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Formation of fluvial xenolandscapes of Martian valleys and channels

Serhii M. Kyryliuk

Yuriy Fedkovych Chernivtsi National University, Chernivtsi, Ukraine s.kyrylyuk@chnu.edu.ua

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Abstract. Contemporary concepts of Martian Valley formation and the current state of their study are examined. Three-dimensional modeling was conducted using the examples of two regions on Mars, the Lani Chaos Region and Kasei Vallis, to determine and map the main morphological features typical of Martian valleys as a basis for identifying xenolandscapes. The xenaxiomatic author's concept was applied as a means of investigating xenolandscape diversity on the surface of Earth-like planets, in this case, Mars. The xenaxiomatic concept is the result of incorporating and utilizing traditional knowledge of the differentiation and application of axioms of cognition. Specialized for xenoplanetological use, this integrative cognitive tool is a variant of an axiomatic approach. The main essence of this approach, in the case of distinguishing xenolandscapes, lies in developing a unified scheme for searching for corresponding xenolandscape elements that are axiomatically elementary fragments of the planet's surface, followed by their classification and xenolandscape interpretation. Scientific awareness has been achieved by filling it with all available information from various natural sciences related to xenoplanetology and subsequent exploratory xenolandscape interpretation and synthetic cartographic representation of characteristic, typical local xenolandscape formations on Mars (part of the Kasei Vallis valley). These depicted objects are extra-rank, meaning they have not yet been ranked in terms of xenolandscape formations but are uniformly formed due to the synergy of influences and interactions of different forces, yet genetically stemming from the same xenolandscape-forming factors of material and energy-field xenonature. A mechanism for the formation of modern Martian valleys is proposed through the influx of heat flow and impact events. Exploratory xenolandscape studies, with their positions verified by this conducted research in terms of theoretical, methodological, and methodical content, have become an unexpected benchmark for the effectiveness of similar theoretical and methodological components of classical landscape science, with which the research capabilities of landscape science can and should be compared.

Keywords: Mars, valleys, channels, xenolandscapes, Lani Chaos Region, Kasei Vallis.

Формування флювіальних ксеноландшафтів марсіанських долин і каналів

Сергій М. Кирилюк

Чернівецький національний університет імені Юрія Федьковича, Україна, s.kyrylyuk@chnu.edu.ua

Анотація. Розглянуто сучасні уявлення формування марсіанських долин і стан їх вивчення. На прикладі двох регіонів Марса Lani Chaos Region та Kasei Vallis виконано тривимірне моделювання з метою визначення та картування головних морфологічних елементів типових для планети долин як підґрунтя для виділення ксеноландшафтів. Застосовано ксеноаксіоматичну авторську концепцію як засіб дослідження ксеноландшафтного різноманіття поверхні планет земної групи (в нашому випадку Марса). Ксеноаксіоматична концепція є результатом залучення і використання знань традиційного для науки вирізнення та застосування аксіом пізнання. Спеціалізований для ксенопланетологічного використання, цей інтегративний засіб пізнання є варіантом аксіоматичного підходу. Основна суть цього підходу, у випадку вирізнення ксеноландшафтів, полягає у вироблені єдиної схеми пошуку відповідних ксеноландшафтним окремостям аксіоматично елементарних фрагментів поверхні планет з подальшою їх класифікацією та ксеноландшафтною інтерпретацією. Здійснено наукове усвідомлення, наповнення усією доступною, належною різним природничим наукам інформацією із ксенопланетологічним і наступним пошуковим ксеноландшафтознавчим інтерпретуванням і синтезним картографічним представленням характерних, типових локальних ксеноландшафтних утворень Марса (частина долини Касей). Причому ці відображені об'єкти – позарангові, тобто ще не визначені щодо рангів ксеноландшафтних утворень, однотипно сформованих внаслідок синергії впливів та взаємодій різної сили, але генетично одних і тих же наявних вихідних ксеноландшафтоутворюючих чинників речовинної та енергетично-польової ксеноприроди. Запропоновано механізм формування сучасних марсіанських долин шляхом надходження теплового потоку та спричиненими імпактними подіями. Пошукові ксенoландшафтознавчі напрацювання, маючи свої верифіковані цим здійсненим дослідженням положення теоретичного, методологічного, методичного змісту, вже є несподіваним репером дієвості аналогічних теоретико-методологічних складників класичного ландшафтознавства, з яким можна і варто порівнювати дослідницькі спроможності науки про ландшафти.

