GEOMORPHOLOGIC ANALYSIS OF DRAINAGE NETWORKS ON MARS

KERESZTURI ÁKOS [1,2]

[1]Polaris Observatory, Hungarian Astronomical Association, H-1032 Budapest, Laborc u. 2/C, Hungary; [2]Konkoly Thege Miklos Astronomical Institute, Research Centre for Astronomy and Earth Sciences, Hungarian Academy of Sciences, H-1121 Budapest, Konkoly Thege Miklós út 15-17., Hungary, E-mail: kereszturiakos@gmail.com

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Abstract
Altogether 327 valleys and their 314 cross-sectional profiles were analyzed on Mars, including width, depth, length, eroded volume, drainage and spatial density, as well as the network structure. According to this systematic analysis, five possible drainage network types were identified such as (a) small valleys, (b) integrated small valleys, (c) individual, medium-sized valleys, (d) unconfined, anastomosing outflow valleys, and (e) confined outflow valleys. Measuring their various morphometric parameters, these five networks differ from each other in terms of parameters of the eroded volume, drainage density and depth values. This classification is more detailed than those described in the literature previously and correlated to several numerical parameters for the first time. These different types were probably formed during different periods of the evolution of Mars, and sprung from differently localized water sources, and they could be correlated to similar fluvial network types from the Earth.

Keywords: planetary science, Mars, water, fluvial, valley, drainage network

1. Introduction

There is a great number of various theories on the ancient fluvial-like structures observed on the Martian surface. The origin of these Martian channels and valleys is still controversial, including models for their formation by precipitation, groundwater sapping or both (Sharp and Malin 1975; Grant 2000; Craddock and Howard 2002; Irwin et al. 2002). Most of the fluvial structures are old, although some small gullies and outflow channels have formed in recent Martian history, and there are also models on the presence (Möhlmann 2007) or even flow (Miyamoto et al. 2004; Horváth et al. 2009) of liquid water on Mars today. Although it is possible that such erosional features produces by lava or in theory liquid CO_2 fluid, we analyzed here only those features, which are thought to be formed by the action of liquid water based on the publication and the view of the scientific community. The climate and environmental parameters, which might have existed during the formation of the old valleys is poorly understood. One possibility to get over the uncertain factors and closer to their origin is the joint analysis of several parameters, based on e.g. their network structure.

The identification of the Martian drainage network types can aid in the reconstruction of paleoenvironment and modeling. A wealth of information is available on the network structure of fluvial systems on Earth, where their characteristics can be correlated with the precipitation and its variation in space and time. As a result basic types can be classified in connection with the origin of water and the produced network structure. Only the latter can be observed on Mars.

There were some attempts to define and describe drainage network types on Mars (Carr and Clow 1981), but most papers analyzed only individual systems (Jaumann et al. 2005; Di Achille et al. 2006) and lacked general morphometric data except for certain cases. The drainage network types may help examine the formation and erosional/depositional processes, connections between water-related structures, relation to other surface features and estimate paleoenvironmental conditions such as discharge values (Irwin et al. 2005; Kleinhans 2005).

The aim of this work is to analyze drainage network types on Mars, and to make it clear if the differently shaped networks have different physical parameters too, and partly correlate them to fluvial networks on Earth (Fig. 1). The knowledge of their characteristics is a step forward to estimate the origin of water and duration of liquid water on Mars. The latter information may help interpret various water related mineral changes in Martian meteorites (Bérczi 2007; Mihályi 2008; Gavin 2010; Gooding et al. 1991; Swindle et al. 2000; Warren 1998) and connect their parameters to possible past microenvironments and it also could be used in the education of planetary science at university level (Horvai and Kereszturi 2009).

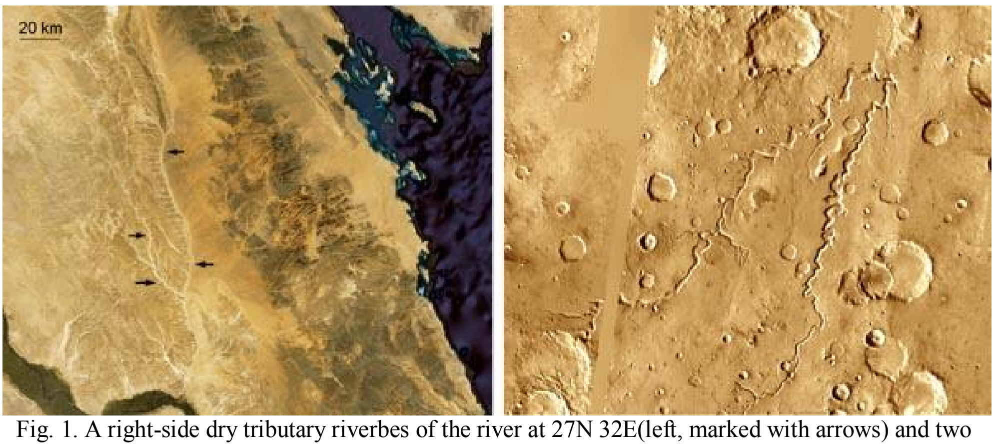

Fig. 1. A right-side dry tributary riverbes of the river at 27N 32E(left, marked with arrows) and two dry branches of Nanedi Vallis on Mars (right) at the same scale for comparison

Regarding the nomenclature (Hargitai et al. 2008), the difference between the terms valleys and channels are not absolutely clear, as in most cases it is unknown how high was there trenches filled with water originally. As a result here we use those versions, which are most widely used by the international scientific literature.

