GEOS 22060/ GEOS 32060 / ASTR 45900

What makes a planet habitable?

Lecture 15

Mars

Tuesday 25 February 2020

Is Earth a fluke, or are habitable climates common?

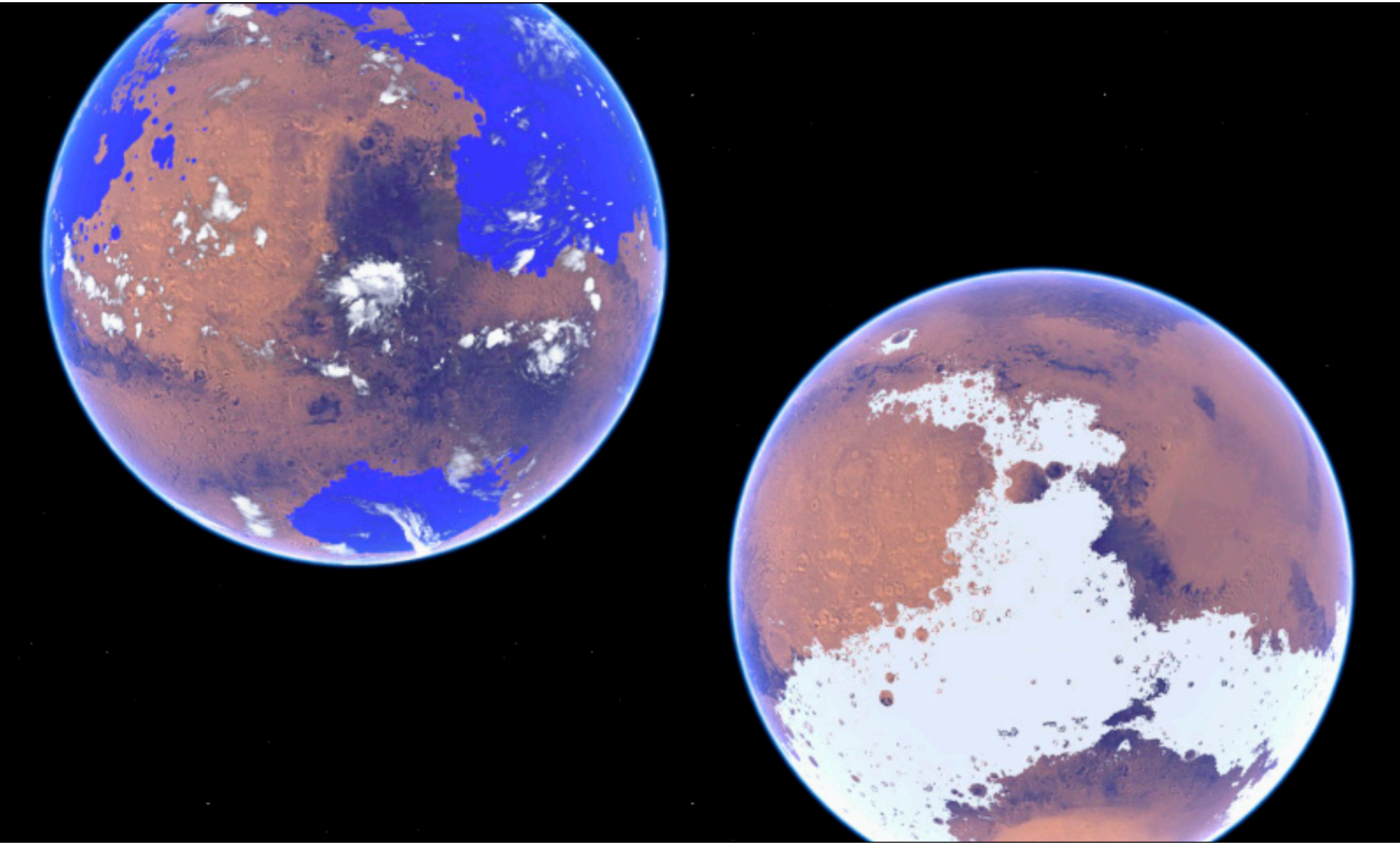
Next steps:

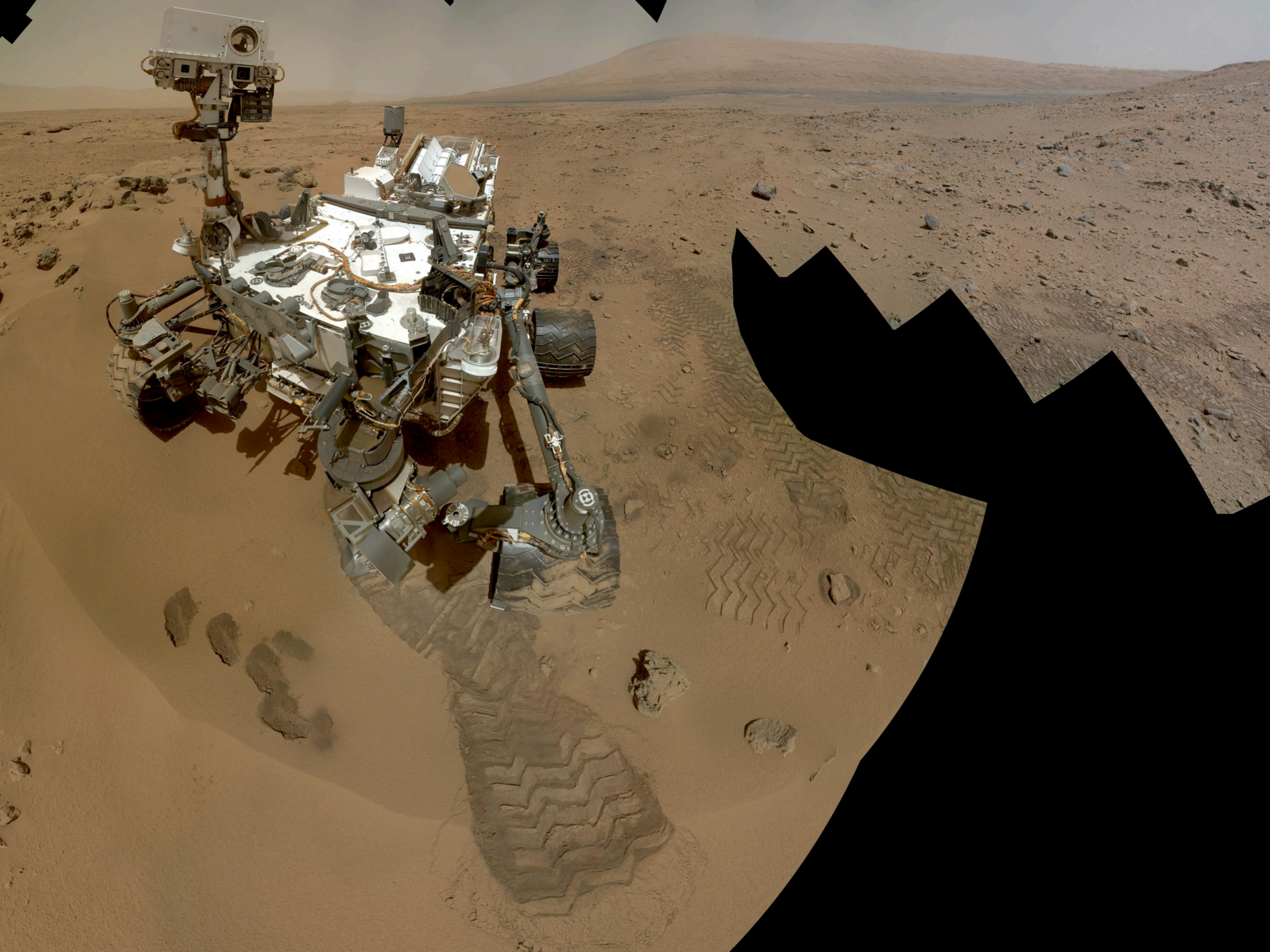
- Present-day habitable planets: one example.
- Rock records of Earth and Mars: provide access to planetary systems operating differently from present-day planets.

Yorkshire Coast, Earth
Toarcian OAE

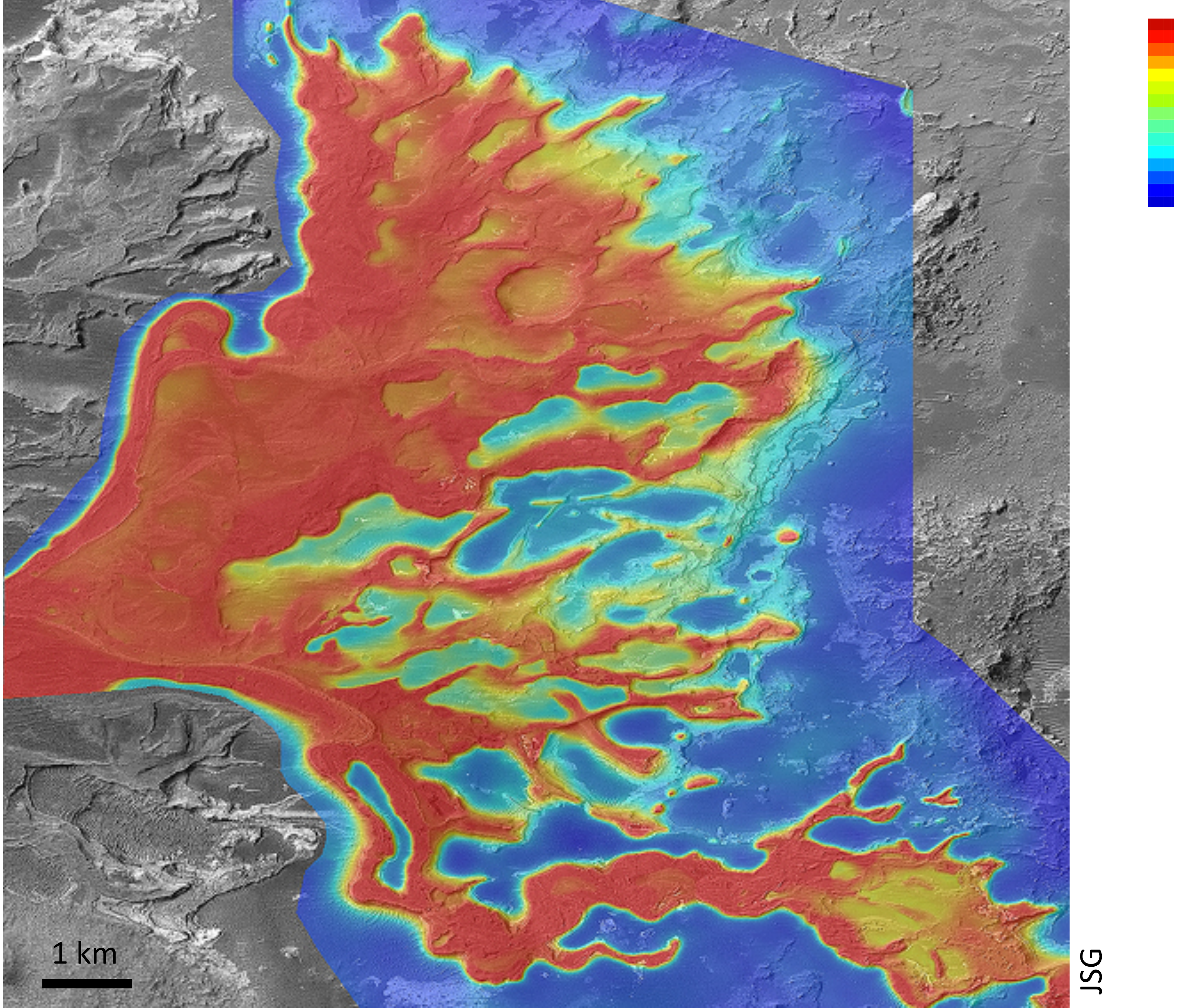
Gale Crater, Mars
Early Mars Climate Problem