Ключові слова: Марс, долини, канали, ксенoландшафти, Lani Chaos Region, Kasei Vallis.

Introduction

Retrospective review of the nature of Martian valleys and channels. Countless valleys of fluvial origin have been discovered on the surface of Mars. Their existence was suspected long before the start of the space age (Baker, 1982). Early telescope observations of Mars revealed Martian shapes, which the Italian astronomer Secchi proposed in 1869 to call the Italian word «canale» (channel) to describe the visible lines on the planet's surface. Between 1877 and 1888 Schiaparelli identified many canals. His work led to the famous Mars controversy (Irwin et al., 2008).

For the first time, detailed photographs of the surface of Mars, where Martian valleys were clearly visible, were taken by a series of American automatic interplanetary stations «Mariner». As a result of their analysis, it was possible to identify two main types of Martian valleys – which for the most part appear on the surface as systems of ravines and wide trough-shaped, branched valleys, as indicated by Brakenridge et al. (1985), Baker (2001). Most of them demonstrate spatial relationships with impact structures, especially young craters, which are associated with systems of small valleys. The formation of large valleys obviously ceased at the end of the period of heavy bombardment, approximately 3.8 billion years ago.

The identification of Martian channels and valleys and the numerous relief morphosculptures associated with them with signs of water origin is of great importance in comparative planetology (Mars Channel Working Group, 1983).

The emergence of fluvial activity and the presence of stagnant water on the surface in the early geological history of Mars is a matter of debate (Mangold & Ansan, 2006). Pieri (1979) identified a range of fluvial landforms in the Thaumasia region, indicating the presence of water flow over geologically long periods. Such a long time is explained by the presence of large deltas found within several impact craters formed at the exit from deep valleys. Obviously, the water filled and overflowed the rims of these craters, creating several inlet and outlet valleys. These landforms clearly show that one of the impact craters in such regions, 25 km in diameter, contained a lake up to 600 m deep. Similar formations are often observed on Earth.

Clay minerals have recently been discovered on the surface of Mars, widely distributed within areas with valleys and canales (Ehlmann et al., 2011). These minerals testify to a long-term interaction between water and rock more than 3.7 billion years ago. An analysis of how they formed should indicate what environmental conditions dominated the geographic envelope of early Mars.

Further evidence of relatively recent fluvial activity on the planet is the discovery of pebbles by the American rover Sojourner, both within the Ares Valley and within rock formations, which may be sedimentary in nature rather than volcanic (Team, 1997).

Numerous models of Martian hydrothermal systems clearly indicate that valley systems are associated with magmatic intrusions. According to these models, it has been found that several hundred cubic kilometers of heavily intruded lithospheric strata could provide sufficient groundwater outflow to form the Martian valleys and canales observed today (Gulick, 1998). In general, this process could last several thousand years, until the ice layers were depleted, and the process of valley formation stopped. However, some of the large canales on Mars show characteristic features, in particular, elements of morphological structure, which indicate their origin under the influence of running water. As for the smaller canales, especially on steep slopes, they could be formed under the influence of precipitation. The systems of dendrite-like canyons widespread on the planet and their morphology indicate significant flooding by groundwater, which was an effective agent for the destruction of their sides. In general, the great plains have evolved through the destruction of large canyons and the subsequent redistribution of the destroyed material.

For the geomorphological processes mentioned above to occur, the climate of early Mars must have supported a complex hydrological system and possibly the Northern Ocean covering up to one-third of the planet's surface (Di Achille & Hynek, 2010).

Later, the remaining separate parts of them were modified by the direct action of the wind and can be considered as relic forms of the fluvial stage of the Martian geological history. At the later stages of the geological history of the planet, when the climate changed dramatically and Mars approached its present state, impact processes began to play the main role in the formation of small valleys. As for the early hydrothermal centers, they may have provided at one time the appropriate environment for the initiation of life or its oases (Carr, 1996).

The high-quality images obtained by the American automatic interplanetary station Mars global surveyor during its three-year intensive work in the orbit of Mars have dramatically changed the views of scientists about this planet (Malin & Edgett, 2001). Among the most important observations and interpretations obtained from these images, it can be noted that most of Mars, at least to a depth of several kilometers, has a layered structure.