2. Methods

In the drainage network analysis on Earth structures of linear erosion are classified, however not all of them formed only via erosion by liquid water (Gábris 1986, Lóki and Szabó 2004, Mihályi et al. 2008). The first classification based on the genetic relations was made by Verstappen (1964), and later used to analyze lithology, geological conditions, and the regional climate, as well as to give information on mechanism of their formation (Timár and Gábris 2005). In the case of Martian drainage network analysis, the same problem emerges as on Earth: the role and dominance of erosion by liquid water can hardly be estimated. In this work, valleys formed dominantly by linear erosion of water were analyzed on the bases of previous publications from other authors. The meter-sized, small-scale recent features, also formed probably by liquid water flow were excluded from the analysis.

In the first step, valleys interpreted from various spacecraft images were identified. To compare different systems, and work on a homogeneous sample, for general analysis the author used only Viking MDIM 2.1 (Mars Digital Image Model, black-and-white mosaic of 4600 Mars images with spatial resolution of 231 m) (Archinal et al. 2003). Later THEMIS (Thermal Emission Mapping Spectrometer onboard Mars Odyssey spacecraft, spatial resolution of 100 m), MOC (Mars Orbiter Camera onboard Mars Global Surveyor spacecraft, with spatial resolution up to 1,5 m) and HRSC (High Resolution Stereo Camera onboard Mars Express spacecraft, with various spatial resolution up to 10 m) images with better resolution were also used. To analyze topography, corresponding profiles were extracted from Mars Global Surveyor MOLA (Mars Orbiter Laser Altimerter) data for information on topography. Instead of gridded MOLA data, individual tracks of Precision Experiment Data Records (PEDR; processing version L) were used (Smith et al. 1999). This data uses IAU2000 planetocentric coordinates, incorporates crossover analysis of individual profiles, and is referenced to the latest Mars gravity model. In all case a small section of each MOLA track was matched to the corresponding image manually, to ensure that it represents the analyzed valley. For the analysis of the above-mentioned datasets we used Surfer, JMARS, ENVI, Photoshop and Excel software.

To approach the real shape of cross-sectional profile and related morphometric parameters (width, depth) for any valley, only those lines of MOLA were used, which intersected the longitudinal axis of the analyzed valley under a smaller angle than 45° (Fig. 2.). Finding the real cross-sectional shape, every track crossing a valley was distorted to a hypothetical one that would have been perpendicular to the longitudinal axes of the valleys.

In the case of the smallest valleys (which were later classified as type 1) the parameters were measured only in those cases, where the traverse profile's morphology could be firmly defined. In many cases the valleys were visible on the images, but not all of them were identifiable in MOLA data, because of the poor spatial resolution. It may cause some selection effect, where several of the smallest systems were left out from the analysis. Although topographic data could not be extracted for the smallest systems, horizontal parameters could still be measured.

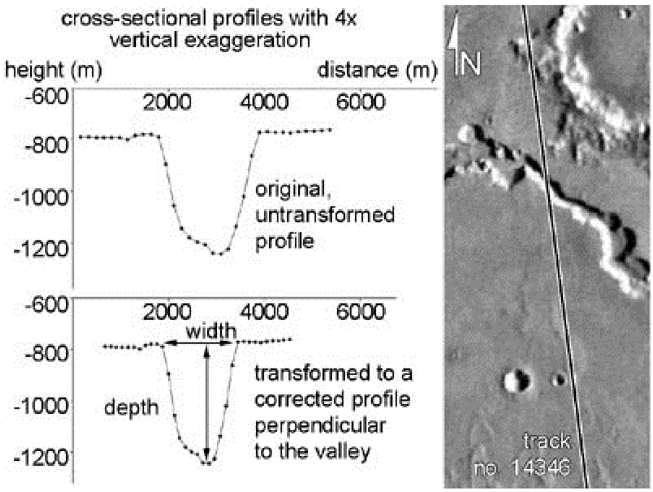

Fig. 2. Acquisition of cross-sectional profiles of a valley: the original MOLA tract of the valley's profile (top left), and a distorted one to the hypothetic profile that would have been perpendicular to the longitudinal axis of the valley (bottom left). The image of the valley and the location of the track is visible on the right.

