GEOS 22060/ GEOS 32060 / ASTR 45900

What makes a planet habitable?

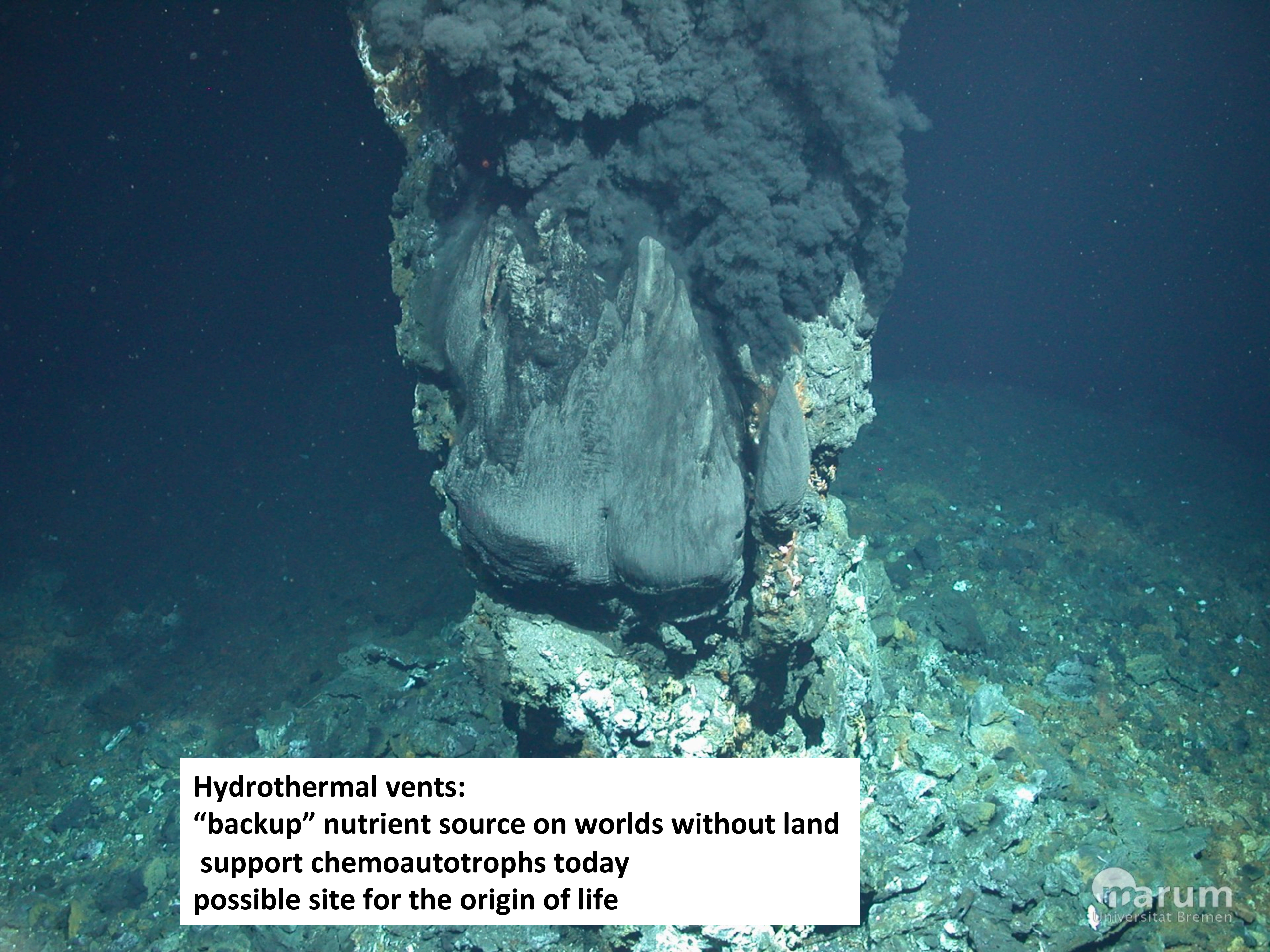
Mars

Lecture 15

Tuesday 21 May 2019

Logistics

- People who have not yet done (or signed-up for) 2 presentations (Adina, Thomas, Aaron, Charlie, Sadhana, Sasha): identify yourselves for presenting either (a) Grotzinger et al. Science 2014 "A habitable fluvio-lacustrine environment at Yellowknife Bay, Gale Crater, Mars" (next Tue) or (b) Spencer & Nimmo Annual Reviews 2014 "Enceladus: An Active Ice World In The Saturn System" (next Thu)



Hydrothermal vents:
“backup” nutrient source on worlds without land
support chemoautotrophs today
possible site for the origin of life

Immediately after the origin of life(?)
Abiotic organic matter for early heterotrophs

Table 7.1 Comparison of various potential sources of organic compounds on Earth around 4.0 Ga.

Source	Organic production: reduced atmosphere ($kg\ yr^{-1}$)	Organic production: neutral atmosphere ($kg\ yr^{-1}$)
Lightning	3×10^9	3×10^7
Ultraviolet light	2×10^{11}	3×10^8
Atmospheric shocks from meteors	1×10^9	3×10^1
Atmospheric shocks from postimpact plumes	2×10^{10}	4×10^2
Interplanetary dust particles	6×10^7	6×10^7
Hydrothermal synthesis	2×10^8	2×10^8

Note: Hydrothermal synthesis data from Shock (1992), all other data from Chyba and Sagan (1992).

Today: 100 Gton C/yr (approx. 2000 Tmol/yr)

K. Konhauser, 'Geomicrobiology,' 2009

Methanogenesis is a possible pre-photosynthetic energy source

$$CO_2 + 4H_2 \Rightarrow CH_4 + 2H_2O$$

Mars: unconfirmed reports of unknown amounts of atmospheric CH4

ExoMars TGO: first science results last month

Early photosynthesis was limited by the availability of reductants

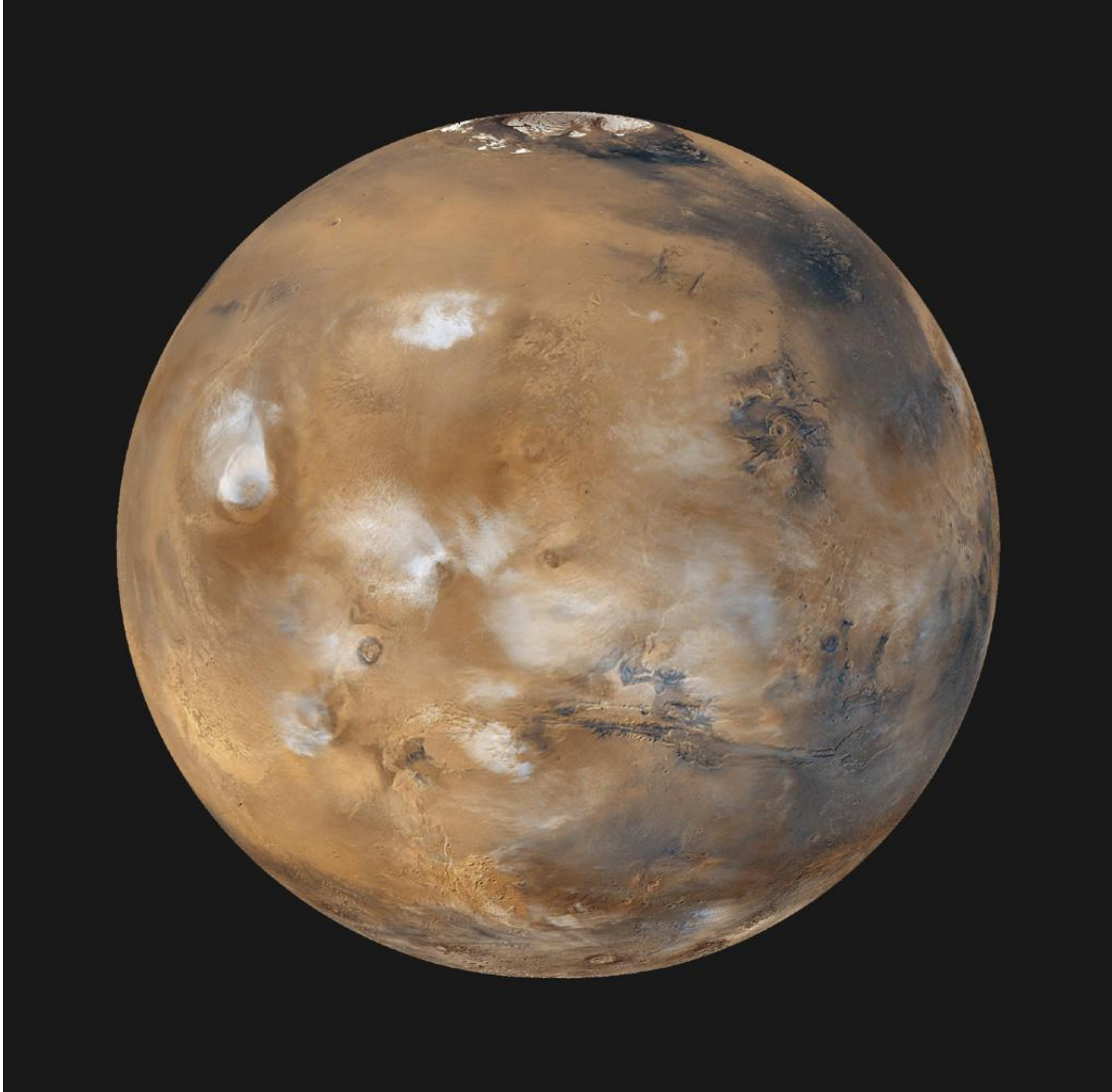
e.g. Fe^{2+} from weathering, sulfides (S^{2-}) from hydrothermal vents …

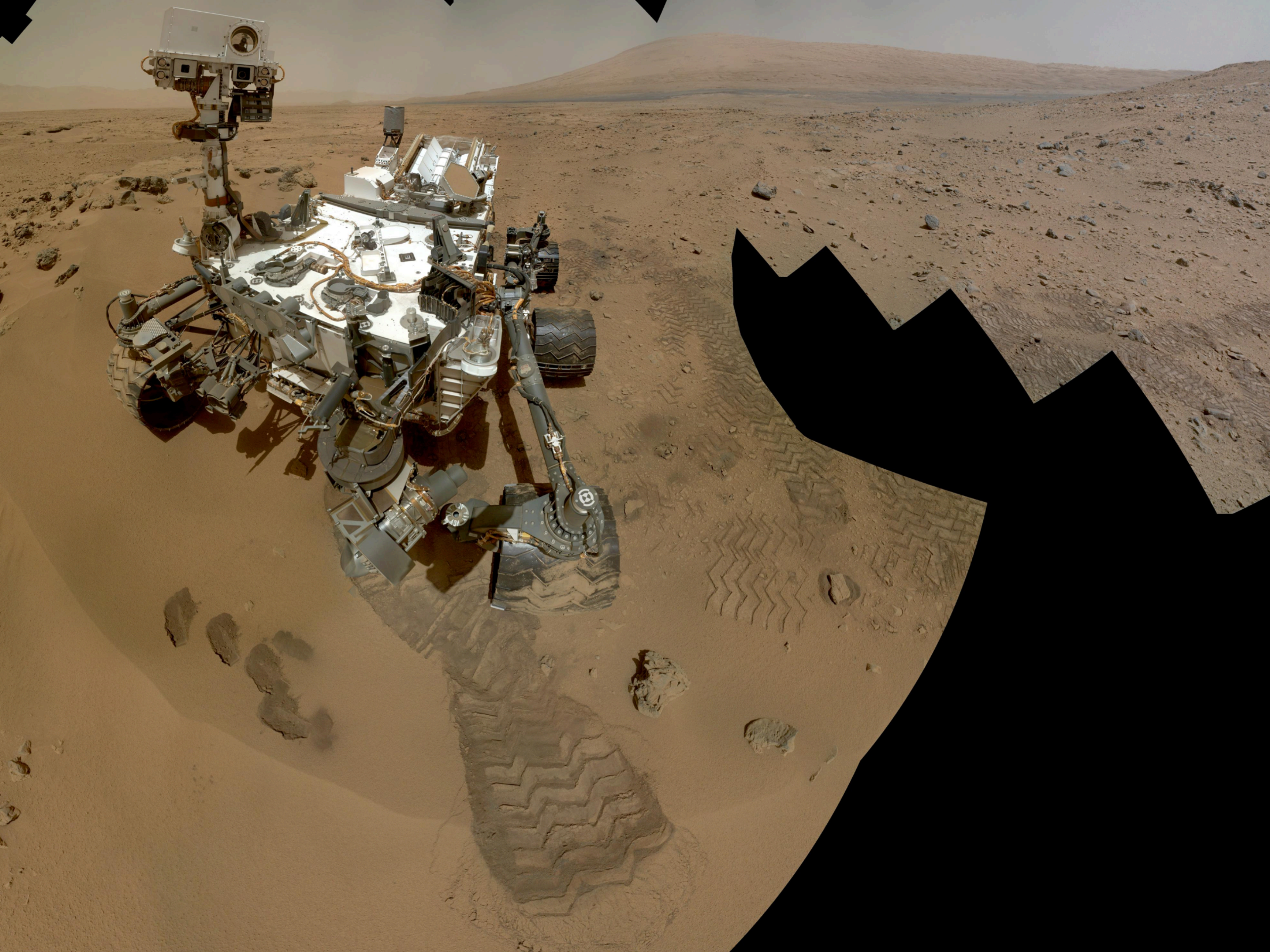
Reduction of H_2O would be ideal, but this required a complicated evolutionary innovation that only happened once in Earth history (in an early cyanobacterium) and may have taken 2 Gyr to occur (Fischer et al., Annual Reviews, 2016). Water oxidation requires an oxidant with a potential of +0.8V (2x what is found in any anoxygenic phototroph). Water splitting system is from one clade of prokaryotes, the other photosystem from a separate clade.

