BHARATHIDASAN UNIVERSITY

Tiruchirappalli- 620024, Tamil Nadu, India

Programme: M.Tech., GEOLOGICAL TECHNOLOGY AND GEOINFORMATICS

Course: Remote Sensing Application in Planetary Studies

Code : MTIGT1004

Dr. J. Saravanavel
Professor
Department of Remote Sensing,
Bharathidasan University, Tiruchirappalli
Email: saravanavel@bdu.ac.in

Unit-5 Mars. Introduction to Mars – Origin of Mars – Crustal evolution of Mars crust – Interior Characteristics of Mars - Martian Timescale – Volcanoes of Mars - Impact Craters, Martian Meteorites. Mars atmosphere - Mars Exploration Missions - Mariner series, Mars series, Mars Odyssey, Mars Pathfinder, MSL Curiosity, Mars Reconnaissance Orbiter, Mangalyaan/ Mars Orbiter Mission and ExoMars - Future Lunar and Mars Missions

- The planet Mars is situated further from the Sun than the other three terrestrial planets of the solar system and has the lowest average surface temperature.

- Mars, like the other terrestrial planets, loses heat and, as its decreasing internal heat sources cannot balance the loss, slowly cools.

- The internal dynamics of Mars is affected by the internal temperature and internal heat transfer because heat is often transported by macroscopic mass motion in terrestrial planets.

Mars: Origin

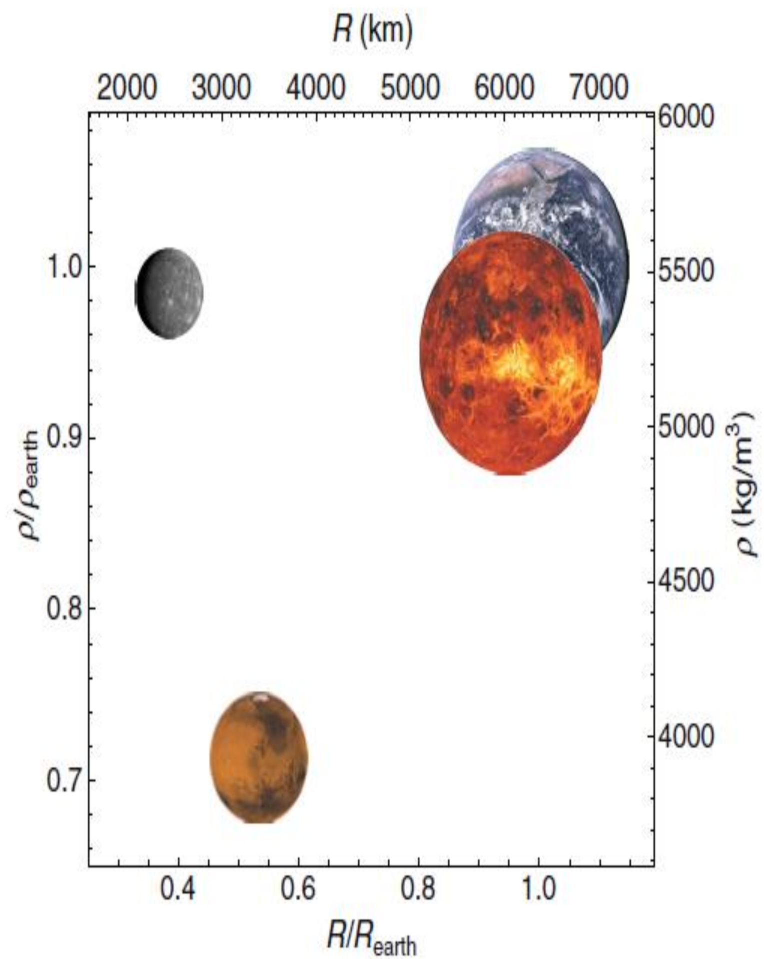


FIGURE 18.2 Radius and density of the four terrestrial planets (Mercury, Venus, Earth, and Mars (relative size to scale)) of the solar system and relative values compared to the Earth.

TABLE 18.1 General Characteristics of Mars

Quantity	Symbol and Unit	Value
Mass	M (10^{23}kg)	6.4186 ± 0.0008
Radius	R (km)	3389.5 ± 0.2
Mean density	ρ (kg/m^3)	3935.0 ± 0.8
Mean moment of inertia factor	$I/(MR^2)$	0.3645 ± 0.0005
Mean surface gravitational acceleration	g (m/s^2)	3.7379 ± 0.0007
Semimajor axis	a (AU)	1.5237
Orbital period	P_{orb} (days)	686.98
Rotation period	P_{rot} (hours)	24 h 37 min 22.662993 s $\pm$ 0.000003
Obliquity	ε (degrees)	$25.189379242 \pm 0.00001°$
Eccentricity	e	0.0934

- Terrestrial planets like Mars form when kilometer-sized planetesimals, which originate from the accumulation of dust grains in less than about 10,000 years, collide under the influence of the gravitational attraction between them and gas drag, a process called accretion.

- The general consensus is that in particular the large impacts at the end of formation strongly heat the deep interior of a planet in a fraction of geological time and can melt at least part of the planet interior producing a magma ocean.

- Iron droplets in the magma ocean could then descend to form the core and at the same time mantle material crystallized at the cold surface layers to form the primordial crust.

Mars: Interior Characteristics

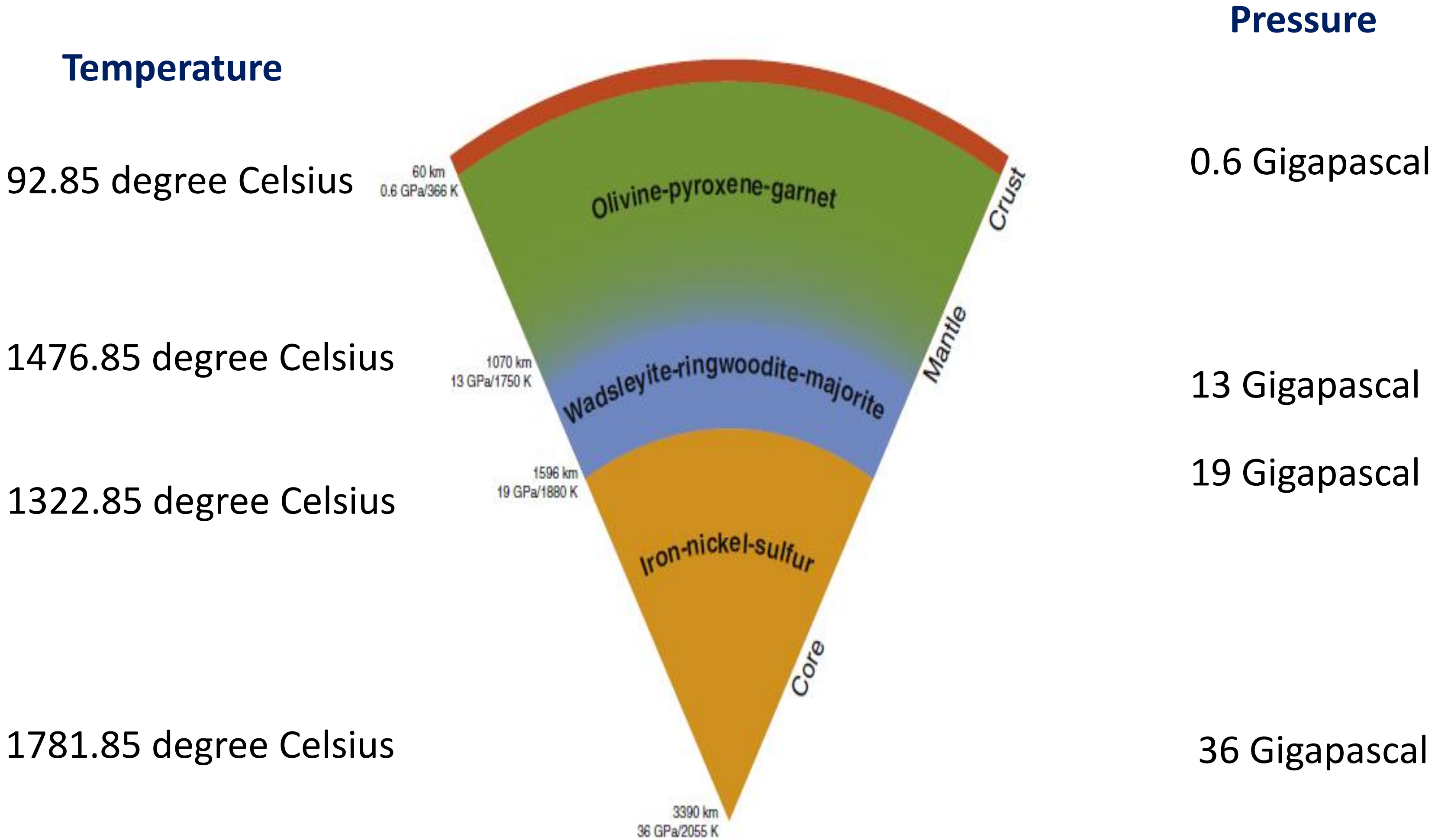


Figure description: Section through the interior structure of Mars depicting the 3 principal reservoirs: crust, mantle, and core. At each interface, depth, pressure, and temperature are given.

- The core is entirely liquid
- Mars is much smaller with a mean radius of 3390
- Because Mars is smaller than the Earth, it is expected to form at a lower temperature
- Mars cool faster than the Earth (heat content of a planet = the planetary volume)
- The mean density of Mars is 3933 kg/m^3

- Origin of planets lies in how deep the energy can be deposited in a planet. If energy can be brought to the deep interior, a very efficient internal heat transport mechanism would be required for a cold formation to occur.

- The general consensus is that in particular the large impacts at the end of formation strongly heat the deep interior of a planet in a fraction of geological time and can melt at least part of the planet interior producing a magma ocean.

- The final formation of Mars took less than about 10 My.

- This is faster than for the Earth, for which the last large impact that formed the Moon is thought to have occurred 30 - 50 My after the formation of the solar system.

- Because of its fast formation, Mars probably suffered less violent impacts with respect to the Earth resulting in a more limited heating.

- Similarly as for the Earth, the core of Mars is thought to be principally made of iron with unknown but small fractions of nickel and light elements.
- Based on the chemical affinity of light elements to iron-nickel mixtures, the main candidate light elements for the Martian core are
    - sulfur,
    - silicon,
    - oxygen,
    - carbon, and
    - hydrogen,

  in binary, ternary or more complicated systems with iron and nickel.
- Finally, hydrogen might also enter the core if the magma ocean contained water and the pressure at the bottom of the magma ocean was higher than about 5 GPa.

Mars Mantle

- Olivine and its high-pressure polymorphs, p

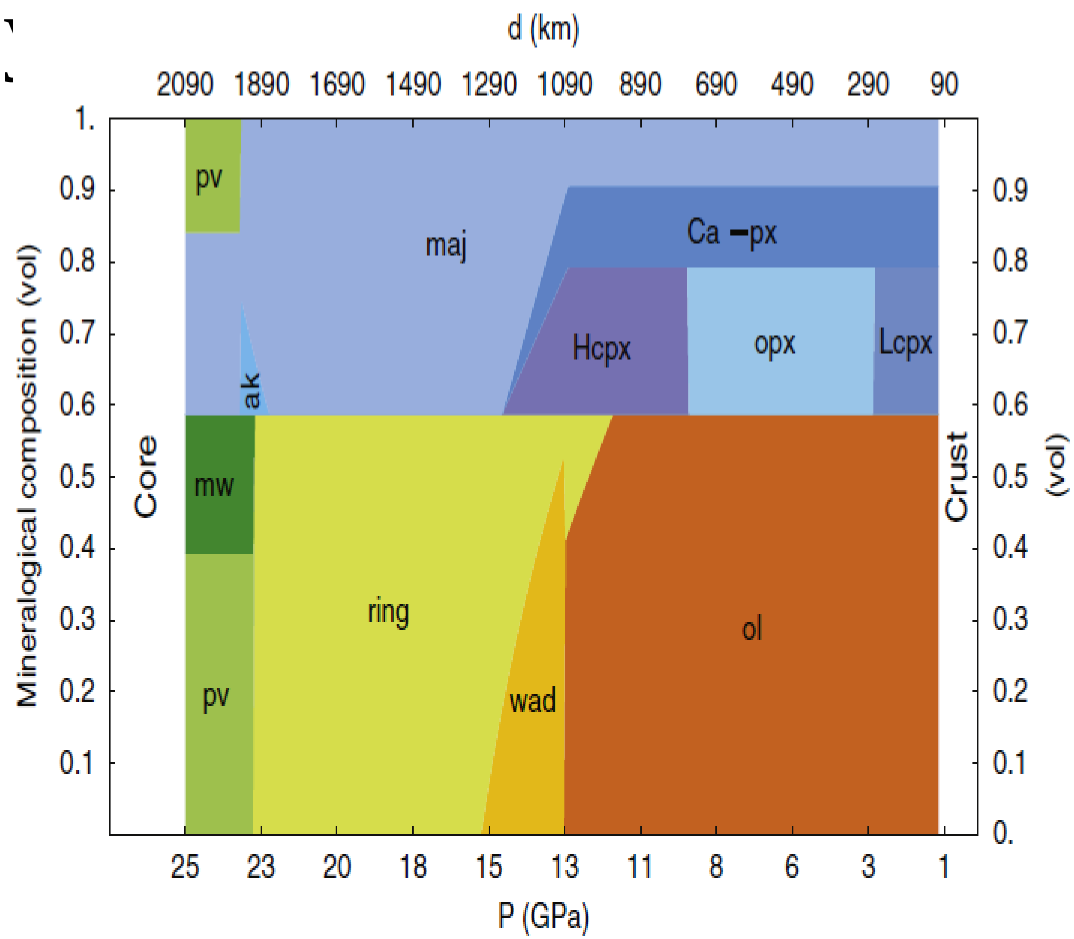
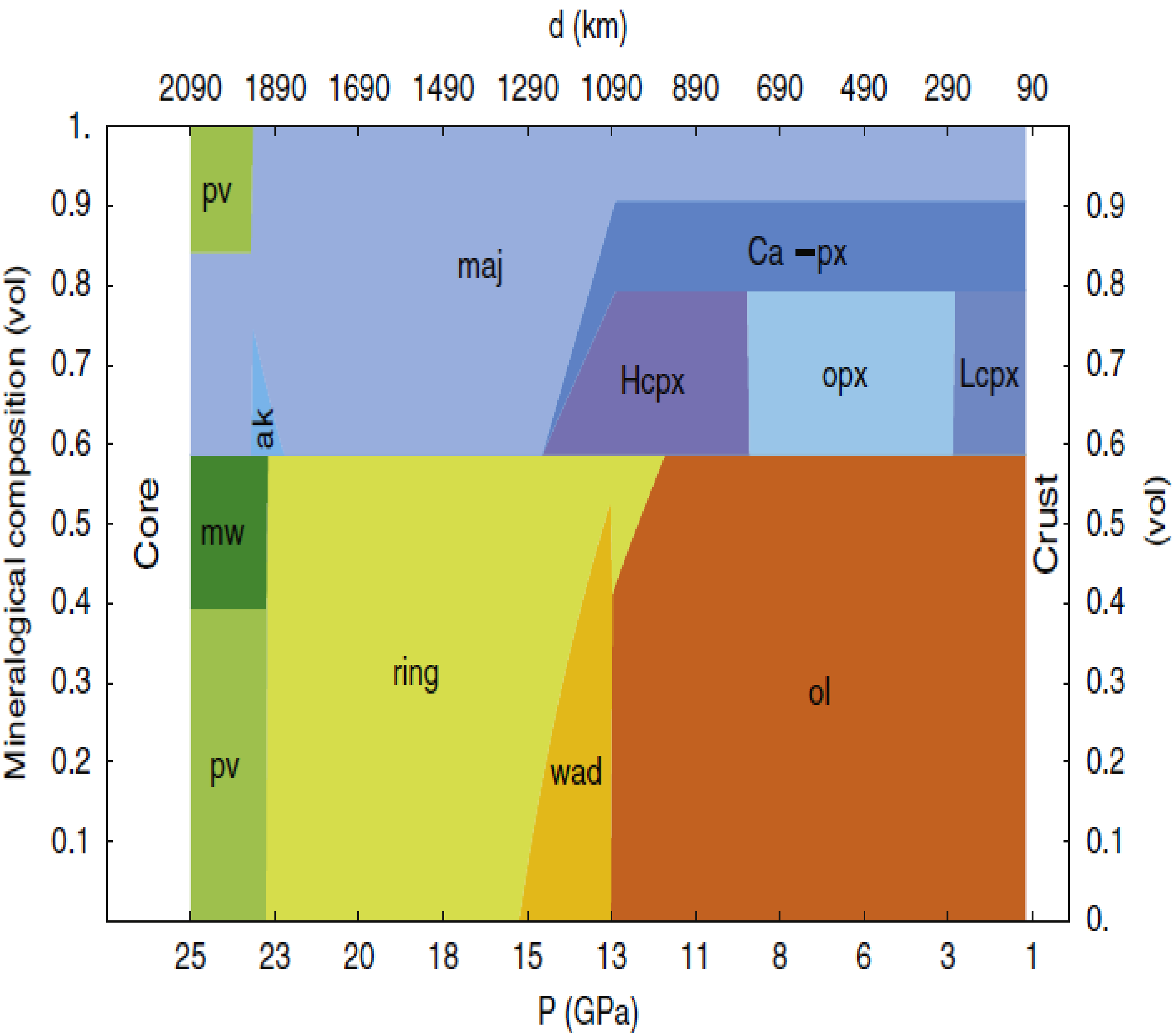


FIGURE 18.3 Phase diagram for the mantle of Mars derived from the chemical analysis of Martian meteorites (Dreibus and Wänke, 1985) assuming a cold end-member mantle temperature profile. The upper mantle is rich in olivine (ol) and pyroxenes (clinopyroxene LP (Lcpx), clinopyroxene HP (Hcpx), orthopyroxene (opx), and Ca-pyroxene (Ca-px)). With increasing pressure the pyroxenes dissociate to majorite (maj) and olivine transforms to its higher pressure polymorphs wadsleyite (wad) and ringwoodite (ring). At the highest possible pressure, close to the core–mantle boundary, ringwoodite starts to dissociates to (Mg,Fe)-perovskite (pv) and (Mg,Fe)-wüstite (mw). At those high pressures, majorite first takes the akimotoite (ak) structure, and subsequently transforms into perovskite.



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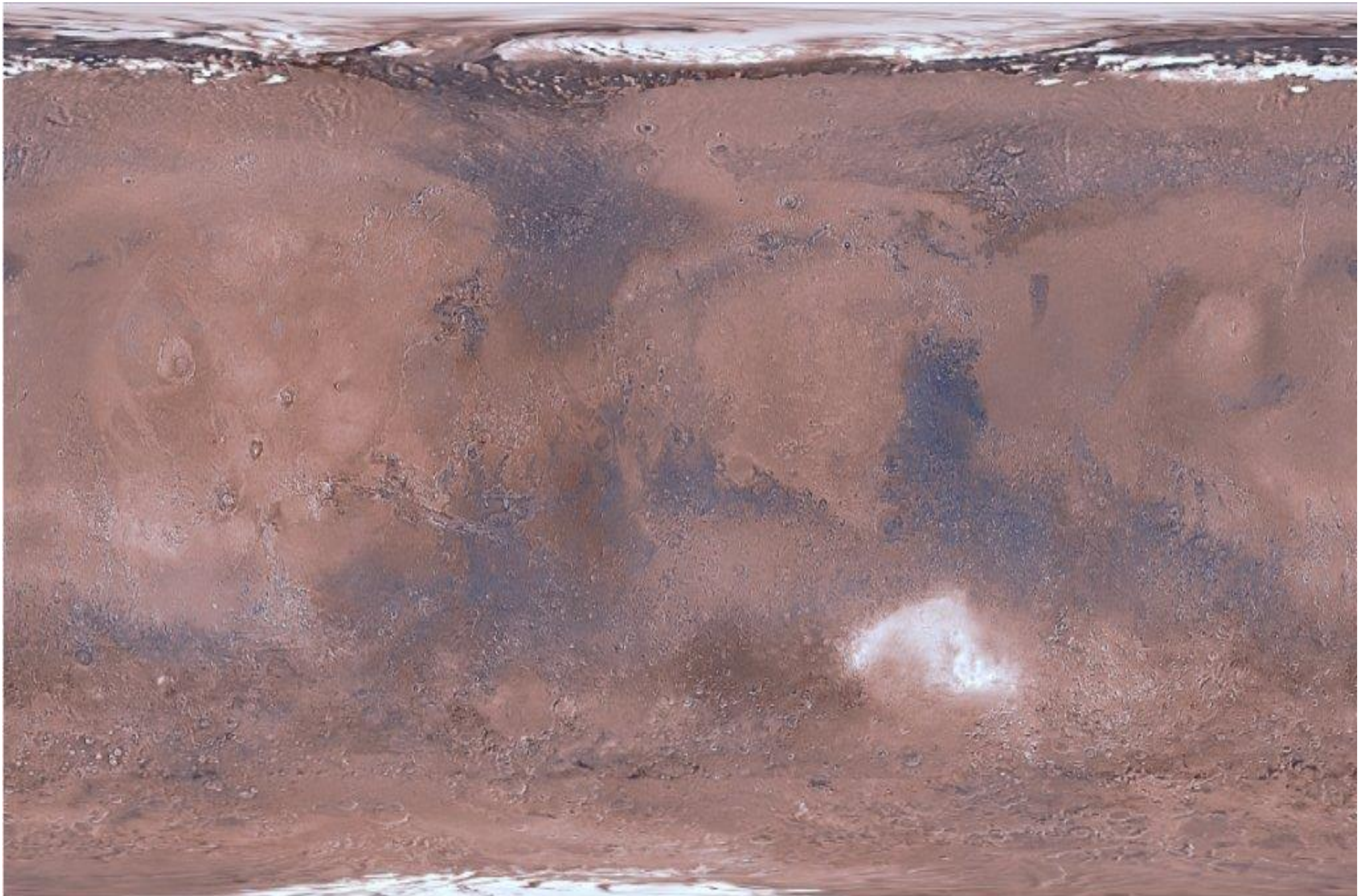


The colorized mosaic was completed by NASA AMES which warped the original Viking colorized mosaic and blended over the latest black/white Mars Digital Image Model (MDIM 2.1).

A Layer of Dust

The rocks and soil on the surface of Mars contain a dust that is primarily made up of iron (in addition to small amounts of other elements, including chlorine). Wind eroded these surface rocks and soil, and ancient volcanos blew out the iron, spreading it all over the planet.

When this happened, the iron within the dust reacted with oxygen, producing a red rust color. So, Mars is red because it has a layer of rusty dust covering its entire surface!

Dust Storms

Mars has some of the largest dust storms in the galaxy, in which the red dust gets whipped into the light atmosphere surrounding the planet. This is why Mars also appears to have a red sky.

Mars: Crustal Composition

- **The crust is the thin upper layer of a terrestrial planet. It consists of silicate rocks like the mantle but is chemically different from the mantle. The crust is more silica rich (SiO_2 contributes 50% or more in mass) and has a lower density than the underlying mantle as a result of its formation from the mantle by melting and crystallization.**

- **Studies of radioactive parent - daughter isotopes in Martian meteorites that separate differently between the liquid and the solid silicate phases show that the bulk of the crust was created within 100 My after formation of the planet**

- **This primordial crust presumably formed from crystallization of the cooling magma ocean. Additional crust is formed later in Mars' evolution when ascending hot material from the mantle partially melts and rises to the crust and surface by volcanism**

- **The crust is basaltic in composition with the older crust being more silica rich.**

- **However, rocks with the highest silica content on the Earth, felsic rocks such as granite, are almost absent on Mars.**

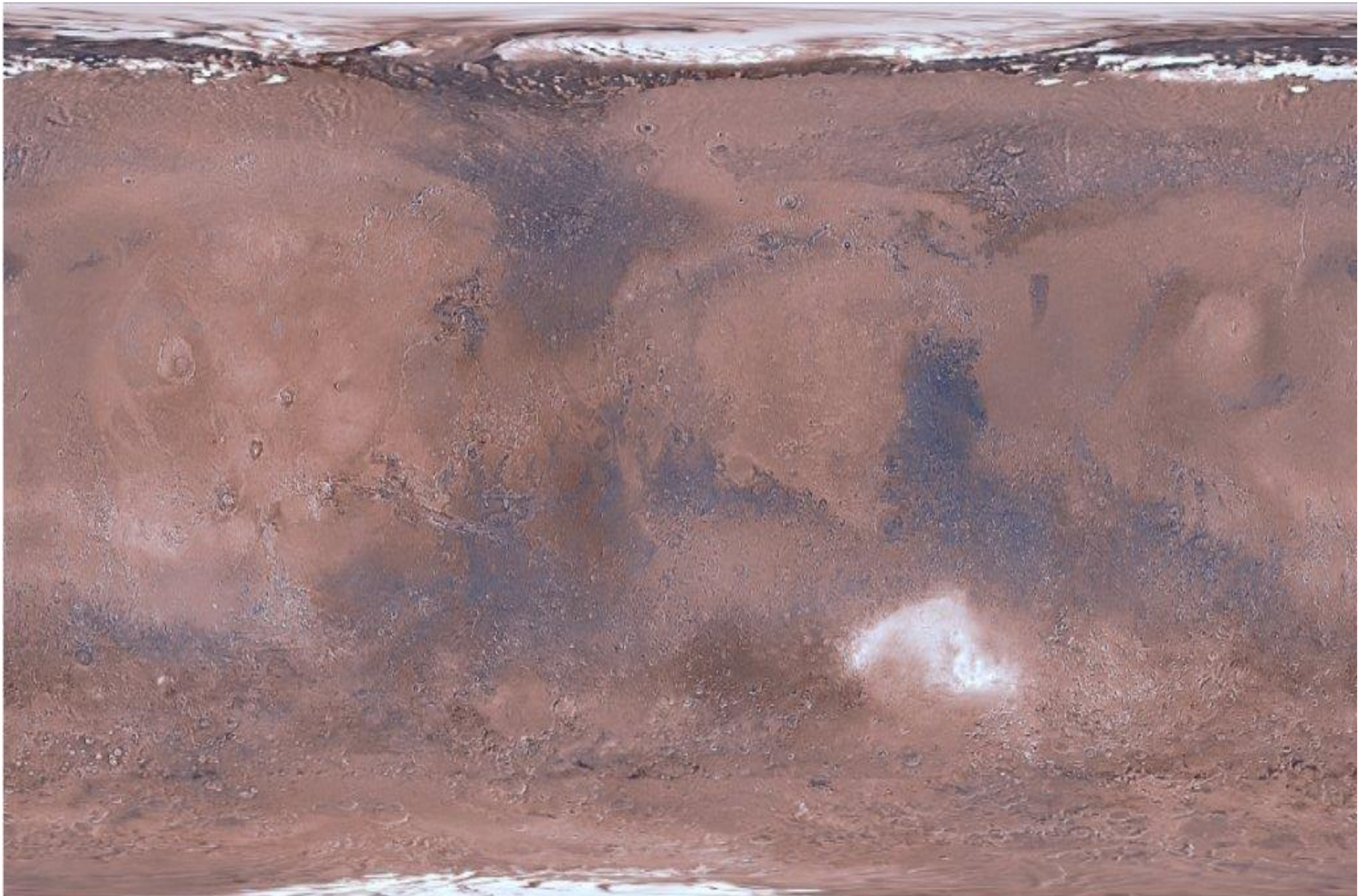
- **On the Earth, plate tectonics, which is absent on Mars, continuously changes the crust: A division in continental crust and oceanic crust as for the Earth can, therefore, not be made for Mars.**

Silicic

Igneous rocks are classified by geologists using various schemes.

