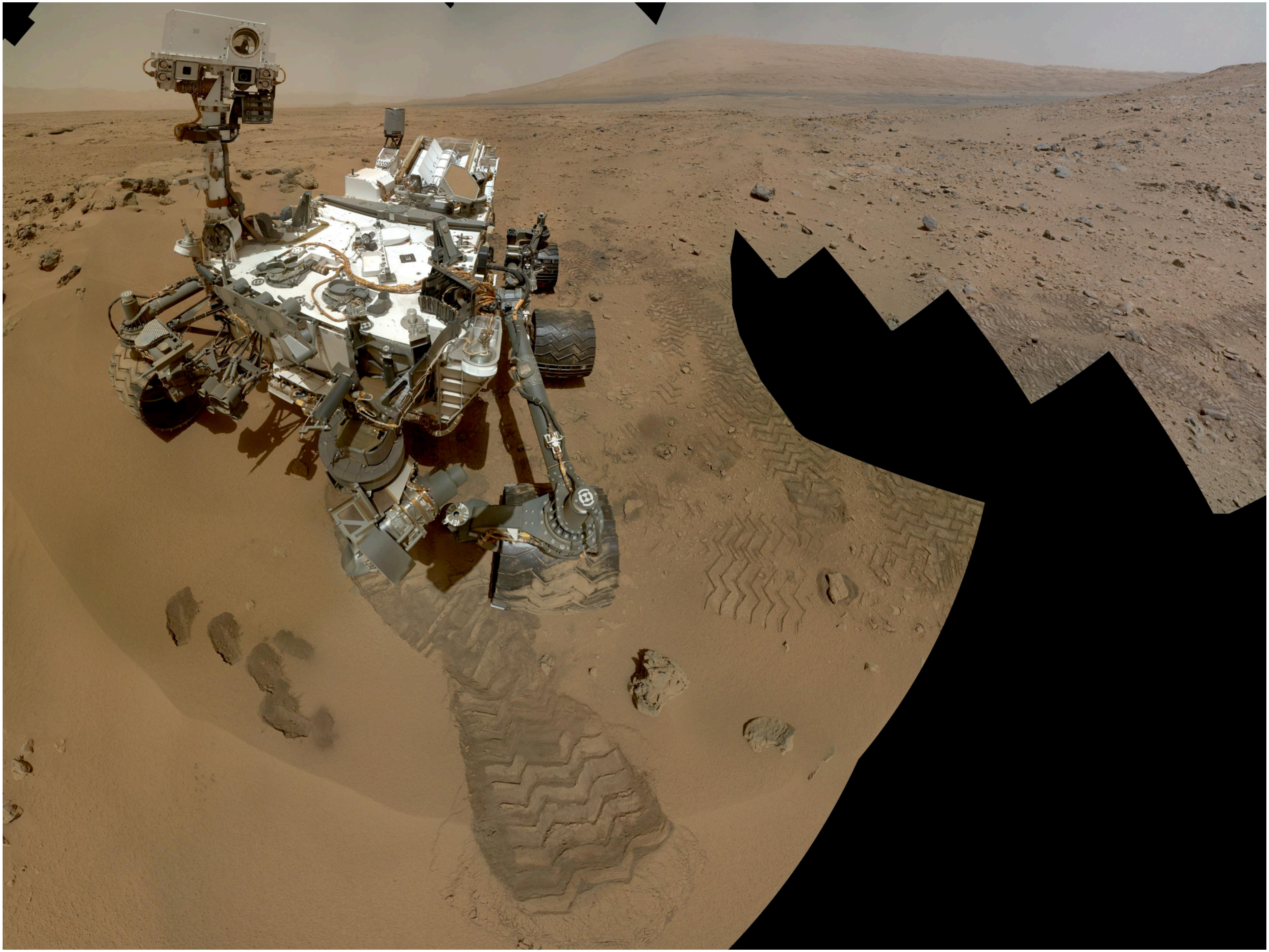
Confronting Early Mars climate models with data

Edwin Kite (U. Chicago)

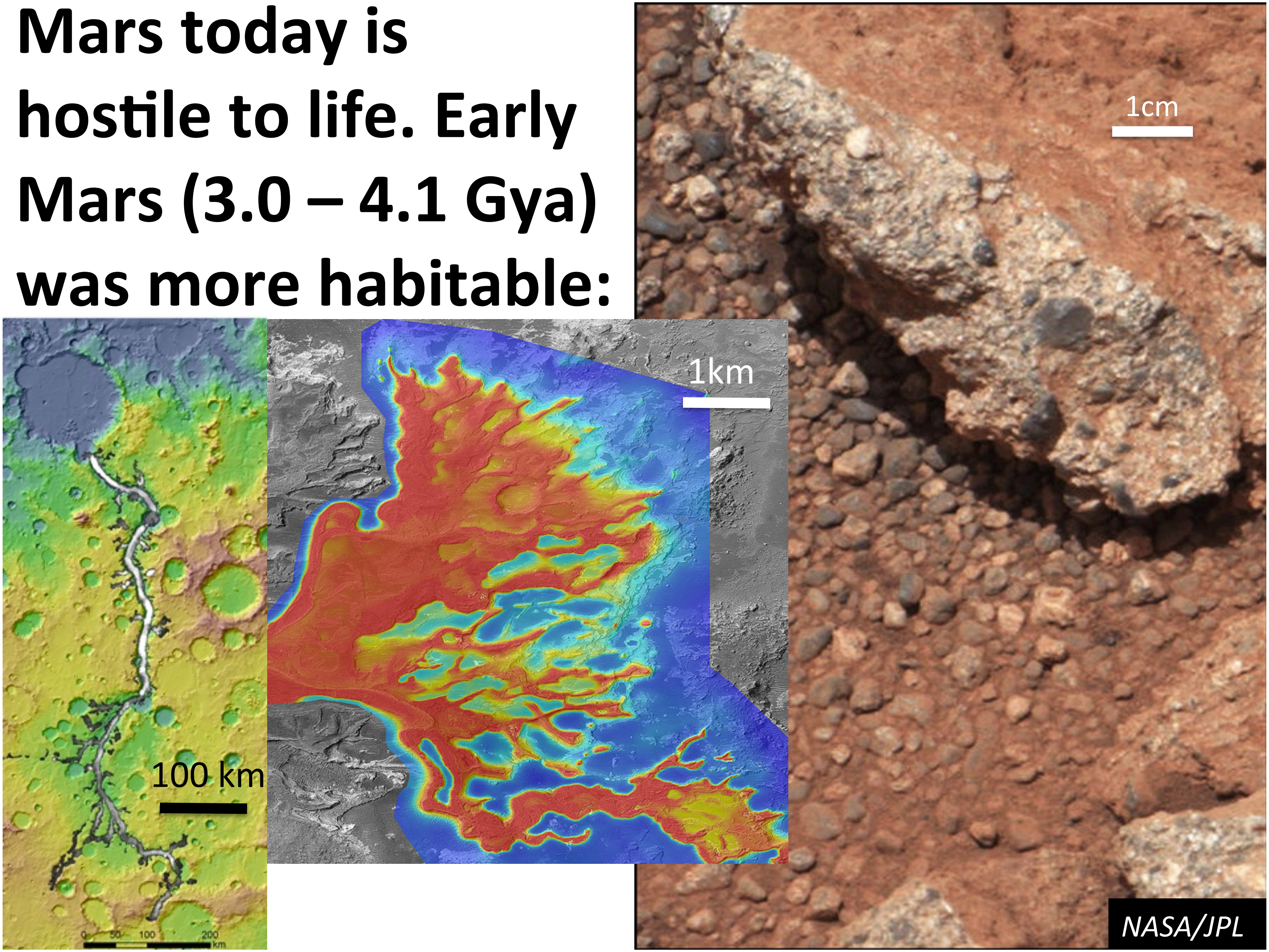
University of Bern, 19 April 2017

Thanks to: **Jonathan Sneed (U. Chicago)**, **David Mayer (U. Chicago → USGS Astrogeology)**, Michael Mischna (JPL), Yuk Yung & Mike Lamb (Caltech), Bill Dietrich & Michael Manga (UC Berkeley), Peter Gao (NASA Ames → UC Berkeley), Sharon Wilson (Smithsonian), Scot Rafkin (SwRI Boulder), **Alan Howard (U. Virginia),** Antoine Lucas (U. Paris), Colin Goldblatt (U. Victoria), **Tim Michaels (SETI Institute)**, Kevin Lewis (JHU), Nicolas Mangold (U. Nantes), Oded Aharonson & **Itay Halevy (Weizmann),** Claire Newman & Mark Richardson (Ashima Research), Caleb Fassett (NASA Marshall), **Jean-Pierre Williams (UCLA).**

THE UNIVERSITY OF CHICAGO



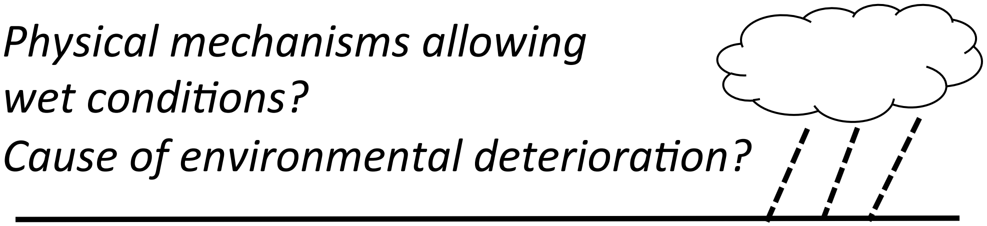
Mars today is hostile to life. Early Mars (3.0 – 4.1 Gya) was more habitable:



NASA/JPL

Understanding Mars' climate change requires physics approach & forensics approach

Physical mechanisms allowing wet conditions?
Cause of environmental deterioration?



