Mars

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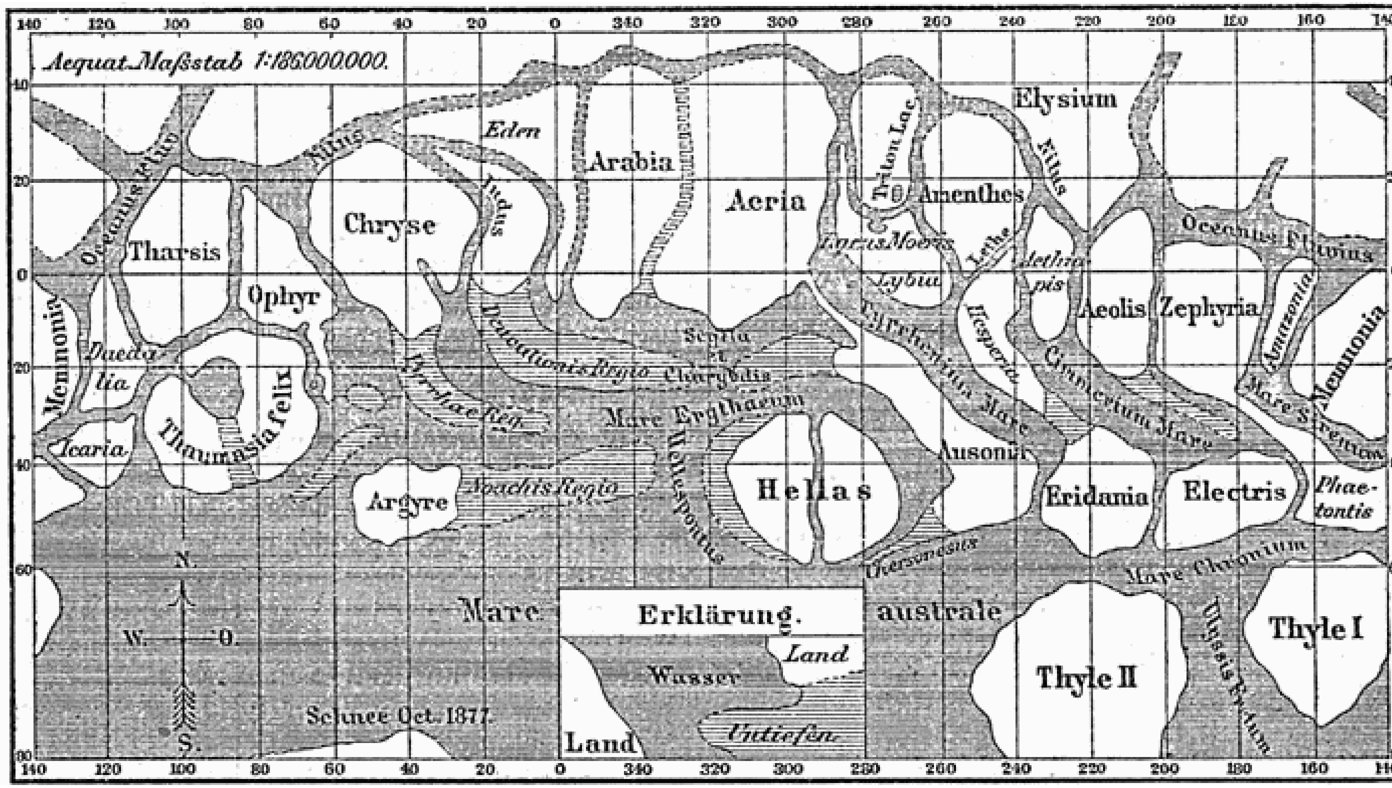
Why this lecture

- Mars is the first planet beyond the Earth suspected of harbouring life.
- It is also the most thoroughly explored planetary body.
- The search for life on Mars is the model for similar searches across the Solar System

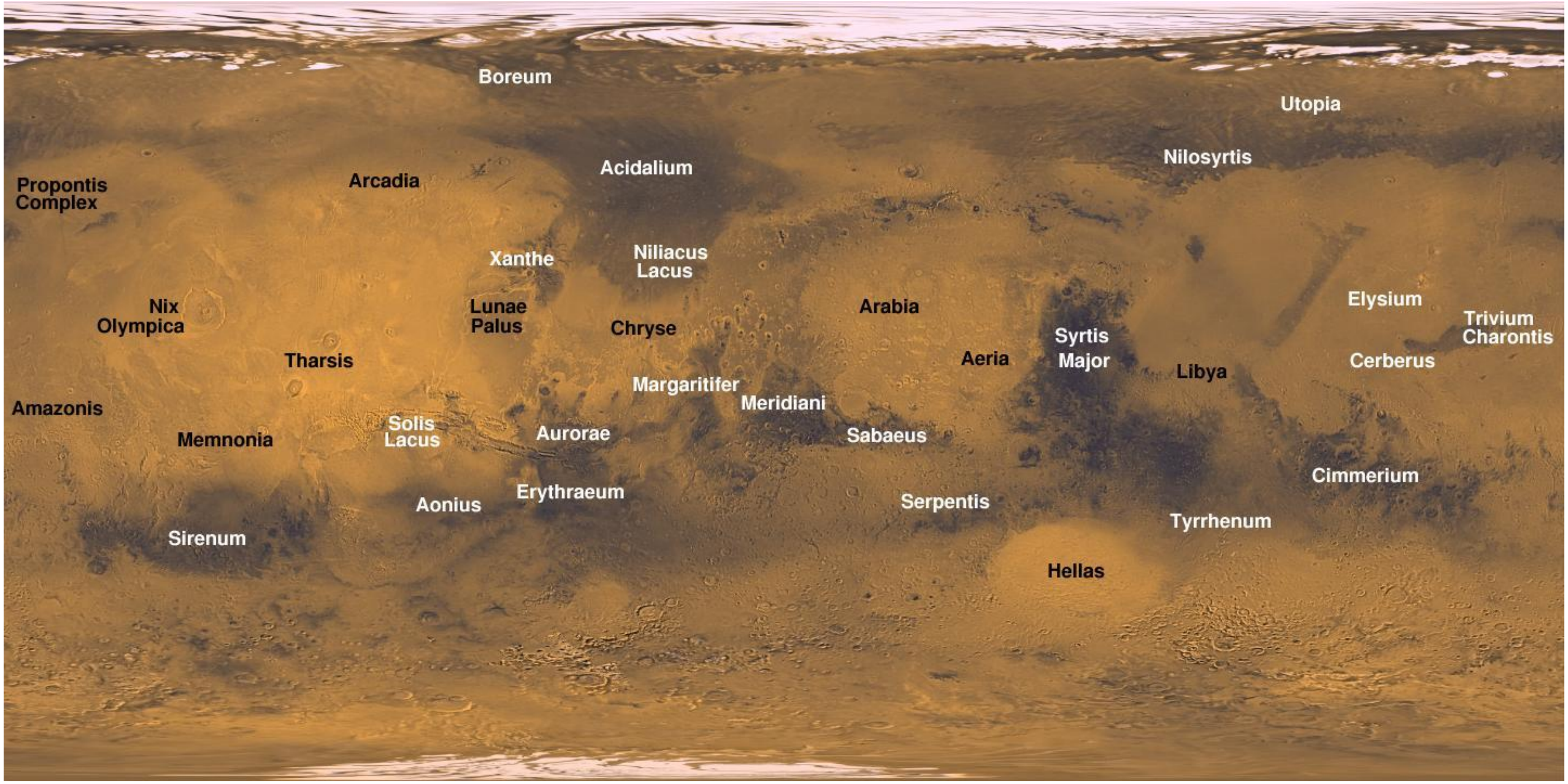
Goals for today

- Learn about the present conditions on Mars.
- Focus on the concept of habitability applied to Mars.
- Learn about the development of understanding of Mars’ past.

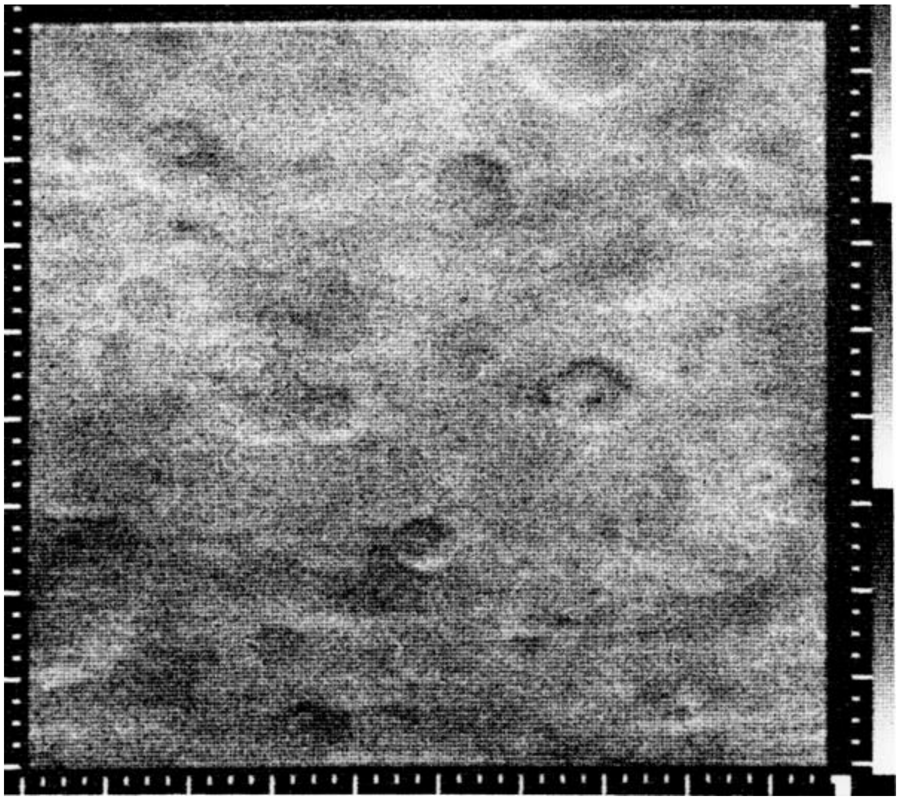
The channels of Schiaparelli



And yet, many of the names in the map of Schiaparelli are still in use



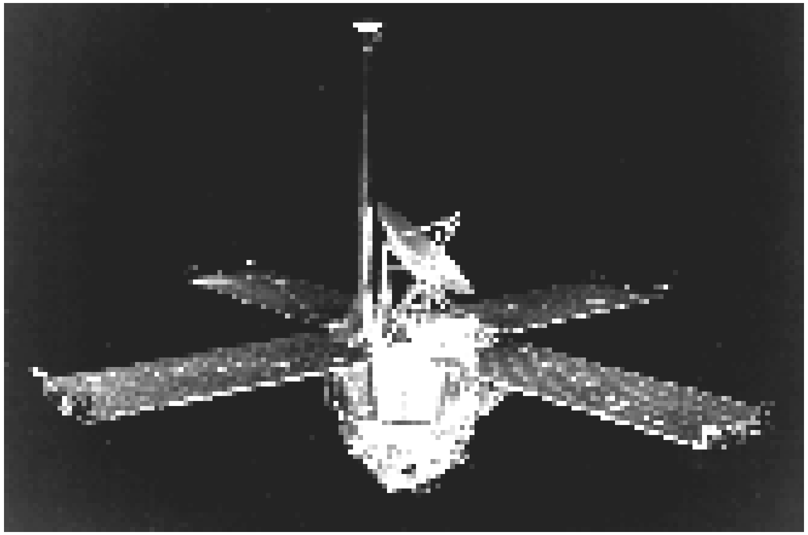
Mariner 4 flew over Mars in 1965



1965-07-15 T 00:28

- The image of the Mariner 4 shows a surface similar to the moon
- The image was taken at 13,000 km and shows a region of 253 by 225 Km.
- Mariner 4 also determined that the atmosphere of Mars is tenuous (1% of Earth's) and composed mostly of CO_2

Mariners 6 and 7



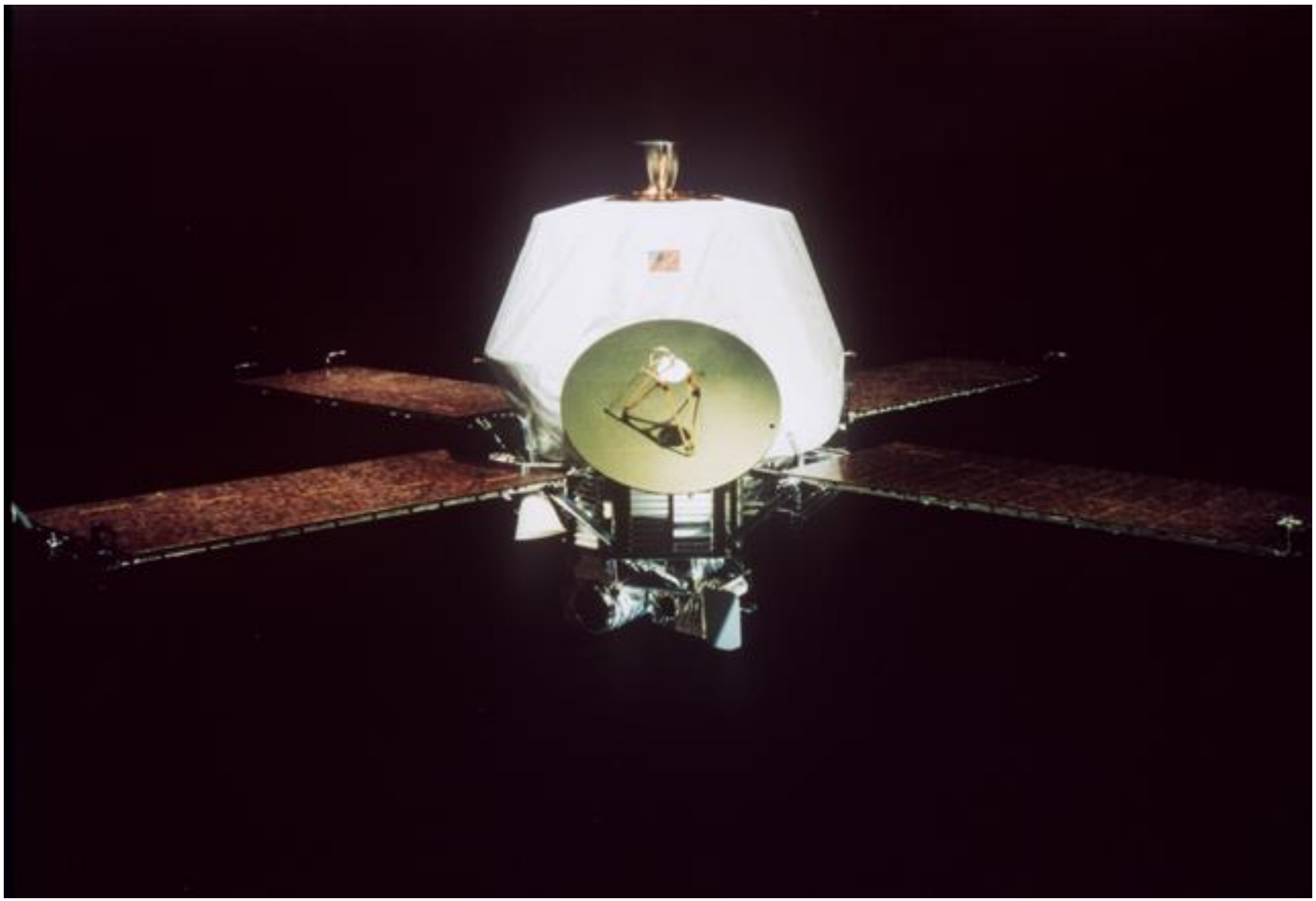
Fly by of Mars on 31 Jul 1969

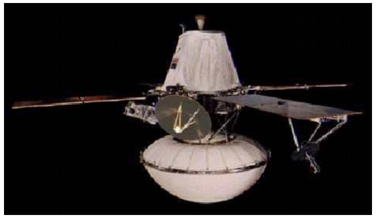
- came within 2,130 miles of Mars
- pictures of ~20% surface (missed important volcanic features)
- sent back ~80 photos (Mar. 6) and ~120 photos (Mar. 7)

Mariners 6 and 7 had scientfic instruments to study Martian atmosphere:

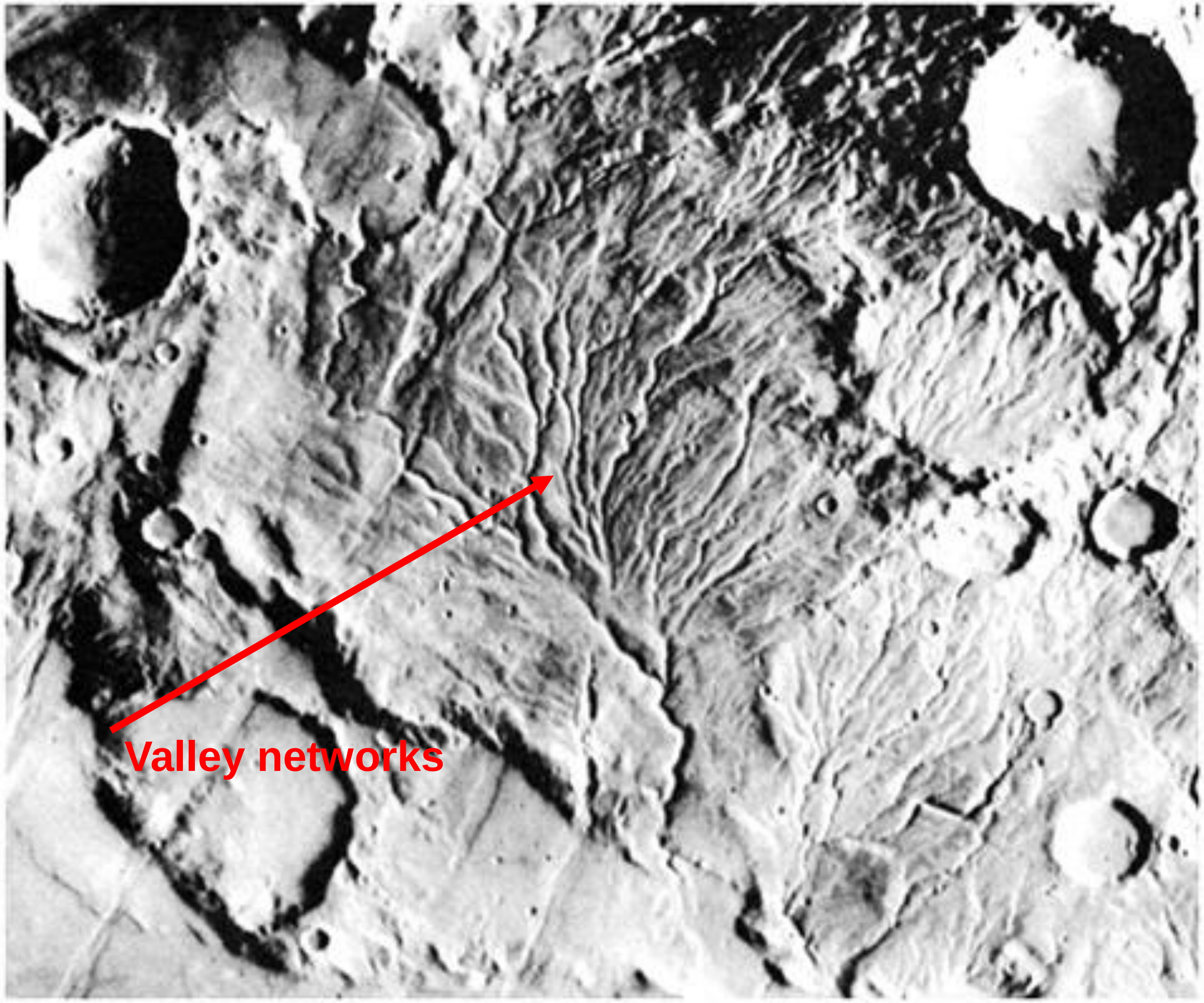
- composition, pressure, density, and temperature
- two cameras
- infrared spectrometer
- ultraviolet spectrometer

Mariner 9 - The first spacecraft to go into orbit around another planet





Viking 1 and 2 – Orbiter & Lander

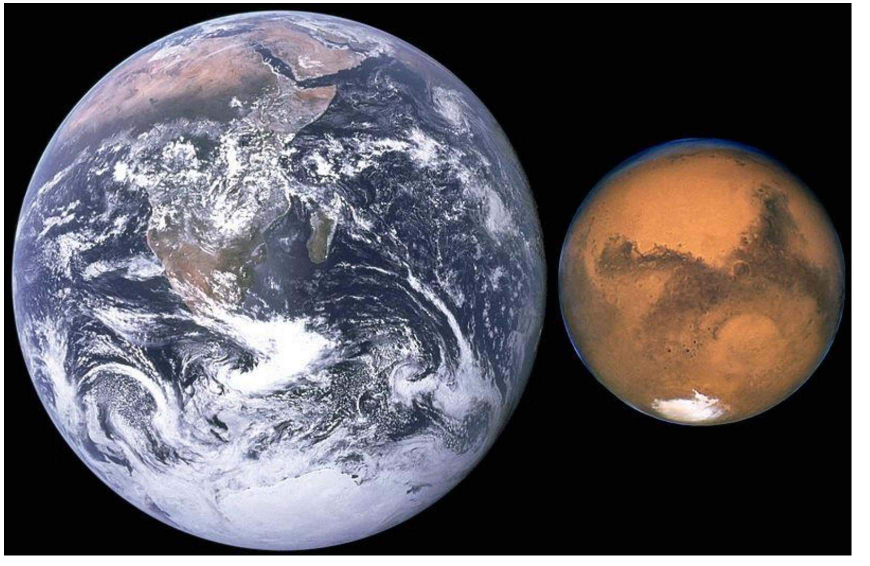


Searching for life with the Vikings

- The Viking landers conducted biological experiments designed to detect life in the Martian soil (if it existed) with experiments designed by three separate teams.
- One experiment turned positive for the detection of metabolism (current life), but based on the results of the other two experiments that failed to reveal any organic molecules in the soil, most scientists became convinced that the positive results were likely caused by non-biological chemical reactions from highly oxidizing soil conditions
- Although there is consensus that the Viking lander results demonstrated a lack of biosignatures in soils at the two landing sites, the test results and their limitations are still under assessment.

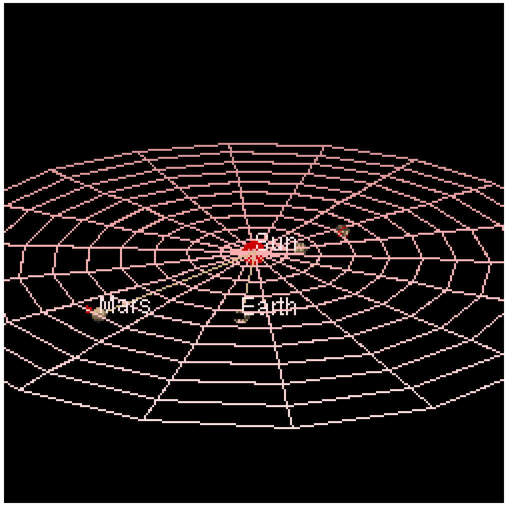
Mars as a planet today

- Mars is approximately half the diameter of Earth
- Its surface area is only slightly less than the total area of Earth's dry land
- Mars is less dense than Earth, having about 15% of Earth's volume and 11% of Earth's mass, resulting in about 38% of Earth's surface gravity
- The red-orange appearance of the Martian surface is caused by iron(III) oxide, or rust

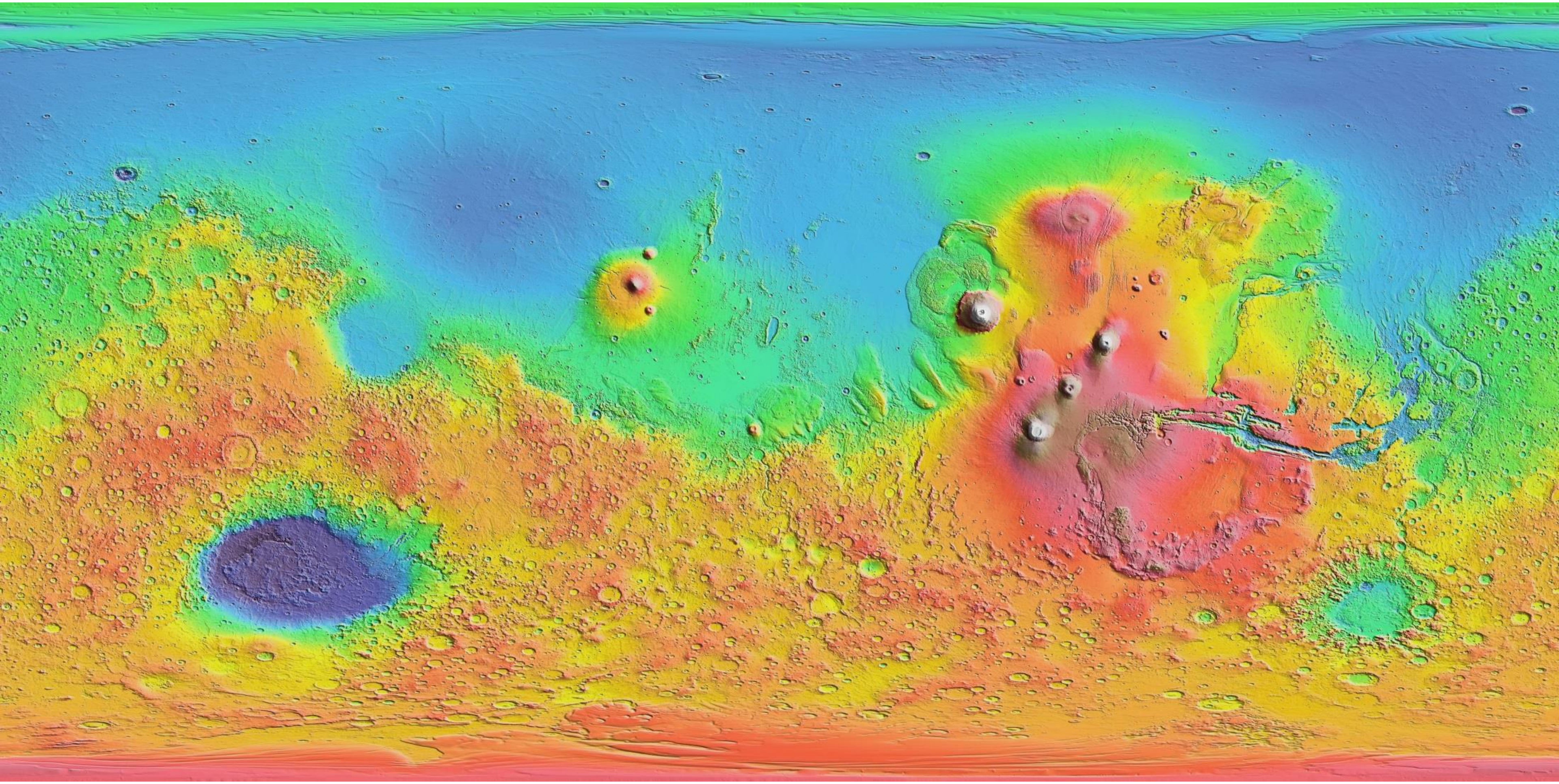


Orbit

- Mars's average distance from the Sun is roughly 230 million kilometres, and its orbital period is 687 (Earth) days
- The solar day (or sol) on Mars is only slightly longer than an Earth day: 24 hours, 39 minutes, and 35.244 seconds
- A Martian year is equal to 1.8809 Earth years, or 1 year, 320 days, and 18.2 hours
- The axial tilt of Mars is 25.19 degrees relative to its orbital plane, which is similar to the axial tilt of Earth
- Mars has a relatively pronounced orbital eccentricity of about 0.09, but it is known that in the past, Mars has had a much more circular orbit than it does currently
- Mars's cycle of eccentricity is 96,000 Earth years compared to Earth's cycle of 100,000 years



