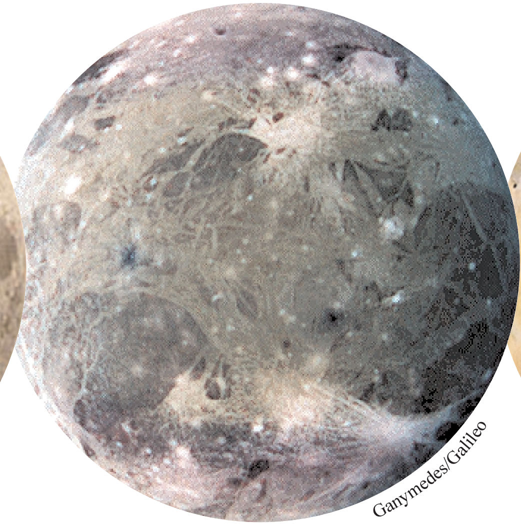
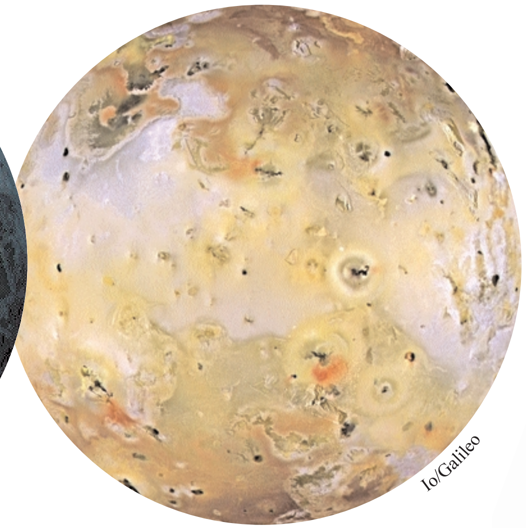
Earth's Moon



Ganymedes/Galileo



Io/Galileo

Ida/Galileo

PLANETOLOGY GROUP
Eötvös Loránd University
CMSRG, BUDAPEST

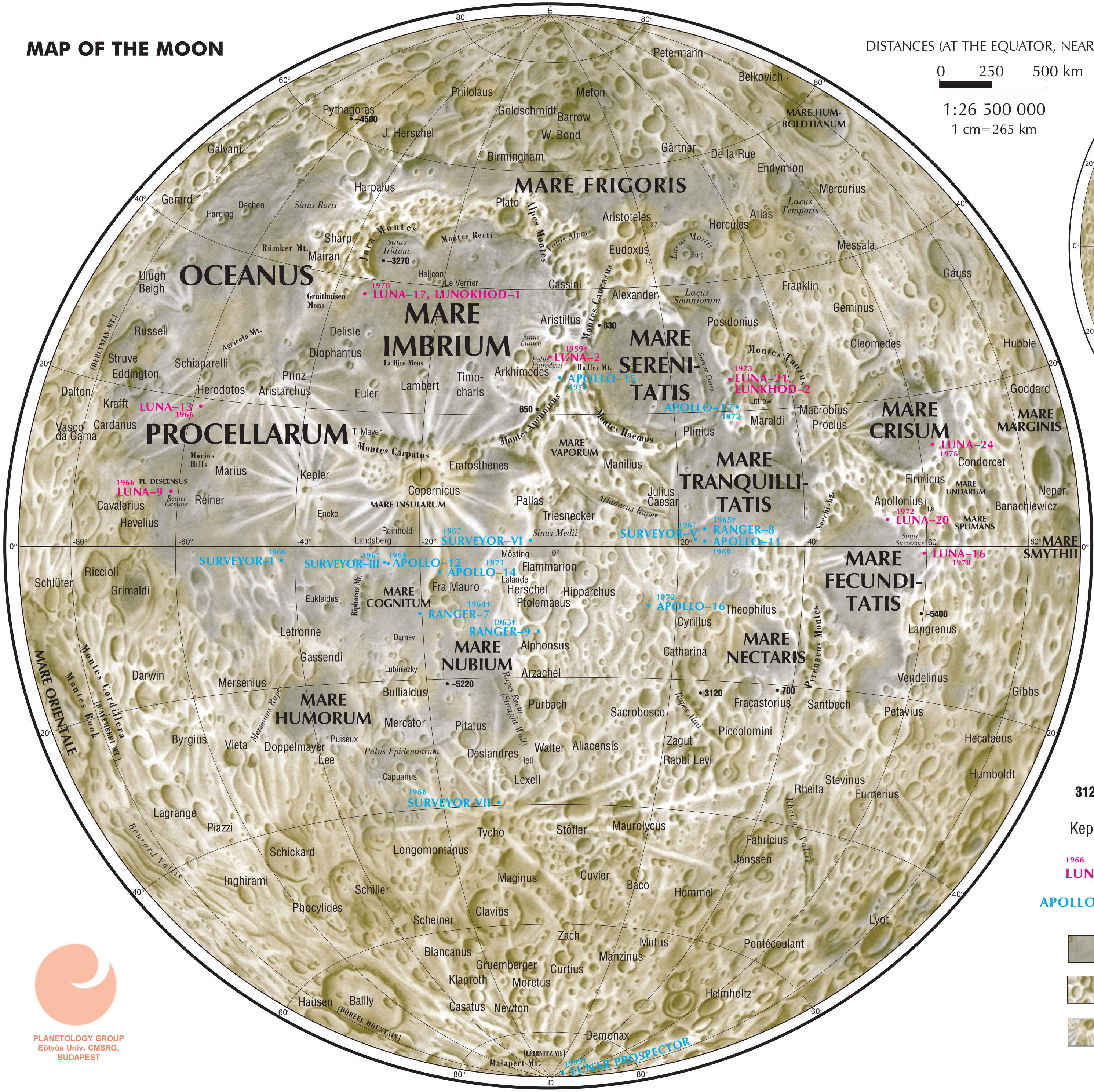
CONCISE ATLAS OF THE SOLAR SYSTEM (3) *electronic edition*

ATLAS OF PLANETARY BODIES

Szaniszló Bérczi, Henrik Hargitai, Ákos Kereszturi, András Sik

Mars / Viking 1

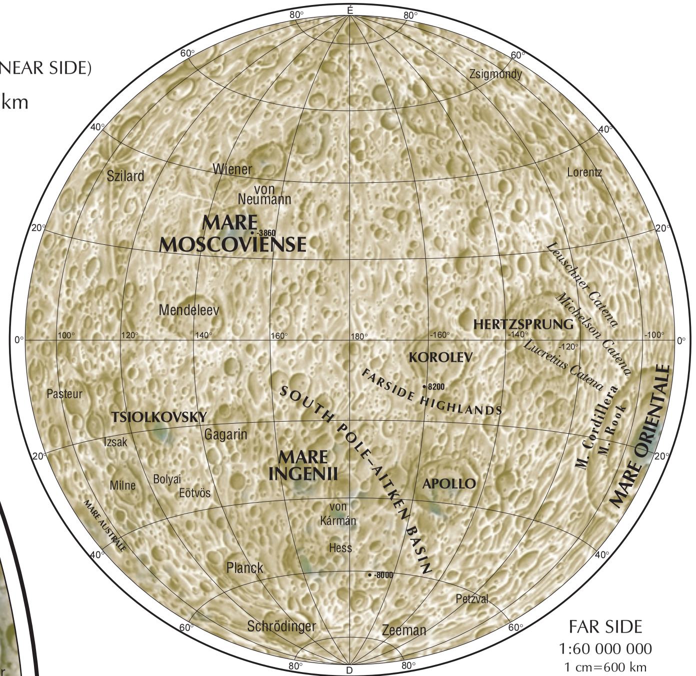
MAP OF THE MOON



DISTANCES (AT THE EQUATOR, NEAR SIDE)

0 250 500 km

1:26 500 000
1 cm=265 km



FAR SIDE
1:60 000 000
1 cm=600 km

MAP OF THE MOON

Lambert Transversal Equivalent Azimuthal Projection. Base map: MIIGAiK, Moscow (L. S. oreshina, L. Yu. Baeva, B. V. Krasnopevtseva, K. B. Shingareva) 0 m level at 1738,2 km radius. Edited by: Eötvös Loránd University Cosmic Materials Space Research Group., Budapest, Hungary 2001–2005. Second English Edition. http://planetologia.elte.hu

Diameter: 3476 km (=0,27 Earth diameter) Lenght of Equator: 10 914 km

Surface area: 38 million km² (= Africa and Australia together)

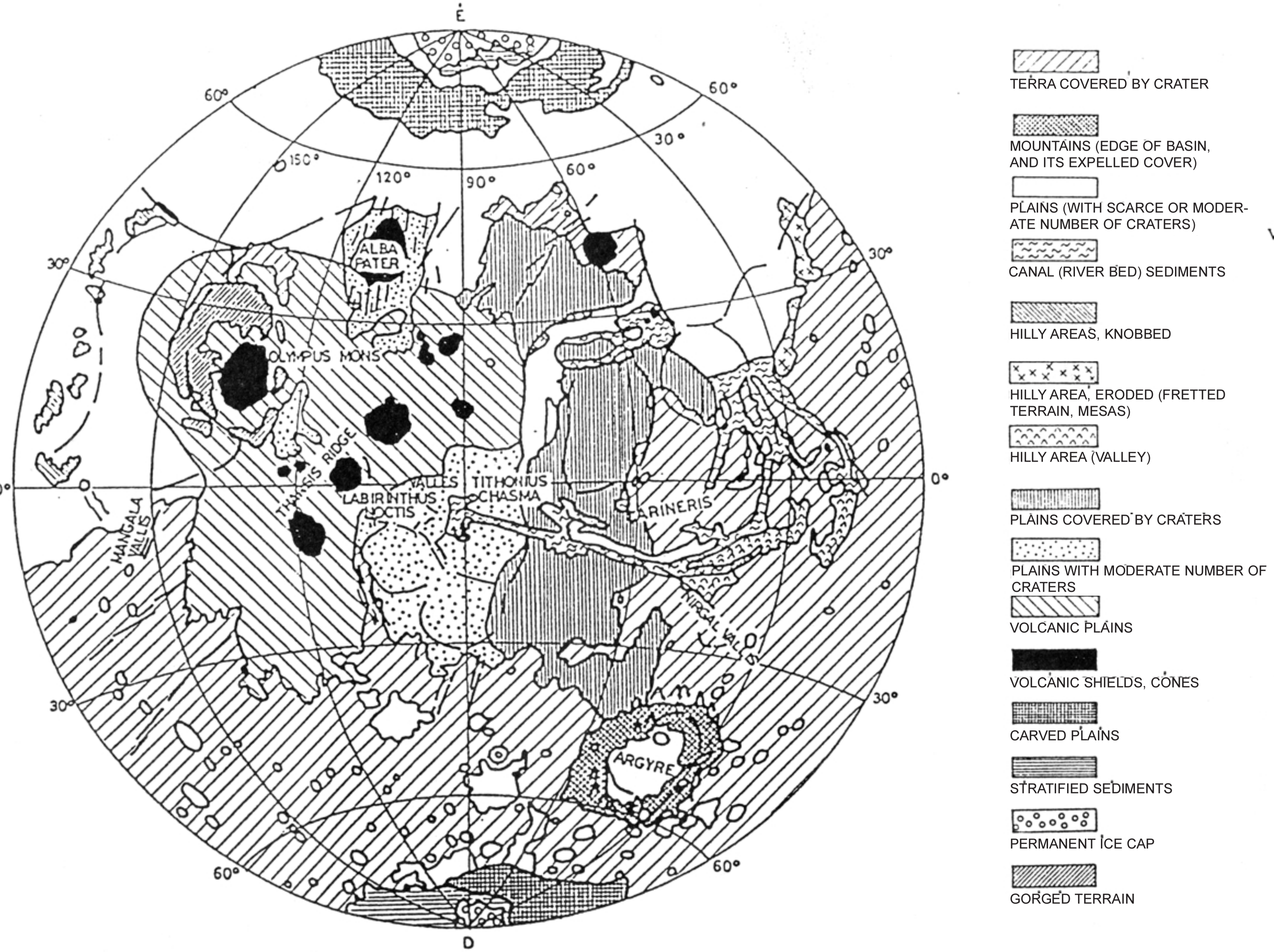
LEGEND

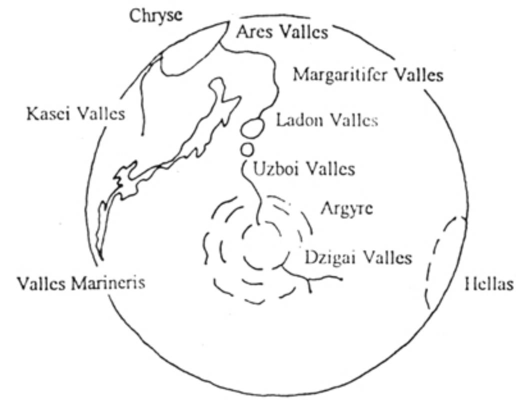
3120 •	Height above 0 datum level
Kepler	Name of impact crater
1966 LUNA–9 •	Soviet landing or crashing site
APOLLO–11 • 1969	American landing or crashing site
(swatch)	Mare (younger basalt plains)
(swatch)	Terra (older cratered highlands)
(swatch)	Relatively young, rayed crater

PLANETOLOGY GROUP
Eötvös Univ. CMSRG,
BUDAPEST

ATLAS OF PLANETARY BODIES

CONTENTS





Mars is expected to be the planet of 21st century, to where the next expedition will probably be organised. Its geological map has already been completed on the basis of the pictures taken by Mariner 9. The maps were made more sophisticated using the data provided by the Viking measurements. Recently the altitude measurements made by Mars Global Surveyor's Laser Altimeter (MOLA) provided many novelties.

The vertical resolution of the measurements made by MOLA is 30 cm. This accuracy made possible the following recognition: the longest river in the Solar System was running from the Argyre Planitia to the Chryse Planitia. The river had run along the a route following Uzboi Valles, Ladon Valles, Margaritifer Valles and Ares Vallis. If the Dziagi Valles is also considered, which starts from the southern polar region, then the length of the huge river system could have been 8000 km (Parker, Clifford, Banerdt, 2000).

Szaniszló Bérczi, Henrik Hargitai, Ákos Kereszturi, András Sik

CONCISE ATLAS OF THE SOLAR SYSTEM (3): ATLAS OF PLANETARY BODIES

Budapest 2005

1. THE ROCKY PLANETS

1.1 THE MOON

1.1.1 Stratigraphic mapping of planets having solid surface

The main “actors" are the rock bodies in the geological maps prepared on the planetary bodies having solid crust. Rock bodies are usually depicted in vivid colours which extend to the surface. The forms observed on the surface are also shown in the maps, and efforts are made to follow them as much as possible in depth. The rock bodies produce a series of stratigraphic units.

1.1.2 Stratigraphic axioms for the Earth

Axioms are preceded by a basic assumption, which should be preferably accepted before we start the work at all. This basic assumption is as follows: the surface of the planetary body consists of blocks, i.e. three dimensional rock bodies, the contours, locations of which, including their relationship to each other, can be measured and mapped.

The most widely known axiom is the law of superposition (set up by the Danish scientist Nicolaus Steno in 16th century). Younger is the rock layer (rock body) which is above the other. In this way the age of the layers becoming less as the layers follow each other upwards.

Two important and recognised axioms is the extension of an observation on Earth: It is possible to recognise

1. the processes that form the rock bodies, e.g. sediment formation in seas, volcanism, etc., as well as

2. the processes that change the relationship of these rock bodies, such as tectonism, intrusion, etc.

The double axiom of extension states that the presently observable processes were acting also in the past and also at other locations of the Earth. The axiom referring to time is also called actualism, and the one referring to space is called principle of uniformity, and both mean the spatial and time extension of the present processes.

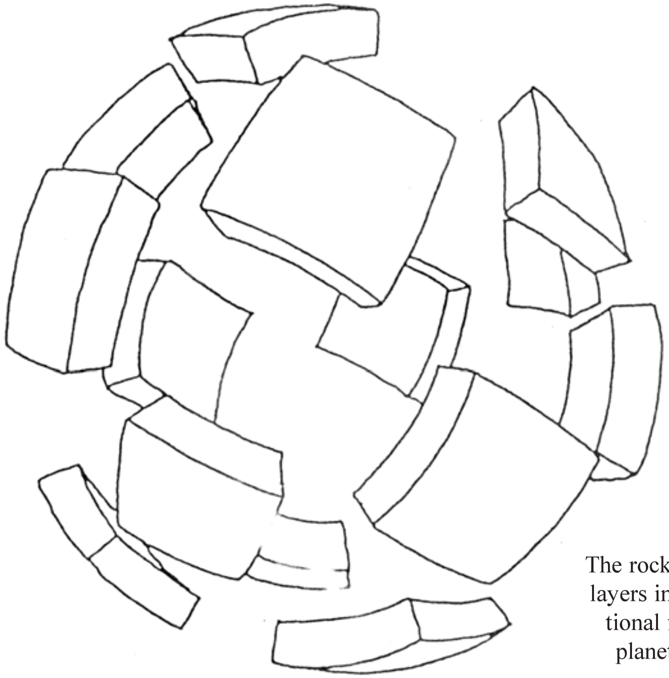
The next two important axioms allows a conclusion for the chronology of the rock bodies. One of the axioms says that the tectonic process, which moves the two rock bodies relative to each other, is younger than the two displaced rock bodies. According to the another axiom any rock body formed by penetrating another one is younger than the surrounding rock body.

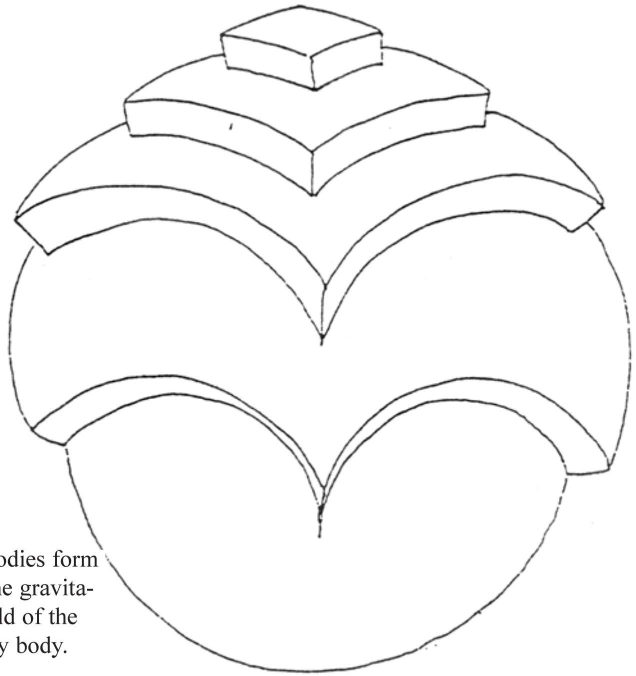
The last axiom related to the possibility of correlation using the inclusions. The axiom of inclusions also refers to a relationship just like the former two axioms, but it also extends the idea of stratification of materials to the entire Universe. This axiom essentially states that any enclosed body (inclusion) is always older that the enclosing rock.

It is necessary to use a geological correlation because the rock bodies do not represent a continuous layer, and because it is also important to determine the contemporary nature of different types of rocks appearing at different locations of the surface of planetary bodies. In brief: with the help of correlation we are able to shown the lateral continuity of layers.

The inclusions, representing an independent anthropogenetic series of fossils of the living world, are used to determine the correlation. In the mean time another kind of inclusions were also fond, such as the radioactive elements, which also form an independent anthropogenesis with their decomposition. In this way the study of stratigraphy can also be conducted by considering and comparing two series of events having their own separate anthropogenesis.

In order to extend the correlation to the range of the planetary bodies within the Solar System it seems to be desirable to consider other kinds of inclusions. We need inclusions, that can be found on the surface of more than one planets, and some of the properties of which change in time. Such inclusions could be craters, as well as the rock provinces which can be brought into correlation, including the crater fields on the surface of planets.





The rock bodies form layers in the gravitational field of the planetary body.

1.1.3 Stratigraphy of the Moon

The Moon was the first planetary body to which the axioms developed for the stratigraphy of Earth was extended (Shoemaker et. al, 1962, Wilhelms, 1970, 1987). The properties of the rock bodies, the conditions of overlapping were initially studied by means of photometry using photographs made with telescopes. Later the pictures taken from space were used for this purpose.

One of the possible summarisation of the stratigraphic mapping is a stratigraphic column of the Moon, which is now demonstrated as a stepped pyramid of the Aztecs. In this diagram the major elements of the stratigraphy of the Moon are listed, which at the same time indicate the major eras of the rock formation on the Moon.

On the Moon the youngest craters are those which have radial rays (Copernican level). This is followed by the craters without radial rays (Erathosthenian level), which still has a youngish divided morphology. The layers of both younger levels are present only in spots of craters on the lunar surface, although Erathosthenian mares also occur (and the crater zones of Tycho and Copernicus crater extend to a large distances which can be seen readily, particularly during full moon). Beneath the spots of stratigraphic units two further levels can be found which consist of large rock bodies. One of them is the Imbrium, which was connected to the Imbrium basin at the area assigned at the definition (Imbrian level). The other still older unit is connected to the Nectar basin (Nectarian level). The lowermost level (pre-Nectarian level) is the terra areas which is covered with crater fields.

A. **Copernican** (young craters which have radial rays)
B. **Eratosthenian** (young craters which have no radial rays)
C. **Imbrian** (expelled mantle mare flooding since the formation of Imbrium basin belong here)
D. **Nectarian** (basins, maria formed since the formation of Nectarian basin belong here).
E. **Pre-Nectarian** (all the rock bodies preceding the Nectarian basin belong to this stratigraphic level).

In the meantime the principles of stratigraphy were applied also to other planetary bodies of the Solar System, such as Mars, Mercury, Galilean satellites of Jupiter. Presently the geological mapping of Venus is in progress (in both Russia and the USA). One of the major projects in the 21st century will be the development of stratigraphy for the entire Solar System.

1.1.4 Circular basins

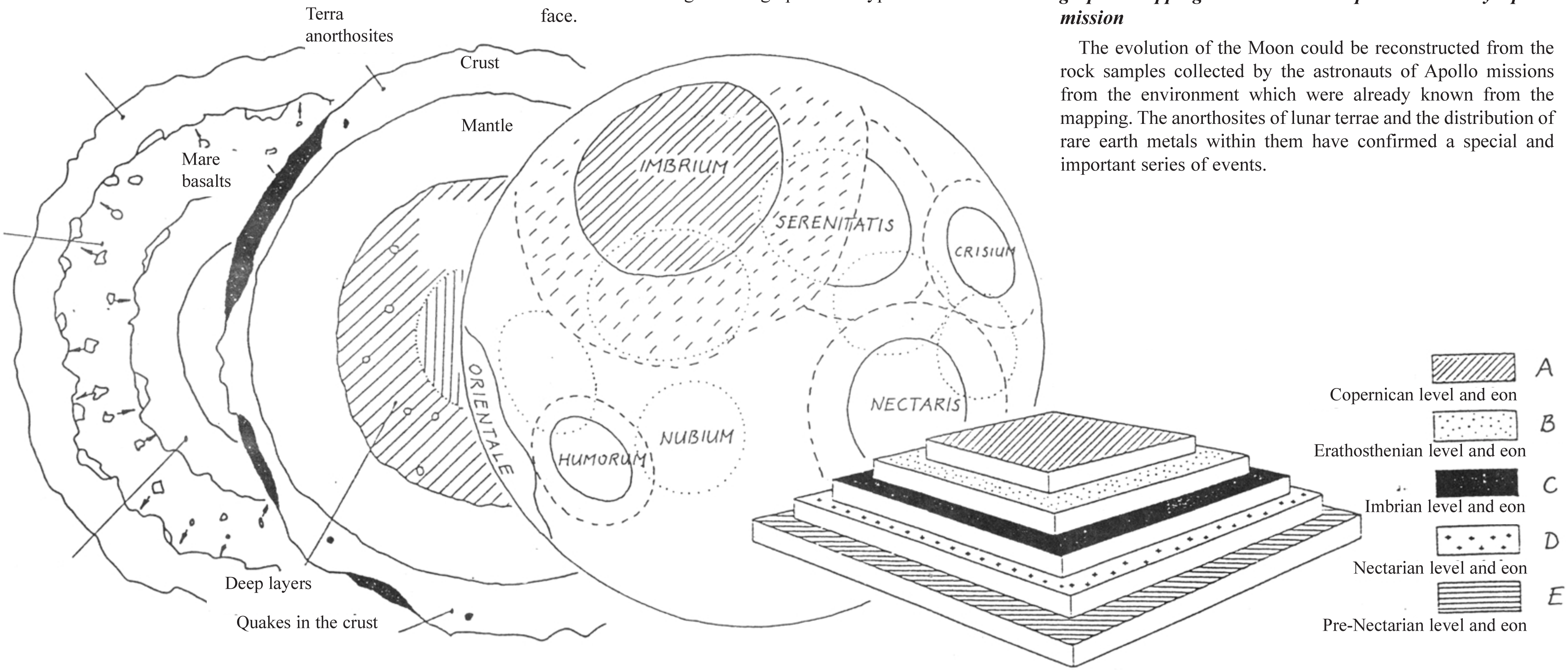
The crust of Moon was hit by a number of large objects during the half billion year long period after its formation. These impacts broke up the anorthositic crust, established circular basins, and spread the ejected material on huge areas.

(As a result, most of the anorthositic rocks forming the crust of the Moon has a breccia texture: the fractured minerals the breccia texture can be observed.) The large impacts produced huge basins which are still recognisable. The expelled mantle of the circular basin and the internal tectonic structure are the constituents of the largest stratigraphic unit type on the lunar surface.