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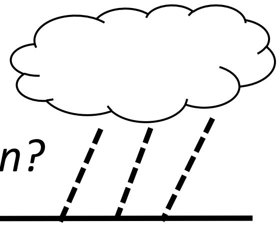
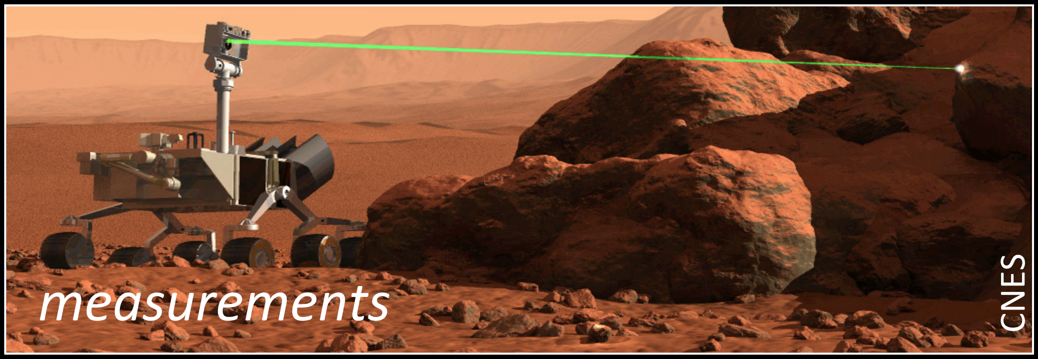
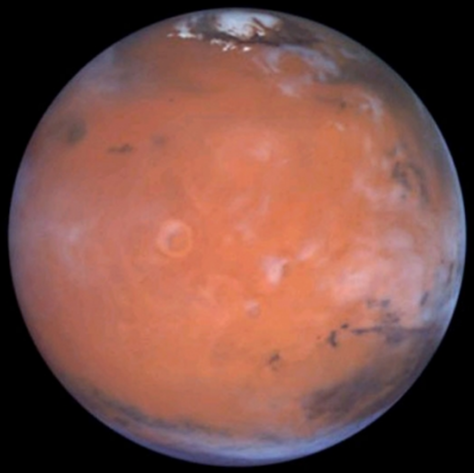
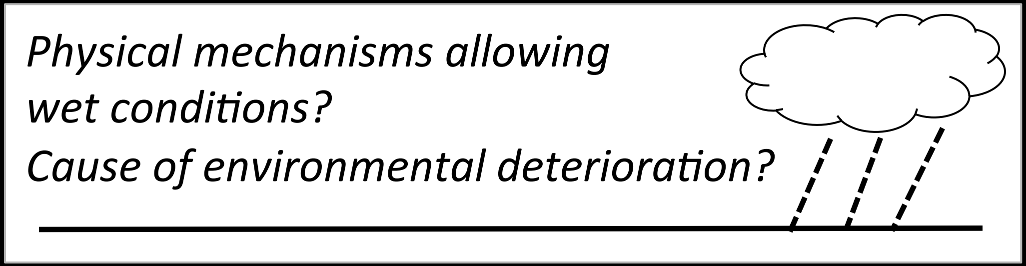




CNES

Understanding Mars' climate change requires physics approach & forensics approach

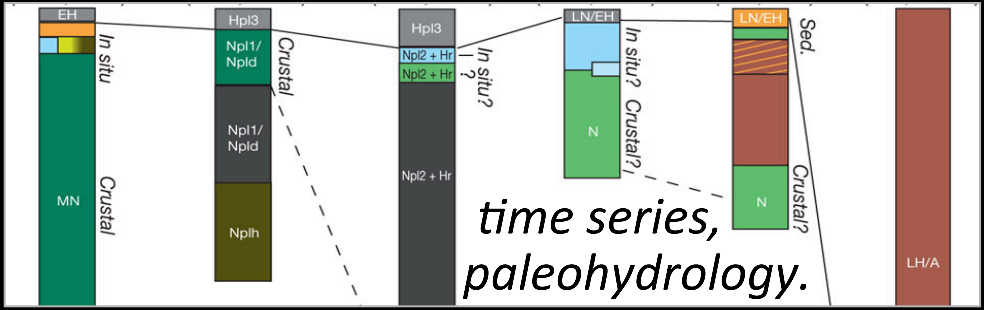




Physical mechanisms allowing wet conditions?

Cause of environmental deterioration?

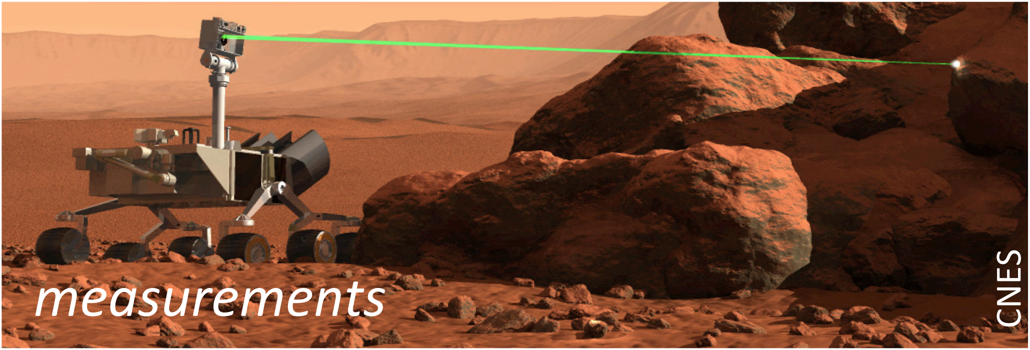
↕ reconstruct climate, mechanisms



time series, paleohydrology.

Ehlmann et al., 2011

↑ geologic synthesis



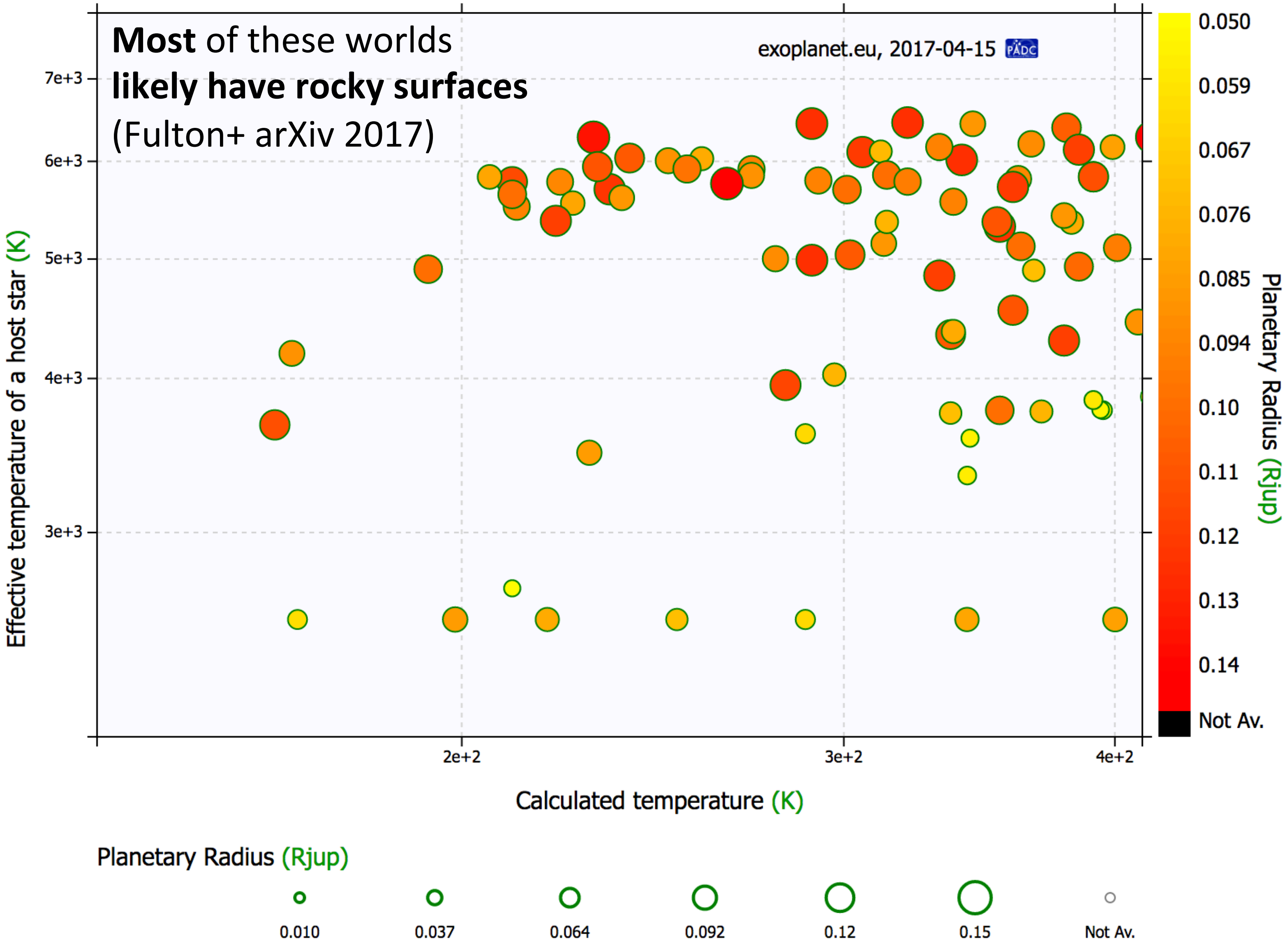
measurements

CNES

Is Earth a fluke, or are habitable climates common?

Habitable planet ≈ maintains surface liquid water over timescales relevant to macroevolution

>¼ Earth-radius rocky habitable zone planets/star - Dressing & Charbonneau ApJ 2015



Most of these worlds
likely have rocky surfaces
(Fulton+ arXiv 2017)

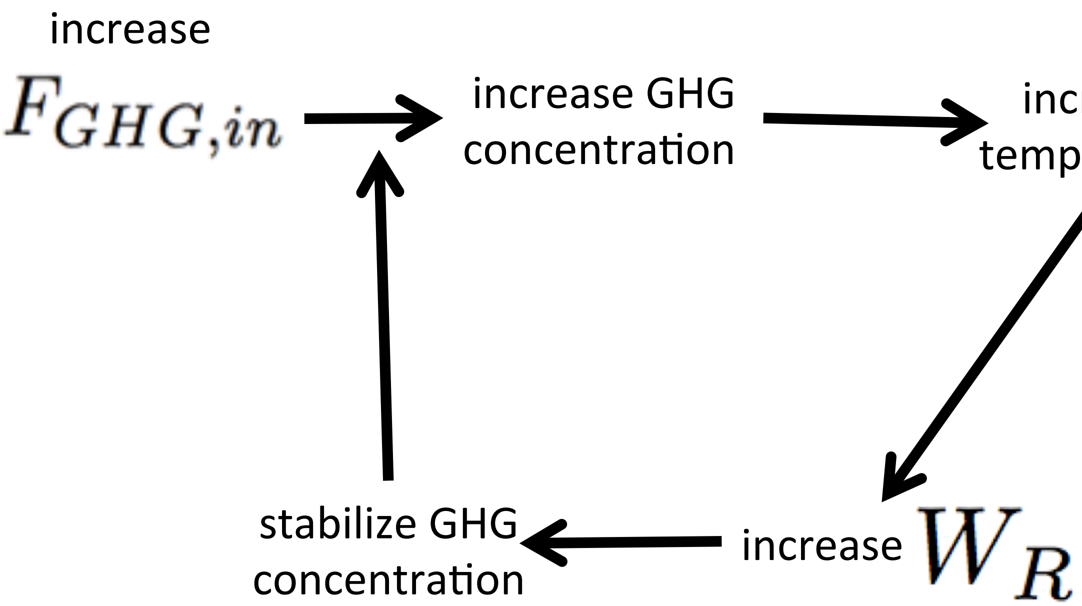
Is Earth a fluke, or are habitable climates common?

Habitable planet ≈ maintains surface liquid water over timescales relevant to macroevolution

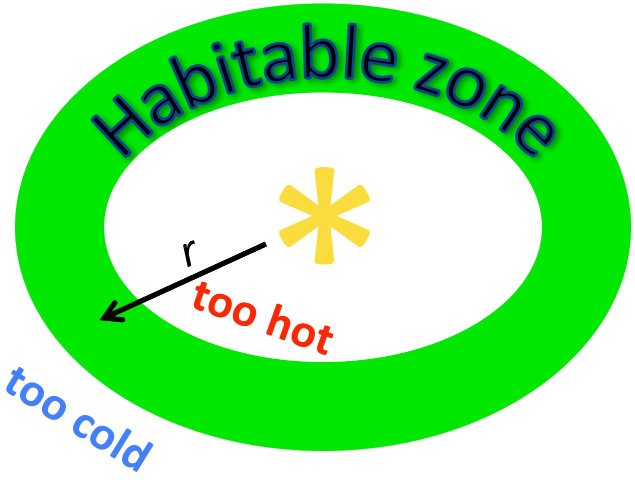
Long-term climate stability on Earth involves nonlinear temperature dependence of greenhouse gas drawdown by weathering.

