Voyage to the Planets
Lecture 4:
Mars
the Red Planet

Presented by

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School of Physics

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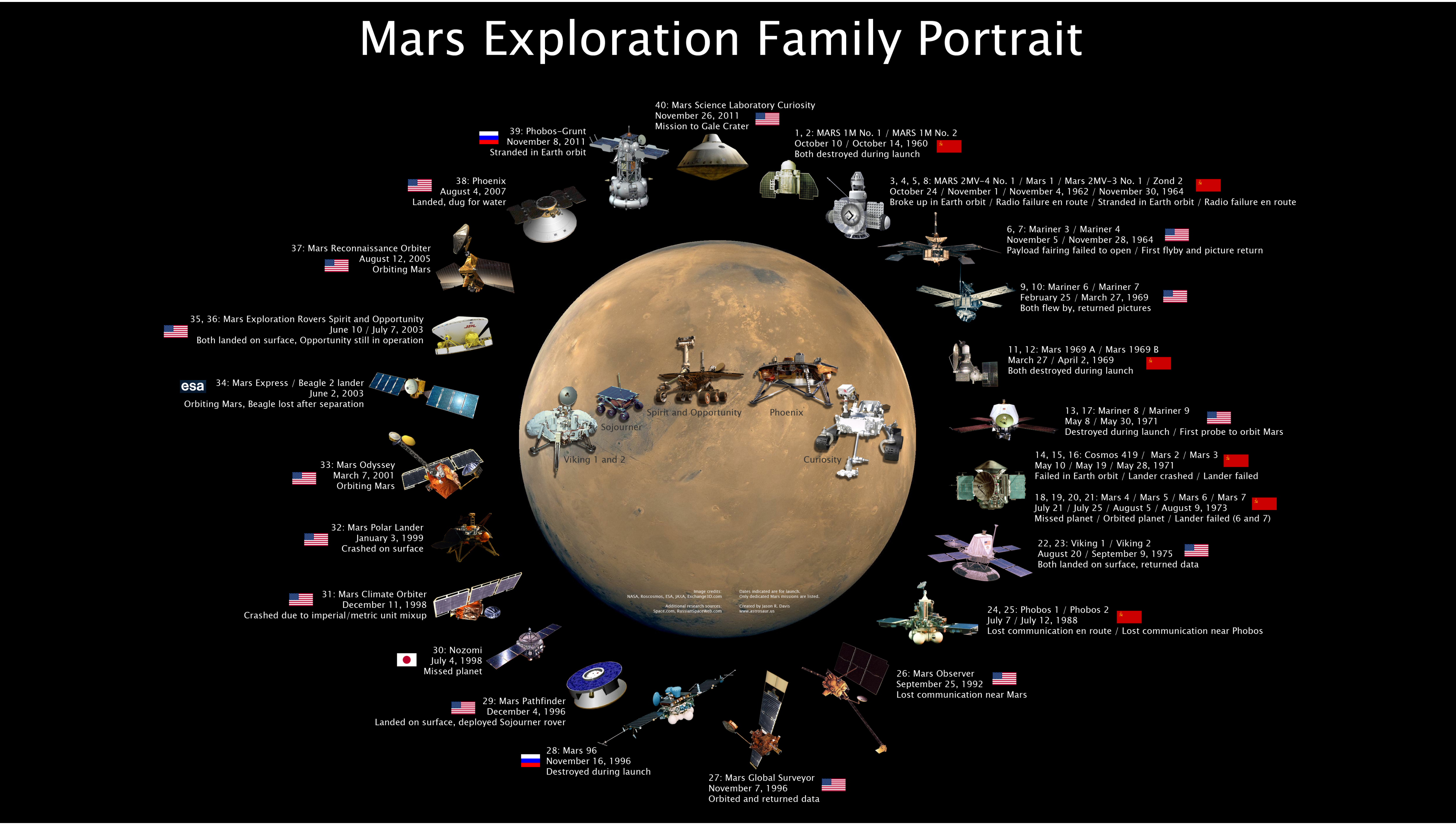
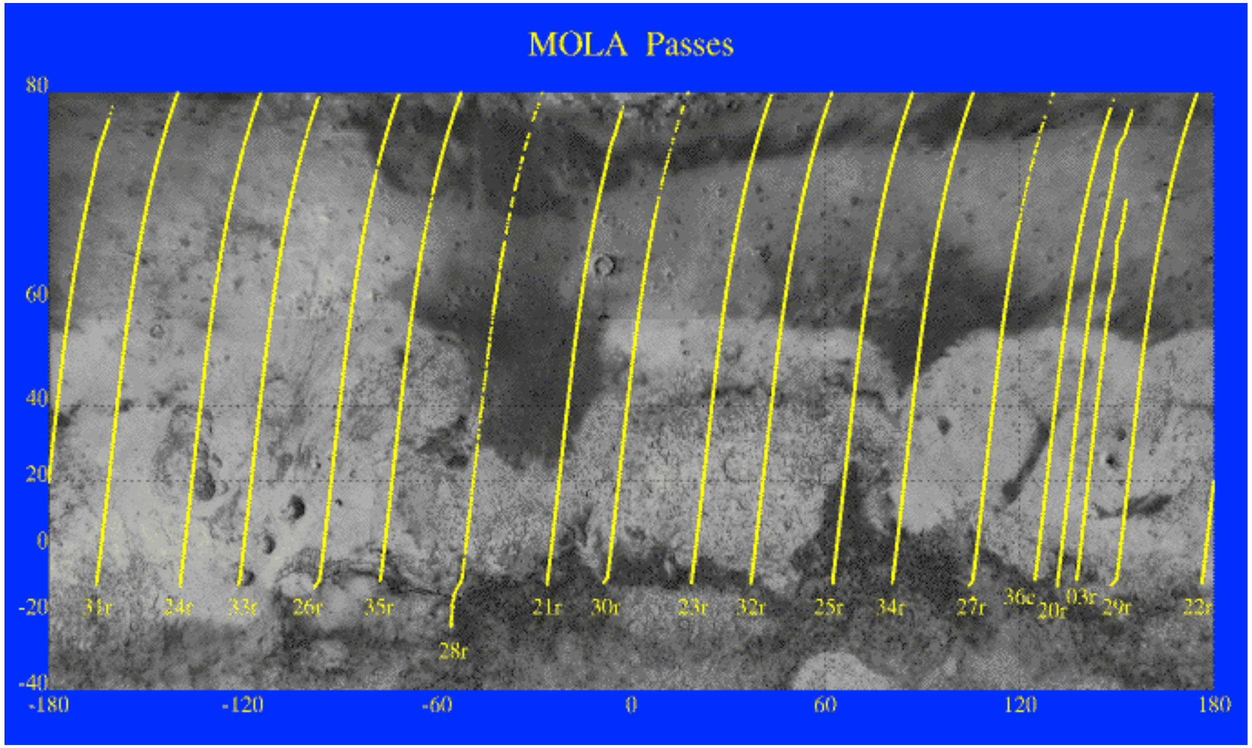
THE UNIVERSITY OF SYDNEY

There have been many spacecraft sent to Mars over the past few decades: more than to any other place in the Solar System except the Moon.

Since 1996, Mars exploration has undergone a renaissance, with data from both orbiters and landed missions developing a revolutionary new view of Mars as an Earth-like world with a complex geologic history.


Mars Exploration Family Portrait
40: Mars Science Laboratory Curiosity
November 26, 2011
Mission to Gale Crater
1, 2: MARS 1M No. 1 / MARS 1M No. 2
October 10 / October 14, 1960
Both destroyed during launch
3, 4, 5, 8: MARS 2MV-4 No. 1 / Mars 1 / Mars 2MV-3 No. 1 / Zond 2
October 24 / November 1 / November 4, 1962 / November 30, 1964
Broke up in Earth orbit / Radio failure en route / Stranded in Earth orbit / Radio failure en route
6, 7: Mariner 3 / Mariner 4
November 5 / November 28, 1964
Payload fairing failed to open / First flyby and picture return
9, 10: Mariner 6 / Mariner 7
February 25 / March 27, 1969
Both flew by, returned pictures
11, 12: Mars 1969 A / Mars 1969 B
March 27 / April 2, 1969
Both destroyed during launch
13, 17: Mariner 8 / Mariner 9
May 8 / May 30, 1971
Destroyed during launch / First probe to orbit Mars
14, 15, 16: Cosmos 419 / Mars 2 / Mars 3
May 10 / May 19 / May 28, 1971
Failed in Earth orbit / Lander crashed / Lander failed
18, 19, 20, 21: Mars 4 / Mars 5 / Mars 6 / Mars 7
July 21 / July 25 / August 5 / August 9, 1973
Missed planet / Orbited planet / Lander failed (6 and 7)
22, 23: Viking 1 / Viking 2
August 20 / September 9, 1975
Both landed on surface, returned data
24, 25: Phobos 1 / Phobos 2
July 7 / July 12, 1988
Lost communication en route / Lost communication near Phobos
26: Mars Observer
September 25, 1992
Lost communication near Mars
27: Mars Global Surveyor
November 7, 1996
Orbited and returned data
28: Mars 96
November 16, 1996
Destroyed during launch
29: Mars Pathfinder
December 4, 1996
Landed on surface, deployed Sojourner rover
30: Nozomi
July 4, 1998
Missed planet
31: Mars Climate Orbiter
December 11, 1998
Crashed due to imperial/metric unit mixup
32: Mars Polar Lander
January 3, 1999
Crashed on surface
33: Mars Odyssey
March 7, 2001
Orbiting Mars
esa
34: Mars Express / Beagle 2 lander
June 2, 2003
Orbiting Mars, Beagle lost after separation
35, 36: Mars Exploration Rovers Spirit and Opportunity
June 10 / July 7, 2003
Both landed on surface, Opportunity still in operation
37: Mars Reconnaissance Orbiter
August 12, 2005
Orbiting Mars
38: Phoenix
August 4, 2007
Landed, dug for water
39: Phobos-Grunt
November 8, 2011
Stranded in Earth orbit
Viking 1 and 2
Sojourner
Spirit and Opportunity
Phoenix
Curiosity
Image credits:
NASA, Roscosmos, ESA, JAXA, Exchange3D.com
Additional research sources:
Space.com, RussianSpaceWeb.com
Dates indicated are for launch.
Only dedicated Mars missions are listed.
Created by Jason R. Davis
www.astrosaur.us

The *Mars Orbiter Laser Altimeter* on board the *Mars Global Surveyor* has provided maps of the topology with unprecedented accuracy.



Artist's impression of the Mars Global Surveyor in orbit. The above shows the tracks obtained by MOLA during aerobraking around Mars.

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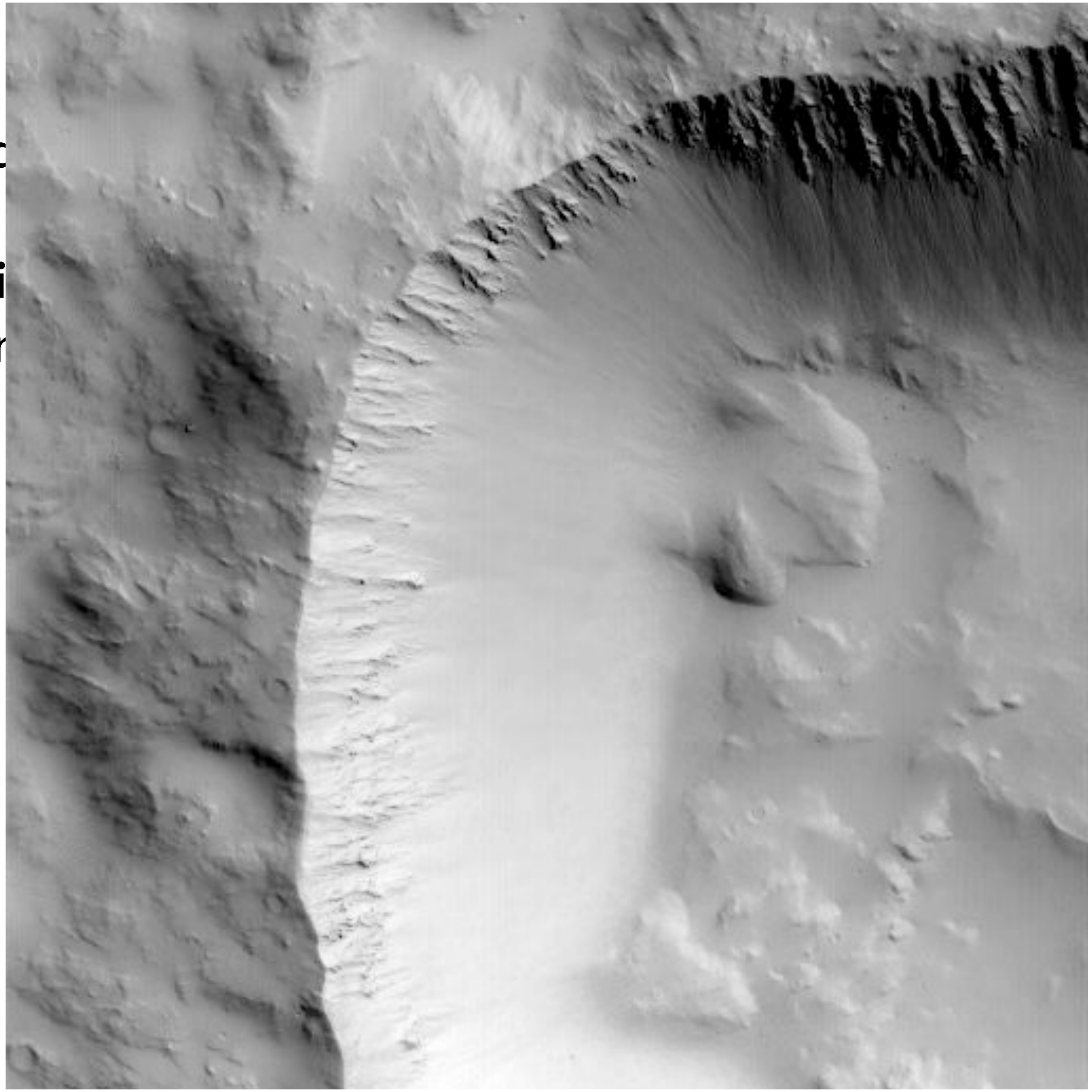
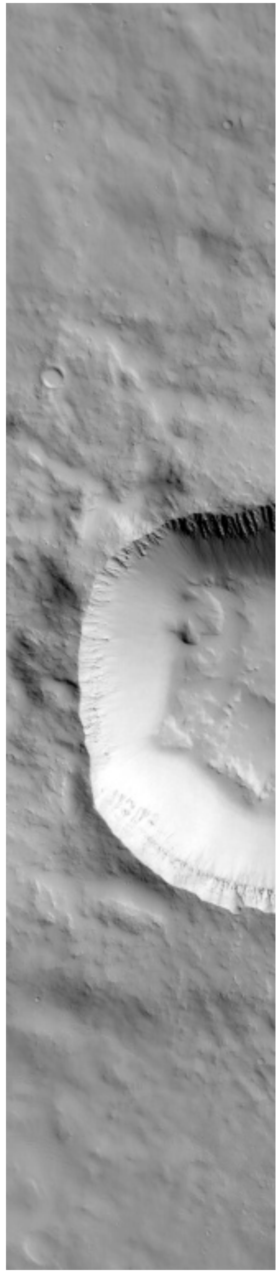
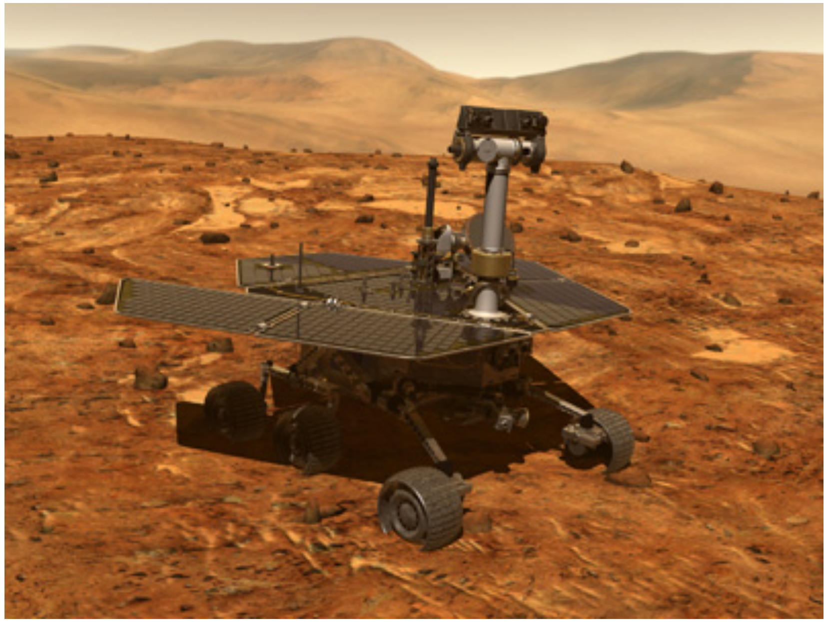
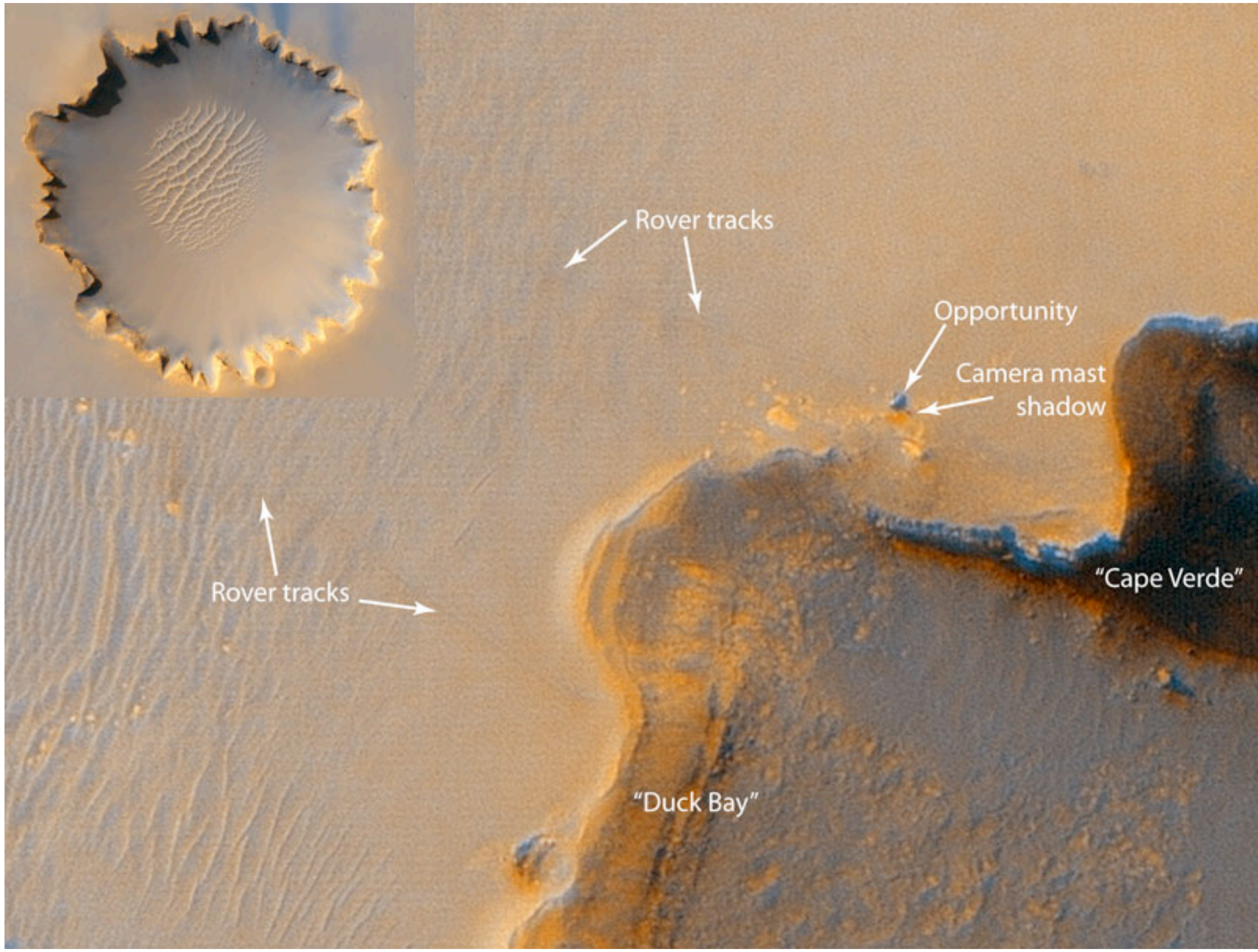
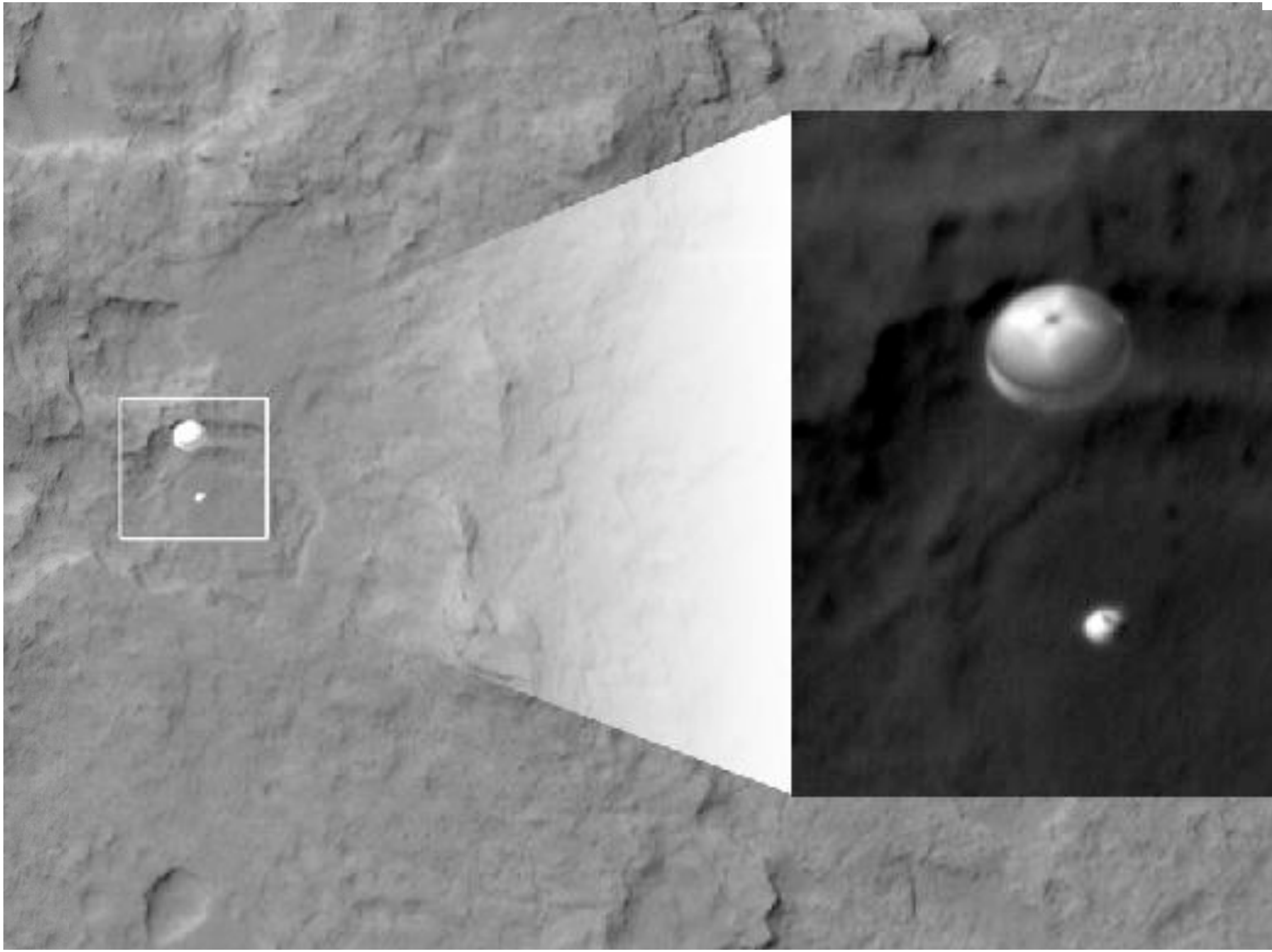




The *High Resolution Imaging Science Experiment* on the *Mars Reconnaissance Orbiter* can produce images of objects on the Martian surface as small as 1 metre across.







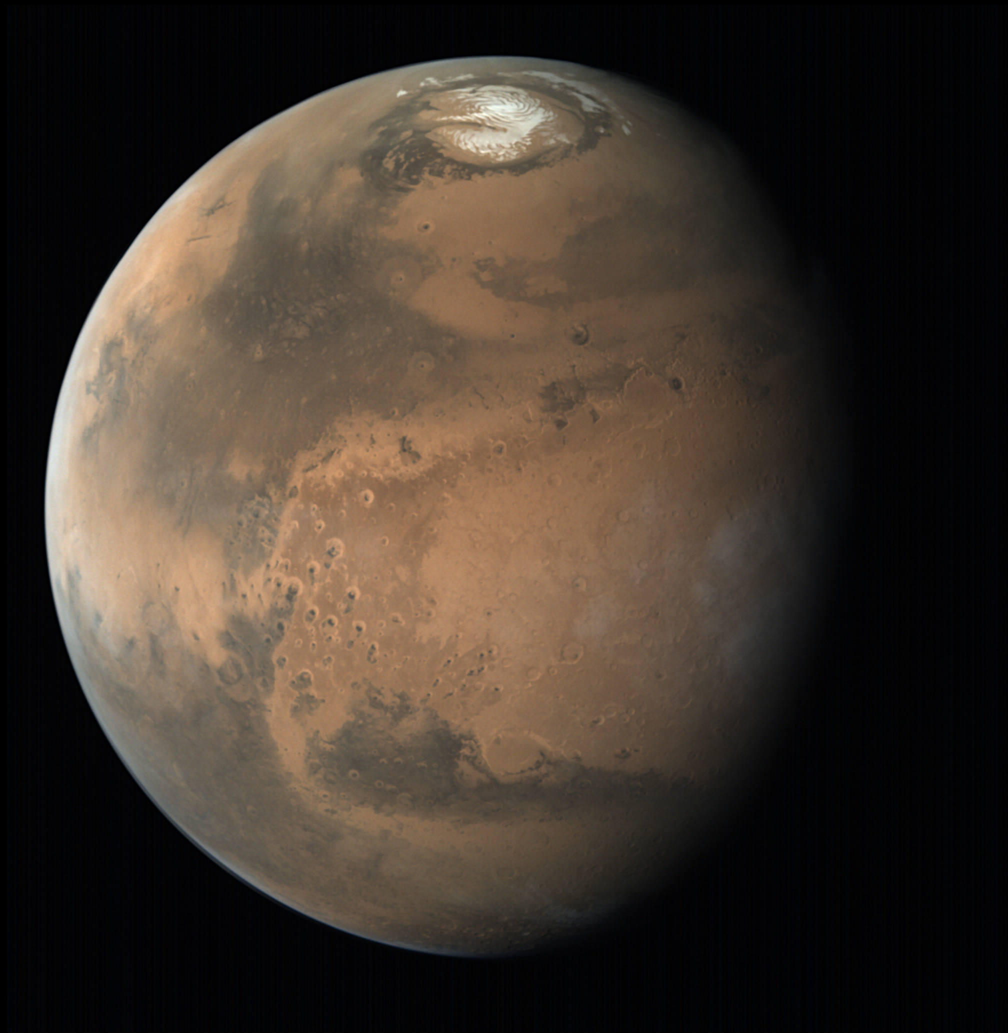
Curiosity during its descent, from MRO

Curiosity with tracks near Mt Remarkable

Panorama of Mt Remarkable by Curiosity, taken at the same time.

Curiosity selfie

The Face of Mars



Basic data

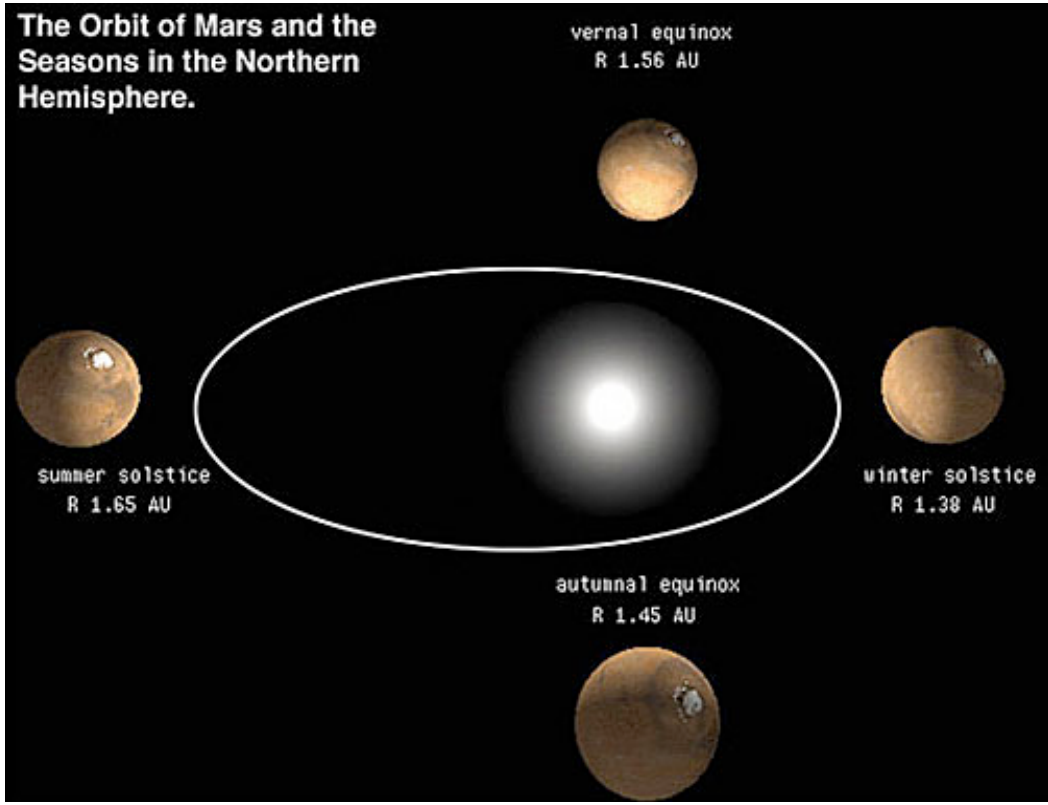
Mars is much smaller than the Earth, but in other ways is extremely similar.

	Mars	Mars/Earth
Mass	0.64185×10^{24} kg	0.107
Radius	3397 km	0.532
Mean density	3.92 g/cm^3	0.713
Gravity (equatorial)	3.71 m/s^2	0.379
Semi-major axis	227.92×10^6 km	1.524
Period	686.98 d	1.881
Orbital inclination	1.85°	-
Orbital eccentricity	0.0935	5.59
Axial tilt	25.2°	1.074
Rotation period	24.6229 h	1.029

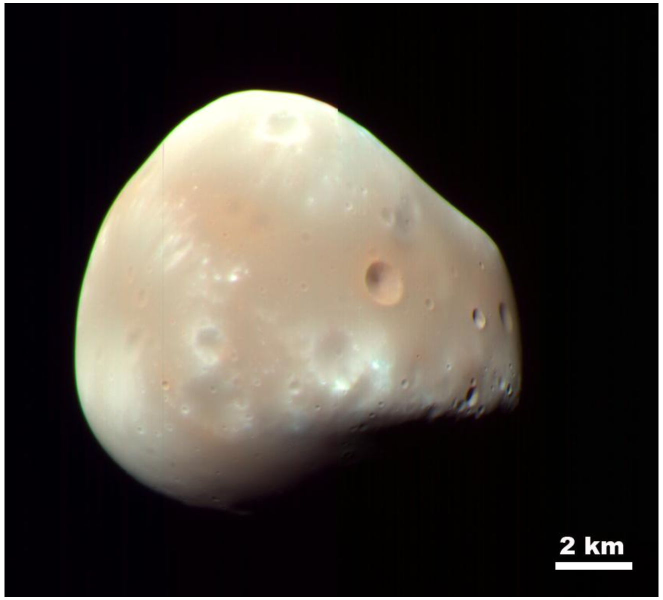
Mars is quite small relative to Earth, but in other ways is extremely similar. The radius is only half that of Earth, though the total surface area is comparable to the land area of Earth. It take nearly twice as long to orbit the Sun, but the length of its day and its axial tilt are very close to Earth's.

The eccentricity of Mars' orbit is much greater than that of Earth, making its orbit distinctly non-circular. The amount of sunlight received is about 40% greater at perihelion than at aphelion, which has important consequences for Martian seasons.

On Earth, nearly all of the annual variation in temperature occurs because of the axial tilt. Mars, however, has a much higher orbital eccentricity than Earth: its distance from the Sun varies from 206 million km to 249 million km during a Martian year. This amounts to a 68% change in the amount of sunlight falling on Mars between the two points! This gives rise to much larger seasonal temperature changes than on Earth. The southern hemisphere has shorter, hotter summers and longer, colder winters than the northern hemisphere. Polar ice loss, weather patterns, and dust storms are all affected by this.



Mars has two tiny moons: *Phobos* (27 km long) and *Deimos* (15 km). They are almost certainly asteroids which approached close to Mars and were captured. They orbit only 9000 km and 23000 km from the surface.



Phobos (left) and Deimos (right)

Image of Phobos over Mars' limb, from Mars Express

Earth's moon is more than 100 times larger than Phobos, the larger of Mars' two moons; but the Martian moons orbit much closer to their planet than the Moon does to Earth. This picture shows the apparent size of the moons from each planet's surface.

Phobos actually orbits faster than Mars rotates, so from the surface of Mars it rises in the west and sets in the east, twice each Martian day.

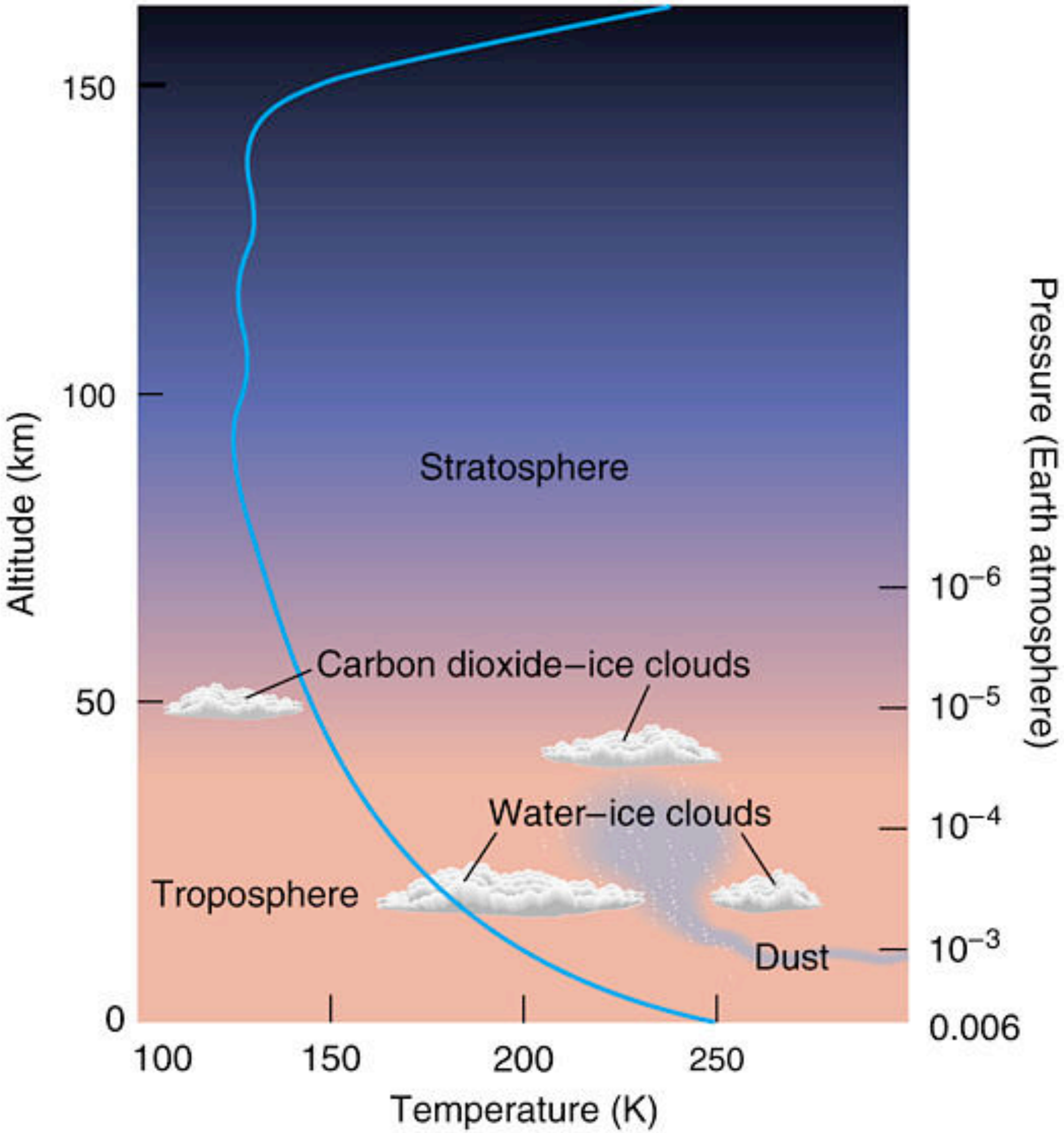
Phobos is being dragged down towards Mars, and will eventually crash into the surface.

Curiosity's view of Phobos and Deimos as they cross the night sky

Atmosphere

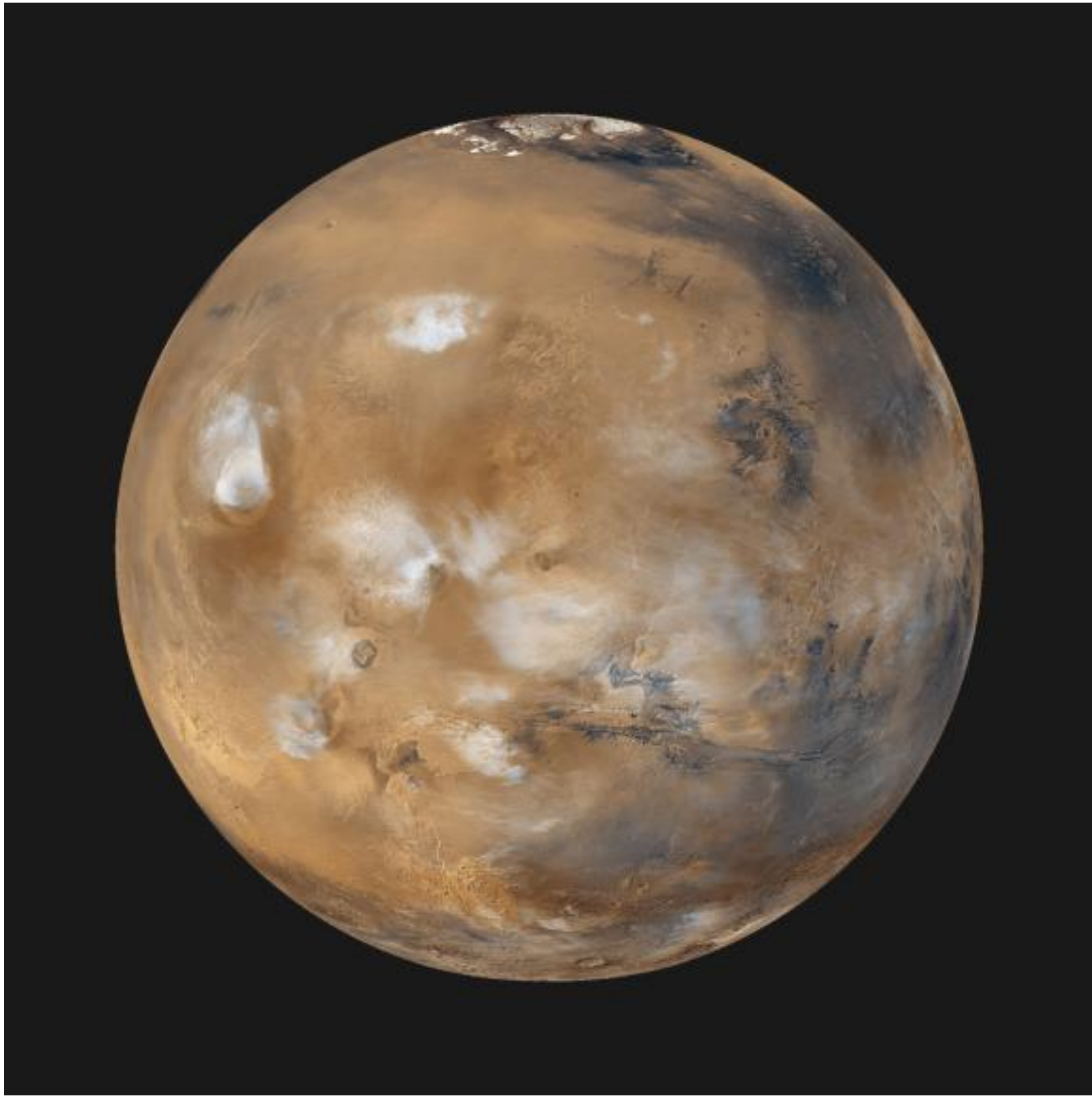
The Martian atmosphere is 95% CO_2, 2% nitrogen, and 1–2% argon. The atmospheric pressure is about 6 millibar (about 1/150th of Earth's). There is a seasonal variation in pressure of about 20%, due mostly to the extra carbon dioxide which freezes out of the atmosphere.