At the visible side of the Moon the basins of large impacts have been filled by basalt lava flows. The lunar volcanism lasted for a long time, and the low viscosity lava has flown to large distances and has spread in thin layers. The age of the lunar basalts extends to one billion year in the Imbrian eon, but certain lava flows occurred in the Erathosthenian eon as indicated by the count of craters. The lava flows mapped in the Imrium basin belong to this category also. The second largest stratigraphic type include the basalt lava layers on the Moon. The circular basins and the basalt layers may also regarded as chronological planes, because many smaller units can be sorted in relative series of layers in comparison with these large units when preparing the stratigraphic mapping.

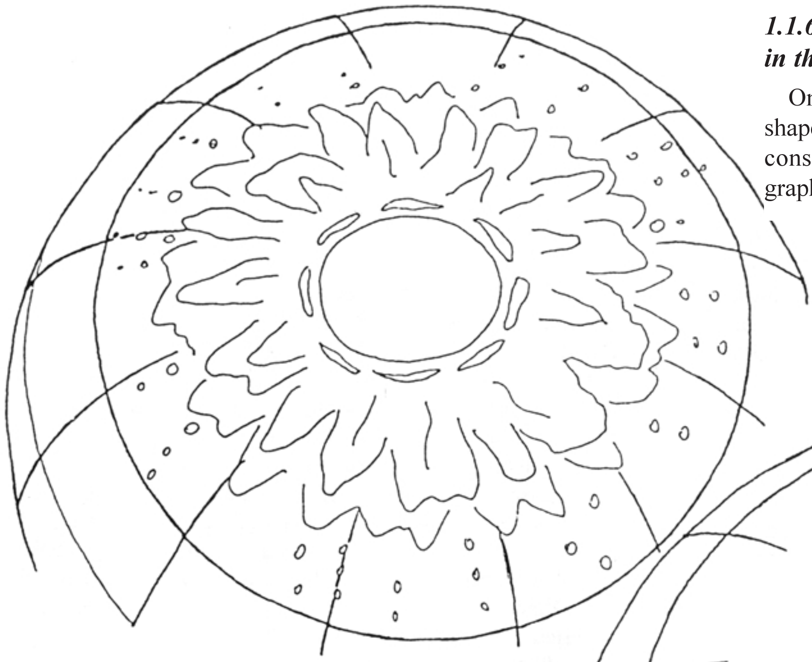
1.1.5 The relationship between the rock bodies of the stratigraphic mapping and the rock samples collected by Apollo mission

The evolution of the Moon could be reconstructed from the rock samples collected by the astronauts of Apollo missions from the environment which were already known from the mapping. The anorthosites of lunar terrae and the distribution of rare earth metals within them have confirmed a special and important series of events.



Long ago the external layers of Moon melted and 4.4 billion years ago the Moon was covered entirely by a magma ocean. The plagioclase feldspar ($CaAl_2Si_2O_8$) accumulated on the melted zone during the cooling of magma ocean, thus creating the light coloured anorthosites of hightlands. The denser minerals sank to the bottom of the melted zone. This differentiation lasted for a long time.

The impacts hit the anorthositic layer, which was becoming thicker at that time, creating circular basins. These impacts ruptured the lunar crust. Basalt lava seeped to the surface through the fractures and filled the basins on the near side of the Moon as a result of volcanic activity that lasted for 1 – 1.5 million years. The basalts came from the mantle of the Moon. Some of them are very rich in titanium, such as the samples collected from the landing sites of Apollo 11 and 17.

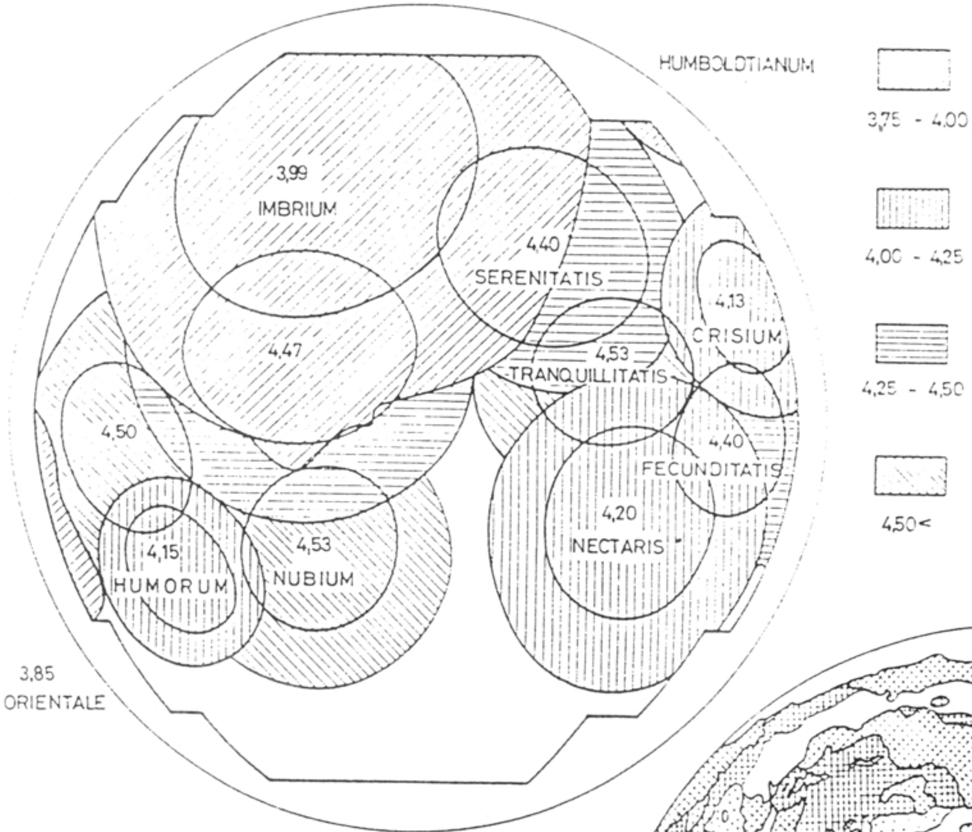


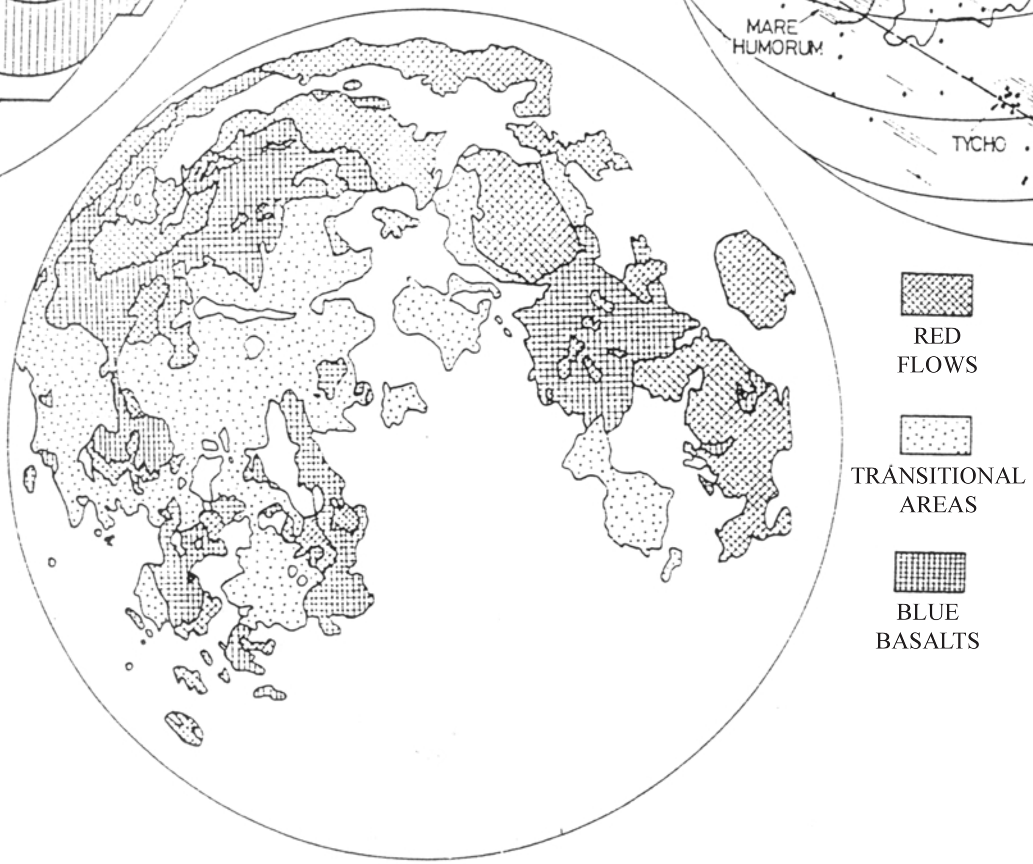
1.1.6 The surface forming episodes in the Imbrium basin

Only the presently visible circular shape of the Imbrium basin could be considered for preparing the stratigraphic map of Moon. In the illustrations the original circular basin produced by a small planet sized impactor is placed at the pole of a spherical cap (first picture). The central depression is bordered by a mountain range (i.e. crater rim). The zone of the expelled material can be observed at the outside, then a zone of secondary craters can be observed which were produced by the ejected boulders. These zones can still be observed outside Mare Orientale, which is the youngest circular basin.

The second episode indicates the era, when the internal territory of the basin has already been covered by a new layer of material, i.e. mare basalt. The ejected cover, which had been continuous originally, can be seen now only in patches.

The third episode shows one of the most recent lava flows. Astronauts of Apollo Missions photographed the youngest lava flows in Mare Imbrium. The lava flow indicated by the arrows is almost 1000 km long. It starts from the south-west edge of Mare Imbrium and branches at the middle of the basin. One of the branches turns to the east, while the other turns to the west. The western branch is terminated at the forefront of Sinus Iridum.





Three different maps are shown here about the Moon. All of them were made about the visible side of the Moon. The first one illustrates the ancient Moon showing circular basins and the areas covered by their expelled material. It can be seen that the surface of Moon had been covered almost entirely by basins, and their external covers are overlapped. The second map shows the basalt plains. In this map the basalt of different compositions can be distinguished if photographed with Whitaker red-minus-blue filter. The "blue" basalts have high titanium content, while the red basalt contain small amount of titanium.

The third map has been prepared during a lunar eclipse, and shows the warm spots of the Moon. Actually, this is a thermal inertia map of the presently observable lunar surface, which particularly emphasizes the craters of fresh impacts (Shorthill and Saari mapped the points which are warmer than their vicinity).

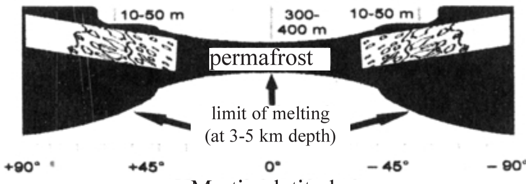
1.2 MARS

During the 4.5 billion year long evolution of Mars – the outer neighbour of Earth – the surface had been formed by various external forces within the different eras. In the meantime the lithosphere was influenced by processes that were controlled from inside the planet, i.e. by tectonism and volcanism.

1.2.1 Era of water – Noachian (4.6 – 3.5 billion years)

The Heavy Bombardment by asteroids and meteoroids at the end of the formation period of planets and during the crust formation, plenty of volatile material, such as water, have evaporated from the inside of Mars. The volatile sphere also increased by celestial bodies coming from the zone of outer planets. For this reason the young Mars resembled much more to Earth than it does today. Both its inside and surface was geologically active, it was surrounded by a thick atmosphere, its surface was covered with oceans and seas, their craters collected lakes, and their valleys were carved further by rivers.

Symmetric zones can be observed in the magnetic pattern of the old Southern terrae. This indicates that the breaking up of plate had started, but the process halted and the reformation of the crust did not start. On the other hand, the volcanic activity was very intense which was initiated in the second half of the era. It produced the Tharsis terra having a diameter of 8000 km, and the basaltic lava flowing onto the surface had built up the largest volcano of the Solar System to a height of 27 km, named Olympus Mons. It is not known when the Martian volcanoes stopped their activity. Certain lava flows seem to be not older than 10-15 million years.



Oceanus Borealis (the hypothetical northern ocean) must have been the largest body of water on the surface, which occupied one third of the planet in the Northern polar region, which is actually a basin-like lowland. Its partial basins, larger moors and shorelines can still be identified with accurate altitude measurements. The old channel system of the Southern terrae also originates from this era. Their branching routes, meandering run, estuary-like termination near the shoreline are very similar to those of their counterparts on Earth.

Emphasis should be given to areas where the volcanic heat and the fluid water acted simultaneously on the planet, because such hydrothermal system could have been excellent cradles of life. Later the volatile sphere started to diminish for a number of reasons.

a) the last large celestial bodies of the planet-forming period had impacted onto the surface, which produced the large impact basins (e.g. Hellas, Argyre), and at the same time, boiling and inflating the significant portion of volatile material;

b) the radioactive thermal sources depleted slowly, the core became solid, and the magnetosphere it had generated ceased to exist. In this way the planet lost its cosmic protection shield, and the charged particles of the solar wind could freely erode the atmosphere;

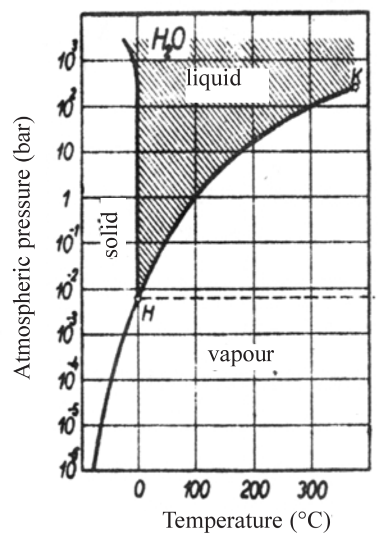
c) the escape velocity on Mars is only 38 % relative to that of Earth because of the small size and mass. For this reason various atmospheric particles can escape from Mars more easily.

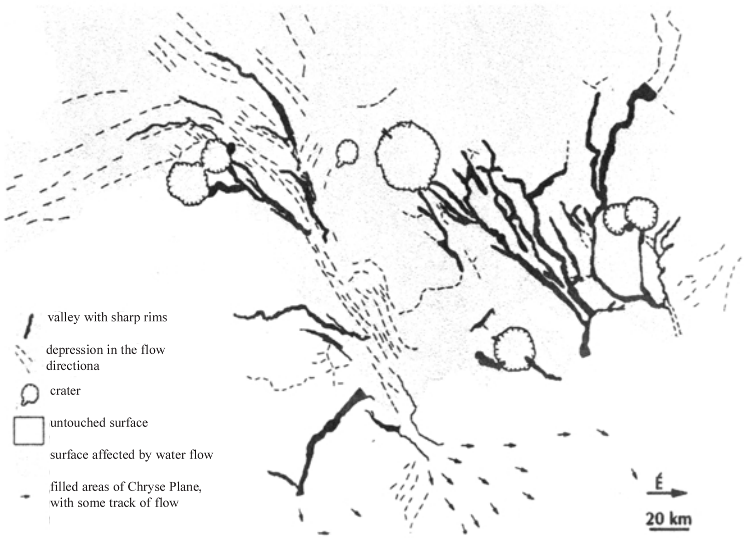
d) the process was further enhanced by the thinning atmosphere, the diminishing greenhouse effect (which was less effective because of the larger distance from the Sun), thus more and more of the residual volatile materials precipitated at the area of the polar ice cap.

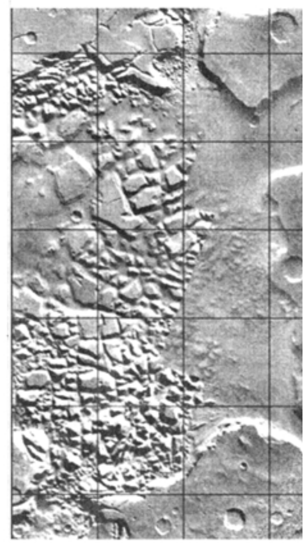
As a result of these processes the temperature and the pressure dropped dramatically (-53°C, 6 hPa), so that water could not remain in fluid state any longer on the surface.

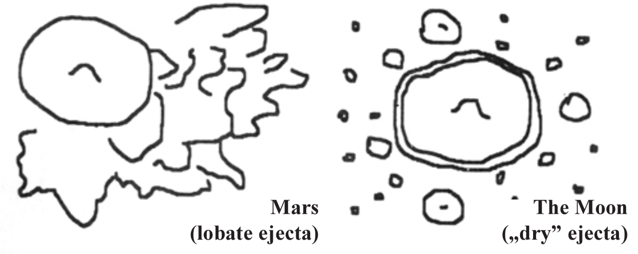
1.2.2 Era of ice – Hesperian (3.5 – 2.7 billion years)

Most of the frozen water was enclosed into the thick layer of fine rock debris, i.e. regolith. As a result a permafrost layer was produced all over the planet. This is also named cryosphere, which seems to be confirmed by a number of features, such as patterns similar to the terrestrial frost polygons, slightly hazy surfaces which had went through topographic relaxation because of the shallow ice layers, as well as the unique lobed craters which was produced as a result of a process consisting of melting the shallow subsurface ice layers into the plastic mass which started to slide after heated by the energy of impacts. It is estimated that a planet could have been covered by several hundred metres of water should the water melted from the cryosphere. It is also possible that liquid water survived at a greater depth or at locations of high salt concentration, which came to the surface at the weak parts of the crust, as well as at impact craters and along tectonic faults of volcanic regions.



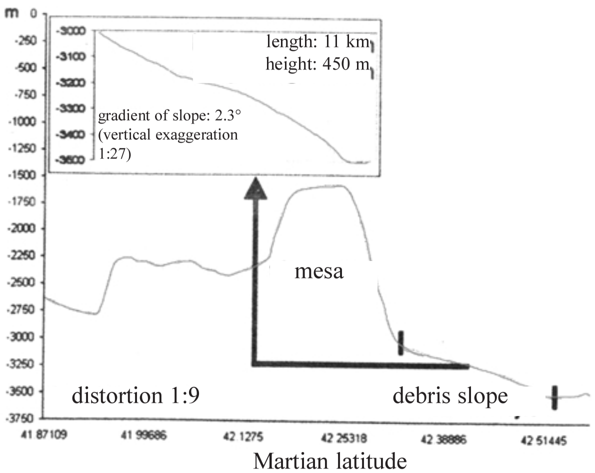






The outflow channels are produced in the following way: The source regions are *chaos areas* having unique patterns, where the surface has broken up into huge blocks as a result of washaway and collapse processes. It appears that the water had surged to the plains as a flood instead of quietly eroding the river beds. These floods produced streamlined islands and variable branches, particularly at areas with moderate width. Considering the environmental conditions, the water movement must have occurred beneath the ice shell with alternating periods of flooding and tranquillity. One of the largest flood channel extents from the canyons of Valles Marineris to the Chryse Planitia, which had been the bay of Oceanus Borealis.

From that time Mars began to resemble a terrestrial area where ice is present below ground level. Characteristic topographical features include the slopes of debris which surrounds the elevated table mountains at the bordering area of the Northern lowlands and Southern highlands. Based on their plastic shapes and detailed investigation it is reasonable to believe that they are rock formations mixed with ice, which are similar to terrestrial rock glaciers. They do not seem active today, but in the warmer periods of the past the ice cores might have melted temporarily and might have moved in the direction of slope.



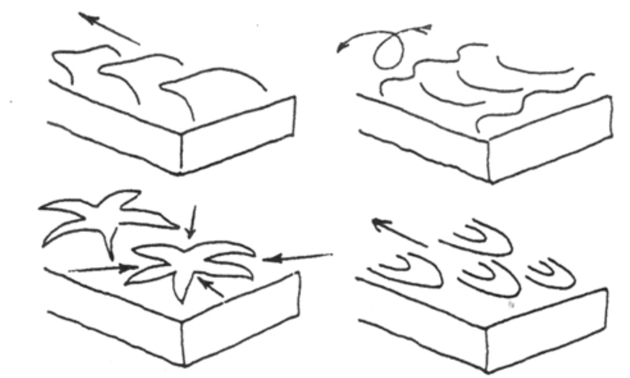
1.2.3 *Era of wind – Amazonian (c. 2.7 billion years – today)*

The wind could become the dominant surface forming agent as the layers close to the surface cooled and dried (the disintegration of rocks is a prerequisite), although the modes of movement associated with ice could still exists.

The present activity of wind can be proven in a number of ways. Dust devils occur on a daily basis which rise dust into the atmosphere. Many formations on the surface could not be covered by the sedimenting airborne dust, because of the frequent wind. Other formations exhibit fresh slides, narrow ridges and sharp edges. However, no microshapes are present, which is a sign of fast change. The best proofs are provided by the observations taking place at the polar areas, where the dark material of the dunes appear in patches from beneath a withdrawing thin ice early in spring. This material is blown by the wind in the same direction for each patch, and it is deposited on the ice which has a maximum age of half Martian year. This means that the process takes place within this period.

Shapes formed by the wind are determined essentially by two factors; atmospheric and surface conditions. The determining factor is the direction of wind, its consistent direction and the wind velocity, as well as the quality, density and particle size of material covering the surface. Modification components could also be considered, such as disintegration and degradation, and vegetation cover, but this latter could not be taken into account in case of Mars. It is important to note that the atmospheric pressure is one thousands of that prevailing on Earth. For this reason the intensity of erosion by wind is minimal. In addition to other external forces, this explains why some ancient surfaces seem to be not very much older than other surely younger areas.

The many different shapes formed by the wind include wind streaks established behind topographical obstacles and having different shades, as well as yardangs which have been exposed after they had been buried earlier. In smaller patters sand ripples can be seen, together with barkans, sand veils without any particular shape, and the most frequents are the dunes.



The ridge of the dunes on Mars are usually perpendicular to the wind direction (as opposed to the longitudinal dunes on Earth), which is an indication of constant wind directions and abundant presence of sand, i.e. debris. Seasonally changing wind direction produce more dynamic shapes, star-like dunes, which are also known on Mars yet. Where the debris layer is thick the material is arranged in heaps, barkans, instead of dunes. These tend to migrate in the nearly constant direction of wind.

Among the shapes formed by the wind there are younger patterns as well: the gullies which were carved by seeping water from the subsurface, water-containing sediment layers.

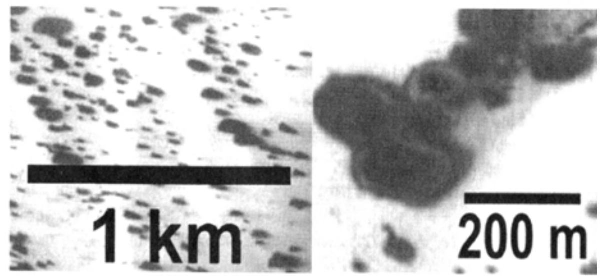
1.2.4 *The possibility of life*

In brief, the present Mars is a cold, dry, windy and dead desert, which has not changed for a long time. Its rocky-gravely-sandy landscapes are red coloured because of the iron oxides. Its seems, on the basis of the great variety of shapes and the orbital parameters (elongated path, inclination of axis varying in a wide range), that this condition will not last forever. The weather system probably changes periodically. Warmer periods occur repeatedly, when certain components of the hydrological cycle start all over again.

Such past cycles could have been beneficial for the development of certain organisms, which like extreme conditions (extremophiles), the counterparts of which are discovered from time to time at various locations of Earth, which were thought to be sterile earlier (e.g. black smokers, cooling water of radioactive reactors, artificial vacuum). In addition to that, Hungarian researches recognised unique patterns of patches on areas covered by ice, the development of which might be explained with biological activity.*

It is possible then that the transition from inanimate material to living material occurred also on Mars, but the anthropogenesis of Mars deviated from that of Earth later. Life was either terminated or withdrawn to special areas waiting there to be discovered…

*T. Gánti, A. Horváth, Sz. Bérczi, A. Gesztesi, E. Szathmáry: Dark Dune Spots: Possible biomarkers on Mars? *Origins of Life and Evolution of the Biosphere* 33: 515–557, 2003.



1.2.5 *Polar areas: Ice caps*

1.2.5.1 *Archives of Martian climatic history*

The existence and size of the ice caps of Mars are determined by the tilt of axis of Mars and the eccentricity of its orbit which determines its climate. The seasonal change of their size is connected to the actual distance at the particular hemispherical season. The inclination of the Martian axis is somewhat larger than that of the Earth. However, the eccentricity of its orbit (in turn the difference between the perihelion and aphelion) is much larger, thus the seasons are more extreme. Both poles have ice cap, which does not disappear entirely during the local summer.

The structure of ice cap can be regarded also as an annual ring system: for millions of years in each summer the winds, dust storms deposit the dark sand on the thinned surface of ice cap. The dry ice is then precipitates on the surface of this dust layer. The layers, which are similar to grooves of vinyl records, are 5–300 m thick, and have various resistant against erosion. Groups of layers with lighter and darker shades appear alternatively. These varying lighter-darker shades have been cause probably by the climatic changes associated with the varying orbital parameters of Mars. The change in the shades of the annual layers are also influenced by other parameters (debris of volcanic eruption and impacts, large dust storms). It is estimated that the ice caps consists of 5% dust and 95% ice.

The ice cap has two main parts: dry ice cap with varying thickness and a permanent water ice cap. At the poles the temperature never rises to the melting point of water, but reaches that of carbon dioxide: in this way the material of the residual cap can be water ice only after the temperature has exceeded the melting point of CO_2.

