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TECTONICS AND VOLCANISM OF MARS

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16. Abstract

Televised images of Mars transmitted from interplanetary stations (Mars, Mariner, Viking) have helped us develop a theory of the structure and development of the planet. Crater chronology is the basis for recreating the history of Mars. Probably the process of continent formation ended about 4 billion years ago. The material accumulated concerning the structure of planetary bodies in the Earth group is the basis for considering comparative planetology an independent scientific approach. A comparison of the Earth planetary bodies makes it possible to draw important conclusions on the evolutionary process of planetary bodies.

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TECTONICS AND VOLCANISM OF MARS

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The numerous televised images of the entire surface of Mars /27* which were received as a result of flights of the automated interplanetary Mars, Mariner and Viking stations made it possible to present the basic features of the structure and development of the planet.

Much here was unexpected--grandiose volcanoes, clearly marked breaks in the crust, broadly expanded series of sedimentary rock, clear traces of erosion in the form of winding river beds, and very real ravines, and broad fields of sand dunes. Now we can already speak of the tectonics of Mars as an independent scientific aspect as we study the structure and history of the formation of the crust of Mars in comparison with other planets of the earth group primarily with Earth. But as to the composition of the rock of Mars as to what kind of lava flowed from the vents of the Martian volcanoes, how the core of this planet was constructed, these are all still only subjects for hypothesis.

The Formation of a Planetary Body and Establishment of the Primary Crust

One can say that Mars as a planetary body emerged approximately 4.6--5 billion years ago simultaneously with other planets of the Solar System in the process of accretion from photoplanetary cloud.

As a result of differentiation of matter of the planet, a center, mantle and primary Martian crust was isolated. The

*Numbers in the margin indicate pagination in the foreign text.

center of Mars, probably, is smaller than that of Earth inasmuch as the total density of the planet is smaller. The composition of the primary crust was, apparently, anorthosite-gabbroic as on the Moon; however, due to the large mass here somewhat more acid differentiates are possible, for example, of average composition.

The relicts of the primary Martian crust can be detected in those sections of the southern hemisphere where the craters are actually scattered. These craters, having the same appearance as the annular structures in the photographs of the Moon and Mercury occurred, in the opinion of most scientists, as a result of explosions of meteorites. On the Moon, the main section of craters was formed about 4 billion years ago in connection with the so-called "heavy bombardment" from the residual meteorite diggings which surround the planetary body formed. It is possible to propose that the sections of the surface of Mars indicated have the same development. In the case of recognizing volcanic hypotheses of the formation of craters, their mass appearance also must be due to the final stage of formation of the primary crust for which the most intense volcanism is characteristic.

In any case, outside the relationship to the genesis of craters, different saturation by them of the surface of the planet is the basis for "cosmochronology." In other words, while we still do not have radiological determinations of the age of the rock, crater chronology is the basis for recreating the history of the development of Mars.

Formation of Continents

One of the characteristic features of the surface of Mars is the sharp separation on the northern (ocean) and southern (continental) hemispheres involving the tectonic asymmetry of the planet. This asymmetry occurred, apparently, as a result of a primary irregularity in the composition of Mars characteristic for all planetary bodies of the Earth group[1].

The continental regions of the southern hemisphere of Mars are elevated over the average level of this planet by 3--5 km. In the gravitational field of the Martian continents, negative anomolies predominate which can be caused by thickening of the crust and its decreased density. Cores, internal and boundary sections, are distinguishable within the limits of the continental regions. The cores usually protrude in the form of elevated massifs, more saturated by craters. On such massifs, the craters of the oldest age predominate which were poorly preserved and are not clearly marked on the photographs. /28

The internal parts, in comparison with the cores of the continents are less saturated by craters and craters of a younger age predominate. The edge section of the continents are shallow scarps extending for several hundreds of kilometers. Systems of step-like faults mark the areas along the boundary scarps. They are particularly noticeable in the region adjacent to the Isidis Plain where on separate sections of the boundary scarp of the series of adjacent faults they extend for tens and hundreds of kilometers. To some degree, these systems can be compared with the extreme faults on the boundaries of the blocks of the Earth's crust of continental and ocean structure.

The systems of faults and cracks in the continental regions of Mars are primarily oriented in northeast and northwest directions. In the photographs, these lines are not very sharply expressed which is evidence of their ancient age. The majority of the faults extend for several tens of kilometers, but by /29

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[1]For more details see Pushcharovskiy, Yu. M., Kozlov, V.V., Sulidi-Kontrat'ev, Ye. D., "Tectonic asymmetry of Earth and other planets," Priroda, No. 3 (1978).

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location they are grouped in lineaments of considerable extent. The clearly apparent orientation of such lineaments at an angle of 45° to the meridian makes it possible to connect their formation with the effect of rotational forces. Probably, the lineament could have occurred even at the stage of the formation of the primary crust. One should note that the lineaments of Mars are similar to the system of the planetary fissured state of the Earth's crust, particularly apparent within the limits of the Archean center of the continents (whose age exceeds 2700 million years).

The formation of the continents of Mars has continued for a long time. This process ended, probably, about 4 billion years ago similarly to the formation of the lunar continents although they could have extended to a later time.

The Occurrence of Oceanic Depressions

The entire northern hemisphere of Mars is a broad plain called the Great Northern Plain. Its level is 1--2 km below the average level of the planet.

