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# New insight on genetic links between outflows and chasmata on Valles Marineris plateau, Mars

# *Nouvel aperçu sur les liens génétiques entre des vallées issues de débâcles et des chasmata sur le plateau de Valles Marineris, Mars*

Antoine Lucas*, Véronique Ansan**, Nicolas Mangold**

**Abstract**

Within the Valles Marineris region on Mars, a huge system of interconnected valleys interpreted as flood channels reveals the presence of braided channels and strong incisions into the bedrock. We focus our study on Ganges Chasma, where two examples of outflow channels lie on the Valles Marineris plateau and take source in depressions. These channels may represent good examples for studying the relationship between the formation of Chasmata and outflow channels. No mass deposition is observed at the mouth of both channels, indicating that outflows were active before the opening of Ganges Chasma. In addition, possible sapping valleys were formed at the mouth in both cases. Residual aquifer could have been responsible for a late hydrogeological activity in this region after the opening and the widening of Ganges Chasma. From these observations and our flux calculations, we concludet hat overpressure due to dyke ascent could have initiated outflows on Valles Marineris plateau, which is consistent with previous studies. Our results suggest that these mechanisms played a role in the opening and the widening of the Chasmata around 3 to 3.5 Gy.

**Key words:** outflow channel, sapping, hydrogeology, Mars.

***Résumé***

*Dans la région de Valles Marineris sur Mars, de nombreuses vallées interconnectées interprétées comme d'anciens chenaux créés par des débâcles sont profondément incisées dans le substratum. Notre étude se concentre sur Ganges Chasma, une région où deux de ces vallées présentes sur le plateau prennent source dans des dépressions fermées. Ces deux vallées pourraient servir de bons exemples pour comprendre les relations entre la formation, généralement découplée, des Chasmata d'une part et celle des vallées issues de débâcle d'autre part. L'absence d'accumulation à l'embouchure suggère que la mise en place de ces vallées est antérieure à l'ouverture de Ganges Chasma. Par ailleurs, des vallées probablement formées par sapement sont observables au niveau des embouchures des deux vallées issues de débâcles. La présence d'un aquifère résiduel pourrait alors expliquer l'activité hydrogéologique tardive dans cette région. À partir de ces observations, de nos calculs de débits, et en accord avec des travaux antérieurs, nous concluons que la surpression causée par la remontée de dykes sur le plateau de Valles Marineris a pu déclencher l'écoulement et ainsi jouer un rôle important dans l'ouverture des Chasmata il y a environ 3 à 3,5 Ga.*

***Mots clés :** débâcle, sapement, hydrogéologie, Mars.*

## *Version française abrégée*

*Valles Marineris est un vaste complexe morpho-tectonique formé de dépressions appelées « chasmata », situées à l'équateur martien. Il s'étend sur 4 000 km de long avec une profondeur atteignant localement 10 km (fig. 1A). Sa formation et son évolution restent aujourd'hui largement énigmatiques (Lucchitta, 1978 ; Peulvast* et al., *2001). Si les dépressions ont une direction préférentielle E-W et un contrôle tectonique clair (failles avec présence de facettes triangulaires, contrôle structural est-ouest), elles sont différentes des grabens par des formes moins prononcées et manifestement moins dépendantes d'un contrôle structural et tectonique, impliquant des phénomènes d'effondrement et d'érosion. Le nord-est de Valles Marineris est une région présentant des vallées interconnectées identifiées comme*

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*d'anciens chenaux créés par des débâcles, dont les débits maximum étaient supérieurs à $10^6$ $m^3s^{-1}$ (Baker, 1978). Les relations entre les dépressions et les vallées issues de débâcles suggèrent de fortes affinités entre les deux types de morphologies. Ganges Chasma, la région étudiée, présente des caractéristiques uniques par la présence de vallées issues de débâcle à la fois sur le plateau surplombant la dépression –* Aurorea Planum *– et dans le fond de la partie est de la dépression elle-même (fig. 1). Cette région présente de bons exemples pour la compréhension des relations entre les vallées issues de débâcles et les dépressions de Valles Marineris.*

*La première vallée, Elaver Vallis, est large de 15 km et s'étend sur 150 km (fig. 2). Utilisant la relation de Komar, (1979) (voir équation 1) et à partir des profils topographiques (fig. 2C) des débits compris entre 6 et 9.$10^6$ $m^3s^{-1}$ ont été obtenus, soit l'équivalent des valeurs obtenues dans les Scablands (Etat de Washington, Etats-Unis) lors de débâcles glaciaires. Ces calculs tiennent compte des dimensions des cannelures (plusieurs dizaines de mètres de hauteur) présentes dans la vallée et témoignant de l'érosion intense et rapide du bâti rocheux. Aucune accumulation n'est observée à l'embouchure d'Elaver Vallis (fig. 2 et fig. 6A). Cette absence témoigne que l'écoulement dans Elaver Vallis était actif avant l'ouverture de Ganges Chasma. Par ailleurs, Elaver Vallis est incisée par une petite gorge de morphologie très différente de la vallée principale (fig. 6A). Alors que les versants de Ganges Chasma présentent des figures d'érosion en éperons et ravins, cette gorge peu érodée présente une forte pente (>20°). L'absence de figures d'érosion suggère une activité plus tardive. Sa morphologie et son incision profonde reflètent des processus d'érosion régressive comme le sapement. Cette gorge incise à la fois la vallée et les versants de Ganges Chasma. La localisation de cette gorge à l'embouchure d'Elaver Vallis laisse penser que l'aquifère initialement présent pendant la débâcle qui a formé Elaver Vallis a pu rester actif après l'ouverture de Ganges Chasma. De plus, les cônes d'accumulation aux pieds des versants de Ganges sont eux-mêmes incisés par de petits chenaux étayant l'hypothèse d'un second épisode d'écoulement (fig. 7A). Plus à l'Ouest, Allegheny Vallis présente de fortes similitudes avec Elaver Vallis. De dimensions plus modestes, les débits calculés (à partir de l'équation 1) ont néanmoins atteint $10^6$ $m^3s^{-1}$. Cette seconde vallée prend source dans une dépression nommée Ophir Cavus située au sud-ouest de Ganges Chasma (fig. 1B, fig. 8A et fig. 10A). Aucune trace morphologique ne témoigne de l'écoulement de ce drain dans Ganges Chasma. De même que pour Elaver, une gorge à forte pente incise la vallée d'Allegheny au niveau de son embouchure. Les relations entre Alleghany Vallis et Ganges Chasma semblent être les mêmes qu'entre Elaver Vallis et Ganges Chasma. Les marqueurs morphologiques des deux vallées témoignent de l'existence d'au moins deux épisodes d'écoulement distincts ; une débâcle violente et brève suivie de résurgences localisées aux embouchures de ces vallées et liées à la présence d'aquifères après l'ouverture de Ganges Chasma. Récemment Hanna et Phillips (2006) ont montré que des fractures ouvertes en surface par des remontées de dykes pouvaient provoquer une surpression déplaçant alors les masses d'eaux souterraines vers la surface. Les débits calculés par ces auteurs sont en accord avec les nôtres. Ainsi, l'ouverture de fractures sur le plateau de Valles Marineris pourrait être à l'origine d'écoulements violents peu avant la formation des Chasmasta, il y a 3 à 3,5 Ga.*

## Introduction

The Valles Marineris trough system is trending EW close to the Martian equator from longitude 40°W to 110°W over 4000 km with a depth reaching 10 km. This depression system includes elongate and steep-sided troughs at the western part that are controlled by tectonic patterns (Masson *et al.*, 1977), but the exact origin and evolution of these chasmata are still enigmatic (Lucchitta*, et al*. 1978; Peulvast *et al.*, 2001). Pits chains have been observed with the same trend direction at each side of Valles Marineris plateau. Based on superposition relations, it has been shown that these pits mainly predate the formation of chasmata (Schultz, 1989b). To the east and north of the depression system, interconnected valleys known as outflow channels reveal braided channels and deep valleys. Outflow channels are characterized by the lack of tributaries, while the source regions consist of chaotic terrains of unknown origin. These chaotic terrains consist of a complex assemblage of depressions connected to the eastern side of Valles Marineris, suggesting a genetic link between the evolution of troughs and the formation of outflow channels that remains to be explained.

Ganges Chasma formed across the Aurorae Planum, a Late Noachian-Early Hesperian cratered plateau North of Coprates Chasma, the main Valles Marineris trough. On this plateau, two valleys, interpreted as being outflow channels, are connected to the depression (fig. 1). Ganges Chasma has unique characteristics in the Valles Marineris system with outflow channels present on the plateau as well as on the easternmost part of its floor. This pattern questions the chronology and formation processes of outflow channels relative to the trough system. Here we examine two examples of outflow channels in this region that appear to be similar in morphology to other outflows, but unusual in their origin because they lie on the Valles Marineris plateau.