During the analyses general appearance and some basic morphometric parameters of 327 valleys were measured, and among them 28 representative ones were analyzed in more detail with 314 cross-sectional profiles. Most of the analyzed valleys are located in Xanthe Terra and Lunae Planum, and southern part of that region, where valleys of various shape and age are present together. The outflow valleys, because of their limited number, were selected from all around the planet. The following parameters were measured: width (distance of the two opposite sides of the valley wall), length (longitudinal distance along the valley, where the valley was continuously visible), depth (vertical difference along cross sectional profiles between the top of valley walls and the deepest point of the bottom), drainage density (cumulative length of all valleys situated at one square kilometer area), volume of material eroded away from the valleys (cubic kilometer of material that is missing from the concavity of the valley along one kilometer), spatial proximity (horizontal distance between the centers of two resembling valleys). Beside these morphometric parameters, the intersection of the valleys and the overall shape as a network were also examined.

Errors might occur in the measured morphometric values. For MOLA data the errors in the vertical height measurements are 0.3-2 m on smooth and horizontal surfaces. At the same time as neighbouring measured points have 200-300 m horizontal distance, the acquired topographic height also may have larger errors on sloping terrains (Malin et al. 2006). The horizontal distance measurements based on THEMIS, and MOC images have smaller errors in the order of 2 m. All of these data were used only for statistical analysis.

3. Results

In the first step of the work, valley identification and morphological analysis were realized for various valley systems. In Fig. 3, valleys of different size are presented on the same scale for comparison. 2x2 degree terrains of various valley systems are indicated in Fig. 4, where the inset images of a Viking Mercator photo mosaic map and their graphical interpretations are shown. These sample terrains are situated at different latitude bands and represent areas with width between 90 and 118 km. Larger valleys are indicated in the rows below each other, and in each row the width of the indicated valleys is close to each other.

In the second step, network structure of the systems was characterized. The Martian systems are less integrated than those on Earth. For estimation the level of integration of the valleys, Shreve (1966) and Strahler (1957) stream orders were used to number interconnected valleys (Fig. 5). The sequence of the valleys in these systems was difficult to estimate in the case of the anastomosing valleys, where beside the many joint points an individual valley may also split into two valleys. The results for both ordering methods are indicated in Table 1.

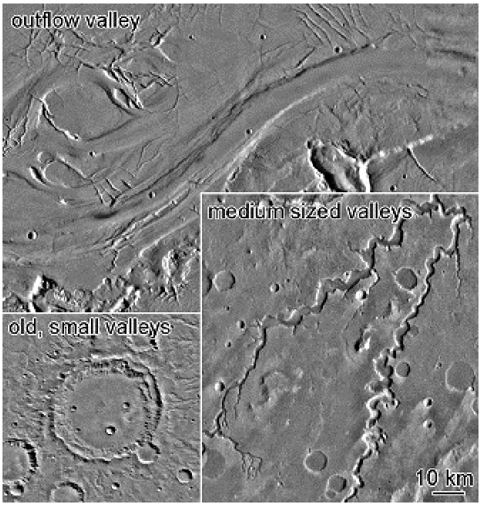

Fig. 3. Examples of valleys of different size at the same scale: an outflow valley: Northern Kasei Valles (upper part), medium-sized Nanedi Valles (middle right), small valleys in old terrain (bottom left)

In the third step, various morphometric values like width, depth, length, drainage density were measured. The certain width values determined of all the analyzed valley sections ranged between 0.5 and 157 km, while the average width values of the valleys varied between 0.5 and 92 km, and in most cases between 0.8 and 5 km. The lower values may represent the limit of the resolution in the images. The length of the analyzed valleys was between 1 and 861 km. As regards the length values in some cases the ending or the beginning of the valleys could not be easily determined.

Two characteristics were used as guidelines for the classification: (1) the measured width/length ratio of valleys and (2) relationships between individual valleys relatively close to each other, which probably have the same origin. In previous studies most authors (Carr and Clow 1981, Craddock and Maxwell1990, De Hon and Washington 2000) classified three large groups: a) the old valley systems or shallow valleys (Mangold et al. 2008), b) sapping valleys (commonly designated as alcoved valleys, or longitudinal valleys, and theater headed valleys) with medium size (larger than the valley systems but smaller than outflow valleys, c) outflow channels (or outflow valleys), the largest ones with two subclasses: confined and unconfined groups. Fretted valleys were excluded from this analysis, because even though they may have formed in contact with liquid water, but their configuration probably had changed dramatically later due to the ice-related erosion. It is important to note that these a), b) and c) groups are not widely accepted as basic types of valleys on Mars, and served here only as temporal classification for the following analysis.

