some of the plains in between the two branches of the Naktong–Mamers Vallis system of valleys corresponded to alluvial plains and sedimentary deposits. However, the fact that Naktong Vallis contains a strong incision at the edge of plain e is not consistent with this hypothesis. The level of water required to deposit the material of plain e should be at the elevation of the plain, not 200 m below. Furthermore, the lack of apparent sedimentary landforms also does not favor this possibility. Several plains located towards the north, such as the one displaying residual deposits over wrinkle ridges, in Fig. 8a, fits the hypothesis of Irwin et al. (2005a). However, local or shallow incisions on discontinuously incised plains, especially on δ, indicate that overland flows did occur on them, but with lower amplitude than on continuously incised plains. These findings suggest that overland flows cannot explain the strong dissection of Naktong Vallis or the extensive connection from degraded terrains valleys to Naktong tributaries over the discontinuously incised plains. They may better correspond to late episodes of activity with slight erosion after plains δ and ε formed. Such reactivation is necessary to explain the incision of the edge of these plains. For example, if the origin of the plain was volcanic, Naktong would have formed before plain ε, and lava flows would have flowed into the lows and filled the Naktong valley. If the plain was of sedimentary origin, the initial valley would have flowed at the level of the plain without such deep incision. The incision of the 200 m plain would then be due to a decrease of plain level, and therefore to fluvial activity that occurred later in plain formation. So, this scenario favors a surface connection previously to plain δ and ε formation, followed by a late-stage reactivation.

Alternatively, a subsurface connection may have existed between degraded terrains of S2/S3 and the heads of Naktong tributaries in plains, which would explain the formation of Naktong Vallis in a single episode. Indeed, these valleys are sub-basins which are part of the large Naktong basin. Therefore, any liquid water involved in their formation should flow downstream, or infiltrate the ground. However, a groundwater connection under plains δ and ε cannot explain the abrupt transition between valleys in sections S2 and S3 and plains δ and ε, as well as the lack of fans or cones on these plains. Observations should show that valleys S2 and S3 were buried by plains δ and ε, and that these valleys formed before these two late plains. Groundwater connections cannot explain the observations in a single episode, despite the fact that these processes likely played a role in the style of erosion. Finally, the explanations provide the presence of at least two stages of fluval erosion, with the first more important before the formation of plains δ and ε, and the second, after their formation, with less efficiency, or duration.

In the chronological point of view, our crater counts are relatively consistent with previous studies that proposed the formation of the major portion of the Naktong valley network either during the Late Noachian or the Early Hesperian (Hoke and Hynek, 2008; Fassett and Head, 2008) and is consistent with late stage reactivation in the Early Hesperian (Howard et al., 2005). The main incision of continuously incised plains, that we date to the Early Hesperian epoch, for α, β, and γ, indicates that the main Naktong system was strongly active during this epoch, before the formation of plains δ and ε. In addition, the late stage of regional activity, identified by incisions in plains δ and ε occurred after their formation at the end of the Early Hesperian or in the Late Hesperian.

No observation indicates that fluvial activity was continuous between the two periods of activity identified, or if the two stages observed were the result of distinct episodes. Knighton (1998) showed that 10^2–10^3 years is enough time to maximize drainage density, depending on bedrock lithology. Simple head geometry in plains δ and ε, and low incisions of valleys inside these plains, show that fluvial activity was less intense in the second episode. This low activity is likely not responsible for the large erosion and the end-to-end activity of the Naktong–Scamander–Mamers system. The connection at point B, Fig. 10, between the branching valley networks and a shallow valley locally visible on plain δ shows that some of these valleys were locally connected at the surface. Such a finding suggests that the two stages were separated in time by plains δ and ε, and better correspond to two distinct episodes of activity rather than to a continuous evolution.

5.2. Fluvial processes and climatic implications

In the proposed scenario, the connection between the Naktong and uphill drainage systems, S2/S3, is still not well understood. Were overland flows or sapping predominant? In plains, Naktong Vallis is connected to small tributaries with heads in amphitheatres. The main valley head is also amphitheatre-shaped with a rectangular profile. Amphitheatre-shaped heads and regular valley widths are generally interpreted as due to sapping processes. Sapping is related to the backward incision of canyons due to the circulation and seepage of groundwater (e.g., Laity and Malin, 1985). Some studies have also suggested that overland flows incise canyons through waterfalls on cliffs (Irwin et al., 2006; Lamb et al., 2006, 2007). Such a scenario would be possible if we saw small fluvial valleys upward of valley heads. In the case of plain δ, Fig. 11d, this is the case; but, in general, no valley is visible where heads join. Despite this finding we cannot rule out the possibility that small valleys once fed these amphitheatre-shaped heads and are now invisible. In other words, subsurface flows that carved these valley heads are plausible.