One of the several schemes based on chemical composition divides igneous rocks into four categories according to silica (silicon dioxide, SiO2) content:

(1)Rocks containing more than 66% silica are silicic (Felsic).
(2) Rocks containing 52–66% silica are classified as intermediate.
(3) Rocks containing 45–52% silica are mafic .
(4) Rocks containing less than 45% silica are ultramafic

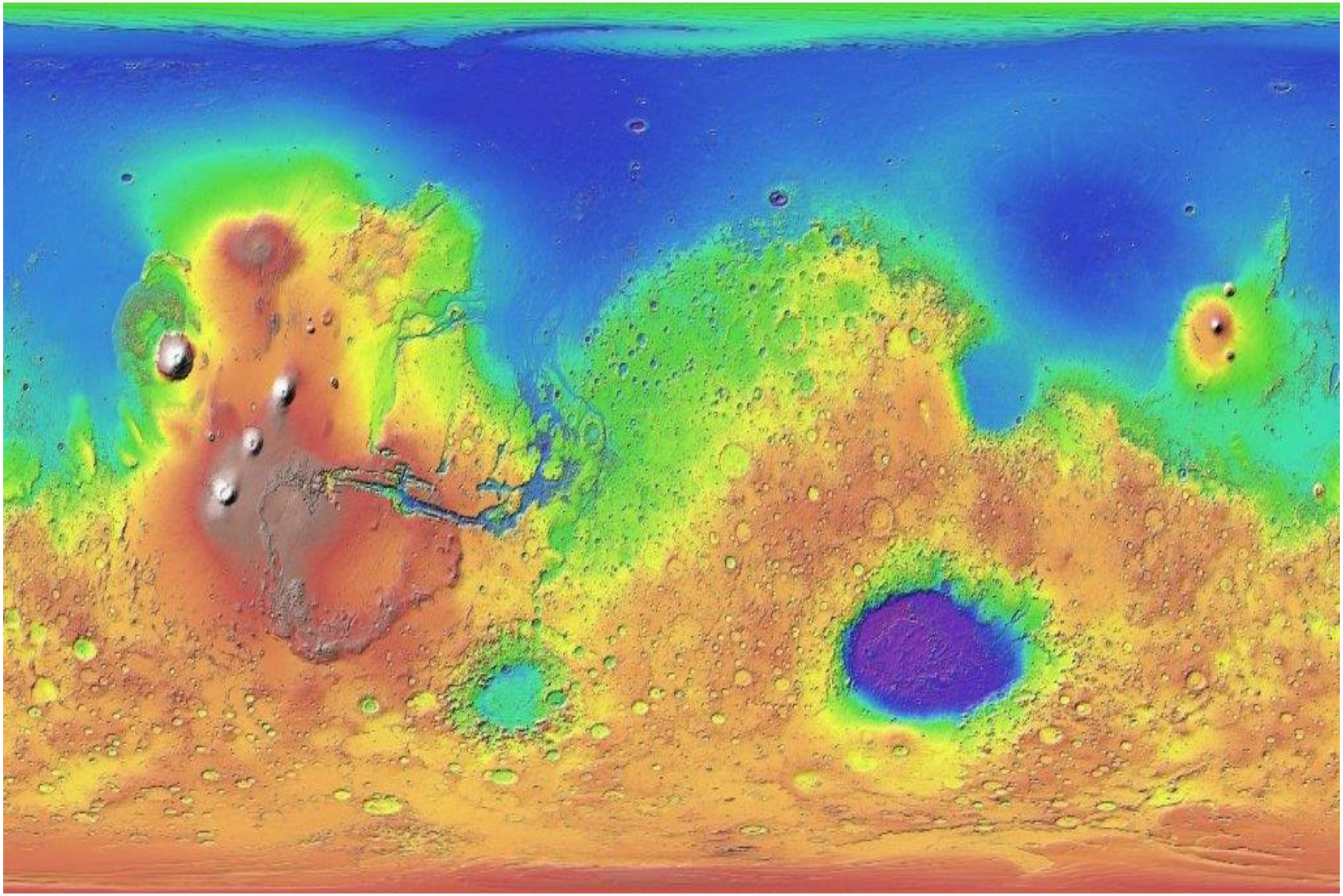


The colorized mosaic was completed by NASA AMES which warped the original Viking colorized mosaic and blended over the latest black/white Mars Digital Image Model (MDIM 2.1).

- The simple explanation for the Red Planet's color is that its regolith, or surface material, contains lots of iron oxide — the same compound that gives blood and rust their hue.

- its surface rusted, the compound iron(III) oxide appears red because it absorbs the blue and green wavelengths of the light spectrum while reflecting the red wavelengths

- Martian dust is reddish mostly due to the spectral properties of nanophase ferric oxides (npOx) that tend to dominate in the visible spectrum.



This map is based on data from the Mars Orbiter Laser Altimeter (MOLA) (Smith, et al., 2001), an instrument on NASA's Mars Global Surveyor (MGS) spacecraft (Albee, et al., 2001).

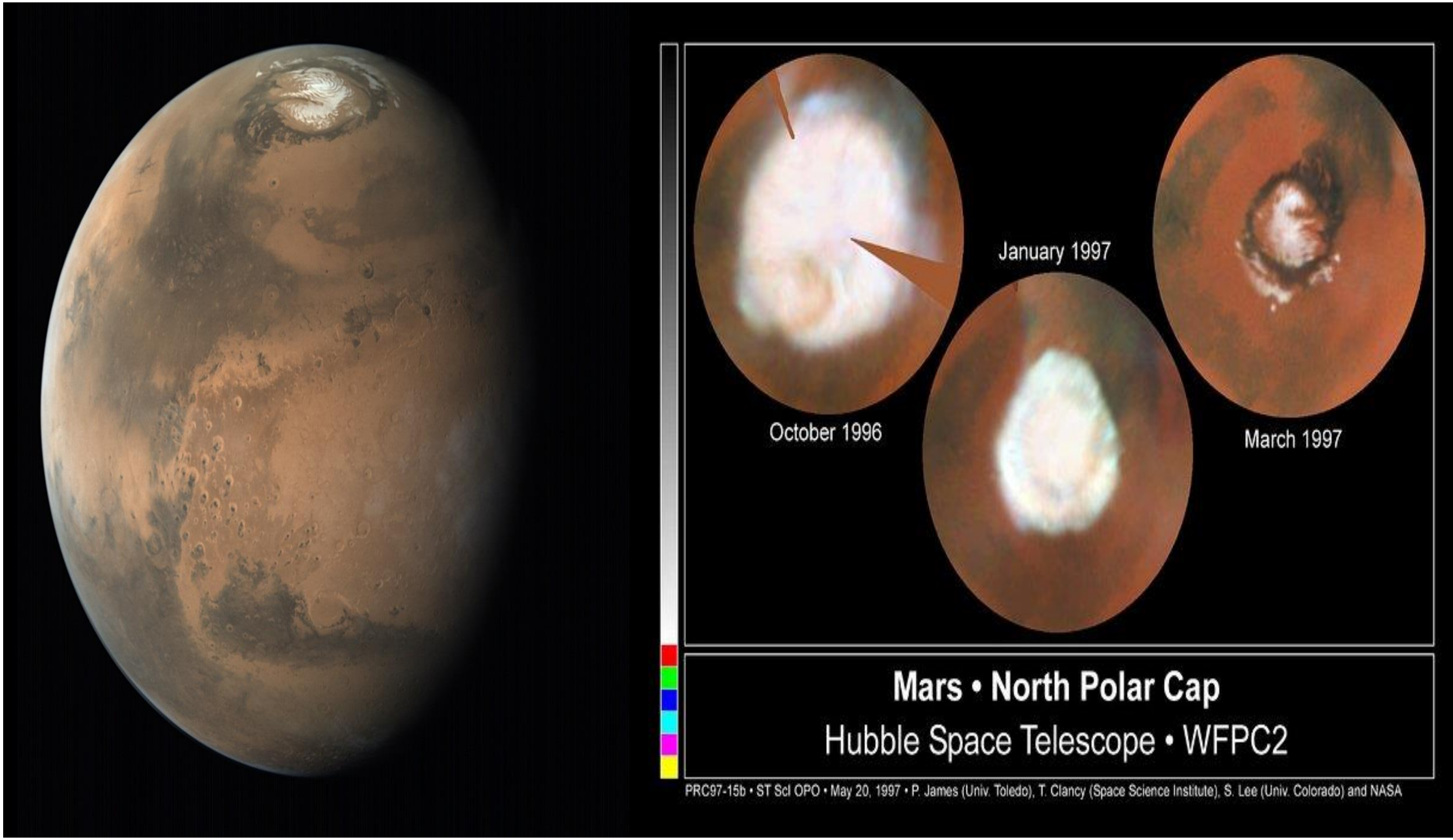
- **Mars' crust exhibits a very notable crustal dichotomy: the northern hemisphere is almost flat and covered with volcanic rocks, whereas the southern hemisphere is a few kilometers higher and cratered by ancient impacts.**
- **The crust is about 25 km thicker in the southern highlands than in the northern lowlands.**

- **The thickness of the crust has been estimated from the topography data measured by the laser altimeter onboard the Mars Global Surveyor (operational between 1997 and 2006) and from the gravity field determined by radio tracking orbiting spacecraft:**
  - **The average crustal thickness is estimated to be between 38 and 62 km, and the average crust density is about 2700 - 3100 kg/m3.**
- **The dichotomy was formed shortly after formation of Mars within the first half billion year and maybe even within the first 50 My.**
- **The dichotomy could have been created by large impactors but could also be due to internal processes such as the crystallization of the magma ocean, an early phase of plate tectonics, or convective motions in the mantle characterized by a large upwelling plume beneath the southern hemisphere.**

- **One of the most prominent topographic features on the surface of Mars besides the dichotomy is the volcanic plateau of Tharsis which is located near the equator in the western hemisphere.**
- **The plateau or bulge is about 5000 km across and up to 7 km high and harbors the largest and highest volcanoes of the solar system. It is thought that Tharsis is created by a volcanic plume, quite similar to the one found beneath the island of Hawaii.**
- **The idea is that a hot column of mantle material rose from the core - mantle boundary through the mantle and delivered substantial volumes of basaltic lava to the surface.**
- **Because of the absence of plate tectonics, high volcanoes could develop over long timescales, with the highest of all, Olympus Mons, rising 22 km above the reference surface.**
- **The lower gravity on Mars (6.4186 10^{23} kg) explains why higher mountains can exist on Mars than on the Earth.**
- **Analyses of the mineralogy of surface rocks and water erosion features such as outflow channels on Mars' surface indicate that Mars had large amounts of liquid water on its surface in the very distant past during intermittent periods.**

These channels, which are between 1 metre and 10 metres wide, are on a scarp in the Hellas impact basin.

- Nowadays, water on the surface is mostly found in the form of solid water ice below the CO_2 ice-covered polar ice caps.



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Chemical Evolution of Crust Formation

- **During its cooling history, the mantle of Mars chemically evolves because of partial melting.**

- **When mantle material ascends beneath the stagnant lid as a result of mantle convection, both the temperature and the melting temperature experienced by the upwelling material decrease because of the lower pressure exerted on the rocks.**

- **Since the temperature in the rising material element decreases slower than the melting temperature, the rocks can reach a region where their temperature is higher than the melting temperature and partially melt.**

- **Only part of a rock melts because rock is composed of several minerals, each with a different melting temperature. Through volcanism the molten rock can rise above the base of the upper thermal boundary layer and will recrystallize in the crust or at the surface, thereby contributing to the growth of the crust.**

- **For rocks to partially melt, the temperature in Mars must be higher than the solidus temperature. As a result of cooling the occurrence of partial melting therefore decreases with time.**

- **Moreover, the thickening of the stagnant lid also moves the melt zone to greater depths.**

- **As the melting temperature increases faster with depth than the mantle temperature, melting is less likely in deeper mantle layers.**

- **Because most of the crust was formed in the first 100 My, partial melting must have been strongly reduced from then on.**

- **Initial mantle temperatures well above 2000 K and high Rayleigh numbers are thought to be implausible as they would lead to a thicker crust than observed and might even destroy the crustal dichotomy.**

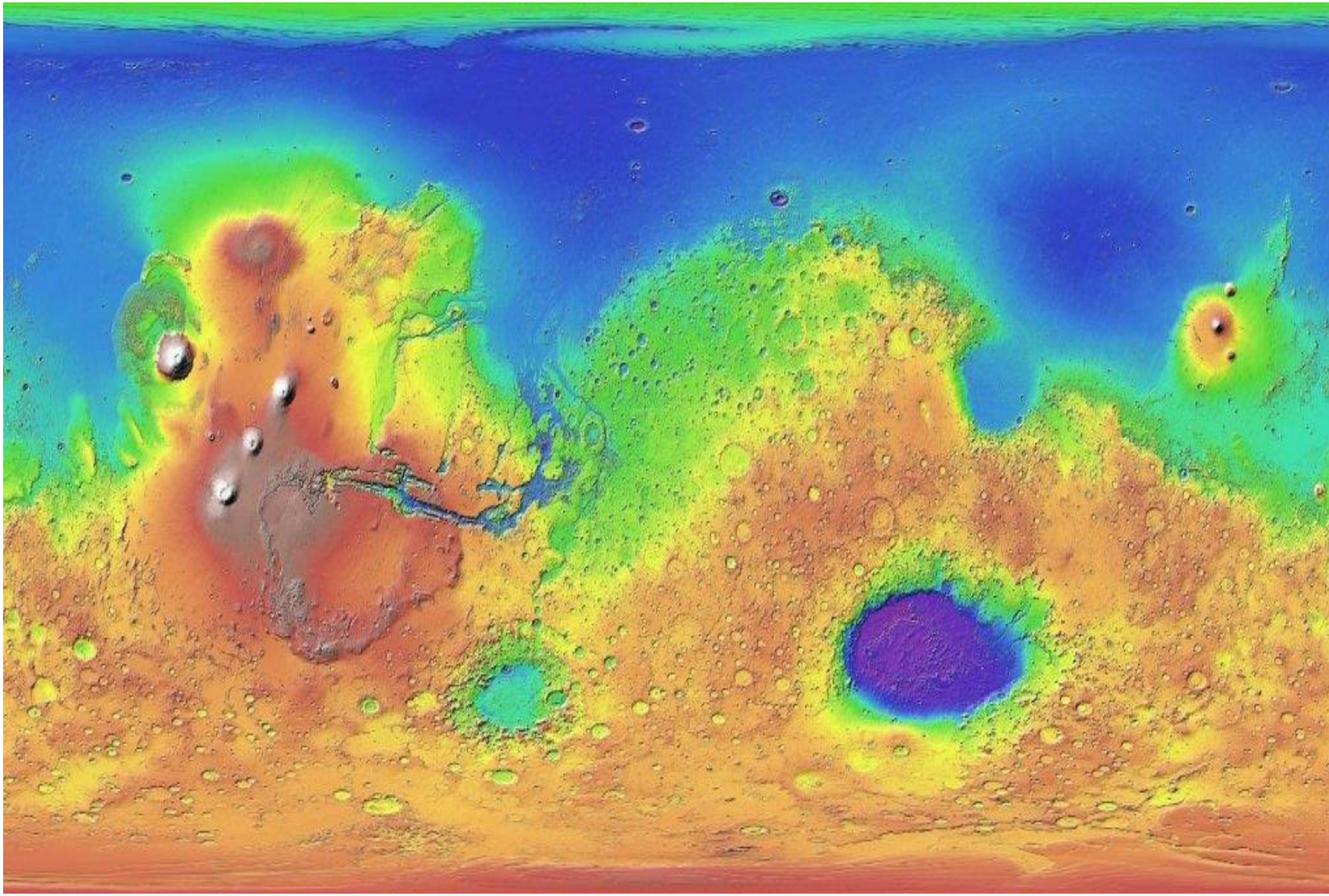
- **The state of the crust therefore sheds light on the initial conditions of Mars.**

- **Locally, volcanism has, nevertheless, continued to create new crust, in particular in the Tharsis region, with evidence of lava flows not older than a few million years.**

- **Volcanism requires melting and penetration of melt into the stagnant lid, which becomes increasingly unlikely with increasing stagnant lid thickness but local melting due to hot upwelling mantle plumes seems not excluded.**

- **Local magmatism observed in the Tharsis region might also be a consequence of the locally thick crust.**

- **If the crust is sufficiently enriched in radioactive elements and has a significantly lower thermal conductivity than the mantle, the crust locally better insulates the mantle leading to higher local temperatures in the upper mantle and partial melting.**



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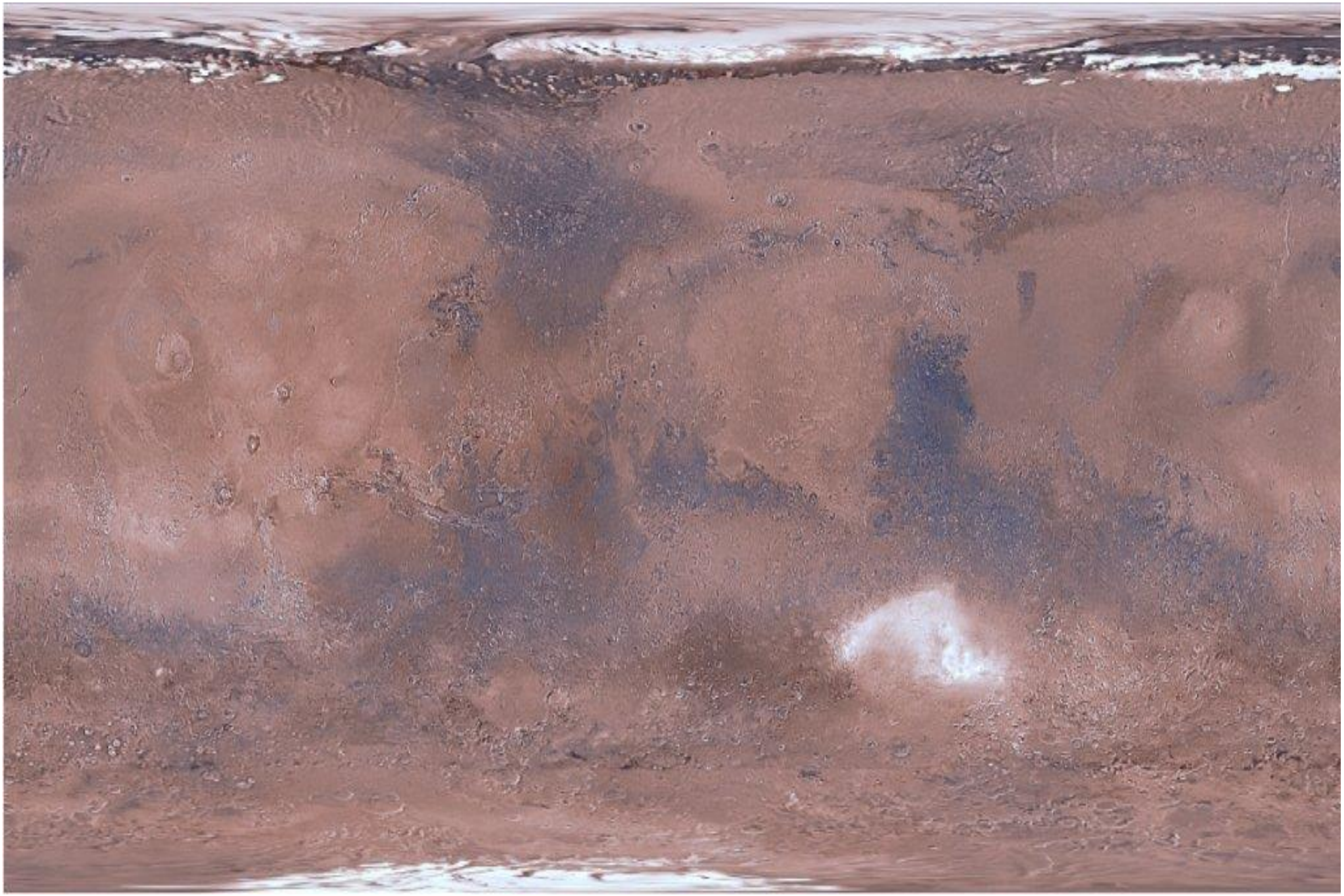

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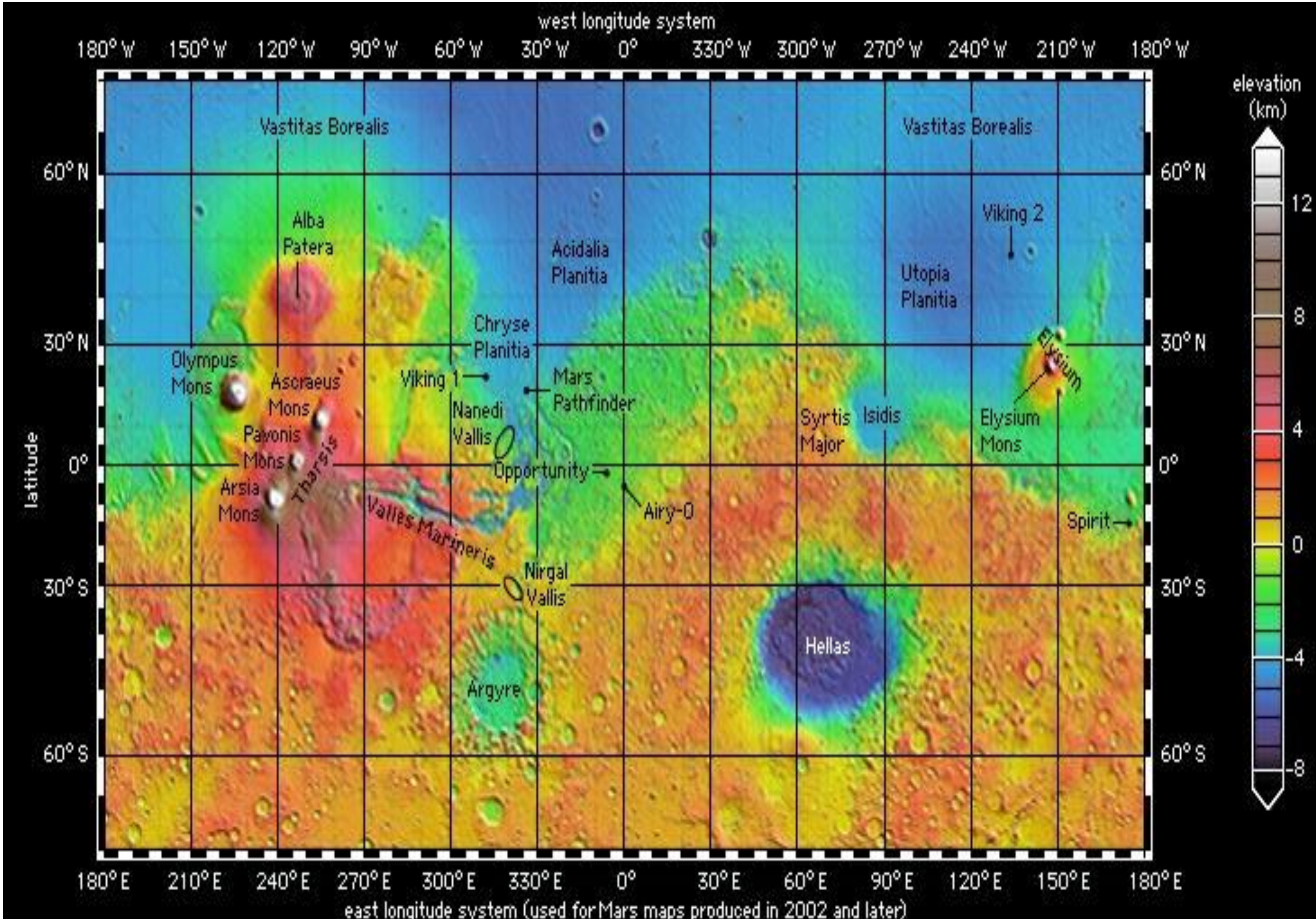
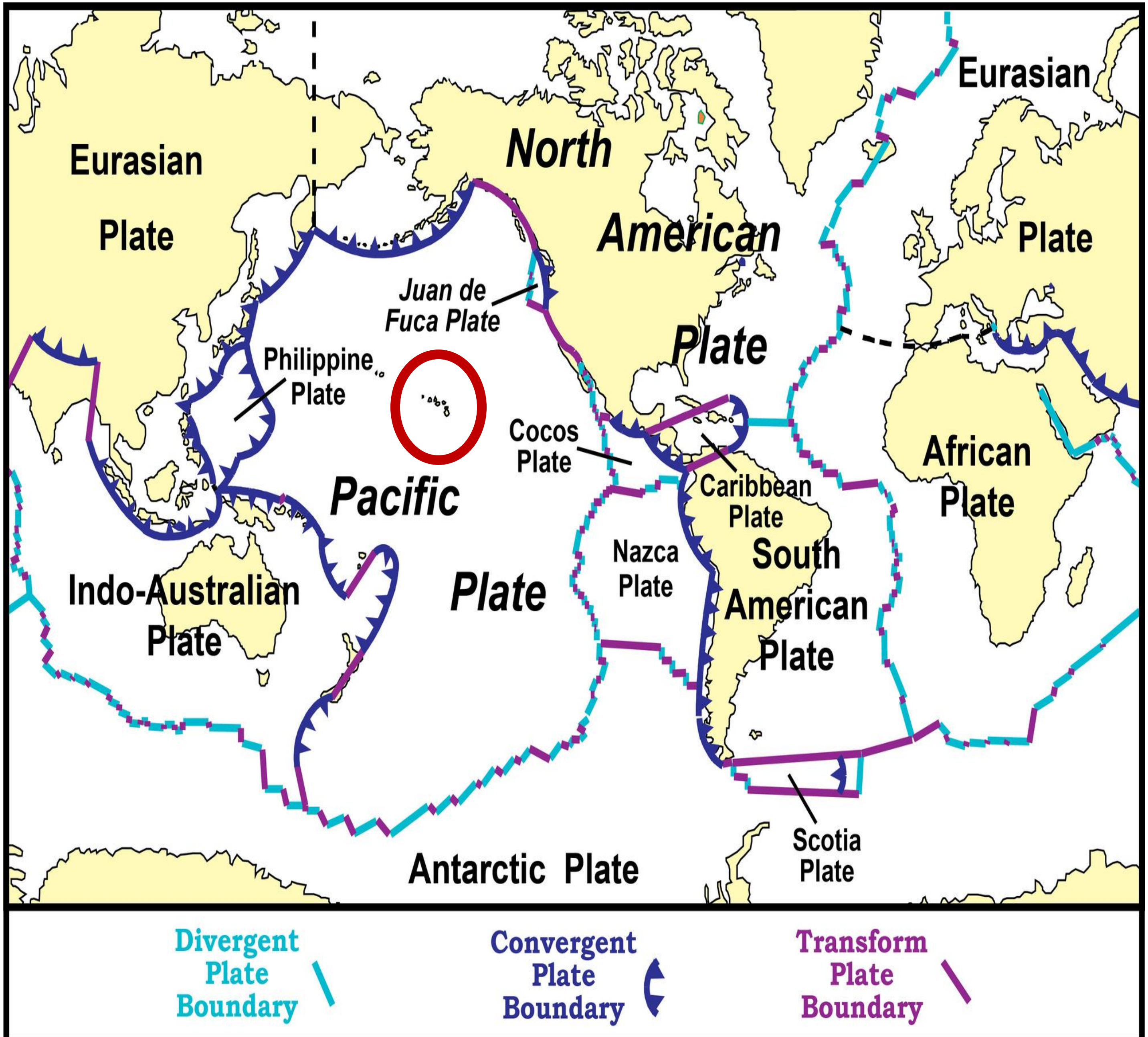


Source: Mars Orbital Laser Altimeter (MOLA) Science Team



Eurasian
Plate
North
American
Plate
Eurasian
Plate
Juan de
Fuca Plate
Philippine
Plate
Cocos
Plate
Pacific
Plate
Caribbean
Plate
African
Plate
Nazca
Plate
South
American
Plate
Indo-Australian
Plate
Scotia
Plate
Antarctic Plate
Divergent
Plate
Boundary
Convergent
Plate
Boundary
Transform
Plate
Boundary