Topography



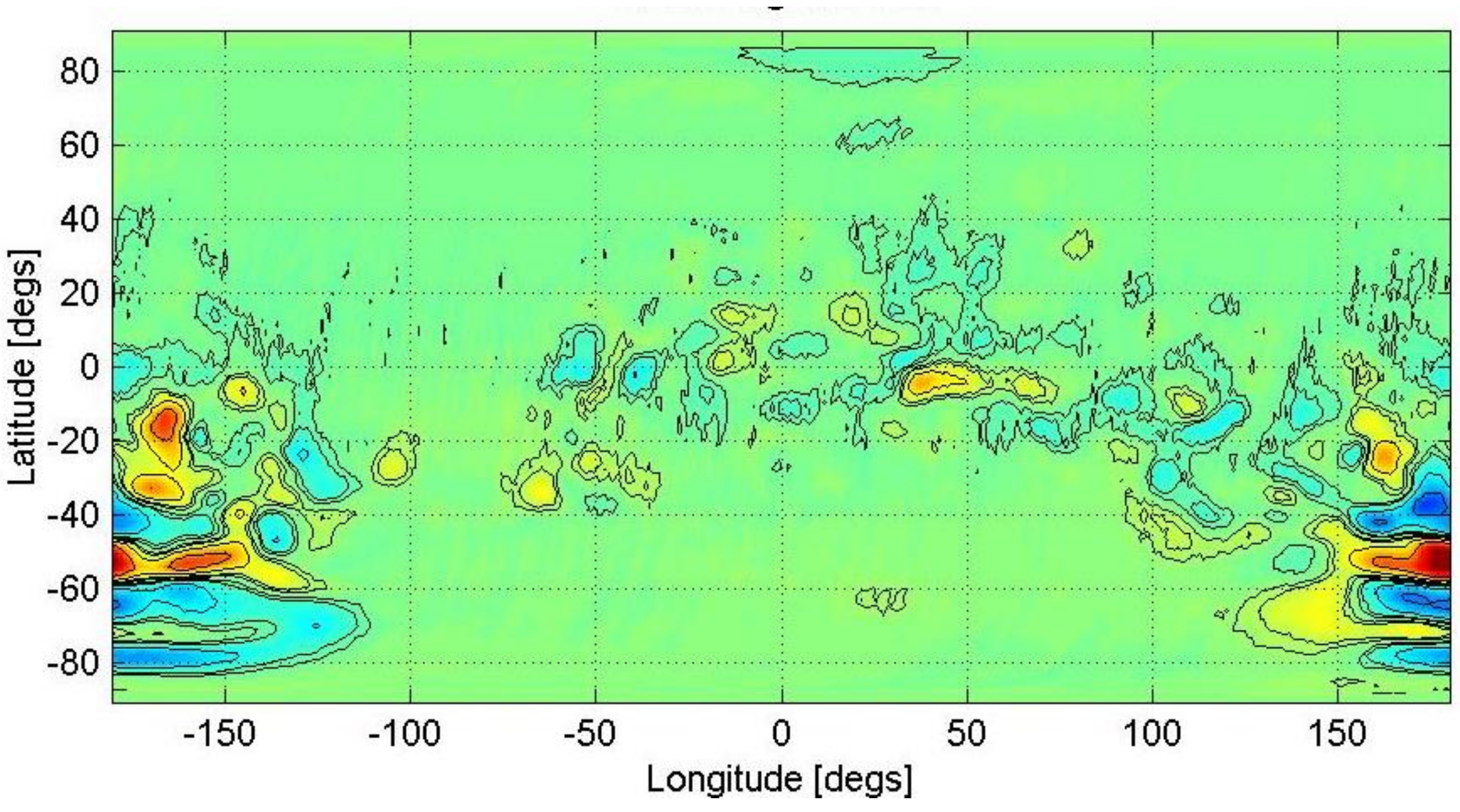
Internal structure

- Like Earth, Mars has differentiated into a dense metallic core overlaid by less dense materials
- Current models of its interior imply a core region about 1,794 ± 65 kilometers in radius, consisting primarily of iron and nickel with about 16-17% sulfur
- The core is surrounded by a silicate mantle that formed many of the tectonic and volcanic features on the planet, but it now appears to be dormant
- Besides silicon and oxygen, the most abundant elements in the Martian crust are iron, magnesium, aluminum, calcium, and potassium
- The average thickness of the planet's crust is about 50 km, with a maximum thickness of 125 km
- Earth's crust, averaging 40 km, is only one third as thick as Mars', relative to the sizes of the two planets

Surface composition

- Mars is a terrestrial planet that consists of minerals containing silicon and oxygen, metals, and other elements that typically make up rock
- The surface of Mars is primarily composed of tholeiitic basalt, although parts are more silica-rich than typical basalt and may be similar to andesitic rocks on Earth or silica glass
- Regions of low albedo show concentrations of plagioclase feldspar, with northern low albedo regions displaying higher than normal concentrations of sheet silicates and high-silicon glass
- Parts of the southern highlands include detectable amounts of high-calcium pyroxenes
- Localized concentrations of hematite and olivine have also been found
- Much of the surface is deeply covered by finely grained iron(III) oxide dust

Paleomagnetism

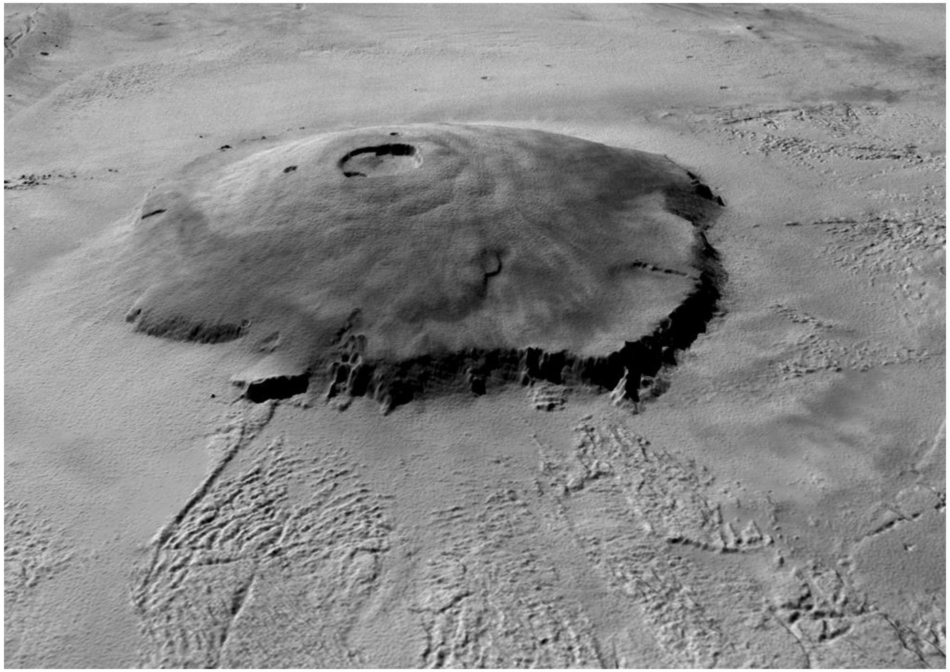


Soil

- The Phoenix lander returned data showing Martian soil to be slightly alkaline and containing elements such as magnesium, sodium, potassium and chlorine
- These nutrients are found in gardens on Earth, and they are necessary for growth of plants
- Experiments performed by the lander showed that the Martian soil has a basic pH of 7.7, and contains 0.6% of the salt perchlorate

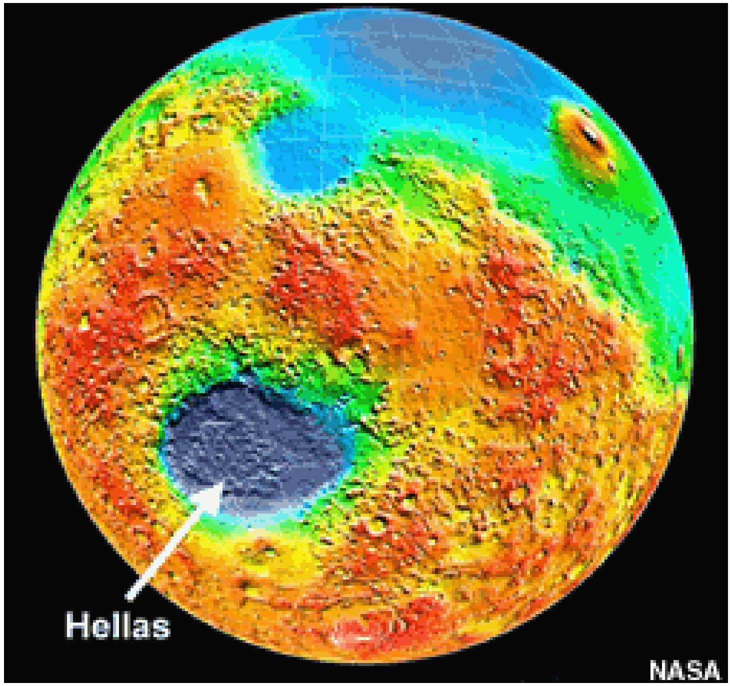
Tharsis and Elysium volcanic provinces

- Straddling the dichotomy boundary in Mars's western hemisphere is a massive volcano-tectonic province known as the Tharsis region or the Tharsis bulge
- This immense, elevated structure is thousands of kilometers in diameter and covers up to 25% of the planet's surface
- Averaging 7-10 km above datum (Martian "sea" level), Tharsis contains the highest elevations on the planet and the largest known volcanoes in the Solar System
- A smaller volcanic center lies several thousand kilometers west of Tharsis in Elysium
- The Elysium volcanic complex is about 2,000 kilometers in diameter and consists of three main volcanoes, Elysium Mons, Hecates Tholus, and Albor Tholus
- The Elysium group of volcanoes is thought to be somewhat different from the Tharsis Montes, in that development of the former involved both lavas and pyroclastics



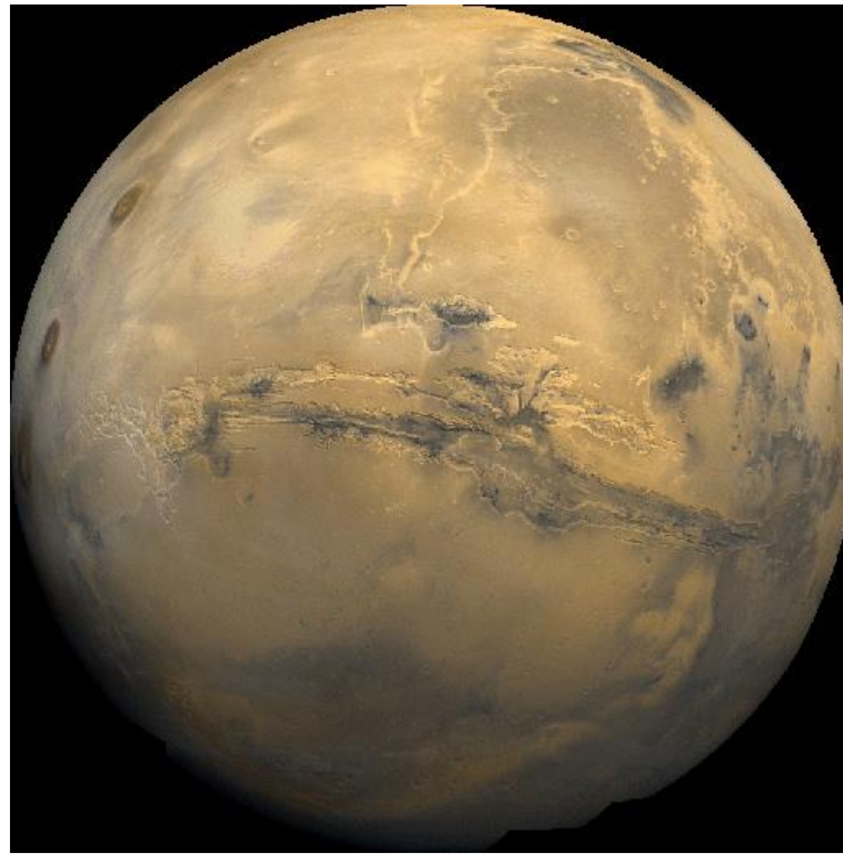
Large impact basins

- Several enormous, circular impact basins are present on Mars
- The largest one that is readily visible is the Hellas basin located in the southern hemisphere
- The lowest elevations on the planet are located within the Hellas basin, with some areas of the basin floor lying over 8 km below datum
- The two other large impact structures on the planet are the Argyre and Isidis basins
- All of the large basins on Mars are extremely old, dating back to the late heavy bombardment
- They are thought to be comparable in age to the Imbrium and Orientale basins on the Moon



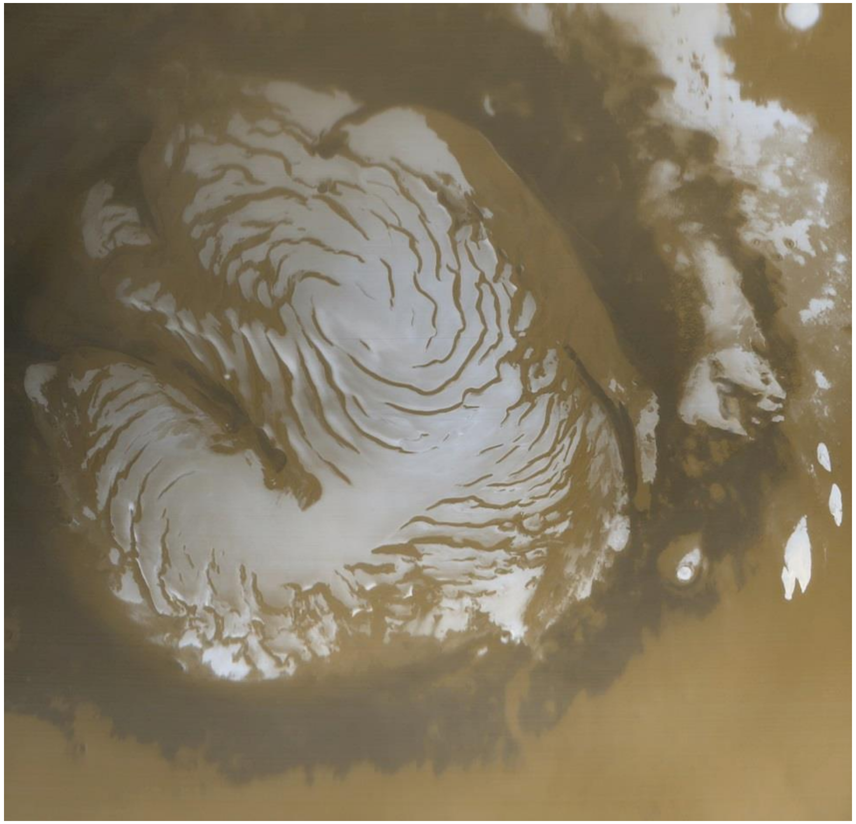
Equatorial canyon system

- Near the equator in the western hemisphere lies an immense system of deep, interconnected canyons and troughs collectively known as the Valles Marineris
- The canyon system extends eastward from Tharsis for a length of over 4,000 km, nearly a quarter of the planet's circumference
- The Martian equatorial canyons were of tectonic origin, i.e. they were formed mostly by faulting
- They could be similar to the East African Rift valleys

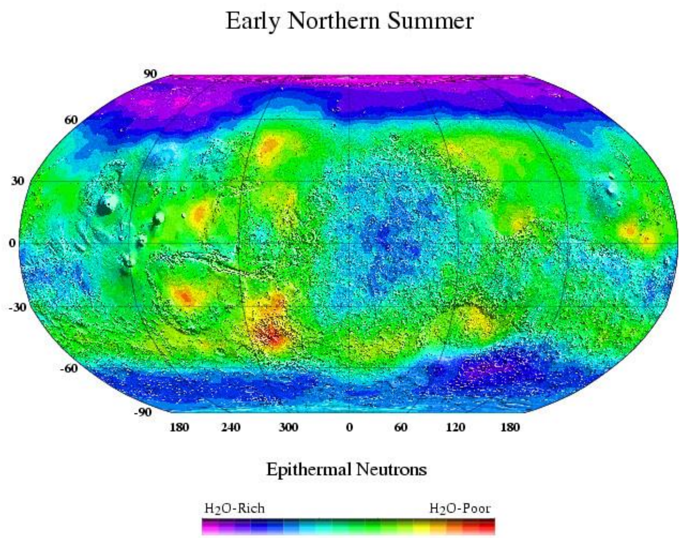


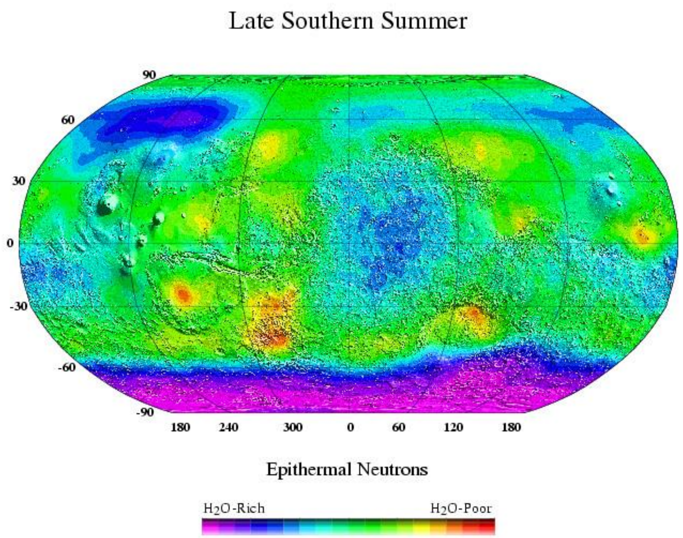
Ice caps

- The seasonal caps (those seen in the telescope to grow and wane seasonally) are composed of carbon dioxide (CO_2) ice that condenses out of the atmosphere as temperatures fall to 148 K, the frost point of CO_2, during the polar wintertime.
- In the north, the CO_2 ice completely dissipates (sublimes) in summer, leaving behind a residual cap of water (H_2O) ice. At the south pole, a small residual cap of CO_2 ice remains in summer
- Both residual ice caps overlie thick layered deposits of interbedded ice and dust
- In the north, the layered deposits form a 3 km-high, 1,000 km-diameter plateau called Planum Boreum
- A similar kilometers-thick plateau, Planum Australe, lies in the south
- The layered deposits probably represent alternating cycles of dust and ice deposition caused by climate changes related to variations in the planet's orbital parameters over time (Milankovitch cycles)
- The polar layered deposits are some of the youngest geologic units on Mars

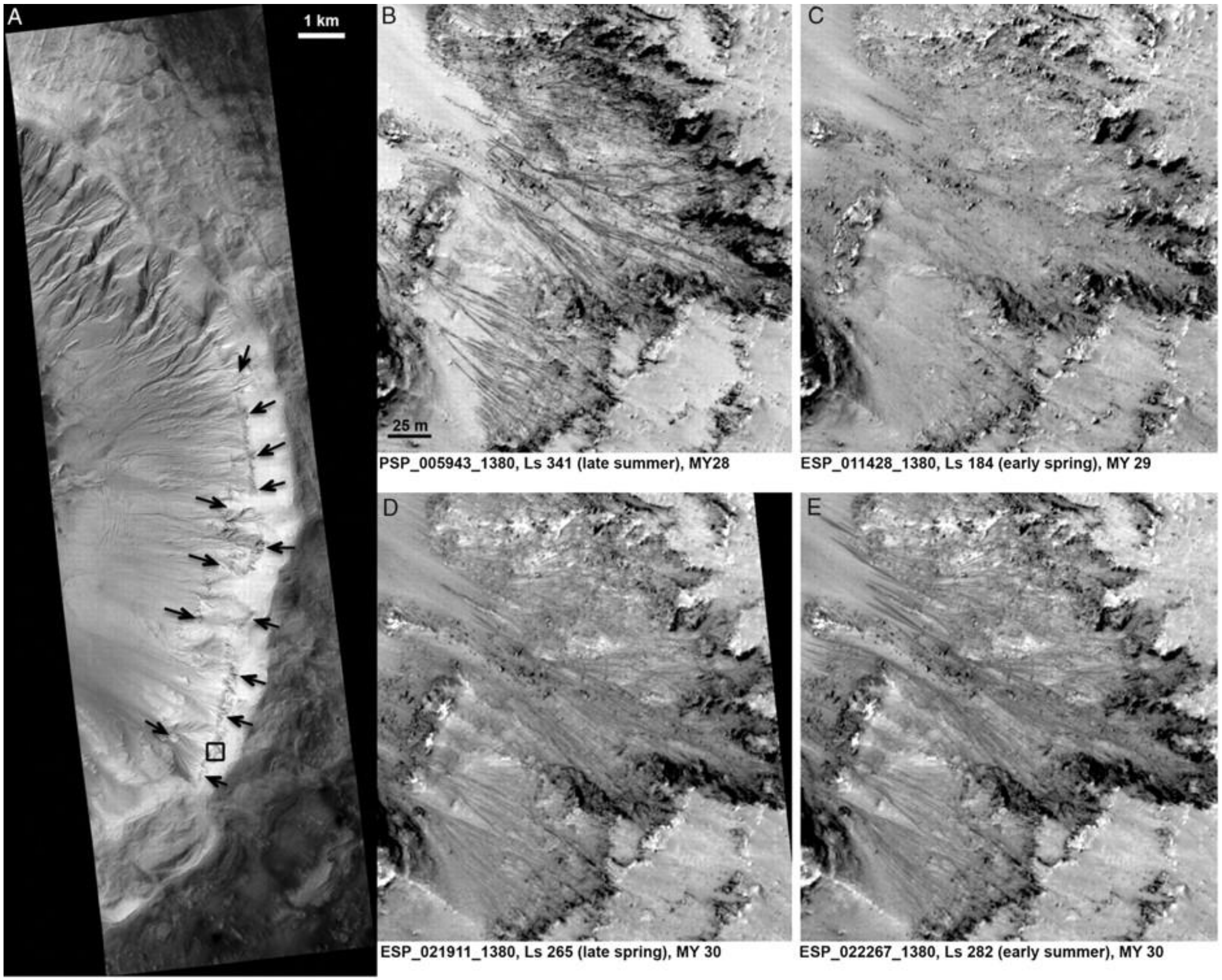


Permafrost

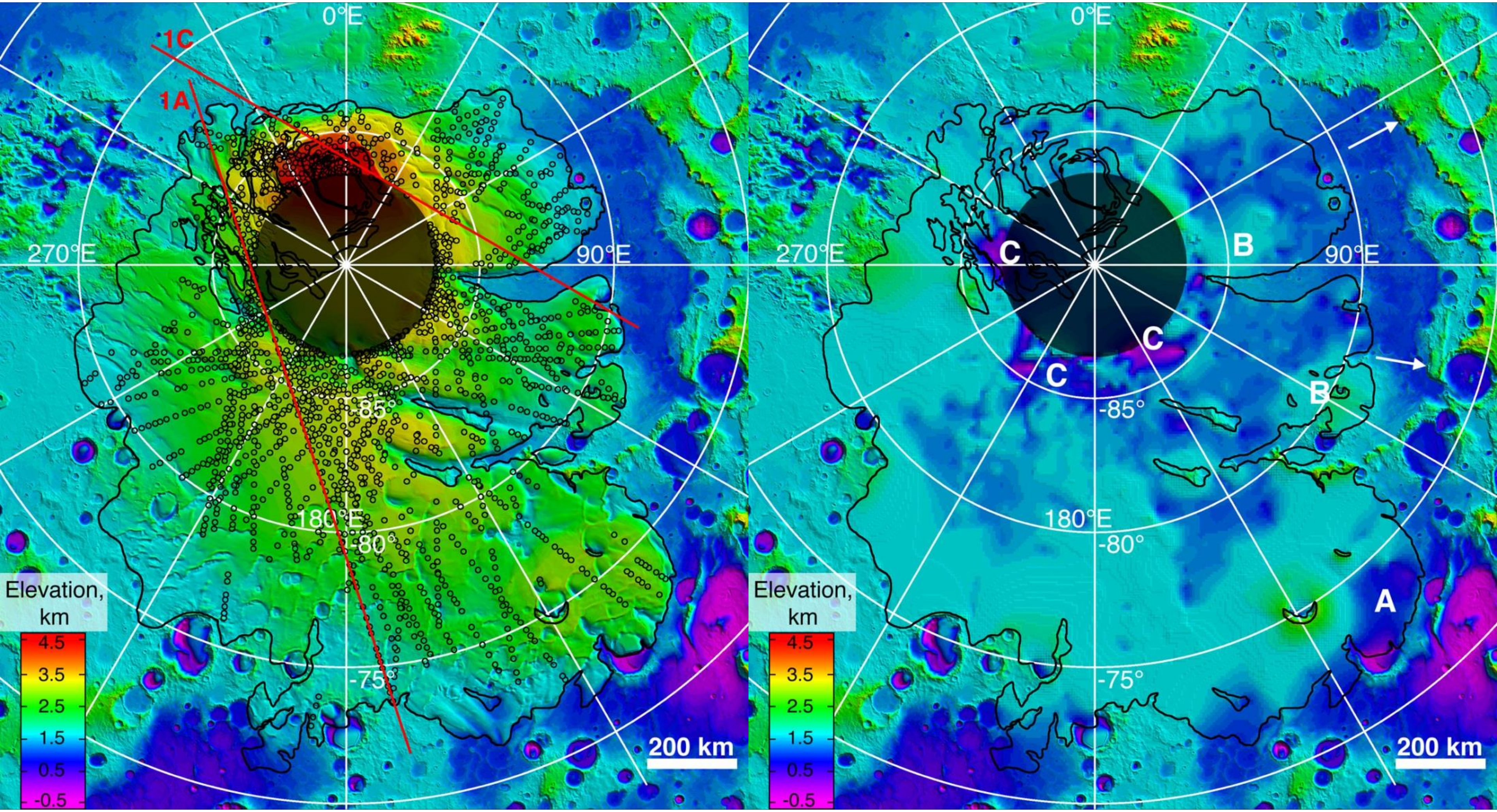

Early Northern Summer
90
60
30
0
-30
-60
-90
180
240
300
0
60
120
180
Epithermal Neutrons
H2O-Rich
H2O-Poor


Late Southern Summer
90
60
30
0
-30
-60
-90
180
240
300
0
60
120
180
Epithermal Neutrons
H2O-Rich
H2O-Poor

Liquid water on Mars (sometimes)