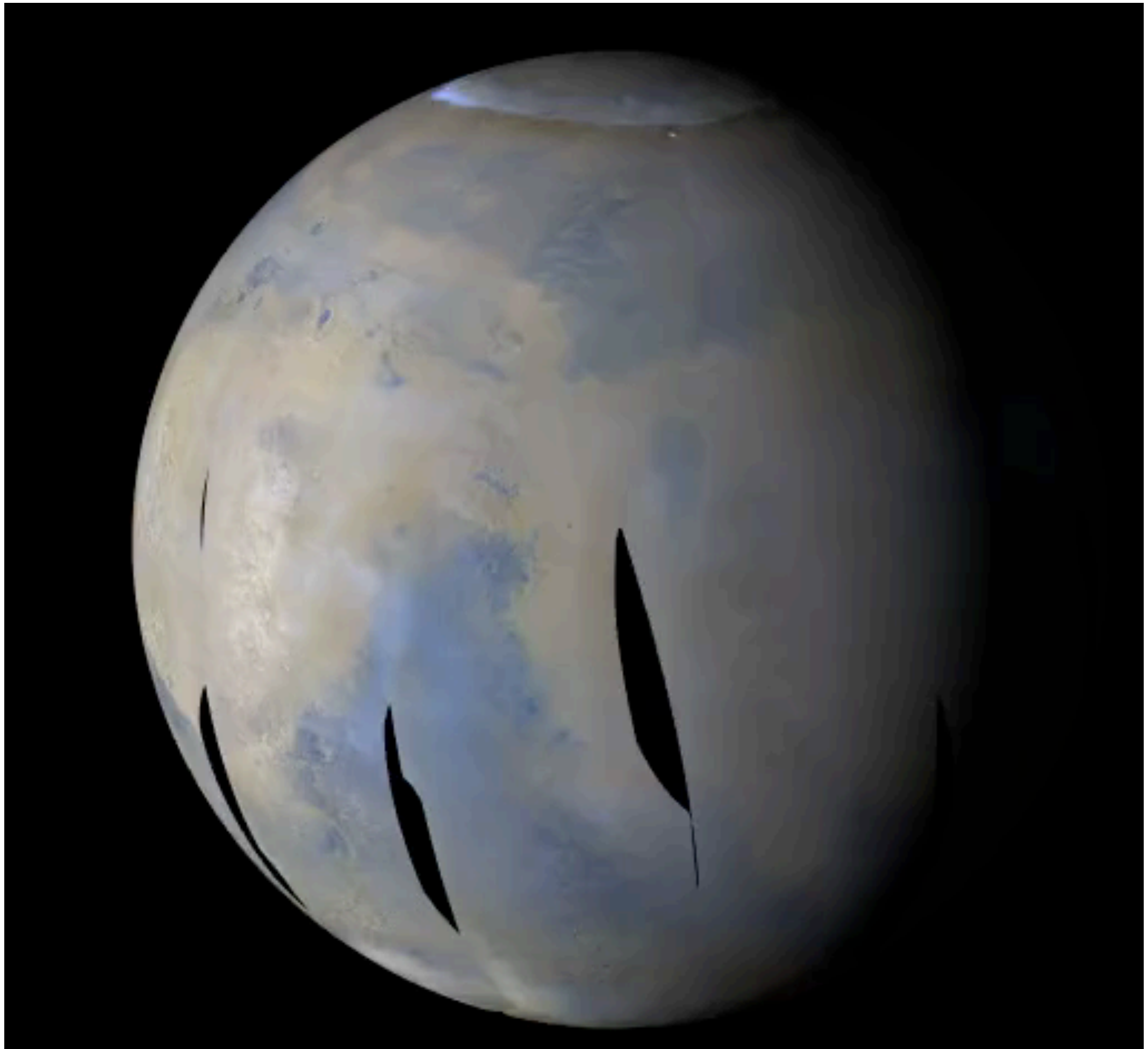
An oblique view of Mars taken by the Viking Orbiter, showing the Martian atmosphere over the Argyre impact basin.



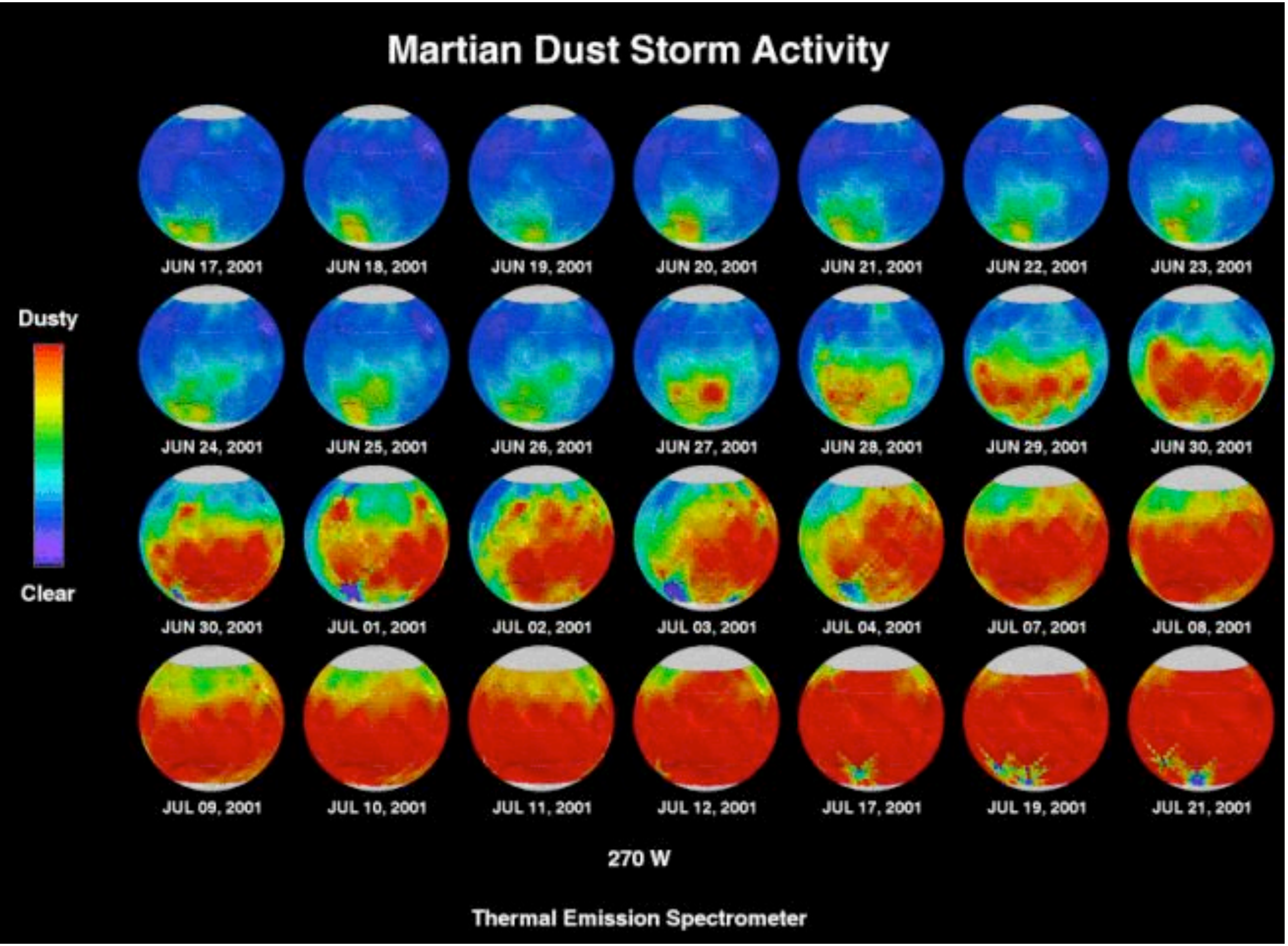
The scale height of the Martian atmosphere is higher than Earth's (11 km compared with 6 km), due to Mars' lower gravity. The Martian atmosphere produces a weak greenhouse effect which raises the surface temperature by about 5°C over what would be expected in the absence of an atmosphere.

Clouds of water ice can form on Mars, particularly around the high volcanos.





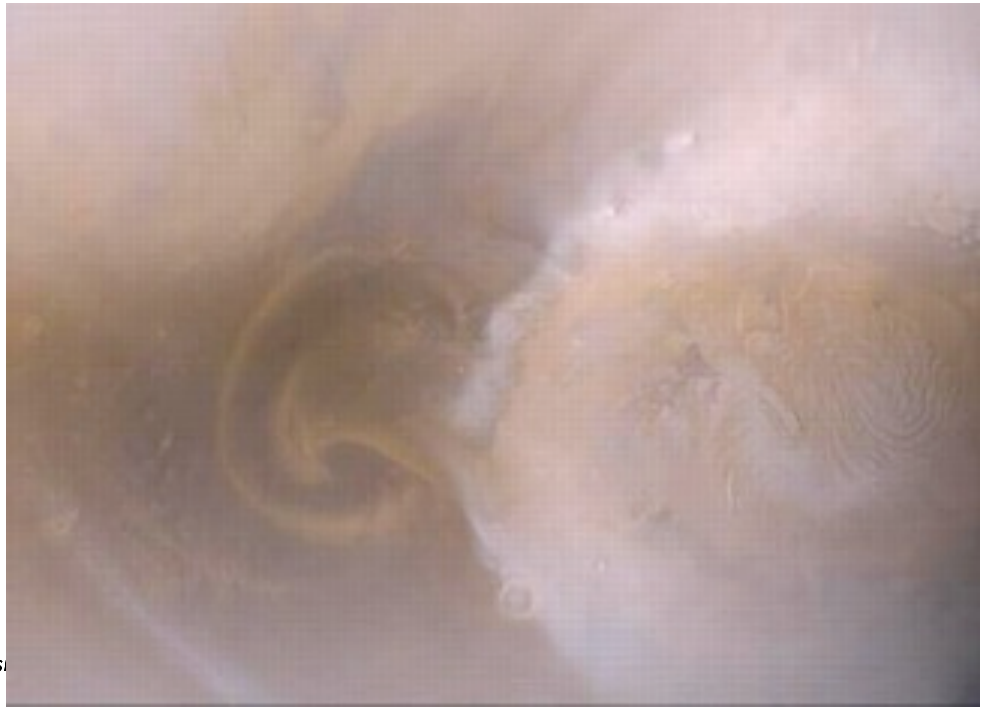
September 18, 2017

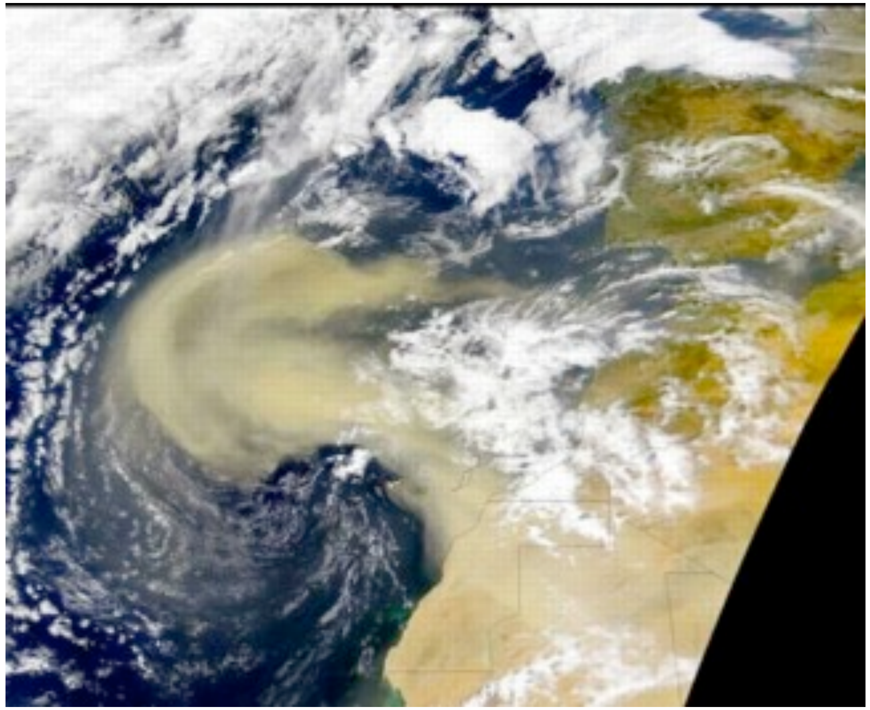


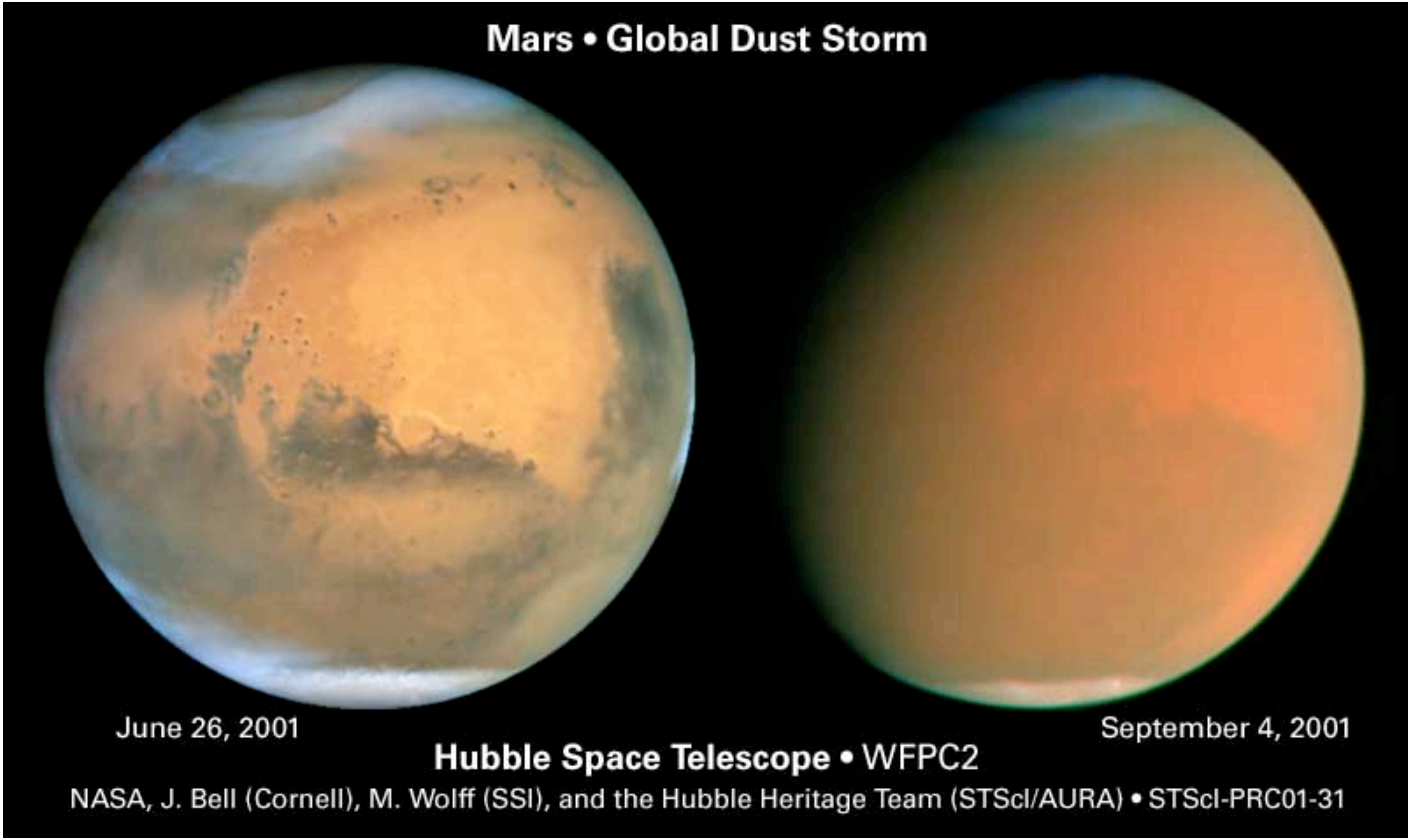
The Martian spring is the time for giant, planet-wide dust storms.

Dust eroded from low latitudes is carried in dust storms to the poles, where it is deposited. These giant dust storms can lead to large-scale changes in the appearance of the planet – which in the 19th century led to theories of seasonal vegetation coverage.

The fine dust settles over most terrains, and is mixed over the whole planet.



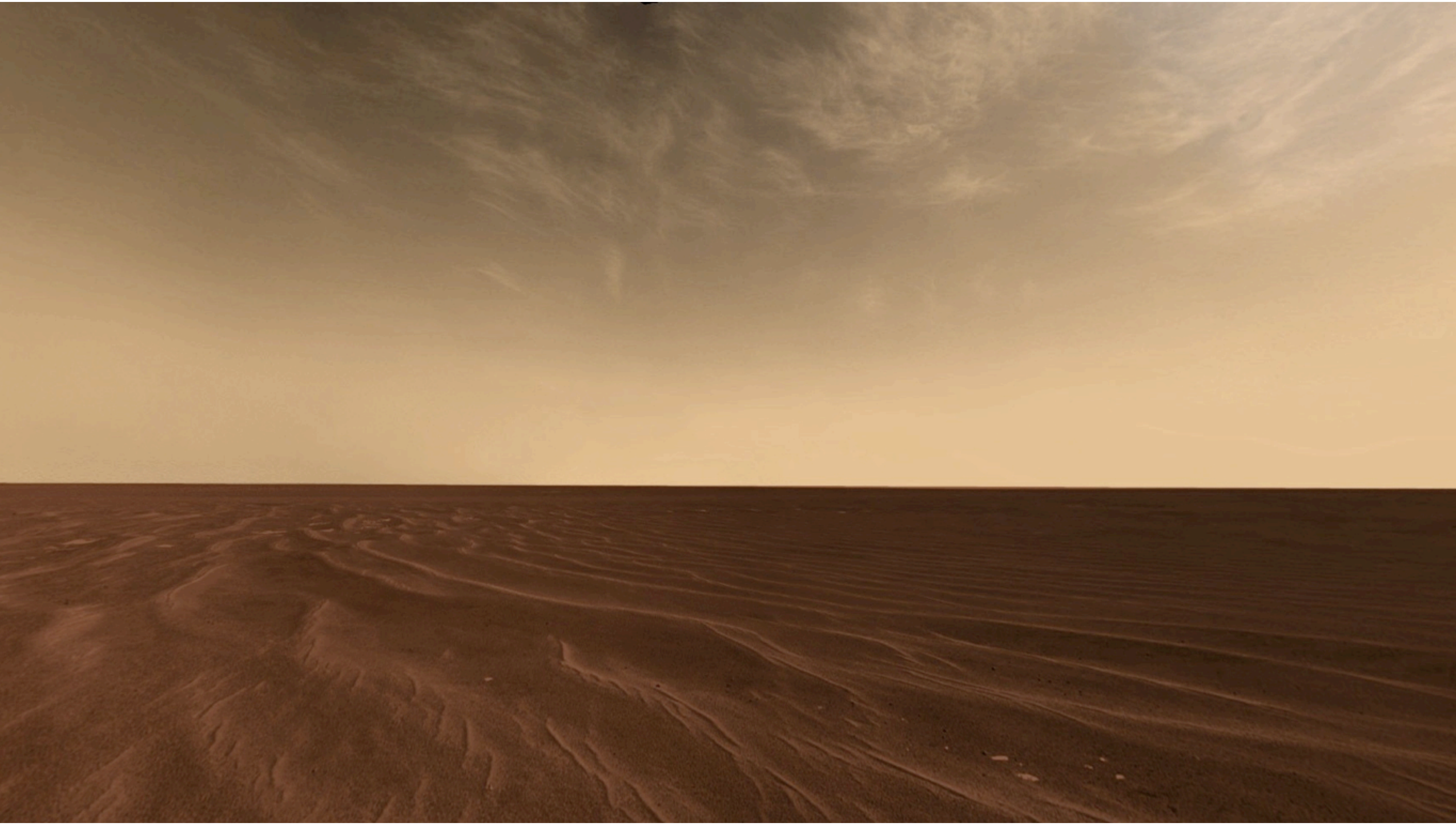




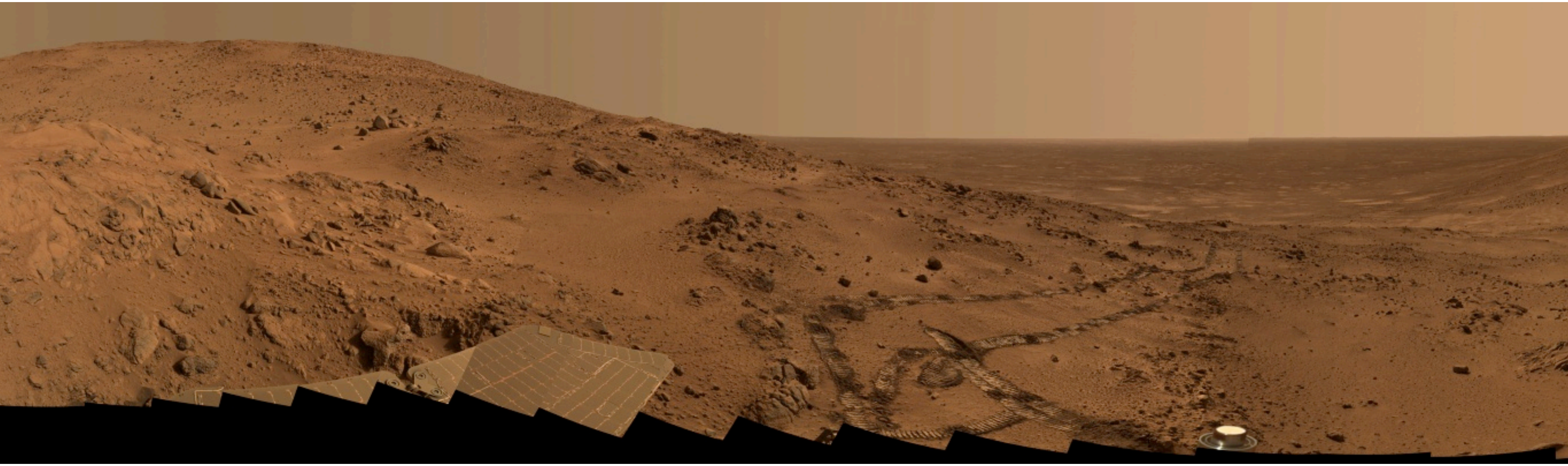
Hubble images of Mars before and during a global dust storm.

The dust frequently gets whipped into dust devils, which have been photographed from orbit. Some of them are as large as 1 to 2 km across at their base.

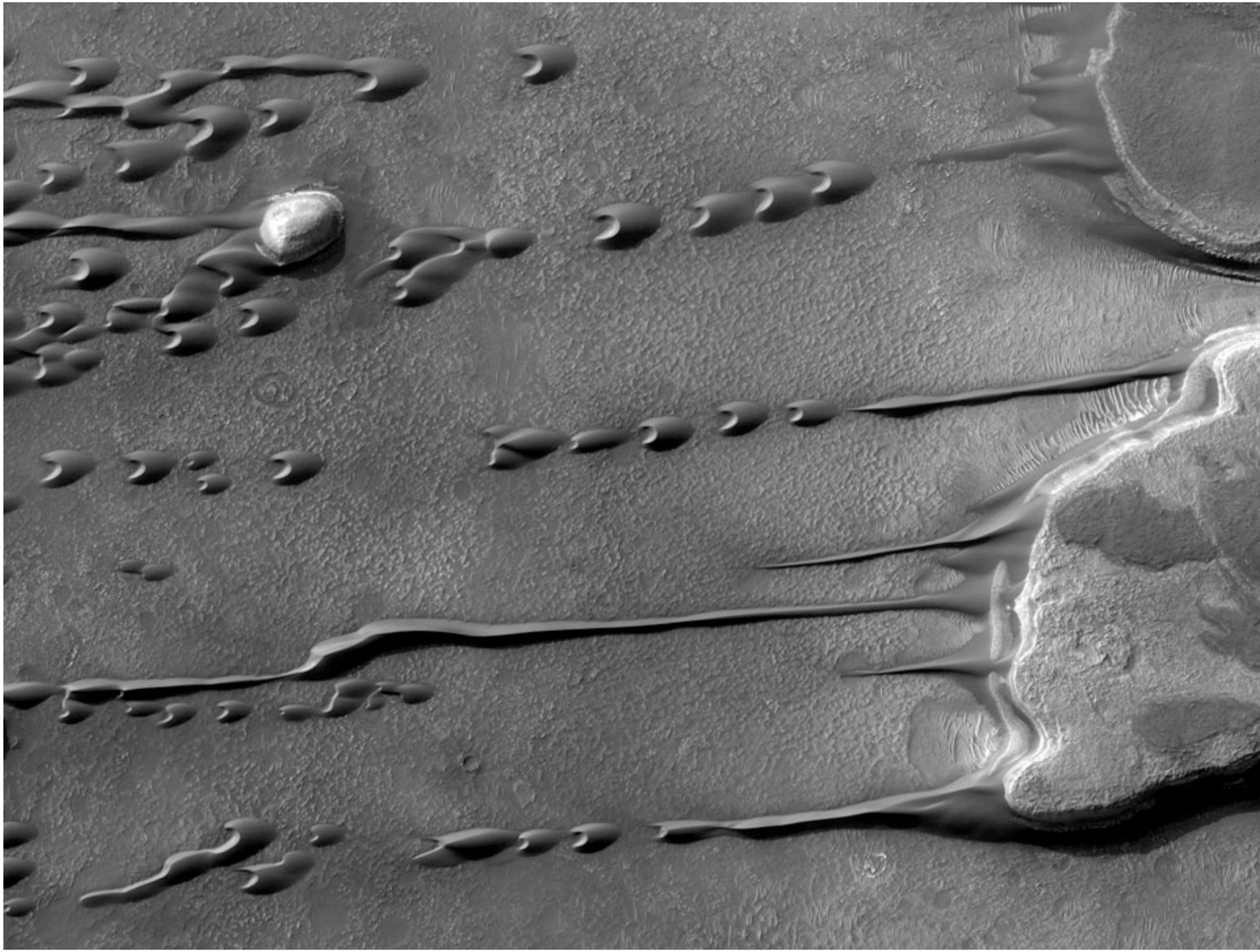
Spirit and *Opportunity* have seen many dust devils; here is one seen in *Spirit's* navigation camera.



Because of the major dust storms, the soil on Mars' surface seems to be remarkably homogeneous. It is rich in iron, magnesium, and calcium, and low in potassium, aluminium and silicon. In general, they look more like rocks in Earth's mantle than the rocks which make up Earth's crust.

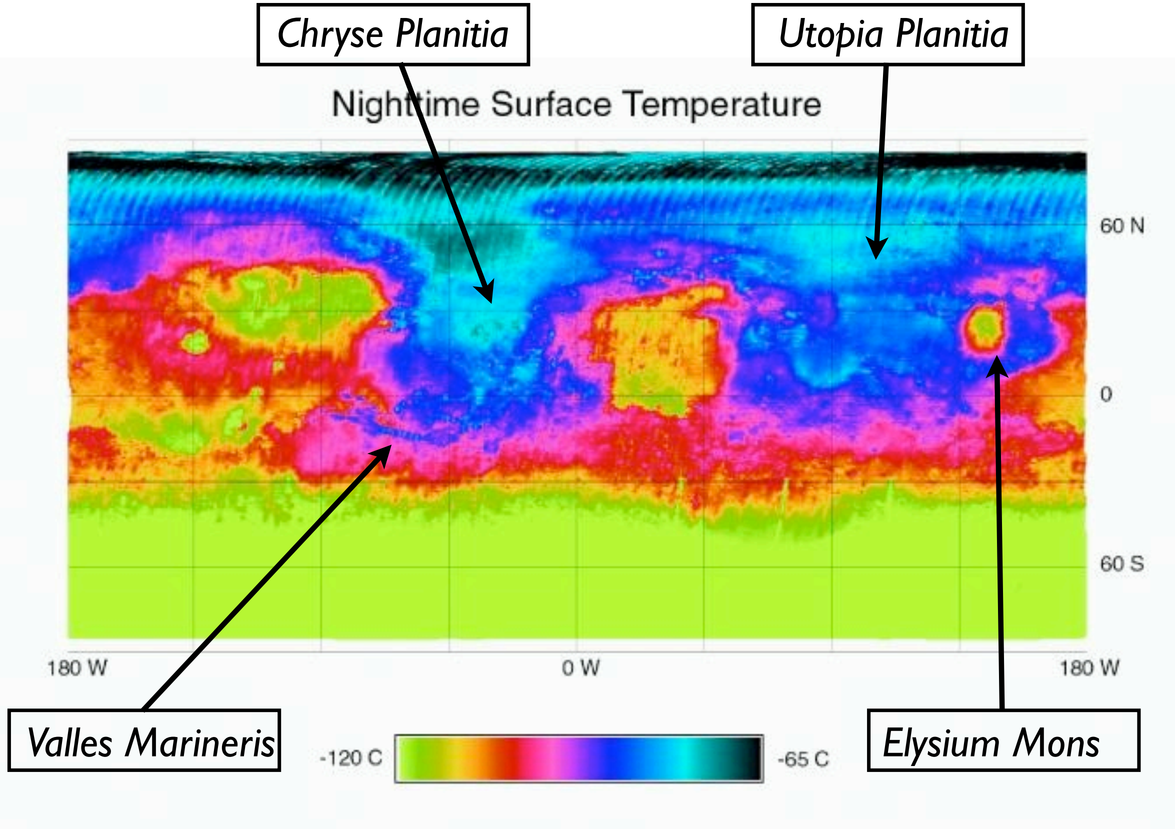


Panorama of Mars from Larry's Lookout, taken by Spirit.



Barchan sand dunes, migrating due to a persistent wind flowing right to left from the mesas on the right.

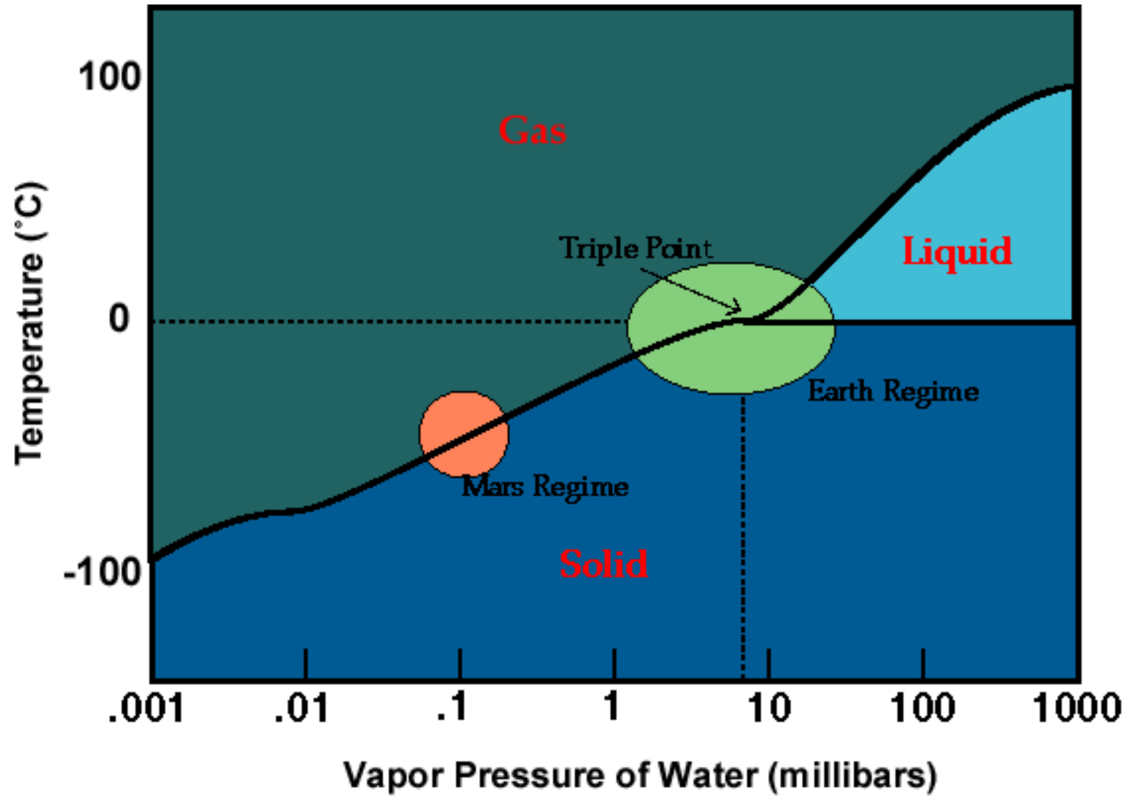
Typical air temperatures on the Martian surface range from –80°C at night to 0°C in the afternoon. Soil temperatures can get as high as 10°C in the afternoon.



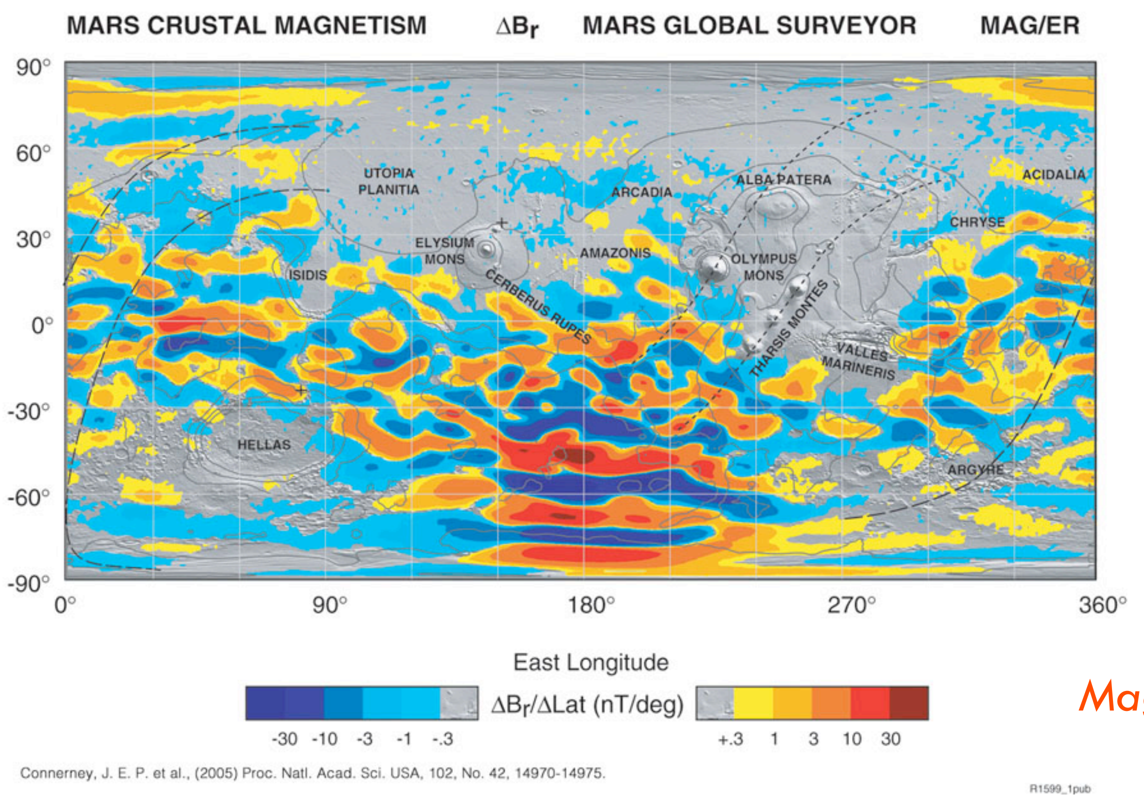
MGS map of night-time temperatures, taken during southern-hemisphere winter. The two red regions near the equator are Chryse Planitia and Utopia planitia: Valles Marineris and the Elysium volcanoes are clearly visible.

Water cannot exist in liquid form on Mars: at its current temperature and pressure, water can exist only as a solid or a gas. Even in the most favourable spots, where the pressure is higher than average, water would boil at 10° C.

Rainfall has probably played little role on Mars, unless the conditions were significantly different early in its history.



Mars has no intrinsic magnetic field, but has permanently magnetised patches on its surface. In several regions, they show stripes of reversed magnetic field, just like the stripes in the Atlantic, recording magnetic field reversals as the plates spread

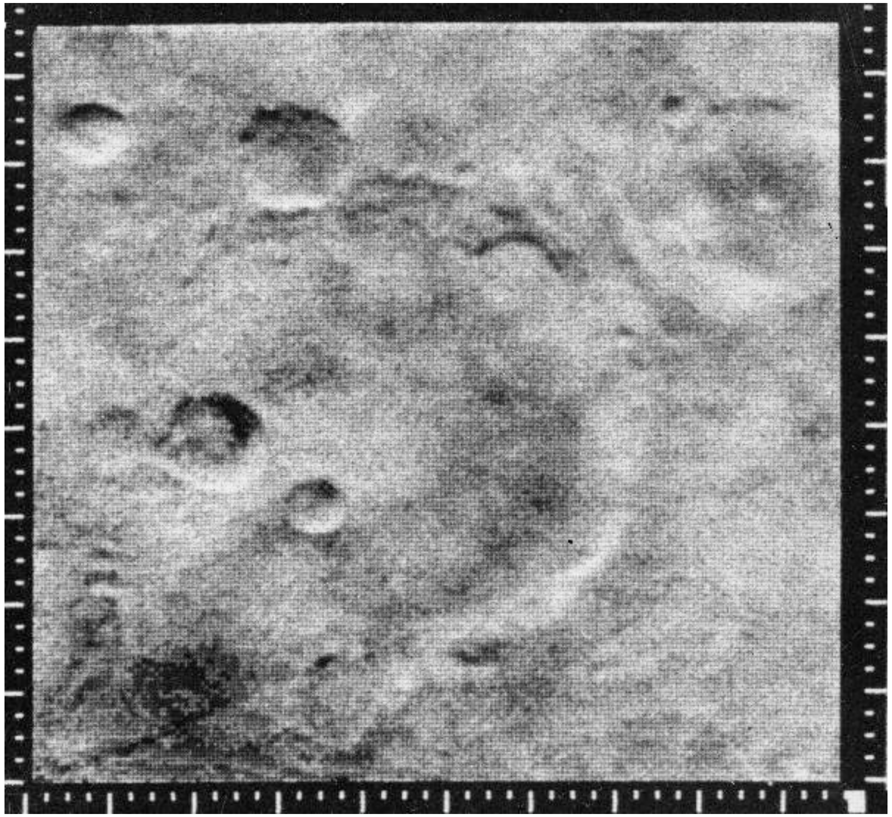


Magnetic field measurement by the Mars Global Surveyor

Areography

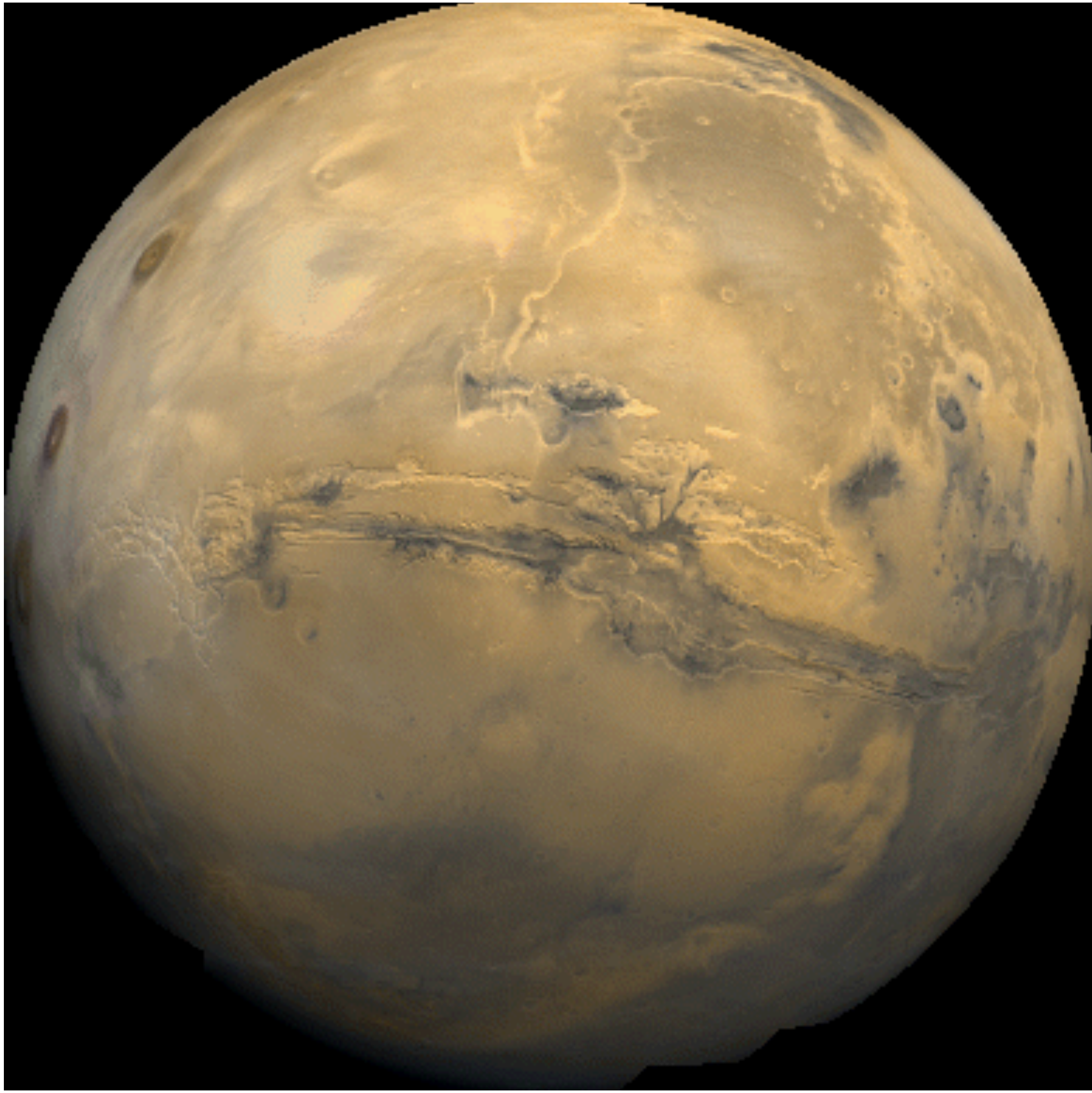
In the early 1960s, the first spacecraft flew past Mars. They showed a landscape covered by craters, very like the Moon or Mercury.

Then in 1971, *Mariner 9* became the first spacecraft to orbit another planet, and our view of the planet was transformed overnight.

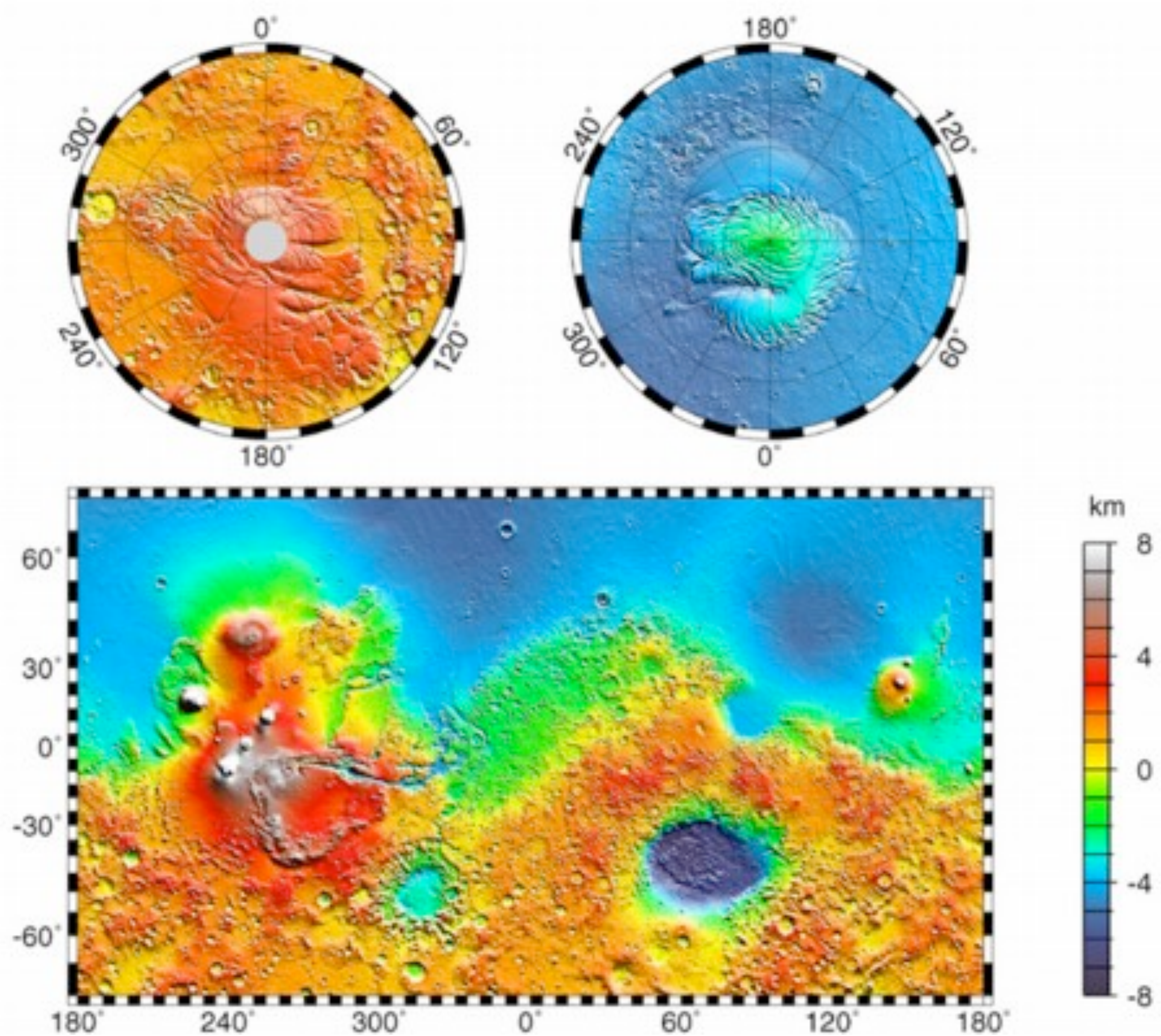


Mariner 4 image of Mars, taken during flyby in July 1965.