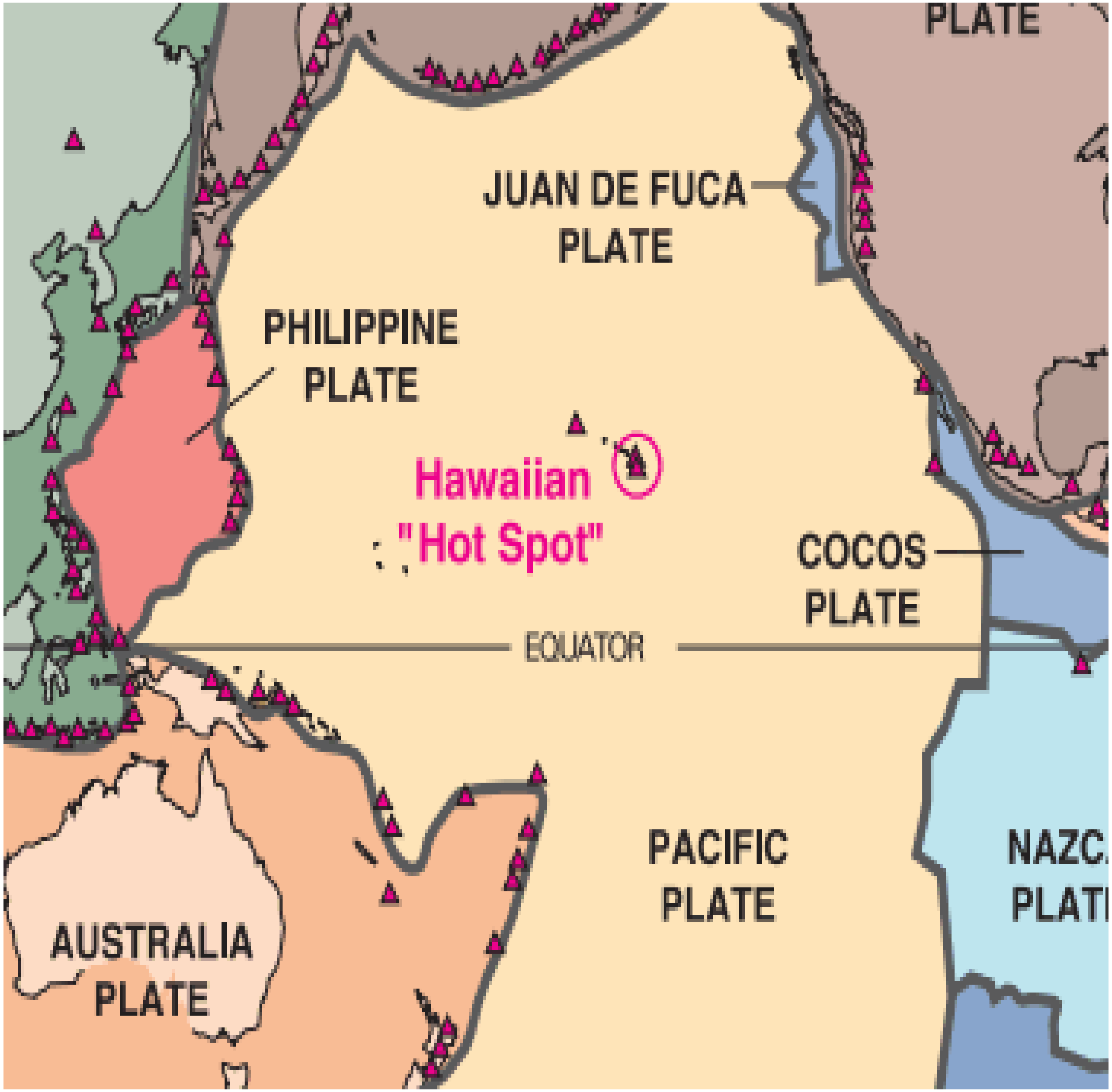
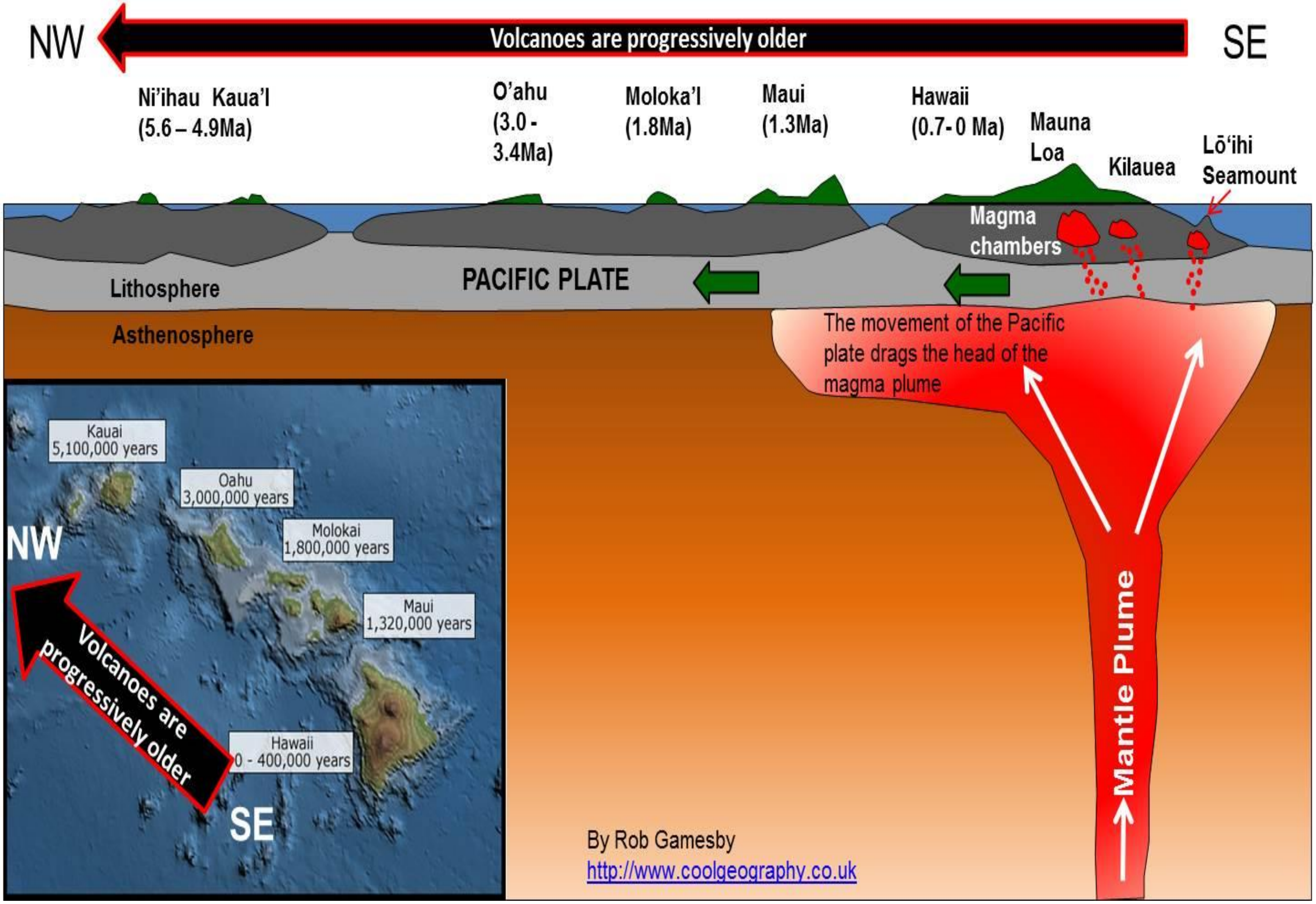


PLATE
JUAN DE FUCA
PLATE
PHILIPPINE
PLATE
Hawaiian
"Hot Spot"
COCOS
PLATE
EQUATOR
PACIFIC
PLATE
NAZC
PLAT
AUSTRALIA
PLATE


NW
Volcanoes are progressively older
SE
Ni'ihau Kaua'I
(5.6 – 4.9Ma)
O'ahu
(3.0 - 3.4Ma)
Moloka'I
(1.8Ma)
Maui
(1.3Ma)
Hawaii
(0.7- 0 Ma)
Mauna Loa
Kilauea
Lō'ihi Seamount
Magma chambers
PACIFIC PLATE
Lithosphere
Asthenosphere
The movement of the Pacific plate drags the head of the magma plume
Mantle Plume
Kauai
5,100,000 years
Oahu
3,000,000 years
Molokai
1,800,000 years
Maui
1,320,000 years
Hawaii
0 - 400,000 years
NW
Volcanoes are progressively older
SE
By Rob Gamesby
http://www.coolgeography.co.uk

Volcanism on Mars

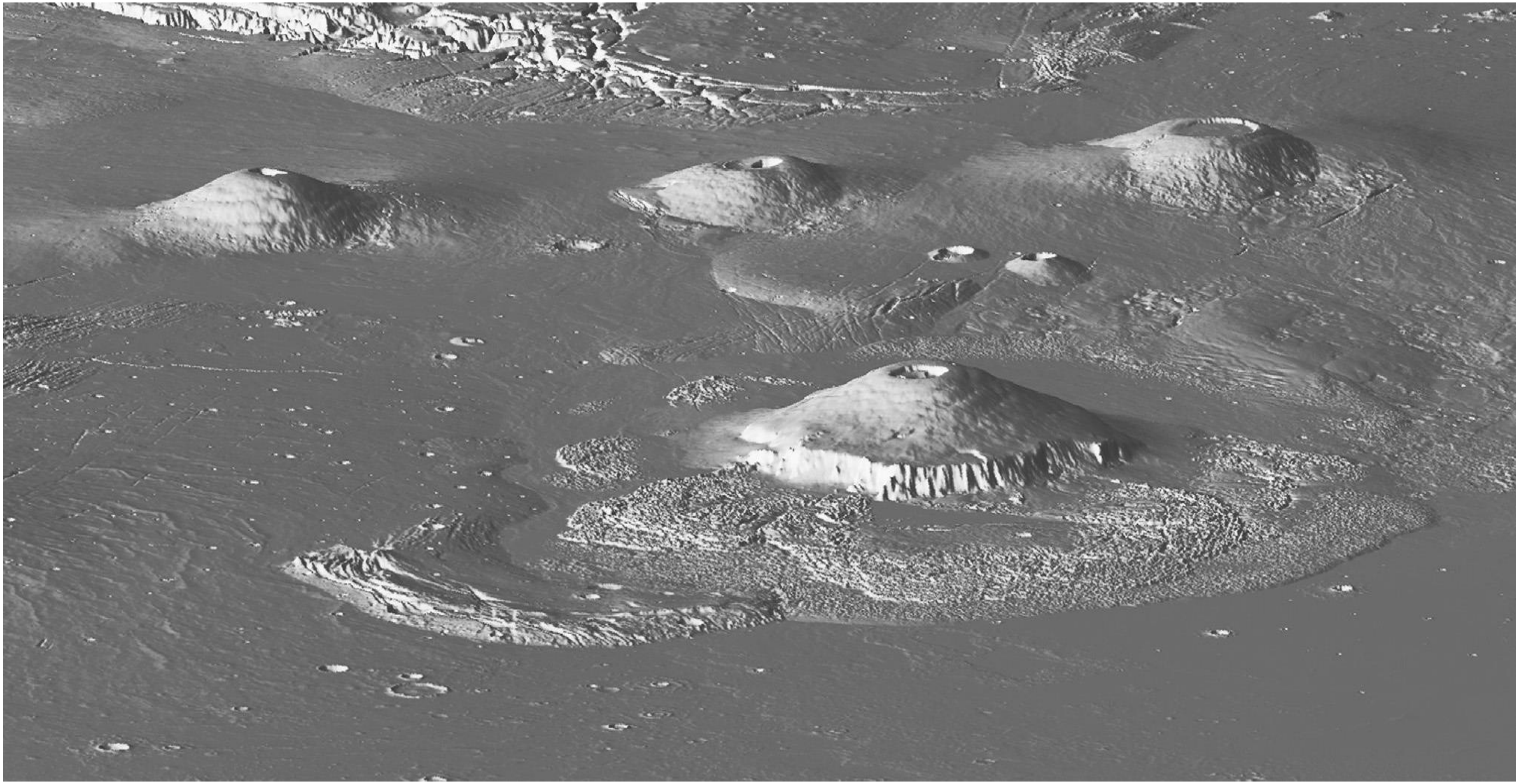
Mars has had a long and varied volcanic history.

Crystallization ages of Martian meteorites as young as 150 million years, and the scarcity of impact craters on some volcanic surfaces, suggest that the planet is still volcanically active, although the rates must be very low compared with the Earth.

The tectonic framework within which Martian volcanism occurs is very different from that in which most volcanism occurs on the Earth. Most terrestrial volcanism takes place at plate boundaries, but these have no Martian equivalents, there being no plate tectonics on Mars.

Perhaps the closest terrestrial analogs to Martian volcanoes are those, such as the Hawaiian volcanoes, that occur within plates rather than on the boundaries.

Most Martian volcanism is basaltic, but basaltic volcanism expresses itself somewhat differently on Mars because of the lower heat flow, gravity, and atmospheric pressure. Eruptions are expected to be larger and less frequent and more likely to produce ash, and ash clouds are more likely to collapse and produce ash-rich surface flows.

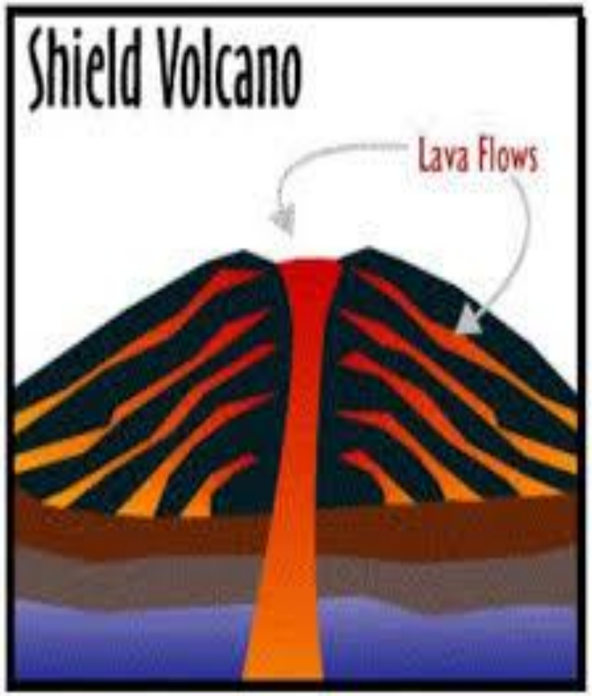


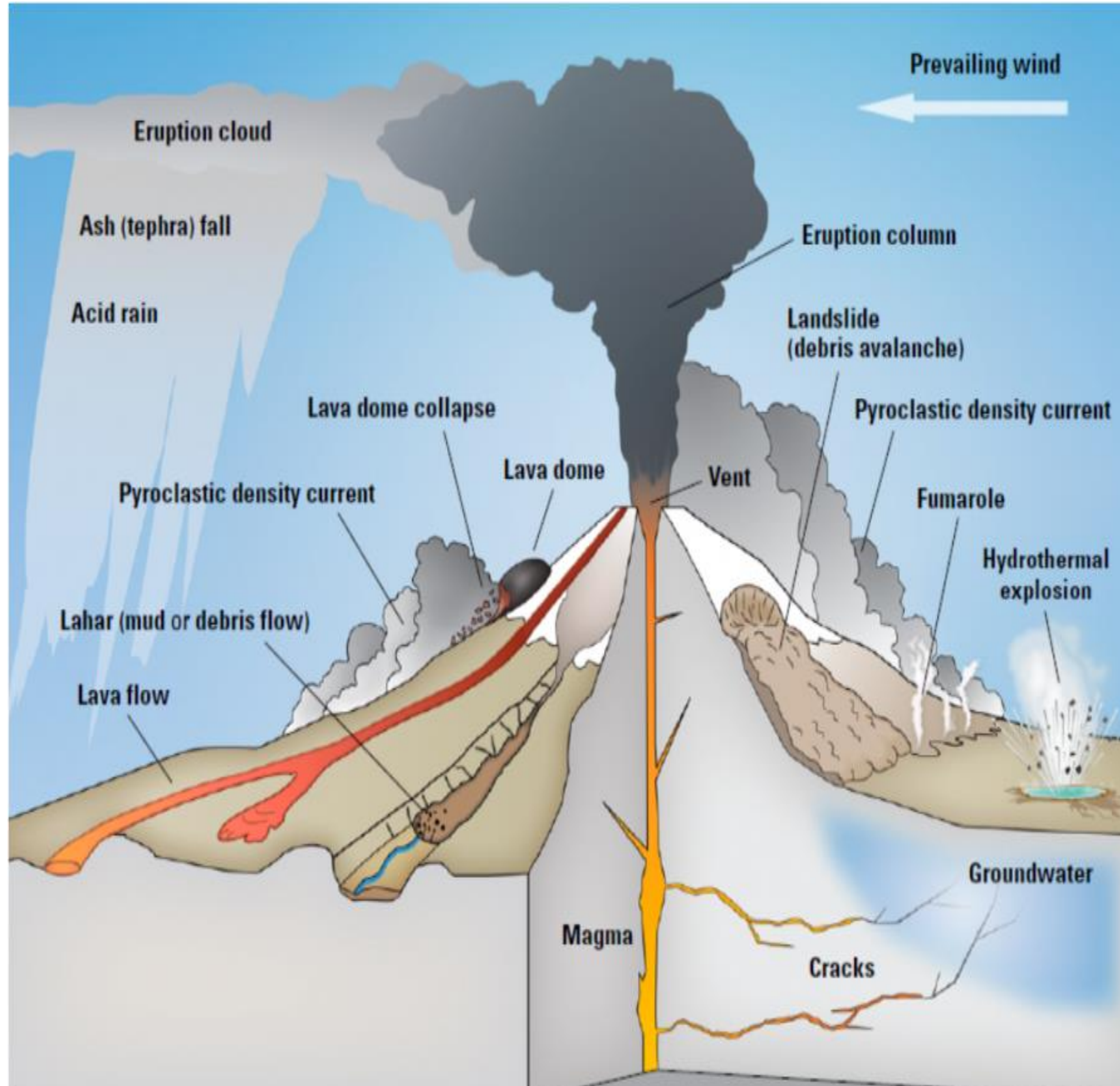
View looking southeast across Tharsis. Olympus Mons, in the foreground, is 550 km across; 21.2 km high; and surrounded by a cliff 8 km high. Lobes of the aureole can be seen extending from the base of the cliff; 10 vertical exaggeration (MOLA).

- **The large shield volcanoes of Tharsis and Elysium present the most spectacular evidence of volcanism**
- **Shield volcanoes, such as those in Hawaii, are broad domes with shallow sloping flanks that form mainly by eruption of fluid basaltic lava.**
- **Each has a summit depression formed by collapse following eruptions on the volcano flanks or at the summit.**
- **In contrast, stratovolcanoes such as Mt Fujiyama, tend to be much smaller and have steeper flanks and a summit depression that is a true volcanic vent.**
- **Explosive, ash-rich eruptions tend to be more common in the building of a stratovolcano and the lava tends to be more volatile rich, more siliceous, and more viscous than that which forms shields.**


North Korea
Sea of Japan
Sendai
仙台
Seoul
서울
South Korea
Japan
Nagoya
名古屋
Osaka
大阪
Tokyo
東京
Hiroshima
広島
Fukuoka
福岡

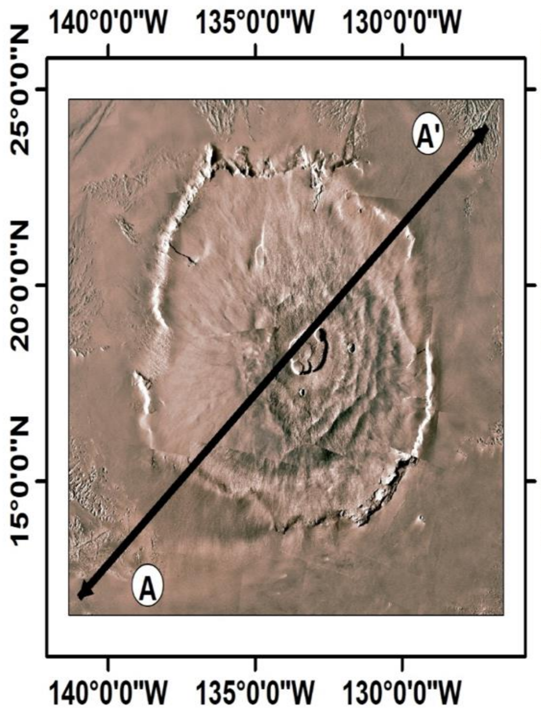
Mt Fujiyama

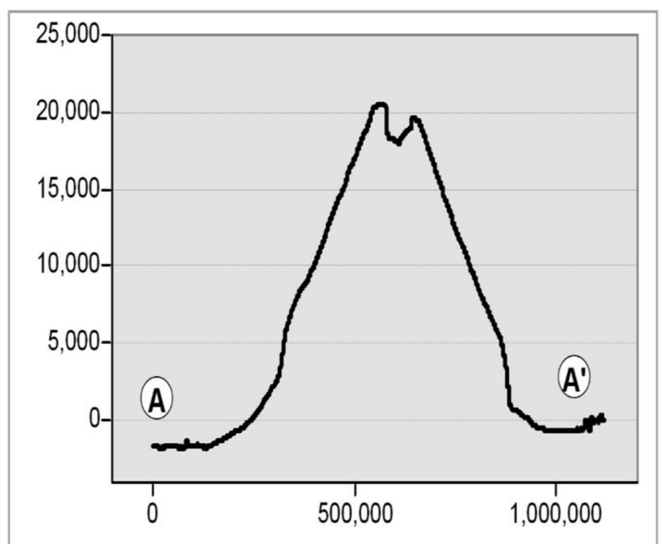

Shield Volcano
Lava Flows


Prevailing wind
Eruption cloud
Ash (tephra) fall
Acid rain
Eruption column
Landslide
(debris avalanche)
Lava dome collapse
Pyroclastic density current
Lava dome
Vent
Pyroclastic density current
Fumarole
Hydrothermal
explosion
Lahar (mud or debris flow)
Lava flow
Groundwater
Magma
Cracks

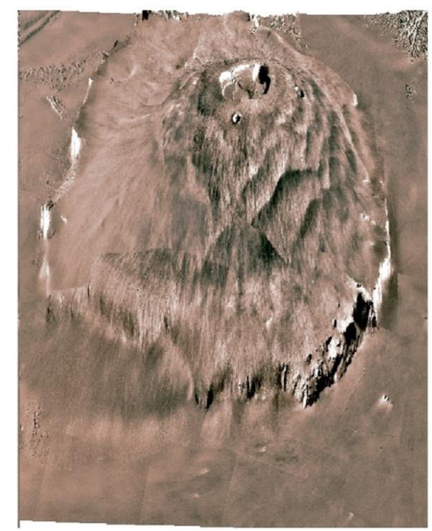
In Tharsis, three large shield volcanoes form a northeast - southwest trending line and 1500 km to the northwest of the line stands the largest shield of all, Olympus Mons, 550 km across and reaching a height of 21 km above the Mars datum.

The three aligned Tharsis Montes shields are only slightly smaller. Olympus Mons has a summit caldera 80 km across and the flanks have a fine striated pattern caused by long linear flows, some with central channels.
The main edifice is surrounded by a cliff, in places 8 km high.





Elevation profile



3D Visualization

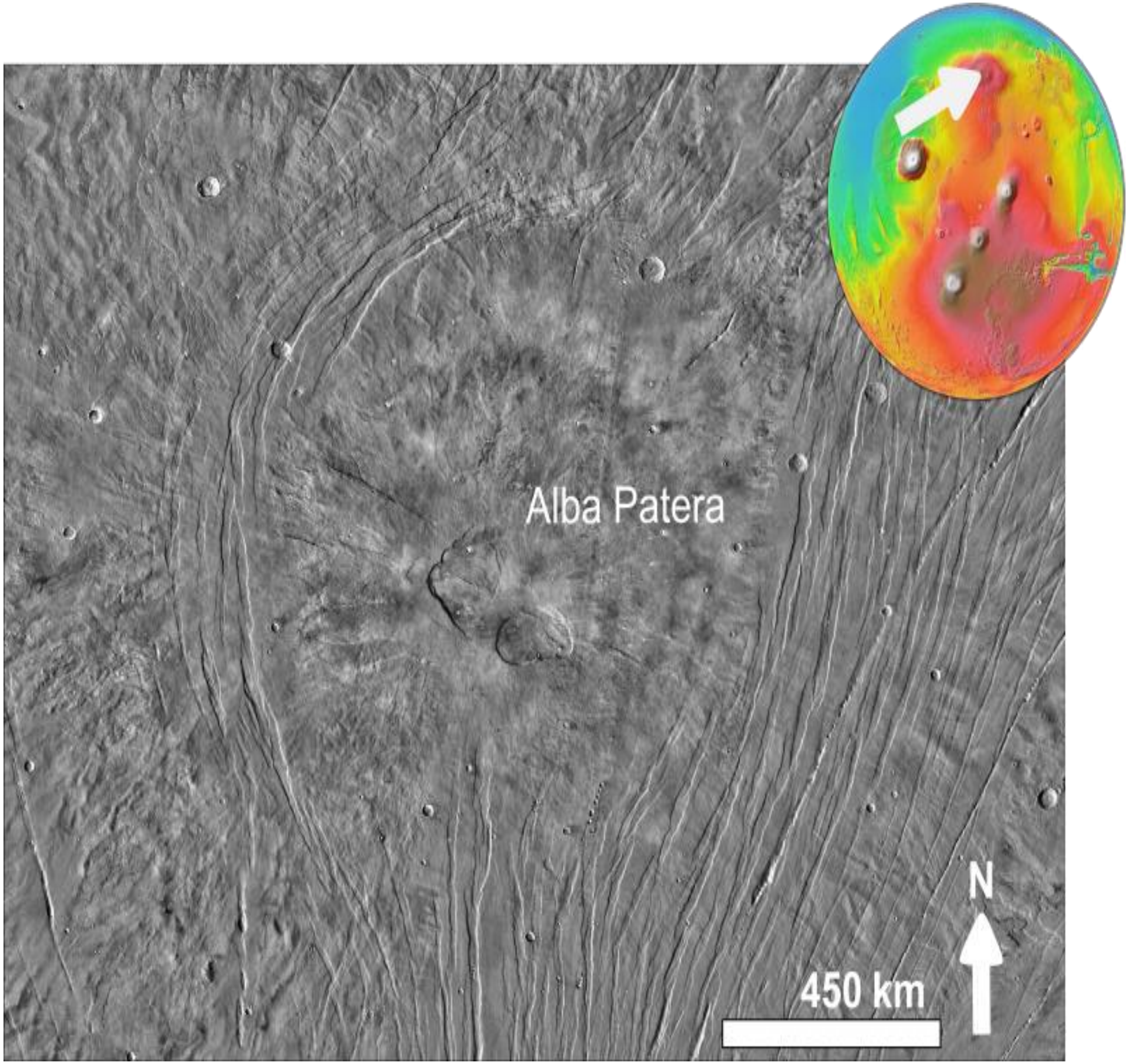
- Outside the main edifice is the aureole that consists of several huge lobes with a distinctively ridged texture.

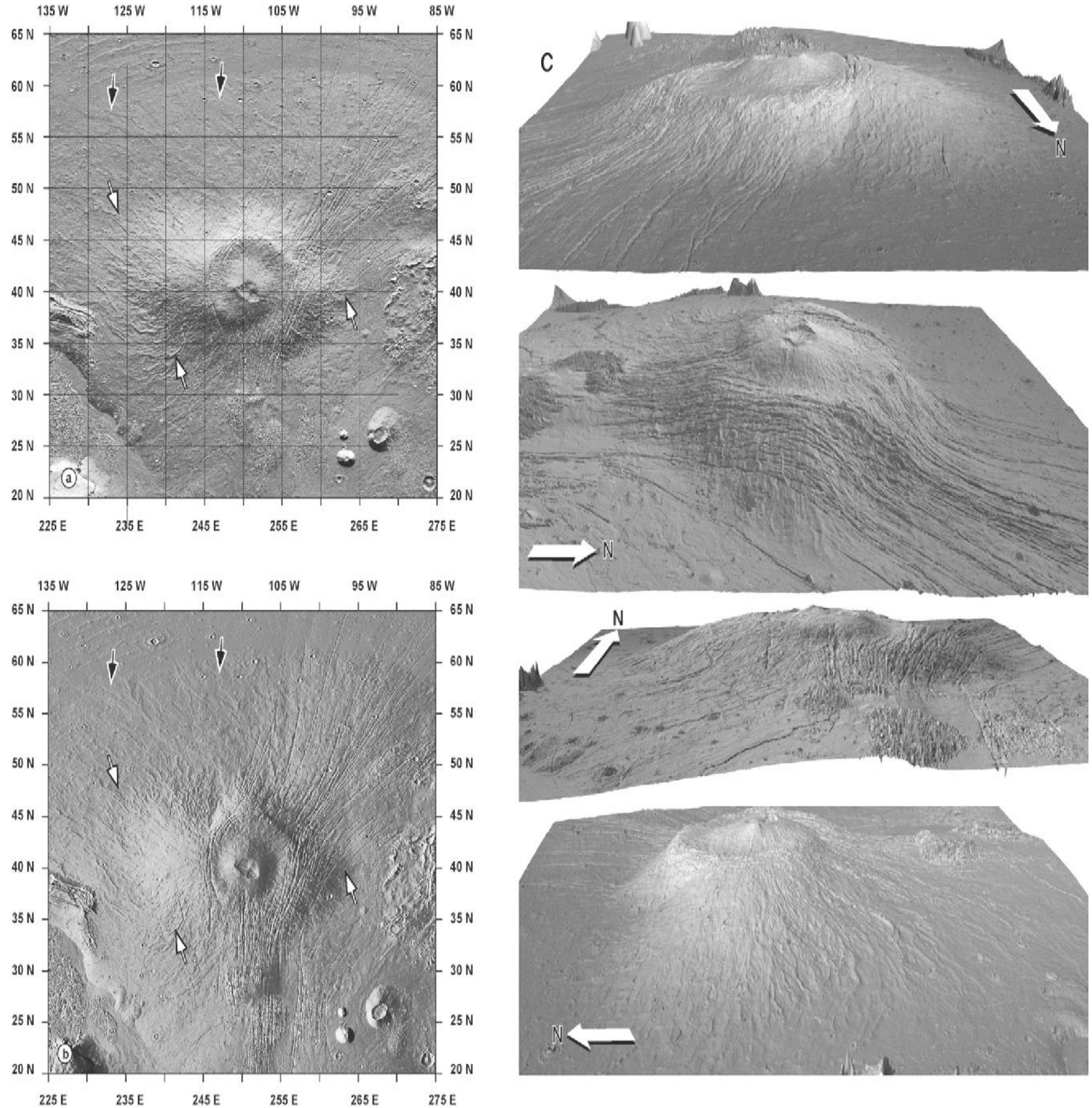
- The lobes are thought to have formed as a result of successive collapses of the periphery of a previously much larger Olympus Mons.