The geomorphology of Martian valleys is also being explored from a hydrological point of view to develop an evidence base for the origin of dendritic valleys through precipitation, global heat flow, and localized hydrothermal systems (Gulick, 2001). Comparison of the morphology and spatial distribution of valleys on surfaces of different ages with the existing surface valleys indicates that most of the Martian linear erosional forms probably did not form due to rains, as well as ambiguously indicate the development of an early, global and uniformly increased heat flow.

In general, the valleys are not evenly distributed over uneven-aged surfaces. They tend to form either as isolated systems or in clusters on a coeval surface with large areas of parts of these surfaces – virtually untouched by linear erosion. Interestingly, most of the branched valley networks are mainly confined to heavily cratered areas. Carr & Chuang (1997) determined the density of horizontal dissection on Mars. Indicators range from 0 in vast areas of volcanic plains to 0.3 – 0.5 km/km^2 inside individual volcanic structures.

In total, over the past 30 years of intensive observations of the surface of Mars and its dynamics, including with the help of space probes, many regularities in the formation and evolution of Martian valleys and canales have been established. Data from the Mars Global Surveyor mission support the view that short water-related episodes, including glaciations, have permeated the entire geologic history of Mars. The last of these episodes probably occurred in the last 10 million years (Erkeling et al., 2012). The interpretation of the new data is controversial, but a consistent explanation of the anomalies leads to potentially fruitful hypotheses for understanding the evolution of Mars concerning the Earth.

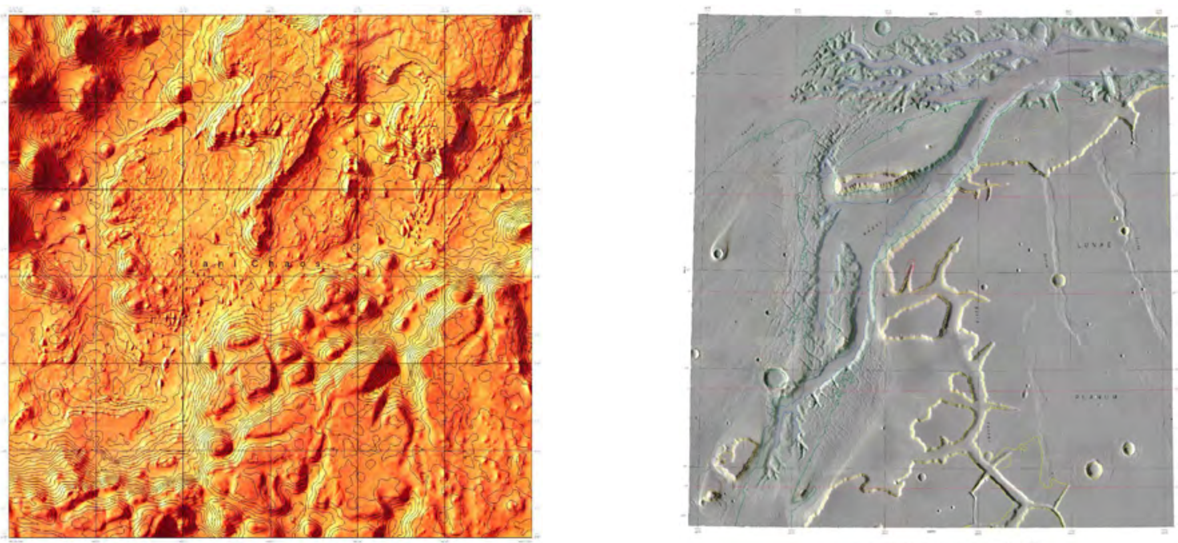
Area of the study

Two sites on Mars were chosen for modeling: the Lani Chaos Region (Neukum, 2006) (Fig. 1a) and the Kasei Valles (Rosiek et al., 2005) (Fig. 1b).

The Lani Chaos Region is a chaotic region with complex terrain, located in the south of the Ares Vallis channel. It is believed that most of this area was formed due to the melting of the cryolithosphere and, as a result, a powerful outflow of groundwater, which led to significant surface flooding and the direct formation of Ares Vallis in the planet's geological past.