Future large segmented telescopes
Exoplanet spectroscopy





Eberswalde Delta



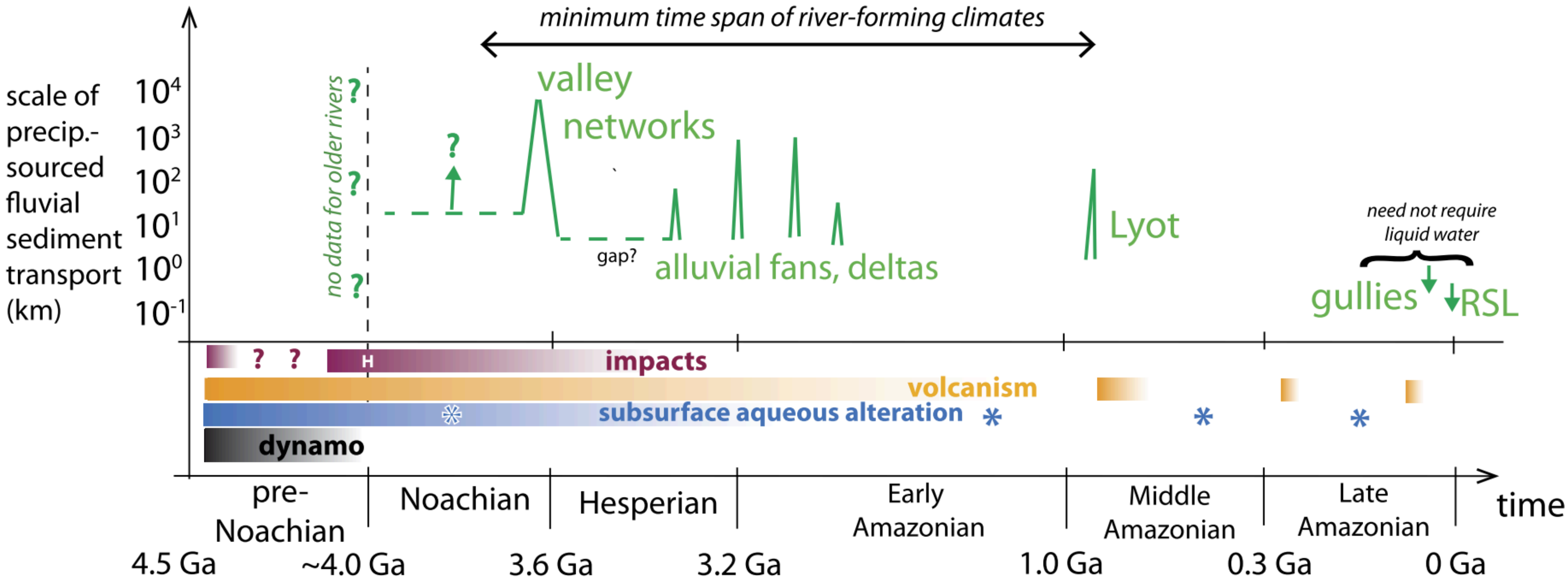
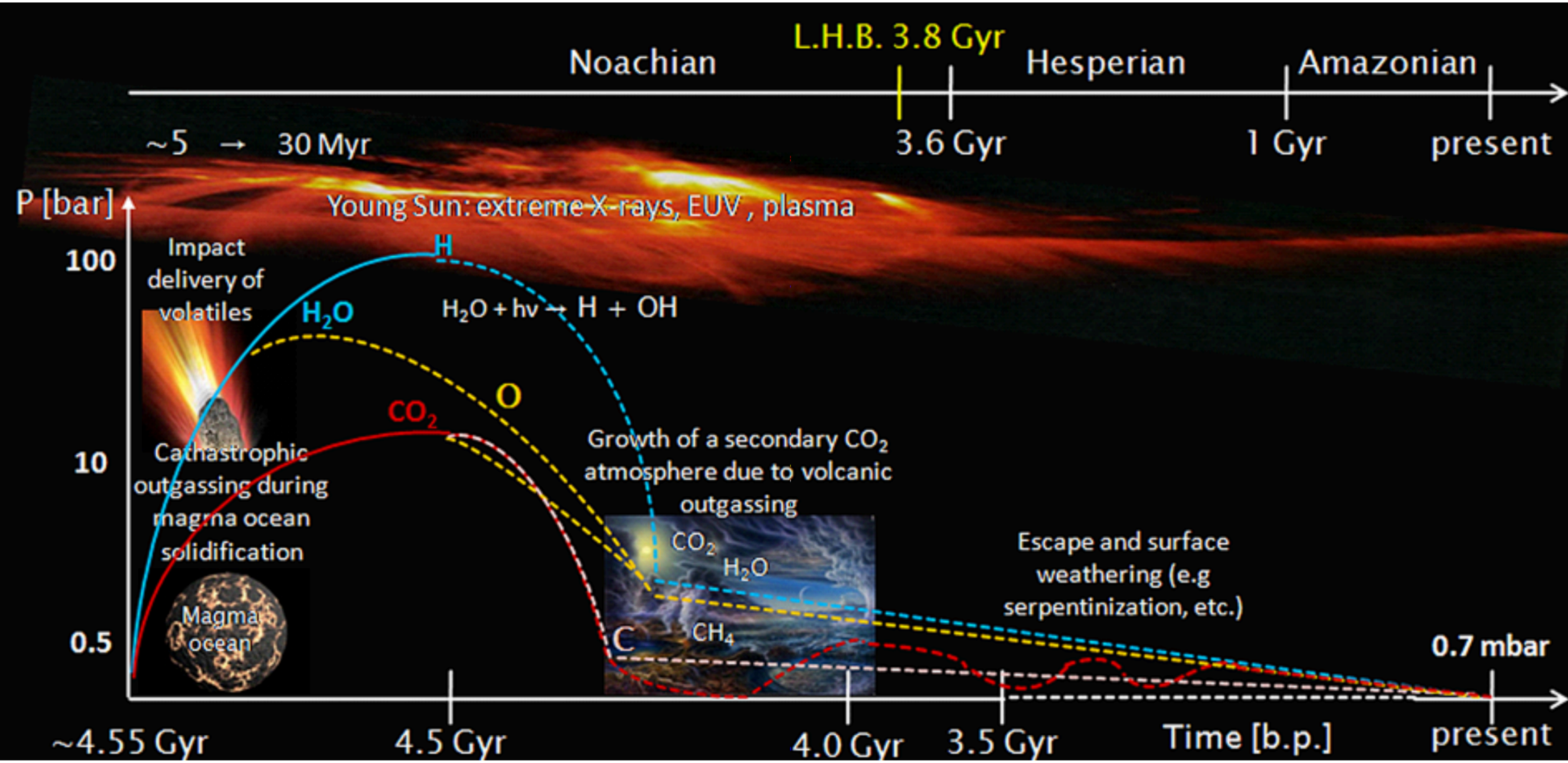


Fig. 3 History of Mars' river-forming climates (modified after Kite et al. 2017b). Y-axis corresponds to the map-view scale of the landforms shown. Neither the durations of geologic eras, nor the durations of river-forming climates, are to scale. Data are consistent with long globally-dry intervals. Dynamo timing is from Lillis et al. (2013). H = Hellas impact event. ∗ = subsurface aqueous alteration as recorded by Mars meteorites (Borg and Drake 2005; Nemchin et al. 2014)

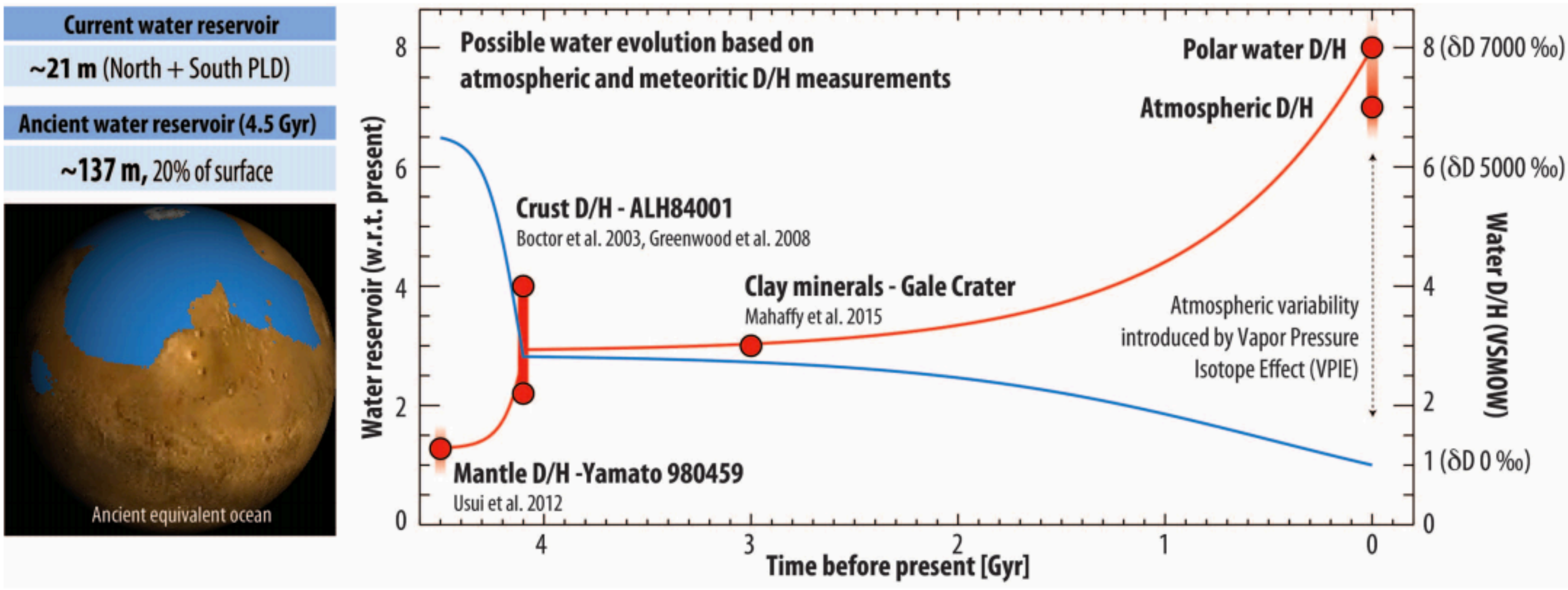
Kite Space Science Reviews 2019

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

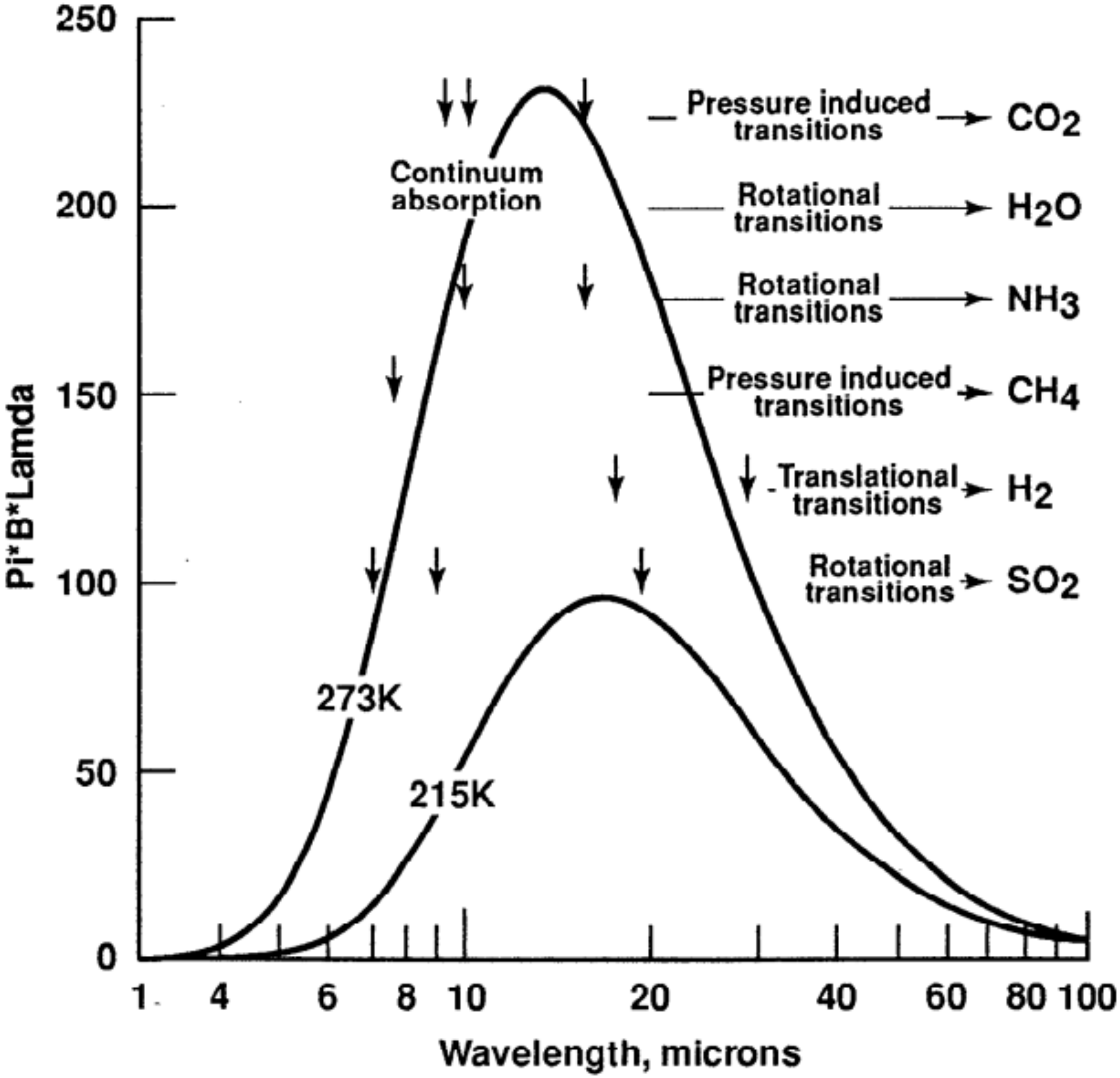
MODERN MARS CLIMATE

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

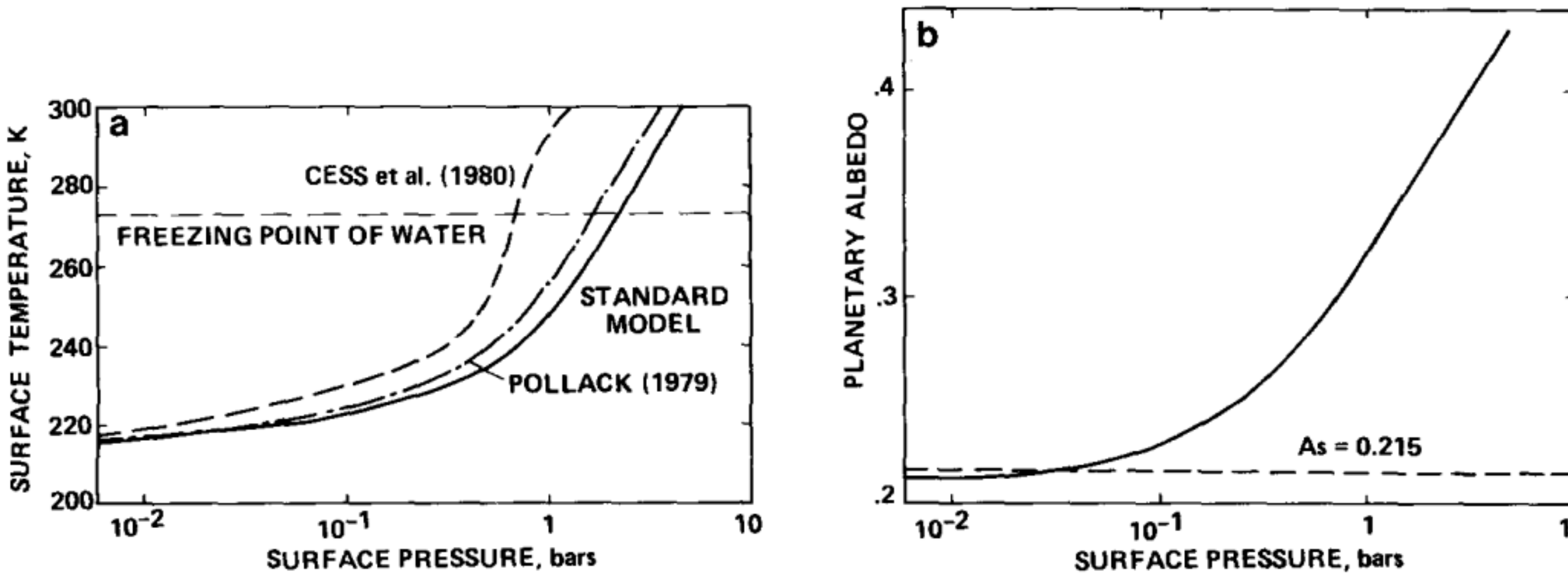


FIG. 1. (a) Surface temperature, T_s, and (b) planetary albedo, A_p, of Mars as the function of the surface pressure of CO_2 for the present surface albedo and globally and orbitally averaged solar flux. In (a), the solid curve presents results from this paper, while the other two curves represent results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