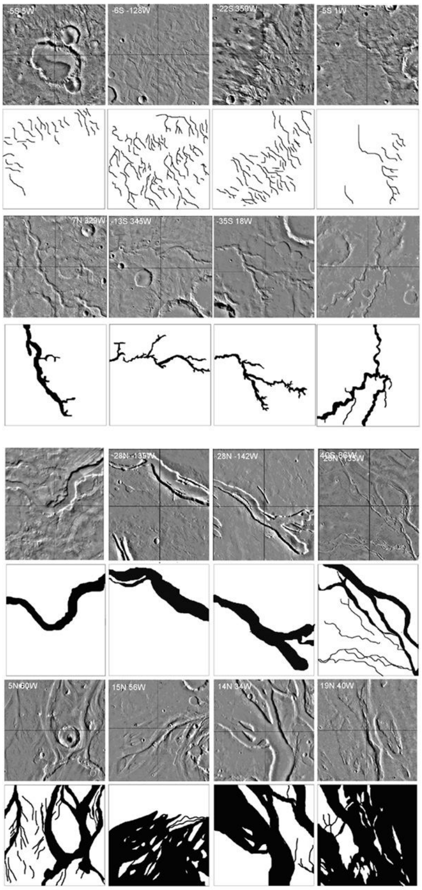

Fig. 4. 2x2 degree sized inset images and the graphical interpretation of the valleys showing their relative sizes and connections. In the last row anastomosing patterned (unconfined) outflow systems are visible where black colour mark the probable area of ancient water coverage

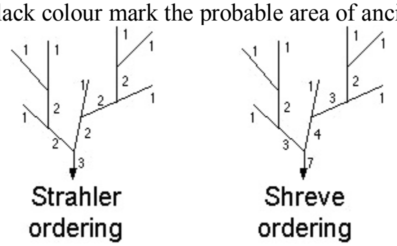

Fig. 5. System of stream ordering according to Strahler (left) and Shreve (right)

Table 1. Summary of characteristics of the five proposed network types.

Types/characteristics	1. weakly integrated	2. integrated, small	3. individual, medium	4. confined outflow	5. braided outflow
Source terrain	steep hills	not marked	not marked	chaos, closed lakes, tectonic faults	chaos, closed lakes, tectonic faults
Range of valley width (km)	<0.1-7.9	0.75-14.9	0.56-11	0.9-16	5.6-60
Average valley width (km)	4.5	6.8	3.5	12	30
Range of valley depth (m)	<34-270	58-200	35-970	135-3300	78-930
Average valley depth (m)	93	130	280	1000	280
Valley length (km)	2-45	1-11	1-400	100-2000	200-3000
Maximal Strahler ordering	3-4	4-5	4-5	4-5	?
Maximal Shreve ordering	7-8	15-30	4-30		?
Drainage density (km/km^2)	0.1-0.16	0.1-0.6	0.01-0.08	0.001-0.005	0.02-0.08
Sinuosity	1.0-1.3	1.0-1.5	1.0-2.2	1.0-1.3	1.0-1.3
Slope angle of the surrounding terrain (degree)	1.56-2.8	0.15-0.26	0.07-0.3	0.02-0.32	0.04-0.7
Eroded volume (km^3/km)	0.001-0.1	0.01-0.6	0.01-5	5-20	hard to estimate
Diameter of the area where the structures are present next to each other (km)	300	25-200	60-300		
Areal distribution of the sources	distributed at 100 km distance scale, individual valleys are 1-10 km from each other	usually 10-40 km wide areas	local	local	local
Examples (name or coordinate – the longitude should be East in every example)	1S 59E, 22S 1E, 6S 232E,	Nanedi northern branch at 4N 311E	Nanedi, Nirgal, Sabrina, Bahram, Naktong, Brazos, Evros	Northern- and Southern Kasei, Shalbatana, Ares	Meumee, Vedra, Maya

The distribution of width/length ratio for all the analyzed valleys is visible in three diagrams of Fig. 6, where each point represents the averaged width/length value pair of one valley. The data points were classified into three main groups (a, b, c) based on their appearance on the images. Based on the visual inspection of images, nearly all of the largest valleys (c) could be identified and measured, while in the case of (b) some, and (a) probably most of them were near to the limit of resolution. The different depth of the three groups may also influence the distribution, because shallow valleys are more difficult to identify than deep valleys, even if they have the same horizontal dimensions.

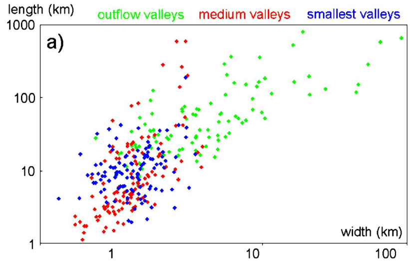

Fig. 6. Width versus length parameters of the analyzed valleys in three groups. One point represents the average width/length of one valley

According to the above mentioned uncertainties, basic differences are visible in the three diagrams. The small (a) and medium-sized (b) valleys have roughly the same width, while in the case of the group (b) there are some long ones with up to 500 km in length. In the case of group (a) there is no visible trend relating to the ratio between the length and width, while in the case of (b) and (c) linear trend is discernible.

In the group (a) and (b) valleys no wider than 2–3 km were found (note: the width means the averaged width of a valley here). In group (b) most of the dots, at the bottom part of the diagrams (valleys shorter than about 10 km), are the branches of the few longest, main valleys, which are visible at the top of the diagram (b). Just like in the case of (b), the largest outflow systems (c) show linear correlation between the width and the length. In the above mentioned groups the correlation factors between the width and length are 0.34 (a), 0.42 (b) and 0.68 (c), respectively.