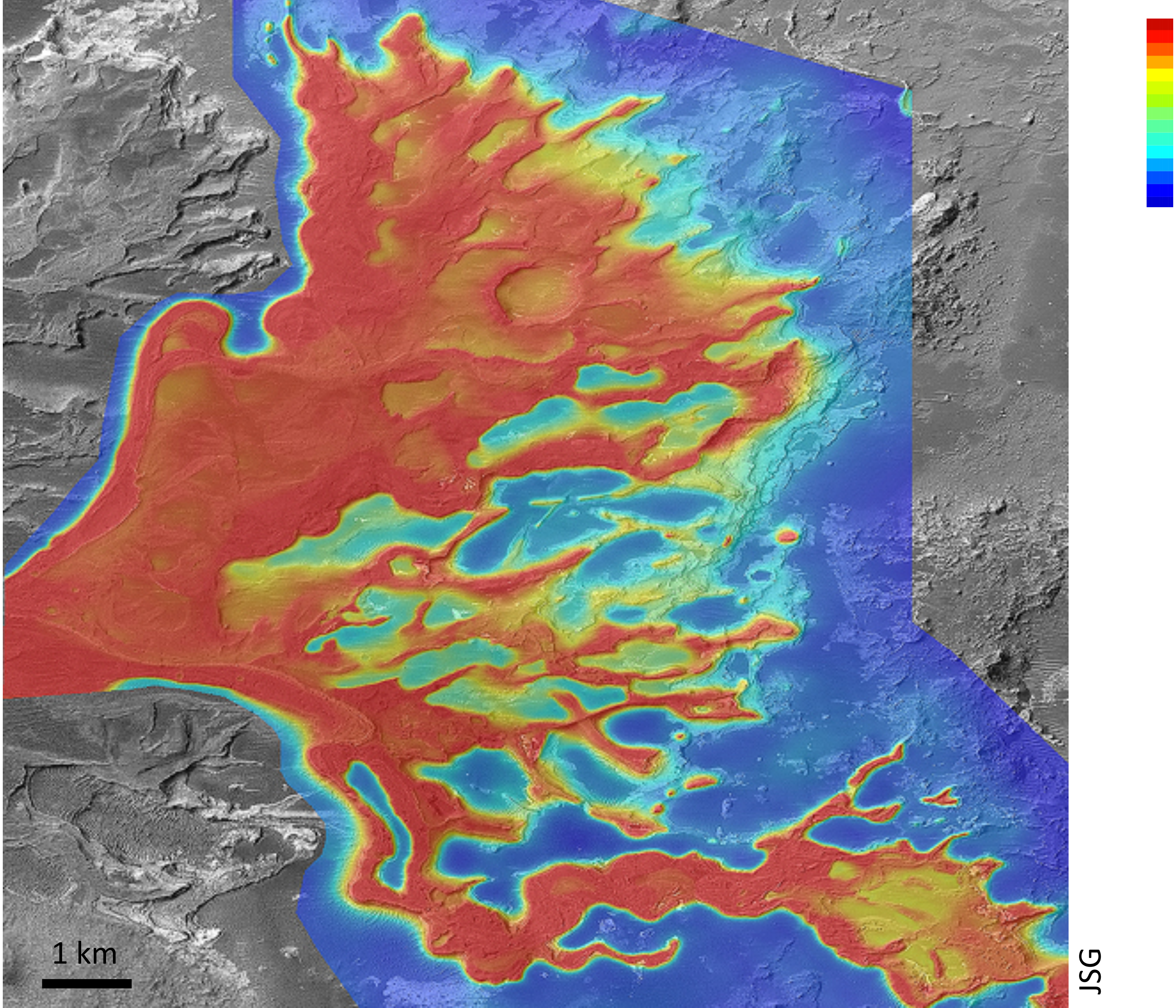
Key points for Lecture 14

- Mechanisms by which biology / organic carbon sequestration might affect long-term climate regulation
- Understand/explain the Daisyworld model
- How ^7Li may be used to track weathering intensity vs. time: examples from the geologic record
- Discuss nutrient limitation on modern Earth; pre-photosynthetic Earth; and Earth when dominated by anoxygenic photosynthesis.

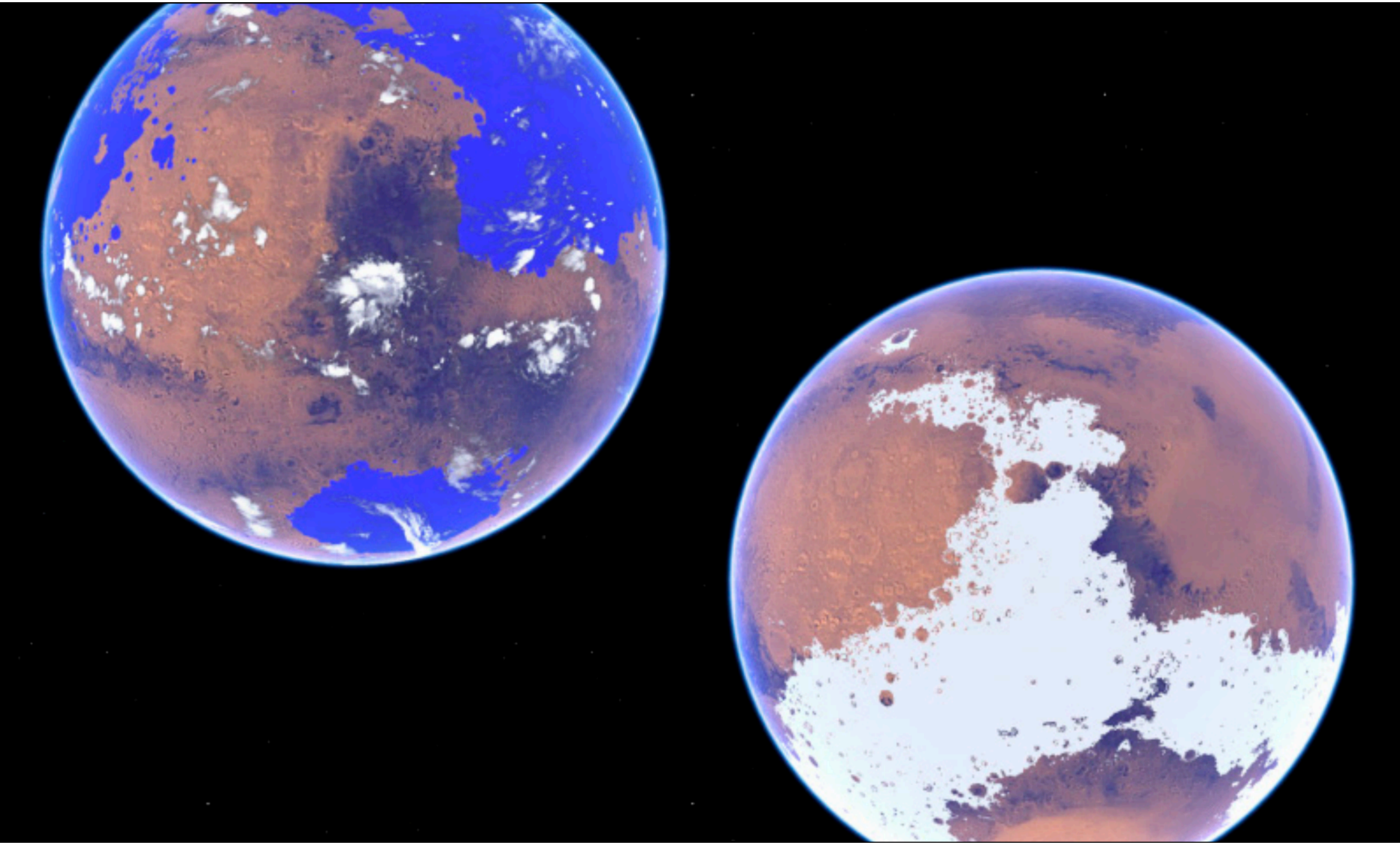
Lecture 15: Mars



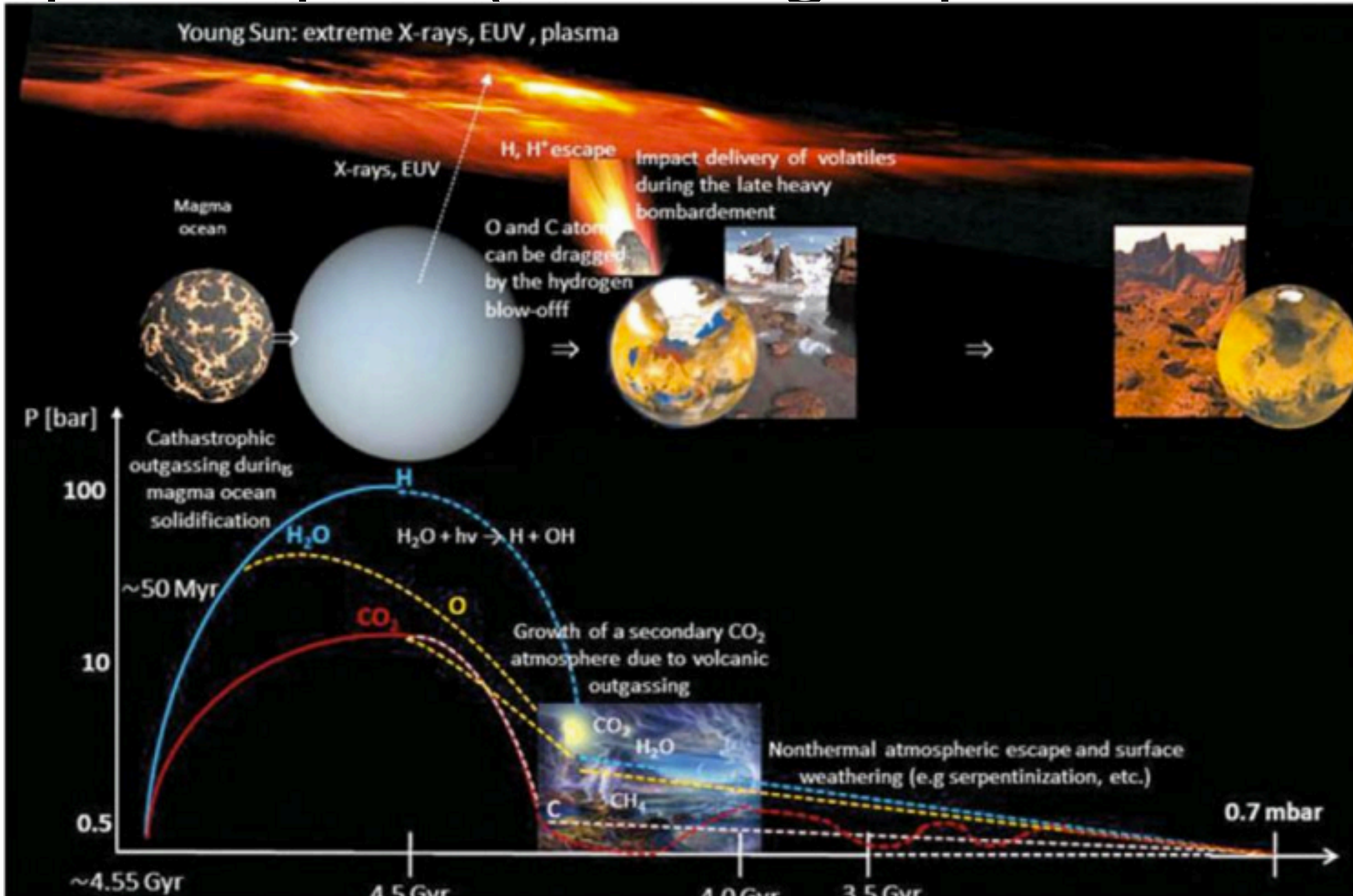



1 km
JSG

(chalkboard)

