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The dominant morphogenetic role of surface runoff in Licus Vallis, Mars: results from geomorphological and morphometric analyses

El papel morfogenético dominante de la escorrentía superficial en Licus Vallis, Marte: resultados del análisis geomorfológico y morfométrico

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ABSTRACT

A watershed analysis was performed to assess the morphogenetic role of surface water on the development of Licus Vallis, an ancient river valley located in the equatorial region of Mars. Terrain analysis in a GIS environment allowed the identification of numerous relict fluvial features such as channels, paired terraces and a delta. Licus Vallis has the characteristics of a young watershed with a non-equilibrium profile, fourth-order streams, V-shaped valleys, very low drainage density, and a dendritic drainage pattern. Erosion related to surface runoff appears to be the dominant process involved in the formation of Licus Vallis. Nevertheless, the presence of theatre-like valley heads seems to indicate that sapping erosion associated with springs may have played some role in the headward expansion of valleys. Moreover, the finding, for the first time in this work, of a possible Gilbert-type delta at the mouth of the fluvial system permitted to define the paleobase level of the drainage basin and suggests the existence of an ancient sea in the region.

Key-words: *Mars, surface runoff, morphometric analysis, fluvial landforms.*

RESUMEN

Se ha analizado la cuenca de Licus Vallis, un antiguo cauce situado en la región ecuatorial de Marte, con la finalidad de evaluar el papel morfogenético que tuvo el agua superficial en su desarrollo. El análisis geomorfológico llevado a cabo en un entorno SIG ha permitido identificar numerosas morfologías fluviales relictas como canales, terrazas simétricas y un delta. Licus Vallis presenta una cuenca con rasgos propios de un relieve joven, con un perfil en desequilibrio, canales de cuarto orden, valles en V, una densidad de drenaje muy baja, y un patrón dendrítico. La erosión generada por la escorrentía superficial parece ser el proceso dominante en la formación de Licus Vallis. Sin embargo, la presencia de valles con cabecera semicircular parece indicar que la erosión asociada a surgencias pudo contribuir a la expansión por erosión remontante de los valles. Además, el hallazgo, por primera vez en este trabajo, de un posible delta de tipo Gilberten la desembocadura del sistema fluvial permitió definir el nivel de base de la cuenca y plantear la posible existencia de un antiguo mar en la región.

Palabras clave: *Marte, escorrentía superficial, análisis morfométrico, morfologías fluviales.*

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Introduction

The surface of Mars is currently too cold and dry to allow the presence of stable, long-standing liquid water. However, the existence of numerous relict fluvial and coastal landforms such as channels, paleolakes, terraces, deltas and probable shorelines seems to indicate that large volumes of liquid water flowed over the Martian surface in the past (Carr, 2012). A combination of surface runoff and sapping (erosion processes associated with springs) has been proposed to explain the formation of valley networks on Mars (*e.g.*, Harrison and Grimm, 2005). Nevertheless, the relative contribution of surface-water erosion and groundwater sapping in valley formation is not yet well understood (*e.g.*, Mest *et al.*, 2010).

A watershed analysis was performed in the catchment of Licus Vallis, an ancient river valley located in the equatorial region of Mars, close to the Martian highland-lowland boundary. The main objectives of this analysis were to shed light on the morphogenetic role played by liquid water in the past and assess the relative contribution of the dominant erosional process, namely runoff versus sapping.

Geographic and geological setting

Licus Vallis is located in the northeastern part of Mare Tyrrhenum quadrangle (centered at 3°S, 126°E) (Fig. 1). This region is incised by channel networks whose mouths terminate at the dichotomy boundary, near the Nepenthes Mensae area, and may have formed during the Late Noachian (Fassett and Head, 2008). Geologically, the Licus Vallis area is situated in the Middle Noachian highland unit (unit mNh), characterised by ancient highland basalts heavily cratered and dissected by fluvial networks (Tanaka *et al.*, 2014).