Walker et al. JGR 1981, Kasting et al. Icarus 1993

<u>Stabilizing feedback:</u>



increase $F_{GHG,in}$ → increase GHG concentration → increase temperature → increase W_R → stabilize GHG concentration → increase $F_{GHG,in}$



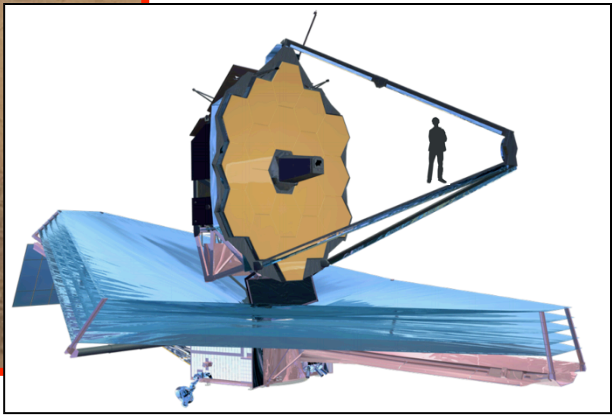
Is Earth a fluke, or are habitable climates common?

Next steps:

Long term planetary habitability is not understood
Mars is a nearby world known to record a major transition in planetary habitability.

Yorkshire Coast, Earth
Toarcian OAE

Gale Crater, Mars
Early Mars Climate Problem



Future large segmented telescopes
Exoplanet spectroscopy

Understanding Mars' climate history is important:

Directs the search for surface (paleo)life on Mars

What time window is best to search for fossil life?

Comparative planetology

Test of Earth-based theories

Apply Earth tools to Mars

Hydrology, sedimentology, geomorphology

Understand distribution of resources
for Mars exploration, settlement, terraforming

Water, halides, rocket propellant …

Early Mars climate

CONSTRAINTS

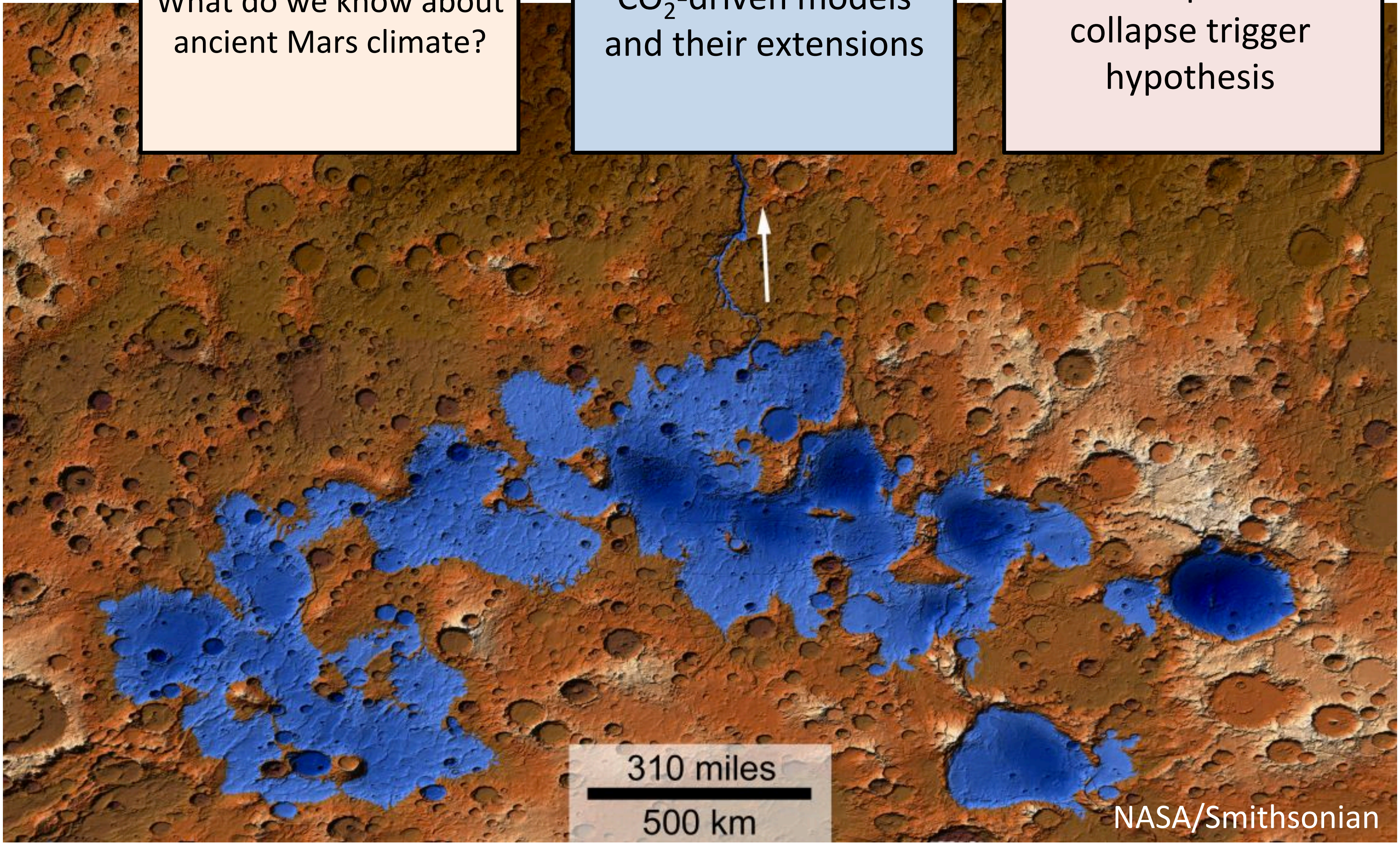
What do we know about ancient Mars climate?