In several cases, the length values of the valleys (the distance between their starting and end points) could not be easily determined. The indicated values at each valley's length give insight only into the minimal length, because it is not evident that two valleys are connected or not. The length was also difficult to define in the case of relatively large, anastomosing outflow valleys, because of their junctions.

Regarding the depth of the valleys, the smallest measured value is 34 m and the largest one is 3274 m. The shape of the cross sectional profiles show some variations for valleys of different size. In the case of the outflow systems, great concavity was observed exhibiting plain bottom levels, except in the case of anastomosing patterned outflow valleys. The medium-sized valleys belong to the V or U shaped cross sectional profiles. At the smallest valleys reasonable shape could rarely be defined because of the finite horizontal spatial resolution of MOLA data. Shape could be firmly defined only for valleys with several (4–6 and more) data points along their cross section. Some examples for the cross-sectional profiles of five valleys for each group are visible in Fig. 7.

The eroded volume was estimated in km^3/km dimension, showing the volume of missing material from the valley along one km (see values in Table 1). This parameter gives information on the paleodischarge and duration of activity together: longer activity and smaller paleodischarge can erode and transport the same volume of surface material as short activity with larger paleodischarge. The greatest error in this value is at the anabranching morphology, where the original surface level could not be determined exactly.

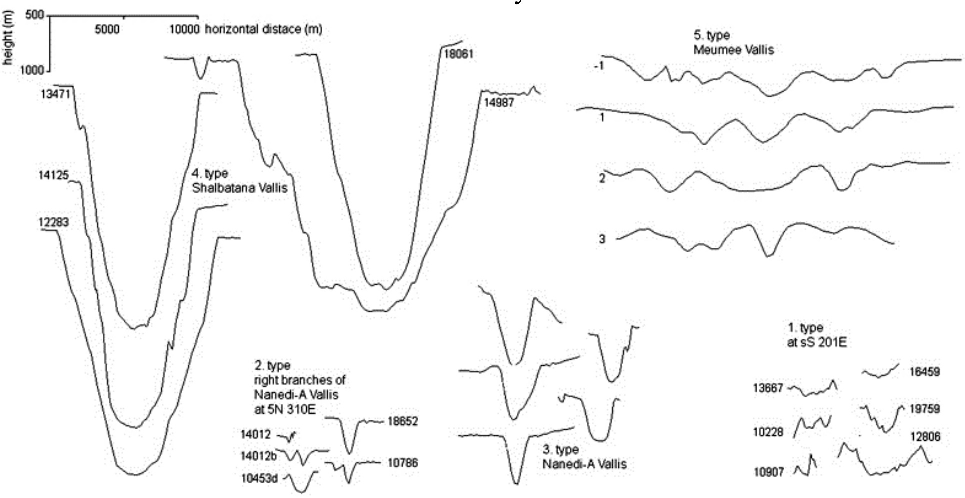

Fig. 7. Examples for five cross-sectional profiles from five valleys. All profiles are scaled the same way and have 4 times vertical exaggeration. Note the great difference in shape and size between 1st, 4th and 5th groups and the similar appearance of 2nd and 3rd groups

The drainage density shows the cumulative length of the valleys in the same kind of network structure, at each 1x1 km surface segment. This value was determined at 20x20 km areas at the analyzed terrains. The origin of this value itself may depend on several factors, but the most important factors are probable the volume and the areal concentration of the water. High drainage density may suggests distributed source of water (like precipitation or ice melting over a large area) equally, while low drainage density may show localized source of water (like local breakup from subsurface reservoir, or localized ice melt by volcanic lava flow). The drainage density was the lowest in the case of confined outflow valleys, with all of the water having sprung from one aquifer and flown into a single valley.

4. Discussion

In the final step, based on all of the above mentioned several parameters combined together, different network types were analyzed. Beyond the original three groups five network types were identified altogether, which differ from each other in some morphometric parameters and the network pattern as well, although there were overlapping ranges of certain parameters. Medium-sized valleys (as previously known sapping channels) are first order valleys in most cases, which empty directly into one long valley. But in other cases several small branches form an integrated part with Shreve ordering up to 30, before they empty into the main long valley. These integrated parts were classified as a new type. Based on our analysis, two kinds of outflow valleys can be grouped separately: with and without anastomosing appearance, e.g. individual confined ones, and branching, anastomosing ones, where the branches join and diverge quite often, forming a complex network. The proposed five groups for Mars are the followings with temporary names and possible terrestrial analogs.

(1). The first group is composed of small valleys on old, undulating terrain (already published by Pieri 1980), running in roughly parallel direction termed valley networks in previous publications (Carr and Clow 1981). The valleys are situated close to each other, and the source of the water having carved them is distributed equally on the distance scale of 10 km. This group is somewhat similar to the centrifugal type form on the Earth, where precipitation fed valleys form on sloping terrain. This first group seems to be weakly integrated, partly because of the limited resolution of images.

(2). Integrated small valleys. This group mostly consists of valleys nearly of the same width as the Group 3. Compared to the Group 3, the valleys in this second group form an integrated network with several interconnecting valleys. This group resembles to the dendritic type form on the Earth that forms an integrated system, and usually is the result of long-term surface evolution controlled by the process of fluvial erosion.