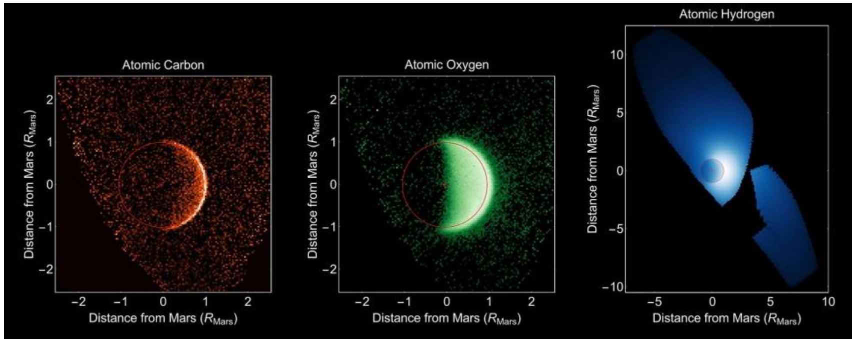


Amount of water on Mars

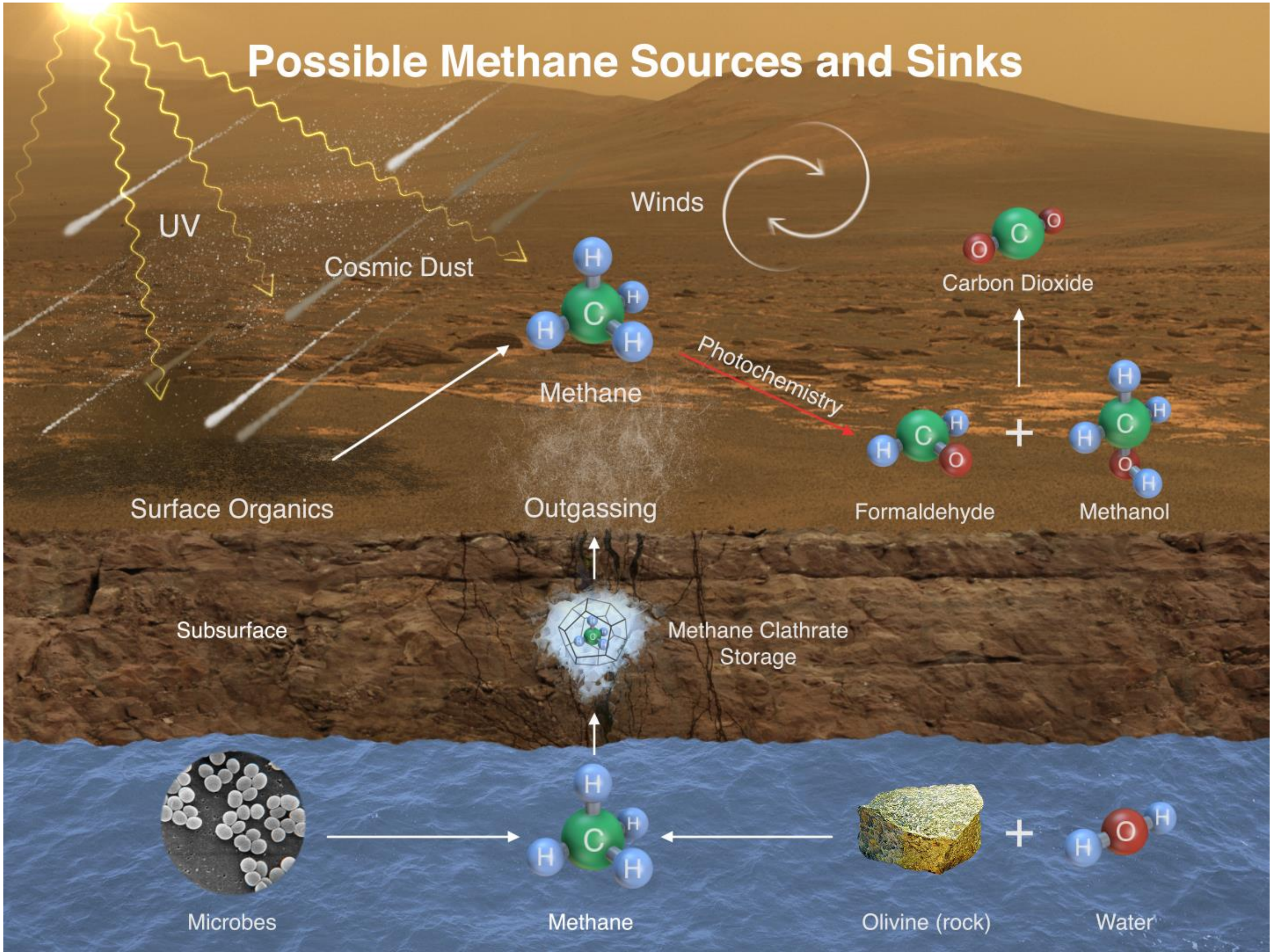


Atmosphere

- Atmospheric pressure on the surface today ranges from a low of 30 Pa (0.030 kPa) on Olympus Mons to over 1,155 Pa (1.155 kPa) in Hellas Planitia, with a mean pressure at the surface level of 600 Pa (0.60 kPa)
- Both Mars Global Surveyor and Mars Express have detected ionised atmospheric particles trailing off into space behind Mars
- The scale height of the atmosphere is about 10.8 km, which is higher than Earth's (6 km) because the surface gravity of Mars is only about 38% of Earth's, an effect offset by both the lower temperature and 50% higher average molecular weight of the atmosphere of Mars
- The atmosphere of Mars consists of about 96% carbon dioxide, 1.93% argon and 1.89% nitrogen along with traces of oxygen and water
- The atmosphere is quite dusty, containing particulates about 1.5 µm in diameter which give the Martian sky a tawny color when seen from the surface



Methane!



Possible Methane Sources and Sinks
UV
Cosmic Dust
Winds
Carbon Dioxide
Methane
Photochemistry
Formaldehyde
Methanol
Surface Organics
Outgassing
Subsurface
Methane Clathrate Storage
Microbes
Methane
Olivine (rock)
Water

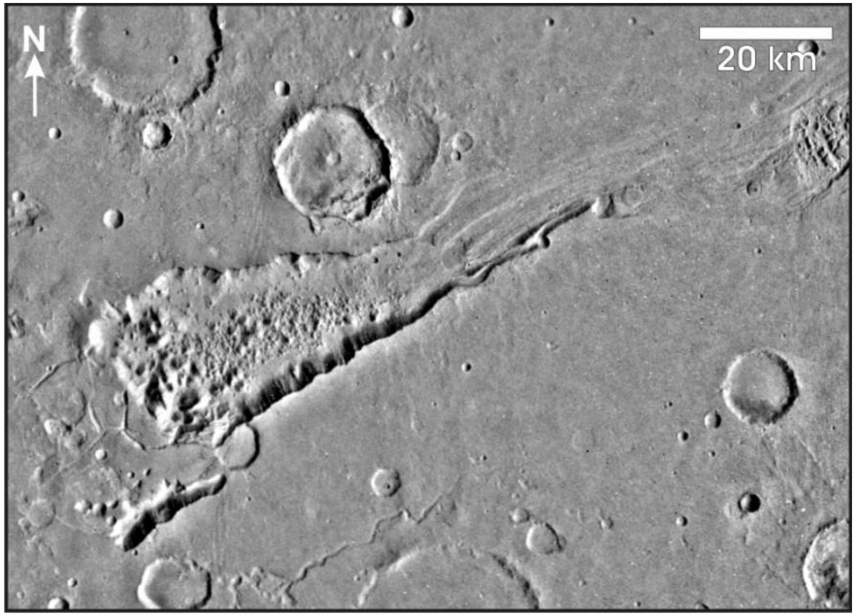
Table 2. A Planetary Habitability Table for Mars

Requirement		Comments and references
Liquid water	Present as brines on the surface and present in the subsurface (?)	McEwen *et al.*, 2011; Rennó *et al.*, 2009; Martin-Torres *et al.*, 2015
Main elements		
C	Organics, CO, CO_2, bicarbonate ions from carbonates	Leshin *et al.*, 2013; Ming *et al.*, 2014; Steele *et al.*, 2012 and citations therein; Ehlmann *et al.*, 2008
H	H_2, organics, H_2O	Presence of serpentine on Mars suggests H_2 production. Ehlmann *et al.*, 2010, 2011; Quantin *et al.*, 2012
N	Organics, N_2, Fixed states of N—such as NO_2^-, NO, NO_3^{2-} (quantities of fixed states of nitrogen not known)	Ming *et al.*, 2014; Stern *et al.*, 2015; and the Mars N problem reviewed in Mancinelli and Banin, 2003
O	Oxygen free radicals, perchlorates, oxides	Present in many oxidized species shown under C, H, N, P, and S
P	PO_4^{3-} (in apatite and merrillite)	McGlynn *et al.*, 2012; Usui *et al.*, 2008
S	SO_4^{2-}, S^{2-}, S	McLennan *et al.*, 2014; Ming *et al.*, 2014; reviewed by Gaillard *et al.*, 2013; Karunatillake *et al.*, 2014
Other elements	Other cations and anions associated with igneous rocks, *e.g.*, Ca^{2+}, Mg^{2+}, K^+, $Fe^{2+/3+}$, many trace elements such as Mn, Cr, Ni, Zn	*e.g.*, McLennan *et al.*, 2014; Meslin *et al.*, 2013; Stolper *et al.*, 2013

Energy—full redox couples	***Electron donor***	***Electron acceptor***	
Chemolithotrophy			
Anaerobic iron oxidation	Fe^{2+}	NO_3^{2-}	Distribution of NO_3^{2-} on Mars not known although fixed nitrogen is inferred (Ming *et al.*, 2014)
Anaerobic iron oxidation	Fe^{2+}	Perchlorates	Perchlorate can be used to oxidize iron, but not shown to be used for growth in organisms. It is included to highlight the need for investigation of perchlorate-containing redox couples.
Methanogenesis, acetogenesis	H_2	CO_2	Hydrogen inferred from presence of olivine and serpentine—substrates and products for H_2-evolving water-rock reactions
Iron reduction	H_2	Fe^{3+}	As above for hydrogen
Sulfate reduction	H_2	SO_4^{2-}	As above for hydrogen
Sulfur oxidation	S	NO_3^{2-}	Sulfur suggested at Gusev Crater (Morris *et al.*, 2007)
Anaerobic sulfur oxidation	S	Fe^{3+}	Occurs in acidic conditions
Anaerobic carboxydotrophy	CO	NO_3^{2-}	Carbon monoxide in atmosphere
Chemoorganotrophy			
Iron reduction	Organics	Fe^{3+}	Distribution and quantity of organics in different locations and depths on Mars is not known
Sulfate reduction	Organics	SO_4^{2-}	As above for organics
Nitrate reduction	Organics	NO_3^{2-}	As above for organics and fixed nitrogen species
Perchlorate reduction	Organics	Perchlorate	As above for organics
Other forms of energy	Photosynthesis unlikely on surface (lack of liquid water). Fermentation depends upon concentration of organics.		Cockell, 2014a

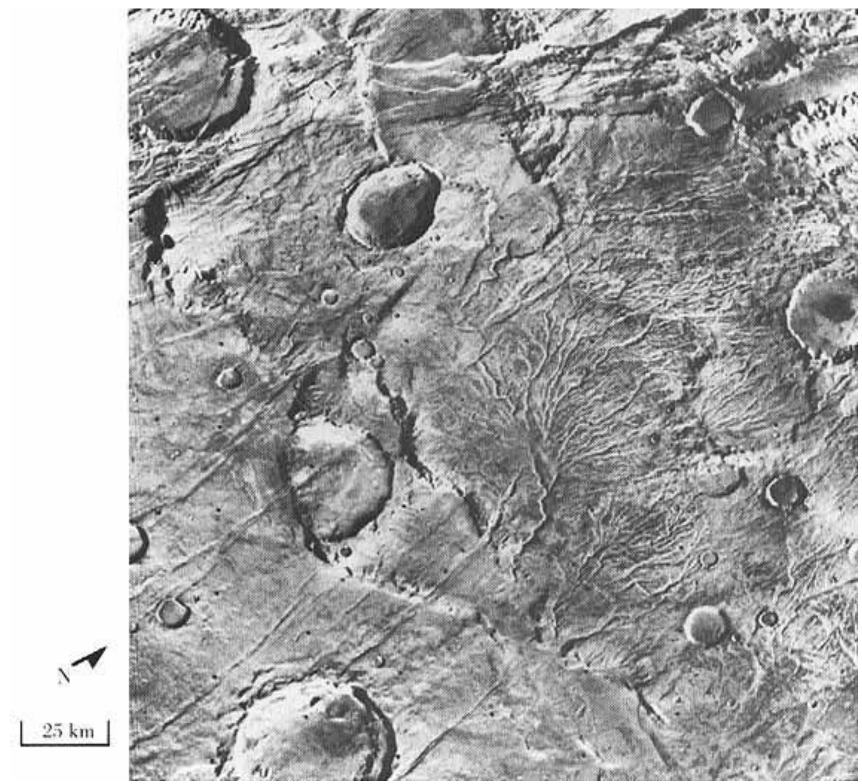
Chaotic terrain and outflow channels

- The terrain at the eastern end of the Valles Marineris grades into dense jumbles of low rounded hills that seem to have formed by the collapse of upland surfaces to form broad, rubble-filled hollows
- Called chaotic terrain, these areas mark the heads of huge outflow channels that emerge full size from the chaotic terrain and empty (debouch) northward into Chryse Planitia
- The presence of streamlined islands and other geomorphic features indicate that the channels were most likely formed by catastrophic releases of water from aquifers or the melting of subsurface ice
- The channels are enormous by terrestrial standards, and the flows that formed them correspondingly immense



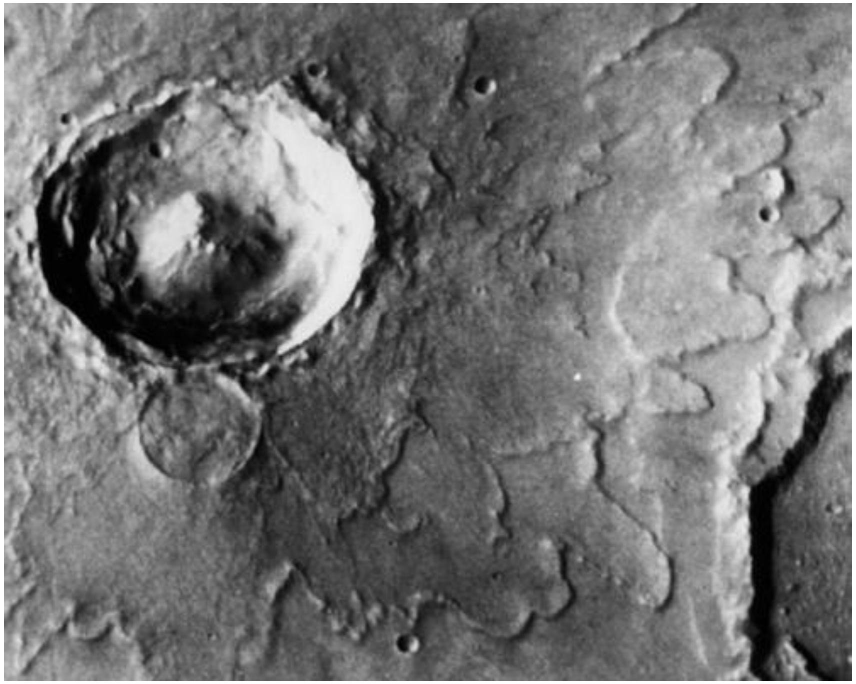
Valley networks

- They are branching networks of valleys on Mars that superficially resemble terrestrial river drainage basins
- They are found mainly incised into the terrain of the Martian southern highlands, and are typically - though not always - of Noachian age (approximately four billion years old)
- The individual valleys are typically less than 5 kilometers wide, though they may extend for up to hundreds or even thousands of kilometers across the Martian surface
- Some authors have argued that the properties of the networks demand that a hydrological cycle must have been active on ancient Mars



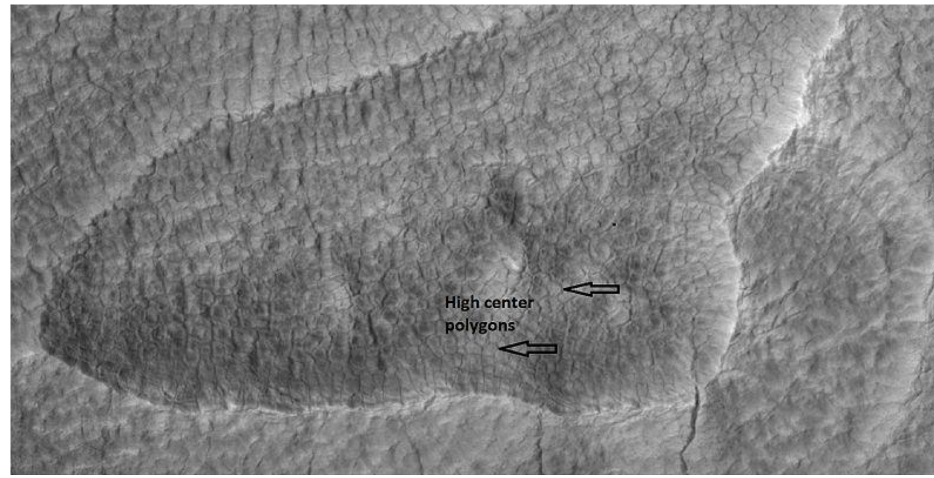
Rampart craters

- Rampart craters show a lobate outer margin, as if material moved along the surface, rather than flying up and down in a ballistic trajectory
- The ejecta look as if they move as a mudflow
- Although rampart craters can be found all over Mars, the smaller ones are only found in the high latitudes where ice is predicted to be close to the surface
- Since ice is thought to be close to the surface in latitudes far from the equator, it does not take too strong of an impact to reach the ice level
- It is generally accepted that rampart craters are evidence of ice or liquid water beneath the surface of Mars
- The impact melts or boils the water in the subsurface producing a distinctive pattern of material surrounding the crater

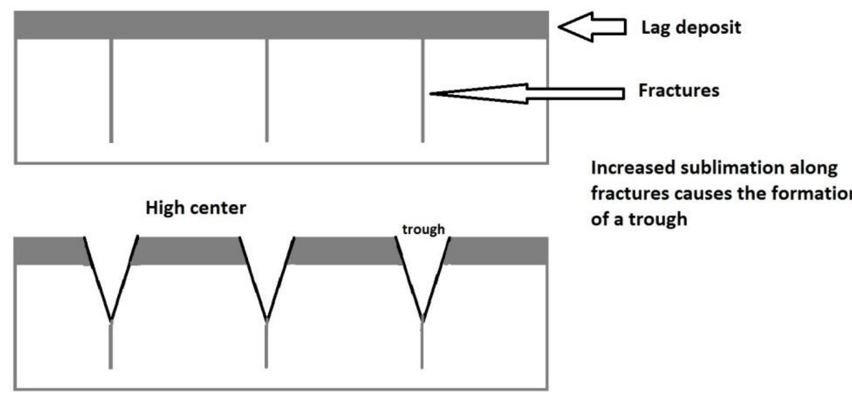


Polygonal patterned ground

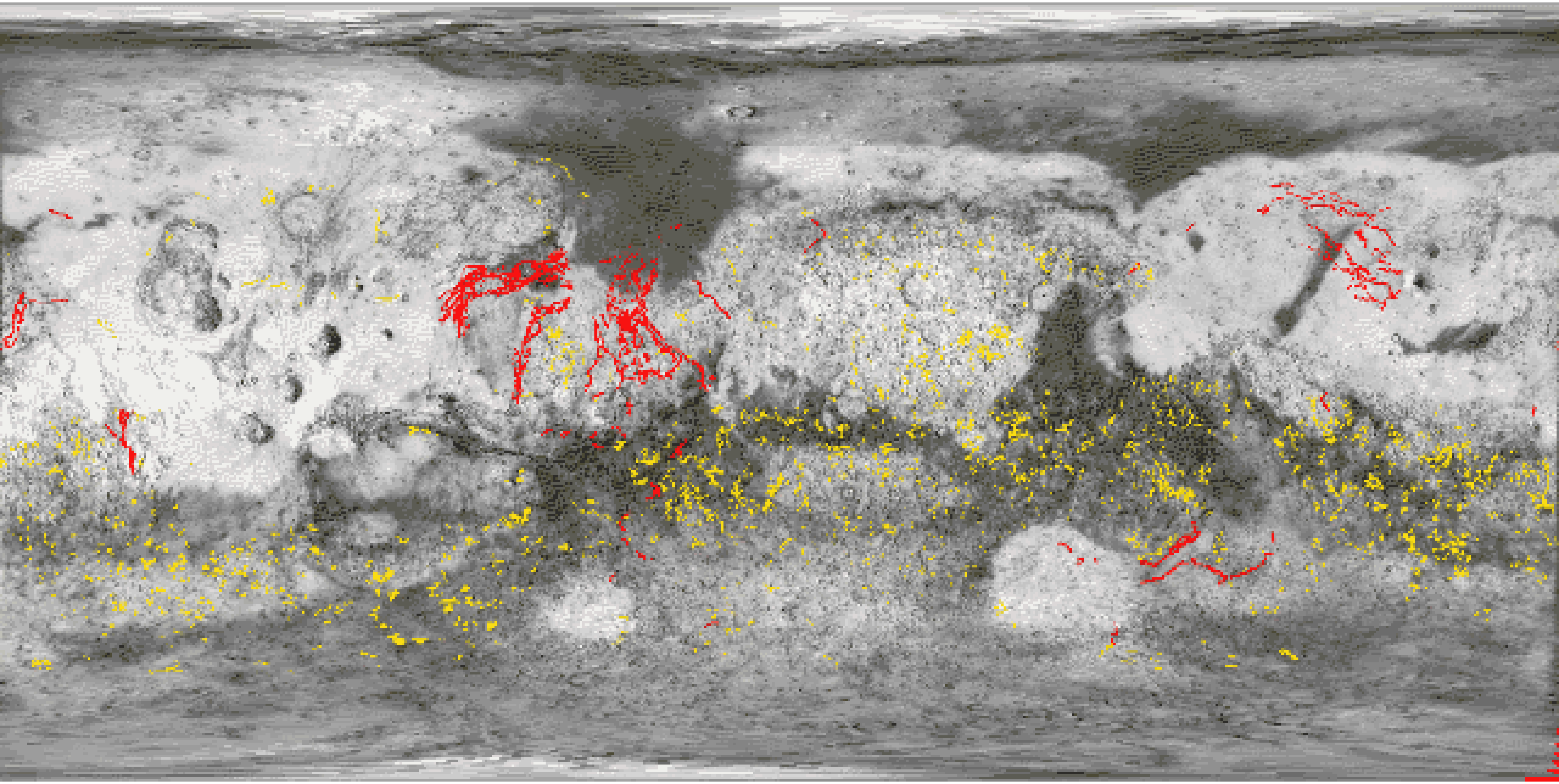
- It is commonly believed to be caused by the sublimation of ice from the ground
- Sublimation is the direct change of solid ice to a gas
- Places on Mars that display polygonal ground may indicate where future colonists can find water ice
- Patterned ground forms in a mantle layer, called latitude dependent mantle



