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THE INFLUENCE OF VOLCANISM ON THE PHYSICAL CHARACTERISTICS OF THE PLANET MARS

VIDMACHENKO A. P., KUZNYETSOVA J. G., OVSAK O. S.

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ABSTRACT

Like all terrestrial planets, Mars has a rocky, mostly basaltic surface. The red hue of its surface is due to the abundance of Fe_2O_3 oxide and an iron hydroxide – goethite. Their formation requires the presence of oxygen and/or water. Although the current atmosphere of Mars is thin and dry, the widespread oxidation of its surface minerals strongly suggests a past history when liquid water was abundant, and the atmosphere was more oxidizing. This mineralogical evidence directly links the present-day appearance of the planet's surface to its early climate, hydrological cycle, weathering processes, and changes over billions of years. The description of the now "desert planet" reflects its current state, but the surface mineralogy reveals a very different and more geochemically active past.

According to some assumptions, water and atmosphere were lost as a result of a powerful bombardment by huge meteoroids. Based on data collected by rovers and orbital modules, the main stages of the planet's development were reconstructed. In the first geological era, the Phyllocian, which began 4.5 billion years ago and lasted ~500 million years, Mars was a fairly wet planet. After global climate changes, probably caused by the action of numerous volcanoes, a new Theiikian era began, which lasted from 4 to 3.5 billion years ago. As a result of powerful volcanic emissions, huge amounts of sulfur entered the atmosphere of Mars. The planet began to dry out; this is evidenced by the presence of gypsum and gray hematite. About 3.5 billion years ago, the third, so-called Siderikan era, began. Then iron oxides were formed that do not hydrate and can give the planet a red color. After extensive ground-based exploration of Mars, since the 1960s, increasingly reliable information about the planet has been obtained using numerous spacecraft. Observational data obtained by various spacecraft have shown that Mars has a weak magnetic field with an intensity of up to 2% of the magnetic field on Earth and a polarity opposite to that of the Earth. Volcanic activity on Mars has been a fundamental force in shaping its geological evolution. Large volcanic formations cover significant parts of its surface. These formations cover a

huge geological time span, from more than 3.7 billion years ago to less than 500 million years ago.

It is believed that the core of Mars is rich in iron and sulfur. And for them, temperatures are characteristic values of 1300-1500 K. Therefore, these elements are in a liquid state in the core. A significant breakthrough in the study of the interior of Mars was achieved thanks to NASA's "InSight" mission, launched in 2018 and operating until December 2022. Measurements from the InSight spacecraft obtained the first direct seismic data on the Martian interior. This additional data provided constraints on the size and layered structures inside Mars. The presence of significant amounts of iron hydroxide in the upper soil is important confirmation of the processes of lowering heavier chemical elements and rocks in the directions towards the planet's core. This indicates the presence of a past phenomenon along the gravitational differentiation of Mars. One of the key results of the "InSight" mission was the refinement of the thickness of the Martian crust. It turned out that it, at least at the landing site of the spacecraft, is thinner than many previous models predicted. Estimates of thickness vary from 10 km to 20 km (if there are two sublayers) or even 37 km (if there are three sublayers). Unlike Earth with its moving lithospheric plates, the crust of Mars is a single, relatively immobile global plate. On Mars, hot spots in the mantle (plumes) remain stationary relative to the stationary Martian surface for long periods of time. This allows for almost continuous eruption and accumulation of huge volumes of lava in one place for hundreds of millions of years; this is what can directly explain the formation of colossal shield volcanoes such as Olympus Mons. The radius of the Martian core has been found to be in the range of 1780 to 1810 km, and the density is 6.2-6.3 g/cm^3. The large size of the Martian core, its liquid state, and the high content of light elements, in particular sulfur, are key factors explaining the absence of a modern global magnetic field.

The extremely thin atmosphere of Mars is one of the key factors that determine its current climatic conditions and distinguish them from Earth. The main component of the Martian atmosphere is carbon dioxide (CO_2), the share of which is 95-96% of its volume. Formations of a condensation nature that periodically arise when CO_2

condenses in the atmosphere of Mars are mainly represented by white clouds and fogs. Most often, clouds and fogs form near the polar caps in winter, when the temperature in the atmosphere drops below the freezing point of carbon dioxide CO_2 (147 K), and on the tops of volcanoes. Mars is now a very cold world. The average temperature on its surface is about 210 K. Aerosol particles in the atmosphere have a significant impact on the formation of the general climate of the planet. When Mars passes near perihelion, this effect is significantly enhanced. And then global dust storms begin to arise, transporting significant amounts of dust across the planet. Volcanism has played a key role in shaping both the geological history of the surface and the evolution of the atmosphere of Mars. Large-scale eruptions over billions of years have led to the formation of large lava flows and vast volcanic plains that now cover a significant part of the planet's surface. Volcanic eruptions were also the main source of gases entering the early atmosphere of Mars. Volcanic activity has historically played a very important role in the evolution of the geological features of Mars. It is it that has allowed the formation of relief on a significant part of its surface. Volcanism on Mars has led to the formation of some of the highest and most powerful volcanic formations in the entire Solar System. There are clear traces of volcanism and tectonic activity, such as gorges, canyons and faults; some of them are several kilometers deep, hundreds of kilometers long and tens of kilometers wide. The age of the youngest volcanic activity on Mars is estimated from several tens of thousands to several tens of millions of years. The presence of cracks and fissures on the surface of Elysium Planitia indicates intense tectonic dynamics in this region, preserving the history of crustal deformation, tectonic plate displacements under the surface of the planet, and relief formations caused by stresses in the crust. And space missions to the Elysium Planitia plain have significantly expanded our understanding of the internal structure of Mars, geological processes, and environmental conditions.

One of the most dramatic examples of the impact of volcanism on the geology of Mars is the possible connection between the formation of the volcanic region Tharsis Regio and the formation of the vast canyon system Valles Marineris. It is believed that the Valles Marineris valley was formed mainly as a result of tectonic processes that

were directly caused by the formation and huge mass of Tharsis Regio. The mechanism of such a connection may be as follows. Prolonged volcanic activity led to the accumulation of a colossal mass of volcanic rocks in the Tharsis Regio province, creating enormous loads on the lithosphere. Such a mass should have caused significant compressive and tensile stresses in the surrounding part of the planetary crust; especially to the east of the highlands. Therefore, the lithosphere literally bent under the weight of Tharsis Regio and significantly stretched along the edges. These tensile stresses significantly exceeded the strength of the planetary crust, and this caused it to crack and form a system of giant parallel grabens; that is, to the lowering of entire blocks of crust between faults. Noctis Labyrinthus, located at the western end of the Valles Marineris valley, with its chaotically scattered network of canyons, is considered a vivid example of the initial stage of such cracking. The very first tectonic cracks and grabens were subsequently significantly widened and deepened under the influence of various erosional processes.

Observations from recent space missions have provided compelling evidence that Mars continues to exhibit significant geological activity. Direct analysis of Martian rocks and more detailed orbital data will provide more precise age dates, compositional information, and understanding of the processes that shaped existing volcanic landscapes.

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1. Physical parameters and orbital characteristics of Mars and its formation

Introduction.

The fourth planet from the Sun, Mars, is classified as a terrestrial planet. It was named after a god who was considered by the ancient Romans to be the god of vegetation, wildlife, and fertility. Therefore, he was initially revered as the patron god of the seasons, different seasons, and especially spring; the first spring month was called Martius (in Ukraine, Berezen). The son of Zeus and Hera, Ares, was identical to this god in ancient Greek mythology. There, he was considered the god of storms and thunderstorms, and later, also the god of war. He was always accompanied by his sister Quarrel ("Eris"), his sons Horror ("Deimos") and Fear ("Phobos"), and the spirits of death. This god was depicted as a young man with a shield and a spear or sword. Therefore, in a figurative sense, Mars and Ares are synonyms for the word "war".

1.1. Origin of the planet Mars.

The process of evolution of the protoplanetary cloud and the formation of planetary bodies from it was divided into two stages. Initially, many bodies with a size of up to 100 km were formed from the dust part of the cloud. At the same time, under the action of gravity, dust grains gradually descended to the central plane and formed a dust disk. At a certain critical value of the average density, gravitational instabilities arose in the disk, and the disk disintegrated into a large number of dust condensations.

Later, collisions of individual dust condensations caused them to merge and form small bodies of asteroid size. With a swarm of such bodies and their fragments, bodies of planetary size were already formed. These bodies moved in almost circular orbits in the plane of the main layer of dust. The bodies that grew the fastest became the embryos of future planets. After their merger into full-fledged planets, their individual movements averaged out, and therefore the orbits of the planets became practically circular and coplanar.

Experimental evidence that terrestrial planets were not formed from gas or dust

components, but rather as a result of the accumulation of solid matter, is a noticeable deficiency on these planets of such inert gases as Ar, Kr, Ne and Xe compared to their content, for example, on the Sun. A careful theoretical study of the processes of formation of the planets of the Earth group indicates that they included almost all the solid matter that was in the zone of formation of these planetary bodies and only a fairly small amount of its mass was thrown out by gravitational perturbation from the ever-increasing size and mass of planetary bodies [3].

Therefore, the planet Mars is characterized by a rocky composition and internal differentiation [51]. And this gives it a fundamental similarity to the Earth (Fig. 1.1). It is one of the most studied objects in the Solar System and the closest neighbor of the Earth among the planets of the outer orbit. Like all terrestrial planets, Mars has a hard, rocky surface, which is mainly composed of tholeiitic basalt.



Fig. 1.1. Comparison of the sizes of Earth and Mars (https://fc.vseosvita.ua/000jlu-4ee2/006.png).

Although some regions exhibit higher silica content, resembling terrestrial andesitic rocks. Mars is currently recognized as the only known example of a desert

planet, characterized by surface morphology and conditions similar to the arid deserts of Earth. The red hue of the surface of Mars (Fig. 1.2) is explained by the prevalence of Fe_2O_3 oxide and iron hydroxide – goethite. It is these colors that allowed the planet to be named after the Roman god of war. However, depending on the local mineralogy, other common surface colors are observed, such as gold, brown, light brown and greenish. A significant part of the surface is significantly covered with fine-grained iron oxide dust (rust).



Fig. 1.2. The cold and dry surface of Mars, bombarded by radiation (https://ichef.bbci.co.uk/news/800/cpsprodpb/93C0/production/_119542873_46102_pia24546-mastcam-z_views_'santa_cruz'_on_mars-b.jpg.webp).

The predominant reddish color of Mars is a profound geological indicator. The formation of iron oxide requires the presence of oxygen and/or water. Although the current atmosphere of Mars is thin and dry, the widespread oxidation of its surface minerals strongly suggests a past history when liquid water was abundant [32, 39, 44, 56] and a more oxidizing atmosphere existed [49]. This mineralogical evidence directly links the planet's present-day surface appearance (Fig. 1.3) to its early climate [38, 48, 50, 54], hydrological cycle, weathering processes, and changes over billions of years.

The description of the present-day "desert planet" thus describes its present state, but the surface mineralogy reveals a very different and more geochemically active past.

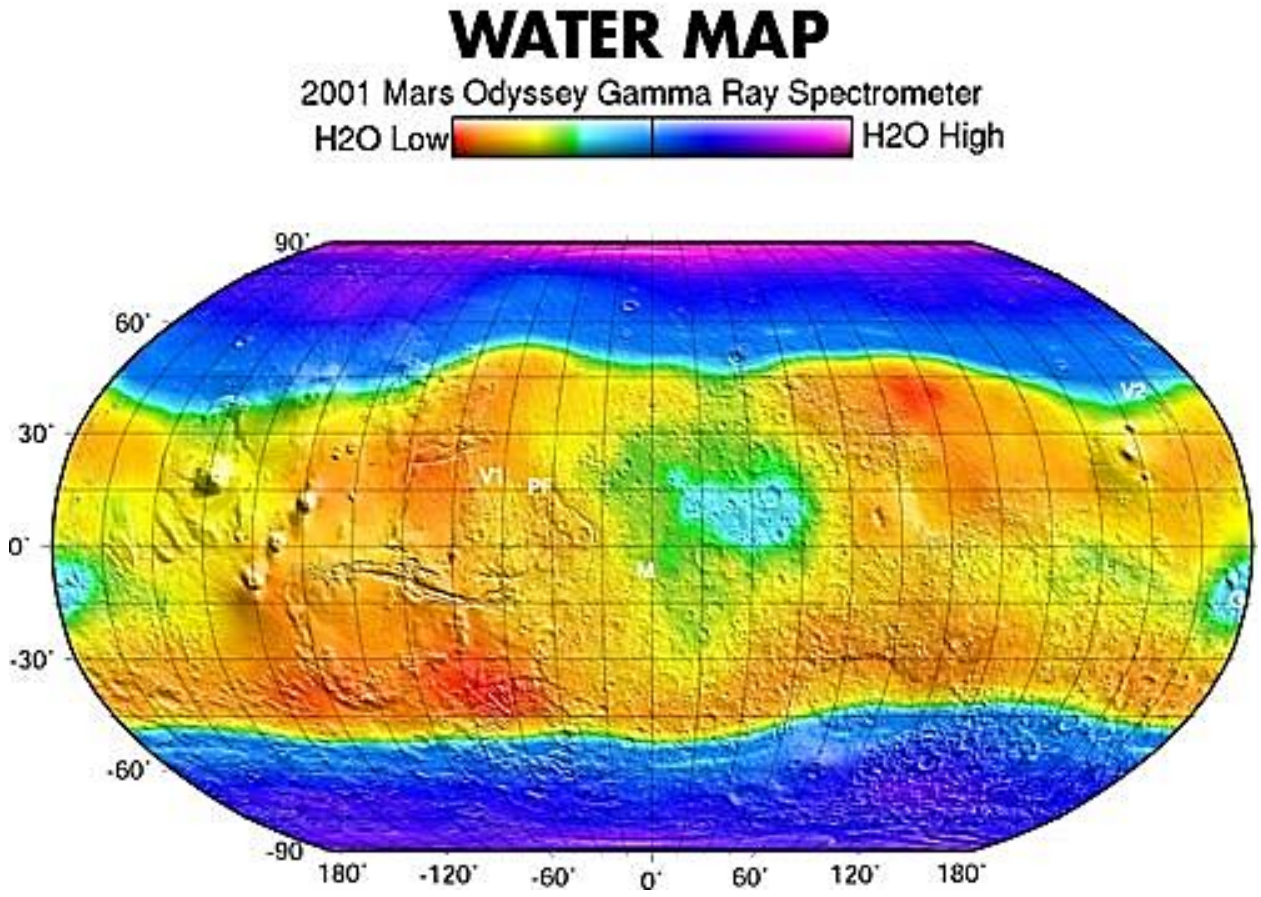


Fig. 1.3. The map is based on observations of gamma-rays from the element hydrogen on Mars. The areas shown in blue, and purple are thought to be 50% water ice by volume (https://science.nasa.gov/wp-content/uploads/2024/03/h2o-map-br.jpg).

The “Mars Odyssey” orbiter carried three scientific instruments that provided information about the Martian atmosphere, surface geology, environmental conditions, and potential biosignatures. For example, the gamma-ray spectrometer GRS measured the abundance and distribution of many chemical elements from the periodic table, including potassium, thorium, hydrogen, silicon, iron, and chlorine. Knowing which elements are currently on or near the surface provides detailed information about how conditions on Mars have changed over time. The experiment used a gamma-ray spectrometer and two neutron detectors to determine the specific elemental

composition of the planet's surface. Gamma rays emitted by atomic nuclei appear as distinct lines of radiation in the spectrum obtained by the instrument. The spectral energy of these radiations, recorded by the instrument, provides a good indication of which elements are present on the surface, and the intensity of the spectrum indicates the concentrations of specific elements. Spectrometric studies have greatly helped to improve our understanding of their origin and the evolution of the entire planet Mars and have also allowed us to investigate the processes that continue to shape it today and have shaped it in the past.

So-called neutron detectors are sensitive to the concentration of hydrogen in the upper meter-thick layer of the surface. By measuring neutron fluxes, it is possible to calculate the hydrogen content above specific places on Mars, and in this way certain conclusions can be drawn about the presence of water there. Thus, the work of the spectrometer allows us to even look into the shallow layers below the surface of Mars and measure the amount of hydrogen that currently exists there. Since hydrogen is most likely present in the form of water ice, the spectrometer could directly measure the amount of permanent ice in the soil and how it changes with the change of season.

Aspects of the radiation environment both on the way to Mars and in Martian orbit have been studied in observational studies (Fig. 1.4) using an instrument such as the Mars Radiation Environment Experiment (MARIE). Since cosmic radiation poses a significant hazard to interplanetary mission crews, this experiment predicted the expected radiation doses that future astronauts could receive. This will allow us to determine the possible effects of such radiation on Mars on humans. When exploring Mars, cosmic radiation comes from cosmic rays emitted by our Sun, and to a small extent even from stars outside the Solar System.

1.2. Stages of change on Mars.

It is believed that Mars used to have water and rivers [13]; it is quite possible that there was a significant amount of oxygen, due to which Mars acquired a red color: it was atmospheric oxygen that was able to oxidize some rocks.

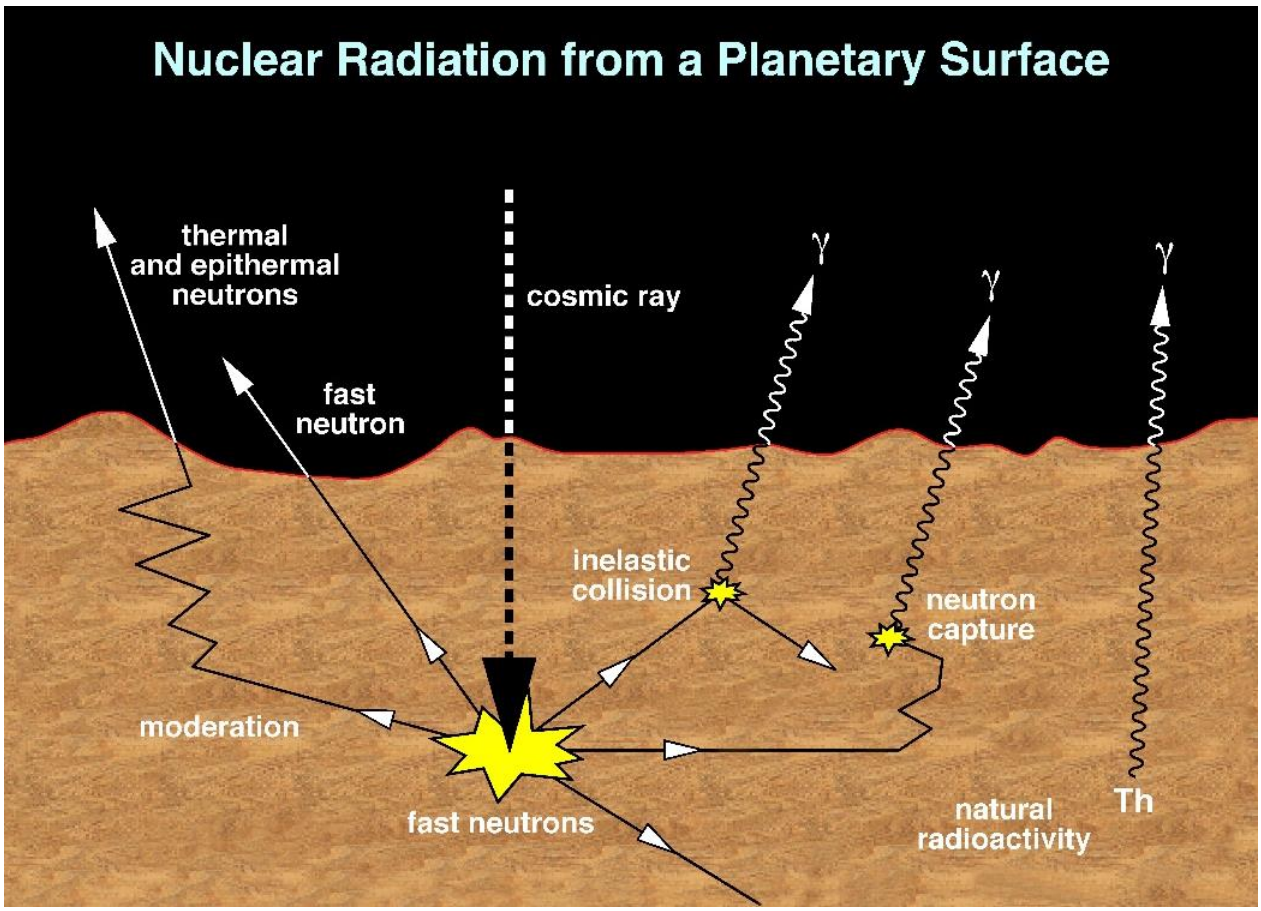


Fig. 1.4. Nuclear radiation coming from the surface of the planet (https://science.nasa.gov/wp-content/uploads/2024/03/grsradiation.jpg).

Therefore, the basis of the surface soil is red-brown iron oxides with impurities of clay (Fig. 1.5) and calcium and magnesium sulfates; and there are also such dark rocks as basalts and andesites with a high content of iron oxides in the composition of silicates. According to some assumptions, water and atmosphere were lost as a result of powerful bombardment by huge meteoroids; they could have appeared, for example, during the gravitational destruction of the once existing third satellite of Mars. Such bombardment is indicated not only by meteorite craters, but also by a large amount of magnetic sand (maghemite) on the surface of Mars. This mineral is formed only during the simultaneous oxidation of magnetite and its strong calcination.

This is a perspective view of clay-rich rocks (blue) on the old plateaus around Mawrth vallis (left) and Oyama crater (center), created from a compilation of data obtained by several instruments.

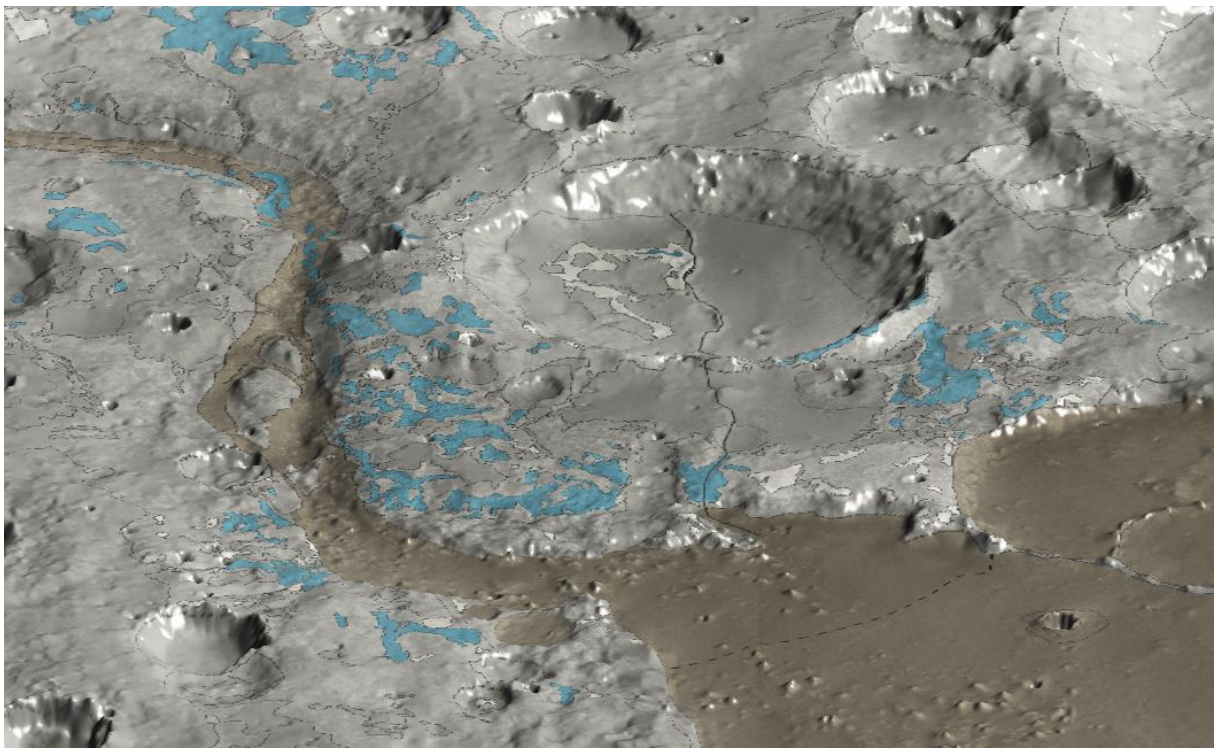


Fig. 1.5. Clay-rich detachments near Mawrth vallis on Mars (https://planetary.s3.amazonaws.com/web/assets/pictures/water-rich-minerals-mars.jpg).

It seems that the powerful flow that created the channel in Fig. 1.5 eroded and exposed ancient, hydrated clay-rich minerals. Based on data collected by rovers and orbital modules, the main stages of the planet's development have been reconstructed [9, 11, 12]. During the first geological era, the **Phyllocian**, which began 4.5 billion years ago and lasted ~500 million years, Mars was a fairly wet planet (Fig. 1.6). This is evident from the fact that the rocks belonging to it underwent significant erosion. Clay minerals, phyllosilicates, have been found in their composition; and their formation requires a large amount of water, a temperature slightly higher than 273 K [19] and low acidity. Currently, many areas with such rocks have been discovered all over the planet, usually located under young volcanic rocks and in many places reaching the surface. After global climate changes, probably caused by the action of numerous volcanoes [15-17, 22], a new **Theiikian** era began, which lasted from 4 to 3.5 billion years ago.

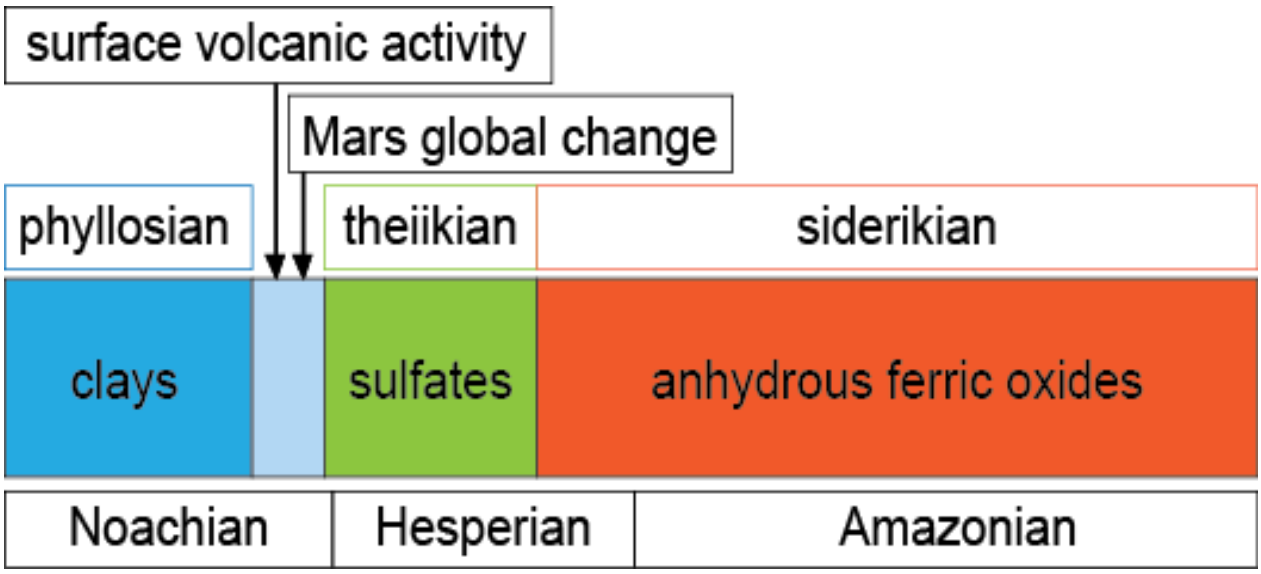


Fig. 1.6. Martian mineralogical time scale (https://planetary.s3.amazonaws.com/web/assets/pictures/Bibring-chronology.png).

As a result of powerful volcanic emissions, huge amounts of sulfur entered the atmosphere of Mars. And for this reason, the entire environment became very acidic. Also, water began to react with sulfur compounds and form sulfates [3, 7]. The planet began to dry out; this is evidenced by the presence of gypsum and gray hematite.

About 3.5 billion years ago, the third, so-called **Siderikan** era began. Then iron oxides were formed, which do not hydrate, and which can give the planet a red color. Thus, although Mars is now a desert, about 4 billion years ago there were numerous volcanoes erupting there, there were powerful ice caps at the poles, a dense gaseous atmosphere with a pressure of up to 0.4 bars surrounded the planet, and water in the form of rain and snow replenished rivers, lakes and seas [13, 14]. According to various estimates, this situation could be maintained from 500 million to 1.5 billion years. Conditions on Mars were the same as on the then Earth. But later the situation began to change: the planet slowly cooled, volcanic activity decreased and gas emissions into the then atmosphere decreased.

In the work [8], three successive eras were proposed for the geological time scale on Mars, which were characterized by the products of their changes on the planet's surface: (i) the so-called non-acidic aqueous change, in which the formation of phyllosilicates is traced (**Phyllosian** era); (ii) the next is an acidic aqueous alteration,

during which sulfates were formed (**Theiikian** era); (iii) and the third is an atmospheric anhydrous alteration, in which the formation of iron oxides is observed under the influence of atmospheric components (**Theiikian** era)".

Observations with better resolution using the visible and near-infrared spectrometer (Compact Reconnaissance Imaging Spectrometer for Mars – CRISM), installed on board the spacecraft "Mars Reconnaissance Orbiter", allowed to improve the results of previous searches for mineralogical signs of past and present water activity on the surface of Mars.

Four (possibly five) different types of hydrated minerals have previously been found in some areas of the surface on Mars: sulfates, which contain hematite, in Meridiani and in the canyons of Valles Marineris, including Candor, Melas, Juventae, Tithonium and Eos chasma; gypsum sand dunes near the north pole; phyllosilicate layers on some slopes in the Valles Marineris valleys; and deep phyllosilicates on the rims of some craters on the central peaks.

New observations have confirmed this list and added five new types of hydrated minerals, visible thanks to the much higher resolution of the CRISM spectrometer. The results of these new observations have revealed tiny mineral outcrops throughout the southern highlands. These appear to be ancient minerals that may have been deposited by meteorite impacts.

Small colored patches have also been found on crater walls, peaks, and vents. Among the new minerals found are: phyllosilicates in the outcrops and deltas between high-altitude craters, most often in the lowest layers of these deltas, sometimes associated with chlorides, and found throughout the southern highlands; phyllosilicates in outcrops and deltas within high-altitude craters such as Holden, Eberswalde, Jezero and Terby; phyllosilicates and sulphates forming distinctive "rings" within several craters in Terra Sirenum (Fig. 1.7); light-coloured layers of hydrated silica – i.e. opal – of Hesperian or perhaps even Amazonian age, located on the plains surrounding the Valles Marineris; carbonates are also found in the Noachian landscape, mainly around Isidis.

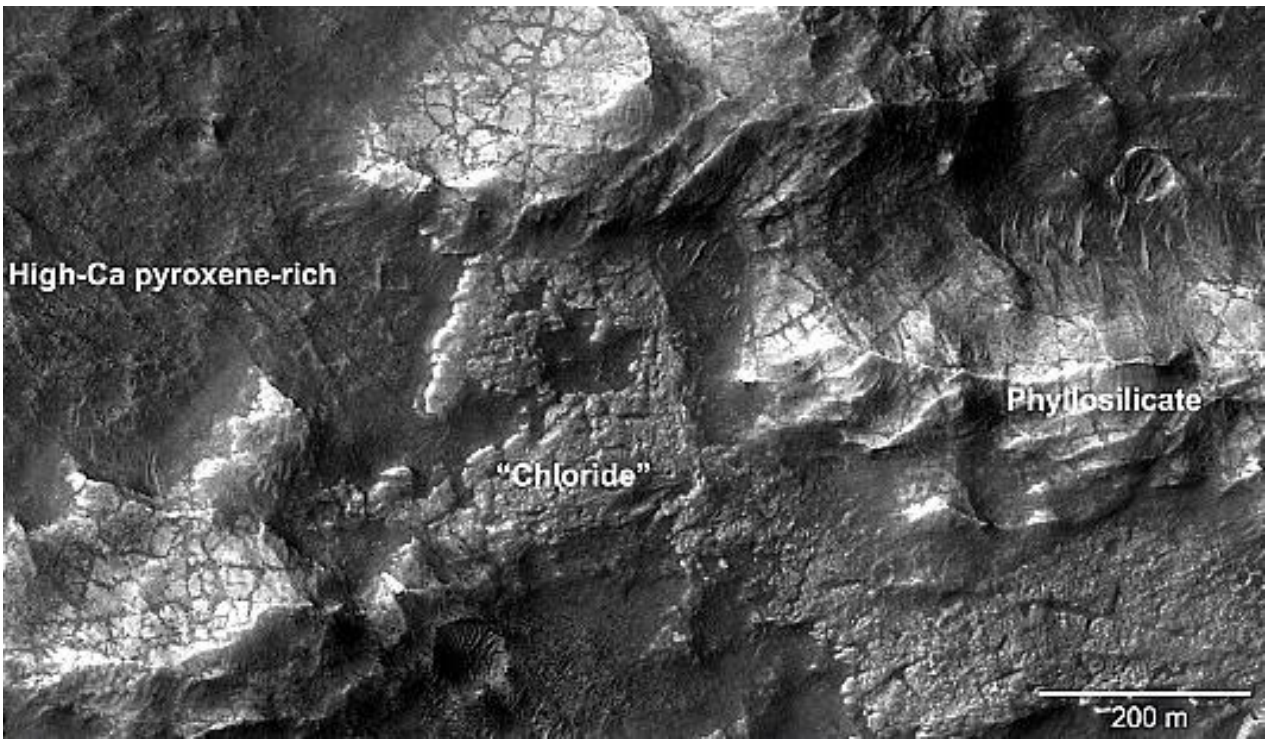


Fig. 1.7. View of intercrater plains located in the relatively flat-bottomed basin of Terra Sirenum, showing stratigraphic relationships of various materials such as phyllosilicates and one of the largest concentrations of chloride deposits [28]

Taken together, the findings of a wide variety of hydrated minerals on Mars suggest that many different types of aquatic environments have existed on the planet throughout its history. With few exceptions, sediments containing phyllosilicates and carbonates stratigraphically fall within the phyllosilicate environment of the Noachian era. Sulfate and silica-containing sediments, which indicate an acidic environment, correspond to the late Noachian and Hesperian eras. These later findings largely confirm earlier findings by other instruments: the Phyllosian, Theiikian, and Siderikian. The diversity of aquatic environments in Mars' past history provided a large number of sites where life could have existed [29, 30, 35-37, 53].

1.3. Exploration of Mars by spacecraft

After long-term ground studies of Mars, starting from the 1960s, increasingly reliable information about this planet began to be obtained using spacecraft. Already on 01.11.1962, the spacecraft (SK) "Mars-1" was sent to Mars. But even during the approach

to this planet, contact with the spacecraft was lost. Later, the USSR and the USA, and starting from 2003, the European Community also performed many successful launches. Let us list them and some of their features.

07.15.1965 The spacecraft **"Mariner-4"** was able to fly within 13,200 km of Mars for the first time. The following equipment was installed on the spacecraft. Four detectors were used to register low-energy particles. Assuming that the shock wave fronts from the solar wind before the magnetopauses on Mars and Earth are the same, it was even possible to estimate the magnetic dipole of the planet Mars, approximately $5 \cdot 10^{-5}$ from the Earth value [1, 10].

To register charged particles with energies greater than 40 KeV, a telescope was used, with three electron detectors installed on it (however, they could not be registered), as well as with proton and α-particle detectors with possible energies from 1 to 170 MeV/nucleon (with their help, they were able to detect an increase in the concentration of protons).

When the spacecraft entered the limb of Mars, it was possible to determine the radius of the planet, atmospheric pressure and some characteristics of the ionosphere from the radio eclipse. 22 images of the planet's surface were also obtained, covering almost 1% of the surface of Mars. They showed some similarity between the structure of the surfaces of Mars and the Moon, and allowed to see 70 craters with diameters from 5 to 120 km.

In the summer of 1969, the spacecraft "**Mariner 6**" and "**Mariner 7**" were also able to fly at a short distance from the planet. They were equipped with the same equipment. With a wide-angle television camera, they began to receive photographs through light filters in the red, green and blue parts of the spectrum with a resolution of 24 km during the approach; on an area of 625 thousand km^2, they were able to detect 156 craters of various sizes; with further rapprochement, they turned on the next camera, and received up to 200 images only in yellow rays with a resolution of up to 270 m; the detected craters were even about 300 m in size [6].

Infrared (IR) spectrometers installed on these spacecrafts in the range of 1.9-14.3 microns, in which there is a carbon dioxide absorption band at a wavelength of 2 microns, made it possible to study pressure drops (and height) over individual surface details with

a resolution of 130×8 km with an error in height of ±1 km. And IR radiometers with a field of view of 7° in the wavelength ranges of 8.2-12.4 microns and 18-25 microns were paired with television cameras.

With their help, it was found that at a latitude of 61°S the temperature decreased to 153 K. A spectrometer in the ultraviolet (UV) range of 110-340 nm was also installed there, as well as devices for conducting radio obscuration experiments and bistatic radar.

On 11/14/1971, the "**Mariner 9"** spacecraft reached Mars. It became its first artificial satellite with a rotation period of 12h 34m and an orbital inclination to the equator at an angle of 64° 24′. The study of the surface of Mars was carried out using a wide-angle television camera, a Fourier spectrometer for the range of 5-50 microns, a spectrometer for the UV spectral region of 110-340 nm, and a device for conducting radio obscuration experiments; they showed large differences in the height of some details with differences in atmospheric pressure values from 2.8 to 10.3 mbar [2].

On 27.11 and 2.12.1971, the "**Mars-2"** and "**Mars-3"** spacecraft reached the planet and became its artificial satellites. During the approach, capsules separated from each of them, and the capsule from the Mars-3 spacecraft was the first to make a soft landing. But the television signal was transmitted only in the first seconds.

Both orbital modules carried the following equipment: a television camera, a radiometer for the spectral range of 8-40 microns, filter photometers for λ=2 microns (CO2 bands), λ=1.38 microns (H_2O), λλ≈121.5, 370, 420, 490, 560 and 690 nm; a 3.5 cm radio telescope, a magnetometer, ion traps, an electrostatic analyzer and a special radio complex.

02/10/1974 the "**Mars-4"** spacecraft flew 2200 km from the planet and transmitted several images of its surface. 02/12/1974 the "**Mars-5**" spacecraft entered the orbit of the artificial satellite of Mars. The orbit was chosen so that during the day it would pass over the area where the probes of the two following spacecraft were planned to land. But the "**Mars-7"** spacecraft passed within 1,300 km of the surface of Mars on March 9, 1974.

While "**Mars-6**" reached Mars three days later and was able to lower the probe to a point with a longitude of 25°E and a latitude of 24°S. This device was the first to determine

the chemical composition of the atmosphere, atmospheric pressure and temperature on the descent route, and then on the surface of the planet [5].

On June 19 and July 7, 1976, respectively, the "**Viking 1"** (**V1**) and "**Viking 2"** (**V2**) spacecraft entered Mars orbit. On July 20 and August 3, 1976, both probes landed at the following coordinates: latitude 22.7°N, longitude L=47.94°E (V1) and latitude 47.67°N, longitude L=225°E (V2) [8]. Both orbital modules carried traditional instruments, and the landing modules were equipped with instruments for optical observations around the modules, for observations of the Sun and the satellites of Mars, for measurements of seismic activity [4], magnetic activity of the soil, chemical analysis of the soil and atmosphere, for determination of pressure, temperature, wind direction and speed, etc. During the mission, the seismometer operated for almost 2,100 hours, but no noticeable seismic activity was detected.

07/04/1997 The "**Pathfinder**" spacecraft landed on the surface of Mars and released the small Mars rover Sojourner. It transmitted images of the environment, studied the chemical composition of the surface using α-proton and X-ray spectrometry, conducted meteorological observations of the atmosphere and a number of technological experiments. 09/11/1997 The "**Mars Global Surveyor"** spacecraft reached Mars and became its next satellite, equipped with several cameras, radio equipment, a thermal spectrometer, a laser rangefinder, two magnetometers and an electronic reflector. 10/24/2001 The "**Mars Odyssey"** spacecraft also became its satellite and lowered a probe to the surface at the border of the northern polar region.

In 2003, the Japanese interplanetary station "**Nozomi" ("Hope"**) flew within 1000 km of the surface of Mars but was unable to enter the planet's orbit. On 19.12.2003, the European Space Agency (ESA) spacecraft "**Mars Express"** was able to reach Mars and become its satellite. But the landing of the British module "**Beagle 2"** was unfortunately unsuccessful.

Two spacecraft "**Mars Exploration Rover"** with the Mars rover "**Spirit"** and the practically identical "**Opportunity**" 3 and 23.01.2004 landed on opposite sides of Mars. Their goal was to answer the question: "Is there water on Mars?".