- The collapses, which could have been catastrophic or gradual, left a cliff around the main edifice. The largest lobe has roughly the same area as France.

- The edifice is thought to have been built slowly over billions of years by large eruptions, widely spaced in


Netherlands
London
Brussels
Cologne
Germ
Belgium
Frankfurt
Luxembourg
Paris
France
Switzerland
Milan
Bay of Biscay
Monaco
Andorra
Barcelona
to
Madrid


Alba Patera
N
450 km


135 W
125 W
115 W
105 W
95 W
85 W
65 N
60 N
55 N
50 N
45 N
40 N
35 N
30 N
25 N
20 N
225 E
235 E
245 E
255 E
265 E
275 E
a
b
C
N

Alba Patera, at the north end of Tharsis is 2000 - 3000 km across, almost the size of the United States. The large size of the Martian shields results partly from the lack of plate tectonics.

The largest shield volcanoes on the Earth, those in Hawaii, are relatively short lived. They sit on the Pacific plate, and the source of the lava is below the rigid plate. As a Hawaiian volcano grows, movement of the Pacific plate carries it away from the lava source, so it becomes extinct within a few 100,000 years.

A trail of extinct volcanoes across the Pacific attests to the long-term supply of magma from the mantle source presently below Hawaii. On Mars, a volcano remains stationary and will continue to grow as long as magma continues to be supplied, so the volcanoes are correspondingly larger.

- **The Elysium province is much smaller than Tharsis, having only three sizeable volcanoes.**

- **One unique attribute of the Elysium province is the array of large channels that start in graben around the volcanoes and extend thousands of kilometers to the northwest.**

- **They may have been formed by dikes injected into ice-rich frozen ground. Other volcanoes occur near Hellas and in the cratered uplands. Not all the volcanoes are formed by fluid lava.**

- **Some appear to be surrounded by extensive ash deposits and some have densely dissected flanks as though they were composed of easily erodible materials such as ash.**

Lava plains may constitute the bulk of the planet's volcanic products. There are several kinds of volcanic plains. On some plains, found mostly between the volcanoes in Tharsis and Elysium, volcanic flows are clearly visible.

On others, mostly found around the periphery of Tharsis and in isolated patches in the cratered uplands, ridges are common but flows are rare.

Others with numerous low cones may have formed when lava flowed over water-rich sediments.

- **Finally, some young, level plains, such as those in Cerberus, estimated to be only a few million years old, appear to consist of thin plates that have been pulled apart, for they can be reconstructed like a jigsaw puzzle. The plates may indicate rafting of pieces of crust on a lava lake.**

- **Geomorphic evidence of volcanic activity that occurred prior to the end of the late heavy bombardment has been largely destroyed by the effects of impacts.**

Cratering Rates and the Martian Timescale

- Craters provide a means of estimating the ages of surfaces. The solar system's most densely cratered surfaces formed more than 3.7 billion years ago, and the cratering rate has been roughly constant since that time.
- Consequently, a 3 billion-year-old surface will have roughly three times more craters on it than a 1 billion-year-old surface.
- **Older surface:** More craters Vs. **Younger surface:** less craters
- Craters have thus been used to divide the history of Mars into different epochs.
- The **Noachian** refers to the period of heavy bombardment that ended around **3.7** billion years ago.

- The rest of the planet's history is divided into **the Hesperian**, roughly **3.7 to 3.0** billion years ago, and the **Amazonian**, roughly **3.0 billion years ago to the present**.

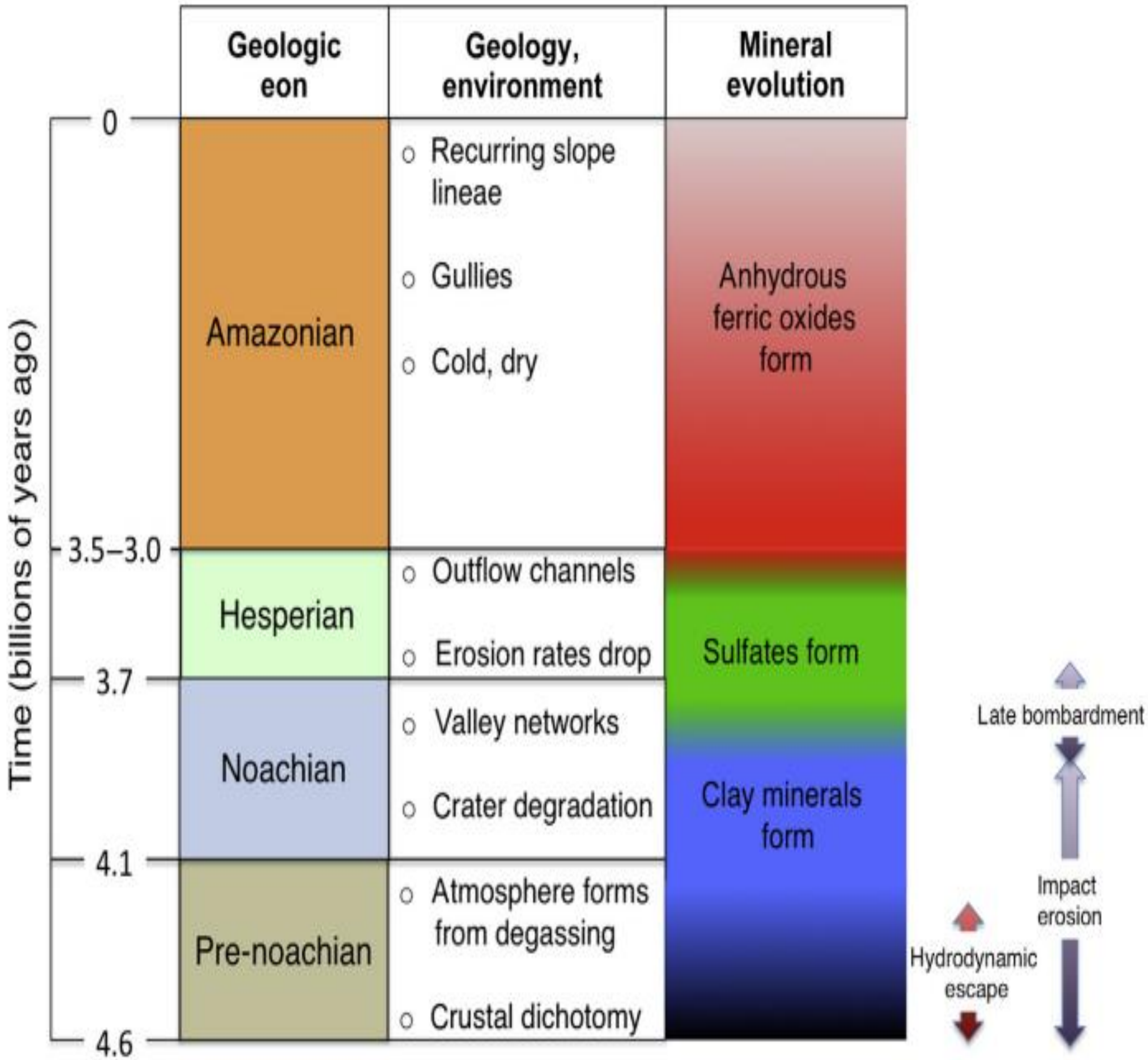
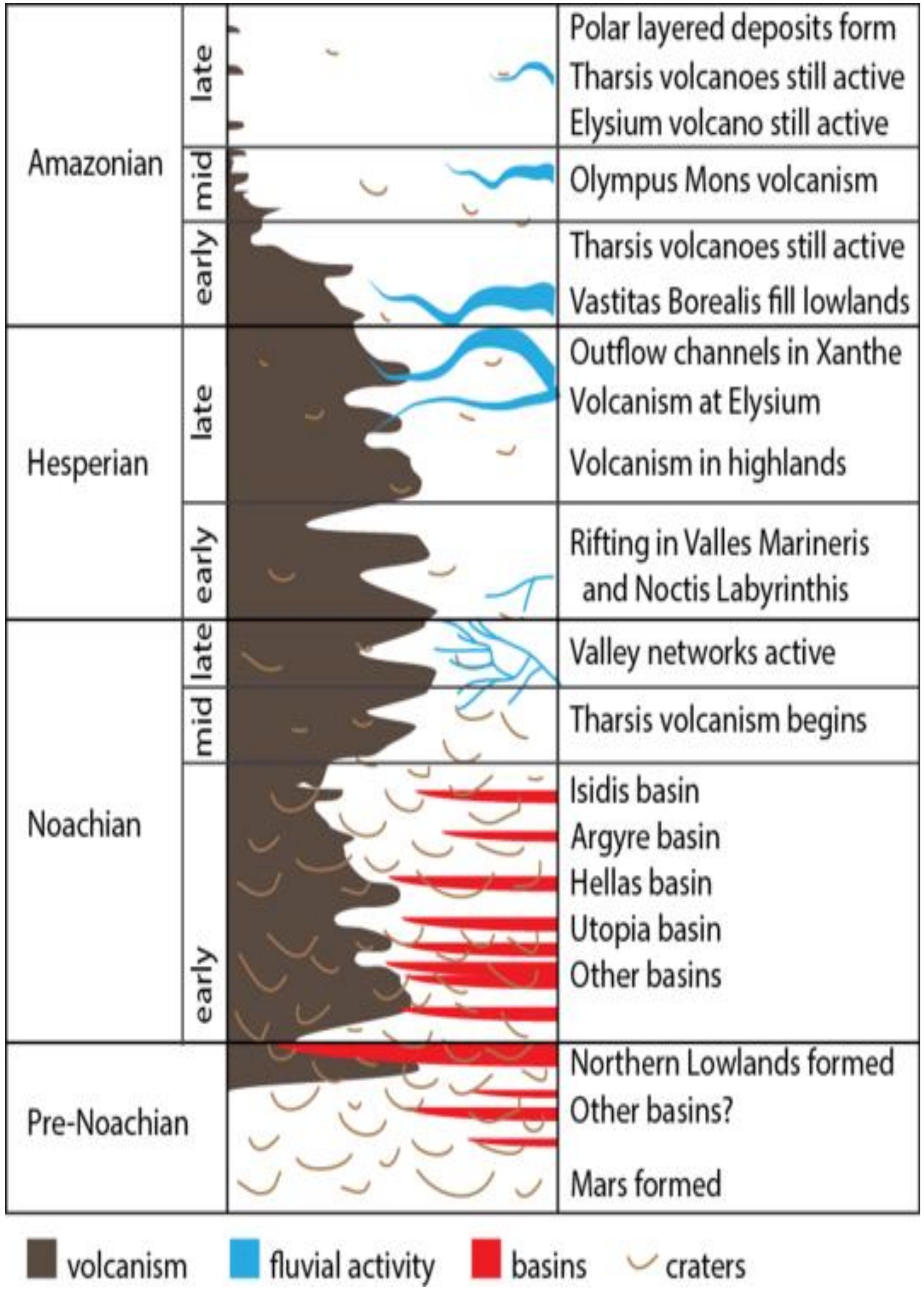
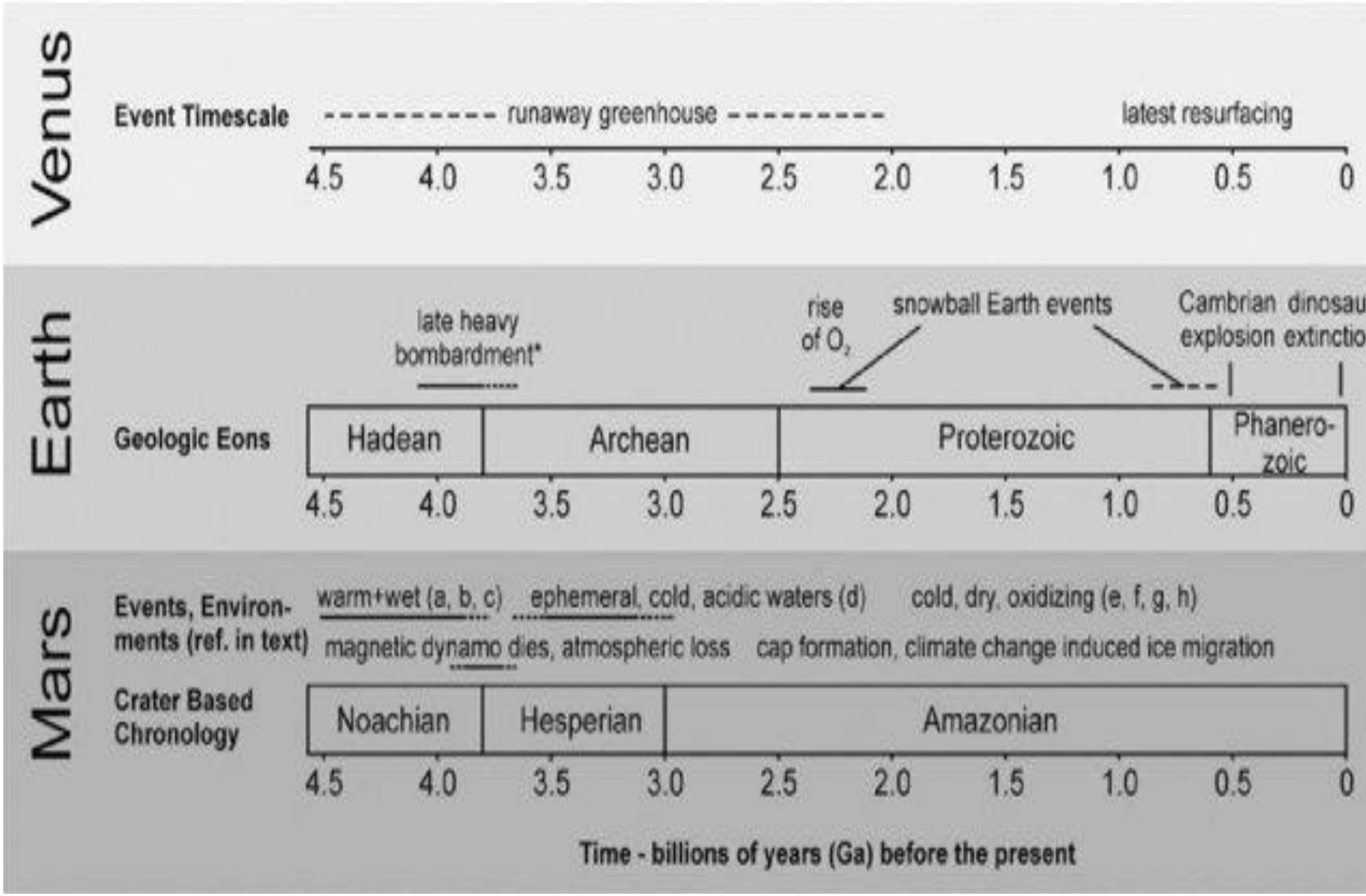


FIGURE 16.10 An overview of the Martian geologic timescale and its relationship to geologic features, predominant minerals, and events affecting the atmosphere.



Amazonian
late
mid
early
Hesperian
late
early
Noachian
late
mid
early
Pre-Noachian
Polar layered deposits form
Tharsis volcanoes still active
Elysium volcano still active
Olympus Mons volcanism
Tharsis volcanoes still active
Vastitas Borealis fill lowlands
Outflow channels in Xanthe
Volcanism at Elysium
Volcanism in highlands
Rifting in Valles Marineris
and Noctis Labyrinthis
Valley networks active
Tharsis volcanism begins
Isidis basin
Argyre basin
Hellas basin
Utopia basin
Other basins
Northern Lowlands formed
Other basins?
Mars formed
volcanism
fluvial activity
basins
craters



Venus
Event Timescale
runaway greenhouse
latest resurfacing
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
Earth
late heavy bombardment*
rise of O2
snowball Earth events
Cambrian explosion
dinosaur extinction
Geologic Eons
Hadean
Archean
Proterozoic
Phanero-zoic
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
Mars
Events, Environments (ref. in text)
warm+wet (a, b, c)
ephemeral, cold, acidic waters (d)
cold, dry, oxidizing (e, f, g, h)
magnetic dynamo dies, atmospheric loss
cap formation, climate change induced ice migration
Crater Based Chronology
Noachian
Hesperian
Amazonian
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
Time - billions of years (Ga) before the present

- **The Noachian refers to the period of heavy bombardment that ended around 3.7 billion years ago.**
- **The Noachian period is characterized by high cratering rates,**
- **formation of valley networks, and**
- **The presence of hydrated minerals such as phyllosilicates.**

Phyllosilicates (Sheet Silicates)

Any silicate mineral having the tetrahedral silicate groups linked in sheets, each group containing four oxygen atoms, three of which are shared with other groups so that the ratio of silicon atoms to oxygen atoms is two to five.

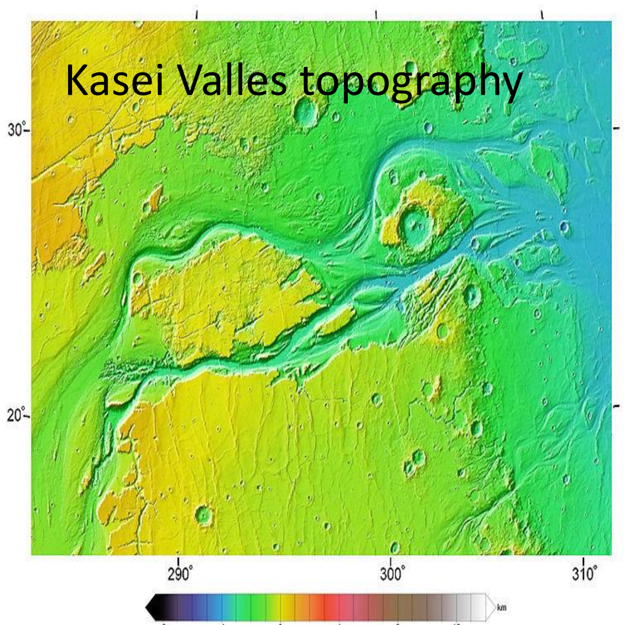
The phyllosilicates, or sheet silicates, are an important group of minerals that includes the micas, chlorite, serpentine, talc, and the clay minerals. Because of the special importance of the clay minerals as one of the primary products of chemical weathering and one of the more abundant constituents of sedimentary rocks

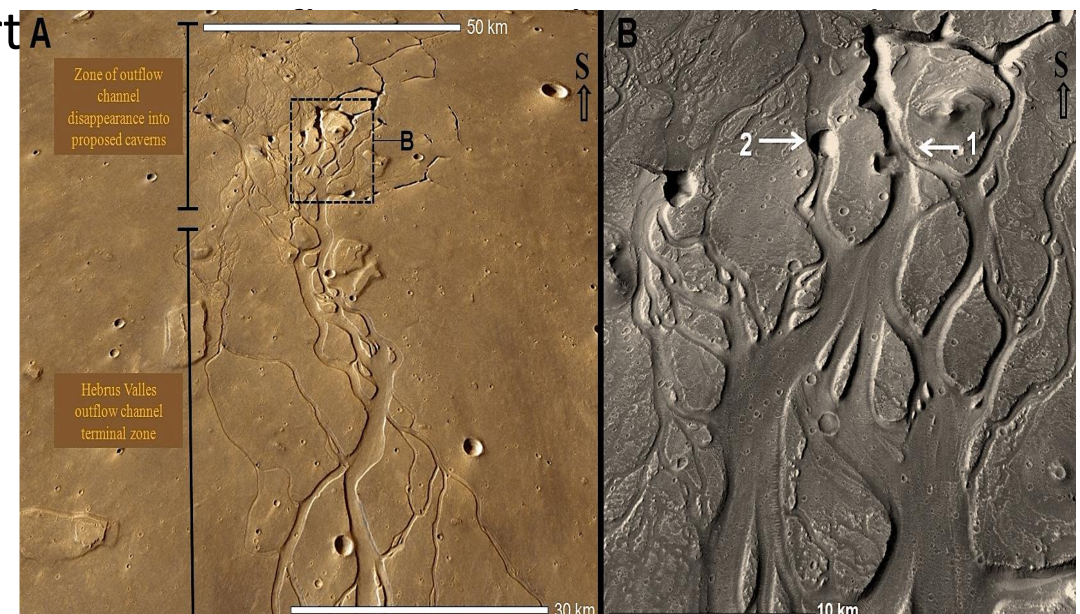
- The rest of the planet's history is divided into the **Hesperian**, roughly 3.7 to 3.0 billion years ago

- The Hesperian period is characterized by large outflow channel floods and extensive lava plains and the presence of abundant **sulfate deposits**.

- and the **Amazonian**, roughly 3.0 billion years ago to the present

- During the Amazonian, most of the processes that occurred earlier continued, but at much lower rates, enabling less-energetic processes ... exert





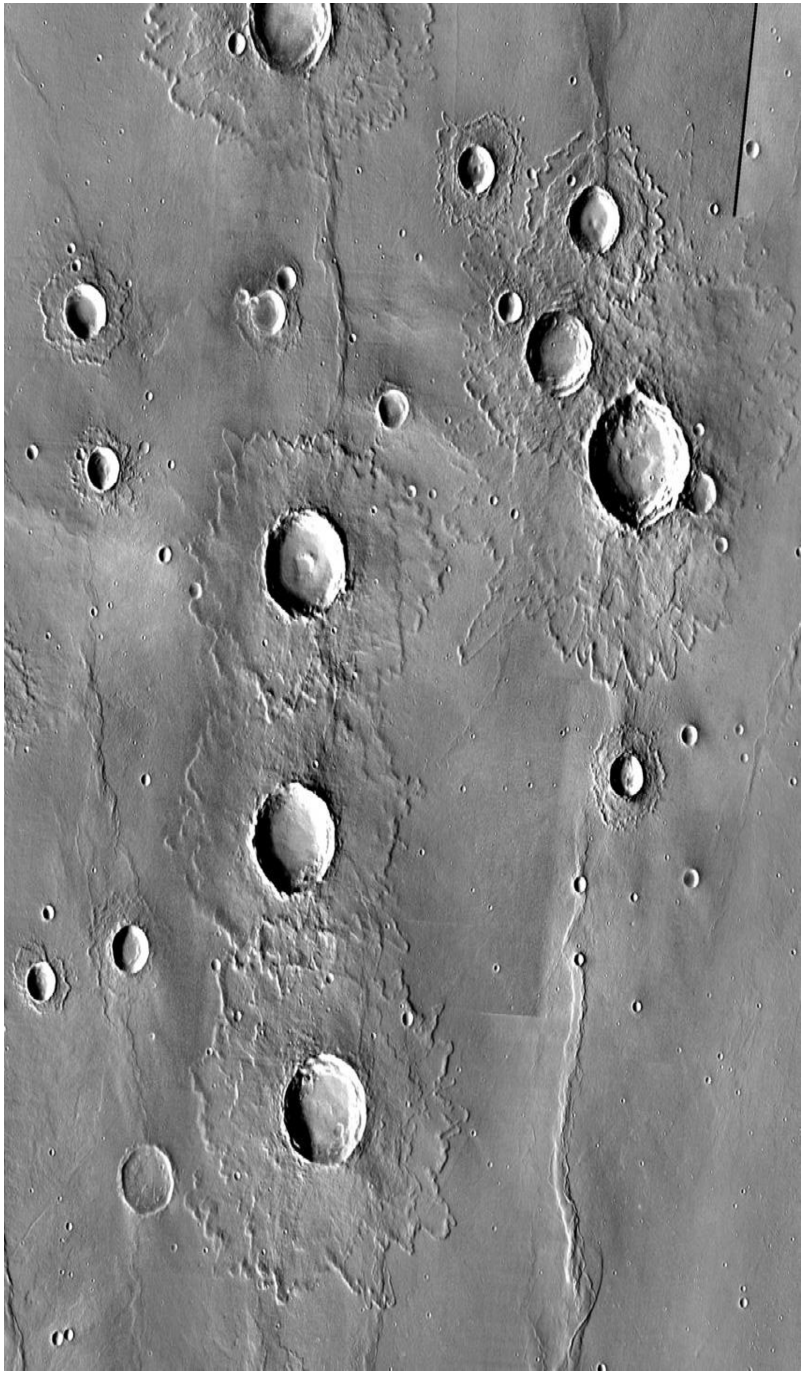
Crater Morphology

Impact craters have similar morphologies on different planets. Small craters are simply bowl-shaped depressions with constant depth-to-diameter ratios.

With increasing size, the craters become more **complex** as central peaks appear, terraces form on the walls, and the depth-to diameter ratio decreases. At very large diameters, the craters become multiringed, and it is not clear which ring is the equivalent of the crater rim of smaller craters.

On Mars, the **transition from simple to complex** takes place at **6 to 7 km**, and the transition from complex craters to multiringed basins takes place at **130 to 150 km** diameter.