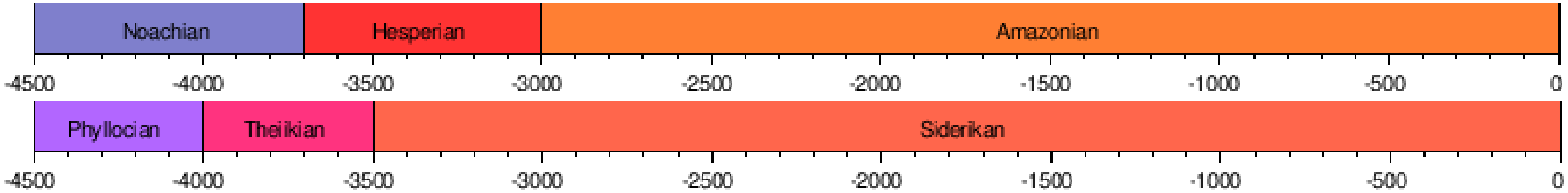
Formation of High-center polygons



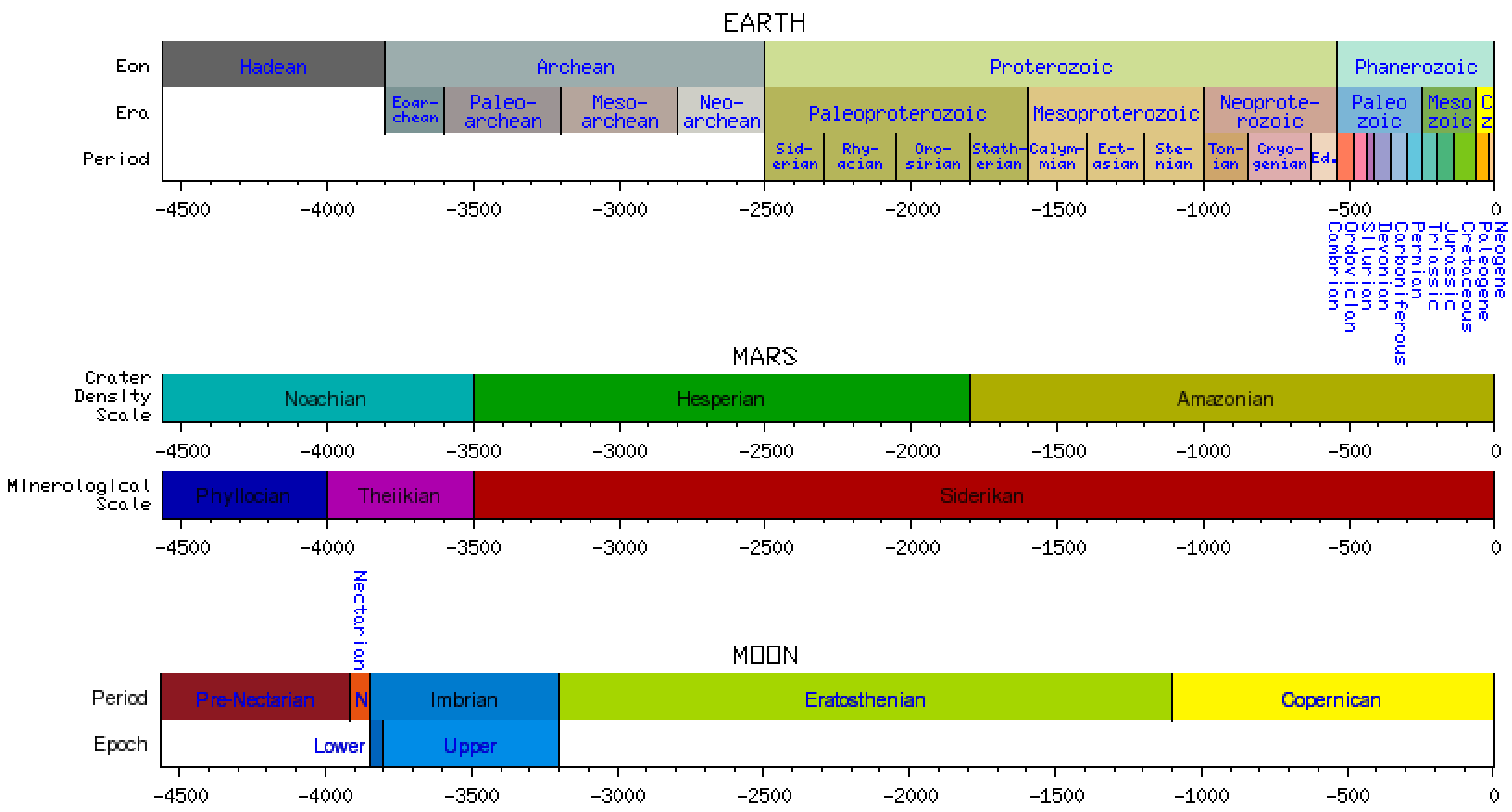
A global view of water-related features

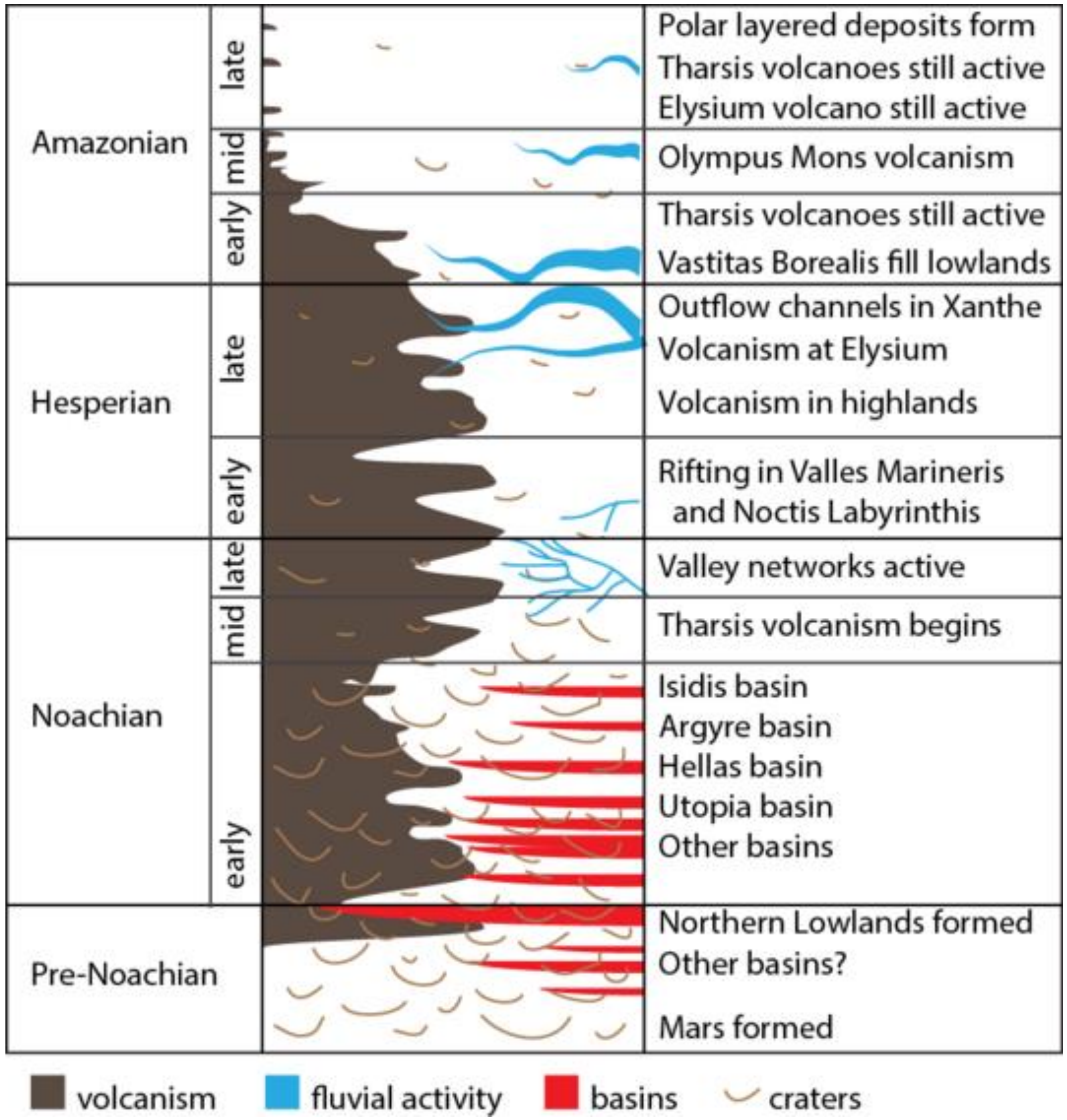


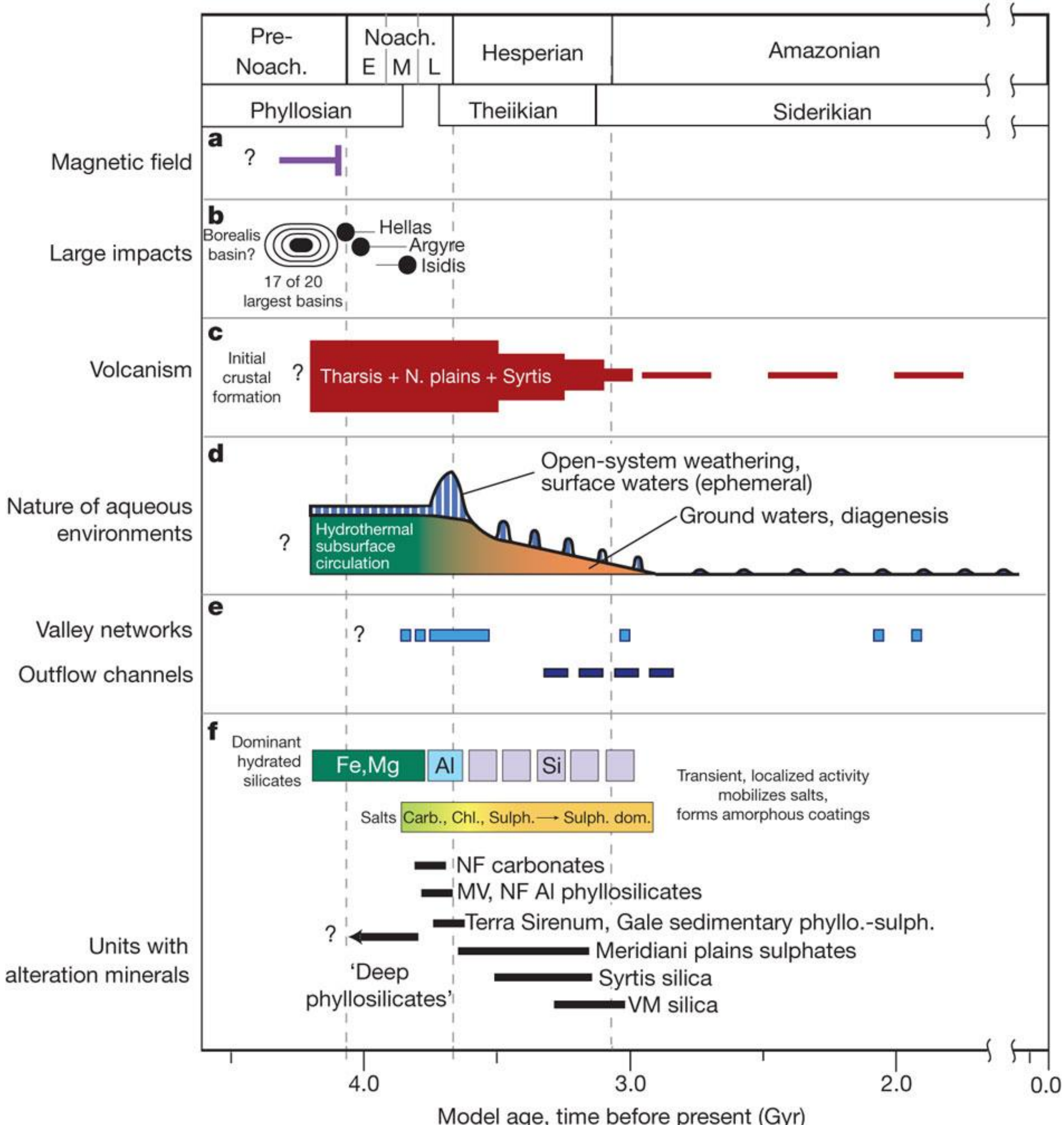
The geological history of Mars



A comparison of geologic timelines




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



Pre-Noach.
Noach.
E
M
L
Hesperian
Amazonian
Phyllosian
Theiikian
Siderikian
a
Magnetic field
?
b
Large impacts
Borealis basin?
17 of 20 largest basins
Hellas
Argyre
Isidis
c
Volcanism
Initial crustal formation
?
Tharsis + N. plains + Syrtis
d
Nature of aqueous environments
Open-system weathering, surface waters (ephemeral)
Ground waters, diagenesis
Hydrothermal subsurface circulation
?
e
Valley networks
?
Outflow channels
f
Dominant hydrated silicates
Fe,Mg
Al
Si
Salts
Carb., Chl., Sulph. → Sulph. dom.
Transient, localized activity mobilizes salts, forms amorphous coatings
NF carbonates
MV, NF Al phyllosilicates
Terra Sirenum, Gale sedimentary phyllo.-sulph.
Meridiani plains sulphates
Syrtis silica
VM silica
?
'Deep phyllosilicates'
Units with alteration minerals
4.0
3.0
2.0
0.0
Model age, time before present (Gyr)

TABLE 1. MARS EARLY EVOLUTION—EARTH-LIKE, BUT… (ALMOST) ALL THINGS BEING UNEQUAL

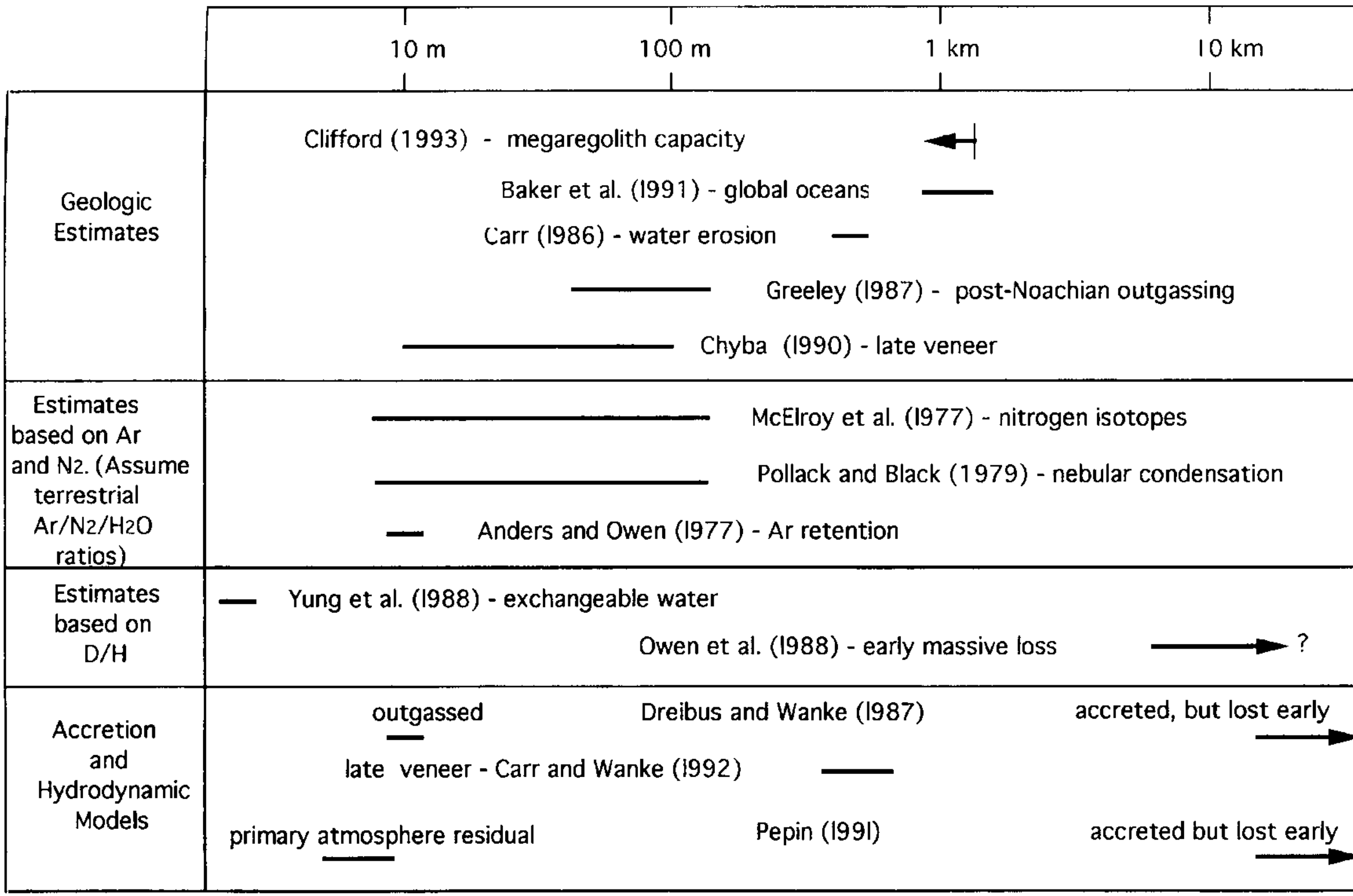
	Time (Ga)	*Events/Models and implications*
Atmosphere	4–5/4.2	Sun T-Tauri stage. No thick primary CO_2 atmosphere[1].
	4.3	Catastrophic outgassing of volatiles[2–4].
	4.2–3.8	Secondary CO_2 atmosphere from volcanic activity[5] and heavy bombardment[6].
	4.2–3.8	Decrease in solar activity and soft X-ray flux[1].
	4.1–Present	Loss of atmosphere from sputtering by solar wind and radiation[7–8].
Magnetosphere	>4.1	Loss of magnetosphere[9]. Lack of magnetization in Hellas. Termination of magnetic field before the end of the valley network formation[10].
		Differences in magnetic properties between both hemispheres due to the formation of the global dichotomy (see below), or an original single-sphere dynamo[11] from nonuniform temperature across the core-mantle boundary[12].
Global dichotomy	4.3?	Its formation affects geography, climate, hydrology, geology[13], and dispersal pathways for life. *Externally driven models:* A megaimpact or multiple impacts[14–18] or a southern polar giant impact by a bolide 0.1–1.0 lunar mass[19]. The resulting magma ocean solidifies to form the thicker crust of the southern hemisphere[20].
		Internally driven models: Removal of the basal lowland crust by mantle convection[21–23] or plate tectonics[24].
		The global dichotomy forms during accretion or right after[25], making it the most ancient geological feature of Mars[26–27].
Impact basins	4.1–3.9	Most large impact basins form during the Noachian (Hellas, Argyre, Isidis, Utopia, other)[27–29].
Structure Volcanism	3.8–3.5	Valles Marineris develops and is subsequently modified by erosion and sedimentation into the Amazonian[30–31]. Volcanic activity into recent geological past[32].
	3.8	The rise of Tharsis generates rifting in Valles Marineris and Noctis Labyrinthus.
	3.4–3.1	Elysium develops[33–34], with activity into the Amazonian[35].

Hydrology	4.3–3.8	Hydrological provinces and flow directions structurally defined early with the formation of the global dichotomy and the heavy bombardment[36].
	4.0–3.7	Peak of valley networks [27,37–39] and lake formation[40–42]. Localized activity in the Amazonian. Networks are not fully integrated with the landscape, suggesting only short favorable conditions for their development[39–47].
	3.7>	Outflow channels. Peak formation in the Hesperian with residual activity in the Amazonian[27].
	4.1> (?)	Ocean in the first billion years of history from subpermafrost aquifer modeling[48] and from proposed geomorphic evidence[49–51]. Disputed model[52].
	3.7>	*Oceanus Borealis* (Hesperian ocean)[53–56]. *Cons:* Difficulty to reconcile the volumes required to form the outflow channels with known volatile sources and sinks[27], lack of fine-grained sediments[57], evaporites[58], carbonates[59–60], no evidence for Noachian glaciation[61], and already thin Noachian atmosphere[62–63]. *Pros:* Lack of carbonates explained by destruction by precipitated H_2SO_4[64], a globally acidic atmosphere[65], or the short lifetime of ocean episodes[54].
		Other potential evidence: The global distribution of Hesperian deltas[66], possibly tsunami deposits[67–69], and shorelines[49–51,70–73]. The existence of shorelines has been debated since originally proposed[53,74]. The water global equivalent layer (GEL) has been used as a pro or con argument depending on models: D/H enrichment factors argue for a large Pre-Noachian water loss (GEL ≥137 m)[75]. Ion-microprobe analysis implies a Pre-Noachian water loss greater than during the rest of the martian history (GEL >41–99 m vs. GEL >10–53 m) and an undetected subsurface water/ice reservoir (~100–1000 m GEL) that exceeds the current observable inventory of ~20–30 m GEL)[76–77]. A recent global reevaluation of eroded volumes of valley networks results in an even larger GEL of ~5 km[78]. Other potential evidence includes polygonal ground in the lowlands[79] and subdued impact craters, whose anomalous depth/diameter ratio could be associated with a Late Hesperian ocean episode.[53,80–83]

	Time (Ga)	Events/Models and implications
Climate and environmental change	4.1>	Episodic periods of warmer and thicker atmosphere after the loss of the magnetosphere contributed by orbital forcing[84–85] and volcanism. Sulfur[86] and sulfates[58,87–88] suggest the release of greenhouse gases[89–92]. Other warming mechanisms (≤10 million years) include carbonate-silicate cycles[93]. Impact cratering provided transient environmental/atmospheric changes[94]. Excursions of warmer periods on a cold early Mars are supported by the presence of phyllosilicates[95–99] and increasingly more arid conditions from the Hesperian on, with an abundance of sulfates and evaporites[58]. Significant variations in obliquity, eccentricity, and precession[84] have also led to a redistribution of water in the polar ice deposits to lower latitudes to create ice ages regularly during martian history[100].

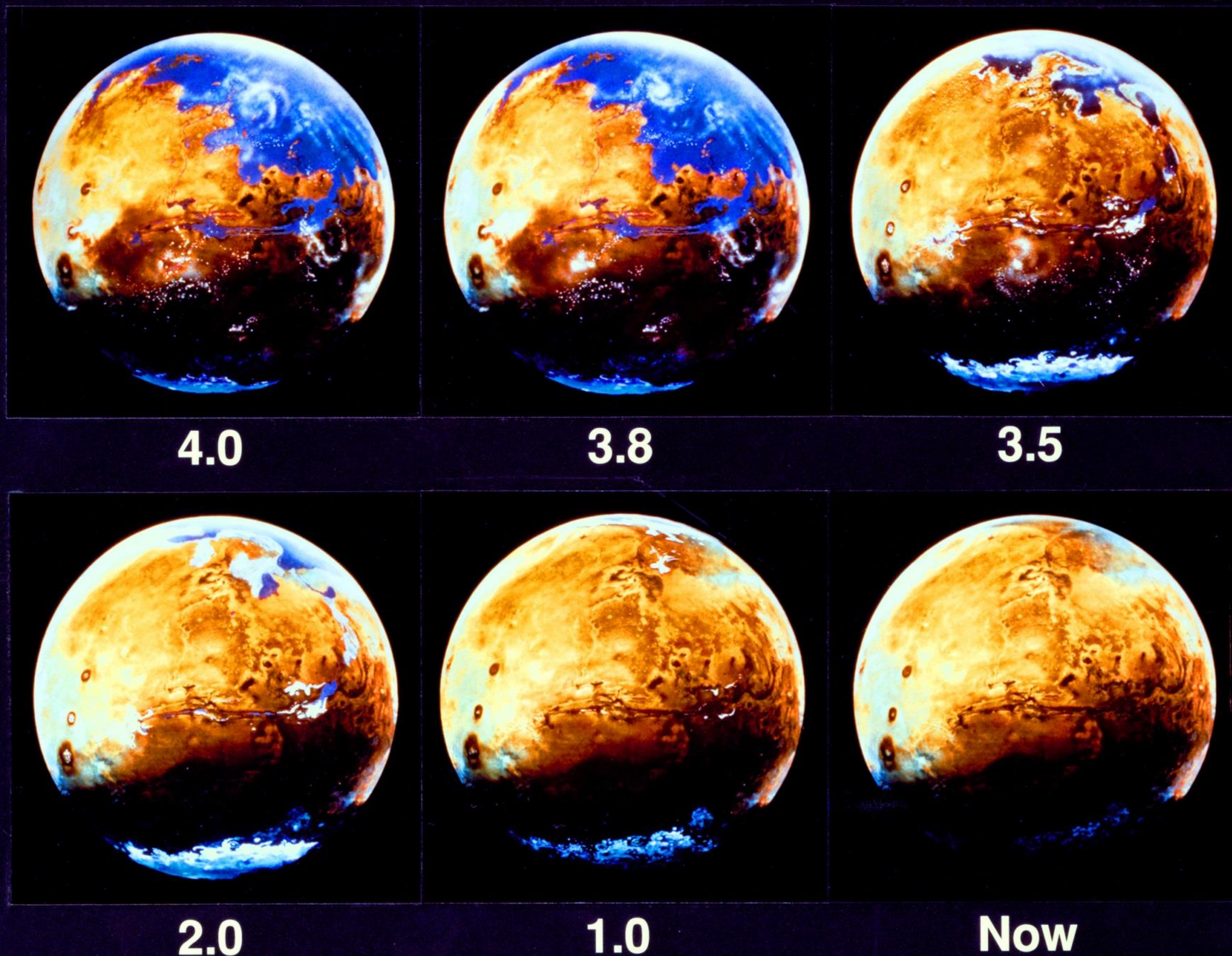
References in the table: [1]Erkaev *et al.*, 2014; [2]Elkins-Tanton, 2008, 2011; [3]Tian *et al.*, 2009; [4]Brasser, 2013; [5]Grott *et al.*, 2011; [6]Alexander *et al.*, 2012; [7]Jakosky and Phillips, 2001; [8]Jakosky *et al.*, 2017; [9]Acuña *et al.*, 1999; [10]Fassett and Head, 2011; [11]Stanley *et al.*, 2008; [12]Zhong and Zuber, 2001; [13]Watters *et al.*, 2007; [14]Frey and Schultz, 1988; [15]Wilhelms and Squyres, 1984; [16]Andrews-Hanna *et al.*, 2008; [17]Marinova *et al.*, 2008; [18]Nimmo *et al.*, 2008; [19]Leone *et al.*, 2014; [20]Reese *et al.*, 2011; [21]Lingenfelter and Schubert, 1973; [22]Wise *et al.*, 1979; [23]McGill and Dimitriou, 1990; [24]Sleep, 1994; [25]Frey, 2003; [26]Solomon *et al.*, 2005; [27]Carr and Head, 2010; [28]Frey, 2008; [29]Andrews-Hanna and Zuber, 2010; [30]Lucchitta, 2010; [31]Watkins *et al.*, 2015; [32]Broz *et al.*, 2017; [33]Werner, 2009; [34]Robbins *et al.*, 2011; [35]Greeley and Spudis, 1981; [36]de Hon, 2010; [37]Carr, 1996; [38]Gulick and Baker, 1989; [39]Craddock and Howard, 2002; [40]Cabrol and Grin, 1999; [41]Cabrol and Grin, 2010; [42]Fassett and Head, 2008; [43]Hynek and Phillips, 2003; [44]Stepinski and Collier, 2004; [45]Howard *et al.*, 2005; [46]Carr, 2012; [47]Craddock and Lorenz, 2017; [48]Clifford and Parker, 2001; [49]Parker *et al.*, 1989; [50]Parker *et al.*, 1993; [51]Head *et al.*, 1998; [52]Carr and Head, 2003; [53]Baker, 2001; [54]Dohm *et al.*, 2001; [55]Dohm *et al.*, 2009b; [56]Świąder, 2014; [57]McEwen *et al.*, 2007; [58]Bibring *et al.*, 2006; [59]Ehlmann *et al.*, 2008; [60]Wray *et al.*, 2009; [61]Wordsworth, 2016; [62]Hu *et al.*, 2015; [63]Kite *et al.*, 2014; [64]Levine and Summers, 2008; [65]Greenwood and Blake, 2006; [66]Di Achille and Hynek, 2010; [67]Rodriguez *et al.*, 2015; [68]Rodriguez *et al.*, 2016; [69]Costard *et al.*, 2017; [70]Thompson and Head, 2001; [71]Perron *et al.*, 2007; [72]Head, 2007; [73]Banfield *et al.*, 2015; [74]Malin and Edgett, 1999; [75]Villanueva *et al.*, 2015; [76]Kurokawa *et al.*, 2014; [77]Stuurman *et al.*, 2016; [78]Luo *et al.*, 2017; [79]Kargel *et al.*, 1995; [80]Boyce *et al.*, 2005; [81]Mouginot *et al.*, 2012; [82]Gulick *et al.*, 1997; [83]Kreslavsky and Head, 2002; [84]Laskar *et al.*, 2002; [85]Mischna *et al.*, 2003; [86]Clark *et al.*, 1976; [87]Gendrin *et al.*, 2005; [88]Ehlmann and Edwards, 2014; [89]Postawko and Kuhn 1986; [90]Yung *et al.*, 1997; [91]Halevy and Head, 2014; [92]Ramirez *et al.*, 2013; [93]Batalha *et al.*, 2016; [94]Segura *et al.*, 2002; [95]Carter *et al.*, 2013; [96]Poulet *et al.*, 2008; [97]Bishop *et al.*, 2005; [98]Fairén *et al.*, 2010; [99]Head *et al.*, 2003; [100]Head *et al.*, 2010.

Estimates of the global water content



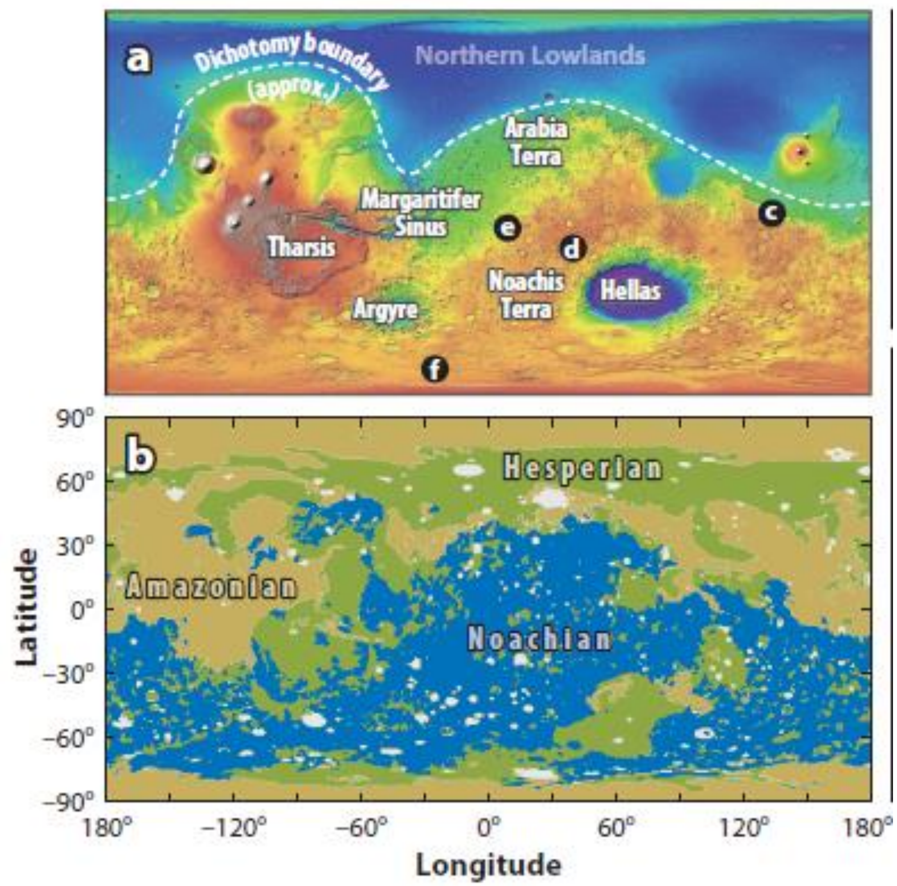
HISTORY OF WATER ON MARS

b.y.a.