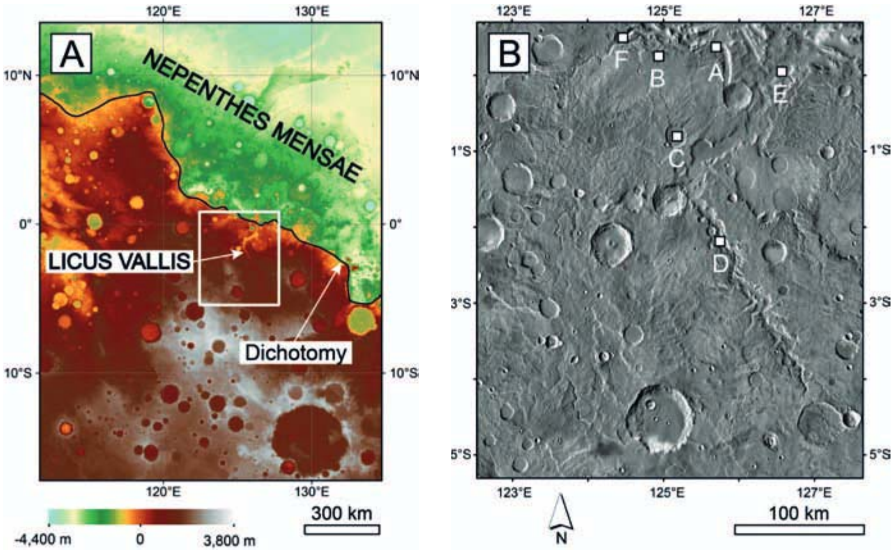

Fig. 1.- A) Regional setting of Licus Vallis (the study area is indicated by the white box) (MOLA topography, NASA). B) Image mosaic of the study area (labelled white boxes are locations of images shown in Fig. 2) (THEMIS-IR day images, NASA). See color figure in the web.

Fig. 1.- A) Situación regional de Licus Vallis (el área de estudio se indica con el recuadro blanco) (topografía MOLA, NASA). B) Mosaico de imágenes del área de estudio (los recuadros blancos etiquetados indican la localización de las imágenes mostradas en la Fig. 2) (Imágenes THEMIS-IR diurnas, NASA). Ver figura en color en la web.

Materials and methods

Topographic and imagery data were used to analyse the geomorphology and morphometry of the study area. Topographic data were extracted from a Digital Elevation Model (DEM) derived from images acquired by the High Resolution Stereo Camera (HRSC) instrument on board the ESA's Mars Express, with a resolution of 50 or 75 m per pixel. Imagery data consisted of panchromatic images from Context Camera (CTX) instrument, on board the NASA's Mars Reconnaissance Orbiter, and HRSC instrument (~6 m and 12.5 m in resolution, respectively). These data were integrated into a Geographic Information System (GIS) for carrying out multiple watershed analyses and describing the identified landforms. The stream network and watershed boundaries were initially mapped automatically using GIS tools. The flow accumulation tool permitted to preliminarily delineate the stream network by applying a threshold value of 14,000 cells (equivalent to an area of 35 km^2) to select cells with a high accumulated flow. The resulting stream network, including numerous artefacts, was improved manually.

Morphometric analysis

To analyse the drainage basin morphometry, we ranked the stream network using Strahler's classification (Strahler, 1952), and calculated morphometric parameters based on Horton's Laws (Horton, 1945). This analysis includes the consideration of linear, areal and relief aspects of the drainage basin. The linear aspects are outlined in Table I.

Drainage density (D_d) is a fundamental areal parameter that appraises the degree of fluvial dissection in a drainage basin, which in planet Earth is related to several factors like local climate, relief, substrate, runoff coefficient or vegetation cover. According to Horton (1945), drainage density (D_d) is defined as the total length of streams of all orders in a drainage basin (L_T), divided by the total basin area (A). It is expressed by the formula:

$$D_d = L_T/A \qquad (1)$$

If all other factors remain equal, higher drainage density values indicate low permeability and highly erodible substrate, while low drainage density occurs in areas of highly resistant and/or permeable substrate.

The relief aspects include, among others, the mean stream slope as a function of order, which is the average gradient expressed in degrees measured along all the stream segments of each order. Another relief parameter is the hypsometric curve. Hypsometric analysis relates the normalised elevation versus the normalised area of a drainage basin. This curve is used to estimate the geomorphic maturity of catchments.

Parameter	Formula	Ref.
Stream order (u)	Hierarchical rank	Strahler (1952)
Number of streams (N_u)	The total number of stream segments of a given order 'u'	Horton (1945)
Stream length (L_u)	The total length for each stream order 'u'	Horton (1945)
Bifurcation ratio (R_b)	$R_b = N_u/N_{u+1}$	Horton (1945)
Mean length ($\bar{L}_u$)	$\bar{L}_u = L_u/N_u$	Horton (1945)
Cumulative mean length ($\bar{L}_\mu$)	The sum of the mean stream length of a given order 'μ' and the mean lengths of all lower orders	Horton (1945)
Length ratio (R_L)	$R_L = \bar{L}_\mu/\bar{L}_{\mu-1}$	Horton (1945)

Table I.- Linear parameters used to analyse the drainage basin of Licus Vallis.

