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A new model for evaluating the duration of water flow in the Martian fluvial systems

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Abstract. To understand the formation mechanisms of Martian fluvial systems and consequently to determine the ancient climate of the planet, we have mapped a sample of Martian valleys longer than 20 km (covering at the moment 65% of the planet) and for a subset extracted among them, containing some of the widest and more developed systems, we have also determined the formation time. To estimate the duration of water flow in these valley networks we have used an original method based on the evaluation of erosion rate of the terrain. Our results, ranging from 10^5 to 10^8 years (depending on erosion rate), are in good agreement with those reported in literature and obtained through more detailed models of sediment transport. These results imply that Mars had at least short periods of clement conditions toward the end of the Noachian Era that supported a hydrologic cycle and potentially a biosphere.

Key words. Mars – Water – Mapping – Fluvial systems – Valley networks – Transport models – Erosion rate

1. Introduction

Since the first observation of valley networks on Mars (Masursky 1973), these systems have aroused great interest because their presence suggests that in the past the planet contained a significant amount of water at the liquid state, that today is totally absent. These valleys show features resulting from a water surface flow likely due to rain or snow melting (Hoke & Hynek 2009a), phenomena now also absent on Mars. This would suggest that early Mars could have been warmer and wetter than today with atmospheric pressure and surface temperature different from the present ones (Craddock & Howard 2002). However, detailed geomorphic analysis of individual valley networks did not lead to a general consensus regarding their formation timescales. Therefore from a paleoclimatic point of view it is interesting to map Martian valley networks and to determine their formation timescales.

In this work we have used QuantumGIS (QGIS), a Geographic Information Software as a tool to create a map of Martian valleys and to calculate their geometric parameters (such as area and volume), based on MOLA (Mars Orbiter Laser Altimeter) and THEMIS (Thermal Emission Imaging System) data. The THEMIS daytime IR imagery, with a resolution of 100 m/pixel, is the highest resolution global dataset for MARS. The MOLA data

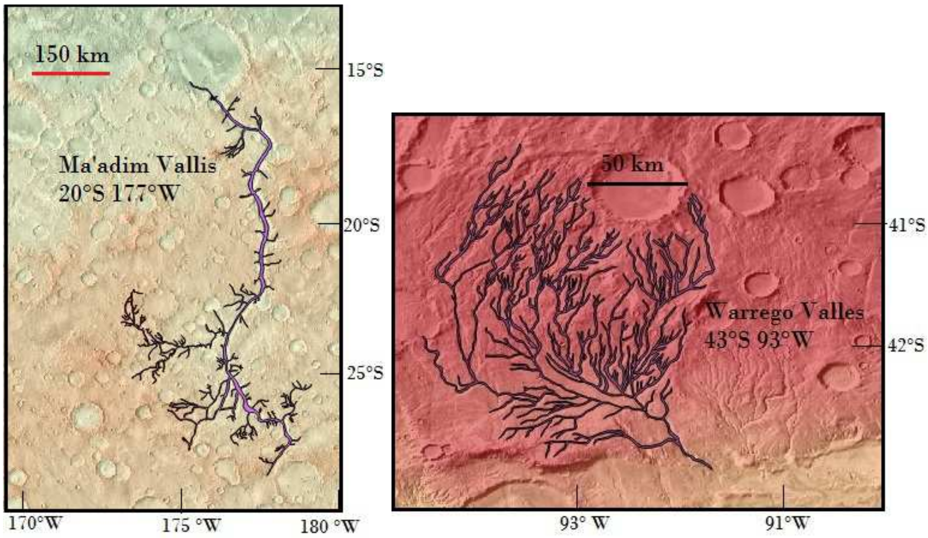

Fig. 1. Maps of Ma'adim Vallis (**left panel**) and Warrego Valles (**right panel**) obtained through the software QGIS using photographic THEMIS data and topographic MOLA data.

have a resolution of 436 m/pixel. Combining THEMIS daytime IR and MOLA topographic data improves the identification of valley networks over THEMIS or MOLA alone, resulting in a superior data set for accurate mapping and analysis of the valley networks on Mars (**?**).