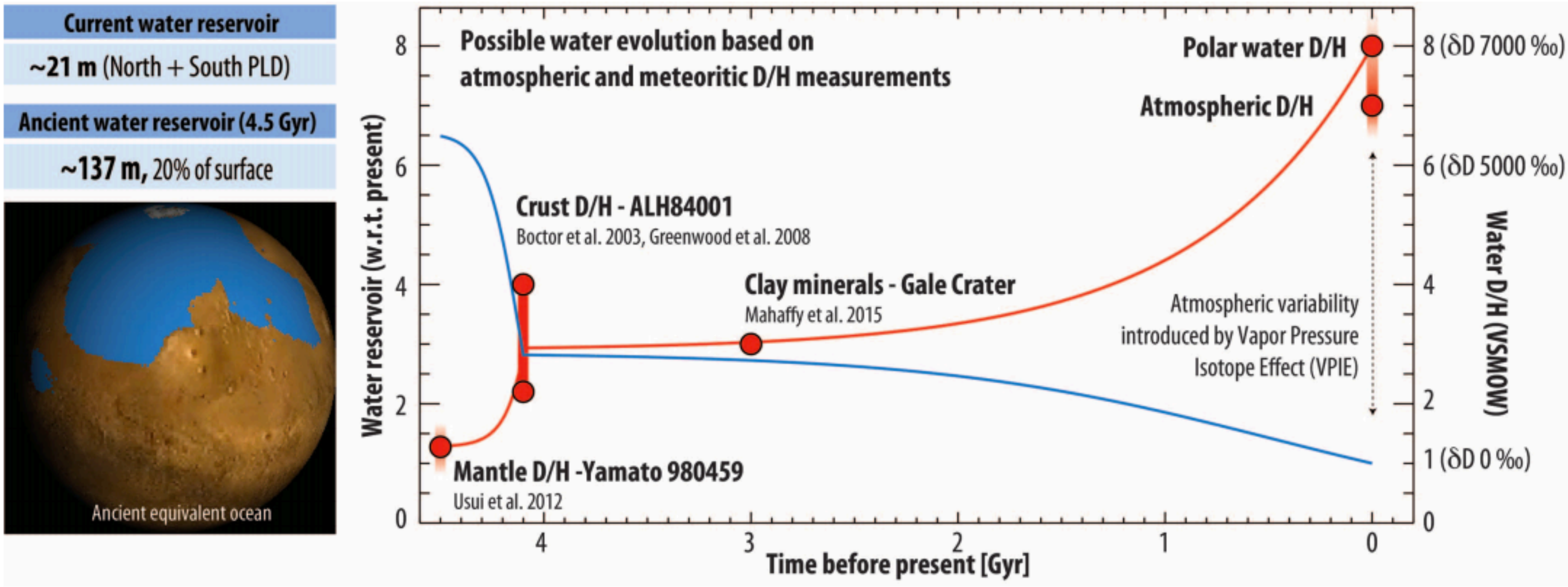


Main drivers of atmospheric decline: escape-to-space (including impact erosion)



Lammer et al., Space Science Reviews, 2013

Evidence for water loss over time



Villaneuva et al., Science 2015

Climate stabilization on early Mars

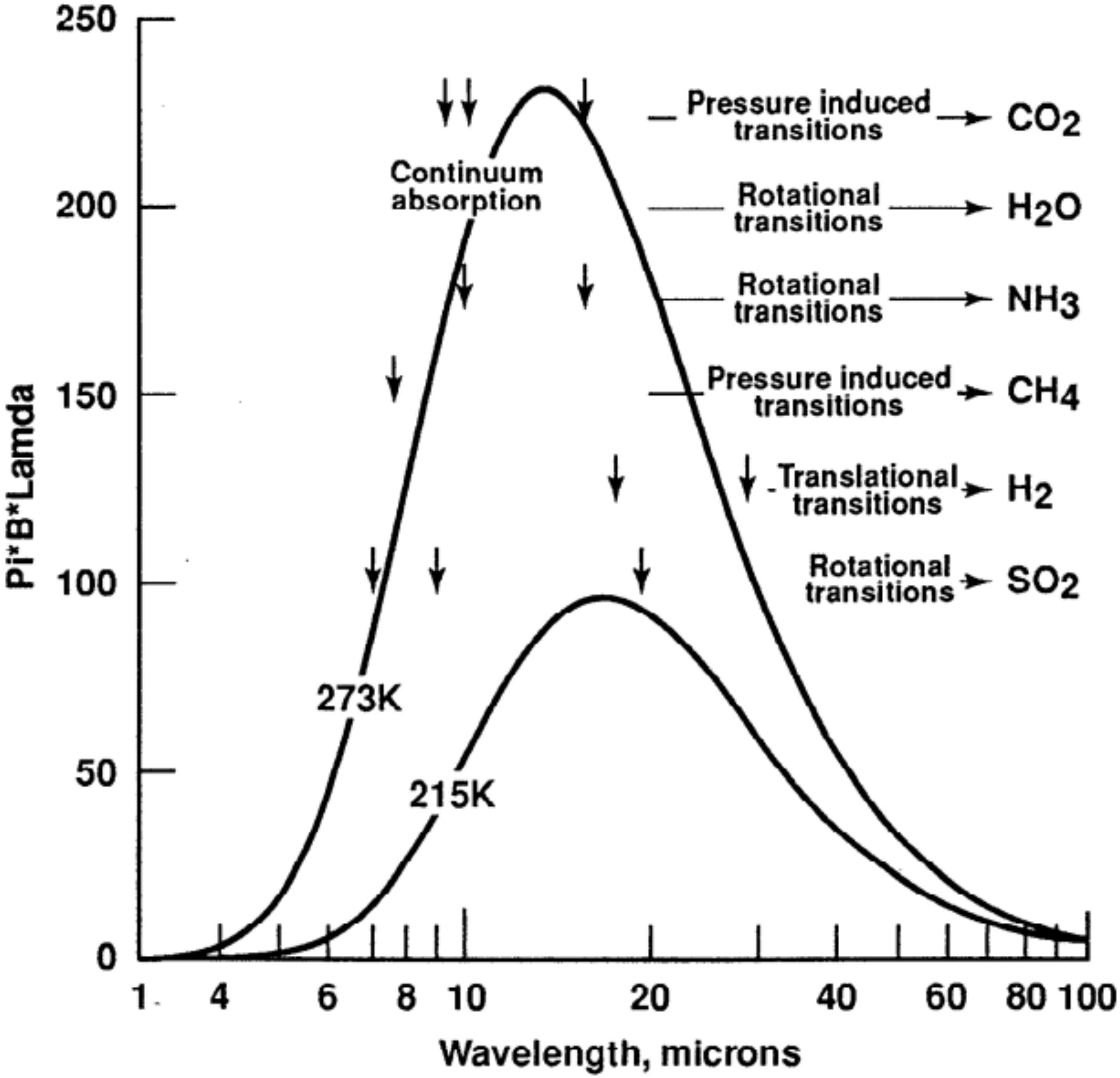
MODERN MARS CLIMATE

CARBON FEEDBACKS?

SULFUR FEEDBACKS?

HYDROGEN?

INTERMITTENCY?



Haberle et al. JGR-Planets 1998

ICARUS 71, 203–224 (1987)

The Case for a Wet, Warm Climate on Early Mars

J. B. POLLACK AND J. F. KASTING

NASA Ames Research Center, Moffett Field, California 94035

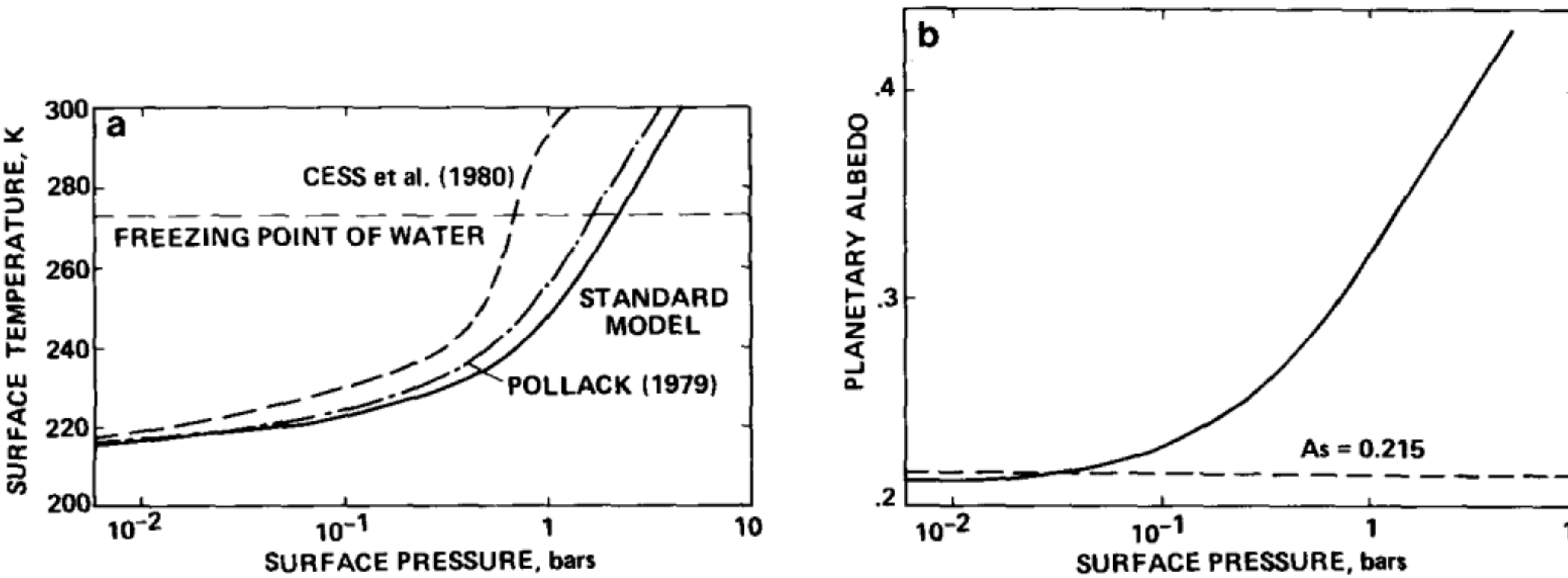


FIG. 1. (a) Surface temperature, T_s, and (b) planetary albedo, A_p, of Mars as the function of the surface pressure of CO_2 for the present surface albedo and globally and orbitally averaged solar flux. In (a), the solid curve presents results from this paper, while the other two curves represent results from two earlier calculations.