Tabla I.- Parámetros lineales utilizados para analizar la cuenca de drenaje de Licus Vallis.

Results and discussion

Main landforms

Terrain analysis allowed the identification of the most relevant landforms on the study area, such as the Martian dichotomy, impact craters, crater paleolakes, fluvial terraces and a delta.

The Martian dichotomy divides the poorly cratered northern lowlands from the heavily cratered southern highlands. It is characterised by a prominent escarpment around 1700 m in local relief, whose upper limit is at an elevation of about 0 m (Fig. 2A).

All impact craters larger than 2 km in diameter were mapped. The presence of rampart craters, characterised by distinctive features ascribable to fluidised ejecta, may indicate evidence of near-surface water or ice (Fig. 2B). Some impact craters may contain paleolakes, which were probably fed by fluvial channels. These relict lake basins may contain terraces and lake sediments (Fig. 2C).

The middle course of the main channel of Licus Vallis shows the development of paired terraces. These terraces, continuous for

Stream order, u	Number of stream, N_u	Bifurcation ratio, R_b	Stream length, L_u (km)	Mean length, $\bar{L}_u$ (km)	Cumulative mean length, $\bar{L}_\mu$ (km)	Length ratio R_L	Max stream slope (º)	Min stream slope (º)	Mean stream slope (º)	Stream area (km^2)
1	121	4.17	1413.96	11.69	11.69	0.33	39.99	0	4.37	89.50
2	29	3.63	689.95	23.79	35.48	0.34	42.60	0	4.90	43.60
3	8	8	555.77	69.47	104.95	0.24	35.40	0	4.80	35.00
4	1		340.03	340.03	444.97		25.20	0	4.50	21.72

Table II.- Results of the morphometric analysis of the drainage network of Licus Vallis.

Tabla II.- Resultados del análisis morfométrico de la red de drenaje de Licus Vallis.

tens of kilometres, possibly record the rejuvenation of the river valley due to a lowering of its base level (Fig. 2D).