In March 2006, the "**Mars Reconnaissance Orbiter"** reached Mars, and then

spent several months braking in the upper atmosphere and conducting a detailed study of the planet's surface in different spectral ranges [18, 20] in order to search for possible landing sites for future expeditions, search for areas of geothermal or water activity for climate research [21]. It was also planned to conduct soil sounding to a depth of 1 km using the :**Subsurface Sounding Radar"** in order to detect liquid, or at least frozen, water.

In 2007, NASA launched the "**Phoenix**" spacecraft. It landed near the north pole on the polar cap of Mars to study the geological history of water, which is a key element for better understanding past climate change, and to search for regions favorable for the emergence of possible life forms [40, 41, 47, 53] in "biologically suitable soil".

NASA's next mission was the launch of the "**Mars Science Laboratory"** spacecraft with the "**Curiosity"** rover on November 26, 2011. On August 6, 2012, it landed on the surface of Mars in Gale Crater. The rover has instruments to study possible existing or previously existing life forms on Mars. During the Martian year, Curiosity's results allowed us to assert that the environment on Mars once had conditions that could be conducive to microbial life.

On November 18, 2013, the "**MAVEN" (Mars Atmosphere and Volatile Evolution**) spacecraft was launched, reaching the planet on September 22, 2014. The purpose of the orbital station was to study the upper atmosphere of Mars, and to serve as a transmitter module for rovers and vehicles that will subsequently descend to the surface of Mars.

On November 5, 2013, the Indian Space Research and Development Organization launched the "**Mangalyaan**" mission, and on September 24, 2014, the vehicle entered Martian orbit. This mission became a testbed for testing technologies for subsequent launches of similar missions. The mission's instruments studied the Martian atmosphere. It became India's first mission to Mars, and India itself became the fourth organization whose spacecraft successfully reached Mars after NASA, the USSR, and the ESA. ESA, together with Roscosmos, built the "**ExoMars Trace Gas Orbiter"**, which entered Mars orbit on October 19, 2016. It investigated the nature of the appearance in the Martian atmosphere of methane, water vapor, and other gases, the

content of which on Mars has been known since 2003.

1.4. Physical and orbital characteristics.

Mars is a much smaller planet than Earth. Its equatorial radius is 3396.2 km, and its polar radius is 3376.2 km. On average, this is only about 53% of the Earth's radius (6371 km). Due to its smaller size, the surface area of Mars is approximately equal to the land area of Earth. The mass of Mars is $6.4169 \cdot 10^{23}$ kg, which is almost 11% of the mass of Earth ($5.9722 \cdot 10^{24}$ kg).

This much smaller mass also leads to weaker gravity. The acceleration of gravity at the equator of Mars is about 3.72 m/s², which is about 38% of the Earth's value. The average density of Mars is 3.93 g/cm³, which is noticeably less than the average density of Earth (5.513 g/cm³). The lower density indicates a number of differences in the internal composition compared to Earth. In particular, this suggests a less dense core and a different core-to-mantle volume ratio. That is, it is a critical parameter that directly constrains models of its internal composition and thermal evolution. This lower density indicates that the interior of Mars, especially its core, contains a higher proportion of light elements mixed with iron than the Earth's core.

This difference in composition has profound consequences: the less dense, light-element-rich core has a lower melting point. This may explain why the Martian core remains completely molten, despite significant cooling since its formation. It also affects the planet's ability to maintain a long-term magnetic field [15], directly linking such a fundamental physical characteristic as density to the history of its geodynamo and to the retention of an atmosphere.

Observational data obtained by various spacecraft have shown that Mars has a weak magnetic field with a strength of up to 2% of that of the Earth's magnetic field; and it has the opposite polarity to the Earth's [1, 6, 33].

According to the results obtained, the magnetic field strength in the equatorial region is less than 45 nT with a magnetic moment of the field within $(2.5\text{-}3.1) \cdot 10^{18}$ Tl/cm^3; this value is almost three orders of magnitude less than the Earth's, equal to $8 \cdot 10^{21}$ Tl/cm^3. This difference for the Mars magnetic field is explained by the

compression in this place of the interplanetary magnetic field space, which flows around an almost non-magnetic planet.

Another explanation is the hypothesis that the magnetic field is insignificant due to the fact that the current studies coincided with the moment of inversion, at which the poles of the Mars magnetic field are changing right now. Magnetic field measurements by the Mars Global Surveyor spacecraft (MS) [1, 16] also showed that Mars does have its own magnetic field, but it lacks a global structure. It consists of magnetic mascons, the intensity of which does not exceed 750 nTl. And they are mainly located in the southern hemisphere (Fig. 1.8) [2].

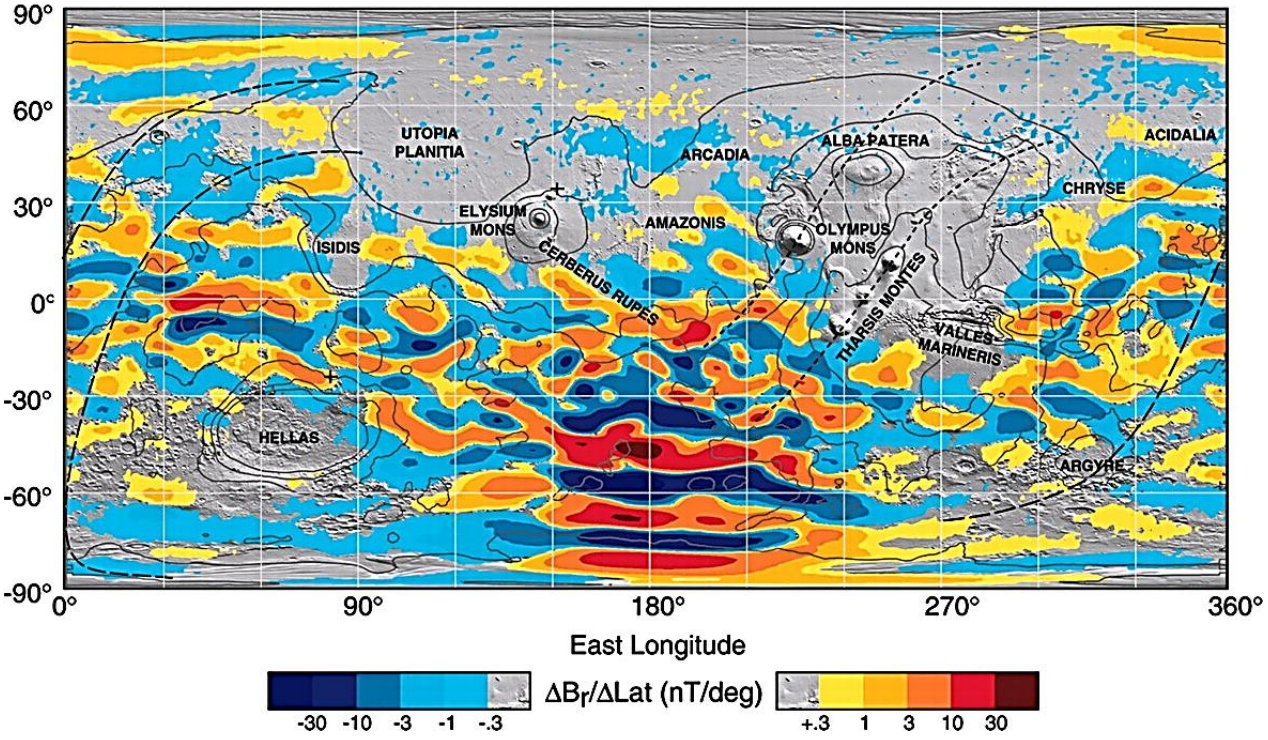


Fig. 1.8. Map of the magnetic field of Mars according to data from the Mars Global Surveyor spacecraft, based on observations over 4 years. Blue and red bands up to 160 km wide and 1000 km long run from east to west; they show adjacent regions of the Martian crust with opposite magnetic field directions. [2].

These magnetic stripes extend from west to east. Moreover, neighboring mascons are almost always magnetized oppositely. Up to 6 such oppositely magnetized pairs were found. To explain this fact, a hypothesis was proposed that these stripes are areas

of the crust that solidified at different polarities of the global magnetic field. And its current state is the remnants of an ancient magnetic field. The map in Fig. 1.8 shows characteristic features of the magnetic field similar to those that arise on Earth in places of tectonic faults.

For example, on Earth, the magnetic field changes its direction several times over a million years; therefore, in faults obtained at different times, different directions of magnetic fields are observed. Something similar was observed on the surface of Mars.

The orbits of the classical planets are close to circular; and their planes are very slightly inclined to the plane of the ecliptic. Like the vast majority of classical planets, Mars rotates around the central body in a counterclockwise direction when observed from the north pole of the world. Among the planets of the terrestrial group, Mars, the farthest from the Sun, has the lowest speed. Mars orbits the Sun at an average distance of approximately 228 million kilometers (1.52 astronomical units (AU)).

Recall that the average distance from the Earth to the Sun is about 149.6 million km. The orbit of Mars is more elongated (elliptical) than the Earth's orbit and has an eccentricity close to 0.0934; this is much higher than that of Earth (0.0167). As a result, Mars' distance from the Sun varies significantly during its year: from about 206.6 million km at its closest point to the Sun (perihelion) to 249.2 million km at its farthest point (aphelion).

This change in distance has a significant impact on the amount of solar energy received by the planet and on climatic conditions [22, 26], including the duration and intensity of seasonal [31, 52] changes. The significant eccentricity of Mars' orbit is a key factor affecting not only the uneven duration of the seasons but also the intensity of solar radiation reaching the planet's surface. The difference in insolation between perihelion and aphelion is almost 45%. This value potentially enhances seasonal climatic contrasts, such as the magnitude of temperature gradients and atmospheric dynamics, compared to Earth [24].

This may be one of the main driving factors for the powerful global dust storms that are often observed when Mars approaches perihelion [3, 7-9, 27].

The Martian year, or the period of one complete revolution around the Sun, lasts

687 Earth days. This is almost twice as long as the Earth year (365.25 days). The inclination of Mars' orbit to the ecliptic plane is small, only 1.85°.

One of the most remarkable features of Mars is the length of its day, which is remarkably close to that of Earth. The sidereal period of rotation (relative to the stars) is 24.623 hours. The length of the average solar day is 24 hours 39 minutes; this is only 2.7% longer than the length of an Earth day. The axis of rotation of Mars is inclined at an angle of 25.19° to the perpendicular to the plane of its orbit. This tilt is also very close to that of Earth (23.44°) and is the main reason why Mars has distinct seasons similar to those of Earth.

However, due to the significant eccentricity of the Martian orbit, the length of the seasons in different hemispheres is not the same. For example, spring in the northern hemisphere and autumn in the southern hemisphere are the longest seasons, lasting 194 revolutions around the axis; while autumn in the northern hemisphere and spring in the southern hemisphere are the shortest, lasting 142 revolutions around the axis of Mars.

The similarity of the length of the day and the tilt of the axis of Mars and Earth has historically made Mars the most "Earth-like" planet in the Solar System in terms of daily and seasonal cycles. Such similarities and clear analogies with Earth conditions have stimulated interest and hypotheses about the possibility of life there [13, 14, 18].

1.5. Comparison with Earth.

As follows from the data in Table 1.1, Mars is a smaller, lighter, less dense and much colder planet than Earth. It is located further from the Sun, which leads to a longer year and less solar energy received. Its orbit is more elongated, which causes larger seasonal fluctuations in surface insolation. However, Mars has a very similar day length to Earth and a similar tilt of its axis of rotation. This causes the presence of daily cycles and seasons similar to those of Earth, although with a slightly different duration. A fundamental difference between the planets is also its very thin atmosphere, which consists mainly of carbon dioxide. The small thickness of the atmosphere leads to the formation of a much larger number of impact craters [4, 5] on the planet's surface.

Table 1.1.

Comparison of physical and orbital characteristics of Mars and Earth.

Characteristics	**Mars)**	**Earth**	**Ratio (Mars/Earth)**
Equatorial radius (km)	3396.2	6378.1	0.533
Polar radius (km)	3376.2	6356.8 km	0.531
Mean radius (km)	3389.5	6371 km	-
Mass (10^{24} kg)	0.64169	5.9722	0.107
Volume (km^3)	1.63118×10^{11}	1.08321×10^{12}	0.151
Surface area (km^2)	1.4437×10^{8}	5.10072×10^{8}	0.284
Mean density (kg/m^3)	3934	5513	0.714
Acceleration of gravity (m/s^2)	3.71 (equator)	9.78 (equator)	0.380
Mean distance from the Sun (AU)	1.524	1.000	1.524
Orbital period (Earth days)	686.980	365.256	1.881
Sidereal period of rotation (h)	24.6229	23.9345	1.029
Inclination of the axis of rotation (°)	25.19	23.44	1.075
Eccentricity of the orbit	0.0935	0.0167	5.599

The following table clearly demonstrates the key parameters that define Mars as a terrestrial planet and its differences from Earth. It emphasizes that Mars is a smaller, lighter, and less dense body, located further from the Sun, but with similar day lengths and seasonality.

Because of its much lower mass, Mars has a surface gravity that is about 38% that

of Earth. The reduced surface gravity is a key physical constraint that has profoundly affected two major aspects of Mars: its volcanic [42, 43, 46, 47, 55] morphology and atmospheric evolution.

In the lower gravitational field, volcanic materials can accumulate to much greater heights before succumbing to gravitational collapse. This explains the colossal scale of Martian volcanoes, such as Mount Olympus, which is much more powerful than the largest mountains on Earth.

This allowed for the formation of much more massive formations that would be structurally unstable on Earth. In addition, the lower gravity means that atmospheric gases are more easily lost to space over geological timescales, contributing to the planet's current thin and rarefied atmosphere [10-12]. Thus, Mars' lower gravity is a fundamental factor shaping both its unique geological landscapes and its atmospheric history.

1.6. The importance of volcanic activity on planetary formation.

Volcanic activity has been a pervasive and fundamental force in shaping the geological evolution of Mars [17, 19-21, 23, 25], with large volcanic formations covering significant parts of its surface.

These formations span a vast geological time span, from the ancient Noachian period (over 3.7 billion years ago) to the relatively late Amazonian period (less than 500 million years ago), suggesting that the planet has been volcanically active throughout its history. Indeed, volcanism is recognized as one of the major factors controlling the morphological evolution of Mars, showing parallels with terrestrial volcanic processes.

The available observational data confirm that volcanism on Mars is not simply a geological phenomenon on this planet, but one of the major factors controlling the geological evolution of Mars; it has been an important process throughout Mars' history. This elevates volcanism to the status of a fundamental, long-term driver that has profoundly influenced the formations on the surface [42] of the planet, the internal thermal dynamics, and the past conditions in its atmosphere.

This suggests a deep, interconnected relationship where the internal thermal state of the planet is directly manifested in surface features and atmospheric chemistry, making volcanism central to understanding the overall planetary evolution of Mars.

References:

1. Acuña M.H. (2003) The magnetic field of Mars. *The Leading Edge*. 22(8), p. 769-771.

2. Acuna M.H., Connerney J.E.P., Ness N.F., et al. (1999) Global distribution of Crustal Magnetization Discovered by the Mars Global Surveyor MAG/ER Experiment. *Science*. 284(5415), p. 790-793.

3. Adams J.B., Filice A.L. (1967) Spectral reflectance 0.4 to 2.0 microns of silicate rock powders. *J. Geophys. Res*. 72(22), p. 5705-5715.

4. Atreya S.K., Gu Z.G. (1994) Stability of the Martian atmosphere: is heterogeneous catalysis essential? *J. Geophys. Res*. 99(E6), p. 13133–13145.

5. Batson R.M. (1973) Cartographic products from the Mariner-9 mission. *J. Geophys. Res*. 78(20), p. 4424-4435.

6. Bertka C.M., Fei Y. (1998) A profile of Martian mineralogy and density up to core-mantle boundary. LPSC. V. 27. P. 107-108.

7. Bi H., Sun D., Sun N., et al. (2025) Seismic detection of a 600-km solid inner core in Mars. *Nature*. 645, p. 67–72.

8. Bibring J.-P., Langevin Y., MustardJohn Y. F., et al (2006) Global mineralogical and aqueous mars history derived from OMEGA/Mars express data. *Science*. 312, p. 400-404.

9. Broquet A., Andrews-Hanna J.C. (2023) Geophysical evidence for an active mantle plume underneath Elysium Planitia on Mars. *Nature Astronomy*. 7, p. 160–169.

10. Cameron A.G.W. (1963) Formation of the solar nebula. *Icarus*. 1(1-6), p. 339-342.

11. Carr M.H. (1999) Retention of an atmosphere on early Mars. *Journal of Geophysical Research: Planets*. 104(E9), p. 21897-21909.

12. Churyumov K.I., Steklov A.F., Vidmachenko A.P., Dashkiev G.N. (2015) Observations of fragments of cometary nuclei in the atmosphere over Kiev. *Astronomical School's Report*. 11(2), p. 99-102.

13. Churyumov K.I., Steklov A.F., Vidmachenko A.P., Dashkiev G.N. (2015) Observations of fragments of cometary nuclei in the atmosphere over Kiev in the summer of 2014. 17 International scientific conference Astronomical School of Young Scientists. 20-22, 2015, Zhytomyr, Ukraine. p. 84-85.

14. Churyumov K.I., Steklov A.F., Vidmachenko A.P., Dashkiev G.N. (2016) Several twilight bolides over Kiev in 2013-2015 – fragments of comets nuclei. International conference Meteoroids 2016, at the European Space Research and Technology Centre (ESTEC), Noordwijk, the Netherlands. 6-10 June 2016. Poster 63.

15. Clinton J.F. (2017) Preparing for InSight: An Invitation to Participate in a Blind Test for Martian Seismicity. *Seismological Res. Letters*. 88(5), p. 1290-1302.

16. Connerney J.E.P., Acuńa M.H., Wasilewski P., et al. (1999) Magntic Lineations in the ancient crust of Mars. *Science*. 284(5415), p. 794-798.

17. de Beule C., Wurm G., Kelling T., et al. (2015) An insolation activated dust layer on Mars. *Icarus*. 260, p. 23-28.

18. Fisher J.A., Richardson M.I., Newman C.E., et al. (2005) A survey of Martian dust devil activity using Mars Global Surveyor Mars Orbiter Camera images. *J. Geophys. Res*. 110(E3), p. 3-4.

19. Fonseca R.M., Zorzano-Mier M.-P., Martín-Torres J. (2018) Planetary boundary layer and circulation dynamics at Gale Crater, Mars. *Icarus*. 302, p. 537-559.

20. Frey H., Schultz R.A. (1988) Large impact basins and the megaimpact origin for the crustal dichotomy on Mars. *Geophys. Res. Lett*. 15(3), p. 229-232.

21. Goins N.R., Lazarewicz A.R. (1979) Martian seismicity. *Geophys. Res. Let*. 6(5), p. 368-370.

22. Goldstein R.M., Melbourne W.G., Morris G.A., et al. (1970) Preliminary radar results of Mars. *Radio. Sci*. 5(2), p. 475-478.

23. Golombek M.P., Cook R.A., Economou T., et al. (1997) Overview of the Mars Pathfinder Mission and assessment of landing site predictions. *Science*. 278(5344), p. 1734-1748.

24. Hartmann W.K. (1973) Martian Cratering. Mariner 9 initial analysis of cratering chronology. *J. of Geophysical Research: Solid Earth*. 78(20), p. 4096-4116.

25. Kerzhanovich V.V. (1977) Mars 6: improved analysis of the descent module measurements. *Icarus*. 30(1), p. 1-25.

26. Leighton R.B., Horowitz N.H., Murray B.C., et al. (1969) Mariner 6 television pictures: first report. *Science*. 165(3894), p. 684-690.

27. Morozhenko A.V., Vid'machenko A.P. (2005) Polarimetry and Physics of Solar System Bodies. Photopolarimetry in Remote Sensing, NATO Science Series II: Mathematics, Physics and Chemistry. 161, p 369-384.

28. Murchie S.L., Mustard J.F., Ehlmann B.L., et al. (2009) A synthesis of Martian aqueous mineralogy after 1 Mars year of observations from the Mars Reconnaissance Orbiter. J. Geoph. Research: Planets. 114(IssueE2). E00D06. P. 1-30.

29. Steklov A.F., Vidmachenko A.P. (2019) In What Places and What Exactly Can be the" Traces" of Life on Mars? 9th International Conf. on Mars. 2089, 6007.

30. Steklov A.F., Vidmachenko A.P. (2019) Where and What Exactly Can Be the "Traces" of Life on Mars? Mars Extant Life: What's Next? Held 5-8 November 2019, in Carlsbad, New Mexico. LPI Contribution No. 2108, 2019, id.5089.

31. Vidmachenko A.P. (1987) Manifestation of seasonal variations in the atmosphere of Saturn. *Kinematics and Physics of Celestial Bodies*. 3(6), p. 9-12.

32. Vidmachenko A.P. (2009) Water on Mars. Astron. almanac. 56, p. 225-249.

33. Vidmachenko A.P. (2012) The magnetic field of planets, satellites and asteroids. *Astronomical School's Report*. 8(2), p. 136-148.

34. Vidmachenko A.P. (2015) Influence of solar activity on seasonal variations of methane absorption in the atmosphere of Saturn. *Kinematics and Physics of Celestial Bodies*. 31 (3), 131-140.

35. Vidmachenko A.P. (2016) Is there life on Mars and where necessary to search for its traces. Astronomy and present: materials of 5 International Scientific Conference

, April 12, 2016, Vinnytsia, Ukraine. / Science ed A.V. Mozhovyi. Vinnytsia: FOP "NP Kostiuk". P. 43-48.

36. Vidmachenko A.P. (2016) Activity of processes on the visible surfaces of Solar System bodies. *Astronomical School's Report*. 12 (1), p. 14-26.

37. Vidmachenko A.P. (2016) Is there life on Mars and where necessary to search for its traces. Astronomy and present: materials of 5 International Scientific Conference , April 12, 2016, Vinnytsia, Ukraine. / Science ed A.V. Mozhovyi. Vinnytsia: FOP "NP Kostiuk". P. 43-48.

38. Vidmachenko A.P. (2016) Processes on the "young" Mars: possible developments of events. 18 International Scientific Conference Astronomical School of Young Scientists. National Aviation University, Kyiv, Ukraine, May 26-27, 2016. P. 16-17.

39. Vidmachenko A.P. (2016) Traces of life on Mars must be sought around the valley Hellas in areas where the water coming out from under the planet's surface. 18 International Scientific Conference Astronomical School of Young Scientists. Kyiv, Ukraine, May 26-27, p. 14-16.

40. Vidmachenko A.P. (2017) What forms of life could have arisen in the ancient conditions of Mars? 19 International Scientific Conference Astronomical School of Young Scientists. May 24–25 2017. Bila Tserkva, Ukraine. P. 16-17.

41. Vidmachenko A.P. (2017) Where Should Search Traces of Life, Which Could Appear on Mars in the First 300 Million Years. 4th ICo on Early Mars: Geologic, Hydrologic, and Climatic Evolution and the Implications for Life. 2014. 3005.

42. Vidmachenko A.P. (2018) Comparative features of volcanoes on Solar system bodies. 20 International Scientific Conference Astronomical School of Young Scientists. May 23–24, 2018. Uman, Ukraine, p. 9-12.

43. Vidmachenko A.P. (2018) Features of volcanic activity on various bodies of the Solar system. Materials of the International Scientific and Practical Conference The Objectives of the Sustainable Development of the Third Millennium: Challenges for Universities of Life Sciences, 5, May 23-25, Kyiv, p. 41-42.

44. Vidmachenko A.P. (2018) Water in Solar system. 20 International Scientific Conference Astronomical School of Young Scientists, May 23–24 2018, Uman, Ukraine, p. 91-93.

45. Vidmachenko A.P. (2019) Traces of Martian Life Should be Sought in Places Around Hellas Crater, Where Water has Recently Spilled Out onto the Surface. Ninth International Conference on Mars, Pasadena, California, Jul 22-25, 2019, LPI Contrib. No. 2089, 6005.

46. Vidmachenko A.P. (2023) About volcanoes on Mars. Proceedings of 11 All-Ukrainian Scientific Conference “Astronomy and present day”, April 12, 2023. Vinnytsia, Ukraine. LLC "TVORY". ISBN 978-617-552-363-6. P. 76-81.

47. Vidmachenko A.P. (2023) Comparison of features of impact and volcanic craters on the surface of Mars. Proceedings of VIII International Scientific and Practical Conference. Progressive research in the modern world (April 27-29). P. 237-246.

48. Vidmachenko A.P. (2023) History of possible climate change on Mars. Proceedings of VII International Scientific and Practical Conference. Science and innovation of modern world. (23-25 March 2023). Chapter 54. Cognum Publishing House, London, United Kingdom, p. 336-345.

49. Vidmachenko A.P. (2023) The atmosphere of Mars. Proceedings of VI International Scientific and Practical Conference. Scientific research in the modern world. (April 6-8). P. 283-293.

50. Vidmachenko A.P. (2023) Thermal properties of the surface of Mars. Proceedings of VII International Scientific and Practical Conference . Progressive research in the modern world (March 29-31, 2023). Chapter 42. P. 243-252.

51. Vidmachenko A. P. (2026) General features of the internal structure of the planet Mars. Modern Science: Research, Economy and Innovation. Collection of Scientific Papers with Proceedings of the 4 th International Scientific and Practical Conference. International Scientific Unity. January 21-23 2026. Zagreb, Croatia. P. 260-265.

52. Vidmachenko A.P., Klimenko V.M., Morozhenko A.V. (1981) Apparent spectral albedos of the disk of Mars in September-October 1977. *Solar System Research*. 14(4), p. 157-159.

53. Vidmachenko A.P., Kuznyetsova Y.G. (2025) About life in “dry rivers” of Mars. Bulletin of Taras Shevchenko National University of Kyiv. Astronomy, no. 72, p. 5-9. DOI: https://doi.org/10.17721/BTSNUA.2025.72.5-9

54. Vidmachenko A.P., Mozghovyi O.V., Steklov O.F. (2023) Historical aspects of climate changes on Mars. Proceedings of 11 All-Ukrainian SCo “Astronomy and present day”, April 12, 2023. Vinnytsia, Ukraine. LLC "TVORY". P. 56-61.

55. Vidmachenko A.P., Steklov A.F. (2022) Features of volcanic structures on Venus. Proceedings of the 9th Intern. Scientific and Practical Conference Modern directions of scientific research development. Chicago, 23-25.02.2022. P195-204.

56. Vidmachenko A.P., Steklov A.F. (2022) How long ago has water flowed on Mars surface? Results of modern scientific research and development. Proceedings of XI ISPCo. Barca Academy Publishing, Madrid, Spain. 16-18.01.2022. P. 226-232.

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2. Features of the structure of layers of the internal structure of the planet Mars

2.1. Differentiated internal structure of Mars.

The chemical composition of Mars is quite similar to all terrestrial planets [22]. However, there are a number of specific differences. For example, it is believed that the core of Mars is rich in iron and sulfur. And for them, the characteristic temperatures are 1300-1500 K. Therefore, these elements are in a liquid state in the core.

The radius of the core can be 800-1000 km and contain about 10% of the entire mass of the planet. Such a core could have formed during the first billion years [3, 4, 6]. Almost the same time was taken by the melting of silicate components in the mantle of Mars, and this should have been accompanied by intense tectonic processes and volcanic eruptions [5, 7, 9, 23]. Therefore, the substance in the mantle of Mars should have been significantly enriched in iron sulfate. Indeed, a significant amount of it was found during studies of rocks on the surface of Mars [8, 11, 13, 14].

Although it should be noted that compared to other terrestrial planets, its content is noticeably lower.

Like other terrestrial planets, Mars has a differentiated internal structure, consisting of a central core, a silicate mantle and an outer crust [27]. Understanding the structure, size and composition of these layers is key to reconstructing the geological history of the planet and comparing it with the Earth.

2.2. Seismological studies of Mars.

A significant breakthrough in the study of the interior of Mars was achieved thanks to the NASA mission “InSight”, launched in 2018 and operating until December 2022. Using its main scientific instrument, the SEIS seismometer, seismic experiments were conducted to study the internal structure of Mars. Then it was possible to “listen” to the interior of the planet by recording waves from marsquakes. That is, measurements from the InSight lander obtained the first direct seismic data on the Martian interior. The SEIS seismometer successfully detected more than 1,300 seismic

events, as well as recorded seismic waves generated by meteoroid impacts on the surface. A pair of images in Fig. 2.1, obtained one day apart using the Mars Color Imager (MARCI) meteorological camera on NASA's "Mars Reconnaissance Orbiter" (MRO) [14], show the appearance of a significant scar on the surface of Mars as a result of a collision with a meteoroid. The dark area in the right image is up to 8 km wide. Images obtained from various orbiters have already made it possible to detect more than 400 fresh impact craters on Mars. More than 50 of the same events were recorded with the InSight lander (Fig. 2.2). They provided sufficiently clear signals to pinpoint their precise location; the highest concentration of high-quality events came from the Cerberus Fossae region; this area is indicative of geologically recent volcanism [24, 25] at this location.

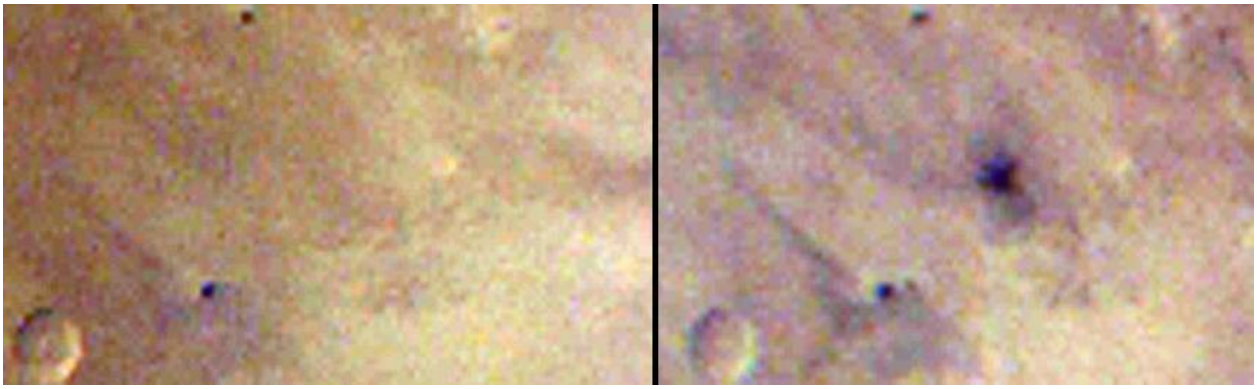


Fig. 2.1. Meteoroid impact on the surface of Mars at 3.34°N 219.38°E; left: image obtained by MRO on the morning of March 27, right: image obtained on the morning of March 28, 2012 (https://d2pn8kiwq2w21t.cloudfront.net/original_images/jpegPIA18381.jpg).

This seismometer was designed to detect P-waves and S-waves, which are crucial for mapping the structure of Mars' interior. In addition to seismology, another experiment on "InSight", the Rotation and Interior Structure Experiment (RI22SE), used the probe's radio antennas to precisely measure the subtle wobble of Mars, which is affected by the planet's interior structure. This additional data provided some constraints on the size and layered structures of Mars' interior.



Fig. 2.2. An image from the “Mars Reconnaissance Orbiter” shows craters (in blue) formed by a meteorite impact with Mars on September 5, 2021. The impact was the first to be detected by “InSight” (https://d2pn8kiwq2w21t.cloudfront.net/original_images/insight_firstimpacts.jpg).

Until the success of the “InSight” mission, detailed seismological studies of Mars were largely theoretical, with limited data from previous missions. The success of the InSight probe with its SEIS instrument, which collected over 1,300 seismic events, represents a significant advance in our knowledge of the interior of Mars. This is similar to how seismology has revolutionized our understanding of the deep interior of the Earth. The ability to directly measure the propagation of seismic waves through the crust, mantle, and core of Mars allows us to empirically determine the thickness of the layers, their density, and their state (solid or liquid). Together, this has moved the field from speculative theoretical models to direct observational data. They have greatly reduced uncertainties and provided a more robust understanding of the formation and thermal evolution [10, 12] of this planet (Fig. 2.3).

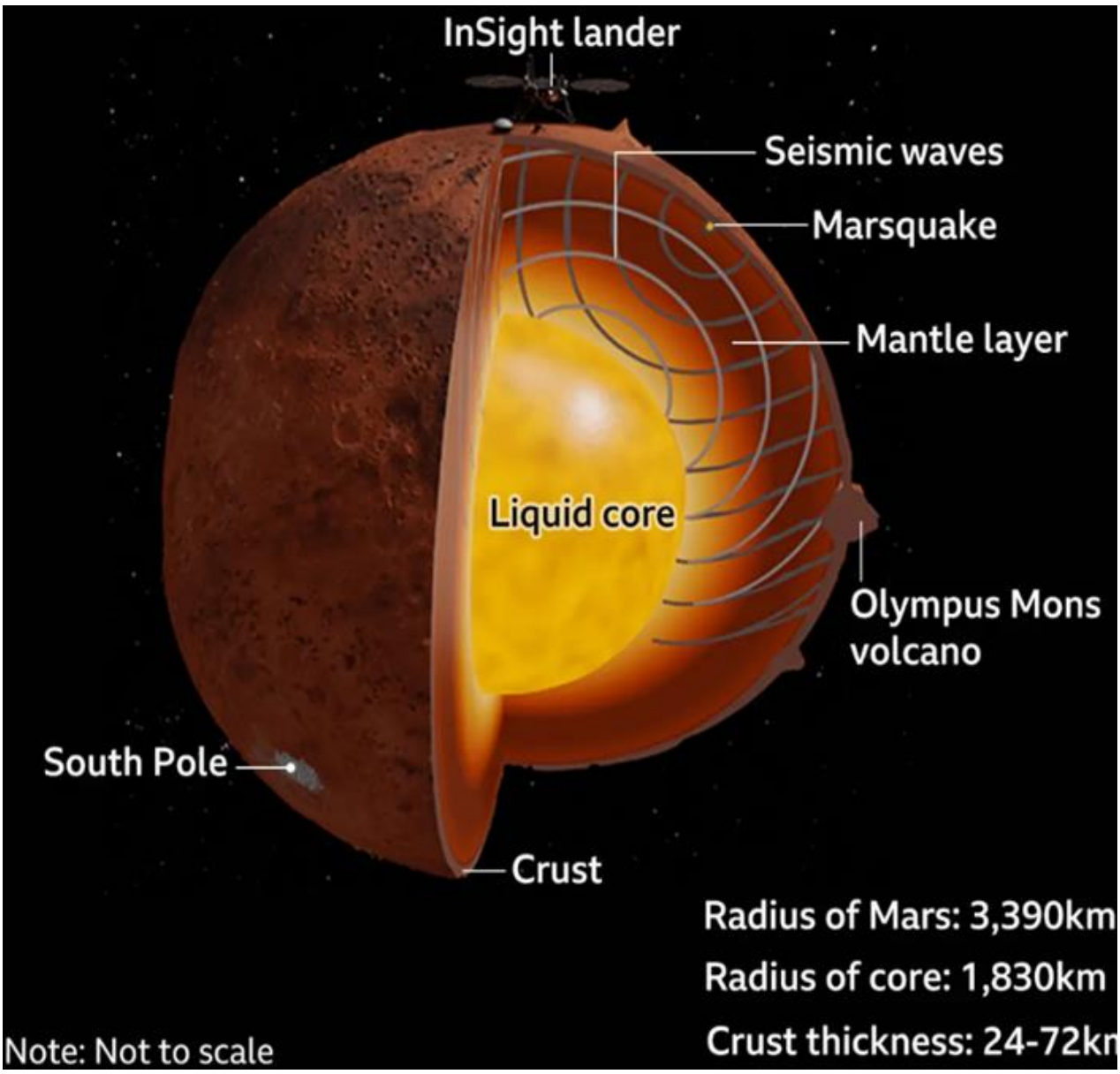


Fig. 2.3. Diagram of the internal structure of Mars (https://ichef.bbci.co.uk/news/800/cpsprodpb/9B2C/production/_119542793_mars_640-2x-nc.png.webp).

The significant impact of the innovative work of the equipment on the “InSight” spacecraft is also manifested in the fact that its work can lead to a better understanding of the internal structure of the Earth, the Moon and all rocky planetary bodies in general. The thickness of the current lithosphere of Mars can be several hundred kilometers.

The upper part of the so-called crust should be rich in iron oxide and olivine. It is believed that it is these components that give the surface of this planet a peculiar "rusty"

color. The presence of significant amounts of iron hydroxide in the upper part of the soil is an important confirmation of the processes of lowering heavier chemical elements and rocks in the directions to the core of the planet. This indicates the presence of a phenomenon in the past along the gravitational differentiation of Mars. But its duration, most likely, was greatly prolonged, and it manifests itself less noticeably than it happens on Earth.

However, changes in the degree of concentration of the planet's mass from the surface to its center are associated precisely with the processes of differentiation of their components. This characteristic is clearly reflected by the parameter, which is the value of the dimensionless moment of inertia equal to I=0.366±0.002. Its value was first determined from observational data obtained by the Mars Pathfinder space mission [1]. It independently confirmed the insignificant size of the metallic core of Mars. The crust of Mars can withstand the load of even the heaviest mountain in the Solar System, Olympus, which is close to 27 km high and has a diameter at the base of almost 1000 km; and three other huge volcanoes located nearby.

This fact independently indicates the presence of a very thick lithosphere on this planet. The combination of models of the crust, silicate mantle and core allowed us to present a global model of the internal structure of Mars. At the moment, an important parameter is the degree of correspondence of the accepted cosmogonic model with the ratio between the chemical elements Fe/Si=1.71 by mass, with respect to modern models of the internal structure of Mars.

One of the models is shown in Fig. 2.4. The presence of a cold outer layer on Mars should be considered as one of the indirect confirmations that this planet has already passed the so-called “magma ocean” stage. After all, it is during the passage of this stage that a significant decrease in the content of radioactive energy sources in the mantle occurs due to their removal due to volcanic activity to the crust. In the landing sites of numerous modules, the local structure of the upper part of the soils of Mars (i.e., the outer layers of the planet’s crust) was determined. It showed significant horizontal heterogeneity of these regions on the planet.

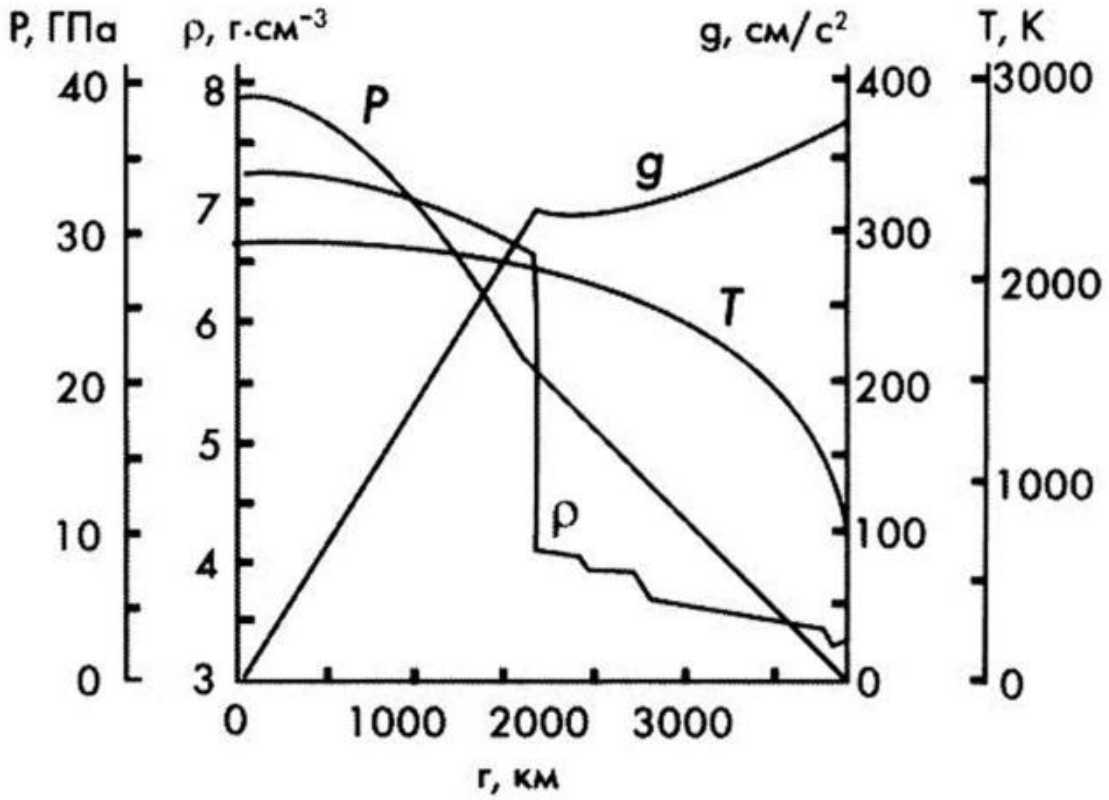


Fig. 2.4. Model of the internal structure of Mars [13].