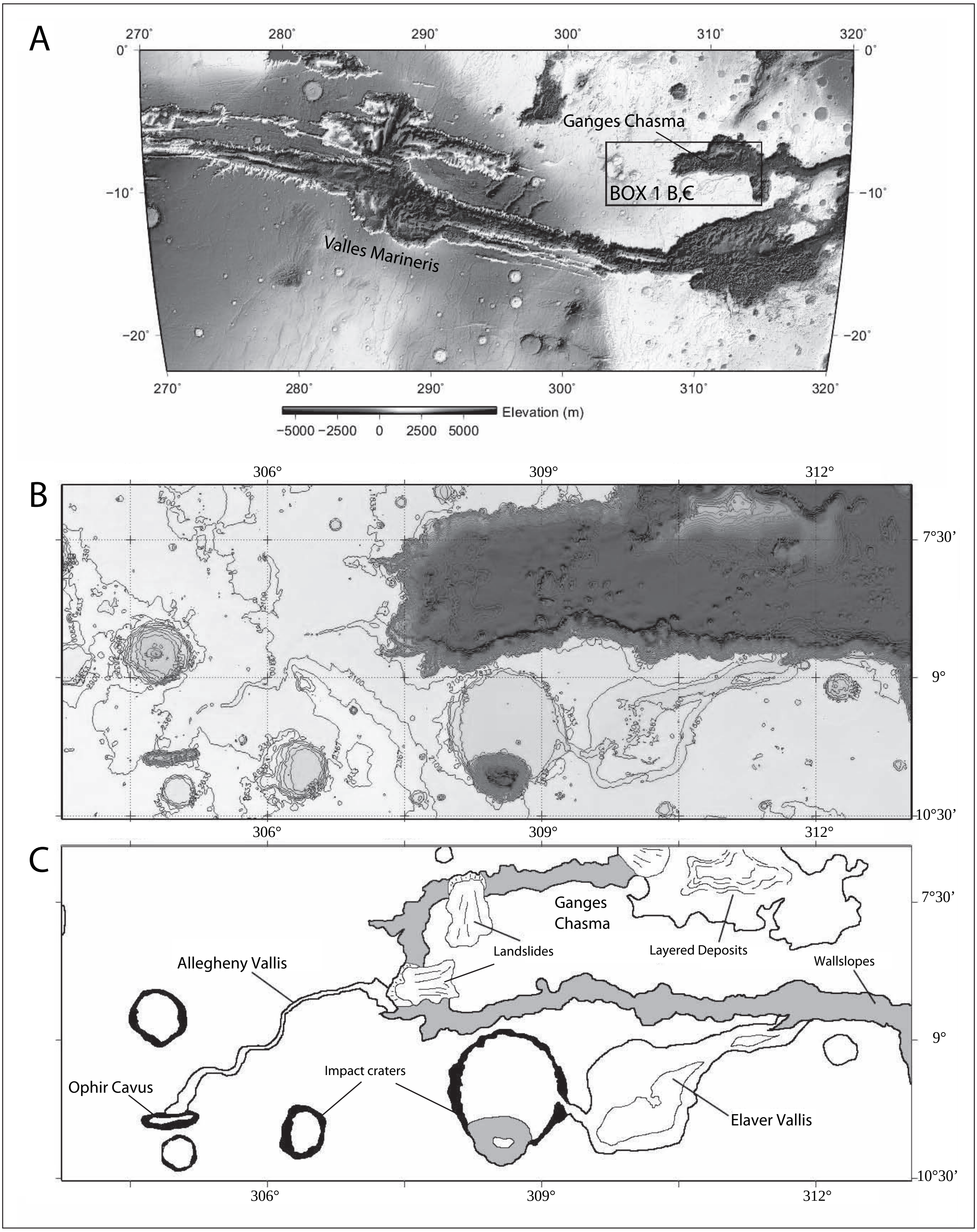
Notwithstanding their localization in their vicinity, outflow channels are usually disconnected from the Chasmata.

Fig. 1 – **Regional map of Valles Marineris**. A: Valles Marineris is a 4000-km-long trough system at the Martian equator; B: Ganges Chasma, the region of interest, is located in the eastern part of Valles Marineris and is a 5-km-deep trough surrounded by Aurorea Planum; C; Major features in the study area: Allegheny and Elaver Vallis with respective source areas; both valleys are connected with Ganges Chasma.

*Fig. 1 – **Carte régionale de Valles Marineris.** A : carte topographique issue des données MOLA à 128 pixels/degré ; B : agrandissement de Ganges Chasma, une dépression entourée par le plateau d'Aurorea Planum ; C : formes principales de la zone d'étude : Allegheny Vallis et Elaver Vallis avec leurs sources respectives. Les deux vallées sont connectées à Ganges Chasma.*

In this study, we document two examples of outflow channels that are associated with depressions at outflow source, showing a possible genetic relationship between the formation of Chasmata and that of the channels.

We will briefly present the geological context and the data used in this study. Both outflow valleys will be described as well as their relationships with Ganges Chasma. We conclude that each outflow valley has similar genetic links with



Ganges Chasma. In addition, backward erosion observed in both cases strongly suggests that a flood event occurred after the opening of Ganges Chasma.

## Geological context and data

Ganges Chasma is a nearly rectangular depression. As other Chasmata, the depth of Ganges is enigmatic (5.2 km). To create such a great volume of extraction of the pore fluid (if there is) is not sufficient and the rock matrix must also be removed. Although mass wasting processes (such as landsliding, gullying and sapping) may have contributed to the widening of the trough, it has been proposed that extensive stress could have led to the opening of the trough. Faulting processes due to Tharsis formation (Mège *et al*., 1996) could have occurred in the western part of Ganges Chasma (Lucchitta, 1978; Peulvast *et al.,* 2001) as suggested by the presence of triangular facets. Nevertheless, which fraction of the formation of the trough is due to mass-wasting and which is due to faulting is still questionable.

Elsewhere, the depression displays very regular wallslopes cut by several landslides. The trough floor is composed of bright layered deposits and dark smooth terrains that appear to be sand dunes. Interior Layered Deposits (also named ILD) are similar to other layered formations present in most depressions with meter-thick layers and strong erosional features such as yardangs (Nedell *et al*. 1987). These layers might have formed through water related processes suggested by the presence of sulfates detected by spectral data (Gendrin *et al.,* 2005). It is important to note that no fluvial landforms are observed on the floor of the Ganges trough.

Two outflow channels exist on the plateau south and west of Ganges Chasma. They are named Allegheny Vallis to the west and Elaver Vallis to the south. These valleys are 150-200 km long and their widths vary from 3 to 20 km. The sources of these valleys are different: a single impact crater for Elaver Vallis and a linear depression named Ophir Cavus for Allegheny Vallis (fig. 1). These valleys have only been the subject of few recent and limited studies (Coleman *et al*., 2003; Komatsu *et al.,* 2004, Coleman *et al*., 2007).

Data provided by recent missions allow us to study these landforms with more detail at present. In order to study outflow channels, we have used Mars Observer Camera (MOC) images with resolution ranging from 2 to 5 m/pixel (Malin and Edgett, 2000), Thermal Emission Imaging System (THEMIS) visible image (18 m/pixel) and IR data (100 m/pixel) from the Mars Odyssey probe (Christensen *et al*., 2003), High Resolution Stereo Camera (HRSC) onboard Mars Express probe (Neukum *et al*., 2000), the Context Camera (CTX) images with resolution of 6m/pixel and the high resolution imaging science experiment (HiRISE) images with resolution down to 0.25m/pixel both onboard Mars Reconnaissance Orbiter. Topographic data were provided by the Mars Observer Laser Altimeter (MOLA) of the Mars Global Surveyor (MGS) probe (Smith, 1999). MOLA data used here consist of the 1/128th degree interpolated Digital Elevation Model (DEM) produced from the individual shots of the laser altimeter. THEMIS data are acquired in five spectral channels from 0.4 to 0.8 $\mu$m for the visible images and in ten channels from 0.8 to 14 $\mu$m for the IR images. IR-THEMIS data provide information on the surface temperature at day or night. In day-time images, the temperature is mainly dependent on the topography and albedo. In night-time images, the temperature is mainly dependent on the thermal inertia of the surface, therefore on the grain size and induration. For example, smooth plains mantled by dust have a low temperature and appear dark on night-time images whereas rocky outcrops such as trough wallslopes are warmer and appear brighter. We used these data as relative indicators of surface properties rather than absolute indicators of temperature.