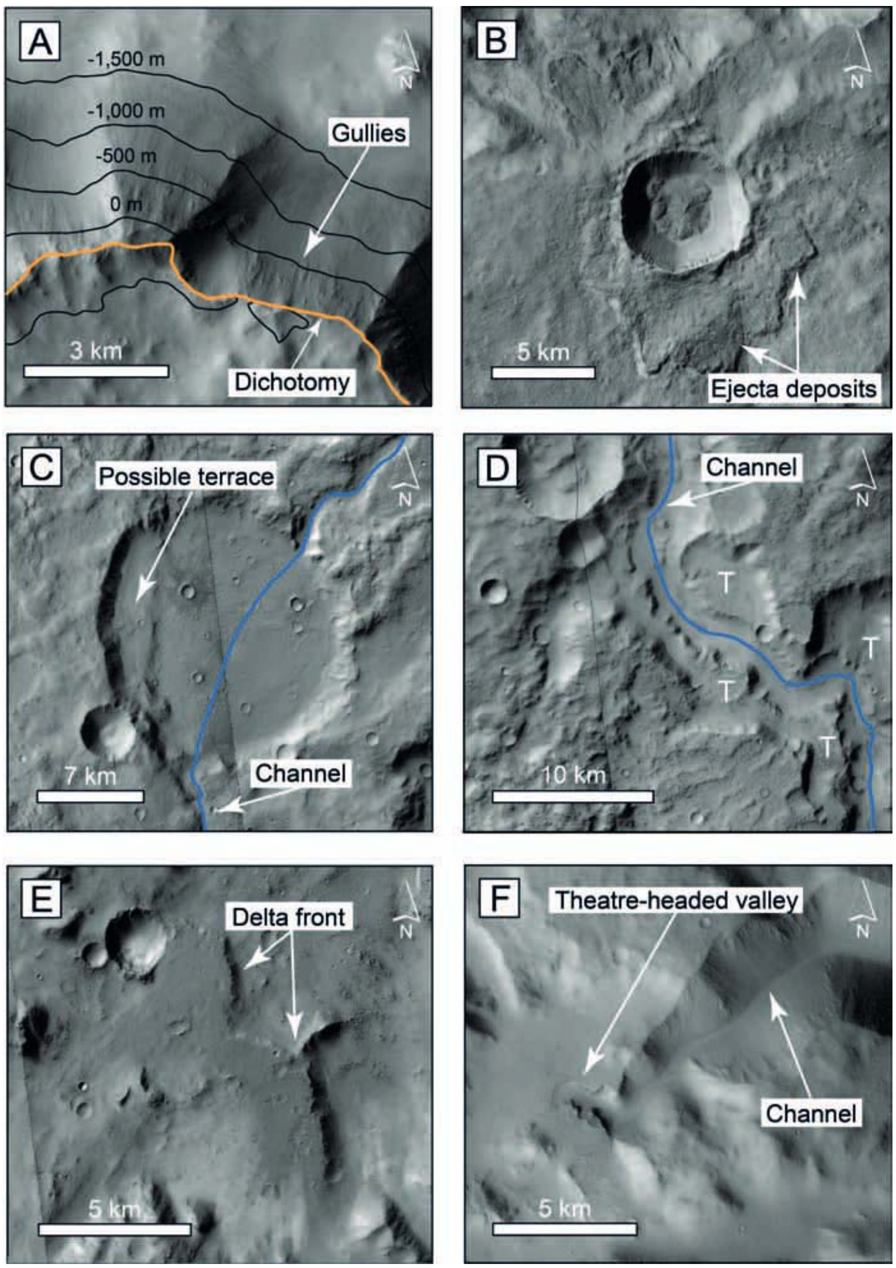

Fig. 2.- A) Martian dichotomy. B) Rampart crater. C) Crater paleolake with a possible terrace. D) Paired terraces (T) in the middle course of Licus Vallis. E) Gilbert-type delta. F) Theatre-like valley head and V-shaped valley (CTX images, NASA). See color figure in the web.

Fig. 2.- A) Dicotomía marciana. B) Cráter amurallado. C) Paleolago de cráter con una posible terraza. D) Terrazas simétricas (T) en el curso medio de Licus Vallis. E) Delta de tipo Gilbert. F) Valle con cabecera remontante y valle en V (Imágenes CTX, NASA). Ver figura en color en la web.

A possible Gilbert-type delta composed of two delta lobes was identified, for the first time, at the mouth of the river basin of Licus Vallis (Fig. 2E). The delta plain occupies an area of 90.1 km^2 with a mean depositional slope of ~3.4º. This delta defines a paleobase level of the drainage basin at -1186 m, given by the edge of the delta plain. Moreover, it seems to record a persistent water level of the ancient sea that possibly occupied the Lowlands at Nepenthes Mensae area (de Pablo and Pacifici, 2008).

Morphometric analysis

The watershed of Licus Vallis presents V-shaped valleys and occupies an area of 55672.6 km^2, with the highest and lowest elevation at 2442 and -1591 m, respectively. The lowest elevation corresponds to an intrabasinal impact crater, rather than to the mouth of the basin. Some valley heads display theatre-like morphologies and lack any evidence of surface runoff, which may be related to sapping erosion (Fig. 2F). Sapping causes the headward migration of channels by preferential erosion (undermining and cliff recession) associated with springs (Goldspiel and Squyres, 2000).

The drainage basin presents a fourth-order network, with a dendritic drainage pattern (Fig. 3A), and low average stream gradients (Table II). Most of the streams are first order and their number declines as the order increases. The mapped streams have a total length of 2999.7 km and the drainage basin has an area of 55672.6 km^2, yielding a drainage density of 0.05 km^{-1}. This is a very low value, in terms of terrestrial drainage density values (*e.g.*, Carr and Chuang, 1997), characteristic of a basin located in a region with a wet climate and resistant substrate, like the basalts (unit mNh) of the area of Licus Vallis. The mean bifurcation ratio is 5.2, which is larger than terrestrial values, typically ranging between 2 and 4 (Horton, 1945). The bifurcation ratio of 8 for third to fourth order channels increases the mean value. It is much larger than the bifurcation ratios obtained with lower