Within the Lani Chaos, low-angle, medium-dark to light-colored rock strata have formed, rich in hydrated minerals that are most likely gypsum and hematite (Gendrin et al., 2005).

The Kasei Vallis is part of one of the largest canyon systems on the surface of Mars. Their total length exceeds 3,000 kilometers. In the southern part, it emerges from the Echus Chasma basin and ends in



a b

Fig. 1. Key sites: the Lani Chaos Region (a) and the Kasei Valles (b)

the Chryse Planitia plain. The eastern boundary of the Kasei Valles smoothly merges into the western margin of the Lunae Planum plateau.

Methodology

Identification of morphological units on the Martian surface is based on the author's method described in (Kyryliuk & Kholiavchuk, 2017) which consists of understanding the fundamental nature of the elementary form on the planet's surface and identifying it with simple geometric shapes (circle, square, triangle) to identify nodes. By moving these figures in space, it becomes possible to reproduce integral images, that is, geosystems. According to the theory of symmetry, the number of such motions is extremely limited, which contributes to the rapid identification of all groups of motions and the formation of their combinations. In our case, a group is a set of elements on which the operation of multiplication is given and satisfies the following axioms:

1. The group is closed concerning the multiplication operation: for any two elements of the group, there is a third one that is their derivative:

$$\forall A, B \in G : \exists C \in GA \cdot B = C, \quad (1)$$

Such cases can be observed during the distribution of individual Martian xenolandscape complexes (secondary craters, crater catenas, etc.).

2. Associativity of the multiplication operation: the order of multiplication does not matter:

$$\forall A, B, C \in G : A \cdot (B \cdot C) = (A \cdot B) \cdot C = A \cdot B \cdot C, \quad (2)$$

For the most part, such groups characterize the uniform distribution of Martian xenolandscapes in a particular area (marine craters, undulating plains with alternating depressions and elevations, etc.).

3. The existence of a single element: in the group, there is a specific element E, the derivatives of which with the favorite element of the group A gives the same element A:

$$\exists E \in G : \forall A \in GA \cdot E = E \cdot A = A, \quad (3)$$

These are single xenolandscape complexes that do not fit into typical forms (volcanic (effusive) formations, sinuses, etc.).

4. Existence of an inverse element: for any element of the group A, there is such an element A–1 that the derivatives give the identity element E:

$$\forall A \in G : \exists A^{-1} \in G : A \cdot A^{-1} = A^{-1} \cdot A = E, \quad (4)$$

A striking example of such a group can be groups of craters that do not differ in shape but have different formation ages.

Results and Discussion

Possible mechanism of modern formation of Martian valleys by subsurface flushing. Thus, the mechanism for the development of large valleys on Mars, according to general ideas, is a combination of rapid movement to the surface of water and ice. It is probably directly related to the influence of hydrothermal systems in the early stages of the geological history of Mars and partly indicates that for the formation of Martian valleys, the planet should not have a dense atmosphere. Fig. 2 shows the formation of modern Martian valleys according to our ideas on the example of one of the valleys in the Lani Chaos Region.

It is believed that at the present stage, valleys do not form on Mars, and all the observed ones arose long ago, even by geological standards. However, an analysis of images of different ages of individual regions of the planet indicates that small valleys are still

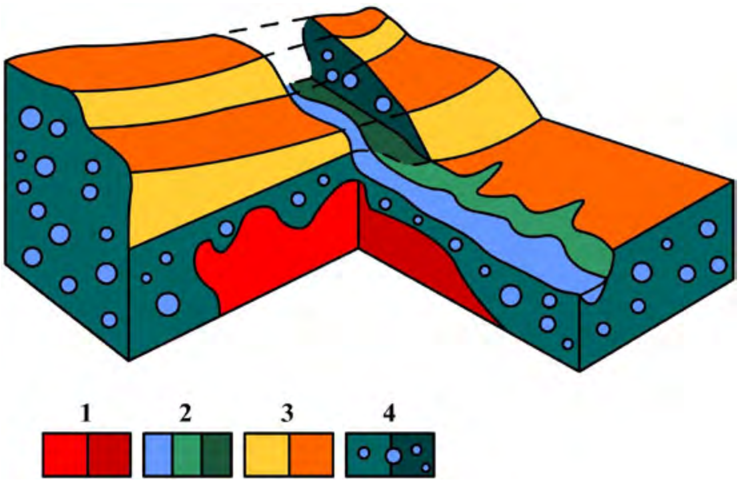


Fig. 2. The possible mechanism of formation of modern Martian valleys: 1 – Heat flow; 2 – Riverbed and the valley of the young channel; 3 – Martian surface; 4 – Cryolithosphere