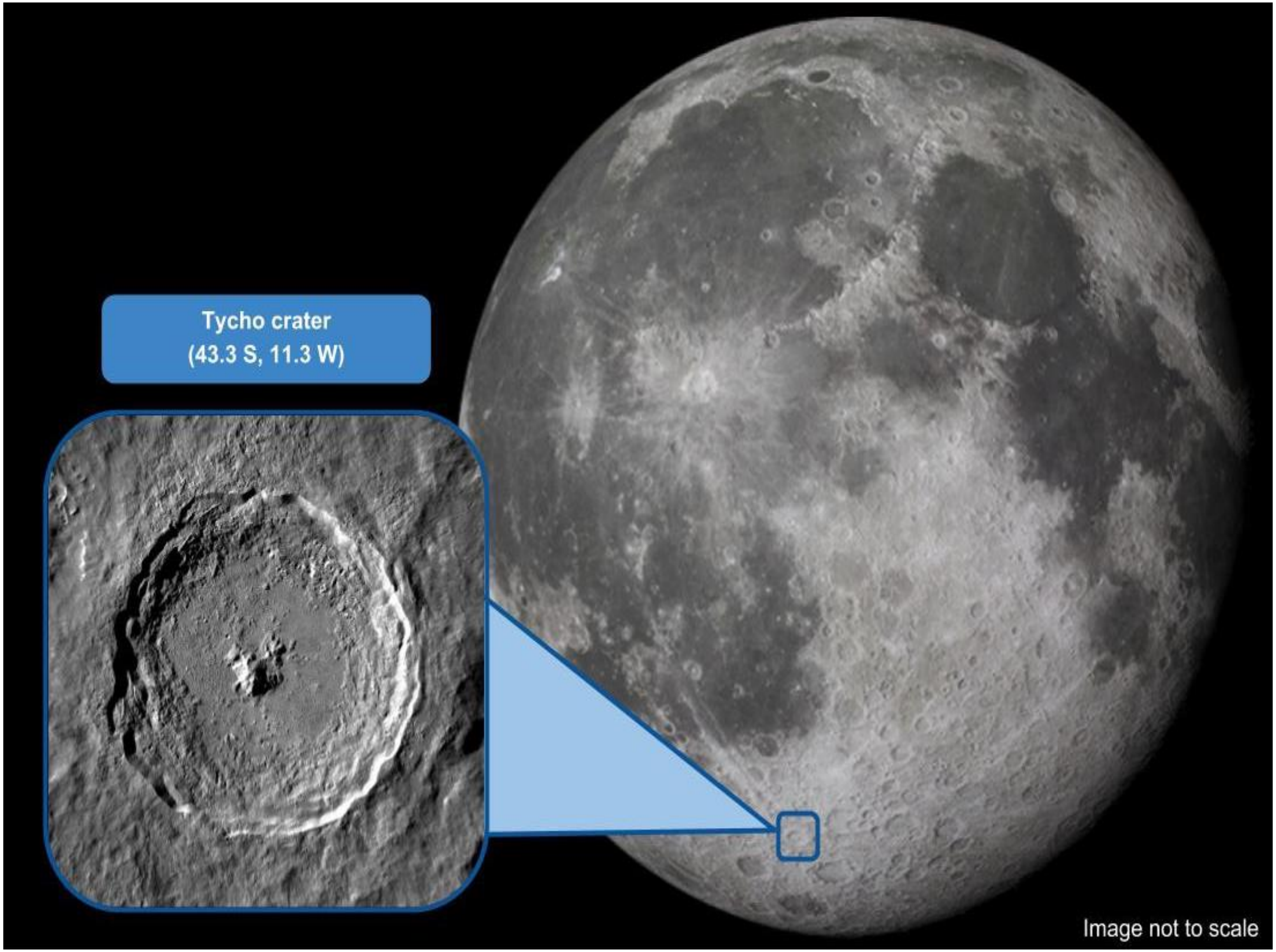
Martian craters, especially those in the 5 to 100 km size range, occur in discrete, clearly outlined lobes

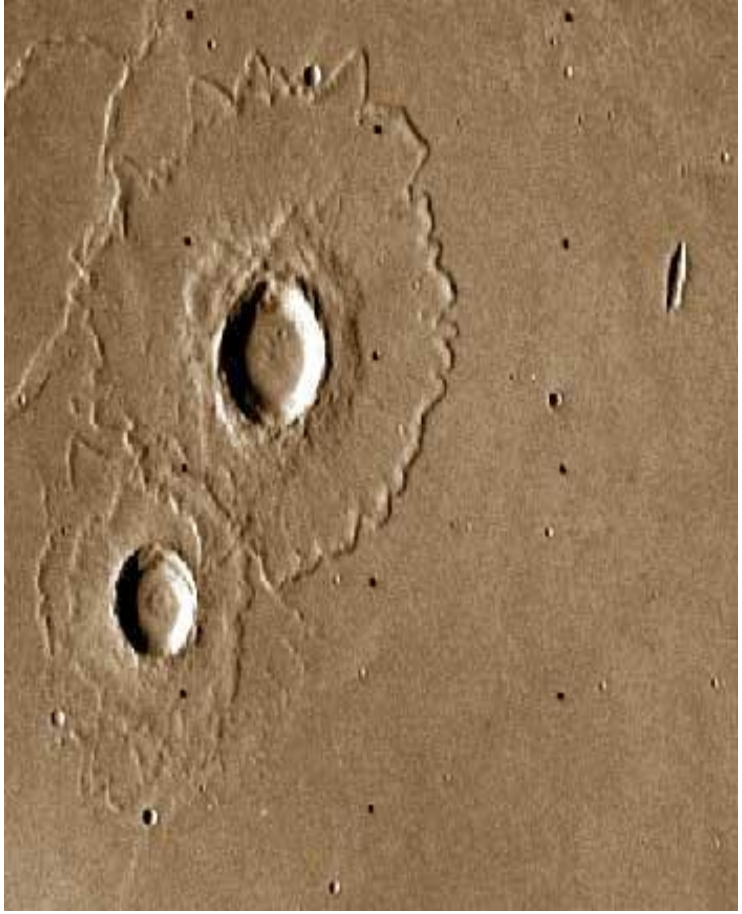


Impact craters in Lunae Planum.

The ejecta are distributed around the craters in lobes, each surrounded by a low ridge or rampart.

The largest crater is 35 km across (Thermal Emission Imaging System (THEMIS)).


Tycho crater
(43.3 S, 11.3 W)
Image not to scale



The complex lobate and radial patterns of the inner ejecta deposits are strikingly displayed. A relatively thick platform of ejecta surrounds the rim. A steep outward facing scarp is variably developed around the innermost ejecta (NASA).

The mudlike ejecta crater of Yuty is typical of the nature of the ejecta of many martian impact craters. The ejecta consists of a series of overlapping lobes. The smooth, rounded fronts of the lobes and their diversion around the small crater rim suggest that the debris moved close to the ground as a surge of mud. The ejecta deposits have nonetheless overtopped the eroded remnants of an older crater's ejecta (on the right side of the photo). The ejecta was fluidized at the time of impact, probably by the melting of near surface ground ice. Yuty lies in the flooded portion of Chryse Basin (NASA).

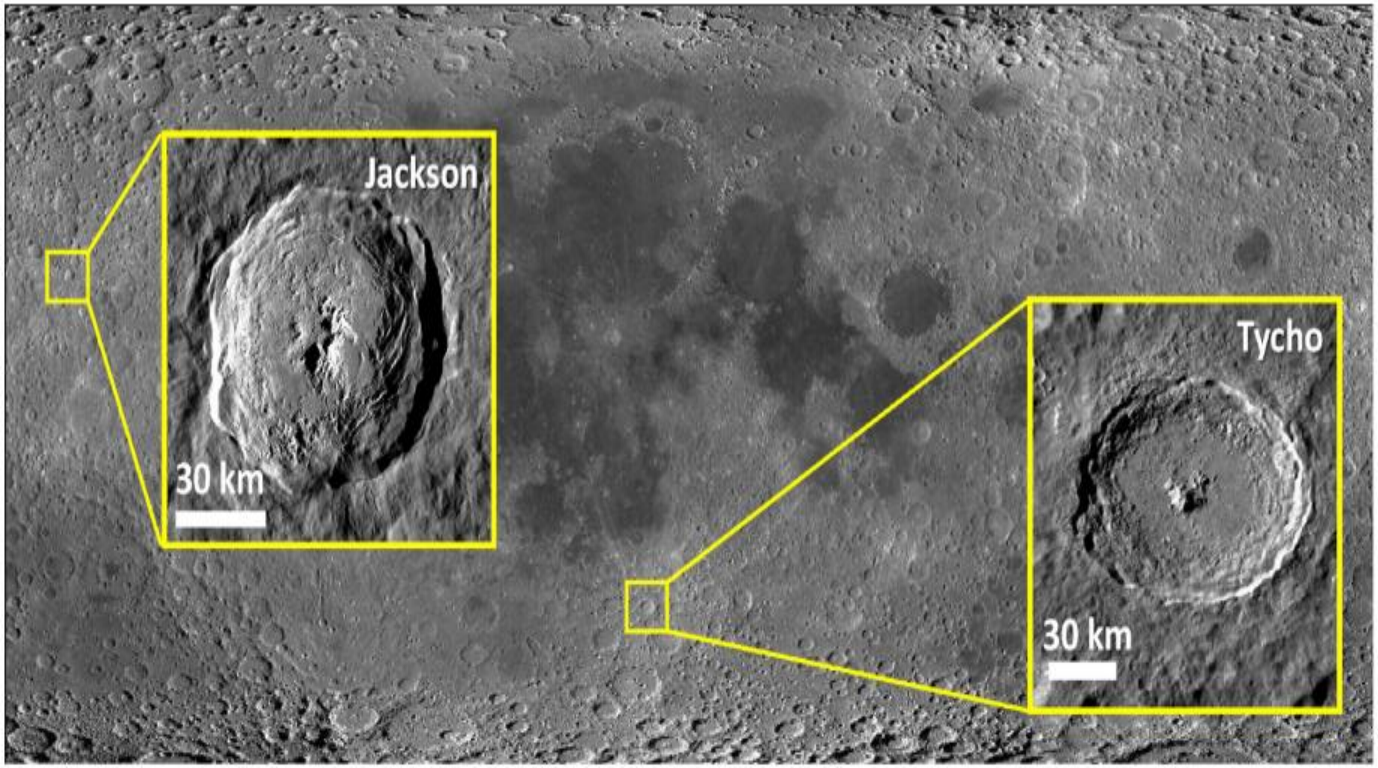


Fig. 1. LRO wide angle camera (WAC) mosaic (centered on the lunar nearside) showing the geologic setting of highland craters Jackson (22.4°N 163.1°W; 71 km) and Tycho (43.29°S 11.22°W, 85 km) on the lunar surface. Their numerous similarities (size, age, target lithology) make them interesting candidates for comparison of impact melt deposits. (Image credit: NASA/GSFC/ASU; Equirectangular projection).

Various patterns are observed. The ejecta around craters smaller than 15 km in diameter are enclosed in a single, continuous lobate ridge or rampart, situated about one crater diameter from the rim.

Around larger craters, there may be many lobes, some superimposed on others, but all surrounded by a rampart.

The distinctive Martian ejecta patterns have been attributed to two possible causes.

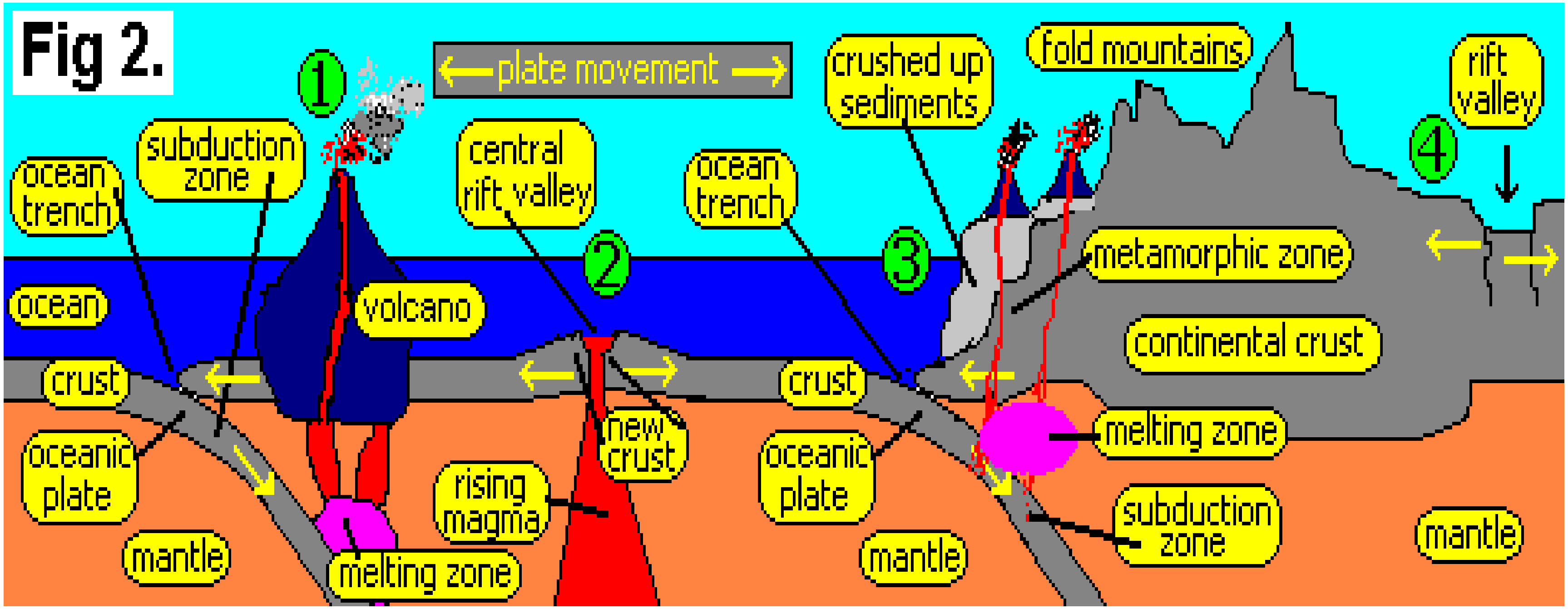
The **first suggestion**, based on experimental craters formed under **low atmospheric pressures**, is that the patterns are formed by interaction of the ejecta with the atmosphere.
The **second** is that the ejecta contained **water and had a mudlike consistency** and so continued to flow along the ground after **ejection from the crater and ballistic deposition**.

This view is supported by the resemblance of Martian craters to those produced by **impacts into mud.**

TECTONICS

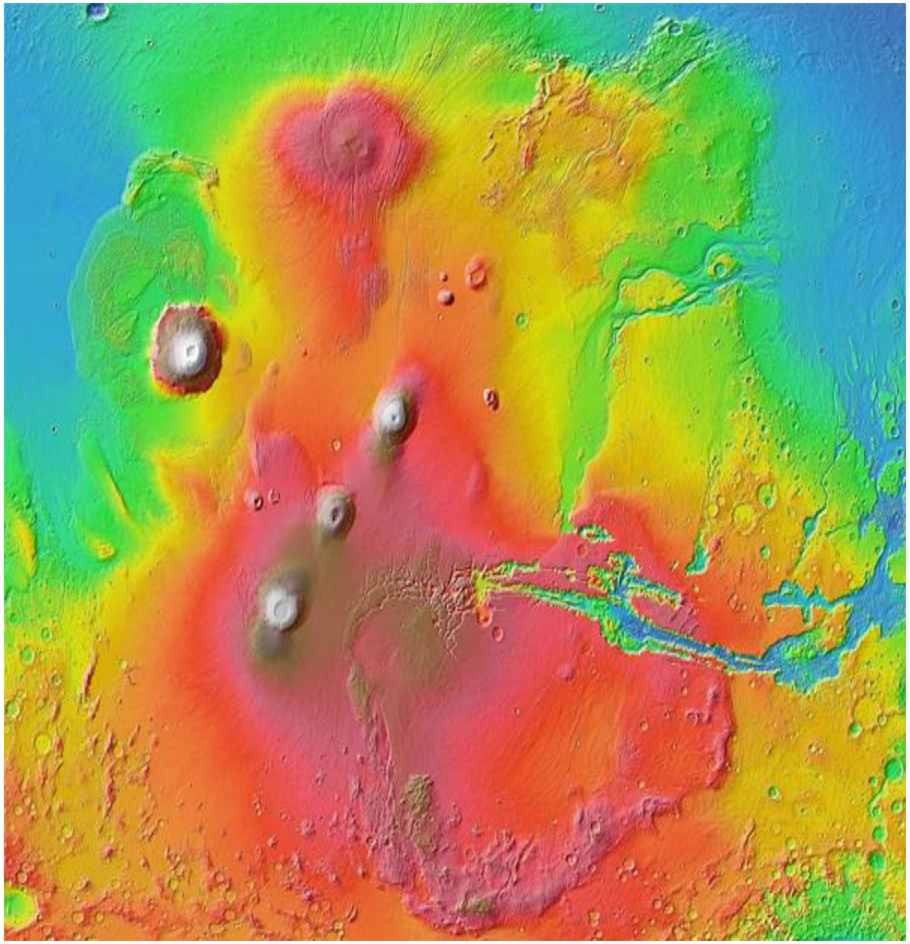
In Earth

Linear mountain chains, transcurrent fault zones, rift systems, and oceanic trenches all result directly from plate tectonics.



- There are no plate tectonics on Mars, so most of the deformational features familiar to us here on the Earth are absent.

- The tectonics of Mars are instead dominated by the Tharsis bulge. The enormous pile of volcanics that constitute the Tharsis bulge has stressed the lithosphere and caused it to flex under the load.



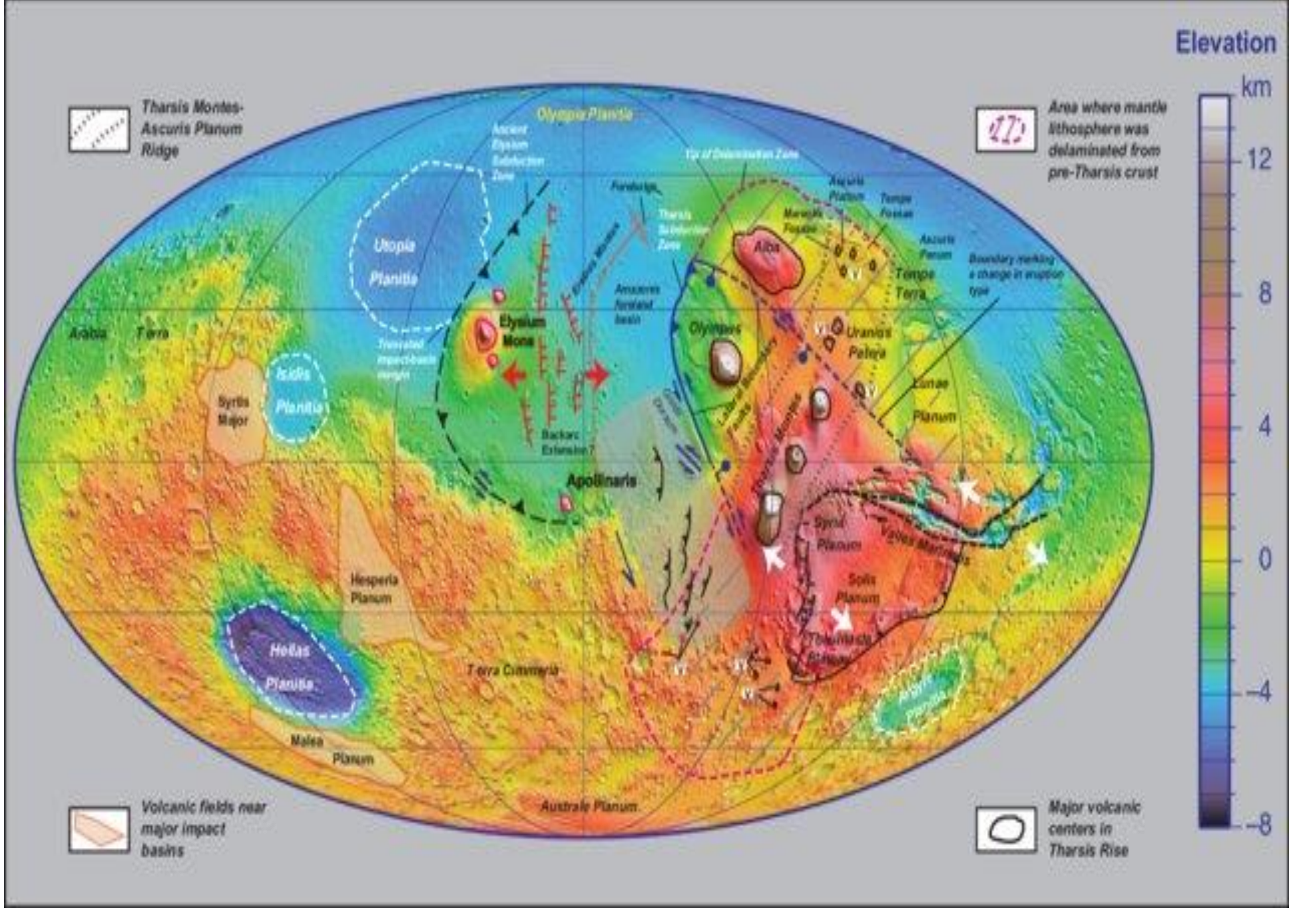
Bulge tensional stresses should be circumferential and compressional stresses should be radial.

- Development of some of the fractures may have been accompanied by emplacement of dikes. The fractures clearly started to form very early in the planet’s history, since many of the young lava plains are only sparsely fractured, whereas the underlying plains, visible in windows through the younger plains, may be heavily fractured.

- **Arcuate faults** around **Isidis and Hellas** clearly result from the presence of the large basins.

- Circular fractures around large volcanoes, such as Elysium Mons and Ascreus Mons, have formed as a result of bending of the lithosphere under the volcano’s load.

- *In particular, folded rocks, although present, are rare.*



Tectonic map of Mars with emphasis on local subduction zones. Two subduction systems are proposed: (1) the inactive Elysium system and (2) the possibly active Tharsis system. The Elysium system accommodates subduction of Utopia Planitia, whereas the Tharsis system accommodates subduction of Amazonis Planitia. The region between Elysium province and the Olympus Mons is marked by a series of north-trending linear scarps possibly representing normal faults (Scott and Tanaka, 1986; Dohm et al., 2008; Anderson et al., 2008). These structures may be induced by downward bending of the northern lowlands lithosphere. There is also a group of northeast-trending, curvilinear scarps aligned in an en echelon pattern on the southwest side of the Tharsis rise. These structures are interpreted as parts of a broad left-slip shear zone accommodating northwestward sinking and retreat of a strip of the subducting northern lowland slab

WATER on Mars

- Water-formed features present some of the most puzzling problems of Martian geology. Valley networks likely formed when the climate was significantly warmer than at present, yet how the climate might have changed is unclear.

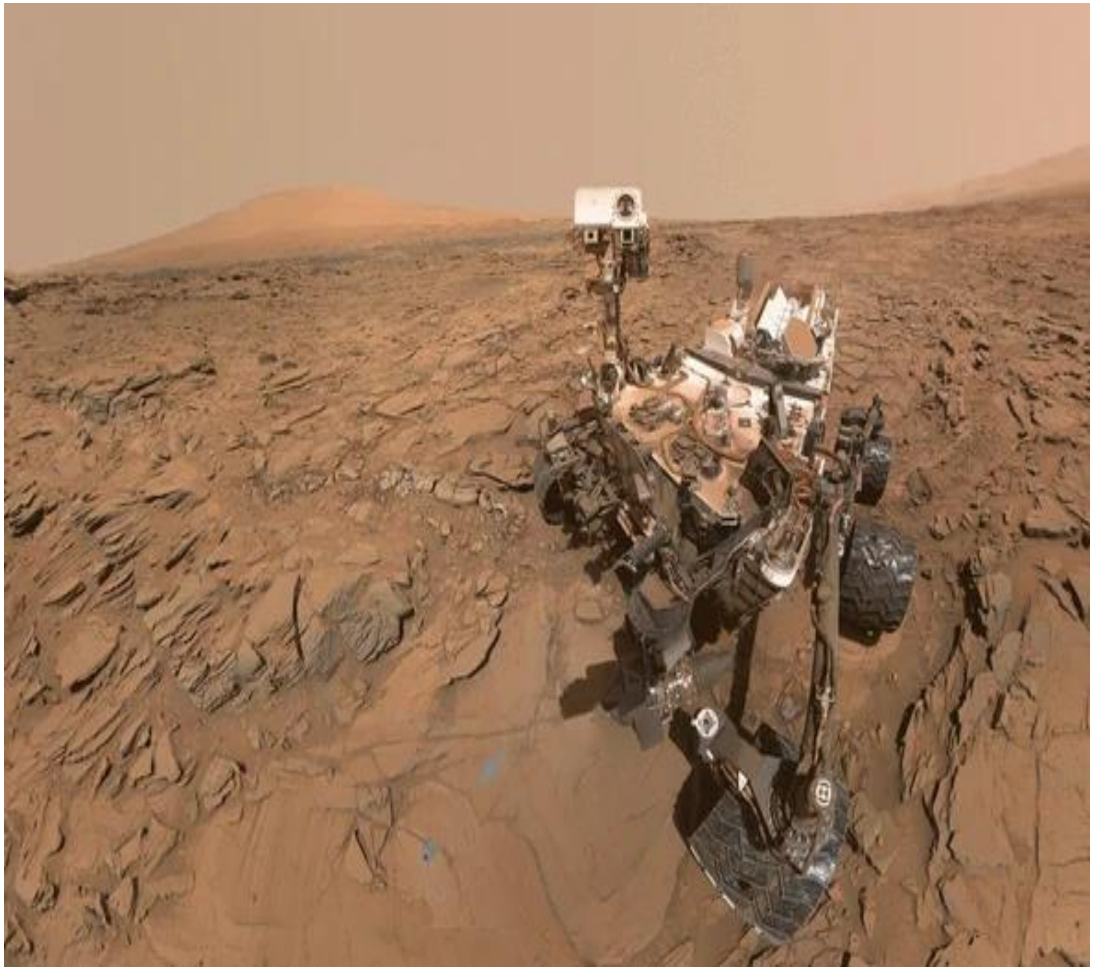
- Huge floods have episodically moved across the surface, yet there is little trace left of the vast amounts of water that must have been involved, and gullies are forming on steep slopes during the present epoch despite the cold conditions.

- Perhaps most puzzling of all is the question of whether there were ever oceans present, and if so how big they were; when did they form; and where did all the water go?

Final conclusion of Mars

- Mars is a geologically heterogeneous planet on which have operated many of the geologic processes (volcanically active, tectonic deformation,) familiar to us here on the Earth.

- Significant mysteries remain. What caused the early warm conditions? What processes were responsible for the early massive amounts of erosion and deposition indicated by the geologic record? Where did all of the water go? How much of the Martian surface and subsurface was (or perhaps still is) habitable, by terrestrial standards? Most important of all, did some form of life ever evolve on the planet, and if so is it extant today?



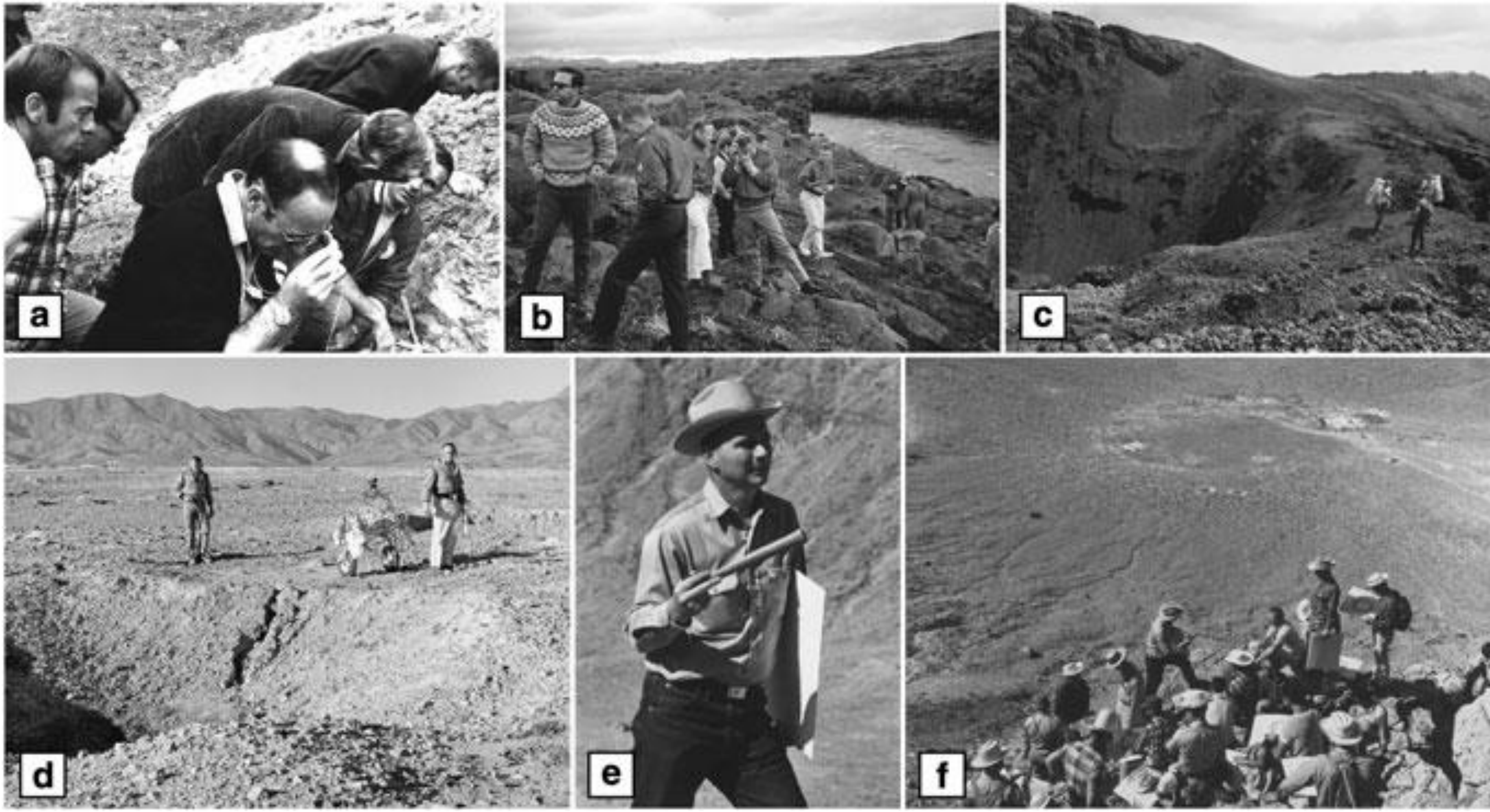
Credit: NASA, JPL-Caltech, MSSS

Next Scientist

Terrestrial Analogs in Planetary Geology

- Classical examples of early terrestrial analogues were impact craters and basaltic volcanic provinces.
- For example, the Apollo astronauts were trained in the Ries impact crater in Germany to prepare for investigations of lunar impact structures and related rocks.
- First–hand experience in the recognition of volcanic rocks and their petrography were obtained by the astronauts in locations such as Iceland, where newly erupted basaltic lava flows and related deposits are abundant.
- Impact craters on other planetary surfaces could be observed early with telescopes and impact craters on the Earth were among the first and most intensely studied analogues.
- most frequently studied impact analogues were the Ries crater in Germany, Meteor Crater in Arizona, U.S., Lonar Crater in India, and the Haughton Crater on Devon Island, Canada