2. Mapping

Valleys, longer than 20 km, were mapped manually using similar determining characteristics to those of Carr (1995) and Hynek et al. (2010). We have searched for sublinear, erosional channels that form branching networks, slightly increasing in size downstream and dividing into smaller branches upslope. The process of manual mapping is subjective and it can be influenced by albedo variations and image quality. Due to geological resurfacing events subsequent to the formation of valley networks, the observed geographic distribution partly represents the original distribution and partly represents the overprinting effects of later geological history. For example, it is increasingly difficult to recognize valley network drainage patterns at high latitude (south of 30° S) due to the effects of recent mantling and terrain softening (Carr 1995; Kreslavsky & Head 2000; Mustard et al. 2001).

3. Formation timescales

We have determined the formation time of a sample of nine Martian valleys: Ma'adim Vallis and Warrego Valles (shown in Fig. 1) along with other seven important valley networks located in Arabia Terra, Meridiani Planum and Terra Sabea (shown in Fig. 2).

Ma'adim Vallis is one of the largest valleys on the Martian highlands. This valley appears to have originated by catastrophic overflow of a large paleolake located south of the valley heads (Irwin et al. 2004) and debouches to Gusev Crater, about 900 km North of his heads. According to Cabrol et al. (1998) the valley was originated in the Noachian Era but the process which brought to his formation lasted 2 billion years.

Warrego Valles is a well-defined network present in Thaumasia region. It develops in a large drainage basin characterised by a concave slope in which a large number of valleys are arranged on both side of the main tributary. Valleys outside the drainage basin are arranged in a parallel pattern, whereas valleys in

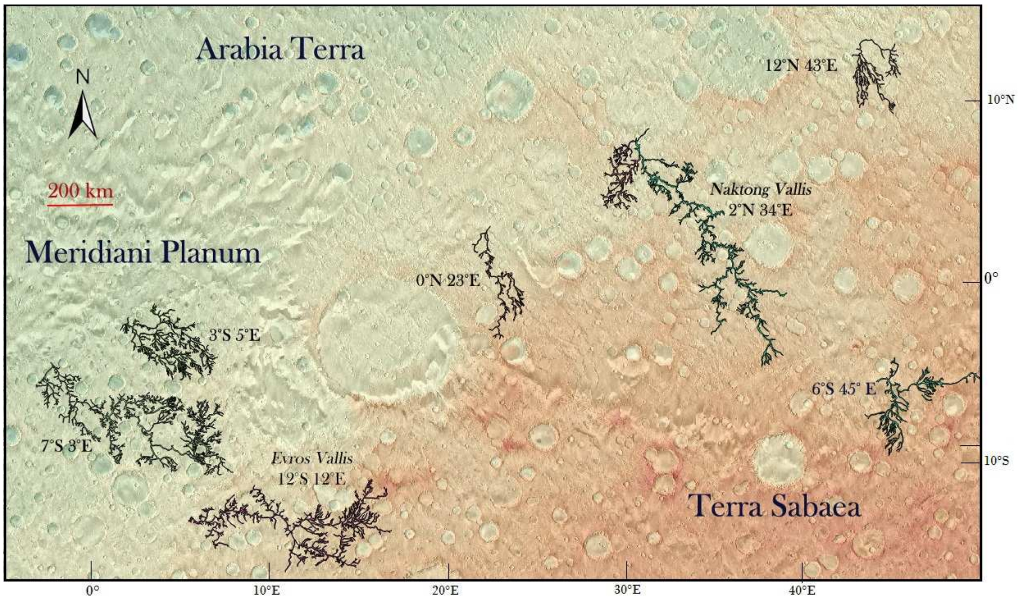

Fig. 2. Map of seven valley networks located in Arabia Terra, Meridiani Planum and Terra Sabea obtained through the software QGIS using photographic THEMIS data and topographic MOLA data.

the inner part of drainage basin shows a subdendritic pattern (Ansan & Mangold 2006).

Among the valleys located in Arabia Terra, Meridiani Planum and Terra Sabea, we have studied Naktong Vallis, centered on 2°N 34°E, Evros Vallis located at 12°S 12°E and other five valleys which have the following coordinates: 12°N 43°E, 0°N 23°E, 3°S 5°E, 6°S 45°E and 7°S 3°E.

Naktong Vallis is the southern part of a very large fluvial basin composed by Mamers and Scamander Valleys (Bouley et al. 2007). This valley shows clear evidence of multiple periods of formation along two separate branches that meet at 7°N 31°E (Hoke & Hynek 2007).

Naktong Vallis contains some evidence of interior channels, braiding, and terracing in their main trunks and/or major tributaries.

These characteristics all point to a widespread, abundant source of water that eroded the Martian surface primarily through overland flow rather than through subsurface erosion.