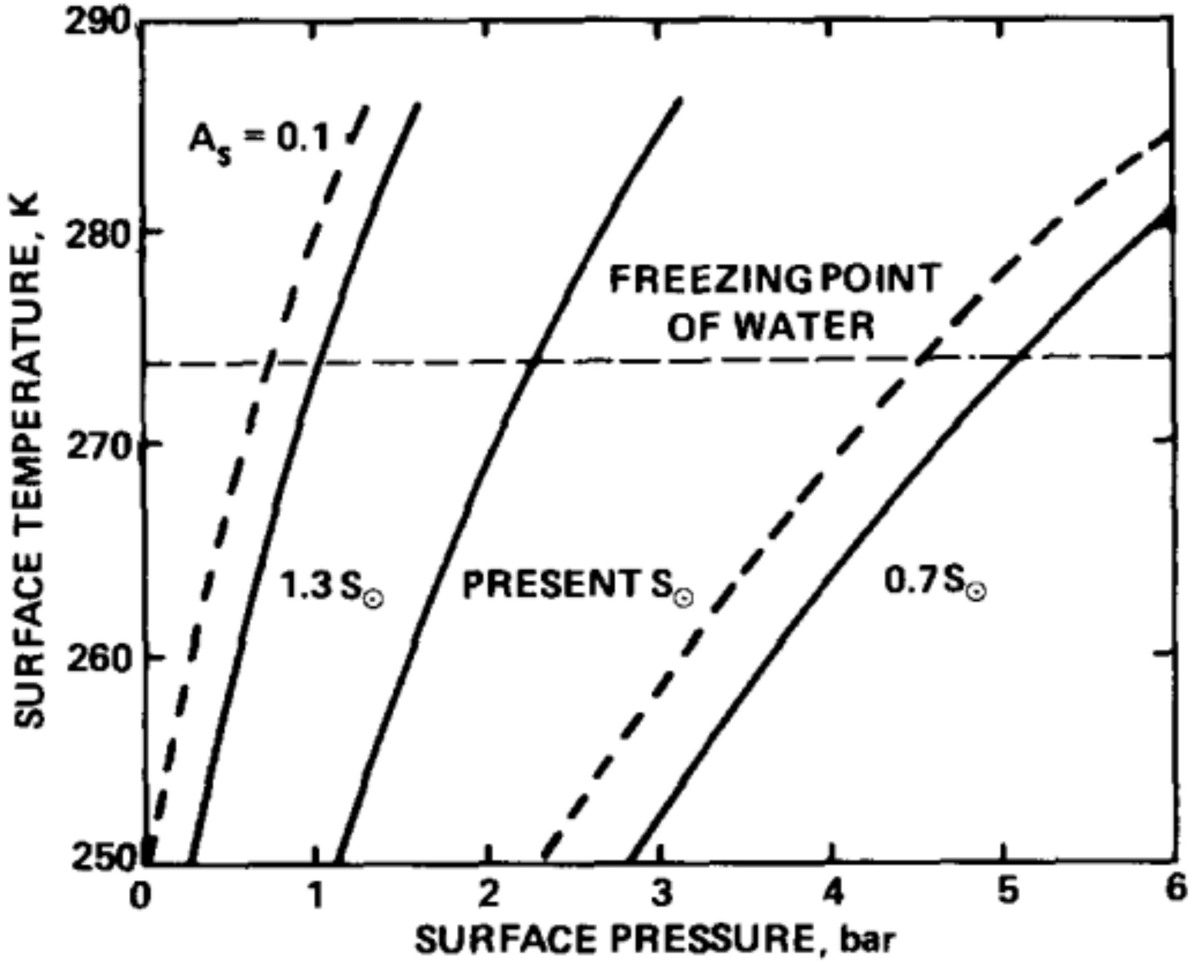


FIG. 2. Surface temperature as a function of surface pressure for several values of the surface albedo and incident solar flux, S. Solid lines refer to results for the current globally averaged albedo of 0.215. $S = 1$ for the present globally and orbitally averaged solar flux at Mars.

CO_2 condensation limits warming

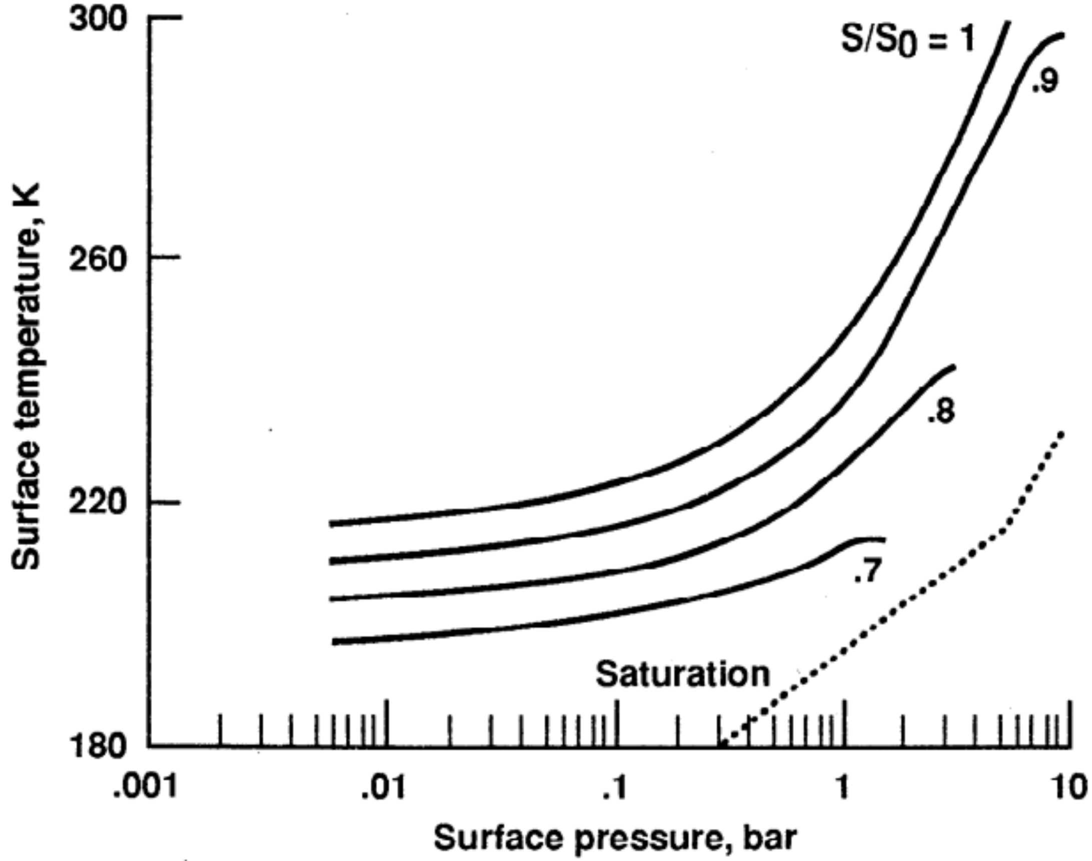


Figure 12. Surface temperature as a function of surface pressure for four different values of the solar luminosity. Dashed line shows the saturation vapor pressure of CO_2. For the 0.7 and 0.8 luminsoity cases, pressures greater than the maximum permitted would discontinuously move the curves down to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

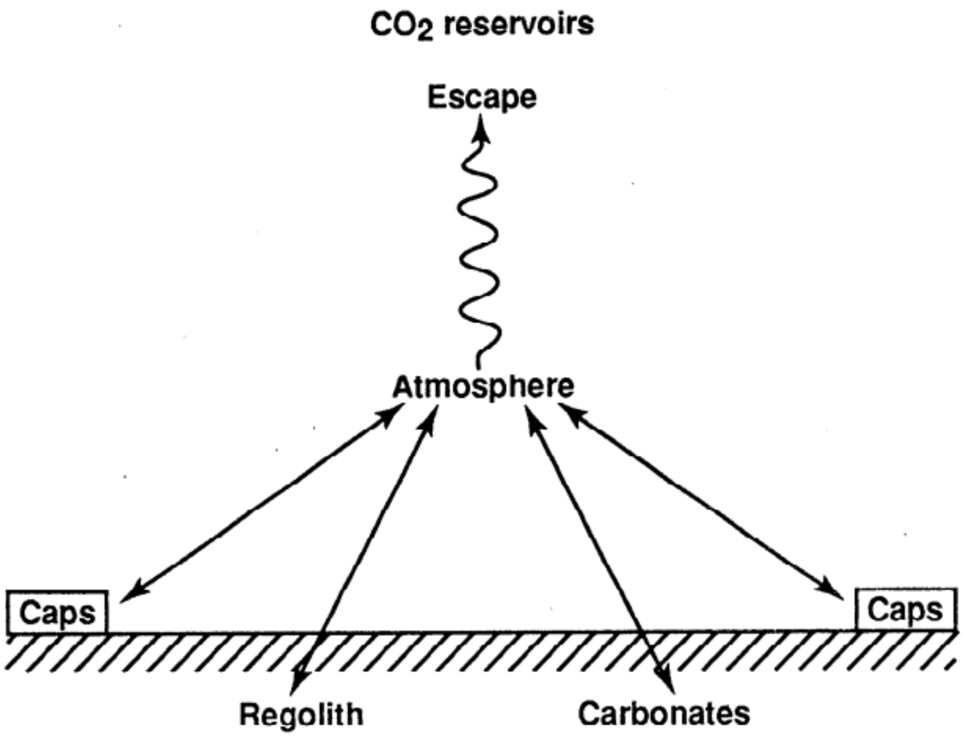
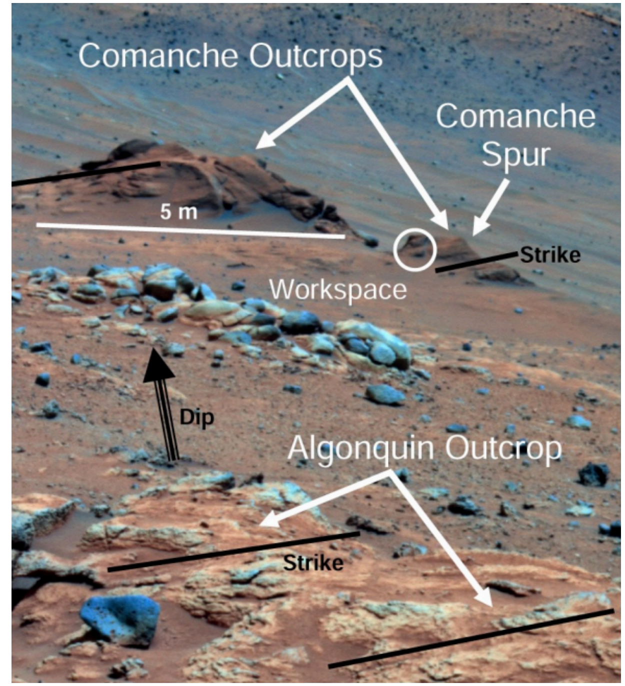
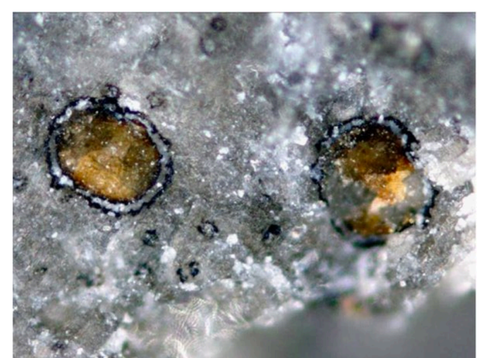


Figure 13. Candidate reservoirs for an early CO_2 atmosphere.

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

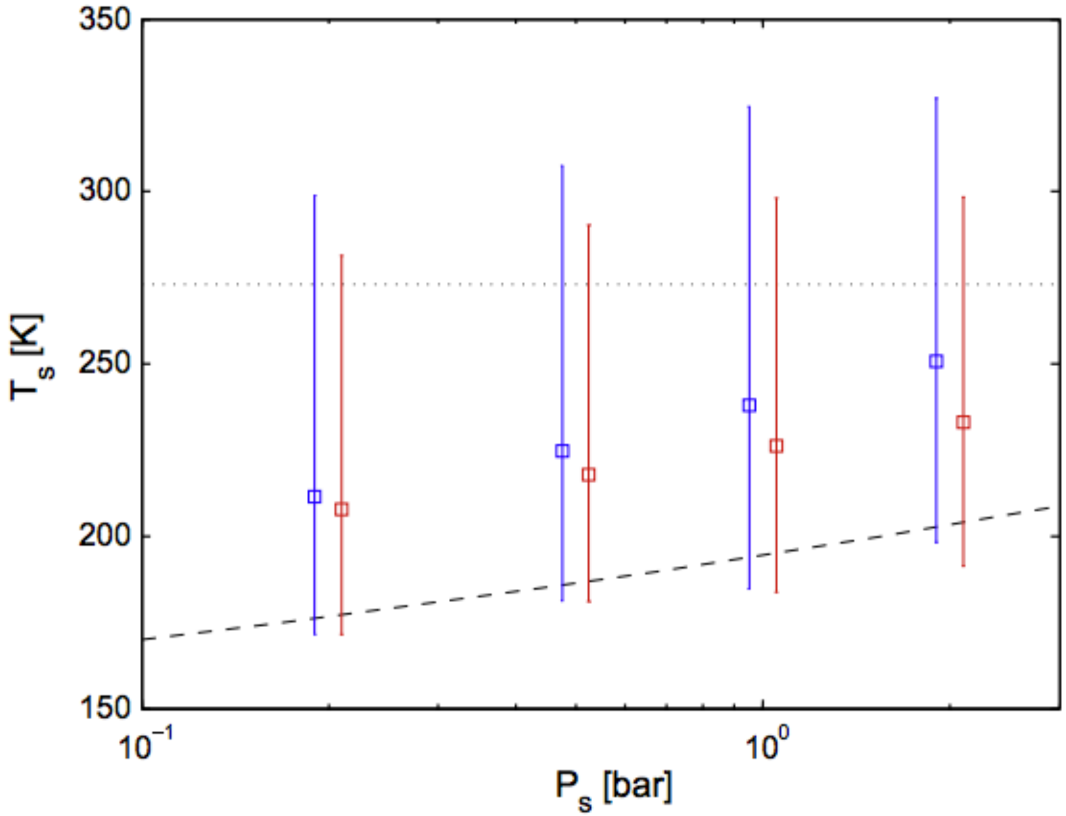
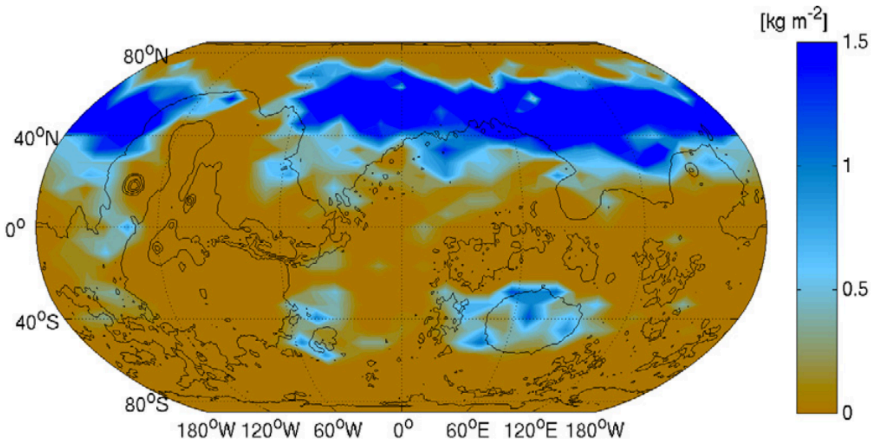


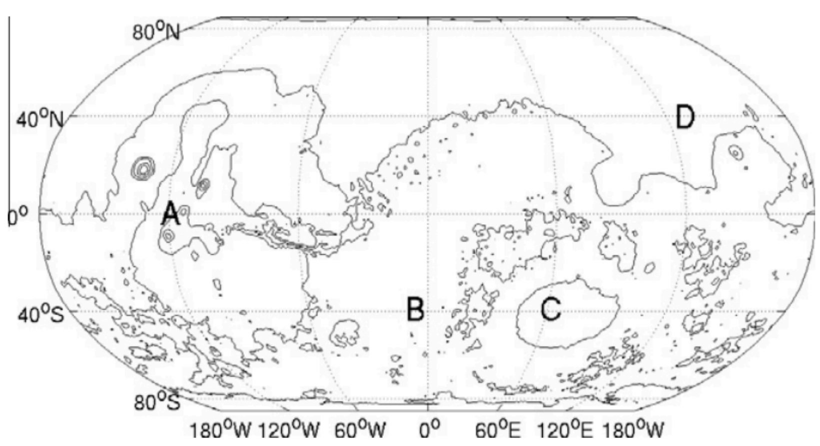
Fig. 2. Effects of atmospheric CO_2 and H_2O on global temperature. Error bars show mean and maximum/minimum surface temperature vs. pressure (sampled over one orbit and across the surface) for dry CO_2 atmospheres (red), and simulations with 100% relative humidity (blue) but no H_2O clouds. Dashed and 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.)