Fig. 2.1 Geological field training for Apollo astronauts was conducted at various terrestrial analogs. (**a**) Quarry at Otting (Nördlinger Ries, Germany); the Ries is an easily accessible, large impact crater that was a convenient analog for lunar craters; *from the left*: A. SHEPARD, F. HÖRZ, E. MITCHELL, W. VON ENGELHARDT, G. CERNAN, and J. ENGLE; (**b**) astronauts on a field excursion on Iceland. Iceland offers easy access to basaltic volcanic landscapes and was considered by some as the most lunar-like place during Apollo crew training; (**c**) the Apollo 15 crew conducts geological training in Apollo Valley on Hawaii's Big Island; (**d**) astronauts A. SHEPARD and E. MITCHELL prepare for Apollo 14 at an artificial crater field in Arizona; (**e**) G. SHOEMAKER, one of the pioneers of planetary geology, was instrumental in Apollo crew field training; (**f**) G. SHOEMAKER (with hammer) lectures to astronauts at Meteor Crater, Arizona, another frequently used terrestrial analog to planetary impact craters (crater floor on top). Source: (**a**) D. Stöffler/NASA. (**b**)–(**c**) NASA. (**d**)–(**f**) USGS



- Analogue studies had their next peak period after it had become clear through the analysis of data returned by the Mariner 9 mission, that Mars was not a dead and dry place like the Moon
- Mariner 9 images showed a plethora of landforms that bear evidence of endogenic and exogenic activity, such as volcanic, fluvial and eolian processes

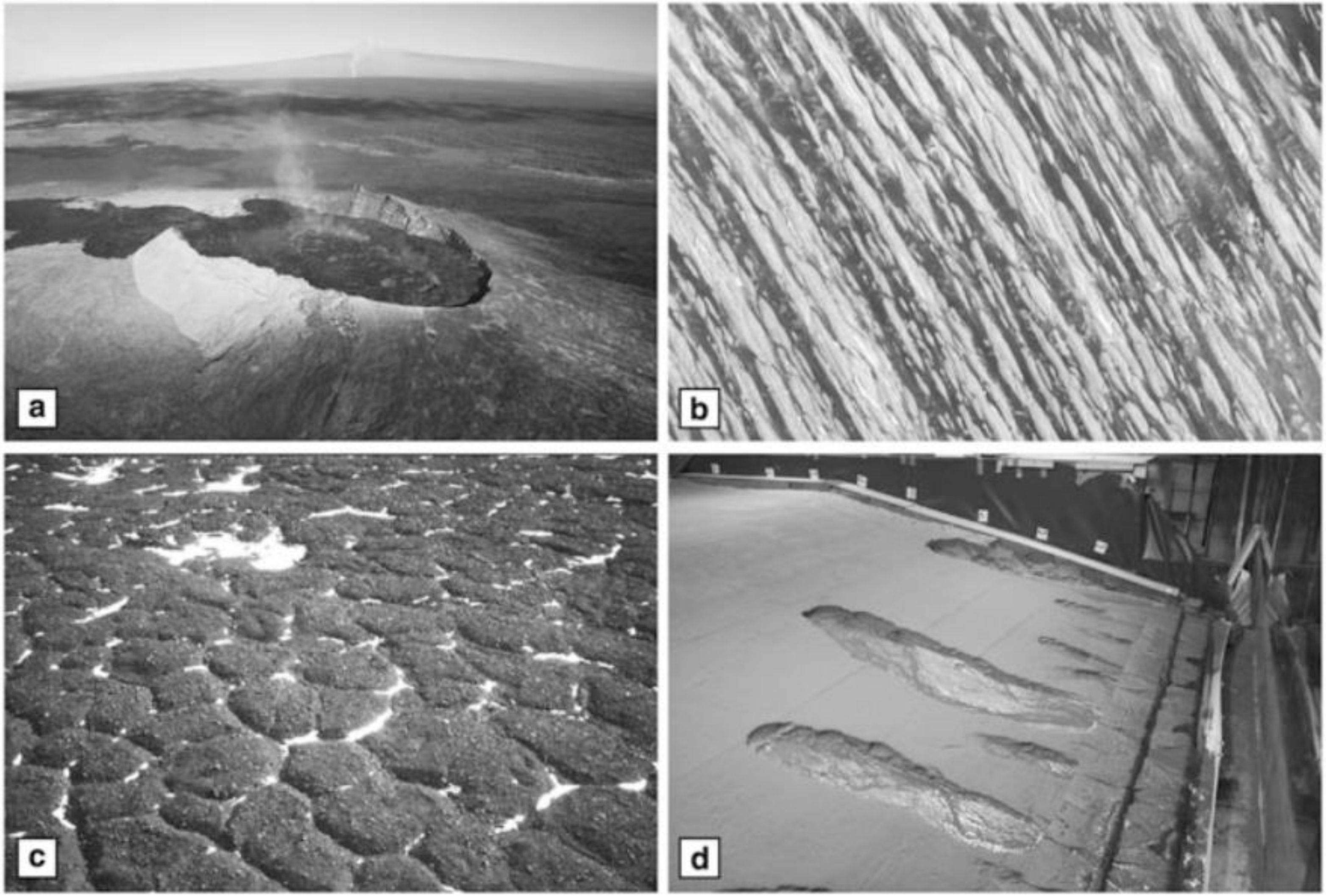


Fig. 2.2 Examples of Earth analogues for Mars research; (**a**) the Pu'u 'Ō ō vent on the slopes of Kilauea, Hawaii, with the huge shield volcano, Mauna Loa, in the background; (**b**) yardangs in the Dasht-e Lut desert (Iran); (**c**) patterned ground (sublimation polygons) in Beacon Valley, part of the McMurdo Dry Valleys in Antarctica; (**d**) groundwater seepage experiments in the *Total Environmental Simulator* facility of the University of Hull (UK). Source: (**a**) USGS. (**b**) NASA. (**c**) D. Marchant/NSF. (**d**) W. Marra/University of Utrecht

- These discoveries led to the development of the Viking mission, the main goal of which was to search for life on the surface of Mars.

- Landforms typical for arid climates were studied in the Egyptian desert, and a class of streamlined erosional landforms on Mars that display a characteristic *inverted boat hull shape were compared to yardangs in Peru.*

- *The* discovery on Mars of deeply incised channels that have an abrupt, amphitheater shaped heads and only few tributaries sparked the question which aqueous process was responsible for this peculiar morphology.

- Analogous valleys on the Colorado Plateau in the southwestern United States were, at that time, thought to have formed by sapping, that is, backward erosion by seepage (the emergence of groundwater at the foot of a cliff). Perhaps one of the most enlightening applications of analogous reasoning in planetary geomorphology led to the hypothesis that enormous fluvial channels on Mars may have formed by catastrophic floods.

- **Morphologically similar, yet smaller channel systems in Washington State, U.S. were formed by several such catastrophic floods, which were triggered by the sudden drainage from glacially dammed lakes in the Pleistocene (Missoula floods).**

- **Iceland hosts volcanic and glacial landscapes and is one of the best sites to study volcano-ice interactions, which are thought to have been important on Mars, too.**

- **Venusian volcanic landforms were compared to a variety of terrestrial analogues. For example, small volcanic domes were compared to basaltic lava shields on Iceland, on the basis of their shapes and volumes.**
- **The volcanic landforms is the unique surface environment of Venus, which is characterized by very high temperature and atmospheric pressure. The terrestrial volcanic environment with the highest ambient pressures is the seafloor; hence a number of analogue studies used seamounts and other submarine volcanic features as analogues to Venusian volcanic landscapes.**

- **The study of these high-resolution images led to new discoveries, e.g., the geologically young gully systems on Mars.**

- **Gullies and alluvial fans were studied in diverse locations on Earth, including the Atacama Desert or Svalbard, Norway. When it became obvious that the mid-latitudes of Mars are characterized by a diverse set of possibly ice-related landforms that are hypothesized to be the result of climate fluctuations, cold climate region on Earth provided useful analogues.**

- **Tuktoyaktuk peninsula in northwest Canada is a prime site to study pingos, which have been hypothesized to exist in some places in the northern hemisphere and the Argyre region of Mars.**

- **Patterned ground has been identified on Mars at many locations, and was compared to analogue sites in permafrost areas in northern Canada and elsewhere in the Arctic.**

- **Representing the most extremely cold, dry land–surface environment on Earth, Antarctica has been selected as a terrestrial analogue for Mars since the early 1970s.**

- **After the discovery of perchlorates in Martian soil by the Phoenix lander, scientists turned to the Atacama Desert in Chile, as it is there where the highest perchlorate concentrations on Earth are measured**

- **Another frequently used geochemical/mineralogical analogue is provided by the hydrothermal environment of the Yellowstone caldera, U.S., where silica-rich soils can be studied**

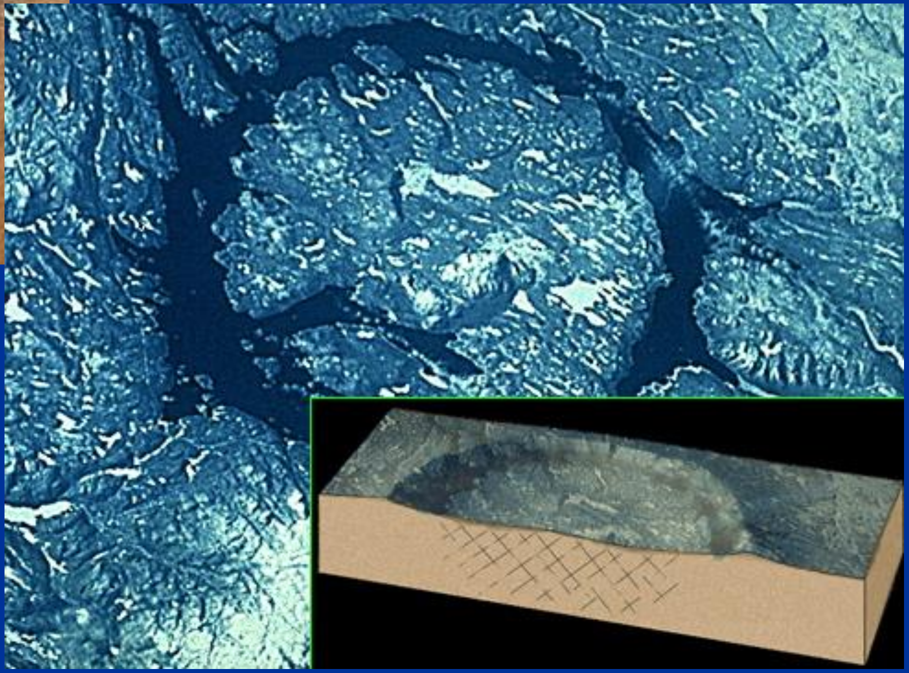
- **The subglacial lakes in Antarctica (e.g., Lake Vostok) may be useful analogues to the sub-ice oceans on Europa or Enceladus, and it will be interesting to see whether they host unique habitats.**

- **The increasing importance of landed missions and in situ investigations will require that more analogues are identified that help to understand compositional observations at small scales and specific geochemical environments.**

Impact cratering on Earth

Barringer Meteor Crater
Arizona

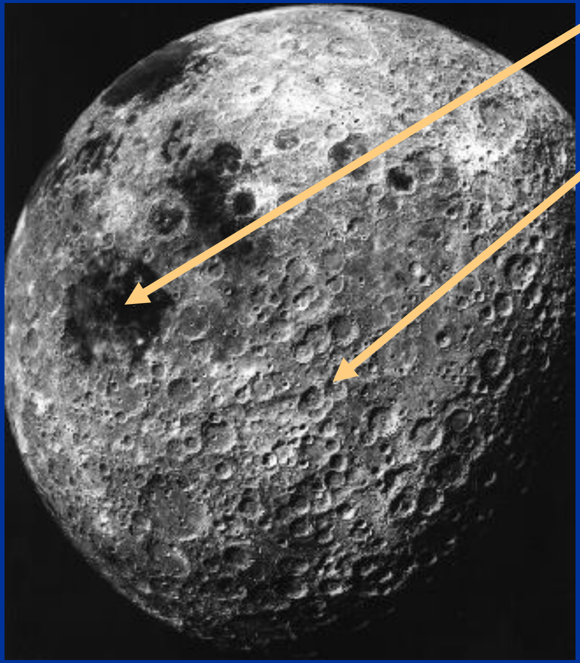
Manacouagan Crater
Canada



Craters on Moon, Mars

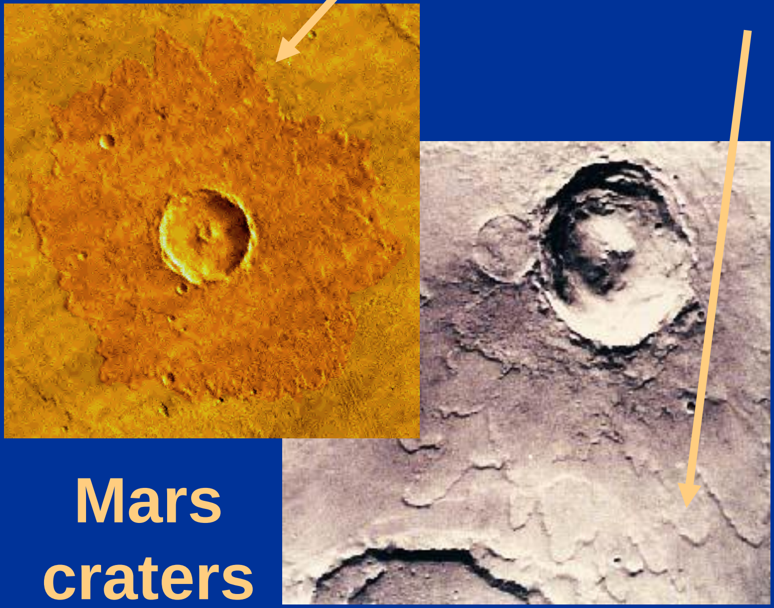
Maria: impact basins filled in with lava

Highlands: ancient and heavily cratered



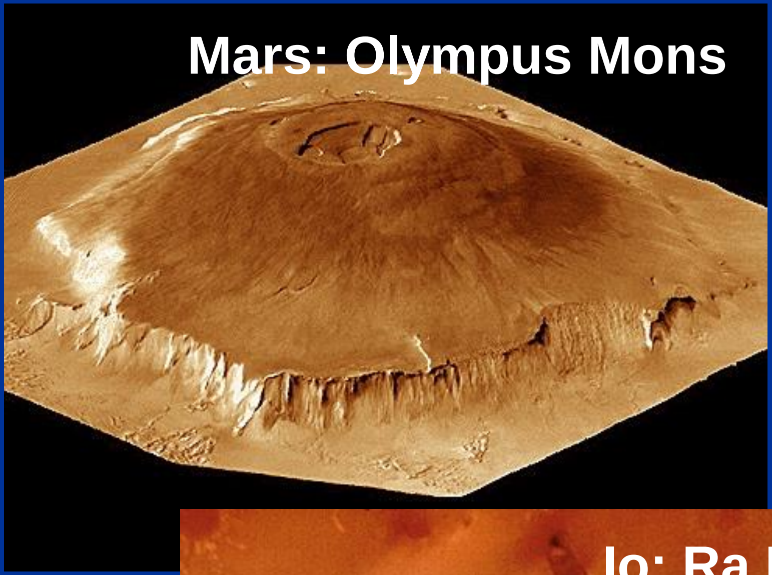
Moon craters

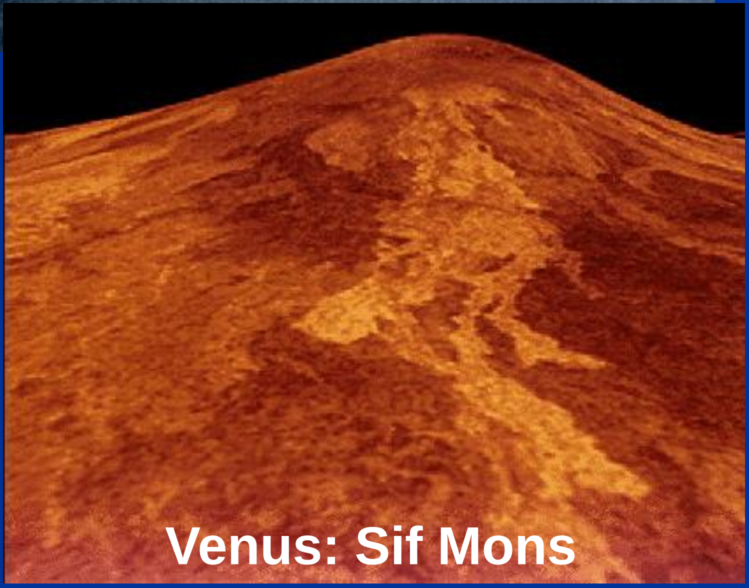
Impacts into icy ground may produce muddy ejecta