The results of the Mars Pathfinder mission [2] have led to the conclusion that the processes that occurred on early Mars and on early Earth are significantly similar. For example, a significant proportion of materials in the Martian crust were found to be similar in silica content to the continental crust on Earth [11].

2.3. The crust.

The Martian crust is the outermost solid layer of the planet. Its composition is mostly basaltic, similar to Earth's oceanic crust and lunar seas. It is rich in silicates, oxygen, iron, magnesium, aluminum, calcium, and potassium.

The characteristic red color of the Martian surface is due to the high content of iron oxides (rust) in the upper layers of the crust and in the regolith [22]. Some studies indicate the possible presence of more evolved rocks, similar to terrestrial andesites, or to quartz glass; this may indicate more complex geological processes in the past. It is also noted that the sulfur content (in the form of sulfates) is significantly higher than in the Earth's crust.

One of the key results of the InSight mission was the refinement of the thickness of the Martian crust. It turned out that, at least at the landing site of the device, it is thinner than many previous models predicted. Thickness estimates from InSight data range from 10 km to 20 km (if there are two sublayers) or even 37 km (if there are three sublayers).

Other analyses of seismic data suggest models with an average thickness of 15–25 km (a “thin” two-layer model) to 27–47 km (a “thick” three-layer model). That is, the crust beneath the landing site consisted of three distinct inner sublayers. The upper crustal layer is estimated to be about 10 km deep, with denser, iron-rich layers extending further down to about 40 km below the surface.

These values contrast with older models that assumed an average thickness of about 50 km and a maximum of up to 130 km; although the crust at the InSight landing site may be closer to 50 km thick.

In comparison, the thickness of the Earth's crust is about 5–10 km under the oceans and 30–50 km under the continents.

The InSight data also support the hypothesis of a possible multilayer structure of the Martian crust, which may consist of two or even three distinct layers [28]. The layering may reflect different episodes of volcanic activity or different types of magma that participated in its formation.

Unlike Earth, with its moving lithospheric plates, the Martian crust is a single, relatively stationary global plate. The absence of active plate tectonics is a fundamental difference between Mars and Earth.

On Earth, plate motion continuously redistributes volcanic activity along plate boundaries. On Mars, mantle plumes (hot spots) remain stationary relative to the stationary Martian surface for long periods of time. This allows for almost continuous eruption and accumulation of huge volumes of lava in one place for hundreds of millions of years; this is what directly explains the formation of colossal shield volcanoes such as Olympus Mons.

Furthermore, the enormous weight of these concentrated volcanic loads, especially the uplift in the Tharsis region, has caused planetary stresses that have led

to the formation of radial faults and grabens. This establishes a direct causal relationship between the unique rigidity of the Martian crust and the scale and distribution of its major volcanic and tectonic features.

2.4. Mantle.

Beneath the crust lies the mantle, a thick layer composed mainly of silicate rocks rich in magnesium and iron. Seismic data indicate that the upper Martian mantle exhibits a zone of low seismic wave velocities. The mantle appears rigid down to a depth of about 250 km, implying a very thick lithosphere compared to Earth. Below this rigid zone, the mantle gradually becomes more ductile, and seismic wave velocities begin to increase again.

A notable difference from Earth's internal structure is the apparent lack of a thermally insulating layer in the Martian mantle, similar to Earth's lower mantle. Instead, below a depth of about 1050 km, the mineralogy of the Martian mantle becomes similar to that of the Earth's transition zone.

Studies from the InSight mission have probed the upper mantle to depths of about 800 km. The Martian lithosphere, which includes both the crust and the rigid upper mantle, extends about 500 km below the surface, resting on a mantle that is relatively cold compared to Earth's.

The description of the Martian mantle as "rigid" down to a depth of about 250 km (giving Mars a very thick lithosphere compared to Earth) is a critical discovery that directly confirms the planet's low level of tectonic activity. The thicker, more rigid lithosphere fundamentally hinders the energetic mantle convective flow that drives plate tectonics on Earth. This rigidity means that heat from the interior [26] is not efficiently transported to the surface by plate reworking and subduction.

Consequently, the planet cools more slowly from its deep interior, and its surface remains relatively stable, preventing the formation of large mountain ranges or dynamic fault systems typical of Earth. This highlights the direct correlation between the physical properties of the mantle and the overall geological dynamism of the planet. The mantle extends from the lower crust to the outer core, and it is the primary driver

of much of the tectonic and volcanic surface features on the planet. Estimates of the thickness of the mantle vary somewhat from 1240 to 1880 km.

Unlike Earth, which has a distinct upper and lower mantle, the Martian mantle is likely to consist of a single layer. Some evidence suggests that the mantle may be partially molten, although its tectonic and volcanic activity is much lower than that of Earth's mantle, especially in the modern era. The lack of active plate tectonics on Mars is likely due to its smaller size, which has led to more rapid cooling compared to Earth, and to the formation of a thick, rigid lithosphere (which includes the crust and upper mantle) that cannot be easily broken into moving plates.

2.5. Core.

Mars has a metallic core at its center. By analyzing the time of passage of seismic waves (Fig. 2.5), it is possible to determine the characteristics of the environment they crossed. The radius of the Martian core was found to be in the range from 1780 to 1810 km, and the density – 6.2-6.3 g/cm^3. It was the data of the "InSight" mission that allowed us to significantly refine its size and properties. Models of the structure of Mars, supplemented by the collected data, indicate that the core of Mars is extremely large relative to the size of the planet itself. According to recent estimates, its radius may be from 1630 km to 1860 km.

Even smaller than these values mean that the core radius is more than half the radius of the planet; and this is a much larger relative fraction compared to Earth, where the radius of the core (~1221 km) is only about 19% of the radius of the planet.

The core is composed primarily of iron Fe and nickel Ni, but contains a significant admixture of lighter elements, estimated at about 20% of the mass of the core. The main light element is sulfur S. Oxygen O and possibly carbon C and hydrogen H are also present. The presence of these light elements makes the core of Mars less dense than if it were composed of a pure iron-nickel alloy. The presence of these light elements lowers the melting point of the core, which helps explain why it remains molten, despite the significant cooling of the planet since its formation.

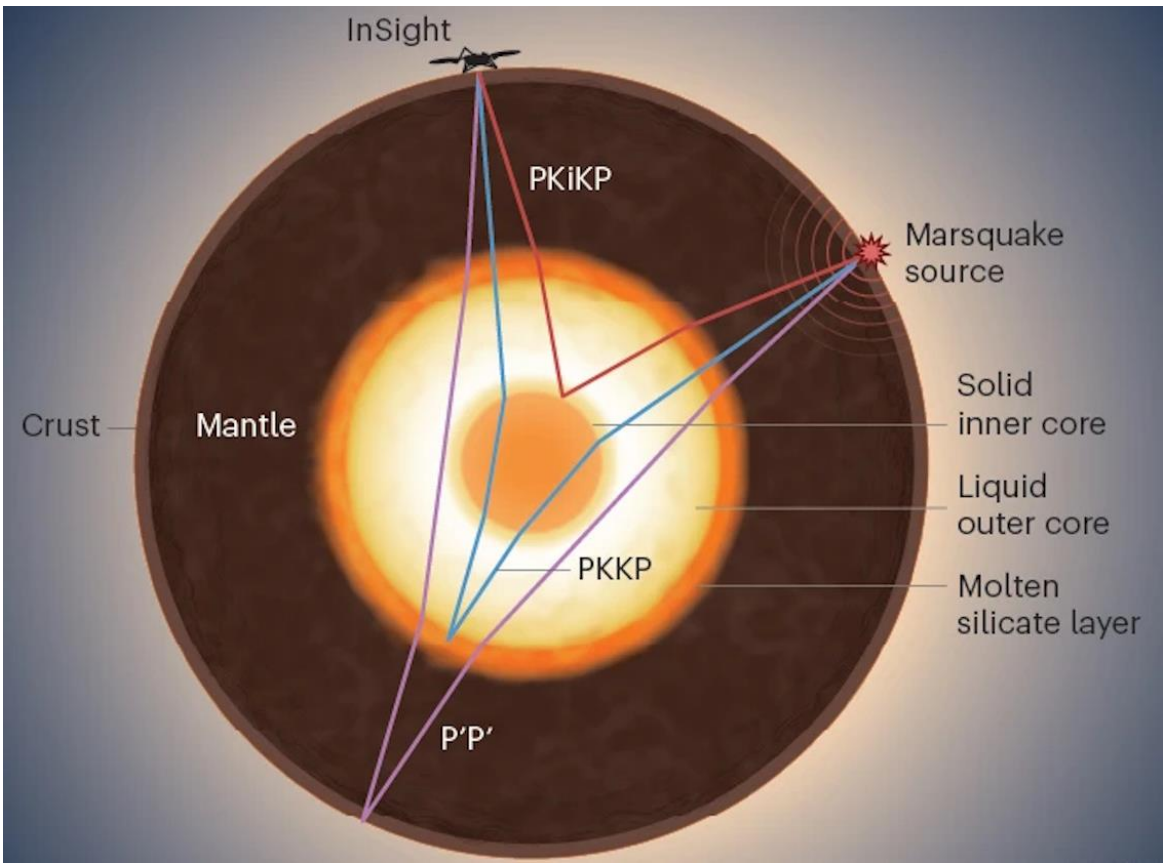


Fig. 2.5. Illustration of how the InSight lander helped detect the solid core of Mars by using seismic waves passing through the planet [4].

Seismic data from the InSight spacecraft have confirmed that at least the outer part of the core of Mars is in a liquid, molten state. The question of the existence of a solid inner core similar to Earth remains a subject of research. Some models suggest its presence, but direct seismic evidence is still lacking. An interesting discovery was the discovery of a possible layer of molten silicates about 150 km thick at the boundary between the mantle and the core. This layer may act as a thermal insulator, affecting the heat flow from the core and its evolution.

The large size of the Martian core, its liquid state, and the high content of light elements, in particular sulfur, are key factors explaining the absence of a modern global magnetic field [21]. It is known that the high sulfur content [10] lowers the melting point of iron, which may prevent the formation of a solid inner core or the efficient convection in the liquid core, which is necessary for the generation of a magnetic field by the dynamo effect. An additional factor may be the recently discovered layer of

molten silicates near the base of the mantle, which acts as a thermal insulator, inhibiting the cooling of the core and convection in it. Without strong convection, the dynamo effect that likely existed in Mars' early history (as evidenced by residual magnetic fields in the crust) has gradually faded.

The core temperature is estimated to be in the range of 2000–2400 K, which is significantly colder than the solid inner core of the Earth (5400–6230 K).

Although the InSight mission confirmed a liquid core, the possibility of a solid inner core could not be definitively ruled out on geophysical grounds. Recent laboratory experiments at high pressures and temperatures suggest that Mars may have a solid inner core composed of the iron sulfide phase ($Fe_{4+x}S_3$) if temperatures in the planet's center drop below about 1960 K; this value is within the estimated temperature range for the core. Sulfur, in particular, stands out as a likely major light element in the Martian core.

Martian quakes have helped determine the composition of the Martian core. The InSight lander has obtained new seismic data. The planet’s center is expected to contain a liquid alloy of iron and nickel. About a fifth of its mass is composed of light elements, with a predominance of sulfur; carbon, oxygen, and hydrogen are also present. Thus, 20 to 22 percent of the core’s mass may be made up of low-melting elements, mostly sulfur; this is consistent with planetary structure. Such results will help refine existing models of Mars’ formation and evolution, including the history of changing conditions on the planet [7, 15, 19]. The Martian core is therefore less dense than the core of our planet. These data will help us understand Mars’ history and why it is currently arid, with a dusty surface [3, 6, 20, 29, 30]. The composition of the Martian core and its predominantly molten state are central to a better understanding of the planet’s past magnetic field.

On Earth, convection in the liquid outer core generates a global magnetic field. Mars also once had a global magnetic field, the remnants of which are "frozen" in its crustal rocks. The loss of this magnetic field, likely due to cooling and slowing of the core dynamo activity, had catastrophic consequences for atmospheric retention and surface habitability [12, 16, 17, 18], allowing the solar wind to strip the atmosphere

and increasing thermal radiation from the surface. Further geophysical observations are needed to confirm the existence, size, and density of the Martian inner core.

The debate over the presence of a solid inner core is still ongoing, as crystallization of the inner core affects the dynamics and longevity of liquid outer core convection; and therefore the potential for a possible dynamo. This directly links the thermal and compositional evolution of the deep interior to the long-term conditions in the planet's environment and its potential to support possible life forms.

For rocky terrestrial planets, the presence of a solid inner core should significantly influence the composition and thermal evolution of their cores; the magnetic history of these planets is also affected. Geophysical observations on Mars have confirmed that the core of this planet is at least partially liquid. However, it remains unknown whether any part of the planet's core is solid. A careful analysis of seismic data obtained by the InSight mission allows us to conclude that Mars must still have a solid inner core [4]. The possibility of an inner core is indicated by the fact that observational data indicate two seismic reflection phases from the interior of the planet: a deep transit phase through the core, and a reflection phase at a certain boundary of the inner core.

Such inversions allow us to limit the radius of the inner core of Mars to approximately 613 ± 67 km with a jump in the compression rate at the boundary of the inner core of almost 30%. This fact can be supported by additional seismic phases that should be associated with the inner core.

These properties imply a concentration of various light elements in the inner core, which must be separated from the outer core by the crystallization of certain parts of the core. This discovery provided a starting point for a more complete understanding of the thermal conditions and chemical state in the interior of Mars. In addition, the connection between the processes of formation of the inner core and the evolution of changes in the magnetic field for Mars can provide insight into the generation of dynamos on such planetary bodies.

2.6. Lithosphere and its features.

Like Earth, Mars has a lithosphere, which is a rigid outer layer that includes both

the crust and the upper part of the mantle (Table 2.1). A distinctive feature of Mars is its exceptionally thick lithosphere, which extends approximately 500 km below the surface. This rigidity contrasts sharply with the more fragmented and dynamically active lithosphere of Earth. And this thickness also contributes to the much lower seismic activity of Mars compared to Earth. That is, the very thick lithosphere, compared to Earth, is a direct consequence of Mars' smaller size and its faster cooling compared to our planet. The thick, rigid lithosphere means that the mantle plumes, which are thought to be the source of Martian volcanism, are less likely to cause large-scale crustal deformation, or to erupt in numerous, distributed locations.

Table 2.1.

The internal structure of Mars: parameters and composition.

Layer	Thickness/Radius	Main composition	Physical state: Key characteristics
Crust	25-40 km (under InSight), average 42-56 km, maximum 117 km	Silicon, oxygen, iron, magnesium, aluminum, calcium, potassium; tholeiitic basalt	Three sublayers, single rigid plate (no plate tectonics)
Mantle	Extends from crust to 1560 km depth (total thickness ~1500 km)	Silicates	Rigid upper mantle (~250 km), ductile lower mantle, relatively cold compared to Earth
Core	Radius ~1830 km (larger than expected)	Iron, nickel, enriched with light elements (sulfur, oxygen, carbon, hydrogen)	Completely molten; less dense than expected; possibility of solid inner core (Fe4+xS3) under certain temperature conditions

Instead, this rigid shell provides a stable, long-lasting conduit for repeated eruptions of magma at the same location on the surface. This explains the formation of the huge, single-source shield volcanoes seen in regions such as Tharsis, because volcanic material accumulates over geological timescales without being dispersed by plate motion. This structural feature of the lithosphere is a key factor in the unique scale and morphology of Martian volcanic features.

2.7. Comparing the internal structure of Mars and Earth.

A comparison of the internal structure of Mars and Earth (Table 2.2) reveals both similarities and significant differences, reflecting their different masses, sizes, and evolutionary paths.

Similarities: Both planets have a differentiated structure: a metallic core, a silicate mantle, and an outer crust; the cores of both planets are predominantly iron; the mantles are composed of silicate rocks.

Table 2.2.

Comparison of the internal structure of Mars and Earth.

Layer	Parameter	Mars	Earth
Crust	Average thickness (km)	10-72 (variable, possibly multilayered)	~5-10 (oceanic),
	Major composition	Basalts, silicates (Fe, Mg, Al, Ca, K), iron oxides, sulfates	~30-50 (continental)
	Structure	Single slab, possibly 2-3 layers	Basalts (ocean), granites /silicates (continent)
Mantle	Thickness (km)	~(1240 – 1880)	Moving tectonic plates
	Major composition	Silicates (Mg, Fe)	~2900
	Structure	Probably single layer, partially molten (?)	Silicates (Mg, Fe)
Core	Radius (km)	~(1630 – 1860)	Upper and lower mantle, convection
	% of planet radius	~(48 – 55)%	~3485 (total),
	Major composition	Fe, Ni, ~20% light elements (mostly S, also O, C?, H?)	~1221 (internal)
	Physical state	Liquid exterior, solid interior (?), possible molten silicate layer at core-mantle boundary	~55% (total),

Differences: the core of Mars occupies a much larger fraction of the planet's volume (>50% of the radius) than the core of Earth (~19% of the radius); the core of Mars contains significantly more light elements ~(20÷22)%, mainly sulfur, compared to the core of Earth; the core of Mars is mostly liquid, the existence of a solid inner core is questionable; a molten silicate layer is possible at the core-mantle boundary; Earth has a well-defined solid inner core and a liquid outer core; the mantle of Mars is probably single-layered, while Earth's has an upper and lower mantle.

The crust of Mars is a single plate, while Earth's is broken into moving tectonic plates. The thickness of the crust of Mars is variable and may be thicker on average than Earth's continental crust, although recent data indicate a slightly thinner crust in some regions. Plate tectonics is active on Earth, but practically absent on Mars. Earth has a strong global magnetic field generated by the dynamo effect in the core. Mars today has no global field, only local residual magnetic anomalies in the crust. This Table 3 summarizes the key differences in internal structure that explain the different geological activity and evolution of Mars and Earth.

References:

1. Adams J.B., Filice A.L. (1967) Spectral reflectance 0.4 to 2.0 microns of silicate rock powders. *J. Geophys. Res*. 72(22), p. 5705-5715.

2. Atreya S.K., Gu Z.G. (1994) Stability of the Martian atmosphere: is heterogeneous catalysis essential? *J. Geophys. Res*. 99(E6), p. 13133–13145.

3. Bertka C.M., Fei Y. (1998) A profile of Martian mineralogy and density up to core-mantle boundary. LPSC. V. 27. P. 107-108.

4. Bi H., Sun D., Sun N., et al. (2025) Seismic detection of a 600-km solid inner core in Mars. *Nature*. 645, p. 67–72.

5. Bibring J.-P., Langevin Y., MustardJohn Y. F., et al (2006) Global mineralogical and aqueous mars history derived from OMEGA/Mars express data. *Science*. 312, p. 400-404.

6. Broquet A., Andrews-Hanna J.C. (2023) Geophysical evidence for an active mantle plume underneath Elysium Planitia on Mars. Nature Astronomy. 7, p. 160–169.

7. Carr M.H. (1999) Retention of an atmosphere on early Mars. *Journal of Geophysical Research: Planets*. 104(E9), p. 21897-21909.

8. Churyumov K.I., Steklov A.F., Vidmachenko A.P., Dashkiev G.N. (2016) Several twilight bolides over Kiev in 2013-2015 - fragments of comets nuclei. International conference Meteoroids 2016, at the European Space Research and Technology Centre (ESTEC), Noordwijk, the Netherlands. 6-10 June 2016. Poster 63.

9. Clinton J.F. (2017) Preparing for InSight: An Invitation to Participate in a Blind Test for Martian Seismicity. Seismological Research Letters. 88(5), p. 1290-1302.

10. Connerney J.E.P., Acuńa M.H., Wasilewski P., et al. (1999) Magntic Lineations in the ancient crust of Mars. *Science*. 284(5415), p. 794-798.

11. de Beule C., Wurm G., Kelling T., et al. (2015) An insolation activated dust layer on Mars. *Icarus*. 260, p. 23-28.

12. Fonseca R.M., Zorzano-Mier M.-P., Martín-Torres J. (2018) Planetary boundary layer and circulation dynamics at Gale Crater, Mars. *Icarus*. 302, p. 537-559.

13. Goins N.R., Lazarewicz A.R. (1979) Martian seismicity. *Geophys. Res. Let*. 6(5), p. 368-370.

14. Golombek M.P., Cook R.A., Economou T., et al. (1997) Overview of the Mars Pathfinder Mission and assessment of landing site predictions. Science. 278(5344), p. 1734-1748.

15. Morozhenko A.V., Vid'machenko A.P. (2005) Polarimetry and Physics of Solar System Bodies. Photopolarimetry in Remote Sensing, NATO Science Series II: Mathematics, Physics and Chemistry. 161, p 369-384.

16. Morozhenko A.V., Vidmachenko A.P. (2020) Dust can affect on the mastering of Mars. 22 International scientific conference Astronomical School of Young Scientists. December 11-12, 2020. Kyiv, Ukraine. P. 71-73.

17. Morozhenko A.V., Vidmachenko A.P., Kostogryz N.M. (2015) Spectrophotometric properties of Moon's and Mars's surfaces exploration by shadow mechanism. *Highlights of Astronomy*. 6, p. 182-182.

18. Murchie S.L., Mustard J.F., Ehlmann B.L., et al. (2009) A synthesis of Martian aqueous mineralogy after 1 Mars year of observations from the Mars Reconnaissance Orbiter. *J. Geophysical Research: Planets*. 114(E2). E00D06. P. 1-30.

19. Sexton M.R., Elwood Madden M.E., Swindle A.L., et al. (2017) Considering the formation of hematite spherules on Mars by freezing aqueous hematite nanoparticle suspensions. *Icarus*. 286, p. 202-211.

20. Vidmachenko A.P. (2009) Research of the Mars by space vehicles. 11 International scientific conference Astronomical School of Young Scientists. May 26-29, 2009. Kherson, Ukraine, p. 11-12.

21. Vidmachenko A.P. (2012) The magnetic field of planets, satellites and asteroids. *Astronomical School's Report*. 8(2), p. 136-148.

22. Vidmachenko A.P. (2014) Study of Earth-like planets. 16 International Scientific Conference Astronomical School of Young Scientists. Kirovohrad, Ukraine. May 29–31, 2014. P. 12-13.

23. Vidmachenko A.P. (2023) About volcanoes on Mars. Proceedings of 11 All-Ukrainian Scientific Conference “Astronomy and present day”, April 12, 2023. Vinnytsia, Ukraine. LLC "TVORY". ISBN 978-617-552-363-6. P. 76-81.

24. Vidmachenko A.P. (2023) Comparison of features of impact and volcanic craters on the surface of Mars. Proceedings of VIII International Scientific and Practical Conference. Progressive research in the modern world (April 27-29). P. 237-246.

25. Vidmachenko A.P. (2023) History of possible climate change on Mars. Proceedings of VII International Scientific and Practical Conference. Science and innovation of modern world. (23-25 March 2023). Chapter 54. Cognum Publishing House, London, United Kingdom, p. 336-345.

26. Vidmachenko A.P. (2023) Thermal properties of the surface of Mars. Proceedings of VII International Scientific and Practical Conference . Progressive research in the modern world (March 29-31, 2023). Chapter 42. P. 243-252.

27. Vidmachenko A. P. (2026) General features of the internal structure of the planet Mars. Modern Science: Research, Economy and Innovation. Collection of

Scientific Papers with Proceedings of the 4th International Scientific and Practical Conference. International Scientific Unity. January 21-23, 2026. Zagreb, Croatia. P. 260-265.

28. Vidmachenko A. P. (2026) General features of the internal structure of the planet Mars. 2. Collection of Scientific Papers with the Proceedings of the 7th International Scientific and Practical Conference «Global Directions in Scientific Research and Technological Development» (February 9-11, 2026, Valencia, Spain). European Open Science Space. P. 174-183.

29. Vidmachenko A.P., Klimenko V.M., Morozhenko A.V. (1981) Apparent spectral albedos of the disk of Mars in September-October 1977. *Solar System Research*. 14(4), p. 157-159.

30. Vidmachenko A.P., Mozghovyi O.V., Steklov O.F. (2023) Historical aspects of climate changes on Mars. Proceedings of 11 All-Ukrainian SCo “Astronomy and present day”, April 12, 2023. Vinnytsia, Ukraine. LLC "TVORY". P. 56-61.

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3. The evolution of the atmosphere of the planet Mars and its seasonal changes.

Introduction.

The atmosphere of Mars has long been a unique object of comparative planetology, the study of which is of critical importance for understanding the evolutionary paths of terrestrial planets [45]. The modern atmosphere of Mars is characterized by an extremely low density and a specific chemical composition, which makes it fundamentally different from the Earth's. It is a dynamic system where the gravitational field of the planet, the absence of global magnetic protection and the significant intensity of the solar wind determine the limits of its stability. In the modern geological era (Amazonian period), the Martian atmosphere is an extremely rarefied gas envelope, consisting mainly of carbon dioxide (CO_2 ≈ 95.32%) with an average surface pressure of about 6.1 mbar (0.61 kPa). Despite such a high relative concentration, the absolute mass in the atmospheric column is insignificant due to the low pressure.

Other significant components are nitrogen (N_2), the share of which is up to 2.7%, and argon (Ar) – up to 1.94%. The oxygen (O_2) content in the atmosphere of Mars is very low, only up to 0.16%. And this makes it completely unsuitable for breathing by terrestrial organisms. Carbon monoxide (CO) is also present at a concentration of 0.06-0.08%. Water vapor (H_2O) is a variable component; its content usually does not exceed 0.03-0.2%, but it plays an important role in the formation of clouds and frost. Among other microcomponents, neon (Ne), krypton (Kr), xenon (Xe), nitric oxide (NO), ozone (O_3) and other gases in trace amounts have been found.

Compared to Earth (Table 3.1), the composition of the Martian atmosphere is radically different. The Earth's atmosphere consists mainly of nitrogen (~78%) and oxygen (~21%). Although the absolute amount of CO_2 in the Martian atmosphere is small due to its overall rarefaction (Fig. 3.1, 3.2), the relative concentration of carbon dioxide on Mars is about 23 times higher than in the Earth's atmosphere. The current composition of the Martian atmosphere is the result of a long evolution that includes

the loss of lighter gases and water into space due to the weak gravitational field and the absence of a global magnetic field [1, 14] to protect against the solar wind, as well as chemical reactions with surface rocks [51], including the oxidation of iron.

Table 3.1.

Comparison of the composition of the atmospheres of Mars and Earth [29].

Component	**Mars (%)**	**Earth (%)**
Carbon Dioxide (CO_2)	95.1 - 96.0	~0.04
Nitrogen (N_2)	2.6 - 2.7	~78.08
Argon (Ar)	1.6 - 1.94	~0.93
Oxygen (O_2)	0.13 - 0.16	~20.95
Carbon monoxide (CO)	0.06 - 0.08	Traces
Water vapor (H_2O)	< 0.2 (variable)	< 4 (variable)
Mean surface pressure	~6.36 mbar	~1013 mbar
Temperature range	from -153°C to +30°C	from 89°C to +58°C
Altitude scale	~11.1 km	~8.5 km
Acceleration of gravity	3.71 m/s²	9.81 m/s²

Below is a detailed comparison of the parameters of the atmospheres of Mars and Earth, demonstrating the fundamental difference in their ability to support life and the thermodynamic stability of water. The data presented in Table 3.1 highlight the fundamental differences between the atmospheres of Mars and Earth, which have a decisive impact on their climatic conditions and potential suitability for life [6, 8].

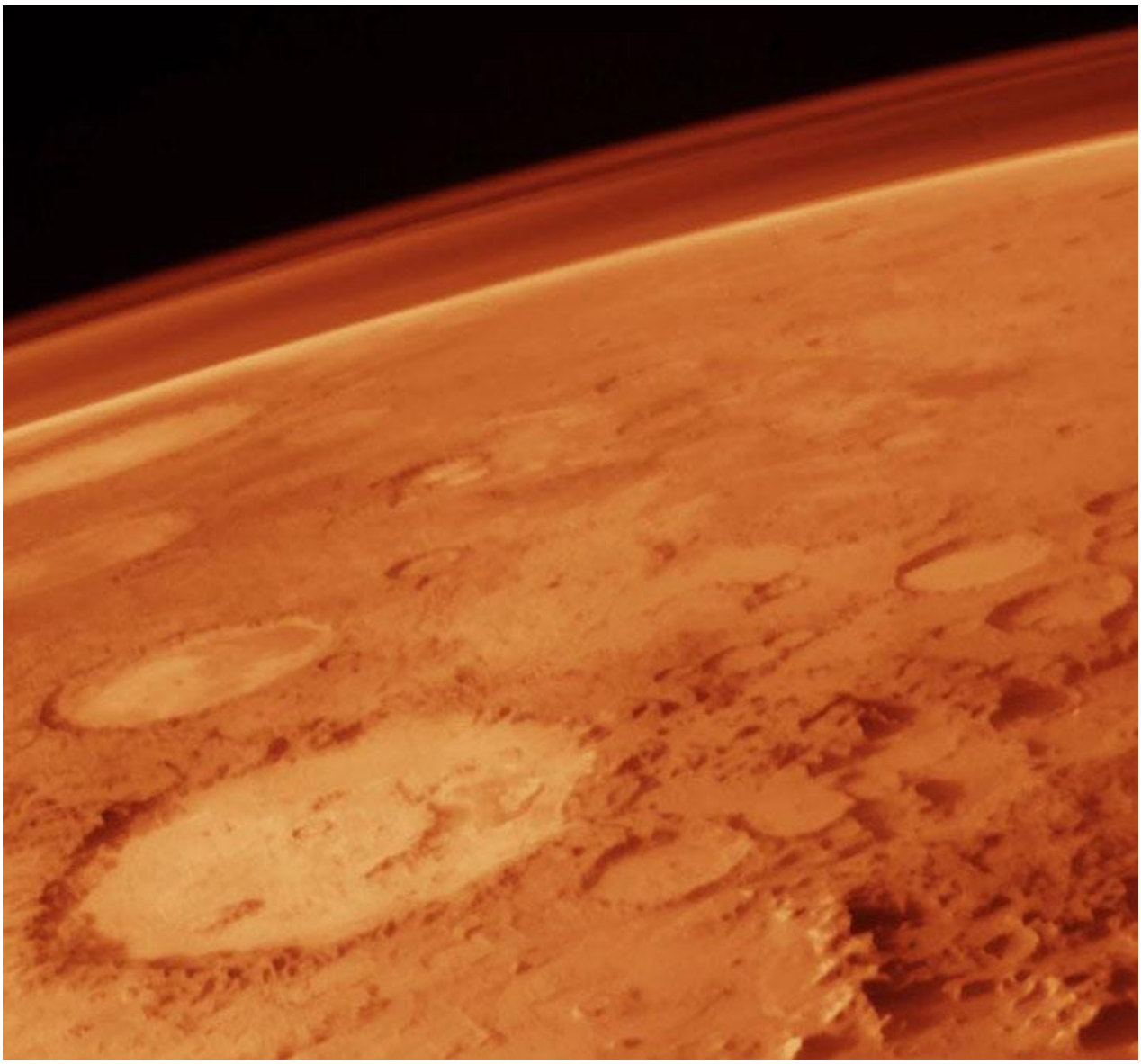


Fig. 3.1. A picture from the Viking orbiter shows the thin atmosphere on Mars over the Argyre region (http://photojournal.jpl.nasa.gov/)

Structurally, the atmosphere of Mars [2] is a very thin shell with an average characteristic height scale of about 11.1 km. However, in model calculations, the atmosphere of Mars is often divided into two main layers: the lower atmosphere (up to about 7 km), where the temperature decreases linearly and quite rapidly with height, and the upper atmosphere (above 7 km), where the temperature also decreases linearly, but with a smaller gradient.

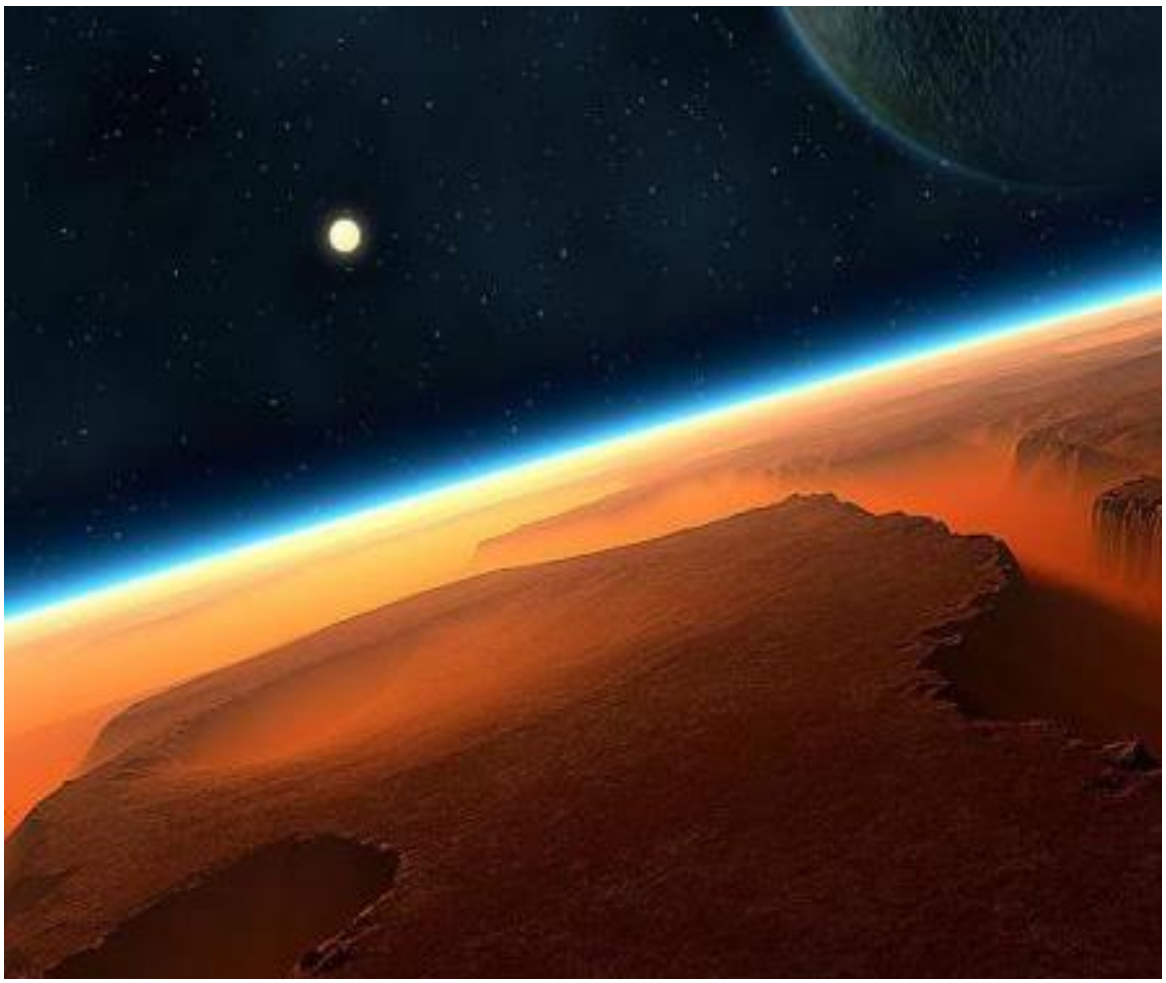


Fig. 3.2. Appearance of the thin atmosphere above the surface of Mars (https://vsviti.com.ua/wp-content/uploads/2016/12/mars_009.jpg).

In the Martian atmosphere, clouds are observed that consist mainly of water ice crystals, and sometimes of dry ice (CO_2). The atmosphere also constantly contains small dust particles that rise from the surface by the wind. On 02.05.2025, NASA's "Mars Odyssey" orbiter received an image of the top of the Martian volcano Arsia Mons, located above a greenish haze of water ice clouds (Fig. 3.3). At the same time, it was possible to record how the clouds rise along the slopes of the volcano, cool and condense. Formations of a condensation nature that periodically appear in the atmosphere of Mars are mainly represented by white clouds and fogs (Fig. 3.4). While the former were discovered during telescopic observations, the latter were discovered thanks to data from spacecraft. High-altitude aerosol formations (at altitudes above 20 km) in the atmosphere mainly arise from the condensation of CO_2. The same process is responsible for the formation of near-surface fogs in the polar regions.

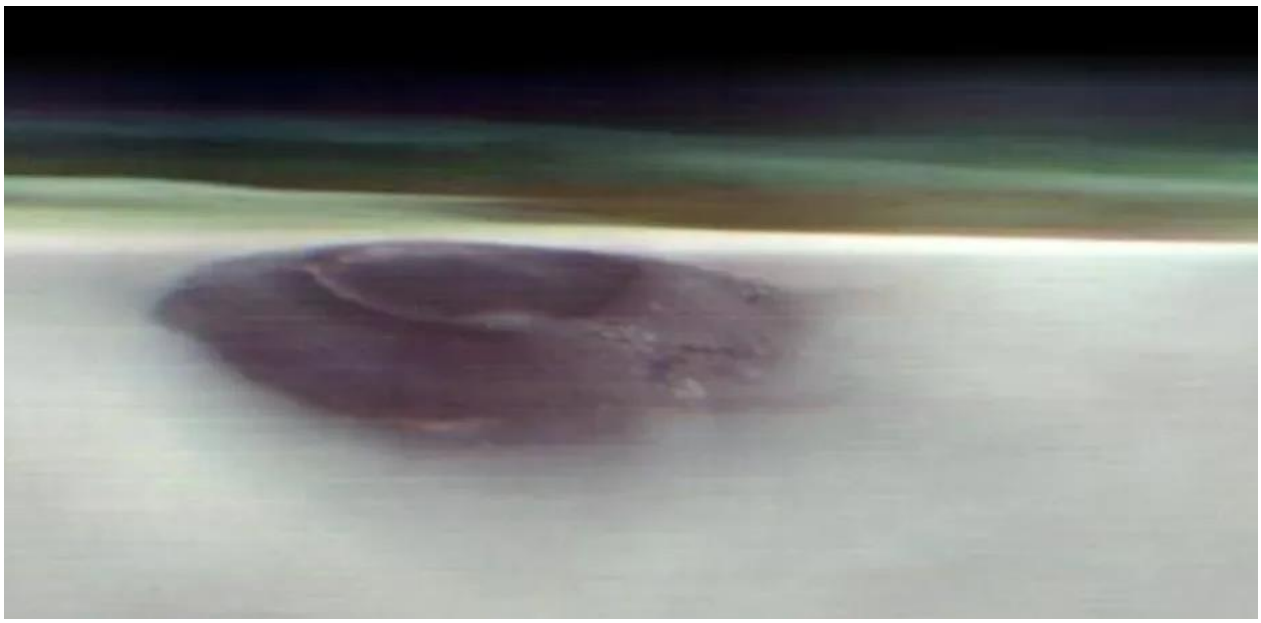


Fig. 3.3. Image of the summit of the Martian volcano Arsia Mons, visible through a haze of water ice clouds (https://cikavosti.com/wp-content/uploads/2025/06/hqz99coo2taj66tmefdb4u-970-80.jpg.webp).

Most often, clouds and fogs form near the polar caps in the winter, when the temperature in the atmosphere drops below the freezing point of carbon dioxide CO_2 (147 K). Clouds beyond the Arctic Circle are usually located quite low above the surface, at altitudes of less than 10 km. And these clouds are quite thin formations of ice CO_2 in winter and H_2O in summer. Infrared spectra of white clouds at mid- and low-latitudes obtained by many spacecrafts have confirmed the fact that white cloud formations consist mainly of water ice crystals. As a rule, such water clouds form above the Martian surface at altitudes of about 20 km. And these clouds are quite thin formations of CO_2 ice in winter and H_2O in summer. Infrared spectra of white clouds at mid- and low-latitudes obtained by many spacecrafts have confirmed the fact that white cloud formations consist mainly of water ice crystals. As a rule, such water clouds form above the Martian surface at altitudes of about 20 km.



Fig. 3.4. Image of dense ground fog in the western part of Valles Marineris, obtained by the «Mars Express» spacecraft on 25.05.2004 (https://cdn.theatlantic.com/media/mt/science/assets_c/2013/07/Marineris%20fog-thumb-570x738-127871.jpg).

In the morning, fog thickens in the valleys (Fig. 3.4). Then winds can lift cooled air masses to the plateau, and white clouds could appear over the high mountains (Fig. 3.3). In winter, the polar cap in the north is also enveloped by a curtain of dust and ice

fog. Similar phenomena, but on a somewhat smaller scale, are observed around the southern polar cap.

Both polar caps change their size in accordance with the changes of the seasons. It is also noted that many such clouds are formed when air masses rise along the windward slopes of large landforms. However, it should be noted that there are very few suitable components for cloud formation in the atmosphere. After all, even if all the moisture were deposited on the surface, it would cover it with a layer less than 0.01 mm. In the cold time of day, fogs often form over some lowlands, as well as at the bottoms of craters.