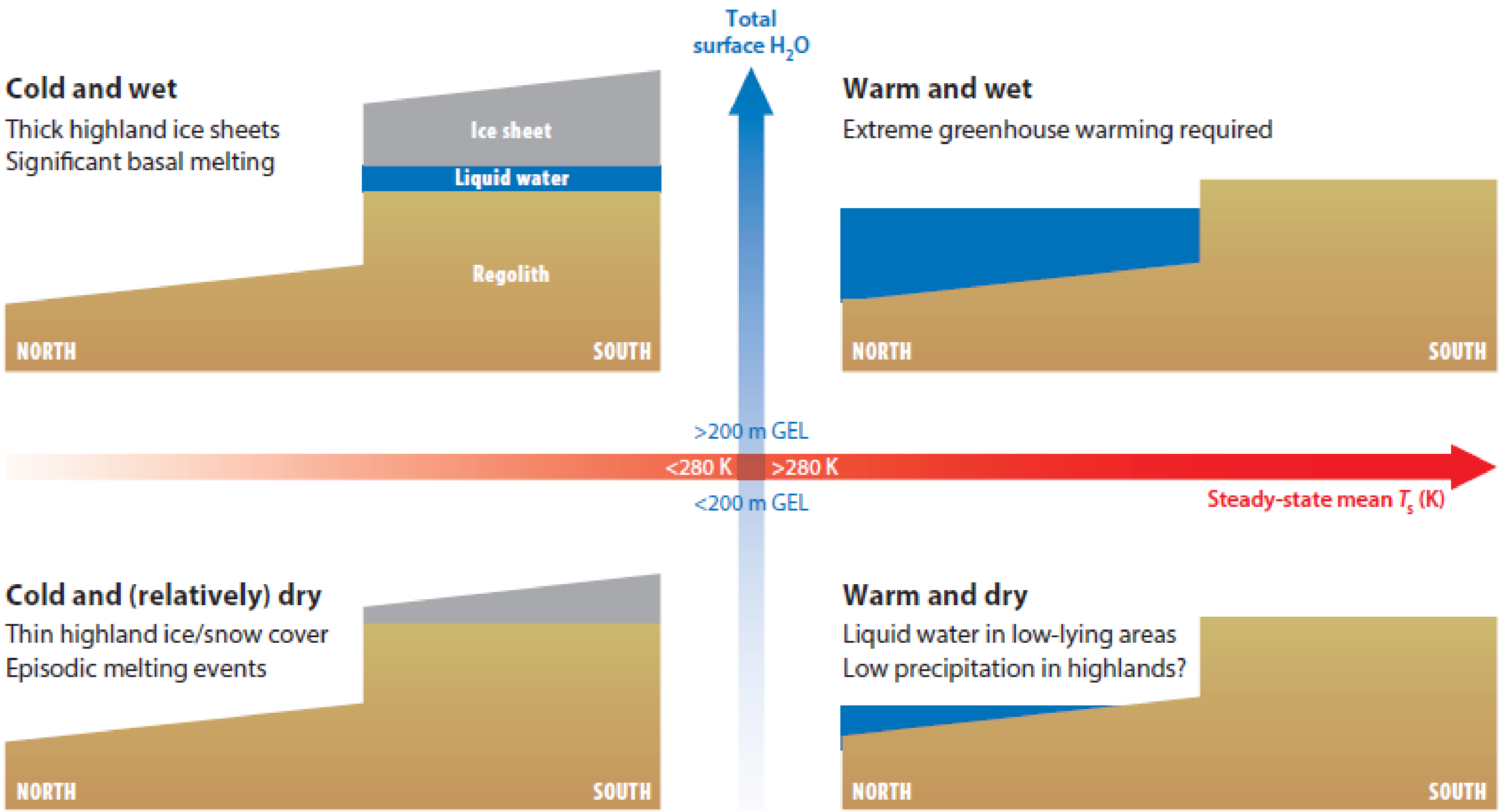


The Martian climate history

- Although evidence for liquid water on the surface of early Mars is conclusive, explaining a wet early climate is problematic.
- The Sun was only 75% of its cirrent luminosity in the Noachian
- A thicker CO_2 atmosphere would have resulted in a strong greenhouse effect, but too dense an atmosphere would have collapsed

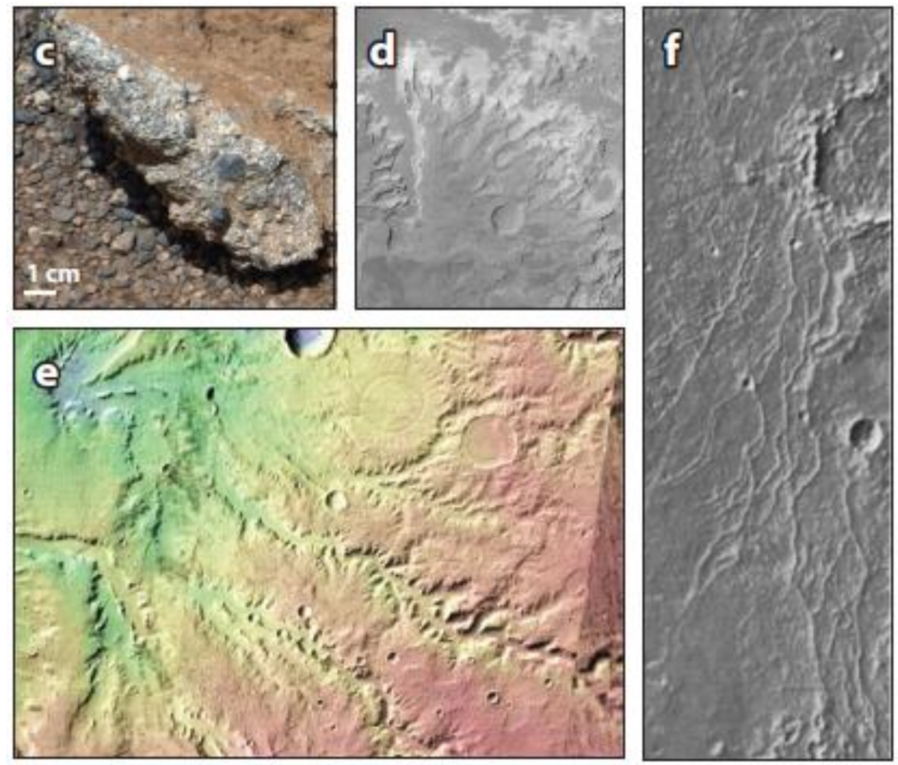


End-member scenarios for the early Martian climate



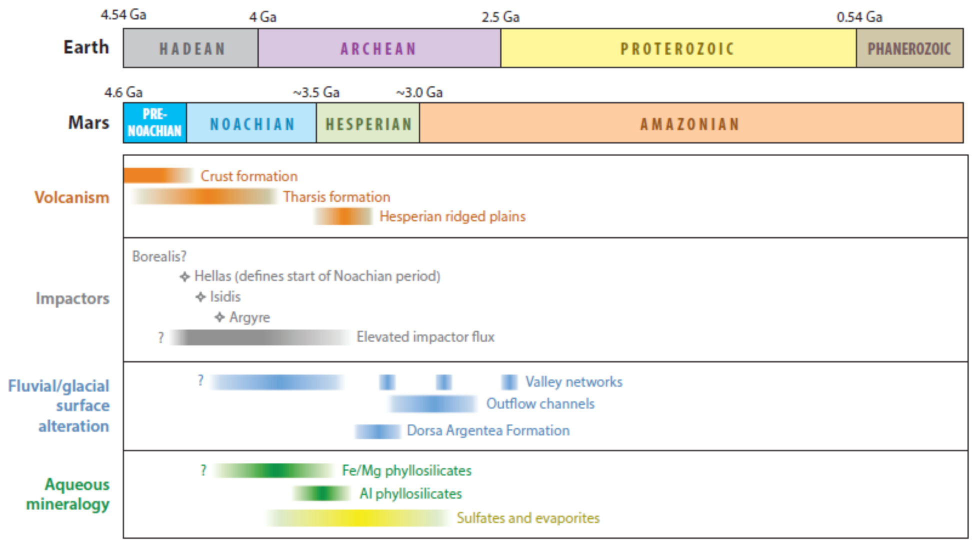
Geomorphological evidence

- Dendritic valley networks are rare on Hesperian and Amazonian terrain but common on Noachian terrain
- They are predominantly seen at equatorial latitudes between 60°S and 10°N
- Landform evolution models suggest minimum formation timescales for the valley networks of 10^5 to 10^7 years under climate conditions appropriate to arid regions on Earth
- Crater lakes interlinked with the valley networks are abundant in the Noachian southern highlands
- Closed-basin lakes greatly outnumber open-basin lakes
- This is seen as evidence against a wet climate



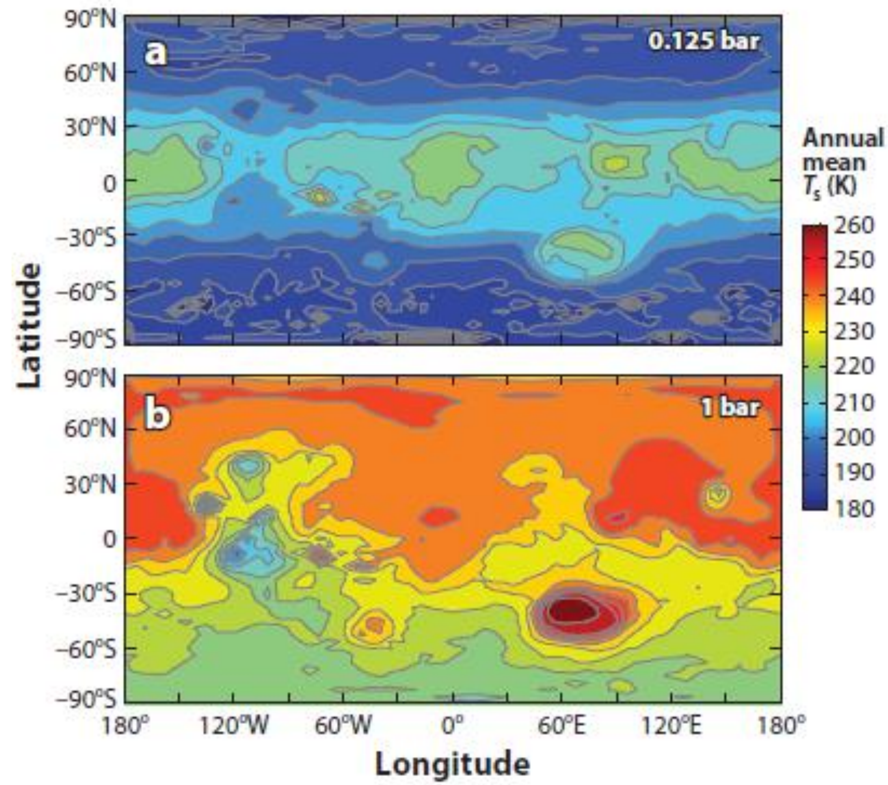
Geochemical evidence

- Iron- and magnesium-rich phyllosilicates (clays) are found extensively over Noachian terrain
- To form, these minerals require the presence of liquid water and near-neutral-pH conditions
- If the phyllosilicates mainly formed on the surface, this would represent evidence in favor of a warm and wet early martian climate
- In most cases their mineralogy may best represent subsurface formation in geothermally heated, water-poor systems
- Carbonate is conspicuous by its low abundance on the martian surface
- Surface carbonate formation should be very efficient on a warm and wet planet with a basaltic crust and CO_2-rich atmosphere
- The absence of surface carbonates is a strong indication that early Mars was either only episodically warm, or very dry

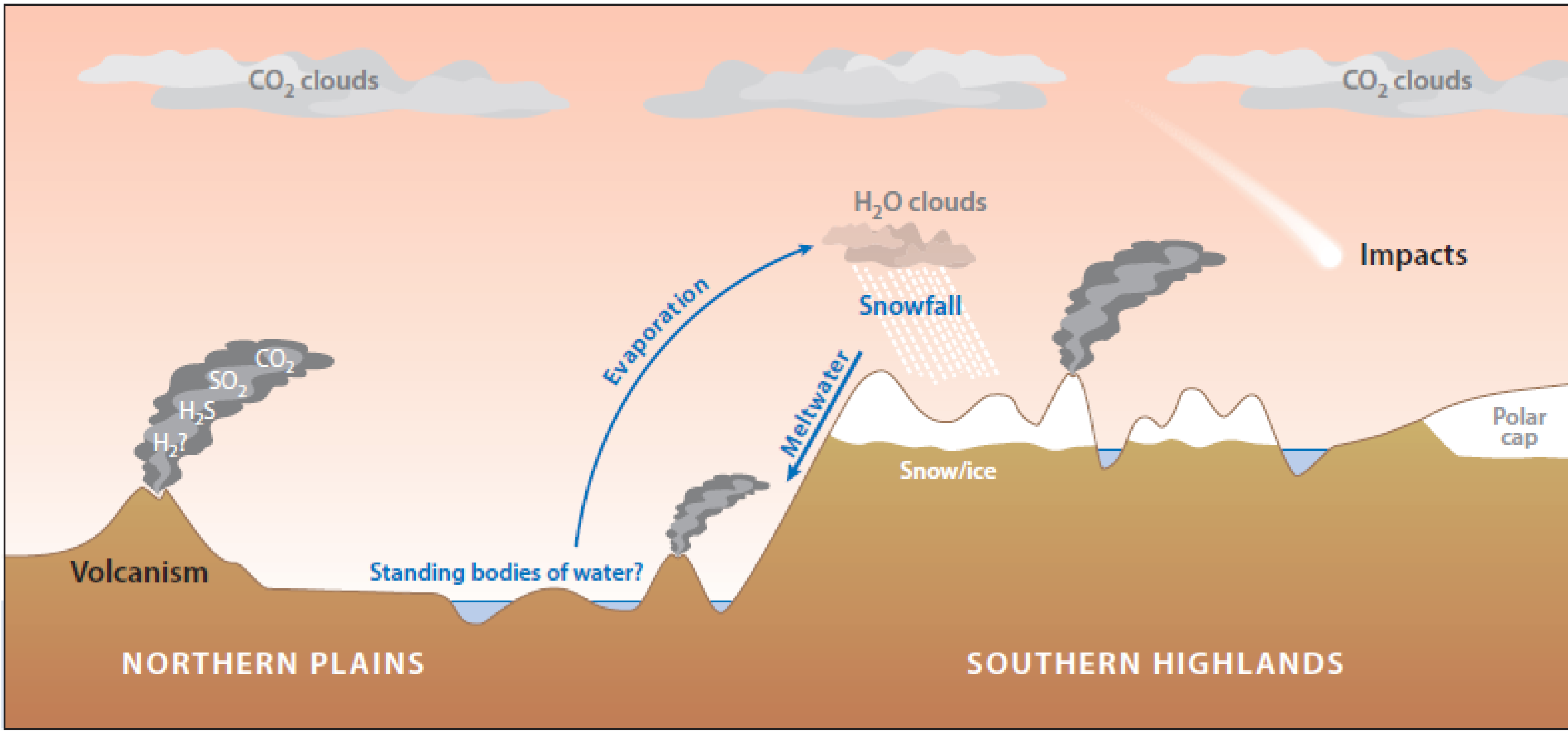


Climate modelling

- Many aspects of Mars's atmospheric evolution are highly uncertain
- It is likely that Mars had a thicker CO_2 atmosphere in the late Noachian
- This atmosphere could have been as dense as 1–2 bar, but likely no more than this
- An atmosphere denser than 1 bar would still have a mean temperature below freezing
- However, it would also change the surface temperature pattern, with temperature depending more strongly on altitude than on latitude



An episodically warm Mars?



To summarize

- Mars underwent an extended period of surface erosion and chemical weathering by liquid water until around 3.5 Ga, during the late Noachian and early Hesperian periods.
- The weight of the observational evidence favors a mainly cold climate with episodic warming events, rather than permanently warm and wet conditions.
- If early Mars was once warm and wet, thick wet-based ice sheets would have formed on the Noachian highlands when the warm period ended, causing significant glacial erosion.
- Constraints on the early solar luminosity, martian orbit, and radiative transfer of CO2 strongly disfavor a warmer climate due to CO2 and H2O only.
- Under a thicker atmosphere, adiabatic cooling of the surface causes transport of snow and ice to the valley network source regions.
- Repeated episodic warming events probably caused ice and snowpacks in the Noachian highlands to melt, carving valley networks and other fluvial features.
- The precise mechanism that caused the warming events is still poorly constrained. The two most likely forcing mechanisms are meteorite impacts and volcanism, although the details remain unclear.

The final word has not been said yet

PERSPECTIVE
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nature geoscience

The geological and climatological case for a warmer and wetter early Mars

Ramses M. Ramirez[1*] and Robert A. Craddock[2]

The climate of early Mars remains a topic of intense debate. Ancient terrains preserve landscapes consistent with stream channels, lake basins and possibly even oceans, and thus the presence of liquid water flowing on the Martian surface 4 billion years ago. However, despite the geological evidence, determining how long climatic conditions supporting liquid water lasted remains uncertain. Climate models have struggled to generate sufficiently warm surface conditions given the faint young Sun—even assuming a denser early atmosphere. A warm climate could have potentially been sustained by supplementing atmospheric CO_2 and H_2O warming with either secondary greenhouse gases or clouds. Alternatively, the Martian climate could have been predominantly cold and icy, with transient warming episodes triggered by meteoritic impacts, volcanic eruptions, methane bursts or limit cycles. Here, we argue that a warm and semi-arid climate capable of producing rain is most consistent with the geological and climatological evidence.

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Late Noachian Icy Highlands climate model: Exploring the possibility of transient melting and fluvial/lacustrine activity through peak annual and seasonal temperatures

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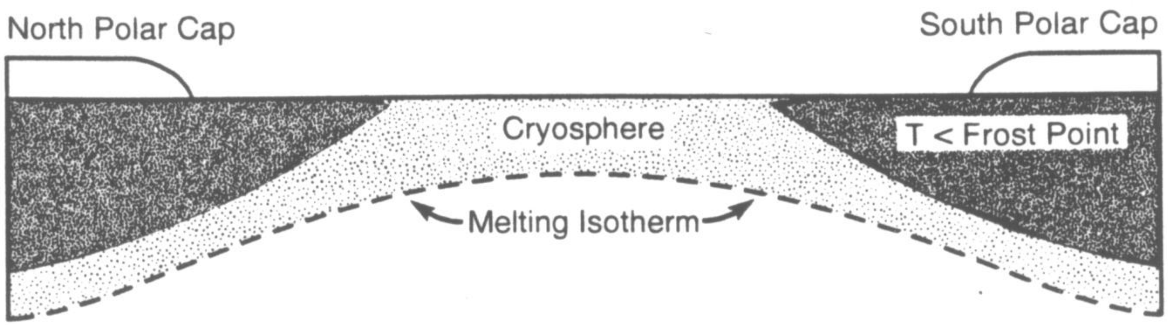
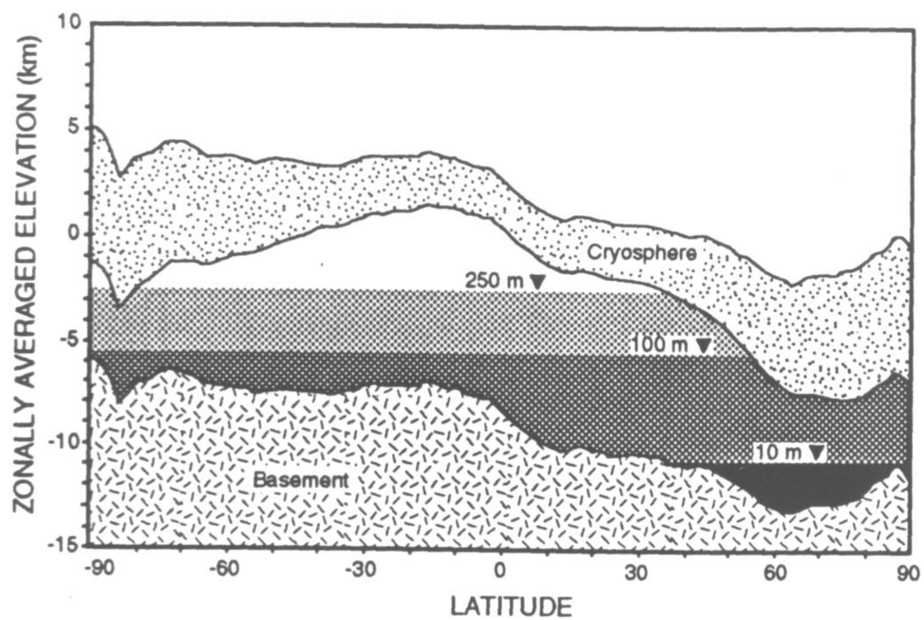
ABSTRACT

The nature of the Late Noachian climate of Mars remains one of the outstanding questions in the study of the evolution of martian geology and climate. Despite abundant evidence for flowing water (valley networks and open/closed basin lakes), climate models have had difficulties reproducing mean annual surface temperatures (MAT) > 273 K in order to generate the “warm and wet” climate conditions presumed to be necessary to explain the observed fluvial and lacustrine features. Here, we consider a “cold and icy” climate scenario, characterized by MAT ∼225 K and snow and ice distributed in the southern highlands, and ask: Does the formation of the fluvial and lacustrine features require continuous “warm and wet” conditions, or could seasonal temperature variation in a “cold and icy” climate produce sufficient summertime ice melting and surface runoff to account for the observed features? To address this question, we employ the 3D Laboratoire de Météorologie Dynamique global climate model (LMD GCM) for early Mars and (1) analyze peak annual temperature (PAT) maps to determine where on Mars temperatures exceed freezing in the summer season, (2) produce temperature time series at three valley network systems and compare the duration of the time during which temperatures exceed freezing with seasonal temperature variations in the Antarctic McMurdo Dry Valleys (MDV) where similar fluvial and lacustrine features are observed, and (3) perform a positive-degree-day analysis to determine the annual volume of meltwater produced through this mechanism, estimate the necessary duration that this process must repeat to produce sufficient meltwater for valley network formation, and estimate whether runoff rates predicted by this mechanism are comparable to those required to form the observed geomorphology of the valley networks.

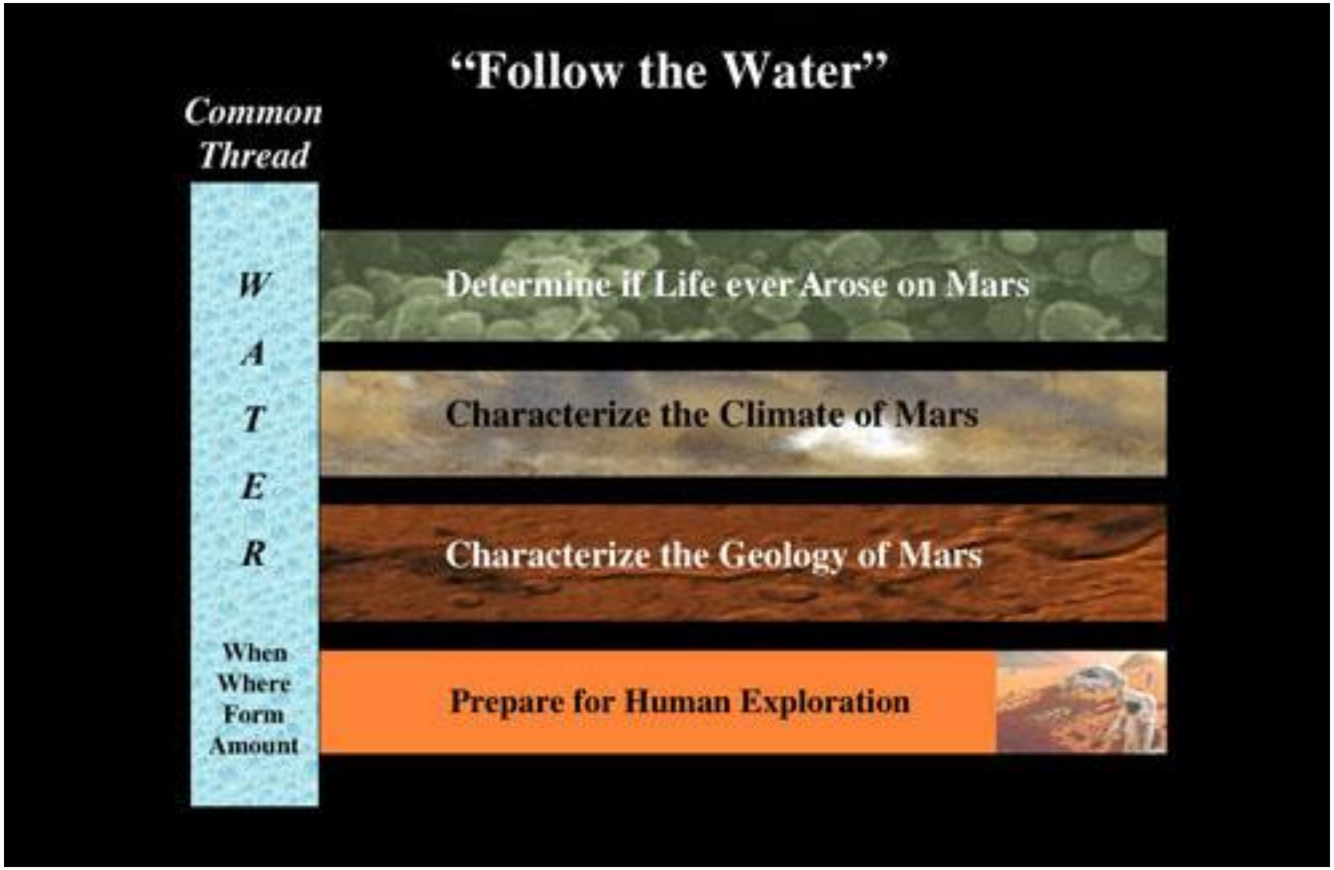
When considering an ambient CO_2 atmosphere, characterized by MAT ∼225 K, we find that: (1) PAT can exceed the melting point of water (>273 K) in topographic lows, such as the northern lowlands and basin floors, and small regions near the equator during peak summer season conditions, despite the much lower MAT; (2) Correlation of PAT > 273 K with the predicted distribution of surface snow and ice shows that melting could occur near the edges of the ice sheet in near-equatorial regions where valley networks are abundant; (3) For the case of a circular orbit, the duration of temperatures >273 K at specific valley network locations suggests that yearly meltwater generation is insufficient to carve the observed fluvial and lacustrine features when compared with the percentage of the year required to sustain similar features in the MDV; (4) For the case of a more eccentric orbit (eccentricity of 0.17), the duration of temperatures >273 K at specific valley network locations suggests that annual meltwater generation may be capable of producing sufficient meltwater for valley network formation when repeated for many years; (5) When considering a slightly warmer climate scenario and a circular orbit, characterized by MAT ∼243 K, we find that this small amount of additional greenhouse warming (∼18 K MAT increase) produces time durations of temperatures >273 K that are similar to those observed in the MDV. Thus, we suggest that peak daytime and seasonal temperatures exceeding 273 K could form the valley networks and lakes with either a relatively high eccentricity condition or a small amount of additional atmospheric warming, rather than the need for a sustained MAT at or above 273 K.

Where has the remaining water gone?