## Geomorphological analysis of Elaver Vallis

### The valley characteristics and morphometry

Elaver Vallis has an average width of 15 km with large variations in width (fig. 2). The valley floor consists of braided channels with streamlined islands and extended areas of erosional grooves (fig. 3A). These landforms indicate discharge flows from the west to the east. Topographic data indicate that the depth of the valley varies from 200 to 400 m. A series of topographic profiles of Elaver shows the evolution of the valley's incision in Aurorae Planum (fig. 2). Section 1 presents the outlet of the crater basin (fig. 2). The depth of the valley is about 250 m. Section 2 shows the valley divided in two main channels. The northern one is deeper than the southern one. Section 3 crosses a streamlined island in the middle with a depth of 400 m. These characteristics are typical of outflow channels as defined for Xanthe Terra such as Ares or Kasei Vallis (e.g., Baker *et al.,* 1978; Carr, 1981), but with a smaller width and length. There is no indication that sediment was deposited inside the valley during low discharge periods. A few chaotic terrains with small hills and knobs are present in the middle of the channel (fig. 3B). These features are in the way of the stream and crosscut the grooves showing that they formed after the channels or at a late stage of the valley evolution. Conversely to other outflow channels, these chaotic features are not a possible source of water for the previously described channels (Carr, 1981).

Close-ups present grooves and scours formed by flows at different elevations in the valley. These grooves suggest that the valleys might have been filled by water over an important depth (at least 200 m). The topographic cross-sections (fig. 2C) allow us to estimate the maximum discharge rate assuming a bankfull discharge using Manning's equation, modified by Komar (1979). This relation reads:

$$Q= A\,(g_m S R^{4/3}/g_e n^2)^{1/2} \qquad (1)$$

where $Q$ is the discharge rate, $A$ is the flow cross-sectional area, $g_m$ and $g_e$ are respectively the gravity on Mars and Earth, $S$ is the local slope, $n$ is the Manning roughness coefficient (Williams *et al.,* 2000) and $R$ is the hydraulic radius defined as the ratio of flow cross-sectional area to wetted perimeter. Use of this equation has been extensive on Mars (Carr, 1996). We use $n=0.05$ as a mean value (typical of gravel bed rivers without vegetation). This equation is used for sections 1 and 3 (fig. 2) where depth is between 250 and 350 m with widths of 10 km assuming a rectangular shape. As chaotic terrains strongly affect the morphometry of the channel, we do not apply the calculation on section 2 (fig. 2).

Using equation 1, the discharge rates calculated for section 1 and section 3 are respectively $3.10^7$ $m^3.s^{-1}$ and $9.10^7$ $m^3.s^{-1}$. Assuming here a bankfull discharge, these values probably overestimate the real values. To obtain a more realistic estimate we can use the apparent depth of grooves, which appears to give a minimum depth of flow. Topographic profiles give about 50 m for the largest grooves. Using this value for the flow depth, we calculate a discharge rate of $6.10^6$ $m^3.s^{-1}$ and $9.10^6$ $m^3.s^{-1}$, one order of magnitude lower than the ones calculated above.

## The source area and the connection with Ganges wallslopes

Elaver Vallis takes its source in a 80-km-diameter impact crater (fig. 4, fig. 5, and fig. 6). The crater is a closed basin: except Elaver to the east no other valleys cut the rim. Its planar topography and shallow depth (300 m) suggest the existence of a post-impact filling. Indeed, a crater 80 km in diameter should have an initial depth that we can estimate from an empirical law (Melosh, 1989) to be around 3 to 4 km after relaxation stage. The crater has therefore been filled by sedimentary or volcanic processes (lava flows, subsurface flows). Of special interest is an ovoid depression present to the south of the crater with a maximum depth of 5 km. Some mass wasting material partially fill the bottom part of this depression (fig. 5A). The formation of this depression is clearly posterior to the filling of the crater. The origin of this closed depression is enigmatic but it enables to observe deep cross section in the crater filling.

Visible images at THEMIS scales show that the crater floor material is layered (fig. 5A). Three different surfaces are identified from their distinct albedo and surface property (fig. 4 and fig. 5). The unit '*c*' covers one third of the crater (fig. 4B). This unit presents a relative bright albedo and a rather weak night time temperature suggesting that bright fine-grained material such as dust covers this unit. The '*uo*' unit is located northwestward within the crater (fig. 4B). Its very high albedo associated to a strong night temperature suggesting a rock outcrop (fig. 5A). Some dendritic valley-like landforms cut this unit creating the darker

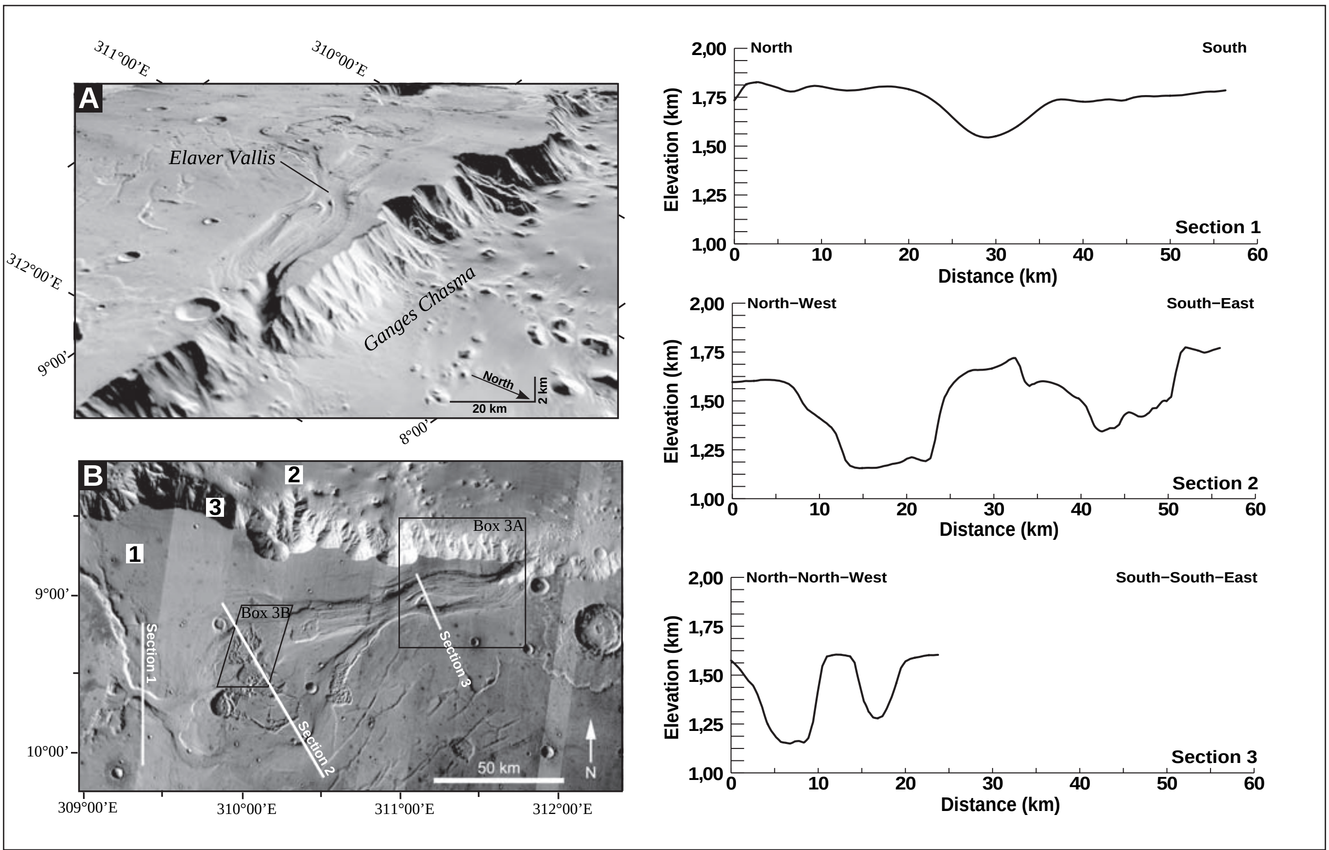



Fig. 2 – **Elaver Vallis outflow channel**. A: Bird's view of a day-time IR-THEMIS mosaic draped on MOLA DEM showing Elaver Vallis and its connexion with Ganges Chasma; B: Aurorae plateau noted 1, surrounds Ganges Chasma noted 2, the depression's wallslopes are noted 3. The three sections correspond respectively to topographic profiles on the right side. The down-flow slope measured between the bottom of section 1 and section 3 is smaller than 0.04 degree.