Such fog most often consists of water ice particles. The Arsia Mons volcano is located in the south of the Tharsis Montes ridge (Fig. 3.5), which consists of three volcanoes; the largest volcano in the Solar System [21 , 22, 50] – Olympus Mons – is located in the same figure at the top left.

However, extensive geological, mineralogical, geomorphological, and geochemical evidence obtained by orbiters and landers over the past decades clearly indicates that Mars had a much denser and warmer atmosphere during the early Noician period (more than 3.7–4.1 billion years ago) [48]. This primordial atmosphere provided a powerful greenhouse effect that supported the stable existence of liquid water on the surface in the form of large-scale river networks, lake basins, and probably a significant northern oceanic reservoir.

Most often, clouds and fogs form near the polar caps in winter, when the temperature in the atmosphere drops below the freezing point of carbon dioxide CO_2 (147 K). Clouds beyond the Arctic Circle are usually located quite low above the surface, at altitudes of less than 10 km. Understanding how the thin, cold, and highly rarefied atmosphere of modern Mars may be related to its internal structure and volcanic past is key to reconstructing the history of water and the potential habitability of this planet. Current data from orbiters and surface missions such as «MAVEN» , InSight, Curiosity, and Perseverance are providing a comprehensive picture of the interactions between the planet's interior and its gaseous envelope.

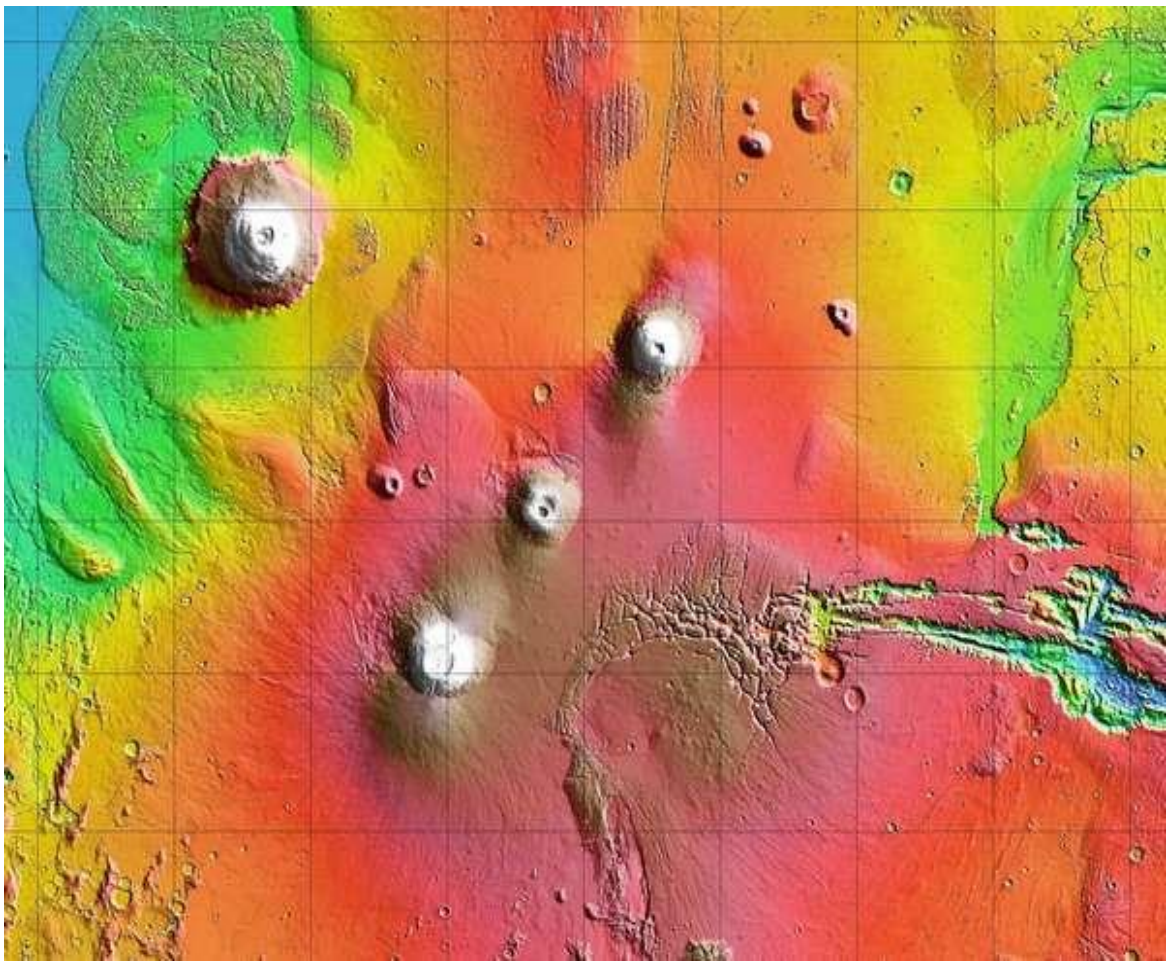


Fig. 3.5. Arsia Mons is the southernmost of the three volcanoes that make up the Tharsis Montes volcanic region. The largest volcano in the Solar System, Olympus Mons, is at the top left (https://cikavosti.com/wp-content/uploads/2025/06/600-443-20-06-25-01.jpg).

After all, the atmosphere of Mars is one of the key factors that determine its modern climatic conditions [26, 32] and distinguish them from the Earth. It has an extremely thin gas envelope, which differs significantly in composition, pressure and structure from the Earth's atmosphere. Below we will consider the structure and dynamics of the very thin atmosphere of Mars, as well as the climatic conditions on its surface and the rather extreme temperature changes on the surface of Mars. The atmospheric system acts as a central thermodynamic and photochemical buffer between the main reservoirs of volatile substances of the planet – the Martian regolith, polar ice caps, lithospheric horizons and the exosphere. The study of the historical evolution of atmospheric pressure, isotopic fractionation of key elements (H, C, N, O,

Ar) and dissipation processes (loss of gases into interplanetary space) allows us to reconstruct the catastrophic transition of Mars from a potentially habitable, warm and humid world [48, 49, 53] to the present-day desert with high radiation. The current state of the Martian atmosphere is characterized by intense seasonal and diurnal dynamics caused by the pronounced eccentricity of the planet's orbit ($e = 0.0934$) and the significant inclination of its axis of rotation ($\varepsilon = 25.19°$). The annual freezing condensation and subsequent sublimation of up to 25–30% of all atmospheric carbon dioxide CO_2 at the polar caps causes large-scale global fluctuations in atmospheric pressure, generates powerful seasonal and regional dust storms, and determines the composition and vertical distribution of microcomponents such as water vapor (H_2O) and carbon monoxide (CO). The involvement of the latest space missions and the James Webb Space Telescope (JWST) reveals new details of the photochemical cycles, isotopic composition, and fundamental dynamics of atmospheric processes on the Red Planet.

3.1. Observational data on the atmosphere obtained by recent space missions and the James Webb Telescope.

The study of the Martian atmosphere is currently experiencing a qualitative leap due to the combination of studies using ground-based observatories, orbiting spacecraft, surface rovers, and the James Webb Space Telescope (JWST). The JWST's location at the L2 Lagrangian point of the Sun-Earth system (about 1.5 million km from Earth) provides the telescope with a unique observation geometry: the ability to simultaneously view the entire illuminated disk of Mars. This allows for continuous monitoring of short-term global and regional atmospheric phenomena, such as transitions between the dawn and sunset zones, diurnal moisture dynamics, the formation of synoptic cloud systems over the volcanic provinces of Tharsis and Elysium, and the rapid sublimation of polar ice.

Infrared observations of Mars using JWST are accompanied by significant technical difficulties due to the extreme brightness of the planet in the near and mid-infrared ranges, which threatens rapid saturation of highly sensitive detectors. To

overcome this effect, specialized techniques have been developed, which include the use of massive detector readout modes, the use of highly selective narrowband filters, and strict adherence to the speed limit of tracking the object's movement.

The first observations of Mars within the Cycle 1 Guaranteed Time Observation (GTO 1415) program were carried out on September 5, 2022, using the NIRCam and NIRSpec instruments:

The NIRCam (Near-Infrared Camera) instrument photographed the eastern hemisphere of the planet in two key spectral ranges. The short-wave infrared filter F212 (2.1 μm) recorded mainly reflected solar radiation, capturing details of the surface albedo, topographic structures (the ringed ridges of Huygens crater, the dark volcanic basalts of the Syrtis Major plateau), and high-altitude dust aerosols. The long-wavelength filter F430M (4.3 μm) recorded the planet's own thermal radiation. At this wavelength, the brightness temperature depends on the physical surface temperature and the absorption capacity of carbon dioxide. The F430M images show a pronounced darkening of the giant Hellas impact basin (over 2000 km in diameter and about 7 km deep), which is explained by the intense absorption of thermal radiation by the thicker layer of atmospheric CO_2 in this deep topographic depression. In addition, NIRCam provided mapping of non-equilibrium fluorescence of carbon dioxide at altitudes in the upper atmosphere. The NIRSpec (Near-Infrared Spectrograph) instrument provided highly detailed spectra with high resolution (≈ 2700) in the range of 0.7–5.2 μm with a spatial resolution of about 100 km at the equator. Spectral analysis revealed clear absorption lines of CO_2, CO, H_2O, deuterated water vapor (HDO), as well as bands of mineral dust and water-ice clouds. The high sensitivity of NIRSpec allowed mapping the deuterium to hydrogen (D/H) ratio, recording the nocturnal glow of molecular oxygen (O_2 at a wavelength of 1.3 microns), and searching for small photochemical components such as methane (CH_4) and hydrogen chloride (HCl).

In parallel with the JWST telescope, the latest research base is formed by a complex of direct and orbital studies (Table 3.2).

Table 3.2.

Characteristics of measurements of atmospheric parameters of Mars.

Space Mission / Instrument	**Orbital/Surface Status**	**Main spectral and physical ranges**	**Measured atmospheric parameters and key results**
JWST / NIRCam	L2 Lagrange Point (1.5 million km)	0.6–5.0 μm (narrowband filters F212, F430M)	Mapping of the disk thermal radiation, CO_2 absorption in the Hellas basin, non-LTE CO_2 emission
JWST / NIRSpec	L2 Lagrange Point (1.5 million km)	0.7–5.2 μm ($\lambda/\delta\lambda \sim 2700$)	High-resolution infrared spectroscopy: CO_2, CO, H_2O, HDO lines, O_2 nightglow (1.3 μm), search for CH_4, HCl
«MAVEN» / NGIMS	Elliptical Martian Orbit	Mass spectrometry of neutrals and ions (1–300 a.u.m.)	Structure of the thermosphere and exobase (120–200 km), $^{38}Ar/^{36}Ar$, $N_2/^{40}Ar$ profiles, sputtering rate
«ExoMars» TGO / ACS, NOMAD	Low Circular Orbit (400 km)	Infrared shadow spectroscopy (0.7–17 μm)	Precision vertical profiles of trace gases, establishment of an upper limit of $CH_4 < 0.05$ ppb, discovery of HCl, CO isotopes
«Curiosity» / SAM (TLS, QMS, GCMS)	Surface, Gale Crater (4.5°)	Mass spectrometry, laser absorption, gas chromatography	Precise chemical composition of the lower atmosphere, daily and seasonal trends of CH4, isotope ratios $\delta^{13}C$, $\delta^{18}O$, δD

The «MAVEN» orbiter (NASA) uses the Neutral Gas and Ion Mass Spectrometer (NGIMS) and other instruments to regularly measure the state of the upper atmosphere, ionosphere, and exosphere at altitudes from 120 to 200 km. «MAVEN» directly measured the altitude profiles of the isotopic fractionation of noble gases ($^{38}Ar/^{36}Ar$), nitrogen and carbon, and calculated the current rates of ion sputtering and photochemical leakage.

The ExoMars Trace Gas Orbiter (TGO, ESA) uses the ACS (Atmospheric Chemistry Suite) and NOMAD spectrometers to probe the atmosphere with a vertical resolution of several hundred meters during observations of solar and stellar eclipses. TGO measured vertical profiles of H_2O, HDO, CO, HCl and set the most stringent upper limits for the methane content in the atmosphere [4].

The Mars rover Curiosity (MSL, NASA), equipped with the SAM (Sample Analysis at Mars) instrument suite, is conducting long-term measurements of the chemical and isotopic composition of the atmosphere in Gale Crater, including the QMS mass spectrometer and the TLS tunable laser spectrometer.

The Mars rover Perseverance (Mars 2020, NASA), equipped with the SHERLOC (Raman scattering and fluorescence spectroscopy) and SuperCam instruments, is analyzing the composition of minerals and organic molecules in Jezero Crater, providing important data on the interaction of the atmosphere with the surface in antiquity.

3.2. Atmospheric pressure and its variations.

One of the key characteristics of the Martian atmosphere is its extremely low pressure. The current atmospheric pressure on the Martian surface varies considerably depending on topography, from only about 30 Pa at the summit of Mount Olympus (Fig. 3.6) to over 1155 Pa in the deepest basins, such as the Hellas Plain. The average pressure on the planet's surface is only about 6.36 mbar. or 636 pascals (Pa). This is less than 1% of the average atmospheric pressure at sea level on Earth (about 1013 mbar). This low pressure has important consequences. In particular, it is very close to the pressure of the triple point of water (about 6.1 mbar) [3]. This indicates that liquid

water cannot stably exist on most of the surface of Mars under present-day conditions.



Fig. 3.6. Around the Olympus volcano, the boundaries of the crustal substance ejected by a kind of "piston" from the middle of Mars are clearly visible (http://photojournal.jpl.nasa.gov/)

At temperatures below 0°C, water exists in the form of ice [5, 13, 25], and at temperatures above 0°C, it quickly boils and evaporates on the surface of Mars, that is, it sublimates from ice due to the low pressure. This feature is a fundamental limitation for the possibility of the existence of terrestrial-type life forms on the modern surface of Mars [24]. Although short-term flows of very salty water, which has a much lower freezing point and a higher boiling point, are still possible under certain conditions on the surface of Mars [9, 17, 18, 19, 20]. Atmospheric pressure on Mars is not constant. It undergoes significant seasonal [10, 15, 16, 43, 46] fluctuations, varying at mean surface level from approximately 4.0 to 8.7 mbar. These fluctuations, which can be as much as 30% of the mean, are caused by a unique process of condensation and sublimation of the main component of the atmosphere, carbon dioxide, at the polar caps. In winter, temperatures at the corresponding pole drop so low that CO_2 freezes, falling out of the atmosphere and forming a seasonal polar cap of dry ice. This leads to a decrease in the total mass of the atmosphere and a drop in global pressure. In spring,

when the corresponding pole warms, the dry ice sublimates, returning CO_2 to the atmosphere and increasing the pressure. Such a large-scale seasonal mass exchange between the atmosphere and the surface, in which the main atmospheric gas participates, is a unique phenomenon in the Solar System and a key factor in Martian climate dynamics.

Pressure also depends significantly on the height above the surface, decreasing exponentially with elevation. For example, at the summit of the giant volcano Olympus Mons (Fig. 3.6), the pressure is only a small fraction of the pressure in deep depressions such as the Hellas Plain.

3.3. Evolution of atmospheric pressure.

The evolution of partial and total atmospheric pressure on Mars reflects a fundamental decrease in the mass of its volatile envelope over geological time. To provide conditions under which liquid water could exist for a long time on the surface during the Noic period (3.7–4.1 billion years ago), the partial pressure of carbon dioxide should have been from 0.5 to 2 bar. The need for such a dense atmosphere is also dictated by the astrophysical factor of the "Faint Young Sun paradox", according to which the luminosity of the Sun in the early history of the Solar System was 25–30% lower than today. Therefore, to maintain the surface temperature above the freezing point of water (273 K), a powerful greenhouse effect was required, created not only by CO_2 and H_2O, but also by additional gases such as H_2, CH_4 or SO_2. The decrease in atmospheric pressure to the present level (6.1 mbar) was due to the action of two main sinks (removal reservoirs) of carbon dioxide:

Lithospheric coupling (carbonate binding): The interaction of dissolved CO_2 in water with silicate minerals of the basaltic crust caused carbonate weathering:

$CaSiO_3 + CO_2 + H_2O \rightarrow CaCO_3 \downarrow + SiO_2 + H_2O$.

However, large-scale orbital spectrometric surveys using CRISM (MRO) and OMEGA («Mars Express») have revealed that exposed carbonate deposits in the Martian crust are geographically localized and do not form thick global layers equivalent to several bars of CO_2. This has given rise to the problem of the "missing

carbon paradox".

Atmospheric dissipation into space: Photochemical leakage and solar sputtering have proven to be much more efficient mechanisms for carbon removal than previously thought. Detailed photochemical and isotopic models developed by scientists at the California Institute of Technology (Caltech) and JPL [30] have described a two-step photochemical mechanism for carbon leakage. In the upper atmosphere, CO_2 and CO molecules dissociate sequentially under the influence of solar ultraviolet ($h\nu$) radiation:

$CO_2 + h\nu \rightarrow CO + O$,

$CO + h\nu \rightarrow C^* + O$.

The carbon atoms C* formed as a result of this dissociation acquire significant excess kinetic energy (they become "hot" atoms). If this energy exceeds the gravitational binding energy of Mars, the atom leaves the planet. In this case, the lighter carbon isotope ^{12}C acquires a higher velocity and escapes into space with a much higher probability than the heavier isotope ^{13}C.

A comparison of the isotope ratio $^{13}C/^{12}C$ in the primary mantle of Mars (determined from the analysis of primary gases in Martian meteorites, where $\delta^{13}C \approx 0‰$) with measurements of the modern atmosphere using the Curiosity rover ($\delta^{13}C \approx +45‰$) indicates a significant enrichment of the residual atmosphere with heavy carbon isotopes [23, 35]. Comprehensive numerical modeling, which takes into account photochemical C leakage, sputtering, and carbonate formation, has allowed us to calculate that the atmospheric pressure 3.8 billion years ago was expressed in values of about 0.5–1.0 bar, which completely resolves the "missing carbon" contradiction, since the bulk of the gas envelope was dispersed in interplanetary space, and not bound in rocks.

3.4. Evolution and loss of the Martian atmosphere.

The process of destruction and dissipation of the Martian atmosphere is determined by the physical mechanisms of interaction between the neutral and ionized components of the exosphere and solar radiation and the solar wind. The decline of the internal dynamo and the extinction of the global magnetic field of Mars at the end of

the Noic period (~ 3.9 billion years ago) left the upper atmosphere defenseless against the influence of plasma flows from the Sun.

The mechanisms of atmospheric escape can be divided into two main categories:

Thermal escape (thermal dissipation): Includes the classical Jeans escape, when atoms from the tail of the Maxwell-Boltzmann velocity distribution exceed the second cosmic velocity for Mars ($v_{esc} \approx 5.03$ km/s), and hydrodynamic escape (hydrodynamic escape / planetary wind), which dominated in the early stages at high extreme ultraviolet (EUV) fluxes of the young Sun. Non-thermal escape (non-thermal dissipation): Includes photochemical escape (dissociative recombination of ions, e.g. $O_2^+ + e^- \rightarrow O^* + O^*$), ion pickup by the electric field of the solar wind, and sputtering.

A crucial contribution to the quantitative assessment of total atmospheric losses was made by the study of the isotopic composition (Table 3.3) of argon, carried out with the help of «MAVEN» [31].

Argon is an inert gas; it does not enter into chemical reactions, does not precipitate, and does not sublime at Martian temperatures. The only physical process capable of removing argon from the Martian atmosphere is sputtering. During sputtering, ions of the upper atmosphere (O^+, O_2^+, CO_2^+), captured by the solar wind, are accelerated and with high kinetic energy crash into the exobase region (~ 200 km), cascading neutral atoms into space. At altitudes above the homopause (~ 120 km), under the action of gravity, diffusion separation of gases by mass occurs: the height of a homogeneous atmosphere for each isotope is determined by the expression:

$$H_i = \frac{k_B T}{m_i g}$$

.

Since the lighter isotope ^{36}Ar has a higher altitude of the homogeneous atmosphere H_{36} than the heavier ^{38}Ar, the exobase region is enriched in the lighter isotope 36Ar. Accordingly, the sputtering process selectively removes mainly ^{36}Ar from the exobase, which over time leads to the depletion of the atmosphere with this isotope and the enrichment of the residual reservoir with the heavier isotope ^{38}Ar.

Table 3.3.

Historical changes in the isotopic composition of various chemical elements.

Isotopic system	**Significance in the modern Martian atmosphere**	**Initial standard / Primary composition**	**Basic physical mechanism of fractionation**	**Estimation of evolutionary loss of matter**
$^{38}Ar/^{36}Ar$	Enriched with heavy ^{38}Ar in the lower atmosphere	Solar / Meteorite ratio (0.182)	Cathodic sputtering of exobase by solar wind ions	~66% of all atmospheric argon and most of CO_2 lost
$\delta^{13}C$ (CO_2)	~ +45‰ (heavy isotope shift)	Mantle Martian meteorites (0‰)	UV dissociation of $CO_2 \rightarrow CO \rightarrow C^*$, selective dissipation of ^{12}C	Initial atmospheric pressure was 0.5–1.0 bar
D/H (Hydrogen)	7.0–8.0 VSMOW	Earth's ocean VSMOW (1.5576×10^{-4})	Preferential dissipation of light hydrogen H over D after photolysis of H_2O	>80–87% of water lost; primary GEL layer ≥ 137 m
$^{15}N/^{14}N$	15N enrichment by ~50% relative to Earth	Earth's atmosphere (N_2) / Jupiter's composition	Photochemical leakage of neutral nitrogen atoms N	>90% of initial atmospheric nitrogen lost
$^{13}C/^{12}C$ (CO)	13C depletion in CO by ~20% relative to CO_2	CO_2 isotopic composition ($\delta^{13}C$ = +45‰)	Fractionation during photolysis of CO_2 and recombination into CO	Reduces calculated absolute C losses, explains organic isotopy

Using measurements of $^{38}Ar/^{36}Ar$ profiles between the homopause and exobase by the NGIMS "MAVEN" mass spectrometer and comparing them with MSL data on the lower atmosphere, it was determined that about 66% (two-thirds) of all argon has been permanently expelled into space during the planet's existence. Since argon is more difficult to disperse than lighter atmospheric gases, this result implies that most of the carbon dioxide (CO_2), nitrogen (N_2), and water vapor (H_2O) have been lost through non-thermal dissipative processes.

The evolution of the Martian water supply is reflected in the ratio of deuterium to ordinary hydrogen (D/H). D/H measurements, made by global infrared mapping [54] using ground-based very high resolution spectrometers (CRIRES/VLT, Keck, IRTF) and confirmed by JWST data, showed that the modern water vapor of the Martian atmosphere is enriched in deuterium by a factor of 7 relative to the terrestrial oceanic standard VSMOW (1.5576×10^{-4}). In polar glaciers, the enrichment reaches ≥ 8 VSMOW. Since hydrogen atoms H leave the planet by thermal leakage much faster than the heavier deuterium D (mass ratio $m_D/m_H = 2$), such a pronounced D/H enrichment confirms that Mars has lost from 80% to 87% of its initial volume of liquid water. Calculations show that the primary water reservoir of Mars 4.5 billion years ago corresponded to a Global Equivalent Layer (GEL) at least 137 meters deep.

3.5. The influence of volcanism on the evolution of the Martian atmosphere.

Volcanism played a key role in shaping both the geological history of the surface [13] and the evolution of the Martian atmosphere [5, 28, 52]. Large-scale eruptions over billions of years led to the formation of large lava flows and vast volcanic plains that now cover much of the planet's surface. Volcanic eruptions were also the main source of gases entering the early Martian atmosphere [18].

The main emissions at that time were water vapor, carbon dioxide, and sulfur dioxide. These gases are thought to have contributed to the creation of a denser and warmer atmosphere on early Mars, which could have been crucial for the existence of liquid water on the surface for long periods of time.

Interestingly, there is a close relationship between volcanism and the presence of

hydrated minerals on Mars. The occurrence of hydrated silica, sulfates, and phyllosilicates in volcanic regions indicates past interactions between magma or lava and water, either in liquid or icy form. These interactions could have created hydrothermal environments that are important for searching for signs of past or even present life on Mars [23, 40, 47].

Thus, volcanic outgassing served as a major internal source of volatiles to the Martian atmosphere during the Noic and Hesperian geological periods. The formation of giant magmatic provinces – the Tharsis volcanic plateau, containing over 300 million km3 of igneous rocks, the Elysium Planitia highlands, and the dark basaltic plains—was accompanied by massive outgassing from the partially molten mantle. The main components of Martian volcanic emissions were carbon dioxide (CO_2), water vapor (H_2O), sulfur dioxide (SO_2), hydrogen sulfide (H_2S), carbon monoxide (CO), and molecular hydrogen (H_2). The enormous volume of volcanic material erupted on Mars, especially in regions such as Tharsis, suggests a massive and sustained release of volatiles that could have dramatically altered the planet's early environment. Estimates of the amount of water and CO_2 released help to understand the potential for oceans and a dense atmosphere in the history of Mars [27].

Volcanism has been a fundamental driver of both the geological and atmospheric evolution of Mars, shaping its surface features [29] and influencing its climate over billions of years. Large volcanic formations and evidence of a thicker, warmer early atmosphere strongly suggest a dominant role for volcanic activity [34] in the Martian past. The presence of hydrated minerals in association with volcanic regions provides compelling evidence for past interactions between magma/lava and water (in liquid or icy form); and this has significant implications for the habitability of the planet [41]. These interactions could have created hydrothermal environments that are known to support life on Earth. The vast volume of volcanic material erupted on Mars, particularly in regions such as Tharsis, suggests a massive and prolonged release of volatiles that could have dramatically altered the planet's early environment. Estimating the amount of water vapor and CO_2 released helps to understand the potential for oceans and a dense atmosphere in Mars' history. Thus, volcanism on Mars

is a major mechanism for transferring matter and energy from the interior to the surface and into the atmosphere.

Studies cited in [28] have shown that even without catastrophic eruptions, Martian volcanoes continuously release water vapor through the process of "passive degassing" [37]. Using climate models, it was found that this vapor can condense in the form of ice up to several meters thick around volcanic centers. If such ice is covered by a layer of volcanic ash or dust, it can persist for millions of years even at the equator. This explains the findings of "excess hydrogen" as a sign of the presence of subsurface ice in tropical latitudes of Mars [38]. The impact of volcanism on the atmospheric system was of a complex chemical-climatic nature.

Greenhouse pulses and temperature increases: Large basalt outpourings were accompanied by the influx of hundreds of millibars of CO_2 and significant volumes of SO_2. Sulfur dioxide is an extremely effective greenhouse gas in the mid-IR range. The presence of SO_2 in concentrations of 10–100 ppm in combination with CO_2 created short-term epochs (lasting from thousands to hundreds of thousands of years) of global warming, during which the temperature exceeded 273 K, providing melting of snowpack and active surface runoff. Hydrospheric acidification and change of mineral phases: Atmospheric SO_2 was rapidly photochemically oxidized, interacting with water vapor to form sulfuric acid droplets (H_2SO_4):

$SO_2 + OH + M \rightarrow HSO_3 + M,$

$HSO_3 + O_2 \rightarrow SO_3 + HO_2,$

$SO_3 + H_2O \rightarrow H_2SO_4.$

Falling to the surface in the form of acid rain, H_2SO_4 acidified surface water bodies. This completely suppressed the precipitation of carbonates (which precipitate in an alkaline environment) and contributed to the massive formation of sulfate minerals (gypsum, kieserite, jarosite) in the Hesperian epoch, which was recorded by orbital spectrometers and Mars rovers.

The extinction of internal tectonic activity, cooling of the mantle and the decline of massive volcanism at the boundary of the Hesperian and Amazonian periods (~ 3.0 billion years ago) deprived Mars of its main source of gas replenishment. The flow of

volcanic degassing fell below the rate of atmospheric dissipation, which led to the final thinning of the gas envelope and its transition to the modern rarefied state.

3.6. Modern conditions in the atmosphere of Mars.

The modern state of the atmosphere is the result of the balance between volcanic replenishment and loss processes into space. With the disappearance of its magnetic field, Mars also became vulnerable to the flow of charged particles from the Sun, the solar wind. The «MAVEN» mission found that the solar wind interacts directly with the upper atmosphere, ionizing and ejecting atoms into interplanetary space. The main mechanism of loss is atmospheric sputtering. Ions accelerated by the electric fields of the solar wind crash into molecules in the atmosphere and push them beyond the limits of gravity. Measurements of argon isotopes have shown that Mars has lost about 65% of this gas over its history. Since argon is an inert gas, its loss is a direct indicator of how much other gases, such as CO_2 and N_2, have also been lost.

The loss of water on Mars occurred through its decomposition in the upper atmosphere under the influence of ultraviolet radiation:

$$2H_2O + h\nu \rightarrow 2H_2 + O_2$$

.

Light hydrogen H escapes into space much faster than heavier deuterium D. This has led to the enrichment of the modern atmosphere with deuterium by almost 6 times compared to Earth. The oxygen remaining after the dissociation of water could actively react with iron in surface rocks, forming iron oxides. This explains why the planet has a characteristic "rusty" color and why there is almost no free oxygen in the atmosphere.

For a long time, it was difficult to explain how Mars could have remained warm about 3.8 billion years ago, when the Sun shone 30% weaker. Under such conditions, ordinary CO_2 would clearly not be enough to create the necessary greenhouse effect. Research in 2025 based on the analysis of Martian meteorites and computer modeling proposed a new theory [7]. Early Martian volcanoes emitted not only CO_2, but also large amounts of “reduced” forms of sulfur: hydrogen sulfide H_2S, sulfur S_2, and sulfur hexafluoride SF_6 [39].

SF_6 is a particularly important element. It retains heat thousands of times more effectively than carbon dioxide. Even small amounts of this gas in volcanic emissions could raise global temperatures by tens of degrees, providing conditions for the existence of liquid water for long periods of time [42]. This theory received direct confirmation in May 2024, when the Mars rover "Curiosity" moved a rock in the Gediz Vallis channel and crushed it, discovering pure crystals of elemental sulfur inside it [42]. Unlike sulfates (sulfur with oxygen), pure sulfur indicates complex redox cycles characteristic of active hydrothermal systems similar to those on Earth, in which microbial life flourishes [42].

Mars is currently a very cold world. The average surface temperature is about 210 K, much colder than the harshest conditions in Antarctica. Temperatures on Mars vary widely. In the warmest conditions, at the equator in summer at noon, the surface temperature can temporarily rise above 0°C, reaching +20°C, or even +30°C, according to the Curiosity rover. However, the extreme lows are much lower: at the poles during the polar night the temperature can drop to -143°C, or even -153°C. The very thin atmosphere of Mars does not retain heat well. This leads to huge daily temperature fluctuations. Even at the equator, the temperature can drop from +20°C during the day to -80°C the next night. That is, daily differences in mid-latitudes can exceed 100°C.

Observations by the Perseverance rover in Jezero Crater recorded a rapid temperature drop of 5°C (from -20°C to -25°C) in just half an hour; this indicates very sharp changes even in local conditions. Temperature also varies significantly depending on the season and geographical latitude. Polar regions are the coldest, especially in winter; while equatorial regions receive more solar heat. A significant amount of CO_2 is currently not participating in seasonal changes, since it does not have time to evaporate from one polar cap, while the rest of it is adsorbed in the regolith.

The current thermodynamic state of the Martian atmosphere is characterized by being near the triple point of water (P_T = 6.11 mbar, T_T = 0.01°C). The average surface pressure is 6.1 mbar (0.61 kPa), varying depending on the relief from 0.3 mbar at the top of the Olympus volcano (altitude 21.9 km) to 11.5 mbar in the deepest depressions of the Hellas basin. At such pressures, liquid pure water is unstable: at the slightest

heating above 0°C, it boils intensively and evaporates. According to precision measurements of the SAM mass spectrometer (MSL "Curiosity") in Gale Crater, the bulk composition of the dry Martian atmosphere near the surface is characterized by the following indicators.

Composition of the dry Martian atmosphere: Carbon dioxide (CO_2): (95.32% ± 0.07%); Nitrogen (N_2): (1.89% ± 0.03%); Argon-40 (^{40}Ar): (1.93% ± 0.01%); Molecular oxygen (O_2): (0.145% ± 0.09%); Carbon monoxide (CO): (0.07% ± 0.01%).

Trace components include inert gases: neon (Ne ≈ 2.5 ppm), krypton (Kr ≈ 0.3 ppm), xenon (Xe ≈ 0.08 ppm), as well as highly variable amounts of water vapor (H_2O ≈ 10–1000 ppm), ozone (O_3 ≈ 0.01–0.1 ppm), and hydrogen peroxide (H_2O_2 ≈ 10 – 40 ppb). The molar ratio of radiogenic argon to nitrogen $^{40}Ar/N_2 = 1.02$ and the value of $^{40}Ar/^{36}Ar \approx 1900$ serve as isotopic markers for the identification of Martian meteorites.

On Mars, the formation of the general climate is significantly influenced by aerosol particles in the atmosphere. When Mars passes near perihelion, this effect is greatly enhanced. And then global dust storms begin to arise [39], transporting significant amounts of dust across the planet [3]. Therefore, a characteristic feature of the Martian climate is dust storms (Fig. 3.7). They can range from small local vortices, known as “dust devils” (Fig. 3.8), to giant global storms that can cover the entire planet and last for months [36]. These storms lift vast quantities of fine reddish dust into the atmosphere, which can also significantly affect surface and atmospheric temperatures by blocking sunlight, as well as atmospheric pressure.

During powerful dust storms, dust rises to heights of 20-40 km. The atmosphere is noticeably dusty and contains particles with a diameter of about 1.5 microns. Their presence gives the Martian sky a reddish or pinkish hue when viewed from the surface due to iron oxide particles suspended in the atmosphere. Seasonal fluctuations in methane concentrations are observed, varying from about 0.24 ppb in the northern winter to about 0.65 ppb in the summer. The current state of the atmosphere is the result of a deep and continuous process of atmospheric loss over geological time, which emphasizes the dramatic climatic and atmospheric evolution.

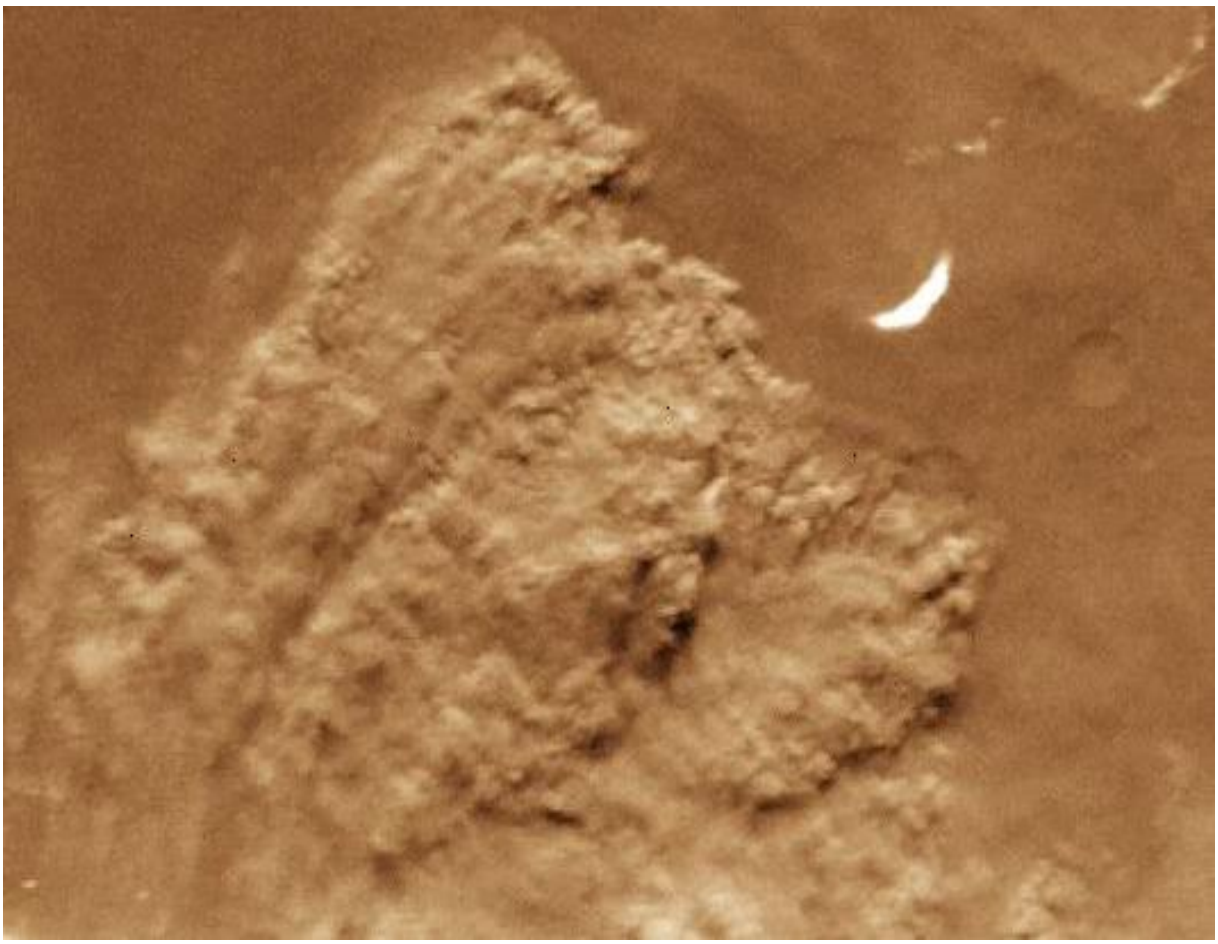


Fig. 3.7. A local type of dust storm that formed at the edge of the southern polar region. Storms typically begin in slightly elevated areas with a high thermal gradient (e.g., near the polar cap), where winds are strongest (http://photojournal.jpl.nasa.gov/).

At an altitude of about 40 km, even an ozone layer has been found in the atmosphere, the thickness of which is close to 7 km. At an altitude of □300 km, atomic oxygen becomes the main component in the atmosphere. Its presence can be explained by the processes of photodissociation of carbon dioxide. This conclusion follows from the fact that the density of another of its products, carbon C, decreases with height faster than the density of oxygen. Starting from an altitude of 400 km, the predominant component of the atmosphere on Mars becomes atomic hydrogen with a concentration of 10^4 atoms per 1 cm^3. It is expected that almost the same amount of helium is retained at the same altitude.



Fig. 3.8. The Perseverance rover recorded the collision of two dust vortices on the surface of Mars; the largest vortices observed by the rover were 4 km² in area (https://benchmark.rs/wp-content/uploads/2025/04/Pustinjski-davoli-na-Marsu.webp).

At an altitude of several thousand kilometers, the atmosphere should consist of almost pure hydrogen. And such an outer atmosphere of Mars from pure hydrogen extends to a height of 20,000 km, forming a kind of hydrogen "corona" of the planet.

It was studied by various spacecraft [44] that used special receivers sensitive to radiation in the hydrogen resonance line Lyman-α. Such radiation arises from the scattering of solar ultraviolet radiation by hydrogen atoms located in the upper part of the Martian atmosphere.

Hydrogen atoms in the upper parts of the planet's atmosphere should dissipate into interplanetary space. But since they are present in the modern atmosphere of Mars, there must also be a constantly operating source of their replenishment at present. It is clear that one of the main such sources can be the dissociation of water vapor from the upper layers of the Martian atmosphere. Thus, even a very small amount of water vapor H_2O, which is currently present there, is sufficient for this purpose.

The vertical structure of the atmosphere is divided into the following

thermodynamic layers:

Troposphere (0–40 km): Region of radiative-convective exchange. The vertical temperature gradient is about 1.5–2.5 K/km. The thermal regime of the troposphere is significantly controlled by the content of mineral dust.

Mesosphere (40–100 km): Region of effective radiative cooling due to infrared CO2 radiation in the fundamental 15 μm band. Thin clouds of dry ice (CO_2) and water ice are regularly observed at altitudes of 50–80 km.

Thermosphere and Exosphere (above 100 km): Region of direct absorption of hard solar UV radiation (EUV). Here, diffusion separation of gases by mass occurs, and the temperature reaches 200–300 K. From here, hydrogen, oxygen and argon are released by the solar wind.

3.7. Seasonal changes in the modern atmosphere of Mars.

The seasonal dynamics of the atmosphere of Mars are determined by two main astronomical parameters: the inclination of the planet's axis of rotation (ε_{var} = 25.19°, which creates a seasonal change similar to Earth) and the pronounced orbital eccentricity (e = 0.0934). The Martian year lasts 687 Earth days. The seasonal state is described using the areocentric longitude of the Sun (Ls): Ls = 0° corresponds to the spring equinox in the northern hemisphere, Ls = 90° to the summer solstice, Ls = 180° to the autumn equinox, and Ls = 270° to the winter solstice. Seasonal processes form three interconnected planetary cycles:

The global CO_2 cycle and seasonal pressure fluctuations. In winter, the temperature in the polar region of the corresponding hemisphere drops below the condensation point of carbon dioxide (Tc ≈ 145 K at P = 6 mbar). Direct phase condensation of atmospheric CO_2 begins on the polar cap, forming a dry ice cover 1 to 2 meters thick.