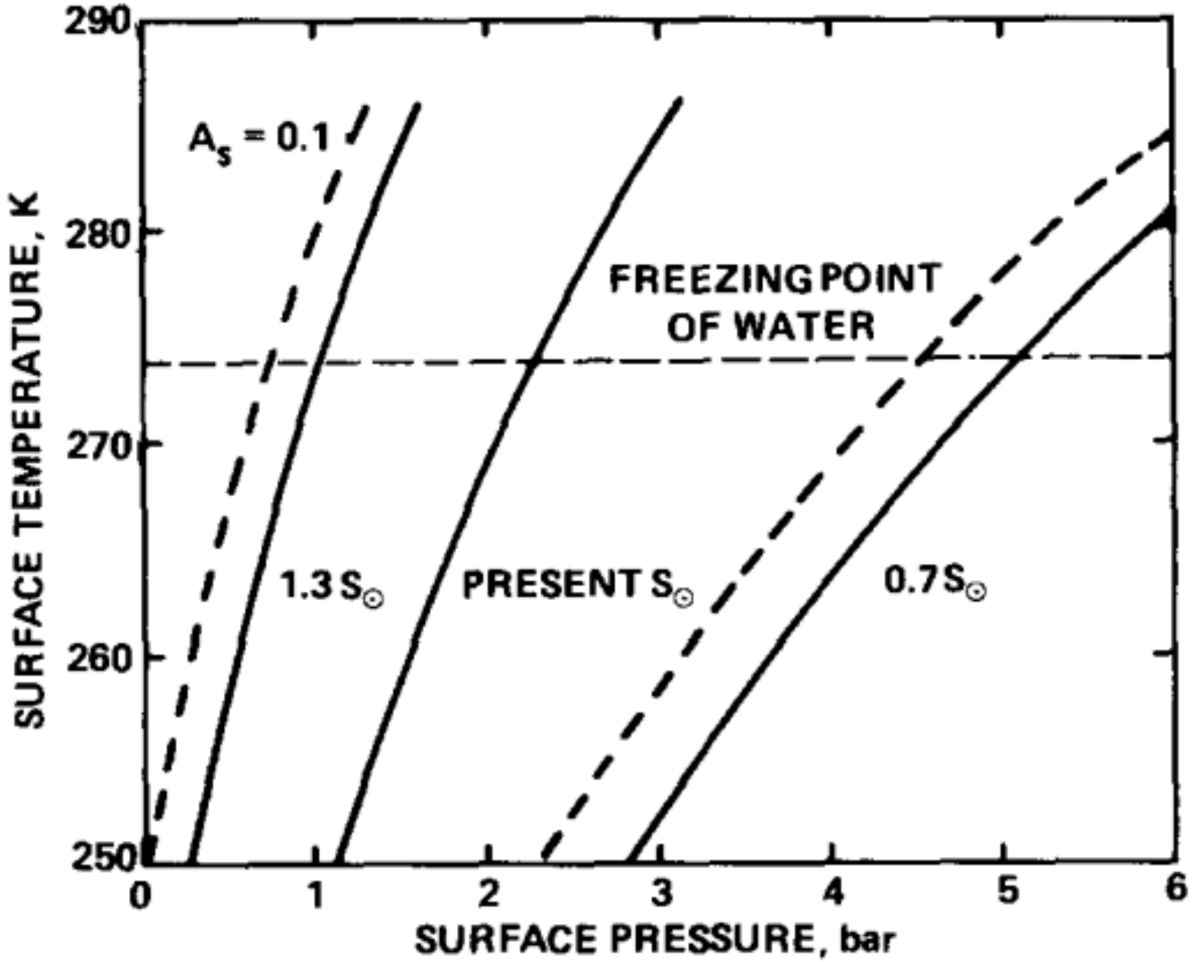


FIG. 2. Surface temperature as a function of surface pressure for several values of the surface albedo and incident solar flux, S. Solid lines refer to results for the current globally averaged albedo of 0.215. $S = 1$ for the present globally and orbitally averaged solar flux at Mars.

CO_2 condensation limits warming

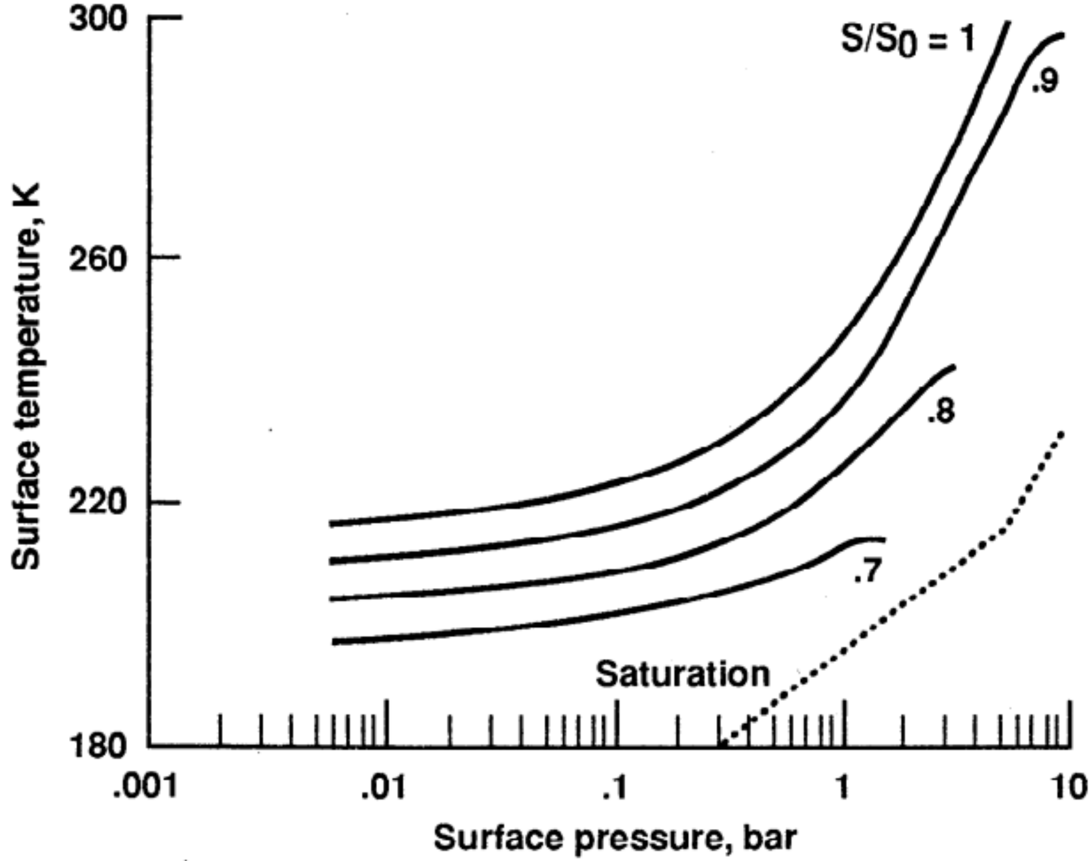


Figure 12. Surface temperature as a function of surface pressure for four different values of the solar luminosity. Dashed line shows the saturation vapor pressure of CO_2. For the 0.7 and 0.8 luminsoity cases, pressures greater than the maximum permitted would discontinuously move the curves down to the saturation vapor pressure [from *Kasting*, 1991].

Haberle, JGR-Planets, 1998

Problem #1: where are the carbonates?

Carbonates are expected to form by water-rock reaction if pCO2 was high and pH was not acidic

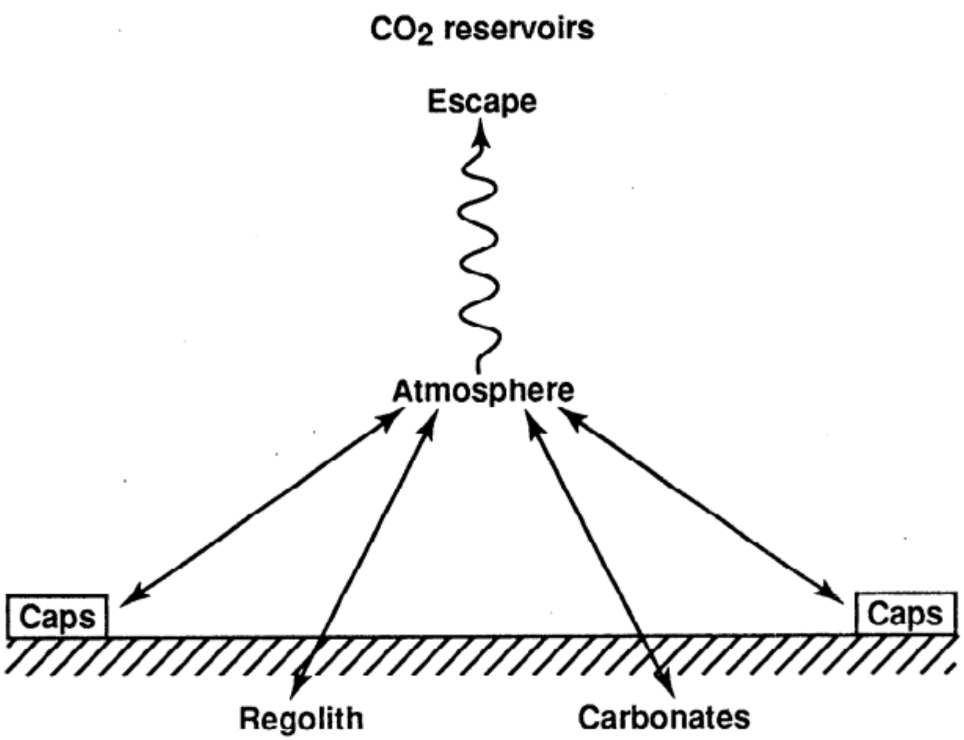
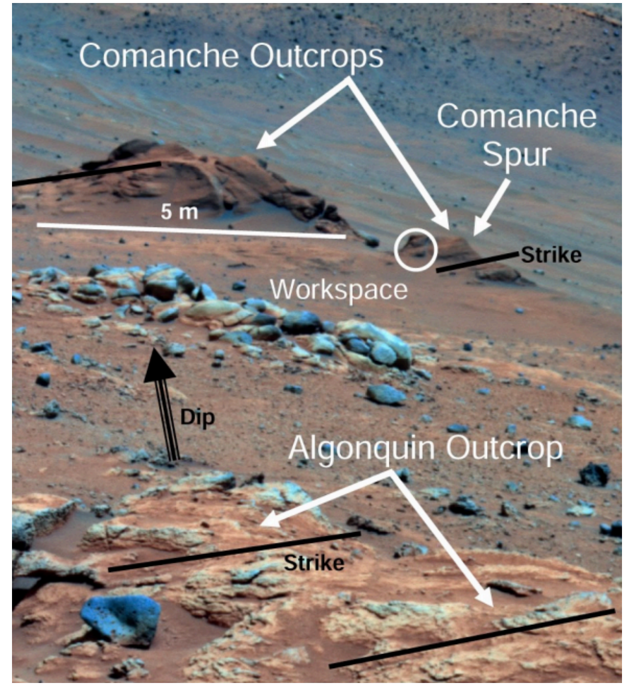
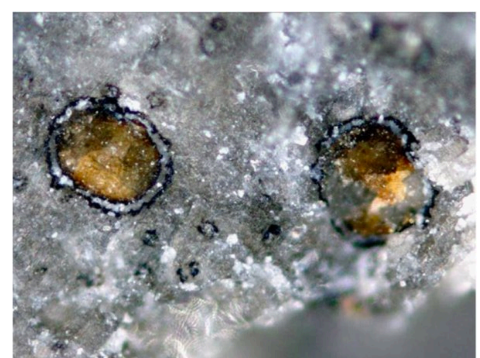


Figure 13. Candidate reservoirs for an carly CO_2 atmosphere.

Haberle, JGR-Planets, 1998



Comanche: 16-34 wt% carbonate (Morris et al., 2010): but such outcrops are rare



Adding up known carbonate reservoirs yields << 1 bar CO_2 equivalent

Insufficient warming from CO2+H2O alone

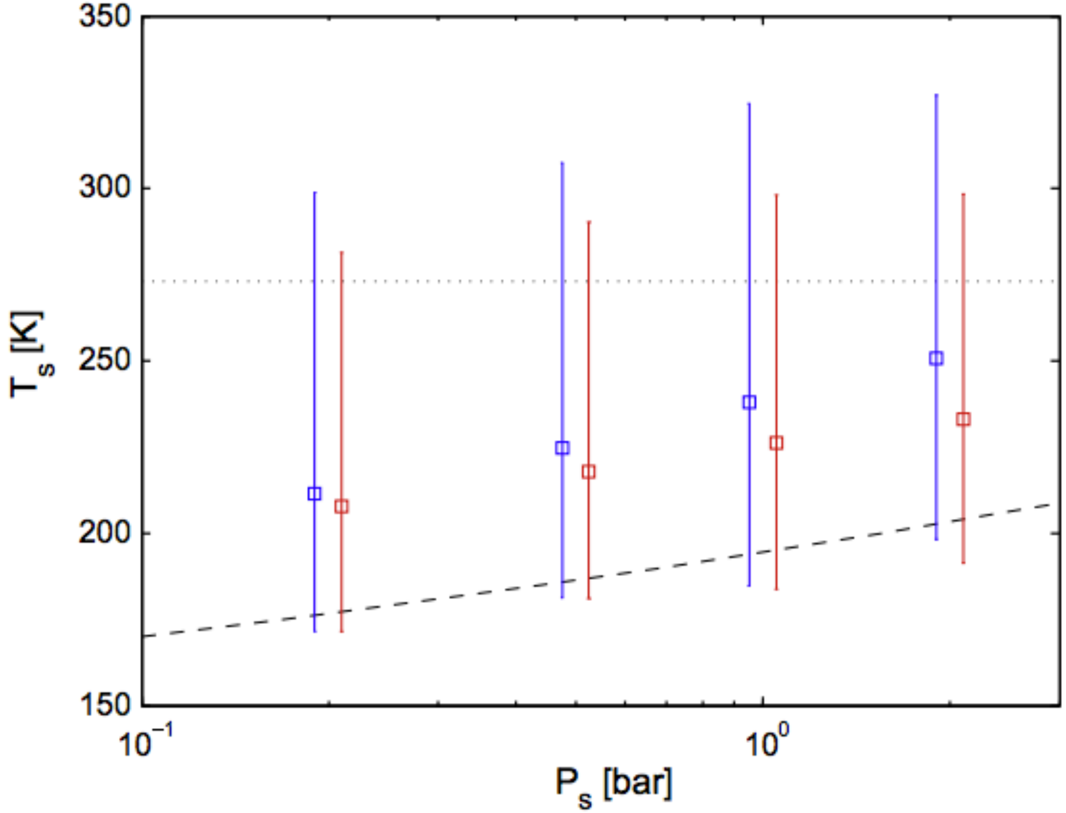
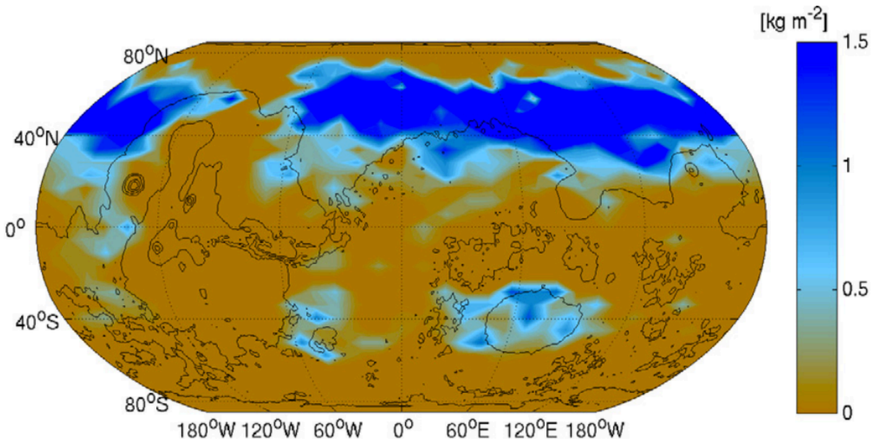