Mariner 9 revealed Mars to be a world with the largest volcanoes in the Solar System, craters, canyons, including a giant fissure 4000 km in length, riverbeds, and everywhere evidence of water and wind erosion.

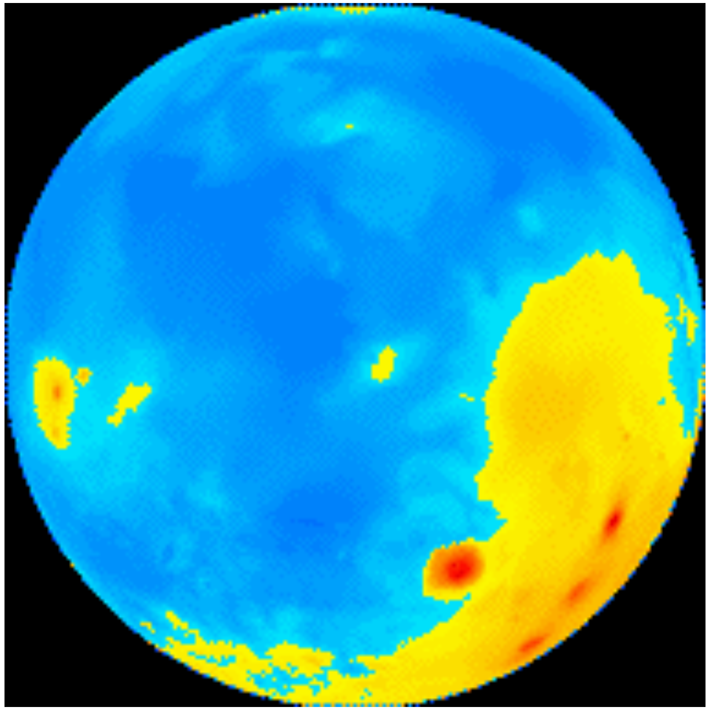


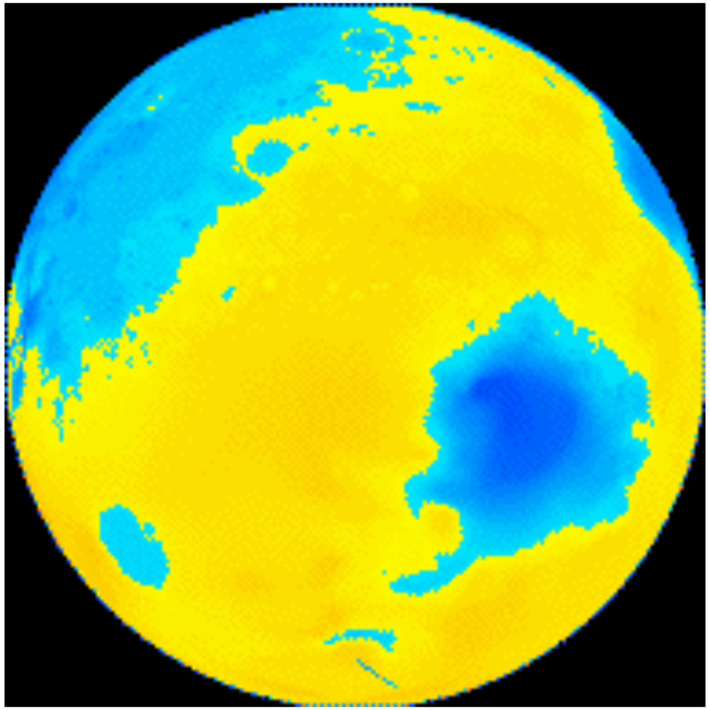
The Valles Marineris hemisphere of Mars, from mosaic of Viking images.

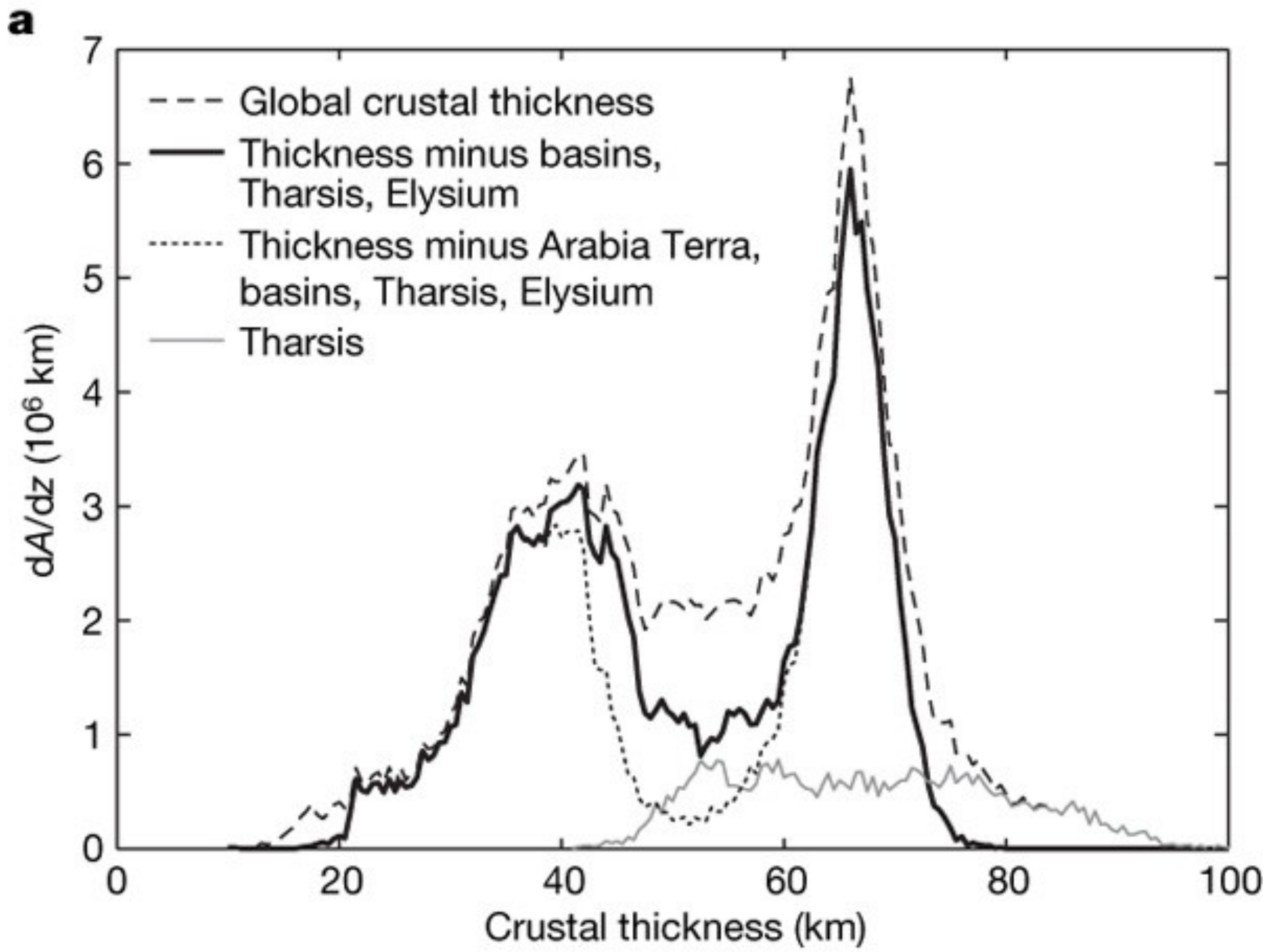


Precision measurements the laser altimeter on MGS show a global asymmetry: the southern hemisphere is several kilometres higher than the northern. Half the planet is heavily cratered and raised 1–4 km, the other is relatively smooth. This is known as the *crustal dichotomy*.

The boundary is not at the equator: the planet is roughly divided in half by a line inclined at about 35° to the equator. This can be seen in the following images, where we can find positions to view the planet from which the side facing us is almost all low (blue – except for the red areas around the volcanoes) and almost all high (except for the Hellas basin).

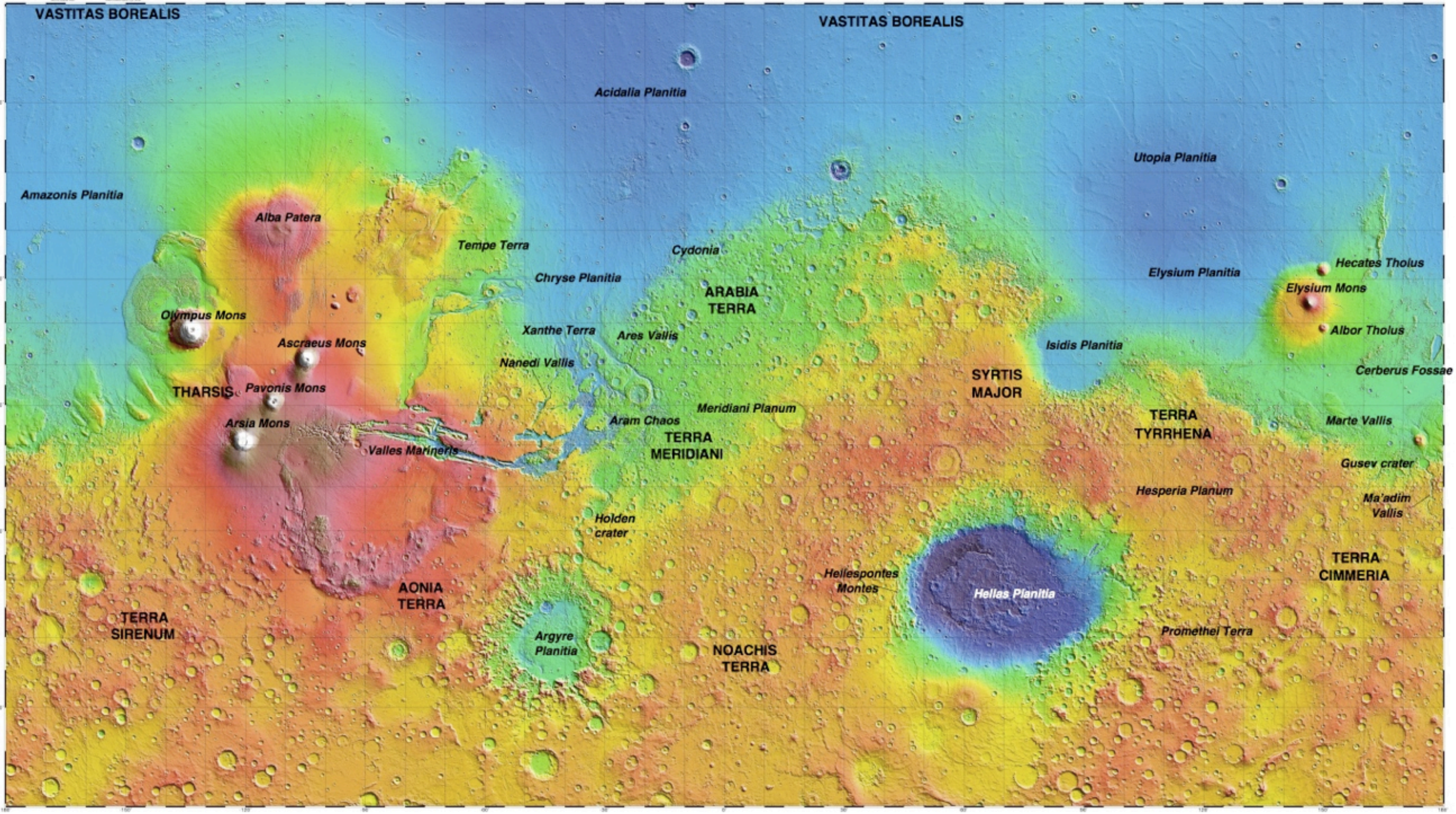


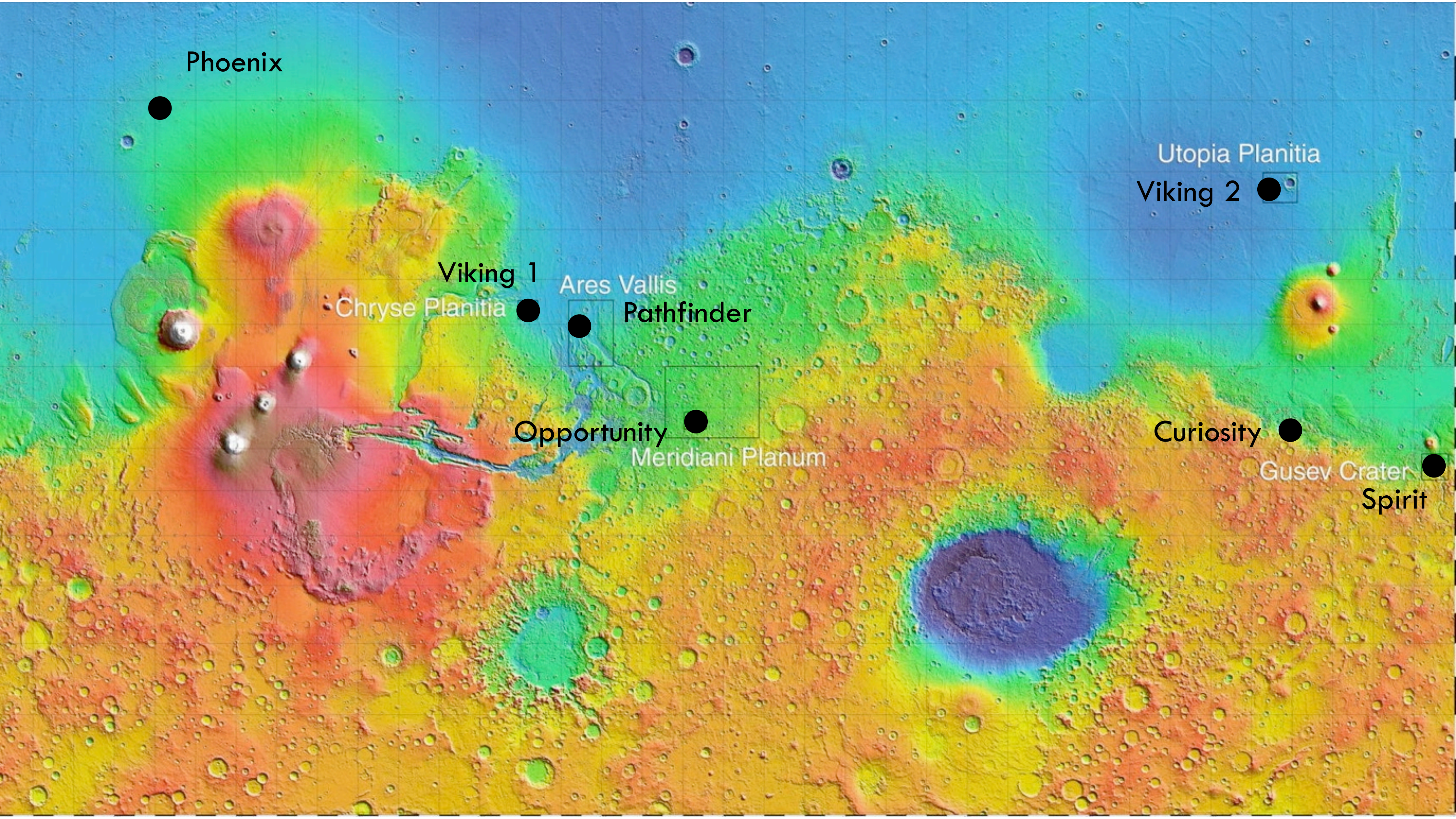




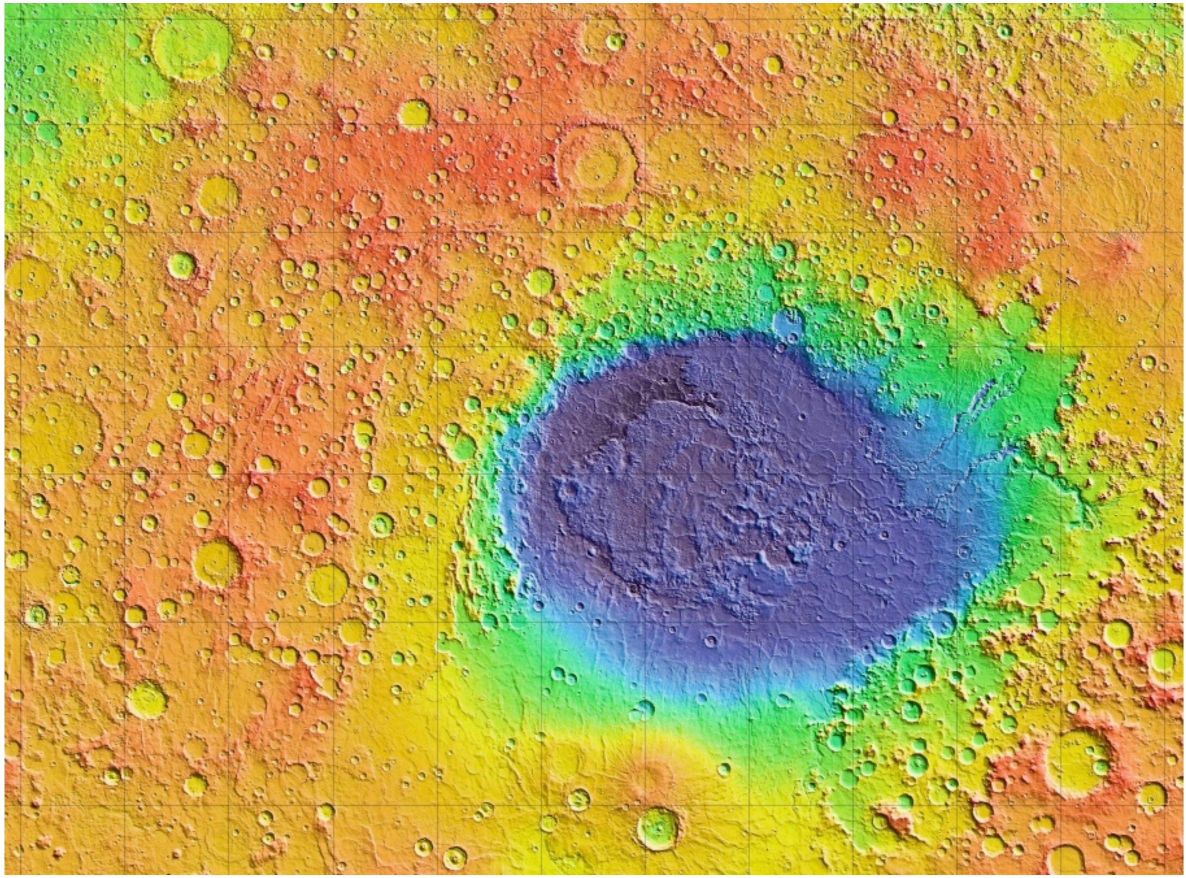
Histogram of crust thickness. Like Earth, Mars has a bimodal distribution of thicknesses.

THE TOPOGRAPHY OF MARS BY THE MARS ORBITER LASER ALTIMETER (MOLA)

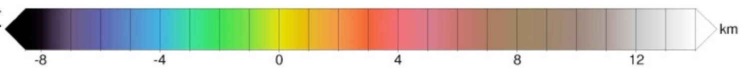



Phoenix
Utopia Planitia
Viking 2
Viking 1
Ares Vallis
Chryse Planitia
Pathfinder
Opportunity
Meridiani Planum
Curiosity
Gusev Crater
Spirit

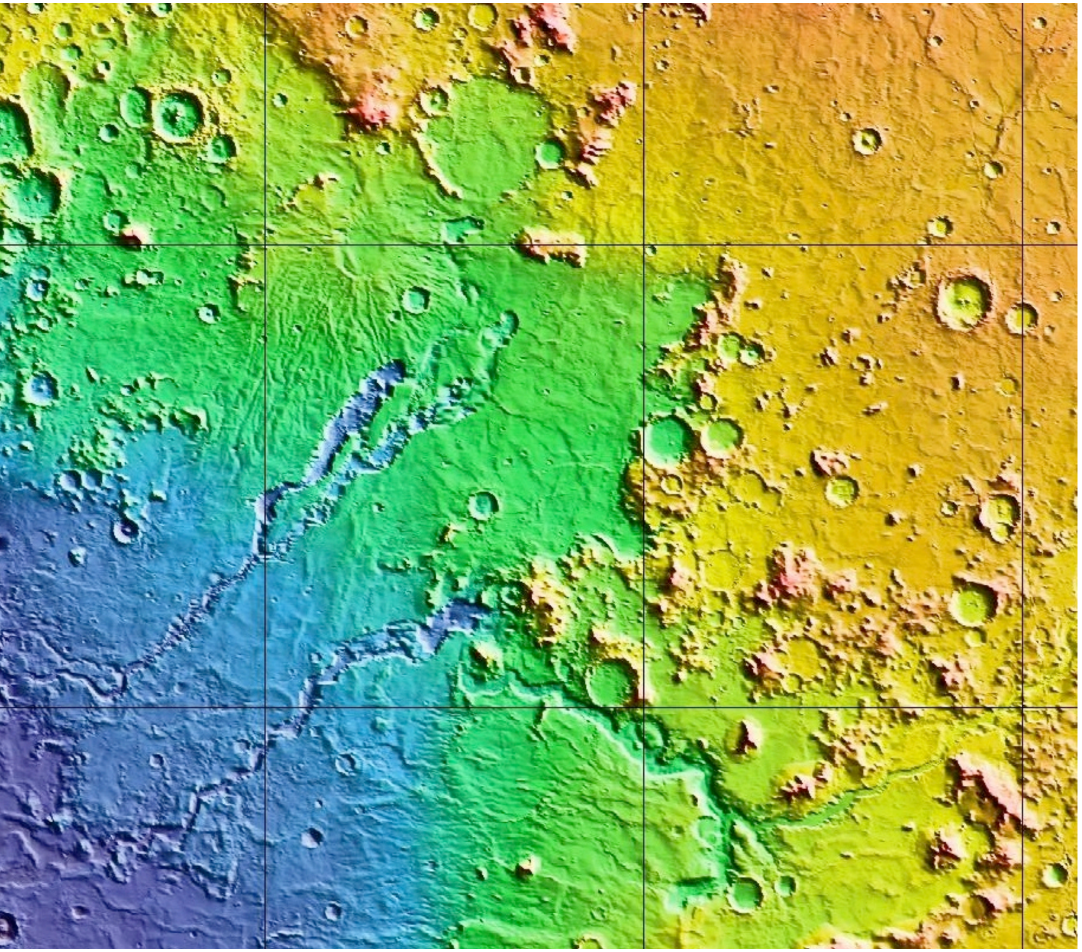
The southern highlands are saturated with craters, indicating they are the oldest regions on the planet. In the midst of this is a giant circular feature 1700 km across: *Hellas Planitia*, a giant impact crater. The floor of the basin is 8.2 km below the surrounding uplands, making it the lowest region on the planet.



Map of the Hellas impact basin from MGS altimeter measurements. The colours code for height, with the blue areas being the lowest; yellow is the global average elevation.

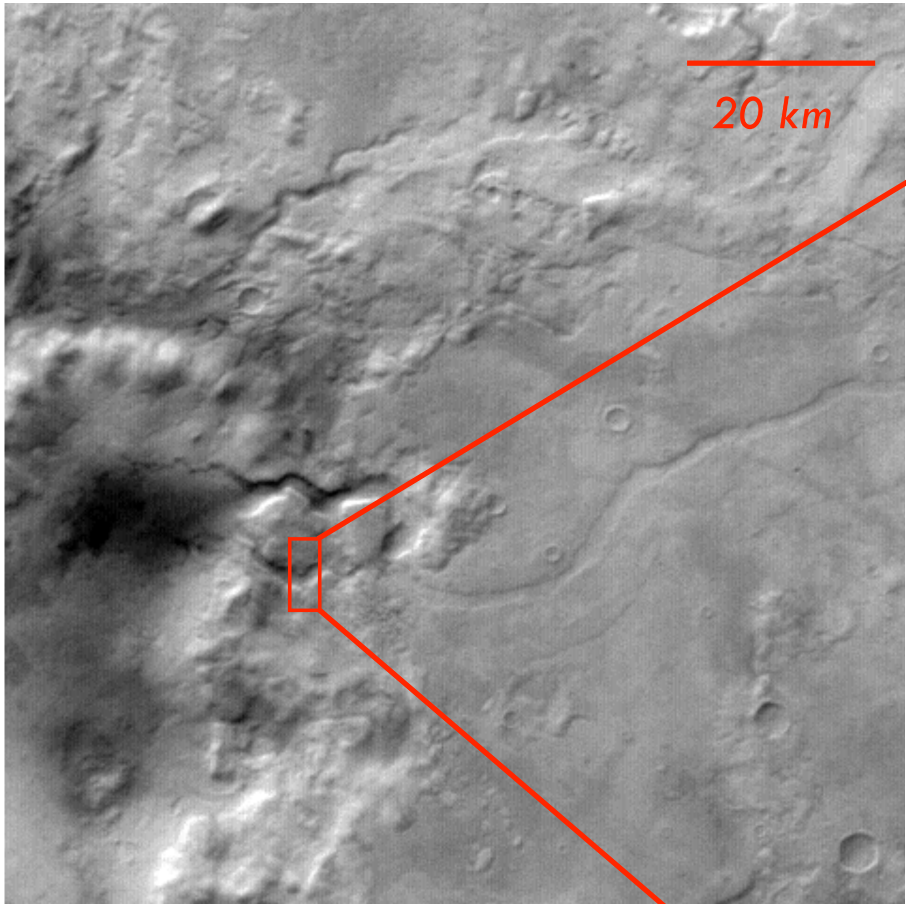


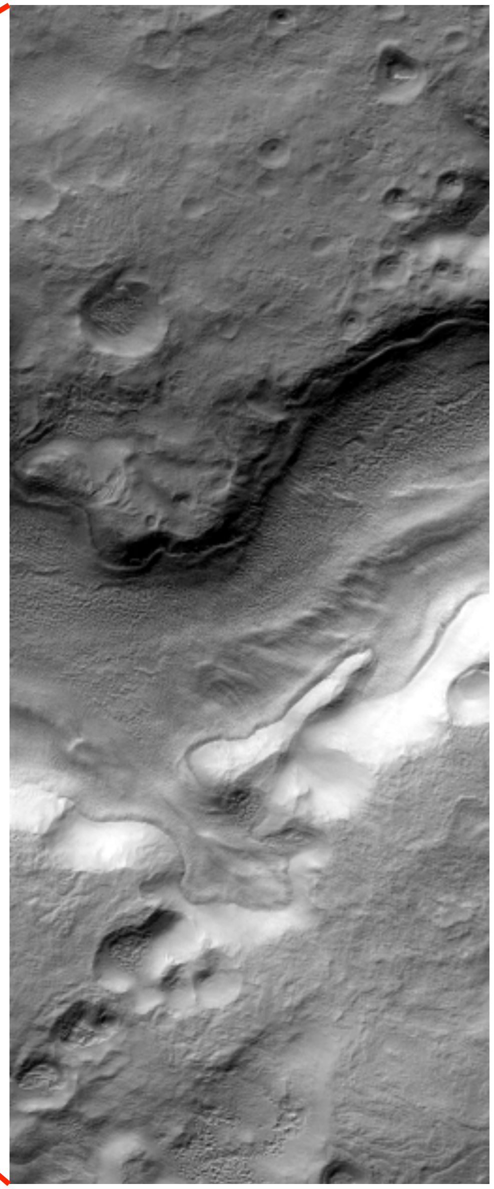
The rim of Hellas is severely eroded, with no sign of a crater rim. Drainage channels hundreds of kilometres long lead into the basin, showing that water was active on Mars at least at some stage.



The floor of the basin is covered in layers of sediment deposited by wind or water, which in some places are being eroded by the wind.

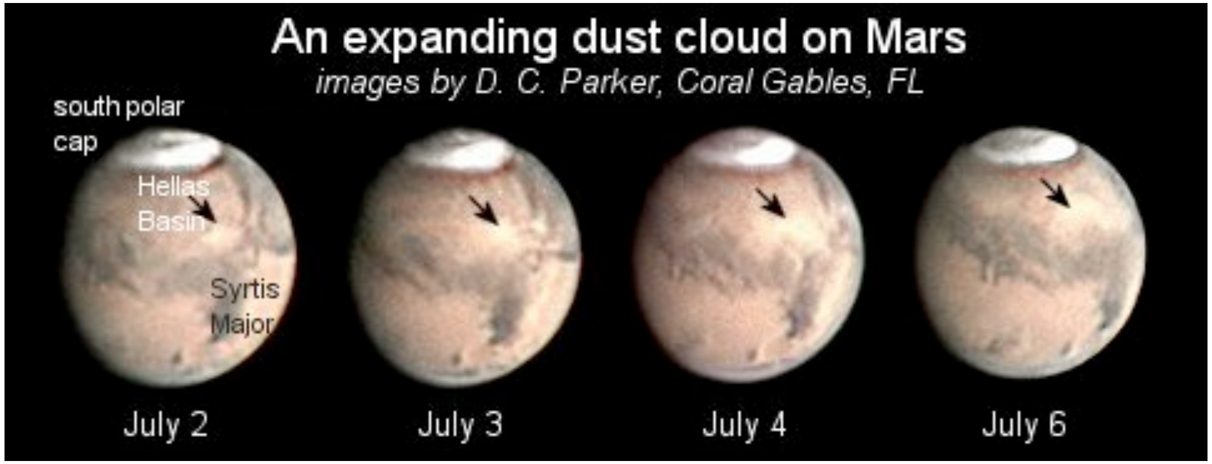
North-eastern rim of the Hellas basin

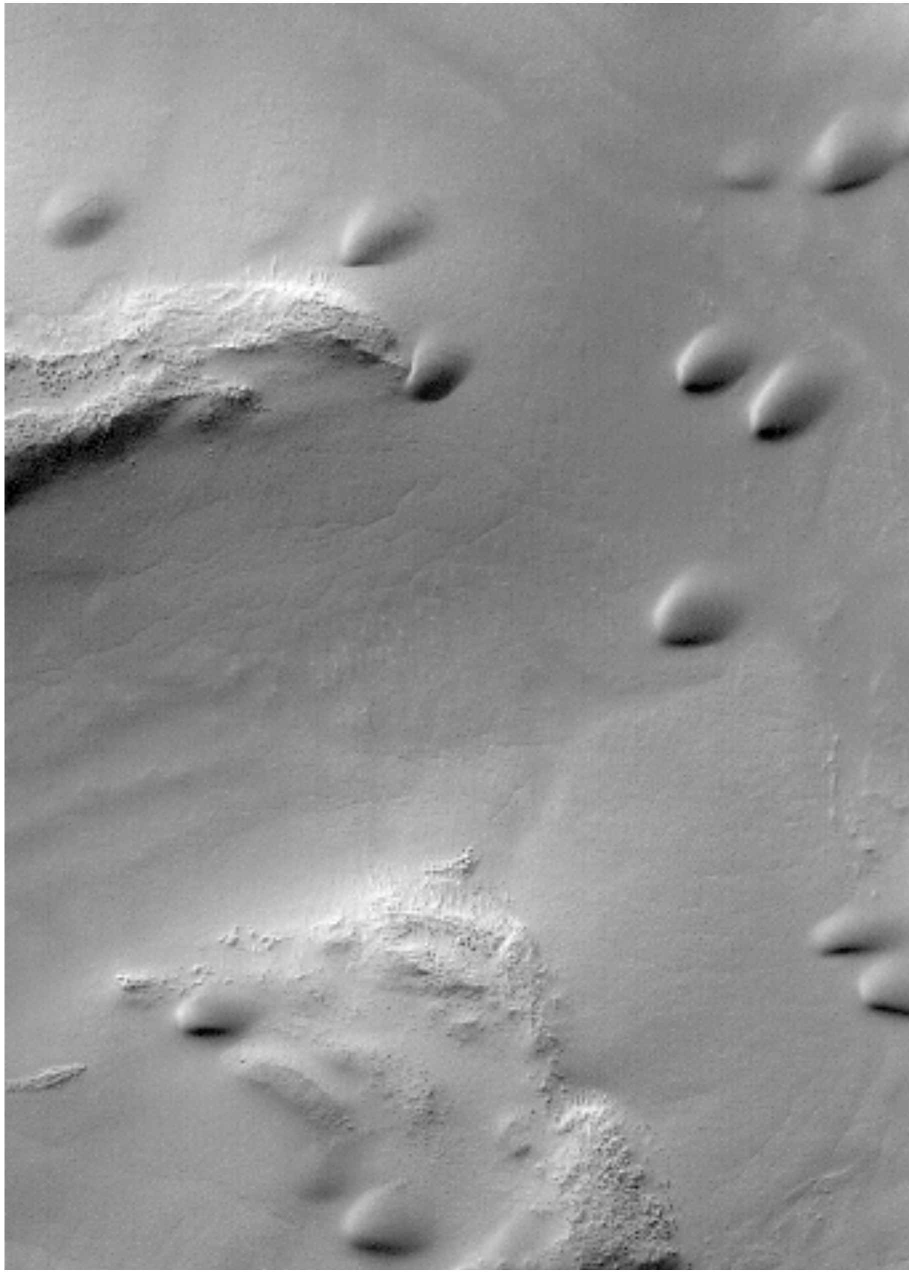




Channels in the wall of the Hellas basin, which in close-up show a dark deposit, like a muddy slurry.

Hellas is the deepest hole in the solar system. The air at the bottom is up to 10° warmer than the air at the top; this gradient drives strong winds, so Hellas is often the source of global dust storms.





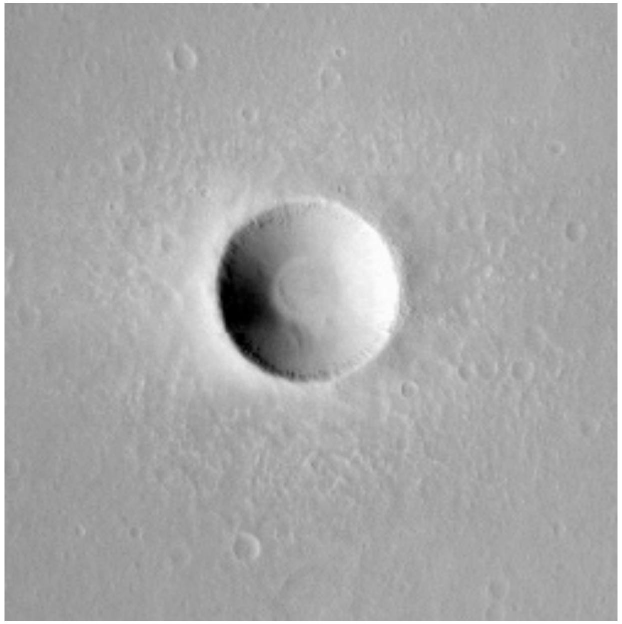
(right) Sand dunes in Hellas; (above) Earth-based pictures of a dust storm originating in Hellas.

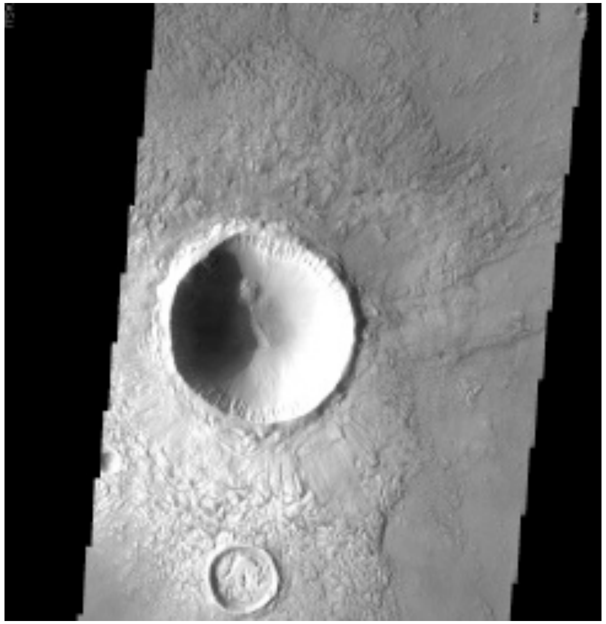
The cratered highlands in the south looks very like the Moon, but there are important differences. Many intermediate sized craters (tens of km) have been nearly obliterated by erosion. This suggests there may have been an intense early period of erosion.

Many craters on Mars have ejecta blankets which appear to have flowed to their current positions. This suggests there was ice or water in the crust during the bombardment.

Ejecta around the crater Yuty (19 km in diameter), with lobes in the ejecta blanket.

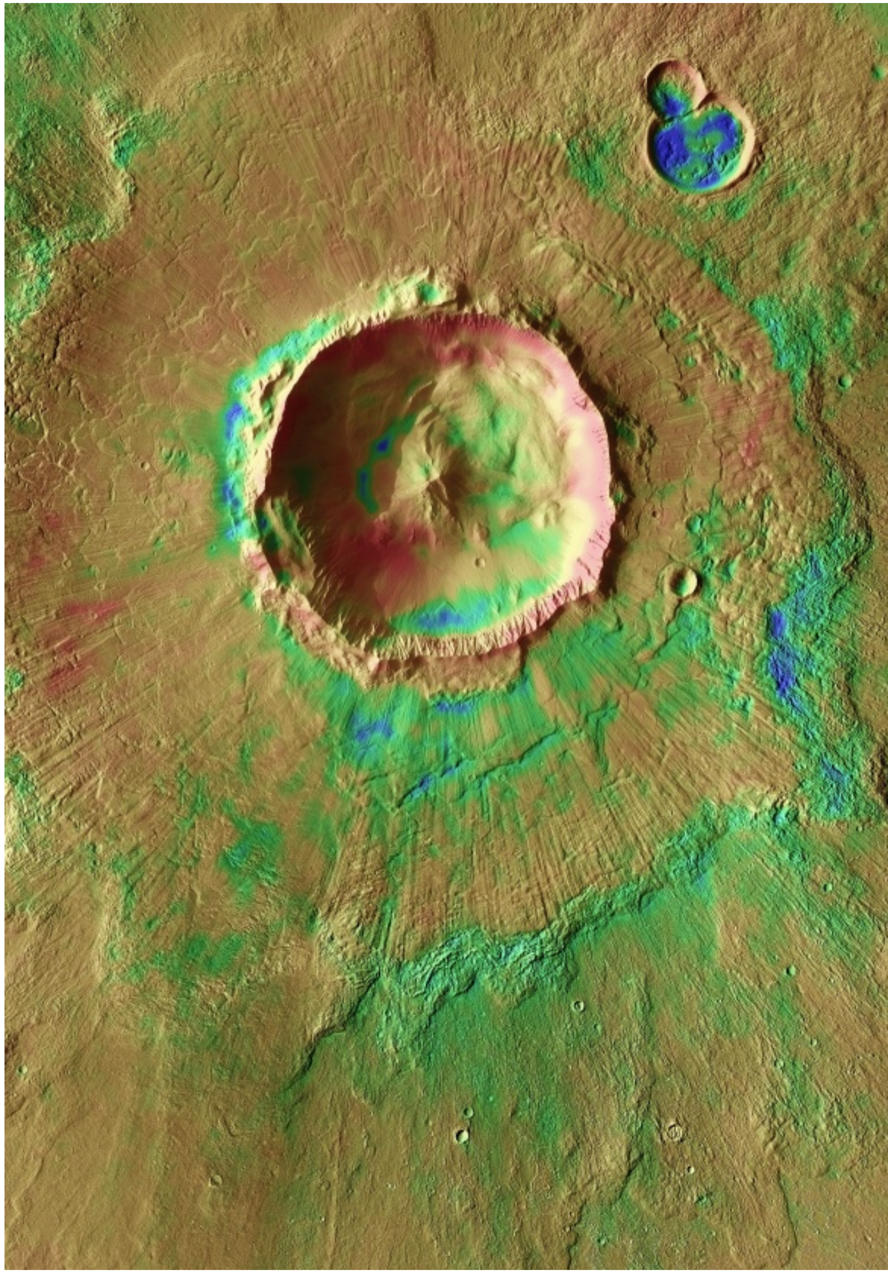
The smallest craters lack evidence of this terrain softening, suggesting that the ice is buried at depth, so that only the largest impacts excavate far enough to reach the ice. At the equator, the top of the ice is about 500 m below the surface; at higher latitudes the depth to the ice is less than 100 m.



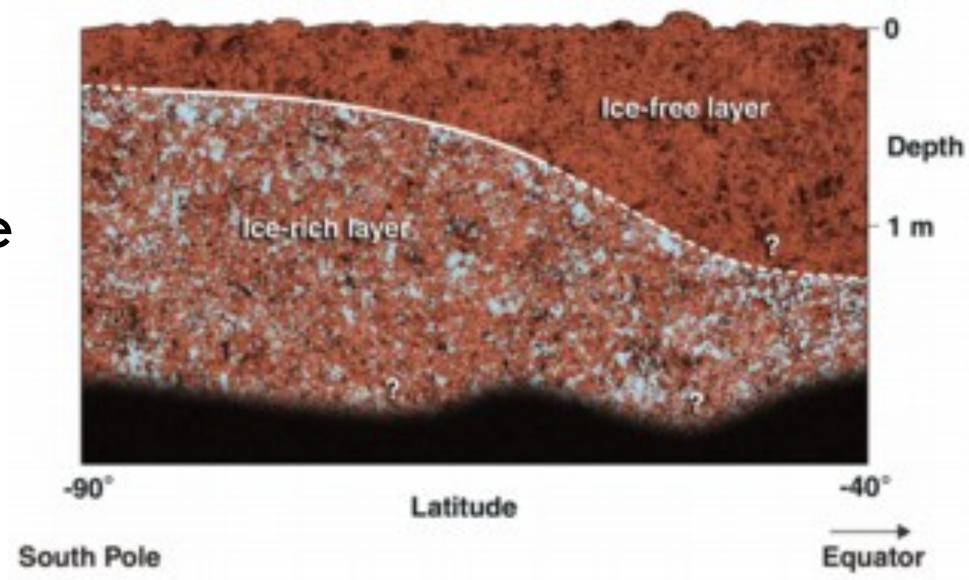


Craters in ice-free (left) and ice-rich (right) soil.