forming on Mars. The process of their formation is especially observed on the outer parts of young ring structures. Obviously, during the impact event, part of the cryolithosphere melts, and the released water either by temporary flows on the surface or by longer underground flows leads to the formation of a system of young valleys.

Thus, cryolithospheric layers experiencing intense intrusion of magmatic bodies or thermal flux during impact-explosive events may provide sufficient underground water drainage for the formation of Martian valleys and channels (Fig. 2). This process could likely span thousands of years until specific icy layers are depleted and valley formation ceases. In this manner, unique hydrothermal systems sustain the viability of an entire complex of relief-forming processes, ultimately leading to the formation of modern Martian valleys and channels.

Basic elements of Martian valleys. Three-dimensional modeling of the key area of the Lani Chaos Region (Figure 1a) made it possible to identify several morphological elements typical of Martian valleys (Fig. 3).

1. Riverbeds. They are clearly traced on the surface but are often fragmentary since in some areas they are disturbed by landslides and accumulations of colluvial and eolian strata.
2. Typical morphological elements of valleys (floodplains, terraces, etc.). Like terrestrial river valleys, typical morphological elements can be traced in the Lani Chaos Region: floodplains, terraces, and riffles, which are convincing evidence that, if not all, then some of the valleys were formed due to surface flowing waters (possibly in a short period).
3. Landslides in the key area are most likely associated with the current subsurface activity of the cryolithosphere. It is obvious that some of its strata sometimes release or vice versa restore H_2O reserves, which leads to surface deformations.
4. The upper layers of the cryolithosphere are saturated with H_2O ice.
5. The cratered surfaces surrounding the valleys have local accumulations of eolian deposits in the form of dunes and small barchans.

Xenolandscape complexes of the Martian valleys. The presented area of Mars is in the region of one of the upper reaches of the Kasei Vallis, lying to the east of the grandiose volcanic region Tharsis (Fig. 1b, 4). The Kasei Vallis are perhaps the largest outflow channels on Mars. The Kasei Vallis themselves were probably formed during giant floods that arose during the intensification of volcanic and tectonic activity in the Tharsis region and in the province of Farsida.

According to the four multiplication groups, the following xenolandscape complexes are identified within the covered territory:

1. The main riverbed of the Kasei Vallis. In the relief, it appears as a flat surface with single depressions caused by permafrost processes in the subsurface layers. Sufficiently wide from 10 to 50 km. Within the complex, there are local accumulations of aeolian material in the form of small dunes and single, rather large dunes. The time of the forma-