(3). Individual, medium-sized valleys. This group consists of similar valleys in width compared to the Group 2, but the whole system is less integrated: the branches usually arrive into the main valley as first order valleys, and one long valley dominates the network. This suggests that the source of water was present along 300-400 km distance in a band-like area. The appearance of this network structure is somewhat similar to the disordered type on the Earth, which is characteristic to the arid or semiarid area with low precipitation.

(4). Confined outflow valleys formed by disastrous floods of subsurface aquifers or lake outburst-like phenomena. They are easily distinguished from the previous groups with their larger size and few tributaries. These valleys resemble in

appearance and partly in origin to valleys formed by some catastrophic floods on the Earth (such as the Columbia river gorge in Fig. 8).
(5). Unconfined, anastomosing valleys were also formed by catastrophic outflows, where the water was carried into several nearly parallel valleys. On the basis of the terrestrial analogy, the dichotomous network type is close to this group. On our planet, it usually appears in areas where the rivers have to carry great mass of sediments, and/or they arrive to terrain with relatively low slope angle.
Examples of the five proposed systems are given in Fig. 8, with (a) image of the Martian surface, (b) geomorphologic sketch of the Martian surface, (c) image of resembling class on Earth is visible. Note the different scales for each subset. The systems may change their classification along the way. It happens most often from 2nd to 3rd group, and less frequently from 4th to 5th group. The shift from one to another type may show the change in the water source or in the ratio between the erosional capacity of the ancient river (discharge, speed) and the resistance (erodibility) of the terrain plus the mass of the sediment carried by the water.

5. Conclusion

During the general analysis of 327 valleys and among them the detailed examination of 314 cross-sectional profiles of 28 valleys; width, depth, length, eroded volume, drainage density, as well as the network structure were studied. Based on the analysis, five different groups and their possible terrestrial analog network types could be distinguished. These are partly corresponding to the already published four groups of ancient Martian fluvial structures: valley networks, sapping valleys and confined plus unconfined outflow systems. Based on the numerical analysis, the above mentioned five groups of networks analyzed in this work differed from each other substantially in the eroded volume, drainage density and depth values; while the members of any network type resemble to the other members of that group. There are also several parameters, which showed overlapping ranges of values, like width, length, spatial proximity. Our proposed 1st type consists of the oldest valleys on undulating, and steep terrains, with areal source of water. The 2nd type also has areal source, but show higher level of integration, with larger main valleys where tributaries arrive and often occur on nearly horizontal plain. The 3rd type is fed by several local sources arranged along the main valley, whereas the 4th and 5th types have highly localized source, formed in more recent part of the planet’s history. From type 1st through 5th the sources are more and more localized, and the eroded volume tends to grow, suggesting that during the geologic history of Mars a growing amount of water was released from an increasing number of localized sources. This trend is supported by the general concept of the Martian evolution.