According to gravimetric data, positive anomolies of the gravitational field predominate on the plains. This makes it possible to speak of the existence here of denser and thinner crusts than in the continental regions. The number of craters in the northern hemisphere is not great and the craters acquire a small dimension with a good degree of retention. Usually, these are younger craters and consequently the northern plains as a whole are considerably younger than the continental regions. Judging by the saturation with craters, the age of the surface of the plain must be estimated at 2--1 billion years, that is, the formation of the northern plains is separated in time from the period of formation of the continents.

The broad areas of the plains are covered with lava of basalt composition. Here, the winding scarps on the boundaries of the lava coverings, clearly distinguishable when decoding the detailed photographs, are confirmed by the locations the lava flows themselves and the volcanic structures. Thus, a hypothesis as to the broad extent of aeolian (that is, wind-borne) inclusions on the surface of the Martian plains are not corroborated.

The plains of the northern hemisphere are very clearly separated into sections with a different age of the surface. Ancient plains which are distinguished by darker or more uneven shades have a more complex relief and a much larger number of craters. And the young plains--are light, relatively smooth with infrequent craters.

In the polar regions, the basalt plains are covered with layers of sedimentary rock with a thickness of several kilometers. The origin of these laminar masses is probably glacial aeolian. The depressions of planetary magnitude similar to those Martian plains described above are conventionally called ocean regions. Of course, this term, applied from geotectonics to the structure of the Moon and Mars, is not completely successful but it reflects the global tectonic principle common for these planets.

The grandiose tectonic events which occurred in the formation of ocean depressions on the northern hemisphere could not but be reflected in the structure of the continental hemisphere formed earlier. Its boundary sections underwent a particularly important change. Here, broad boundary plateaus arose of irregular shape with smooth relief formed as if it were a step on the edge of continents. The number of craters which cover the boundary plateau is smaller than on the continent and larger than on the ocean plains.

The boundary plateaus in most cases have the darkest color on the surface of Mars. Under telescopic observations, they were compared with lunar seas. Probably here the small thickness of the regolith and the crust of erosion, and the color of the surface to a significant degree defined the underlying basalt with a dark coloration. One can postulate that the formation of boundary volcanic plateaus accompanied the initial stages of formation of the ocean depression and therefore determination of the age of these sections can be done by estimating the time of transition from continental to oceanic stage in the history of Mars.

Besides the ocean plains on the charts of Mars, the circular depressions of the Argyre and Ellada are sharply separated with cross sections of 1000 to 2000 km respectively.

On the flat bottom of these depressions which are 3--4 km /30 below the average level of Mars, even separate young craters with small dimensions and good preservation are visible. The depressions are filled by aeolian deposits. On a gravitational map, these depressions correspond to abrupt positive anomolies.

Along the periphery of the depression, mountain elevations rise with a width of 200--300 km with differentiated relief which one can call cordillera according to the analogy with lunar cordillera adjacent to the annular seas. The formation of these elevations on all of the planets, undoubtedly, involves the formation of the circular depressions themselves.

The circular depressions and the cordillera are accompanied by radial-concentrated systems of faults. The depressions are bounded by abrupt annular scarps with the height of 1--4 km which gives us the basis for assuming their fault nature. The arc faults are locations visible within the limits of the cordillera. Along the periphery of the circular depressions, radical faults are noted although they are not very clearly distinguishable.

The question of the origin of the Argyre and Ellada depressions however has not been unambiguously solved. On the one hand, the depressions remind one of gigantic craters which could have formed with the explosion of meteorites of asteroid dimensions--the so-called planetessimals. In this case, the remaining masses of meteorite bodies hidden under the basalt covering and sand deposits can be the source of significant positive anomolies of the force of gravity. /31

On the other hand, the similarity of gravitational characteristics and relief make it possible to propose that the Argyre and Ellada depressions were formed as the result of natural evolution of the planet explained by differentiation of matter in the nuclei.

Arches, Volcanoes, Grooves

Whereas on the Moon, after formation of the basalt "ocean" and "sea," the tectonic details became less clear on Mars fairly young (post oceanic) deformations and volcanism are widely accepted. In many locations, primarily in regions of the Farsida, Coprates and Elysium, they have led to a significant restructuring of the ancient structures.

The gigantic arch elevation of Farsida which has a circular outline is most sharply separated. Its central section rises 10 km over the average level of Mars (this is without taking into account the height of the volcanoes themselves located on the elevation). A cross section of the elevation equals 5--6 thousand km. At the center of the arch elevation of the Farsida, the steepest volcanic structures of Mars are found. The broken down volcanoes to the north of Olympus Mons and in the region of the Pater Alba are the most ancient among them. These volcano relicts have the shape of circular, very gently sloping elevations striated with many cracks and ridges. In places they form radial-concentric figures characteristic