During the winter solstice in the southern hemisphere (Ls = 270°), up to 25–30% of the entire mass of the Martian atmosphere freezes on the southern polar cap. This causes a global decrease in atmospheric pressure across the planet. In spring, when the polar cap sublimates under the influence of increasing insolation, CO_2 returns to the

atmosphere, causing the pressure to increase to a maximum.

Since the southern winter coincides with Mars's near aphelion (when the planet receives 40% less solar energy than at perihelion), the southern winter cap is much larger than the northern one, and the seasonal amplitudes of pressure fluctuations are asymmetric between the hemispheres.

Seasonal water cycle and atmospheric clouds. The main long-term source of atmospheric moisture is the northern polar cap, which consists of a thick layer of water ice. During the northern summer (Ls = 90–120°), the layer of seasonal CO_2 ice completely evaporates, exposing the eternal water ice. The temperature rises above 200 K, accompanied by intense sublimation of H_2O into the air. Water vapor is transported by the global meridional circulation (Hadley cells) to the south.

During the aphelion season (Ls = 50–150°), a global decrease in troposphere temperature leads to the dew point being reached above equatorial latitudes. This causes the formation of an equatorial belt of water-ice clouds (Aphelion Cloud Belt).

Measurements of the isotopic composition of water vapor (HDO/H_2O) using JWST NIRSpec and ground-based spectrometers revealed pronounced seasonal fractionation anomalies: vapor released during sublimation of the northern polar cap is more deuterium-enriched than mid-latitude vapor, due to condensation fractionation processes during freezing (Table 3.4).

Dust cycle and global dust storms (GDS). Martian dust is the main radiative agent of the lower atmosphere. Microscopic dust particles (radius $r \approx 1.5$ μm) effectively absorb solar radiation, causing direct heating of the air column. The active dust season falls on the perihelion period (Ls = 200–300°), when the southern summer creates maximum temperature gradients between the polar caps and the illuminated equatorial plateaus. Intense solar heating forms powerful dust devils and local squalls that raise dust to heights of up to 40–80 km.

Under certain synoptic conditions, local dust storms merge into regional and global dust events (GDS – Global Dust Storms), which completely envelop the planet with a dust curtain for several months.

Table 3.4.

Seasonal changes in aerosol and dust components in the Martian atmosphere.

Seasonal longitude (Ls)	**Astronomical state / Hemisphere**	**CO_2 dynamics and pressure**	**Water vapor (H_2O) dynamics**	**Dust activity and aerosols**
Ls = 0° – 90° (Northern Spring / Southern Autumn)	Approaching aphelion	Sublimation of CO_2 at the North Pole; increase in total pressure	Beginning of moisture release from the northern ice	Low dust activity; clear atmosphere
Ls = 90° – 180° (Northern summer / Southern winter)	Aphelion (maximum distance from the Sun)	Maximum CO_2 condensation at the South Pole; minimum pressure	Peak H_2O content in the air; formation of an equatorial cloud belt	Formation of water-ice clouds over volcanoes
Ls = 180° – 270° (Northern autumn / Southern spring)	Approaching perihelion	Sublimation of southern CO_2 ice; rapid increase in pressure	Meridional moisture transport to the equator	Increased dust activity; occurrence of local storms
Ls = 270° – 360° (Northern winter / Southern summer)	Perihelion (closest point to the Sun)	Maximum CO_2 sublimation, peak global atmospheric pressure	Altitude rise of H_2O and intense UV photodissociation	High probability of global dust storms (GDS)

Important effect: Heating of the atmosphere by dust during GDS causes its

expansion and a rise in the height scale. This leads to the rise of water vapor to altitudes above 70–80 km, where it is directly decomposed by solar hard UV radiation, which accelerates the escape of hydrogen into space by tens of times, especially during dust storms.

3.8. Organic chemistry and the search for biosignatures in the atmosphere.

The detection and characterization of organic compounds on Mars is a cornerstone of modern astrobiology, aimed at clarifying the potential suitability of the planet for life in the past and present.

"In-situ" studies of organics in geological deposits. Thanks to the chemical analyzers Sample Analysis at Mars (SAM) ("Curiosity" rover) and SHERLOC ("Perseverance" rover), a wide range of ancient organic molecules have been recorded in Martian sedimentary and volcanic rocks aged 3.2–3.8 billion years:

Chlorinated hydrocarbons: In the Sheepbed clayey mudstones (Yellowknife Bay, Gale Crater), GCMS SAM detected chlorobenzene (150–300 ppbw) and C_2–C_4 dichloroalkanes.

Aromatic and organosulfur compounds: Thiophene, benzene, toluene, and small alkane chains have been recorded in the Murray Formation sediments. The presence of sulfur in the thiophene rings contributed to their long-term preservation and protection from radiation degradation (a natural vulcanization process).

Higher fatty acids and their fragments: Analysis of the Cumberland sample revealed long-chain aliphatic hydrocarbons such as decane ($C_{10}H_{22}$), undecane ($C_{11}H_{24}$), and dodecane ($C_{12}H_{26}$). These compounds are thought to be degradation fragments of ancient carboxylic or fatty acids.

Complex organics at Glen Torridon (Mary Anning samples): Using wet chemistry (using the TMAH reagent) SAM has identified over 20 organic compounds, including the first identification of a nitrogen-containing heterocycle (a molecular precursor to RNA/DNA nucleobases), methyl benzoate, and benzothiophene. Total organic carbon concentrations in the mudstones range from 273 to 430 ppm.

In addition, in July 2024, the Perseverance rover explored a rock called Cheyava Falls in the Jezero crater. The SHERLOC instrument was used to detect signatures of aromatic organic molecules in the Máaz and Séítah formations of the Jezero crater using fluorescence and Raman spectroscopy. This indicates the prevalence of abiotic or biotic organic synthesis on early Mars. They found millimeter-sized bright centers surrounded by dark rings containing iron and phosphate [11]. On Earth, such patterns are typical of bacterial metabolism in sedimentary rocks. Although a chemical origin is also possible, the combination of organic molecules, specific minerals, and unusual texture is the strongest indirect evidence to date for the existence of ancient life on Mars [11].

3.9. Methane paradox: discrepancies between Curiosity and ExoMars TGO data.

Methane CH_4 is one of the most important potential biosignatures. In the strongly oxidizing Martian atmosphere under the influence of solar UV radiation and OH radicals, the photochemical lifetime of methane is only about 300–400 years. The presence of stable methane sources requires the existence of a modern active process - biological (methanogenesis) or geological (serpentinization during the interaction of water with olivine). However, methane studies have created a large-scale discussion due to the fundamental difference in the obtained observational data:

Measurements in Gale Crater ("Curiosity" / TLS): The TLS laser spectrometer has regularly recorded a low background level of methane in the near-surface air layer for more than 10 years with pronounced seasonal fluctuations: from 0.24 ppb in winter to 0.65 ppb in late summer, as well as spikes to 10–20 ppb.

Orbital measurements (ExoMars TGO/ACS, NOMAD): Results published in [33] showed that TGO spectrometers during orbital shadowing of the atmosphere did not detect traces of methane throughout the planet, setting a strict upper limit for methane abundance at < 0.05 ppb (which is 10–100 times lower than the “Curiosity” measurements). Several fundamental physical hypotheses have been proposed to resolve this controversial discrepancy.

Diurnal Boundary Layer trapping: Methane release from soil microcracks occurs slowly and accumulates near the surface mainly at night during the formation of the inverted near-surface layer of the atmosphere when Curiosity made its measurements. During the day, solar heating creates strong convection that quickly washes away and dilutes methane in the atmosphere to concentrations invisible to TGO.

Abnormally rapid near-surface oxidation: The existence of an unknown photochemical or electrostatic mechanism for methane destruction near the surface (e.g., oxidation by perchlorate microparticles or by electrical discharges during dust storms).

Local technological or micro-extrusion: The release of methane purely locally in Gale Crater from subsurface clathrate hydrates under the action of rover wheel pressure or local heating.

3.10. Atmosphere-surface interaction and the future of the planet.

The modern Martian regolith serves not only as a mechanical basis, but also as an active chemical and physical buffer that regulates the atmospheric composition.

Chemical and physical interaction of the regolith with the atmosphere. Adsorption exchange: The porous basaltic regolith and clay minerals adsorb significant volumes of CO_2 and H_2O. Diurnal and seasonal temperature fluctuations cause cyclic absorption and release of moisture by the soil. The presence of perchlorate salts ($Mg(ClO_4)_2$, $Ca(ClO_4)_2$) in the regolith causes the effect of absorbing atmospheric vapor with the formation of liquid micro-films of brine at temperatures below 273 K.

Oxidative chemistry of perchlorates and photolysis: The presence of perchlorates in the soil at concentrations of 0.5–1% creates a harsh oxidative environment. Under the influence of solar UV radiation, perchlorates generate active oxygen species (hydrogen peroxide H_2O_2, superiodines O_2^-), which destroy organic compounds on the surface.

Weathering and Surface Color: Photochemical hydrogen leakage is accompanied by the release of oxygen, which participates in the slow further oxidation of iron-

bearing crustal minerals (Fe2+ □ Fe3+), maintaining the characteristic red color of Martian hematite and maghemite.

Long-term future of the Martian atmosphere. In the long-term geological perspective, the Martian atmosphere will continue to be irreversibly depleted:

Further leakage into space: The lack of an internal magnetic field means that the solar wind will continue to "stripped" the exosphere at an average speed of about 100 grams/second (during solar storms, this speed increases dozens of times).

Impact of Obliquity Cycles: The tilt of Mars' rotational axis is chaotically unstable, varying from 10° to 45° with a period of about 120,000 years (due to the lack of a massive moon-like satellite near Earth). At high tilts (~45°), the polar caps receive maximum sunlight, causing complete sublimation of CO_2 and a temporary increase in pressure to 10–20 mbar. At low tilts (~10°), almost all of the CO_2 freezes at the poles, creating a very thin atmosphere.

Theoretical concepts of artificial atmospheric restoration (terraforming) face a fundamental limitation: according to data from «MAVEN» and «Mars Express» , the total available supply of CO_2 in the polar caps and adsorbed soil, upon complete evaporation, can create a pressure of no more than 20–30 mbar, which is absolutely insufficient to create a stable greenhouse effect without importing volatiles from external asteroids or comets.

Conclusions.

Systematization of modern scientific data on the evolution and seasonal dynamics of the Martian atmosphere allows us to formulate the following final conclusions:

A grand evolutionary transformation: Mars went from a dense, warm and humid world with an atmospheric pressure $P \approx 0.5–1.0$ bar in the Noachian period (> 3.7 billion years ago) to a cold desert with a surface pressure $P \approx 6.1$ mbar in the modern Amazonian era.

Key role of non-thermal dissipation: Analysis of the argon isotope composition (38Ar/36Ar) by the «MAVEN» mission has shown that over 66% of all atmospheric gas was lost to space through sputtering and photochemical leakage induced by the

solar wind after the magnetic dynamo died down. Carbon ($\delta^{13}C \approx +45‰$) and deuterium (D/H ~ 7–8×VSMOW) isotope enrichments confirm the loss of most of the CO_2 and over 80–87% of the primary water resources (GEL ≥ 137 m).

High-intensity seasonal cycles: The modern atmosphere is subject to global cycles of CO_2, H_2O, and dust. Condensation of up to 30% CO_2 at the polar caps causes seasonal pressure drops, and dust storms near Mars' perihelion (GDS) expand the atmosphere, accelerating the high-altitude decomposition of H_2O and the escape of hydrogen into space.

Complexity of organic chemistry and the methane paradox: Mars rovers (Curiosity, Perseverance) have confirmed the presence of a variety of ancient organics (chlorobenzene, thiophenes, fatty acids, nitrogen-containing heterocycles). However, the discrepancy between the near-surface seasonal methane detections of Curiosity (0.24–0.65 ppb) and the orbital constraints of the ExoMars TGO observations (< 0.05 ppb) suggests the presence of as yet unexplored near-surface diurnal blockages or local emissions.

Contribution of the James Webb Space Telescope (JWST): Observations from L_2 opened up new possibilities for spectroscopic probing of the entire Martian hemisphere, providing measurements of HDO/H_2O, non-LTE CO_2 emissions, O_2 noctilucent glow, and high-spatial resolution thermal and cloud mapping.

References:

1. Acuña M.H. (2003) The magnetic field of Mars. *The Leading Edge*. 22(8), p. 769-771.

2. Acuna M.H., Connerney J.E.P., Ness N.F., et al. (1999) Global distribution of Crustal Magnetization Discovered by the Mars Global Surveyor MAG/ER Experiment. *Science*. 284(5415), p. 790-793.

3. Adams J.B., Filice A.L. (1967) Spectral reflectance 0.4 to 2.0 microns of silicate rock powders. *J. Geophys. Res*. 72(22), p. 5705-5715.

4. Alday R., Trokhimovskiy A., Patel M.R., et al. (2023) Carbon isotopic fractionations in atmospheric carbon monoxide on Mars measured by the ExoMars Trace Gas Orbiter. *Nature Astronomy*, 7(6), p. 650–658.

5. Atreya S.K., Gu Z.G. (1994) Stability of the Martian atmosphere: is heterogeneous catalysis essential? *J. Geophys. Res*. 99(E6), p. 13133–13145.

6. Batson R.M. (1973) Cartographic products from the Mariner-9 mission. *J. Geophys. Res*. 78(20), p. 4424-4435.

7. Bellino L.G., Sun Ch. (2025) Volcanic emission of reduced sulfur species shaped the climate of early Mars. *Science Advances*, 11(36).

8. Bertka C.M., Fei Y. (1998) A profile of Martian mineralogy and density up to core-mantle boundary. LPSC. V. 27. P. 107-108.

9. Bi H., Sun D., Sun N., et al. (2025) Seismic detection of a 600-km solid inner core in Mars. *Nature*. 645, p. 67–72.

10. Bibring J.-P., Langevin Y., MustardJohn Y. F., et al (2006) Global mineralogical and aqueous mars history derived from OMEGA/Mars express data. *Science*. 312, p. 400-404.

11. Bishop J.L., Parente M. (2025) Mystery Martian minerals hint at the planet's complex geochemical past. *Nature*, 645(8080), p. 317-318.

12. Broquet A., Andrews-Hanna J.C. (2023) Geophysical evidence for an active mantle plume underneath Elysium Planitia on Mars. *Nature Astronomy*. 7, p. 160–169.

13. Cameron A.G.W. (1963) Formation of the solar nebula. *Icarus*. 1(1-6), p. 339-342.

14. Carr M.H. (1999) Retention of an atmosphere on early Mars. *Journal of Geophysical Research: Planets*. 104(E9), p. 21897-21909.

15. Churyumov K.I., Steklov A.F., Vidmachenko A.P., Dashkiev G.N. (2015) Observations of fragments of cometary nuclei in the atmosphere over Kiev. *Astronomical School's Report*. 11(2), p. 99-102.

16. Churyumov K.I., Steklov A.F., Vidmachenko A.P., Dashkiev G.N. (2015) Observations of fragments of cometary nuclei in the atmosphere over Kiev in the summer of 2014. 17 ISCo of YS. 20-22, 2015, Zhytomyr, Ukraine, p. 84-85.

17. Churyumov K.I., Steklov A.F., Vidmachenko A.P., Dashkiev G.N. (2016) Several twilight bolides over Kiev in 2013-2015 – fragments of comets nuclei. International conference Meteoroids 2016, at the European Space Research and Technology Centre (ESTEC) in Noordwijk, Netherlands. 6-10 June 2016. Poster 63.

18. Clinton J.F. (2017) Preparing for InSight: An Invitation to Participate in a Blind Test for Martian Seismicity. *Seismological Research Let*. 88(5), p. 1290-1302.

19. Connerney J.E.P., Acuńa M.H., Wasilewski P., et al. (1999) Magntic Lineations in the ancient crust of Mars. *Science*. 284(5415), p. 794-798.

20. de Beule C., Wurm G., Kelling T., et al. (2015) An insolation activated dust layer on Mars. *Icarus*. 260, p. 23-28.

21. Fisher J.A., Richardson M.I., Newman C.E., et al. (2005) A survey of Martian dust devil activity using Mars Global Surveyor Mars Orbiter Camera images. *J. Geophys. Res*. 110(E3), p. 3-4.

22. Fonseca R.M., Zorzano-Mier M.-P., Martín-Torres J. (2018) Planetary boundary layer and circulation dynamics at Gale Crater, Mars. *Icarus*. 302, p. 537-559.

23. Freissinet C., Glavin D.P., Mahaffy P.R., et al, & «Curiosity» Science Team. (2015) Organic molecules in the Sheepbed Mudstone, Gale Crater, Mars. *Journal of Geophysical Research: Planets*. 120(3), p. 495–514.

24. Frey H., Schultz R.A. (1988) Large impact basins and the megaimpact origin for the crustal dichotomy on Mars. *Geophys. Res. Lett*. 15(3), p. 229-232.

25. Goins N.R., Lazarewicz A.R. (1979) Martian seismicity. *Geophys. Res. Let*. 6(5), p. 368-370.

26. Goldstein R.M., Melbourne W.G., Morris G.A., et al. (1970) Preliminary radar results of Mars. *Radio. Sci*. 5(2), p. 475-478.

27. Golombek M.P., Cook R.A., Economou T., et al. (1997) Overview of the Mars Pathfinder Mission and assessment of landing site predictions. *Science*. 278(5344), p. 1734-1748.

28. Hamid S.S., Kerber L., Clarke A.B. (2025) Precipitation induced by explosive volcanism on Mars and its implications for unexpected equatorial ice. *Nature Communications*. 16, 8923. https://doi.org/10.1038/s41467-025-63518-8

29. Hartmann W.K. (1973) Martian Cratering. Mariner 9 initial analysis of cratering chronology. *J. of Geophys. Research: Solid Earth*. 78(20), p. 4096-4116.

30. Hu R., Kass D.M., Ehlmann B.L., Yung Y.L. (2015) Tracing the evolution of Martian atmosphere with carbon isotopes. *Nature Communications*. 6, Article 10003.

31. Jakosky B.M., Slipski M., Benna M., et al. (2017) Mars' atmospheric history derived from upper-atmosphere measurements of 38Ar/36Ar. *Science*, 355(6332), p. 1408–1410.

32. Kerzhanovich V.V. (1977) Mars 6: improved analysis of the descent module measurements. *Icarus*. 30(1), p. 1-25.

33. Korablev O., Vandaele A.C., Montmessin F., et al, & ACS and NOMAD Teams (2019) No detection of methane on Mars from early ExoMars Trace Gas Orbiter observations. *Nature*. 568(7753), p. 517–520.

34. Leighton R.B., Horowitz N.H., Murray B.C., et al. (1969) Mariner 6 television pictures: first report. *Science*. 165(3894), p. 684-690.

35. Mahaffy P.R., Webster C.R., Atreya S.K., et al, & MSL Science Team. (2013) Abundance and isotopic composition of gases in the Martian atmosphere from the «Curiosity» rover. *Science*. 341(6143), p. 263–266.

36. Morozhenko A.V., Vid'machenko A.P. (2005) Polarimetry and Physics of Solar System Bodies. Photopolarimetry in Remote Sensing, NATO Science Series II: Mathematics, Physics and Chemistry. 161, p 369-384.

37. Morozhenko A.V., Vidmachenko A.P. (2017) Optical Parameters of Martian Dust and Its Influence on the Exploration of Mars. Dust in the Atmosphere of Mars and Its Impact on Human Exploration, Proceedings of the conference held 13-15 June 2017 in Houston, Texas. LPICo No. 1966, 2017, id.6010.

38. Morozhenko A.V., Vidmachenko A.P. (2017) What and how can affect the exploration of Mars. 19 International Scientific Conference Astronomical School of Young Scientists. May 24-25, 2017. Bila Tserkva, Ukraine. P. 67-69.

39. Morozhenko A.V., Vidmachenko A.P. (2020) Dust can affect on the mastering of Mars. 22 International scientific conference Astronomical School of Young Scientists. December 11-12, 2020. Kyiv, Ukraine. P. 71-73.

40. Steklov A.F., Vidmachenko A.P. (2019) In What Places and What Exactly Can be the" Traces" of Life on Mars? 9th Internat. Conference on Mars. 2089, 6007.

41. Steklov A.F., Vidmachenko A.P. (2019) Where and What Exactly Can Be the “Traces” of Life on Mars? Mars Extant Life: What's Next? Held 5-8 November 2019, in Carlsbad, New Mexico. LPI Contribution No. 2108, 2019, id.5089.

42. Vidmachenko A.P. (2026) Major volcanic formations on the surface of Mars in the Elysium Planitia region. Research in Science, Technology and Economics. Collection of Scientific Papers with Proceedings of the 6 th International Scientific and Practical Conference. International Scientific Unity. February 18-20, 2026, Luxembourg, Luxembourg. P. 365-370.

43. Vidmachenko A.P. (1987) Manifestation of seasonal variations in the atmosphere of Saturn. *Kinematics and Physics of Celestial Bodies*. 3(6), p. 9-12.

44. Vidmachenko A.P. (2009) Research of the Mars by space vehicles. 11 International Scientific Conference Astronomical School of Young Scientists, May 26-29, 2009, Kherson, Ukraine. P. 11-12.

45. Vidmachenko A.P. (2014) Study of Earth-like planets. 16 International scientific conference Astronomical School of Young Scientists, May 29-31, 2014. Kirovohrad, Ukraine. P. 12-13.

46. Vidmachenko A.P. (2015) Seasons on Saturn. 1. Changes in reflecting characteristics of the atmosphere at 1964-2012. *Astron. School’s Rep*. 11(1), p. 1-14.

47. Vidmachenko A.P. (2016) Traces of life on Mars must be sought around the valley Hellas in areas where the water coming out from under the planet's surface // 18 International scientific conference Astronomical School of Young Scientists, the program and abstracts. National Aviation University, Kyiv, Ukraine, May, 26-27. P. 14-16.

48. Vidmachenko A.P. (2023) History of possible climate change on Mars. Proceedings of VII International Scientific and Practical Conference. Science and innovation of modern world. (23-25 March 2023). Chapter 54. Cognum Publishing House, London, United Kingdom, p. 336-345.

49. Vidmachenko A.P. (2023) Thermal properties of the surface of Mars.

Proceedings of VII International Scientific and Practical Conference. Progressive research in the modern world (March 29-31, 2023). Chapter 42. BoScience Publisher, Boston, USA. P. 243-252.

50. Vidmachenko A.P. (2026) The evolutionary role of prolonged volcanism on the formation and changes of the Martian atmosphere. Collection of Scientific Papers. Proceedings of the 4th International Scientific and Practical Conference «Innovative Solutions in Science: Balancing Theory and Practice» (February 2-4, 2026, San Francisco, USA). European Open Science Space. P. 211-220.

51. Vidmachenko A.P., Klimenko V.M., Morozhenko A.V. (1981) Apparent spectral albedos of the disk of Mars in September-October 1977. *Astronomicheskii Vestnik*. 14(4), p. 157-159.

52. Vidmachenko A.P., Mozghovyi O.V., Steklov O.F. (2023) About volcanoes on Mars. Proceedings of 11 All-Ukrainian Scientific Conference “Astronomy and present day”, April 12, 2023. Vinnytsia, Ukraine. LLC "TVORY", p. 76-81.

53. Vidmachenko A.P., Mozghovyi O.V., Steklov O.F. (2023) Historical aspects of climate changes on Mars. Proceedings of 11 All-Ukrainian Scientific Conference “Astronomy and present day”, April 12, 2023. Vinnytsia, Ukraine. LLC "TVORY", p. 56-61.

54. Villanueva G.L., Mumma M.J., Novak R.E., et al. (2015) Strong water isotopic anomalies in the martian atmosphere: Probing current and ancient reservoirs. *Science*, 348(6231), 218–221.

DOI: 10.46299/979-8-90671-552-4.4

4. Features of volcanic terrain on Mars.

Introduction.

Remote sensing of the surface of Mars, and then its study from orbiters, indicated that a significant part of the planet's surface is covered with approximately equal parts old and fairly young craters, as well as flat erosional deposits [3, 12]. Among the craters, both volcanic and so-called impact (or meteorite) craters were found. Their age ranges from more than 4 billion years to only a few months, and possibly days. Moreover, in the southern regions of the planet, significantly more craters were found than in the lowlands in the north and on the lowland plains of Hellas Planitia [5, 13, 15, 16] and Argyre Planitia, which are located in the southern hemisphere in the middle of huge ring structures (Fig. 4.1).

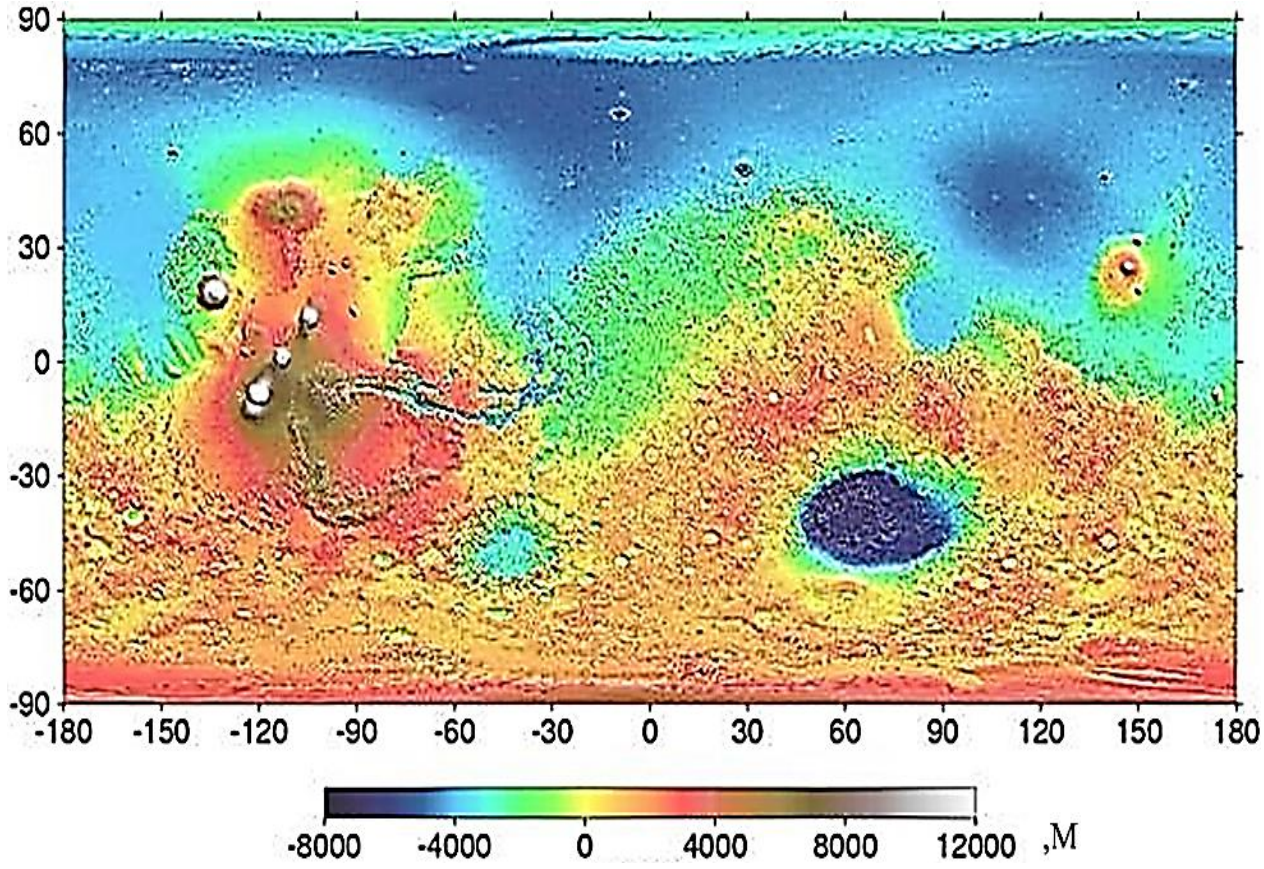


Fig. 4.1. Surface relief of Mars according to data from the Mars Global Surveyor spacecraft (MS) (http://photojournal.jpl.nasa.gov/).

Volcanic activity has historically played a very important role in the evolution of the geological features of the terrestrial planet Mars. It is it that has allowed the formation of relief on a significant part of its surface. Volcanism on Mars [26] has led to the formation of some of the highest and most powerful volcanic formations in the entire Solar System.

That is, even during remote observations of the planet Mars [8-11], distinct traces of volcanism and tectonic activity were found, such as gorges, canyons and faults; some of them are several kilometers deep, hundreds of kilometers long and tens of kilometers wide.

4.1. Volcanic and impact craters on Mars.

An extensive fault system is located on the eastern and western edges of the Mariner Valley, which may have been formed by the displacement of the Tharsis Regio region. When the very first images from the “Mariner 4” spacecraft were obtained, it was concluded that the surface of the planet Mars closely resembles the relief of the Earth's satellite, the Moon (Fig. 4.2).

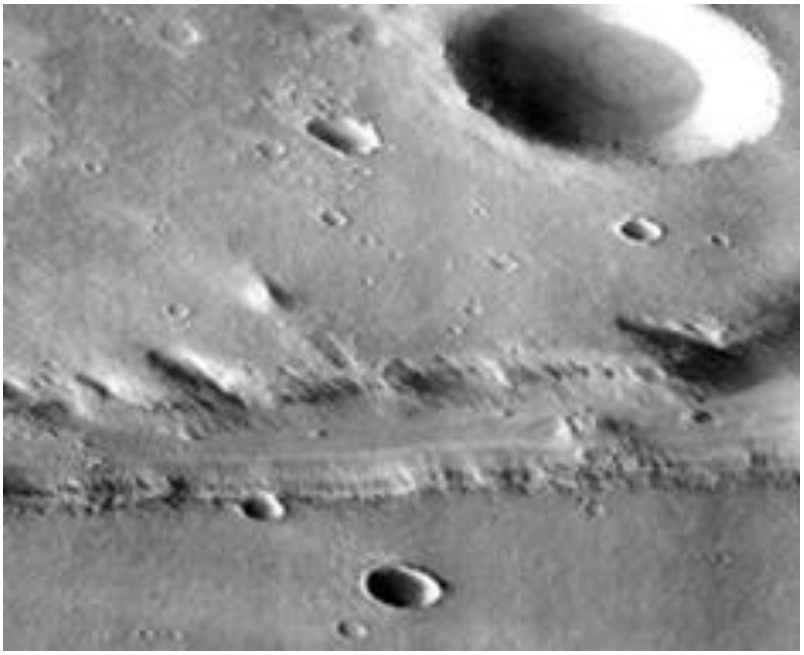


Fig. 4.2. The surface of Mars is dotted with large and small craters and valleys (http://photojournal.jpl.nasa.gov/).

The appearance of specific details was supplemented by images obtained with the help of later missions and landing modules.

The entire surface of Mars was dotted with reddish-colored stone blocks (most likely due to impurities with ferric oxides); they may be fragments of volcanic rocks formed by the fall of meteoritic bodies, or as a result of erosion processes. With the exception of a few plains, the rest of the surface of Mars was heavily cratered [31, 33]. But all the craters are much more destroyed compared, for example, with the same objects on the Moon or Mercury [4].

It turned out that significantly more craters were found in the southern hemisphere than in the northern. According to their origin, craters can be divided into impact (or meteorite) and volcanic; most of them are quite old, but some of them turned out to be quite young. About half of the surface of Mars is covered with old craters, while the other half is found with young flat deposits [1]. Most craters are found in the southern regions of the planet. Although low-lying formations located in the southern hemisphere in the middle of such giant ring structures as Hellas Planitia [27] and Argyre Planitia have a minimum density of craters.

Observational data have indicated that the shape of impact and volcanic craters is quite different. Impact craters have been found to have almost circular ring rims and outer and inner terraces.

Depending on their size, they may also have central elevations (in fairly large craters), and in extremely large ones – an additional inner rim. Whereas volcanic craters are characterized by smooth edges; and their surroundings are covered by lava flows; they are mostly located on the tops of dome-shaped formations. The most prominent representatives of volcanic crater formations are the craters on the tops of the four highest volcanoes: Olympus, Arsya, Pavonis and Askraeus. In addition, all craters of significant size are covered by smaller crater formations (Fig. 4.3).

A very small number of relatively fresh large impact craters have a developed field of ejecta and ray structures. While in the vast majority of them the ejecta field is noticeably destroyed or covered by later ejecta.

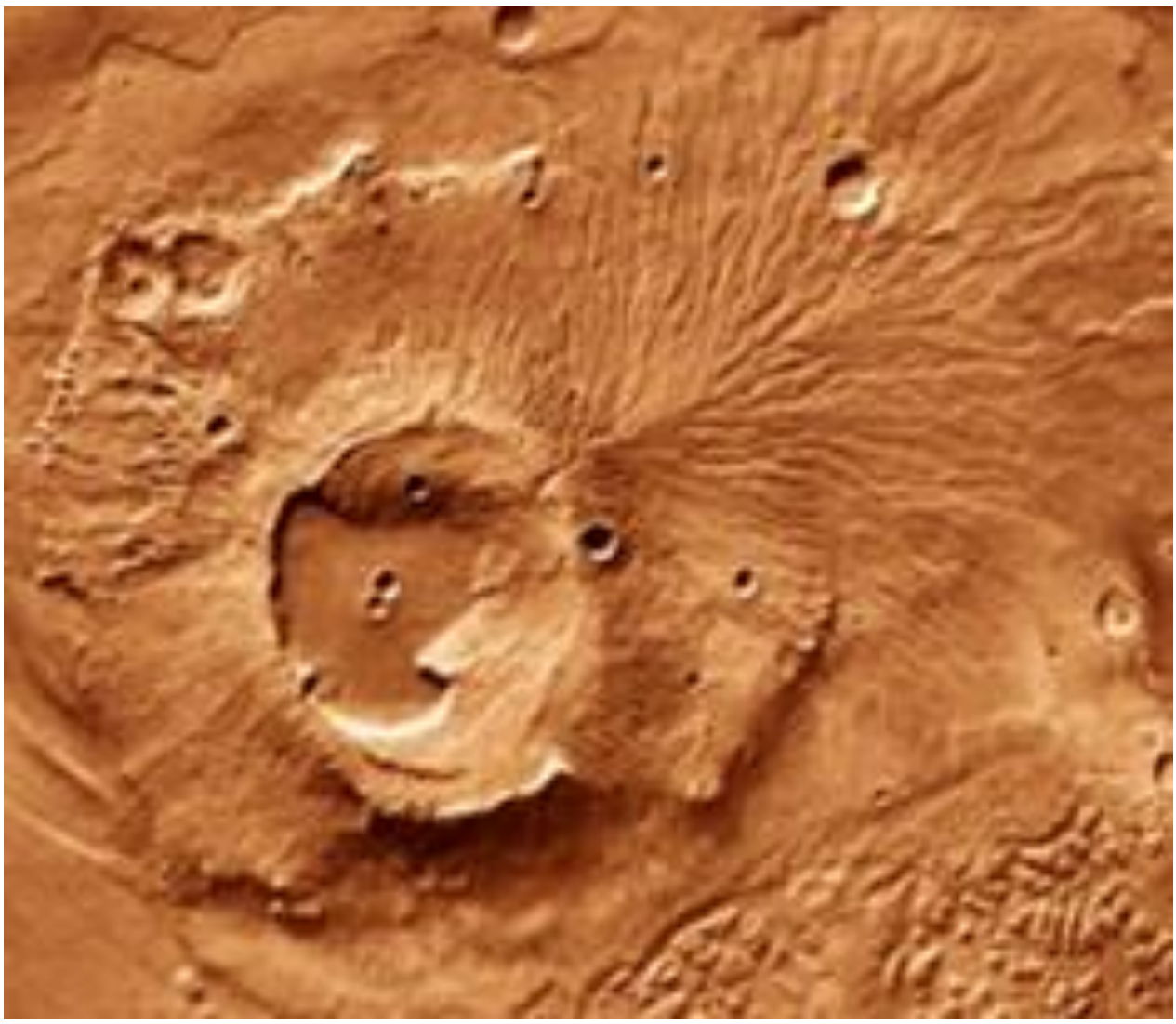


Fig. 4.3. Apollinairs Patera volcano on the Martian surface with coordinates φ=8°S, λ=186°W (http://photojournal.jpl.nasa.gov/).

A characteristic feature of younger craters is significant layers of ejecta around them and rather low ridges on their outer edge; and on “young” lava flows, three times more secondary craters are observed than on plain or mountainous areas. These young craters were divided into 6 such types [3].

To the 1st – craters with one shaft and with diameters less than 10 km were attributed; to the 2nd – not much larger, but with two shafts; to the 3rd type, craters surrounded by several craters of small sizes were attributed; to the 4th – craters with a radial structure of the outer shaft and sizes from 10 to 30 km. Craters with diameters less than 10 km do not have a similar structure, while the structure of craters whose diameter is more than 30 km looks much more complex, and they were attributed to

type 5. To type 6, the so-called "pancake-shaped" craters with diameters less than 5 km were attributed.

On young lava flows, three times more secondary craters are observed than on flat or mountainous areas, and 10 times more than on old areas of the surface. All volcanoes on Mars were divided into the following 3 types: large volcanic formations of the shield volcano type, on domes and on sinking calderas or pateras. Due to the presence of the latter type of structures, Mars differs markedly from Mercury and the Moon.

Estimates of the amount of lava output from Martian volcanoes calculated using the example of Mount Arsya were $3.5 \cdot 10^5$ m^3/s. The morphology of lava flows around volcanoes in Tharsis Regio indicates a rather low value of the viscosity of the lava material. The value of the viscosity of the lava turned out to be lower than for lunar seas, and significantly lower compared to the lava of terrestrial volcanoes.

For this reason, with a lower value of the gravitational force, lava flows on the planet Mars spread over significantly greater distances. Observational data on the density of impact craters on the slopes of the largest volcanoes on Mars indicate their rather young age: for example, for Olympus and Pavonis, the age is about 300 million years, and for Arsya and Askraeus (Fig. 4.4) – 400 million years [46, 50].

All four of these volcanoes on Mars are impressive in their scale, and on their slopes radiate lava flows, channels and ridges with a width of several and a length of hundreds of kilometers. That is, they are much larger than those on Earth, and their lava flows are much longer (Fig. 4.3).

The reason for this may also be that very hot volcanic regions under the crust of Mars have been fixed for hundreds of millions of years in almost one place on the planet's surface.

Whereas on Earth, tectonic plates moved along rather hot volcanic regions, and therefore this did not allow volcanoes of significant sizes to form.

In addition to the so-called shield volcanoes of gigantic size, there are also more modest in size but more numerous volcanic formations on the surface of Mars - the so-called volcanic domes (Fig. 4.5).

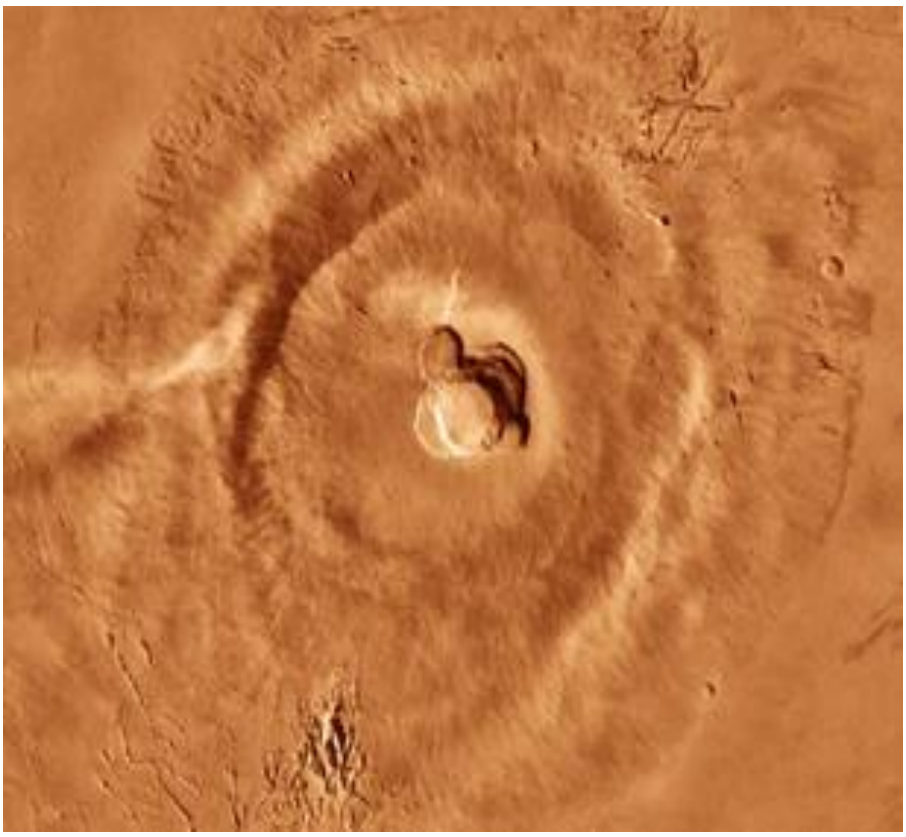


Fig. 4.4. The caldera of the volcano Ascraeus Mons is composed of several discrete depressions; the lower wall of the caldera is over 3 km high (http://photojournal.jpl.nasa.gov/).