1.2.5.2 *The northern ice cap*

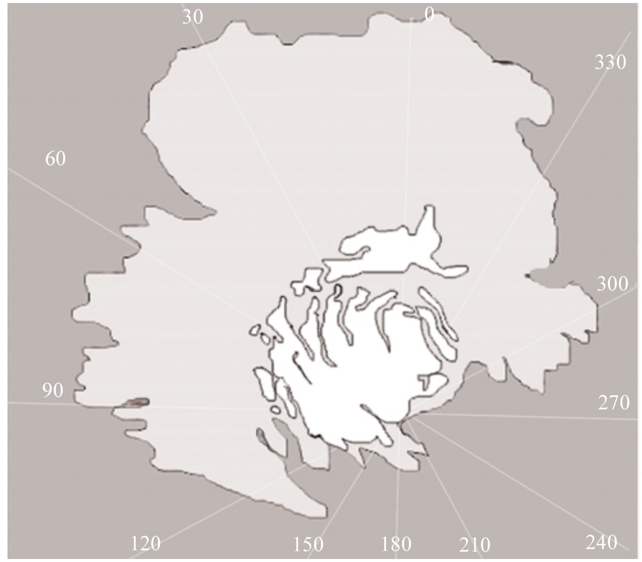
From the ice cap, consisting of water ice and dry ice, the latter, i.e. CO_2 sublimes into the atmosphere during the spring (that is why it is called dry ice: it becomes gas immediately without becoming liquid first).

In winter the CO_2 freezes again, and precipitates back on the surface. The permanent cap consisting of water ice is bisected by a horn shaped Chasma Borealis. The northern cap never freezes to the extent that the southern does, because the summers are cooler as a result of the larger aphelion. The ice cap, that has a diameter of 500 km, is bordered by an almost continuous dark sand dune ring, which is formed by the polar winds. The dunes, as well as the inside of craters close to the polar region, are covered with CO_2 ice and frost.

1.2.5.3 *The southern ice cap*

The CO_2 ice never melts entirely at the region of the south pole, in this way the layers below never get to the surface. The (dark) winter period on the southern hemisphere occurs when the Mars is at aphelion (far from the Sun), therefore it is long and cold. The summer on the southern hemisphere, however, occurs when Mars is at perihelion (close to the Sun), i.e. it is warmer and shorter than that of the northern hemisphere. Even if the ice cover swells to a diameter of 1800 km, the size of the remaining permanent cover in summer has only few hundred km diameter.

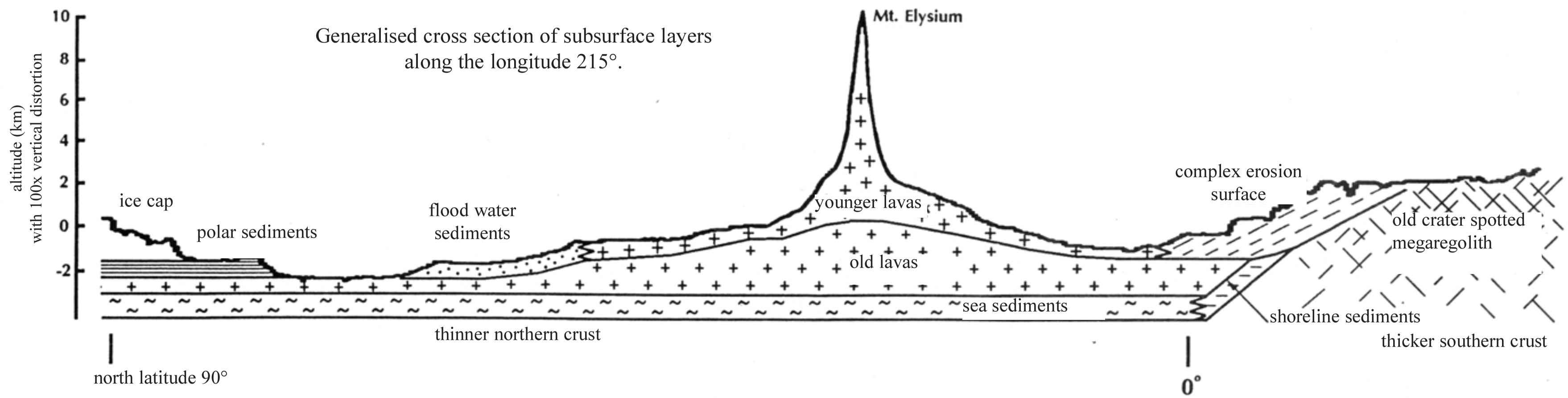
The quantity of dust is much higher in the southern polar layers, because the ice sublimes quickly into the atmosphere during the hot perihelion period. In this way the atmosphere is increased, its density grows, and the air pressure becomes higher by as much as 25 % (from 6.9 to 8.9 mbar). The dense atmosphere is warmer as well because of the closeness of the Sun, thus its size is also larger. This gives rise to strong winds which start to carry the dust. The dusty air is darker, which absorbs the sunshine more readily, becoming warmer. The process has a positive feedback, which may lead to global dust storms.

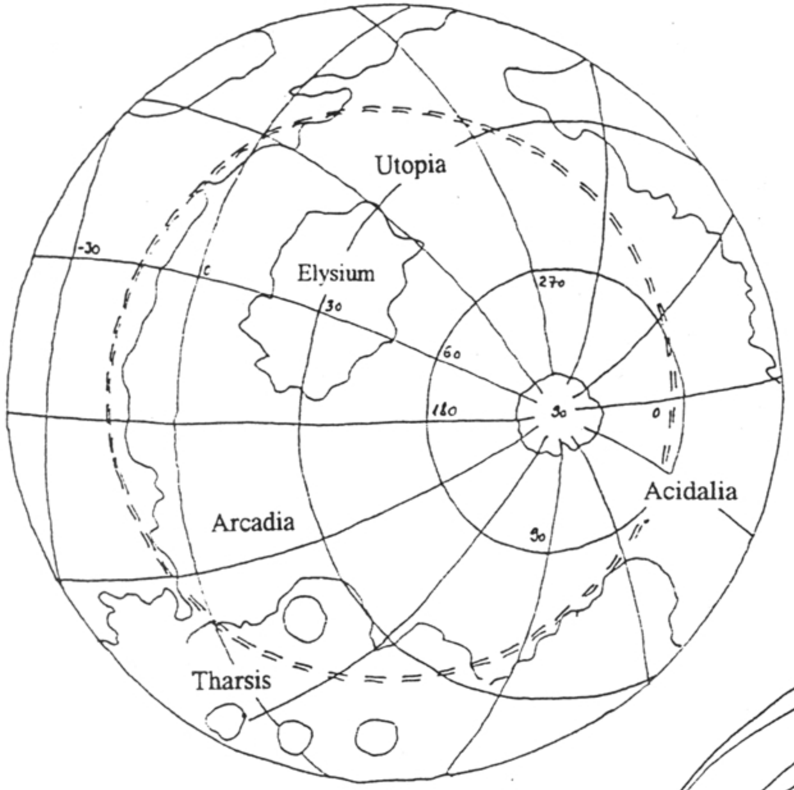


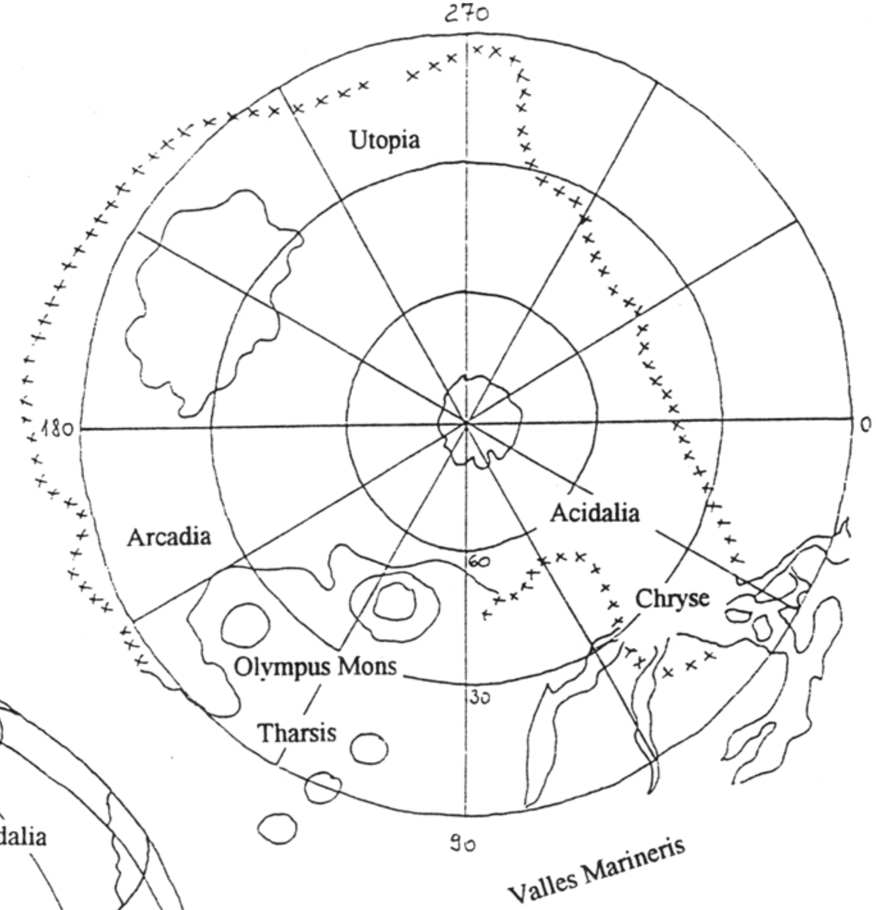
Vicinity of the southern pole. In winter the light grey areas are also covered with dry ice (frost). By summer, only the central part of the of the ice cap remains as shown in white.

Large quantity of airborne dust, sand settles primarily in the southern ice cap.

The southern ice cap is also surrounded by sand dunes, but not in a continuous ring, like in the north. Dark, generally round spots appear on the dunes during the thawing period. Unique round holes can also be seen at the southern regions, which are produced as the thawed soil collapses (like Emmentaler cheese).







At the time of Viking expeditions the researchers tried to find the origin of the southern plains of Mars in large impacts and in basins produced by the impacts (Wilhelms et al.). It was possible to prepare ancient "hydraulic" maps about Mars by using the laser altitude measurements made by Mars Global Surveyor's Laser Altimeter (MOLA), and the picture taken by MOC. The largest catchment area is the Northern Ocean of Mars. Its shoreline was found at a number of places (Parker et al.). Viewed from the direction of the pole the Northern Ocean exhibits three downward "lobes"; one of them being the Acidalia Planitia (Chryse is its southern bay), the second being the Utopia Planitia, and the third one being the Arcadia Planitia next to the Olympus Mons.

Recommended further reading to the Atlas of Planetary Bodies:

Abonyi Iné., Almár I., Apáthy I., Bérczi Sz., Echter T., Érdi B., Ferencz Cs., Gesztesi A., Gombosi T., Herczeg I., Horváth A., Ill M., Illés E. Kőháti A., Major Gy., Mihály Sz., Nagy I. Gy., Sárhidai Gy., Szentesi Gy., Tänczer T. (1981, 1984) *Űrhajózási Lexikon* Szerk: Almár I., Horváth A., 1002 oldal. Akadémia – Zrínyi Kiadók, Budapest

Almár I., Both E., Horváth A. (szerk.) 1996: *Űrtan*. Springer, Bp.

Bérczi Sz. 1977: *Planetológia*. Egyetemi jegyzet, Tankönyvkiadó, Bp.

Bérczi Sz. 1991: Kristályoktól bolygótestekig. Akadémiai K. Bp.

http://planetologia.elte.hu/ http://adswww.harvard.edu/

http://www.lpi.usra.edu/meetings/lpsc2000/pdf/ABCD.pdf

1.3 VENUS

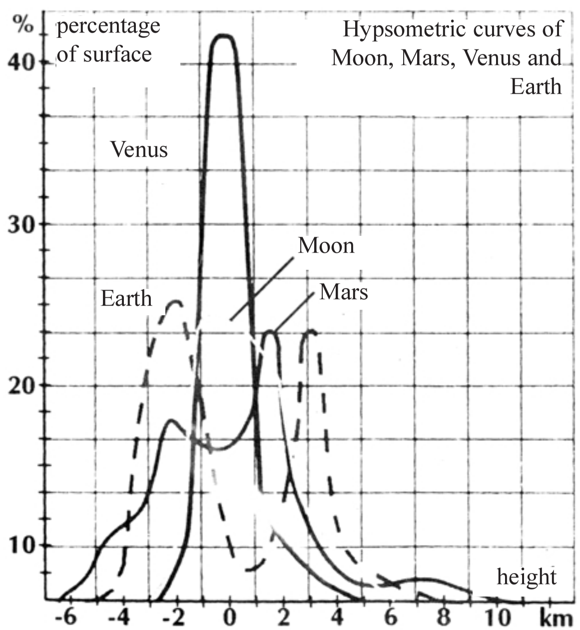
1.3.1 Twin of our Earth?

In geological terms Venus – the immediate inner neighbour of the Earth – is the most similar to Earth within the Solar System among the planets. It could even be the sister of Earth, as far as its size, mass and density are concerned, but the differences are also very extensive. The surface of Venus is relatively young, its age 0.5–1.0 billion years. Volcanic eruptions and plate movement could not be observed directly on its surface, but there are a number of reasons to believe that the surface is still active.

The height distribution of a planet is illustrated with a hypsographic curve, which indicates the ratio of various height ranges occurring on the planet. The hypsographic curve of Earth and Mars indicate two peaks according to the two different kinds of crusts. Only one peak can be seen in the curve of Venus. It means that most of its surface is made of a single rock type, which is similar to the basalt in chemical composition. It was not possible to accurately determine the composition yet. The surface of Venus similar to a hypothetical situation on Earth, i.e. as if only one ocean crust were on Earth, or if thinner parts of crust existed then they were buried by lavas beneath the plains. (In this case, however, the very definition of the crust should also be reconsidered.) Yet another characteristic is that the surface is dry, not a trace of water can be detected. The dryness is a characteristic feature of the entire rock cover. The deformation of lithosphere is quite different relative to that on Earth.

On Earth the water intrinsic in the minerals provides a kind of lubrication, that allows an easier sliding of plates and eruption of volcanoes. On Venus another factor plays a beneficial role for the deformation: the high temperature. As a huge greenhouse, the atmosphere maintains a temperature of 450-550 °C all through the day. The crust that cannot cool below 450 °C even on the surface must be relatively plastic. This condition acts against the formation of large solid and uniform rock plates.

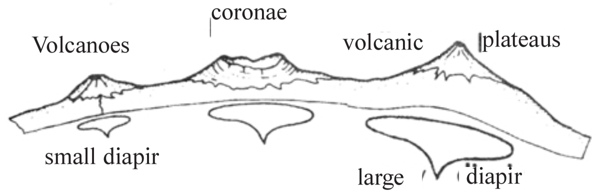
Generally, Venus can be characterised as a planet, that is active, having many volcanoes and weak zones in its crusts (which may be borders of plates), high surface temperature, and a crust that has a basaltic chemical composition. All of these features are resembling to what we think about the development of crust in the Archaean eon of Earth.

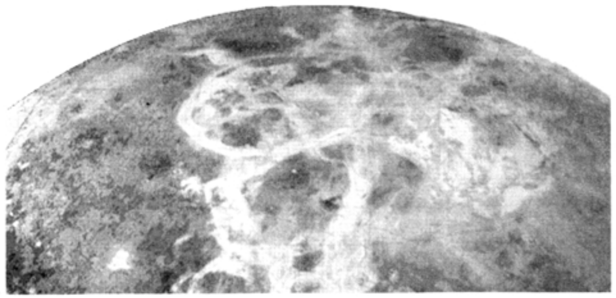


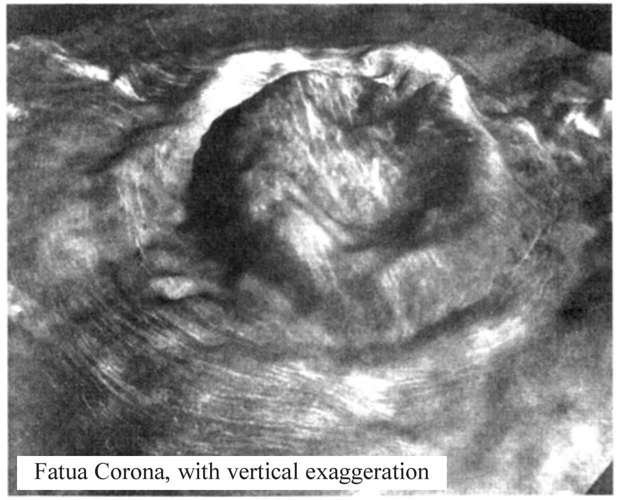
Hypsometric curves of Moon, Mars, Venus and Earth

1.3.2 Coronae: volcanism and plate tectonics together?

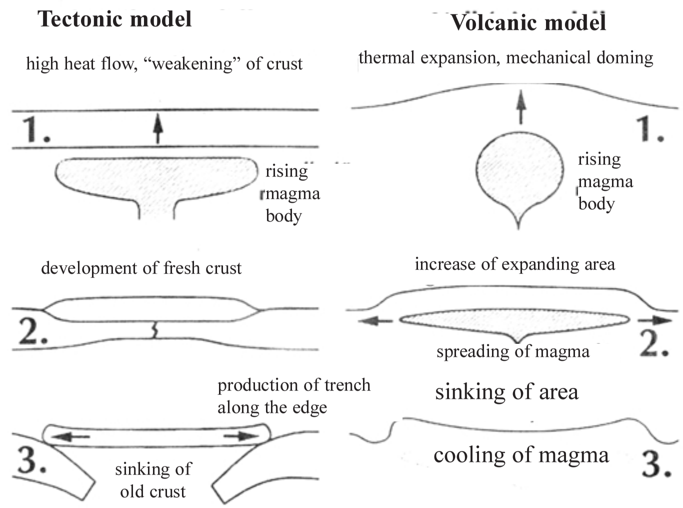
Coronae are unique formations of Venus. 176 of them could be positively identified until now. Their size is in the range of 200-300 km generally, the largest has a size of 2600 km. The ringed appearance was the origin of their name. In a corona the relatively low level internal area is surrounded by concentric system of fissures, with depressed or elevated topography along the rings. Volcanic formations, various dome fields often occur within them, which are at about the same topographic level as their vicinities.






Fatua Corona, with vertical exaggeration

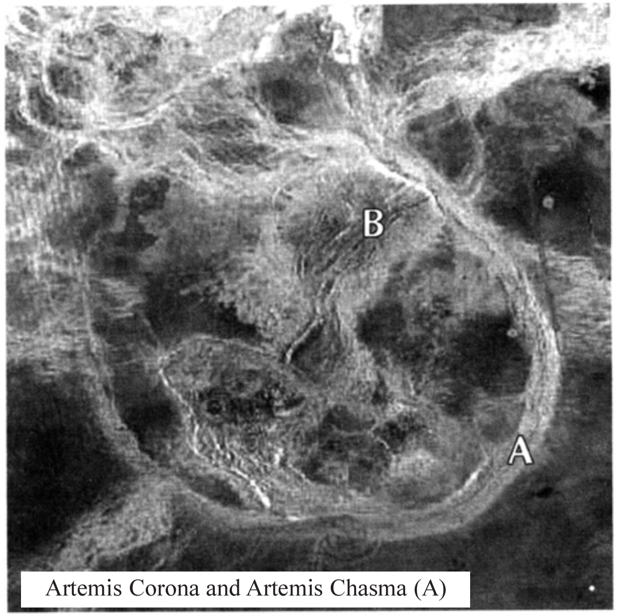
These are probably volcano-tectonic structures, which lead to the appearance, reinforcement, then elimination of rising mantle diapirs and associated lava intrusions. In theory, their development can follow the scheme below: 1. Magmatic diapiric intrudes the crust. 2. Mechanical and thermal expansion take place within the area, the terrain bulges, and volcanic activity starts within the internal parts. Radial fissures are produced by the mechanical stress of the bulge. 3. Because of cooling and shrinking and/or partial discharge of lava to the surface the area sinks and a system of concentric fissures is produced.



The steps produced at the edge of the original intrusion get emphasised during the settling stage. Trenches are often produced at the outer edge partly by the settling caused by shrinkage, and partly by the mechanical deflection of the thinner crust next to the terrain steps. There is another explanation that emphasises the role of tectonic activity. Accordingly, the new material coming to the surface above the diapir moves outwards from the centre, and the earlier crust next to the elevated edge sikns by subduction, thus creating a depression at the edge of the ring. The group of coronae also includes the so-called arachnoids and novae, which represent certain stages and varieties of the development of coronae with their heterogeneous system of grabens. It is also assumed that the size and nature of diapirs essentially influence the formations produced on the surface. Several "simple" volcanic centres occur above the smaller diapirs, and extended volcanic plateaus occur above the large diapirs. The coronae might be the transitional state between two.

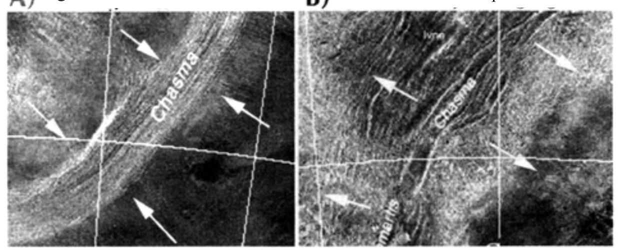
1.3.3 *Artemis Corona: Rosetta Stones of surface development*

With its 2600 km diameter, Artemis Corona is far the largest such structure on Venus. The second largest corona, the Hang's corona, is also huge with its 1060 km diameter. The absolute relief is 7.5 km in the ring system along the edge of Artemis. The bottom of the depression is 4 km below the surrounding terrain. The graben system along the edge is very similar to the Diana and Dali Chasma, their topography resemble to that of subduction zones on Earth. The inside of the corona is rather heterogeneous. A rift appears to be present at its NE part, which is comparable to the tectonic structures where the crust is being formed at the mid ocean ranges on Earth. The internal terrain of this corona is very diversified. It differs from other coronae, because it is not uniform, but is divided into many sub-systems, which were produced by different volcano-tectonic processes.



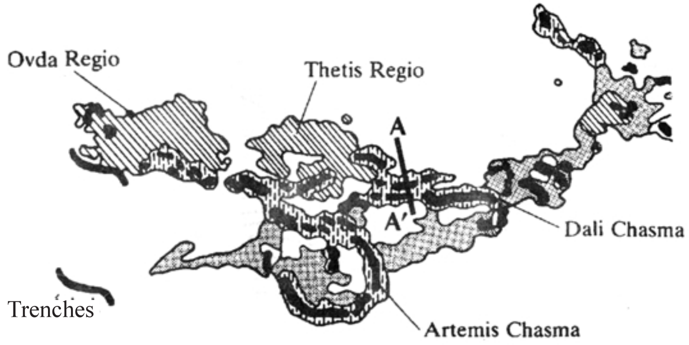
Artemis Corona and Artemis Chasma (A)

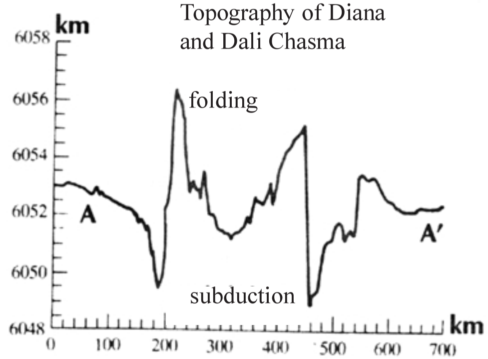
In brief: we can investigate the effect of the flow of mantle at Artemis Corona, including the volcanic activity, the deformation of mantle, the formation of mantle, and subduction (or something similar to it) at the edges. It seems that this is a transitional surface formation, where the major stages in the surface development of an terrestrial planet is being "replayed" at regional scale. Based on its size, it represents a transition between coronae and volcanic plateaus. If it could be transferred to Earth, then its linear structures would be in the size range of the subduction zones.



A) Edge of Artemis: subduction? B) Inside of Artemis: expansion of crust?