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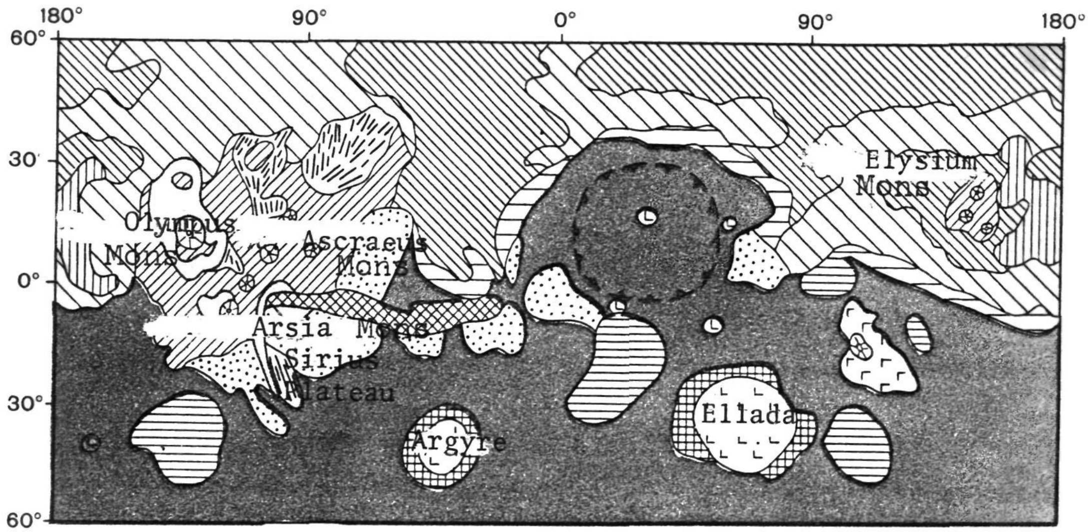

Basic tectonic structures of Mars.

Continental regions:

- Centers of continents
- Internal sections of continental regions
- Boundary sections of continental regions
- Tallassoids (large crater formations)
- Interior volcanic plateaus

Ocean regions:

- Ancient
- Young
- Circular depressions

Transition regions:

- Boundary volcanic plateaus
- Microcontinents
- Circular mountain elevations (cordilleras)

Regions of post-ocean deformation and volcanism:

- Grooved systems
- Systems of contiguous parallel faults
- Systems of winding crests (possibly, pleated deformations)
- Volcanic plateaus on arch elevations with shield volcanoes and cupolas
- Shield volcanoes and cupolas

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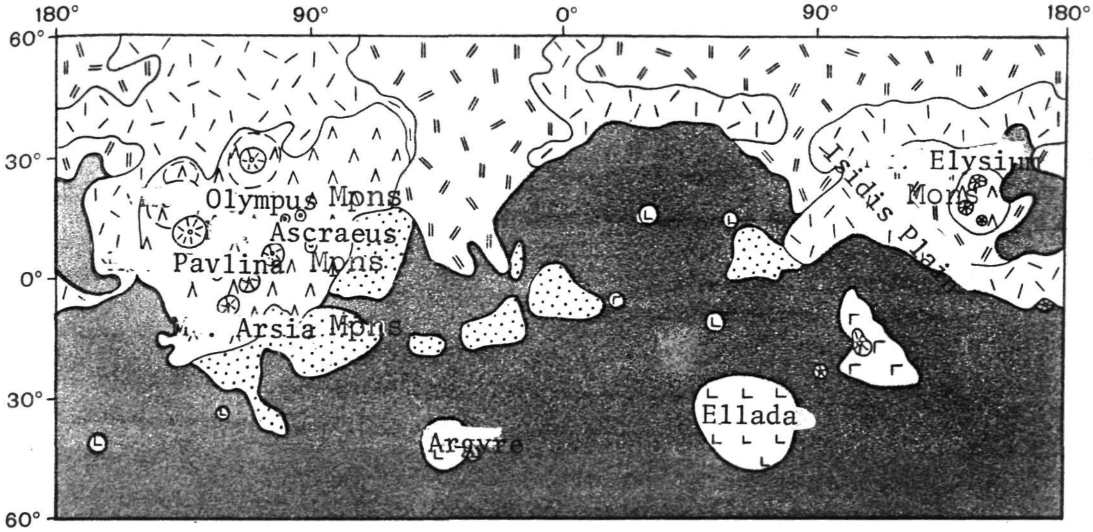

A diagram of Mars' volcanism

- Continental regions
- Smooth plateaus of continents, made up probably of volcanic rock
- Ancient volcanic plains
- Young volcanic plains
- Circular ocean depressions filled with lava covering
- Boundary volcanic plateaus
- Free-volcanic elevations
- Shield volcanoes and cupolas
- Annular volcano-tectonic structures

for ancient volcano-tectonic annular structures on Earth. A cross section of these gigantic volcanoes is 750--850 km, and over the surrounding locality they rise for a total of 0.5 km. Probably, the shield volcanoes were formed at the early stages of formation of the arch elevation of Farsida. Later, the ancient caldera of Pater Alba and Pater Uranus occurred. These are gently sloping very broken down elevations with relative rise 0.2--0.3 km and with a diameter of the base 250--300 km. They are capped with a very marked caldera with diameter 75--100 km of regular form. A study of detailed photographs from the /32

Viking station made it possible to establish that the Pater Alba is a complex volcanic structure with lava flows of different ages. And only then did the gigantic shield volcanoes occur which are so visible on the photographs of Mars.

The steepest shield volcanoes of the Farsida-Olympus Mons arch with a cross section of about 600 mm rises over the average level of Mars by 27 km. The apex of the volcano is capped with a broad caldera with diameter 65 mm. In the interior part of the caldera, steep scarps are visible and two craters with diameter about 20 km. On the external side of the caldera, it is surrounded by comparatively steep cones along whose periphery lava flows with a radial outline spread out. The younger flows are located close to the apex which indicates the gradual damping of volcanic activity. The shield volcano of Olympus Mons is surrounded by steep and fairly high scarps whose formation can explain the increased viscosity of the magma of the volcano. This hypothesis agrees with data on its significant height in comparison with the volcanoes located next to it of Mt. Farsida.