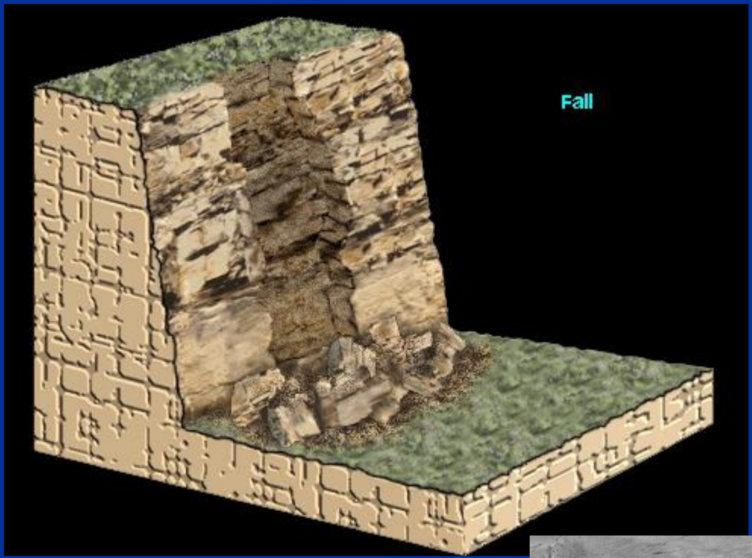
Mars craters

Shield volcanoes on Earth, Venus, Mars, Io

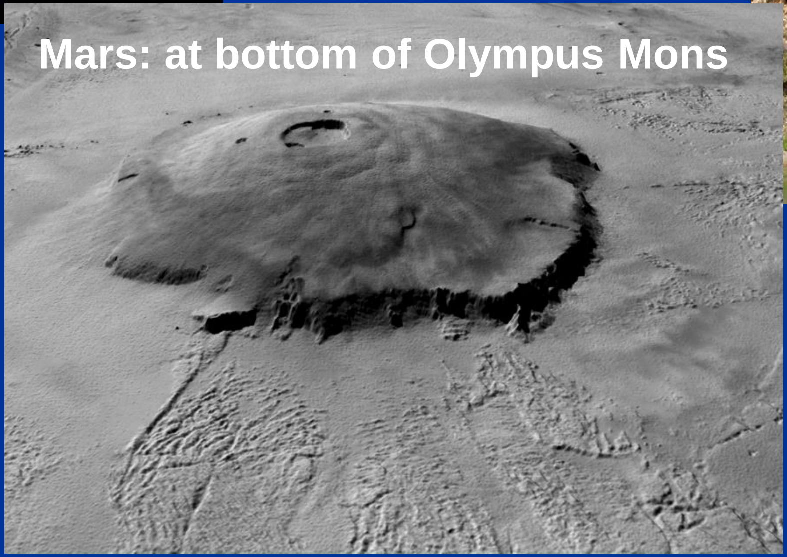




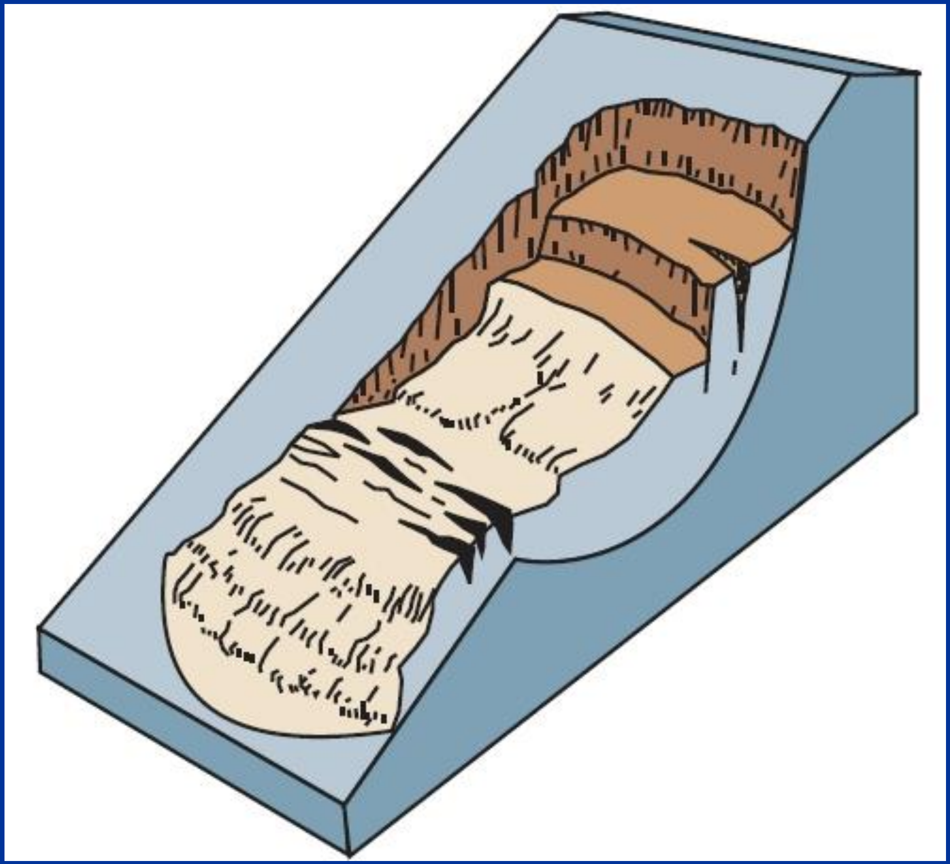
Erosion: rockfalls



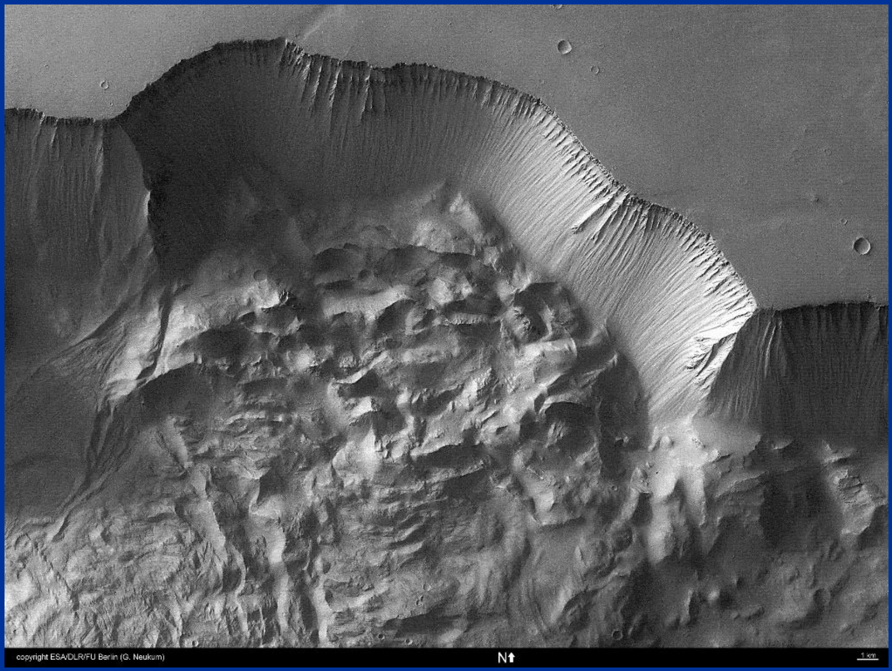
Earth:
Grand
Canyon



Erosion: slumps



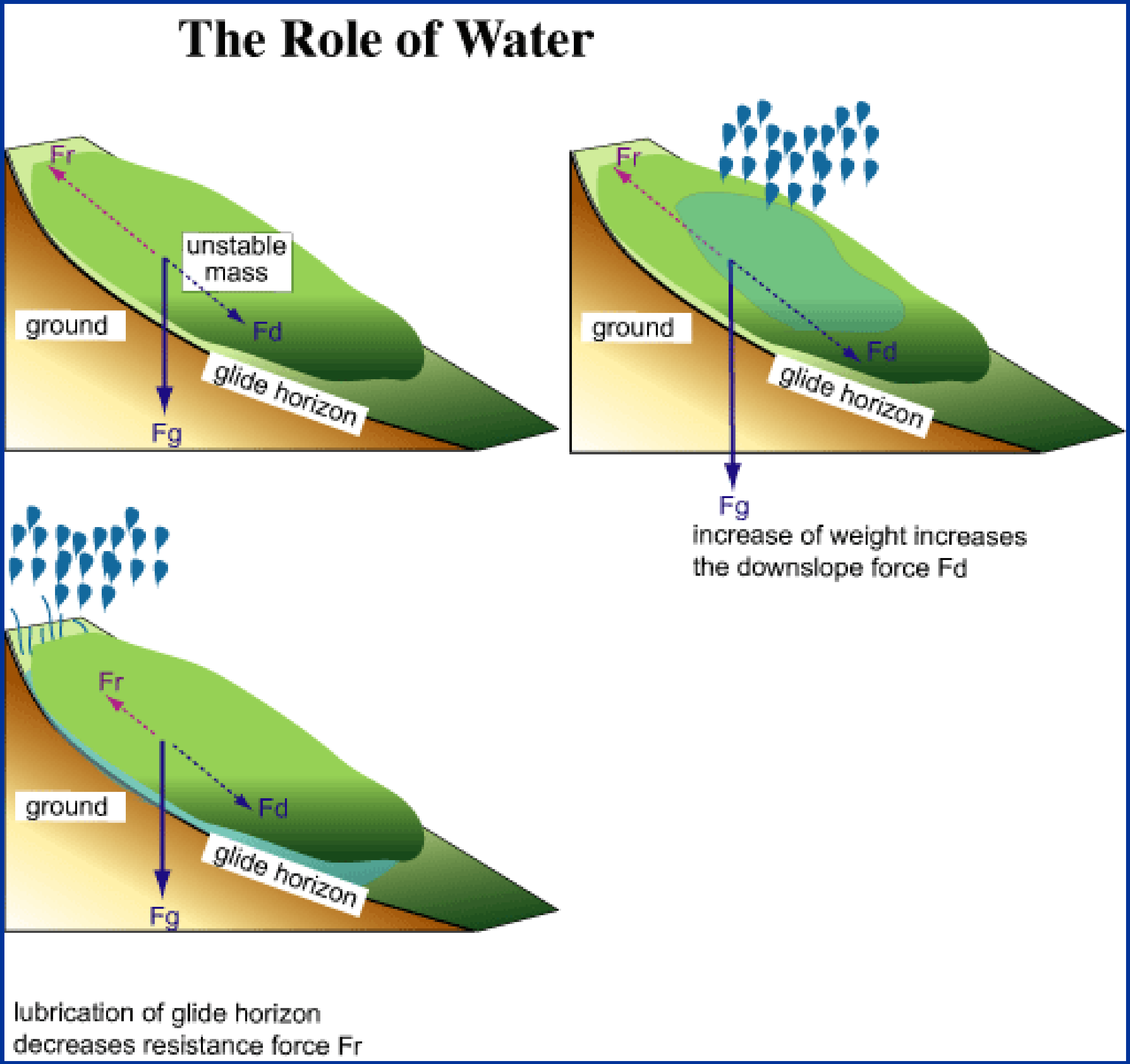
Slump on Mars



Slump in Berkeley CA

On Wildcat Canyon Road

Slumps on Earth are usually due to liquid water

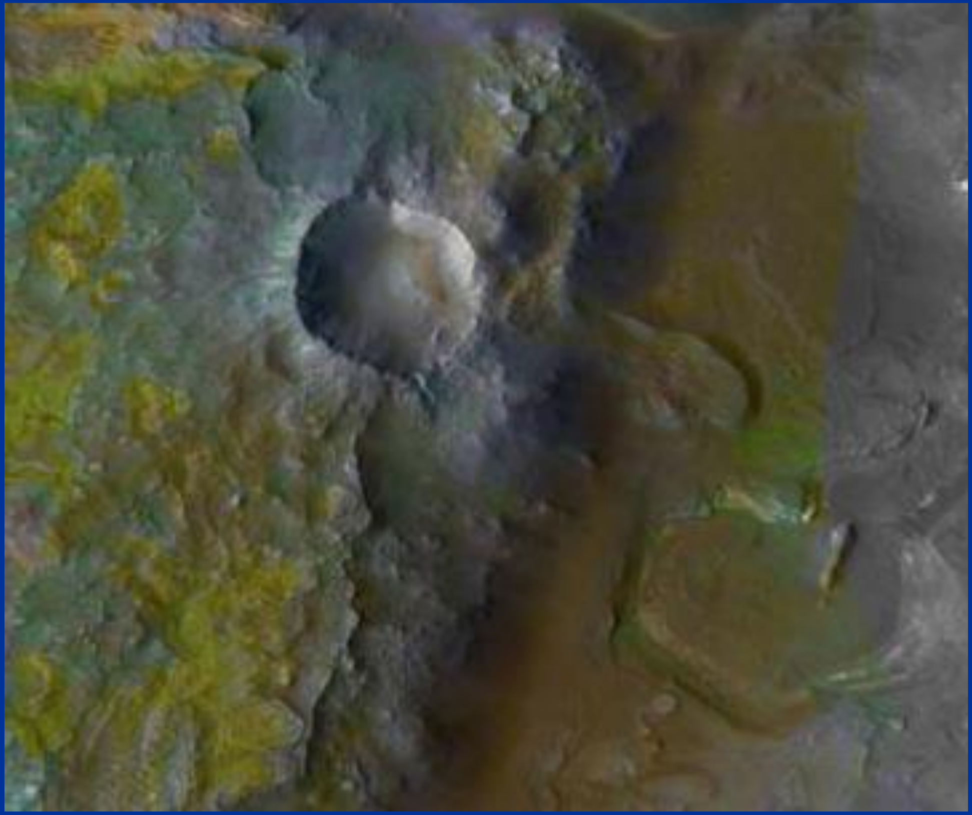


- **Is this indirect evidence for liquid water on Mars?**

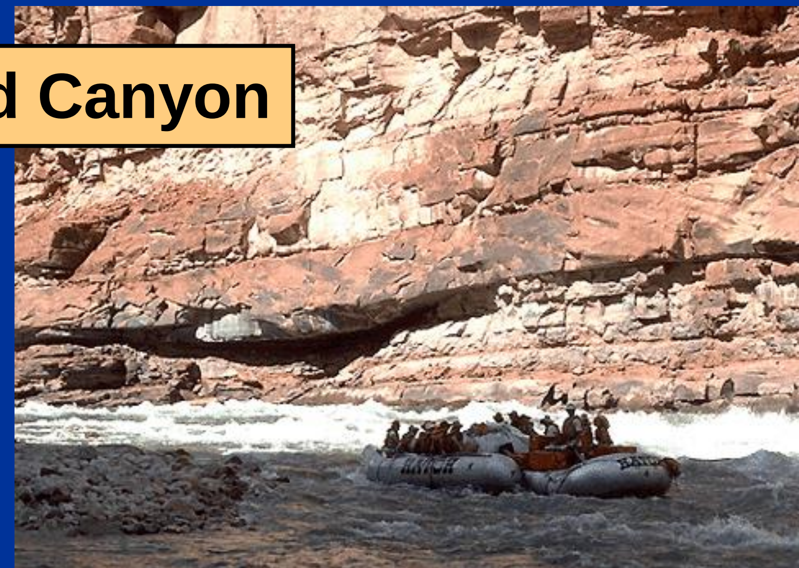
Erosion: debris flows on Earth and Mars

Earth: San Jacinto Mountains, CA

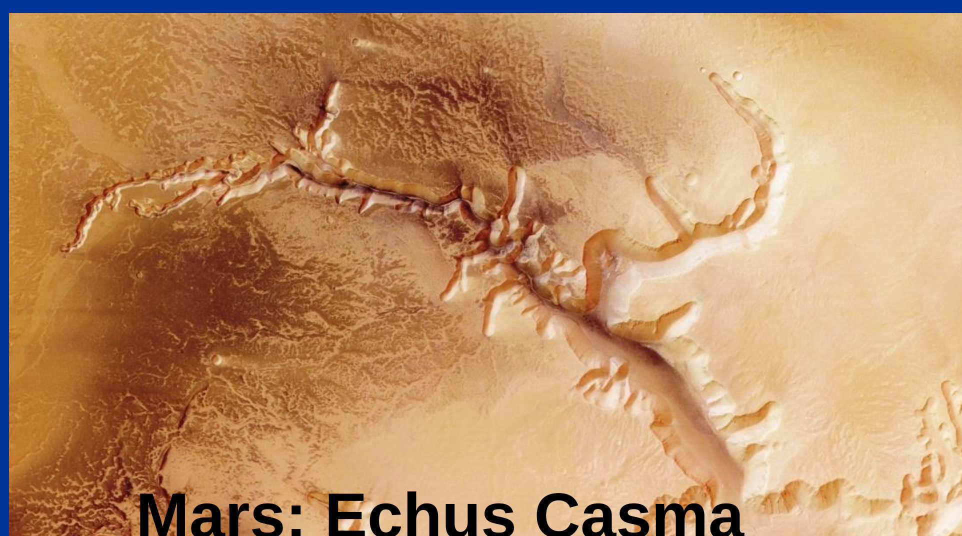
Mars: (wet?) debris flow



Erosion: water can carve canyons



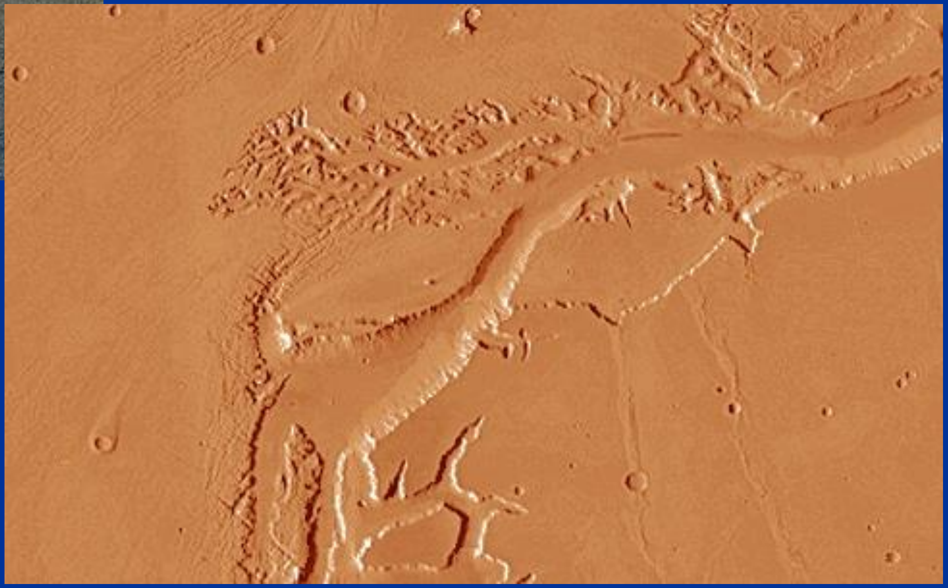
Earth: Grand Canyon



Mars: Echus Casma

Erosion: flood channels on Earth, Mars

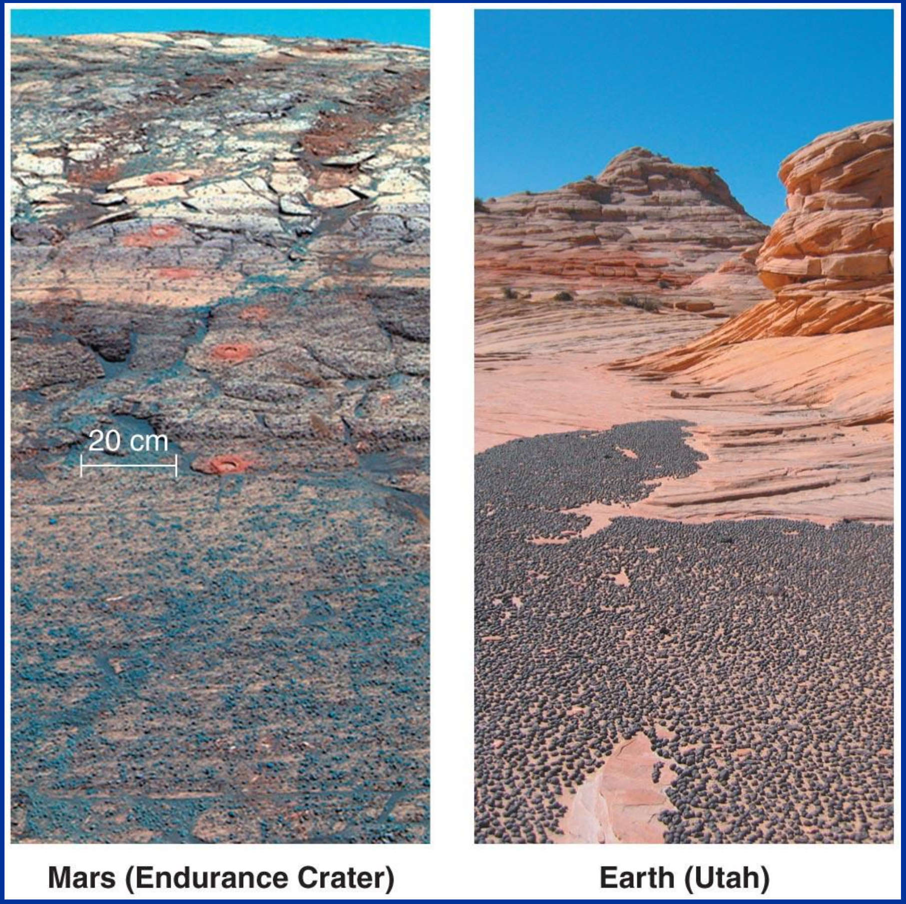
Washington State: channeled scablands
Giant flood 13,000 yrs ago



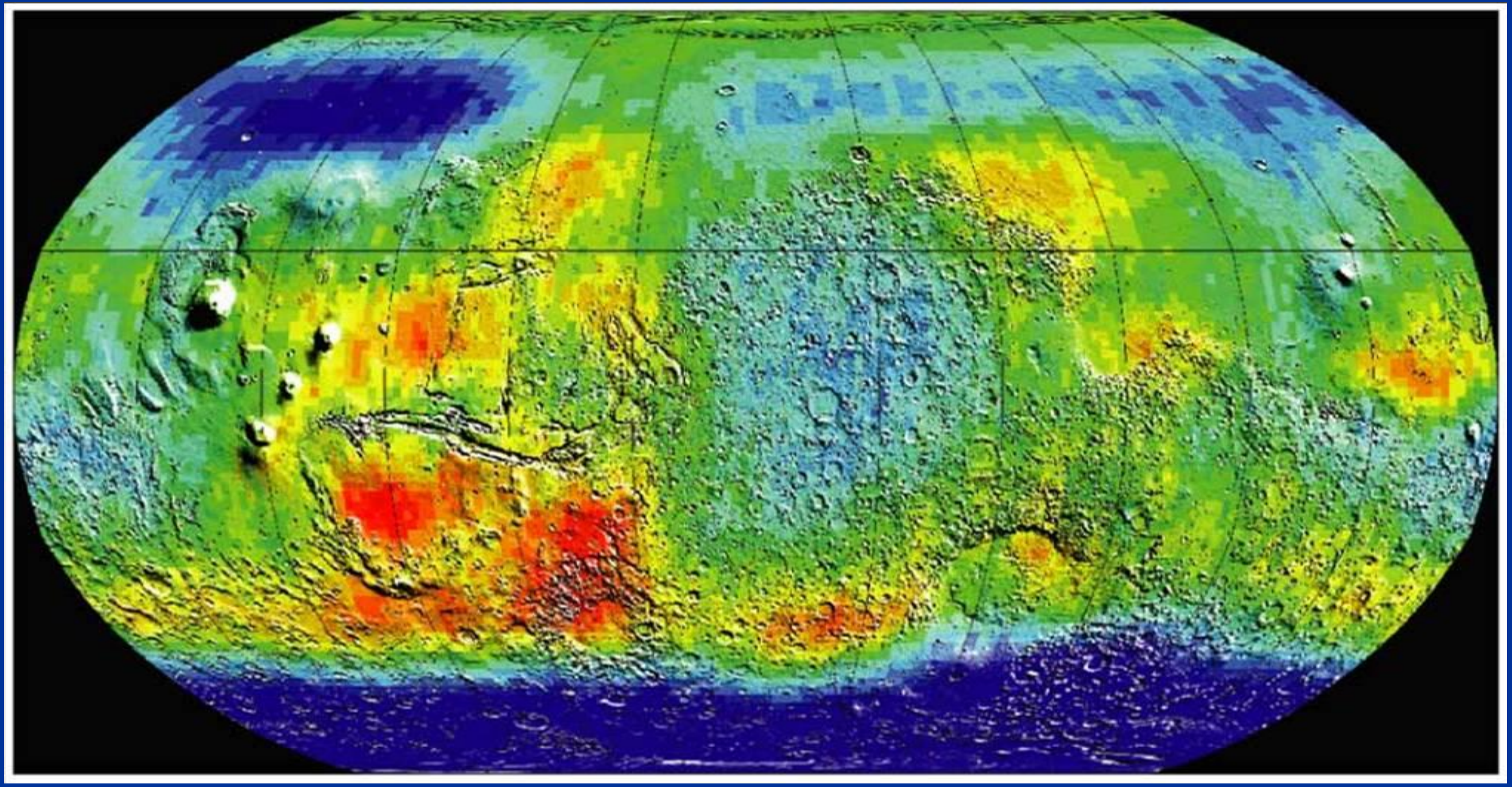
Mars: Kasei Valles flood channel

Some Martian rocks appear to have formed in water

- **Mars rovers (Spirit, Opportunity)**
- **Found rocks of a type that typically forms in water, on Earth**
  - **Hermatite "blueberries"**
  - **Formed in sedimentary layers (in background)**
  - **Later eroded out and rolled downhill**

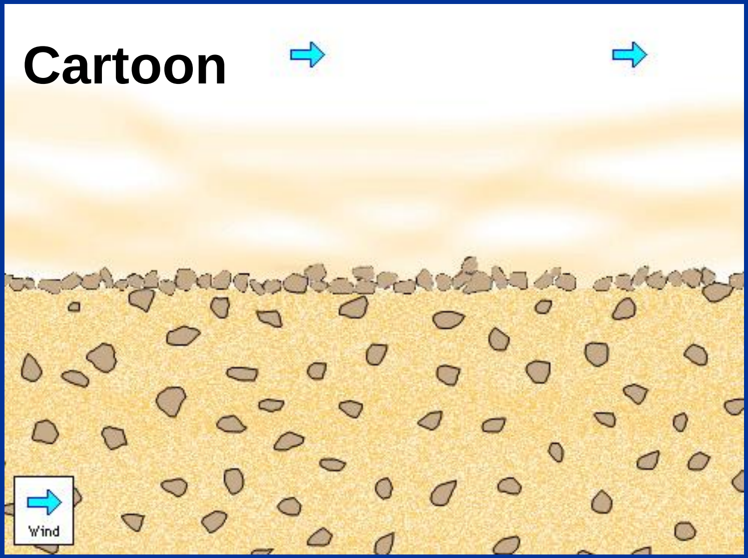


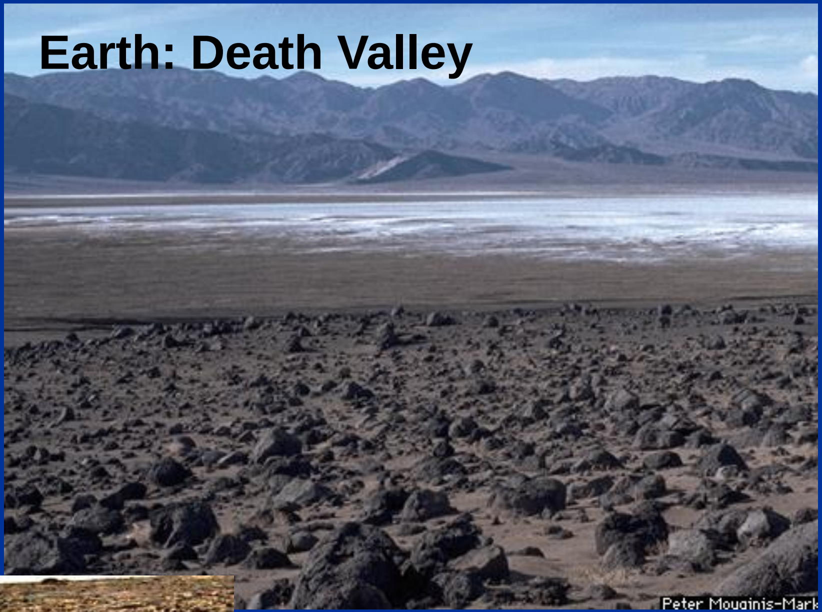
Mars' Hydrogen Content: further evidence of liquid water in the past



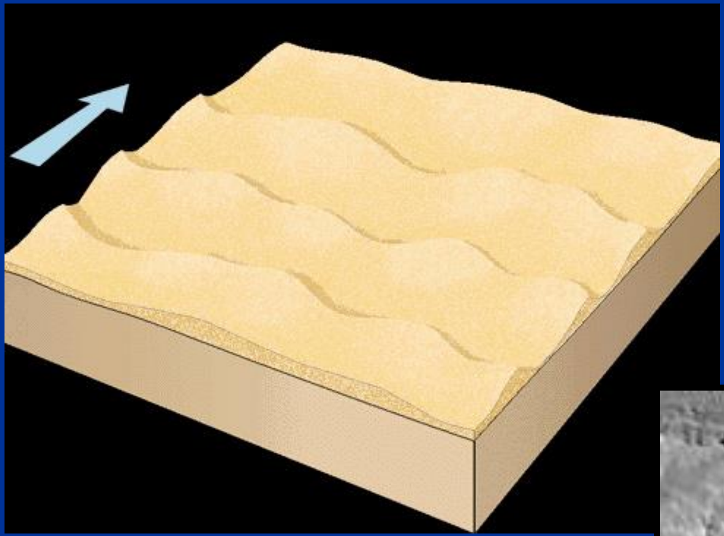
- **Map of hydrogen content (blue) shows that low-lying areas contain more water ice.**

Erosion: desert pavement on Earth, Venus, Mars

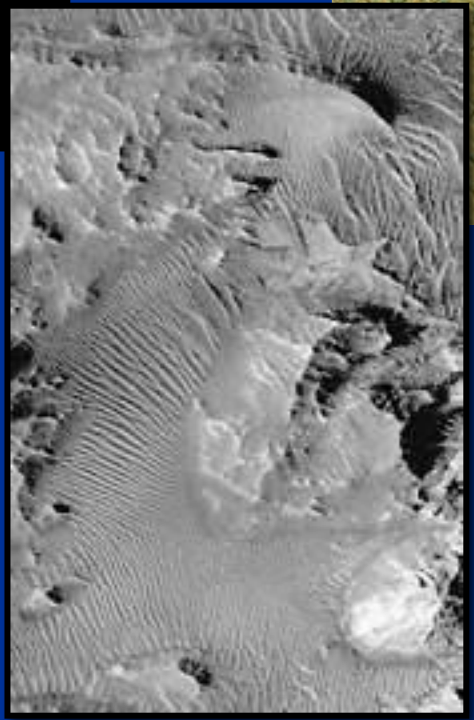




Erosion: transverse sand dunes

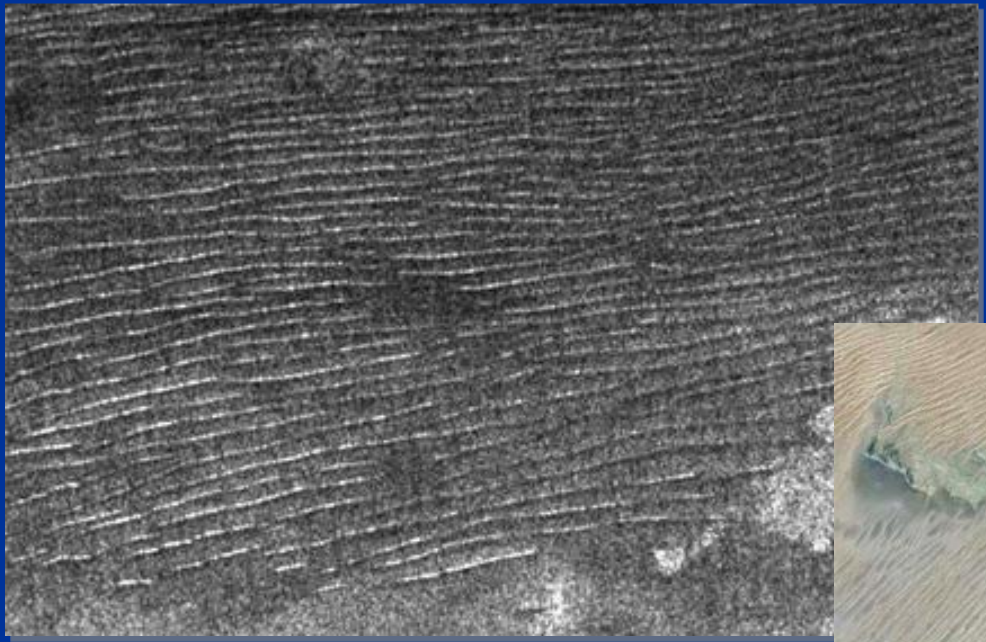


Earth: Namib desert



Mars:
Hebes Casma dunes

Dunes on Saturn's moon Titan



Titan dunes
(radar image)

Earth dunes
in Yemen

The Mars Desert Research Station (MDRS) is the simulated Mars analog habitat

The Mars Society's Mars Desert Research Station located near Hanksville, Utah.

Mars or Earth?

Mars or Earth?

Columbia Hills, Mars

Atacama Desert, Chile

Columbia Hills, Mars

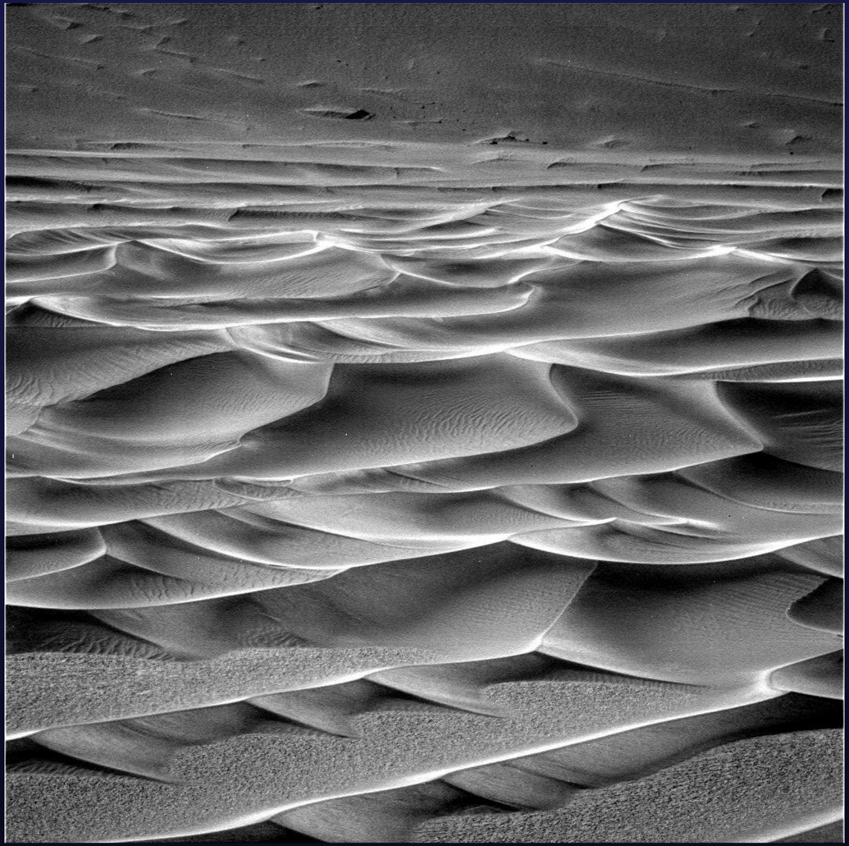
Mars or Earth?

Mars or Earth?

Kilauea Volcanoe, Hawaii

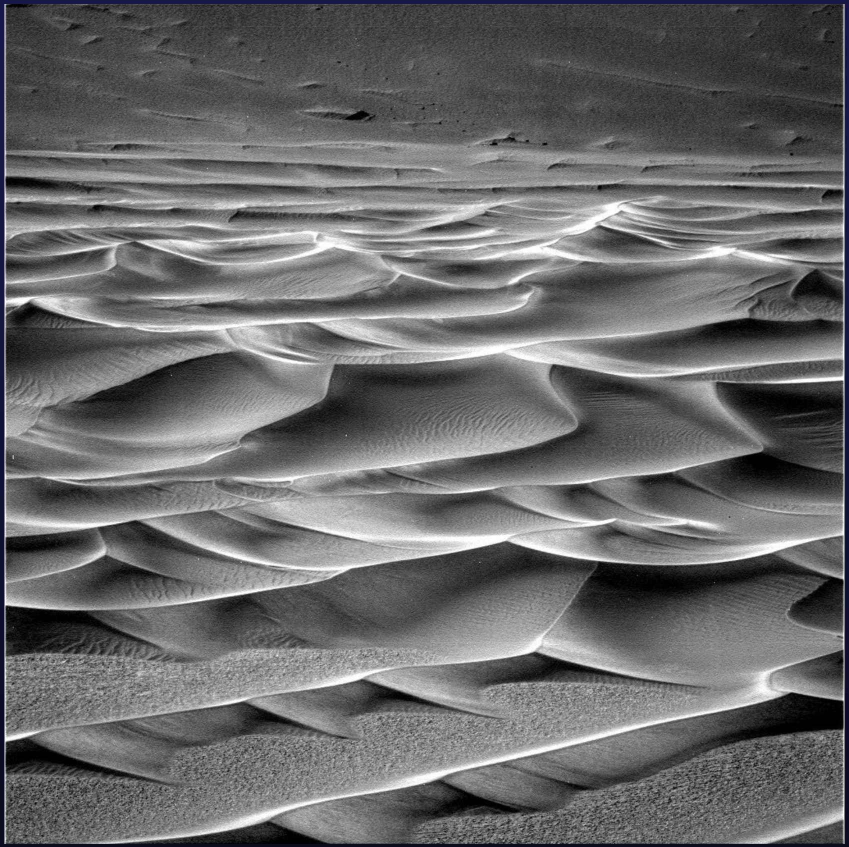
Olympus Mons, Mars

Mars or Earth?



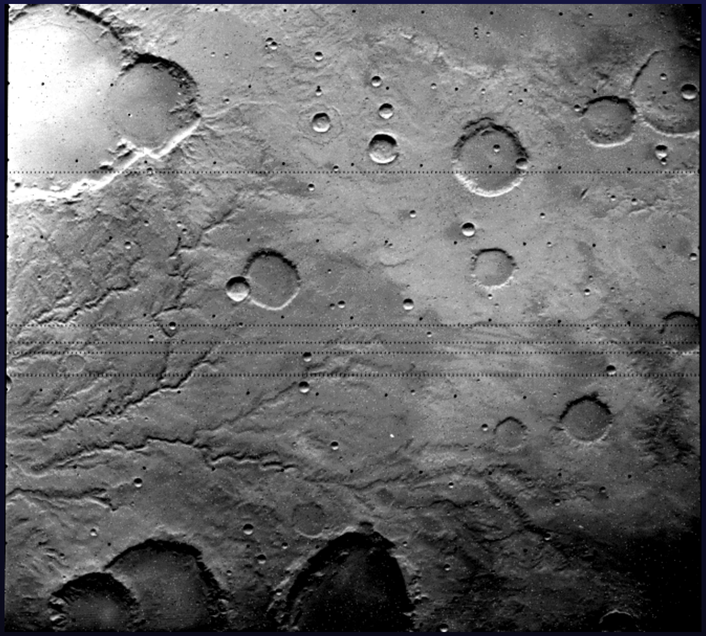
Mars or Earth?