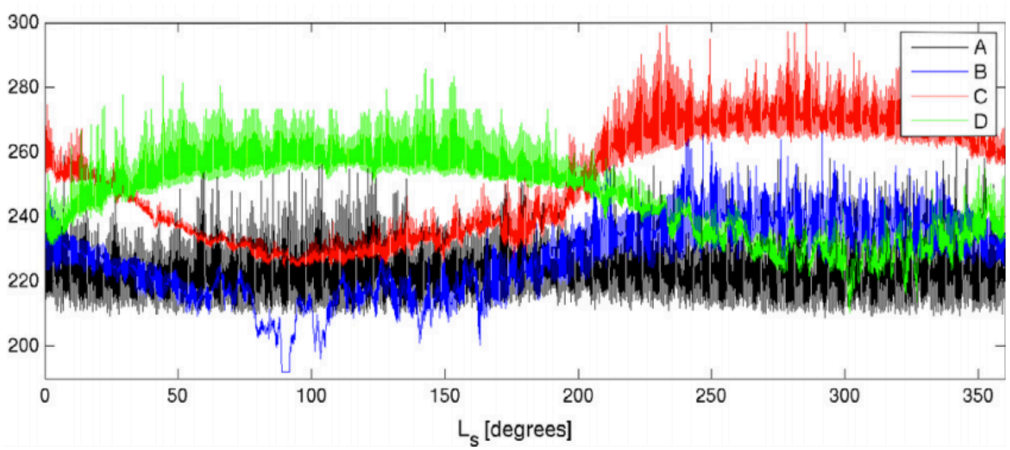
Wordsworth et al. Icarus 2013

Problem #2: how much CO2 is enough?

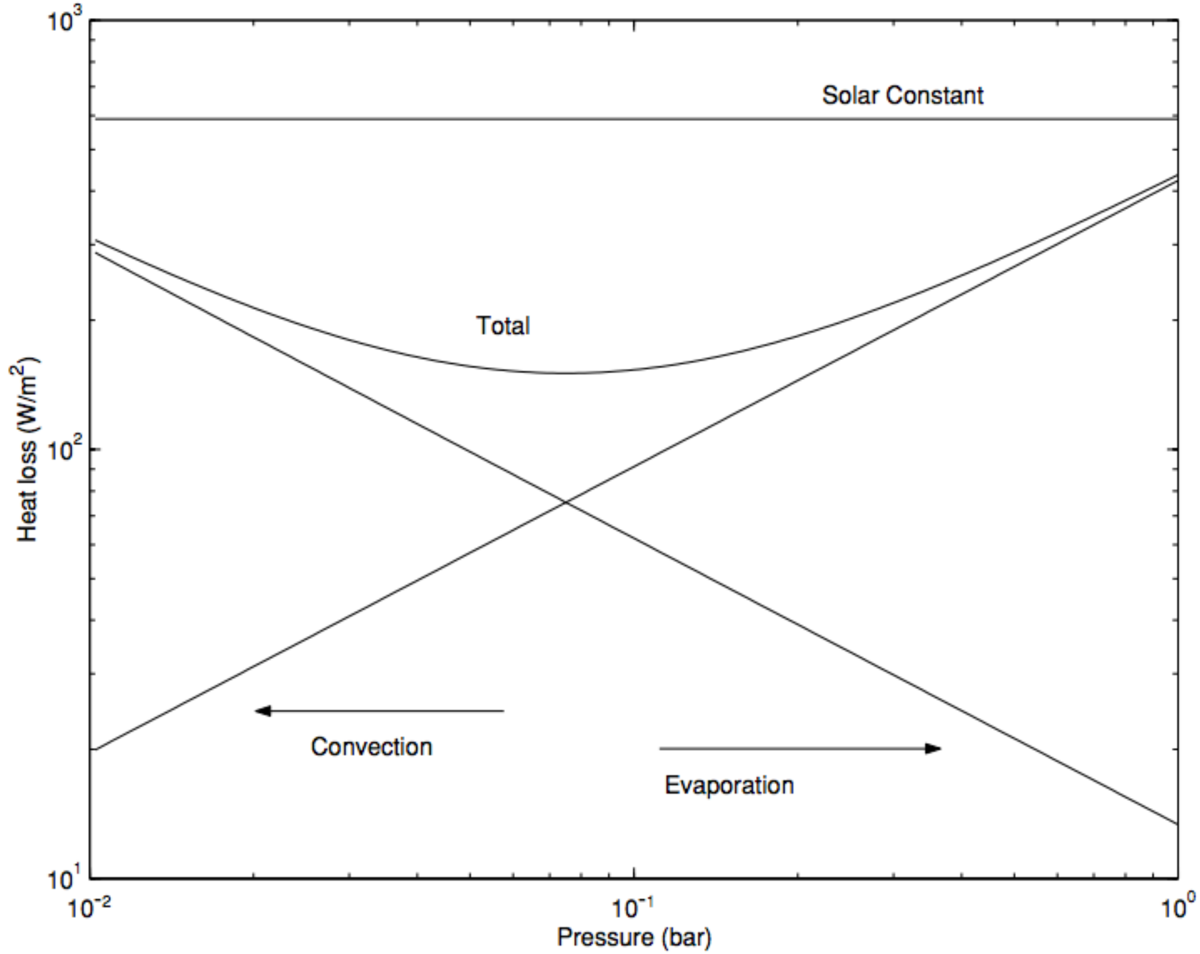
Wordsworth et al. Icarus 2013







In addition to greenhouse warming, a thicker atmosphere is still useful for suppressing evaporitic cooling



Assumes 273K surface & 200K atmosphere

Hecht 2002 Icarus

Climate stabilization on early Mars

MODERN MARS CLIMATE

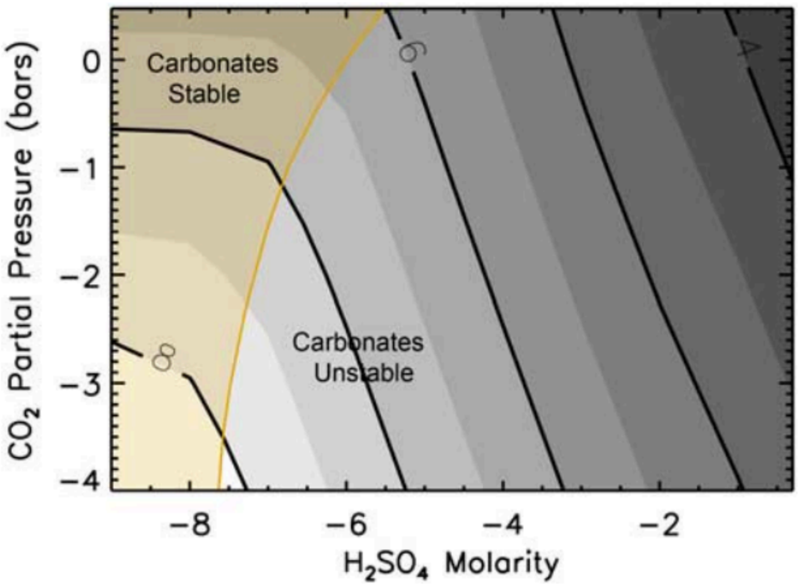
CARBON FEEDBACKS?

SULFUR FEEDBACKS?

HYDROGEN?

INTERMITTENCY?

SO_2 inhibition of carbonate precipitation?



Bullock & Moore, GRL 2007
(contours = pH)

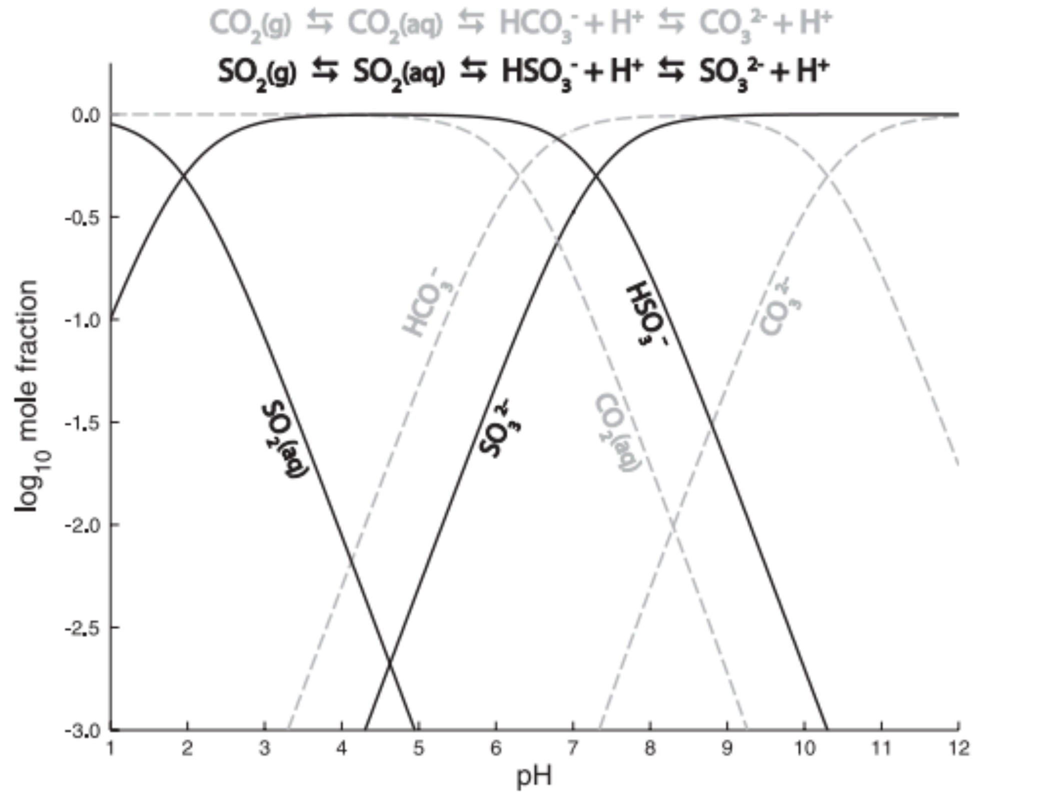
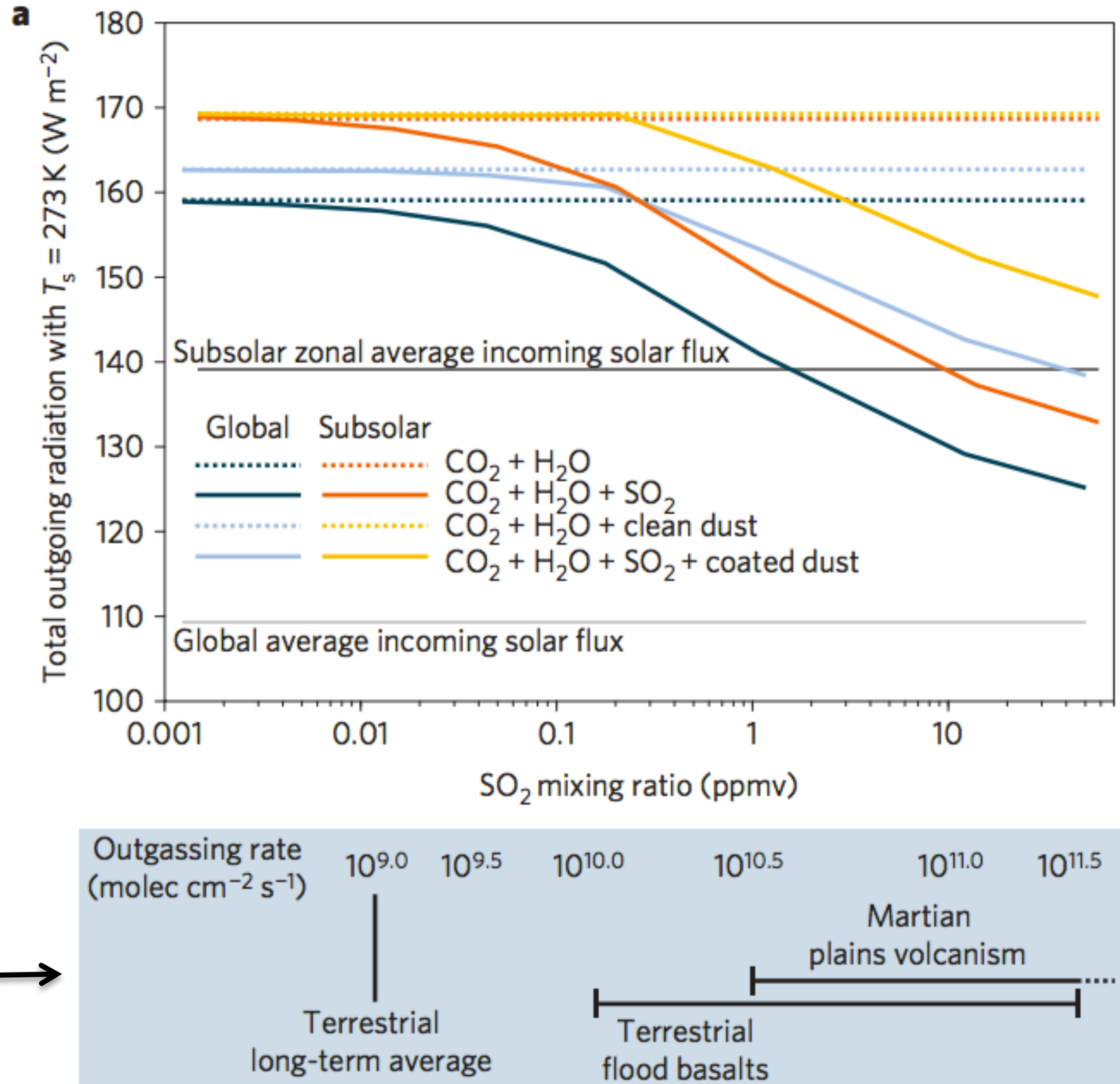


Fig. 1. pH dependence of aqueous S^{4+} (black) and C (gray) speciation, expressed by the chemical equilibrium reactions in the figure. At pH between 2 and 6, most of the S^{4+} is present as HSO_3^- (bisulfite), whereas carbon is predominantly in the form of CO_2 (aq).