The shield volcanoes of Farsida Mons, Arsia Mons, Pavlina Mons and Ascraeus Mons form a volcanic series in a northeastern direction with almost uniform spacing between them. The length of the chain of volcanoes is 1800 km. These volcanoes look like twins; a cross section of each of them amounts to 300 km, their "absolute height" over the average surface of Mars is 27 km. Mt. Arsia is separated by the caldera in the form of a regular circle with diameter 125 km. The other volcanoes of this series have cross sections of the caldera which do not exceed 60 km.

The shield volcanoes of the Farsida arch are noted by arc faults along the periphery. They are particularly marked along the framing of Arsia Mons, Pavlina Mons and Ascraeus Mons. The formation of similar cracks is explained by the stresses which involve devastation of volcanic chambers in the process of eruption. Similar arc-shaped faults characteristic for many volcanic regions of Earth lead to the formation of numerous volcanic and tectonic annular structures.

Volcanic cupolas are also distributed on the Farsida arch (Farsida, Cheravnus, Uranus, Jupiter) which are smaller than the shield volcanoes. The cupolas having a circular shape in the plain with the diameter of the base 100--120 km, and rise to a total of 1--3 km over the surrounding surfaces. On their apices, there are clearly marked craters or caldera distributed; the slopes of the cupolas are comparatively steep with an even or convex longitudinal profile. A number of scientists consider that the cupola is more ancient than the shield volcanoes. This hypothesis is based on the varying degree of destruction of their slopes as a result of meteorite bombardment. Moreover, in the character of its relief the cupola is very close to the apical cone of the shield volcanoes. The cupolas are located along the periphery of the volcanic series of Farsida Mons. Most probably of all, the shields and cupolas have a formation which is close in time.

Younger volcanism was detected in other regions of Mars: /36
on the Elysium Plateau, on the Hesperia Plateau, and also in the northern near-polar region. Separate volcanic formations are apparent within the limits of the continental regions. On the Elysium elevation, there are two shield volcanoes, Elysium Mons and Hecate Mons. Possibly they are somewhat older than the shield volcanoes of Farsida Mons. Their slopes are strongly disrupted and the apical caldera are much less clear. The diameter of the base of the shields is about 200-250 km. They rise a total of 5 km over the level of the base and 10--12 km over the average level of Mars.

On the Hesperia Plateau, there is a comparatively small volcano the Pater Terrenskaya. Its height does not exceed 1 km,

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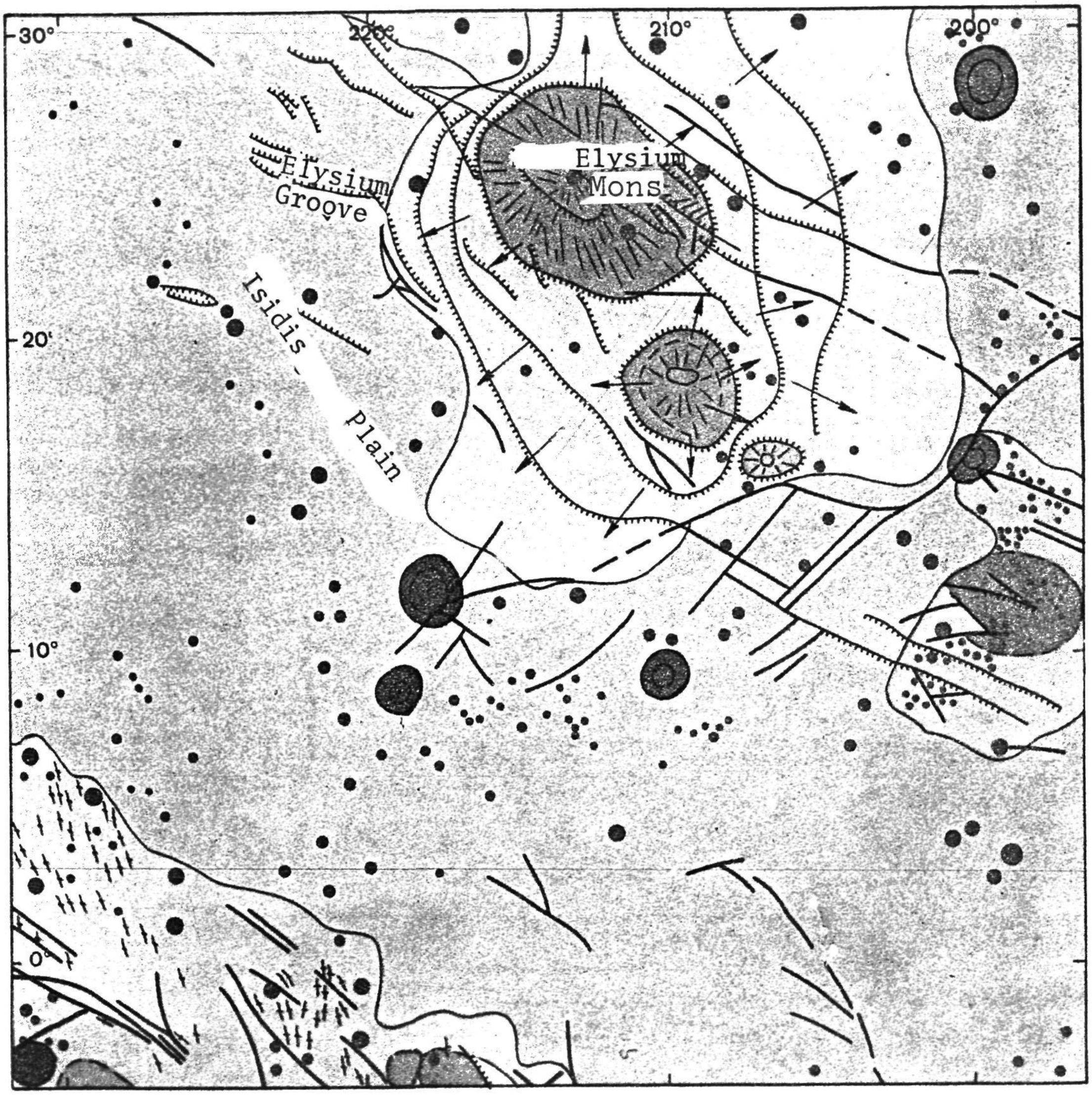
A section of the grooved system of Coprates. This and the following photographs were taken by the automatic interplanetary Viking-1 station.