For this reason, Naktong Vallis belong to the so called "degraded valleys" which are characterized by jagged, irregular walls, indicating they have experienced more slumping and erosion (**?**). Degraded valleys also exhibit both U- and V-shaped cross sections. Also Evros Vallis and the valleys located at 7°S 3°E, 3°S 5°E are degraded vallis (**?**).

Instead, the valleys located at 6°S 45°E, 12°N 43°E and 0°N 23°E are "pristine valleys" characterized by smooth walls with sharp boundaries between the valley and surrounding terrain (**?**) .

All of the valley networks studied in this work show features consistent with formation by precipitation, including densely spaced dendritic form with interior channels that increase in width and depth downstream; sinuous main trunks and major tributaries that occasionally also exhibit multiple interior channels, braiding, and terracing.

So these valleys could give valuable information on the climate of the Red Planet during their formation/activity.

Table 1. Values of width, slope, area and volume obtained for the valleys of our sample.

Valley	width [m]	slope [m/m]	area [m^2]	volume [m^3]
12°N 43°E	1800	0.003	2.09E+9	1.64E+12
0°N 23°E	1870	0.004	1.87E+9	2.01E+12
3°S 5°E	1930	0.004	5.09E+9	5.47E+12
6°S 45°E	1800	0.003	2.63E+9	2.71E+12
7°S 3°E	1462	0.003	9.11E+9	9.13E+12
Evros Vallis	2430	0.003	7.07E+9	1.50E+13
Ma'adim Vallis	2900	0.004	7.12E+9	1.61E+13
Naktong Vallis	1375	0.004	1.16E+9	1.32E+13
Warrego Valles	1550	0.006	2.56E+9	6.92E+12

Table 2. Formation timescales (in yr) obtained for the valleys of our sample depending on erosion rates.

E (t km^{-2} yr^{-1})	E'(t km^{-2} yr^{-1})	0°N 23°E	Ma'adim Vallis	Evros Vallis	7°S 3°E	5°E 3°S	Naktong Vallis	12°N 43°E	6°S 45°E	Warrego Valles
$E_{Imin} = 16$	8.1	4.51E+8	9.49E+8	8.89E+8	4.21E+8	4.51E+8	4.78E+8	3.29E+8	4.32E+8	1.13E+9
$E_{Imax} = 257$	130.1	2.81E+7	5.91E+7	5.54E+7	2.62E+7	2.81E+7	2.97E+7	2.05E+7	2.69E+7	7.06E+7
$E_{Amin} = 17$	8.6	4.25E+8	8.93E+8	8.37E+8	3.96E+8	4.25E+8	4.50E+8	3.10E+8	4.07E+8	1.07E+9
$E_{Amax} = 102$	51.6	7.08E+7	1.49E+8	1.39E+8	6.60E+7	7.08E+7	7.49E+7	5.17E+7	6.78E+7	1.78E+8
$E_D = 53200$	26900	1.06E+5	2.23E+5	2.09E+5	9.90E+4	1.06E+5	1.12E+5	9.91E+4	1.02E+5	2.67E+5
$E_{Smin} = 17$	8.4	3.42E+8	7.20E+8	6.75E+8	3.19E+8	3.42E+8	3.62E+8	3.19E+8	3.28E+8	8.61E+8
$E_{Smax} = 47$	22.8	1.25E+8	2.64E+8	2.47E+8	1.17E+8	1.25E+8	1.33E+8	1.17E+8	1.20E+8	3.16E+8

3.1. Method

Until now, the formation timescales of Martian fluvial systems have been evaluated using complex models of sediment transport as those developed by Kleinhans (2005), Kraal et al. (2008), Hoke et al. (2011), Morgan et al. (2014), Palucis et al. (2014). These models are based on the evaluation of water and sediment discharge rates using "predictors" of transport and require the knowledge of various parameters which in same cases are very difficult to determine, such as the size of the inner channel of the valley and the grain size distribution of the sediment.

To estimate the duration of water flow in these fluvial systems we have used a method never used before for Martian valleys and based on the evaluation of the eroded mass given by:

$$m_s = \frac{M_s}{A} \tag{1}$$

where A is the area of the valley and M_S the total mass removed from the valley. M_S can be expressed as:

$$M_s = \rho_s V_s \tag{2}$$

with V_s, volume of the eroded sediment. We have chosen the basalt density

$$\rho_s = 3.4 \times 10^9 tkm^{-3}, \tag{3}$$

as spectroscopic analysis showed that the southern highlands, on which most Martian fluvial systems have been carved, consist of basaltic rock (Bandfield et al. 2000).