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

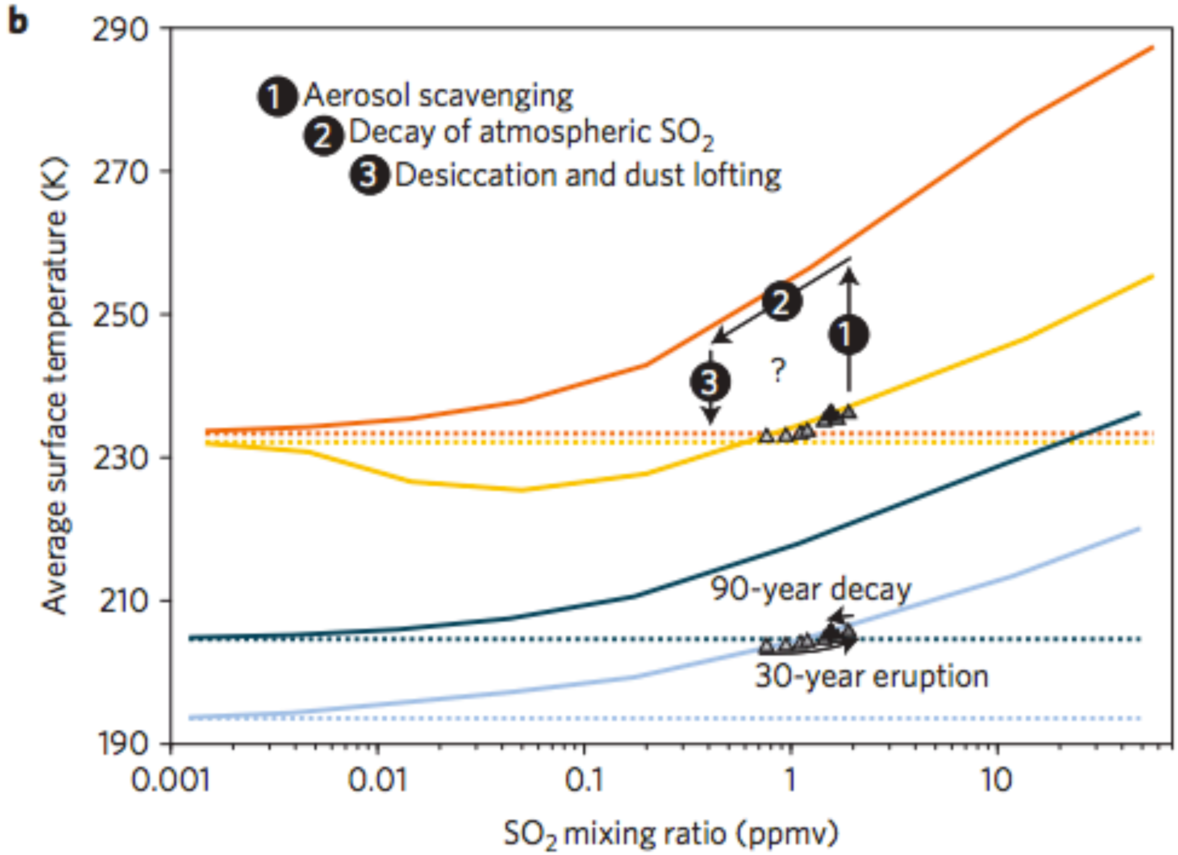


Figure 2 | Radiative forcing by SO_2 and H_2SO_4-coated dust. a, Global (dark and light blue) and subsolar zonal (red and orange) average outgoing radiation at the steady state, compared with the incoming solar flux (black and grey). **b**, Global and subsolar zonal average surface temperature at the same steady states as in **a**, and during a ~30-year punctuated eruption (triangles, see Methods). Volcanic emission rates corresponding to the steady-state SO_2 mixing ratios on the horizontal axis are shown in the centre, along with estimated emission rate ranges of terrestrial and Martian volcanism. Numbered arrows show a possible positive feedback, described in the text.

Halevy & Head, Nature Geoscience, 2014

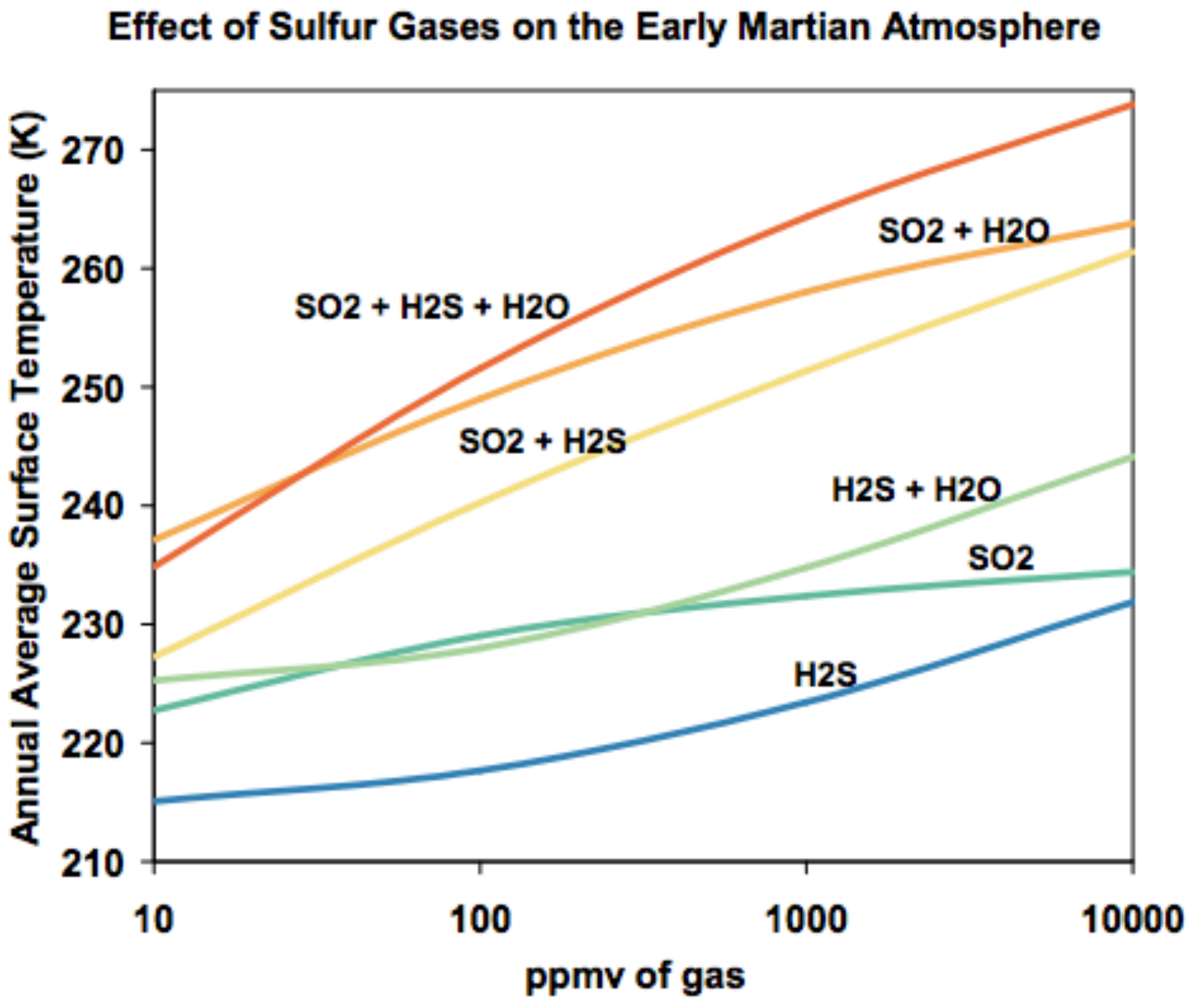
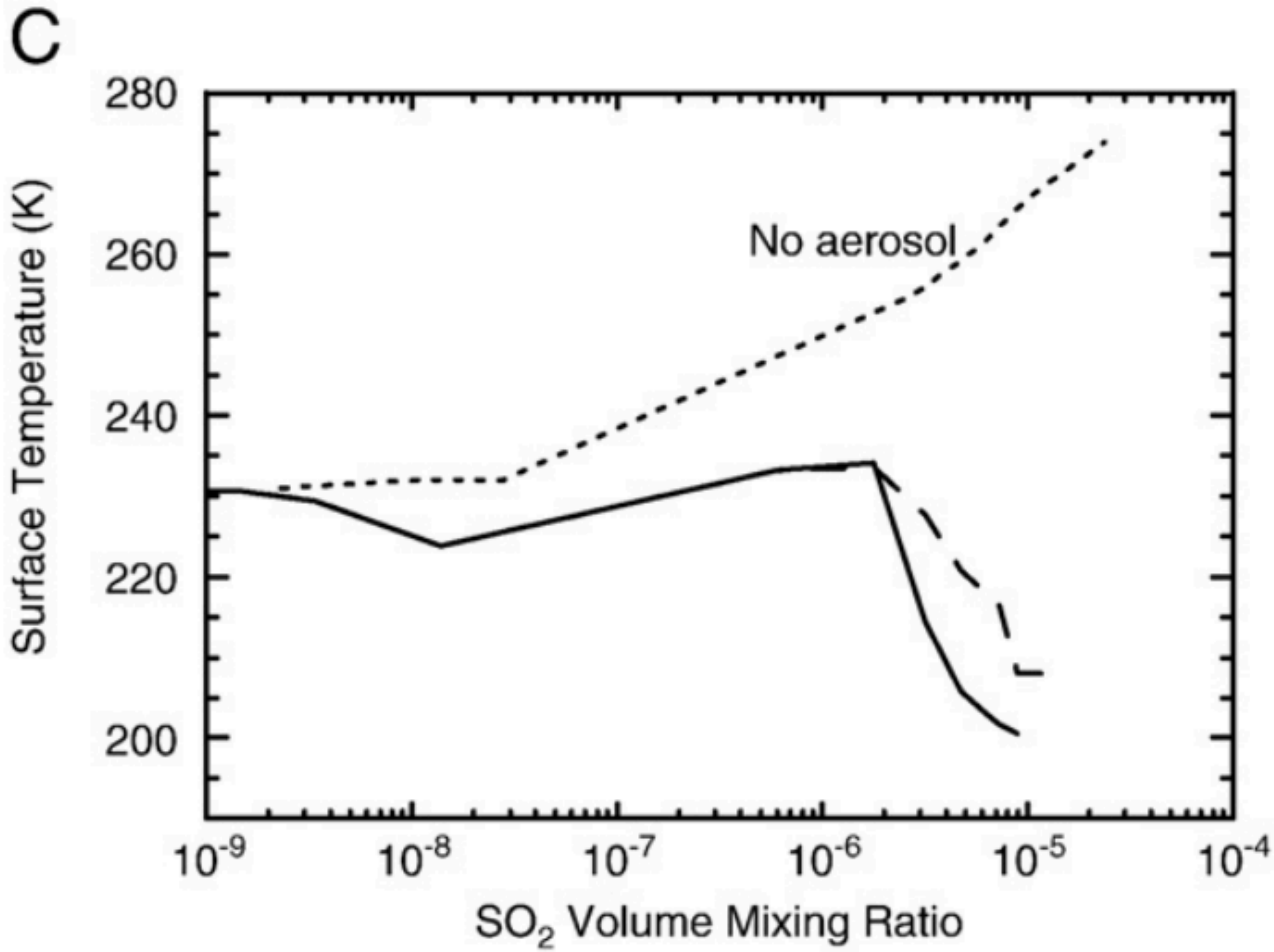


Figure 1.

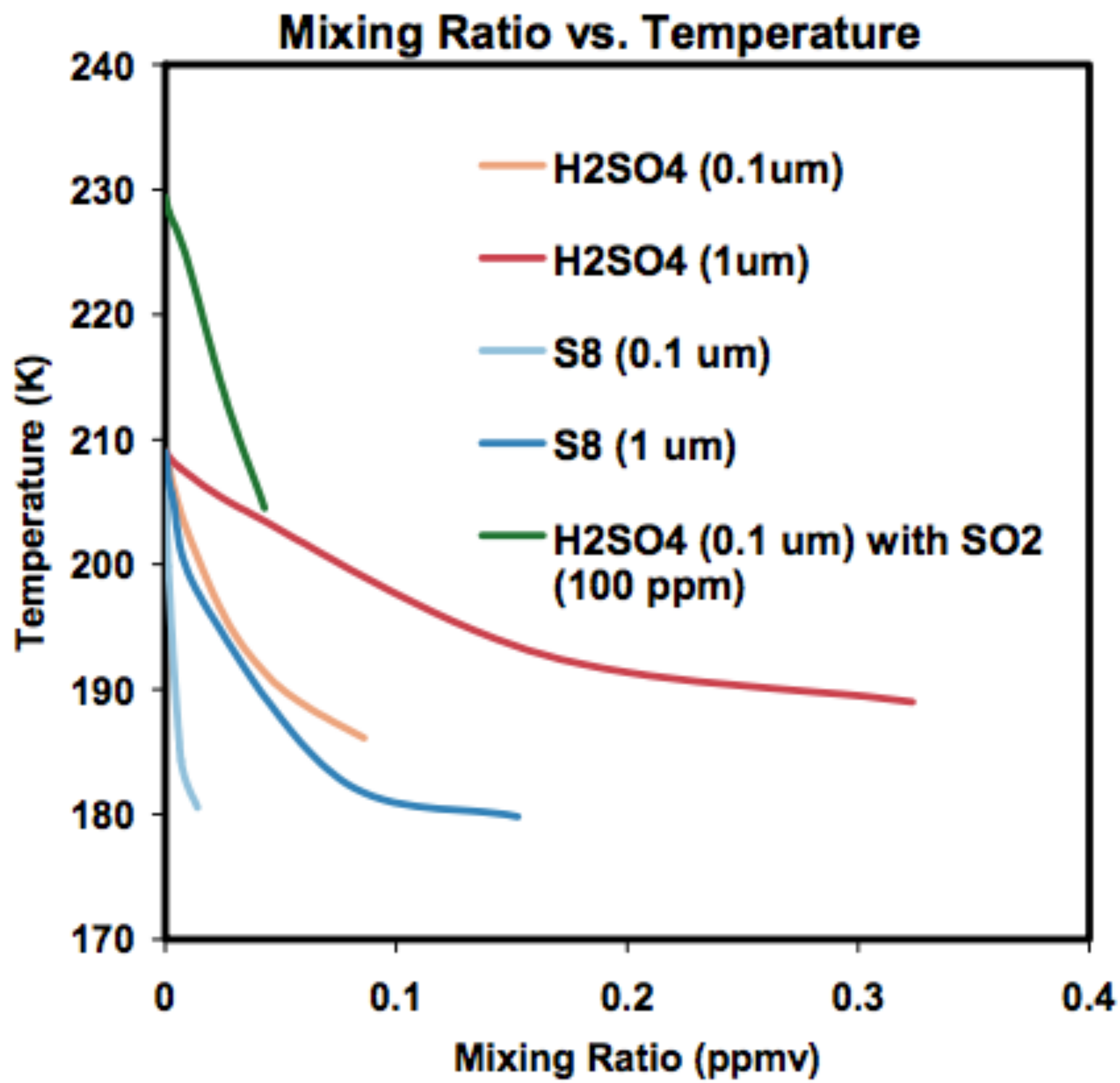
Even in the cases where large amounts of SO_2 and H_2S are added to the atmosphere, the annual global average surface temperature does not rise above freezing. H_2S provides significantly less warming than SO_2.