A tectonic map of the Isidis Ravine and Elysium Mons

Continental regions
Ocean regions
Microcontinents
Faults
Lava plateaus
Ante-maria annular structures
Post-maria annular structures
Post-maria impact craters
Shield volcanoes
Discontinuous abnormalities

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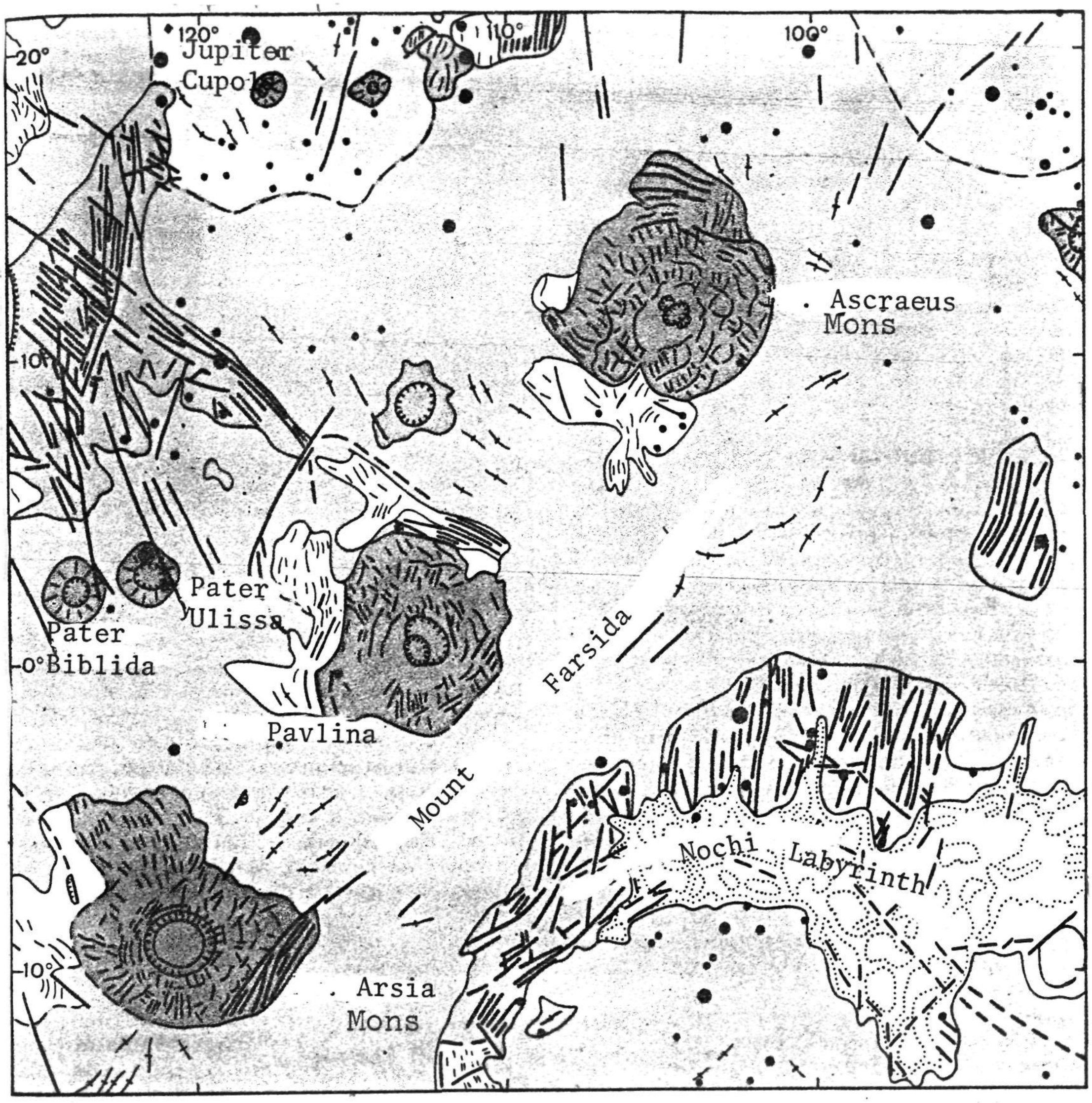

Tectonic map of Mt. Farsida

- Ancient volcanic plain
- Microcontinents
- Tectonic faults in the form of a complex system of depressions of the labyrinth
- System of parallel faults
- System of winding ridges
- Young volcanic plains with discontinuities and ridges
- Ante-maria annular structures
- Post-maria impact craters
- Shield volcanoes and cupolas

the slopes are smooth, the apex is crowned with a caldera of uneven shape. /36

A large group of volcanic cupolas are located on the extreme north of Mars in direct proximity to the northern polar ice cap (Kison, Ortygia, Yaksart). Here they form isolated volcanic regions within whose limits there are more than 10 volcanoes crowned by apical craters. One can still speak only hypothetically about the age of the post-oceanic volcanism on Mars. For the large shield volcanoes it is estimated at several humdreds of millions of years. The clear form of volcanic formations gives us the basis for considering that volcanic activity ended fairly recently and its final conclusion can be discussed only with large stipulations.