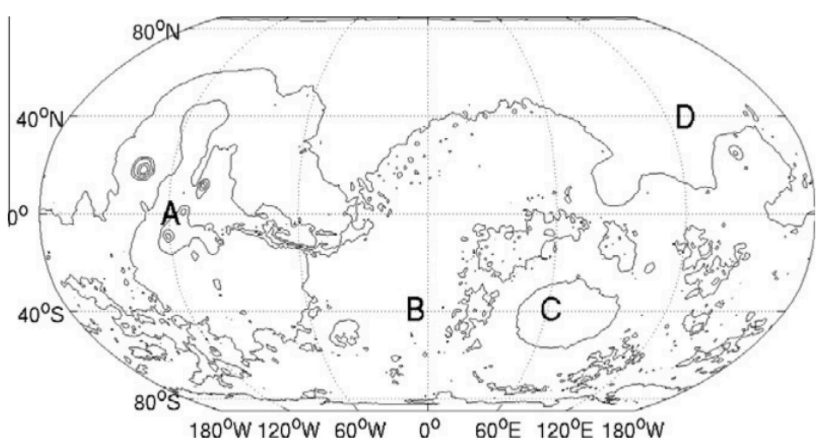
Fig. 2. Effects of atmospheric CO_2 and H_2O on global temperature. Error bars show mean and maximum/minimum surface temperature vs. pressure (sampled over one orbit and across the surface) for dry CO_2 atmospheres (red), and simulations with 100% relative humidity (blue) but no H_2O clouds. Dashed and dotted black lines show the condensation curve of CO_2 and the melting point of H_2O, respectively. For this plot simulations were performed at 0.2, 0.5, 1 and 2 bar; the dry and wet data are slightly separated for clarity only. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

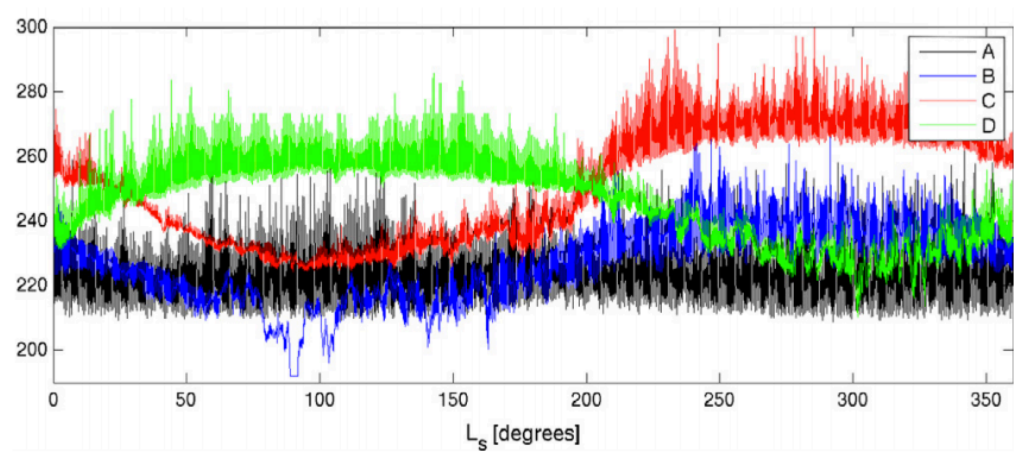
Wordsworth et al. Icarus 2013

Problem #2: how much CO2 is enough?

Wordsworth et al. Icarus 2013







Climate stabilization on early Mars

MODERN MARS CLIMATE

CARBON FEEDBACKS?

SULFUR FEEDBACKS?

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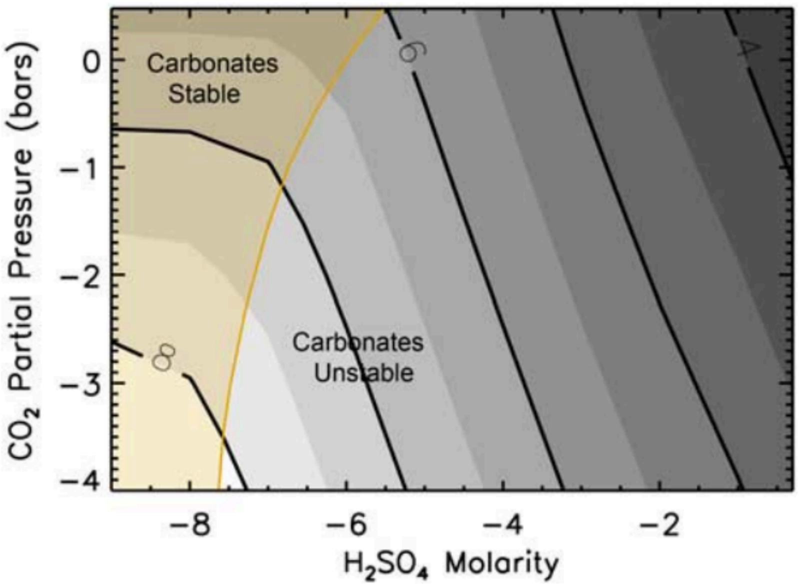
INTERMITTENCY?

SO_2 inhibition of carbonate precipitation?



Bullock & Moore, GRL 2007
(contours = pH)

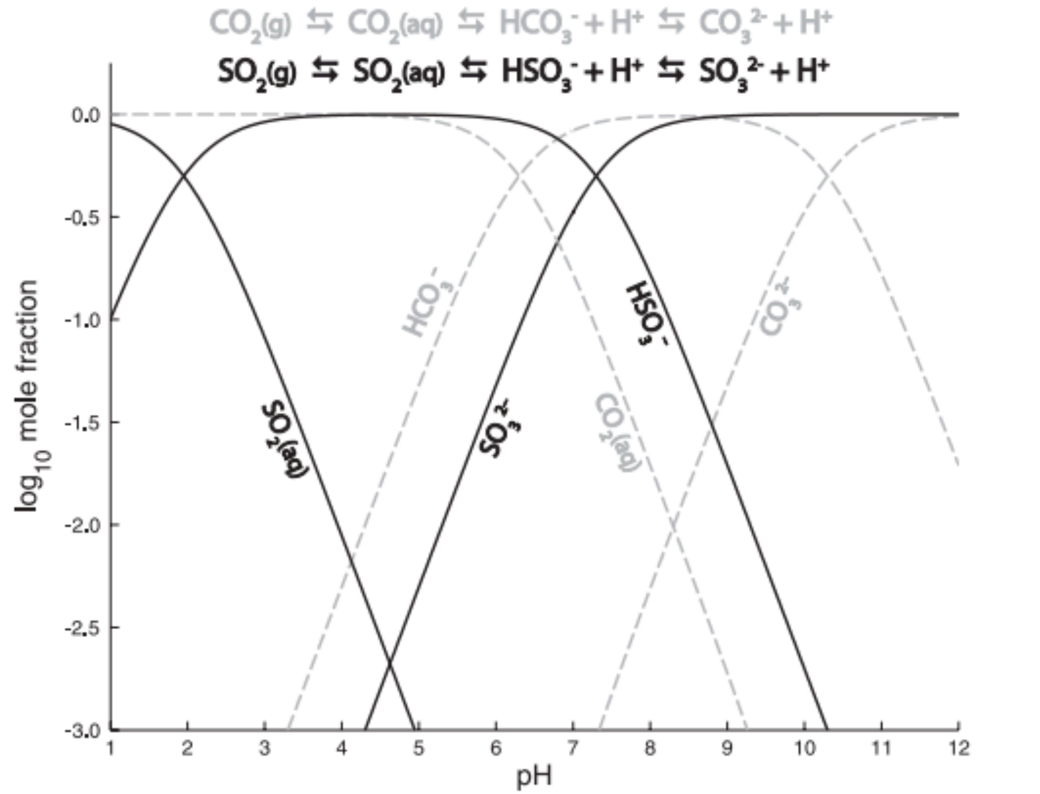
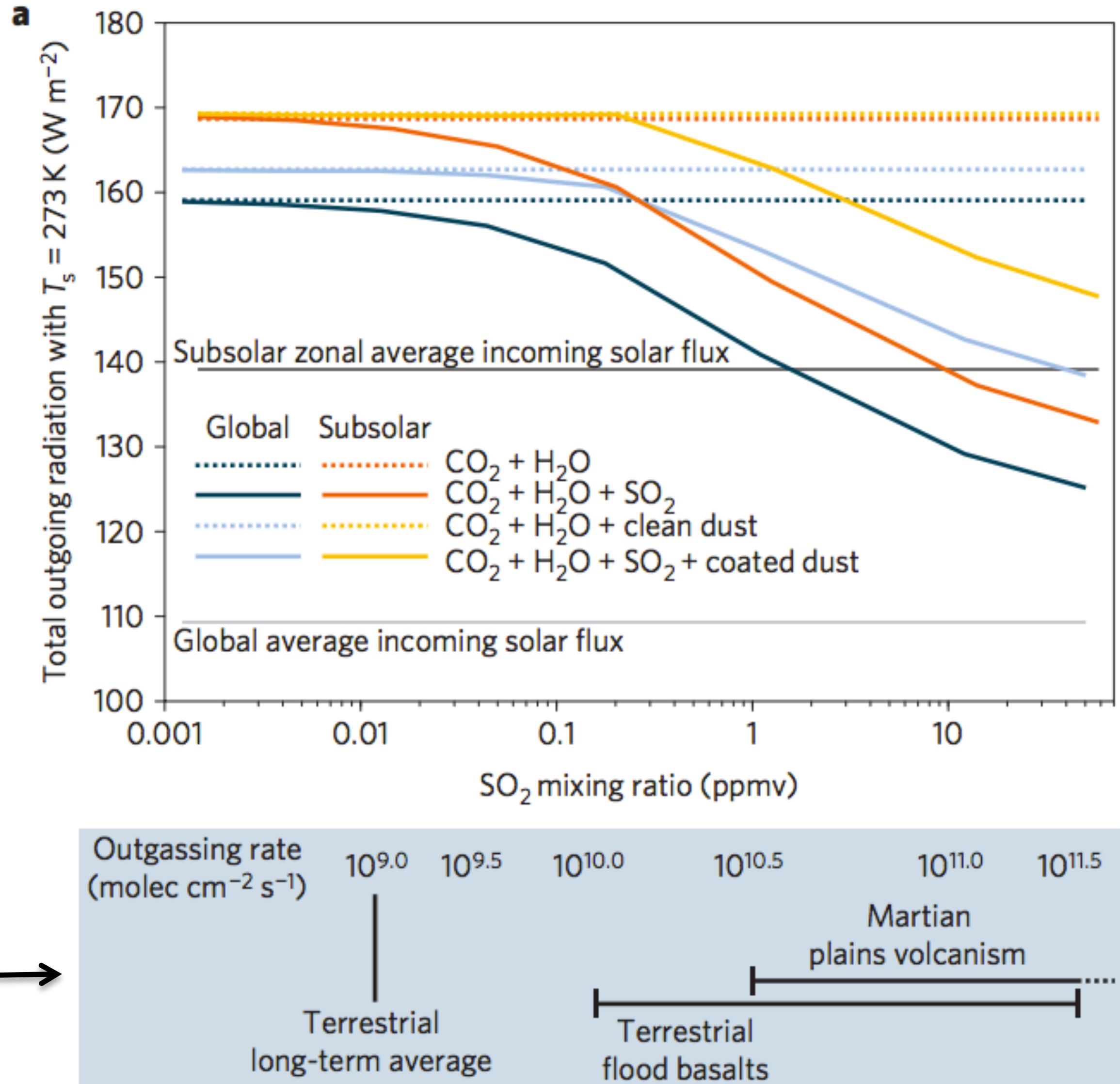


Fig. 1. pH dependence of aqueous S^{4+} (black) and C (gray) speciation, expressed by the chemical equilibrium reactions in the figure. At pH between 2 and 6, most of the S^{4+} is present as HSO_3^- (bisulfite), whereas carbon is predominantly in the form of CO_2 (aq).