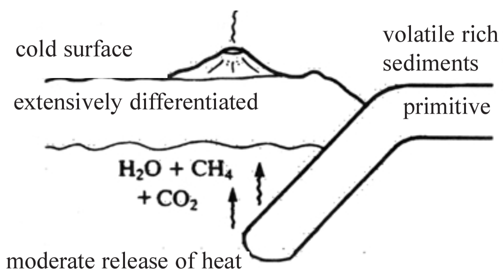
Trench (Chasma) system of Aphrodite Terra



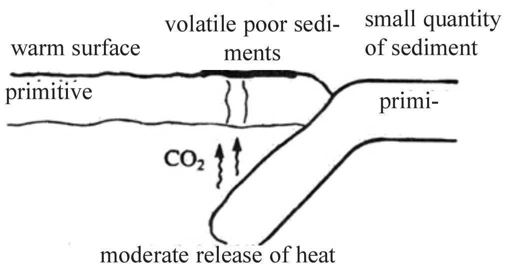


Topography of Diana and Dali Chasma

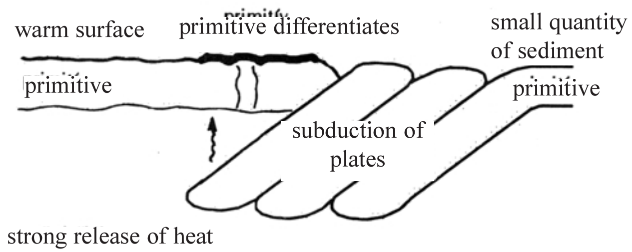
The contemporary Earth



The contemporary Venus



The Earth in the Archaean



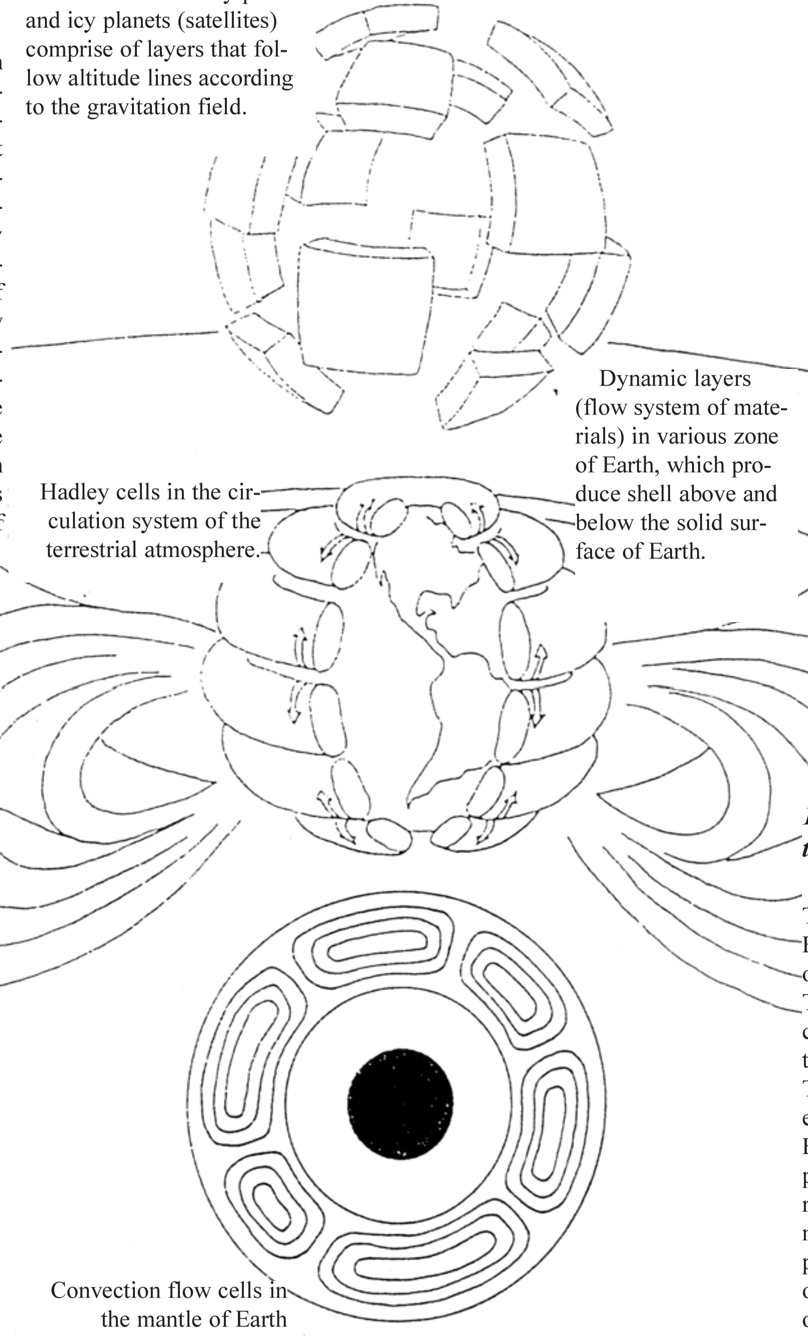
1.4 THE EARTH

1.4.1 Review of flow systems occurring above and below the solid surface of the Earth

The important belts of Earth are made of flow systems both above ground level and beneath ground level. Among the systems the gravitation field of Earth "extends" to the farthest distance. Spherical symmetry of the gravitation field is somewhat distorted by oblong shape of Earth which is caused by the rotation. The unevenness within Earth also contributes to the distortion, which is "felt", "followed" and sometimes measured by space probes flying around Earth on close orbits. The modification of orbits of space probes can also be caused by effects of the upper atmosphere and the magnetosphere. The largest flow zone consists of "radiation zones" occurring in the magnetosphere of Earth, that was named after Van Allen. Charged particles move within this belt. Certain charged particles originate from the upper atmosphere, while other particles come from the solar wind. The magnetic field of Earth supports the radiation zones, which have an onion-like structure. The source of this magnetic field is the material (magma) flow within the body of Earth. The mechanism of this flow is not known in detail yet.

1.4.2 Flow pattern of terrestrial atmosphere

The flow system of the terrestrial atmosphere is influenced by many factors. One of the major components is the radiation of the Sun, which tends to heat the air more at close vicinity of the equator then the air around the poles. The air masses start to flow as a result of temperature differences, and the flow is diverted by the Coriolis force caused by the rotation of Earth. These effects give rise to flow zones that are characterised by belts and cells. Six such large flow belts, Hadley cells, are distinguished. In the two equatorial cells the prevailing direction of flow is eastern. In the two belts of the temperate zone the flow is directed to the west, and again, the direction is eastern in the two polar cells. There is a turbulent flow zone between the polar cold air mass and the equatorial warm air mass (this is the Hadley flow cell in the moderate climatic zone). The energy exchange between the two air masses takes place in the form of cyclones and anticyclones.



1.4.3 Flow pattern of terrestrial atmosphere

Over two third of the surface of the Earth is covered by ocean. The average depth of the ocean is 5 km. Complicated flow patterns are produced in the ocean by the combined action of temperature differences, rotation of the Earth and topographical features. The Golf Stream is one of the most widely known among these systems. There are other ocean flows which also influence the climate significantly (El Nińo). The denser the media of the flow the longer the cycle periods are. In the radiation belts the effect of the solar flares appear within hours or days. The cycle time of effects in the high atmosphere (e.g. ozone depletion) is in the range of weeks/months. Movements in the atmosphere can have cycle times of many months (seasonal), and the flow patterns in the ocean are also in the annual range. As soon as we reach the geological formations of the earth the cycle time jumps to million years.

1.4.4 Geologic flow pattern of the Earth body: the plate tectonics

Energy is flowing from the inside of Earth toward it surface. This energy produces a convection movement in the mantle of Earth. The result of this process on the surface is the movement of continents, which had not been recognised for a long time. The theory of plate tectonic was the first scientific principle that combined the knowledge about the formation of mountains with the knowledge on horizontal movements of the surface of Earth. The lithospheric plates of the earth move with a velocity of several cm/year. The materials flowing upward from the mantle of Earth appear at close vicinity of the surface at the mid ocean plateaus. The magnetic patterns in the rocks of the ocean floors retain the sequence of their movements after their formation. A mirror symmetry, relative to the central line of the mid ocean plateaus, can be recognised in the magnetic patterns of the rock of ocean floors. The magnetic patterns consists of a series of opposite magnetic poles which were produced when the magnetic poles of the Earth themselves were reversed.

Suppose we peel off the layer of ocean from the Earth, then we could distinguish two important types of rock: basalts of the sea bed, and the surface sediments appearing in association with the averagely granitic composition of the continents. If we look at the Moon with similar resolution what we can observe is dark "seas" (we already now that they contain basalt), and light plateaus (we know that they contain anorthosite). We can conclude then that the "common" rock range of the two planetary bodies is basalt.

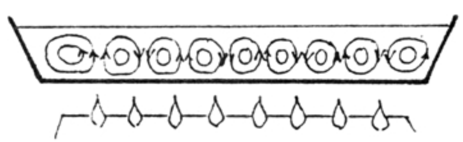
In addition to the investigation of the spectrographic pictures of rocks, the petrography of magma has taught us that the "common denominator" among the rocks of rocky planets is basalt. Based on the dark shade of the seas of the Moon it was assumed long ago that the plains consist of basalt essentially. This assumption was first confirmed by the measurements made by Surveyors. The knowledge about the rocks were further refined on the basis of rock samples taken by the Apollo missions. Actually, the former findings were confirmed.

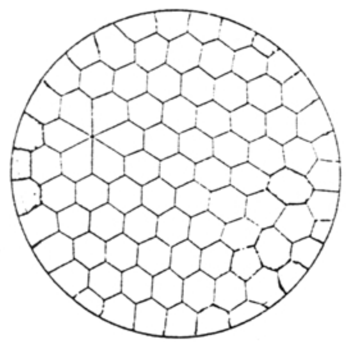
This special role of basalt was recognised only in the sixties even in the terrestrial research, i.e. the basalt flowing on the terrestrial surface are the partial melts of the crust of Earth. In turn the crust of Earth basically has a contrite composition, except that the iron has melted out and cumulated in the core. The condritic material is the ancient material of the Solar System, and it is still retained in certain meteorites. For this reason the essentially contrite crust can be found on all the planets, as well as on the Moon. Basalt could be formed after the melting out of iron even on the small planets having diameters of several hundred kilometres. (Vesta is such a small planet). Such basaltic meteorites were known even before we had opportunity to examine rocks from the Moon. Some of them proved to be young when measured in the time scale of the Solar System. It was assumed and later confirmed that these meteorites had originated from Mars. But we had no material from the Moon, and we were not able to identify any meteorite coming from the Moon until we started studying rocks actually brought from the Moon.

Development of convection cells as a result of lower/internal heating/heat flow

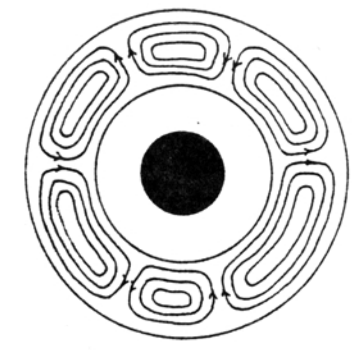
Pattern produced by the cells seen the surface

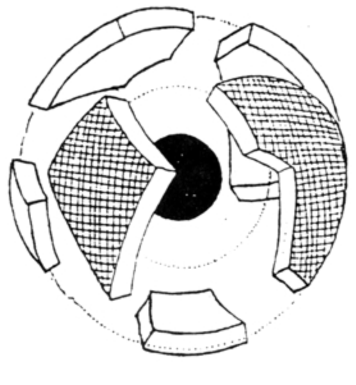
Cells of Bénard instability in a tray as a result of heating at the bottom





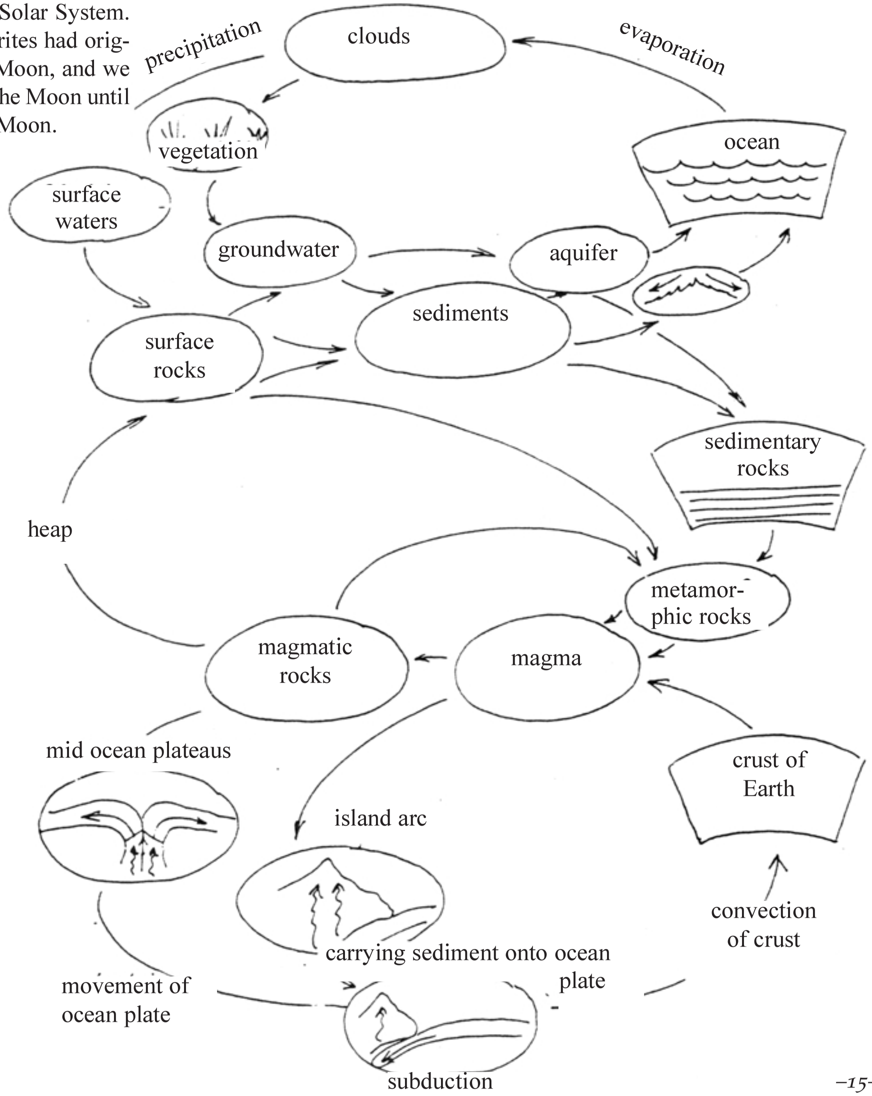
Pattern of terrestrial crust caused by the internal heating





1.4.5 Model for combining the three major flow systems that knead to the surface of Earth

Three major material circulation systems are present on the surface of Earth, including circulation of water, erosion processes on the surface, geological processes producing the rocks and the magnetic processes taking place deep inside Earth, together with the convection flow driving the plate tectonics. These systems are generally depicted separately. In this Concise Atlas, however, they are shown as a model of interwoven circulations as follows:



2. GALILEAN SATELLITES

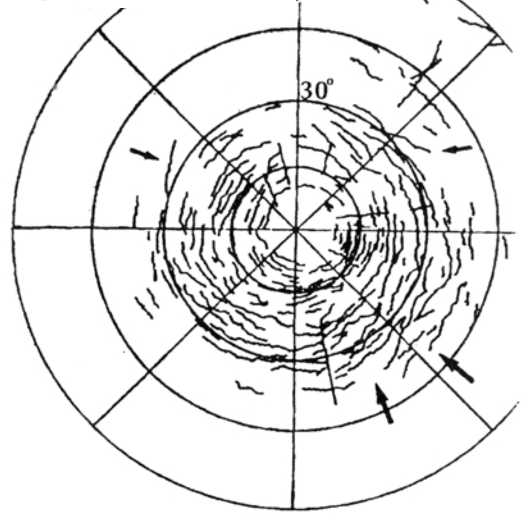
2.1 Callisto

Callisto has a special position among the giant satellites of Solar System. Its density is around 1.86 g/cm³. About half of its mass is water ice, and the other half consists of rocks. In the satellite systems the most important energy source is the tidal heat. Callisto is the outermost Galilean satellite, for this reason its development is the least influenced by the tidal effect of Jupiter. Its inner part did not went through separation entirely, however, it exhibits a moderately stratified structure. Its surface is ancient, but small fresh craters could not be seen at certain areas, and traces of recent slides can be seen at certain locations. Several km thick water ocean is probably located beneath several 10 km of the icy surface. The water is maintained as a result of limited energy still available inside. The insulating effect of the thick ice shell also contributes to this phenomenon. Its surface changed little since the era of great meteorite bombardment has ended, i.e. it has conserved the ancient conditions very well. It exhibits the initial conditions of the development of the surface of icy satellites. A water ocean developed beneath the ice shell also, but it is much thinner and is located at a greater depth relative to those of its two inner companions. A global differentiation has not started because of the minimal tidal effect, which could have acted also as a heat source. The shell did not break up into blocks, and there has not been any significant volcanic activity. Callisto exhibits the formation of craters, which is the most basic stage of the development represented by the four Galilean satellites.

The surface is covered with craters almost entirely. The morphology of these craters, however, is different from those observed on rocky planetary bodies because of the special rheology of ice. The ice is much more plastic at low temperatures relative to the usual terrestrial rocks. Intrusions of ice become flat after a time, and the depressions get raised. For this reason, old craters can be recognised only because of their colour. This group of forms is called the palimpsest.

Many concentric arches of rings can be observed outside the ridges of large craters of Callisto. These structures are similar to the huge impact basins seen on rocky planets. The most widely known example of such structure is Mare Orientale of the Moon. The origin of large ringed structures has not been clarified yet fully. The attached figures show four possible models of their formation.

The Valhalla structure in stereographic projection



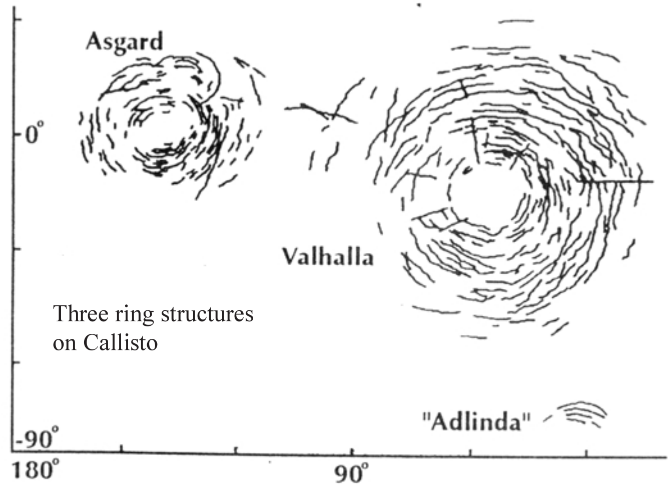
Case A: The concentric structure is within the crater, and it is caused by the layer heads protruding from the base in an isostatic case.

Case B: The concentric structure is within the crater, and it has been developed by internal slides after the crater was formed, as well as by the deformation of any central peak.

Case C: The concentric structure is outside the crater, and has been formed by huge slides occurring in the vicinity.

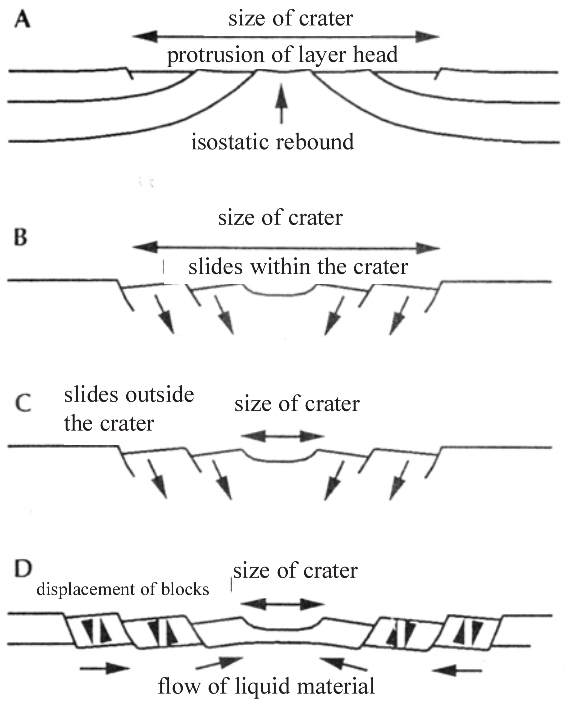
Case D: This explanation is the most likely for Callisto. The ringed structures are outside the crater. Plastic material tends to flow back below the surface into the area from where the impact expelled material. The solid ice shell above the flow has been broken into blocks and slightly shifted the blocks to form the surface rings.

Similar structures can be observed also on Ganymede. On Europe, however, the situation is quite different. The ice layer floating on the plastic ocean is much thinner. Here, the flow of low viscosity water does not cause breaking into blocks. On the other hand, the isostatic rebound at the crater area is much stronger and faster. Ringed structures can be found here in the original depression.



Three ring structures on Callisto

Possible models for the development of Valhalla structures

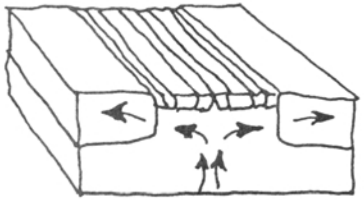


Four models of the formation of multiringed structures on Callisto. See text for explanation.

2.2 GANYMEDE

2.2.1 Dark fractured ancient plates, with circular impact structures

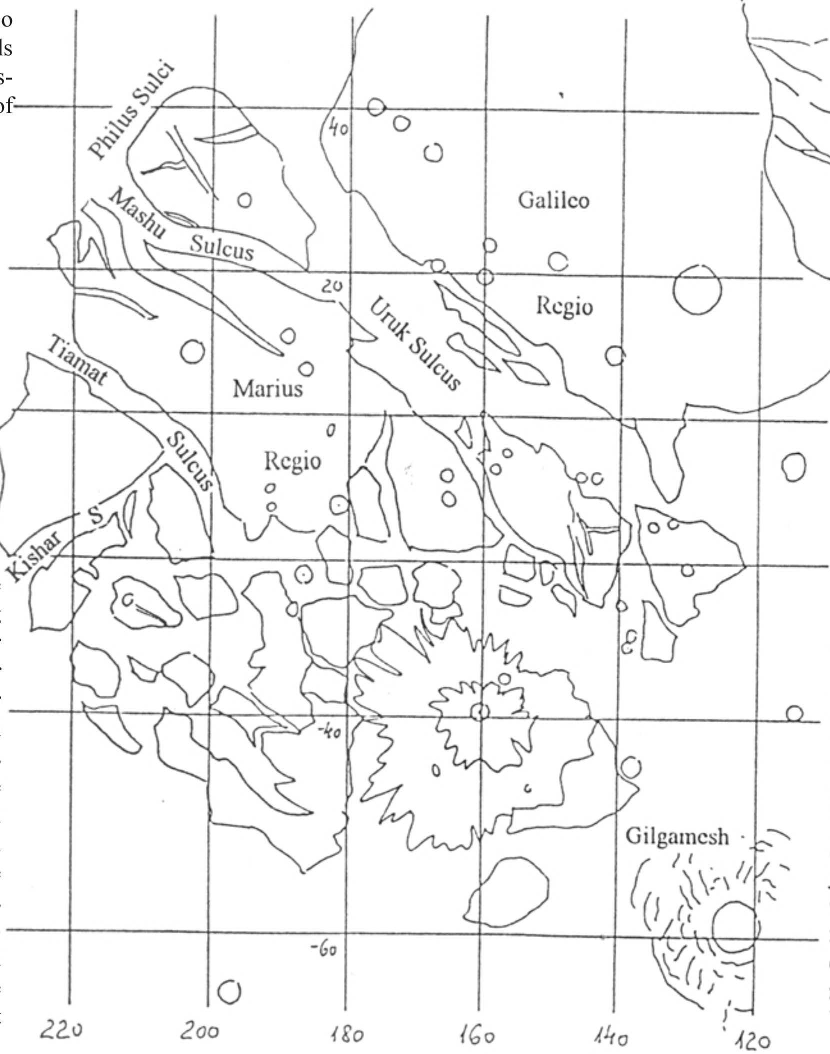
While Callisto exhibits the remnants of the ancient impacts all over its surface, the surface of Ganymede has partially renewed as a result of internal forces. A process has just started on Ganymede, which had caused a comprehensive renewal of surface of Europa. The fractured pieces of the dark ancient blocks are separated by wide zones "ploughed" by parallel trenches and ridges. The zones are the remnants of the material containing ice of water flowing upward from the depth. The parallel mountain and trench system is similar to the sheeted dike structure of the mid ocean plateaus on Earth. Its origin is supposed to be also similar: in the opening and then closing cracks the materials coming from the depth got solidified. Such mechanism is suspected to be the reason of the "ploughed" zone system of Europa.



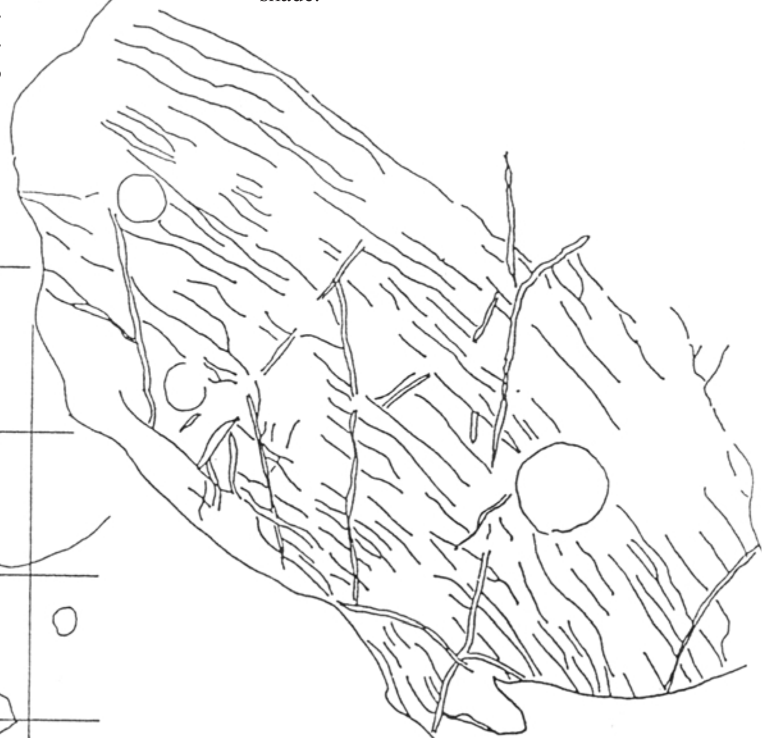
A large circular pattern system can be seen on the surface which seem to confirm that the ancient plates were touching each other in the past. The largest dark plate was named after Galileo. This ancient piece of the surface is located on the far side of Ganymede relative to Jupiter. (The situation is similar to the relationship of Moon to Earth, because the four Galilean satellites of Jupiter – as all other satellites – are on locked orbits around the central planet). A system of arched gorges can be observed on the surface. The gorges are filled with a material having a lighter shade, which had infiltrated to the surface from the depth. (Arched system of gorges can also be seen on the Moon around the impact basins. The Campanus-Hippalus gorges around Mare Humorum are examples of this phenomenon.) The Galileo plate are separated by trenched-ploughed zones of Uruk Sulcus from the other large dark plate, the Marius Regio. The minor gorges on the Galileo plate did not developed into larger displacement.