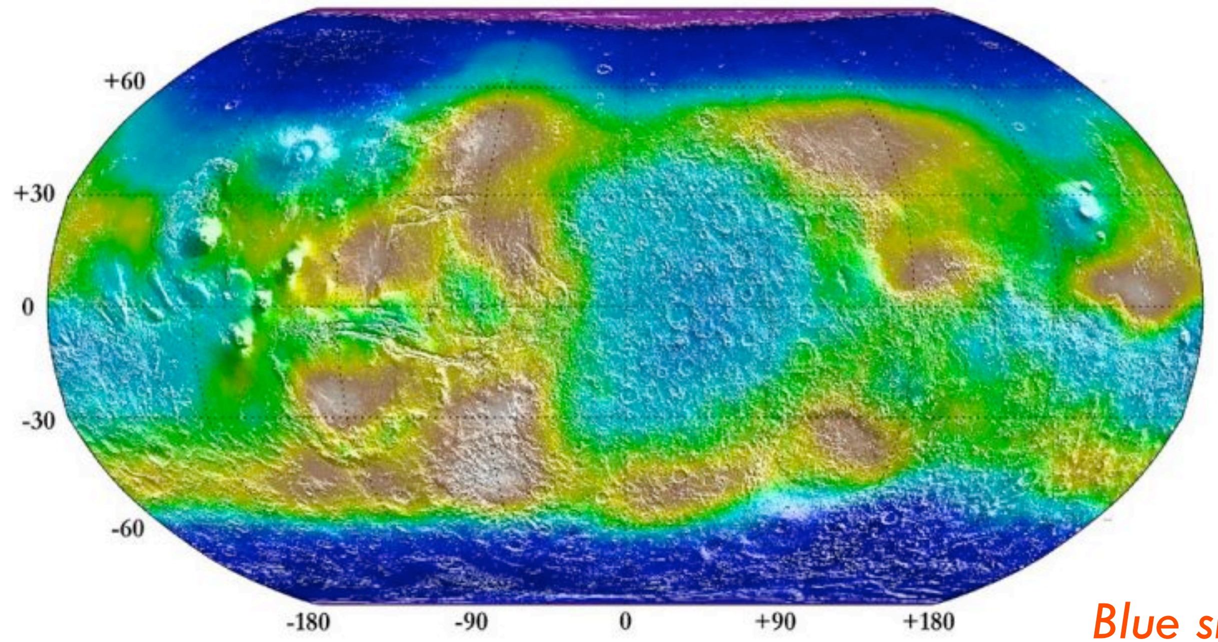
Combined infrared and visible image of Bacolor crater in Utopia Planitia: the colour represents the thermal image taken at night, with blue representing the coldest temperatures. The crater is 20 km wide, and shows many signs that at the time of impact, the subsurface held a lot of water, presumably as ice.



Direct support for this came from *Mars Odyssey*, which found evidence for large quantities of water ice in Martian soil. The ice is mainly at the poles, but there are also substantial amounts in a band near the equator.



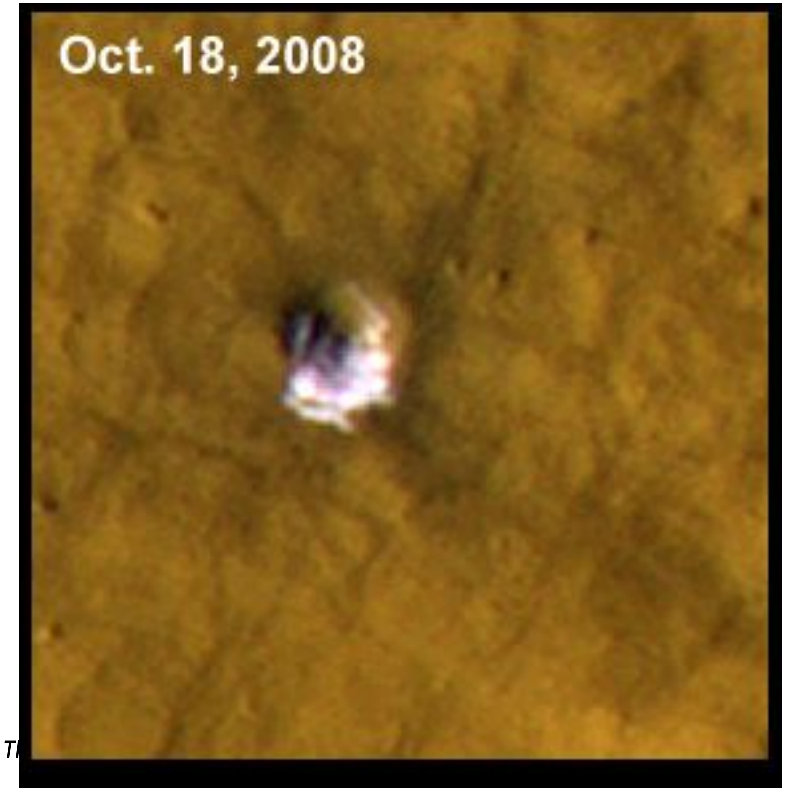
At high latitudes, ice makes up 20–50% of the soil by mass, below an ice-poor half metre of soil. At this concentration, the soil starts behaving like a glacier.



Blue shows regions with more water ice.

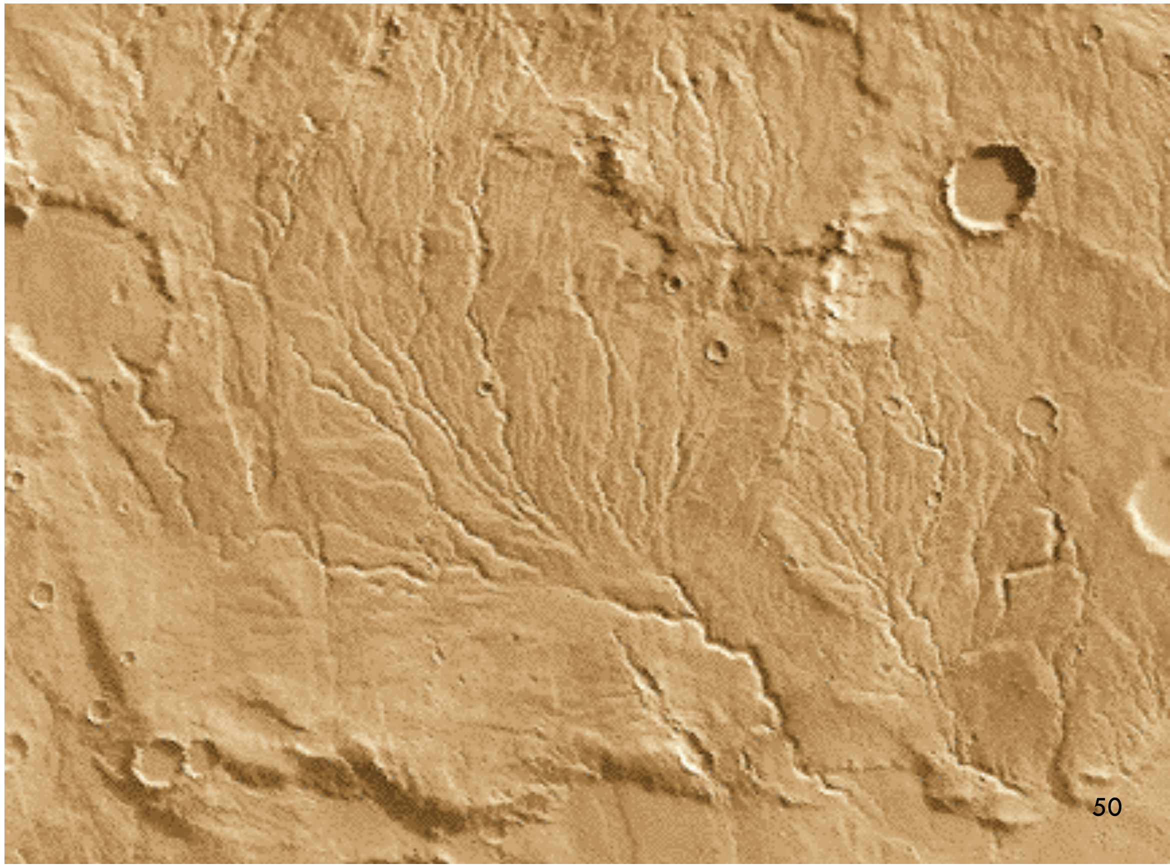
MRO is detecting fresh craters all the time; there are more than 200 impacts producing craters with diameter of at least 4m every year.

Water ice excavated by a meteor impact that formed a 12-m crater.



Dramatic, fresh impact crater, about 30 m in diameter, which appeared between July 2010 and May 2012.

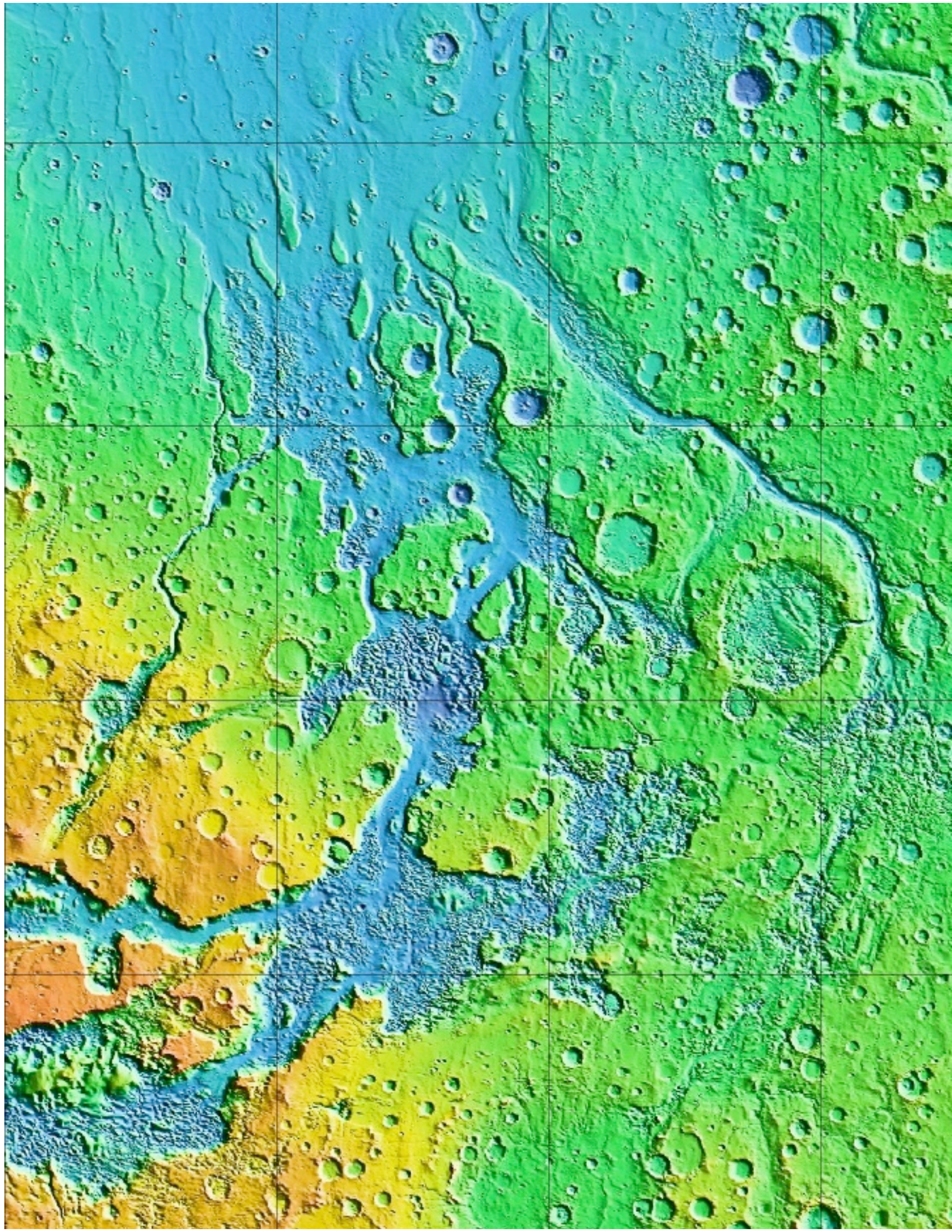
The Martian surface has many channels which look exactly like river systems on Earth, evidence that liquid water must have been present on the surface in large quantities. These networks are confined to old regions, suggesting the Martian climate may once have been warmer and wetter.



Network of drainage channels, suggesting sustained flows of water.

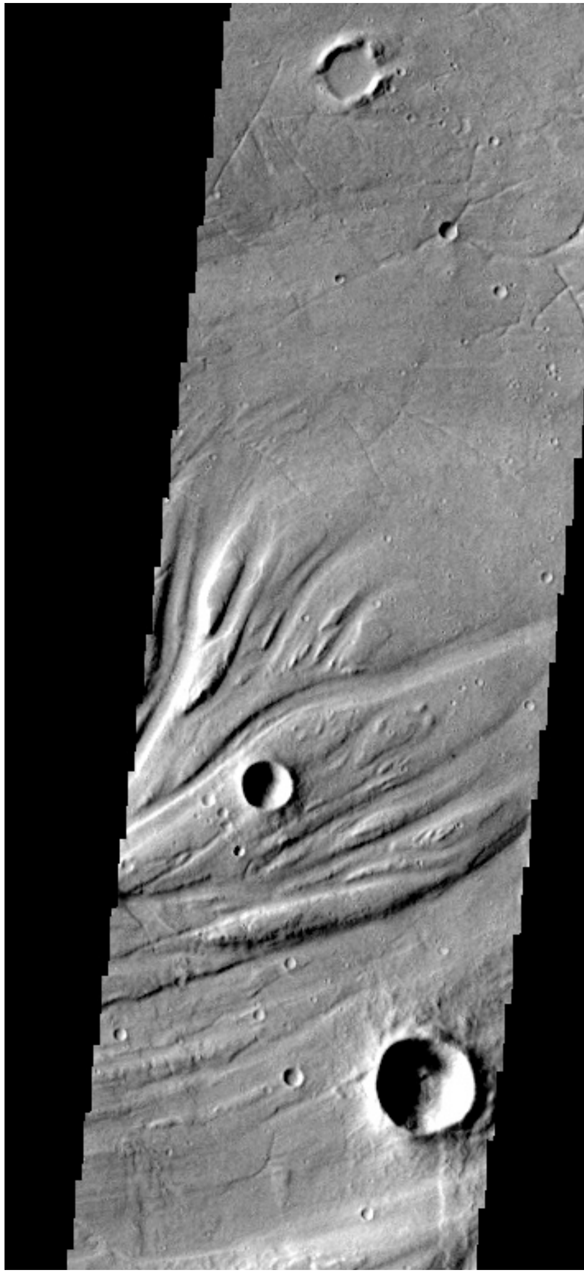
Much more dramatic are the outflow channels, immense dry riverbeds carved by the Solar System's largest-ever flash floods.

The volumes of liquid required to erode these features are enormous. The estimated flow rates require peak discharges of several cubic km of water *per second*, sustained for weeks or months.



Outflow channels Nanedi Vallis and Ares Vallis leading to Xanthe Terra

The minimum volume of water required to carve the outflow channels would produce a global ocean as much as 400 m deep, if it was all collected together.

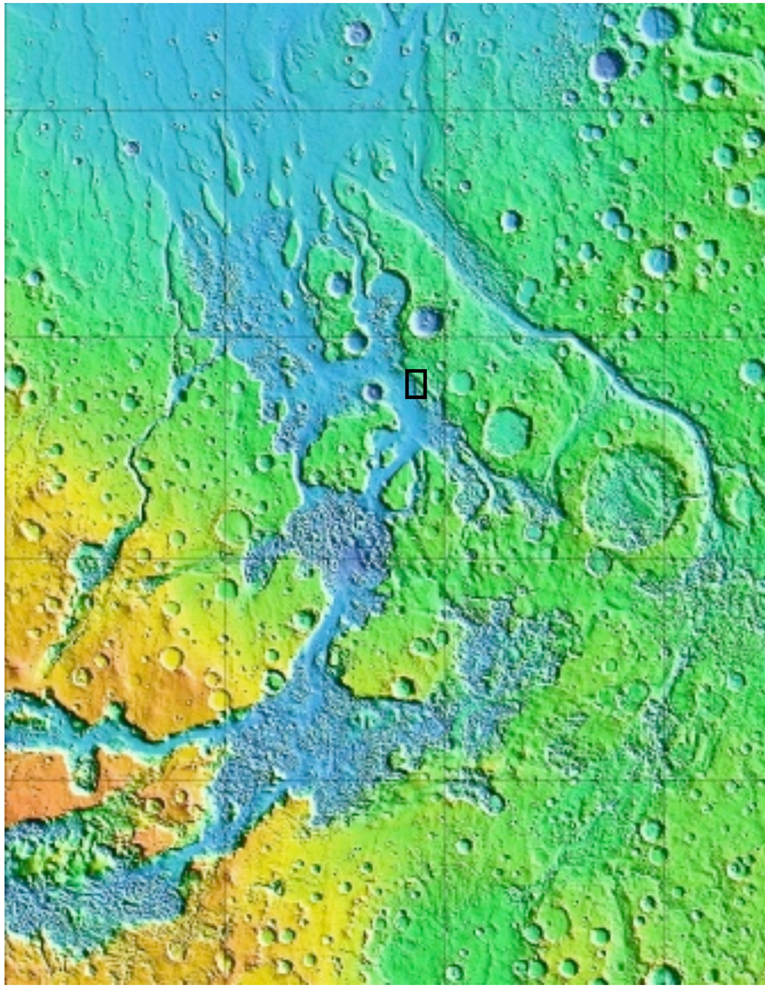


Outflow in Chryse Planitia, about 20 km across. The crater at the top pre-dates the flow, while the bottom craters post-date it.

Teardrop-shaped islands suggest vast, catastrophic flows of water, flooding the plains.

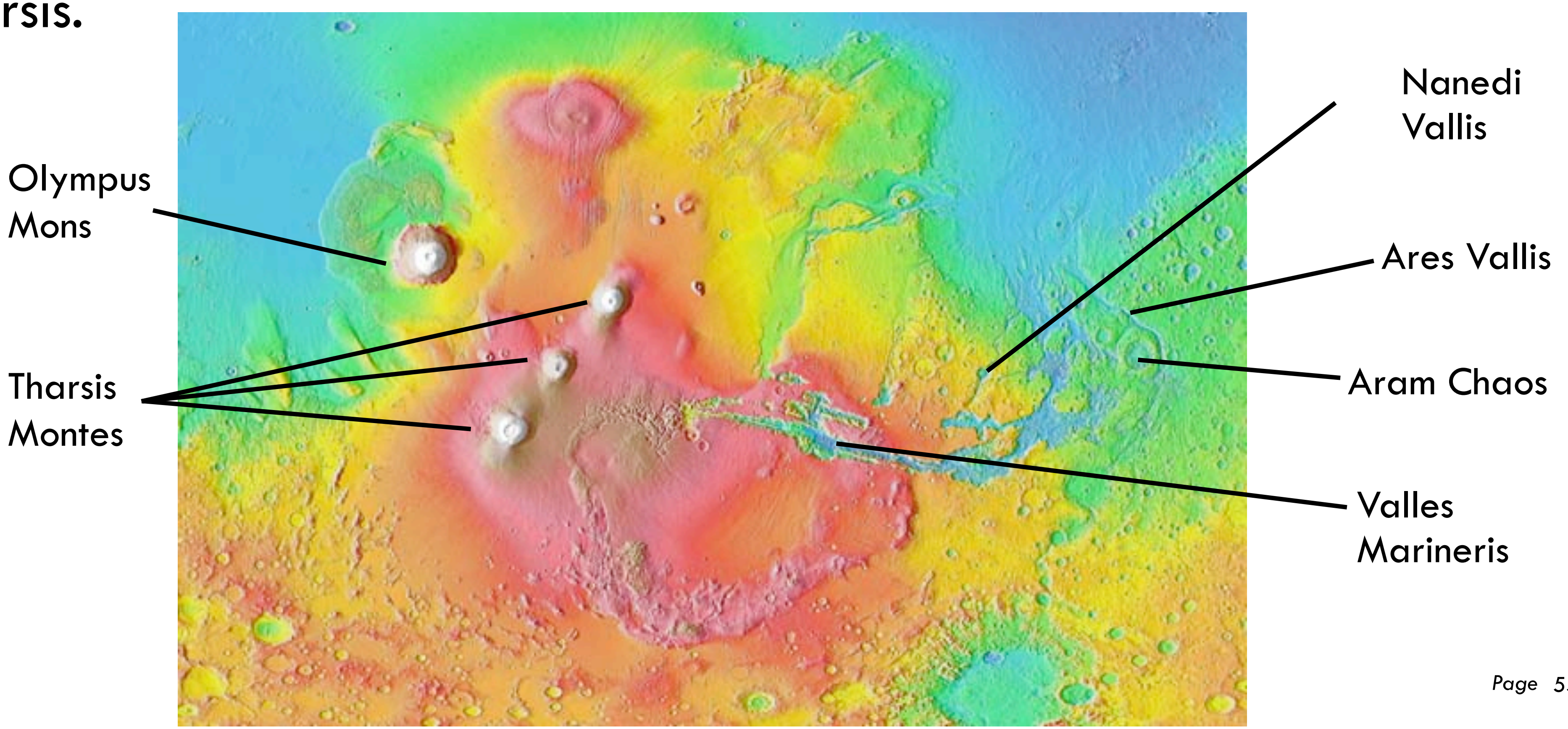
Islands carved as water was diverted by craters near the mouth of Ares Vallis in Chryse Planitia.

Many outflow channels originate in *chaotic terrain*: huge areas of collapsed landforms. Images show blocks tens of km wide, which collapsed when the ice in the sediments melted.



Mars Express image of a region in Aram Chaos, out of which the Ares Vallis channel drained.

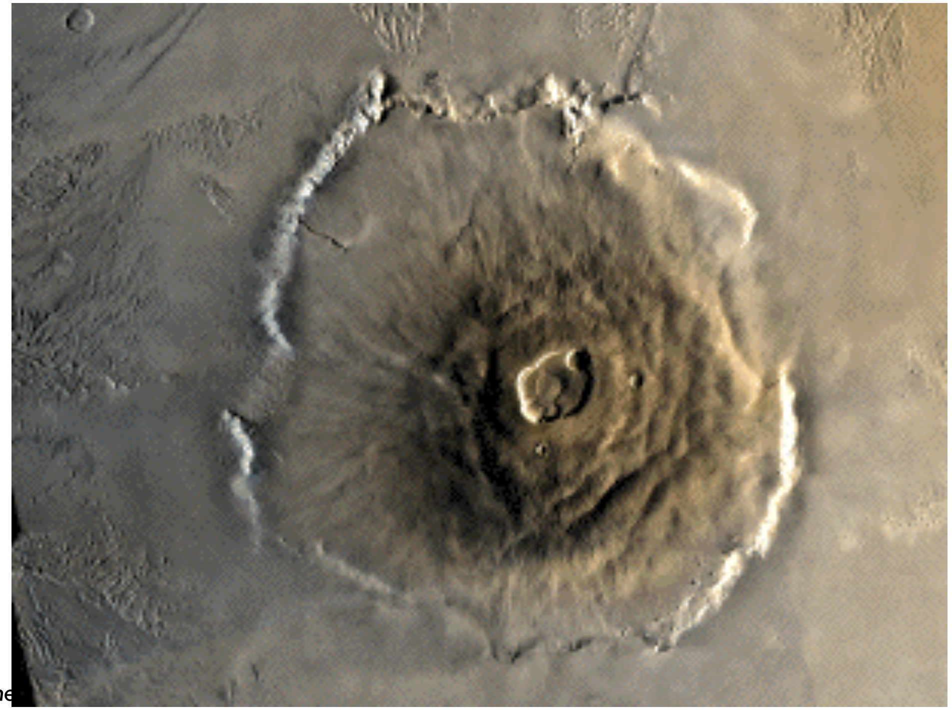
The *Tharsis region* is huge dome of lava, 10-km high and several thousand km in radius. It contains the three Tharsis Montes, as well as the largest volcano in the solar system, *Olympus Mons*. The dome is surrounded by radial fractures; *Valles Marineris* extends from the heart of Tharsis.

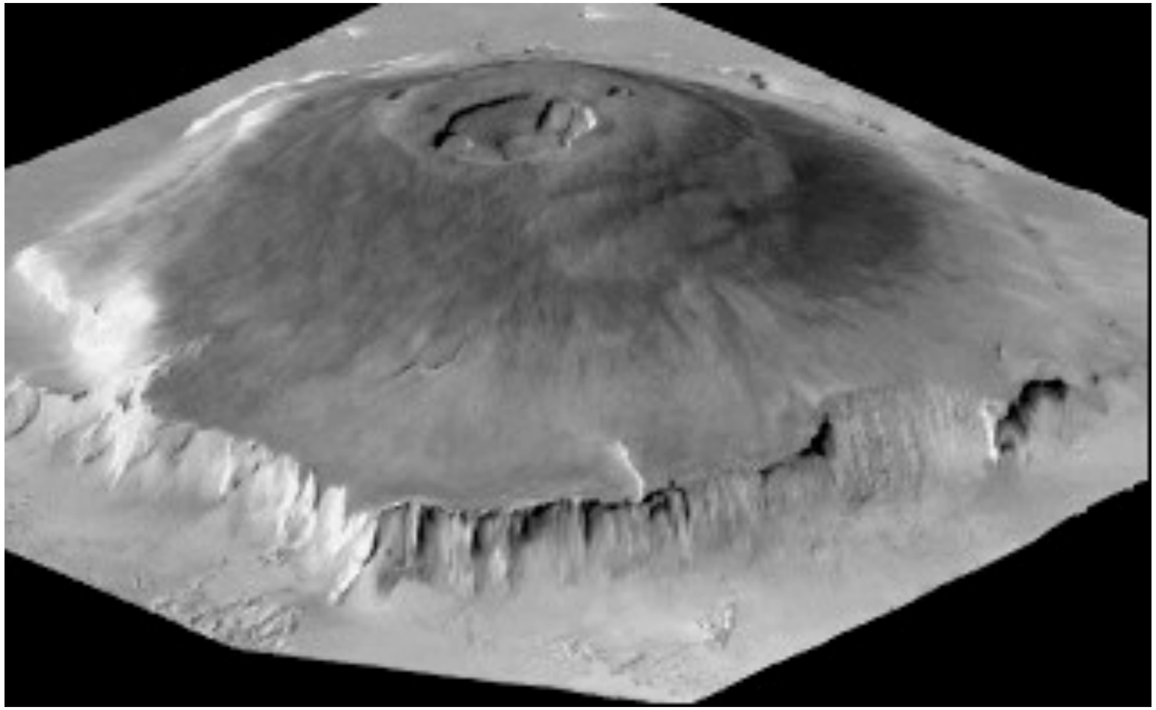


The Tharsis dome began to pile up very early in Mars' history; its immense weight put an enormous stress on the Martian crust. 300 million cubic km of lava was erupted to form the main Tharsis bulge. This would have emitted enough gas to transform the Martian atmosphere, as well as enough water to cover the planet with 120m of water.

Viking mosaic of the Tharsis region, showing the three Tharsis Montes and the beginning of the Valles Marineris

The three Tharsis Montes – Ascraeus, Pavonis, and Arsia – rise another 15 km higher than the Tharsis bulge, while Olympus Mons rises 18 km above the surrounding high plains, to a total height of 27 km. Its base is nearly 600 km wide, and the caldera is 70 km across.





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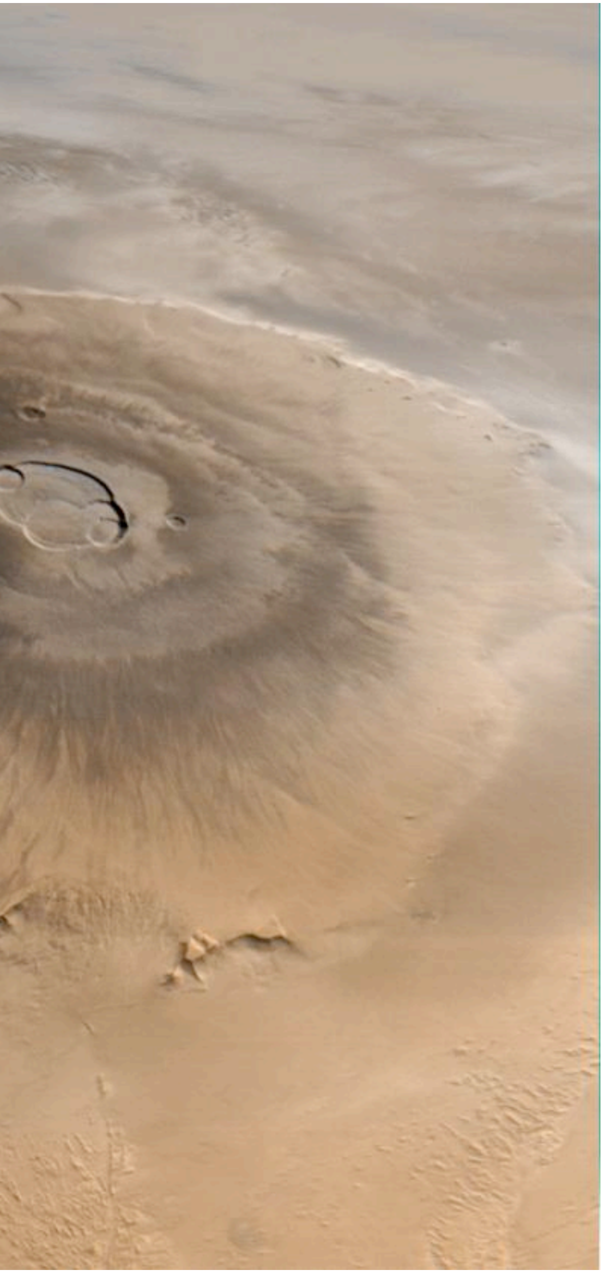
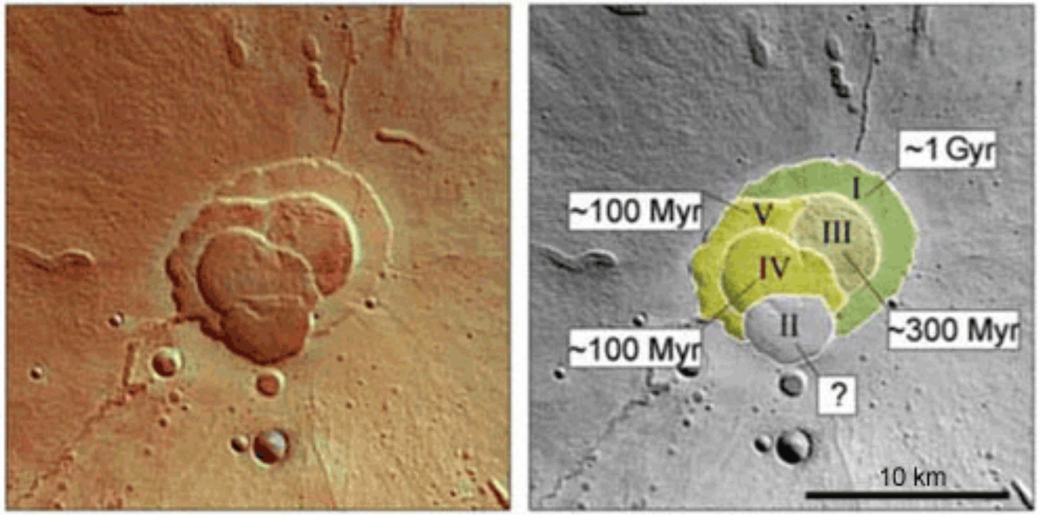


The slope of Olympus Mons is extremely gentle: six degrees or less.

Spectacular wide-angle view of Olympus Mons taken by the Mars Global Surveyor satellite.

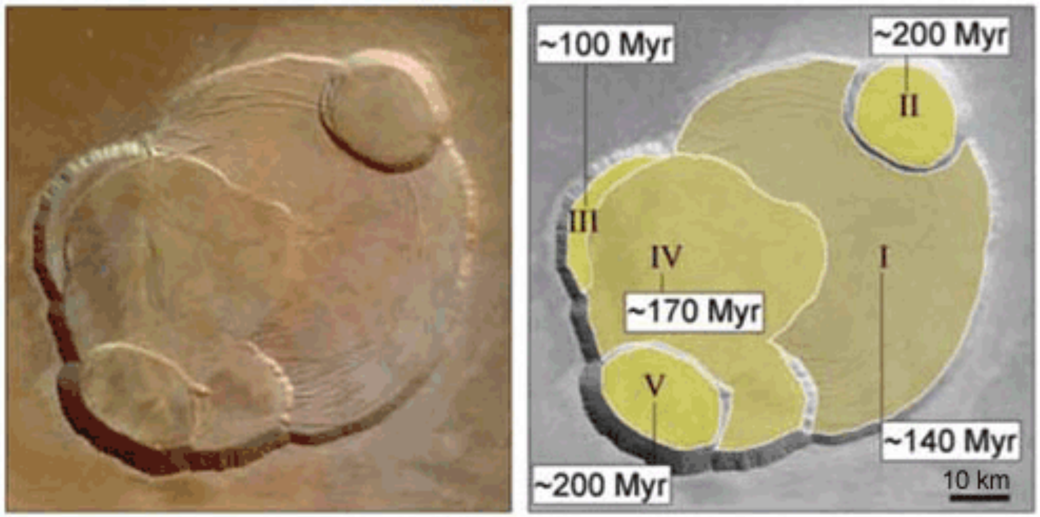
Crater counts in the calderas of volcanoes in high resolution images suggest that the volcanoes have been active for billions of years, and that the most recent lava flows on Mars may be as young as two million years. This implies the volcanoes may be still active.

Hecates Tholus



(From Neukum *et al.*, 2004, *Nature*, v. 432, p. 972.)

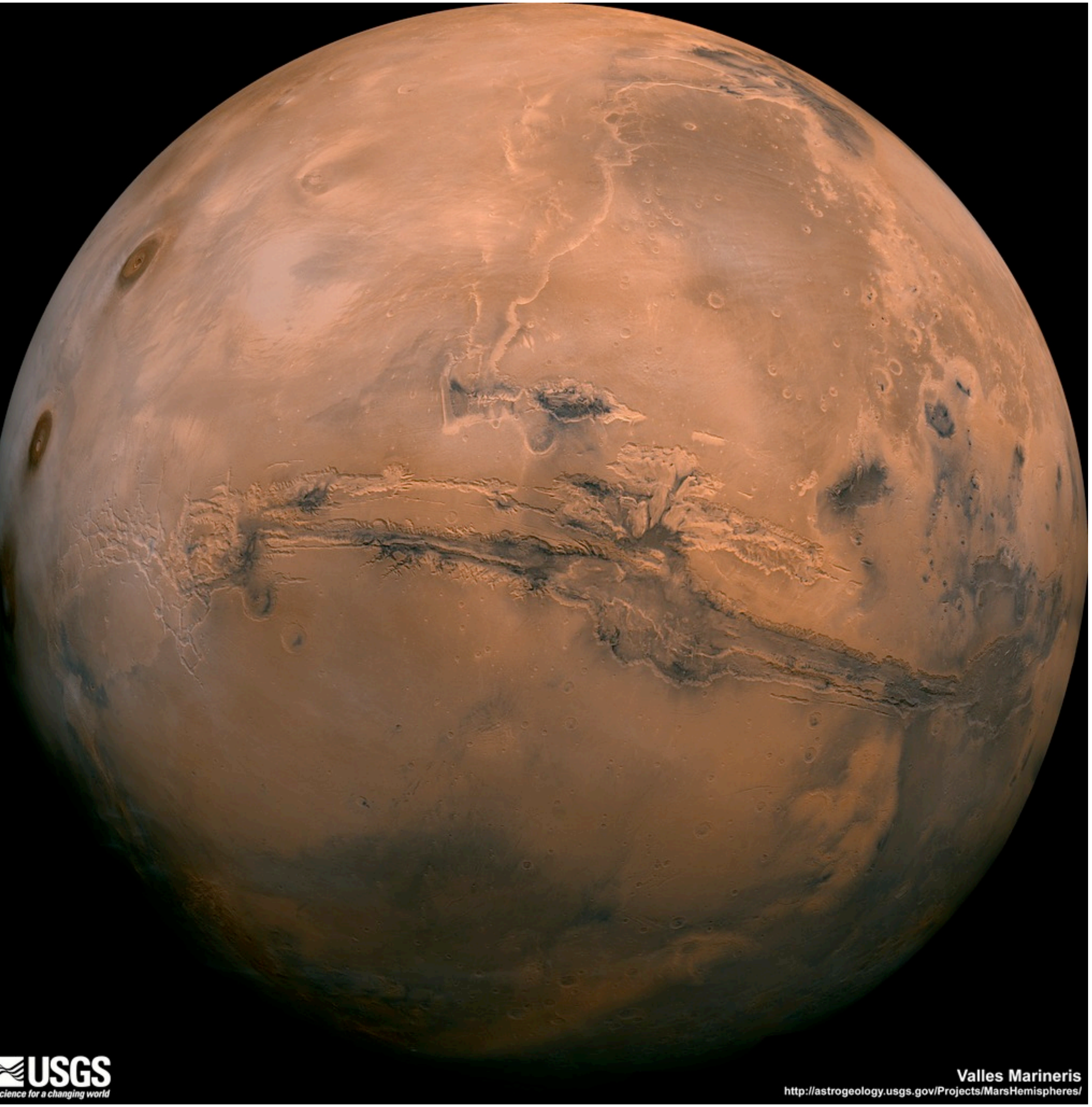
Olympus Mons



(From Neukum *et al.*, 2004, *Nature*, v. 432, p. 972.)

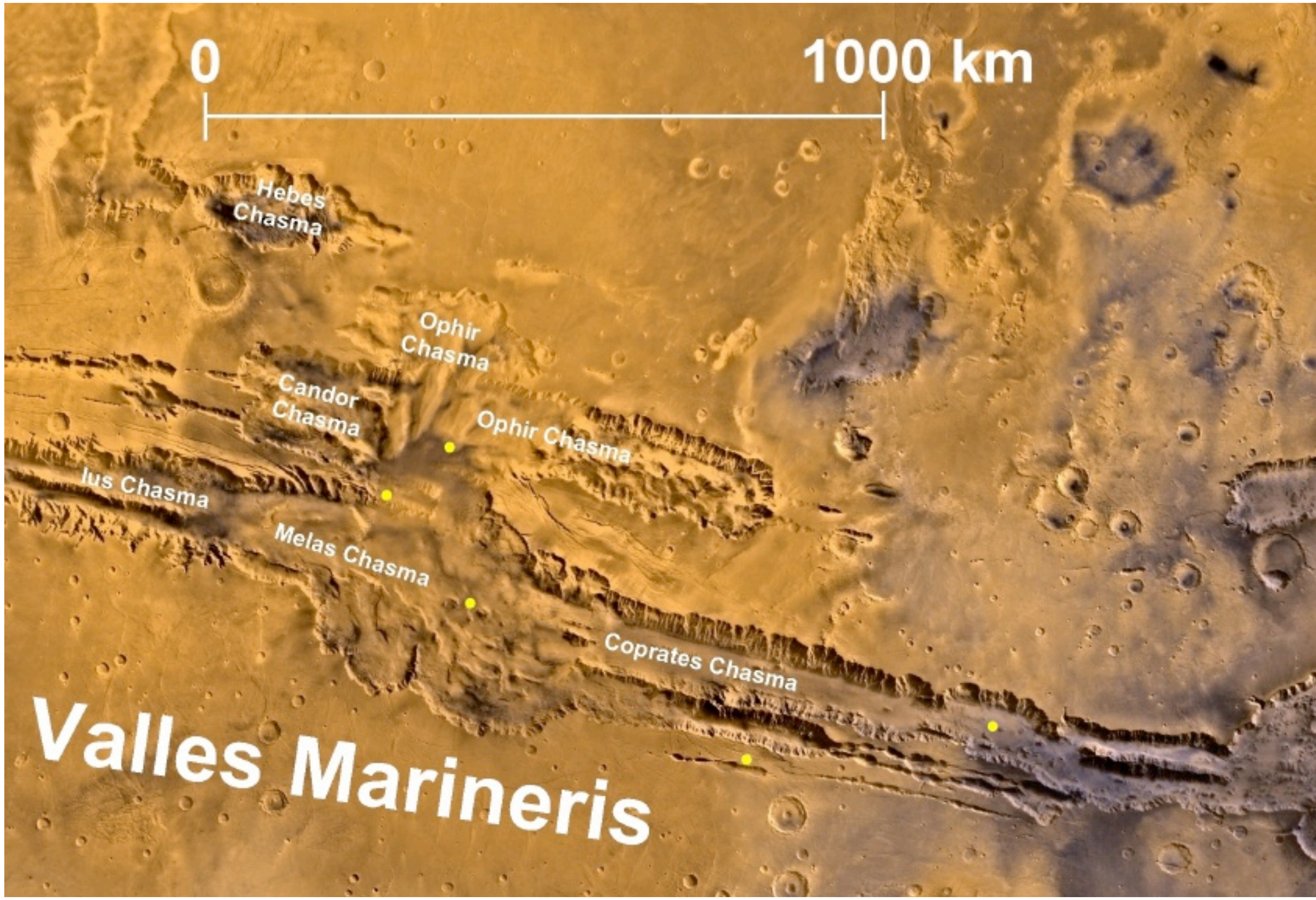
Images of two volcanic calderas, with the crater-counting areas and their derived absolute ages.