Halevy et al. Science 2007

SO_2-driven warming?



fluxes required to maintain these SO_2 concentrations, at steady state

Halevy & Head, Nature Geoscience, 2014

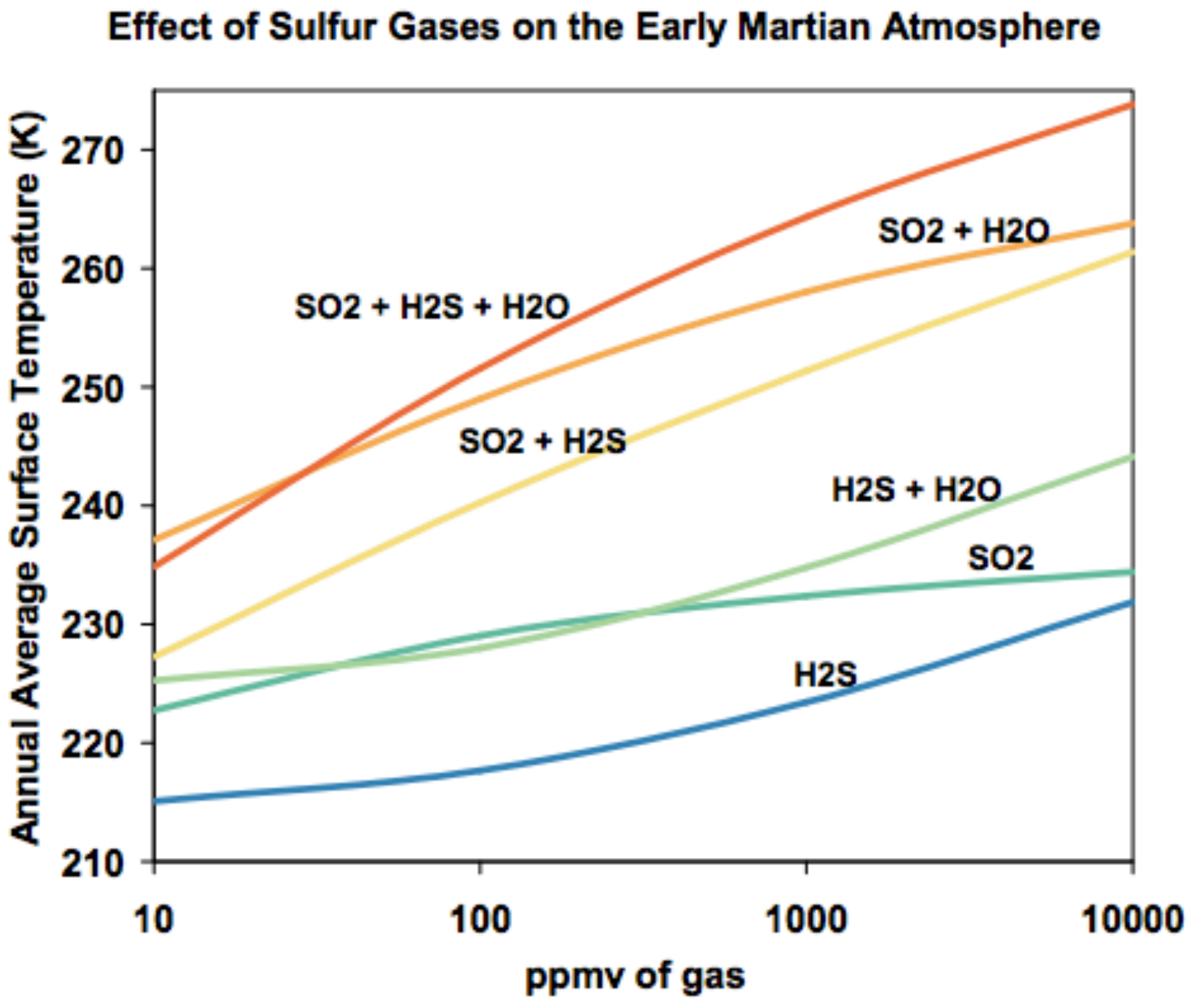
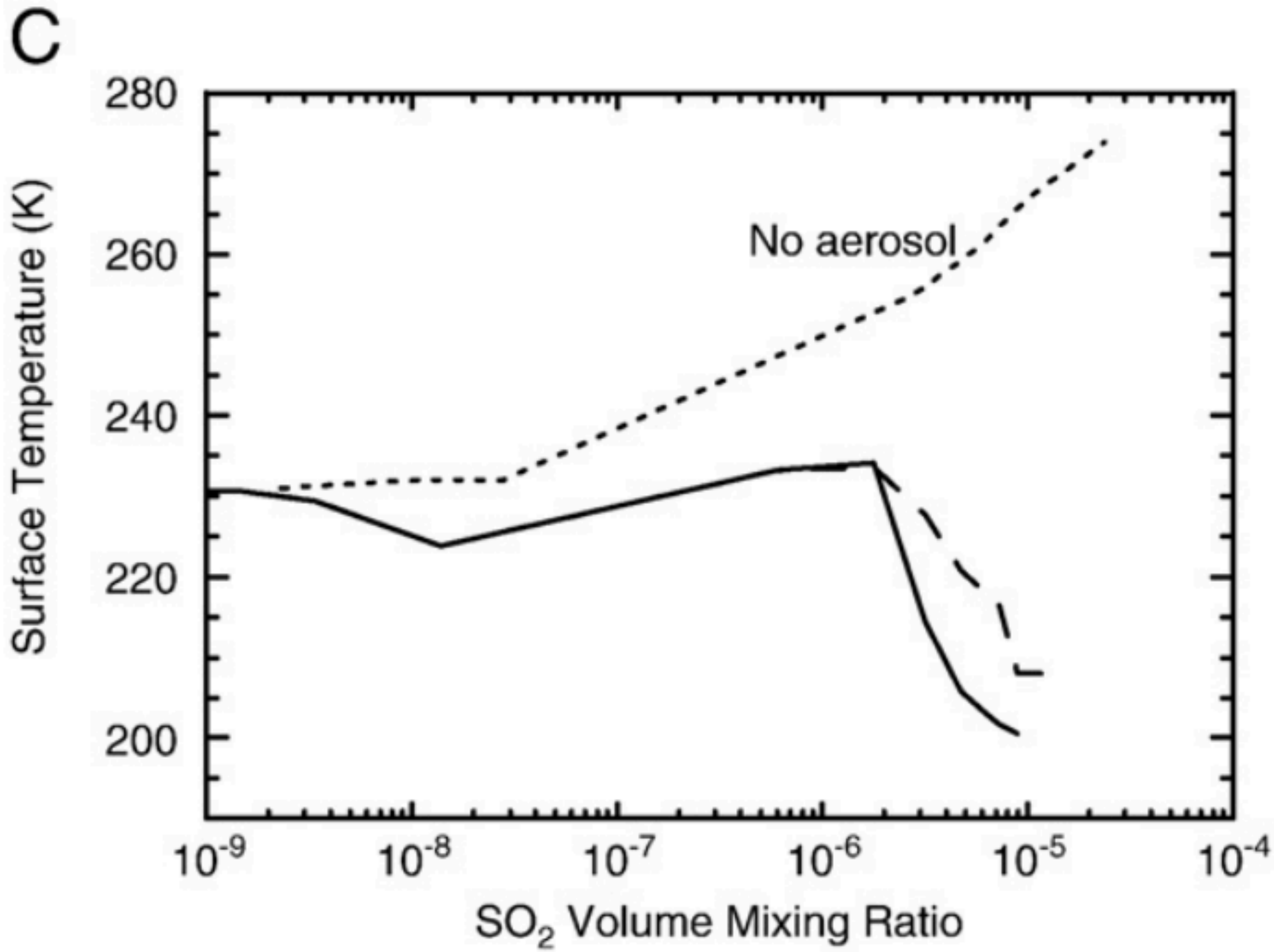


Figure 1.

Even in the cases where large amounts of SO_2 and H_2S are added to the atmosphere, the annual global average surface temperature does not rise above freezing. H_2S provides significantly less warming than SO_2.