*Fig. 2 – **Vallée d'Elaver Vallis créée par une débâcle**. A : vue en perspective d'une mosaïque d'images THEMIS IR de jour illustrant la morphologie d'Elaver Vallis ; B : le plateau d'Aurorae est noté 1,Ganges Chasma est noté 2,les versants de ce dernier sont notés 3. Trois sections (1-3) représentent les profils topographiques respectivement de haut en bas. La pente mesurée au fond de la vallée dans la direction d'écoulement entre la section 1 et 3 est inférieure à 0,04 degré.*

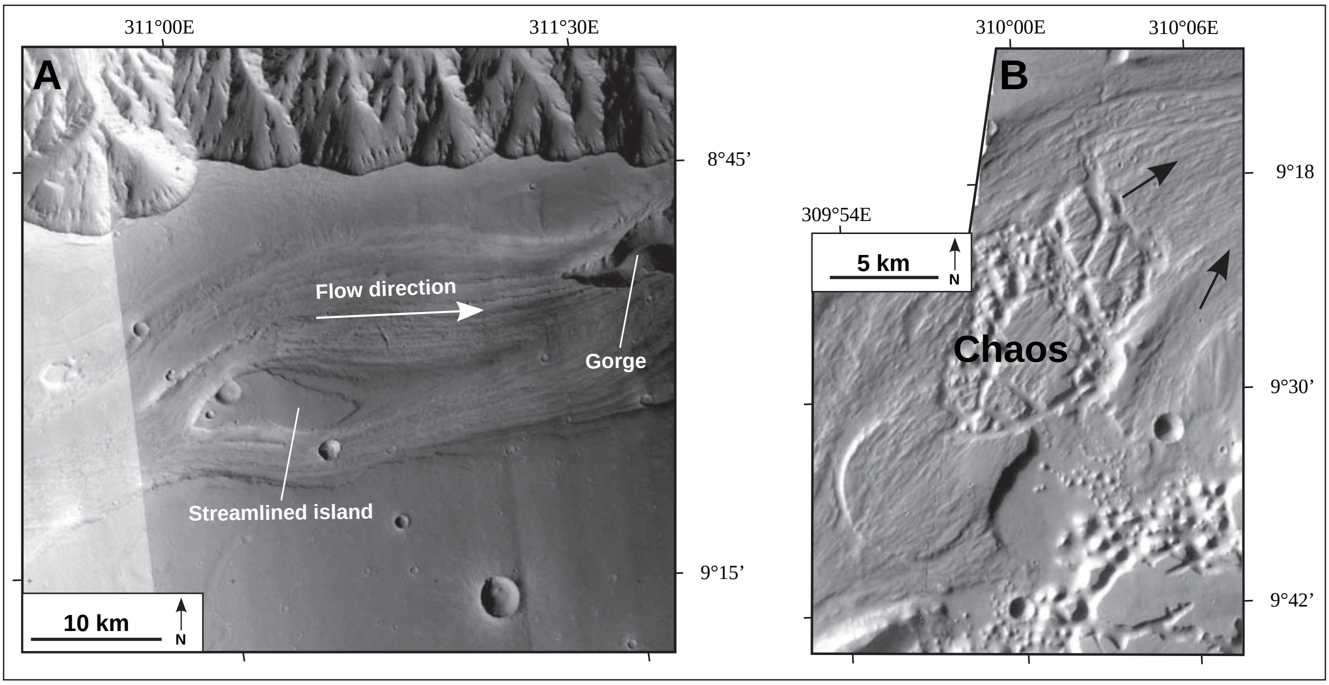



Fig. 3 – **Close up on Elaver Channel.** A: CTX image close-up of a part of Elaver Vallis. A streamlined island with acute angle indicating the direction of the flow from left to right (west to east). Note the incision of the tiny gorge at right; B: Visible THEMIS images of chaotic features, mainly hummocks, located in the area of cross-section 2 (see fig. 2). Grooves indicated by black arrows result from strong erosion by aqueous flows or ice. Cross-cutting relationships of grooves with chaotic terrains imply that chaotic landforms formed after the flow.

*Fig. 3 – **Agrandissement de la région de la vallée d'Elaver.** A : Image CTX illustrant Elaver. La forme profilée et anguleuse de l'île suggère une direction de l'écoulement de la gauche vers la droite de l'image (d'ouest en est). Noter l'incision de la petite gorge dans le fond du chenal sur la droite ; B : image « THEMIS visible » de morphologies chaotiques situées à l'emplacement de la coupe n°2. Les relations stratigraphiques entre les cannelures et les terrains chaotiques suggèrent que ces derniers sont postérieurs à l'écoulement lui-même.*

'*cn'* unit (fig. 5B). This unit appears as positive relief therefore possibly consisting of aeolian infill of pre-existing erosional landforms.

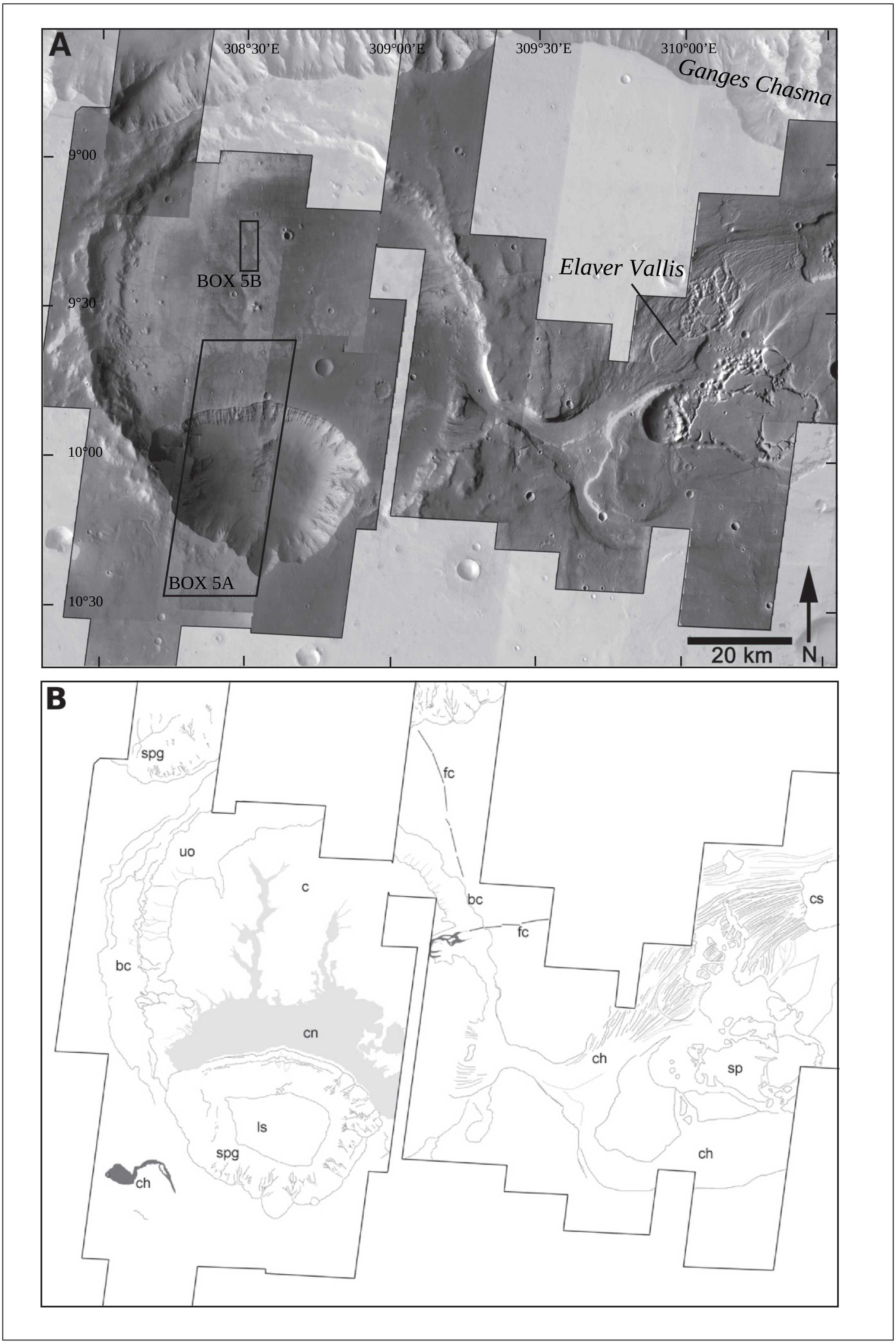
From the data collected by the OMEGA spectrometer onboard Mars Express probe the presence of olivine was identified (Mustard *et al*., 2005) on the unit named '*uo'* (fig. 5B). Lack of olivine detection in the wallslopes of this closed depression suggests that the olivine-rich layers are thin. No hydrated minerals seem to be present together with olivine here (Poulet *et al*., 2005). This thin olivine unit may therefore correspond to a volcanic filling of the crater, or possibly to a thin sedimentary mantle of aeolian origin (e.g., sand predominantly composed of olivine).