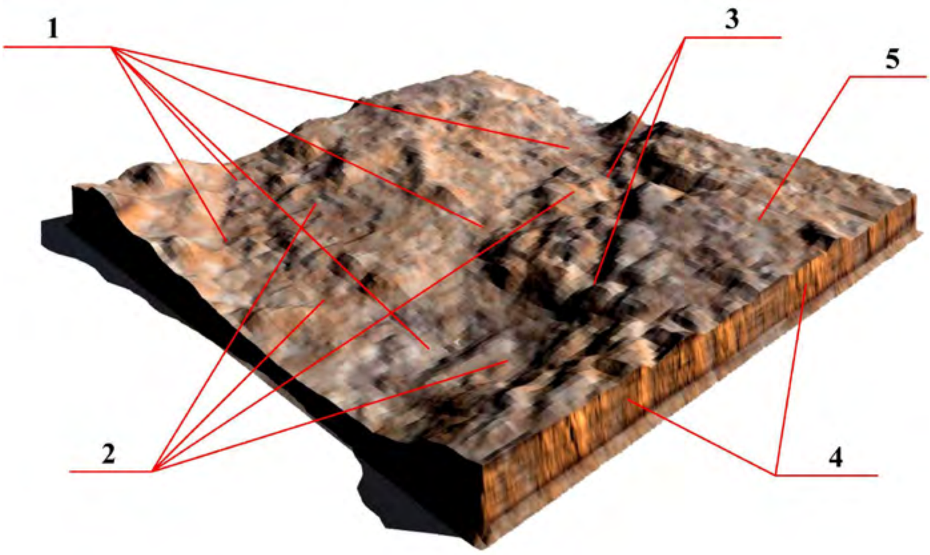


Fig. 3. The main elements of the surface forms of the Martian valleys (for example, part of the Lani Chaos Region): 1 – Riverbeds; 2 – Typical morphological elements of valleys (floodplains, terraces, etc.); 3 – Landslides; 4 – Upper layers of the cryolithosphere; 5 – Cratered surfaces

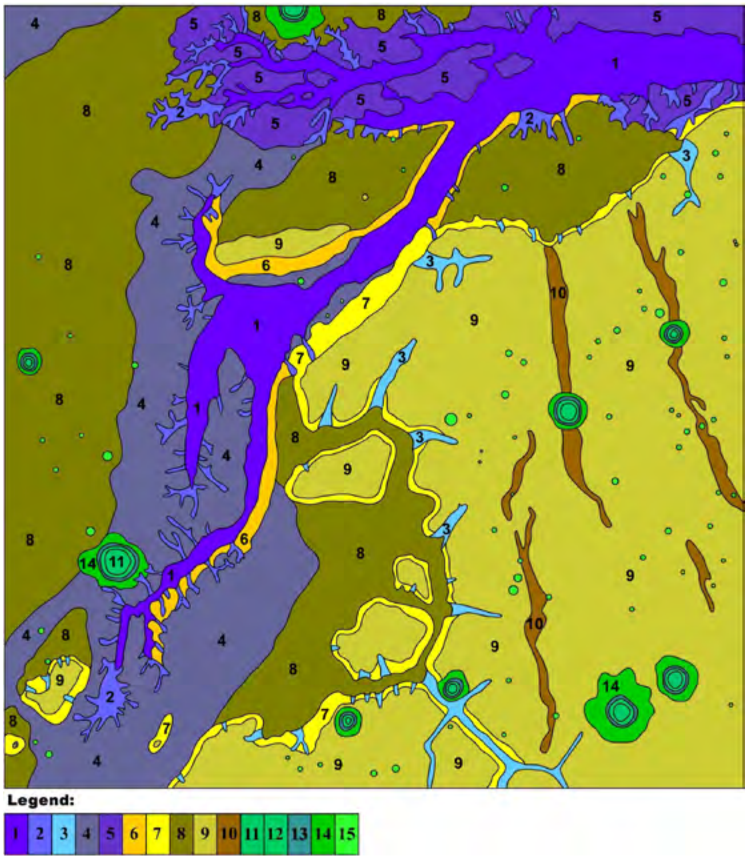


Fig. 4. A section of the Mars region «Upper reaches of the Kasei Vallis» with xenolandscapes typical of the planet: 1 – The main riverbed of the Kasei Vallis; 2 – Tributaries of the main riverbed with signs of subsurface flushing; 3 – Forms of subsurface flushing second and third terraces; 4 – First terrace; 5 – First terrace with chaotic relief; 6 – Steep slopes of first terrace; 7 – Steep slopes of terraces second and third; 8 – Second terrace; 9 – Third terrace; 10 – Ridge-like dorses; 11 – Crater bottoms; 12 – Internal crater slopes; 13 – Crater rims; 14 – Outer crater slopes and crater rims; 15 – Small craters.

tion of the early Hesperian epoch is the time of the global reformatting of the planet's nature.