Kerber et al.
JGR-Planets
2015

Aerosol formation reduces SO_2 warming



Tian et al. EPSL 2010



Kerber et al., Oxford Conference on Mars' Atmosphere, 2014

Climate stabilization on early Mars

MODERN MARS CLIMATE

CARBON FEEDBACKS?

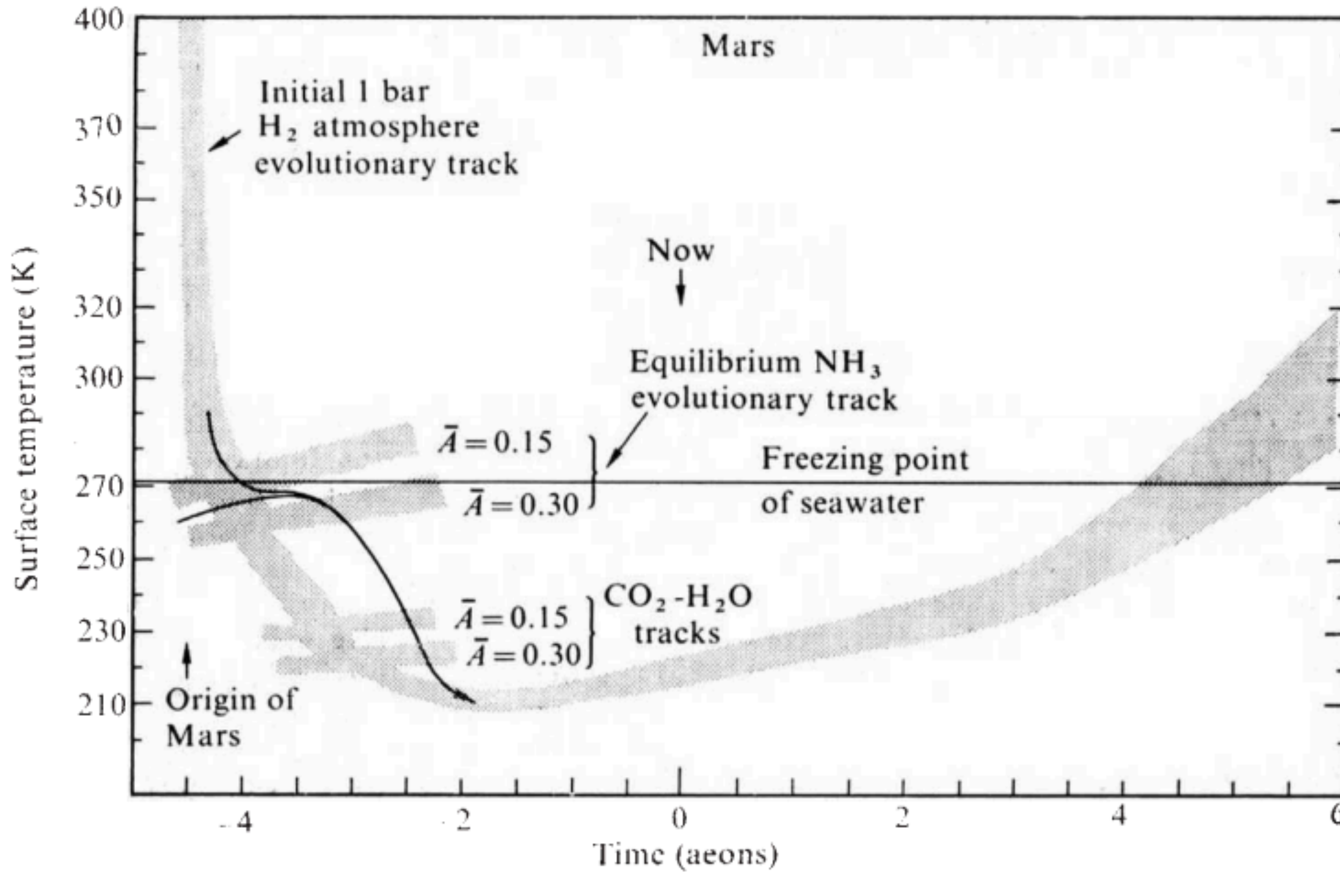
SULFUR FEEDBACKS?

HYDROGEN?

INTERMITTENCY?

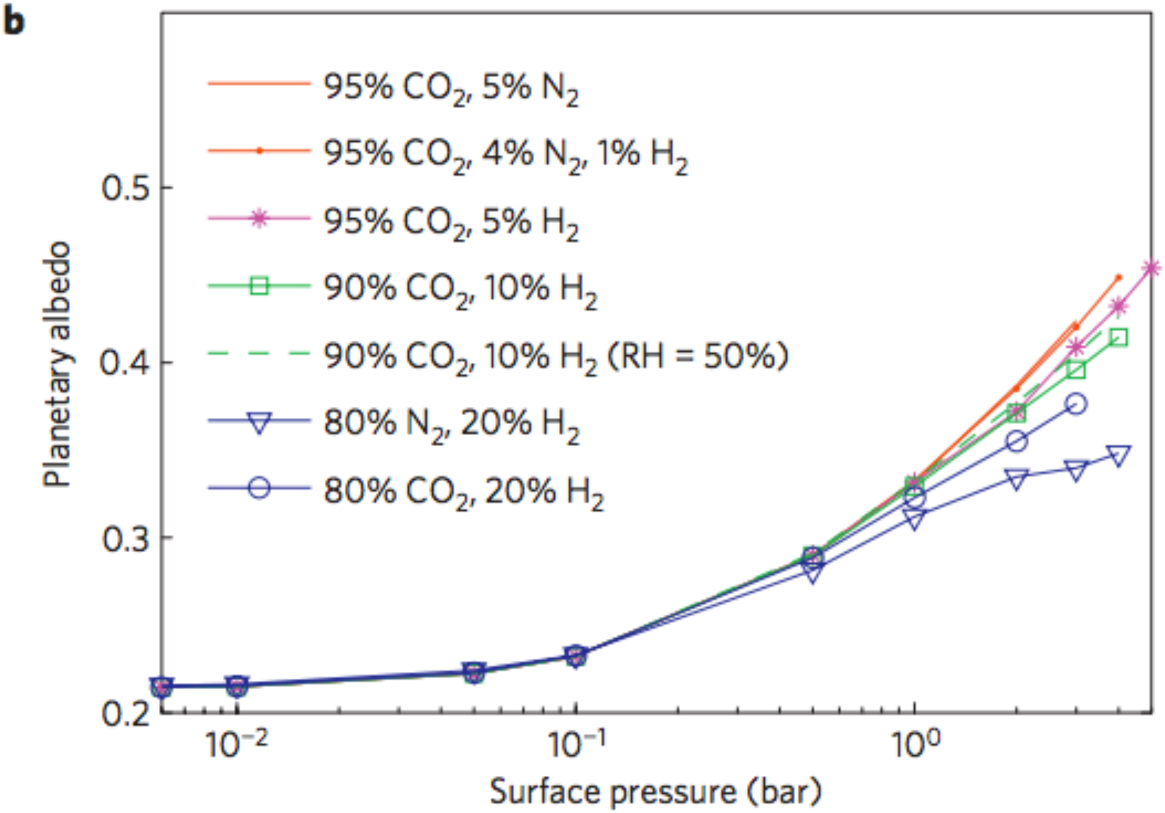
H2 collision-induced absorption

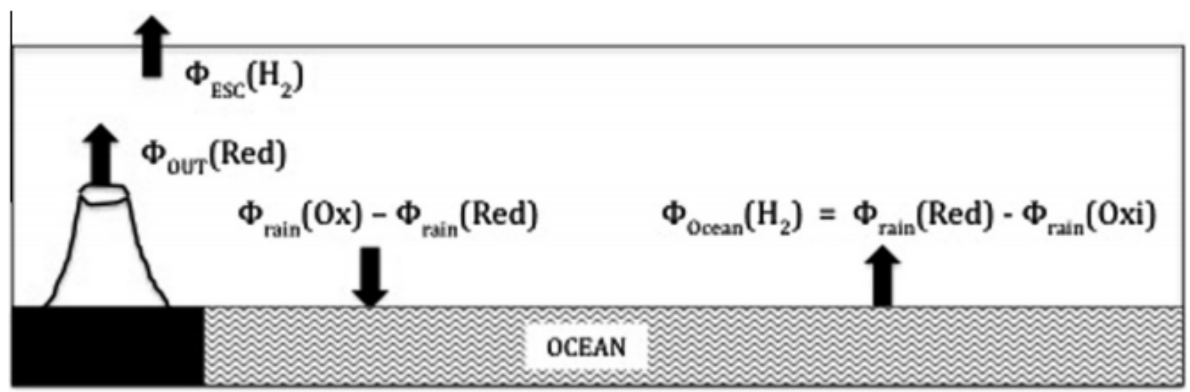
Fig. 2 Evolutionary tracks for the time dependence of surface temperature for Mars for three early compositions and two different bolometric Russell–Bond albedos.



Sagan, Nature, 1977

Ramirez et al. Nature Geoscience 2014





Batalha et al. Icarus 2015

Weathering reactions make hydrogen

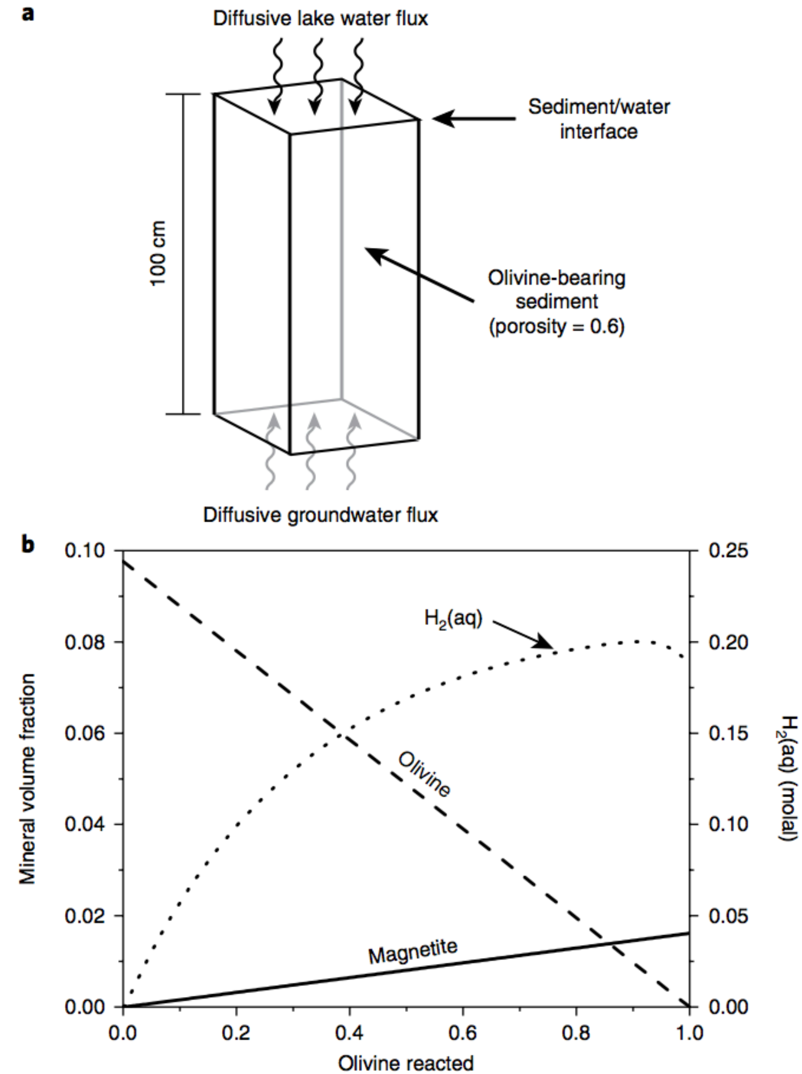
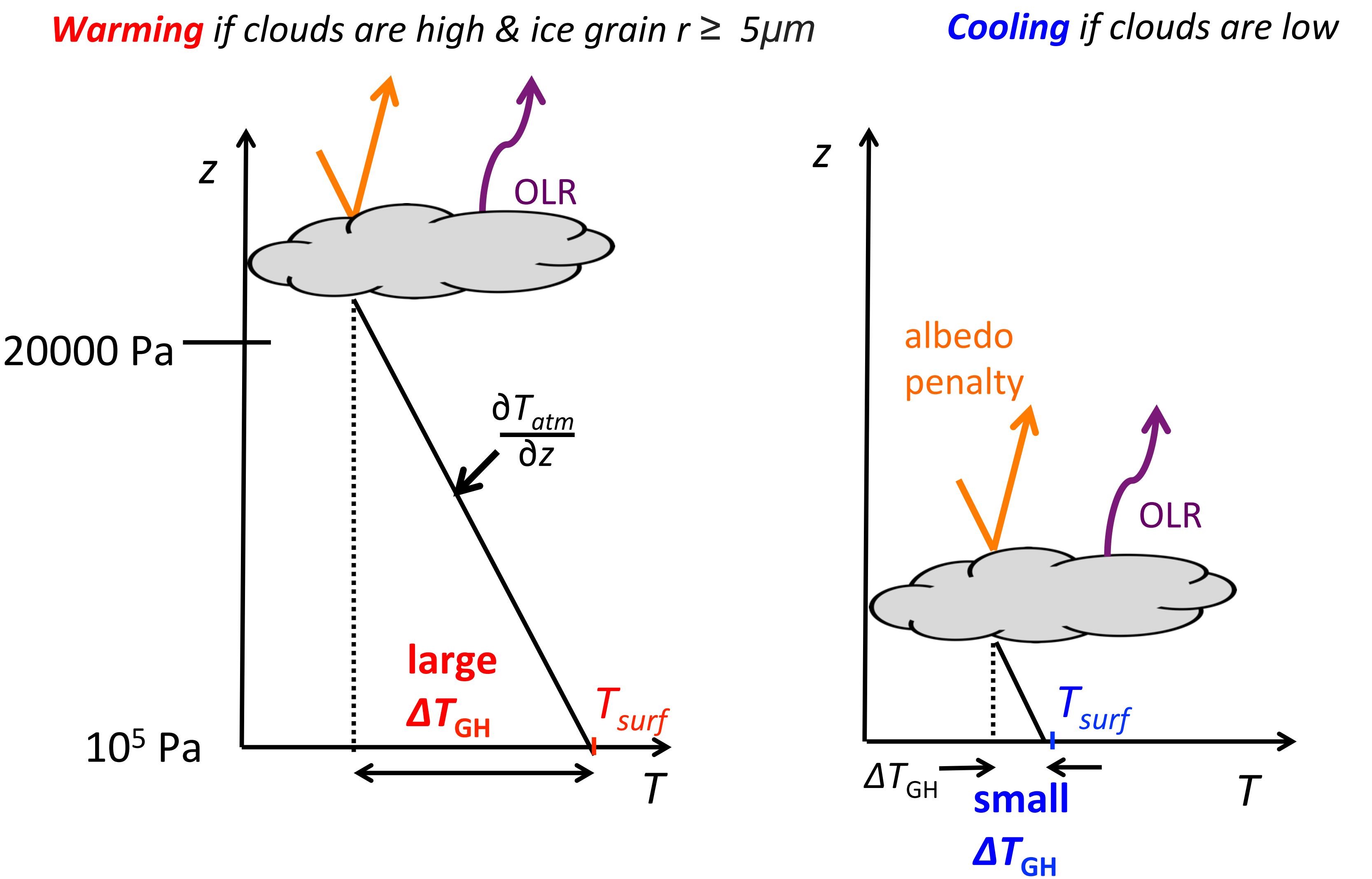