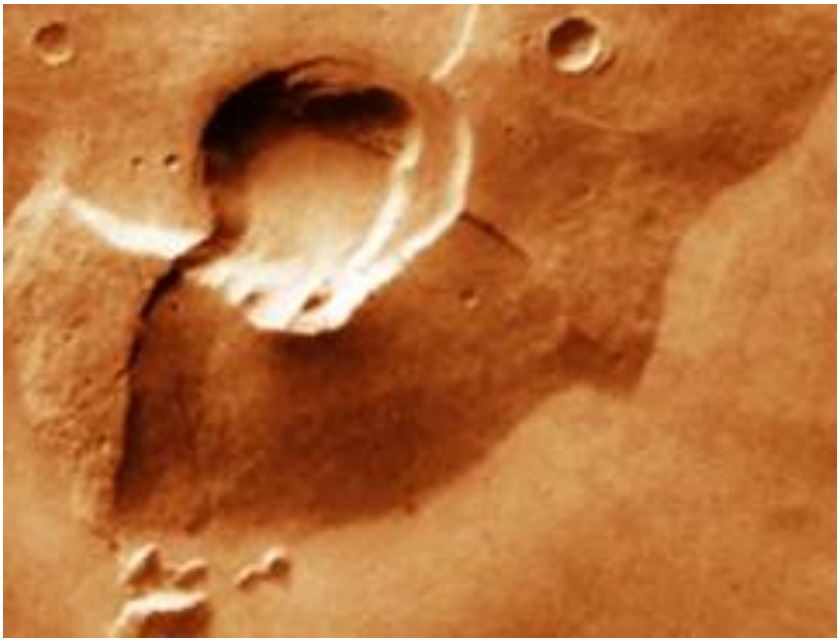


Fig. 4.5. One of the domes in the Tharsis Tholus region (http://photojournal.jpl.nasa.gov/).

The majority of them are also located in the Tharsis Regio region. The height of these domes is less than 8 km, and their tops are often complicated by multi-tiered caldera-type depressions. The largest volcanic dome on Mars, Hecate, is located in the Elysium region. Its diameter is about 200 km. In contrast to large shield volcanoes, they are characterized by a much higher surface density of impact craters and a larger ratio of caldera diameter to dome diameter. It can be assumed that at least some of the domes in Tharsis Regio are the remains of ancient and most likely, larger volcanic formations that were partially covered by later eruptions.

Some of the smaller domes are somewhat more convex than is typical for shield volcanoes and have much steeper slopes. Such differences between shield and dome volcanoes may be due to the fact that the lava material erupted from the domes was somewhat more viscous, or the eruption sites from which the domes were formed occupied a smaller volume, and therefore the lava flows accumulated closer to their source.

The next type of volcanoes is the so-called Paterae of various shapes [23, 29, 30, 32]. The inclination of their slopes is insignificant; on their slopes they have radial channels, and some of them are noticeably changed under the influence of erosion. Due to the strong sensitivity of the Paterae volcanoes to erosion, it can be assumed that they are composed of fairly light materials such as ash flows. Among them, the Alba patera is unique (Fig. 4.6).

It is comparable in size (with a diameter of about 1,600 km) to Mount Olympus and has a central caldera. However, its height above the surrounding plains is less than 3 km. This suggests that Alba Patera was formed by lava flows that were either significantly more powerful or, possibly, much longer than such flows in other regions of the planet. The presence of very significant erosion in some pateras also suggests that these formations are the oldest volcanoes on Mars. It is also possible that volcanic activity on Mars continued much longer than previously thought. Updated estimates based on the number of volcanic craters in images from the Mars Express spacecraft showed that volcanoes could have been active only 1-20 million years ago.

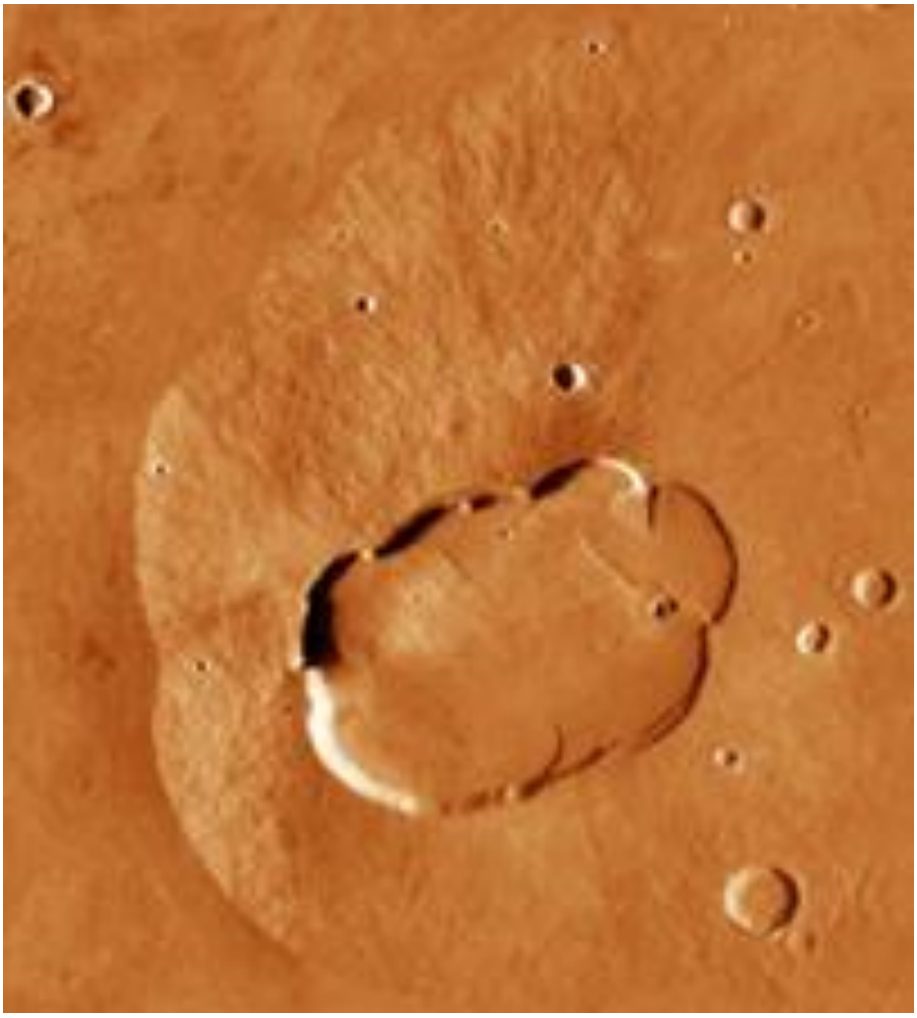


Fig. 4.6. The dome of the Alba Patera volcano (http://photojournal.jpl.nasa.gov/).

And until now, their active activity was estimated at 500-600 million years ago. The longest volcanoes could have been active in Tharsis Regio (Olympus volcano and 3 other largest volcanoes). It was even suggested that volcanic activity continues now. Therefore, for example, it is necessary to search for signs of hydrothermal activity on the planet. The Mars Reconnaissance Orbiter spacecraft in the Vernal crater in the Arabia Terra region was the first to register hills similar to hydrothermal springs. They have an elliptical shape and a small height. And in their appearance, these formations are very similar to hot springs found in Australia. The elevations on Mars shown in Fig. 4.7 may be so-called mud volcanoes.

Their infrared images show that these mounds cool faster than the surrounding rocks during the day; therefore, they are believed to be dried mud. Moreover, the colors of these mounds are in good agreement with the assumption that they can be formed in

the presence of water [40]. And the gas jets in which methane is found could be emissions from mud volcanoes [8], if only this warm mud contains microorganisms [14, 15] that can produce methane.

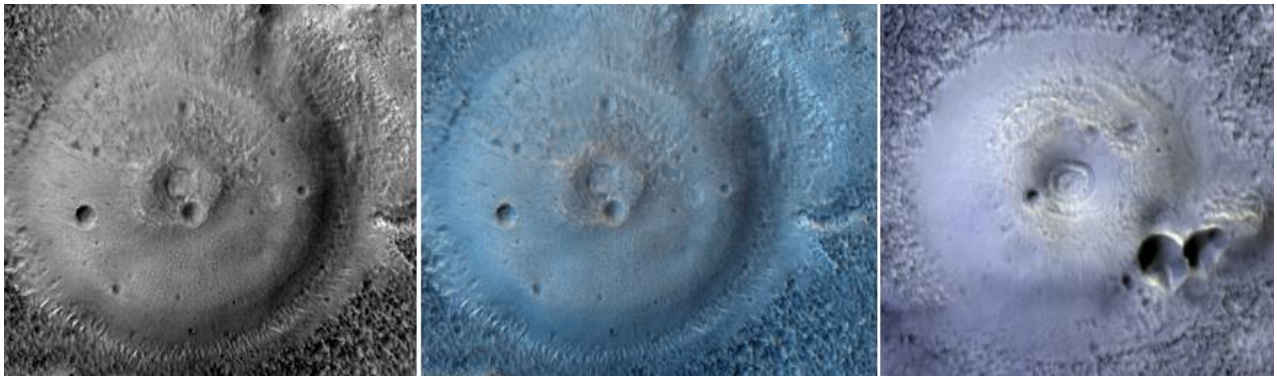


Fig. 4.7. Possible mud volcanoes with a diameter of more than 100 m on the northern plains of Mars in the Acidalia Planitia region. They are high-albedo formations (http://photojournal.jpl.nasa.gov/).

These cones are usually found near large Martian volcanoes, such as Olympus Mons; “dry” channels have also been found near them. This suggested that such cones could have been formed as a result of heating by heat from a volcano located under a layer of water ice.

And when the ice was able to evaporate, water vapor could pierce holes in the soil, through which the vapor came to the surface of the planet. If the elevations shown in Fig. 4.7 are still mud volcanoes, then it is in these places that it is necessary to search for traces of the activity of microorganisms.

Amazonis Planitia is a plain in the northern equatorial region of Mars. It is quite young, with the age of rocks on the surface of 10-100 million years. Some of these rocks are solidified volcanic lava. However, there are no volcanoes themselves, which have the appearance of a mountain with a crater in its center, in this area. Therefore, it is believed that the lava simply poured out onto the surface through cracks in the Martian crust.

It is very interesting that numerous traces of large lava flows, which occurred here repeatedly, were found on the surface [41, 42]; and the lava flowed along the same

system of channels as the water (or ice). Based on the study of these multilayer structures, which were formed during repeated eruptions of lava, a conclusion was drawn about the possibility of volcanic processes on this planet even now. The very first studies of the planet Mars using the Opportunity rover indicated the validity of the statement about the predominantly volcanic formation of the relief of the planet's surface. They confirmed that the rover moves on soil with several sand layers with granules of almost spherical shape interspersed in it (Fig. 4.8).

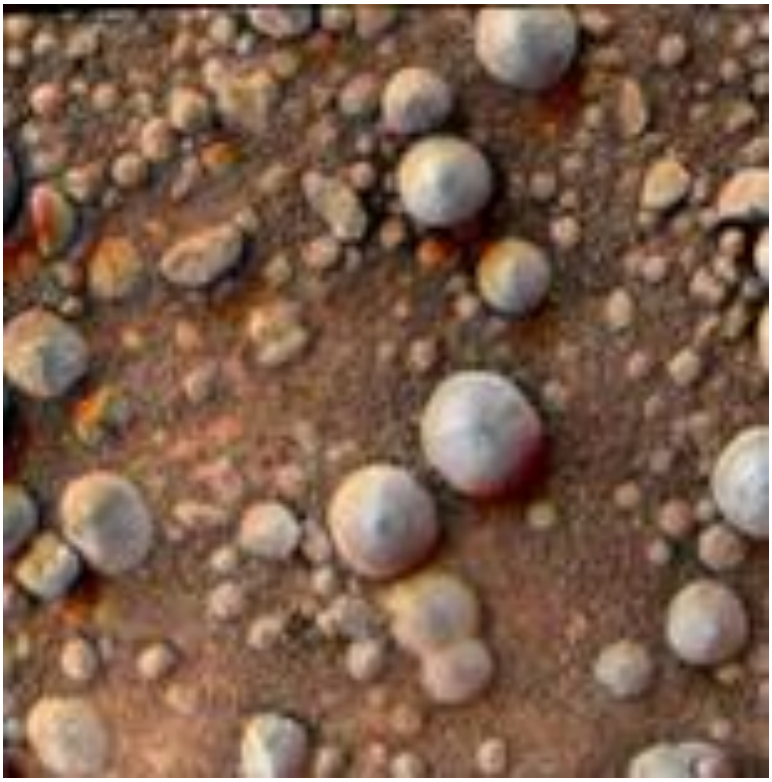


Fig. 4.8. Spherical granules on Mars (http://photojournal.jpl.nasa.gov/).

These granules are clearly volcanic in origin; they have been processed by gas jets that have emerged from the planet's mantle. In contrast to the aqueous solutions of volcanic materials characteristic of Earth, the fluidity of mud lava on Mars can be determined by fluids of the following possible compositions: carbon disulfide (CS_2), carbon chlorofluorocarbon (CCl_4), or hydrochloric anhydride (Cl_2O_7). The granules shown in this figure are characterized by a shiny surface, which can be determined by the substances listed above. Although the final composition of the liquid components

of these Martian volcanic materials can only be determined by direct chemical analysis. Volcanism there took place 3-4 billion years ago.

However, there is some evidence of fairly recent volcanic activity on Mars, with volcanic eruptions occurring even in the last 50 thousand years. For example, using observations from an orbiting Mars satellite, evidence of a very recent eruption in the Elysium Planitia region has been found (Fig. 4.9).

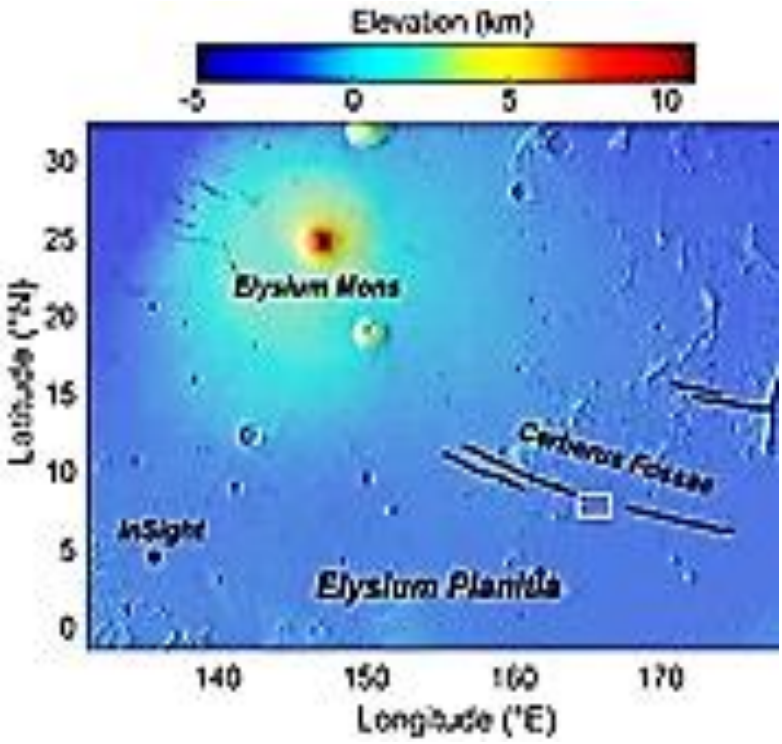


Fig. 4.9. The white box shows the region of recent volcanism and the location of the InSight lander (https://ostannipodii.com/data/anatoliy/images/-21-05/mars.jpg).

This volcanic region has high thermal inertia, and the soil on the surface includes pyroxene-rich material with a fairly high calcium content. It is such a soil that is symmetrically distributed around the Cerberus Fossae cracks in the Elysium Planitia region; and it is very atypical for the predominantly aeolian deposits in this region. Similar properties are possessed by dark spots on Mercury and the Moon, which are also attributed to volcanic eruptions.

4.2. Formation of relief features.

Volcanism was the main mechanism for the initial formation and modification of the crust on Mars for billions of years. The vast majority of the surface on the planet bears traces of volcanic activity to varying degrees. Volcanic activity has also played a key role in creating some of the largest features of the Martian landscape. For example, the Elysium and Tharsis regions are huge topographical uplifts that dominate much of the surface of Mars. They were formed over billions of years by the accumulation of lava and other materials erupted from the planet's interior. Modern lava flows are the result of repeated outpourings of molten basaltic rock during non-explosive eruptions. In this case, the flows moved downward from the site of the eruption. As they moved over the newly formed surface, each subsequent flow expanded, creating new lateral branches. Therefore, they could extend for many hundreds of kilometers. Eruptions usually occur at a temperature of 1400-1500 K.

Inside such lava flows, so-called lava tubes are usually formed, which look like peculiar pipelines through which lava with a fairly low viscosity flow. When such a lava flow spreads from the source of the eruption from the volcanic vent, the material on its surface slowly cools and hardens; and under the hardened layer, the lava inside still remains quite hot. When the entire flow finally stops, the lava can only partially fill the space of the pipe under the hardened layer, or it can completely flow down, leaving the pipe empty. In the case when the lava tube passes close enough to the surface, the roof can partially or completely collapse (Fig. 4.10).

Moreover, the lines of the edges of such pits can repeat the course of the entire lava tube. Sometimes only a small part of the ceiling of the lava tube can collapse. In this case, only small openings, similar to cave entrances or "light windows" will be visible on the surface (Fig. 4.11). Significant areas of the surface, and especially in the northern hemisphere of the planet, are covered with fairly smooth plains, which were formed during the outpouring of fairly fluid lava. The lava material on such plains filled ancient eruption craters and impact basins and depressions, leveling the overall relief.

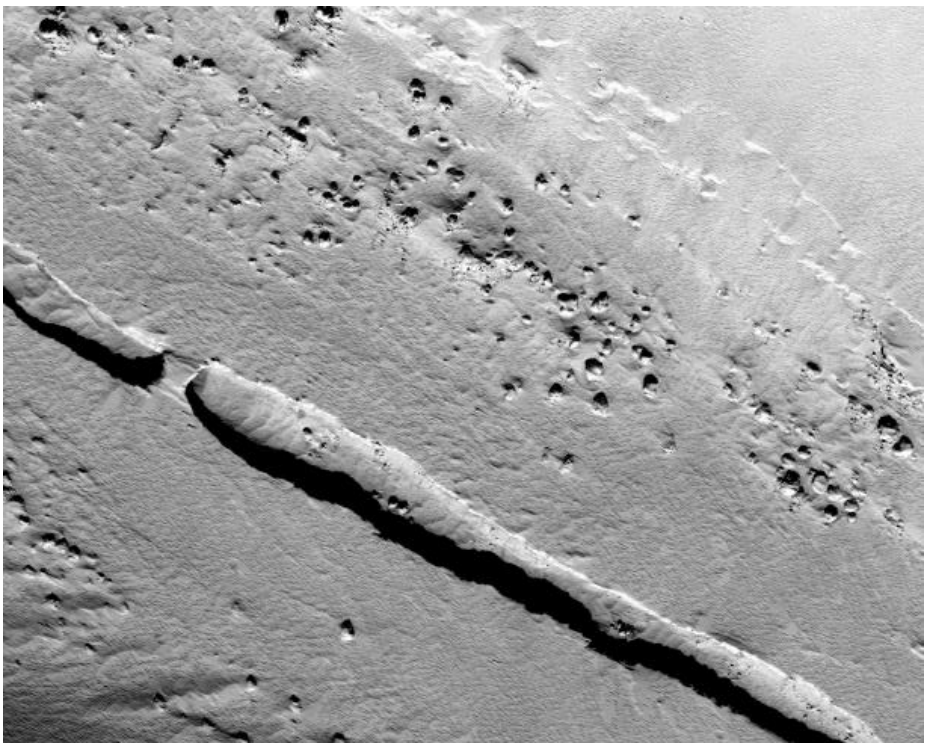


Fig. 4.10. A snapshot of a trough running down the center of a valley in Tartarus Colles region, (https://media-cldnry.s-nbcnews.com/image/upload/t_fit-1000w,f_auto,q_auto:best/MSNBC/Components/Photo/_new/111230-mars-lava-tube-hmed-142p.jpg).

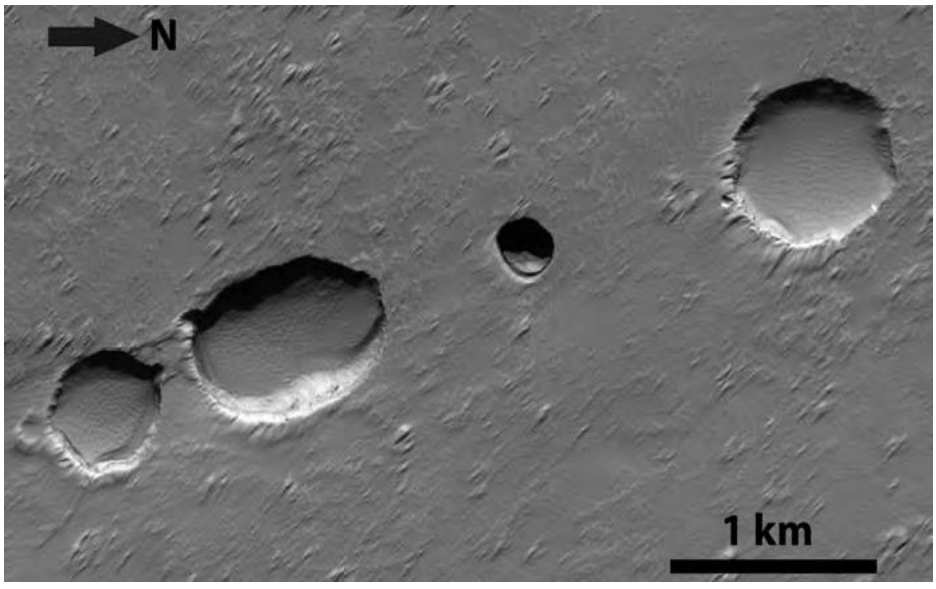


Fig. 4.11. "Light holes" that appeared when part of an underground lava tube collapsed on Mars (https://globalnews.ca/wp-content/uploads/2016/12/3-arsia8.jpg?quality=85&strip=all).

Separate volcanic structures on the Martian surface are volcanic mountains. Among their considerable number, one can distinguish such formations as the gigantic shield volcano Olympus and three other volcanoes in the Tarsis Regio region, such as Mount Askriyska, Pavych and Arsia.

All of them are the highest points on the planet and also dominate the landscape of this region. Many of the channels on the planet's surface were carved, most likely, by water, but not all. After all, molten rocks could also flow and create similar features that resemble the channels of water streams. However, lava behaves somewhat differently from liquid water.

Therefore, for a better understanding of the history of a particular region of Mars, it is very important to identify and distinguish between lava and water channels. After all, Martian lavas are quite fluid. Therefore, the flow coming out of the volcanic vent can spread in a wide layer, which, until it cools and hardens, has the ability to cover large areas. And if the eruption continues further, then the newer lava will have the ability to gradually erode the channels in the lava layer, which is somewhat colder and harder. And such erosion of lava is quite similar in its effect to erosion by water.

One way to distinguish channels formed by lava from channels of water flows is that in the channel formed by water at its bottom you can find sand, small stones, other debris. However, of course, water can also flow through the channel created by lava. So it is not always enough to simply distinguish one type of channel from another. As an example, the Cerberus Fossae region is cited, in the soil of which a rather long crack was found, in which both water and lava were observed. When the lava rose to the surface through cracks in the crust, the lava melted the ice in the soil on its way, which also broke through the cracks to the outside. At the same time, the water flows also eroded its channels.

And when the lava reached the surface, it also had the opportunity to pour out. For the most part, the lava passed through valleys and channels carved by water; however, it could also pour out over completely untouched terrain, covering it with lava for the first time.

4.3. Volcanic caves of Mars.

Careful studies have shown that the shape of impact craters of meteorite origin is significantly different from volcanic craters [24]. The shape of impact craters is almost round; around such craters there is a shaft with an inner and outer terrace. If the craters are large enough, they usually also have central peaks, and sometimes an internal ridge. Volcanic craters, on the other hand, have fairly smooth edges; their surroundings are covered with lava flows and cracks; and they are usually located on the tops of dome-shaped elevations.

The most characteristic volcanic craters are those located on the highest peaks of Mars, such as Olympus, Arsya, Pavonis, and Askraeus [17]. Few recent large impact craters with significant amounts of ejected material have been recorded. The vast majority of them have a very destroyed area with ejected material, which is always covered by later erosional formations [2]. In the early 2000s, seven mysterious dark spots of a rounded shape were first seen in photographs of the Tharsis volcanic plateau obtained by the Mars Odyssey spacecraft [9]. It is on this vast Martian plateau that the peaks of the largest volcanoes in the Solar System are located [29]. And on the slopes of one of them, the Arsia volcano, rather dark depressions were first noticed (Fig. 4.12), called the “Seven Sisters” with the following female names: Wendy, Dana, Jeanne, Abby, Annie, Chloe and Nikki.

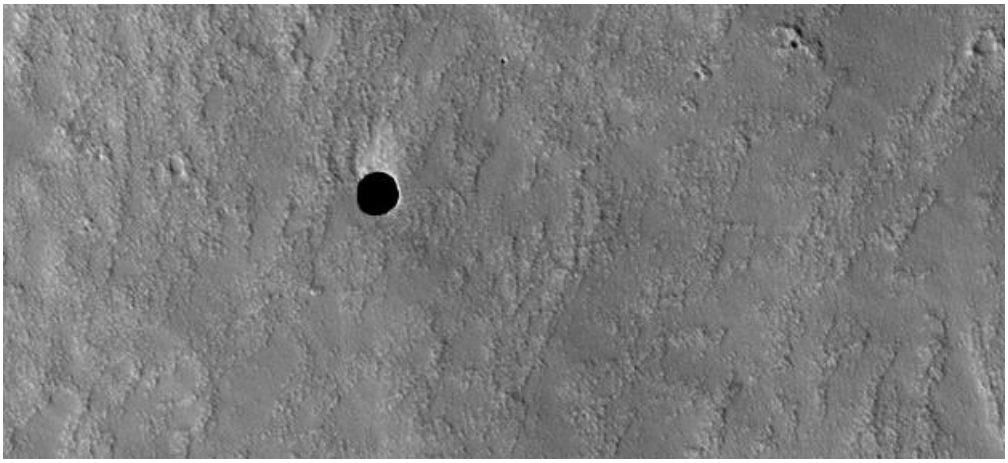


Fig. 4.12. One of the dark spots on the slopes of the Arsia volcano (http://photojournal.jpl.nasa.gov/).

These dark spots on the Martian surface turned out to be sinkholes that could be entrances to extensive caves below the surface. That is, they are sinkholes in the ceiling of these large caves. The hole shown in Fig. 4.12 is 100×150 m in size, and it is very deep, since its bottom is not illuminated by sunlight.

Fig. 4.13 (left) shows the dark Jinn sinkhole with a size of 150×157 m. It also lacks any hint of the existence of a bottom, walls, or outer perimeter wall, which are usually present in classic impact and volcanic craters. This photo was obtained at about noon when the sinkhole was illuminated by vertical rays.

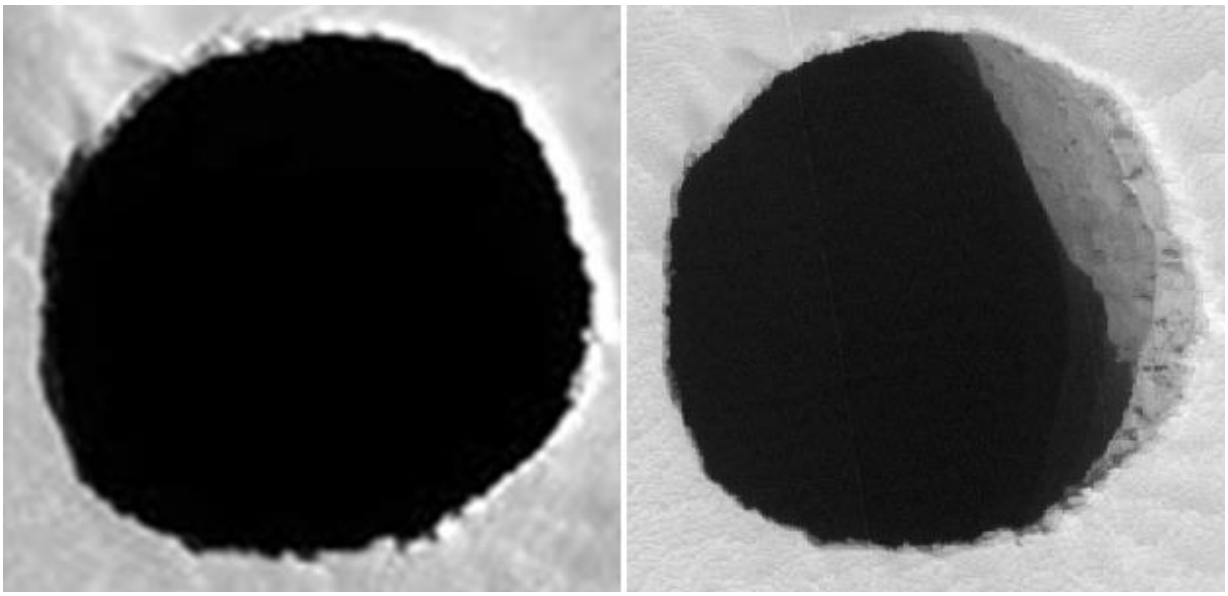


Fig. 4.13. The Jinn Chasm on 08.08.2007 is illuminated – on the left – vertically from above and – on the right – by oblique sunlight (http://photojournal.jpl.nasa.gov/).

In the image in Fig. 4.13 (right), individual details became clearly visible on the eastern walls inside this object due to their illumination by oblique sunlight. This happened when the Sun at the location of the shooting moved somewhat to the west [7, 8]. It is noticeable that in such a place the walls run almost vertically. However, it still remained unclear how deep this chasm is. It was only clear that at a depth of almost 80 m there is still no bottom.

Since in this hole with almost vertical walls the bottom illuminated by the Sun is

still not visible, it becomes clear that it cannot be a simple eroded chasm [24, 35]. Since all the above-mentioned holes were found near volcanic craters on the summit, at the moment of their eruptions, flows of molten lava burn out voids under the surface, which gradually flow down the slopes of the volcano.

Due to certain, for example, as a result of earthquakes, the outer layers of the soil can collapse into previously formed cavities. The photographs in Fig. 35 show depressions with very little eroded and rather sharp edges. They may indicate the youth of these formations.

But it is known that Mars has an atmosphere, albeit a weak one; there the winds constantly move air masses, which constantly fill the newly formed pits with loose soil on the surface [17].

The age of traces of the youngest volcanic activity on Mars is estimated from several tens of thousands to several tens of millions of years; and the age of individual areas on the Tharsis plateau is estimated at 0.5-3 billion years [1].

The diameters of the found sinkholes were in the range of 100-252 m. Their study using infrared photography allowed us to find out that their temperature practically does not change during the day. This speaks in favor of the fact that these sinkholes are a kind of “windows” in the ceiling of volcanic caves.

Images obtained by the Mars Reconnaissance Orbiter spacecraft indicated that similar sinkholes on the surface of Mars were found in other places. They all appear when rock collapses over channels that were formed after lava flows descended.

Now in the province of Tharsis alone, the Mars Reconnaissance Orbiter has discovered more than a hundred such sinkholes of almost cylindrical shape with sharp edges. They have diameters from 50 to almost 350 m. According to the results of observations from the same orbital device, it was possible to detect a significant number of such sinkholes in the region of another volcanic region, somewhat older than the Tharsis region - Elysium. There, near one of the highest volcanoes - the Elysium volcano, 16 km high, many collapse craters were also discovered. Sometimes they are located in the form of peculiar linear formations.

4.4. The main volcanic formations on the surface of Mars.

Tharsis Regio (Fig. 3.5) is the most impressive manifestation of volcanism on Mars. This region is a huge volcanic plateau located not far from the planet's equator. It is located at altitudes of more than 10 km relative to the average level of the Martian surface. Tharsis Regio is one of the most geologically significant regions on Mars. It has unique features, which include the highest volcanoes in the Solar System and many signs of rich and long-term geological activity.

Let's consider the geographical location of the Tharsis Province, its geological composition, geomorphological features, as well as space missions that have explored this region. This vast plateau, covering an area of about 4 million square kilometers, is located around the Martian equator between latitudes 30°N and 30°S, and extends in longitude from 70° to 135°W. Due to its large scale and location near the equator, Tharsis Regio serves as one of the key places for a deeper understanding of ancient hydrological cycles, features of the planet's tectonic history [22] and Martian geology. The surface of the Tharsis Province is formed mainly by basaltic lava flows. This emphasizes that this region is of predominantly volcanic origin. Many space missions have used spectroscopic methods to study it. They have allowed to detect various minerals on its surface; among them, iron oxides, olivines and pyroxenes were found.

The range of mineral formations indicated indicates a variety of magmatic sources, which indicate the presence of different styles and numerous phases of volcanic activity. Sulfates and clays have also been found in some areas of the Tharsis Province. Recall that these minerals indicate their interaction in the distant past with liquid water. This fact significantly enriches the geological history of this province. This territory is further complicated by the presence of huge shield volcanoes on it. After all, they demonstrate a great variety of geological formations, which include vents in cracks, extensive calderas and quite complex networks of lava tubes. Among the rather important findings in the Tharsis Regio area are the huge and rather long-lasting scales in its volcanic activity. For example, Mount Olympus (Fig. 4.14) is powerful evidence of the action of colossal volcanic processes, which, with repeated eruptions over time, led to the fact that this volcano became the highest and most

extensive shield volcano in the entire Solar System.

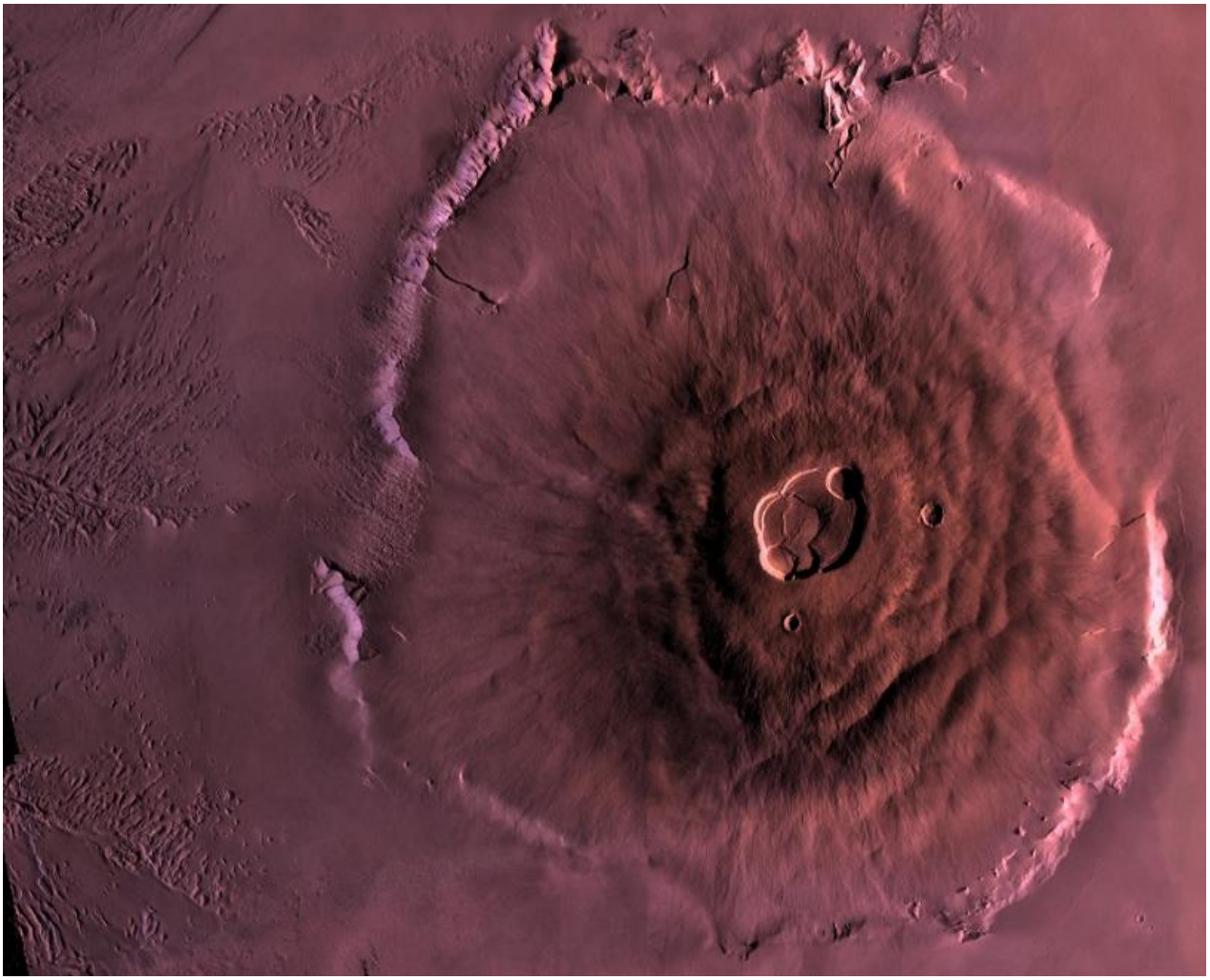


Fig. 4.14. Volcano Olympus (https://www.whiteclouds.com/wp-content/uploads/2023/09/Olympus-Mons.jpg).

The Tharsis Province is also a hotbed of intense tectonic activity. It is here that a complex network of large cracks, deep faults, and rift zones is located. These features of the relief are convincing evidence that in this area the crust on Mars has undergone enormous deformations. Such tectonic features lead to the formulation of a number of questions regarding the features of the internal structure of this planet and the mechanical properties of its crust. In some parts of the Tharsis Regio, geomorphological features are also manifested, which indicate the former activity of water resources in this area [15, 22, 27, 31, 44].

Among them, we can point out the remains of structures that are similar to ancient

river valleys and the bottom of several lake basins. The Viking 1 and Viking 2 missions managed to obtain detailed images of Tharsis Regio. Another mission, Mars Global Surveyor, used advanced topographic instruments to provide complex models to explain the features of the area.

The Mars Reconnaissance Orbiter was equipped with advanced systems for detailed visualization with a fairly high spatial resolution and several instruments that allowed spectroscopic observations [26, 27, 29].

The work of these instruments allowed us to decipher the geological features and mineralogical composition of the surface in Tharsis Regio, identifying many different minerals. In this place on the Martian surface, the landscape features are dominated by shield volcanoes with fairly gentle slopes, which could have been formed by slow lava flows with fairly high fluidity.

The large number of rift valleys, cracks, and calderas may indicate a high level of complexity of this region. After all, these relief elements indicate a combination of tectonic forces and volcanic formations. They led to the formation of the largest volcanoes in the entire Solar System in this region. For example, Olympus Mons is the highest mountain in the Solar System and the most famous volcano on Mars.

Its height is almost 21.9 km above the average level of the Martian surface, or 27 km from its base to the summit. The diameter of its base is more than 600 km. At the summit of the Olympus volcano is a rather complex caldera, which is a complex complex of six nested calderas that form an irregular depression with dimensions of 85□60 km and a depth of up to 3.2 km, formed after the eruption; that is, it consists of several craters that overlap in places (Fig. 4.15). Along the edges of this volcano are steep ledges (or escarpments), the height of which in some places reaches 8 km.

Other volcanoes in Tharsis Regio – Tharsis Montes – are located in a chain to the southeast of Olympus volcano; they are a group of three also very large shield volcanoes. These include Ascraeus Mons, Pavonis Mons and Arsia Mons. The diameter of the base of each of them is several hundred kilometers, and the height is from 14 to 18 km above the mean level.



Fig. 4.15. View of the caldera of Olympus volcano with several craters in its middle (http://upload.wikimedia.org/wikipedia/commons/e/eb/Olympus_Mons_caldeira.png)

The southernmost of the three Tharsis Montes volcanoes, Arsia Mons, is located near the equator, has the widest caldera with a diameter of about 130 km and a depth of 1.3 km. Its height is about 11.7 km, and its diameter is 435 km. Arsia Mons is considered the second largest volcano on Mars after Olympus Mons by volume. Ascraeus Mons, located in the central part of the Tharsis Uplift, is the northernmost and highest of the three shield volcanoes known as the Tharsis Mountains. Its height is about 18.1 km above the Martian mean sea level. This makes it the second highest mountain on Mars. Ascraeus Mons is approximately 480 km in diameter. The volcano's summit is dominated by a caldera complex consisting of a central caldera about 24 km in diameter and 3.4 km deep, surrounded by four smaller, merged calderas.