2.2.2 The palimpsests (circular basins with flattened topography)

The huge system of fissures constituting the circular arches of Galileo plate covered half of the surface of Ganymede in the past. A depression could have been its centre. Similar depression could be have been observed at other location of Ganymede, that had been caused by minor impacts. The pieces of crust have been displaced and turned somewhat along the arched fissures. By now the differences in altitudes diminished, that is why the ancient circular structures are called palimpsests on the Galilean satellites of Jupiter. (No such features are found on Io.)



Southern part of Galileo Regio showing the circular structures with arched gorges caused by ancient impacts, where the gorges were filled with a material having a lighter shade.



2.2.3 The Gilgamesh basin

The Gilgamesh basin is a younger circular structure. The basins located at the central areas are surrounded by circular and radial groove and mountain ridge system inside and outside, respectively. From the inner circular and the outer radial topographical patters the circular part will survive for a longer period (Buto Facula, Ganymede). Such formations can also be found on the thinner icy crust of Europa (e.g. the Callanish Macula having a smaller diameter). The circular basins are the largest impact formations on the solid surface plants of the Solar System: they occur everywhere starting from the Mercury to the Galilean satellites of Jupiter, except Io having active volcanoes and the Venus.

2.3 EUROPA

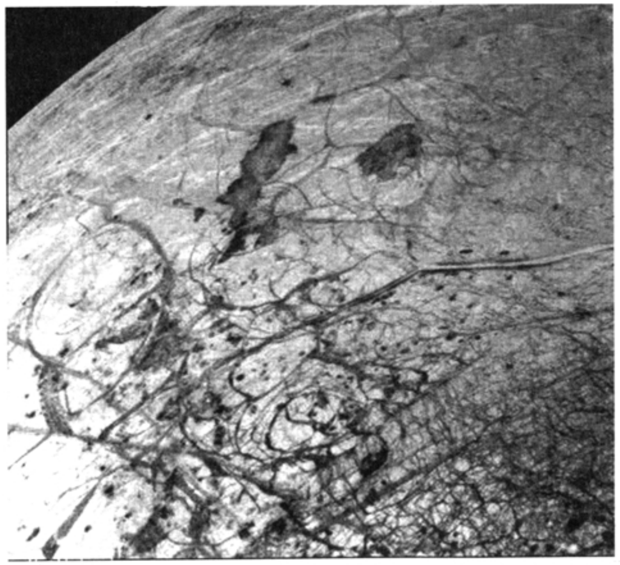
2.3.1 The largest ocean of the Solar System

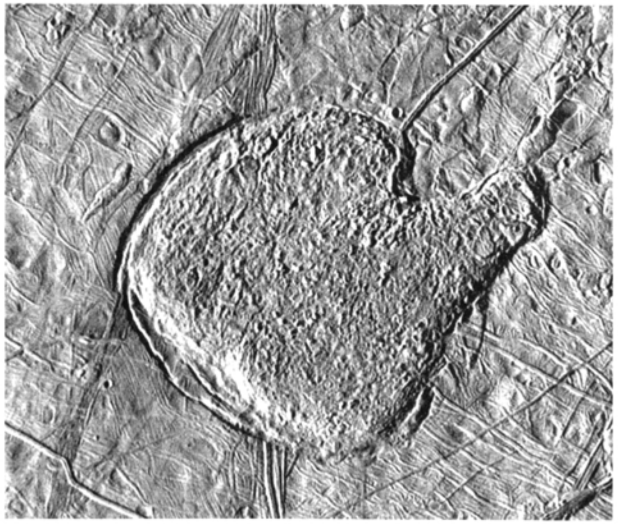
Europa is the most active satellite of Jupiter, that was able to retain a large proportion of its water. The heating produced by the tides is able to keep 80-90 % of the H_2O in liquid phase. Its surface is covered by 4-8 km thick ice, which acts as a thermal insulator for the 50-100 km deep liquid ocean below. (It is possible that solid ice is beneath the frozen shell, but most of the observations indicate the presence of liquid water.) A "second" surface of the satellite is located below the ocean. i.e. the floor of the ocean consisting of silicate material. The heat flowing out of the inner part of Europe and the volcanic activity injects energy into the ocean consistently, which keeps the water in liquid state. Three interfaces are located above the rocky shell as a result of a stratified inner structure, namely: rock/water, water/ice and top of the ice shell. Extensive and unique surface forming activities are excepted to occur at all of the three interfaces.

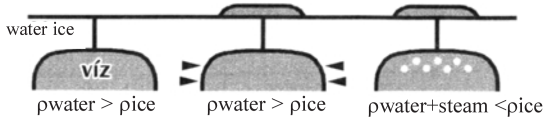
2.3.2 Cryo-volcanism

The characteristic activities on Europe include silicate volcanism at the top of the rocky shell and cryo-volcanism on the surface of the ice. The essential driving force of the cryo-volcanism is the fact that the density of the liquid water (hydro-magma) exceeds that of the ice. For this reason the propagation of water to the surface is facilitated either by a mechanical pressure produced by crystal growth or by the increase of density when forming of bubbles occur. No mountains are produced by the ice volcanoes on Europe. Similarly to other icy moons, the characteristic features produced here are the lava plains and lava lenticulae.

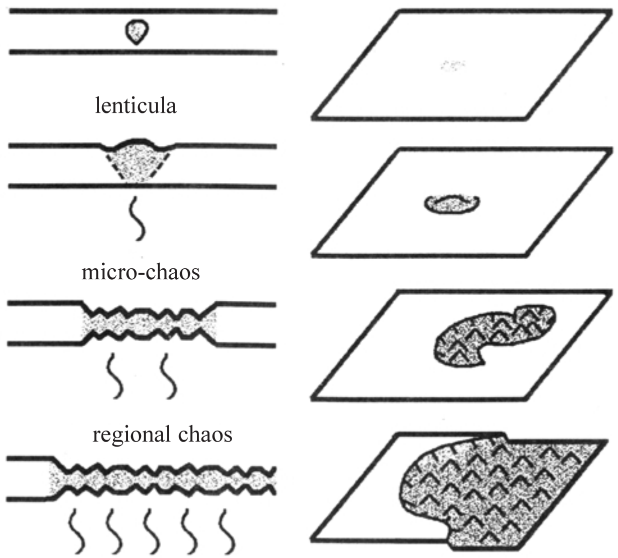
The ice of Europa is not entirely clean. Dark contaminants can be observed which probably come from the areas of the ocean where active volcanoes are present. Water inclusions of various sizes could be detected in the ice during the investigation of polar icy regions of the Earth. The same is possible on Europa as indicated my morphological features. Drops of hydro-magma penetrate the into the ice from the ocean as a result of heating, movement along faults, or local melting-freezing processes. Unstable zones are formed at the areas where the high heat flow is present and the salt content or melting point deviated from those of the environment. At this locations the ice gets molten and collapses. Small hydro-magma drops can be seen only as dark spots if they are close to the surface. Dome shaped lenticulae are formed first as the heat flow from below increases, then micro-chaos is developed having several km in size. Finally, regional chaos areas develop where debris of the former surface remain embedded in the thinner ice matrix after the collapse.







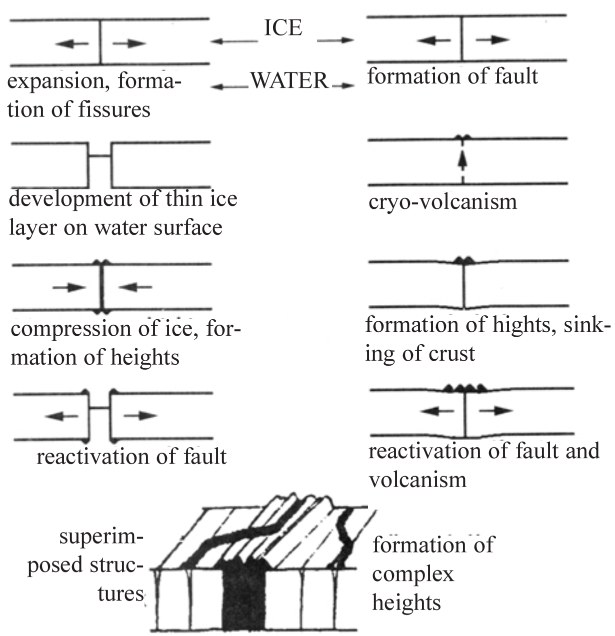
The distribution and colour of the chaos areas indicate the location of "thermal centres" at the ocean floor and the character of the material dissolved in water. Their tectonic structures can be studies to reveal the movements, the stress spaces, and for reconstructing the situation before the activities.



2.3.3 Ice tectonics

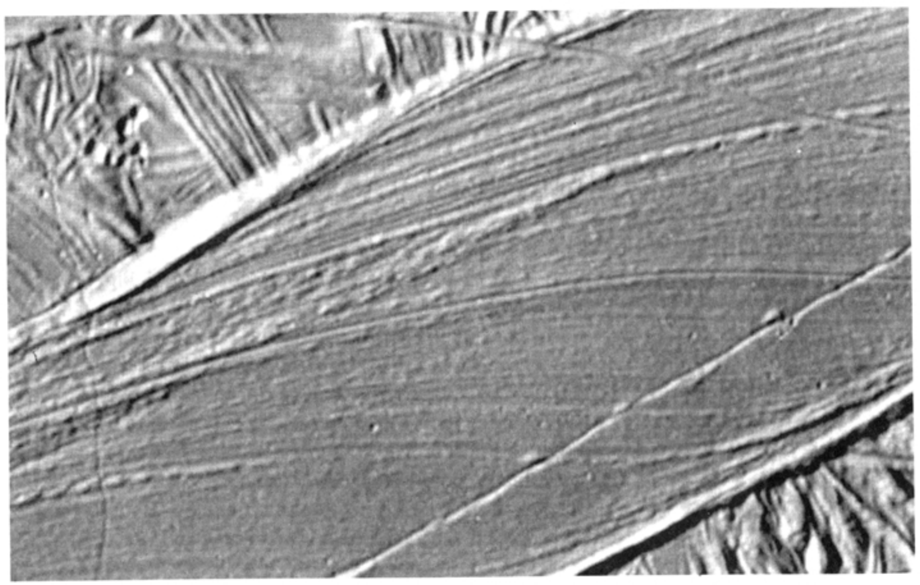
The deformation of ice is significantly influenced by the hydrostatic pressure, e.g. the thickness of the ice layer. The present thickness of ice facilitates the formation of faults, but it is possible that certain surface features were produced when the ice thickness was larger. At that time the dominant process was the plastic deformation instead of fault forming, and solid state convection took place in the ice. Maybe the ice got thicker at that time because of the less heat production inside the satellite. It is similarly important that the ice shell floats on a water ocean, which enhances mobility substantially. In addition to that, the water of the ocean flows as a result of the tide, which tends to lift and lower the ice layer above. This phenomenon leads to many fissures that can be observed on the surface. It is also possible to observe structures produced by expansion and sliding at these fissures. Europa has a nearly constant axial rotation, as have the other Galilean satellites. Actually, the orbits of the satellites are not exactly circular. As a result, the tidal bulge of Jupiter is somewhat shifted on their surfaces. This is one of the reasons why certain tidal harmonics appear, which act somewhat against the constant axial rotation. As a result of all these effects the ice crust gets easily shifted on the top of the ocean. The mass distribution of the ice crust changes because of the tectonic and volcanic processes, which acts against the formation of an equilibrium state, thus giving work consistently to be done by the tide and the gravity.

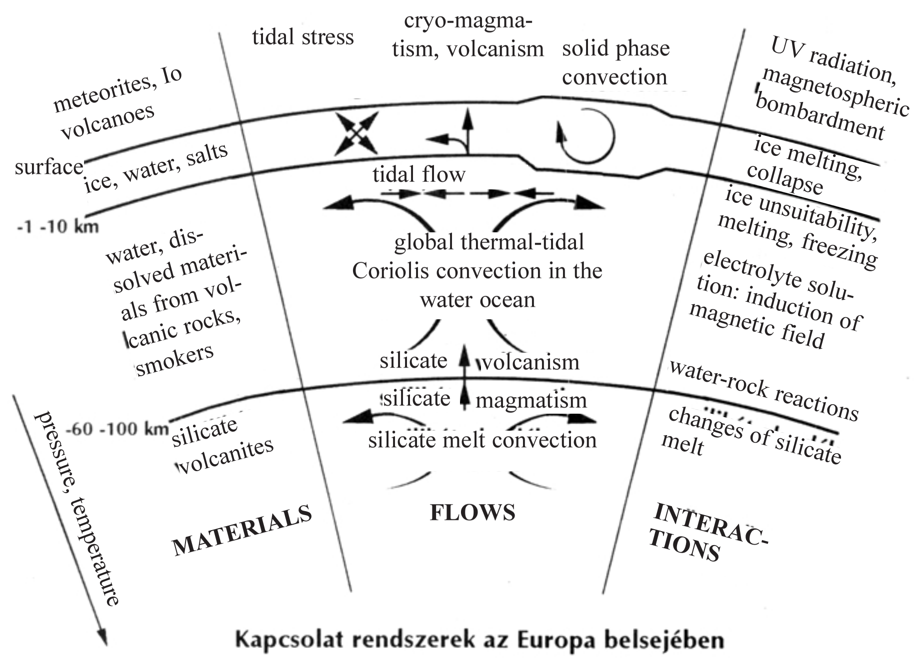
Formation of rift-like faults on Europa



2.3.4 The active satellite

The processes driven by the energy of the tide cause significant changes on the surface of Europa. Extensive flow systems exist in the well distinguishable water-ice-rock spheres. Substantial chemical changes, migration of materials are caused by these processes in the aqueous environment downward from the surface at least to a depth of 2-4 km below the ocean floor. Continuously changing conditions are thus caused by a number of factors such as the dynamic equilibrium environment occurring the interfaces, the young ice surface, the magnetic field induced in the ocean and the circulation of material. Considering all of these processes it is reasonable to believe that some kind of life may exists beneath the surface of Europa. The essential conditions necessary for the formation of a life similar to that of the Earth include energy source, variable chemical environment, liquid water which provide the possibility of reactions and changes, and time. All of these conditions seem to be present on Europe, however, the time factor might be problematic, since it is not known how stable the tide-heated ocean can be. It is an interesting analogy that the environment of the volcanoes and heat sources located on the ocean floor is similar to the zones of the mid ocean plateaus on Earth, where special symbiotic life exists.





Kapcsolat rendszerek az Europa belsejében

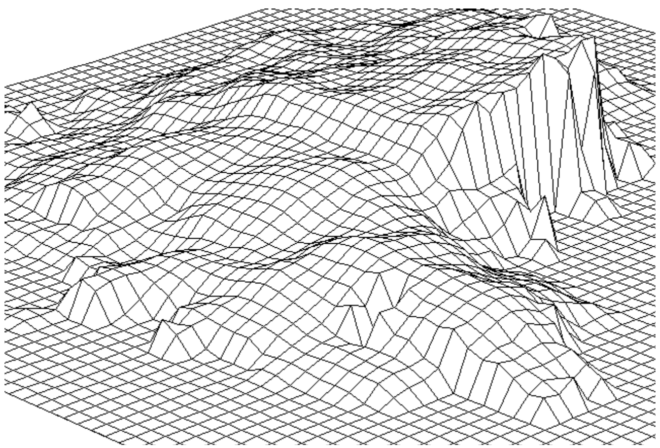
2.4 IO

2.4.1 Home of volcanoes

Io has the youngest surface and it is the most active planetary body in the Solar System. The material flowing out from its inside can be observed continuously (by means of volcanoes), and it can be seen how this material becomes part of the solid crust. This process is identified as resurfacing: the recreation of the surface, because new material covers the surface repeatedly. One can only wonder why the surface of the innermost satellite of Jupiter is so young, and why the volcanic activity is so strong, while the other planets that were formed at about the same time are “cooling down” as their radioactive heating sources decompose slowly.

2.4.2 Tidal forces

Only few cases are known in the history of planetary research when something had been discovered by means of calculation before the evidence could be observed. Such case is the discovery of Uranus (on the basis of the orbits of known planets LeVerrier calculated the location of a possible planet that disturbs the orbits of other planets). Yet another such idea predicted that volcanism exists on Io just a few month prior to the arrival of Voyager in the vicinity (Peale et al. 1979). The reasoning of the researchers pivoted on the assumption that the inside of Io is kept hot constantly by the gravitation, tidal forces caused by Jupiter and the nearby Galilean satellites that have resonant orbits with Io. The heat that is produced by this process can be released from the inside by means of volcanism only. Io is tended to be pulled of its orbit by the outside satellites, but it is retained by Jupiter. This tug of war produces heat inside Io, because the sliding friction at the interface of the plastic rocky core and the solid crust. Io is kept active by this additional heat.



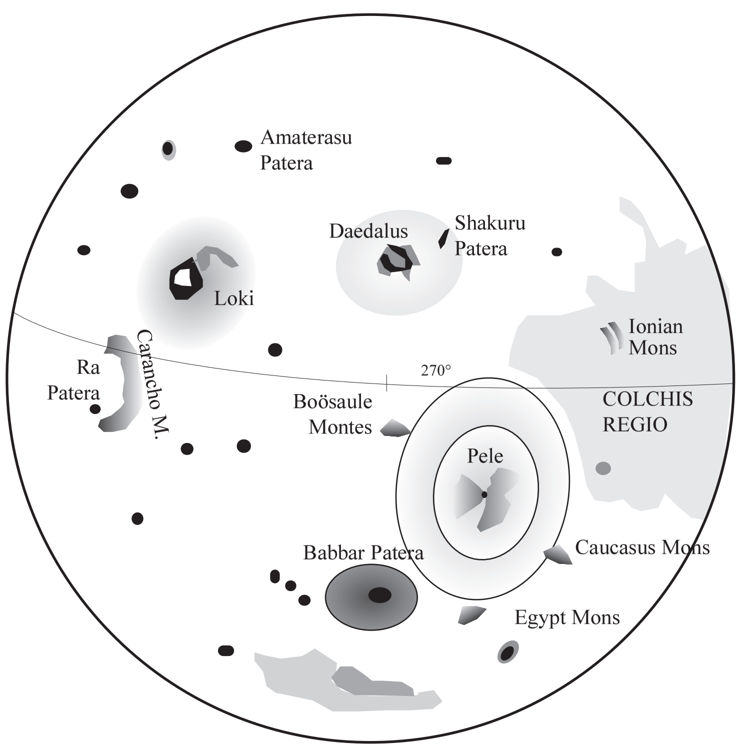
Digital terrain model of an unnamed mountain at 14 ° S, 15° W, size 85 × 100 km).

2.4.3 Resurfacing

The age of the lava material presently seen on the surface is about 1 million years. Older material might be in mountains scattered randomly on the surface. No impact craters can be seen on Io, and that is the main proof of the young age of the surface, in addition to other presently observable eruptions and lava flows. There are about 400 volcanoes (or calderas and other volcanic centres) on Io. Most probably, Io had been developed together with the rest of Galilean satellites, and it had been hit by impacts with the same frequency. The resulting craters, however, were covered long ago by the lava flows and volcanic eruptions. It is possible that these lava flows occurred not so long ago. This cannot be judged properly until the subsurface strata can be determined. Certain theories (Keszthelyi, McEwen, 1997) predict that the volcanic activity of Io is a cycling process. For a certain time the surface is quiet, while the inside becomes hotter and hotter until a heat suddenly escapes from below the crust. This phase is called the “catastrophic resurfacing”. The inside of planet is “turned out” in such events, and a global magma ocean is produced on and/or below the surface. The surface of Venus is calculated to be 0.5–1 billion years on the basis of crater count. It means that the former craters were deleted at that time on Venus as well, the same way it is happening on Io now, It is not known how many times such global renewal of the surface have occurred.

2.4.4 Lavas of Io

For a long time it was believed that the lava material on Io is not silicate like on Earth, but sulphur. This theory has been abandoned after having a look at the steep caldera edges and mountain sides, which could not possible be supported by the soft sulphur. In the volcanic activity sulphur plays a role (it gives its yellowish colour), but the role of silicate is more important. Recent measurements indicate that the temperature of the lavas is 1800 K, i.e. they are much hotter then the hottest basalt lava on Earth (1300-1500 K, while the rhyolite lava on Earth has a temperature of 900-1100 K only). Radioactivity contributes to the heat to a decreasing extent inside Earth. For this reason the temperature of the lavas was higher in earlier periods (the volcanic activity was also stronger). For this reason, at the time after formation, the surface of Earth could have looked like the present surface of Io. Lava fountains have been observed on Io, which are the results of similar basalt volcanism of Hawaii type on Earth. Long flows of lava can also be seen, which is the indication of a low viscosity lava.

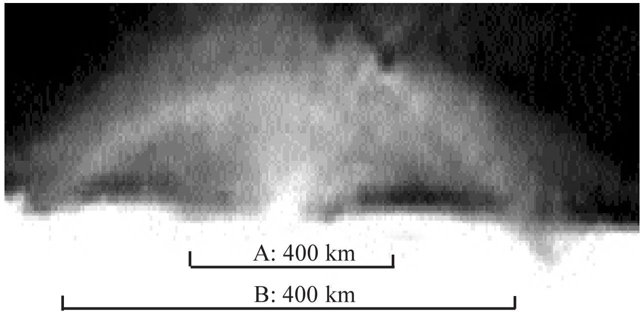


2.4.5 Volcanoes of Io

The volcanoes of Io has moderate heights with shallow slopes because of the thin lava. However, the height is enough to allow a long flow of lava. Depressions can always be found at the middle of the flat volcanic protrusion, called calderas.

2.4.6 Mountains of Io

On Earth mountains are generally produced by the slow folding of sediments. On the Moon the mountains consists of the debris accumulated along the edges of impact craters. The mountains of Io are probably the skewed protruding parts of blocks of crusts “floating” in the astenosphere. The mountains are often wrinkled, which indicate a layered structures: it is possible that the layers have been developed by the subsequent lava flows. The highest mountain (Boösaule) is 16 km high.*



Eruption cloud spreading as an umbrella (A: in case of Pele type volcanism, B: in case of Prometheus type) The picture shows the Prometheus eruption cloud.

Compression forces are generated while the crust sinks slowly. The cool crust is suddenly heated up by the lava flowing on the surface; the material of the heated crust expands. The crust is weakened and ruptured at randomly distributed locations (in a chaotic way) by these two processes acting simultaneously. The compression forces elevate the material of the mountains to the surface along the faults produced by the stresses. At the same time, the crust in the vicinity keeps on sinking together with the fresh lava cover. This is how the mountains of Io are produced by the heat of lava and the compression forces.

2.4.7 Layered plains

Many plateaus, terraces with altitude not reaching 1 km can be seen on the surface, which are bordered by the steep edge (step of layer). These are thought to be monadnocks which maintain the level of the earlier surface. Their edges are continuously "consumed" by some kind of erosion process. The material of these layered plateaus can be a kind of loosely bound tuff (outfall from eruptions). It is also possible that they are produced by the rising crust along faults.

2.4.8 Eruptions

Eruptions usually last for months continuously. During this period an eruption cloud is generated which spreads out like an umbrella. The material from the cloud falls back within a regular circle/ellipse because of the lack of atmosphere. The erupted materials contains lots of volatile substances. (The velocity of the erupted material is 1 km/s, the maximum height is 50-300 km. Note that on Earth the velocity is in the range 200-600 m/s and the height is 10-40 km).

The magma chamber collapses after the entire magma mass has been erupted. The collapse produces calderas with a diameter of 30-150 km on the surface of Io. The largest calderas on Earth have diameter of 20-25 km. Many calderas on Io are filled by and large with dark material – possibly a lava lake.

2.4.9 Mass movements

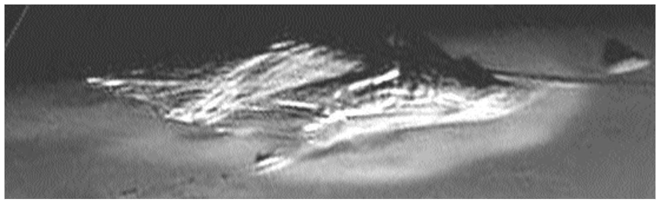
The toe of certain mountains of Io is covered by debris cover originating from slides of variable extent. Layers of rocks tend to slide down the mountains which are somehow different from the substrate (rock quality of time of development), where the interface acts as a sliding surface. One of the most extensively studied mountain is Euboea Montes, which has a sharp ridge and a huge debris cover can be found at its base. The layered plateaus surrounding Euboea Montes was here before the mountain had risen; the top of the mountain consists of the material of the plateau. This layer has slid down (Schenk, 1998).