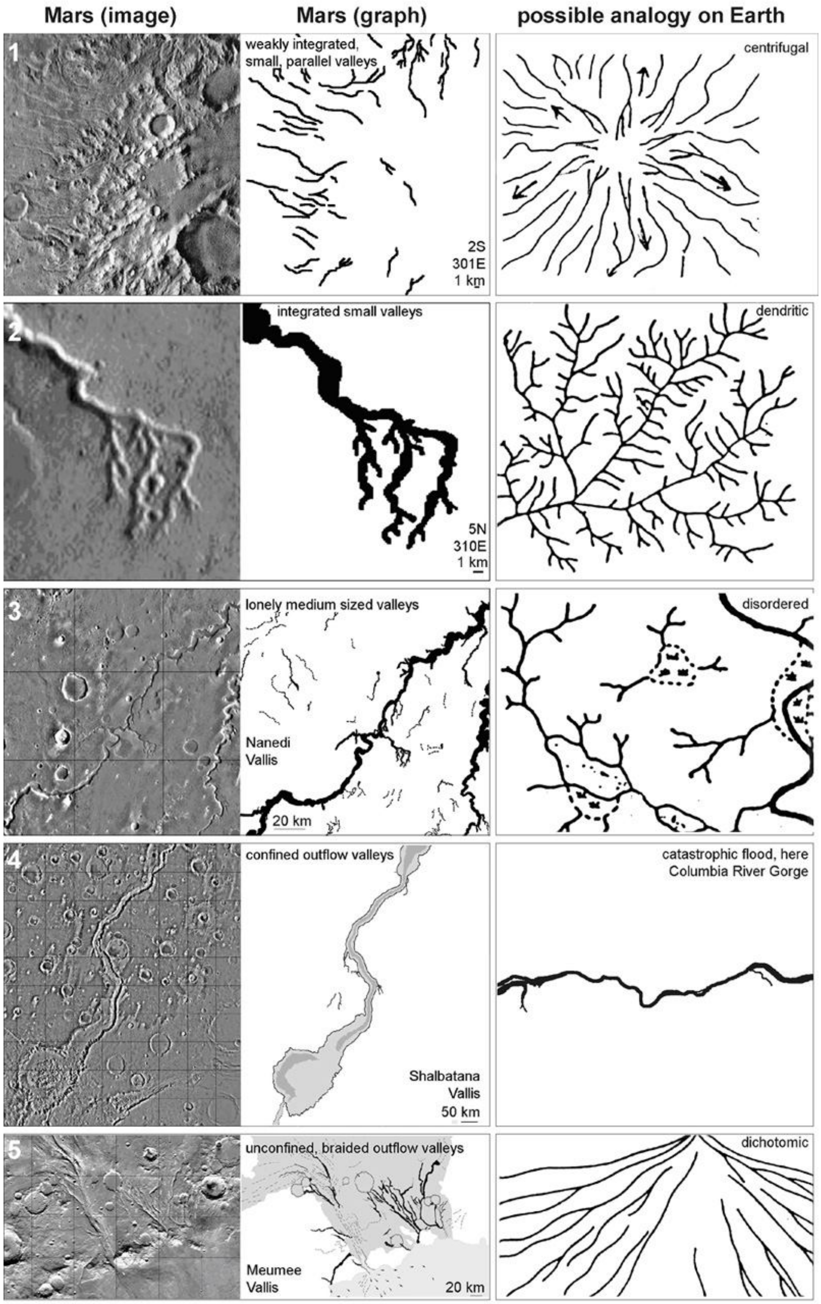

Fig. 8. Examples for the five proposed network types, where the Martian surface is represented by an image (left) and graphics (middle, and a similar network structure from the Earth is discernible on the right. Note the different sizes of the terrains

The proposed five network types, beside their pattern, also differ in several morphometric parameters. Based on analogy from the Earth, all the five types partly resemble the fluvial network types from our planet. It is suggested that the above five system types can work as a starting point for more detailed analysis on a larger sample – although it is probable that the proposed five systems eventually will prove these basic classes as of utmost importance.

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References

Archinal, B.A. – Kirk, R.L. – Duxbury, T.C. – Lee, E.M. – Sucharski, R. – Cook, D. (2003): Mars digital image model 2.1 control network. 34th Lunar and Planetary Science Conference abstract 1485.

Bérczi, Sz. (2007): A Mars kőzetei a marsi meteoritok alapján (Martian rocks based on the analysis of Martian meteorites – in Hungarian language) – *Fizikai Szemle* 2007/8, p 260.

Carr, H.M. (1981): The surface of Mars. Yale University Press, p. 135-156.

Carr, M.H. – Clow, G.D. (1981): Martian channels and valleys - Their characteristics, distribution, and age. *Icarus* **48**:91-117.

Craddock, R.A. – Howard, A.D. (2002): The case for rainfall on a warm, wet early Mars. *Journal of Geophysical Research* **107**(E11):5111-5122.

Craddock, R.A. – Maxwell, T.A. (1990): Resurfacing of the martian highlands in the Amenthes and Tyrrhena region. *Journal of Geophysical Research* **95**(B9):14265-14278.

De Hon, R.A. – Washington, P.A. (2000): Implication of sapping channels on Mars. 31th Lunar and Planetary Science Conference abstract 1147.

Di Achille, G. – Marinangeli, L. – Ori, G.G. (2006): Geological evolution of the Tyras Vallis paleolacustrine system, Mars. *Journal of Geophysical Research* **111**(E4):E04003.

Gábris, Gy. (1986): A vízhálózat geomorfológiai célú elemzése (in Hungarian-Eng.: "Drainage patterns and ther physical geomorphological applications). Dissertation thesis for candidate degree, p. 34-38.

Gavin, P., Chevrier, V., Ninagawa, K, Gucsik, A, Hasegawa, S. (2010): Experimental Investigation into the Effects of Meteoritic Impacts on the Spectral Properties of Phyllosilicates on Mars. 41st Lunar and Planetary Science Conference, abstract 1533.

Grant, J.A. (2000): Valley formation in Margaritifer Sinus, Mars, by precipitation-recharged groundwater sapping. *Geology* **28**:223–226.

Gooding, J. – Zolensky, L. – Michael, E. – Wentworth, S.J. (1991): Aqueous alteration of the Nakhla meteorite. *Meteoritics* **26**:135-143.

Gulick C.V. (2002): The Valley Networks on Mars. American Geophysical Union, Fall Meeting 2002, abstract P51B-0344

Hargitai, H. – Császár, G. – Bérczi, Sz. – Kereszturi, Á. (2008): Földön kívüli égitestek geológiai és rétegtani tagolása és nevezéktana. (Stratigraphic classification and nomenclature of extraterrestrial bodies – in Hungarian language) *Földtani Közlöny* **138**/4:323-338.

Horvai, F. – Kereszturi, Á. (2009): Geology of Mars: new university course in Hungary. 40th Lunar and Planetary Science Conference, abstract 1673.

Horváth, A. – Kereszturi, Á. – Bérczi, Sz. – Sik, A. – Pócs, T. – Gánti, T. - Szathmáry, E. (2009): Analysis of Dark Albedo Features on a Southern Polar Dune Field of Mars. *Astrobiology* **9**:90-103.