The University of Sydney

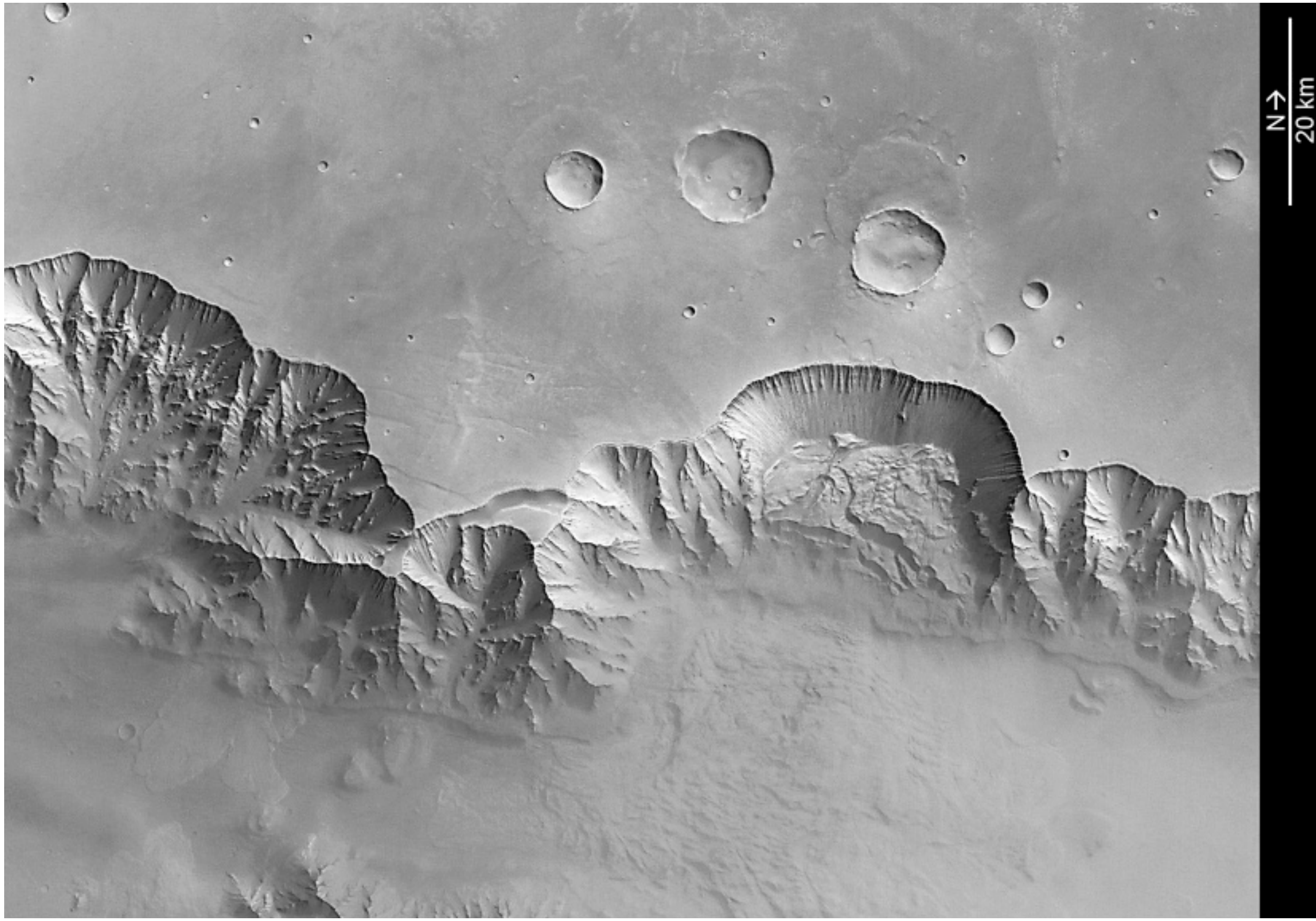


The giant canyon to the east of Tharsis, up to 100 km wide and several thousand kilometres long, is *Valles Marineris*. It covers about a fifth of the circumference of Mars.

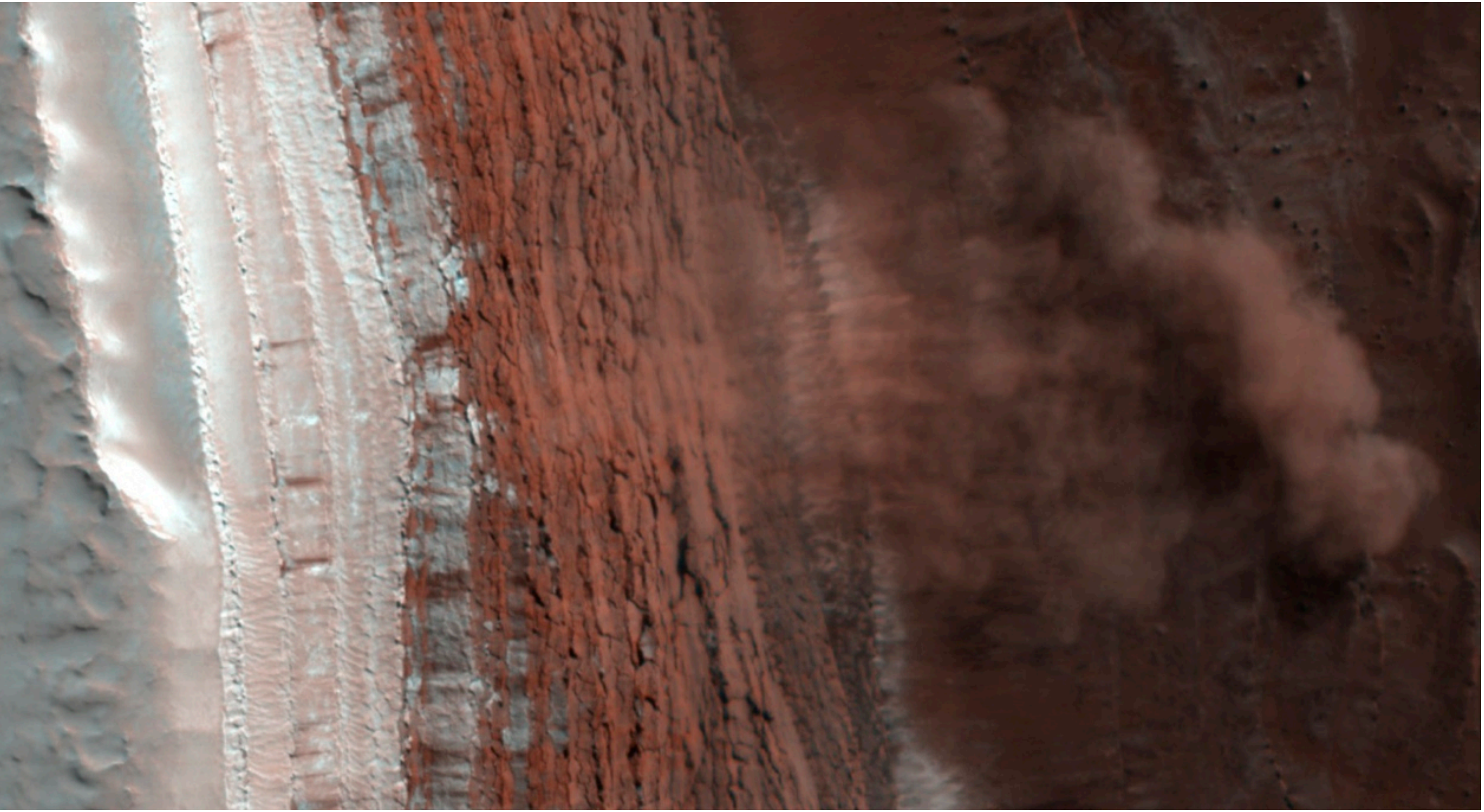
This canyon shows that Mars had active plate tectonics at some stage in the past. The crust pulled apart to create parallel faults, between which the crust subsided, then erosion and landslides widened the canyons.



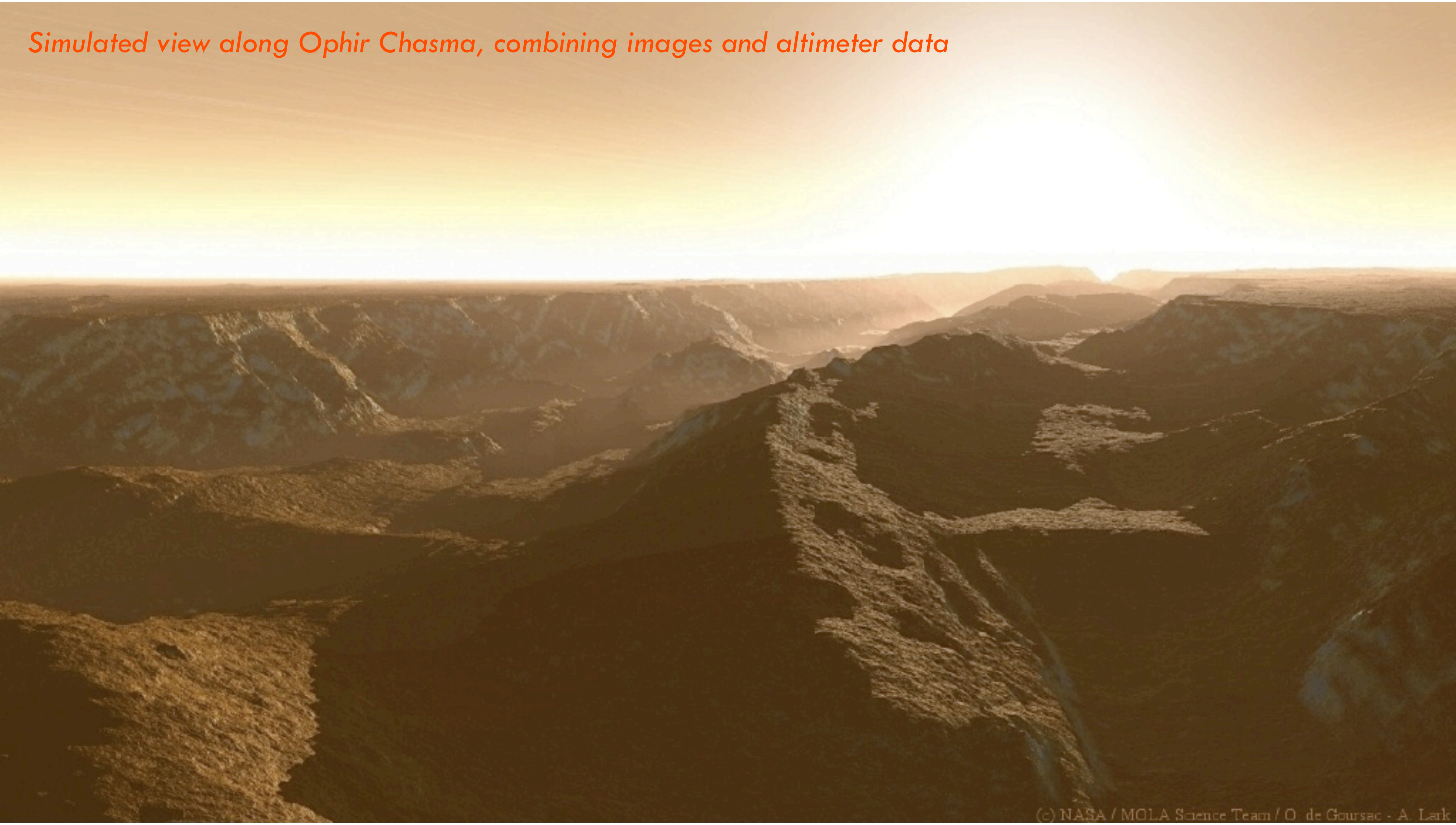
Huge avalanches have also altered the shapes of many of the canyons and other surface features.



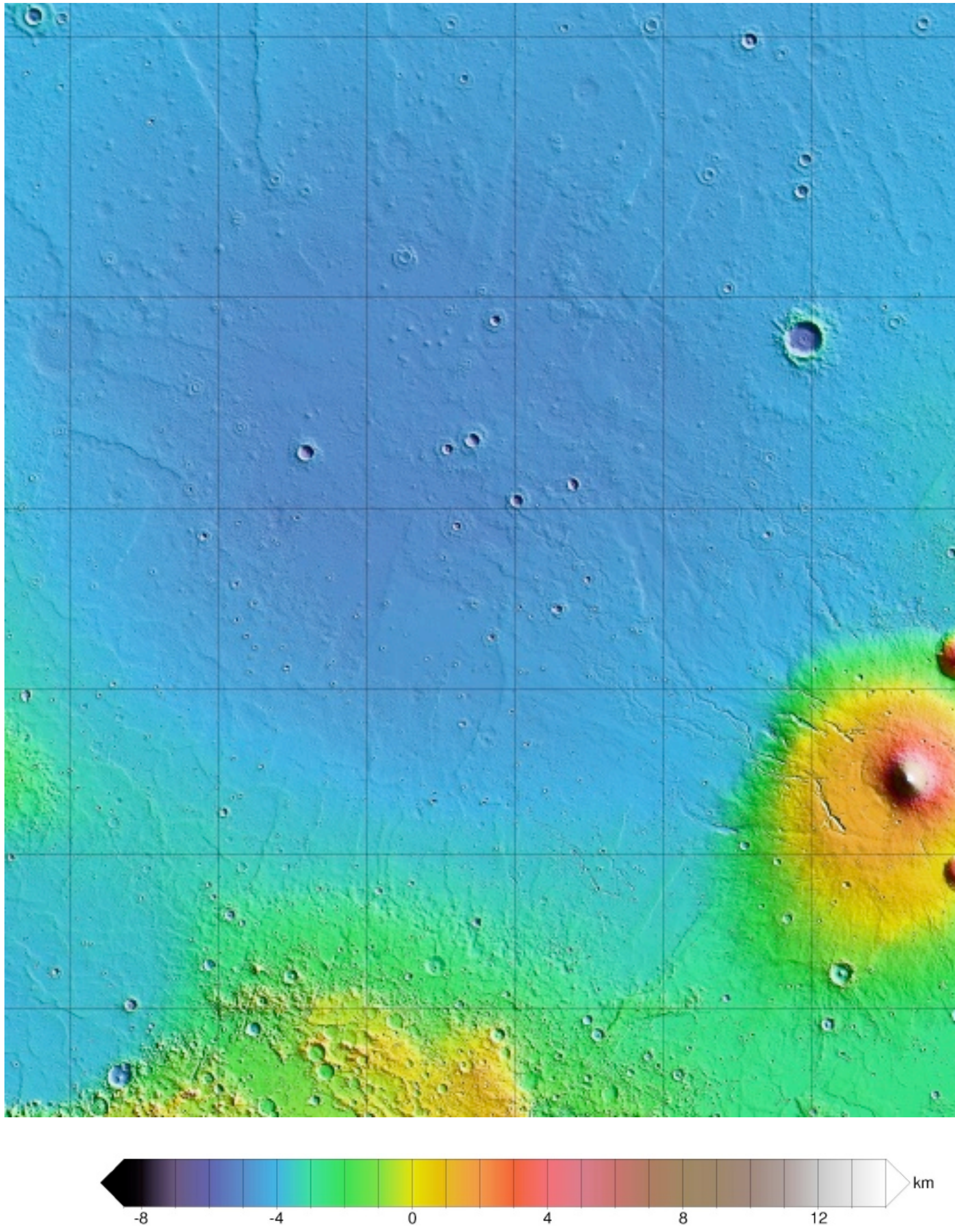
Mars Express image of landslides in Coprates Chasma



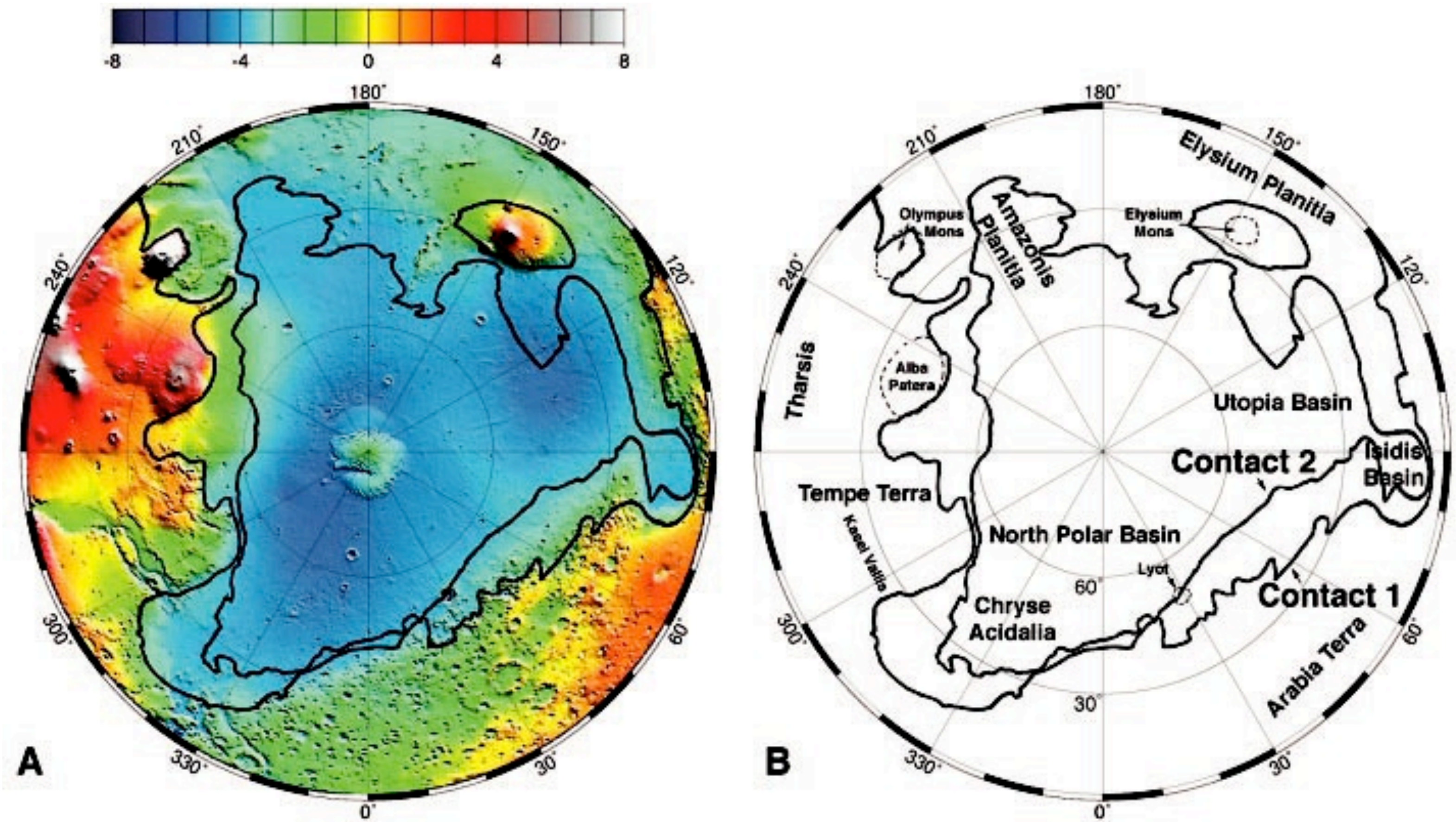
The Mars Reconnaissance Orbiter captured an avalanche in action in February 2008


Simulated view along Ophir Chasma, combining images and altimeter data
(c) NASA / MOLA Science Team / O. de Goursac - A. Lark

The northern lowlands – the *Vastitas Borealis* – is a broad plain that covers much of Mars's far northern latitudes. They lie 4–5 km below the mean altitude, and are notably smoother than any plains in the south.



The immense floods which formed the outflow channels would have left behind immense bodies of water. Some scientists have suggested there is evidence that the northern plains were once covered by a vast ocean.



Proposed shorelines of an ancient ocean, from Clifford and Parker (2001)

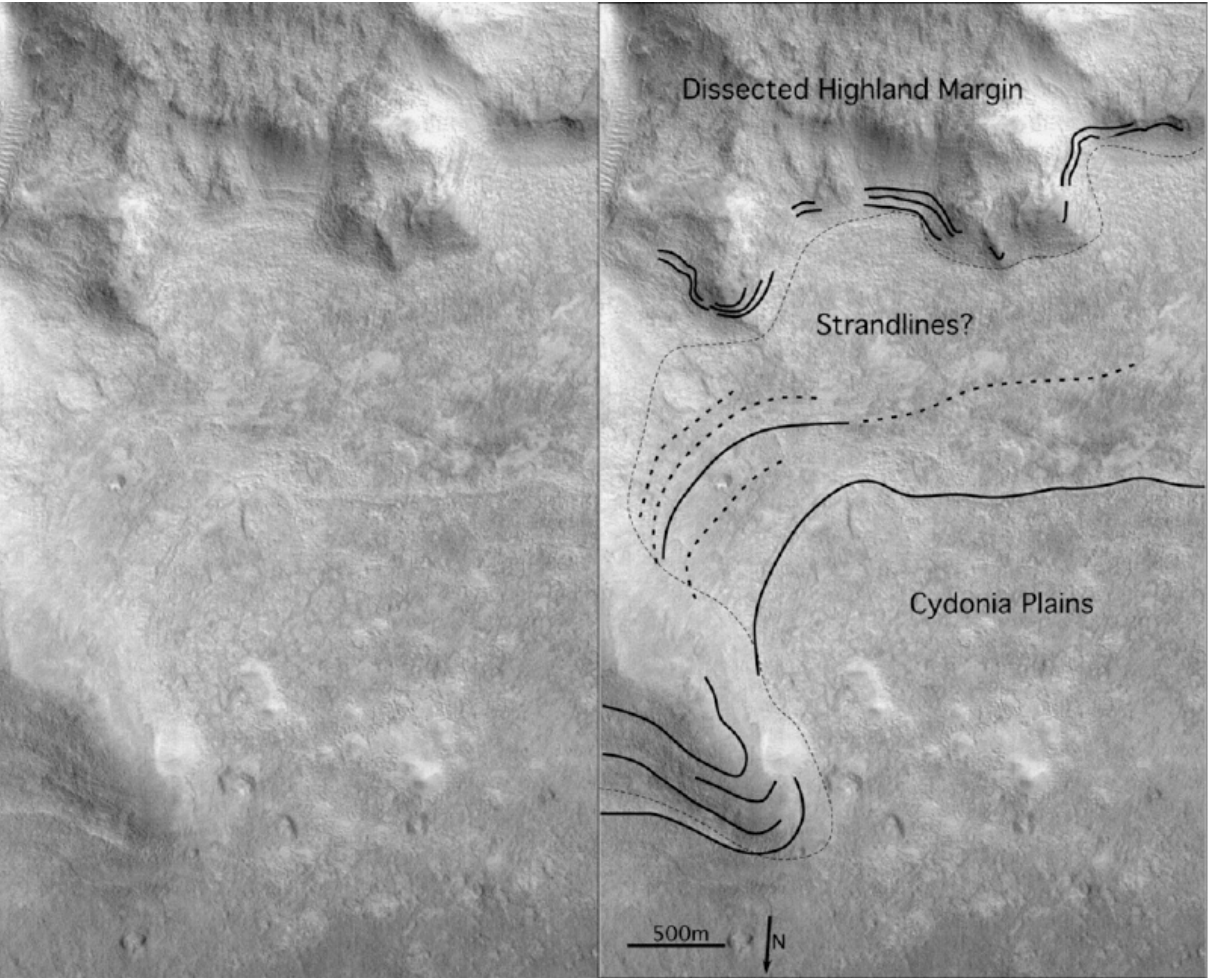
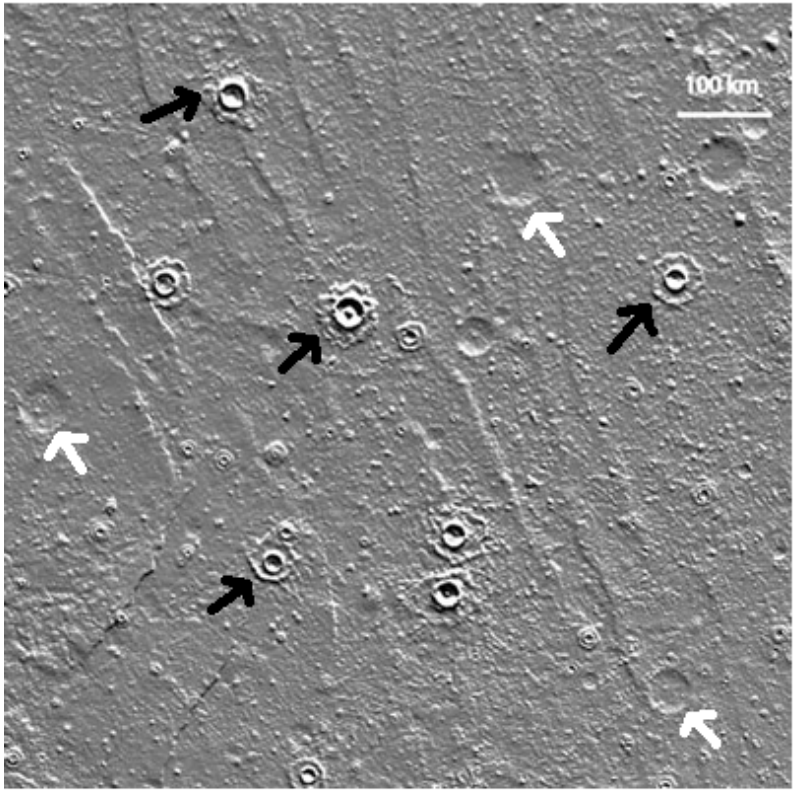


Image of the boundary between the highlands and the plains, showing possible shorelines left by a retreating ancient ocean. From Clifford & Parker (2001), Fig. 4

The northern plains are buried by layers of material at least 100 meters thick. These deposits have buried older craters and volcanic plains, smoothing the wrinkled surface and leaving behind shallow, almost rimless craters called stealth craters. The northern lowlands were at one time as cratered as the southern highlands.

Vastitas Borealis Formation Surface



(From Carr and Head, 2003, *JGR*, 108(E5),5042, doi:10.1029/2002JE001963,2003; Fig.15.)

Typical region of the northern plains. White arrows point to examples of stealth craters, interpreted to be older craters buried by the VBF. Black arrows indicate fresher looking craters with ejecta blankets, which are younger than the VBF.

How did the crustal dichotomy form? It has been suggested it could have been formed by a giant impact, if the impactor only struck a glancing blow.

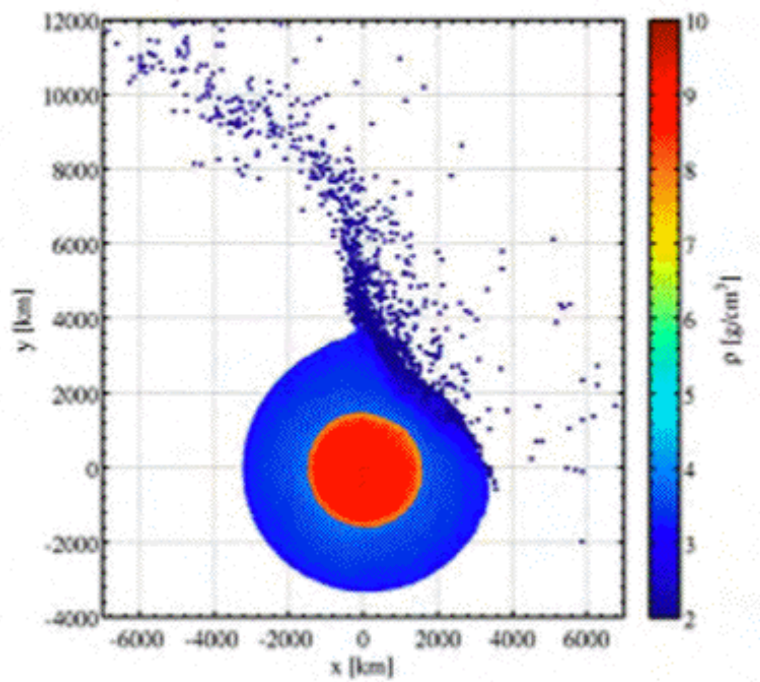
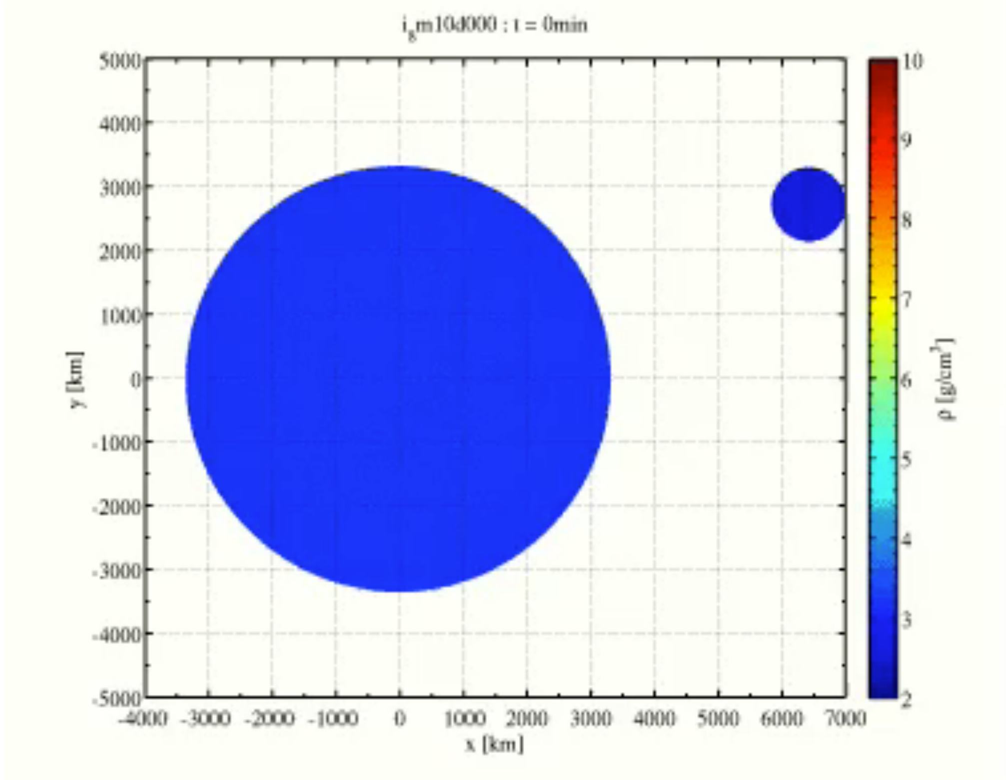
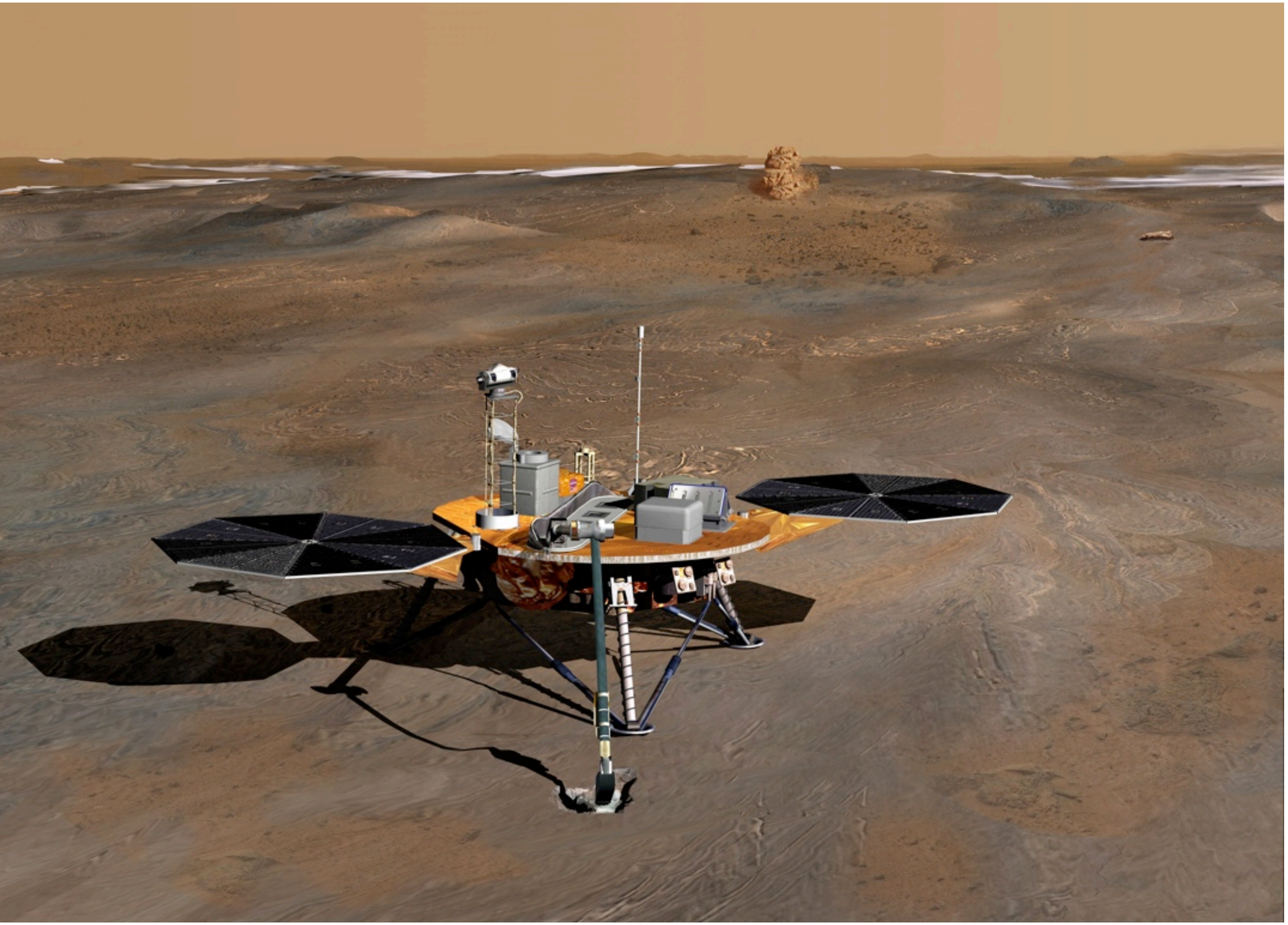


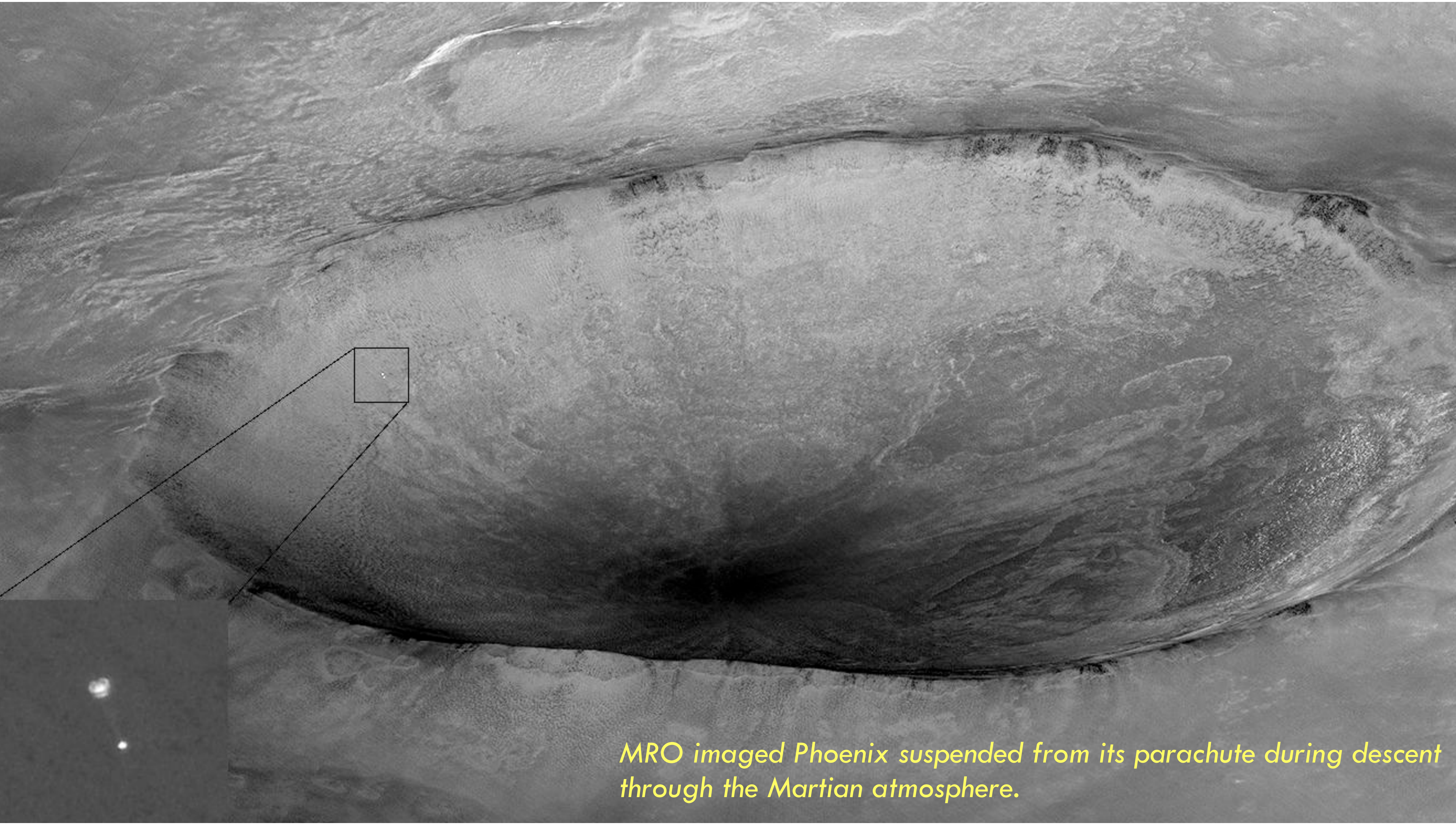
Figure 1. Snapshot of an impact simulation: t = 25 min after impact. Half-space shown. Impact parameters v = 6 km/s, $D_{impactor}$ = 860 km, 1.45×10^{29} J, D_{crater} ~ 8000 km, impact angle = 30 deg.



The *Phoenix* lander landed in the Vastitas Borealis in May 2008, and



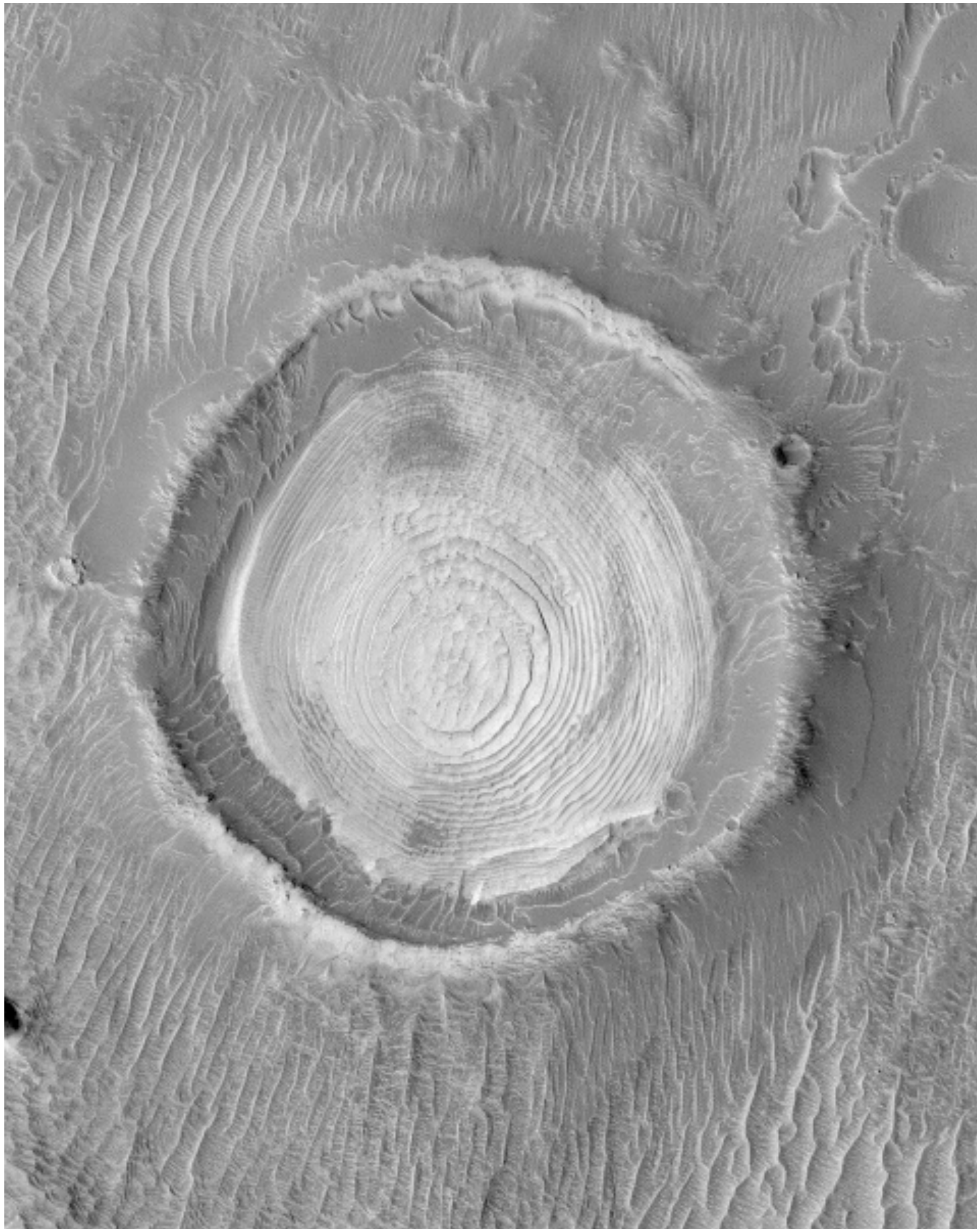
survived until November. Its mission was to look for water and microbial life.


MRO imaged Phoenix suspended from its parachute during descent through the Martian atmosphere.

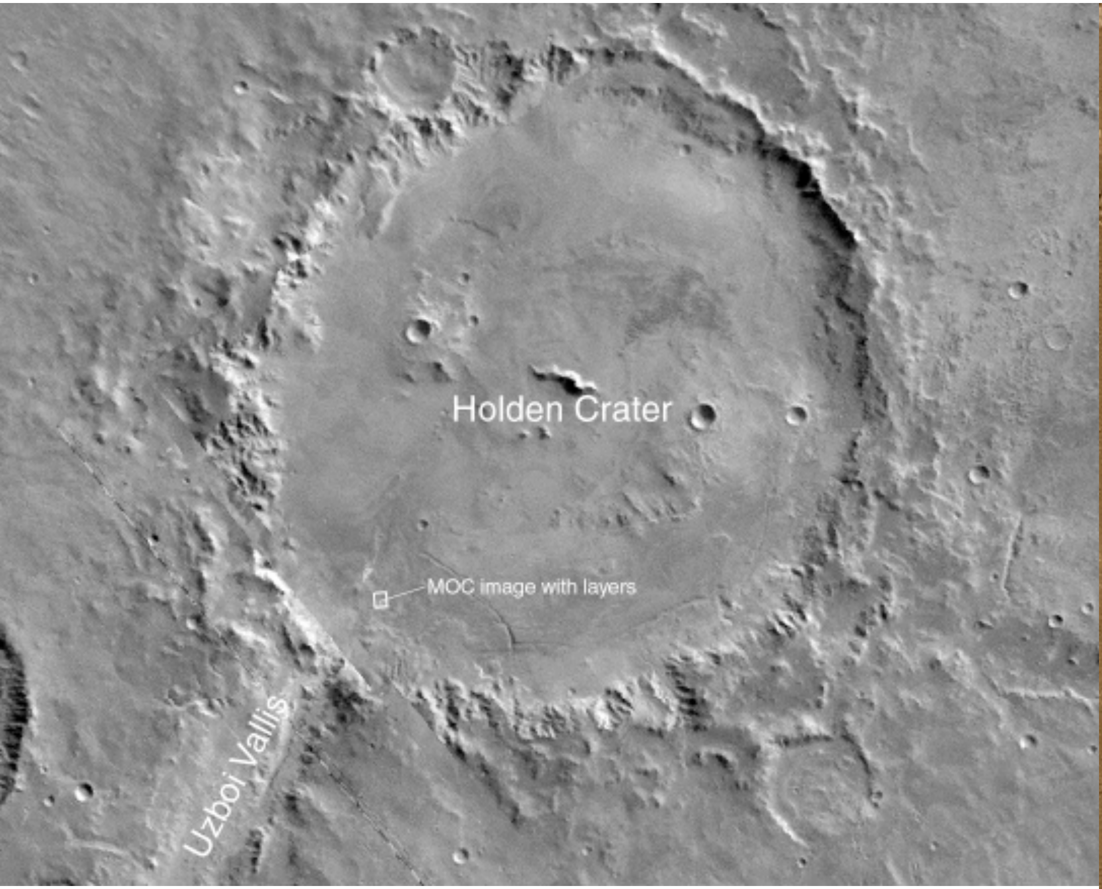
Immediately after touchdown, it found ice directly beneath the spacecraft.