Fig. 3 | Groundwater–lake water mixing to form magnetite and H_2(aq). **a**, Schematic of domain used in reactive transport simulations. **b**, Mineral volume fraction and H_2(aq) concentrations in coexisting solutions plotted as a function of olivine reaction progress. Note that H_2(aq) concentrations plotted here exceed the solubility of H_2(aq) in ambient-pressure solutions, and would be expected to generate a free gas phase within the sediments. The curvature in H_2(aq) is related to the diminishing reactivity of olivine as its volume fraction is depleted, and the increased diffusional gradient of H_2(aq) out of the domain.

Tosca et al. Nature Geoscience 2018

Cloud warming?

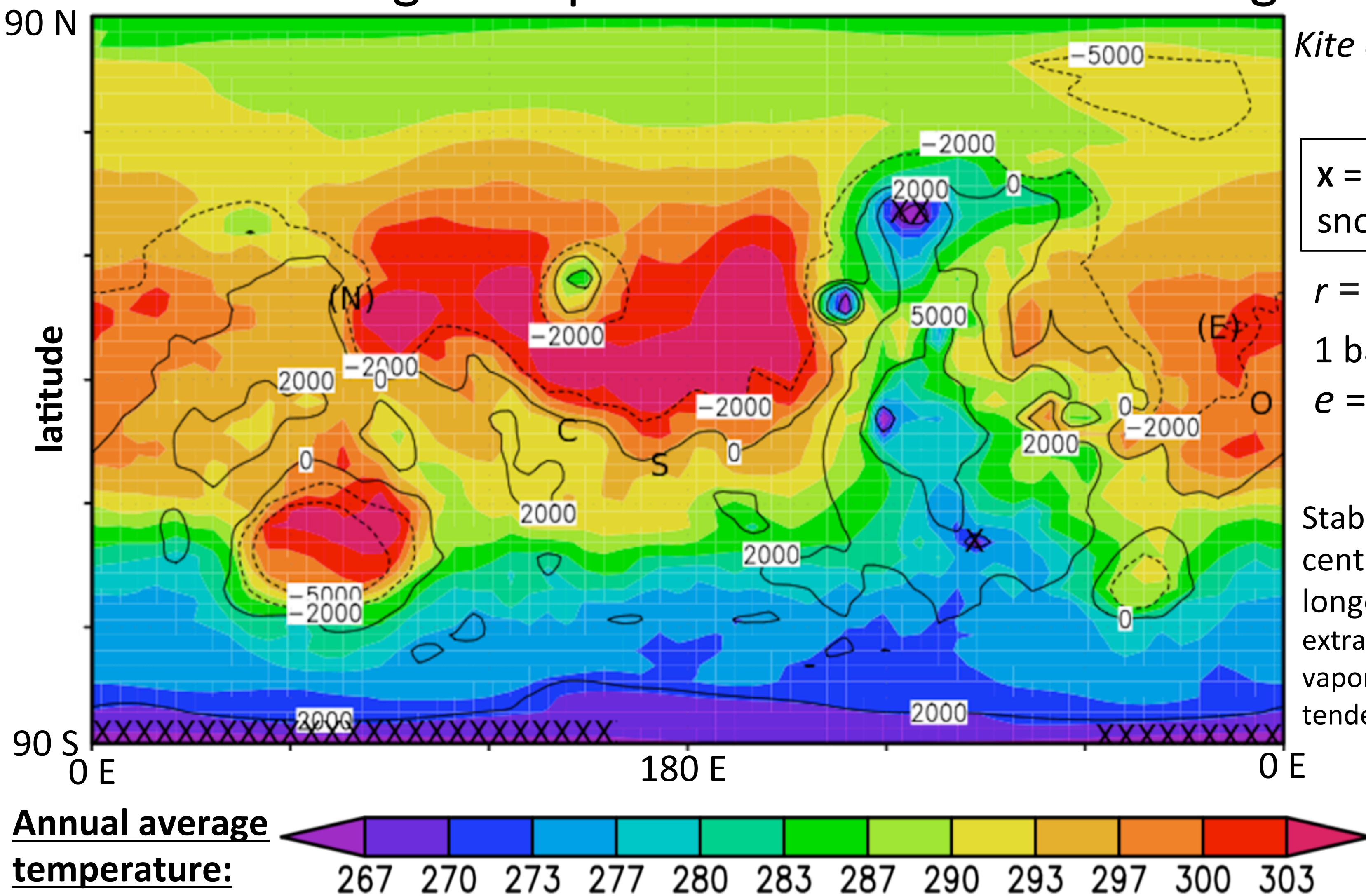
The H_2O-ice cloud greenhouse for Early Mars[1] has proven difficult to replicate[2], and has been argued to require unrealistic cloud lifetimes and unrealistic cloud coverage.[3,4]



1. Urata & Toon 2013. 2. Wordsworth 2016.
3. Ramirez & Kasting 2017. 4. Turbet, PhD thesis, 2018.

Warm climates emerge in our simulations

Annual average temperature > 290K on Mars highlands



Kite et al. in prep

x = stable snow/ice

r = 5*μm*

1 bar CO_2

$e = 0$, $\phi = 0°$

Stable for centuries or longer, based on extrapolation of vapor column tendencies.

Cold/dry start. Contours mark elevation in m.

Letters are current (**C**,**S**,**O**) and future (**N**ASA, **E**SA) rover sites.

Climate stabilization on early Mars

MODERN MARS CLIMATE

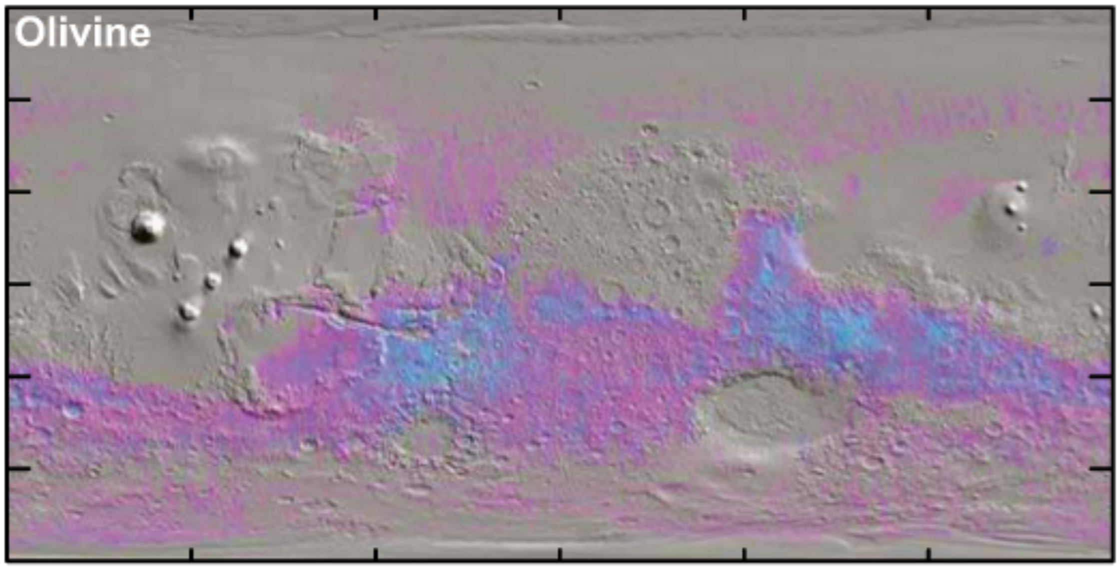
CARBON FEEDBACKS?

SULFUR FEEDBACKS?

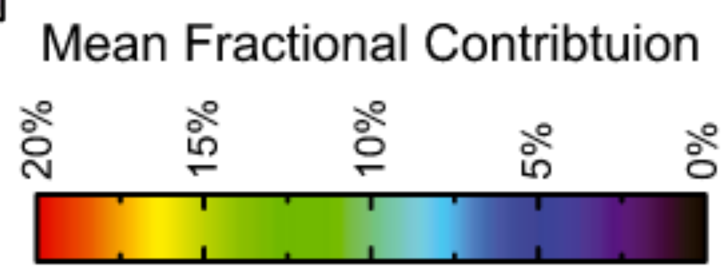
HYDROGEN?

INTERMITTENCY?