Irwin, R.P. – Craddock, R.A. – Howard, A.D. (2005): Interior channels in Martian valley networks: discharge and runoff production. *Geology* **33**(6):489-492.

Irwin, R.P. – Howard, A.D. (2002): Drainage basin evolution in Noachian Terra Cimmeria, Mars. *Journal of Geophysical Research* **107**(E7):5056.

Jaumann, R. – Reiss, D. – Frei, S. – Neukum, G. – Scholten, F. – Gwinner, K. – Roatsch, T. – Matz, K.D. – Mertens, V. – Hauber, E. – Hoffmann, H. – Köhler, U. – Head, J.W. – Hiesinger, H. – Carr, M.H. (2005): Interior channels in Martian valleys: Constraints on fluvial erosion by measurements of the Mars Express High Resolution Stereo Camera. *Geophysical Research Letters* **32**, L16203, doi:10.1029/2005GL023415.

Kereszturi, Á. (2007): Climate change on Mars I. *Légkör* **52**(2):12-17. (in Hungarian)

Kereszturi, Á. (2007): Climate change on Mars II. *Légkör* **52**(3):6-9. (in Hungarian)

Kereszturi, Á. – Gábris Gy. (2007): Proposal for drainage network types on Mars. 38th Lunar and Planetary Science Conference, abstract 1045.

Kleinhans, M.G. (2005): Flow discharge and sediment transport models for estimating a minimum timescale of hydrological activity and channel and delta formation on Mars. *Journal of Geophysical Research* **110**(E12) E12003.

Kuti, A. – Kereszturi, Á. (2009): Inszolációs aprózódás a Marson. (Insolation driven weathering on Mars – in Hungarian language) *Földrajzi Közlemények* **133**(1):1-12.

Kuti, A. – Kereszturi, Á. (2009): Analysis of frost outliers in the circumpolar region of Mars. *Földtani Közlöny* **139**(4):395-402. (in Hungarian)

Lóki, J. – Szabó, J. (2004): Geomorphology of exogenic forces. Debrecen (in Hungarian language)

Malin, M.C. – Edgett, K.S. – Posiolova, L.V. – McColley, S.M. - Noe Dobrea, E.Z. (2006): Present-Day Impact Cratering Rate and Contemporary Gully Activity on Mars. *Science* **314**(5805):1573 – 1577.

Mangold, N. – Ansan, V. – Masson, Ph. – Quantin, C. – Neukum, G. (2008): Geomorphic study of fluvial landforms on the northern Valles Marineris plateau, Mars. *Journal of Geophysical Research* **113**, E08009, doi:10.1029/2007JE002985.

Mihályi, K. – Gucsik, A. – Szabó, J. (2008): Drainage Patterns of Terrestrial Complex Meteorite Craters: A Hydrogeological Overview. 39th Lunar and Planetary Science Conference, abstract 1200.

Miyamoto, H. – Dohm, J.M. – Beyer, R.A. - Baker V.R. (2004): Fluid dynamical implications of anastomosing slope streaks on Mars. *Journal of Geophysical Research* **109**(E6) E06008.

Möhlmann, D. (2007): The influence of van der Waals forces on the state of water in the shallow sub-surface of Mars. *Icarus* **195**:131–139.

Pieri, D.C. (1980): Martian valley morphology, distribution, age and origin. Science **210**:895-897.

Sharp, R.P. – Malin, M.C. (1975): Channels on Mars. *Geol. Soc. Am. Bull.* **86**:539–609.

Shreve, R.L. (1966): Statistical law of stream numbers. *Journal of Geology* **74**:17–37.

Smith, D. – Neumann, G. – Ford, P. – Arvidson, R.E. – Guinness, E.A. - Slavney, S. (1999): Mars Global Surveyor Laser Altimeter Precision Experiment Data Record. NASA Planetary Data System, MGS-M-MOLA-3-PEDR-L1A-V1.0.

Strahler, A.N. (1957): Quantitative analysis of watershed geomorphology. *Transactions, American Geophysical Union* **38**:913–920.

Swindle, T.D. – Treiman, A.H. – Lindstrom, D.J. – Burkland, M.K. – Cohen, B.A. – Grier, J.A. – Li, B. – Olson, E.K. (2000): Noble gases in iddingsite from the Lafayette meteorite: Evidence for liquid water on Mars in the last few hundred million years. *Meteoritics and Planetary Science* **35**:107-115.

Timár, G. – Gábris, Gy. (2005): Fluvial meander generations and abandoned river channels of the Great Hungarian Plain on the SRTM elevation dataset. *Geophysical Research Abstracts* **7**:03907.

Verstappen, H.Th. (1964): Geomorphology and environment. ITC Publ. Delft. 44. p.

Warren, P.H. (1998): Petrologic evidence for low-temperature, possibly flood evaporitic origin of carbonates in the ALH84001 meteorite. *Journal of Geophysical Research* **103**(E7):16759-16774.