EXISTING MODELS

CO_2-driven models and their extensions

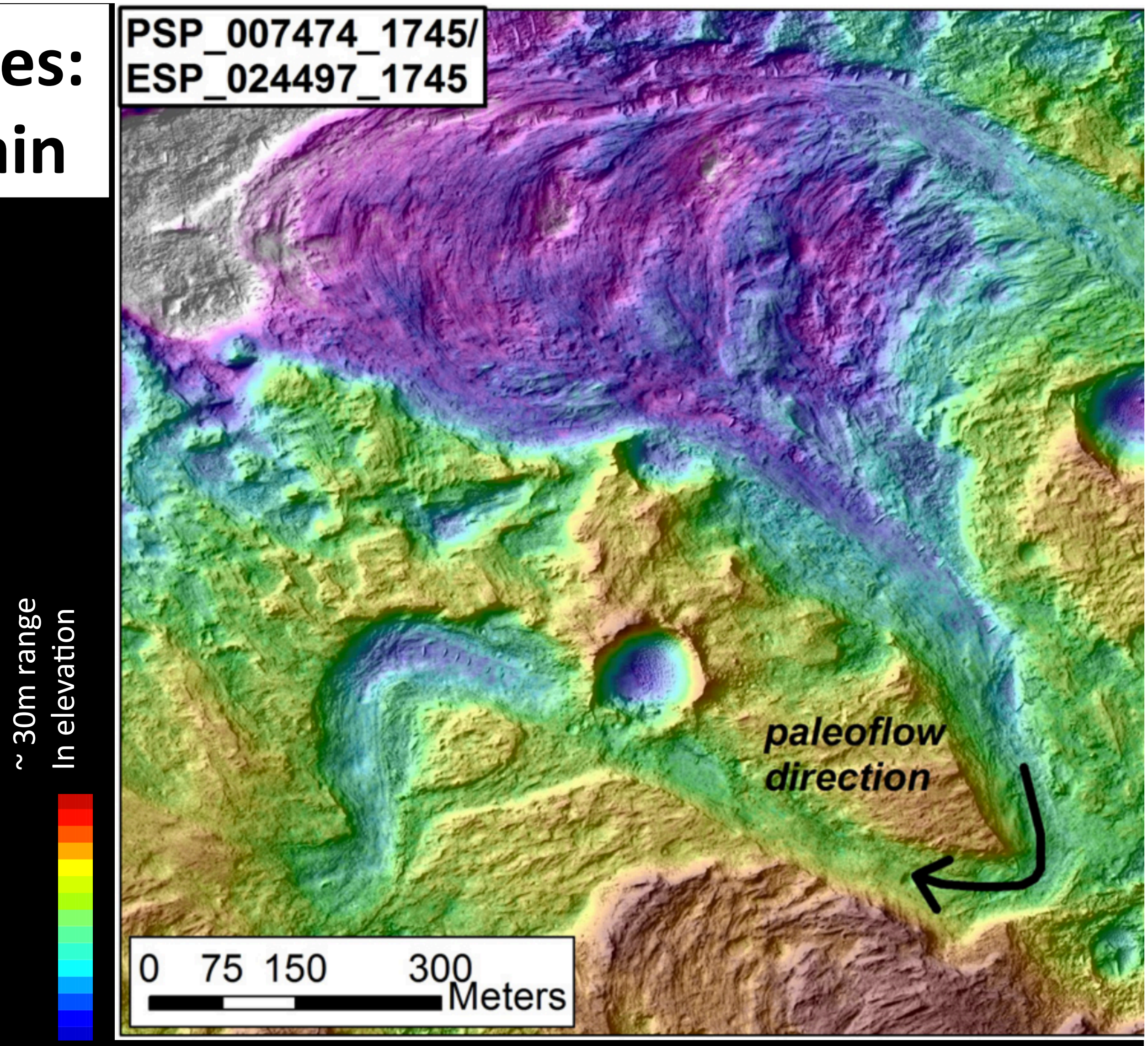
NEW MODEL

Atmospheric-collapse trigger hypothesis



NASA/Smithsonian

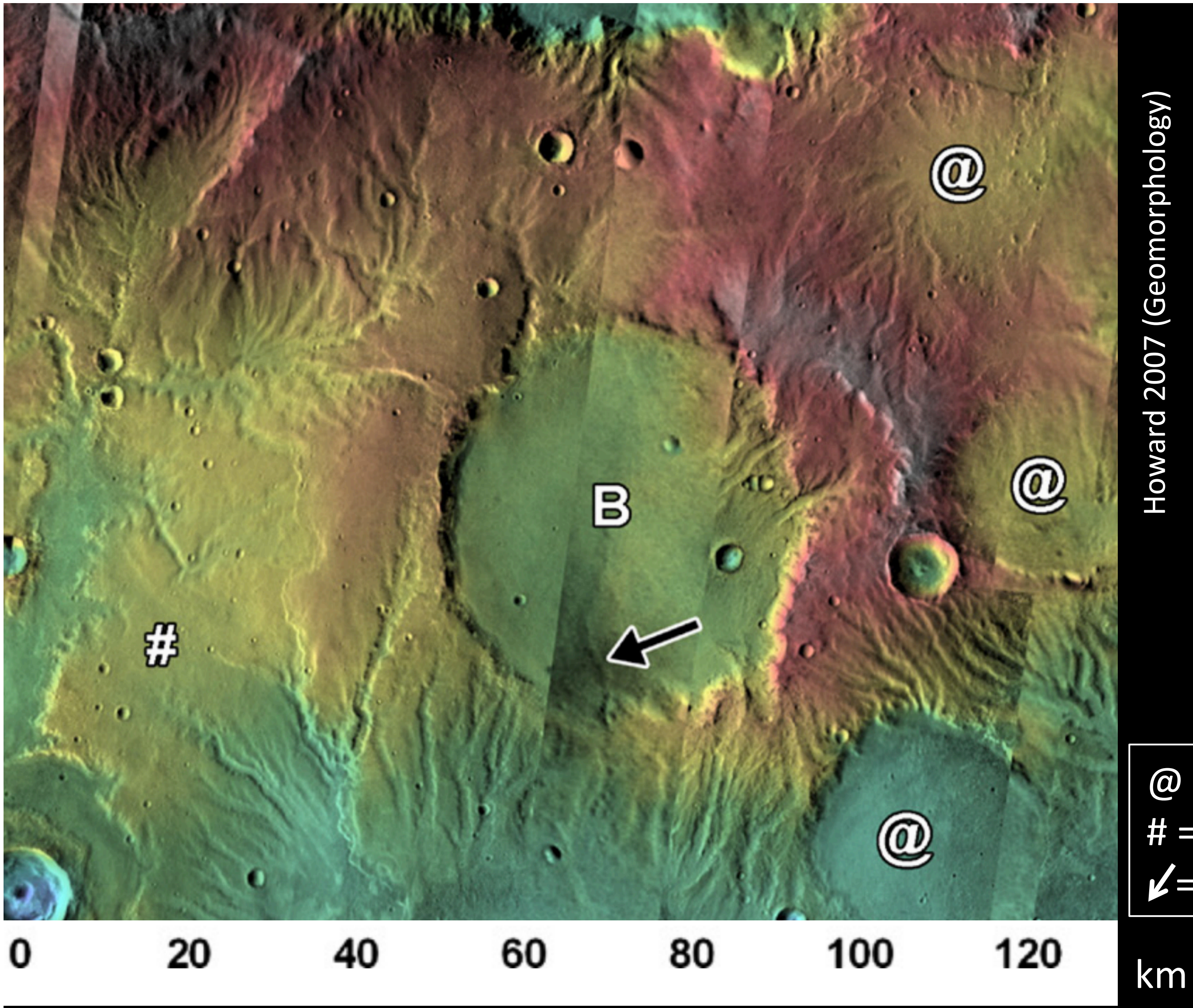
Ancient rivers & lakes: challenging to explain



unambiguous:
H_2O-precipitation-fed rivers
(rain or snowmelt)

Kite et al. Icarus 2015; Kite et al. EPSL 2015;
Kite et al. JGR 2016; Kite et al. GRL 2017

River canyons are ~100m deep. Many but not all crater lakes overflowed



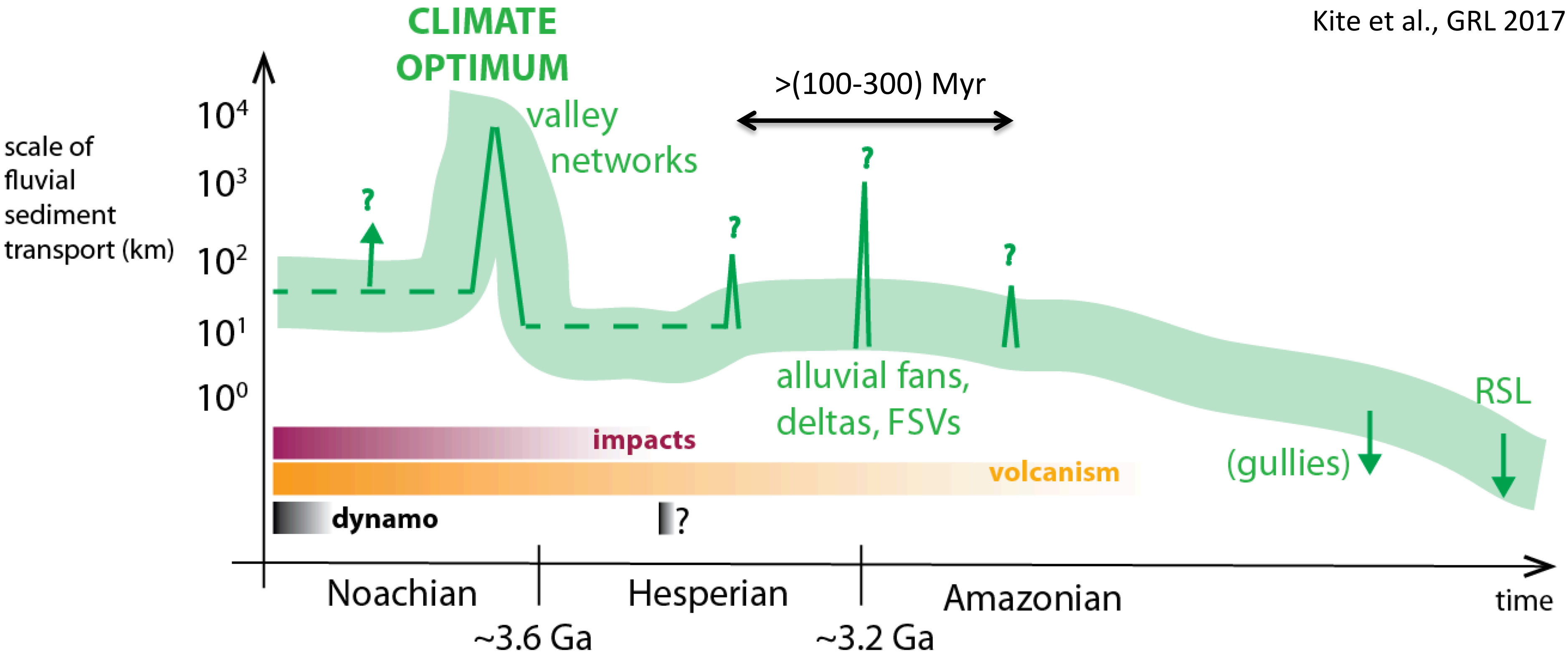
Howard 2007 (Geomorphology)

@ = infilled craters
# = broad platforms
↙= exit breach

Optimum was not catastrophic (because not all lakes overflowed; Barnhart et al. 2009)
Hydrological cycle lasted >10^5 yr (Barnhart et al. 2009, Hoke et al. 2011)

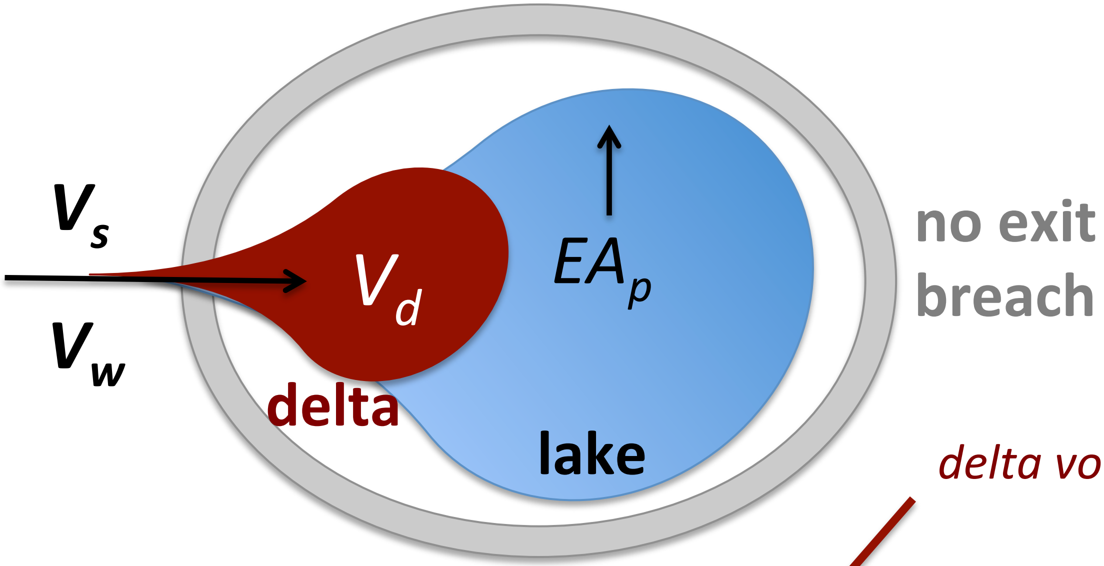
Geology shows multiple river-forming climates spanning >10^9 yr

Kite et al., GRL 2017



e.g. Howard 2007 Geomorphology; Golombek et al. 2014 JGR; Irwin et al. 2015 Geomorphology; Wilson et al. 2016 JGR; Irwin et al. 2013 JGR; Mangold et al. 2012; Mangold et al. 2004; Kite et al. 2015 Icarus; Grant & Wilson 2011 GRL; Barnhart et al. 2009; Fassett & Head 2008. Omitted: cryosphere-melt deltas, outflow channels.

Lifetime >(2-10) Kyr for individual lake-forming climates:



delta volume

$$\tau_l > V_d \underline{(V_w/V_s)}/EA_p$$

water:sediment ratio

max. evaporation rate

lake area

e.g. Irwin et al., Geomorphology, 2015; Palucis et al., JGR-Planets, 2016; Williams & Weitz, Icarus, 2014; Kite et al., arXiv 1611.01717. Consistent with *Curiosity* rover data (e.g. Grotzinger et al. Science 2015)… but perennial lakes can exist at T_{ave} = 254K (e.g. Doran et al. JGR 2002)

$<10^7$ yr soil wetting
to permit globally persistent olivine

"[A] fundamental paradox"
– S. McLennan, SEPM Sp. Pub. 102, 2012

Hausrath et al. 2006, Olson & Rimstidt 2007,
Tosca & Knoll 2009, Bishop & Rampe 2016, Berger et al. 2009,
Zolotov & Mironenko 2016. See also Carter et al 2015.