Valleys on degraded terrains display more branching organization with valley heads displaying local amphitheatres, but in much smaller sizes than on plains, and with increasing valley widths. These valleys likely formed as a result of overland flows, which gave the branching features and seepage and formed small amphitheatre-shaped heads or cones in the source area. A pure sapping system is unlikely due to the increasing widths and valley heads that are close to the local maximum of the topography. Small amphitheatre-shaped heads were also observed for the plateau valleys upward to S2 and S3 valleys, but interpretation in terms of subsurface processes is not as important due to the presence of gullies and local incision on plateau scarps. In these areas, overland flows may have worked together to carve the observed heads, as seen in Fig. 18.

The bedrock of degraded terrains is found in the continuity of plateau bedrock material, with the vertical shift possibly due to the putative fault that separates degraded terrains and plateau L. Therefore, it is likely that this material corresponds to the same geologic unit displaying different types of erosion. Yet, these two units were defined as distinct for morphological reasons. As they likely correspond to the same bedrock, a difference in lithology is unlikely to explain the difference in erosional style between the two locations. In contrast, the major difference between degraded terrains and plains and plateaus is that the main slope of these terrains of approximately 0.2°, for degraded terrains is less than that slope for plateaus, less than 0.06°. This difference may explain the difference in the erosional style and the enhanced fluvial erosion on degraded terrains.

The consequence of these observations is that water flows originate at the highest sections of the basin, i.e. the plateaus. Plateaus exhibit both overland flows and sapping landforms at these locations as a consequence of their flat surfaces which allow infiltration as well as local erosion of plateau scarps. A pure groundwater origin is unlikely, since they are close to the
uppermost area of the basin. Nevertheless, the formation of aquifers at very high elevation, > 2 km, when compared to Naktong Vallis heads inside plains is possible. The crater retention ages of plateaus and degraded terrains suggest that overland flows were still active during the Early Hesperian history of this basin, at the time when valleys were active in the Naktong section of the basin. These data lead us to the conclusion that aquifers feeding Naktong valleys are possible, but they were associated with overland flows during the same period. Our results show that sapping and runoff both occurred during the Early Hesperian, implying that overland flows continued during this period.

Recharges of groundwater were thus coeval to surface activity in this period, as proposed by Craddock and Howard (2002), and contrary to the findings of Harrison and Grimm (2005) who favored sapping during this period. Observed geometries are likely the result of variation of slope coupled with permeable lithology which enhanced infiltration.

The main activity of Naktong valleys system is chronologically limited between the two types of plains—those that are incised (CIpl) and those that are poorly incised (DIpl) in the Early Hesperian epoch, Fig. 21. In many previous studies (Craddock and Maxwell, 1993; Craddock and Howard, 2002; Harrison and Grimm, 2005; Fassett and Head, 2008), Early Hesperian fluvial incisions were observed, but were determined to be less important than Noachian incisions. The Naktong basin shows evidence that extended activity including overland flows occurred during this period. Our investigation suggests that precipitation, snowfall and subsequent melting, or rainfall, was especially present in the source region within highly elevated plateaus, suggesting that precipitation was limited or nonexistent in the downstream region where the Naktong Vallis displays constant width and a poor connectivity with sub-basins. An altitude dependency in precipitation has not been observed, as models (e.g., Craddock et al., 1997) suggest a decrease in altitude for precipitation due to an atmospheric pressure decrease through time. However, altitude dependency can be compared with the occurrence of high-elevation precipitation-fed valleys observed in other regions in the Early Hesperian epoch such as in Warrego Vallis (Ansan and Mangold, 2006).

6. Concluding remarks

Naktong Vallis is located in the southern part of the longest system of valleys on Mars. The Naktong basin is of interest since the main valley, Naktong Vallis, disconnects intercrater plains that formed in the Early Hesperian. Naktong Vallis joins Scamander and Mammers Vallis to complete a 4700 km valley system that contains isolated heads in plains without a directly connected branching organization. A contradiction exists between the length of the system of valleys and its poor branching organization which suggests episodic outflows rather than sustained flows.

Our study can explain part of the specific characteristics of Naktong Vallis in the context of a classic terrestrial-like valley system. During the Early Hesperian, Naktong Vallis was connected to branching valley networks located at higher elevations, that were formed by a combination of overland flows and sapping processes, aided by groundwater flow. Connections between valleys in uplands and Naktong Vallis could explain the total length of the entire system of valleys in Naktong and Mammers Vallis, and its high discharge rate. Our investigation also suggests that precipitation, snowfall and subsequent melting, or rainfall, was especially present in the source region of high-elevated plateaus, but that precipitation was limited or nonexistent in the downstream region where Naktong Vallis displays constant width and a poor connectivity with sub-basins. In addition, a local reactivation of the valleys was observed at the end of the Early Hesperian or beginning of the Late Hesperian. This may signal a late episode of activity after most of the valley system was already carved, for which the origin and amplitudes are unknown.

In summary, the Naktong basin shows: (1) that sustained fluvial activity with long main tributaries could still occur during the Early Hesperian epoch; (2) that the Naktong basin formed from the coeval activity of overland flows and sapping from groundwater, dependent on lithology and the slopes over which flows occurred; and (3) a late, local episode of activity occurred at the end of the Early Hesperian or beginning of Late Hesperian, after most intercrater plains were formed.

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