From the northeast and southwest edges of the volcano, extensive lava flows extend more than 100 km into the surrounding plains, giving the volcano an overall size of about 375 by 870 km, if included in its structure. Pavonis Mons is a medium-sized volcano in the Tharsis Montes chain, also located near the equator. It rises 8.7 km above mean sea level and has a diameter of about 375 km. At the summit of Pavonis Mons is a deep, circular caldera with a diameter of 47 km and a depth of almost 5 km. To the northeast of it is a slightly larger, about 90 km in diameter, but less deep, but more complex, depression.

Alba Mons is located in the northern Tharsis region (see Fig. 3.5). It is the largest volcano on Mars by area, with gentle lava flows that extend at least 1350 km from its summit.

Despite its enormous size, its maximum height is only 6.8 km. This volcano has an oval central part measuring approximately 1500 by 1000 km, surrounded by a wide, almost flat belt of lava flows that extend outward for more than 1000 km.

4.5. Volcanic features in the Elysium Planitia region.

The Elysium Planitia region is the second largest volcanic region on Mars (Fig. 4.16). It is located significantly west of the Tharsis Province. Several volcanoes of quite large size have also been found there, although somewhat smaller than the gigantic features in the Tharsis Regio.

This map shows the main features of the relief around the Elysium Mons mountain range, the landing site of the “InSight” lander (designated NSY) [4], the “Viking Lander” 2 lander (VL2), the “Mars Science Laboratory” (MSL) “Curiosity” rover in Gale crater, and the “Mars Exploration Rover” (MER) “Spirit” in Gusev crater. “InSight” is notable for landing on the surface almost at the boundary between the heavily cratered highlands to the south and the lowlands to the north.

Elysium Mons is the most massive volcano in the Elysium Planitia region; it is about 12.6 km above its base and about 240 km in diameter. At its summit is a caldera of about 14 km in diameter.

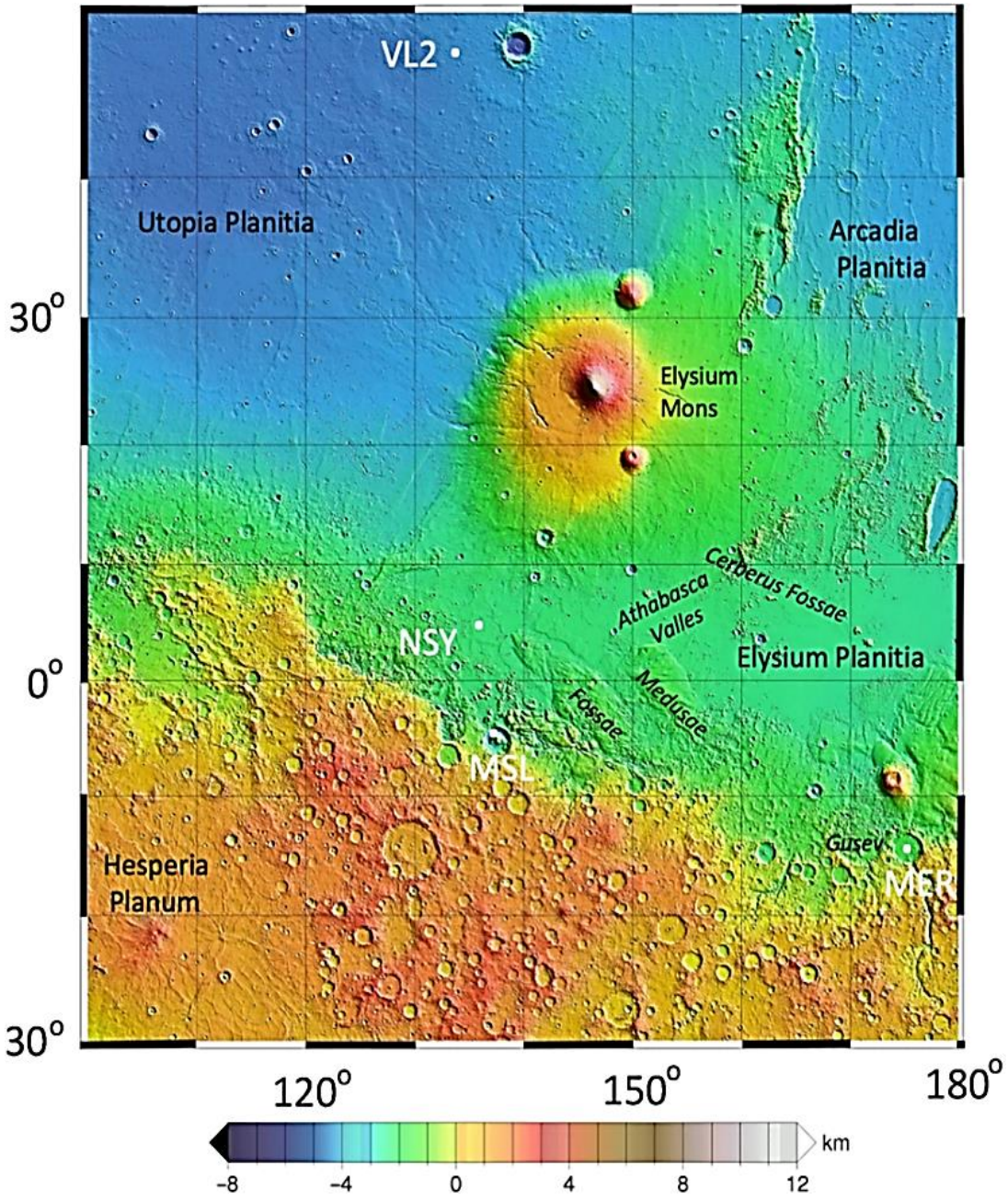


Fig. 4.16. The Elysium Planitia Volcanic Region is the second largest on Mars after Tharsis Regio (https://media.springernature.com/full/springer-static/image/art%3A10.1038%2Fs41467-020-14679-1/MediaObjects/41467_2020_14679_Fig1_HTML.png?as=webp).

Elysium Mons is surrounded by smaller volcanoes: Hecate Tholus to the northeast and Albor Tholus to the southeast. Hecate Tholus, located in the Elysium Volcanic Province; it is the northernmost of the volcanoes in the Elysium Province. Its diameter is 182 km. On the western slope of the volcano is a caldera 10 km in diameter, formed by an eruption about 350 million years ago. Albor Tholus is another volcano in the

Elysium Province. It is located south of the volcanoes Elysium Mons and Hecate Tholus. It is 4.5 km high and 160 km in diameter at its base. Albor Tholus has a caldera 30 km in diameter and 3 km deep; this is a significant depth compared to calderas on Earth.

Analysis of the terrain of the Elysium Planitia plain shows that volcanic lava flows from the Elysium Mons volcano should have flowed in a southerly direction, and on the east side of the lander, the location of very young lava flows over 150 km long, which flowed from Cerberus Fossae down the Athabasca Valles valley, is visible. Studies from the InSight lander were aimed at studying the internal structure of Mars. Therefore, the choice of this landing site was oriented towards the fairly flat surface of the Elysium Planitia plain.

The center of the InSight landing site has coordinates 4.5ºN, 135.9ºE; This is almost 600 km from the location of the Curiosity rover in Gale Crater. Therefore, immediately after the launch of the mission in May 2018, throughout the entire flight to Mars, it was the European Space Agency (ESA) that supported the InSight mission with a network of its ground stations.

The Elysium Planitia region is characterized by a rather complex geological history. It has a rather diverse and multifaceted relief structure [21, 24] and geological formations, which are an example of the rich geological history of Mars. After all, this region contains many volcanic plains bordering extensive, winding lava flows and materials that are predominantly basaltic in origin.

All of them indicate active past volcanic activity, which left noticeable traces behind. Witnesses of this tectonic history are a large number of faults and cracks that cross the now fairly flat surface. These features are evidence of the interaction between stresses in the Martian crust and volcanic formations that have shaped the existing landscape of the planet's surface over many millennia.

The geological history of the formation of the Elysium Planitia plain complex was also influenced by aeolian and fluvial processes. Ancient river channels and so-called dust devils [3, 8, 10b 45] have made their additional contribution to the geological and ecological history of Mars. The study of these features allows us to reveal historical

climate changes [21, 26, 34, 43, 44] and understand past geological processes.

Radar studies conducted by scientific instruments using advanced technological tools on several spacecraft have revealed large volumes of water ice deposits under the Martian crust, which are located below the surface of the planet in the Elysium Planitia region. This discovery has improved our understanding of the rather complex hydrological cycles on Mars and has revealed the peculiarities of the presence of ancient water resources and their potential participation in the formation of various forms of life [19, 20, 25-28].

The presence of numerous impact craters of various sizes there, and the study of the morphology of surface formations on the Elysium Planitia plain, have allowed us to delve into the chronology of evolution, geological changes, and also climatic changes [17, 21, 24] that occurred on the surface of Mars over many millions of years.

This plain, Elysium Planitia, has been studied by several scientific missions, each of which has attempted to decipher the ecological and geological mysteries characteristic of this Martian plain. For example, the main goal of the NASA mission "InSight" was to study seismic activity [18] and measure thermal [14, 22, 36] flows from the Martian interior to better understand the dynamics of tectonic activity, internal structure and geological processes that have shaped and continue to shape the interior of Mars.

The results obtained by the mission "InSight" were one of the decisive ones in building a comprehensive model of the geology of Mars.

With the help of the spacecraft "Mars Reconnaissance Orbiter" detailed mapping and study of geological features on the plain Elysium Planitia was carried out. It was for this space mission that several tools and devices were developed that allowed us to expand our knowledge of the geological composition and study the history of changes in this region.

The European Space Agency's Mars Express mission has deepened our understanding of the subsurface structure of Elysium Planitia and the morphological characteristics on the visible surface. The information obtained with the help of the Mars Express spacecraft has allowed us to improve our understanding of the vertical

structure under the Martian surface, to investigate the peculiarities of the interaction of the planet's atmosphere [8, 16] with surface processes, etc.

Each of the geomorphological features on the Elysium Planitia plain speaks of a specific type of geological history of this region. For example, extensive volcanic plains dominate the entire landscape of the plain. They are evidence of ancient volcanic activity that once shaped this region. Therefore, this plain is a kind of repository that preserves the features of past processes, the history of a significant number of eruptions that have shaped this region on the surface of Mars over time.

And the study of this plain is crucial in reconstructing the historical changes on the planet, allowing us to reflect the evolution and climatic changes on Mars.

The presence of cracks and fissures on the surface of Elysium Planitia indicates intense tectonic dynamics in this region, preserving the history of crustal deformation, tectonic plate displacements under the planet's surface, and relief formations caused by stresses in the crust. And space missions to the Elysium Planitia plain have significantly expanded our understanding of the internal structure of Mars, geological processes, and environmental conditions.

References:

1. Bibring J.-P., Langevin Y., MustardJohn Y. F., et al (2006) Global mineralogical and aqueous mars history derived from OMEGA/Mars express data. *Science*. 312, p. 400-404.

2. Connerney J.E.P., Acuńa M.H., Wasilewski P., et al. (1999) Magnetic Lineations in the ancient crust of Mars. *Science*. 284(5415), p. 794-798.

3. Fisher J.A., Richardson M.I., Newman C.E., et al. (2005) A survey of Martian dust devil activity using Mars Global Surveyor Mars Orbiter Camera images. J. *Geophys. Res*. 110(E3), p. 3-4.

4. Hartmann W.K. (1973) Martian Cratering. Mariner 9 initial analysis of cratering chronology. *Journal of Geophysical Research: Solid Earth*. 78(20), p. 4096-4116.

5. Kerzhanovich V.V. (1977) Mars 6: improved analysis of the descent module measurements. *Icarus*. 30(1), p. 1-25.

6. Leighton R.B., Horowitz N.H., Murray B.C., et al. (1969) Mariner 6 television pictures: first report. *Science*. 165(3894), p. 684-690.

7. Morozhenko A.V., Vid'machenko A.P. (2005) Polarimetry and Physics of Solar System Bodies. Photopolarimetry in Remote Sensing, NATO Science Series II: Mathematics, Physics and Chemistry. 161, p 369-384.

8. Morozhenko A.V., Vidmachenko A.P. (2017) Optical Parameters of Martian Dust and Its Influence on the Exploration of Mars. Dust in the Atmosphere of Mars and Its Impact on Human Exploration, Proceedings of the conference held 13-15 June 2017 in Houston, Texas. LPICo No. 1966, 2017, id.6010.

9. Morozhenko A.V., Vidmachenko A.P. (2017) What and how can affect the exploration of Mars. 19 International Scientific Conference Astronomical School of Young Scientists. May 24-25, 2017. Bila Tserkva, Ukraine. P. 67-69.

10. Morozhenko A.V., Vidmachenko A.P. (2020) Dust can affect on the mastering of Mars. 22 International scientific conference Astronomical School of Young Scientists. December 11-12, 2020. Kyiv, Ukraine. P. 71-73.

11. Morozhenko A.V., Vidmachenko A.P., Kostogryz N.M. (2015) Spectrophotometric properties of Moon's and Mars's surfaces exploration by shadow mechanism. *Highlights of Astronomy*. 6, p. 182-182.

12. Mouginis-Mark P. (1979) Martian fluidized crater morphology: Variations with crater size, latitude, altitude, and target material. *Journal of Geophysical Research: Solid Earth*. 84(B14), p.8011-8022.

13. Murchie S.L., Mustard J.F., Ehlmann B.L., et al. (2009) A synthesis of Martian aqueous mineralogy after 1 Mars year of observations from the Mars Reconnaissance Orbiter. *Journal of Geophysical Research: Planets*. 114(IssueE2). E00D06. P. 1-30.

14. Pollack J.B., Kasting J.F., Richardson S.M., Poliakoff K. (1987) The case for a wet, warm climate on early Mars. *Icarus*. 71(2), p. 203-224.

15. Rummel J.D., McKay C.P. (2017) Water on Mars: A Status Report and Suggestions for Further Study. 48th Lunar and Planetary Science Conference, held 20-24 March 2017, at The Woodlands, Texas. LPICo No. 1964, id.2945.

16. Schmidt F., Chassefière E., Tian F., et al. (2016) Early Mars volcanic sulfur storage in the upper cryosphere and formation of transient SO2-rich atmospheres during the Hesperian. *Meteoritics & Planetary Science*. 51(11), p. 2226-2233.

17. Sexton M.R., Elwood Madden M.E., Swindle A.L., et al. (2017) Considering the formation of hematite spherules on Mars by freezing aqueous hematite nanoparticle suspensions. *Icarus*. 286, p. 202-211.

18. Sleep N.H. (1994) Martian Plate Tectonics. J. *Geophys. Res*. 99(E3), p. 5639-5655.

19. Steklov A.F., Vidmachenko A.P. (2019) In What Places and What Exactly Can be the" Traces" of Life on Mars? 9th International Conf. on Mars. 2089, 6007.

20. Steklov A.F., Vidmachenko A.P. (2019) Where and What Exactly Can Be the “Traces” of Life on Mars? Mars Extant Life: What's Next? Held 5-8 November 2019, in Carlsbad, New Mexico. LPI Contribution No. 2108, 2019, id.5089.

21. Vidmachenko A.P. (2009) Research of the Mars by space vehicles. 11 International Scientific Conference Astronomical School of Young Scientists, May 26-29, 2009, Kherson, Ukraine. P. 11-12.

22. Vidmachenko A.P. (2009) Water on Mars. Astron. almanac. 56, p. 225-249.

23. Vidmachenko A.P. (2014) Study of Earth-like planets. 16 International Scientific Conference Astronomical School of Young Scientists. Kirovohrad, Ukraine. May 29–31, 2014. P. 12-13.

24. Vidmachenko A.P. (2016) Activity of processes on the visible surfaces of Solar System bodies. *Astronomical School’s Report*. 12(2), p. 14-26.

25. Vidmachenko A.P. (2016) Is there life on Mars and where necessary to search for its traces. Astronomy and present: materials of 5 International Scientific Conference , April 12, 2016, Vinnytsia, Ukraine. / Science ed A.V. Mozhovyi. Vinnytsia: FOP “NP Kostiuk”. P. 43-48.

26. Vidmachenko A.P. (2016) Processes on the “young” Mars: possible developments of events. 18 International Scientific Conference Astronomical School of Young Scientists. National Aviation University, Kyiv, Ukraine, May 26-27, 2016. P. 16-17.

27. Vidmachenko A.P. (2016) Traces of life on Mars must be sought around the valley Hellas in areas where the water coming out from under the planet's surface. 18 International Scientific Conference Astronomical School of Young Scientists. Kyiv, Ukraine, May 26-27, p. 14-16.

28. Vidmachenko A.P. (2016) Where is Necessary to Search Traces of Life on Mars? Biosignature Preservation and Detection in Mars Analog Environments, Proceedings of a conference held May 16-18, 2016, in Lake Tahoe, Nevada. LPI Contribution No. 1912, id.2002.

29. Vidmachenko A.P. (2018) Comparative features of volcanoes on Solar system bodies. 20 International Scientific Conference Astronomical School of Young Scientists. May 23–24, 2018. Uman, Ukraine, p. 9-12.

30. Vidmachenko A.P. (2018) Features of volcanic activity on various bodies of the Solar system. Materials of the International Scientific and Practical Conference The Objectives of the Sustainable Development of the Third Millennium: Challenges for Universities of Life Sciences, 5, May 23-25, Kyiv, p. 41-42.

31. Vidmachenko A.P. (2019) Traces of Martian Life Should be Sought in Places Around Hellas Crater, Where Water has Recently Spilled Out onto the Surface. Ninth International Conference on Mars, Pasadena, California, Jul 22-25, 2019, LPI Contrib. No. 2089, 6005.

32. Vidmachenko A.P. (2023) About volcanoes on Mars. Proceedings of 11 All-Ukrainian Scientific Conference “Astronomy and present day”, April 12, 2023. Vinnytsia, Ukraine. LLC "TVORY". ISBN 978-617-552-363-6. P. 76-81.

33. Vidmachenko A.P. (2023) Comparison of features of impact and volcanic craters on the surface of Mars. Proceedings of VIII International Scientific and Practical Conference. Progressive research in the modern world (April 27-29). P. 237-246.

34. Vidmachenko A.P. (2023) History of possible climate change on Mars. Proceedings of VII International Scientific and Practical Conference. Science and innovation of modern world. (23-25 March 2023). Chapter 54. Cognum Publishing House, London, United Kingdom, p. 336-345.

35. Vidmachenko A.P. (2023) Macrorelief of the surface of Mars. Proceedings of XIV International Scientific and Practical Conference . Prospects for the development of science and the environment. (April 10-12, 2023). Chapter 7. P. 34-39.

36. Vidmachenko A.P. (2023) Thermal properties of the surface of Mars. Proceedings of VII International Scientific and Practical Conference. Progressive research in the modern world (March 29-31, 2023). Chapter 42. P. 243-252.

37. Vidmachenko A.P., Klimenko V.M., Morozhenko A.V. (1981) Apparent spectral albedos of the disk of Mars in September-October 1977. *Solar System Research*. 14(4), p. 157-159.

38. Vidmachenko A.P., Morozhenko O.V. (2014) The physical characteristics of surface Earth-like planets, dwarf and small (asteroids) planets, and their companions, according to distance studies. Main Astronomical Observatory NAS of Ukraine, National University of Life and Environmental Sciences of Ukraine. Kyiv, Publishing House "Profi". -388 p.

39. Vidmachenko A.P., Morozhenko A.V. (2014) The study Earth-like planets using spacecraft. *Astronomical School's Report*. 10 (1), p. 6-19.

40. Vidmachenko A.P., Morozhenko O.V. (2019) Physical parameters of terrestrial planets and their satellites. Kyiv, EP Department of NULESU. -468 p.

41. Vidmachenko A.P., Mozghovyi O.V., Steklov O.F. (2023) About volcanoes on Mars. Proceedings of 11 All-Ukrainian Scientific Conference “Astronomy and present day”, April 12, 2023. Vinnytsia, Ukraine. LLC "TVORY", p. 76-81.

42. Vidmachenko A.P., Mozghovyi O.V., Steklov O.F. (2023) Features of the relief on the surface of Mars. Proceedings of 11 All-Ukrainian Scientific Conference “Astronomy and present day”, April 12, 2023. Vinnytsia, Ukraine. LLC "TVORY". P. 66-71.

43. Vidmachenko A.P., Mozghovyi O.V., Steklov O.F. (2023) Historical aspects of climate changes on Mars. Proceedings of 11 All-Ukrainian SCo “Astronomy and present day”, April 12, 2023. Vinnytsia, Ukraine. LLC "TVORY". P. 56-61.

44. Vidmachenko A.P., Steklov A.F. (2022) How long ago has water flowed on Mars surface? Results of modern scientific research and development. Proceedings of XI International Scientific and Practical Conference. Barca Academy Publishing, Madrid, Spain. 16-18.01.2022. P. 226-232.

45. Wang H. (2017) Major dust storms and westward traveling waves on Mars. *Geophysical Research Letters*. 44(8), p. 3493-3501.

DOI: 10.46299/979-8-90671-552-4.5

5. The influence of volcanism on the formation of the relief of the surface of Mars.

5.1. On the connection of volcanism in the Tharsis Regio with the formation of Valles Marineris.

One of the most dramatic examples of the impact of volcanism on the geology of Mars is the possible connection between the formation of the Tharsis Regio volcanic region and the formation of the vast Valles Marineris canyon system (Fig. 5.1).

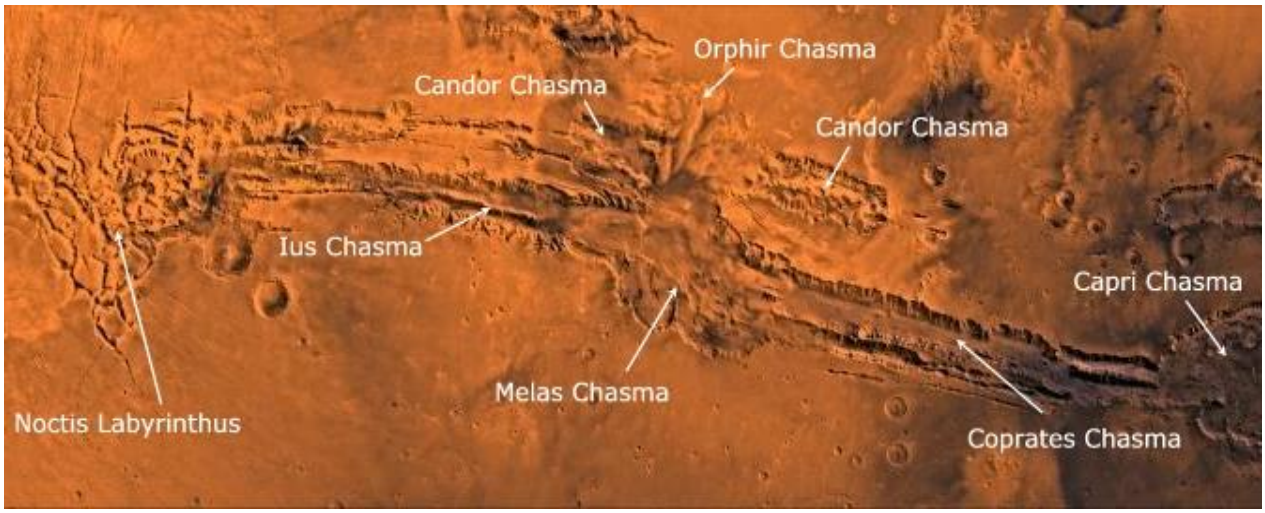


Fig. 5.1. Valles Marineris canyon systems with names of individual parts (https://dic.academic.ru/pictures/wiki/files/118/vallesmarinerisnames.jpg).

This canyon system is located around the equator and extends from the Noctis Labyrinthus region to the region with chaotic relief, from east to west for more than 4000 km, from south to north – for 700 km, reaches a depth of up to 8 km and is one of the largest in the entire Solar System. Many huge ancient river channels begin their journey from the region with chaotic relief, stretching northward. The faintly bright, bluish areas in Fig. 5.2 show cloud formations that are in the atmosphere of Mars [3, 8, 11, 15, 32]. The deep regions of Valles Marineris are also shrouded in haze and fog, which forms near the surface in vast Martian depressions.

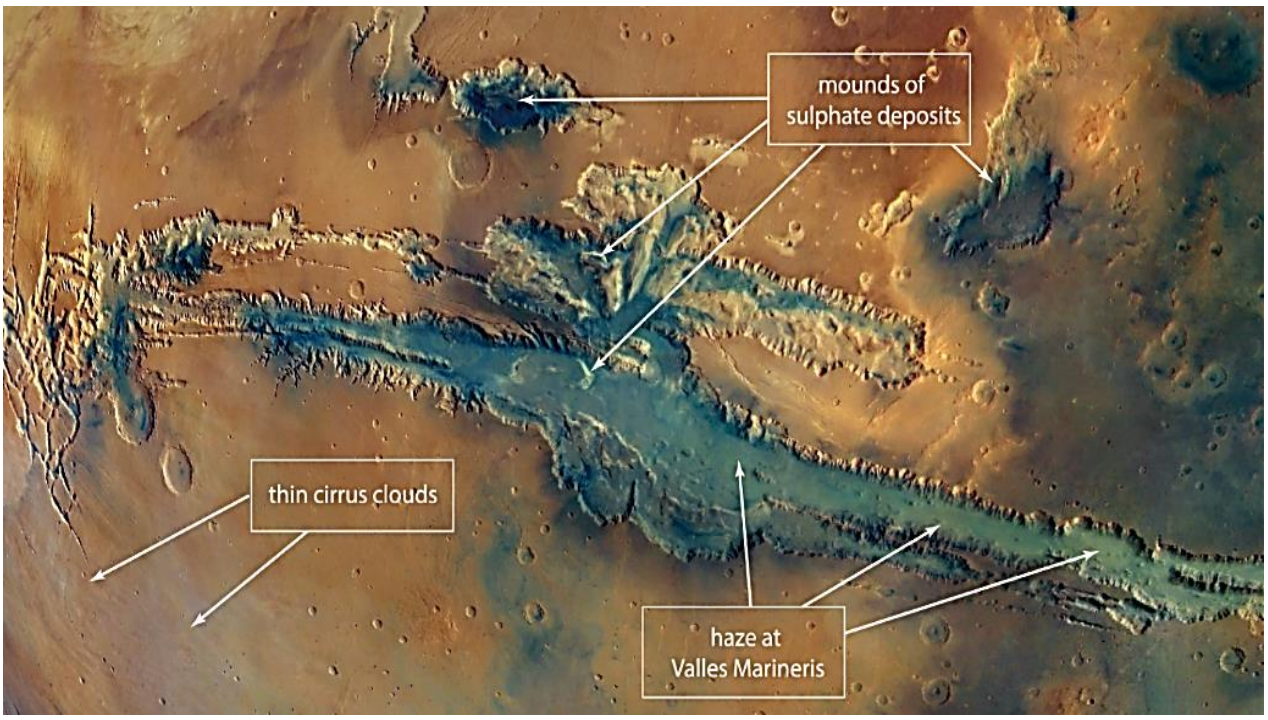


Fig. 5.2. Mosaic of the canyon system near Valles Marineris with surface details marked: sulfate deposits, haze, fog, and cloud cover (https://www.esa.int/var/esa/storage/images/esa_multimedia/images/2023/05/close-up_of_valles_marineris_from_global_mars_colour_mosaic_annotated/24894597-4-eng-GB/Close-up_of_Valles_Marineris_from_global_Mars_colour_mosaic_annotated_pillars.png).

Valles Marineris is believed to have formed primarily through tectonic processes [18], directly caused by the formation and enormous mass of the Tharsis Plateau. The mechanism for this connection may be as follows.

The long-term volcanic activity [25] led to the accumulation of a colossal mass of volcanic rocks in the Tharsis Regio province, creating enormous loads on the lithosphere. Such a mass should have caused significant compressive and tensile stresses in the surrounding part of the planetary crust; especially to the east of the highlands. Therefore, the lithosphere literally bent under the weight of Tharsis Regio and stretched significantly at the edges.

These tensile stresses significantly exceeded the strength of the planetary crust, and this caused it to crack and form a system of giant parallel grabens; that is, to the lowering of entire blocks of crust between faults.

Noctis Labyrinthus, located at the western end of the Valles Marineris valley, with its chaotically scattered network of canyons, is considered a vivid example of the initial stage of such cracking. The earliest tectonic cracks and grabens were subsequently significantly widened and deepened under the influence of various erosional processes (Fig. 5.3).

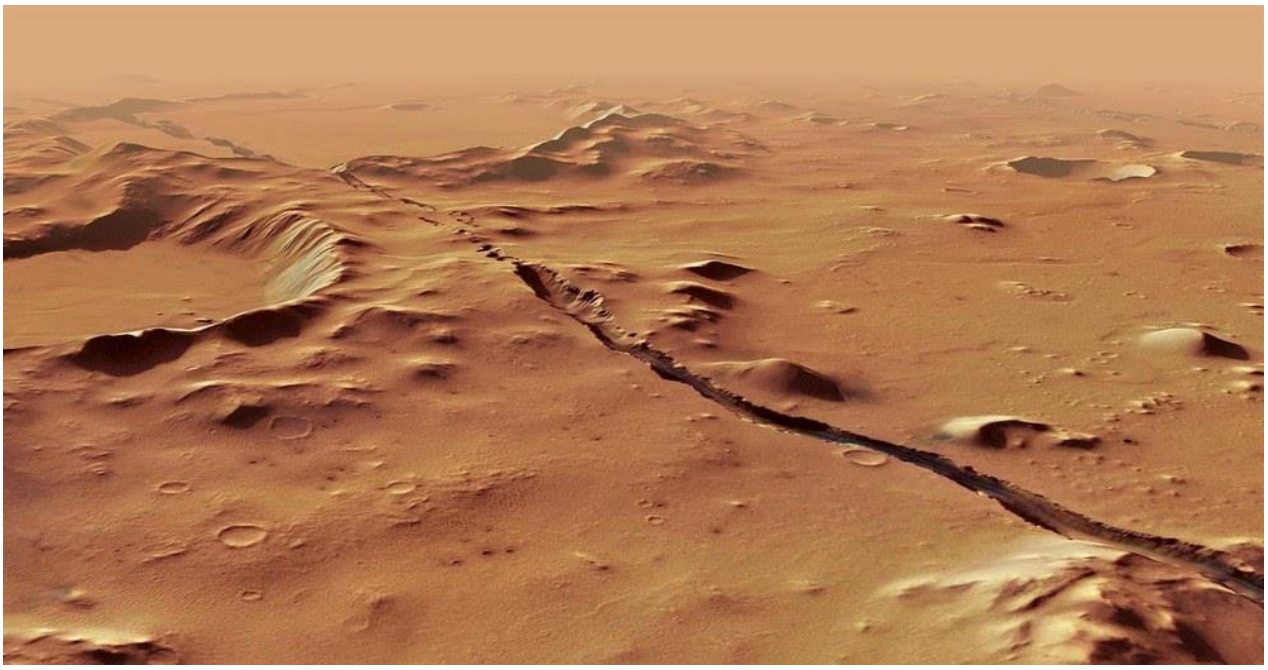


Fig. 5.3. Perspective view from southeast to northwest over the young tectonic rifts of Cerberus Fossae, several thousand kilometers long (https://www.dlr.de/en/images/2018/3/view-south-east-to-north-west-cerberus-fossae/@@images/image-1000-809458fcb55e124e5352b685fe0f2d01.jpeg).

These include massive collapses on canyon walls, wind erosion, and the possible influence of liquid water [16, 23, 27, 45] on the early history of Mars [21, 30, 43], which could have flowed along faults from subsurface horizons.

That is, the formation of the Tharsis Regio highlands was not some local phenomenon of volcanic activity, but an event of a planetary scale that could fundamentally change the global geology and general topography of Mars. A direct consequence of this event was the formation of the Valles Marineris valley, which became evidence of the colossal forces that operated in the Martian crust. The

landscape in the Cerberus Fossae region looks as if it had been cut by a blade. According to various estimates, these tectonic, crack-like structures were formed less than 100 million years ago, and possibly even less than 10 million years ago.

This is evident from their profiles, which are bounded by very steep, and sometimes almost perpendicular walls, the height of which in places is more than 500 meters. On the Elysium Planitia plain [7] all the elongated cracks of the Cerberus Fossae extend only from northwest to southeast.

The forces that caused such a rupture of the planetary crust must have acted perpendicular to this direction. The smooth areas of the surface are composed of solidified lava with very low viscosity. And the small number of impact craters [10, 12] on their surface indicates that volcanic eruptions could have occurred in the very recent geological past. This makes the equatorial Cerberus Fossae region one of the geologically youngest structures on the planet Mars.

5.2. More about the types and sizes of volcanoes on Mars.

In addition to the two main provinces, there are other significant volcanic formations on Mars. The Hadriacus Mons volcano, located in the Hellas Planitia region, is distinguished by its shallow, wide crater, resembling an ancient amphitheater. The ancient Tyrrhena Patera volcano is located in the southern hemisphere of Mars, northeast of the Hellas Planitia plain. It is considered one of the oldest volcanoes on the planet, having the form of a shield volcano with a flat top - a patera. Its slopes are cut by numerous valleys; this indicates erosion caused by either water or winds over a very long time.

More recently, on the eastern edge of Tharsis Regio in the Noctis Labyrinthus region, located south of the equator, the existence of another large, although very heavily eroded volcano, called Noctis Volcano (Fig. 5.4), has been indicated. It has a height of over 9.022 km and a width at the base of about 450 km. That is, this volcano is somewhat smaller than its neighbors; however, it has a significant diameter at its base and its slopes are significantly more destroyed by erosion.

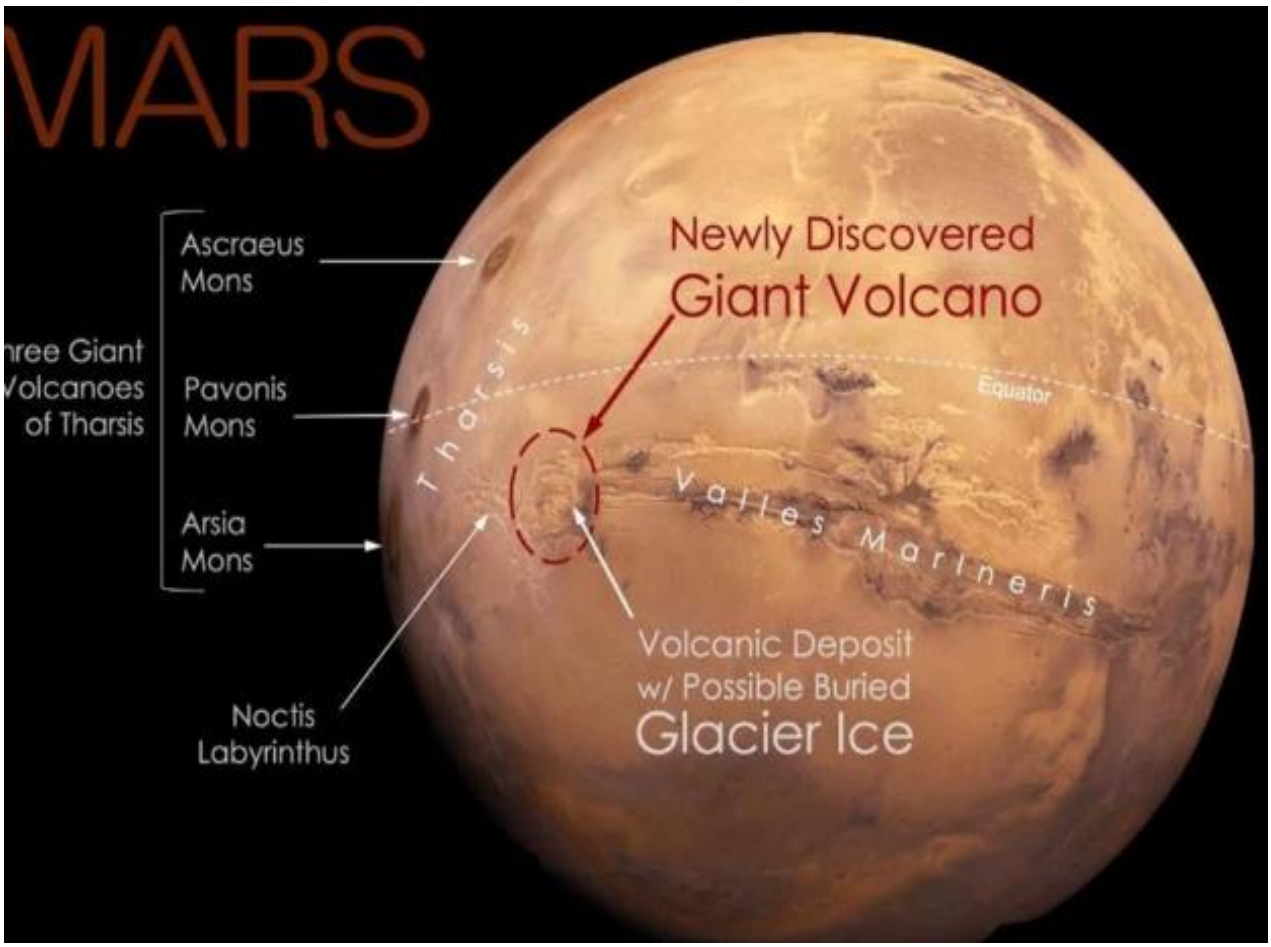


Fig. 5.4. Location of a recently discovered giant volcano on the surface of Mars (https://nauka.gov.ua/media/images/vulkan_2.width-800.png).

The enormous size of this volcano and its significantly changed relief [31, 36] indicate that it was active quite a long time ago and for a fairly long period of time. A thin layer of relatively recent volcanic sediments was found in its southeastern part, under which, perhaps, there was water ice [20, 26]. Indeed, a wide variety of hydrated minerals [4, 6, 13, 44] were found on this part of the Martian surface, which were formed over a long period of Martian history [22]. The volcanic origin of such minerals [1, 2] has been indicated for a long time.

A vast area with a large number of volcanic deposits was discovered along the perimeter of this volcano. These low mounds have a rounded, somewhat elongated shape. This type of terrain could have been formed as a result of explosive type of water vapor emissions, provided that a thin layer of highly heated volcanic material would cover a surface rich in water or ice.

In addition, in this volcanic terrain, through one of the erosion holes of considerable size, it was possible to find the remains of an ancient glacier. It was found a light deposit of sulfate salt and with morphological signs of a glacial structure [17]; it is such signs that usually indicate the possibility of the presence of a thick layer of water ice under the frozen cover of volcanic emissions [33].

Martian volcanoes mainly belong to the type of so-called shield volcanoes [24, 28, 29, 41]. These volcanoes are formed as a result of the eruption of large volumes of liquid basaltic lava, which spreads over considerable distances. This is how broad, gentle slopes with angles of inclination that do not exceed 5-7 degrees were formed.

The summits of shield volcanoes are often located calderas - large depressions formed by the collapse of the surface after the eruption of magma. In many Martian volcanoes, calderas are complex, which may consist of several nested depressions. This indicates multiple episodes of eruptions and collapses. The diverse morphology of Martian volcanoes, from the classic shield shape of Olympus Mons and other Tharsis Regio mountains to the heavily eroded appearance of Noctis volcano and the low profile of Alba Mons volcano, is the result of variations in eruption styles, lava composition and the degree of subsequent alteration.

Alba Mons – is a unique shield volcano with an extremely low profile (height about 6.8 km) and enormous dimensions at the base (width spanning over 1000 km). This makes it one of the most interesting geological formations in the Solar System. The low profile is due to the eruption of very liquid lava, which spread over vast distances, forming wide, rather than high, volcanic structures. Its surface is covered with lava flows, channels, and tectonic faults. Alba Mons is an example of the large-scale, but very "flat" volcanism that is also characteristic of the Martian Tharsis Regio.

Note that different types of volcanoes are formed by different geological processes and evolve over time under the influence of erosion, tectonic activity, and subsequent volcanic events. The presence of calderas, often nested or composed of several, at the summits of many Martian volcanoes indicates multiple phases of volcanic activity and the dynamics of magma chambers within individual volcanoes.

The formation of such calderas is closely related to the outflow of magma after

eruptions, and numerous calderas on the same summit indicate repeated cycles of magma accumulation and eruption throughout the history of these volcanic giants. And it is the so-called shield volcanoes that are the predominant type of volcanic formations on Mars, which were formed after numerous eruptions with very fluid, low-viscosity lava, most likely basaltic in composition; it spread over considerable distances from the place of initial ejection, with the formation of broad peaks with fairly gentle slopes (Fig. 5.5).