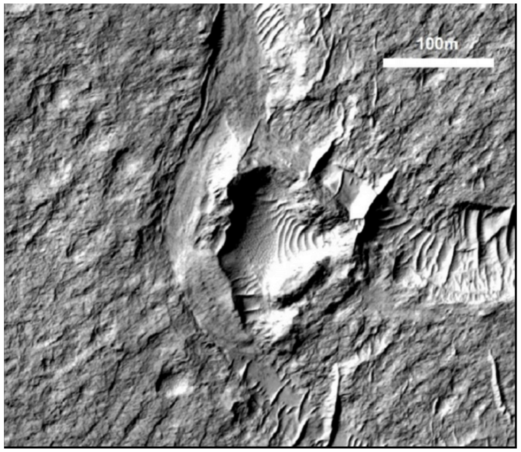
Impact-filtering paleo-barometer for planetary atmospheres

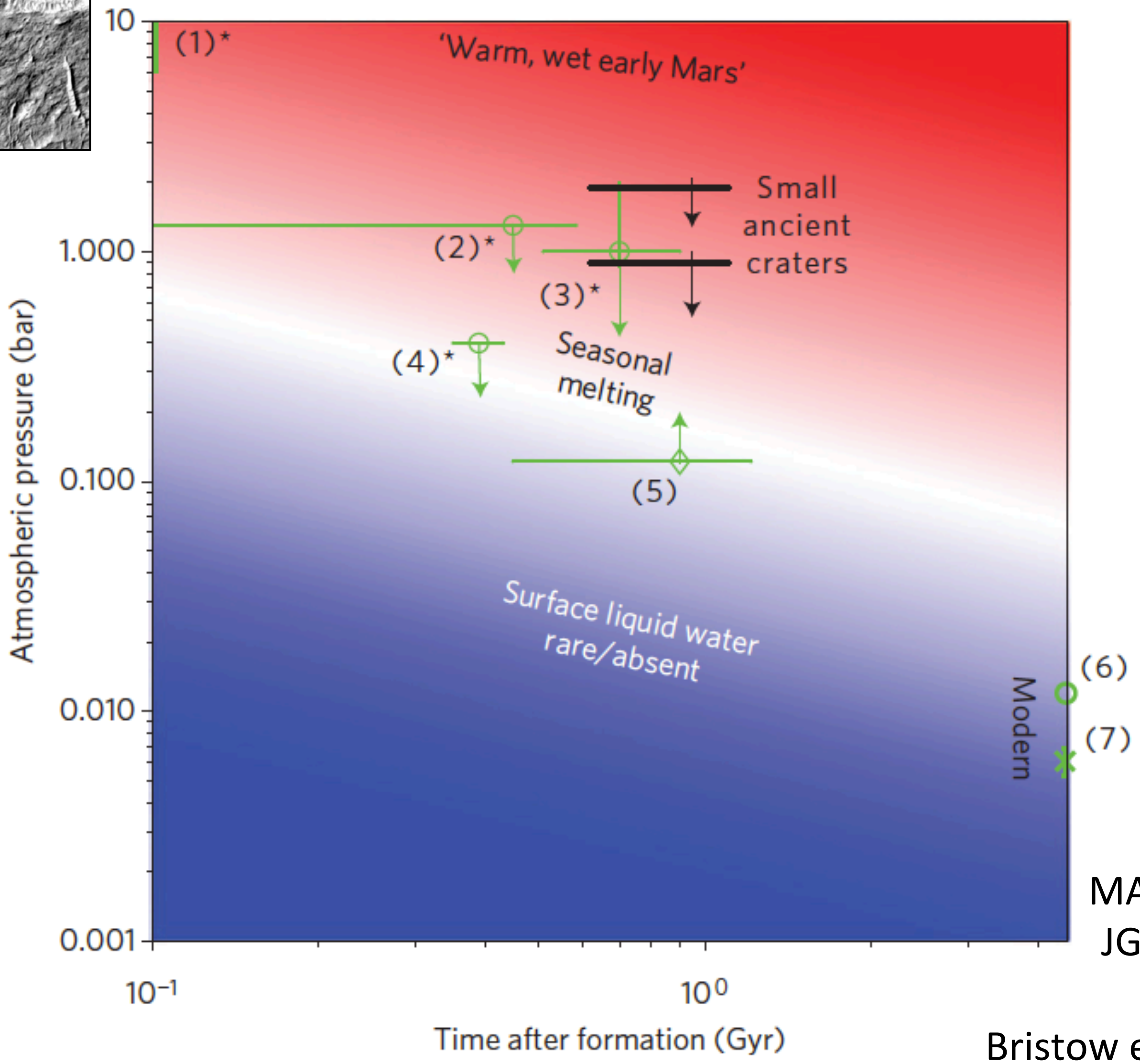
Kite, Williams, Lucas & Aharonson, Nature Geoscience, 2014

Chelyabinsk fireball, 2013

$P_{atm} \lesssim$ **1 bar by 3.6 Ga** from first implementation of impact-filtering atmospheric paleobarometer

Kite, Williams, Lucas & Aharonson, Nature Geoscience, 2014





Consistent with MAVEN (Lillis et al. JGR-Space Physics 2017). See also Bristow et al. PNAS 2017

Early Mars climate data

CONSTRAINTS

What do we know about ancient Mars climate?

Among wet-era features, the most challenging to explain are rivers and lakes. Many of Mars' rivers and lakes were rain- or snowmelt-fed. Individual lakes lasted $>10^3$ yr. Lake-forming climates *span* $>10^9$ yr, but minor weathering suggests intermittency. A relatively brief (but $\gtrsim 10^5$ yr) climate optimum started $>3 \times 10^8$ yr after Mars formed. $P_{atm} \lesssim 1$ bar by ~3.6 Ga.

Early Mars climate models

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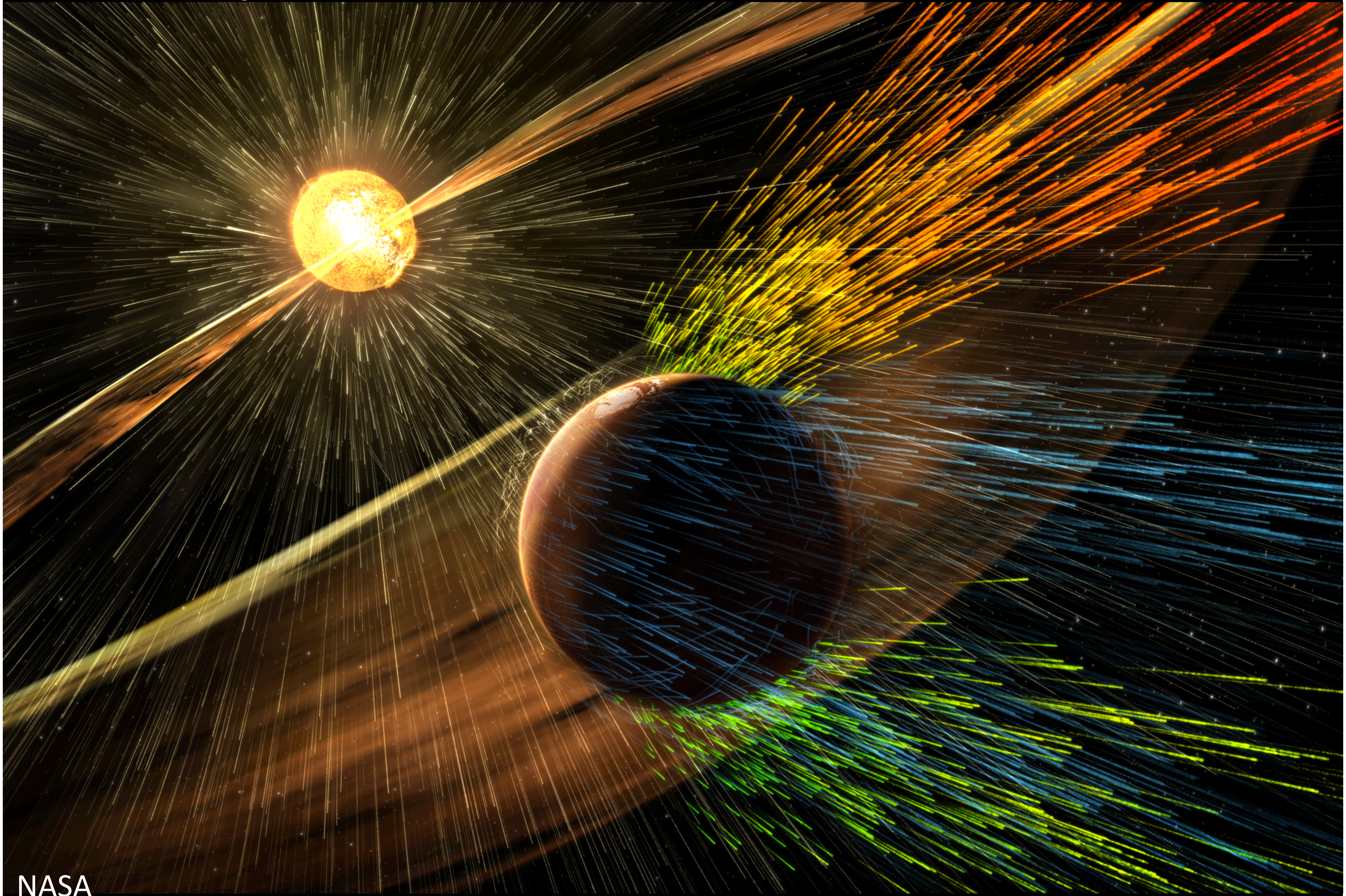
EXISTING MODELS