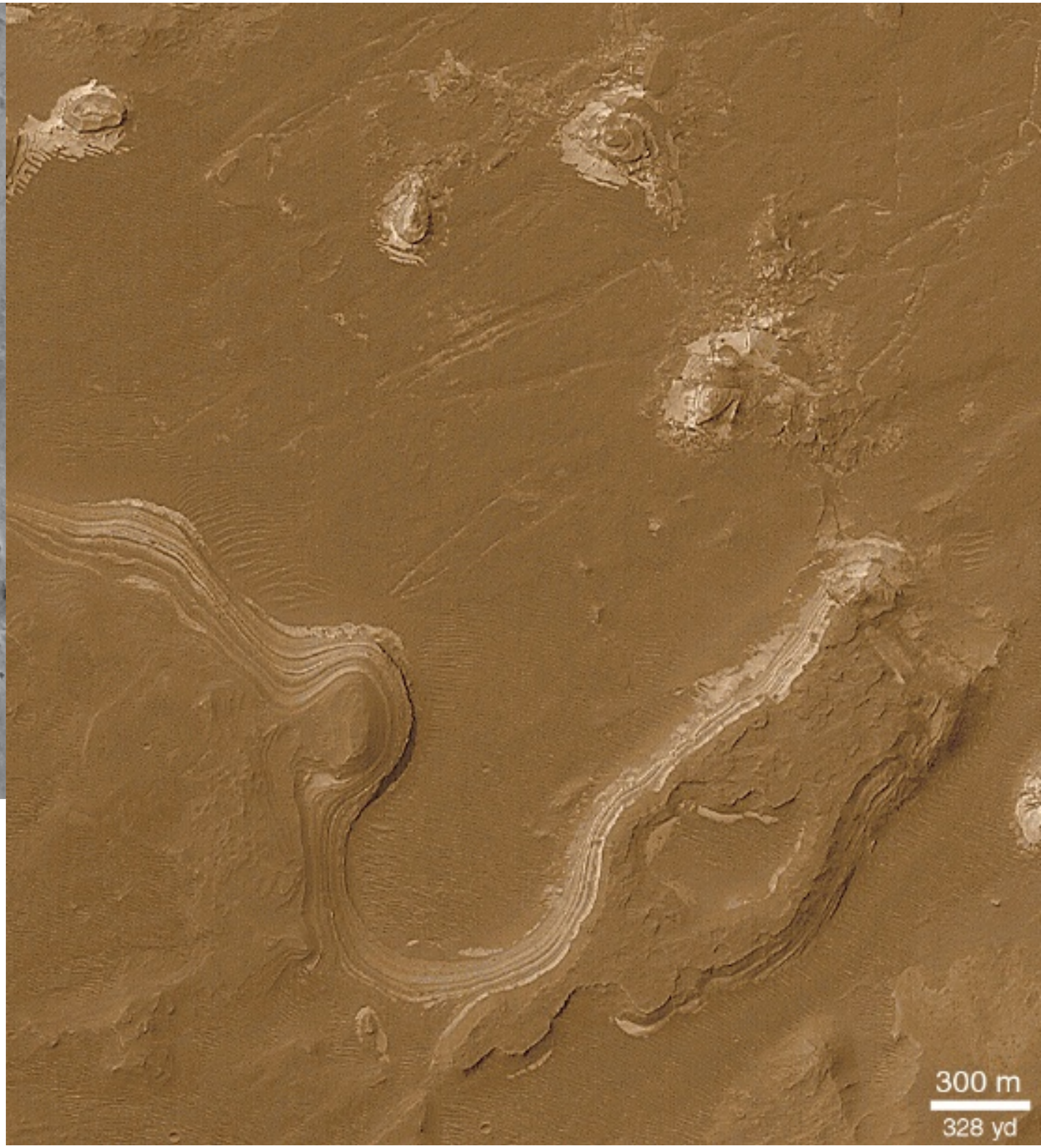
The soil near the lander was slightly alkaline, and contained calcium carbonate, which usually forms in the presence of water.

Layered rocks and sediments show that sediment was deposited in standing water in many areas of the planet, often as lakes inside craters.



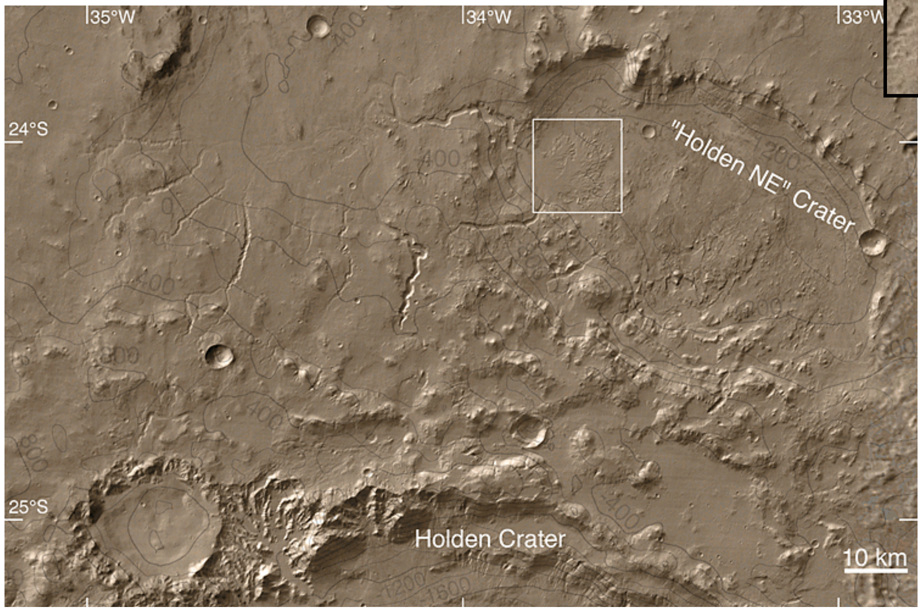
Eroded sedimentary layers in a 2.3 km crater inside the giant crater Schiaperelli.

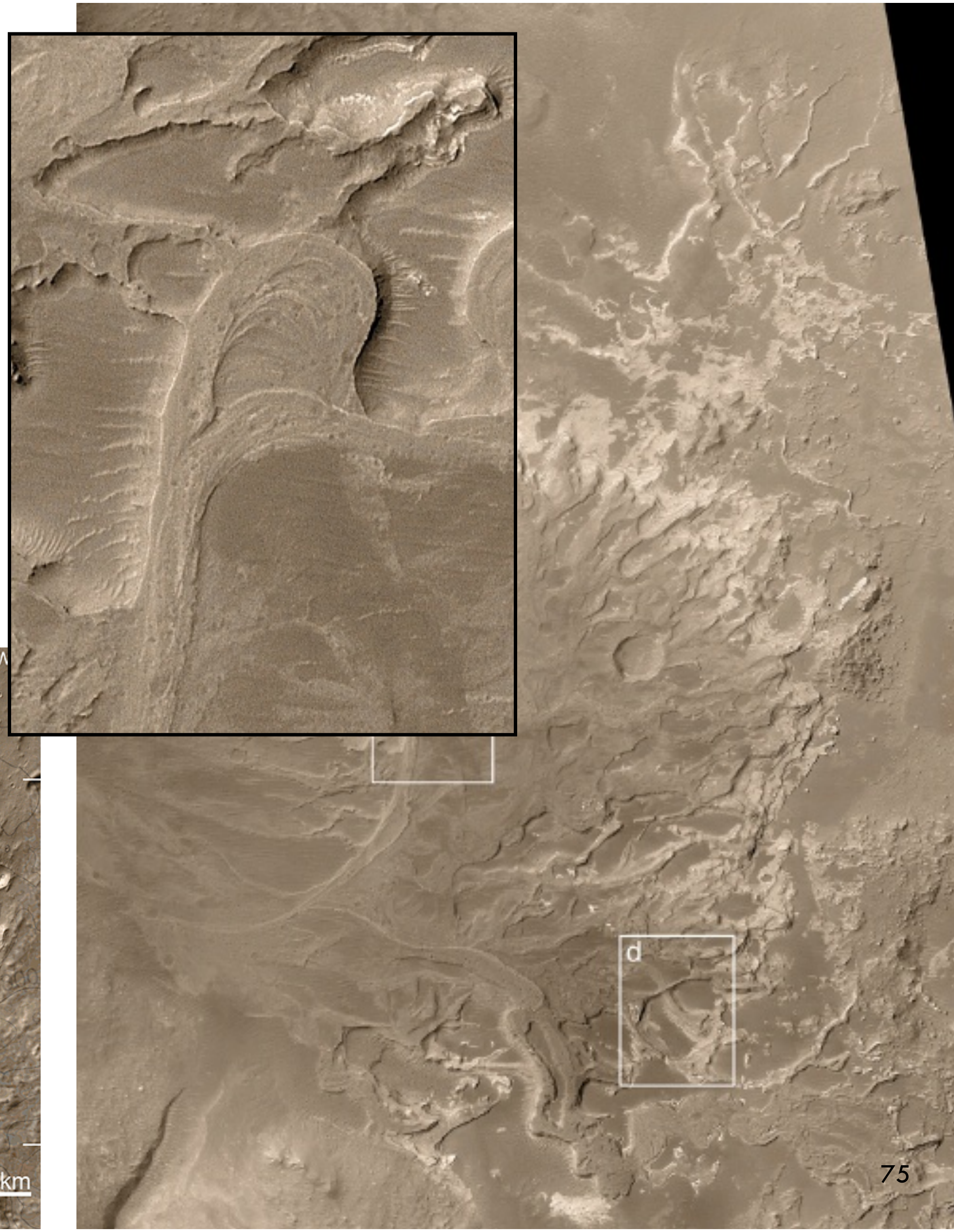




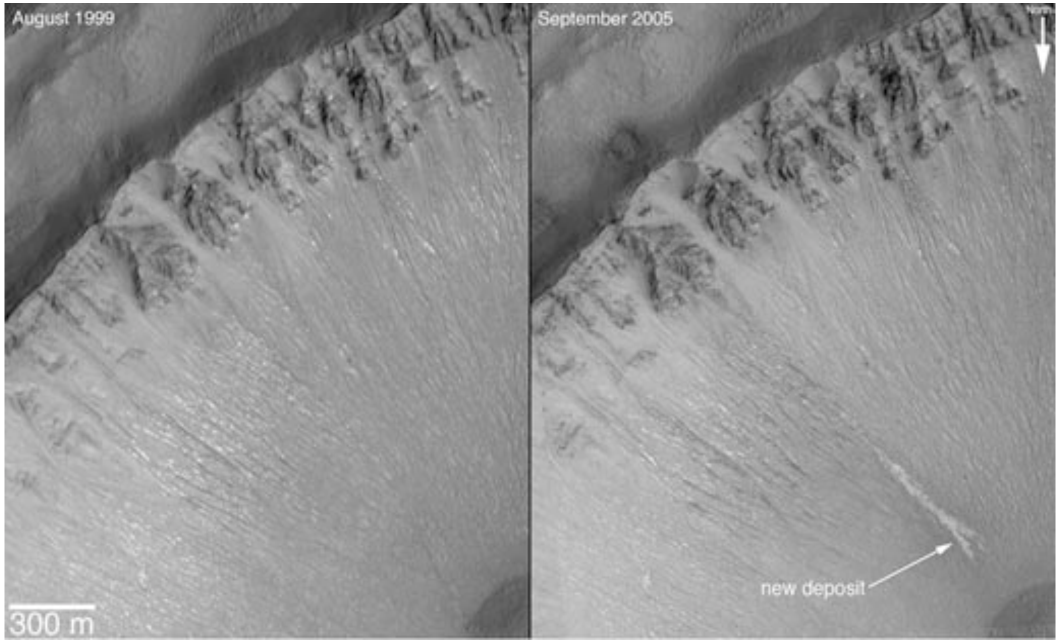
Layered sedimentary material in southern Holden Crater, which might result from deposition in a lake.

The discovery of an ancient delta fan showed that at least some of these flows of water were persistent, not transient events. Deltas form when a river meets a standing body of water; meanders like these would take 100–1000 years to form.

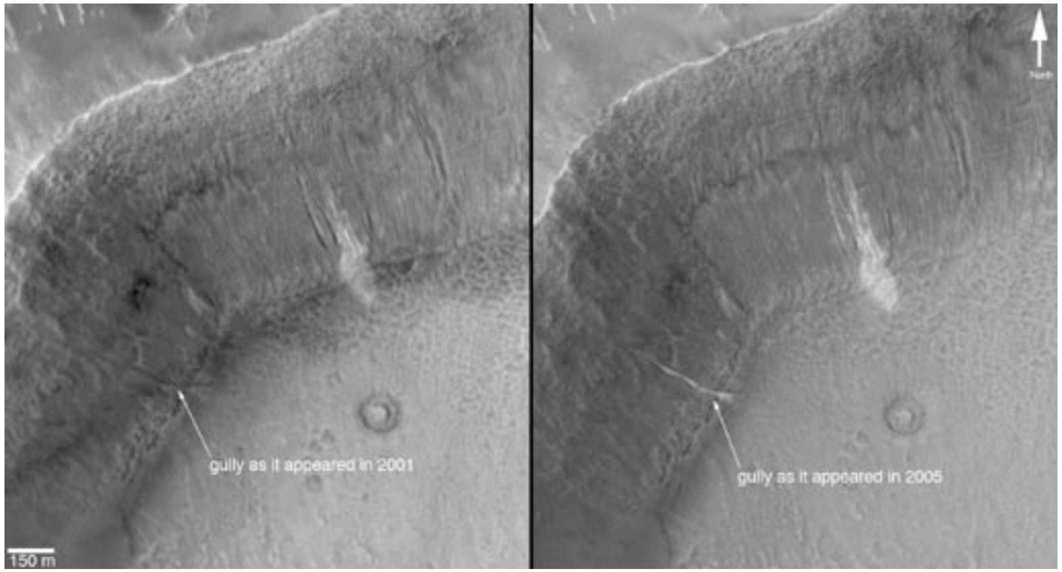


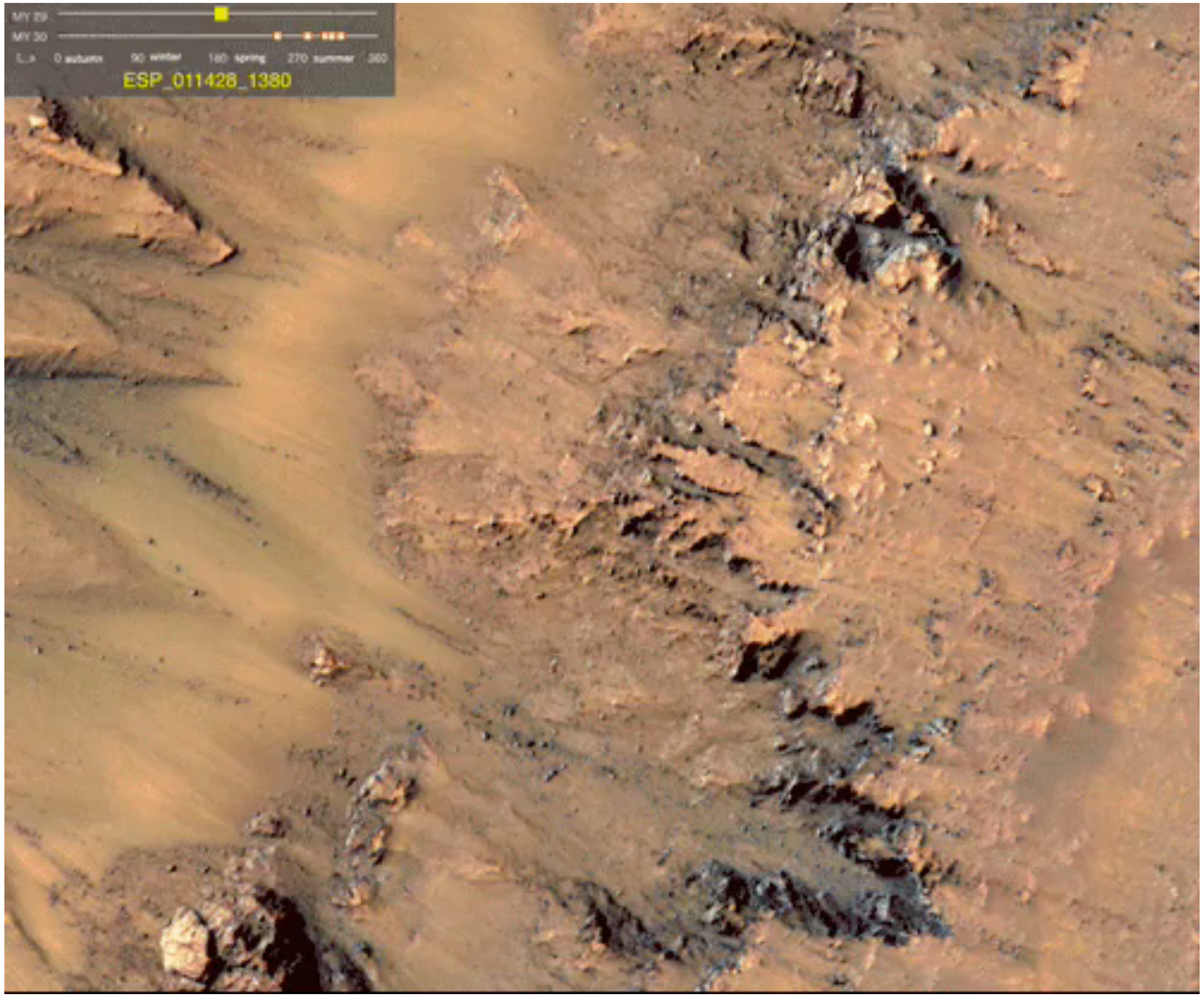


Delta fan in Northeast Holden Crater.



Recent images suggest that water still flows on Mars, even if only briefly. Two gullies show bright new deposits that suggest water carried sediment through them sometime during the past decade.

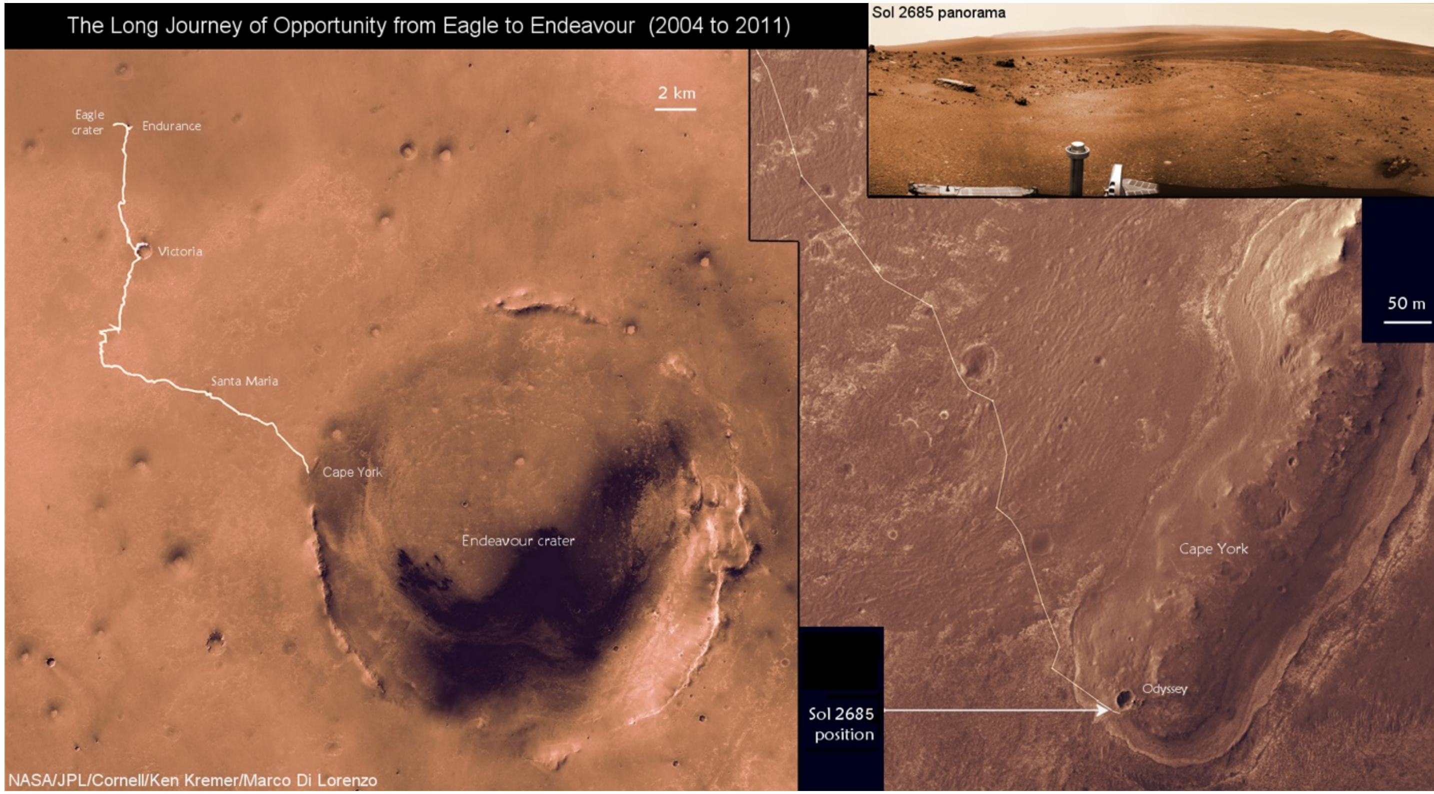




Series of 6 images of Newton Crater spanning slightly more than one Martian year. Dark tendrils appear in warmer weather and flow down to the plains, then fade in winter.

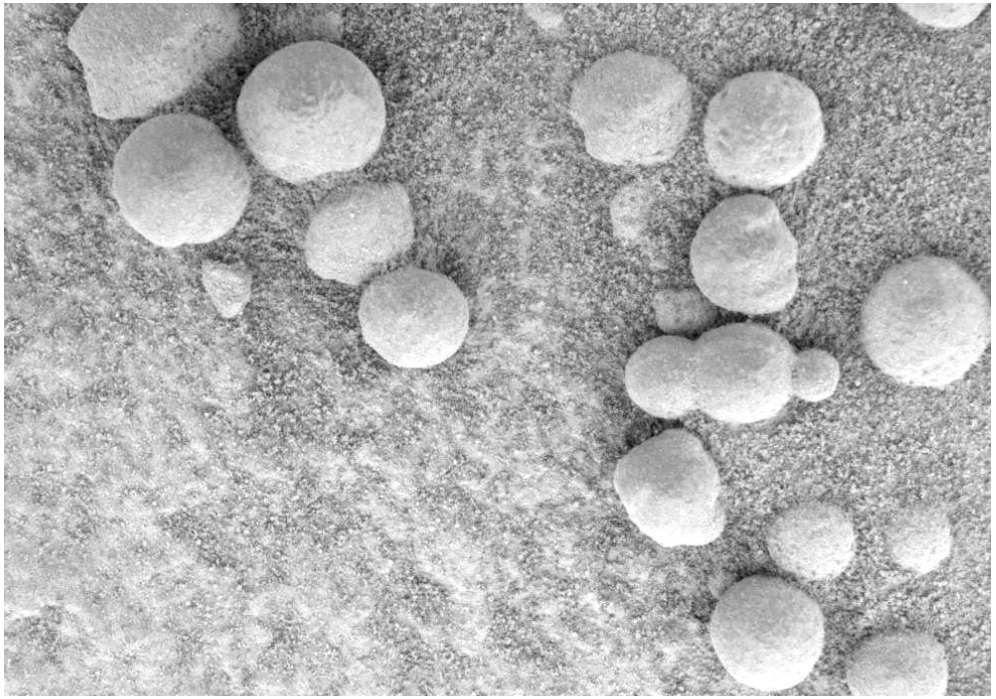
The Martian rovers *Spirit* and *Opportunity* have now been on Mars since 2004. They have found abundant evidence for water on Mars, at least in the past.

Spirit landed at Gusev Crater, which had appeared to be an ancient lake bed, while *Opportunity* landed at Meridiani Planum, which had showed an unusual concentration of haematite, a form of iron oxide which (on Earth) usually forms in water.



Opportunity's route to Endeavour Crater

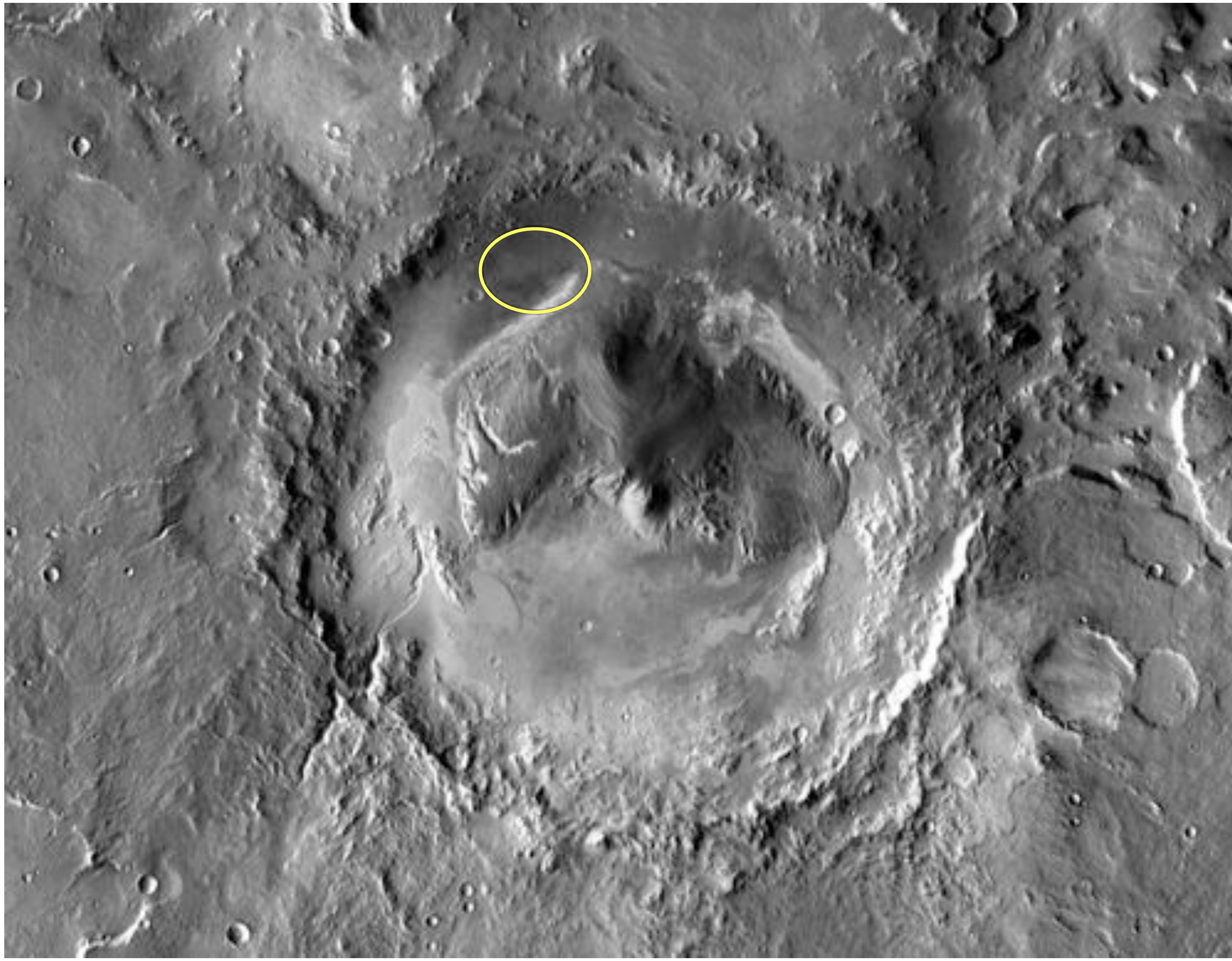
Inside the Endurance crater, *Opportunity* found tiny spherules, dubbed "*blueberries*", which contain a large proportion of the iron mineral haematite. They appear to have formed in liquid water.



TIny spherules of haematite, shown in close-up (right).

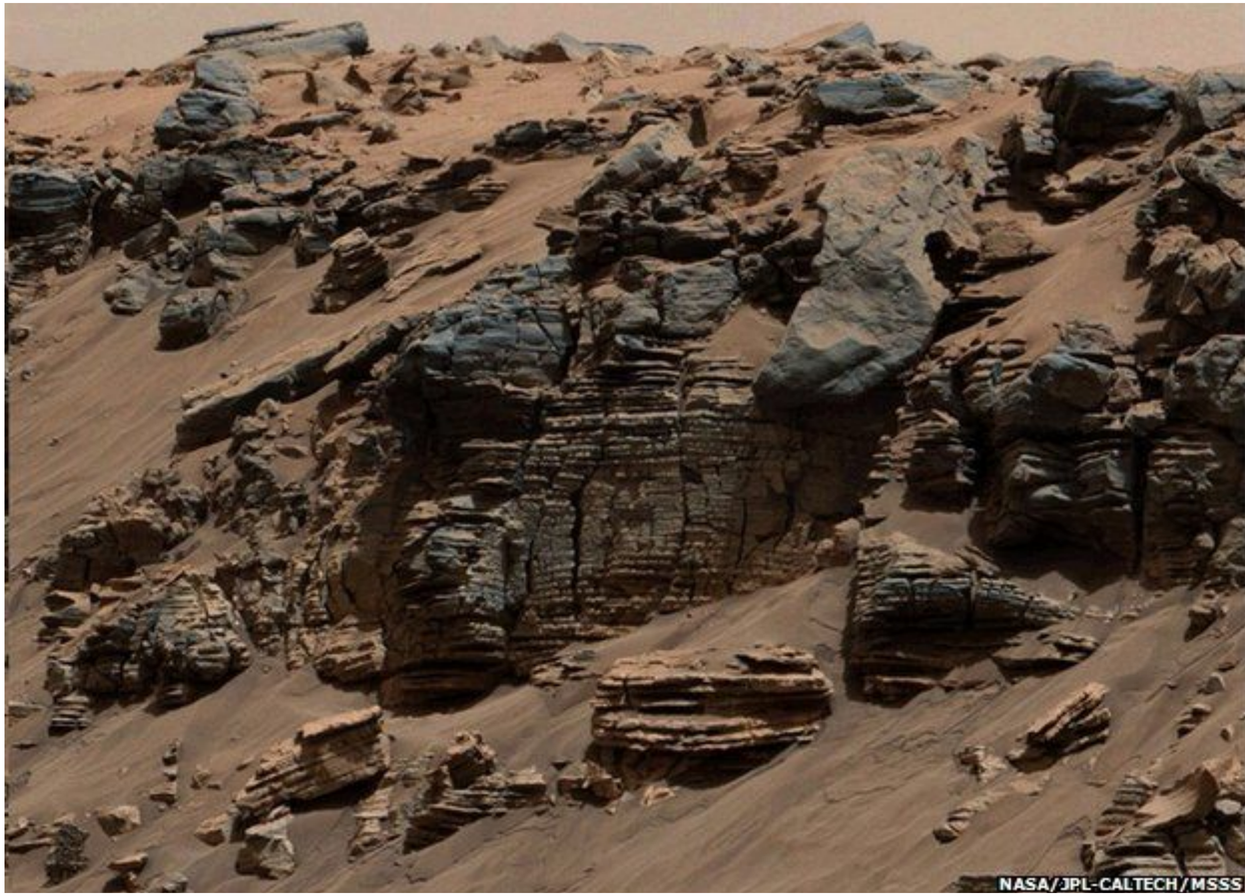
False colour image of sand dunes at the bottom of Endurance Crater. The blue colour results from the presence of "blueberries".

Curiosity has found clays that must have formed through sustained reactions between water and rocks; they typically form in the sediments of lakes.



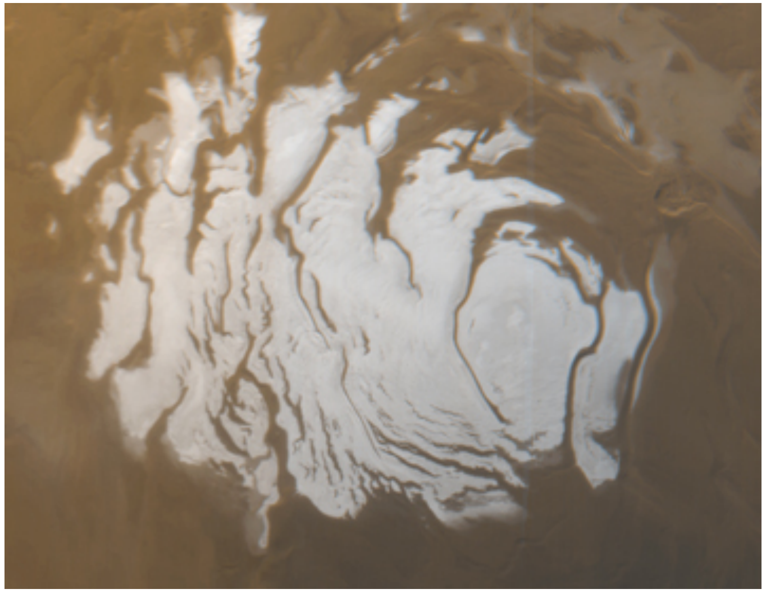
Gale Crater, with the Curiosity landing site indicated.

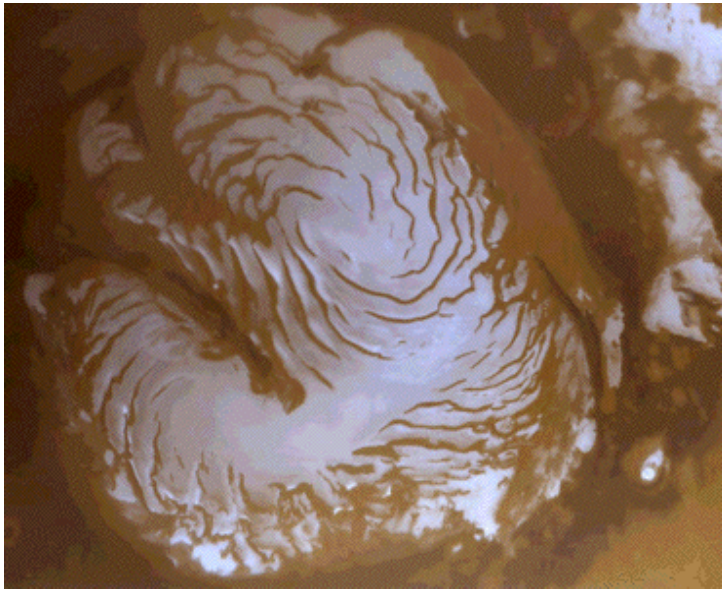
Curiosity has also found spectacular layered rocks – the consequence of past water activity. The evidence suggests that Gale Crater contains sediments laid down in lakes over a long time, probably tens of millions of years. This means it is likely that Gale Crater was flooded, possibly to a depth of more than a kilometre, for long periods of time.



Polar caps

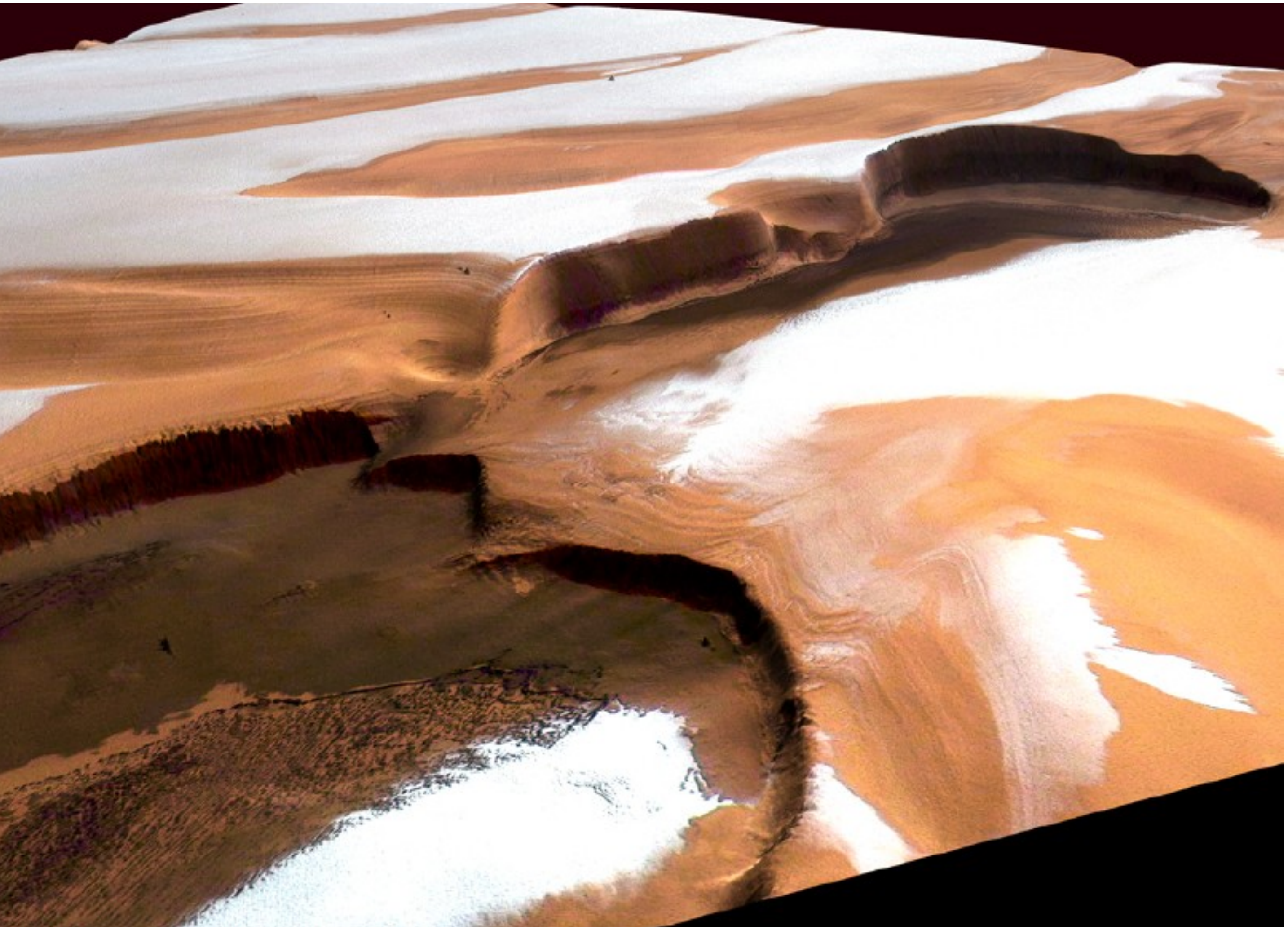
Mars has two permanent polar caps. At the poles, water is permanently frozen. In winter, the temperature drops below the freezing point for carbon dioxide, which condenses out to form a seasonal polar cap of dry ice.





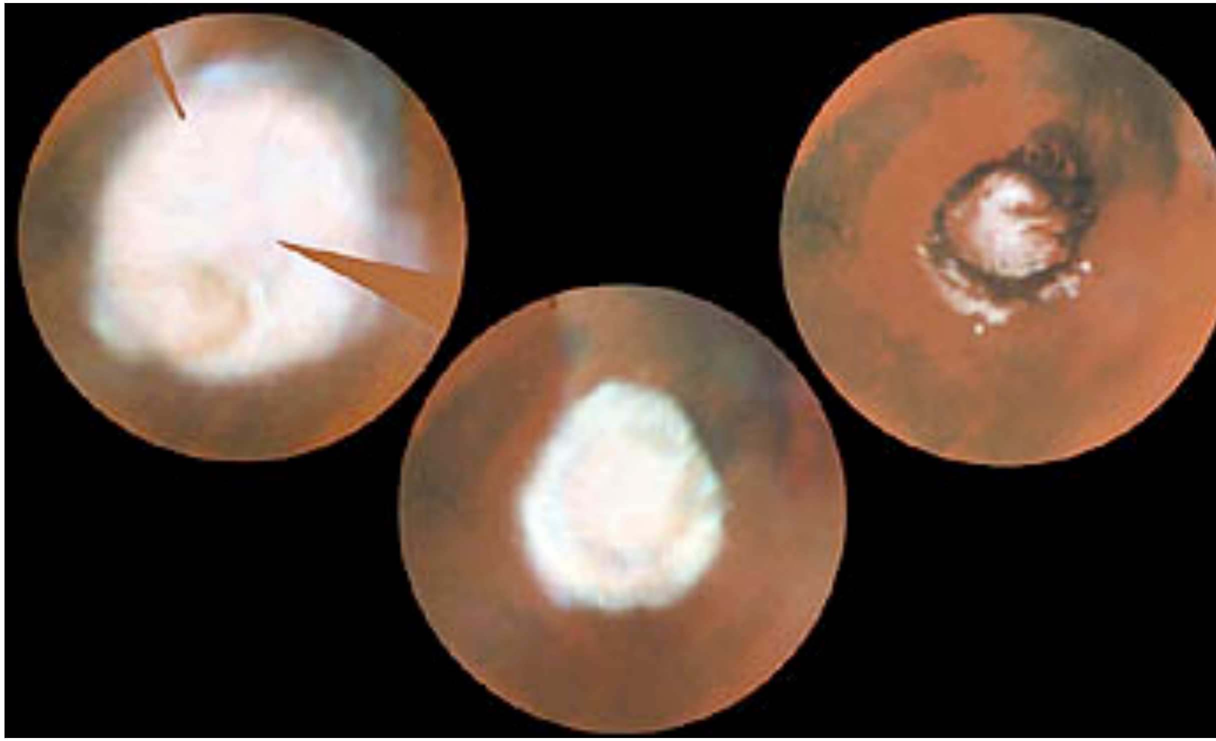
The southern (left) and northern (right) ice caps during summer, at their minimum sizes of about 420 km and 1100 km respectively.

In winter the ice extends to a latitude of about 60°. In summer, the ice sublimes, leaving dust behind: this produces a layering of dust and ice.