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

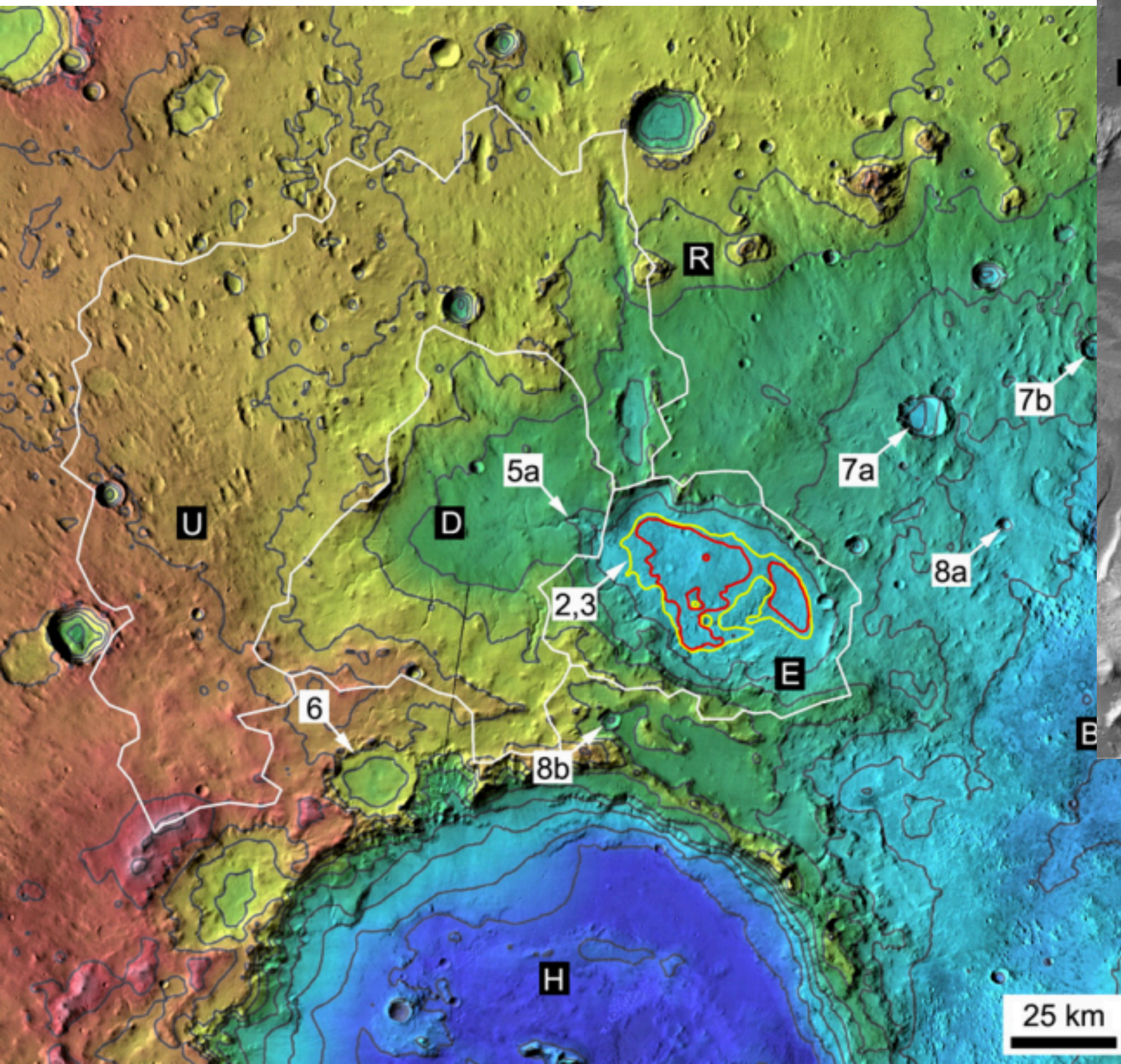


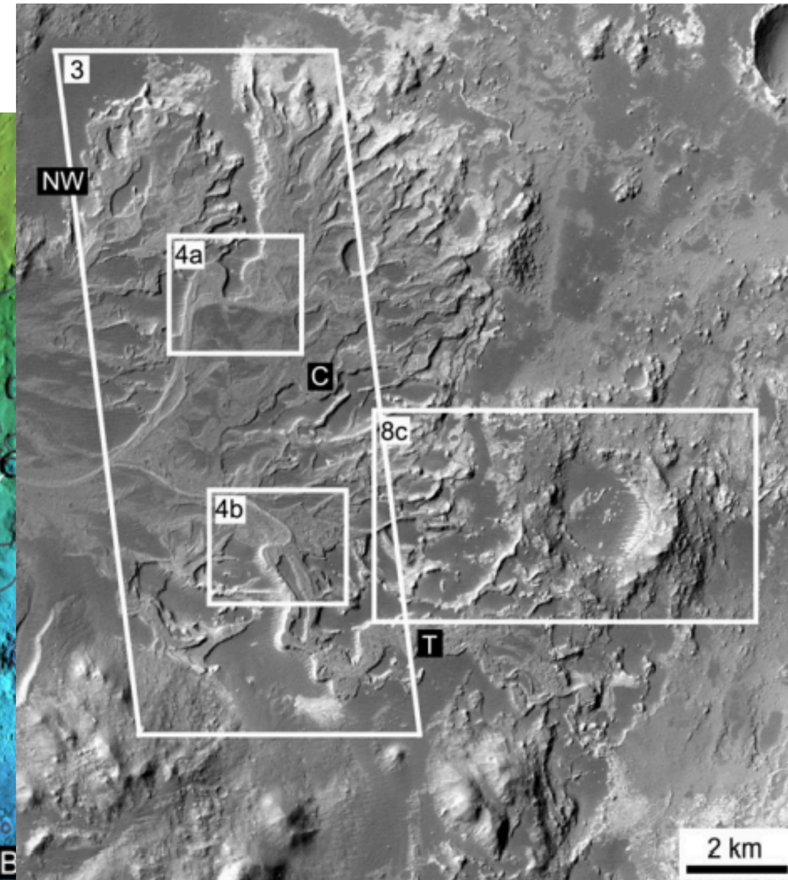
Koeppen & Hamilton, JGR-Planets, 2008



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

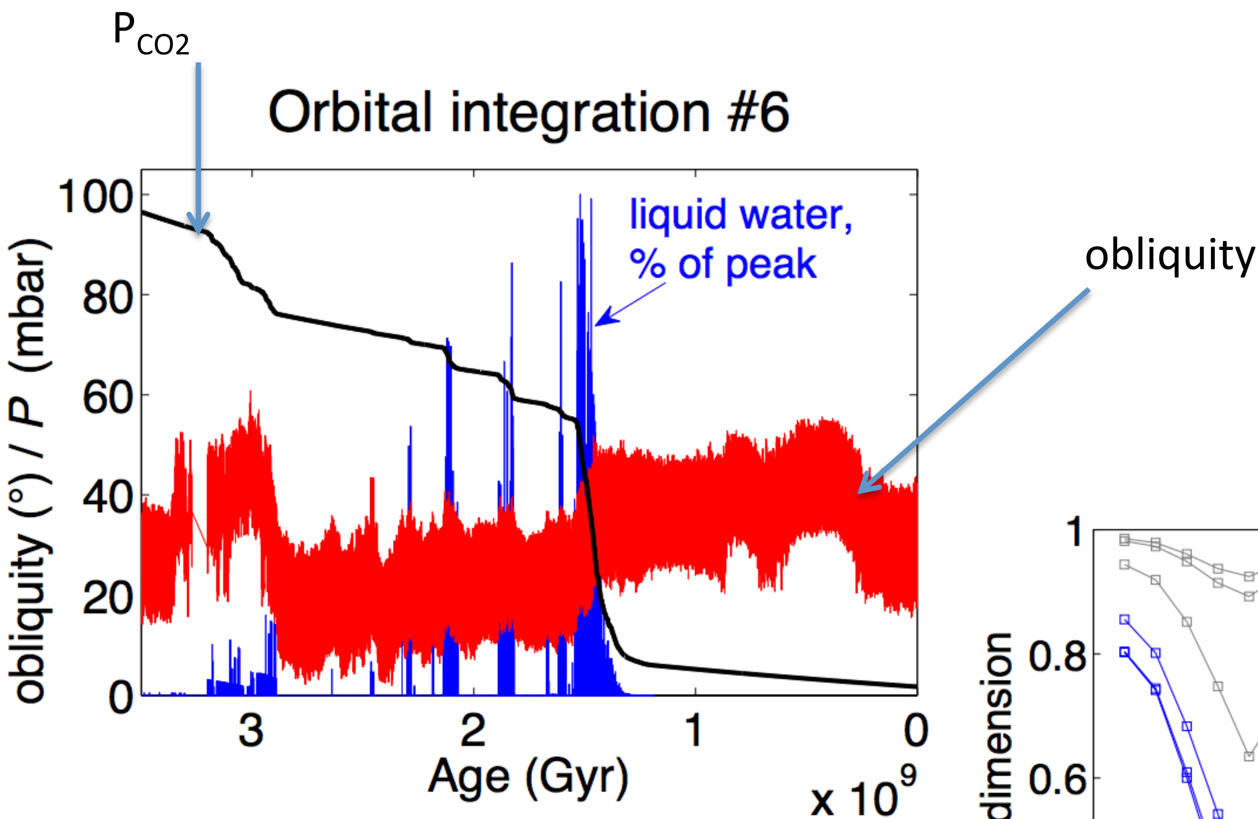
Paleolake hydrology requires >$10^{4\text{-}5}$ continuous wet years (e.g., seasonal runoff)

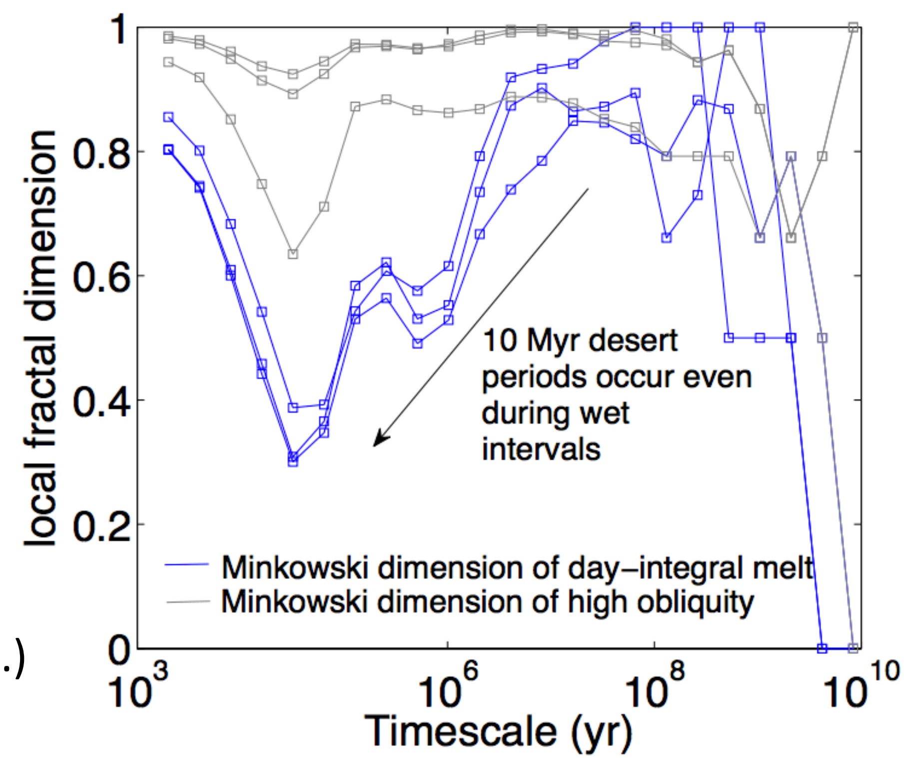




Irwin et al., Geomorphology 2015

Statistics of intermittent habitability on Mars





Ongoing work
(Kite et al. LPSC 2015; Mansfield et al. JGR 2018.)

Can Mars be made habitable in the near future?
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 (21^{st}-century) technologies
Goal: Habitable for photosynthetic algae/ plants
Asteroid kinetic energy, nuclear bombs, e.t.c. is insufficient

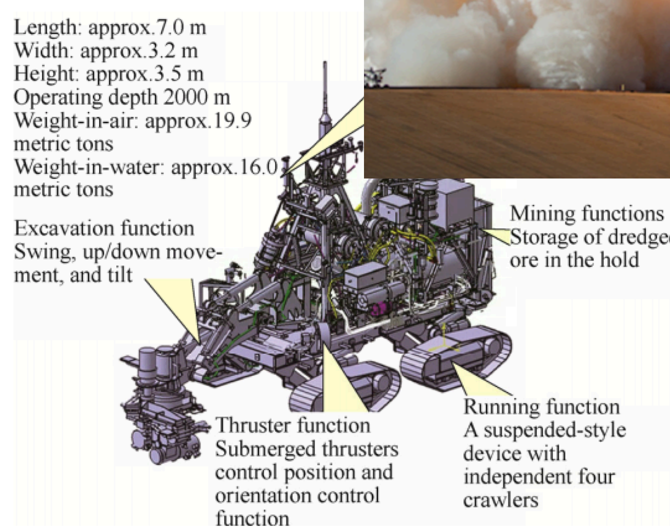


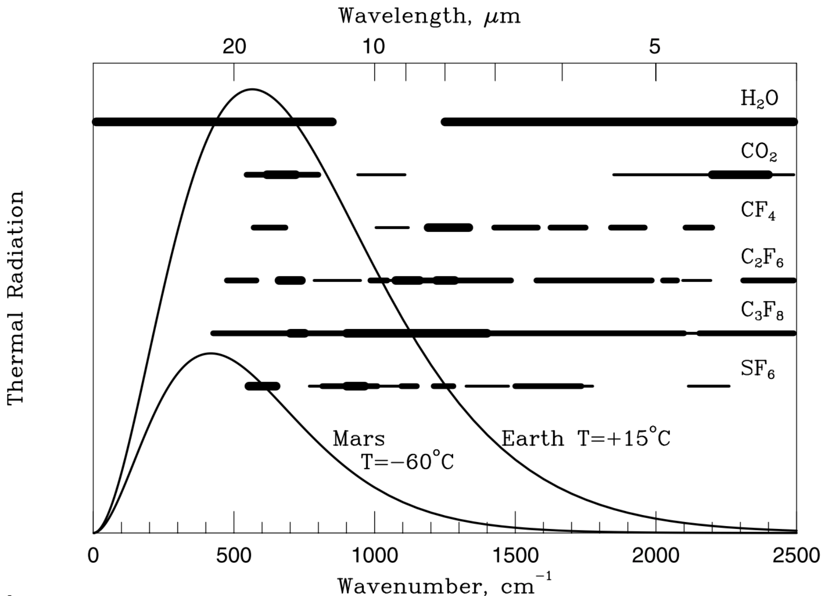
Fig. 12. Structure of SMS deposit mining machine developed by Japan

Liu et al. *Chinese J. Mech. Eng.* 2016

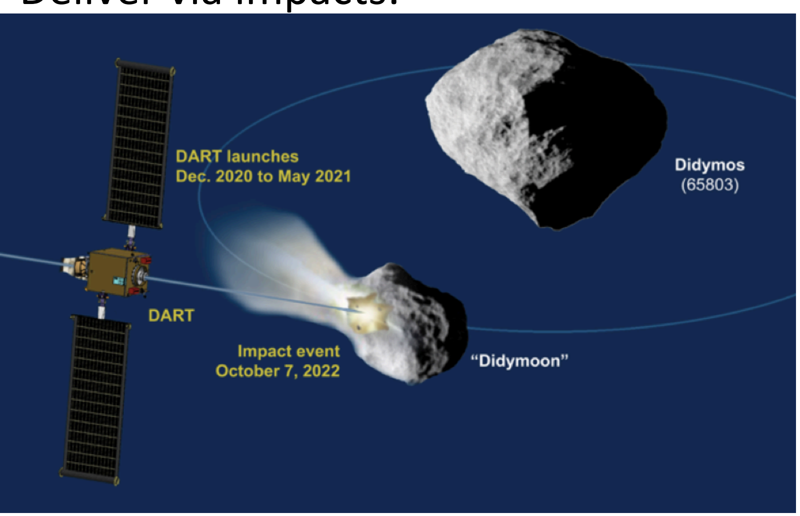
Practical robot mining vehicles exist

Can Mars be made habitable in the near future? Gases vs. particles

Gases option: Make on surface: Marinova+ 2005 JGR



Deliver via impacts:



Double Asteroid Redirection Test (launch 2020)

Particles option: inject resonant absorbers at stratospheric height

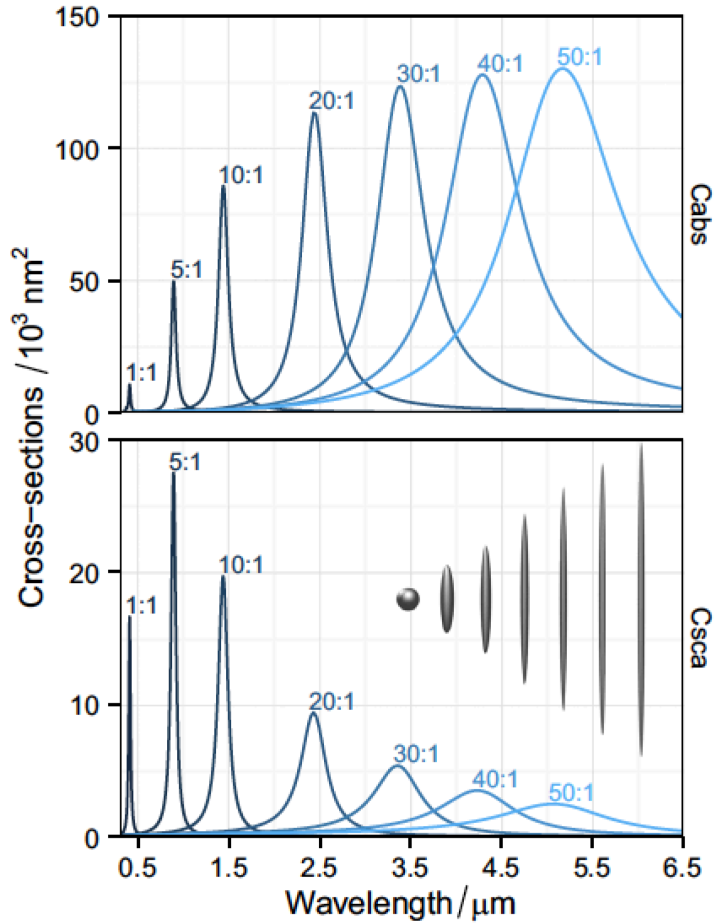


Fig. 2. Example calculation of scattering and absorption spectra of prolate Ag spheroids in water with varying aspect ratio h (1–50), with a fixed equivalent-volume radius r_V=20 nm.

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

See also Teller et al., Lawrence Livermore National Lab report UCRL-231636/UCRL JC 128715

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.

Backup/additional slides