2. Tributaries of the main riverbed with signs of subsurface flushing. The younger formations, which were formed due to subsurface flushing caused by the cyclical activation of volcanic processes in the Tharsis region, which led to local rapid melting of accumulated ice in the subsurface layers, and as a result formed a dense network of erosional forms, mainly on steep slopes.
3. Forms of subsurface flushing on the first and second terraced surfaces. The formations are like the previous ones, however, they are characterized by much larger manifestations on the surface and, mainly, by remoteness from the main «riverbed».
4. First terrace. Predominantly flat surfaces formed by the catastrophic flow of large volumes of water. It is characterized by a significant accumulation of eolian deposits, among which sand accumulations predominate in the form of localized fields of dunes and low barchans. Eluvial deposits are distinctly distinguished by individual islets.
5. First terrace with chaotic relief. Surfaces with intensely rugged relief, have all the signs of repeated flushing and repeated activation of subsurface flushing, which as a result was reflected in the formation of an extremely complex relief system.
6. Steep slopes of the first terrace. Slopes of intensive incision of the ancient riverbed. In the relief, they appear as steep, sometimes more than 40° slopes with numerous subsurface shallow rinsing.
7. Steep slopes of second and third terraces. Like the previous formations but are characterized by much larger manifestations in the relief and distribution within the covered territory.
8. Second terrace. Relatively flat surface compared to previous terraces. Within its limits, there are very few eolian deposits, but much more eluvial ones.
9. Third terrace. Like the previous one, but on a larger scale. It is in this terrace that the largest subsurface flushes are incisions. Individual islands here are distributed as complexes of dunes and barchans, as well as surfaces with rather thick accumulations of eluvial deposits.

10. Ridge-like dorses. One of the oldest formations within the region, which in the relief appears as elongated low ridges, extending mainly from north to south. These are probably fragments of ancient rocky formations buried under layers of eolian material, and even earlier covered by fluvial sediments during the formation of the Kasei Vallis.
11. Crater bottoms. Within the mapped region, only a group of relatively small, young craters formed during the Amazonian period can be traced. All of them have clear elements inherent in the ring structures characteristic of Mars. The bottoms are mostly flat, in some craters there are small islands of low dunes.
12. Internal crater slopes. Distinct, relatively steep, without visible gravitational landforms.
13. Crater rims. Well-preserved, mostly simple structures, uncomplicated by axial uplifts.
14. Outer crater slopes and crater rims. Clear, with pronounced elements of the fluidity of the material during the excavation stages, are generally similar to each other in most craters. The difference is only in the intensity of manifestation of the fluidity of the substance in different craters, which indicates the differentiation of the ice content during the formation of a particular ring structure.
15. Small craters. Craters in which it is impossible to distinguish their structural parts at a given scale.

Thus, within the region of the «Upper reaches of the Kasei Vallis», ancient fluvial forms are well preserved on the surface, which was formed during the intense volcanic stage in the Tharsis region. This largely represents the main riverbed of the Kasei Vallis and terraced surfaces, which are now significantly modified by landslides, collapses, impacts, and intense aeolian activity. Alongside ancient forms, young, small valleys are clearly observed, mostly representing forms of modern sub-surface erosion on the first and second terraced surfaces. Signs of intense fluvial activity in the past are clearly expressed in well-preserved and familiar features of river valleys on our planet, such as riverbeds, floodplains, and terraced surfaces. These mentioned elements are well traced in the three-dimensional model of the Lani Chaos area (Figure 3).

Conclusions

The identification of Martian channels and valleys and numerous relief morphosculptures associated with them with signs of water origin is of great importance in comparative planetology. The existence of many channels and valleys on Mars indicates a significant transformation of its atmosphere over the course of geological history. However, the morphology of individual channels clearly indicates the possibility of their formation through local activation of hydrothermal systems. We argue that the formation of most of the Martian channels and large valleys is associated with the intrusion of a heat flow into the upper layers of the cryolithosphere. They lead to the rapid melting of ice accumulated in it and the release of large volumes of water, which for a relatively short time form surface linear erosional forms. Also, similar events occur during impact events when high temperatures are reached. Evidence is provided by numerous young impact formations with a network of small valleys both on the inner and outer crater slopes. The emergence of fluvial activity and the presence of stagnant water on the Martian surface in the early geological history of Mars remains the subject of intense scientific debate.

All the special factors of xenolandscape formation mentioned in the article have certain regular components in their manifestations, but in general, the author considers a somewhat conditional division of the components of xenolandscape influences to be acceptable for their systematic consideration. The general specificity of the xenolandscape formation depleted of active material components is also obvious: a rarefied atmosphere, and the absence of a liquid phase of the hydrosphere and biosphere. Such impoverishment turned out to be decisive in the author's possibilities of revealing the topic of xenolandscapes, in some of his forced limitations to inventory representations, and not the resulting synthetic ones.

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