In terrestrial conditions, arches, volcanoes and groups often form a single volcanic-tectonic association. Such a principle was apparent on Mars. Thus, a system of faults named for the large fault of the Coprates system is traced in a latitude directed along the equator for a distance of 2500--2700 km, encompassing almost 80° of its arc. The width of this system in the region of the Melas Canyon reaches 500 km. It consists of a whole series of groove-shaped faults with width up to 100--250 km and depth 1--6 km.

On comparatively large photographs of the fault, there are usually uneven outlines which are caused by the development of landslides and cave-ins, and also valleys which remind one of terrestrial ravines. On the small scale photographs, the scarps can be approximately straight or slightly curved lines corresponding to a tectonic fault. This system of faults is so close to the terrestrial groove that putting it in this category of structures causes almost no doubts amoung Mars researchers.

To the northeast and north of the eastern boundary of the groove system, there extend winding broad valleys clearly of erosion origin. As a whole, the groove system has a slant along the slope of the free elevations and therefore the tectonic faults were transformed by erosion activity of flows. On the western boundary of the groove system, is a complex system of faults named the Nochi labyrinth. Here, many elongated depressions are separated with steep slopes oriented in different directions. The depressions are clearly connected to faults and separate straight line depressions form a mosiac of blocks. Here, a unique structural outline is observed for which there are no analogies on Earth.

On other slopes of the Farsida arch, also systems of faults are visible, oriented, as a rule, radially in relation to the arch. These are the Claritas, Cheravnus and Tantalus grooves in whose regions systems of closely placed parallel faults are clearly outlined in the photographs of Mars. They form straight or slightly curved faults which have the appearance of modern grooves or gaping cracks. Often it is a linearally extended system of horsts and faults with a width in all of several kilometers. The extent of separate faults varies from tens to many hundreds of kilometers. In the region of the Cheravnus Groove, the spaces between these faults amount to about 10 km. Also lateral and diagonal faults in relation to the main direction of this system of faults are apparent but they have a subordinate significance. On the surface of Earth there are no complete analogs to a system of closely located parallel faults on Mars although such an outline of faults is apparent in cosmic images of certain volcanic regions, for example, Iceland.

Another outline has faults distributed to the southwest of the free elevation of Farsida and going further into the depths of the continental region. This system of faults consists of a /39 whole series of very precise almost parallel lines and extends for 1800 km with a width of 700--800 km. The faults are grouped

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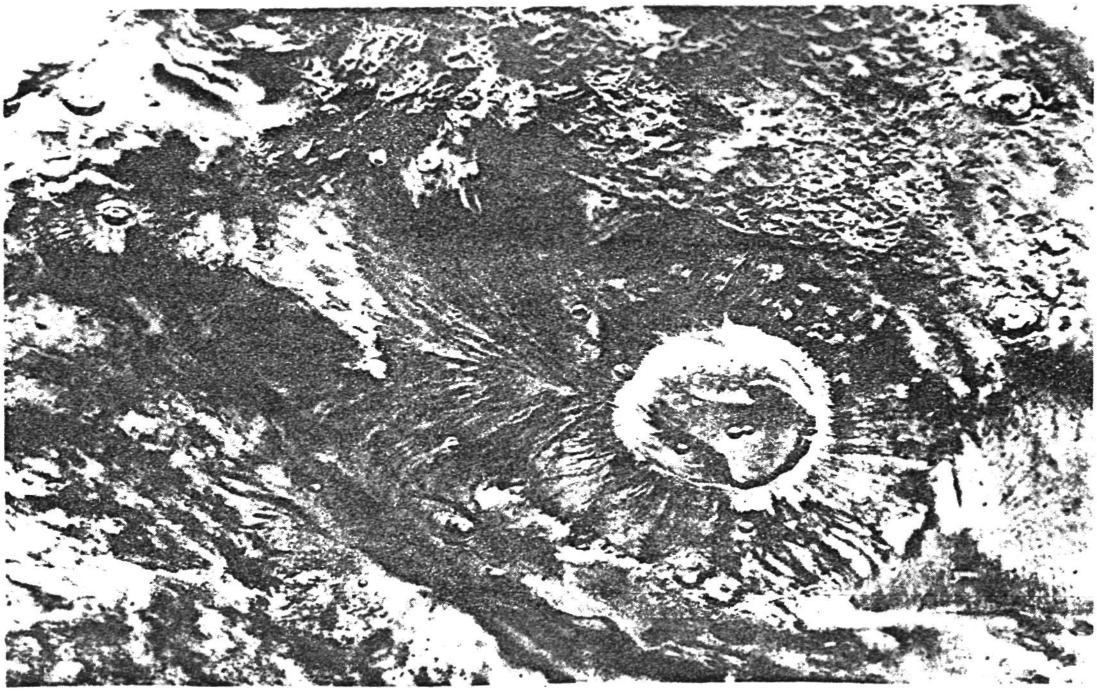
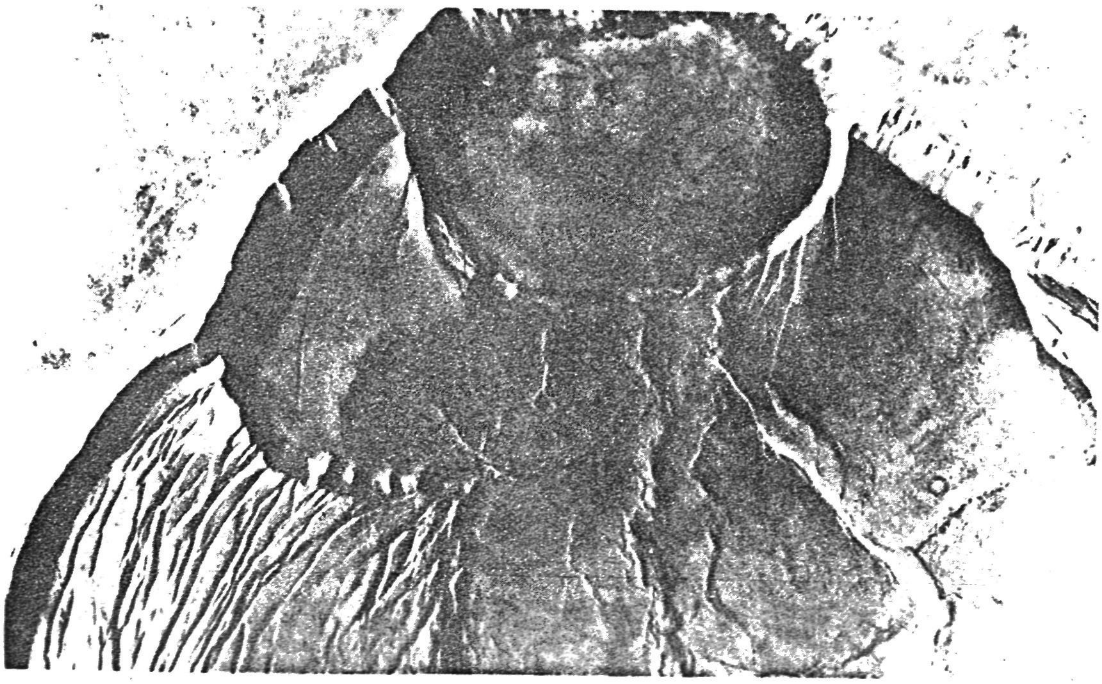