Dubai, UAE

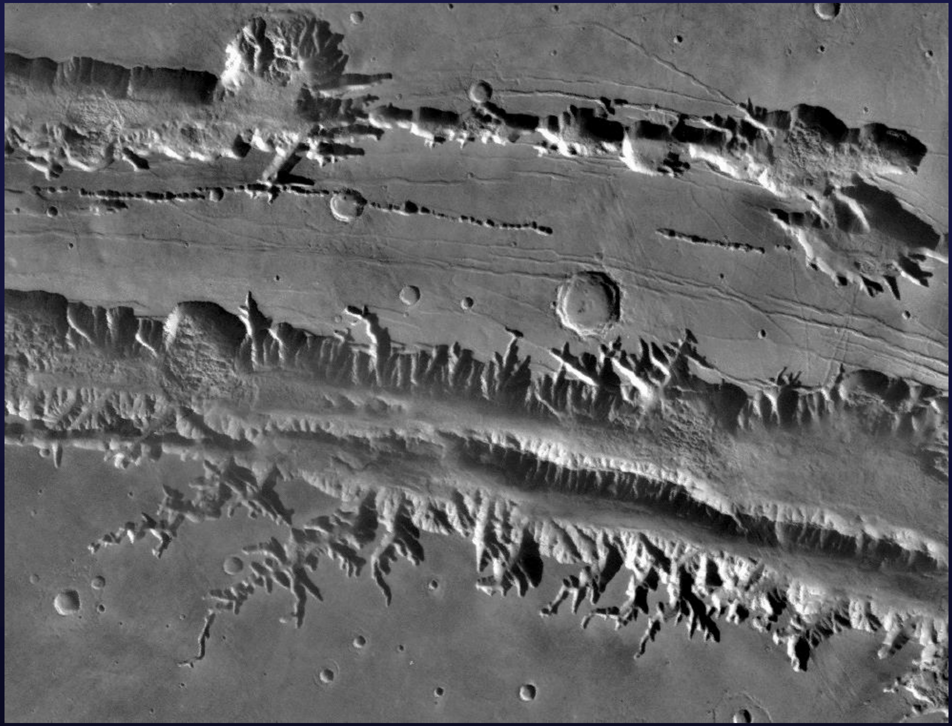


Endurance Crater, Mars

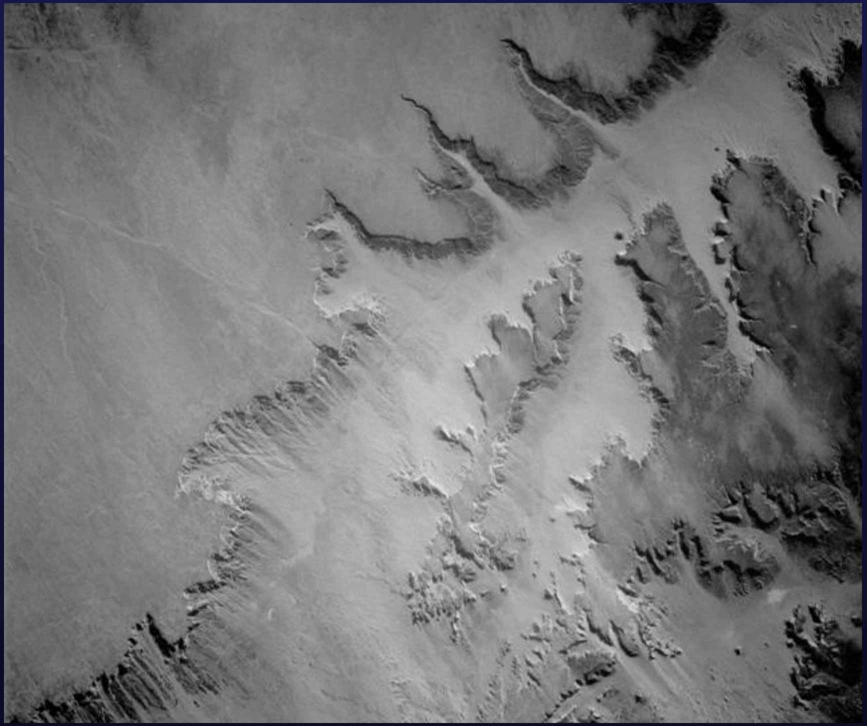
What is the evidence for past water on Mars?



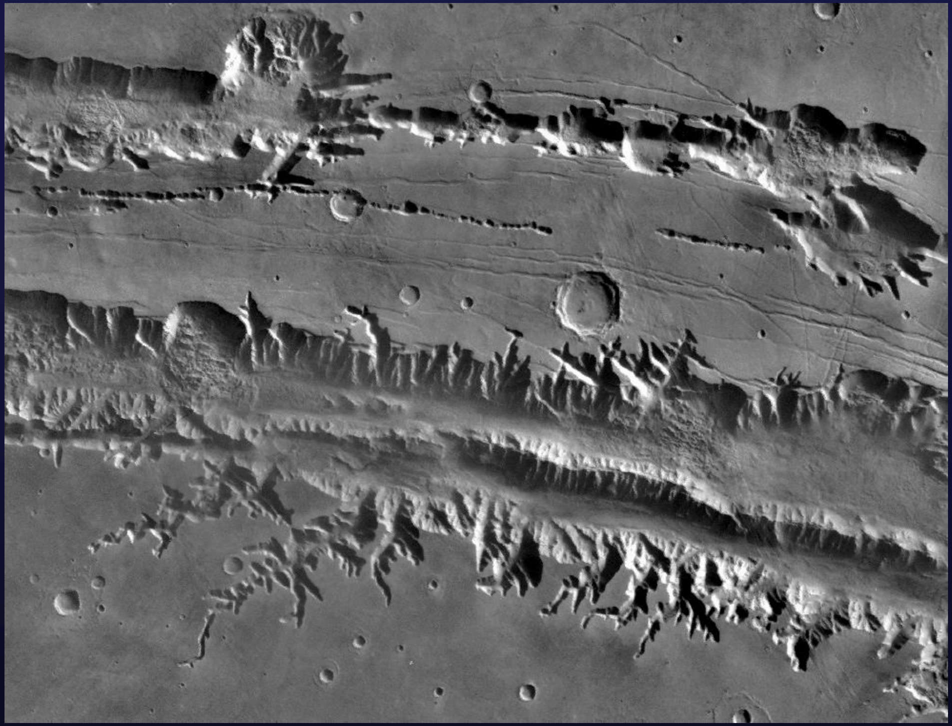
Mars or Earth?



Mars or Earth?



Djado Plateau, Niger



Valles Marineris, Mars

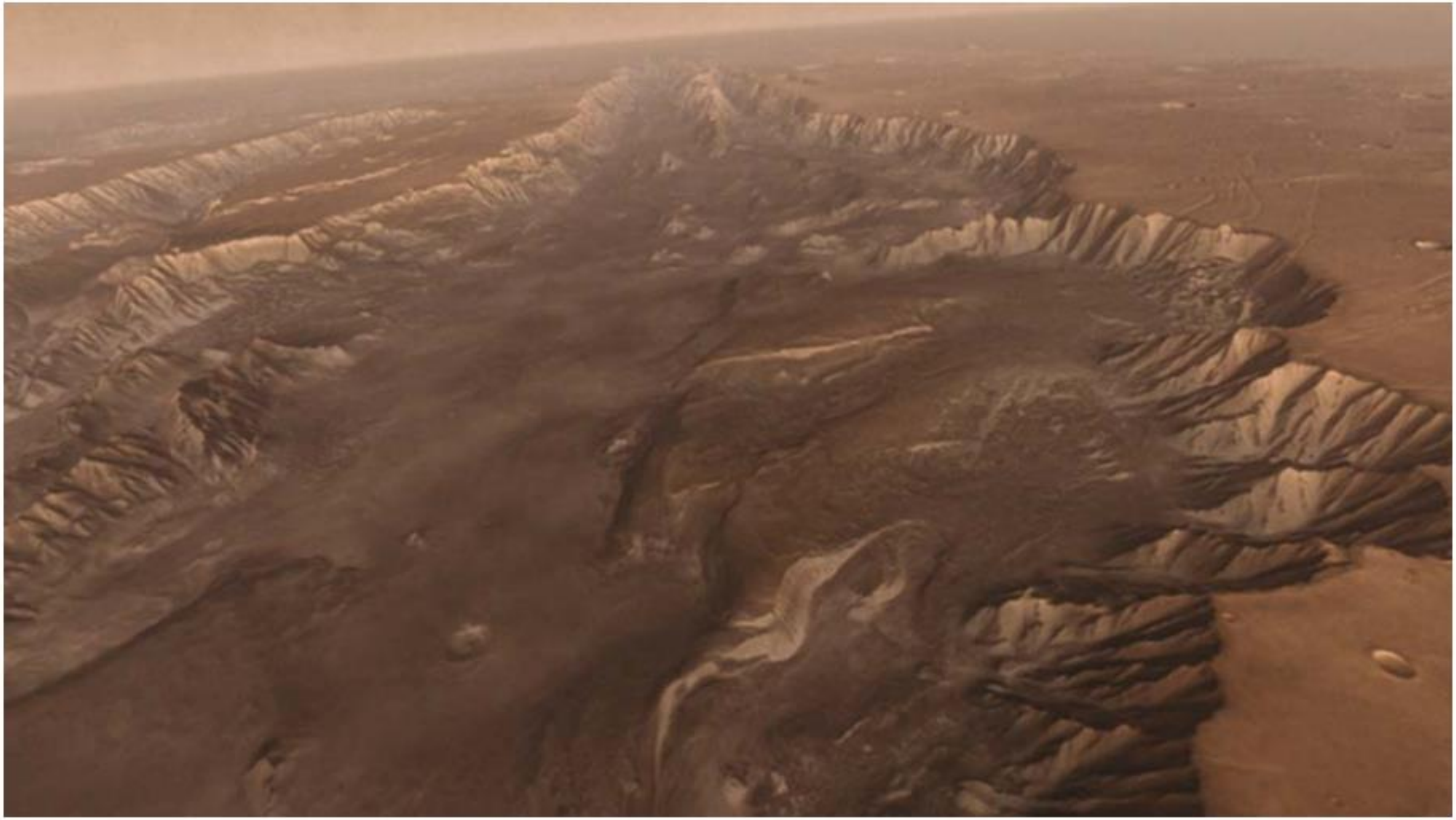
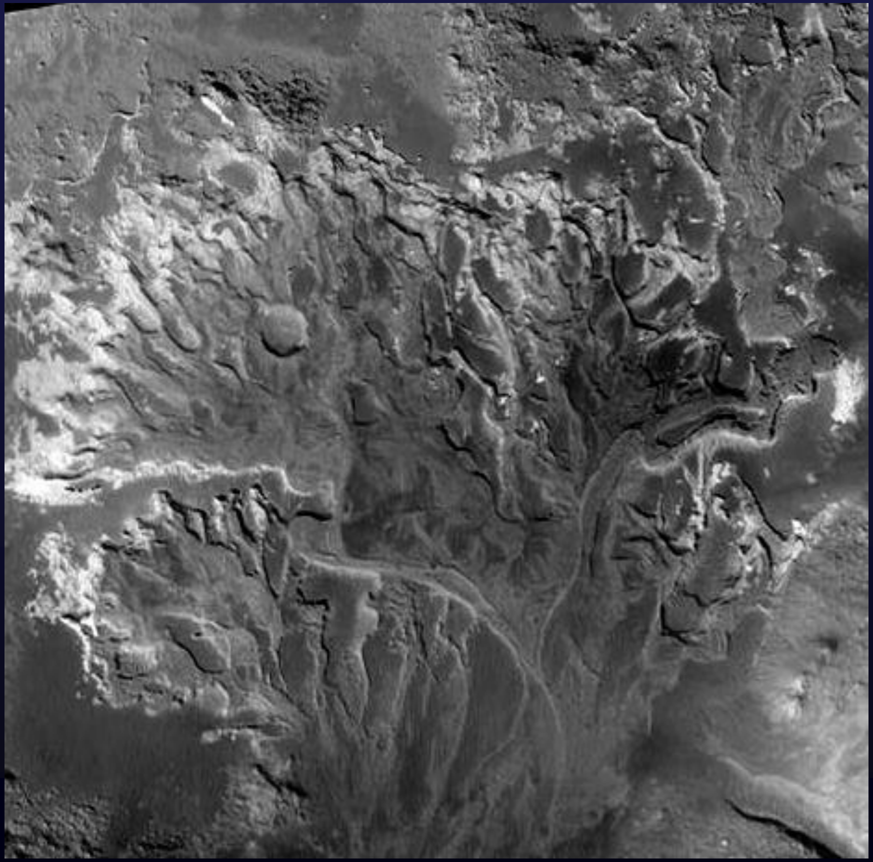
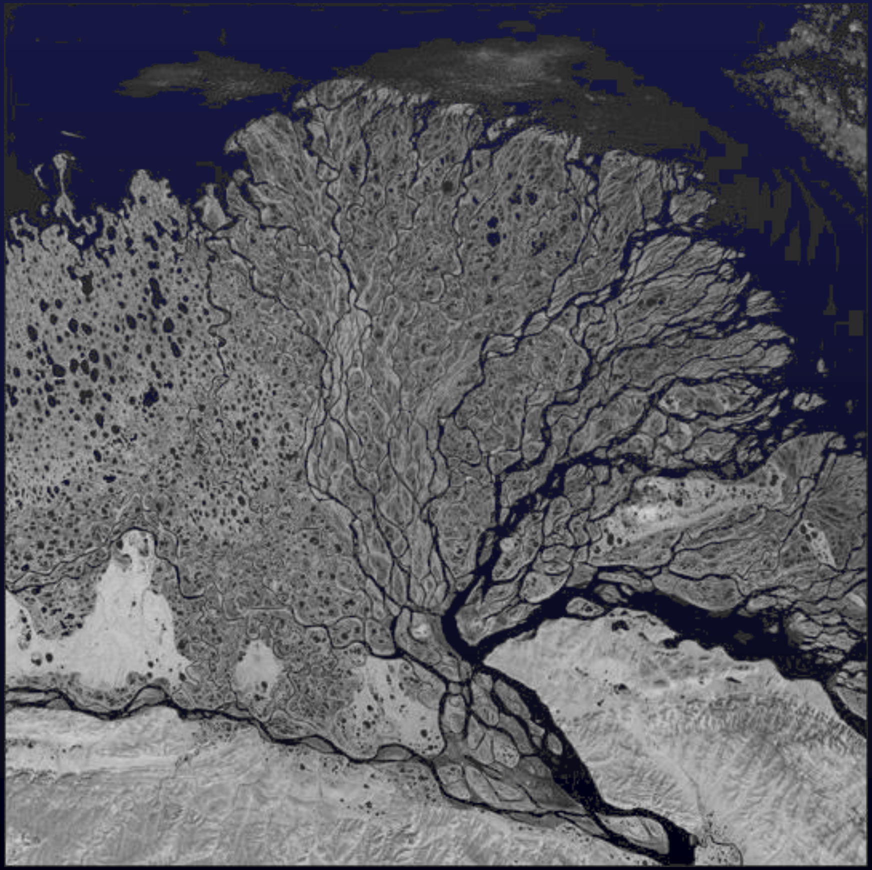


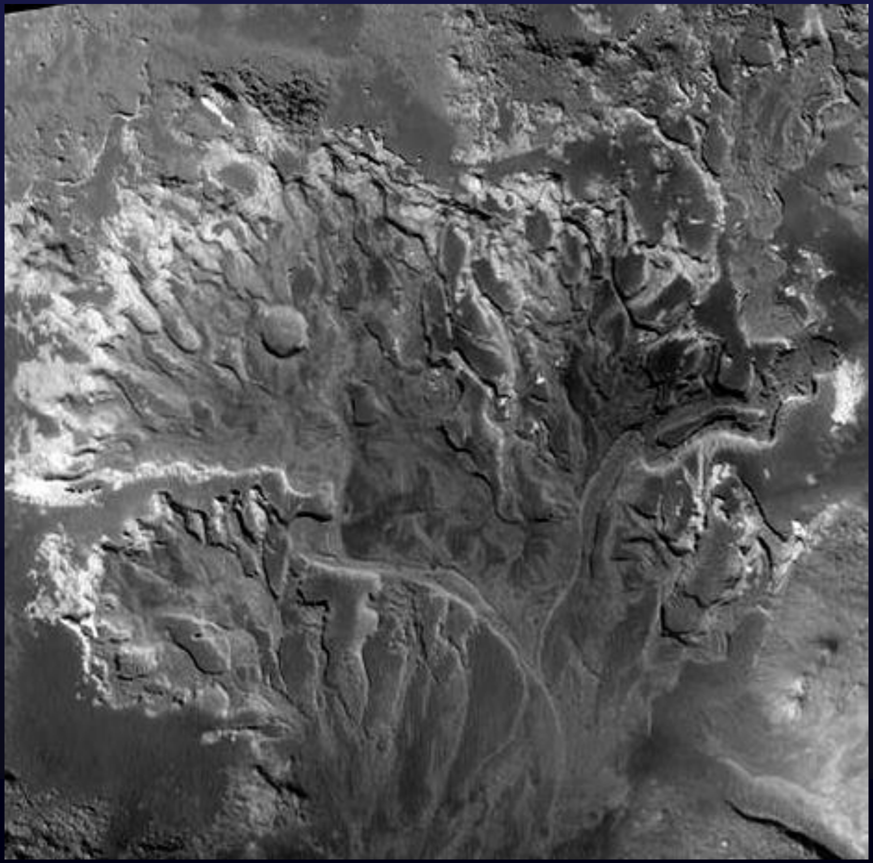
Figure 12.6. This oblique view of the long axis of the Valles Marineris illustrates how landslides have widened the main branch of the canyon and how the canyon walls have been eroded by gullies cut by water flowing downslope. The landslide deposits that cover the valley floor contain only a few impact craters indicating their comparatively low exposure age. (Mosaic of images recorded by the Thermal Emission Imaging System of the Mars Odyssey spacecraft and assembled in March of 2006. Courtesy of NASA/JPL/Caltech)

Mars or Earth?

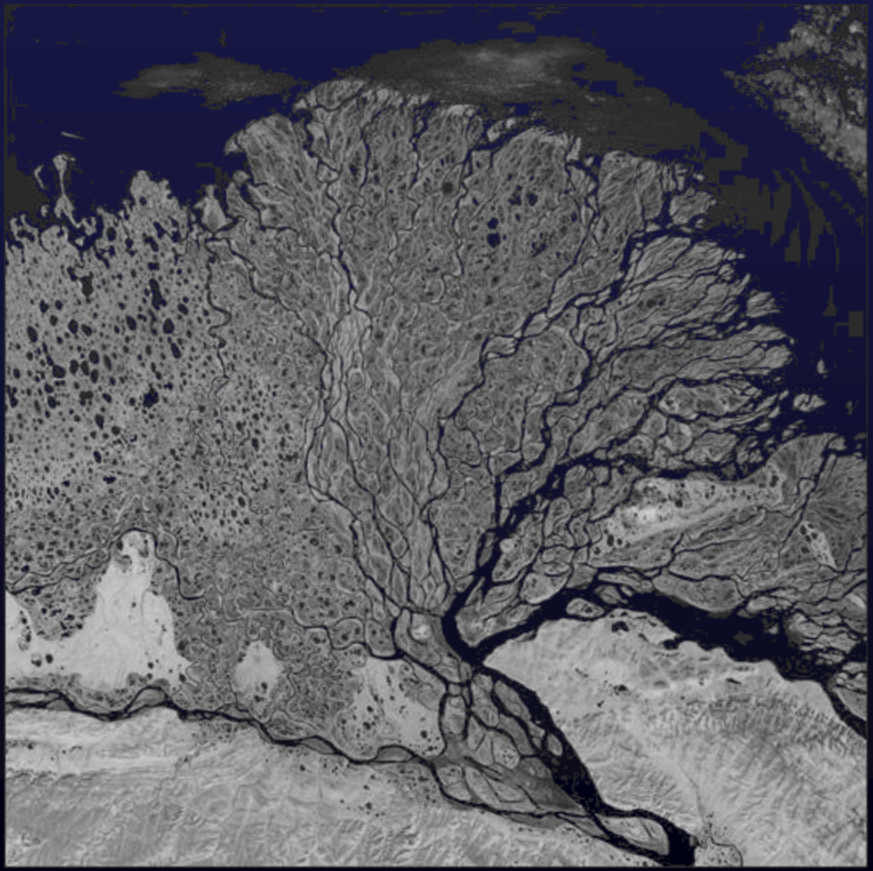




Mars or Earth?

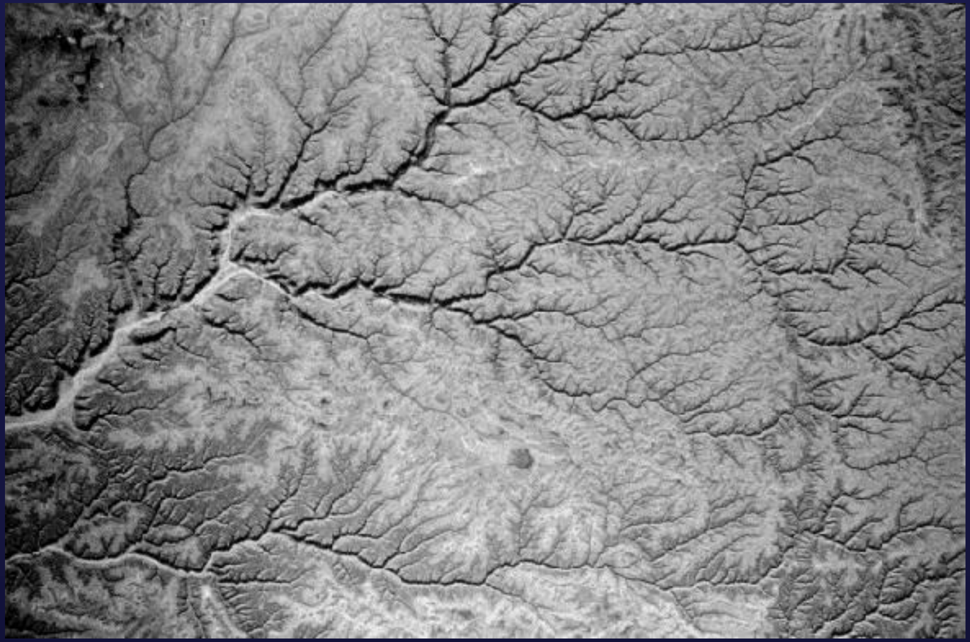


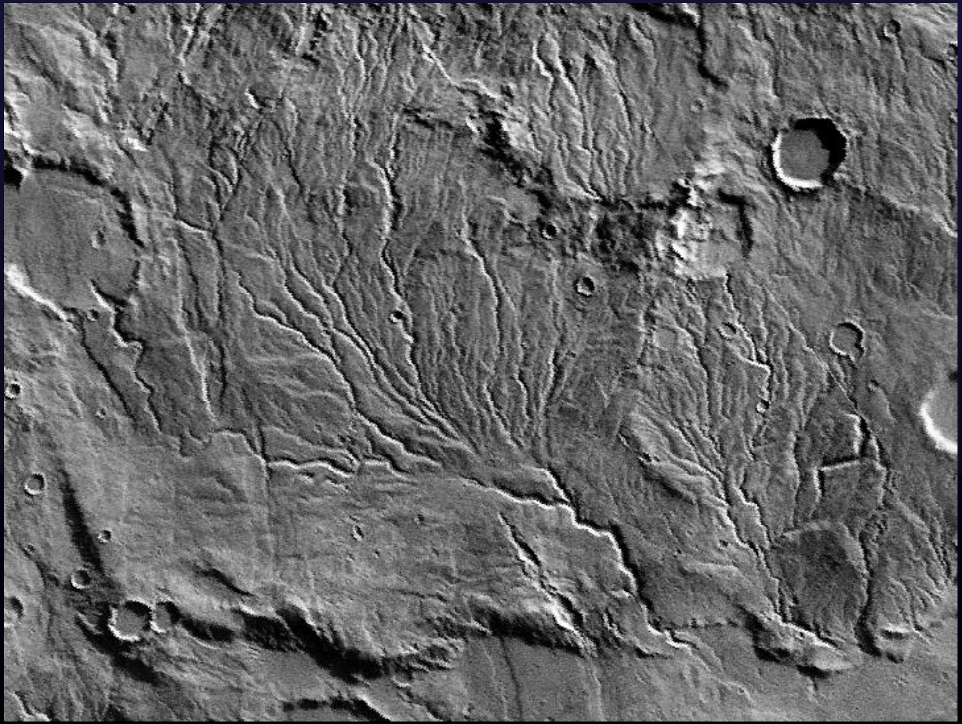
Holden Crater NE, Mars



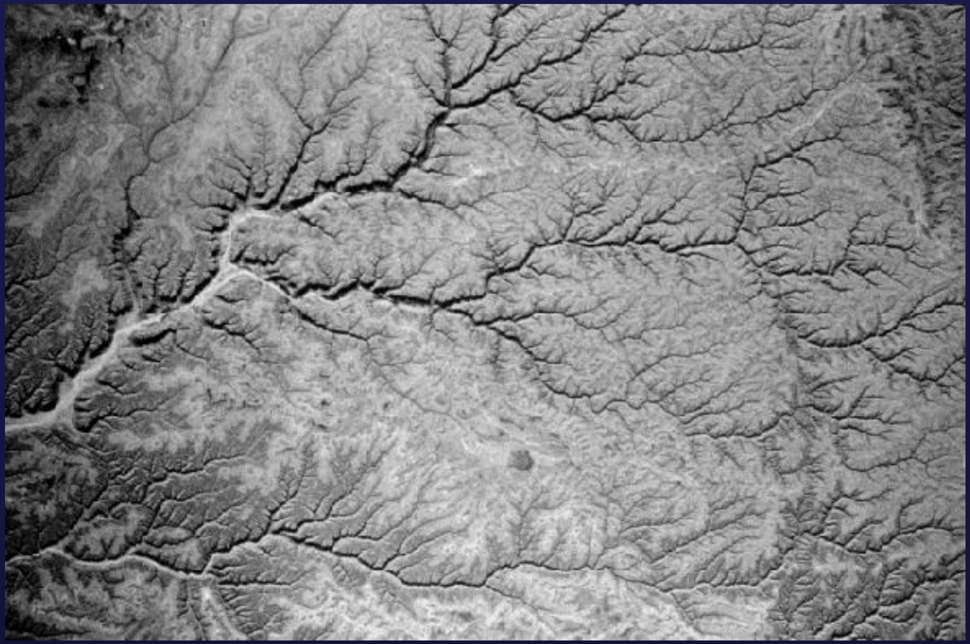
Lena Delta, Argentina

Mars or Earth?



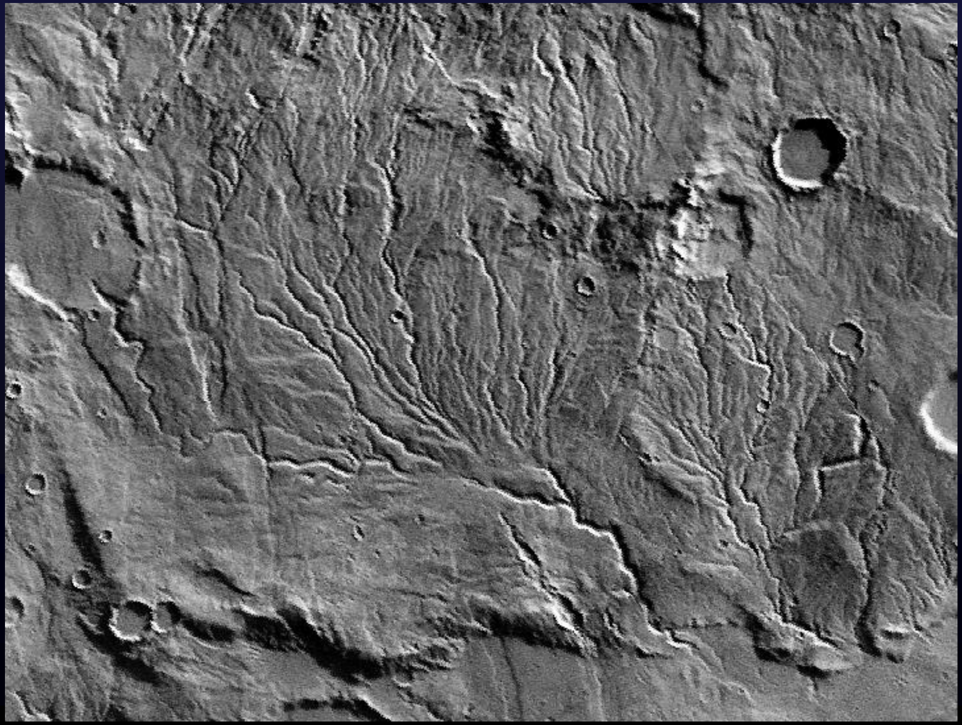


Yemen



Mars or Earth?

Mars



Mars or Earth?

Mars or Earth?

Niger

Mars