The lack of other valleys indicates that the crater is not a catchment basin for the outflow channel. The crater might have contained a lake; however this would require to understand the origin of the water. We propose three distinct alternatives: (1) the impact crater was filled by rainfall and was subject to overflow; (2) the impact crater was filled by subsurface aquifers that later overflowed; (3) subsurface water came to surface from the deep depression at the southern edge of the impact crater. This deep depression is located just at the boundaries of the impact crater suggesting that its formation was favored by rock weakness and fracturing due to the impact itself.

The connection between Elaver Vallis and Ganges Chasma walls is of interest for chronological relationships as well as for processes implications. The valley is incised by a small V-shaped channel exactly at the location of this connection. This channel is very different in shape from the main outflow channels. On the other hand, the Ganges floor does not show a clear signature of the event that formed Elaver Vallis, either

Fig. 4 – **Source of Elaver Vallis.** A: Mosaic of THEMIS visible images (18 m/pixel). Light comes from top left. Elaver Vallis takes its source in an impact crater, temporally named Elaver Crater, measuring 80 km in diameter. Three different units of albedo and morphologies are present in the crater; B: Legend of geomorphologic features: The south depression is 5 km deep and small landslides accumulated at the bottom (noted ls). The plateau between the two parts of Elaver presents valleys typical of undermining sp. In the valley Elaver circular depressions cs cut the valley of Elaver. spg: spur-and gullies features on wallslopes; fc: fracture; ch: channels; sp: sapping; cs: collapse; bc: impact crater edges. The three albedo units are respectively noted uo, cn and c (see text for description of each unit).

*Fig. 4 – **Source de la vallée d'Elaver**. A : mosaïque d'images « THEMIS visibles » à 18m/pixel éclairée d'en haut. Elaver Vallis prend sa source dans un cratère d'impact de 80 km de diamètre. Trois unités, d'albédo et de morphologies différents, sont identifiables dans ce cratère ; B : légende ; au sud, la dépression de 5 km de profondeur est partiellement comblée de petits glissements de terrain ; dans la vallée, des dépressions circulaires cs recoupent les morphologies d'écoulement. spg : versants érodés ; fc : fracture ; ch : chenaux ; sp : vallées formée par sapement ; cs : effondrements ; bc : bordures du cratère ; ls : glissements de terrain. Les trois unités sont notées uo, cn et c.*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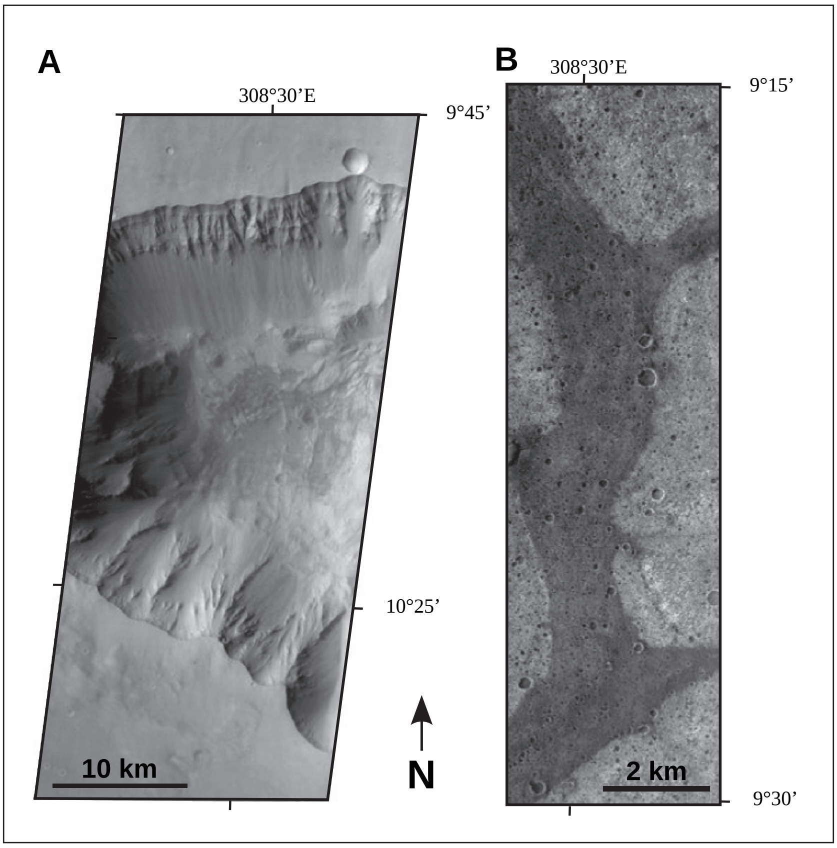


Fig. 5 – **Close up inside Elaver Crater**. A: THEMIS visible image. Depression trough present at the southern part of the source of Elaver Vallis. Layered terrains are observed on the top part of the wallslopes. However, the layers seem to be thinner in the northern slope rather than on the southern one, which suggests a different lithology. On the northern outcrop, layered terrains correspond to the filling up of the crater. On the contrary, the southern layered terrains remind those of Valles Marineris scarps, suggesting a similar lithology (e.g., flood basalt): they correspond to the Aurorea plateau composition. The bottom part of this depression is filled up by mass wasting materials (noted ls); B: MOC image close up on the filling of the crater. Two different albedos characterise two geological units. The dark one is the cn unit described previously. Its ramified shape remains enigmatic.

*Fig. 5 –* ***Agrandissement de l'intérieur du cratère source d'Elaver Vallis.*** *A : zoom sur la dépression située dans le cratère source de Elaver. Les morphologies observées sur les versants de cette dépression suggèrent la présence de terrains stratifiés. Cependant, cette stratification apparaît plus fine sur le versant nord comparée à celle observée sur le versant sud. Il pourrait s'agir d'une composition lithologique différente. Ces terrains stratifiés au nord correspondent au remplissage du cratère. A l'inverse, les terrains observés sur le versant sud correspondent aux terrains qui composent* Aurorea Planum. *Des processus gravitaires (glissements, effondrements granulaires) ont rempli partiellement le fond de la dépression (notés ls) ; B : l'image MOC présente un agrandissement du centre du cratère. Les variations d'albédo indiquent clairement la présence de deux unités géologiques distinctes. La plus sombre, notée cn, présente une morphologie ramifiée dont l'origine reste énigmatique.*

in erosion or deposition. A small valley incises the trough floor in the continuation of the outflow valley. Nevertheless, its size does not correspond to the discharge rate calculated previously for Elaver Vallis. These observations suggest that the formation of Elaver Vallis probably predates the formation of the Ganges Chasma. A deep inset valley (noted as gorge on fig. 3A) cuts at its headwater into the Elaver Vallis in the westward direction (fig. 3A and fig. 6). We interpret this valley as the result of backward erosion due to sapping. Ganges's wallslopes consist of spurs and gullies landforms, whereas this deep inset valley shows fresh wallslopes with slopes over 20° suggesting a late activity. In addition, the fact that this backward erosion occurred through the floor of Elaver Vallis suggests a genetic link such as the preservation of aquifers in the subsurface well after the outflow at the surface.

On both sides of the Elaver's mouth, alluvial cones were observed at the bottom of the trough's wallslopes (fig. 7A). Their size ranges between 2 and 4 km in length. They are themselves incised by small valleys (fig. 6 and fig. 7A). The presence of cones at the bottom of slopes suggests surface flow. Their morphology looks like alluvial cones on Earth and could suggest a water activity after the Ganges Chasma formation.

## Geomorphologic analysis of Allegheny Vallis

### The valley characteristics and morphometry

Allegheny Vallis, west of Ganges Chasma, presents landforms similar to those of Elaver Vallis (fig. 8A). The valley is 190 km long and its width varies from 2 to 10 km. Its depth is about 150 m at maximum (fig. 9B). Streamlined islands and grooves indicate a flow from south-west to north-east (fig. 8). Terraces visible on the border of the valley likely correspond to erosion of the bedrock rather than accumulation patterns (fig. 8 and fig. 10). There are no tributaries: only a single source area and a single termination.