Pater Apollinarius: diameter of the caldera 100 km, width of the lava flow 200 km.



Part of the Olympus Mons caldera.

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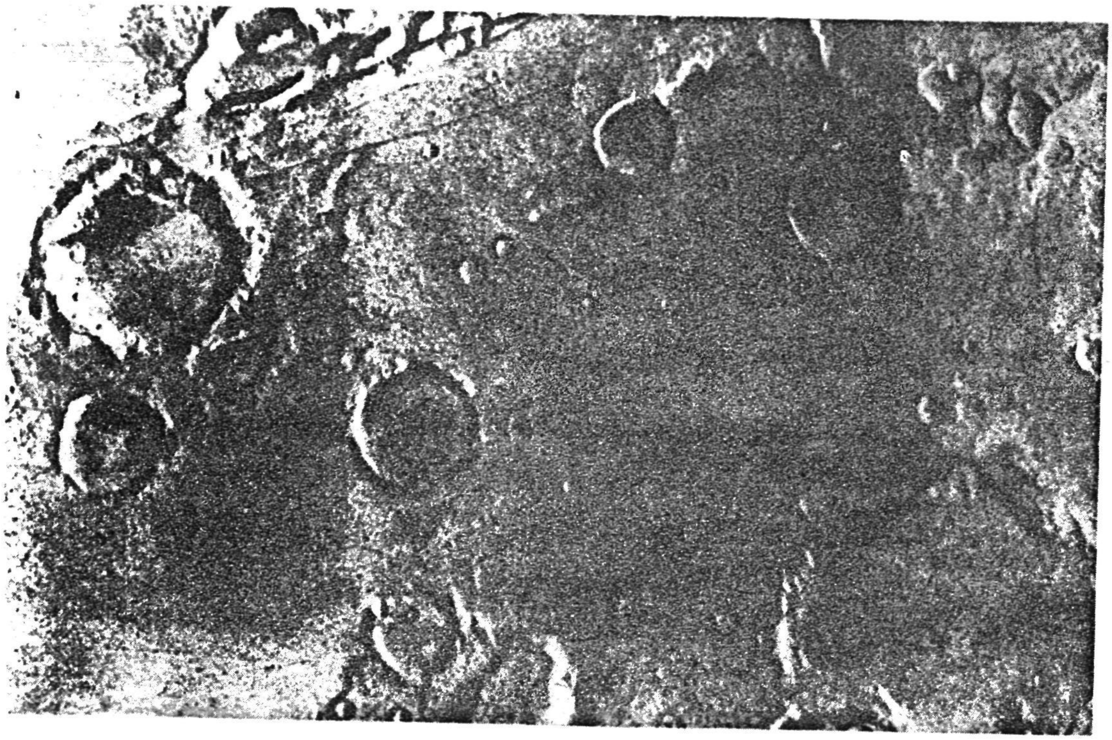
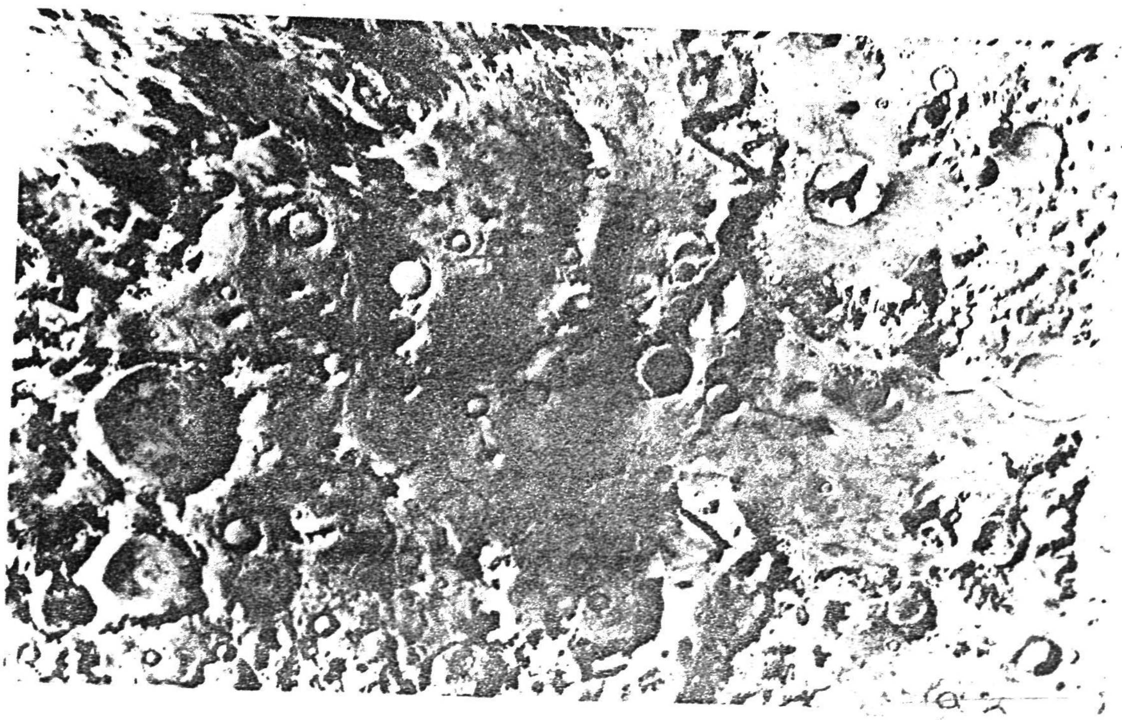