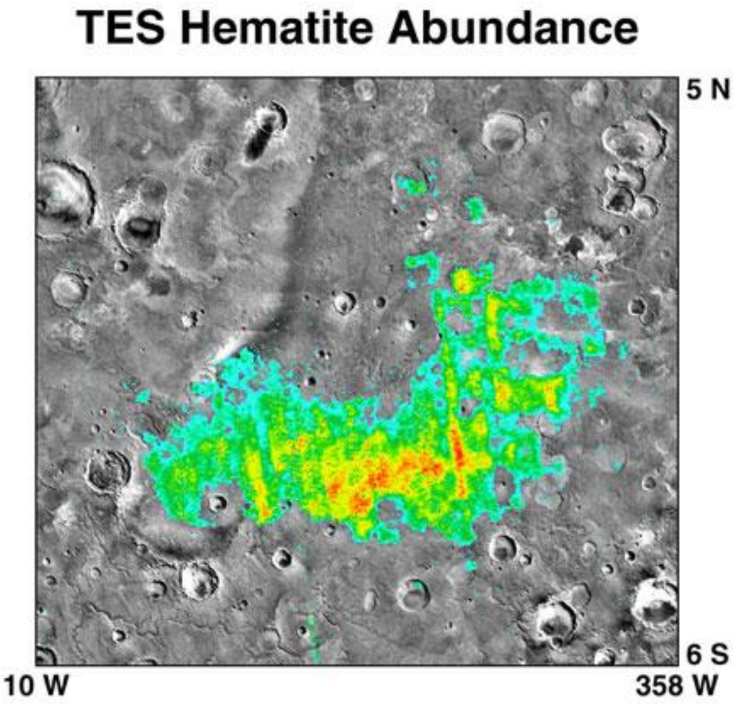


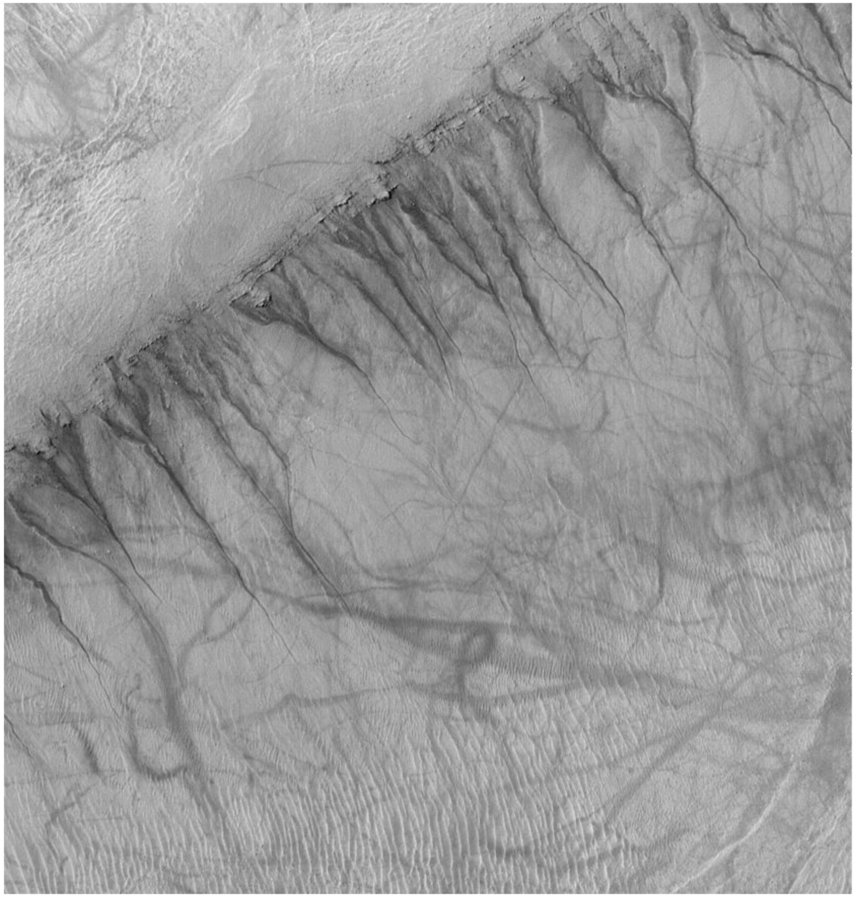


NASA's strategy

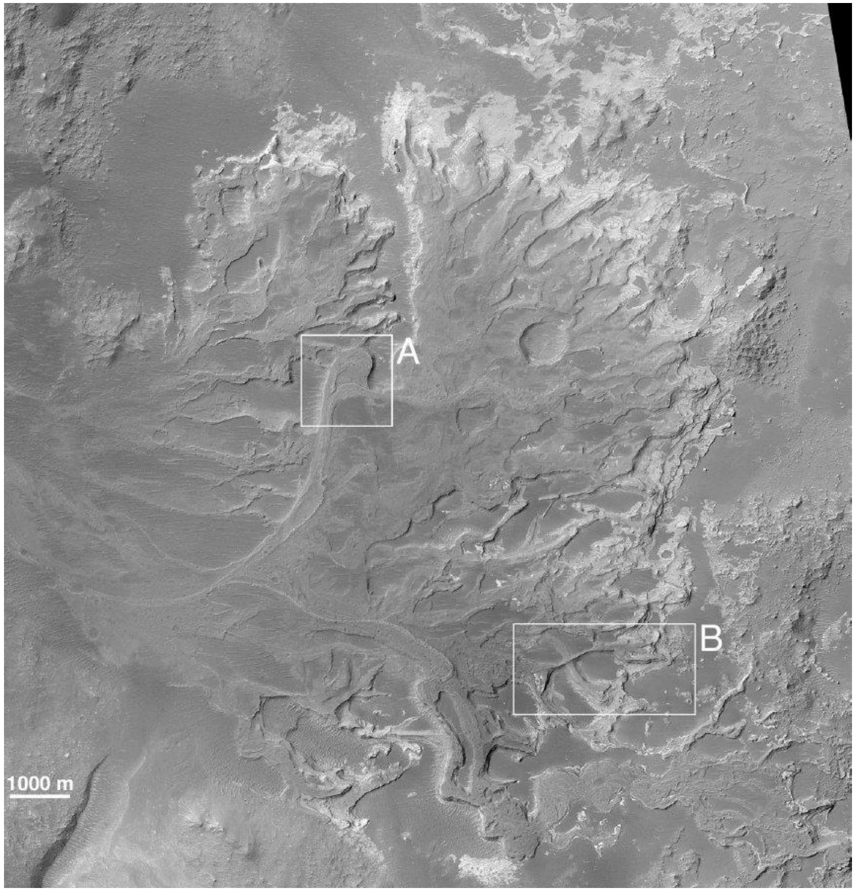


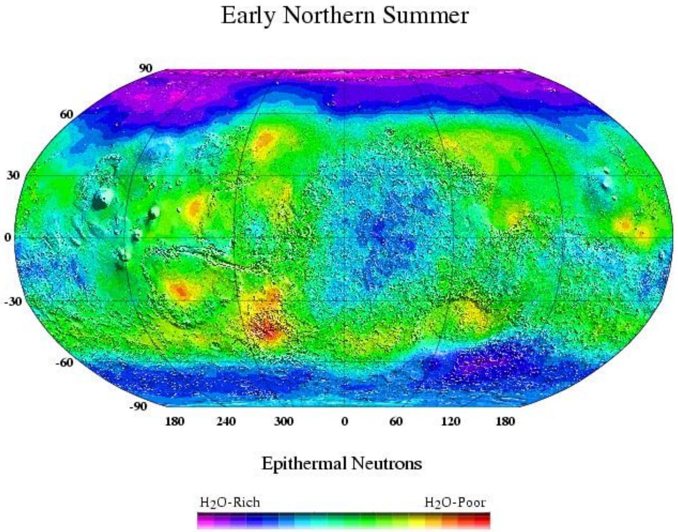
Mars Global Surveyor (1996)



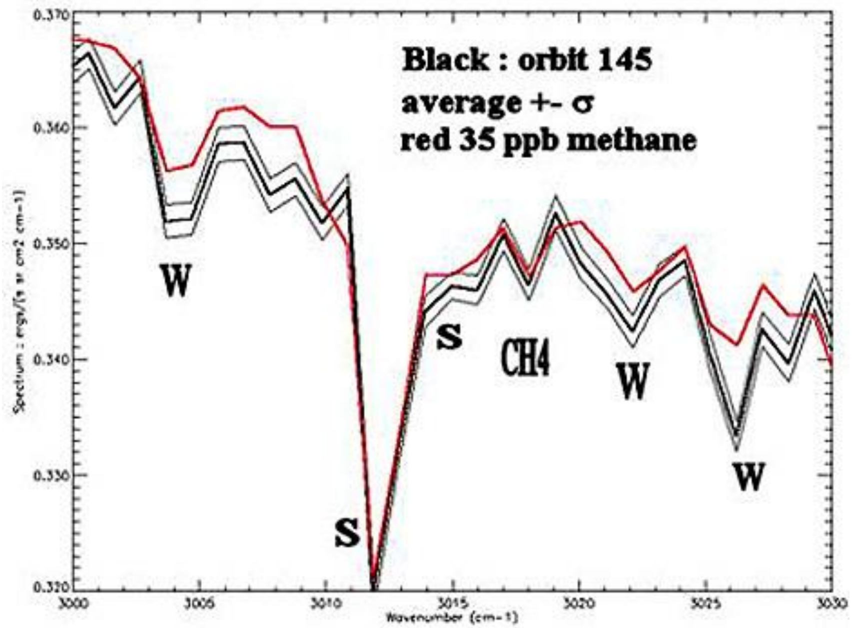


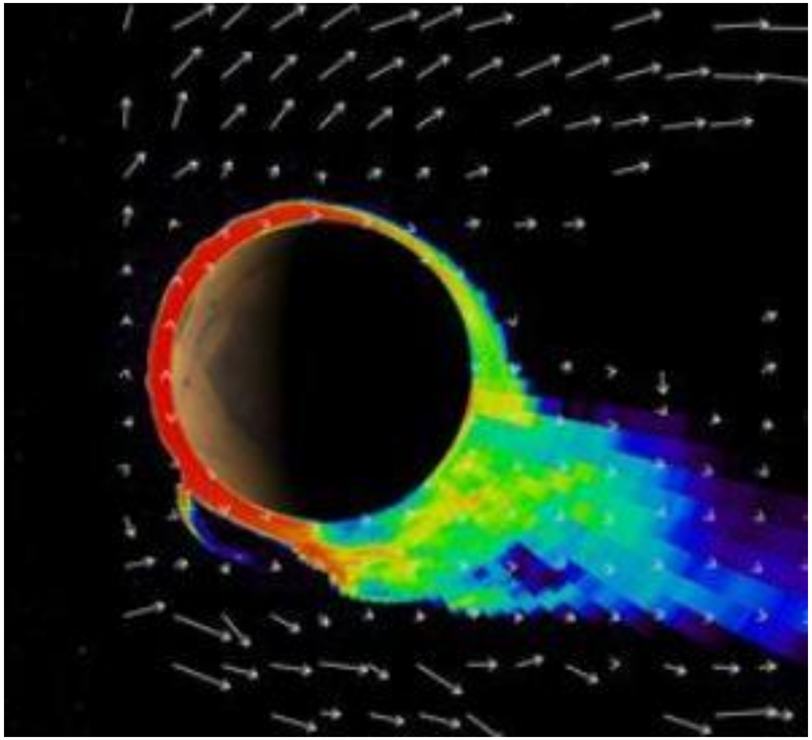
Mars Odyssey (2001)



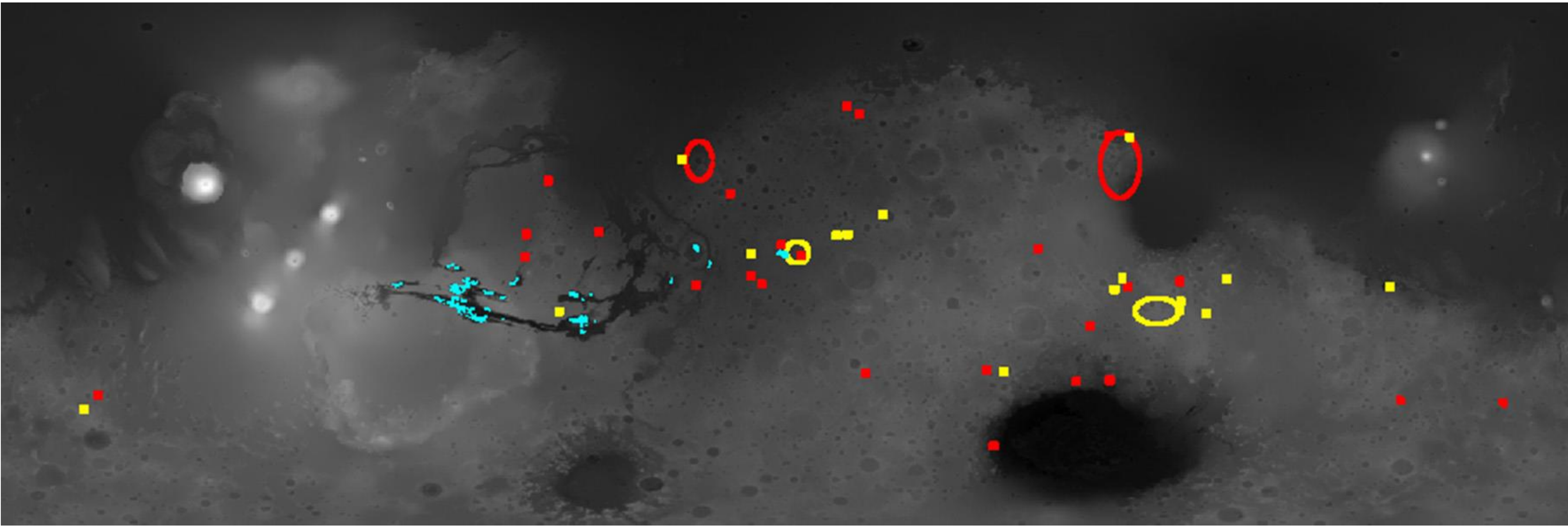


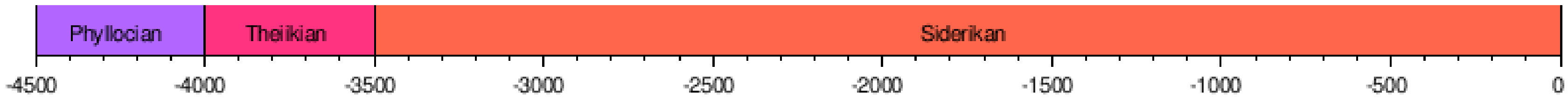
Mars Express (2003)



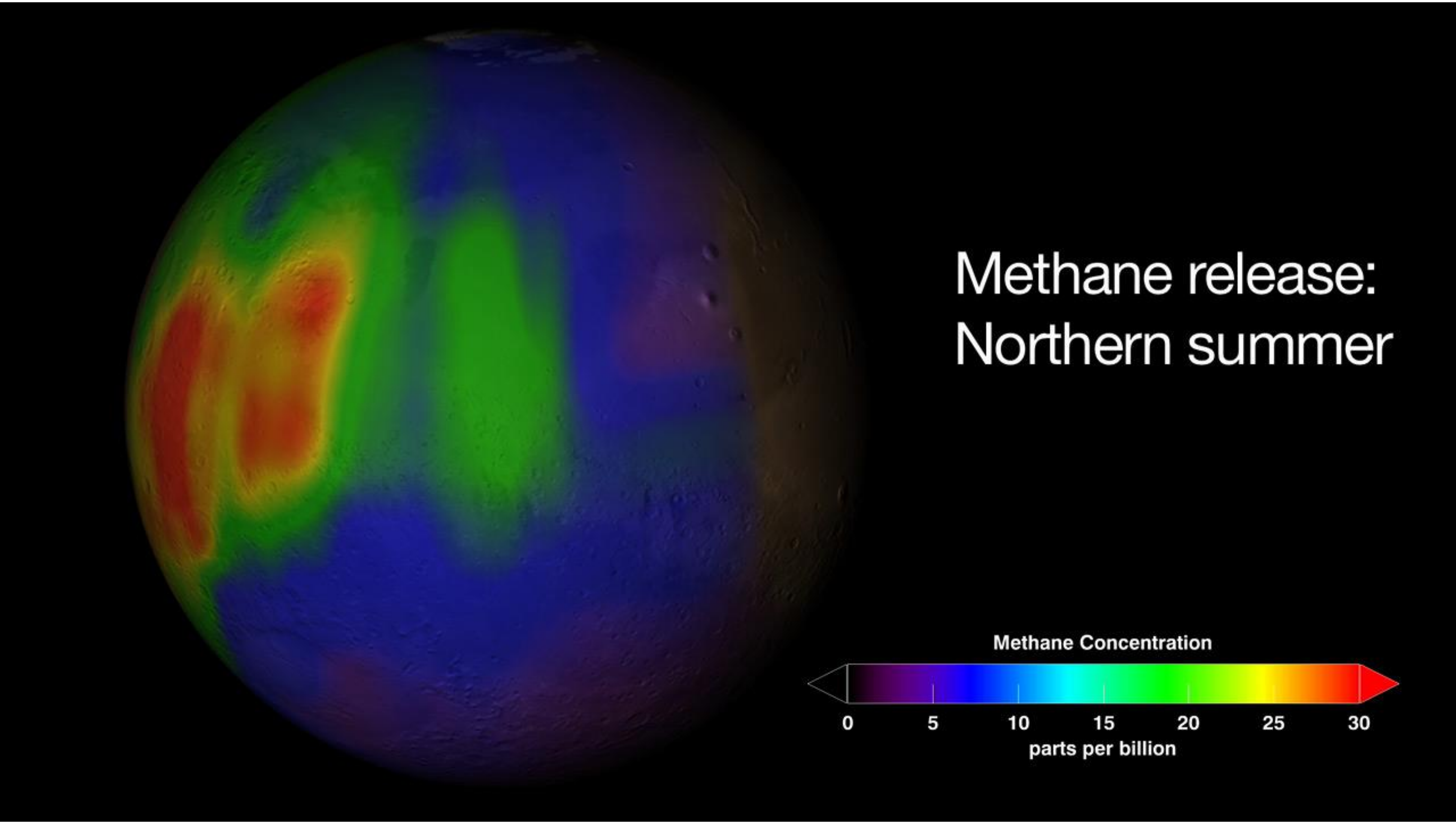


Hydrated minerals



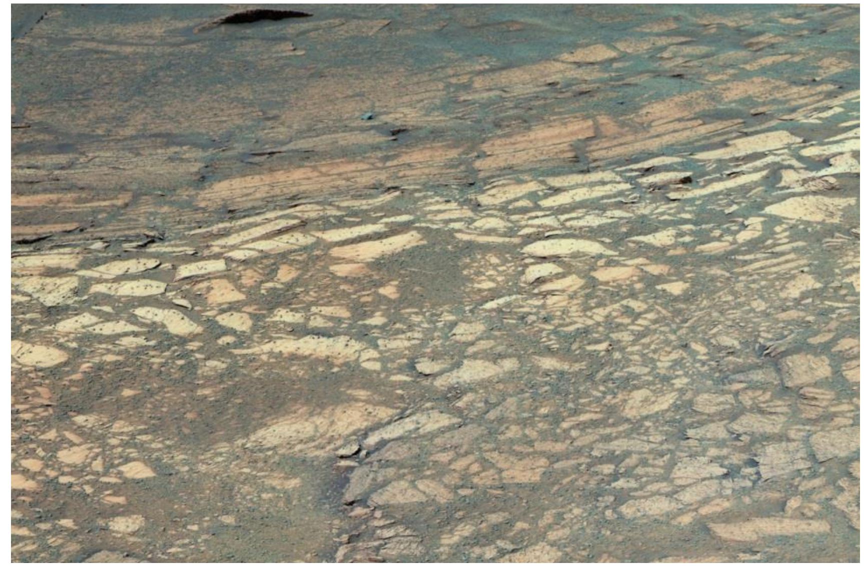


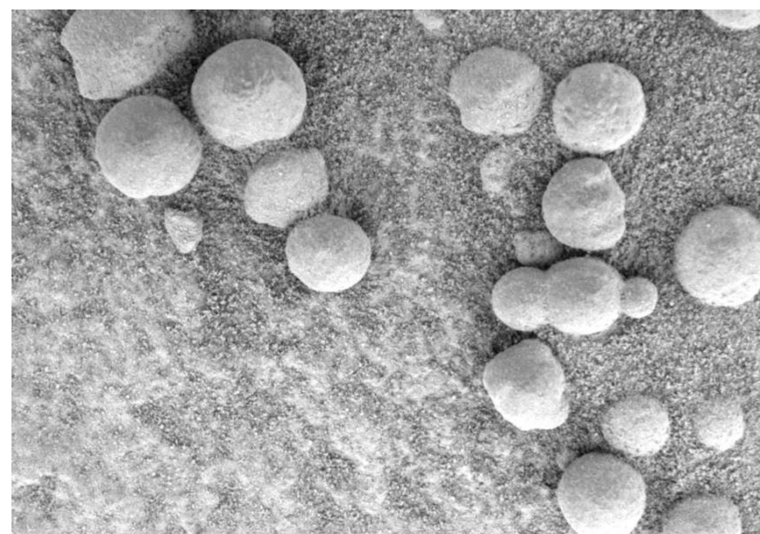
Methane



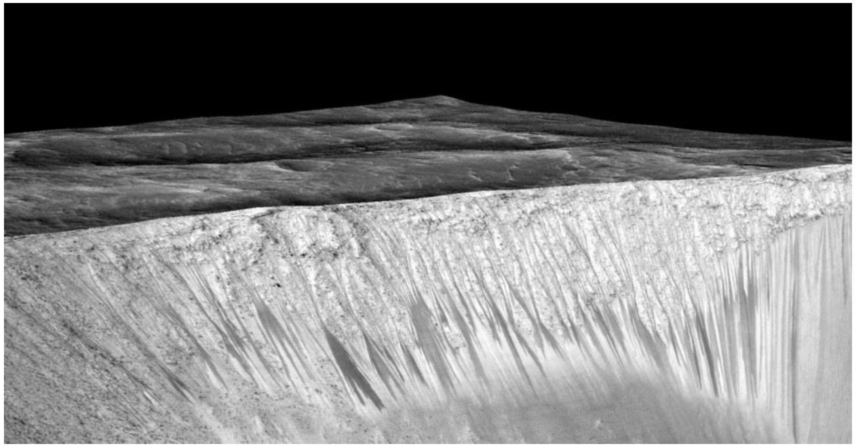
Methane release:
Northern summer
Methane Concentration
0
5
10
15
20
25
30
parts per billion

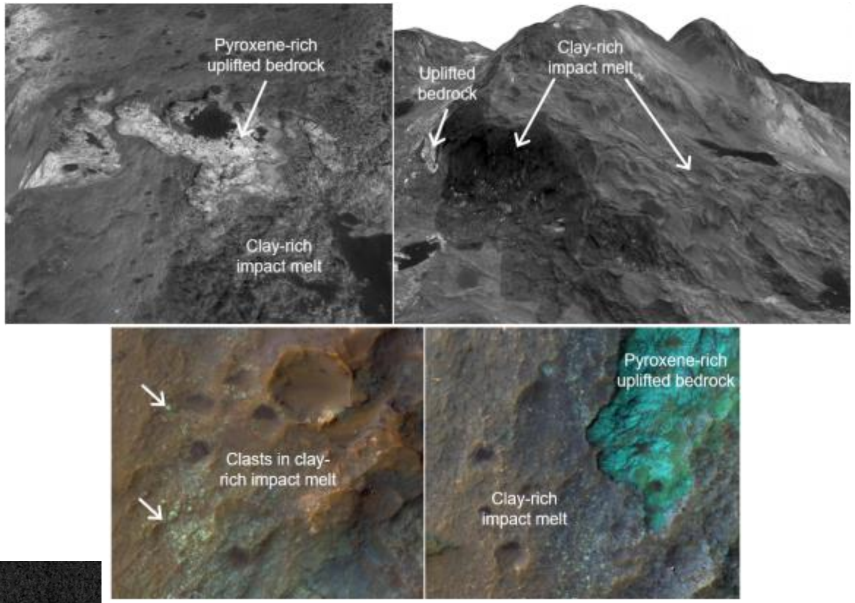
Mars Exploration Rovers (2003)

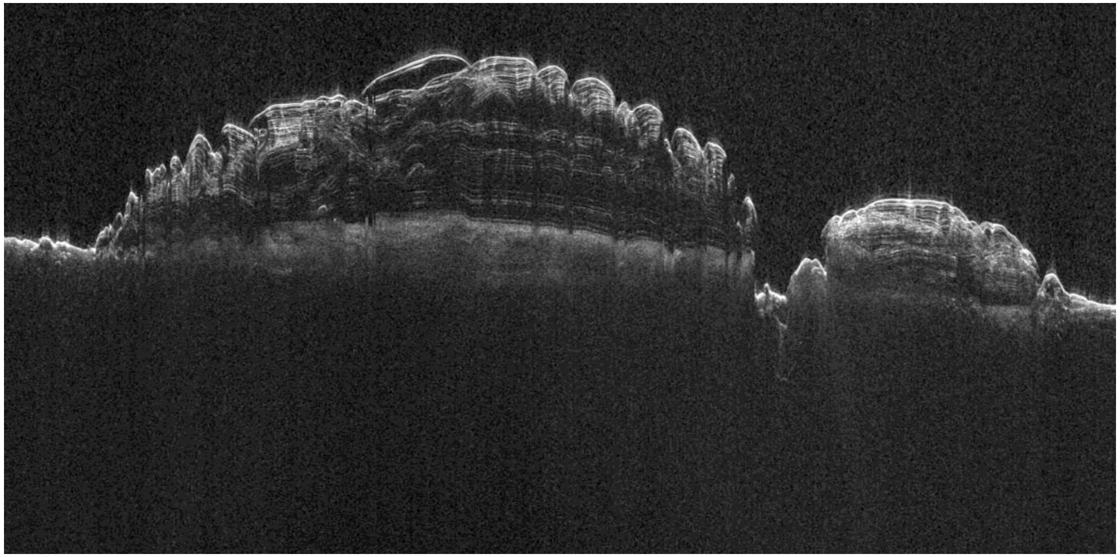




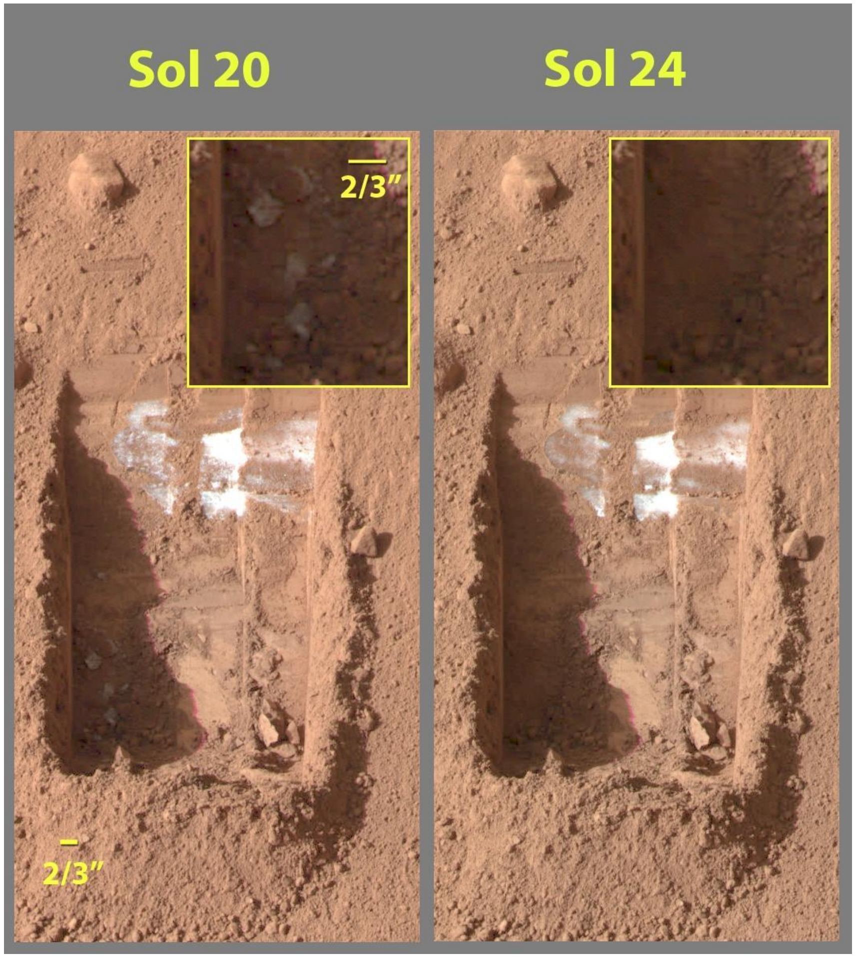
Mars Reconnaissance Orbiter (2005)