CO_2-driven models and their extensions

Early Mars had a thicker atmosphere

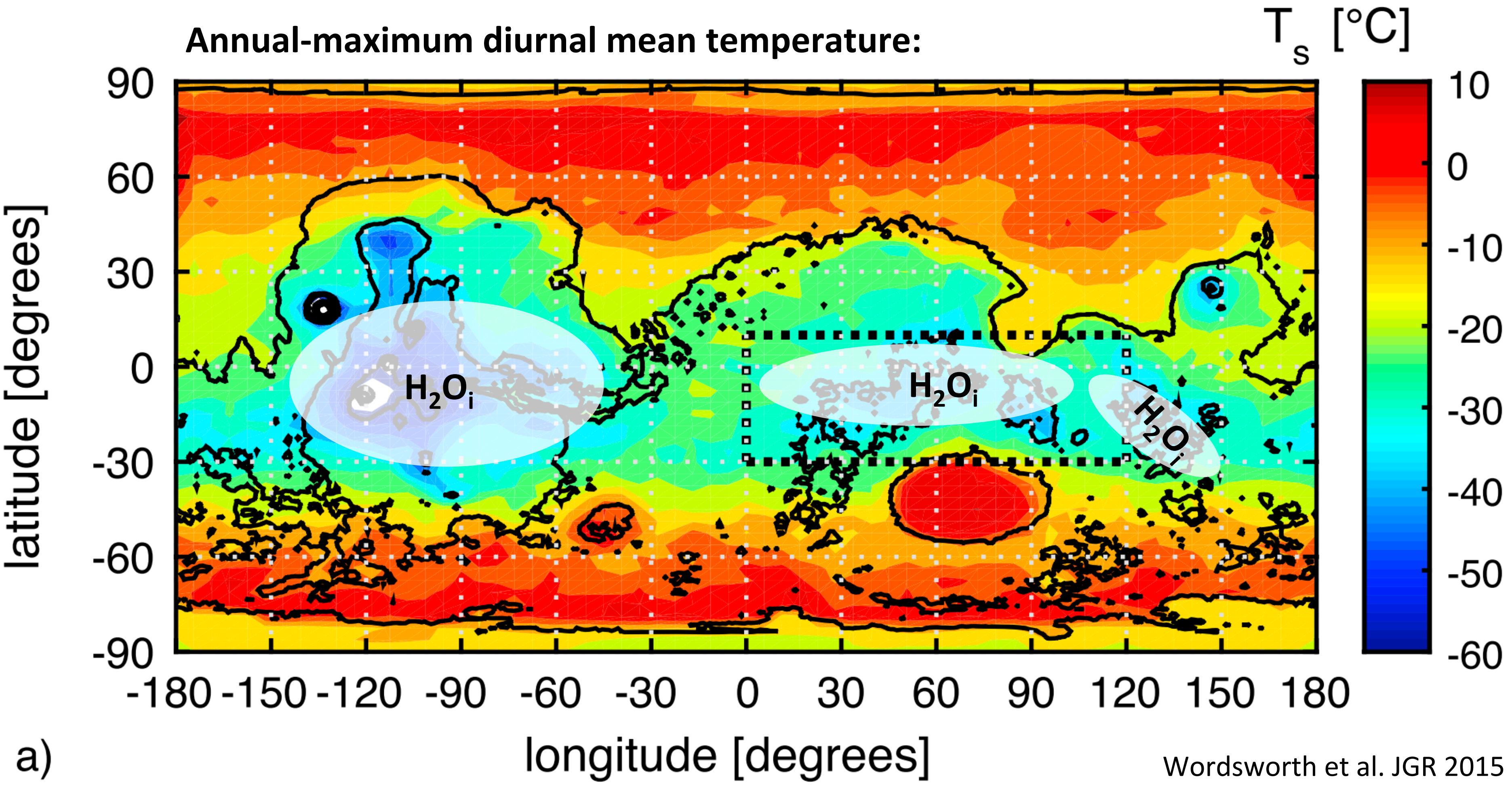


NASA

More CO_2 → necessary but insufficient for lake-forming climates on Mars

Ozak et al. JGR 2016, Haberle et al. JGR 1998
Forget et al. Icarus 2013

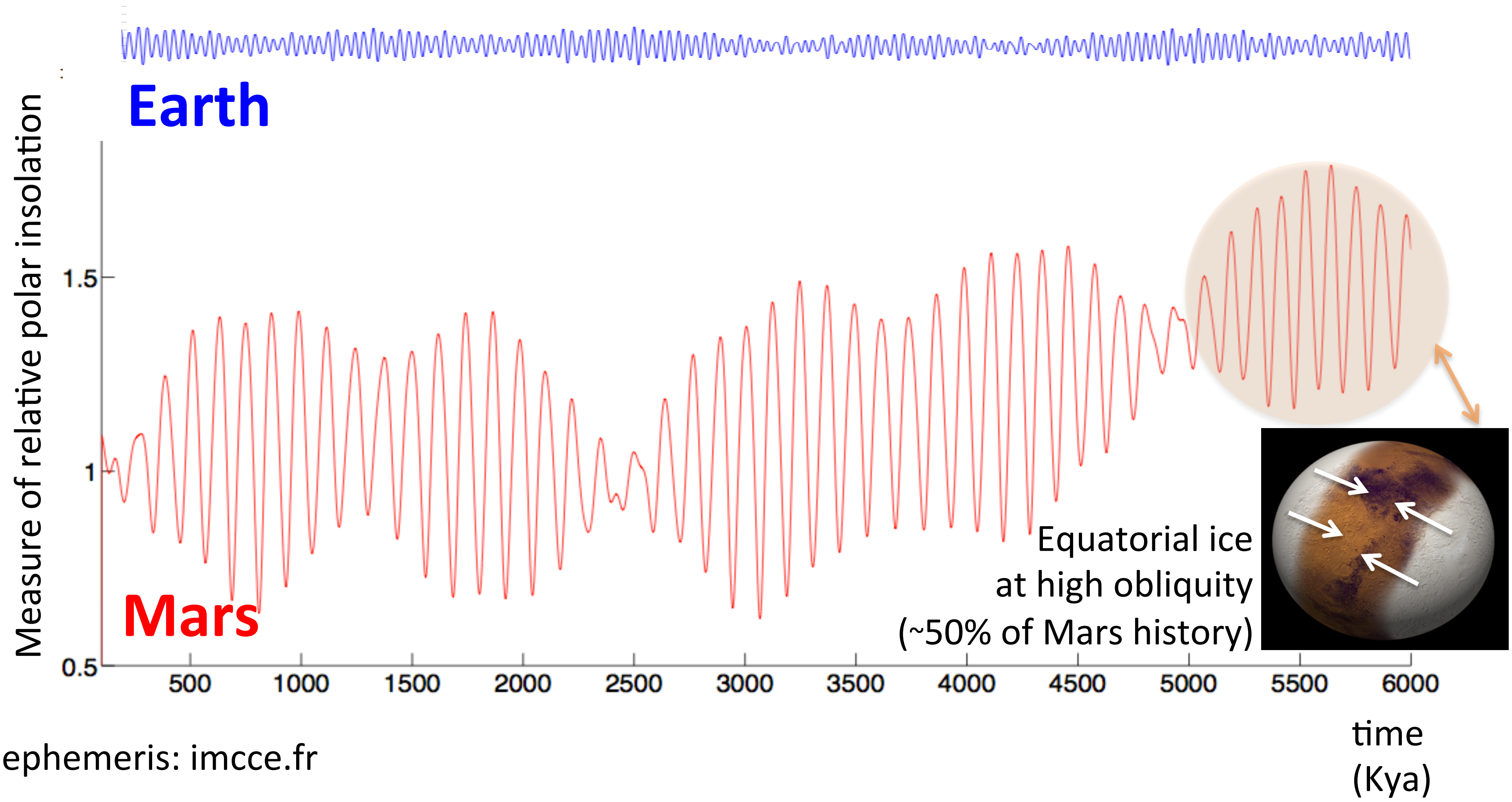
Annual-maximum diurnal mean temperature:



Wordsworth et al. JGR 2015

Mars’ extreme orbital variations influence climate

Kite et al., ‘Seasonal melting …,’ Icarus, 2013



Equatorial ice
at high obliquity
(~50% of Mars history)

ephemeris: imcce.fr

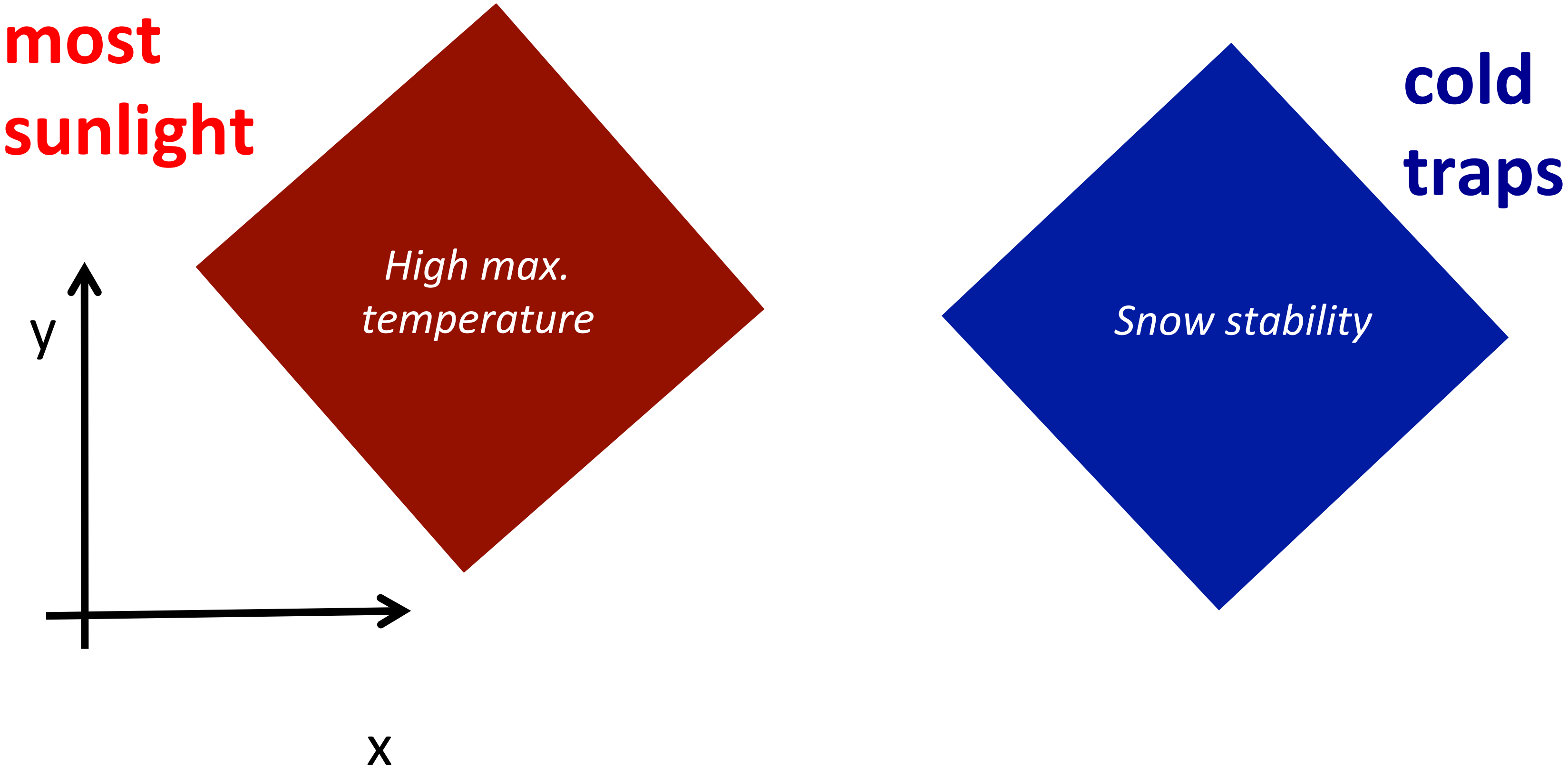
Need to track orbital forcing

Sedimentary record has been ‘wet-pass filtered’