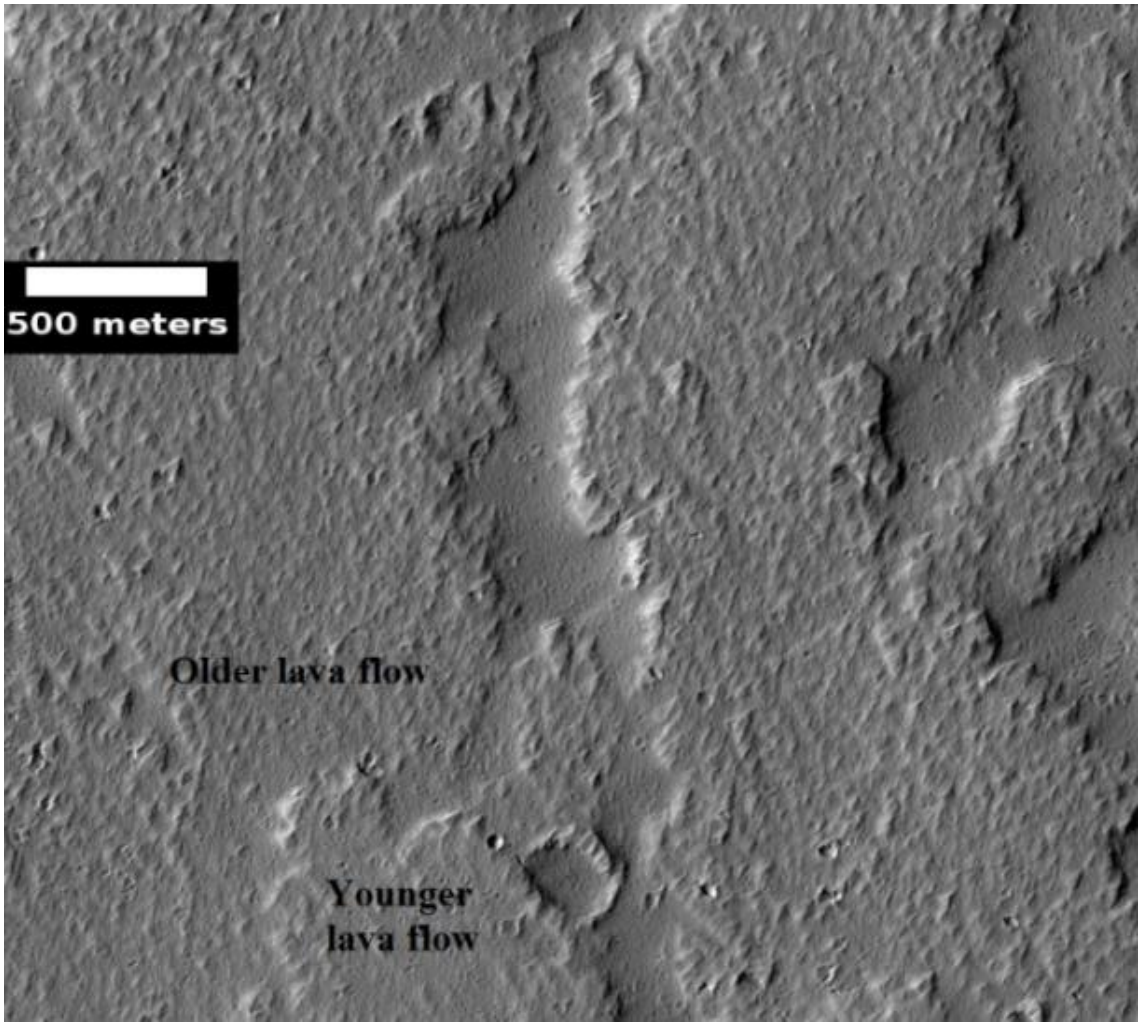


Fig. 5.5. Lava flows obtained by the HiRISE (High Resolution Imaging Science Experiment) camera on the "Mars Reconnaissance Orbiter" (https://marspedia.org/File:WikiESP_035095_1975lavalobestharsiswide.jpg)

Examples of huge shield volcanoes are Olympus Mons, the mountains in Tharsis Regio (Ascraeus Mons, Pavonis Mons, Arsia Mons) and Elysium Mons. Table 5.1 demonstrates the enormous scale of volcanism on Mars, especially in the Tharsis Regio

region. The sizes of these volcanoes are much larger than their terrestrial counterparts. In addition to giant volcanoes, other forms of volcanic landform are widespread on Mars. Among them are large lava plains and lava flows that cover large areas.

Table 5.1.

Characteristics of the largest shield volcanoes in the Tharsis Regio.

Volcano name	**Type**	**Height (above mean level, km)**	**Height (from base, km)**	**Base diameter (km)**	**Caldera size (km)**
Olympus Mons	Shield	~21.2	~26-27	~540-600	85×60
Ascraeus Mons	Shield	~18	-	~460	~50
Pavonis Mons	Shield	~14	-	~375	~45
Arsia Mons	Shield	~16-17	-	~435	~130
Noctis Volcano	Shield	~9	-	~450	-

Most of them are located around the above-mentioned volcanic centers and in the northern lowlands. Some of these flows are hundreds of kilometers long (Fig. 5.6). There is also evidence of several pyroclastic deposits that were formed during explosive eruptions near some of the volcanoes; one of them, for example, was found near Noctis Volcano. Small cones are observed on the surface of some lava flows, which may be the result of the interaction of lava with underground water reserves, or with ice.

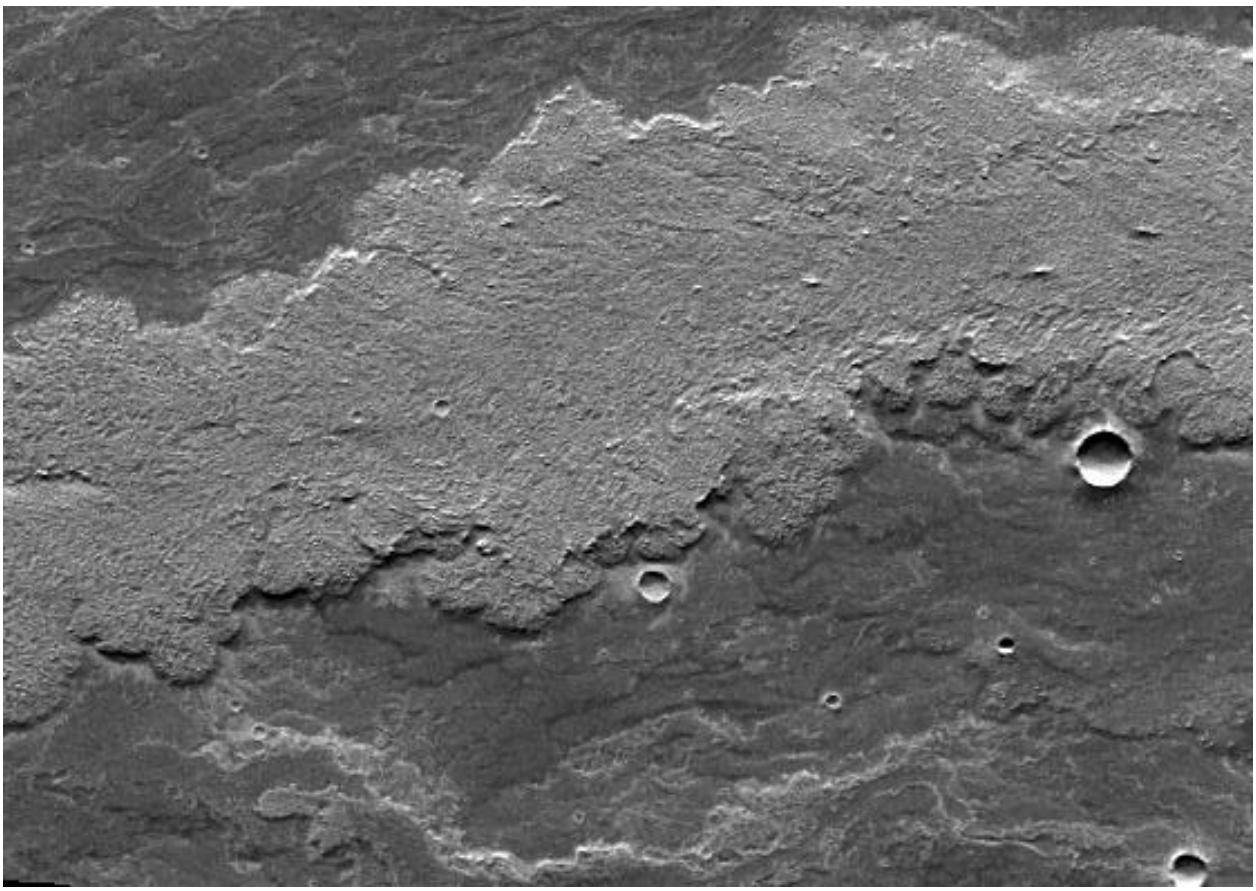


Fig. 5.6. The image, 30 km wide, shows one lava flow on top of another. This is how the Arsia Mons volcano formed from many lava flows (https://marsed.mars.asu.edu/sites/default/files/images_mep/V48253003.gif).

Recent spacecraft studies [19] have also found evidence of lava domes and stratovolcanoes in the ancient crust of Mars, indicating a more complex volcanic history than previously thought. The presence of large calderas, especially in the heavily cratered Arabia Terra region, which is about 1.75 km high, suggests that the planet was subject to large explosive eruptions in its early history [14]. The irregular craters (Paterae) in this region are thought to be the remnants of super volcanoes that erupted there billions of years ago. Evidence has also been found of large basaltic lava flows that could have formed large areas on the surface. The potential for explosive eruptions on Mars, especially in its early history, suggests that volcanism may have played a more significant role in shaping both the atmosphere and the surface relief [40] than previously thought.

Hadriacus Mons is an ancient, low-lying volcano with a base diameter of about

450 km. Its central caldera, formerly known as Hadriacus Patera, is 66 km in diameter. It is one of the oldest volcanoes on Mars, having formed during the Late Nocturnal period (3.7–3.9 billion years ago). Hadriacus Mons is often associated with explosive eruptions caused by magma contacting groundwater, which led to the formation of a large caldera. This volcano is located in the southern hemisphere of Mars, northeast of the famous Hellas impact basin and southwest of another similar volcano, Tyrrhenus Mons. It is also one of the oldest volcanoes on Mars and is now in a severely degraded state due to erosion. Its base diameter is about 300 km, and its relative height is about 2 km. The central caldera of Tyrrhena Patera is 12 km in diameter and is surrounded by a larger ring of faults 45 km in diameter. Tyrrhenus Mons is known for its large lava flows, which are traced for at least 1350 km from its peak.

The concentration of major volcanoes in Tharsis Regio and Elisium Regio indicates that these regions have been areas of intense mantle activity for a long time. These areas are characterized by significant crustal uplift and active magma generation. This indicates the presence of specific thermal and compositional anomalies in the Martian mantle.

Interestingly, the comparison of the Tharsis Mons volcanoes has given rise to discussions about the possible plate tectonic activity in the past of Mars. But today the theory that explains their formation by a stationary, constantly active hot spot under the lithosphere prevails.

On the other hand, the recent discovery of Noctis Volcano highlights that our understanding of Martian volcanism is still incomplete, and even large volcanic structures may remain unrecognizable for a long time due to erosion, or because of their current location under later geological layers. This reminds us that further research and careful analysis of the geological features of Mars are needed to gain a more complete picture of its volcanic history. The classification of Martian volcanoes into shield volcanoes, Paterae, and so-called tholis reflects differences in their size, shape, and likely eruption styles, as well as in the properties of the magma itself at different parts of the surface. These categories provide a basis for understanding the diversity of volcanic landscapes and the processes by which they were created.

Paterae are volcanic formations that differ from shield volcanoes in their more gentle slopes and complex, often jagged caldera rims. Paterae are thought to be formed by ash-rich eruptions or by the collapse of large magma chambers. Examples of Paterae include Hadriaca Patera and Tyrrhena Patera. Alba Mons, formerly known as Alba Patera, is a large shield volcano with an extremely low profile, located north of Tharsis Regio.

Tholus are small, dome-shaped mountains with steeper slopes than shield volcanoes. They are thought to be formed by the eruption of more viscous lava, or by the eruption of smaller volumes of lava that accumulate much closer to the site of the eruption. Examples of tholus include Hecates Tholus and Albor Tholus.

Recent discoveries of lava domes and stratovolcanoes on the surface of Mars challenge the traditional view of Mars as a planet of mostly shield volcanoes. All of this points to a much more complex history of volcanism on the planet. Indeed, such different types of volcanoes in different parts of the surface imply significant variations in the viscosity, composition, and explosive properties of magma in different areas. This indicates a fairly wide range of magmatic processes on Mars.

The potential for explosive eruptions on Mars, especially in the early stages of the planet's history, indicates that volcanism could have played a more significant role in shaping the atmosphere and environment on the surface than previously thought. After all, explosive eruptions release a much larger amount of various volatiles and ash; this could have had a much more significant impact on the composition of the surface and on the climate on Mars.

5.3. Age and history of volcanic activity on Mars.

Volcanic activity on Mars continued for a significant period of its geological history. It covered three main eras: the Noachian, the Hesperian, and the Amazonian. The Noachian era is the oldest. It was characterized by very intense volcanic activity, which contributed to active processes in the formation of a significant part of the primary crust of the planet. During the Hesperian era, volcanism continued, although it was no longer so intense; but it was accompanied by very active tectonic activity.

The Amazonian era is the latest. It was marked by a further decrease in volcanic activity. However, some of the volcanic eruptions remained very active for long periods of time.

Determining the age of volcanoes on Mars and the location of the volcanic provinces in which they erupted is important for a general understanding of their evolution. For example, Olympus Mons is considered one of the youngest large volcanoes on Mars; it was formed mainly during the so-called Hesperian period. However, according to the lava history on its slopes, eruptions from its vent continued until the Amazonian period.

For example, age studies show that lava flows on the northwest slope of Olympus Mons range in age from 115 million to only about 2 million years old. Other mountains in the Tharsis Regio, including Pavonis Mons, Ascraeus Mons, and Arsia Mons, also show a fairly long history of volcanic activity; it began as early as the Noachian period and also continued until the Amazonian.

Elysium Mons and the volcanoes of the Elysium Province [38], such as Hecates Tholus and Albor Tholus, also indicate a rather complex history, with volcanic activity spanning several billion years. Alba Mons has on its slopes some of the oldest volcanic deposits known in the entire Tharsis Regio [37, 39]; their age covers the period from the beginning of the Hesperian to the early Amazonian.

Recall that evidence for both long-term and episodic volcanic activity on Mars is obtained by various methods. For example, the crater dating method is based on counting the number of impact craters on the surface. It allows us to estimate the age of various volcanic features. The fewer such craters, the younger the surface under study.

If the tops of some of the volcanoes, such as Ascraeus Mons and Olympus Mons, have covered calderas, this indicates multiple episodes of collapses, which should be associated with active magmatic activity.

Radiometric dating of meteorites that have flown from Mars and hit the Earth's surface also provides a lot of valuable information about the age and past history of eruptions on Mars. There is also evidence for potential modern volcanic activity on

Mars. For example, in regions such as Elysium Planitia, quite young lava flows have been found, estimated to be only a few million or even tens of thousands of years old.

This may indicate that volcanism on Mars has not completely ceased. In addition, seismic activity recorded by the InSight apparatus in the Elysium Planitia area should also be associated with the movement of magma under the planet's surface; this also supports hypotheses about possible potential volcanic activity under modern conditions [34].

Thus, volcanism on Mars was a rather long process, covering almost the entire history of Mars. This indicates the presence of persistent internal heat and significant magmatic activity on the planet. Such a significant range in the age of volcanic formations in different regions of the planet indicates that Mars was able to survive numerous phases of volcanic activity over many billions of years.

The above methods used in dating volcanoes on Mars (crater method and radiometric dating of Martian meteorites) have certain limitations and therefore can sometimes give different ages. This speaks of the difficulties in remotely studying the geology of a particular planet. After all, the crater assessment method depends on many assumptions about the rates of impact crater formation. But the origin of specific meteorites can be very uncertain; and this leads to a potentially significant inaccuracy in determining their age. However, the existing evidence of fairly recent volcanic activity (several million or perhaps even tens of thousands of years) still indicates the possibility that the planet Mars is not currently a geologically dead planet. This is evidenced by the relatively young lava flows and the ongoing seismic activity of Mars.

5.4. Reasons for the gigantism of volcanoes on Mars and their differences from terrestrial volcanoes.

The enormous size of shield volcanoes on Mars is explained by a combination of several main factors that distinguish the physical characteristics on Mars and on Earth. The most important of these factors is the absence of plate tectonics [35]. After all, on Earth, lithospheric plates are constantly moving over stationary "hot spots" in the mantle. This causes a constant shift in the locations of volcanic activity over time,

leading to the formation of chains of volcanoes, instead of accumulating material in one place. Whereas on Mars, the entire planetary lithosphere is a single, immobile plate.

In this regard, the "hot spot" under the Martian lithosphere will remain in the same place relative to the surface for millions, or even billions of years. This fact allows lava from the same source to accumulate layer upon layer, "building" a huge volcanic mountain. Therefore, it is the giant volcanoes on Mars that are evidence of its immobile lithosphere and the long-term stability of the source of magma eruption [36].

In addition, the gravity on the surface of Mars is about 2.6 times less than on Earth. This fact allows volcanoes on Mars to reach significantly greater heights and widths before the pressure of their own weight causes their destruction and limits further growth. At the same time, the weaker gravity leads to the fact that lava flows can spread a much greater distance from the eruption vent; this allows the formation of much wider bases of volcanic mountains.

The concentration of the most powerful volcanoes on Mars in Tharsis Regio indicates the existence of a large and long-lived region in the mantle for the generation of magma under this region, which was the main source of volcanic material and heat for this province for a long part of the geological history of Mars. Recent observational data indicate the possible active and current magma plume under the Tharsis Regio region, strengthening this hypothesis.

Despite their significant differences in size, shield volcanoes on Mars share many similarities with some shield volcanoes on Earth. Both types have gentle slopes and are formed by the eruption of molten basaltic lava. However, Martian volcanoes are much larger in scale. This suggests that, in addition to magma composition and eruption style, other factors must have played an important role in their formation and accumulation. Comparing volcanoes on Mars and Earth highlights the significant role of plate tectonics on a given planet in shaping volcanic activity. The immobility of plates on Mars has allowed the development of unique, massive volcanic structures that are very different from those on Earth, where volcanic activity is greatly reduced by plate movement. However, Martian volcanoes still have a shield morphology that is quite

similar to some Earth volcanoes. Of course, their scales differ significantly. This suggests that, in addition to the composition of the magma and the style of eruptions, some other factors contribute to their enormous size. The significantly lower gravity and the absence of crustal movement have allowed volcanoes on Mars to grow to sizes that are impossible on Earth. Comparing Martian and terrestrial volcanoes provides valuable information about the geological processes that take place on such different planets. This is what helps to understand the conditions that are necessary for the formation of volcanic structures of significant size.

5.5. Evidence of recent (and possibly modern) volcanic activity.

Mars was long considered a geologically extinct planet. However, observations collected by recent space missions, in particular data obtained by the SEIS seismometer installed on the InSight lander, have provided reliable evidence that the planet Mars continues to demonstrate noticeable geological activity. Thus, the InSight mission has recorded over one thousand seismic events, or Martian earthquakes, since its landing in 2018 [34].

Although most of them were quite weak (with magnitudes less than 3-4 points), their registration is direct evidence that the processes that generate seismic waves in the bowels of this planet are still occurring today. Most likely, they should be associated with a kind of discharge of existing tectonic stresses in the crust of Mars. Analysis of the data obtained by the InSight mission showed that the vast majority of all recorded Martian earthquakes come from a region known as the Cerberus Fossae active region (Fig. 5.7).

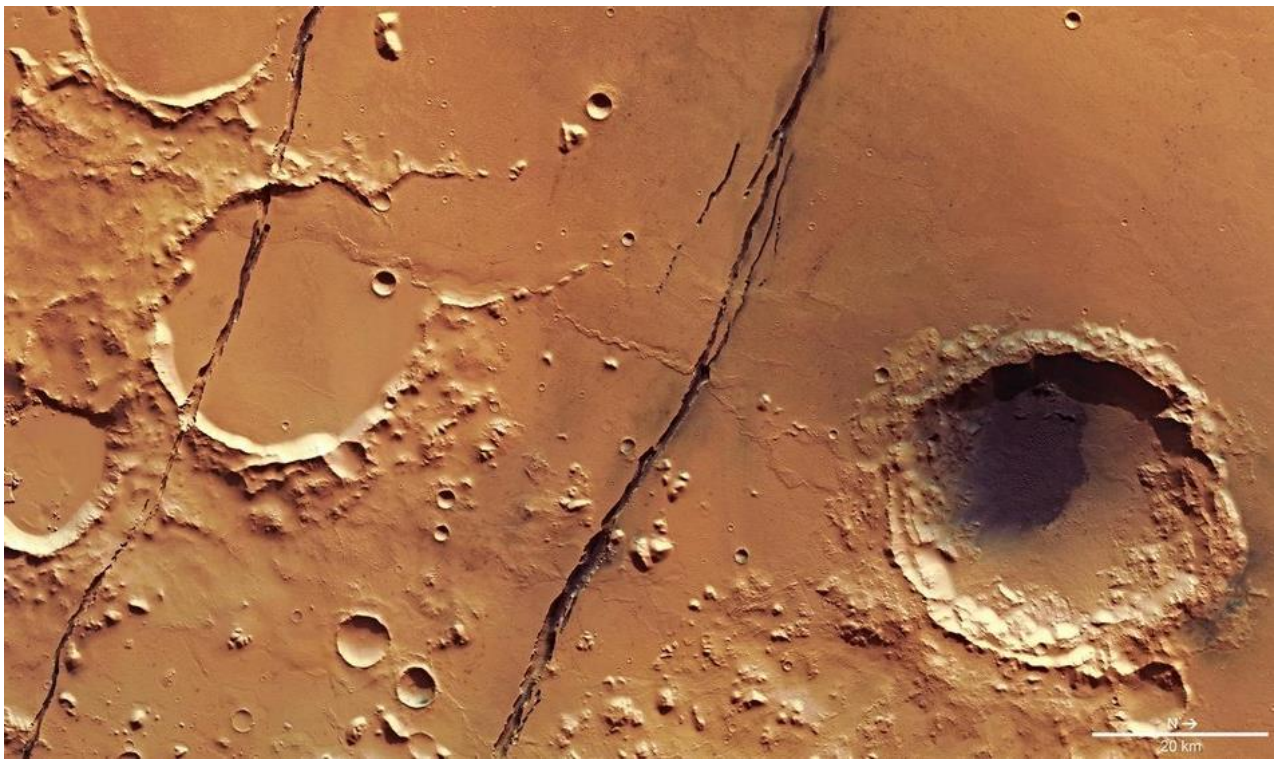


Fig. 5.7. Cerberus Fossae – young tectonic cracks thousands of kilometers long (https://www.dlr.de/en/images/2018/3/vertical-plan-view-cerberus-fossae-region/@@images/image-1000-809458fcb55e124e5352b685fe0f2d01.jpeg).

It is in this region that systems of so-called grabens have been found, which are almost parallel tectonic faults that extend over a distance of more than 1000 km on the Elysium Planitia plain. This region is considered geologically very young. Thus, the age of these faults is estimated at less than 100 million years; perhaps even less than 10 million years. This is indicated by the almost uneroded slopes of these grabens, as well as traces of very recently displaced rocks; they are evidence of recent tectonic activity (Fig. 5.8).

This is also evident from the profiles of some of the pits, which are bounded by very steep, and sometimes almost perpendicular, walls with a height of over 500 m in some places. The localization of mars-quakes precisely at this location points to Cerberus Fossae as an identifier of a seismically active region on Mars.



Fig. 5.8. Image of the young seismically active Cerberus Fossae region on Mars [2].

The system of fault trenches shown on the surface of Mars may cover a vast plume of hot rocks rising from the planet's interior. It can be assumed that they can change our idea of Mars as a geologically frozen world. And this area was most likely volcanically active only a few tens of thousands of years ago. Alternatively, the method of formation of the cracks that make up Cerberus Fossae [2] can be explained by the presence of a mantle plume. A mantle plume appears when hot material begins to rise from the core of Mars through the mantle, causing tremors and increased volcanic activity [5, 9]. Modeling shows that such a plume could have a diameter of more than 3500 km, and its temperature should be almost 300 degrees higher than the surrounding area.

Such heat may also be a kind of potential for the presence of some life forms on Mars. Data obtained from the analysis of the planet's gravitational field indicate the possible presence of an active magma plume up to 1,700 km wide, which slowly rises from the mantle under Tharsis Regio. Therefore, in the future, the possibility of

eruptions for even such a giant volcano as Olympus Mons should not be ruled out. Thus, the observational data obtained in recent years have radically changed our ideas about the planet Mars as a geologically inactive planet. The registration of marsquakes by the InSight lander has irrefutably proven the presence of modern tectonic activity. The detection of fairly young volcanic deposits and a possible active plume in the planet's mantle makes even modern volcanism on Mars likely.

This is of great importance for understanding the current thermal state of the planet and opens up new prospects for the search for an environment potentially suitable for life. After all, modern volcanic activity can create hydrothermal systems under the surface, in which there will still be heat, water (even in frozen form) and other chemical elements can interact and create conditions that will be potentially favorable for the development of microbial life forms.

Conclusions on the influence of volcanism on the formation of relief of Mars.

Thus, the planet Mars appears as a world of many contrasts and geological changes. As a planet belonging to the terrestrial type, it is largely similar to the Earth in its fundamental features. These include a differentiated internal structure with a crust, mantle and core; also common is the presence of an atmosphere and seasonal changes, caused by the tilt of the axis of rotation, which is almost the same as for Earth.

However, Mars is still much smaller than Earth, has almost three times lower gravity and lower density. The atmosphere of Mars is very thin, consisting mainly of carbon dioxide, and the pressure at the surface is less than 1% of that of the Earth. Such data lead to extreme changes in daily and seasonal temperature fluctuations and to the practical impossibility under current conditions of the stable existence of water in a liquid state on the surface of the planet.

The data of the InSight mission have also significantly changed our understanding of the internal structure of the planet Mars; it was possible to detect a liquid core of unexpectedly large sizes and enriched in light elements (especially sulfur); the mantle should probably be single-layered, and the crust, which may be significantly thinner than previously thought, and have a multi-layered structure.

It is these features, in particular the characteristics of the entire core and the possible layer in a molten state at its boundary, that help explain the current absence of a global magnetic field on Mars. It is also believed that volcanism was dominant among geological processes throughout almost the entire history of the planet. And the absence of plate tectonics, combined with lower gravity, allowed the formation of giant shield volcanoes, such as Mount Olympus and the Tharsis Plateau volcanoes, which have no analogues on Earth. The accumulation of huge masses of soil in Tharsis Regio had planetary consequences, causing such tectonic stresses that caused the formation of an unprecedented system of canyons in the Valles Marineris. Volcanic eruptions also played a key role in shaping the atmosphere and probably influenced the climate of early Mars. An important discovery in recent years has been the confirmation that Mars is not a geologically "dead" planet. The registration of marsquakes by the InSight mission, the localization of seismic activity in the young Cerberus Fossae region, the detection of fairly young volcanic deposits on the surface there, and the possible presence of a fairly active mantle plume under Tharsis Regio may indicate ongoing active processes in the depths of Mars. These observational data open up the possibility of the existence of modern hydrothermal systems under the surface of the planet, which can also be considered potential places for microbial life forms.

Ongoing exploration of Mars using orbiters, stationary platforms, and rovers continues to provide crucial information about the evolution of terrestrial planets, the conditions necessary for the emergence and maintenance of possible life forms, and the geological processes that shaped these planets. Further study of the internal structure of Mars, the history of water resources, details of past volcanic activity, and the search for possible biosignatures remain priorities for future space missions to this planet. Thus, volcanism has played a major role in shaping the geological history and evolution of the Martian atmosphere. Large-scale eruptions over billions of years have led to the formation of significant lava flows and vast volcanic plains that now cover much of the planet's surface.

Volcanic eruptions would have been the primary source of gases entering the early atmosphere of Mars. Among the main emissions were water vapor, carbon dioxide, and

sulfur dioxide. These gases are thought to have contributed to the creation of a denser and warmer atmosphere on early Mars, which could have been crucial for the existence of liquid water on the surface for long periods of time. Interestingly, there is a close relationship between volcanism and the presence of hydrated minerals on Mars. The discovery of hydrated silica, sulfates, and phyllosilicates in volcanic regions suggests past interactions between magma or lava and water, either in liquid or icy form. These interactions could have created hydrothermal environments, which are important for searching for signs of past or even present life on Mars. The vast volume of volcanic material erupted on Mars, particularly in regions such as Tharsis Regio, suggests a massive and sustained release of volatiles that could have dramatically altered the planet's early environment. Estimates of the amount of water and CO_2 released help to understand the potential for oceans and a dense atmosphere in Mars's history. Volcanism has been a fundamental driving force in the geological and atmospheric evolution of Mars, shaping its surface features and influencing its climate over billions of years. Large volcanic formations and evidence of a thicker, warmer early atmosphere strongly suggest a dominant role for volcanic activity in Mars' past. The presence of hydrated minerals in association with volcanic regions provides compelling evidence of past interactions between magma/lava and water (in liquid or icy form), with significant implications for the planet's habitability. These interactions could have created hydrothermal environments that are known to support life on Earth.

Thus, volcanoes on Mars are evidence of intense geological activity that has occurred on the planet over billions of years. From the colossal Olympus Mons to the diverse shield volcanoes, paterae, and tholos, these formations provide valuable information about the internal structure, thermal history, and evolution of Mars. Their enormous size, due to the absence of plate tectonics and lower gravity, contrasts sharply with terrestrial volcanoes. The study of Martian volcanism is important for planetary science because it helps us understand the fundamental processes that shape planetary bodies.

Further study of Martian volcanoes should address a number of questions that remain open. Determining the precise age of many volcanic features and establishing

the presence of modern volcanic activity are important tasks. Applying radiometric dating to Martian rock samples that may be returned to Earth by future missions will allow for more precise age estimates. Further study of the variety of volcanic types on Mars will help to better understand the composition of the magma and the eruption styles that prevailed at different times in the planet's history. Of particular interest is the study of the relationship between volcanism and the presence of hydrated minerals, as this may provide clues to understanding the past and potential future habitability of Mars.

The study of Martian volcanism is an ongoing and dynamic field, where new discoveries and evolving theories are constantly refining our understanding of the Red Planet. The recent discovery of the ancient Noctis Volcano and evidence of very recent volcanic activity demonstrate that there is still much unknown about the volcanic history and potential of Mars. Future research efforts, including sample return missions and advanced remote sensing techniques, will be crucial to resolving remaining questions about Martian volcanism and its implications for the planet's past, present, and potential future.

Direct analysis of Martian rocks and more detailed orbital data will provide more precise age dates, compositional information, and understanding of the processes that shaped existing volcanic landscapes.

References:

1. Acuna M.H., Connerney J.E.P., Ness N.F., et al. (1999) Global distribution of Crustal Magnetization Discovered by the Mars Global Surveyor MAG/ER Experiment. Science. 284(5415), p. 790-793.

2. Adams J.B., Filice A.L. (1967) Spectral reflectance 0.4 to 2.0 microns of silicate rock powders. J. Geophys. Res. 72(22), p. 5705-5715.

3. Atreya S.K., Gu Z.G. (1994) Stability of the Martian atmosphere: is heterogeneous catalysis essential? J. Geophys. Res. 99(E6), p. 13133–13145.

4. Bertka C.M., Fei Y. (1998) A profile of Martian mineralogy and density up to core-mantle boundary. LPSC. V. 27. P. 107-108.

5. Bi H., Sun D., Sun N., et al. (2025) Seismic detection of a 600-km solid inner core in Mars. Nature. 645, p. 67–72.

6. Bibring J.-P., Langevin Y., MustardJohn Y. F., et al (2006) Global mineralogical and aqueous mars history derived from OMEGA/Mars express data. Science. 312, p. 400-404.

7. Broquet A., Andrews-Hanna J.C. (2023) Geophysical evidence for an active mantle plume underneath Elysium Planitia on Mars. Nature Astronomy. 7, p. 160–169.

8. Carr M.H. (1999) Retention of an atmosphere on early Mars. Journal of Geophysical Research: Planets. 104(E9), p. 21897-21909.

9. Clinton J.F. (2017) Preparing for InSight: An Invitation to Participate in a Blind Test for Martian Seismicity. Seismological Research Letters. 88(5), p. 1290-1302.

10. Hartmann W.K. (1973) Martian Cratering. Mariner 9 initial analysis of cratering chronology. J. of Geophysical Research: Solid Earth. 78(20), p. 4096-4116.

11. Morozhenko A.V., Vidmachenko A.P. (2017) Optical Parameters of Martian Dust and Its Influence on the Exploration of Mars. Dust in the Atmosphere of Mars and Its Impact on Human Exploration, Proceedings of the conference held 13-15 June 2017 in Houston, Texas. LPICo No. 1966, 2017, id.6010.

12. Mouginis-Mark P. (1979) Martian fluidized crater morphology: Variations with crater size, latitude, altitude, and target material. Journal of Geophysical Research: Solid Earth. 84(B14), p.8011-8022.

13. Murchie S.L., Mustard J.F., Ehlmann B.L., et al. (2009) A synthesis of Martian aqueous mineralogy after 1 Mars year of observations from the Mars Reconnaissance Orbiter. Journal of Geophysical Research: Planets. 114(IssueE2). E00D06. P. 1-30.

14. Pollack J.B., Kasting J.F., Richardson S.M., Poliakoff K. (1987) The case for a wet, warm climate on early Mars. Icarus. 71(2), p. 203-224.

15. Ramirez R.M., Kasting J.F. (2017) Could cirrus clouds have warmed early Mars? Icarus. 281, p. 248-261.

16. Rummel J.D., McKay C.P. (2017) Water on Mars: A Status Report and Suggestions for Further Study. 48th Lunar and Planetary Science Conference, held 20-24 March 2017, at The Woodlands, Texas. LPICo No. 1964, id.2945.

17. Schmidt F., Chassefière E., Tian F., et al. (2016) Early Mars volcanic sulfur storage in the upper cryosphere and formation of transient SO2-rich atmospheres during the Hesperian. Meteoritics & Planetary Science. 51(11), p. 2226-2233.

18. Sleep N.H. (1994) Martian Plate Tectonics. J. Geophys. Res. 99(E3), p. 5639-5655.

19. Vidmachenko A.P. (2009) Research of the Mars by space vehicles. 11 International Scientific Conference Astronomical School of Young Scientists, May 26-29, 2009, Kherson, Ukraine. P. 11-12.

20. Vidmachenko A.P. (2009) Water on Mars. Astron. almanac. 56, p. 225-249.

21. Vidmachenko A.P. (2014) Study of Earth-like planets. 16 International Scientific Conference Astronomical School of Young Scientists. Kirovohrad, Ukraine. May 29–31, 2014. P. 12-13.

22. Vidmachenko A.P. (2016) Processes on the “young” Mars: possible developments of events. 18 International Scientific Conference Astronomical School of Young Scientists. National Aviation University, Kyiv, Ukraine, May 26-27, 2016. P. 16-17.

23. Vidmachenko A.P. (2016) Traces of life on Mars must be sought around the valley Hellas in areas where the water coming out from under the planet's surface. 18 International Scientific Conference Astronomical School of Young Scientists. Kyiv, Ukraine, May 26-27, p. 14-16.

24. Vidmachenko A.P. (2018) Comparative features of volcanoes on Solar system bodies. 20 International Scientific Conference Astronomical School of Young Scientists. May 23–24, 2018. Uman, Ukraine, p. 9-12.

25. Vidmachenko A.P. (2018) Features of volcanic activity on various bodies of the Solar system. Materials of the International Scientific and Practical Conference The Objectives of the Sustainable Development of the Third Millennium: Challenges

for Universities of Life Sciences, 5, May 23-25, Kyiv, p. 41-42.

26. Vidmachenko A.P. (2018) Water in Solar system. 20 International Scientific Conference Astronomical School of Young Scientists, May 23–24 2018, Uman, Ukraine, p. 91-93.

27. Vidmachenko A.P. (2019) Traces of Martian Life Should be Sought in Places Around Hellas Crater, Where Water has Recently Spilled Out onto the Surface. Ninth International Conference on Mars, Pasadena, California, Jul 22-25, 2019, LPI Contrib. No. 2089, 6005.

28. Vidmachenko A.P. (2023) About volcanoes on Mars. Proceedings of 11 All-Ukrainian Scientific Conference “Astronomy and present day”, April 12, 2023. Vinnytsia, Ukraine. LLC "TVORY". ISBN 978-617-552-363-6. P. 76-81.

29. Vidmachenko A.P. (2023) Comparison of features of impact and volcanic craters on the surface of Mars. Proceedings of VIII Internat. Scientific and Practical Conference. Progressive research in the modern world (April 27-29). P. 237-246.

30. Vidmachenko A.P. (2023) History of possible climate change on Mars. Proceedings of VII International Scientific and Practical Conference. Science and innovation of modern world. (23-25 March 2023). Chapter 54. Cognum Publishing House, London, United Kingdom, p. 336-345.

31. Vidmachenko A.P. (2023) Macrorelief of the surface of Mars. Proceedings of XIV International Scientific and Practical Conference . Prospects for the development of science and the environment. (April 10-12, 2023). Chapter 7. P. 34-39.

32. Vidmachenko A.P. (2023) The atmosphere of Mars. Proceedings of VI International Scientific and Practical Conference. Scientific research in the modern world. (April 6-8). P. 283-293.

33. Vidmachenko A.P. (2023) Thermal properties of the surface of Mars. Proceedings of VII International Scientific and Practical Conference . Progressive research in the modern world (March 29-31, 2023). Chapter 42. P. 243-252.

34. Vidmachenko A. P. (2026) Causes of volcanic gigantism and evidence of “young” volcanic activity on Mars. Modern Challenges in Economic and

Technological Innovation: Collection of Scientific Papers with Proceedings of the 2nd International Scientific and Practical Conference. International Scientific Unity. Bologna, Italy. March 4-6, 2026. P. 415-419.

35. Vidmachenko A. P. (2026) Conclusions about the influence of volcanism on the formation of the relief of Mars. The Integration of Research, Innovation and Economy: Collection of Scientific Papers with Proceedings of the 2 nd International Scientific and Practical Conference. International Scientific Unity. Seville, Spain. March 11-13, 2026. P. 326-331.

36. Vidmachenko A. P. (2026) Features of volcanic and impact structures in the relief of Mars. Collection of Scientific Papers with the Proceedings of the 6th International Scientific and Practical Conference «Scientific Exploration: Bridging Theory and Practice»(February 16-18, 2026, Berlin, Germany). European Open Science Space. P. 212-221.

37. Vidmachenko A. P. (2026) Major volcanic formations on the surface of Mars in the Tharsis Regio province. Science And Information Technologies in The Modern World: Collection of Scientific Papers with Proceedings of the 5th International Scientific and Practical Conference. International Scientific Unity. February 11-13, 2026. Athens, Greece. P. 371-376.

38. Vidmachenko A. P. (2026) Major volcanic formations on the surface of Mars in the Elysium Planitia region. Research in Science, Technology and Economics. Collection of Scientific Papers with Proceedings of the 6 th International Scientific and Practical Conference. International Scientific Unity. February 18-20, 2026, Luxembourg, Luxembourg. P. 365-370.

39. Vidmachenko A. P. (2026) On the relationship of volcanism in Tharsis Regio with the formation of the Valles Marineris. Collection of Scientific Papers with the Proceedings of the 4th International Scientific and Practical Conference «Scientific Research: Modern Innovations and Future Perspectives» (February 23-25, 2026, Montreal, Canada). European Open Science Space. P. 355-359.

40. Vidmachenko A.P., Klimenko V.M., Morozhenko A.V. (1981) Apparent spectral albedos of the disk of Mars in September-October 1977. Solar System

Research. 14(4), p. 157-159.

41. Vidmachenko A.P., Mozghovyi O.V., Steklov O.F. (2023) About volcanoes on Mars. Proceedings of 11 All-Ukrainian Scientific Conference “Astronomy and present day”, April 12, 2023. Vinnytsia, Ukraine. LLC "TVORY", p. 76-81.

42. Vidmachenko A.P., Mozghovyi O.V., Steklov O.F. (2023) Features of the relief on the surface of Mars. Proceedings of 11 All-Ukrainian Scientific Conference “Astronomy and present day”, April 12, 2023. Vinnytsia, Ukraine. LLC "TVORY". P. 66-71.

43. Vidmachenko A.P., Mozghovyi O.V., Steklov O.F. (2023) Historical aspects of climate changes on Mars. Proceedings of 11 All-Ukrainian SCo “Astronomy and present day”, April 12, 2023. Vinnytsia, Ukraine. LLC "TVORY". P. 56-61.

44. Vidmachenko A.P., Steklov A.F. (2020) Mineral resources can be mined on different bodies of the Solar System. 22 International scientific conference Astronomical School of Young Scientists. December 11-12, 2020. Kyiv, Ukraine, p. 89-92.

45. Vidmachenko A.P., Steklov A.F. (2022) How long ago has water flowed on Mars surface? Results of modern scientific research and development. Proceedings of XI International Scientific and Practical Conference. Barca Academy Publishing, Madrid, Spain. 16-18.01.2022. P. 226-232.