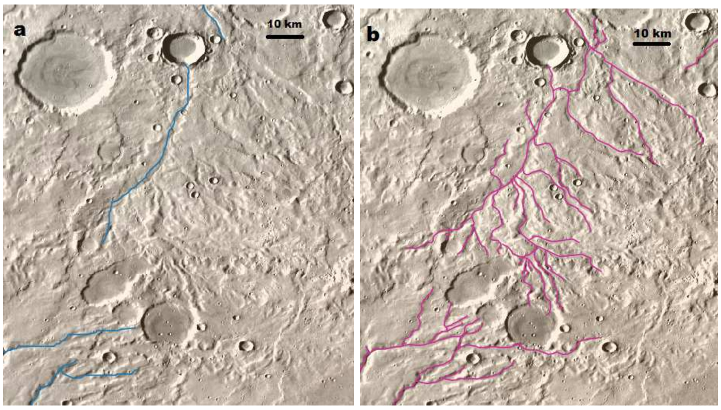

Fig. 3. Comparison between the valleys mapped by Hynek et al.(2010) from THEMIS data with a resolution of 200 m/pixel (a) and those identifiable from THEMIS data at 100 m/pixel (b). The area is centered around 32 °S, 162°E.

The timescale of formation has been obtained by the ratio between the eroded mass and the erosion rate:

$$T = \frac{M_s}{E} \tag{4}$$

The erosion rate E is a key parameter for calculating the timescale of formation of these valleys and depends on a large number of factors such as the size of the river, the nature of the load, the speed of the current, the gradient of the fluvial valley and finally the climatic and environmental conditions. The erosion rate has been evaluated using values obtained on Earth for regions of Martian interest assuming different possible situations. As a lower limit we have chosen the values obtained for Icelandic river carved on basaltic rocks E_I (Vigier et al. 2006), assuming that Martian valleys was formed in temperate climate conditions. While as an upper limit we have used a the value obtained by Hubacz (2012) E_D which considers incoherent materials. We have also used the erosion rate obtained for Atacama desert E_A (Hoke & Jordan 2010) assuming that Martian valleys was formed in pseudo-arid climatic conditions. Finally we have assumed a different lithology using the values obtained by Duxbury (2009) for siliciclastic rocks E_S.

All these values was extrapolated to the Martian case. In fact the erosion rate is connected to the gravity by this relation: E $\propto g^{0.7}$ (Irwin et al. 2004). So the erosion rate on Mars E' is linked to the terrestrial one E by:

$$E' = \left(\frac{g_M}{g_T}\right)^{0.7} E \tag{5}$$

where g_M and g_T are the Martian and Terrestrial gravity accelerations.

3.2. Results

Volume, area, slope and width has been evaluated for each valley (Table 1) in order to apply the method of erosion rates and others methods reported in literature which use various models of sediment transport (Kleinhans 2005; Kraal et al. 2008; Hoke et al. 2011; Morgan et al. 2014; Palucis et al. 2014). The obtained results for the method of eroded mass, range from 10^5 to 10^8 years (depending on erosion rate) (Table 2) and are in good agreement with those reported in literature and obtained through more detailed models of sediment transport (Hoke et al. 2011; Fassett & Head 2008).

When compared with the latter models our method of the eroded mass has the advantage of being independent from the particle size of transported sediment and other parameters difficult to determine as depth, slope and width of the internal channels that in many cases are not visible. All this makes our method most advantageous since it is also applicable to smaller and/or more degraded valley networks where the internal channels are no visible.

4. Conclusions

Up to now 65% of Martian surface has been mapped. Thus far, the use of 100 m/pixel global mosaic allowed us to identify more developed valley systems with respect to previous studies based on the 200 m/pixel mosaic (Fig. 3). Moreover, the obtained results for the formation timescales lead to two possible scenarios: 1)Mars could have been continuously warmer and wetter than the present during a period between the end Noachian Era and the beginning of Esperian Era; 2)Mars could have experienced, probably on a regional scale, brief but intense periods of temperate and humid climate. Unfortunately our results do not allow us to discriminate between the two scenarios. So in the future we will extend our sample of valleys and the analysis of the erosion rates in order to do statistical considerations on a global scale.

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