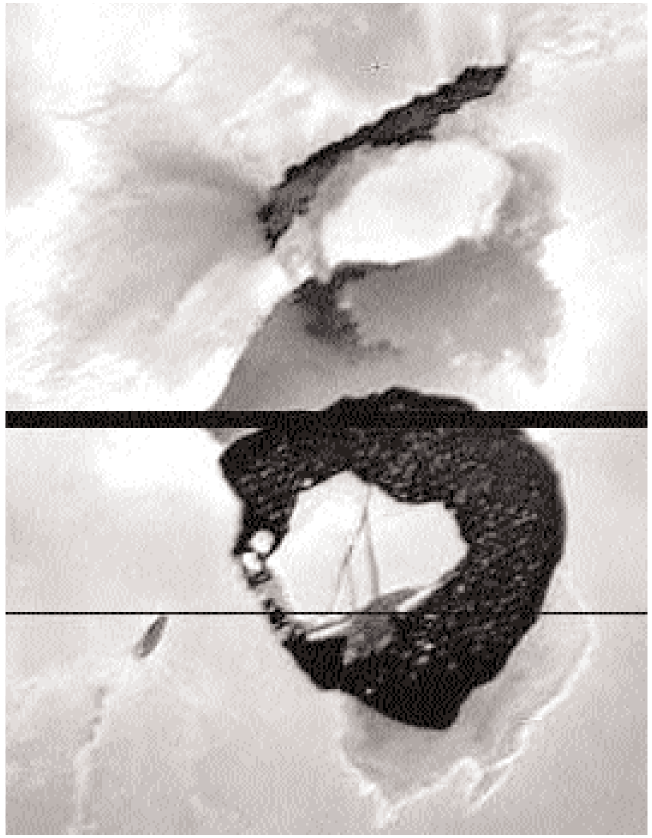
2.4.10 Major structures

One of the famous volcanoes of Io is the Pillan Patera, which was developed in 1997. The Galileo space probe photographed active lava flows and lava fountains at the edge of the caldera of Thvastar Catena. The lava flows, which are described most extensively, start from Ra Patera. The major features of the surface of Io are either of tectonic origin, such as the mountains (100 of them, including *ridges, peaks, plateaus)*, layered plains, or of volcanic origin, such as volcanic centres (about 400 *calderas,* and one smaller *cone,* 2 *tholi* - pancake volcanoes, volcanic plains, lava fields, lava flows (finger like, lobed, and sometimes long, originating from fissure volcano), active volcanoes.

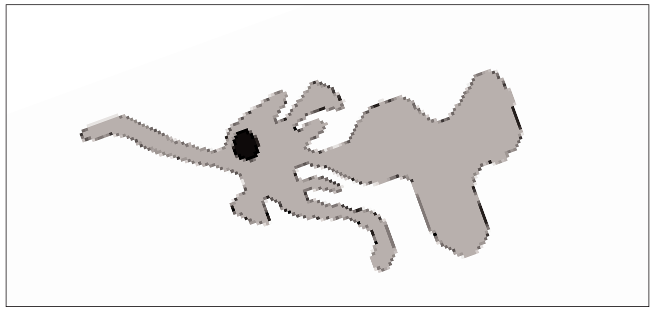
2.4.11 Mapping

The surface of Io is in constant change. New lava flows occur, volcanoes erupt and cover their environment with fallout. As a consequence, it is not easy to prepare a map of Io. The colour of lava fields changes slowly and produces a transitional shade until another field is reached. Any map drawn can become obsolete in days when new volcanoes erupt.





Loki Patera is the largest caldera and lava lake at the same time. The lava flows built on one another can be well distinguished. The middle of the lava lake is occupied possibly by fissured "Silicate ice plates" which are in the process of solidification. Lava lake of fissure volcano can be seen on the upper part of the picture. To the left of this lake the darker fallout of an earlier eruption can be seen.



Lava flow with central caldera from the geological map of Io

*The database of the mountains of Io is available at http://planetologia.elte.hu/io

3. SMALL PLANETARY BODIES

3.1 ASTEROIDS AND SMALL SATELLITES

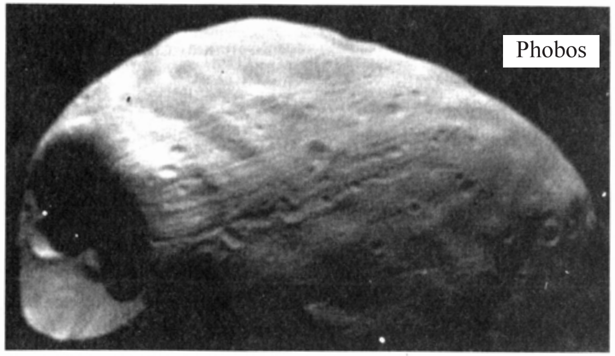
Several 100,000 planetary bodies exist in the Solar System which are transitional features regarding their sizes between the planets, their satellites and small pieces of debris. Often these bodies are referred to by a single word: asteroids. Their investigation is exciting and important, because asteroids are the remnants of the materials which formed the planets, and as such, they have kept their pristine material ever since.

3.1.1 The asteroid of love

The asteroid named Eros is well known thanks to the investigation conducted by the NEAR-Shoemaker space probe. Eros belongs to the group of near-Earth asteroids, because it can be as close as 240 million km to Earth.

The space probe was on orbit for a year around Eros, then it "landed" on its surface. This operation, however, is also referred to as impact by some parties. Anyway, the probe measured the most important features of Eros, determined its shape, which is similar to that of a peanut, having a size of 33 × 13 × 13 km, and its rotation time, which is 5 hours and 17 minutes.

Eros has a small surface area, it has no atmosphere, and its crater spotted old surface exhibit a rather heterogeneous appearance. The largest crater, named Psyche, can be found on the western hemisphere having a diameter of 5.3 km and a depth of about 1 km. The most characteristic feature of the eastern hemisphere is a saddle-like depression (Himeros), the largest size of which is nearly 10 km and its depth is about 1.5 km. Actually, this is what causes the peanut shape of Eros. The number of craters in Himeros is low, which indicates that it was established well after the Eros had been formed, probably as the result of a landslide.



3.1.2 Wrinkles everywhere

The most characteristic feature of Eros, however, is the network of wrinkles, which was named Rahe Dorsum. This system of wrinkles surrounds Eros almost entirely, and each wrinkle appears on the surface along the same imaginary plane. The wrinkles intersect many surface formations. Based on the considerations of geology it is believed that the wrinkles were formed after the "overwritten" surface features were established.

The elongated depressions of the surface can also be observed on many other asteroids and small moons as well, e.g. on Phobos, the satellite of Mars. This is a former asteroid which has been captured by gravitation. On its surface the wrinkles exhibit a very interesting pattern. The deepest and largest wrinkles start from the Stickney crater in radial direction, indicating the close relationship with the crater formation. Ridges also indicate the result of the Stickney impact, which had been almost devastating according to the calculations. These ridges surround the scar in concentric circles, and were formed most probably as the result of the mechanical shock wave produced by the impact.

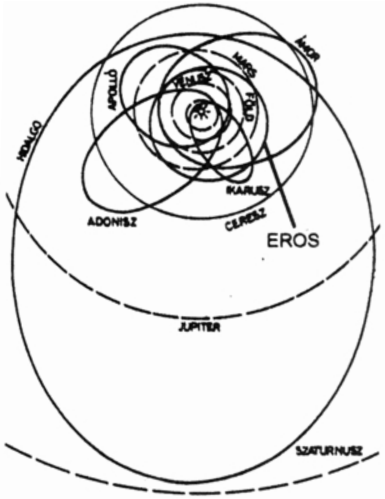
Yet another system of wrinkles can be observed on the surface, which has a quite different orientation. It appears as the surface appearance of adjacent plains which are perpendicular to the equator. In other words, the satellite seems to be consisting of layers, i.e. it has a global stratification. This is confirmed also by the craters, where the assumed layers appear on the side walls of the craters as zones of different albedo.

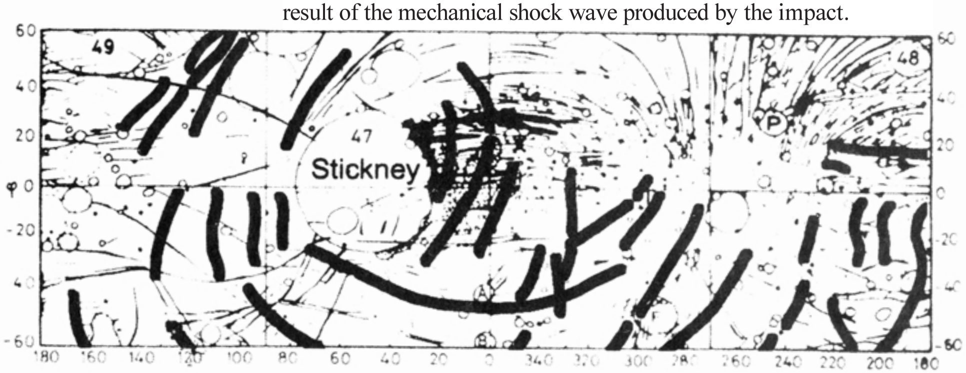
Similar vertically arranged zones appear on the side walls of crater of Eros, as well as on Himeros. After eliminating the disturbing shadow effect it is evident that there are real albedo differences, which are the indication of qualitative/compositional differences among the layers.

According to one of the many theories existing today the explanation is not in the history of formation of these small planetary bodies. Geological processes are necessary for the formation of such layers for which these small bodies do not have sufficient heat source. It is reasonable to believe that asteroids were part of a larger planet, where the mechanism leading to the formation of layers were present. Then this enigmatic planet broke up somehow, and its pieces have scattered away in its cosmic environment, and the pieces retained the memory of their parent in their structures.

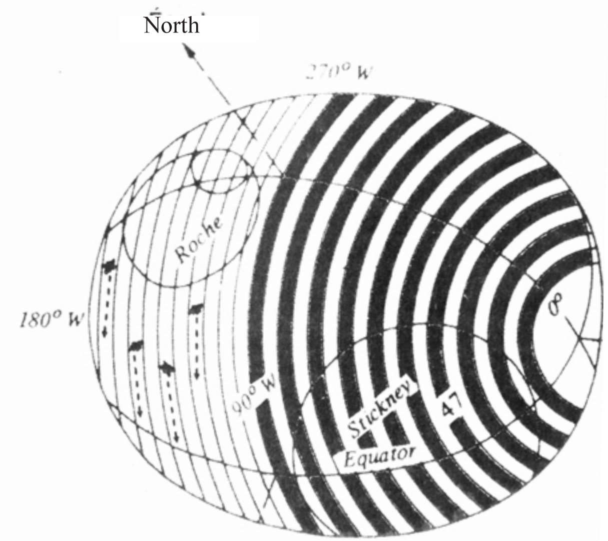
In case of Phobos the explanation is rather unusual. It is assumed that the wrinkles were produced by pieces of rocks that rolled over the surface after the planet hit them in the plane of its orbit.

If the surface topography and the density of Phobos are considered, then it seems possible that a long system of complex voids, large caves and hundreds of corridors are within the satellite. If this is really the case, then Phobos could be used as a closed base in future missions sent out for examining Mars, and from here it will be possible to see the rising and setting of Mars.





Map of linear features of Phobos



3.1.3 Rock particles and boulders

The asteroids are covered with regolith debris consisting of fine particles. Unexpectedly, large boulders having the size of several ten metres can be seen densely scattered on Eros. Their origin is rather enigmatic. It would be also interesting to know why do they not disintegrated to debris.

In this case it is not very probable that the boulders came from impactors or from the fallout of the material expelled by the impacts. In such a case the boulders would be arranged in concentric patterns and their distribution would match the distribution of the impact craters.

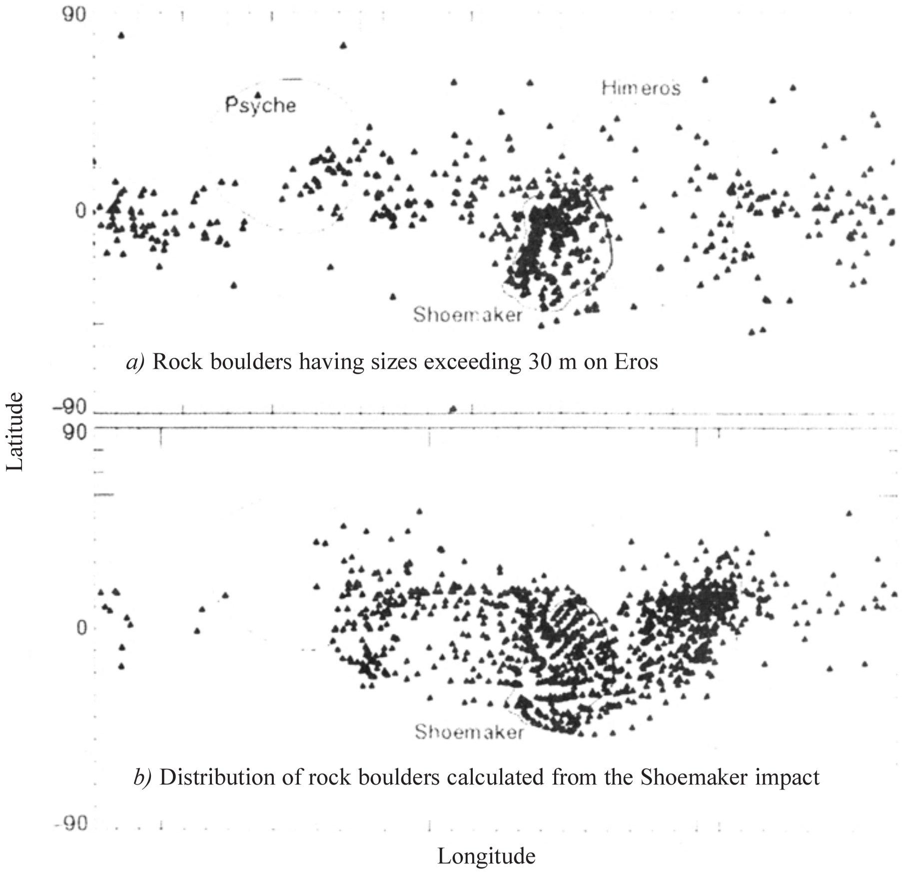
Possibly, the answer could be found in the internal structures of the asteroids. An asteroid can be a fragmented solid block, or an "aggregate of loose rubble" kept together by gravitation depending on suffered bombardment and the resulting fracturing. The internal part of Eros is possibly in between these two extremities. The regolith particles fall into the small fissures of the fractured inner parts as a result of the shocks, and thus the larger boulders remain on the surface. The process seems to be similar to an experiment when a mix of various sized grain is shaken, and the small particles migrate downwards, while the larger ones apparently move upward and get to the top of the mixture after a certain time.

In this way the rock boulders came from the inside of the asteroid to the surface, and they reproduce regolith during their disintegration, and the circulation is maintained in this way.

On the other hand, the shock explains the globally uniform distribution of the lose regolith, as well as the lack of small craters on Eros, because such craters have been filled up.

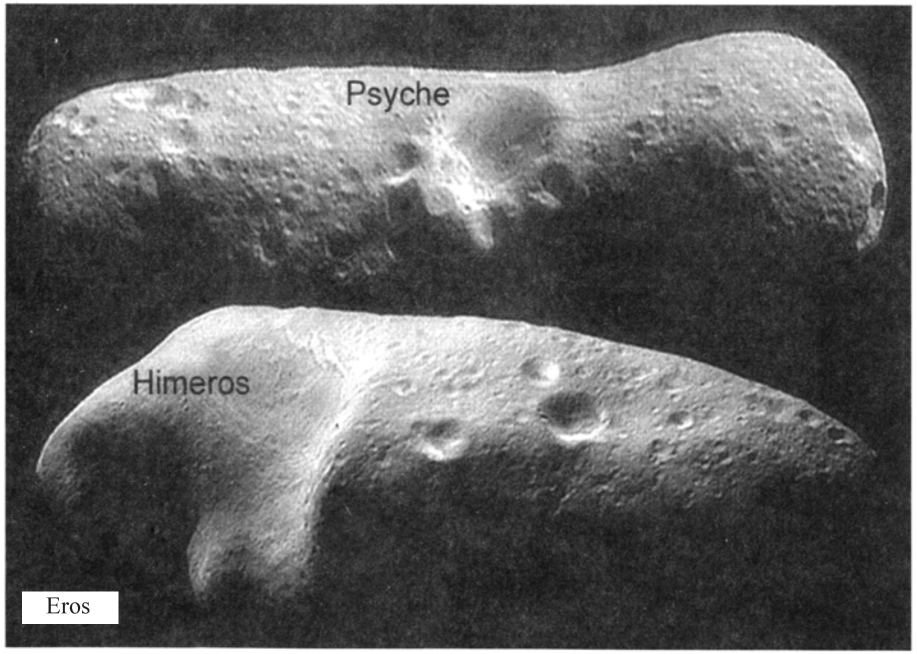
3.1.4 Minute rocks of the rings

Finally, it is worth mentioning that the debris zone is repeated at a much smaller scale around the outer gas giants in a zone where small rock (and ice) particles travel around the planet along individual orbits, forming a number of rings. Naturally, the most beautiful example is Saturn. The pieces of the rings were not investigated in detail yet, but it is sure that such investigations will reveal many interesting surprises.



a) Rock boulders having sizes exceeding 30 m on Eros

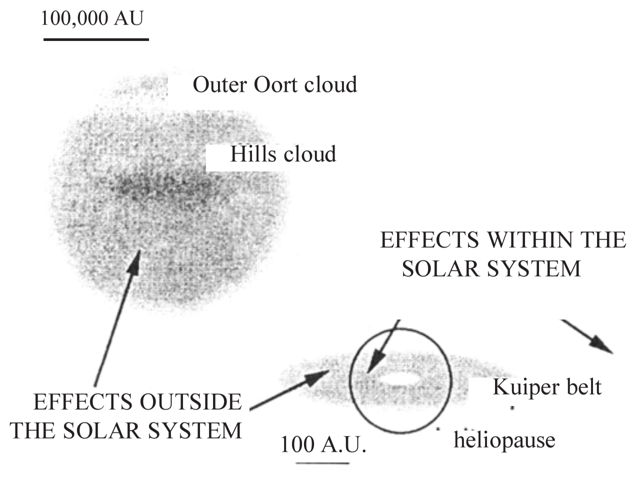
b) Distribution of rock boulders calculated from the Shoemaker impact



3.2 DISTANT SMALL ICY PLANETARY BODIES

3.2.1 Comet cores and their companions

The orbit of the outermost large planet Neptune delineate the border of the inner border of the cometary clouds, where the icy planetary bodies mentioned in the title can be found. Most of the volume of the Solar System is located in the space counted from here to a distance of 100,000–200,100 A.U., where only a fraction of the total mass of Solar System is located. The total mass of the 1000 billion objects within this zone can be equivalent to several times the mass of Earth. This zone is characterised by the material, which either was produced locally, or migrated to here from the region of the large planets. The objects orbiting in this zone are generally referred to as comet nuclei, however, the opinion of various experts vary. Many planetesimals remained from the time of formation of the planets, which did not became the material of the planets. Two zones can be observed where such planetissimals can be found in large quantities. One of them is the main asteroid belt between Mars and Jupiter. The other one is the region of the cometary clouds beyond Neptune. All of these can be mentioned under the common name minute planetary bodies. The basis for the traditional classification of small bodies/comet nuclei is the composition: small planets consists of rock of higher density, while the comet cores contain mainly frozen gases of small density, which is "contaminated" with much less rocky material. In reality the situation is much more complicated. Cometary nuclei tend to lose most of their volatile material, and become denser objects. At the same time the Trojan asteroids travelling on the same orbit as Jupiter contain more volatile material relative to their inner minor planets. In addition to that, the comet clouds contain small planets as well in spite of their name.

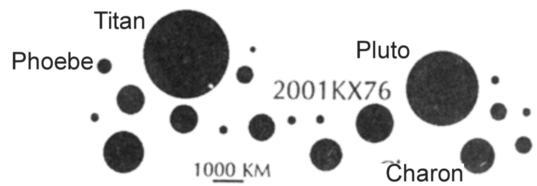


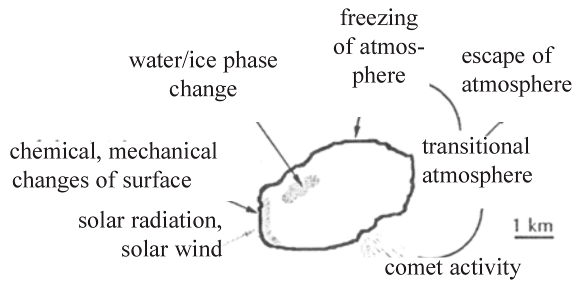
3.2.2 Centaurs and visiting comet nuclei

Small number of cometary nuclei occur also within the space between the large planets. Their position is unstable for two reasons. The gravitation field of the large planets disturb and expel such comet nuclei out of the region. At the same time, their surface begins to sublime, and their mass is decreased as a result of the strong radiation close to the Sun. For this reason, the quantity of icy objects is limited within the region of large planets. The changing of the surface and orbits of such bodies are fast. The density of surface layer becomes higher as it is dried by sublimation, and this process produces a hard crust after certain period of time. Activity coming from the inside is not very evident, maybe some indirect indication can be observed. Such phenomena included the freezing of water while the comet core get farther apart from the sun. The freezing of water increases the volume, which result in a surface activity, which seems to come from the inside.

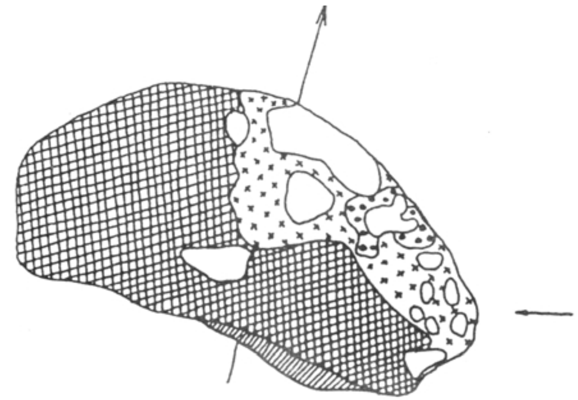
3.2.3 The Kuiper belt: a storage of ancient material

The Kuiper belt starts at the orbit of Neptune and extends to a distance of several 100 AU. The included mass of materials approximately equals to that of the Earth, and it exhibits a concentration in the main axis of the Solar System. It contains two major units. One of them contains the original Kuiper population consisting of the planetary bodies, which were formed and retained here. The materials started to coalesce into planetissimals also 4.6 billion years ago. The process halted after a while, and large planets did not emerge. One of the reason is the rare impacts because of the slow speed at their distant orbits from the Sun, and at the same time the original quantity of material became less at the large distance from the Sun. The original Kuiper popular, particularly its more distant region has retained the ancient material of the Solar System possibly in the most heterogeneous form as compared to the rest of the planetary bodies. Some changes occurred within the inner active zone of the Kuiper belt as a results of impacts. This process is comparable to that of the formation of the main asteroid belt.

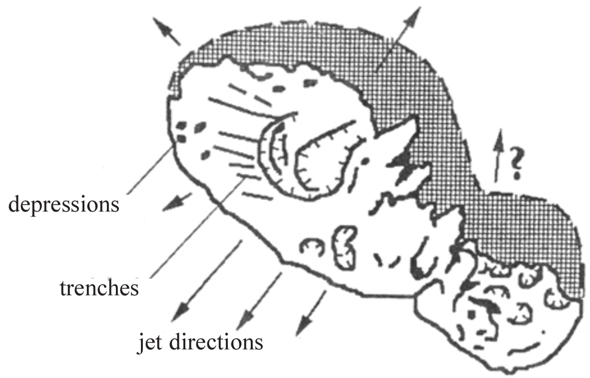




Nuclei of comet Halley



Nuclei of comet Borelly



The other part is the scattered disk of Kuiper population. These bodies are also at the above mentioned distance from the Sun, but they have perturbed out from the giant planets, primarily Uranus and Neptune. Their origin is indicated by the elongated orbits and by the occasional large inclination of orbit. As opposed to the original Kuiper population their quantity increased with the distance from the Sun, and represent a continuos transition to the Hills cloud. The heliopause being at a varying distance of 60–100 AU (i.e. within the Kuiper belt) delineates the border of the solar wind and the interstellar material, i.e. within which dominant effects contributing to the slow development of planetary bodies takes place. Some of the objects orbiting in the inner part of the scattered disk regularly intersect heliopause, thus they are exposed to the surface forming effects of both regions.

3.2.4 The Hills cloud: transition to the interstellar space

The Hills cloud or the inner Oort cloud stretches out in the range from 1000 to 10000 A.U. distance from the Sun. It exhibits a very weak concentration in the main plane of Solar System. Actually it is the continuation of the scattered population of the Kuiper belt.

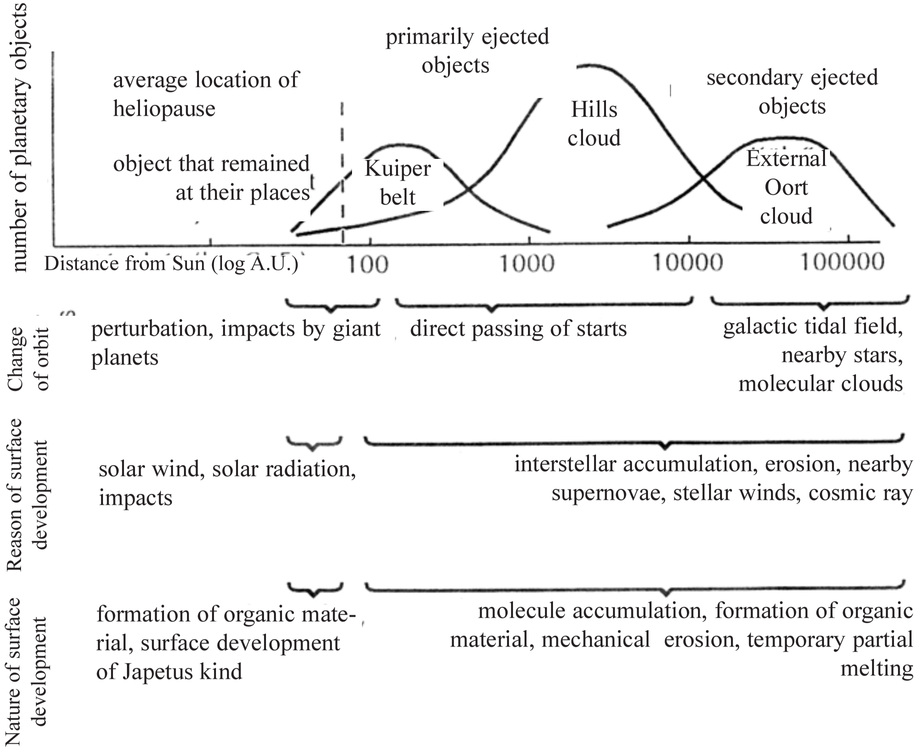
This is the zone where the largest mass of comets is located. The total mass is equivalent to several times the mass of Earth. It status has a transitional nature. Although its planetary bodies belong to the Solar System, but their development is influenced by interstellar factors. Interstellar material get deposited on their surface, and also their material is eroded. This erosion is the dominant factor according to the theoretical calculations because of the dense molecular clouds. This erosion removed about 1 m thick layer from the surface of planetary bodies since the formation of the Solar System. In addition to that, many chemical reactions are initiated by nearby supernova explosions, stars emitting large amount of energy and stellar wind of young clusters, as well as by the cosmic rays bombarding the surface. In this process a significant amount of organic material is produced. The Hills cloud has lost about half of its original planetary bodies by now as a result of the gravitational effect of the stars passing though it.