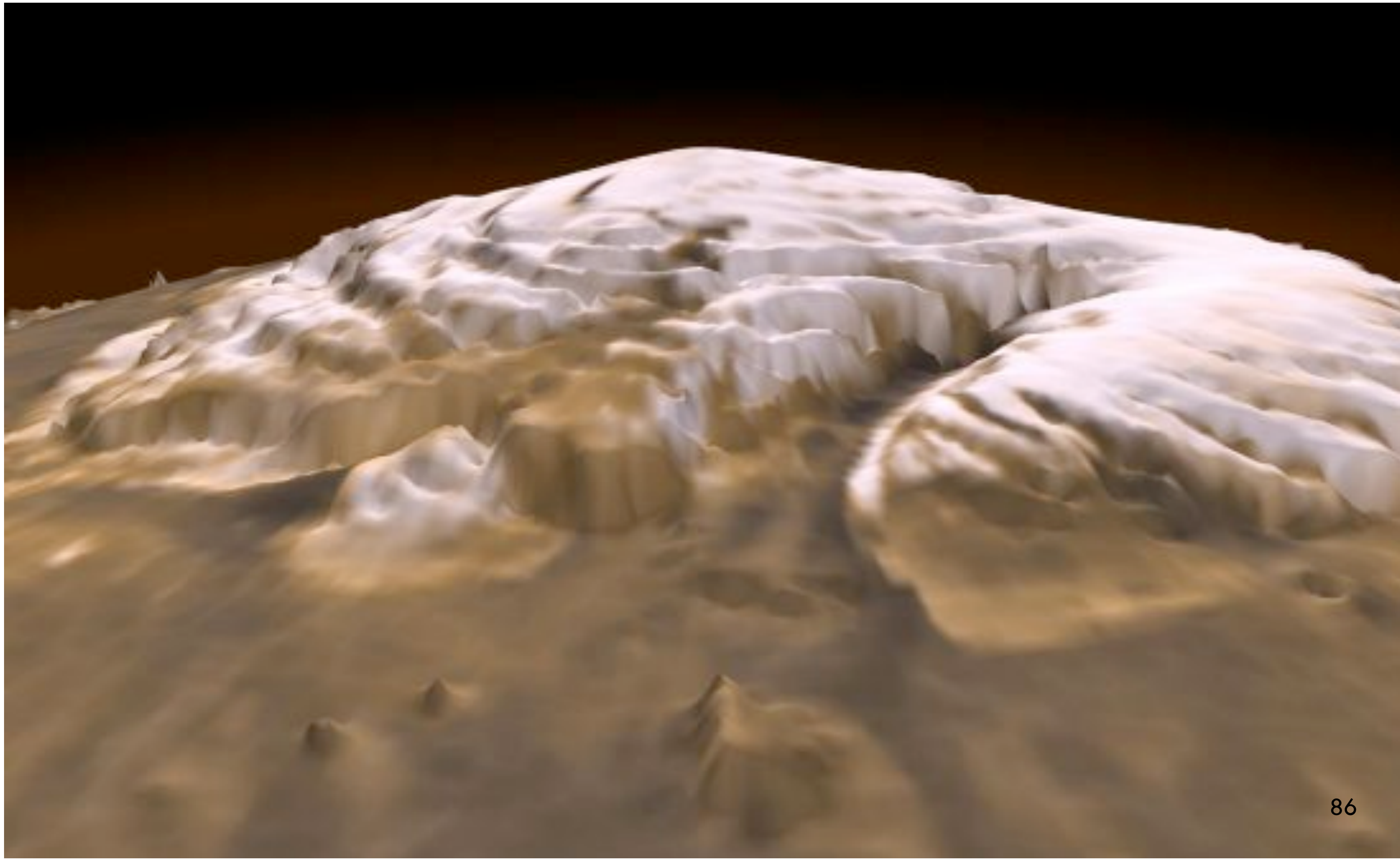
Mars Express picture of the north polar cap.

In the north, the CO_2 sublimes away completely during summer, leaving a permanent ice cap of water-ice about 1000 km in diameter. In the south, the CO_2 never completely sublimates away, leaving a permanent cap of ice about 350 km in diameter. The OMEGA spectrometer on Mars Express recently found that the ice at the south pole has only a thin veneer of CO_2, which covers huge deposits of water ice.



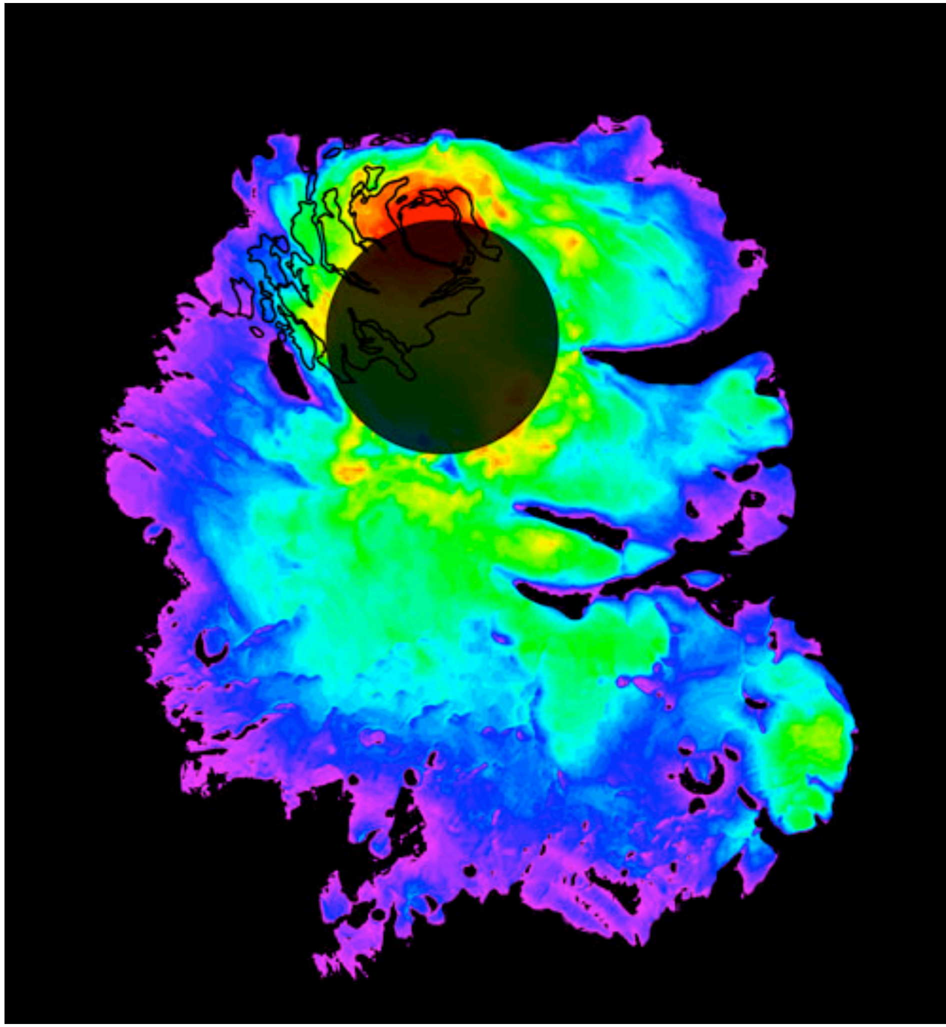
Images of Mars' North Pole, created by assembling mosaics of three sets of images taken by HST in October, 1996 and in January and March, 1997. They show the ice cap in early spring, mid-spring, and early summer.

Laser altimeter measurements from *Global Surveyor* show that the north polar cap is up to 3 km thick and is cut by canyons up to 1 km deep.



3-D visualisation of Mars' north pole based on elevation measurements made by an orbiting laser.

Radar measurements of the south polar cap by *Mars Express* show the ice is more than 3.7 km thick in places, and contains enough water to cover the planet in 11 m of water.



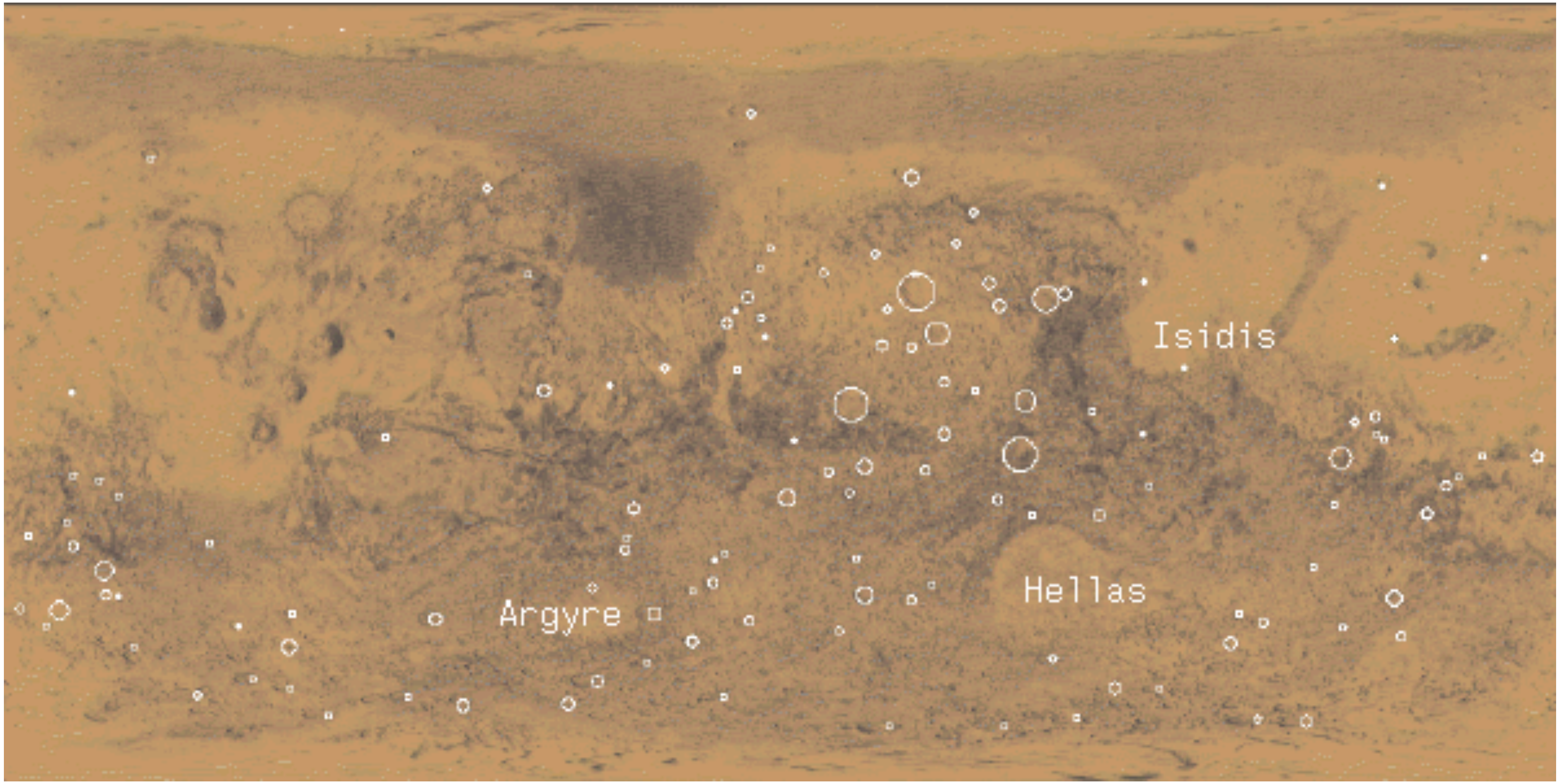
The thickness of the layered deposits is shown by colors, with purple representing the thinnest areas, and red the thickest. The map covers an area 1670 by 1800 kilometres

Putting it all together

It seems clear that Mars had flowing liquid on its surface at least at some stage during its history.

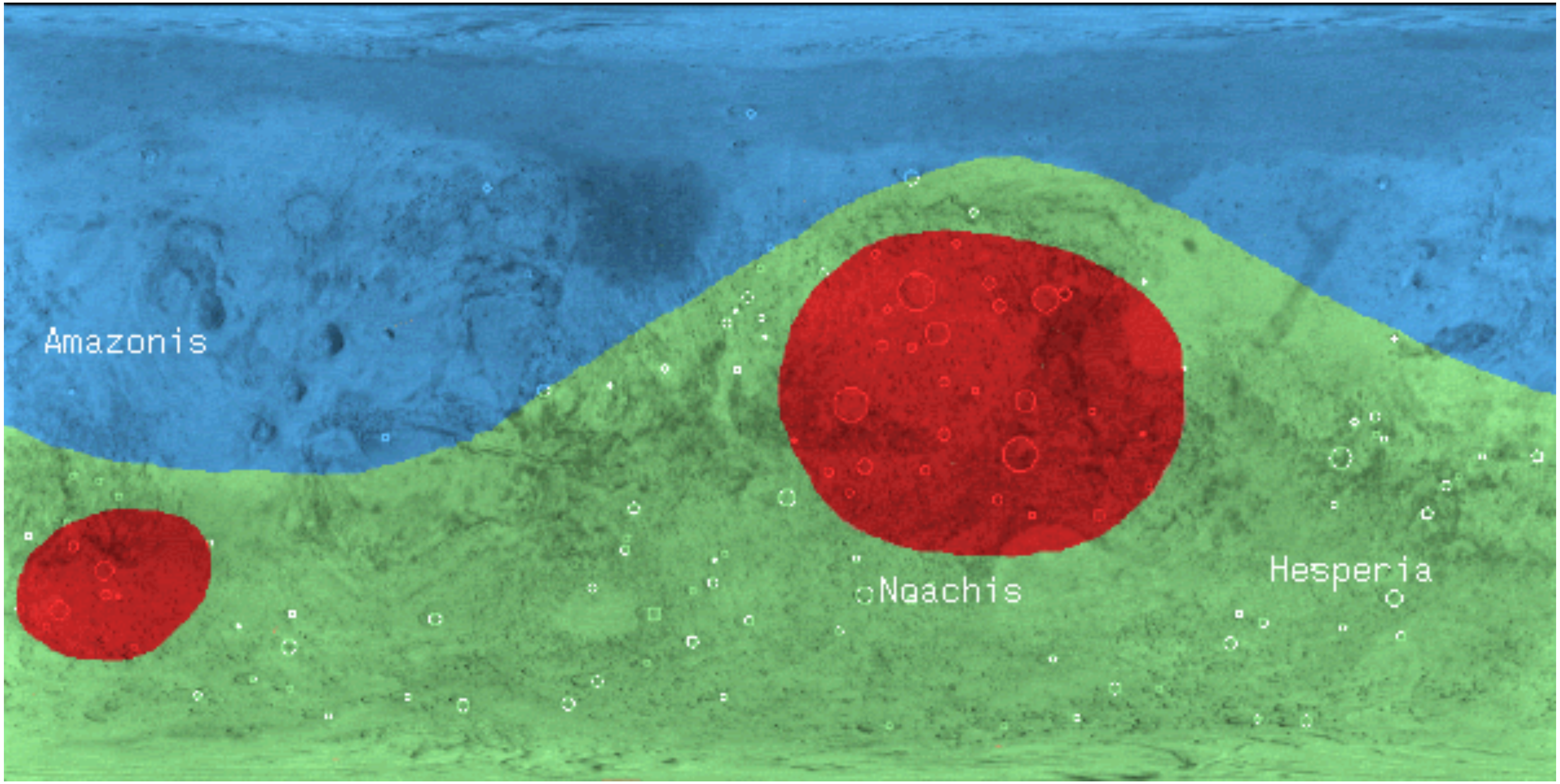
The problem is that water cannot exist in liquid form on Mars: at its current temperature and pressure, water can exist only as a solid or a gas. Even in the most favourable spots, where the pressure is higher than average, water would boil at 10° C.

The other key question is *when* there was water present. We can get some clues by looking at the position of all craters larger than 100 km in diameter. Their distribution is not at all uniform:

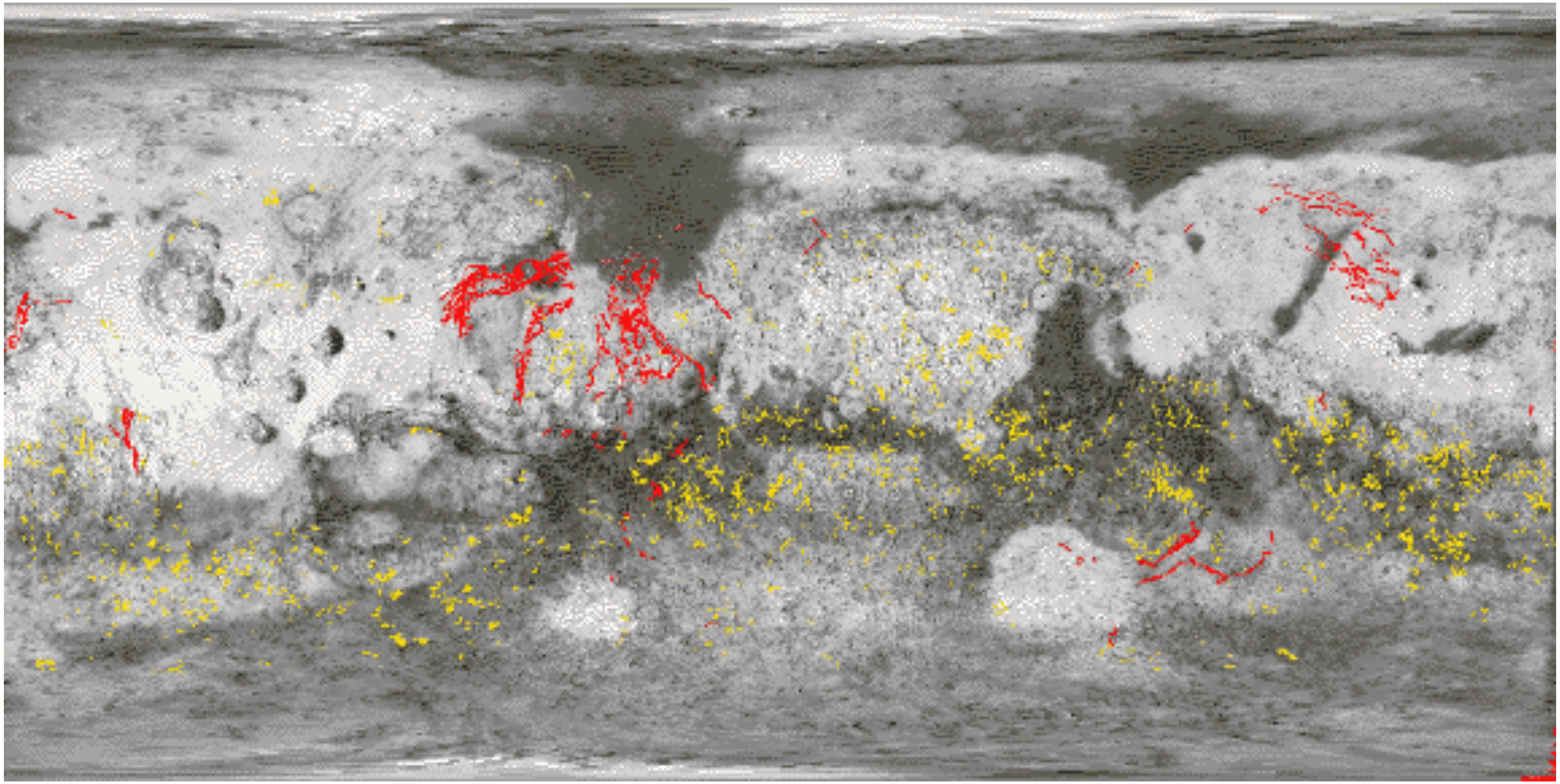


We can colour-code these regions: red for heavily cratered areas, green for intermediate, and blue for least cratered.

Roughly speaking, these represent the ages of the surfaces on Mars.

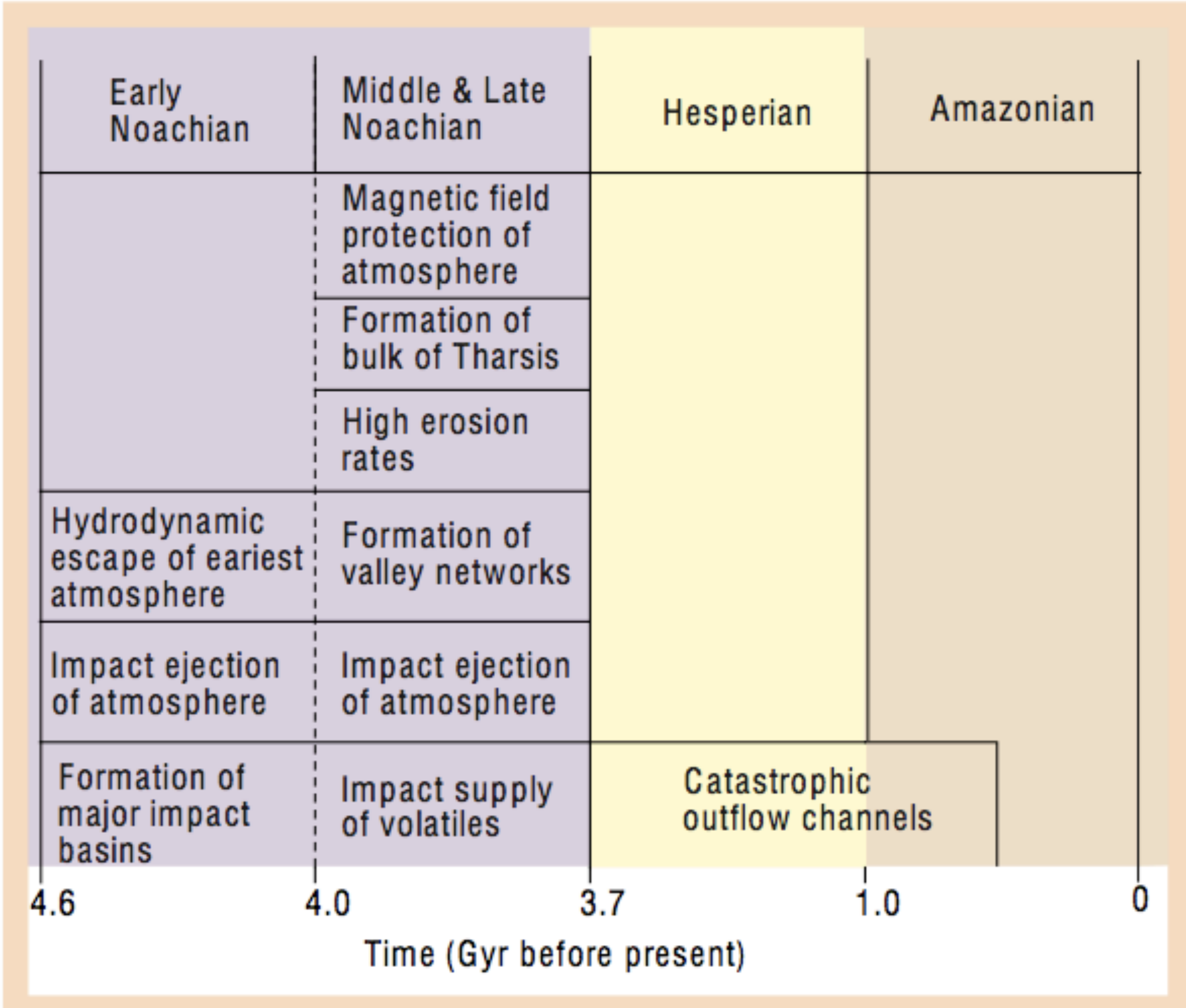


If we look at where the river-like networks (yellow) and outflow channels (red) are, the networks are found in the old regions, and the outflow channels in the youngest regions.



These three phases are given the names of regions which approximate these ages. The absolute ages are very uncertain:

1. the *Noachian* period (4.5 Gy–3.7 Gy): Heavy bombardment, producing a lunar-like, heavily cratered terrain, though more degraded than on the Moon. Plate tectonics appears to have been active, and liquid water appears to have been on the surface for at least some of the time. Formation of Tharsis uplift and Valles Marineris canyon system
2. the *Hesperian* period (3.7 Gy–??1 Gy): Rate of bombardment lessened. Extensive lava flooding.
3. the *Amazonian* period (??1 Gy– present): Northern plains fill; very low impact flux. Volcanoes form. Outflow channels from Valles Marineris.



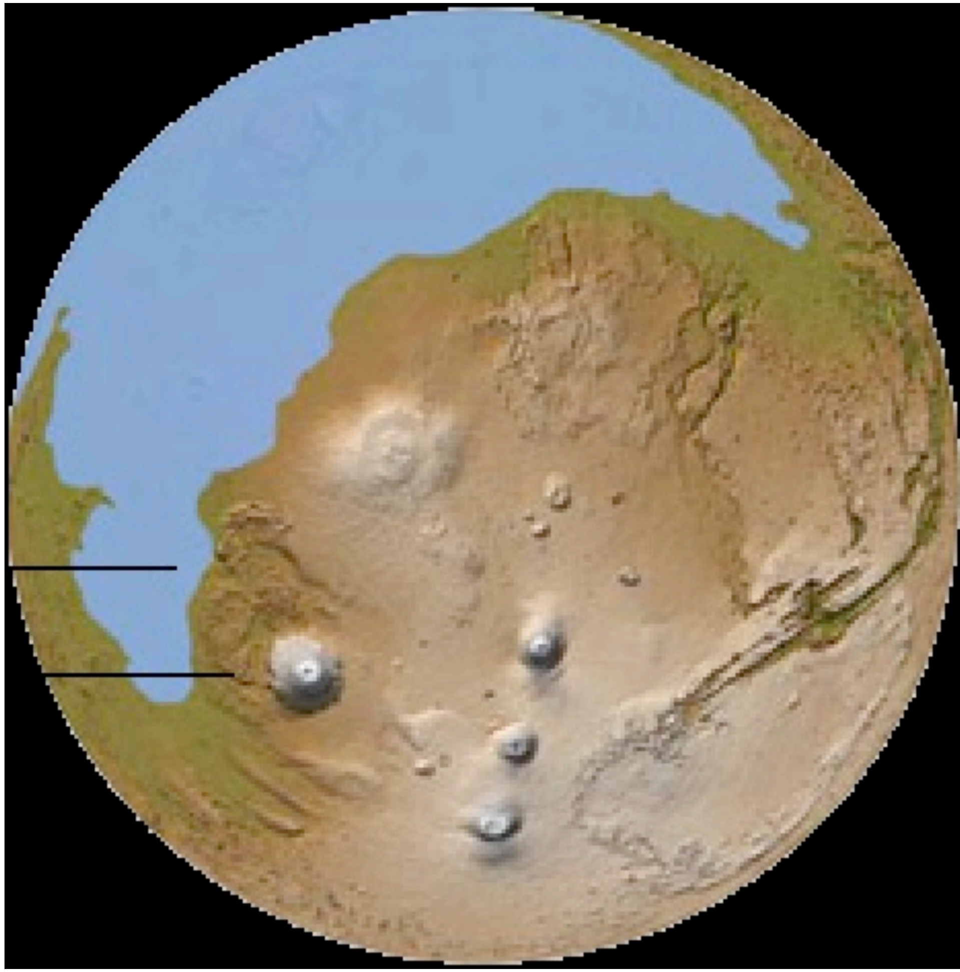
Schematic diagram showing the Martian timeline and processes which occurred within each epoch (From Jakosky & Phillips 2001)

In this view, Mars had liquid water on its surface in the distant past, but it has since been lost or locked up, so water is no longer an active agent.

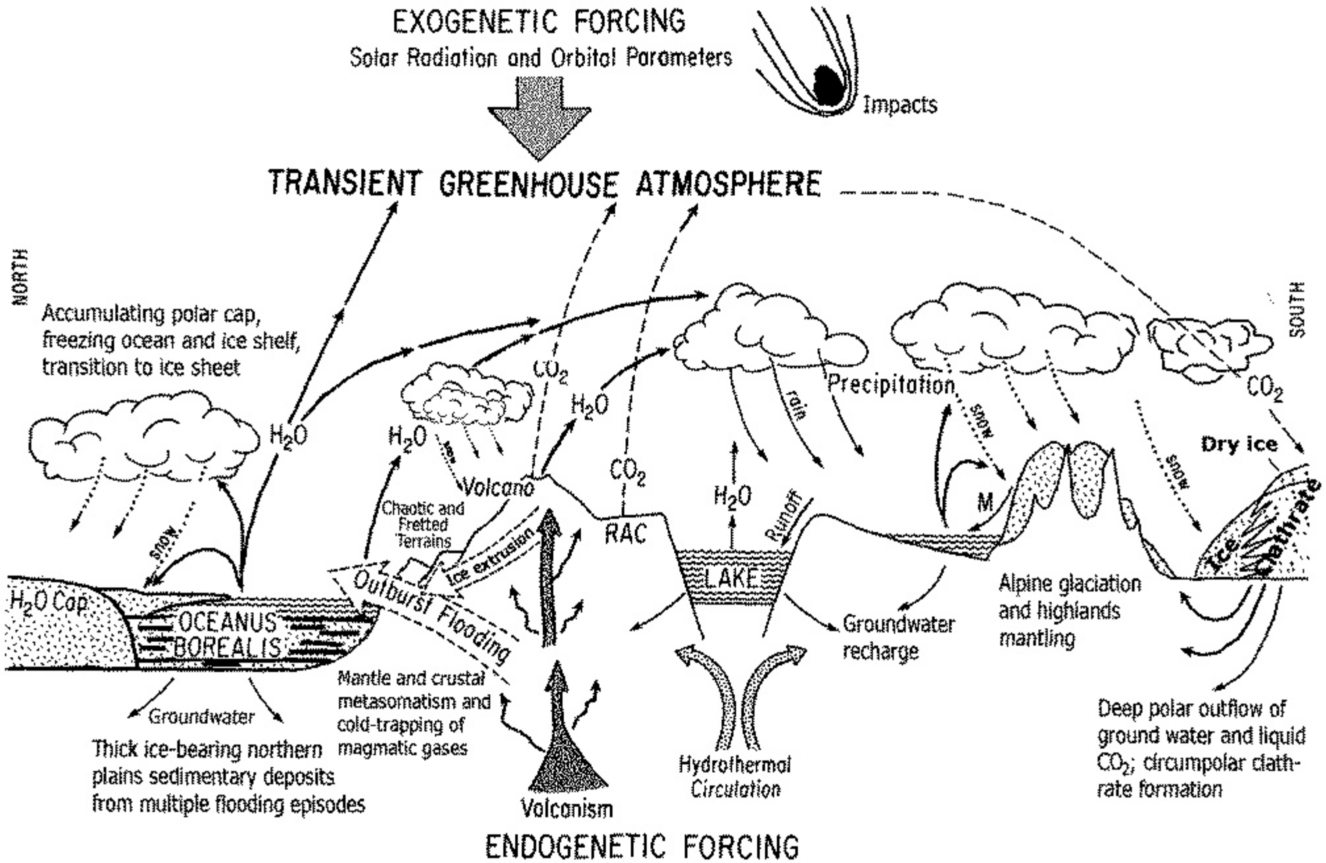
This scenario has been dubbed the *Warm Wet Early* Mars.

There are several other models which have been suggested.

The MEGAOUTFLO hypothesis (Mars Episodic Glacial Atmospheric Oceanic Upwelling by Thermotectonic Flood Outbursts) suggests that internal heating periodically melts the subsurface ice to form a northern ocean, and releases CO_2 into the atmosphere to provide 100,000 years or so of relatively mild, wet climate before the ocean and atmosphere return to the subsurface.

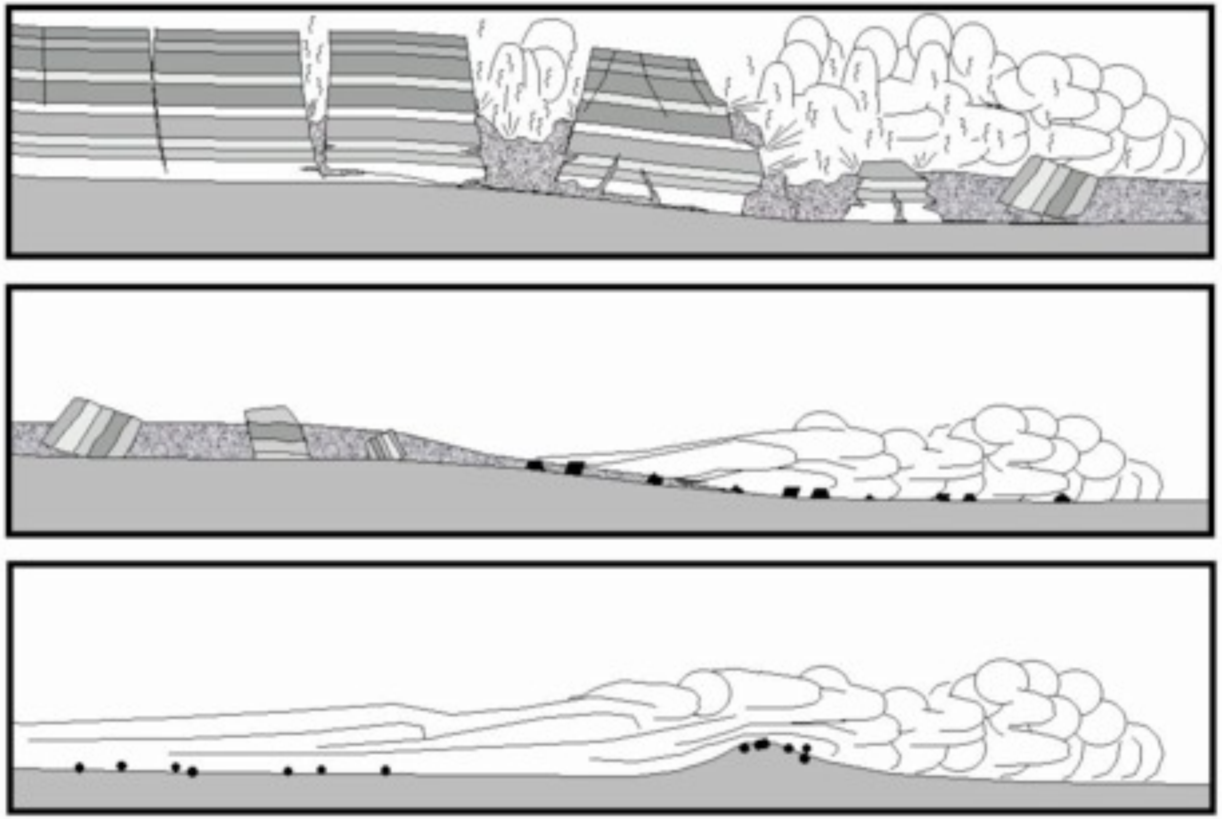


This model postulates a transient greenhouse atmosphere, and stresses the importance of glacial processes.



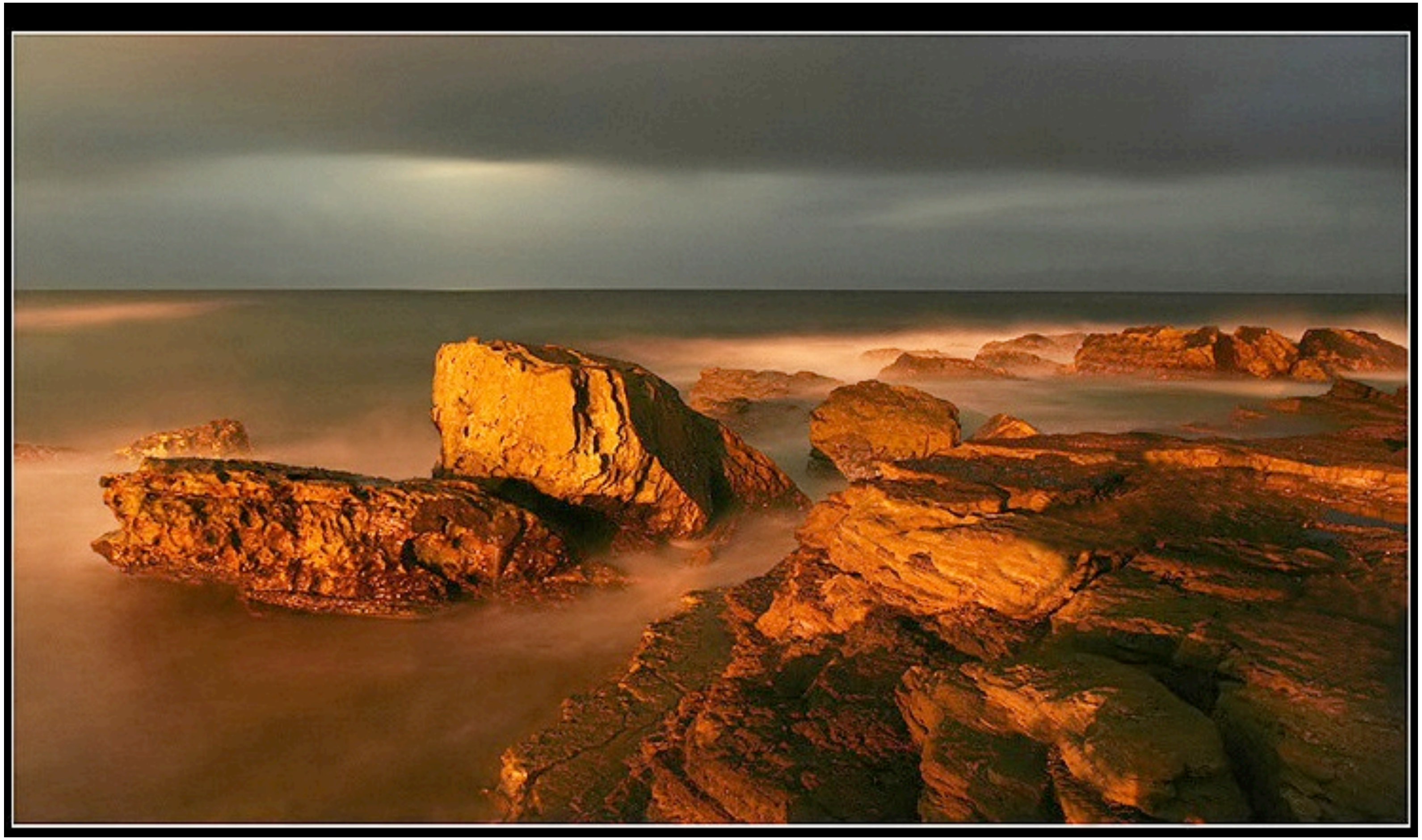
from Kargel 2004, p. 174, after Baker et al. 1991

Some authors have suggested that there was never liquid water on Mars, and that the flow features were formed by carbon dioxide instead of water: cold and dry avalanches instead of warm and wet floods.

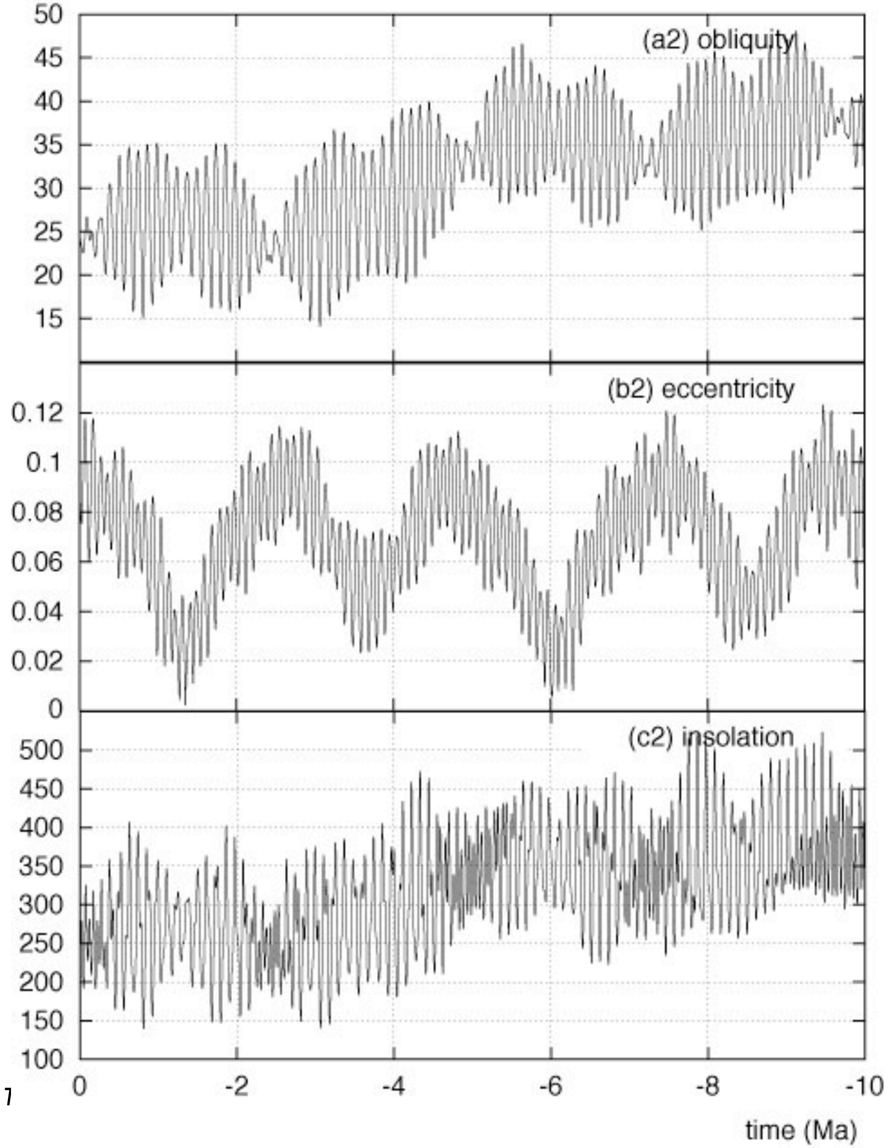


The "White Mars" model: layers of solid CO_2 ("dry ice") embedded in layers in rock, are released during a quake. Exposed to low pressure, the CO_2 fizzes and floods over the lowlands.

Others suggest there was never a truly liquid water ocean, but instead a vast mud ocean in the northern plains.



Artist's impression of an ocean on Mars



Why would Mars' climate have been radically different in the past?

One possibility is that changes in Mars' orbit could result in large climate changes.

Mars axial tilt (its *obliquity*) is strongly chaotic: over millions of years it varies between 15° and 35° over roughly 125,000 years, and has probably tilted as far as 0° and 60° over the past few tens of millions of years.