Using Manning equation with a mean depth of 150 m and a width of 5 km (see equation 1), a discharge rate Q = 0.9. $10^6$ $m^3.s^{-1}$ was calculated. This value is in the same range as those calculated by Coleman *et al.,* (2007), but with respect to Elaver, Allegheny shows a lower discharge rate. The calculated peak discharge rates, for both outflows, are 100 to 1000 times lower than those calculated for the large outflow of Kasei or Ares Vallis with values of up $10^9$ $m^3.s^{-1}$ (Komar, 1979; Robinson and Tanaka, 1990), but they are about similar to the values found for late episodes of floods in Kasei Vallis (Williams *et al.*, 2000). These discharge rates are also in the range of calculated rates of terrestrial megafloods, such as the glacial surge of the Lake Missoula in the Scabland region with 20x$10^6$ $m^3.s^{-1}$ (Baker, 1973) or the overflow of the Lake Bonneville of the order of $10^6$ $m^3.s^{-1}$ (O'Connor, 1993).

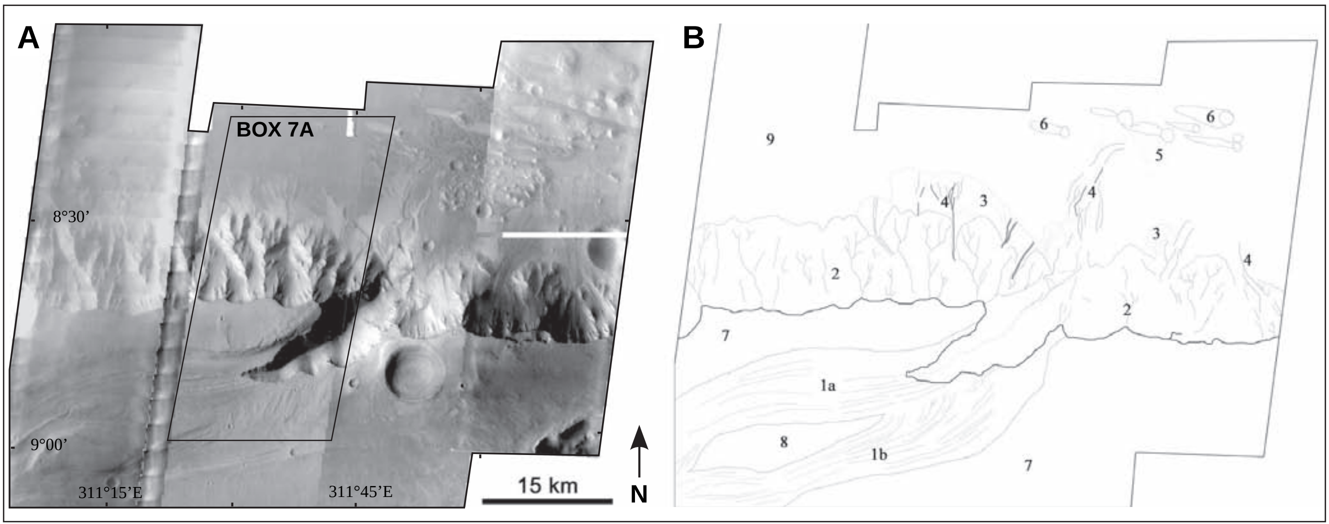


Fig. 6 – **Elaver Vallis mouth.** A: Mosaic of THEMIS visible images closed up on Elaver Vallis mouth. The light comes from top left; B: Interpretation of geomorphologic features and their legend: the shape of the valley 1b suggests that this valley joined the other one (noted 1a). Consequently, valley 1b is posterior to valley 1a. 2: wallslopes of Ganges; 3: alluvial cones; 4: small channels; 5: barkhanes; 6: nebkha-like dunes; 7: Aurorӕ Planum; 8: island in the valley; 9: floor of Ganges.

*Fig. 6 – **Embouchure d'Elaver Vallis**. A : mosaïque d'images « THEMIS visibles » éclairée d'en haut ; B : la concavité de la vallée en 1b suggère que celle-ci s'est greffée sur la première notée 1a. Légende : 1a et 1b : Elaver Vallis ; 2 : versants de Ganges Chasma ; 3 : cônes alluviaux ; 4 : petits chenaux tardifs ; 5 : barkhanes ; 6 : dunes de type nebkhas ; 7 : plateau de Aurorea ; 8 : îlot au milieu de la vallée de Elaver ; 9 : fond de Ganges Chasma.*

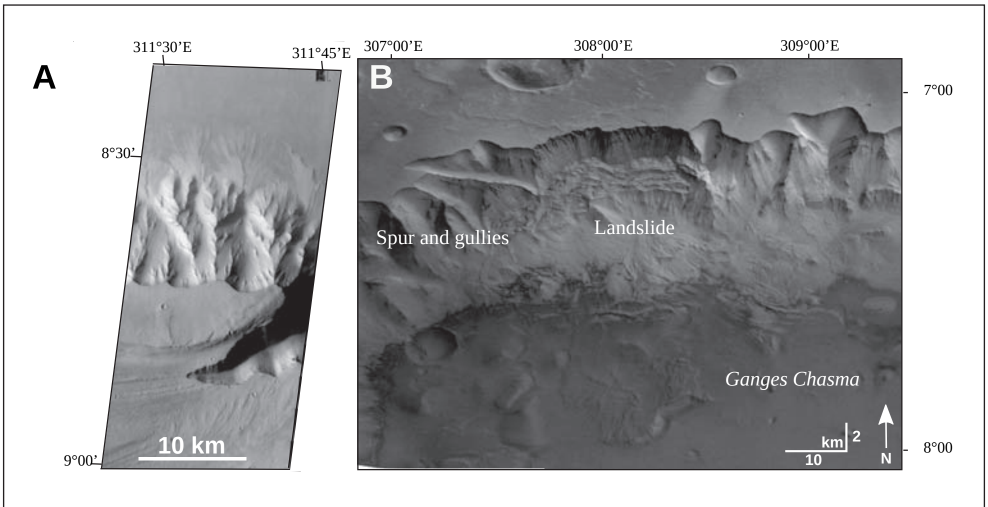


Fig. 7 – **Ganges wallslopes features.** A: Fans are present at the bottom part of wallslopes of Ganges Chasma; (A and B) spur-and-gully topographies are observable along the wallslopes; B: HRSC bird's view on landslide which cuts the wallslopes of Ganges Chasma.

*Fig. 7 – **Morphologie des versants de Ganges Chasma.** A : cônes présents au bas des versants ; (A et B) morphologies d'éperons et ravins sont observables sur l'ensemble des versants ; B : vue en perspective HRSC sur un glissement de terrains recoupant les versants de Ganges Chasma.*

flow itself. In the surroundings of this depression, there are no other signs of flows (or other outflows) that would lead to another source area. One exception is a small valley, provisionally named Walla Walla Vallis (Dinwiddie *et al.*, 2004), which joins Allegheny. Its size is smaller and cannot explain the flows in Allegheny. In addition, the source area of Walla Walla Vallis itself is an open depression too, of the same axial direction than Ophir Cavus. This observation leads to the unique possibility for the source of Allegheny: Ophir Cavus was involved in its formation. In terms of outflow events, at least two major branches have been observed (fig. 9B). On figure 9B the branch noted 1 seems to be deeper than the branch 2 suggesting a later activity or a higher discharge rate.

Nothing indicates that the flow was once discharging into Ganges Chasma. The trough floor is incised at the mouth of the Vallis by a deep and narrow gorge suggesting backward erosion over about 20 km. This gorge does not display any spur and gully morphology and has steeper slopes (>20°) than the depression wallslopes, suggesting a younger age of formation. The characteristics of this deep and narrow gorge

## The source area and the connection with Ganges wallslopes

No catchment or tributary can be identified at the starting point of Allegheny Vallis. The source area is characterized by an ovoid depression, Ophir Cavus, which is 4 km long, 15 km wide and 3 km deep (fig. 8A and fig. 9A). No channel or valley is observed on the opposite side of the Cavus that would indicate that its formation is younger than the