Kerber et al.
JGR-Planets
2015

Aerosol formation reduces SO_2 warming



Tian et al. EPSL 2010

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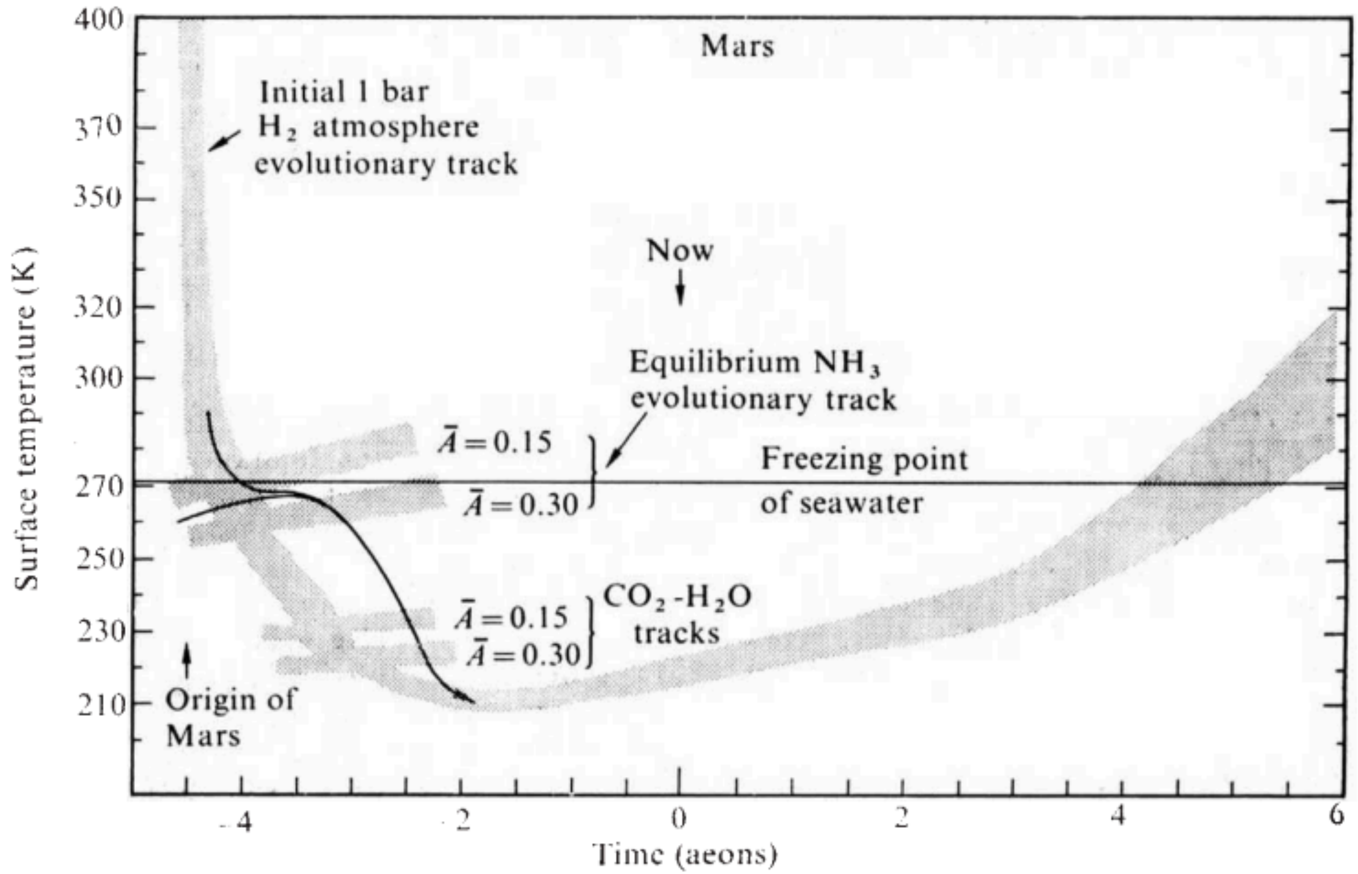
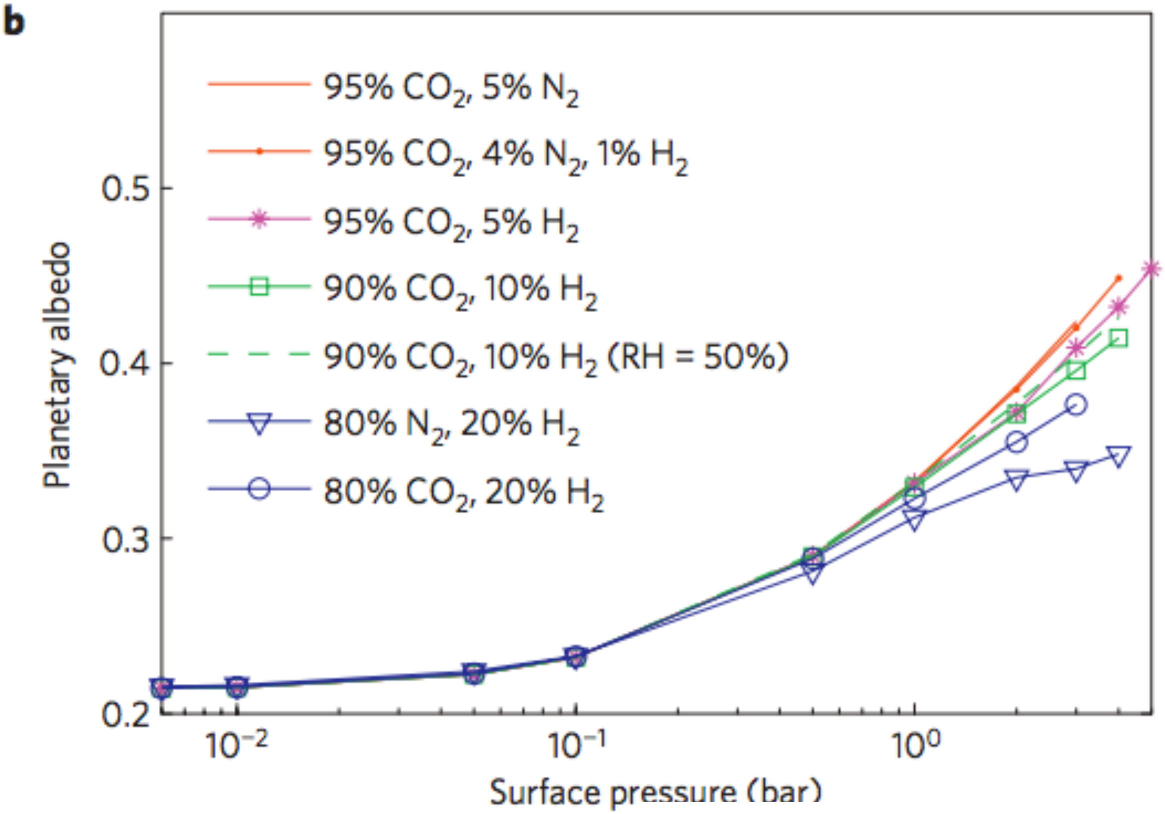
H2 collision-induced absorption

Fig. 2 Evolutionary tracks for the time dependence of surface temperature for Mars for three early compositions and two different bolometric Russell–Bond albedos.

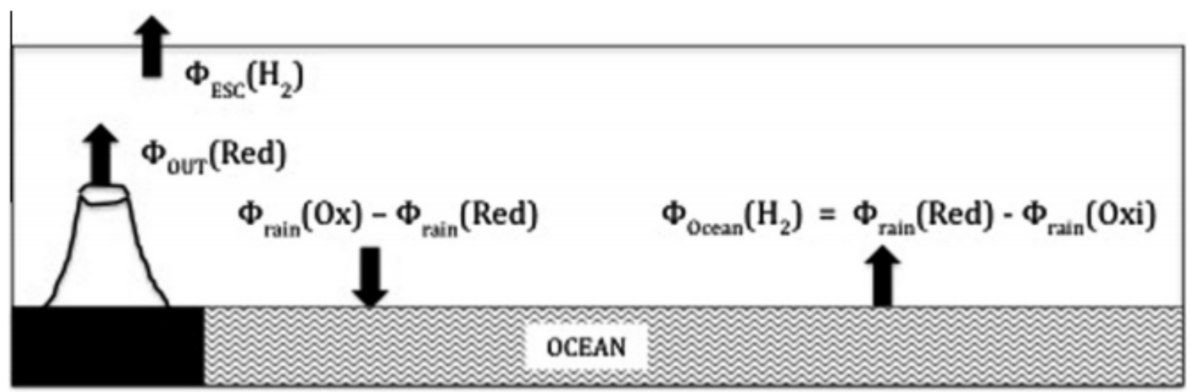


Sagan, Nature, 1977

H_2 collision-induced absorption



Ramirez et al.
Nature Geoscience 2014



Batalha et al. Icarus 2015

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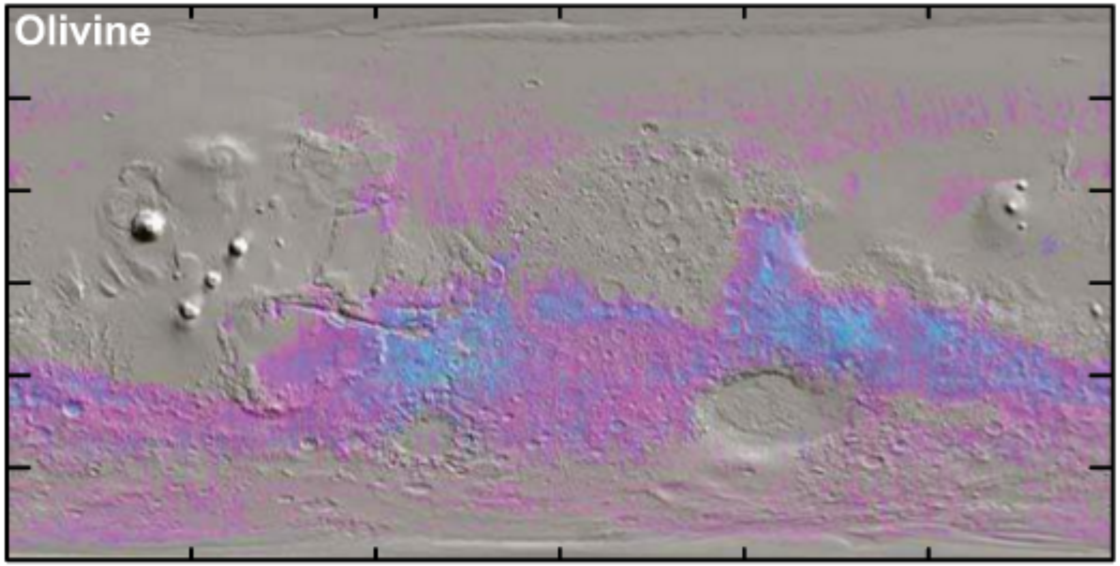
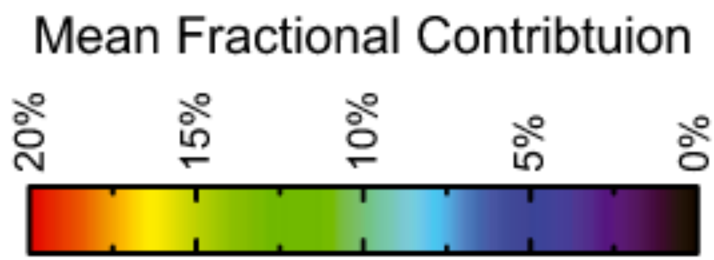
Olivine places an upper limit of 10^7 yr of water over most of the surface

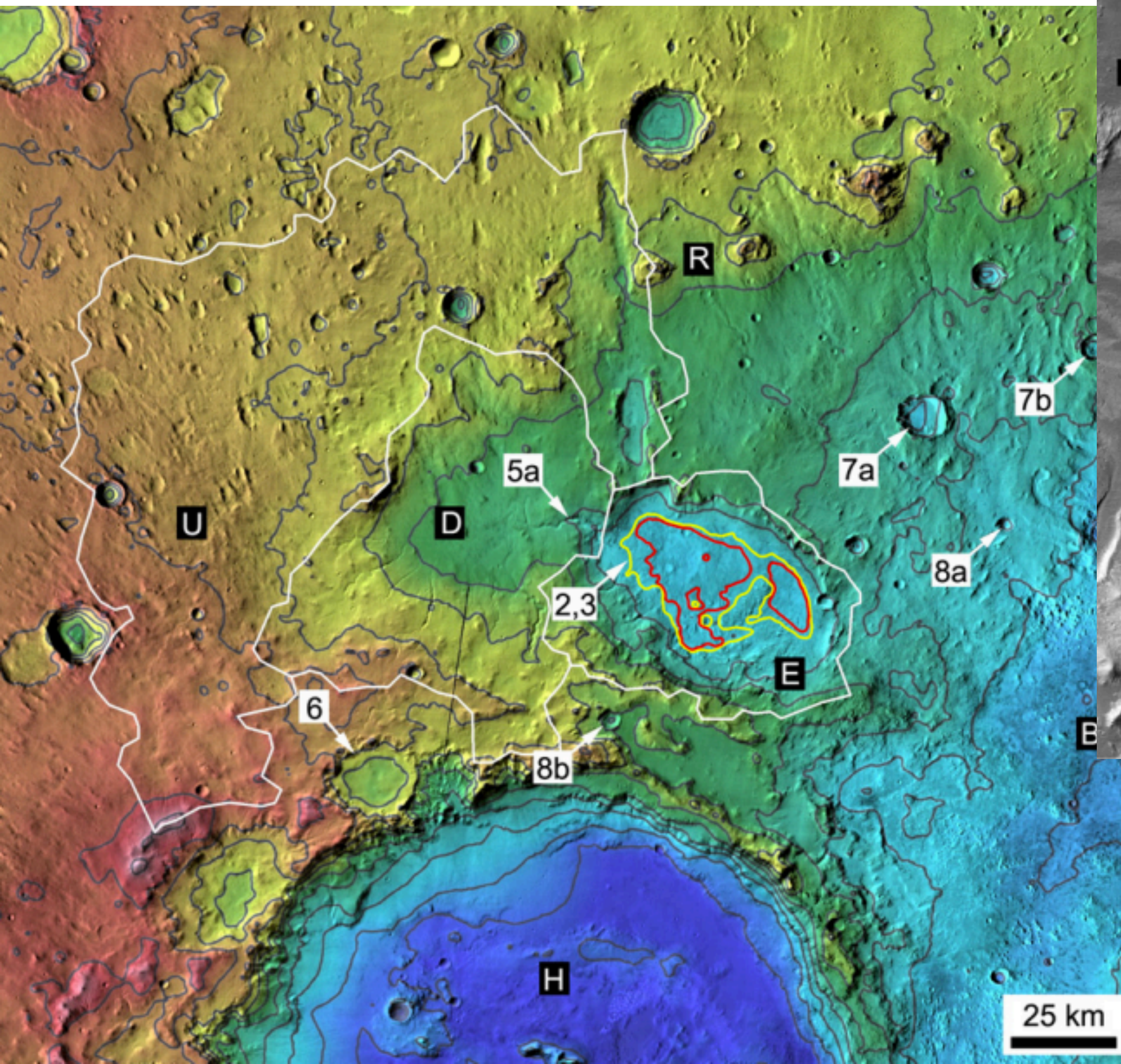


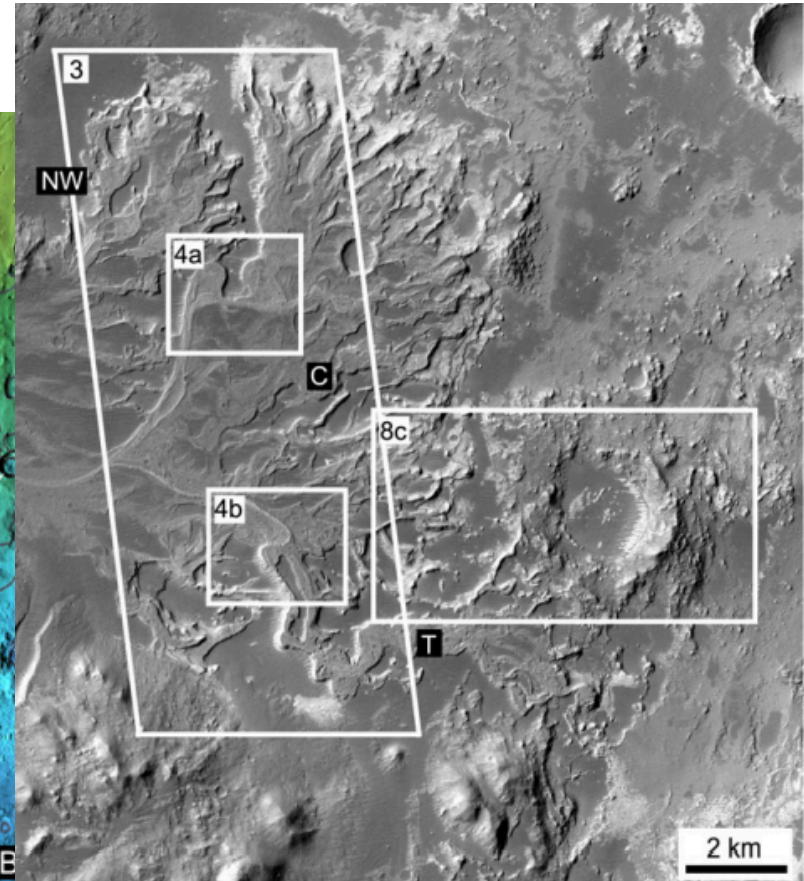
Koeppen & Hamilton, JGR-Planets, 2008



- Refers to soil-water contact (ice can shield soil from water)
- Physical erosion can ‘reset’ the surface