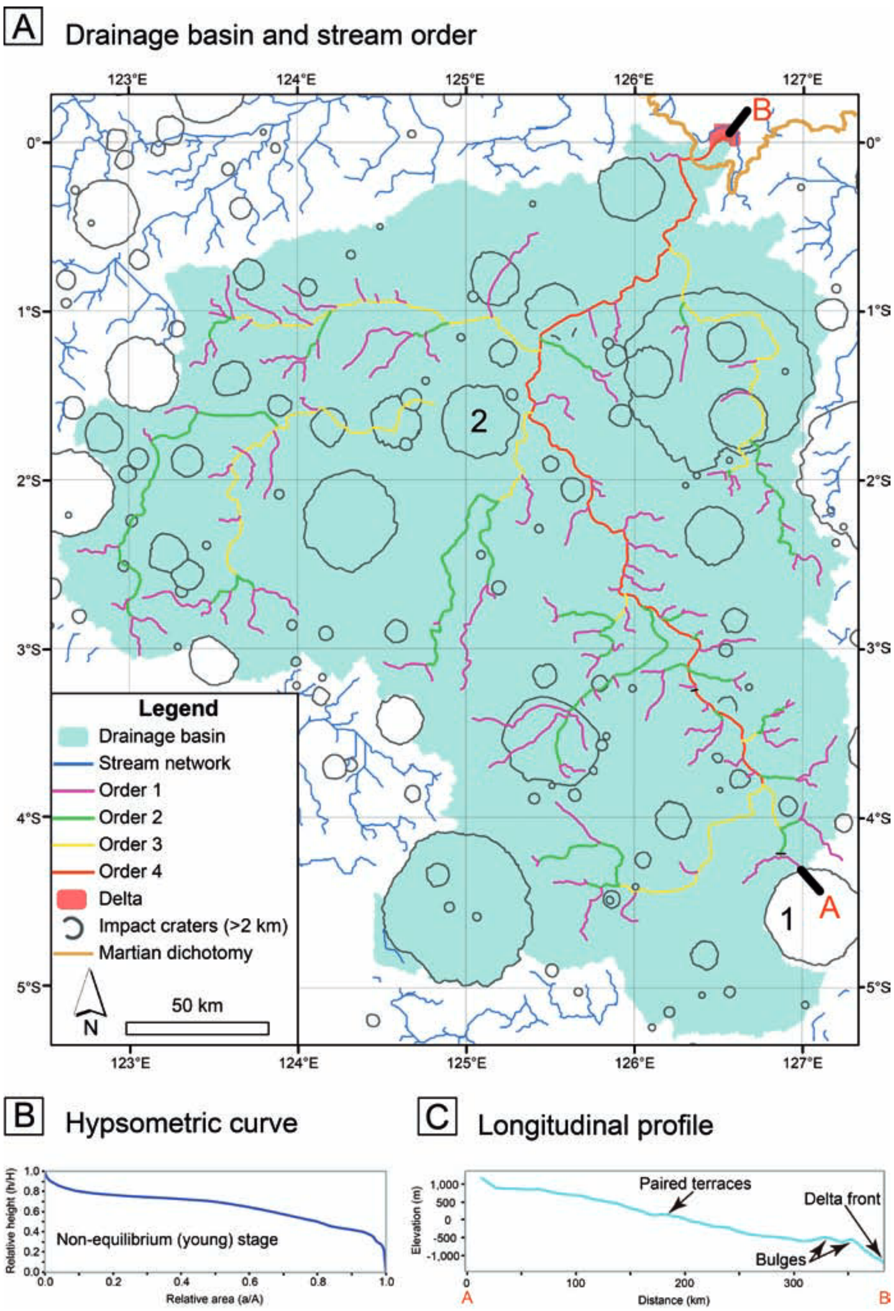

Fig. 3. A) Licus Vallis basin and stream ordering according to Strahler's classification. 1: Impact crater with a possible paleolake that eventually overflowed; 2: Channel interrupted by impact craters. B) Hypsometric curve of the basin. C) Smoothened profile of the main channel. See color figure in the web.

Fig. 3.- A) Cuenca de Licus Vallis y orden de canales según la clasificación de Strahler. 1: cráter de impacto que albergó un posible paleolago que alimentaba al canal principal; 2: canal interrumpido por cráteres de impacto. B) Curva hipsométrica de la cuenca. C) Perfil suavizado del cauce principal. Ver figura en color en la web.

order channels (Table II), which may indicate a poorly developed stream network. The hypsometric curve of the drainage basin shows that Licus Vallis has an immature topography (Fig. 3B), as corroborated by its non-equilibrium profile (Fig. 3C). Bulges near the mouth are probably related to tectonic deformation, as supported by the presence of morphostructural lineaments along the dichotomy boundary (Martín-González *et al.*, 2007).

Conclusions

The analysis of the identified landforms and their spatial relationships permitted the identification of water-related landforms like channels, paleolakes, paired terraces and a delta. Licus Vallis presents a young watershed, as indicated by its hypsometric curve and its non-equilibrium profile. The V-shaped valleys and a dendritic drainage pattern suggest that surface runoff was the main morphogenetic process in the formation of Licus Vallis. The presence of some valleys with theatre-like headcuts supports that sapping may have played a role in their headward expansion. In fact, the existence of rampart craters indicates the presence of large amounts of near-surface water or ice in the region during the impact events. On the other hand, the mapped putative Gilbert-type delta defines a paleobase level of the drainage basin and indicates the possible existence of an ancient standing body of water in the Lowlands. River terraces and the shape of the non-equilibrium profile may indicate an episodic water level drop of the ancient sea.

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