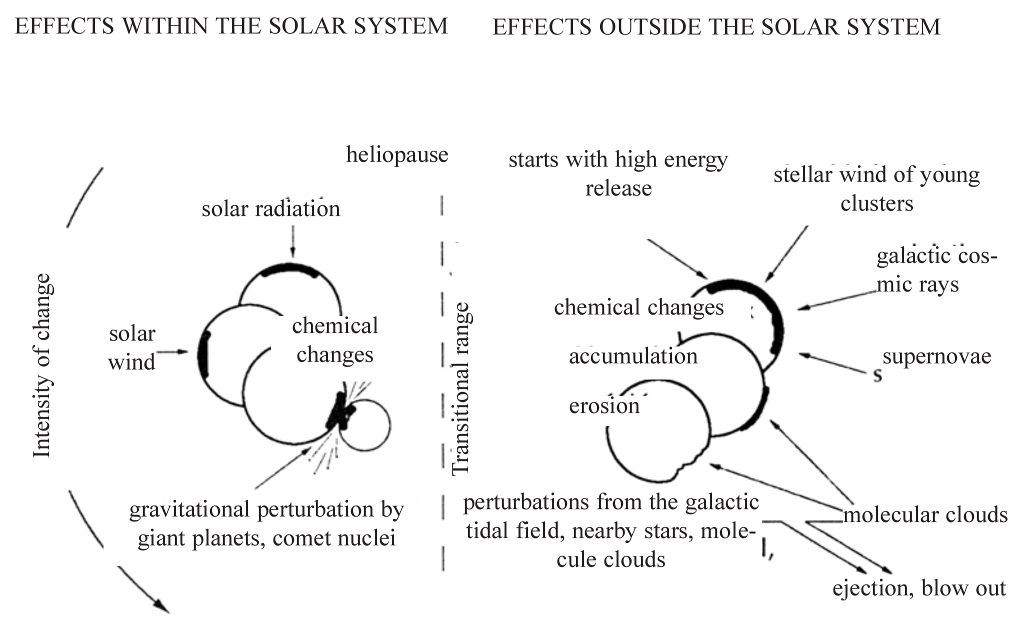
3.2.5 The outer Oort cloud: at the far end

The external Oort cloud may reach out to a distance of 100,000-200,000A.U. Its border cannot be delineated, because its farthest members keep escaping the Solar System continuously. Its life span is shorted than that of the Solar System because of the loss of material.

Objects ejected by the starts passing through the Hills cloud tend to provide new planetary bodies in the outer Hills cloud. The surface forming effects mentioned for the Hills cloud also act here. The orbits of objects tend to be the less stable here because they are significantly influenced by the gravitation of stars passing nearby and by the large molecular clouds. Yet another factor is the galactic tidal field. The combined gravitational effect of the many object also disturbs the movement of the bodies. In spite of the large distance from the Sun comets with large periods abundantly come to the region of large planets from this zone because of the above mentioned instability.

The cometary cloud play and important role in the “material management” of the Solar System. 4.6 billion years ago, at the time when the Solar System was formed, the giant planets being in the making ejected material equivalent to several times the mass of Earth, into the interstellar space. After the end of the great bombardment period the release of material from the Solar System had decreased. The degree of the present loss of mass is hard to estimate. Anyway, it is less by several order of magnitude relative to the initial period





PROPERTIES OF PLANETARY BODIES WITH SOLID SURFACE

Planets	Diameter km	Oblate-ness	Distance from Sun mlo. km	A.U.	Density g/cm^3	g (est.) g	Magnit. visual	Albedo %	Orbital period	Rotational (siderical)	Inclination (i) (eclipt.	/ rot.ax.)	Eccentr. e	T surface C°	T equil. K	Pressure atm.	Relief km max/min	Atmosph. composit.
Mercury	4878	1/30000	57.9	0.47	5.43	0.37	-0.2	9.6	87.9 d	58.6 d	7°00	0°	0.205	167°	176°	10^{-15}	3 km	
Venus	12104	1/85000	108.2	0.72	5.24	0.90	-3.6	72	224.7 d	-243.0 d	3°39	177°	0.006	457°	55°	93	11.3	CO_2 (96%). N_2 (3%)
Earth	12756	1/298	149.6	1.00	5.52	1.00		39	365.2 d	23h56m	—	23°.45	0.016	14°	6°	1	8.8 / -11	N_2(78%). O_2(21%). Ar
Mars	6787	1/156	227.9	1.52	3.93	0.38	1.8	16	686.9 d	24h37m	1°85	25°.19	0.093	-60..20°	-47°	0.007	21 / -8	CO_2(93%). N_2(3%). Ar
Pluto	2274		5900	39.7	2.03	0.09	15	30-60	250.3 év	-6.38 d	17°2	122°.52	0.250	-230°	-229°			N_2. CH_4. CO

Satellites	Diam.	Distance from Sun	Distancer from planet 1000 km	/ planetary R	Density	g (estim.)	Magnit.	Albedo	Orbital period	Inclin.. (i)	Eccent.	Year of discovery	Discov.
Moon	3476	Earth 149	384	60 R	3.34	0.16	-12.7	7%	27.32 d	5.1°	0.055		
Io	3632	Jup. 778	412	5.7	3.53	0.18	5	60	1.76 d	0.027	0.000	1610	Galilei
Europa	3138	Jup. 778	670	9.4	2.97	0.14	5.3	60	3.55 d	0.486	0.000	1610	Galilei
Ganymede	5276	Jup. 778	1070	15	1.93	0.15	4.6	40	7.15 d	0.183	0.001	1610	Galilei
Callisto	4820	Jup. 778	1880	26.3	1.83	0.12	5.6	20	16.68 d	0.253	0.007	1610	Galilei
Mimas	394	Sat. 1427	185	3.0	1.43	0.007	12.9	60	0.94 d	1.517	0.020	1789	Herschel
Enceladus	502	Sat. 1427	238	3.9	1.83	0.008	11.8	100	1.37 d	0.023	0.004	1789	Herschel
Tethys	1060	Sat. 1427	297	4.8	1.25	0.015	10.3	80	1.88 d	1.093	0.000	1684	Cassini
Dione	1120	Sat. 1427	377	6.2	1.43	0.022	10.4	62	2.73 d	0.023	0.002	1684	Cassini
Rhea	1530	Sat. 1427	527	8.7	1.33	0.028	9.7	60	4.51 d	0.35	0.001	1672	Cassini
Titan	5150+	Sat. 1427	1222	20.3	1.9+	0.1	8.4	35	15.94 d	0.33	0.029	1655	Huygens
Iapetus	1460	Sat. 1427	3560	59	1.2	0.02	11.9	5–50	79.33 d	14.7	0.028	1671	Cassini
Phoebe	220	Sat. 1427	12930	215		0.005	16.5	5	-550 d	150	0.163	1898	Pickering
Miranda	484	Uran. 2869	129	5.0	1.26	0.004	16.5	24	1.41 d	4.22	0.027	1948	Kuiper
Ariel	1160	Uran. 2869	190	7.4	1.65	0.01	14.4	31	2.52 d	0.31	0.003	1851	Lassell
Umbriel	1190	Uran. 2869	266	10.4	1.44	0.008	15.3	19–50	4.14 d	0.36	0.005	1851	Lassell
Titania	1610	Uran. 2869	463	17.0	1.59	0.02	14	28	8.70 d	0.14	0.002	1787	Herschel
Oberon	1550	Uran. 2869	583	22.8	1.50	0.1	14.2	24	13.46 d	0.10	0.001	1787	Herschel
Triton	2705	Nept. 4496	354	14.3	2.02	0.06	13.6	27–90	5.87 d	14.36	0.001	1846	Lassell
Nereida	340	Nept. 4496	5510	222.6			18.7	14	-359.8 d	222.6	0.75	1949	Kuiper
Charon	1186	Pluto 5900	19.6	17.0	1.3	0.02	17	38	6.38 d	17.06	0.0001	1978	Christy
Phobos	27	Mars	9.38	2.76	1.9	0.000	11.6	6	0.319 d	1.02	0.018	1877	Hall
Deimos	12	Mars	23.5	6.91	2.1	0.000	12.7	5	1.262 d	1.82	0.002	1877	Hall

Small Bodies	Diameter km	Dist from Sun	Type	Density	Magnit.	Albedo	Rotation	Orbital period	Inclinat.	excentr.	Year of discovery	Discov.
951. Gaspra	20x12x11	205	S			20	7.04 h	3.28 yr	4.1	0.173	1916	Neujmin
433. Eros	33x13x13	218	S		12.3		5h16m	643d	10.8	0.223	1898	Witt/Charlois
243. Ida	56x24x21	270	S	2.2-2.9		23	4h38m		1.14	0.451	1884	Palisa
4. Vesta	525	353 (basaltic)		3.9		38-42	5.34 h	1325d	7.1	0.091	1807	Olbers
1 Ceres	960x932	457	C	2-2.7	7-8	10	9.075 h	1680d	10.6	0.079	1801	Piazzi
2. Pallas	570x525x482	414	U	4.2	9	14	7.81 h	1685d	34.8	0.235	1802	Olbers
2060. Chiron	148-208	2049	B				5.9h	50.7 yr	6.93	0.383	1977	Kowal
Halley Comet	16x8x8	87.8 (aphelion)		0.1		3		76.1 yr	162.24°	0.967	BC1059	

The definition of a Planet *(IAU Working Group on Extrasolar Planets)* 1) Objects with true masses below the limiting mass for thermonuclear fusion of deuterium (currently calculated to be 13 Jupiter masses for objects of solar metallicity) that orbit stars or stellar remnants are “planets” (no matter how they formed).

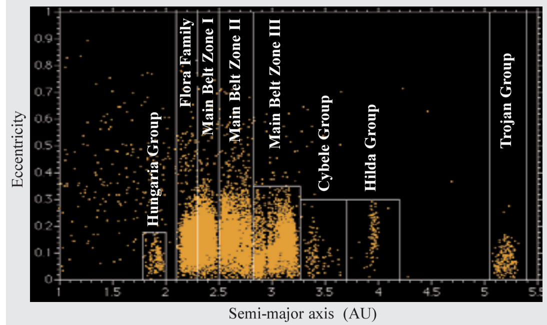
2) Substellar objects with true masses above the limiting mass for thermonuclear fusion of deuterium are “brown dwarfs”, no matter how they formed nor where they are located.

3) Free-floating objects in young star clusters with masses below the limiting mass for thermonuclear fusion of deuterium are not “planets”, but are “sub-brown dwarfs”.

Asteroid (Minor Planet, Planetoid) A small, solid object in our Solar System, orbiting the Sun. Most asteroids are believed to be remnants of the protoplanetary disc which were not incorporated into planets during the system's formation. Some asteroids have moons. As of Oct. 19, 2005, from a total of 299,733 minor planets with calculated orbits, 118,161 asteroids had been calculated well enough to be given official numbers and 12,712 of these had been officially given proper names to go along with the numbers. Current estimates put the total number of asteroids in the Solar System at several million. The largest asteroid in the inner solar system is 1 Ceres, with a diameter of 900-1000 km. Two other large inner solar system belt asteroids are 2 Pallas and 4 Vesta; both have diameters of ~500 km.

Asteroid composition types: *C type:* 75% albedo: dark (3%) (Carbonaceous); *S type:* 17%: 10-22% albedo (Ni-Fe and silicates: piroxene, olivin) reddish color (Silicaceous) *M type:* 10-18% albedo, pure Ni-Fe (Metallic)

Asteroid distribution



Sources: Illés Erzsébet: Planetofizikai adatok (1997.) The Nine Planets; Wikipedia. / Magnitudo: visual (apparent) brightness from the Earth. Albedo: 1-100%.

GROUPS OF SMALL PLANETARY BODIES

Groups inside the orbit of Earth

Vulcanoids: aphelion < 0.4. This is a hypothetical band of asteroids within the orbit of Mercury. There has not been found any such asteoid so far.

Apoheles: aphelion < 1, i.e., the orbit is inside that of the Earth. Other proposed names are IEOs **(Inner-Earth Objects)** and Anons (as in "Anonymous"). So far, one probable object has been found in this group: 1998 DK36. ("Apohele" is Hawaiian for "orbit")

Groups near the orbit of Earth

NEOs Near Earth Objects NEOs are asteroids and comets with perihelion distance less than 1.3 AU

NECs Near-Earth Comets (NECs) include only short-period comets (i.e orbital period less than 200 years) with perihelion distance less than 1.3 AU.

NEAs The vast majority of NEOs are asteroids, referred to as **Near-Earth Asteroids** (NEAs). NEAs are divided into groups (**Aten, Apollo, Amor**)

PHAs Potentially Hazardous Asteroids: NEAs whose Minimum Orbit Intersection Distance (MOID) with the Earth is 0.05 AU or less and whose absolute magnitude (H) is 22.0 or brighter. Asteroids that can't get any closer to the Earth (i.e. MOID) than 0.05 AU (roughly 7,480,000 km) or are smaller than about 150 m in diameter (i.e. H = 22.0 with assumed albedo of 13%) are not considered PHAs. There are currently 744 known PHAs (2005).

Arjuna: Fuzzily defined to be "in orbits like that of Earth", meaning a near to 1, low eccentricity, and low inclination.

Earth Trojans: Objects at these points would always be at about 60 degrees east and west of the Sun at Earth's distance. No such object has been found yet.

Atens: $a < 1$ (inside Earth's orbit)

Apollo: $q < 1.017$, but $a > 1$ (crossing Earth's orbit)

Amors: $1.017 < q < 1.3$ (outside Earth's orbit)

Groups near the orbit of Mars

Mars-crossers: either $q < 1.52$ and aphelion > 1.52, because Mars' $a = 1.52$;

Mars Trojans: There are five of them, (5261) Eureka, 1998 VF31, 1999 UJ7, 2001 DH47, 2001 FG24, and 2001 FR127.

Main Belt groups and families

Asteroid Families are result from the catastrophic breakup of a large parent asteroid sometime in the past.

Asteroid Groups are loose dynamical associations.

Hungarias: $1.78 < a < 2$, $e < .18$, $16 < i < 34$. Very inner-main belt/just outside Mars objects of high inclination, such as (15964) Billgray. Possibly attracted by the 2:9 resonance.

Phocaeas: $2.25 < a < 2.5$, $e > .1$, $18 < i < 32$.

Floras: $2.1 < a < 2.3$, $i < 11$.

Nysas: $2.41 < a < 2.5$, $e > .12$, $e < .21$, $1.5 < i < 4.3$

Main Belt I: $2.3 < a < 2.5$, $i < 18$.

Alinda: $a = 2.5$, $.4 < e < 0.65$ These objects are held by the 1:3 resonance with Jupiter. Some Alindas, such as (4179) Toutatis, have perihelia very close to the earth's orbit; the result is a series of close passes at four-year intervals.

Pallas: $2.5 < a < 2.82$, $33 < i < 38$.

Marias: $2.5 < a < 2.706$, $12 < i < 17$.

Main Belt II: $2.5 < a < 2.706$, $i < 33$.

Main Belt IIb: $2.706 < a < 2.82$, $i < 33$.

Koronis: $2.83 < a < 2.91$, $e < .11$, $i < 3.5$.

Eos: $2.99 < a < 3.03$, $.01 < e < .13$, $8 < i < 12$. Eos, Koronis, and Themis are families, each derived from a common ancestor object.

Main Belt IIIa: $2.82 < a < 3.03$, $e < .35$, $i < 30$.

Themis: $3.08 < a < 3.24$, $.09 < e < .22$, $i < 3$.

Griqua: $3.1 < a < 3.27$, $e > .35$. These are in stable 2:1 libration with Jupiter, in high-inclination orbits.

Main Belt IIIb: $3.03 < a < 3.27$, $e < .35$, $i < 30$.

Cybele: $3.27 < a < 3.7$, $e < .3$, $i < 25$. A cluster of objects around the 4:7 resonance with Jupiter.

Hildas: $3.7 < a < 4.2$, $e > .07$, $i < 20$. Objects in a 2:3 resonance with Jupiter.

Thule: (279) Thule, in a 3:4 resonance with Jupiter.

Between the Hildas and the Trojans (roughly $4.05 < a < 5.0$), there's a "forbidden zone". Aside from Thule and five objects in unstable-looking orbits, Jupiter has swept everything clean.

Groups near the orbit of Jupiter

Trojans: $5.05 < a < 5.4$, in elongated, banana-shaped regions 60 degrees ahead and behind of Jupiter. These can be considered the "Greek" and "Trojan" nodes respectively; with one exception apiece, objects in each node are named for members of that side of the conflict. (617) Patroclus in the Trojan node and (624) Hektor in the Greek node are "misplaced" in the enemy camps.

Groups in the Outer Solar System (beyond Jupiter)

Damocloid/"Oort cloud group": Objects that have "fallen in" from the Oort cloud, so their aphelia are generally still out past Uranus, but their perihelia are in the inner solar system. They therefore have high e, and sometimes high inclinations (including retrograde orbits).

Centaurs: $5.4 < a < 30$? These are currently believed to be TNOs that "fell in" after encounters with gas giants.

Neptune Trojans: 2001 QR322

Trans-Neptunian Objects (TNOs): a.k.a. **KBO (Kuiper-Belt Object)** or **EKO (Edgeworth-Kuiper Object.)** any object in the Solar System which orbits the Sun at a greater distance on average than Neptune. The Kuiper belt, Scattered disk, and Oort cloud are names for three divisions of this volume of space. Anything with $a > 30$, with some falling into the following sub-categories:

Plutinos: 2:3 resonance with Neptune, like Pluto. The perihelion of such an object tends to be close to Neptune's orbit, but when the object comes to perihelion, Neptune alternates between being 90 degrees ahead of and 90 degrees behind of the object, so there's no chance of a collision. Or: any object with $39 < a < 40.5$ to be a Plutino.

Cubewanos: Also known as "**classical KBOs**". The name comes from '1992 QB1', the first TNO ever found. $40.5 < a < 47$. Objects in the Kuiper belt that didn't get scattered and didn't get locked into a resonance with Neptune.

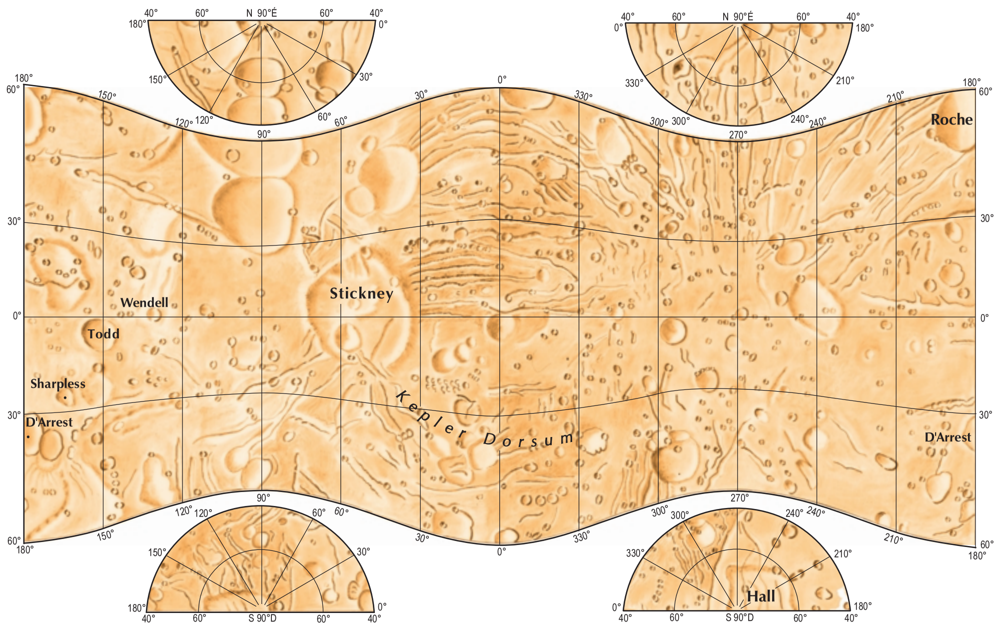
"Hyperplutinos": Objects in resonances with Neptune other than the 2:3 one occupied by Plutinos and the 1:1 occupied by Neptune Trojans. Objects in the 2:1 resonance have been christened "Twotinos" . These objects all have roughly a=48, e=.37. Also, there are several objects in the 2:5 resonance (a=55), which we could call "two-and-a-half-inos" or "tweenos". Then there are objects in the 4:5, 4:7, 3:5, and 3:4 resonances.

Scattered-Disk Objects (SDOs): These objects generally have very large orbits of up to a few hundred AU. Objects that encountered Neptune and were "scattered" into long-period, very elliptical orbits with perihelia that are still not too far from Neptune's orbit.

a=aphelion; q=perihelion; e=eccentricity; i= inclination

Source: Bill Gray: Minor planet groups, www.projectpluto.com/mp_group.htm; Wikipedia.

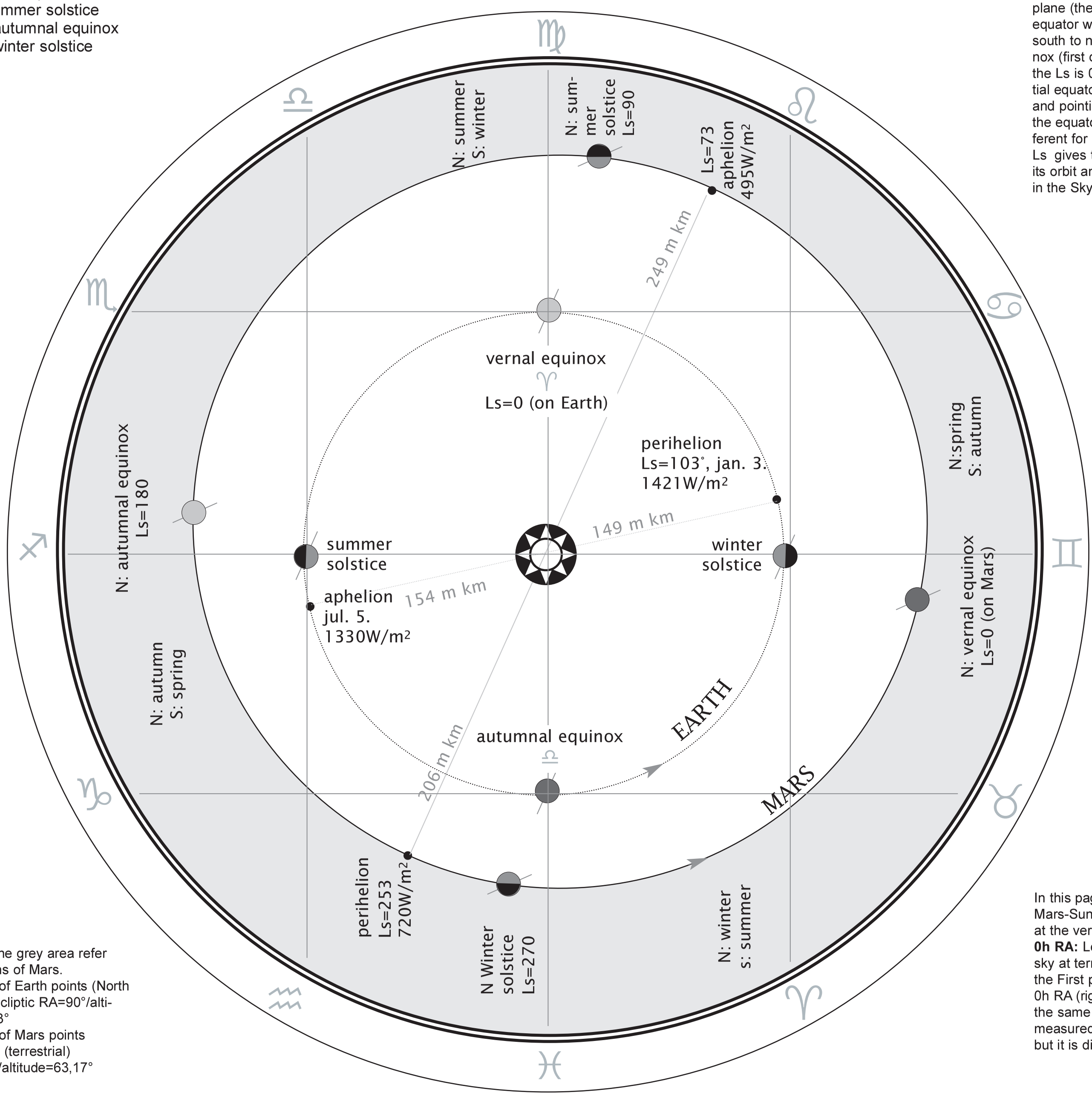
MAP OF PHOBOS



3-axial ellipsoid projection. Shaded Relief Map © L.S. Oreshina, L.Yu. Baeva, B.V. Krasnopevtseva, K.B. Shingareva. Published and edited by the Cosmic Material Space Research Group of Eötvös Loránd University, Budapest.