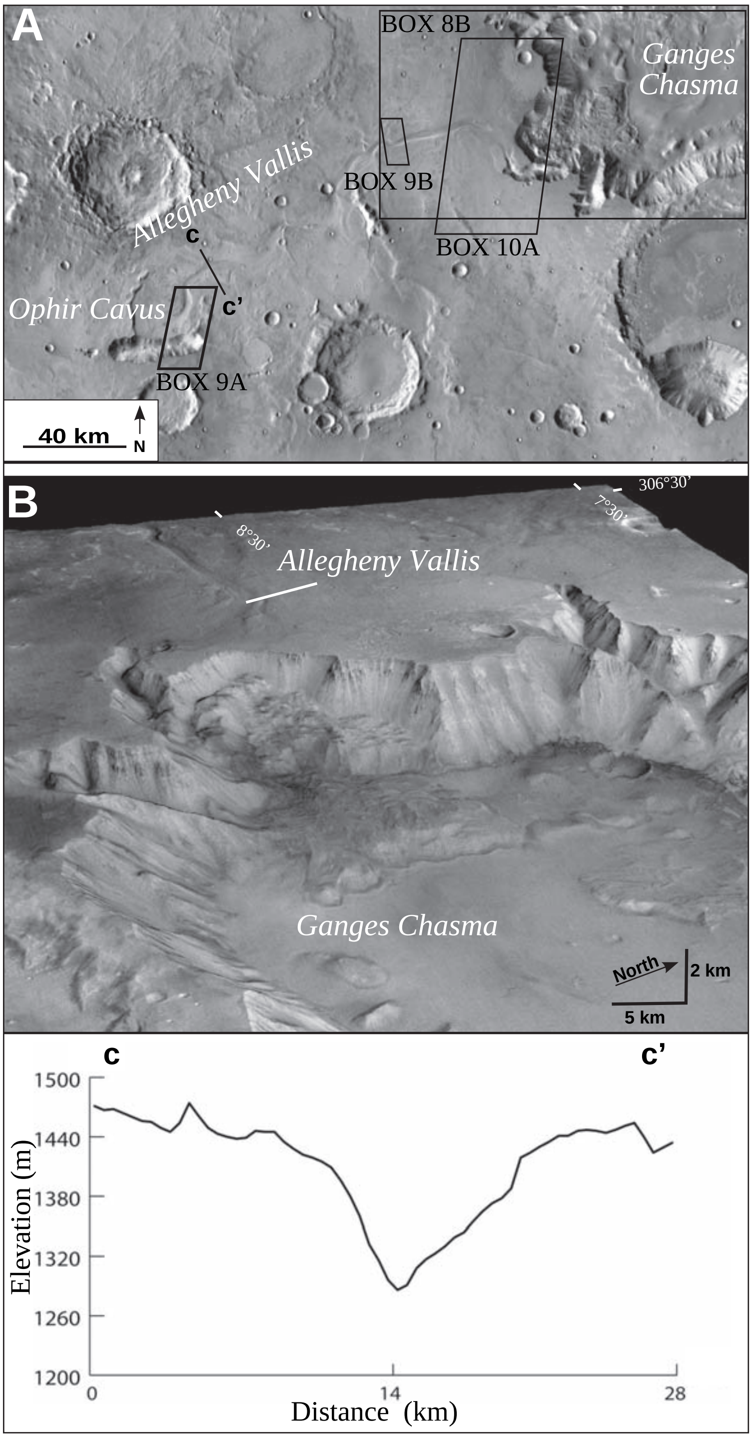


Fig. 8 – **Allegheny Vallis.** A: IR-THEMIS Mosaic of Allegheny Vallis and its source named Ophir Cavus; B: Bird's view from HRSC of the connexion between Allegheny Vallis and Ganges Chasma; C-C': MOLA topographic profile of Allegheny Vallis.

*Fig. 8 – **Allegheny Vallis**. A : mosaïque d'images THEMIS IR de la vallée Allegheny et sa source nommée Ophir Cavus ; B : vue en perspective HRSC de l'embouchure de la vallée d'Allegheny ; C-C : profil topographique MOLA à travers la vallée d'Allegheny.*

are very similar to those of the gorge incised at the mouth of Elaver Vallis (fig. 2A and fig. 8B). Landslide and collapse deposits covering the floor of Ganges at the northern side of the gorge prevent the identification of any fluvial landform on the depression floor downstream of the gorge (fig. 8B). The chronological relationship between the landslide and the gorge's formation is doubtful, but it seems that this landslide cuts the left hand side of the gorge's mouth, and is younger than the incision.

## Interpretation of flood events

Both outflow channels linked to Ganges Chasma have similar characteristics: their dimensions and their calculated discharge rates are within the same range of magnitudes. They are both connected with Ganges Chasma and in both cases the mouth does not present any deposition landform over the trough's floor. Finally, backward incision of a deep and narrow gorge has been observed at the mouth of the two outflow channels (fig. 6A and fig. 10A). From these similarities, it may be deduced that both Elaver Vallis and Allegheny Vallis have the same relationships with Ganges Chasma also suggesting a genetic link in the origin of the water involved in the flows.

### Source of flows

The source areas of both channels correspond to very deep and narrow pits. At Elaver source the origin of the flow is uncertain due to the coexistence of an impact basin and a pit. However, the observation of another flood associated with a pit allows us to interpret the ovoid depression as the unique source for the water flood events that produced Elaver Vallis. The difference between the two cases would be that the impact basin of Elaver Vallis had stored the water before releasing it through a channel. Thus, Elaver has been formed by a breach in a crater wall after storage of large quantities of water in the basin. In this interpretation, the difference in discharge rate between the two channels may be explained by this accumulation in the crater basin rather than a difference in source discharge rates. In addition, possible terraces, representative of shorelines, have been identified by Komatsu *et al*. (2004) in the crater walls.

These observations lead to an apparent contradiction: olivine is present on the floor of the crater which is the source area of a large channel whereas this mineral is quickly altered by water forming clays and serpentine (Gislason *et al.,* 1993). Nevertheless, the activity of Elaver could have occurred during a short time interval because the shape of the valley suggests a high discharge flood over a short duration (Baker *et al*., 1978; Carr 1991). This short time of activity would not have allowed a significant alteration of the rocks on the crater floor. Indeed, olivine alteration requires a wet period over at least 1,000 years so as to be effective especially if ambient temperatures are low (Gislason *et al.,* 1993; Stopar *et al.,* 2006).

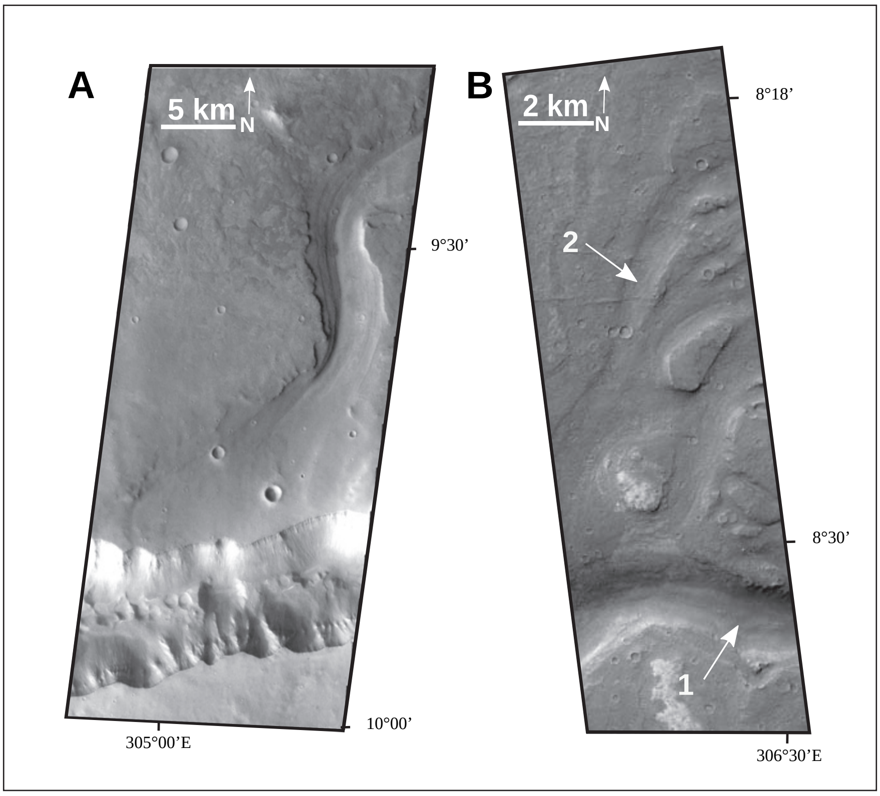


Fig. 9 – **Close up of Allegheny Vallis source and valley.** A: THEMIS visible image close up on the connection between Ophir Cavus and Allegheny Vallis; B: Close up on valleys (HiRISE image); channel 1 seems to be deeper than channel 2 suggesting a longer activity of channel 1.