Memnonia Groove



Reull Valley

in four zones with approximately equal intervals between them. /39
On the surface of the fault there are scarps, and sometimes grooves. It is not impossible that this system was formed by faults of ancient origin renewed in the process of development of the Farsida Arch. There are no analogous systems of faults on the surface of Earth and other terrestrial planets.

Problems of Comparative Planetology

Accumulated material on the structure of planetary bodies of the terrestrial group gives us the basis for considering comparative planetology as an independent scientific approach. Its job includes not only the study of the surface and the core of other planets but also the use of these data for solving the cardinal problem of geotectonics. In this connection, data on the structure of the surface of Mars which occupies an intermediate position in value between the Moon and Mercury on the one hand and of the Earth on the other is of particular interest. In these planetary bodies, the tectonic processes occurred to a nonuniform degree and at different stages of development. In terrestrial conditions and right now, active tectonic activity is continuing accompanied by significant volcanism. On the surface of Mars, traces of comparatively recent tectonic deformations and volcanism are detected. On the Moon and Mercury, only ancient deformations have been established. These differences correlate well with the tectonic evolution of planetary bodies which is predetermined by the mass of the planetary bodies and includes the resources of internal energy.

Moreover, for all the planets of the terrestrial group, one notes a general character of the tectonic structure with isolation of the regions of the continental and oceanic types, the existence of transition areas and general directivity of evolution from the occurrence of the primary gabbroic-anorthosite crust, subsequent outflow of basalt ocean depressions to transformation of the crust to transition regions. The scale of all these processes depends on the mass of the planetary bodies.

A comparison of the planetary bodies of the Earth group make it possible to draw the following conclusions as to the basic stages of their evolution and the degree of the complexity of the evolutionary process for each of the planetary bodies:

1. In accordance with the existing cosmogenic concepts, the early stage of formation of a planetary body includes accretion of matter from the protoplanetary cloud. According to the present day concept, the process of accretion was comparatively brief, not exceeding a few hundred million years. It is proposed that even at this stage, differentiation of matter began with isolation of a center with iron and nickel composition. Even the Mars satellites which have the shape of bumpy fragments occurred by separation from the planetary body formed.

2. At the subsequent stage, separation of the silicate phase occurred and its delamination which resulted in the formation of the mantle and the primary crust.

3. Later on, the process of isolation of the basalt occurred in the oceanic depressions as a result of warming up of the upper mantle. The small planets (the Moon, Mercury), to a significant degree having used up the reserves of internal energy at this stage, developed without significant restructuring of the lithosphere. The drop of volcanic and tectonic activity of the Moon as a result of gradual cooling after 1--2 billion years after formation, was confirmed by thermodynamic calculations.

Large planets in a later time entered the stage of polycyclic transformations of the crust as a result of continuing heating of the nucleus and periodic breakdown of the temperature and pressure equilibrium in the subcrust layers. Considering the intensity of tectonic processes and magmatism, one can assume that the asthenosphere where differentiation of the mantle matter which exists on Earth (and probably is similar to the value on Venus) occurs, can appear partially in smaller dimensions on Mars.

An analysis of the structure of the surface of Earth, Mars, Mercury and the Moon according to data existing at this time indicates the presence in these planets of a large number of fully comparable tectonic elements whose number will probably grow as the study of the planets increases.