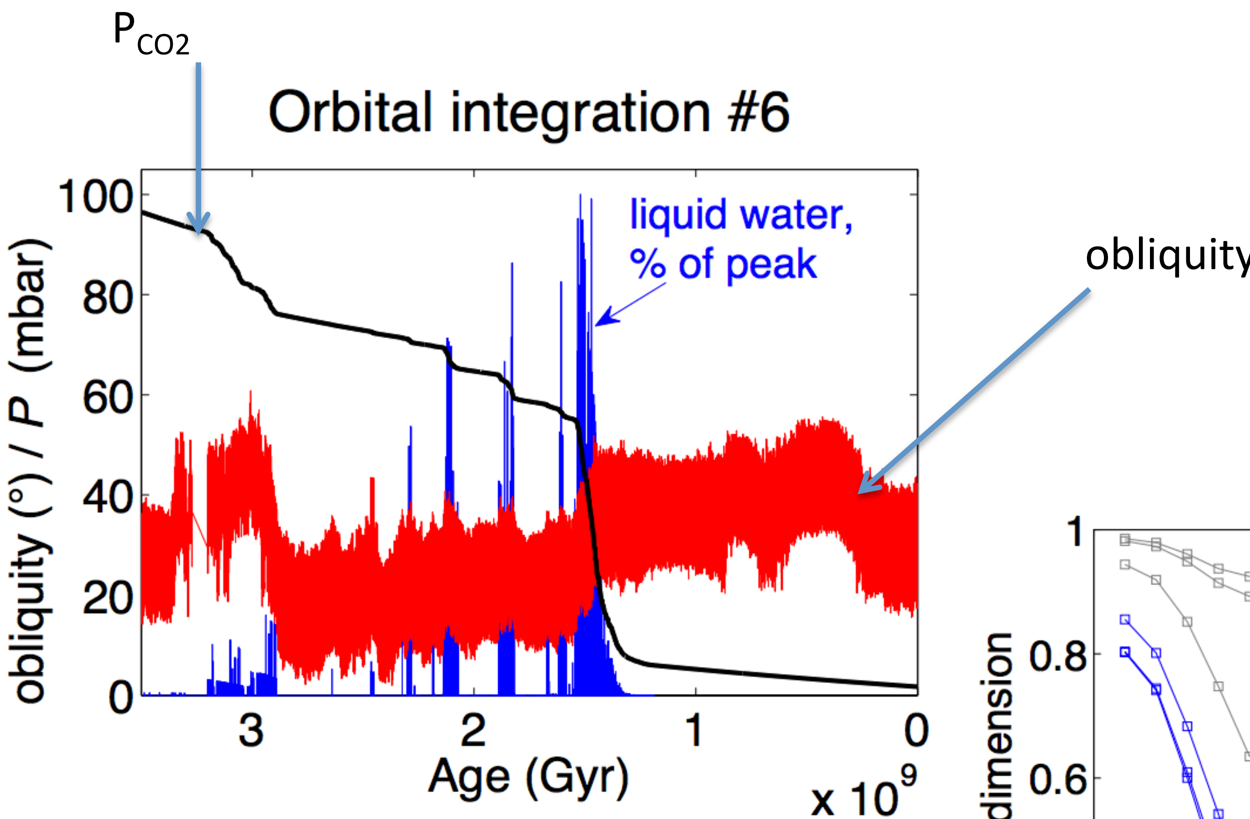
Paleolake hydrology requires $>10^{4\text{-}5}$ continuous wet years (e.g., seasonal runoff)

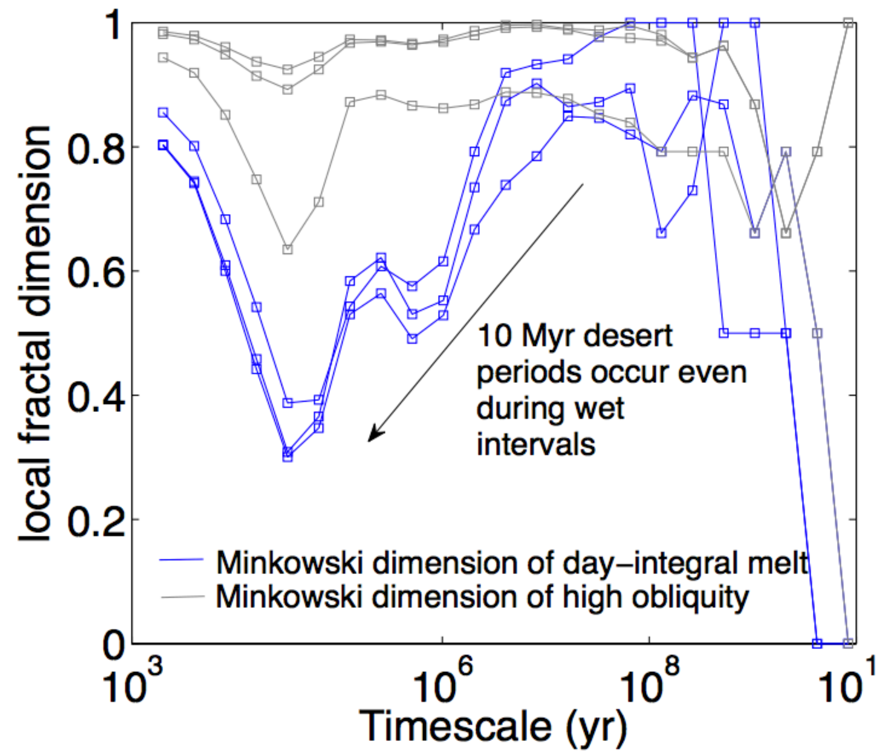




Irwin et al., Geomorphology 2015

Statistics of intermittent habitability on Mars





Ongoing work
(e.g. Mansfield et al. JGR 2018.)

[Not required for final]
Mars terraforming: very difficult at best

Falcon Heavy:
17 tons to Mars

Bad news: No credible source for breathable levels of O_2

Good news: ~1 bar CO_2 would be sufficient to warm surface *for modern solar luminosity*

Bad news: The CO_2 may have all (or mostly) escaped to space (Ehlmann & Edwards, Geology, 2014)

Good news: CFCs or SF_6 can provide very strong warming (Marinova et al., JGR-Planets, 2005)

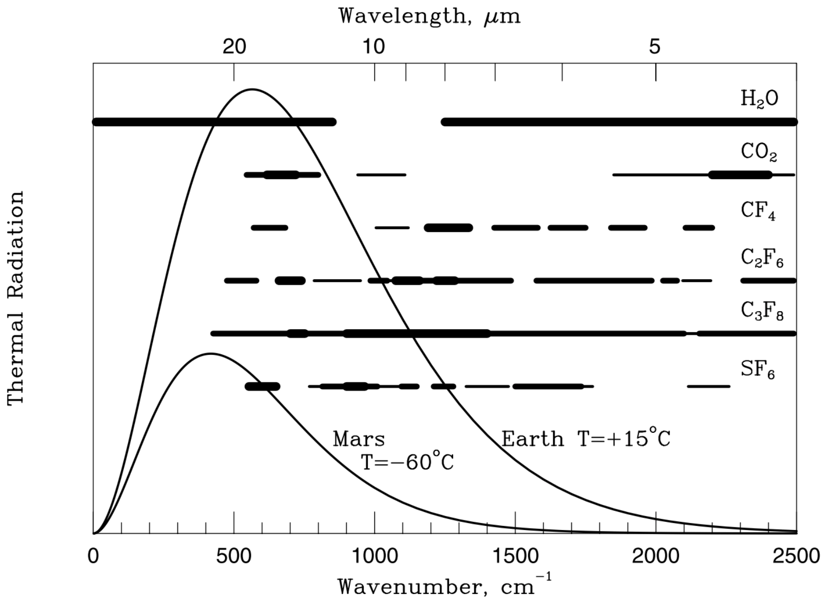
Bad news: CFC/SF_6 warming would probably not trigger runaway atmospheric re-inflation (Bierson et al. GRL 2016)

Good news: …?

Common assumptions in the literature:
Initiate with relatively near-term (21st-century) technologies
Goal: Habitable for photosynthetic algae/plants
Asteroid kinetic energy, nuclear bombs, e.t.c. is insufficient

[Not required for final] Mars terraforming: gases vs. particles

Gases option: Make on surface: Marinova+ 2005 JGR



Particles option: inject resonant absorbers at stratospheric height

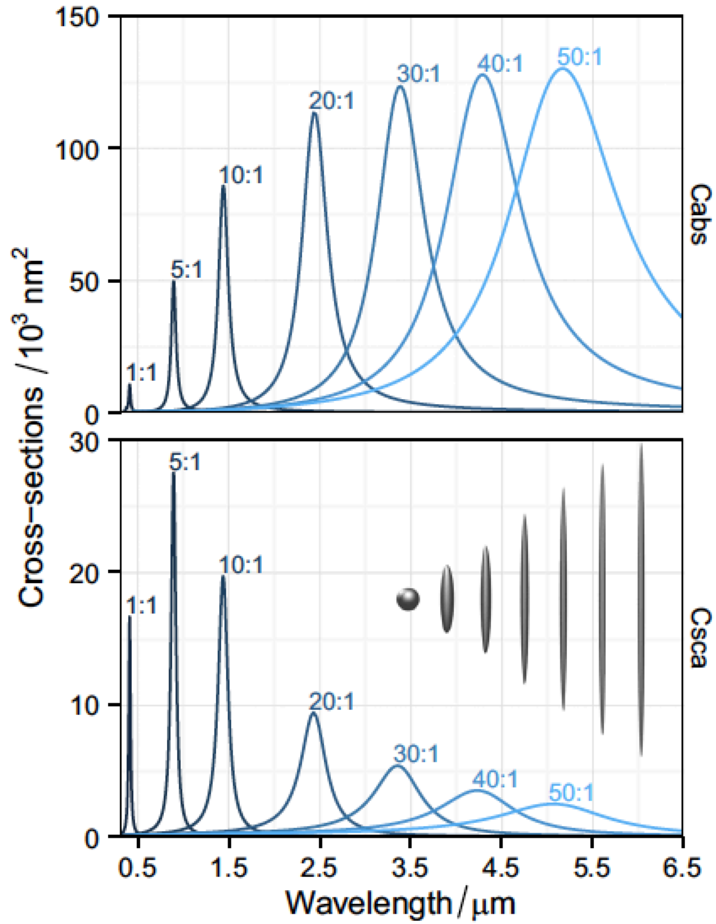


Fig. 2. Example calculation of scattering and absorption spectra of prolate Ag spheroids in water with varying aspect ratio h (1–50), with a fixed equivalent-volume radius r_V=20 nm.

Somerville et al. Journal of Quantitative Spectroscopy & Radiative Transfer 2016

Key points: Mars

- Current Mars T, P, and magnitude of present day annual cycles of H_2O, CO_2, and dust;
- reasons in favor of, and problems with, the CO_2, SO_2, and H_2 solutions to the

  Early Mars Climate Problem;
- significance of the olivine and paleolake-hydrology constraints on Early Mars climate.