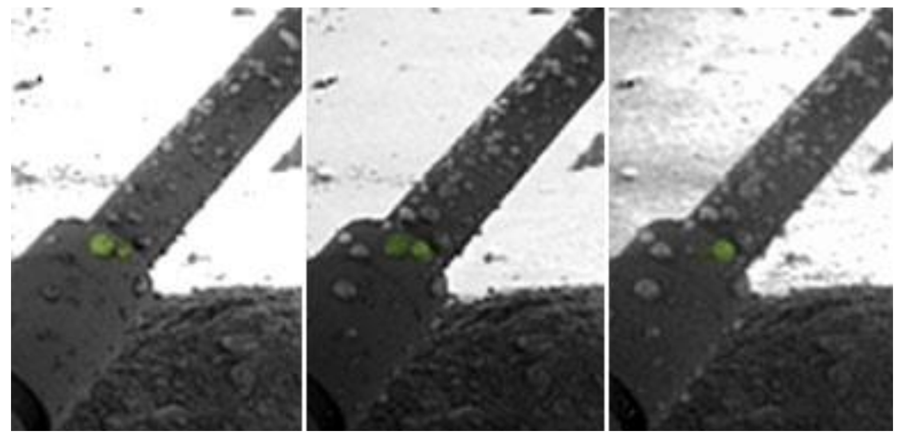






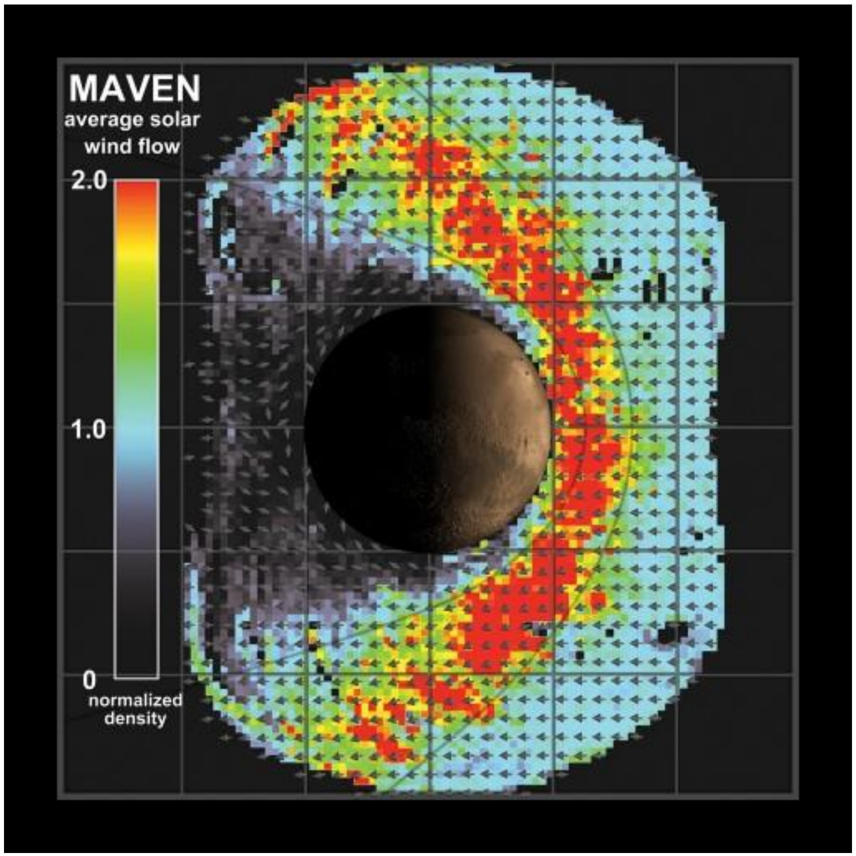
Phoenix (2007)

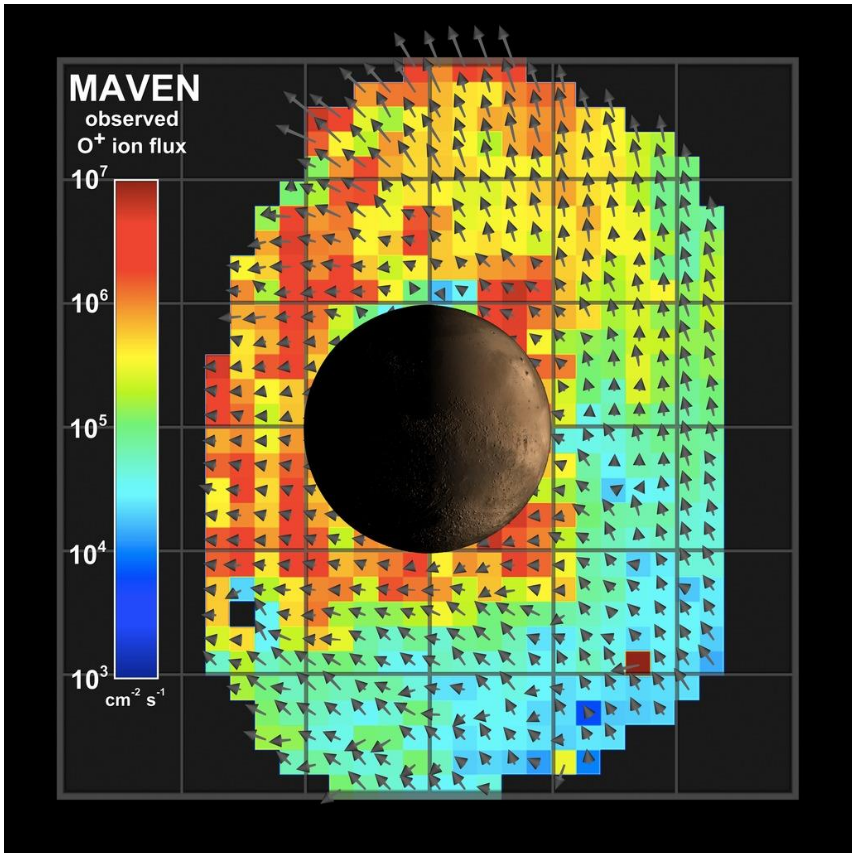




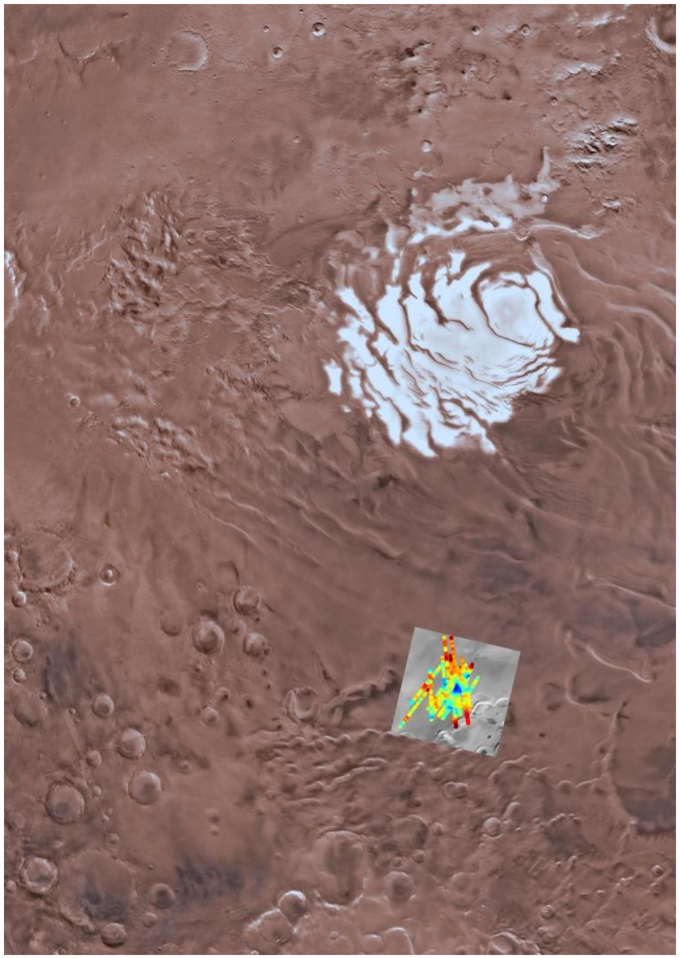
Mars Science Laboratory (2011)

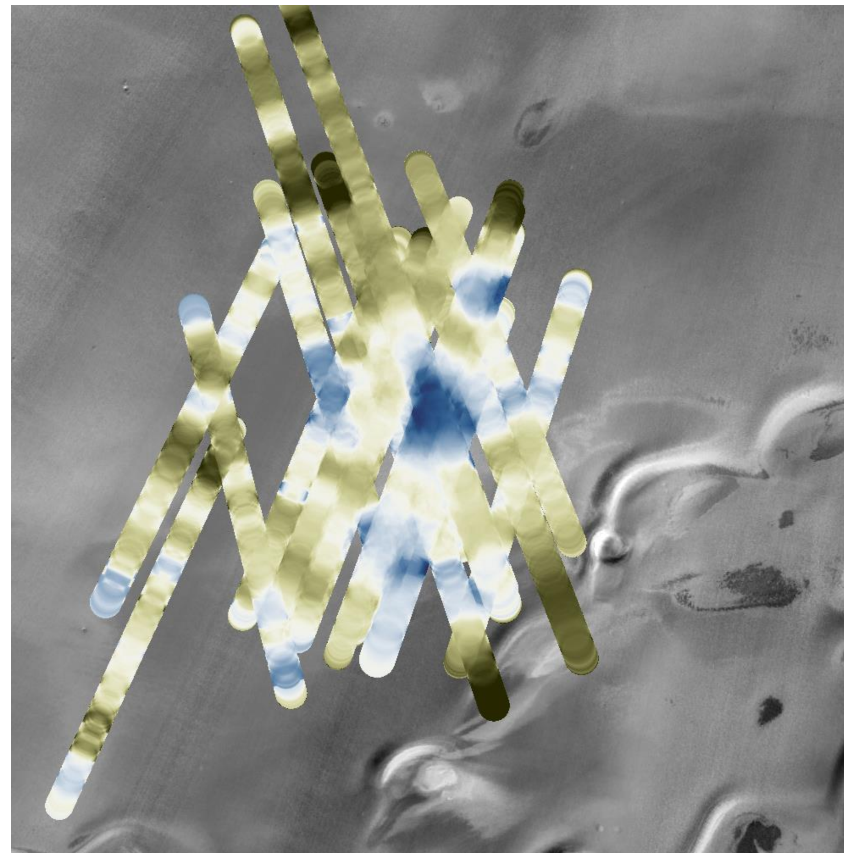
Mars Atmosphere and Volatile EvolutioN Mission (2013)





Mars Express (2018)





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Volume 18, Number 9, 2018
Mary Ann Liebert, Inc.
DOI: 10.1089/ast.2017.1805

Research Article

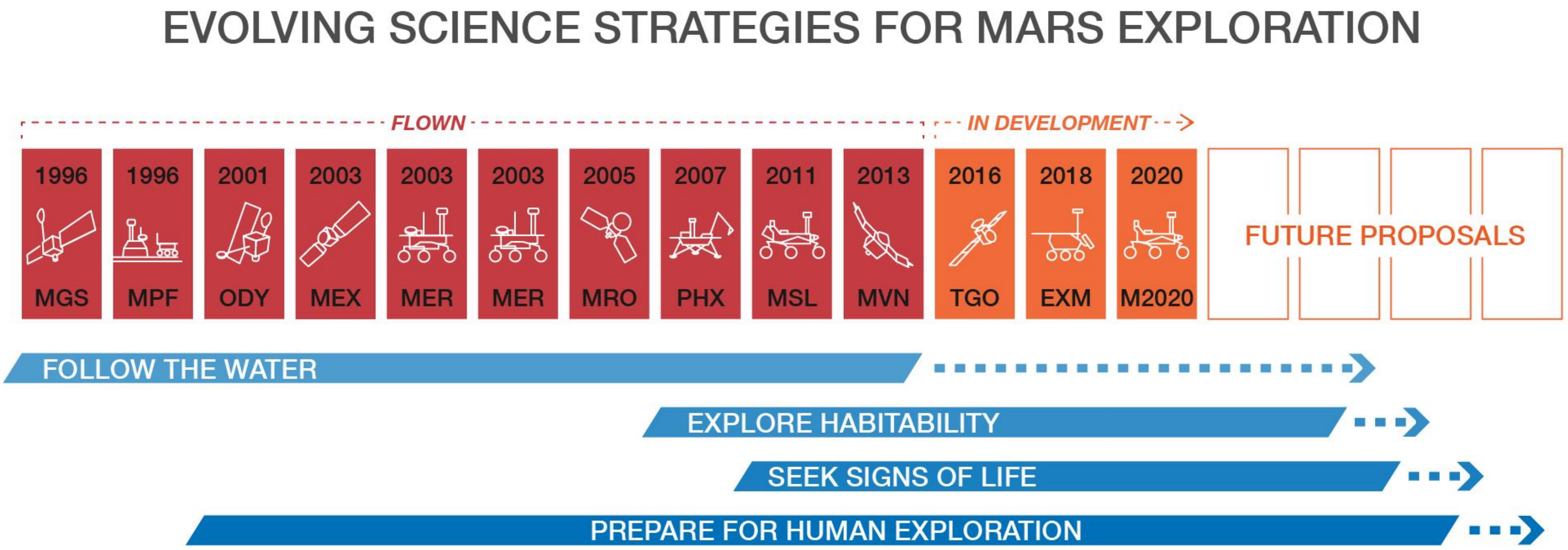
Enhanced Microbial Survivability in Subzero Brines

Jacob Heinz,[1] Janosch Schirmack,[1] Alessandro Airo,[1] Samuel P. Kounaves,[2,3] and Dirk Schulze-Makuch[1,4]

Abstract

It is well known that dissolved salts can significantly lower the freezing point of water and thus extend habitability to subzero conditions. However, most investigations thus far have focused on sodium chloride as a solute. In this study, we report on the survivability of the bacterial strain *Planococcus halocryophilus* in sodium, magnesium, and calcium chloride or perchlorate solutions at temperatures ranging from +25°C to −30°C. In addition, we determined the survival rates of *P. halocryophilus* when subjected to multiple freeze/thaw cycles. We found that cells suspended in chloride-containing samples have markedly increased survival rates compared with those in perchlorate-containing samples. In both cases, the survival rates increase with lower temperatures; however, this effect is more pronounced in chloride-containing samples. Furthermore, we found that higher salt concentrations increase survival rates when cells are subjected to freeze/thaw cycles. Our findings have important implications not only for the habitability of cold environments on Earth but also for extraterrestrial environments such as that of Mars, where cold brines might exist in the subsurface and perhaps even appear temporarily at the surface such as at recurring slope lineae. Key Words: Brines—Halophile—Mars—Perchlorate—Subzero—Survival. Astrobiology 18, xxx–xxx.

Future developments



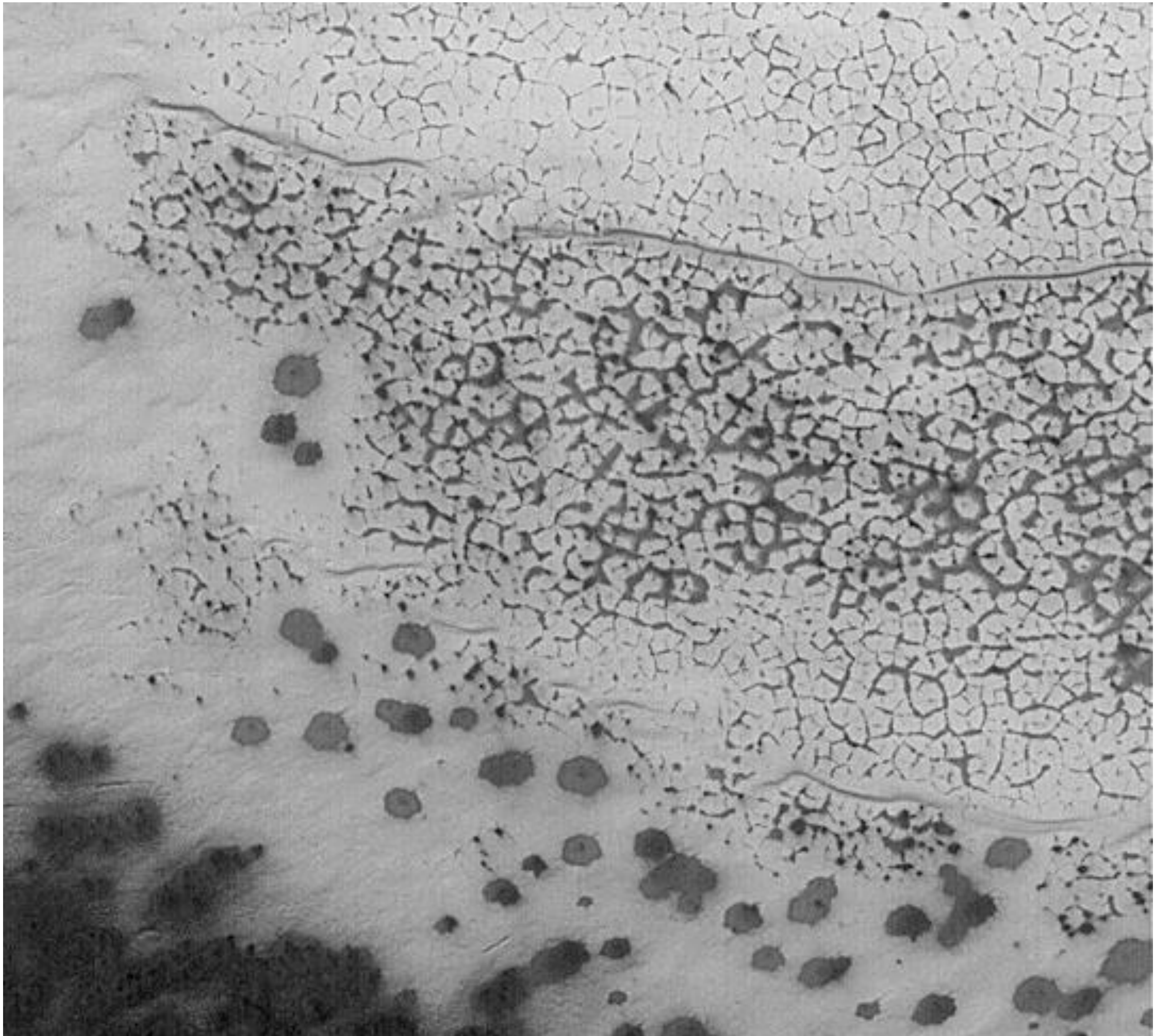
References

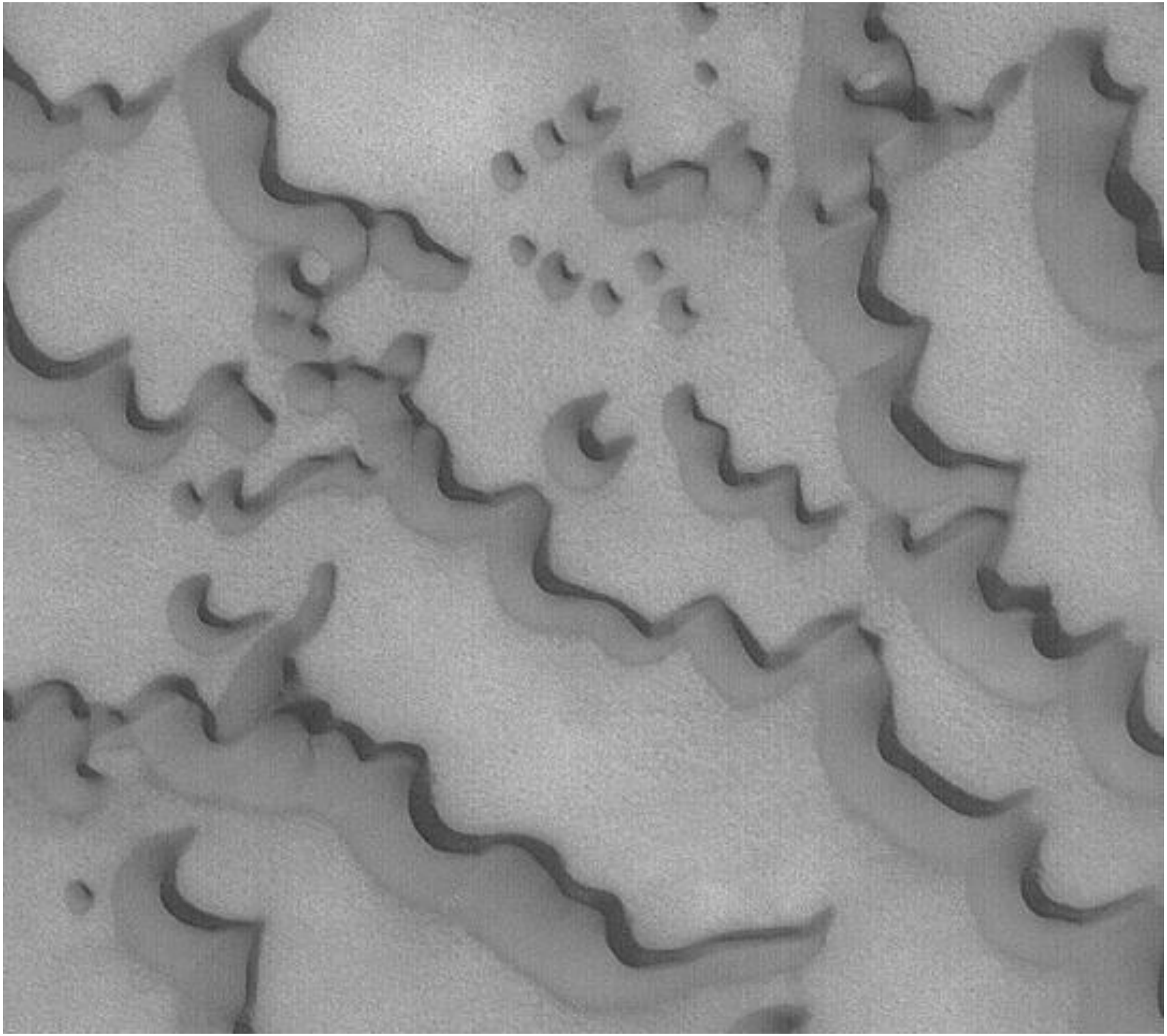
- This presentation is largely based on Chapter 12 of the book "Astrobiology – A Multidisciplinary Approach", by Jonathan I. Lunine, Addison Wesley, 2005

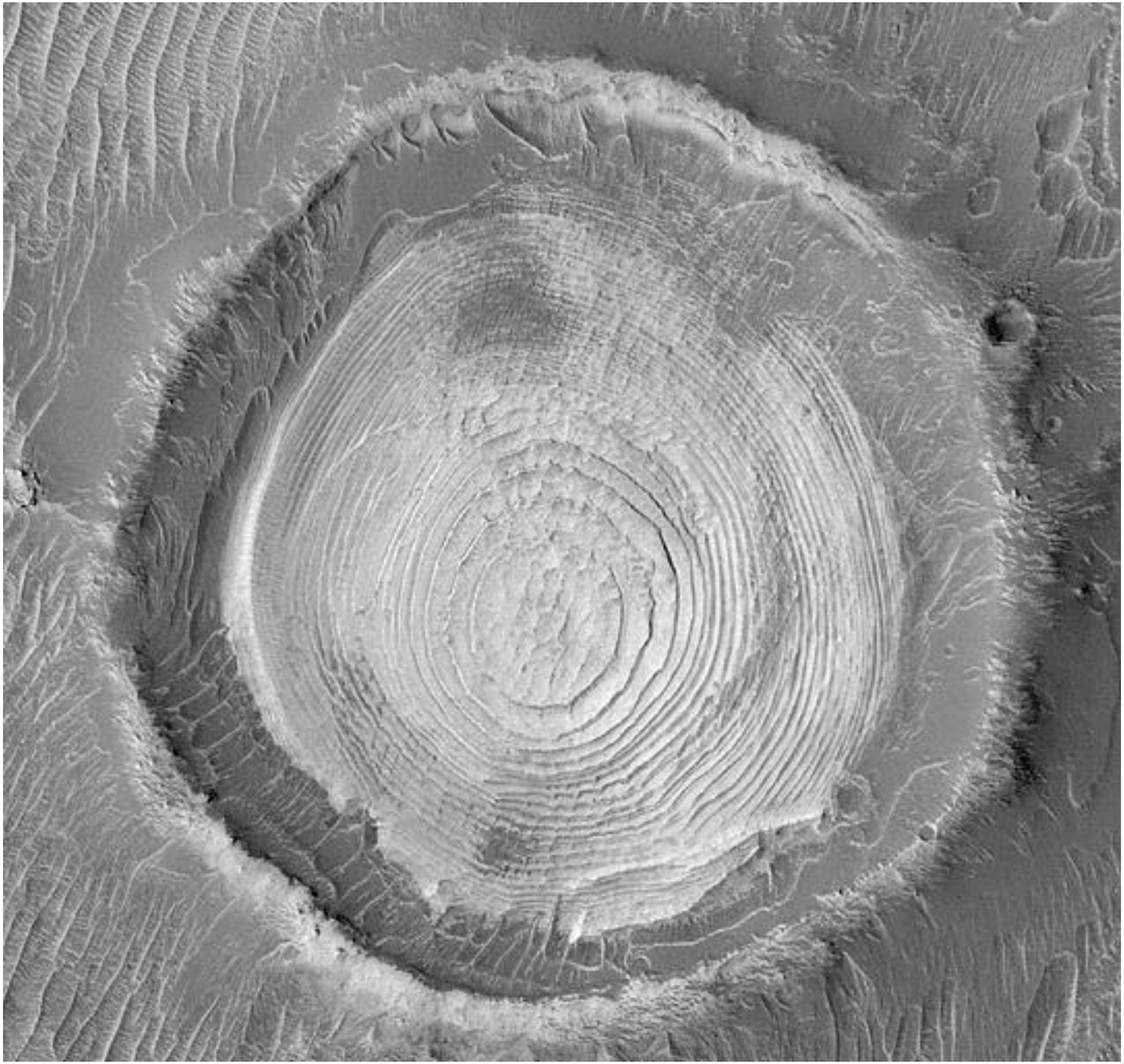
Further reading

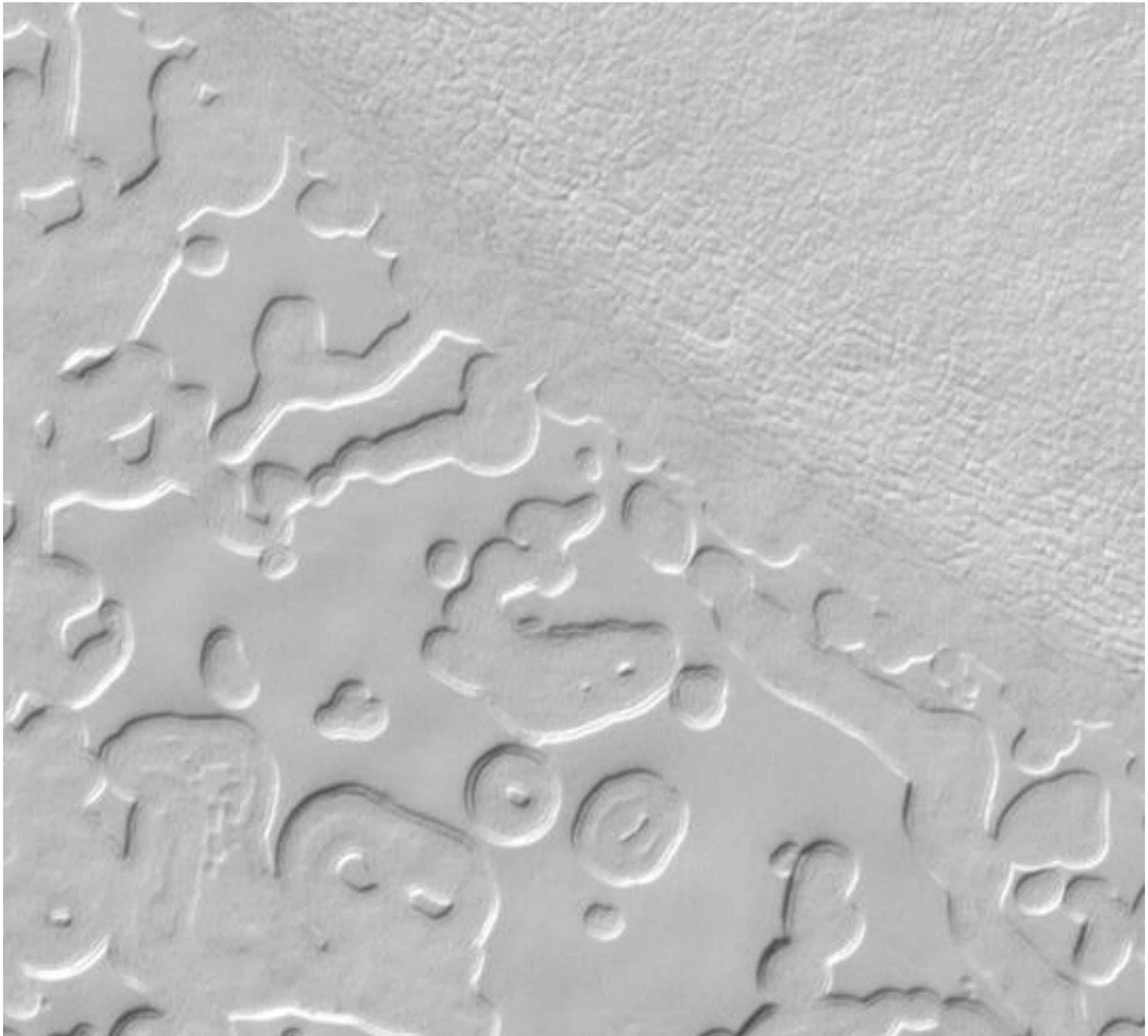
- Des Marais, D. J. et al. 2008. The NASA Astrobiology Roadmap, Astrobiology, Volume 8, Number 4, pages 1-16. Freely available at http://www.geology.wisc.edu/~astrobio/docs/Astrobiology_Roadmap_9AB346.pdf