THE ORBITS AND SEASONS OF EARTH AND MARS

L_s0: vernal equinox
L_s90: summer solstice
L_s180: autumnal equinox
L_s270: winter solstice



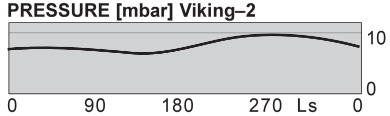
Texts in the grey area refer to seasons of Mars.
The axis of Earth points (North pole) to ecliptic RA=90°/altitude=66,3°
The axis of Mars points to ecliptic (terrestrial) RA=353°/altitude=63,17°

Solar longitude (L sub S or L_s): The angular distance along a planet's orbit measured eastward from the intersection of the planets orbital plane (the ecliptic) and the celestial equator where the Sun moves from south to north, i.e. from, vernal equinox (first day of spring). In this point the Ls is 0. The position of the celestial equator depends on the axis tilt and pointing direction (or position of the equator) of the planet, so it is different for each planetary body.
Ls gives the position of a planet in its orbit and also the Sun's position in the Sky as seen from the planet.

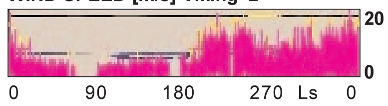
In this page Ls is the angle from the Mars-Sun line to the Mars-Sun line at the vernal equinox.
0h RA: Location of the Sun on the sky at terrestrial vernal equinox isin the First point of Aries.
0h RA (right ascencion) and 0°Ls is the same (a celestial longitude measured from the vernal equinox), but it is different for each planet.

THE CLIMATE OF MARS

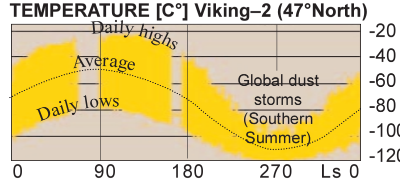
PRESSURE [mbar] Viking–2



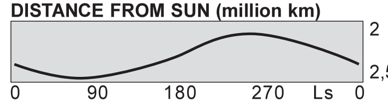
WIND SPEED [m/s] Viking–2



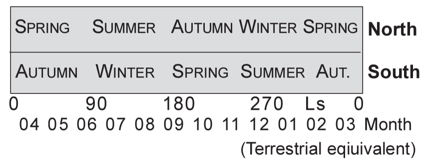
TEMPERATURE [C°] Viking–2 (47°North)



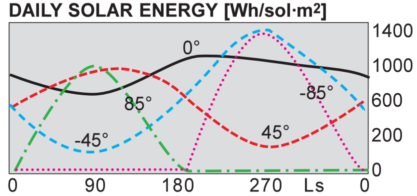
DISTANCE FROM SUN (million km)



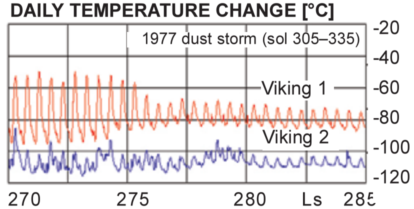
SEASONS



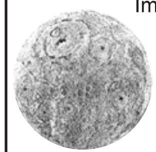
DAILY SOLAR ENERGY [Wh/sol·m²]



DAILY TEMPERATURE CHANGE [°C]



COMPARISON OF CHRONOSTRATIGRAPHIC UNITS OF PLANETARY BODIES OF THE SOLAR SYSTEM

billion years ago	Earth	Venus	Mars	Mercury	Moon	Callisto	Ganymede	Others
Present 0,5 1	0,002-: Ice age, holocene 0,002-0,06: Tertiraty 0,06-0,23: **Mesosoic:** Pacific Mts, Pangea. Dionsaurs 0,23-0,57: **Paleosoic**: 0,4: Life on continents 0,5: Trilobites, Fish 0,4-0,6: Caledonian Mts. 0,5: Cambrian explosion. **Precambrian:** 0,57-2,5: 0,6-0,7: Snowball Earth 0,8: Panthalassa global ocean	**Aurelian** **Guineverian** **Fortunian** 1-0.5: Global resurfacing (volcanic activity)	c. 2,7-: **Amazonian** Dust storms. Dust devils. Wind erosion (aeolic forms), Sand dunes. Polar caps. Dirt flows. Gullies.	**Kuiperian** Young, bright craters with rays. (Kuiper).	Since 1,2: **Copernican** (young craters, e.g. Copernicus, Tycho, Aristarkhos). 	Mass movements Thin ocean under crust. (?)	Mass movements. Bright ray craters, Thin ocean under crust. (?)	**Io:** 1 million years old surface (volcanic lava plains, older mountains.), **Europa:** 10 million years old ice crust. **Enceladus:** 100 million years old or younger surface. Older features and processes are unknown.
1,5 2	Oxygen: 10% of present level. Ozone layer. ~1,5: Rhodinia continent 1,8: Eucariotes (algae) 2: Oxygen in air. Firts biogenetic limestones - stromatolites	**Pre-Fortunian**	*Early Amazonian:* Tharsis Montes younger flows, Olympus Mons older parts. Lava flow at Amazonis Planitia.	**Mansurian** Shrinking crust, folds.	1,2-3,2 **Eratostenian** Craters and young mares (basaltic flows)		Bright, grooved material and palimspsests.	
2,5 3	2.3 snowball Earth 2,5-4,6: **Archaic** Photosyntesis. Oxygen in oceans. 2,8: 500 days = one year	?	2,7-3,5: **Hesperian:** Northern basaltic plains, Elysium, Valles Marineris and its outflow channels, chaos areas. Climate: colder, dryer. *Late Hesperian:* volcanic activity (lava flows) at Tharsis Montes. Northern crust formed.			1,1-3,7: Bedrock of young, bright ray craters. Cratering. Plaimpsests formed, later relaxed.	Temporary criovolcanic activity.	
3,5 4	3,5: Procariotes (bacteria) 3,8: Life appeares. No oxygen in air (CO_2, N_2, NH_3, CH_4). 3,8-4,6: **Hadean** 3.8: Most ancient known rock from Earth (Greenland)		3,5-4,6: **Noachian** 3,9: Giant impacts (Argyre, Hellas) Climate: warmer, denser atmosphere, liquid water. Volcanic activity stronger. Southern highlands crust formed. *Late Noachian:* channel networks formed in the south. *Middle Noachian:* southern highlands average age	**Calorisian** Caloris impact, mare basalts. **Tolstojian** Tolstoj impact basin	3,2-3,85 **Imbrian.** Maria (basins filled by lava), eroded craters, Late imbrian: *volcanic activity* Early Imbrian: Imbrium and Orientale Basins, Fra Mauro, intense bombardment  3,9-4,2 **Nectarian:** ringed impact basins: greatest impacts	3,96 Valhalla multiringed basin.	Palimpsests. 3,8-4,0: Dark cratered materials. No crater preserved before that era. Furrow systems.	
4,6	4,5: Volcanogenetic atmosphere, surface cools: liquid water 4-4,5: intensive bombardment 4.6: Mars sized planetesimal impacts to Earth: Moon formed		**Pre-Noachian**: Northern lowland's buried basins *Early Noachian:* intensive bombardement.	**Pre-Tolstojian**: old intercrater plains	4,2-4,6 **Pre-nectarian**: anortozitic crust, intensive bombardment, basins (SP-Aitken) (4,6-4,4: magma ocean, cust formed)	4,0 Asgard multiringed basin.	4,6: Intensive bombardment. Boy formed from water ice and silicate rich materials.	

CONCISE ATLAS OF THE SOLAR SYSTEM (3)
ATLAS OF PLANETARY BODIES

Szaniszló Bérczi, Henrik Hargitai, Ákos Kereszturi, András Sik; Budapest 2001–2005

The investigation of the planetary bodies is one of the outstanding research and education projects conducted by the Planetology Group of Cosmic Materials Space Research Group under the auspices of Faculty of Natural Science at the Eötvös Loránd University of Sciences. The science of comparative planetology started with the exploration of the Moon in the sixties of the last century. Its subject was extended to a number of planets only at the end of the seventies, when the Voyagers had flown by Jupiter and had photographed the surface of the four Galilean satellites. In the first part of Concise Atlas we introduce the four inner planetary bodies, i.e. the Moon, Mars, Venus and Earth with some of their characteristic features. The four Galilean satellites are dealt with in the second part. Finally a review is included about the belts of small planetary bodies of the Solar System. In this new volume of the series Concise Atlases we would like to give an introduction to the processes that shape the surfaces of planetary bodies.

***

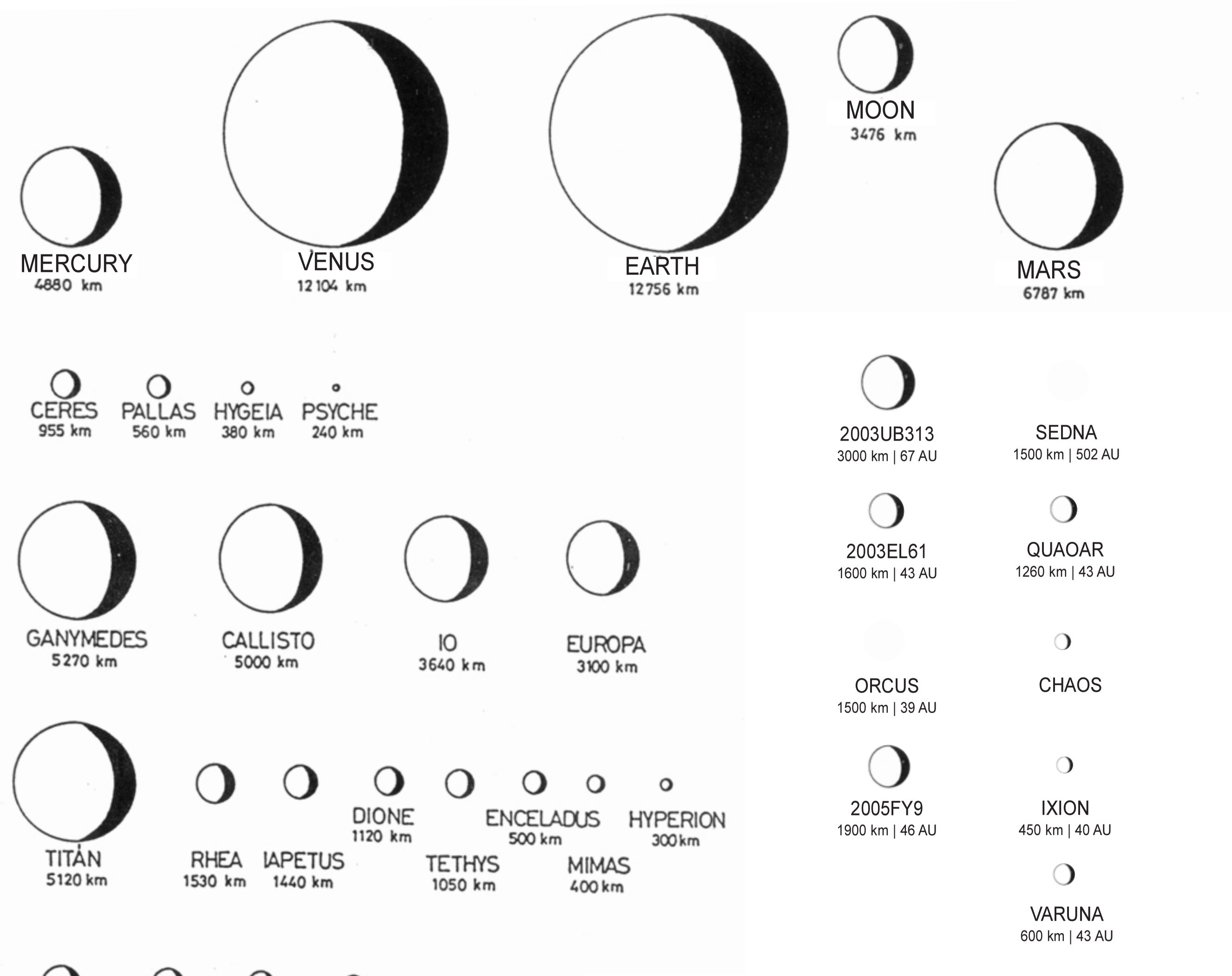
Cosmic Materials Space Research Group, Department of General Physics, Faculty of Natural Sciences at the Eötvös Loránd University, Faculty of Science, Institute of Physics, Department of General Physics, H-1117, Budapest, Pázmány Péter sétány 1/a, Hungary. E-mail: bercziczani@ludens.elte.hu, tel.: +36-1-372-2986

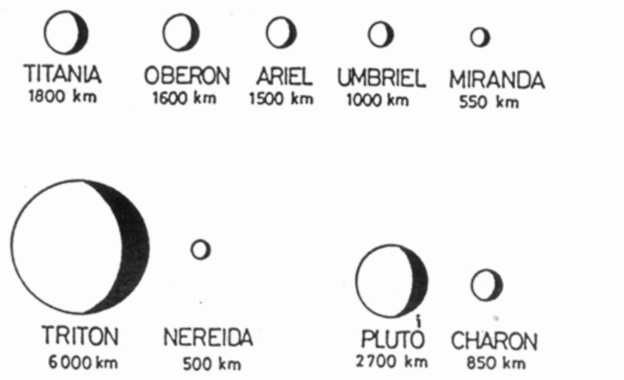
The publication of this work was supported by the Hungarian Space Research Bureau under grant No. TP-190/2005 provided to the Cosmic Material Group of Geonomy Committee of ELTE TTK/MTA.

Published by the Cosmic Materials Space Research Group of Eötvös Loránd University, Institute of Physics, Department of General Physics and the Planetology and Meteoritics Subcommittee of the Geonomy Scientific Committee of the Hungarian Academy of Science and UNICONSTANT, Budapest, Püspökladány, 2005. First edition (in Hungarian): 2001

Translated by Sándor Kabai.

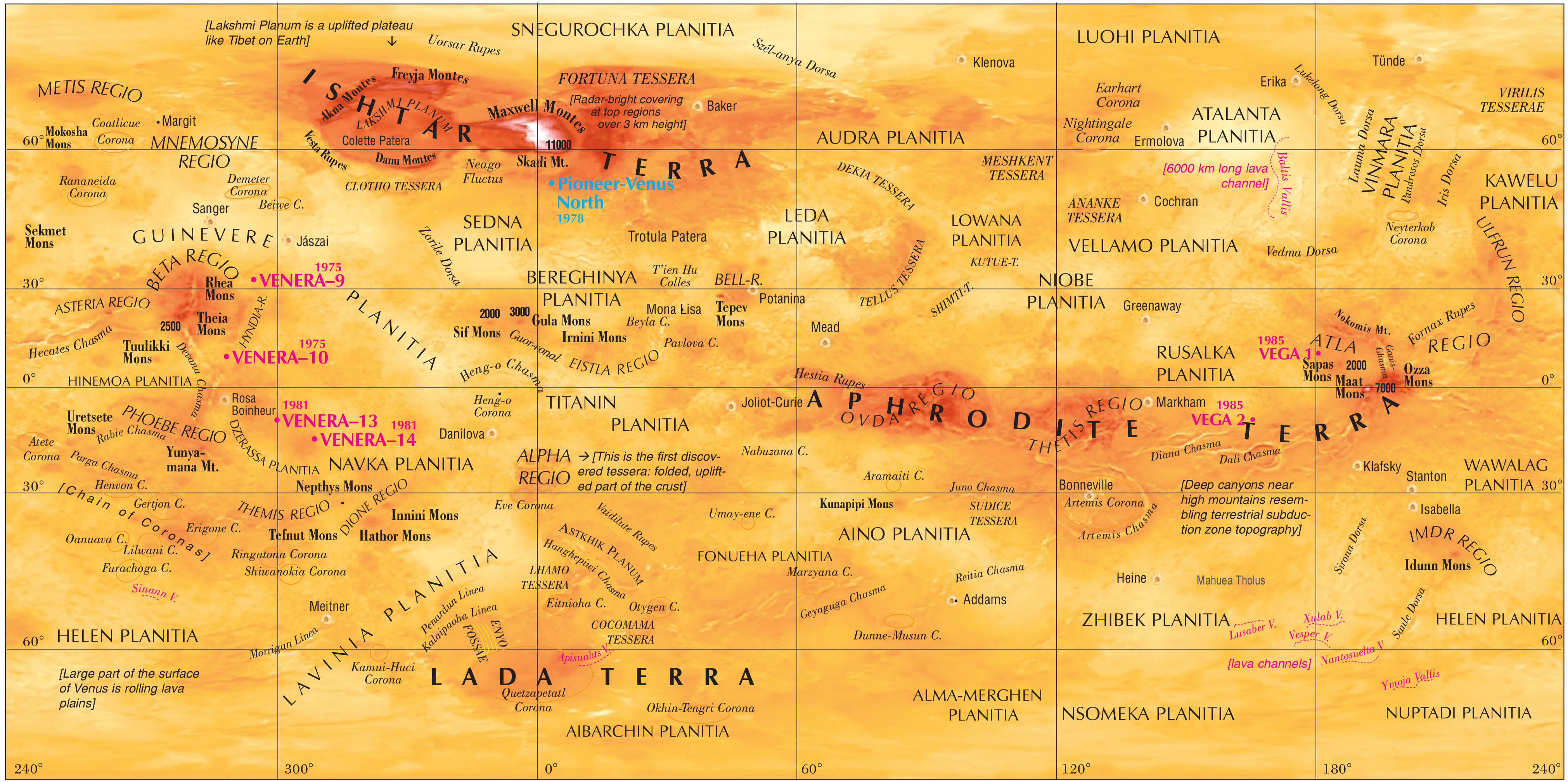
ISBN 963 00 6314 XÖ (series)
ISBN 963 86873 3 9
Printed by PIREMON, Vámospércs





VOLUMES OF THE SERIES CONCISE ATLAS OF THE SOLAR SYSTEM

(1): *Planetary and Material Maps on: Lunar Rocks, Meteorites* (2000);
(2): *Investigating Planetary Surfaces with the Experimental Space Probe Hunveyor Constructed on the Basis of Surveyor* (2001); (E)
(3): *Atlas of Planetary Bodies* (2001); (E 2005) (this volume)
(4): *Atlas of Planetary Atmospheres* (2002);
(5): *Space Research and Geometry* (2002);
(6): *Atlas of Microenvironments of Planetary Surfaces* (2003); (E)
(7): *Atlas of Rovers and Activities on Planetary Surfaces* (2004);
(8): *Space Research and Chemistry* (2005);
(9): *Planetary Analog Studies and Simulations: Materials, Terrains, Morphologies, Processes.* (2005); (E)
(E) and bold letters mark the English language editions



VENUS DATA

Distance from the Sun: 0,723 A.U.
Orbital period: 224,7 Earth day (=1.9 Venus day)
Rotational period: 243 Earth days
Direction of rotation: retrograde
One day on Venus: 116 Earth days
Diameter: 12 104 km
Equator: 38 000 km
Surface area: 460 million km²
Magnetosphere: none
Satellites: none

MAP OF VENUS

Mercator Projection. Source of topographic data: Magellan Radar Altimeter 1990–94.
0 m level at 6051 km radius.
Made by: Eötvös Loránd University Cosmic Materials Space Research Group., Budapest, Hungary 2001–2005.
First English Edition. http://planetologia.elte.hu

HEIGHTS AND DEPTHS

-2 0 2 4 6 11km

DISTANCES (AT THE EQUATOR)

0 1000 2000 km

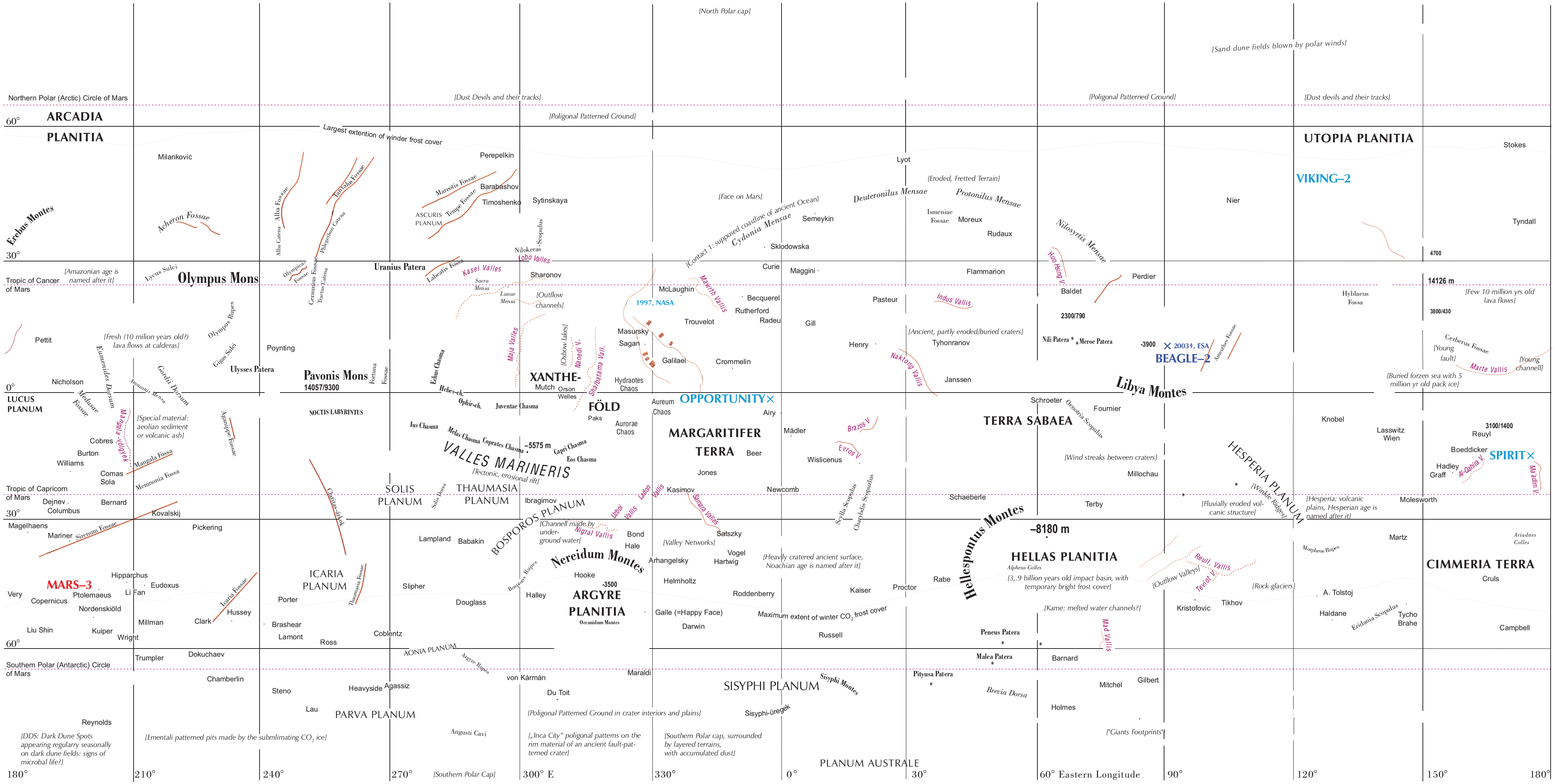
1:143 400 000
1 cm=1430 km

LEGEND

Lava channel
Corona
Impact crater
1985 VEGA 2 Landing probe with date of landing
Fossa

PLANETOLOGY GROUP
Eötvös Univ. CMSRG,
BUDAPEST

ATLAS OF PLANETARY BODIES



PLANETOLOGY GROUP
Eötvös Univ. CMSRG, BUDAPEST

HIGHTS AND DEPTHS

-9 -8 -6 -4 -2 0 2 4 6 8 10 12 14 16 18 20 21 km

DISTANCES (AT THE EQUATOR)

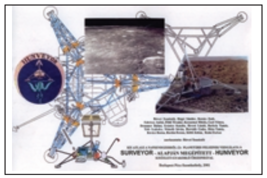
0 500 1000 1500 2000 km

LEGEND

- × Landing Site
- 1971 Year of Landing
- † Unsuccesful Soft Landing
- Valley Network
- Outflow Valley
- Fossa
- 4600/1300 Height above 0 m level (peak/caldera height)

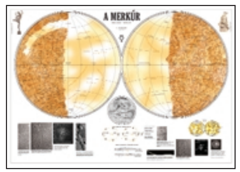
CONCISE ATLAS OF THE SOLAR SYSTEM
TEXTBOOK SERIES FROM THE COSMIC MATERIALS SPACE RESEARCH GROUP, EÖTVÖS LORÁND UNIVERSITY, BUDAPEST
http://planetologia.elte.hu

Also available:
- Multilingual wall maps of Mercury; Mars; the Moon, Venus 2001–2005.
- Planetary Science educational DVD Video; 2004. in English and Hungarian
- Concise Encyclopaedia of the Solar System 1: Impact cratering (in Hungarian)



From Surveyor to Hunveryor
How we constructed an experimental educational planetary lander model. In English and in Hungarian 2001-2.

Atlas of Microenvironments of Planetary Surfaces
In English and in Hungarian 2004.



Bilingual Map of Mercury
In English and in Hungarian 2004.