Variations of Mars' axis tilt, eccentricity, and sunlight received at the north pole surface, computed over 10 million years. These variations result from the gravitational planetary perturbations exerted by the other planets of the solar system. (From Laskar et al. 2002)

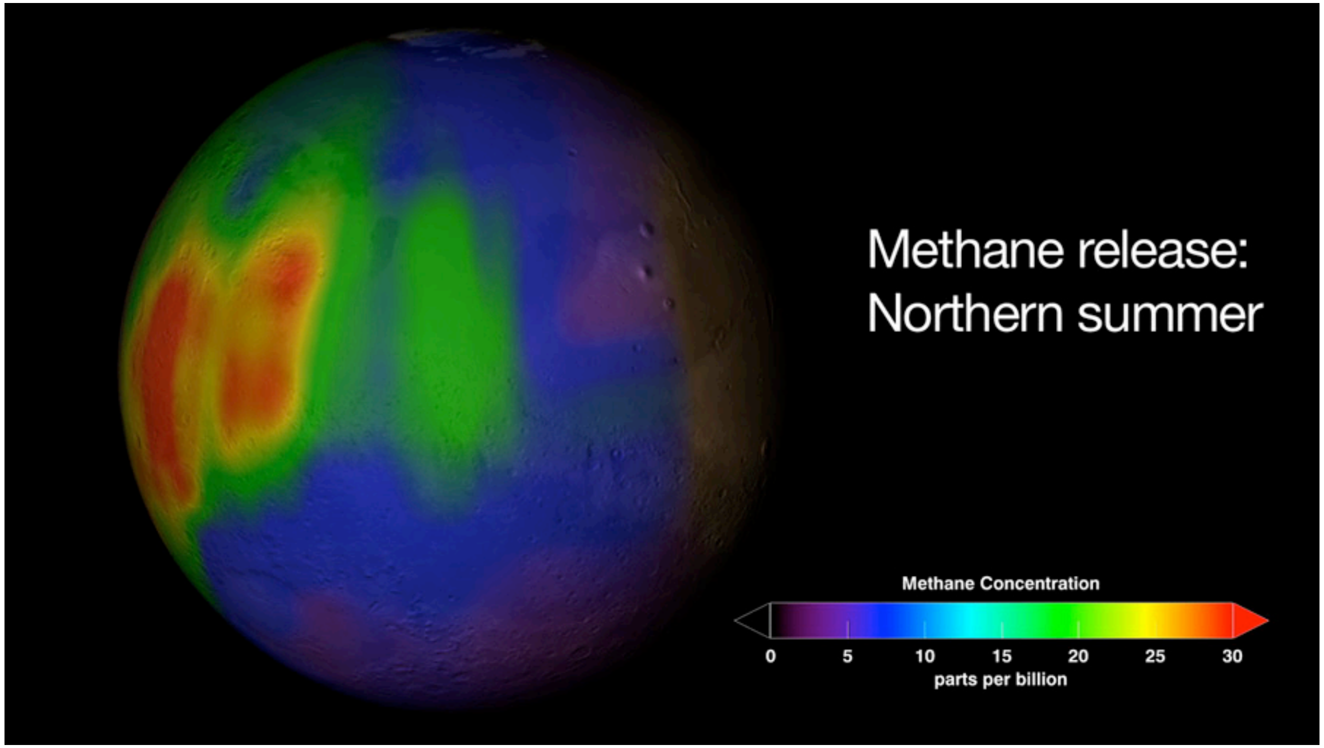
According to some theories, as Mars’ axis tilts further, increased sunlight at the poles warms the poles significantly. This thaws the polar CO_2, releasing it into the air, so Mars' air pressure increases significantly.

This still leaves its air pressure only a tiny fraction of Earth's (at most, about 4%) – but it produces enough of a greenhouse effect to warm Mars by another 10° C. And it also raises Mars' air pressure enough that liquid water can exist on its surface.

As the axial tilt reduces again in its long cycle, the CO_2 freezes out again, returning Mars to its current state.

In 2004 methane was detected in Mars' atmosphere, by *Mars Express* and ground-based observations. The methane is concentrated in areas where water vapour and underground water ice are also concentrated, suggesting an underground source. The amounts were small (10 parts per billion), but methane will only survive in the Martian atmosphere for a few hundred years.

Possible sources are microbial life, or geological activity.

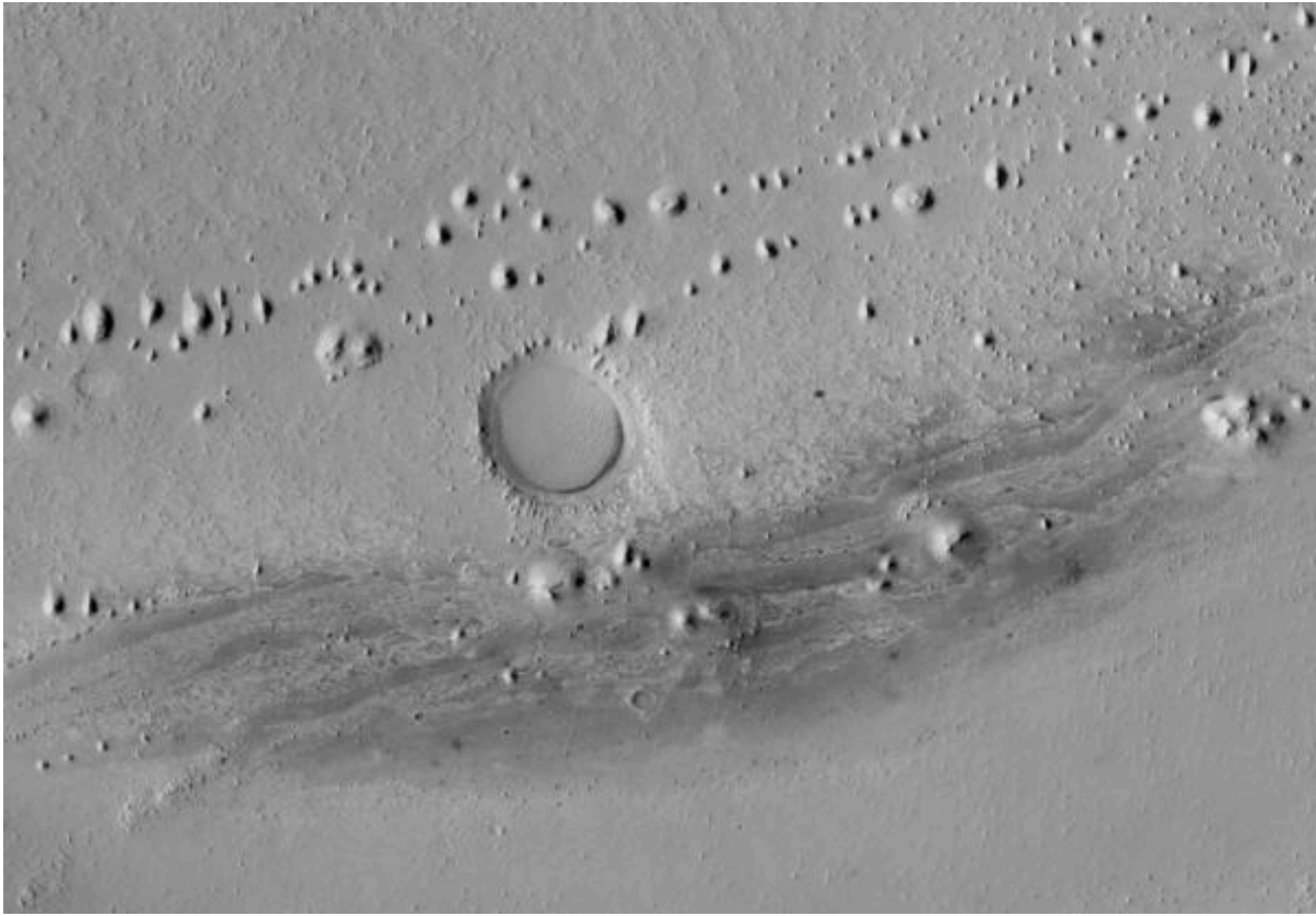


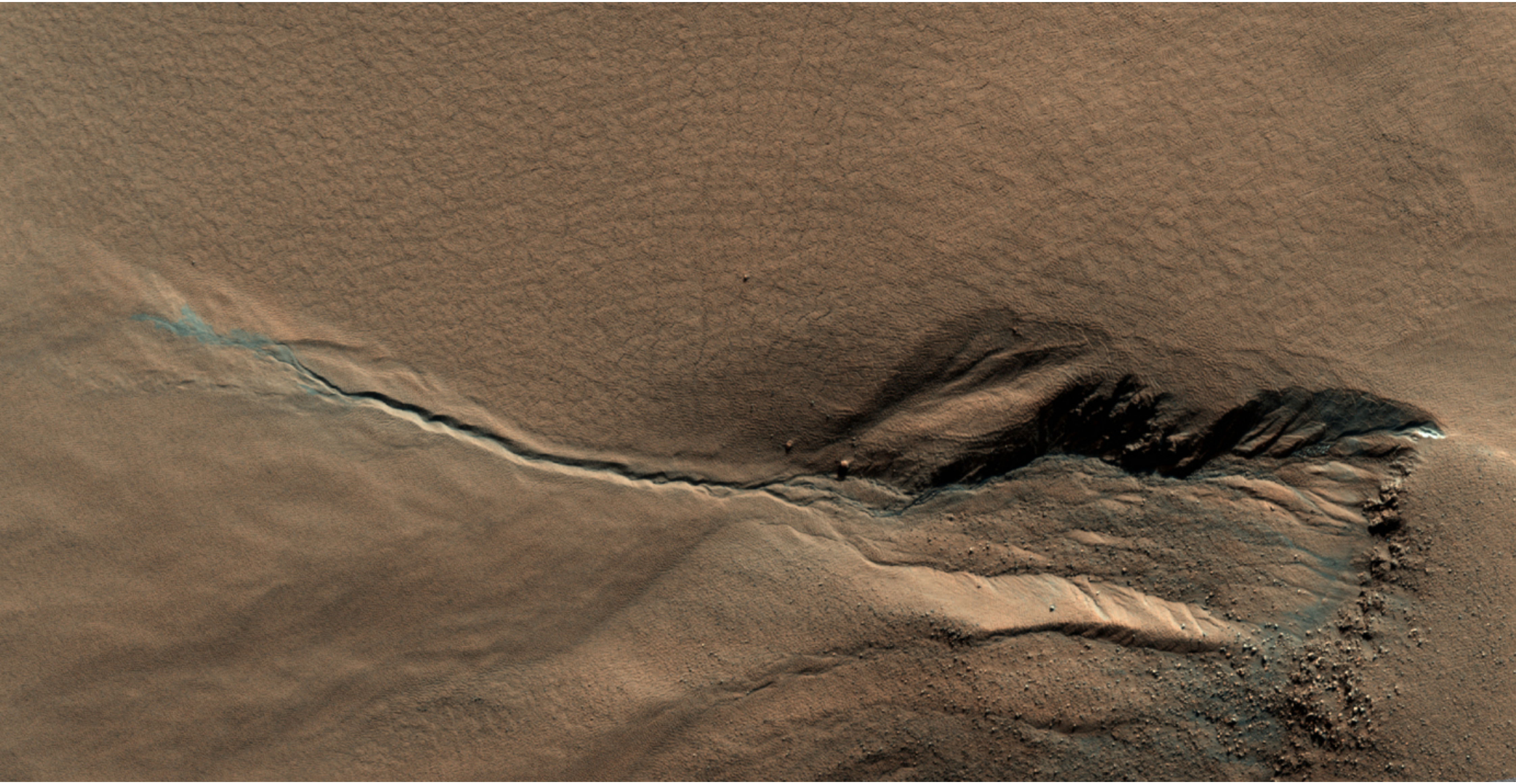
Over the last few years, some scientists are becoming more pessimistic about there ever having been liquid water on Mars.

“...Models of the ancient Martian climate ... fail to predict temperatures high enough for rain, or for liquid water to persist on the surface at all. The young Sun was fainter than it is today, and even if the young Mars had a thicker atmosphere, its greenhouse effect would probably not have warmed the planet above freezing... Sulphurous bouts of volcanic activity could have warmed the atmosphere for brief periods, just enough to melt the icy highlands and unleash torrents that could have carved the valley networks.”

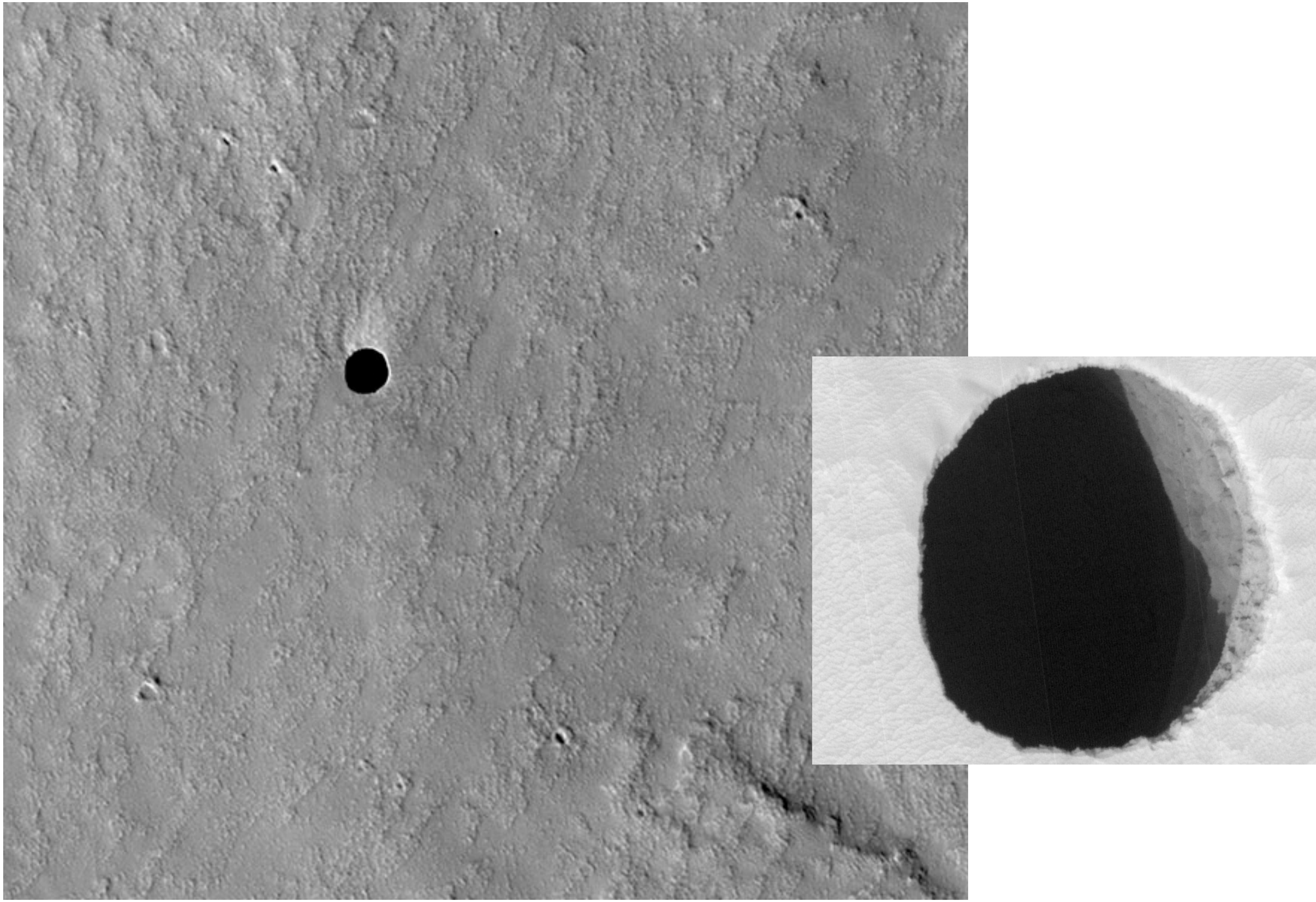
– Eric Hand, “Dreams of water on Mars evaporate”, Nature 484, 153 (2012)

Hot springs?

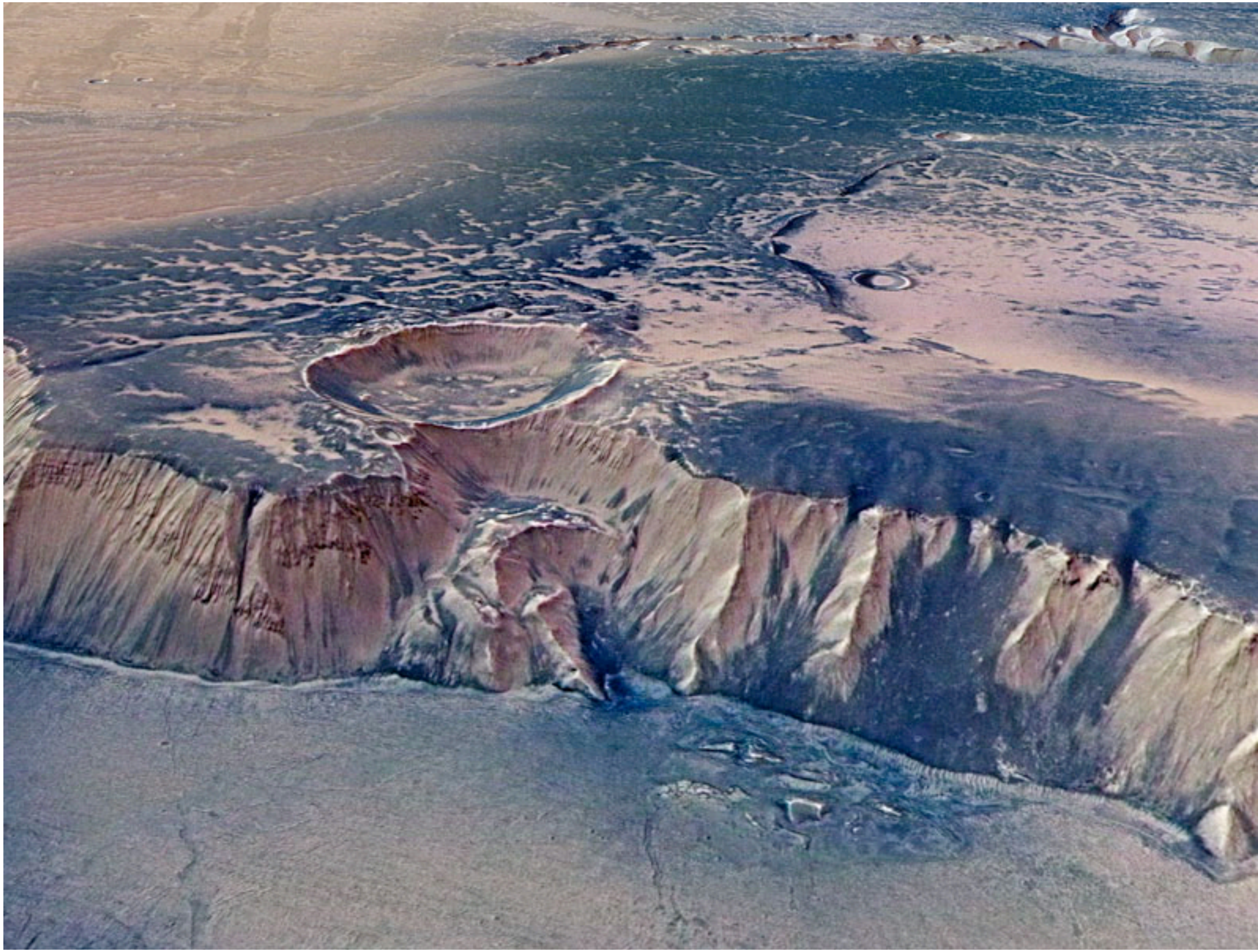




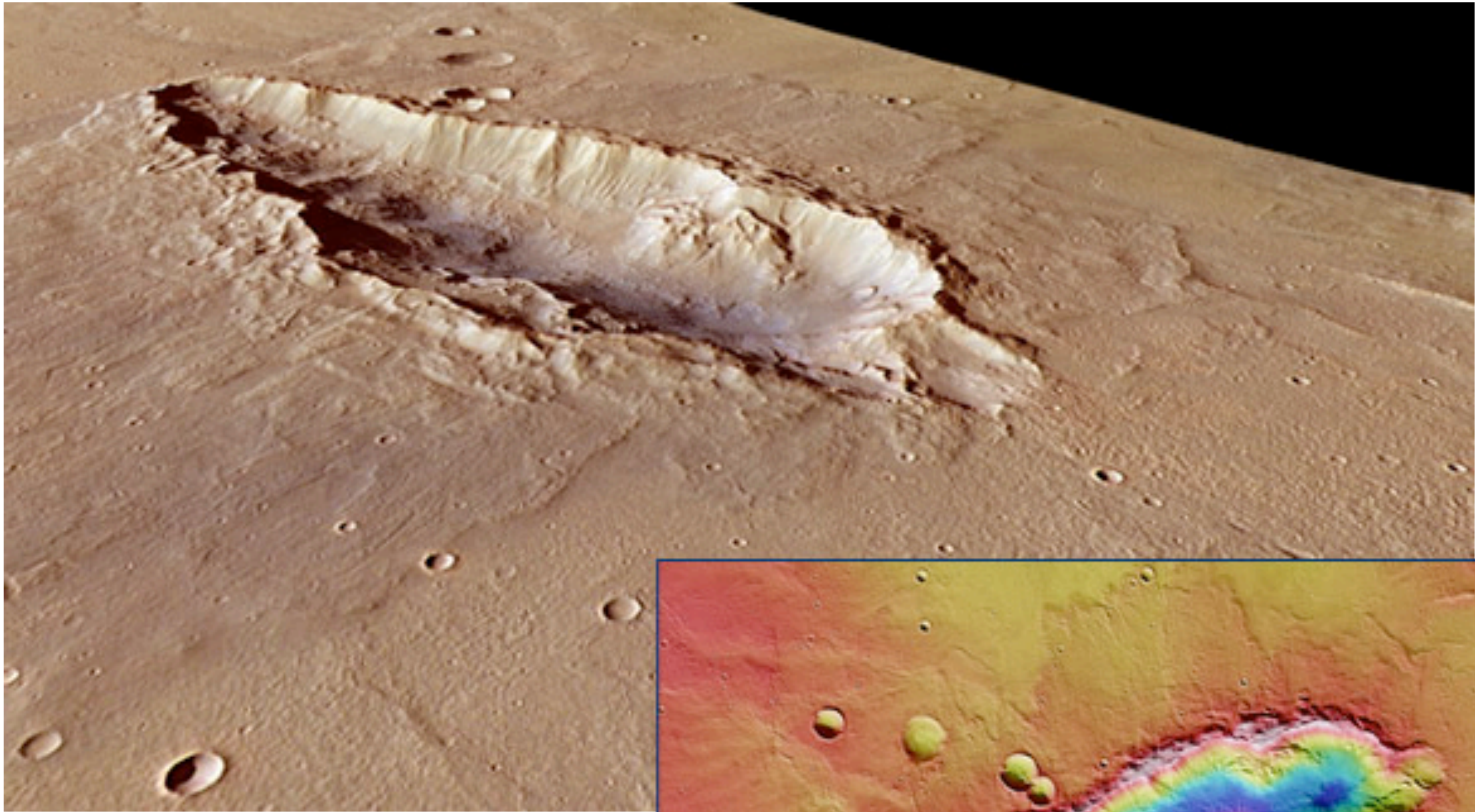
Gully in a crater wall

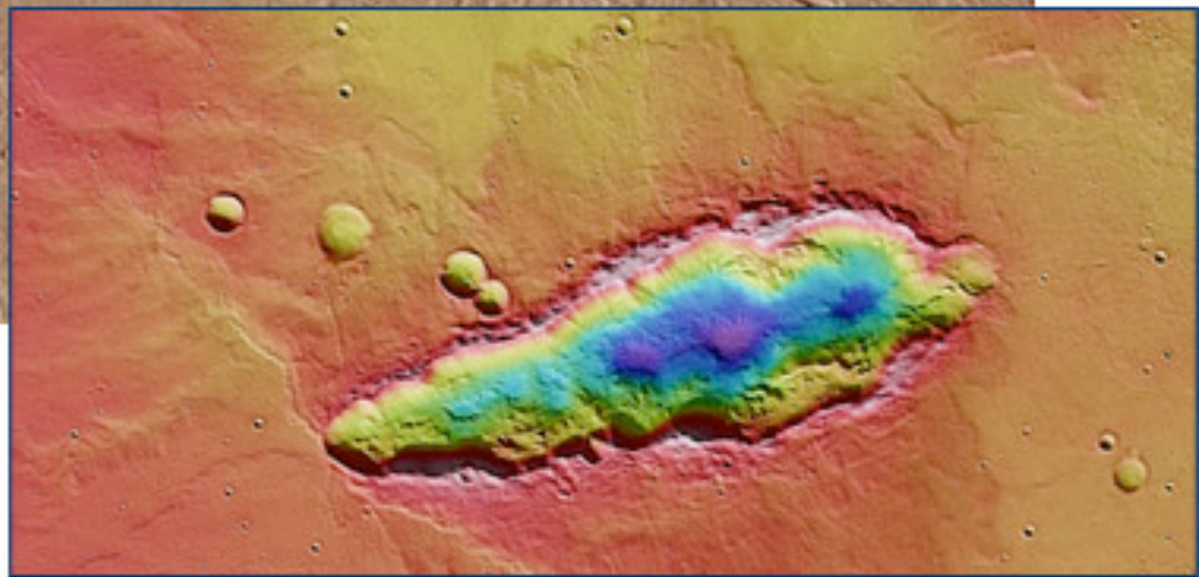


Caves?



4-km high cliffs around Echus Chasma: waterfalls or lava?





Unusually elongated crater: gouged by several object striking at a shallow angle?

Grooves on sand dunes: dry ice sleds?

Sedimentary "stairs" – evidence of climate cycles?

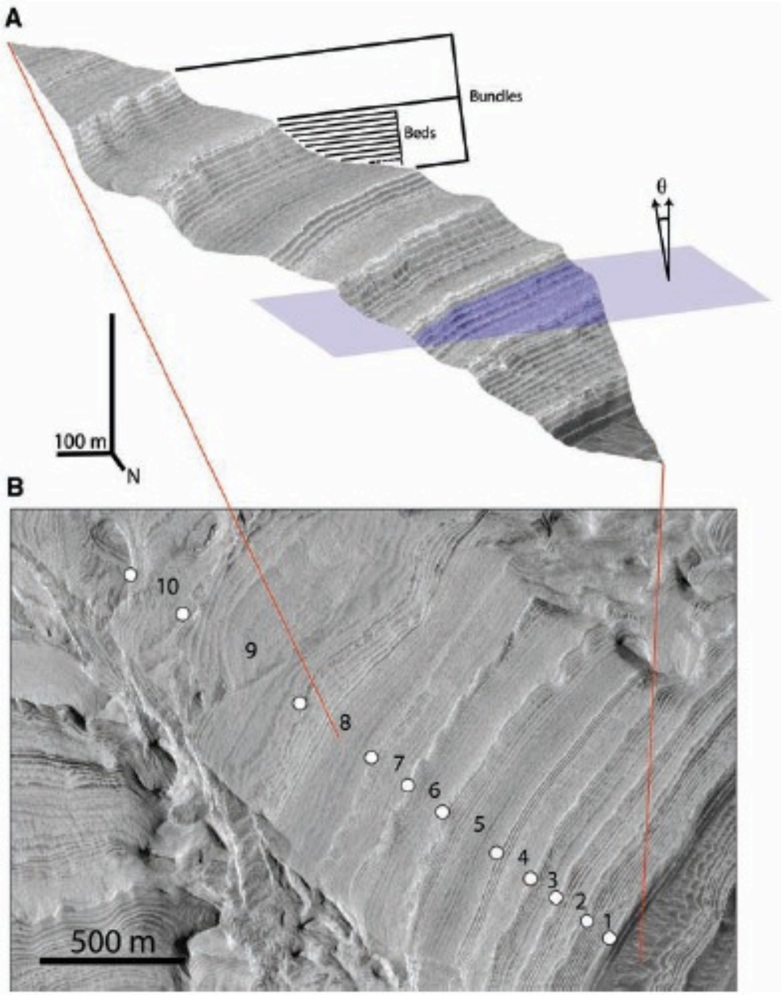
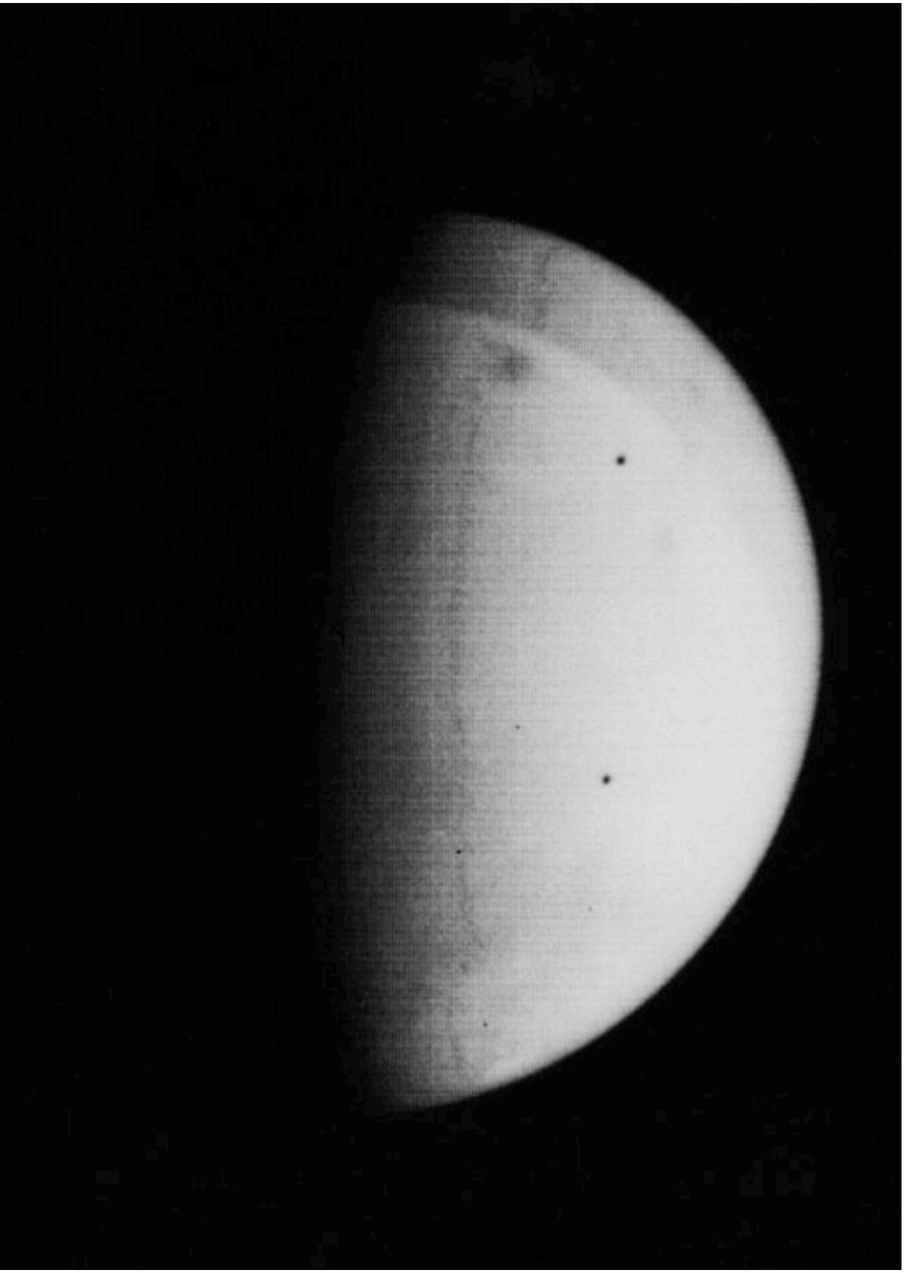


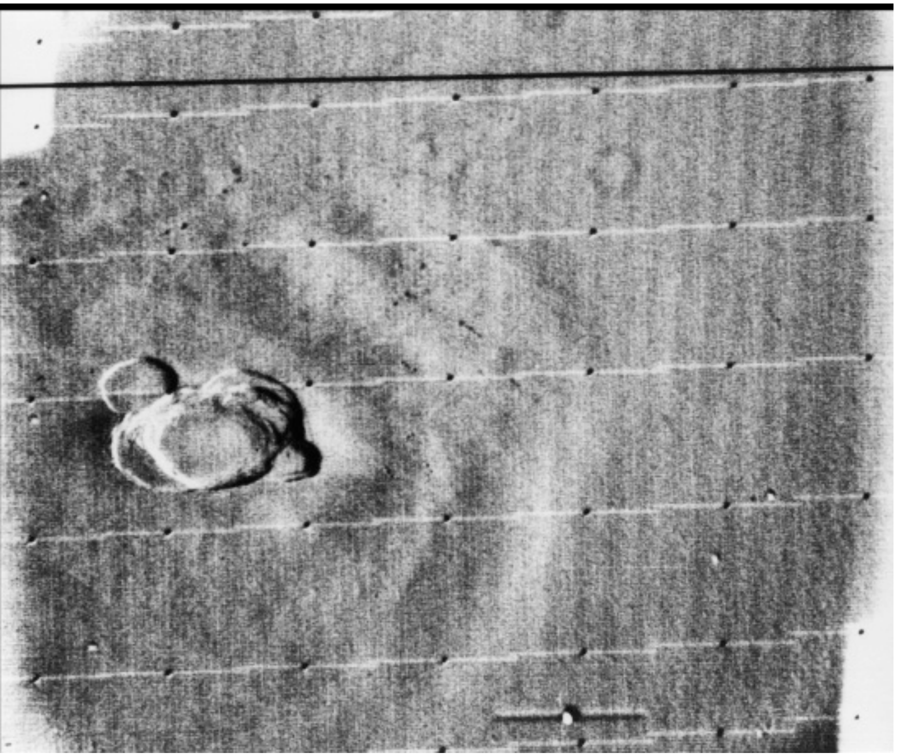
Fig. 3. (**A**) Three-dimensional view of the stratified deposit within Becquerel crater. This location shows two scales of quasi-periodic bedding, marked as beds and bundles. The ratio of these characteristic thicknesses is a potential clue to the forcing mechanisms responsible for the cyclicity seen in the rocks. The blue plane indicates the best-fit orientation of the bedding, which has a dip of ~3°. To obtain true thicknesses, it is necessary to account for both the erosional morphology and the tilt of the bedding from horizontal (indicated by θ). HiRISE image PSP_001546_2015 is shown draped over digital stereo topography. Scale bars, 100 m (both horizontal and vertical). (**B**) Plan view of HiRISE image PSP_001546_2015, showing context for (A); north is down. Numbers mark the boundaries between successive bundles as revealed in the topography.



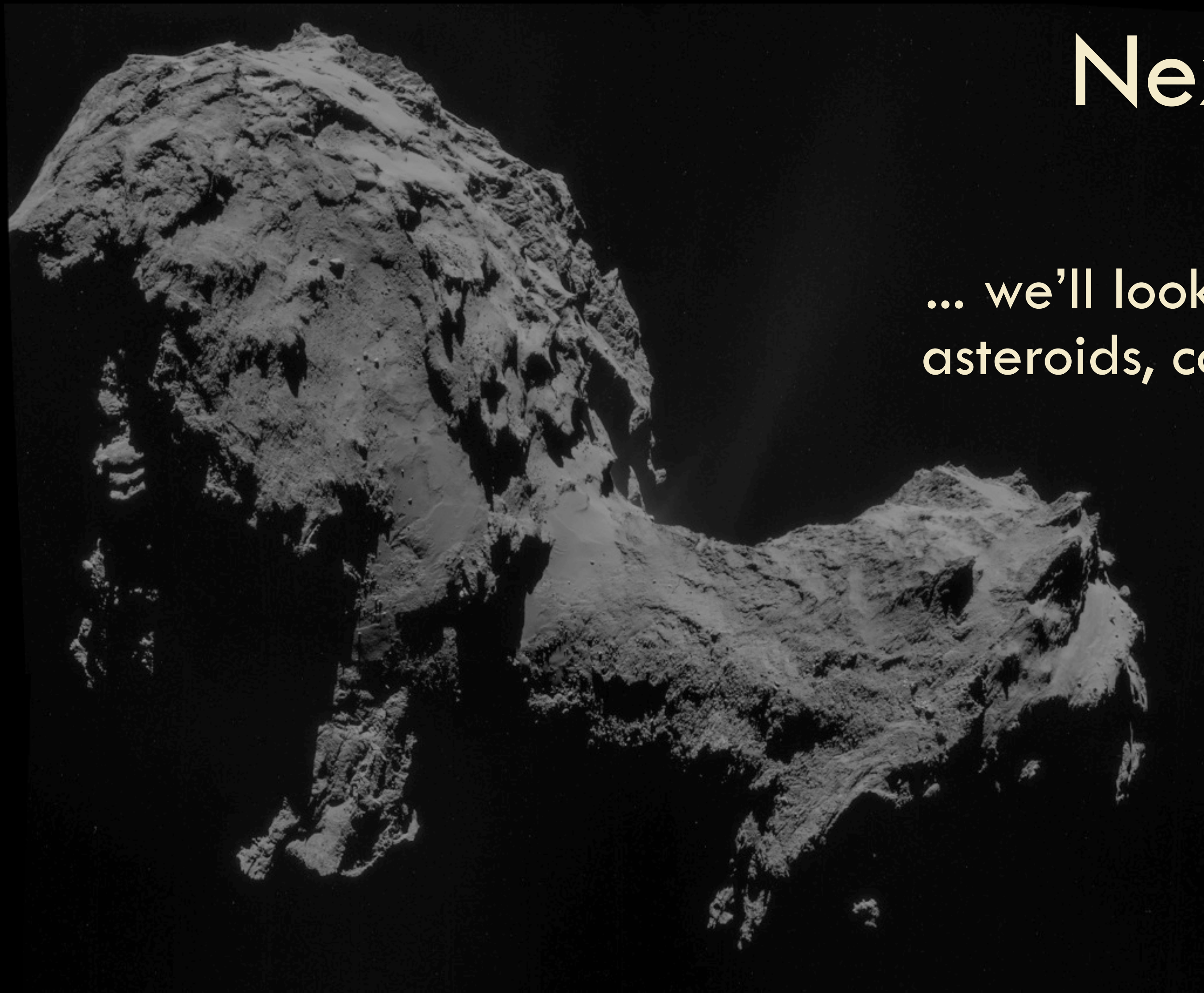
Mariner 9 arrived at Mars in late 1971… By chance, a huge, planetwide dust storm was raging when we approached Mars… The dust pall covered up all the traditional features, and in our approach photos the planet showed a disappointingly featureless disk. Closer examination of the accumulating photos showed four mysterious dark spots on the otherwise bland surface – in the region of Tharsis.

Over the next few weeks, the dust slowly settled back to the surface of Mars, and the lower flanks of Olympus Mons were exposed in all their majesty.

– William Hartmann,
"A Traveller's Guide to Mars"



Mariner 9 view of Olympus Mons standing above the Martian dust storm



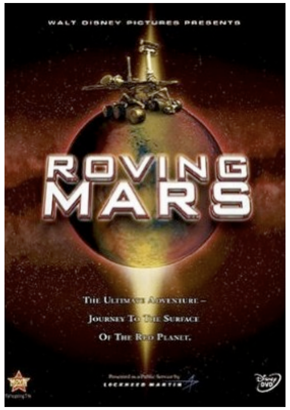
Next week

… we'll look at rocks in space:
asteroids, comets and meteors

Further reading

There are an enormous number of books on Mars out there, but most of them are organised around the various missions to Mars instead of the planet itself, and a great many tend towards a decidedly breathless style! At least they all have great pictures in them. Of course, anything which appeared more than a couple of years ago is going to look very dated, very soon. With that caveat, here are a few recommendations.

- By far the best one I found is "**A Traveler's Guide to Mars**" by William K. Hartmann (Workman Publishing, 2003). The author is a scientist with Global Surveyor, so the book is fairly up-to-date as well as very readable. One of the best planet books I've read.
- "**Roving Mars: Spirit, Opportunity and the exploration of the Red Planet**" by Steve Squyres (Hyperion, 2005) is an entertaining account of the design, launch and operation of the Mars Rovers, by the lead scientist of the mission. It ends less than a year after landing, so doesn't have any of the later discoveries from the mission, but is good fun.
- The IMAX movie, also called "**Roving Mars**", is out on DVD, and is extremely good. It has interesting interviews with many of the main players (incuding Steve Squyres and Wayne Lee), and fabulous animations of the launch and landing.
- "**Postcards from Mars: The First Photographer on the Red Planet**" by Jim Bell (Dutton Adult, 2006) is a beautiful coffee-table book of pictures from the Mars Rovers.



- If you want to dig a lot further into the question of water and ice on Mars and the origin of many of the landscape features, try "**Mars: A warmer wetter planet**" by Jeffrey S. Kargel (Springer, 2004). A lot of what the author says is speculative in the extreme – I doubt we'll know which bits he's right about for years – but he lays out the evidence very well, including a fabulous set of pictures illustrating all sorts of landforms in detail. Mind you, I can't work out what audience he's written the book for: much of it is perfectly readable with no background in geology, then he'll suddenly spend pages on gory details of glacial features or some such. He also assumes a fair amount of previous knowledge about Mars – he doesn't explain terms like "Noachian" at all – so whatever you do, don't make this the first book you read about Mars. Definitely one for people who want to see bleeding-edge science.

- We didn't have time to discuss the possibilities for Mars exploration by humans, but if you're interested, "**The Case for Mars**" by Robert Zubrin with Richard Wagner (Touchstone, 1997) is the blueprint for the "Mars Direct" mission. It's a bit of a polemic, but makes for interesting reading, including a bit about the "Mars Underground" that I liked. (You can even join, if you want!). There's a discussion of the Mars Direct plan on the web at "Mars Direct: Headquarters for the Mars Direct Manned Mars Mission" http://www.marssociety.org/, plus a Scientific American article by Robert Zubrin in the March 2000 issue: "The Mars Direct Plan" http://www.sciam.com/article.cfm?articleID=00087E38-5B46-1C75-9B81809EC588EF21

- Most people have probably now heard about the novel (and associated movie), "**The Martian**" by Andy Weir (Del Rey, 2014), about an astronaut marooned on Mars. An excellent depiction of all the ways Mars can kill you, and a rip-roaring good yarn.

- Keep an eye out for two books about Curiosity by Emily Lakdawalla: "**The Design and Engineering of Curiosity**: How the Mars Rover Performs Its Job (Springer Praxis Books), due out 2018, and "**Curiosity and Its Science Mission**: A Mars Rover Goes to Work", due out 2019.

There are an unbelievable number of websites out there devoted to Mars. Here are a few I found useful as starting points:

- Mars is now available in Google Earth! Check out http://earth.google.com/mars/
- The US Geological Survey published an updated map of Mars at https://www.usgs.gov/media/images/geologic-map-mars; there's a nice article about the new map at https://www.nytimes.com/2014/07/23/science/space/brand-new-look-at-the-face-of-mars.html.
- If you need to find out what all that Latin means in Martian place names, take a look at the USGS "Gazetteer of Planetary Nomenclature", Appendix 5: Descriptor Terms http://planetarynames.wr.usgs.gov/append5.html
- The various missions and instruments all have their own web-sites, often with their own "Image of the Day". They're all linked at http://mars.jpl.nasa.gov/ – just find the mission you want and you'll be pointed to the home page. It's hard to keep up with the latest fabulous images found by the Mars Reconnaissance Orbiter, so check back frequently with their news page http://mars.nasa.gov/mro/news/whatsnew/index.cfm. Don't forget the NASA Photojournal http://photojournal.jpl.nasa.gov/index.html is the easiest way to find images.
- The MGS topographic map is available many places, but usually at reduced resolution. If you want the whole thing, you can get it at http://ssed.gsfc.nasa.gov/tharsis/mercat.jpg, but beware! it's enormous: 12000 × 7000 pixels.
- Check out the "Phobos Arts and Crafts" page, where you get the plan for an assemble-your-own Phobos: http://www.planetary.org/blogs/emily-lakdawalla/2008/1348.html
- A nice article about Curiosity's findings: http://www.bbc.com/news/science-environment-30390143

Sources for images used:

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- Craters: from Mars Odyssey Mission THEMIS: Topic Gallery: Craters
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