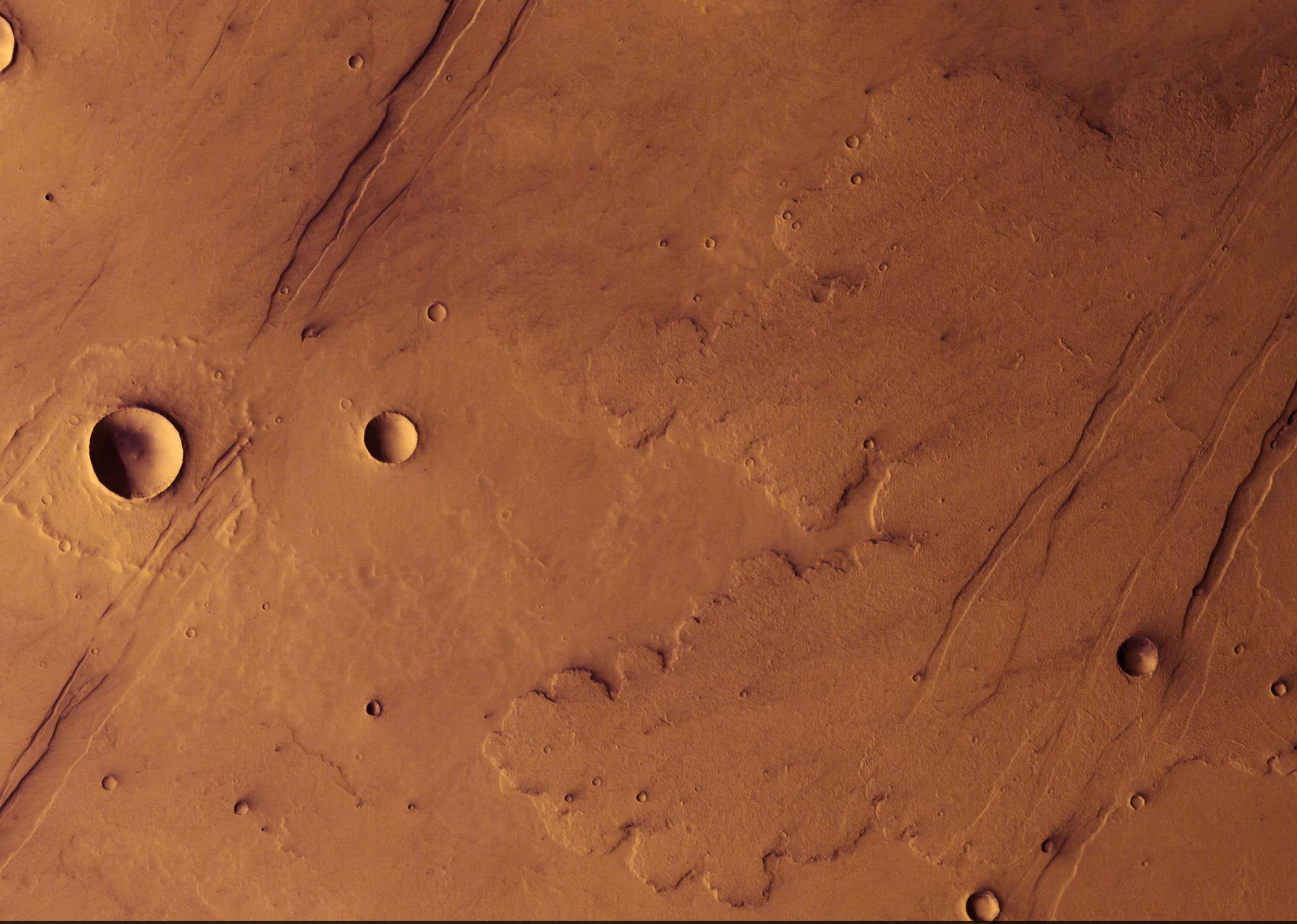
Postcards from Mars







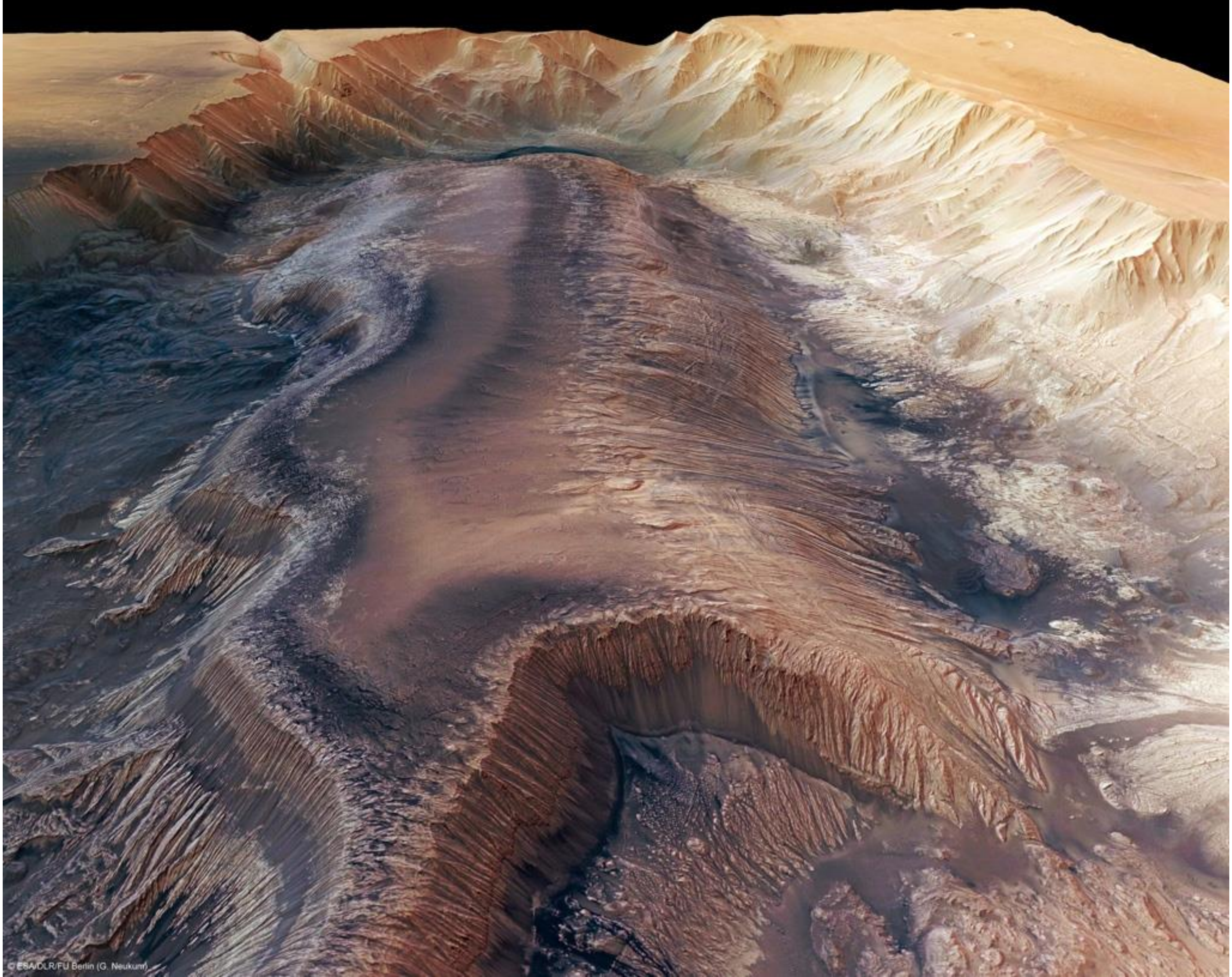


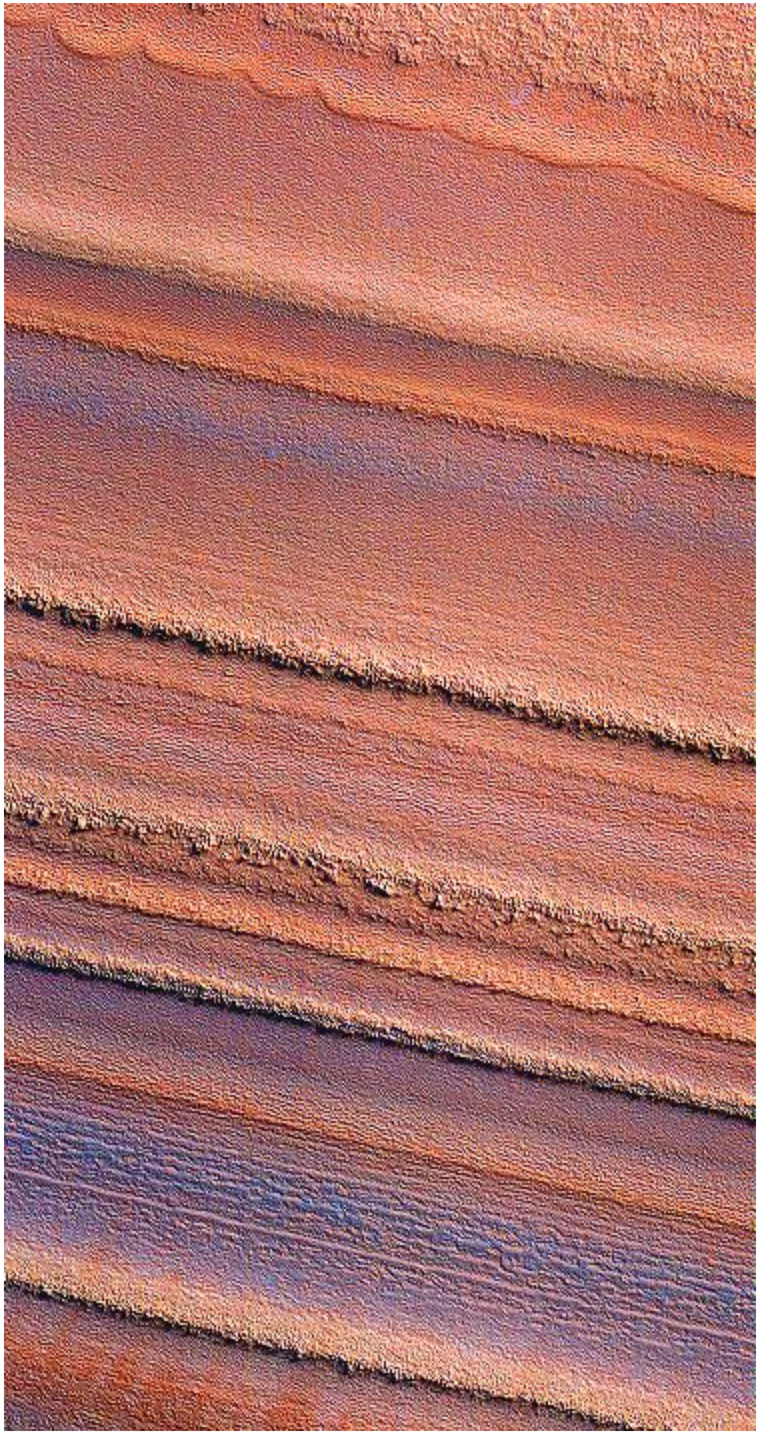


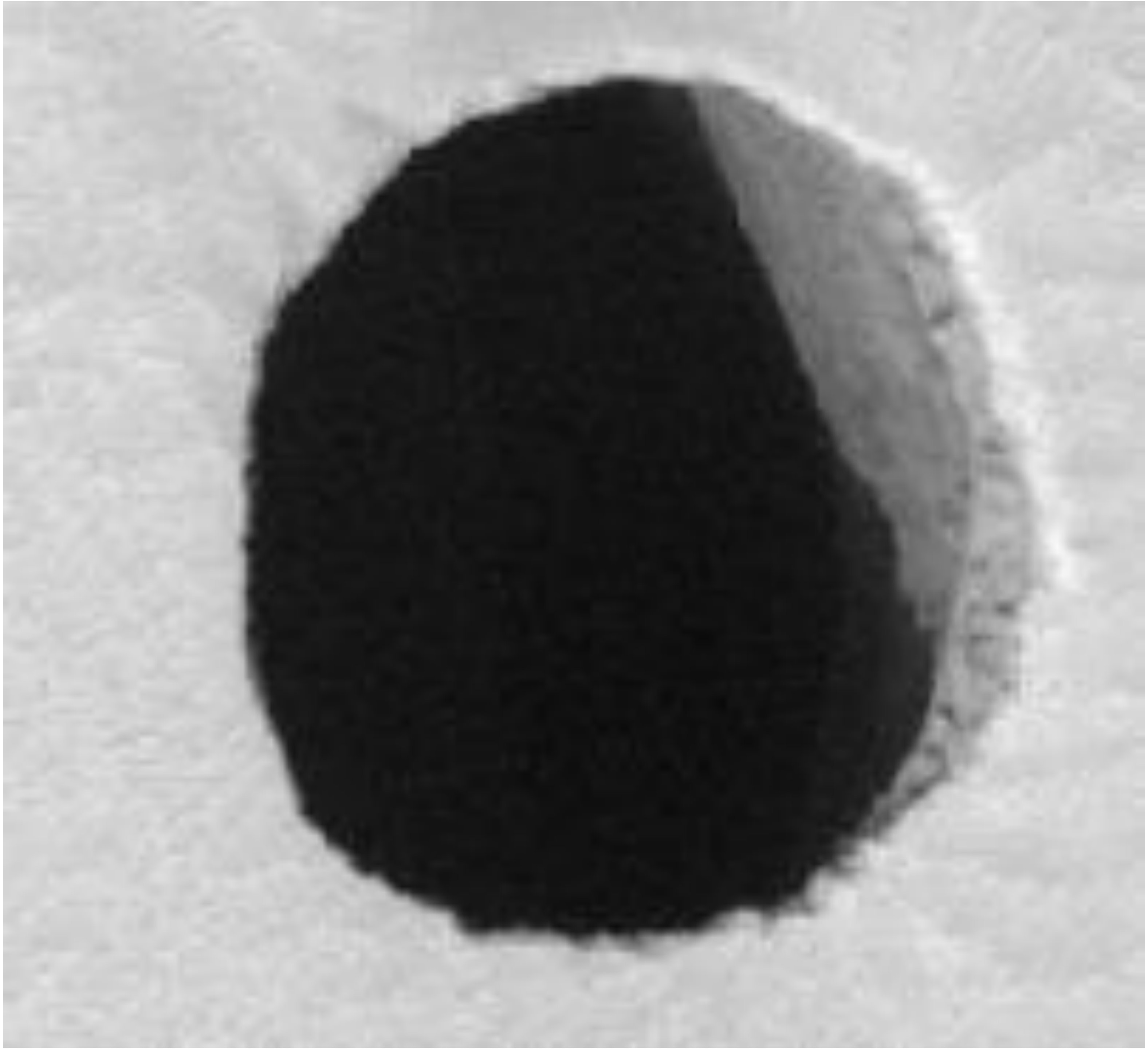
Mars Express High Resolution Stereo Camera in Orbit 1937

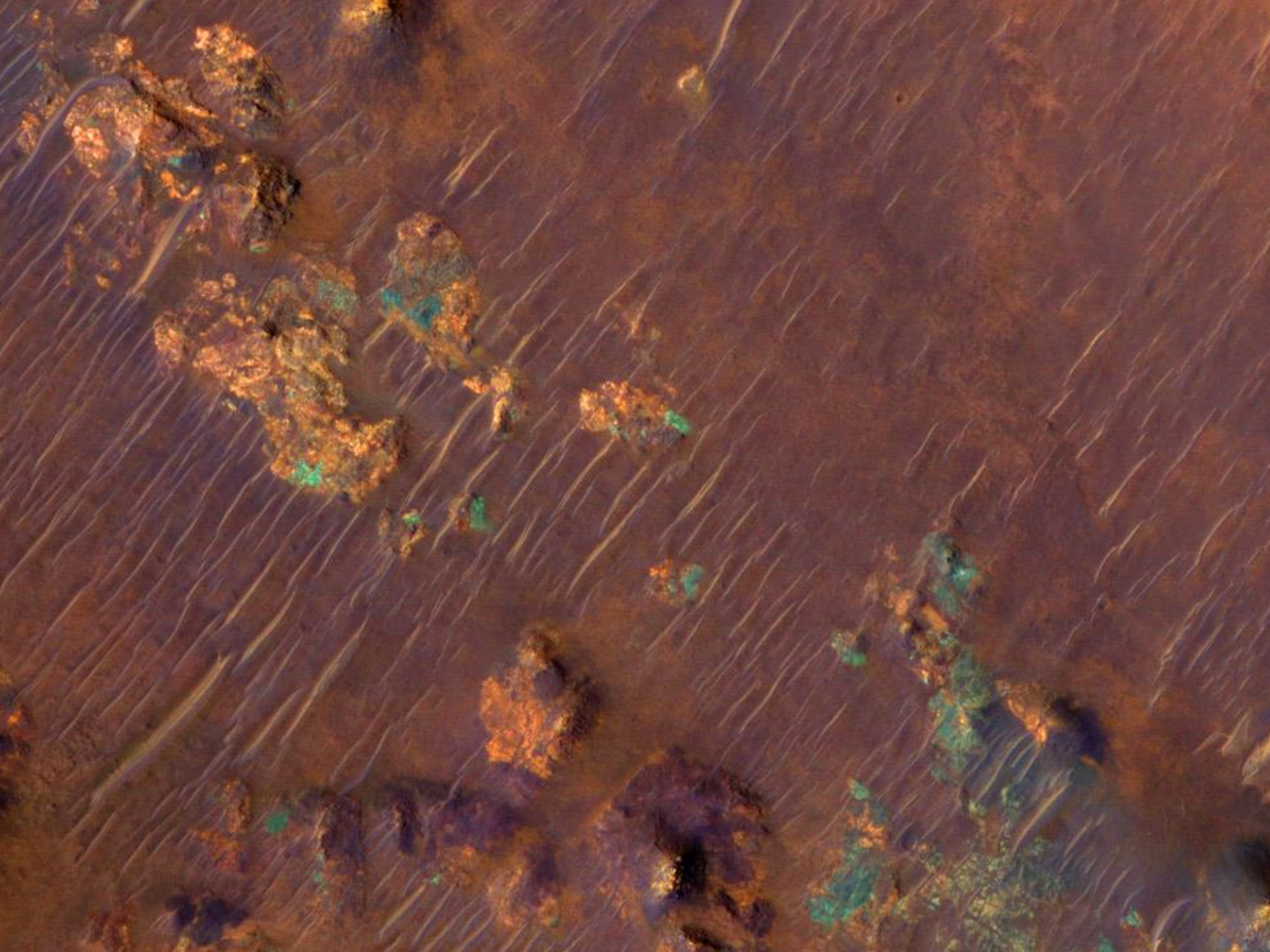
ARSIA MONS LAVA FLOWS

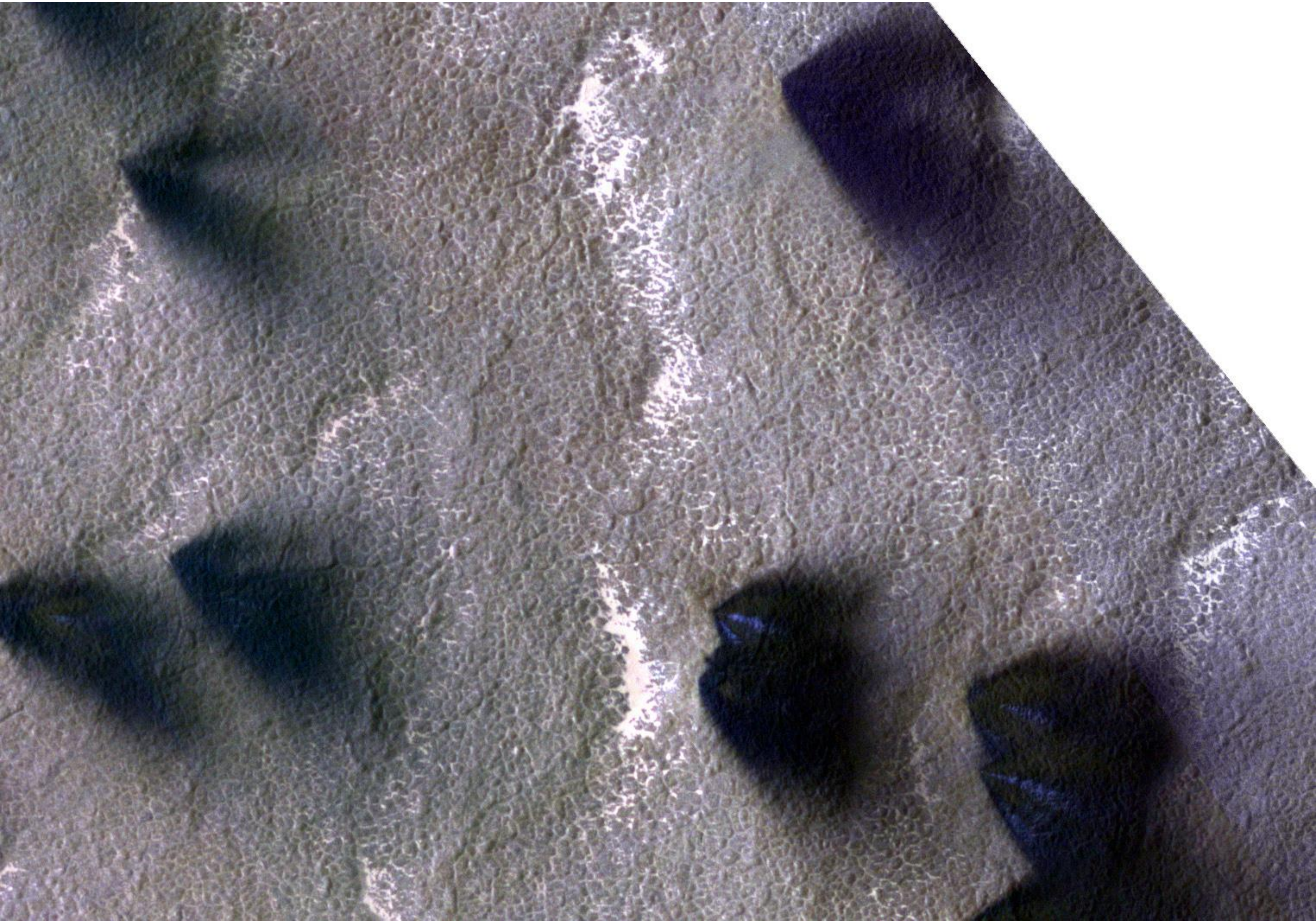
Image Center at 235.4°E, 26.2°S. Image Width: 100 km


© ESA/DLR/FU Berlin (G. Neukum)









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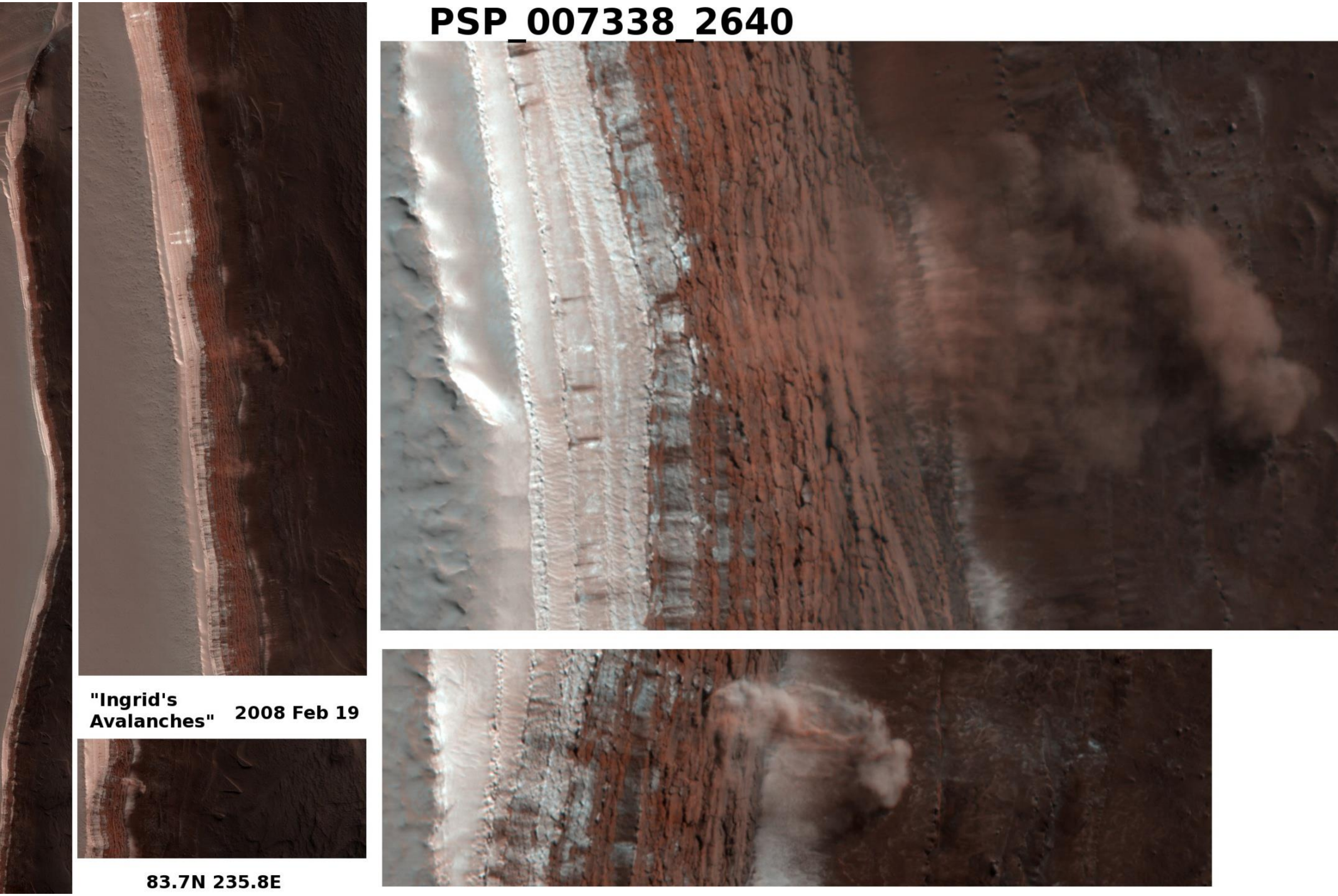

"Ingrid's Avalanches" 2008 Feb 19

83.7N 235.8E