*Fig. 9 – **Agrandissements de la source et la vallée d'Allegheny.** A : connexion entre Allegheny et sa source Ophir Cavus ; B : agrandissement de la vallée (image HiRISE) ; le chenal noté 1 apparaît plus profond que le chenal 2, suggérant une activité plus longue du premier.*

The origin of flows from open pits is questionable. On Earth, artesian wells could be formed by over pressurized groundwater; but this usually does not lead to high discharge floods. The regional map shows that both pits are aligned over an EW fault direction (fig. 1), the same direction as Valles Marineris. Hanna and Phillips (2006) proposed that overpressure in the subsurface related to the faulting stress could trigger the presence of flood at surface. According to this model, a flow of several millions $m^3.s^{-1}$ can be formed (Hanna and Phillips, 2006). These values are on the same order of magnitude as those calculated for the outflow channels. This mechanism requires a strong overpressure in the subsurface of the plateau at the period of formation of the outflow.

## Chronology of events

As mentioned previously, the Valles Marineris system lies along a structural trend that is clearly radial to the Tharsis dome (McCauley *et al.*, 1972; Lucchitta *et al.*, 1992). This

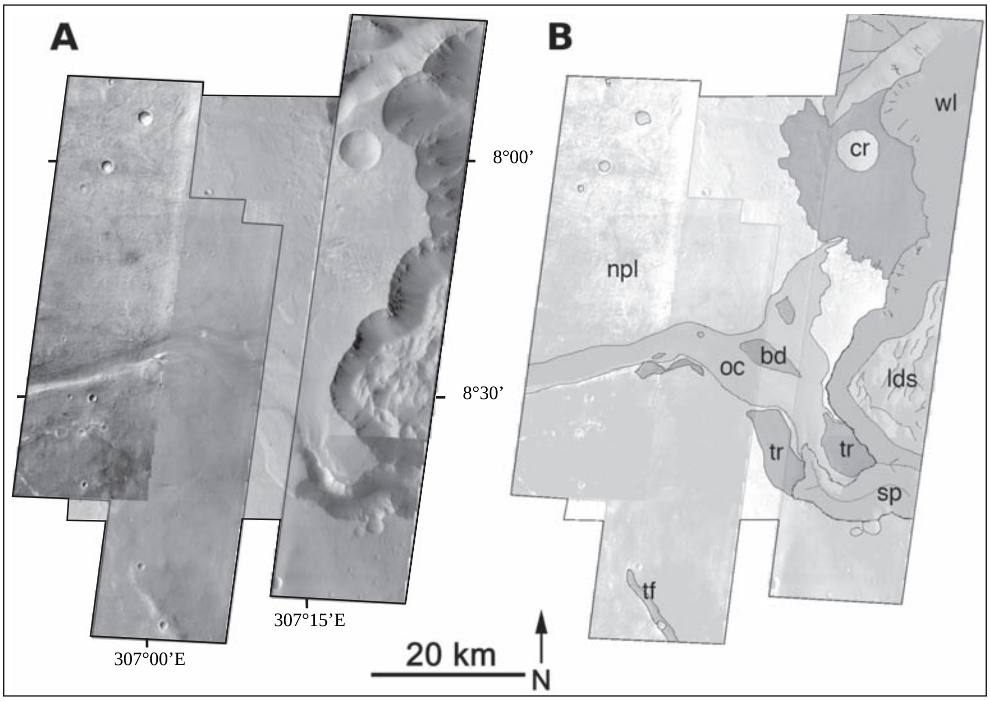


Fig. 10 – **Connection between Allegheny Vallis and Ganges Chasma.** A: Mosaic of THEMIS Visible images. Allegheny Vallis has similar dimensions compared with Elaver Vallis. A ramification of the valley is visible at the centre of the image. The principal direction of flow is indicated by the morphology of small islands in the valley; B: Interpretation and geomorphic features; caption: npl: Noachian Plateau; oc: outflow channels, tr: terraces; bd: fluvial bands; cr: impact Crater; tf: fractures; wl: Ganges's wallslopes; lds: landslide; sp: sapping-like valley

*Fig. 10 – **Connexion entre Allegheny Vallis et Ganges Chasma**. A : mosaïque d'images « THEMIS visibles ». Allegheny Vallis présente des dimensions similaires à celles de Elaver Vallis. Au centre de l'image, une ramification est observable. La direction principale de l'écoulement est indiquée par la morphologie de la petite île située dans la vallée. Situé à la connexion entre Allegheny Vallis et Ganges Chasma, des terrains étagés, surmontant la vallée, présentent une morphologie apparentr de terrasses ; B : légende ; npl : plateau Noachien ; oc : vallée de débâcle ; tr : terrasses ; bd : bancs fluviaux; cr : cratère d'impact ; tf : fractures ; wl : versants de Ganges Chasma ; lds : glissement de terrain ; sp : vallée créée par sapement.*

structural orientation is expressed in tectonic grabens responding to extensional stresses due to Tharsis Rise formation by huge volcanic activity (Blasius *et al.,* 1977; Wise *et al.,* 1979). Whatever is the rheological model used, it appears that Valles Marineris should be affected by the rising up of Tharsis dome (Willemand and Turcotte, 1982; Schultz, 1989; Mège *et al.,* 1996). Moreover, trough-boundary faults have been shown to be the result of orderly collapse by tectonic blocks (Shultz, 1989a).

In addition, it has been proposed that dyke intrusions could have formed pits by cracking the surface (Schultz, 1989a). As we already mentioned, Hanna and Phillips (2006) based on Schultz *et al.* (2004), have shown that dykes at depth infer extensive stress conditions at tip. Furthermore, Delaney (1982) has shown that the cryosphere could be pressurized by dykes and thus induce an outflow at the surface. Besides, the radial fracturing due to Tharsis formation (and thus making possible the presence of dykes) may affect the Ganges Chasma area (Mège *et al.,* 2003). As a consequence, we consider here that Ophir Cavus for Allegheny Vallis and the depression inside the impact crater for Elaver Vallis could be the result at surface of emplacement of dykes during or hereafter Tharsis formation, then causing overpressure of the groundwater inferring outflows. Moreover, the absence of any depositional landforms over the trough's floor and the almost flat down flow valley for both outflow channels (assuming that outflows could have been tilted by the initiation of the opening of Ganges by E-W normal faults) strongly suggest that outflow channels had been formed before the formation of Ganges trough. This chronology is thus different from most that of Xanthe Terra outflows, which have been formed after the Chasmata (Lucchitta, 1978; Baker *et al.,* 1978).

As suggested by their absence on wall surfaces (e.g. fault scarps), spur-and-gully features formed early in the Valles Marineris history (Lucchitta, 1987; Peulvast *et al.,* 2001). In addition, it is commonly thought that these features have been formed in a wet environment (Sharp, 1973; Lucchitta, 1987; Peulvast *et al.,* 2001). Deep and narrow gorges observed at the mouth of each outflow channels seem to be younger than these spur-and-gully features. These gorges incise backward into the floor of the outflow channels indicate a specific erosion process at the exact location of the channel mouth. This can be explained by a continuation of the flow inside the valley after the chasma formation with less energy, either by a subsurface flow created by sapping generated by high aquifer level beneath each valley. The first interpretation does not fit with the characteristics of the deep and narrow gorge, which do not suggest formation by surface runoff. In contrast, the outflows likely induced a strong infiltration in the subsurface of the channel, generating a high hydraulic head under the valley. The fans visible at surroundings wallslopes might correspond to flows generated by subsurface water sources in fewer quantities. All these observations strongly suggest a continuous activity of liquid water since the outflow formation, followed by the opening and widening of the Chasma by some massive collapses and mass wasting processes (Lucchitta, 1978; Peulvast *et al*., 2001, Quantin *et al*., 2004) until the re-incision of the outflows. This interpretation slightly differs from that of Coleman *et al*. (2007) according to which these outflows would have been formed after the formation of the trough. These outflow channels do not follow a tectonic direction, and may have been formed by the conjunction of surface and subsurface water flows. Relationships between subsurface water flows and opening and widening of the chasma are not clear at this stage. The origin of the high groundwater level is still to be questioned, but the observation of valleys networks in a few locations over the Tharsis plateau suggests that rainfall (or snowmelt) might have induced a recharge of aquifers (Mangold *et al*., 2004).

## Conclusions

In summary, the geomorphic study performed here strongly suggests that the outflow channels on Aurorae Planum pre-dated the opening of Ganges Chasma. The absence of deposits at the mouth of the outflow channels within the Ganges Chasma supports this chronology. Subsequently, mass wasting processes such as gullying and landslides have widened the depression of Ganges. Moreover, the formation of Tharsis plateau was associated with magmatic and volcanic activity and extensional faulting (Schultz *et al.,* 1989b; Mège *et al.,* 1996). As proposed by Hanna and Phillips (2006), this may have led to overpressure in groundwater aquifers and surface water discharge. In agreement with this model, this study suggests that groundwater has played a major role in the evolution of Ganges Chasma late after the end of the opening stage as shown by the occurrence of sapping at the mouth of outflow channels.

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