Optimal orbital forcing can produce seasonal snowmelt …

Kite et al., ‘Seasonal melting …’ Icarus, 2013

Typical orbital conditions



most sunlight

High max. temperature

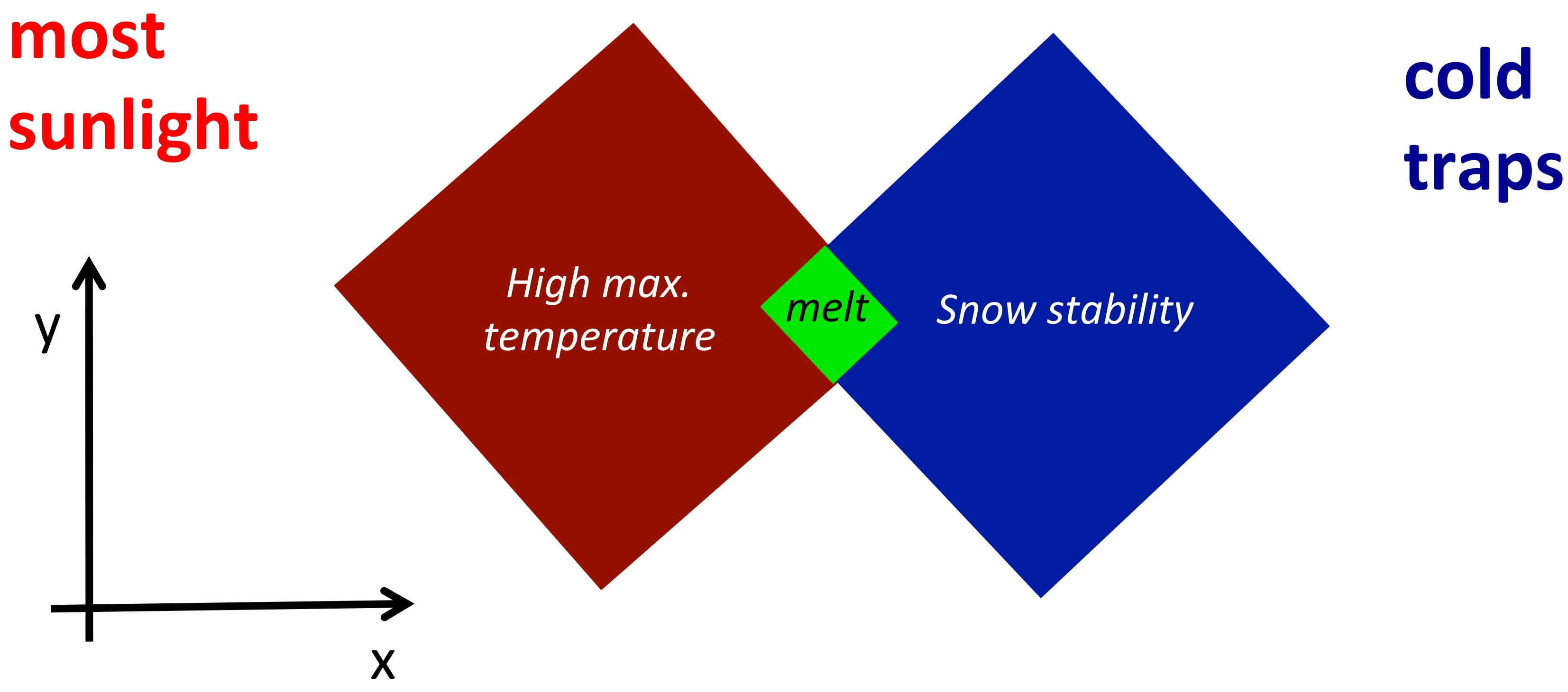
Snow stability

cold traps

However, even optimal orbital forcing struggles to produce enough melt for valley networks.

Kite et al., “Seasonal melting …” Icarus, 2013

Infrequent orbital conditions



most sunlight

High max. temperature

melt

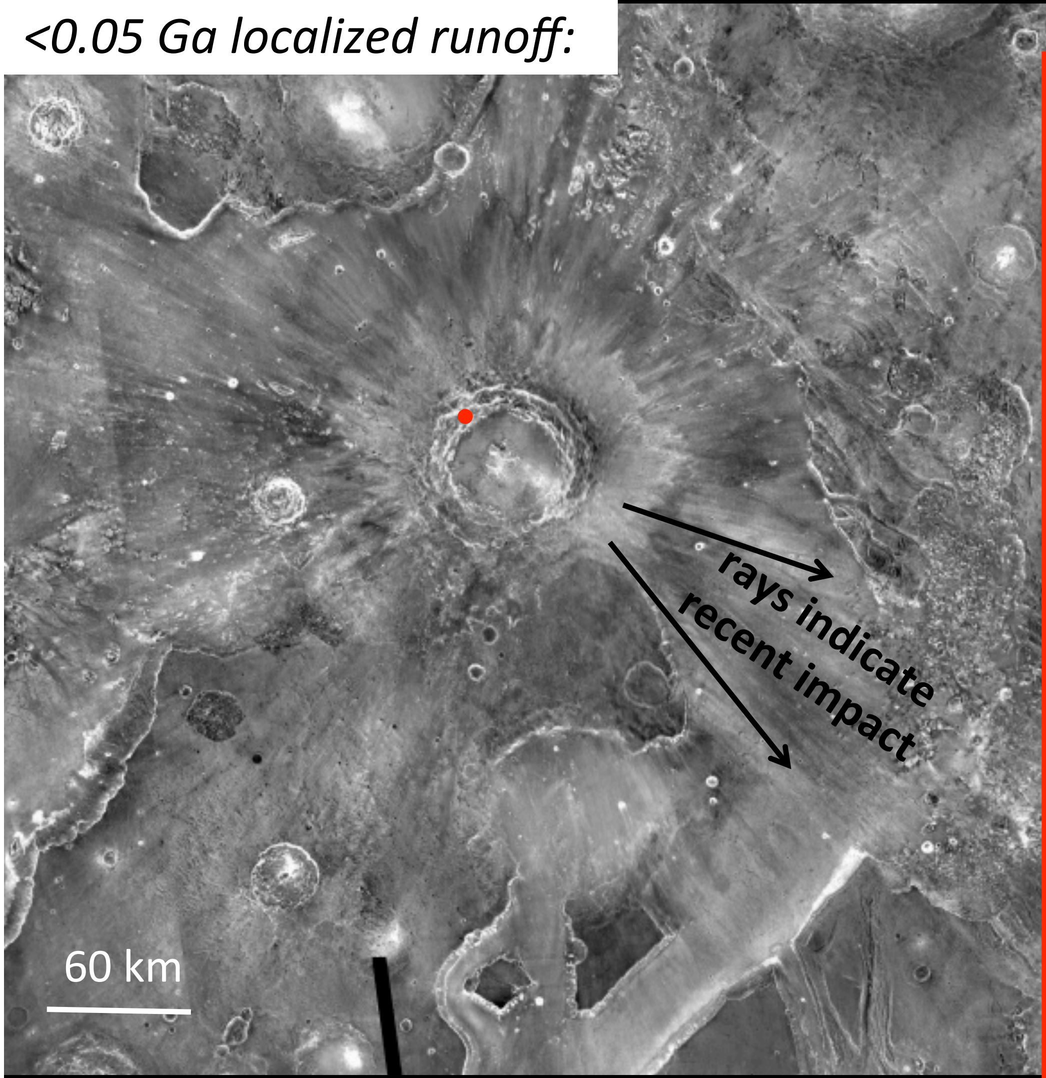
Snow stability

cold traps

Pattern of orbitally-paced seasonal snowmelt matches sedimentary rock outcrops

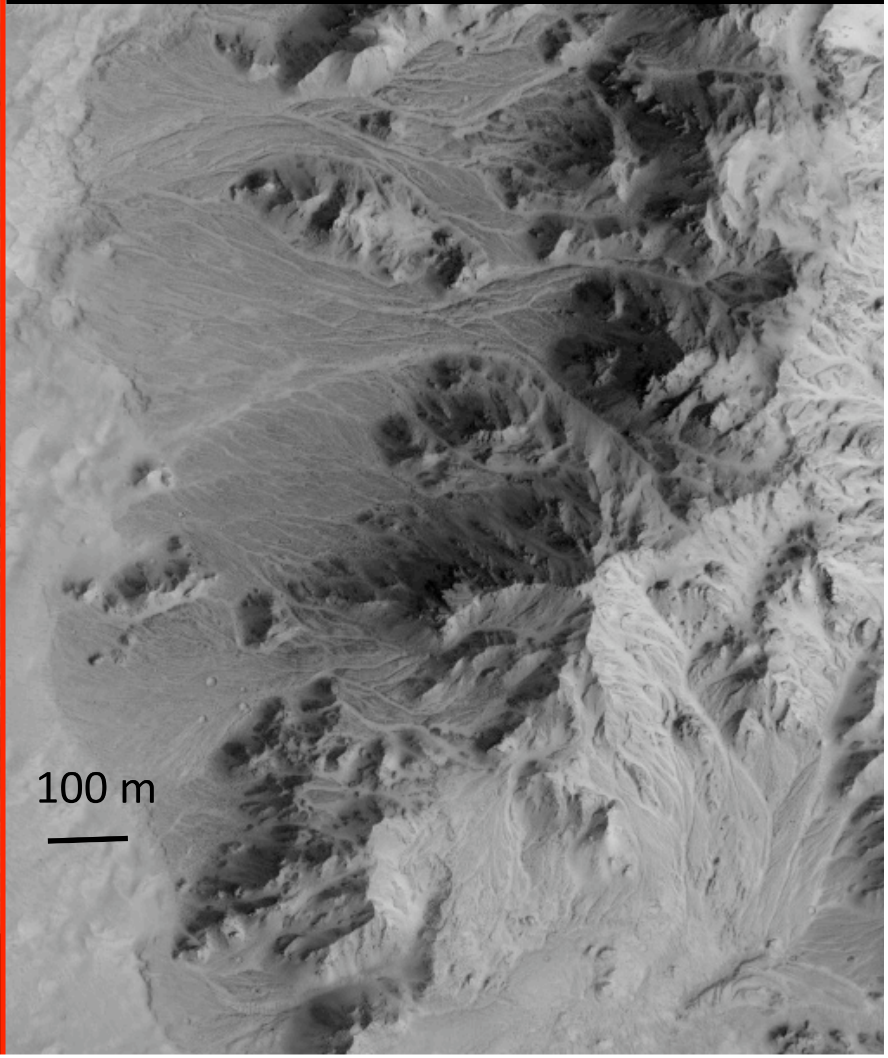
Transient impact-triggered runoff has occurred on Mars …

<0.05 Ga localized runoff:



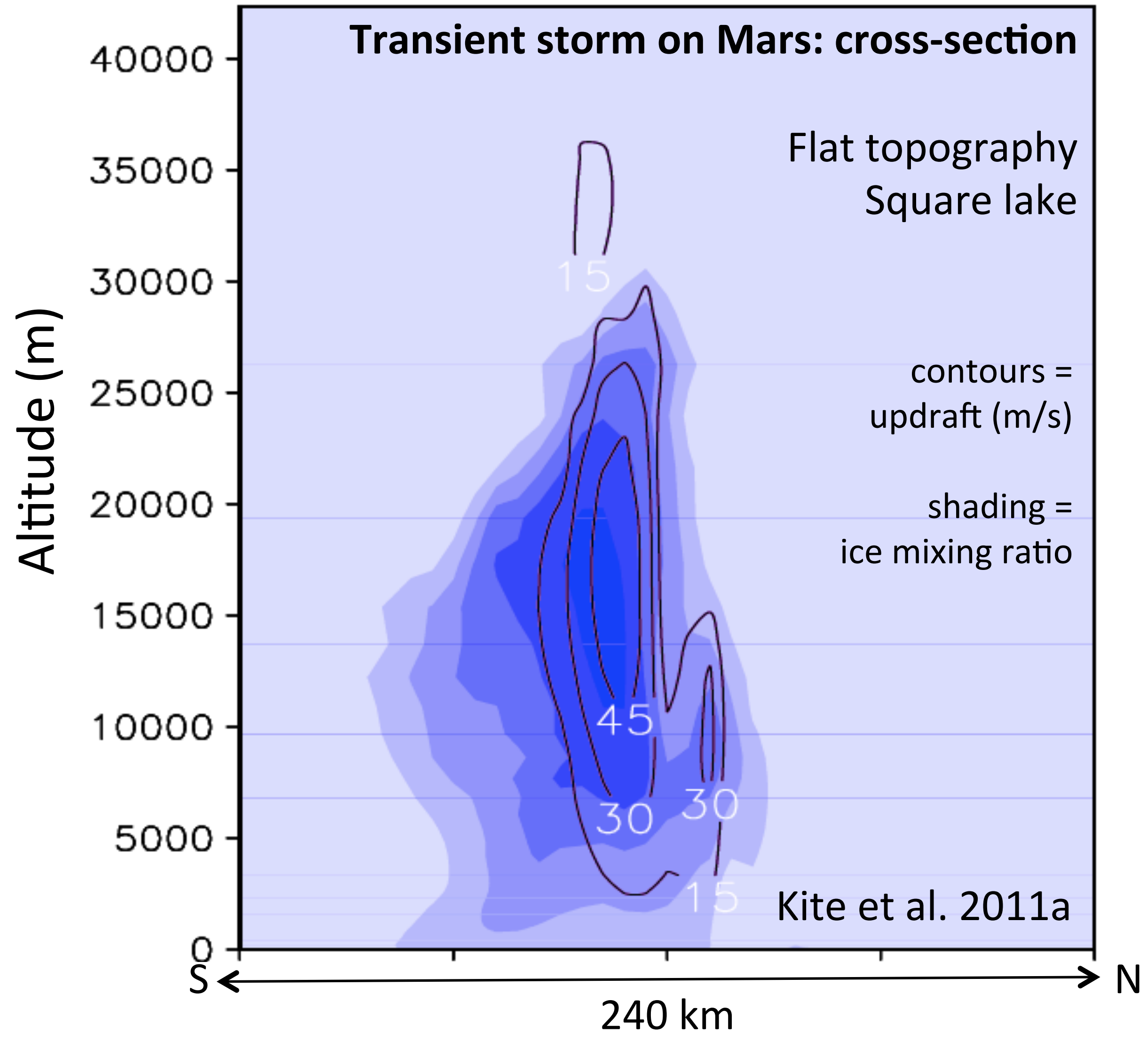
THEMIS nighttime IR

Williams & Malin, Icarus, 2008

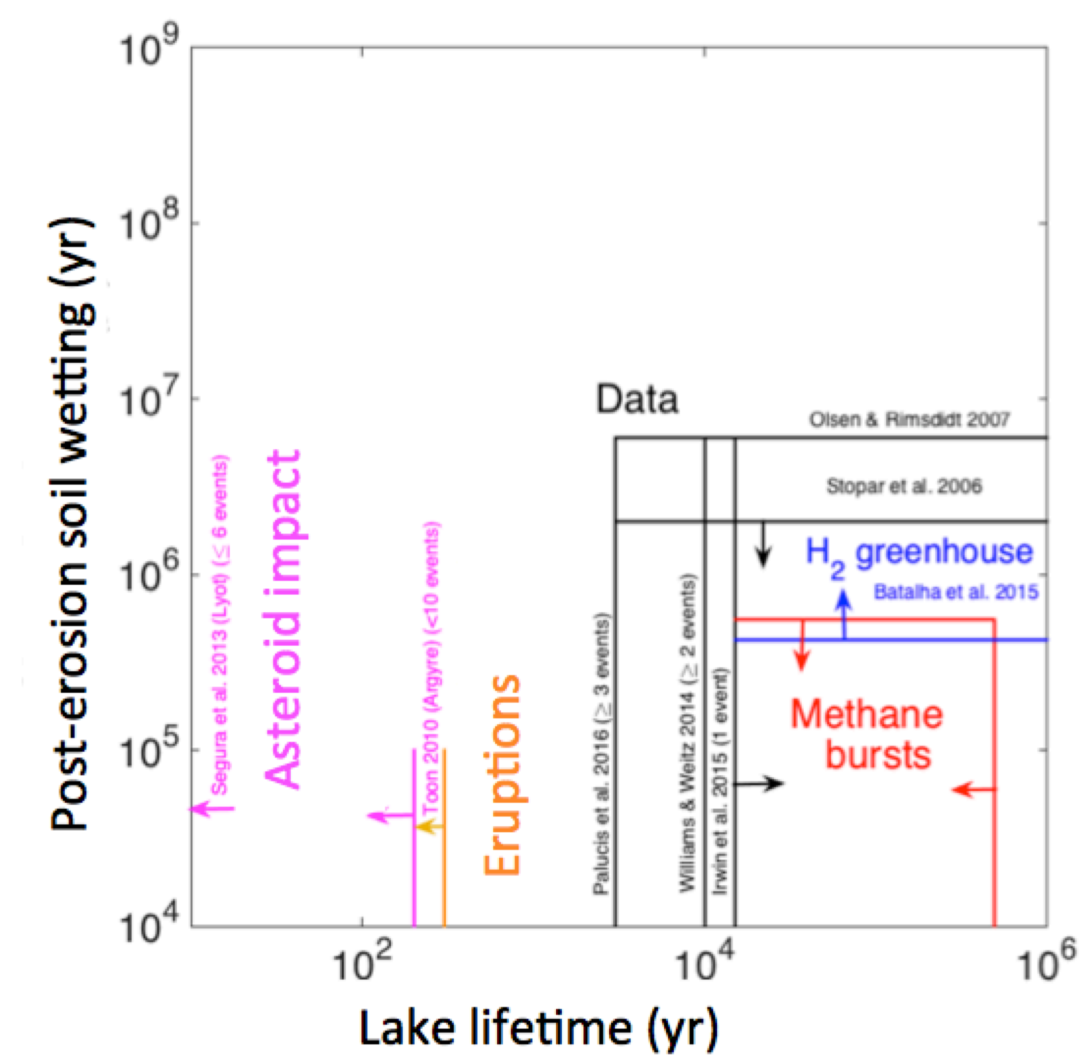


However, even big impacts / big outburst floods produce precipitation that is too brief and/or localized

Kite et al., ‘Localized precipitation,’ JGR 2011a;
Kite et al., ‘Chaos storms …’ JGR, 2011b;
Turbet et al., JGR, 2017.



Summary: Early Mars climate models underpredict the duration of individual lakes, or overpredict weathering



Kite et al., arXiv:1703.06386

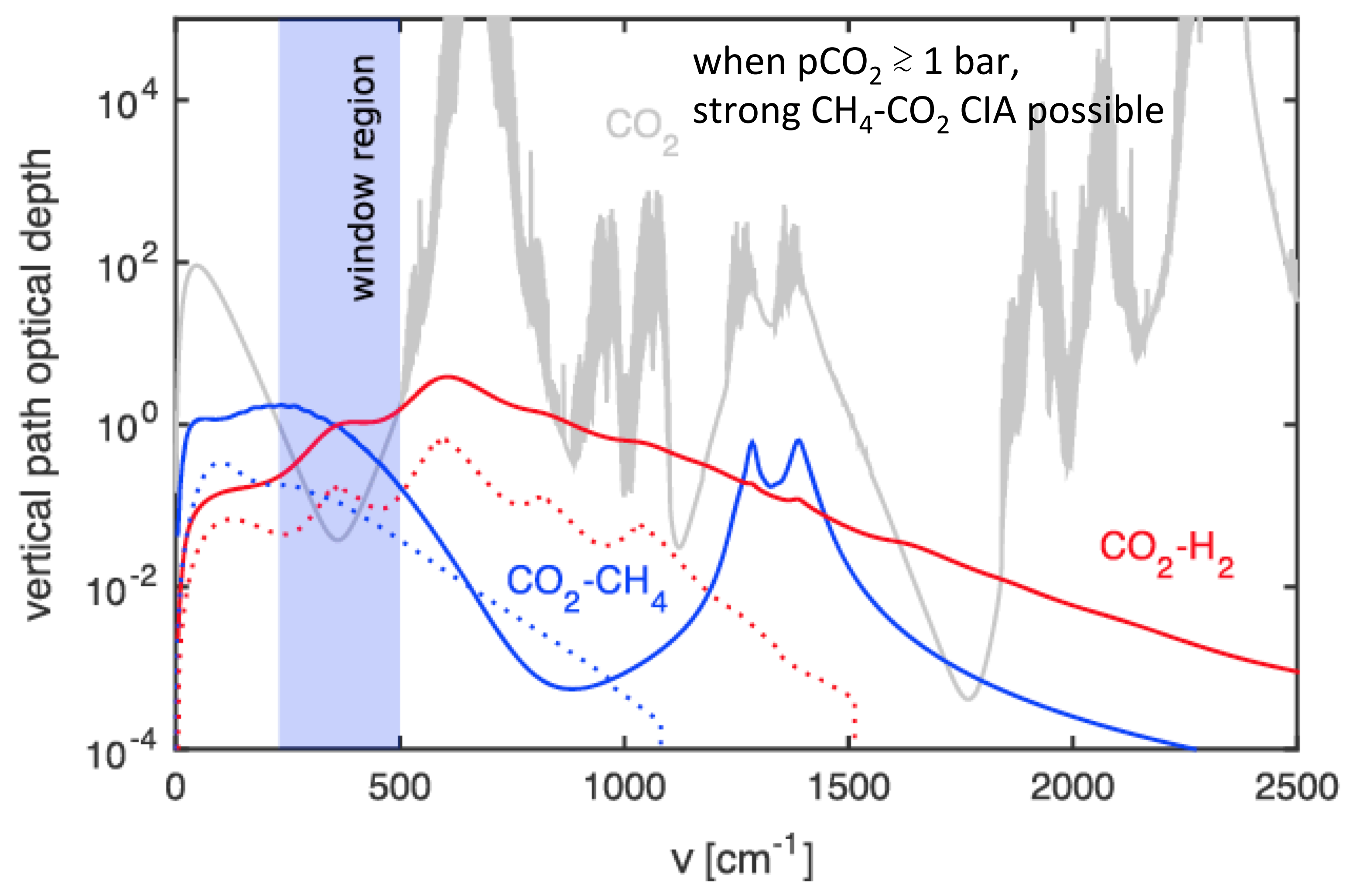
Tuning required to avoid overpredicting weathering for metastable wet climate / cirrus clouds (Urata & Toon 2013)

H_2-CO_2 greenhouse (Batalha et al. 2015) + weathering limit cycles (Batalha et al. 2016) match geologic constraints, but require high outgassing fluxes and late massive CO_2 removal.

A recent breakthrough (?)

CH_4-CO_2 Collision-Induced Absorption (CIA)

Wordsworth, Kalugina, Lokshtanov, Vigasin, et al., GRL, 2017



940 mbar CO_2
30 mbar H_2
30 mbar CH_4
T_{surf} = 250K

Early Mars climate models

CONSTRAINTS

What do we know about ancient Mars climate?

Among wet-era features, the most challenging to explain are rivers and lakes. Many of Mars' rivers and lakes were rain- or snowmelt-fed. Lake-forming climates *span* $>10^9$ yr, but minor weathering suggests intermittency. A $\gtrsim 10^5$ yr climate optimum started $>3 \times 10^8$ yr after Mars formed. $P_{atm} \lesssim 1$ bar.

EXISTING MODELS

CO_2-driven models and their extensions

↑CO_2(± H_2O_v) is necessary, but insufficient.
Volcanism and impacts underpredict lake lifetimes.
Metastable wet climates and cirrus clouds require fine-tuning.
(CH_4/H_2)-CO_2 collision-induced absorption (CIA) may provide an intermittent boost to CO_2 warming.

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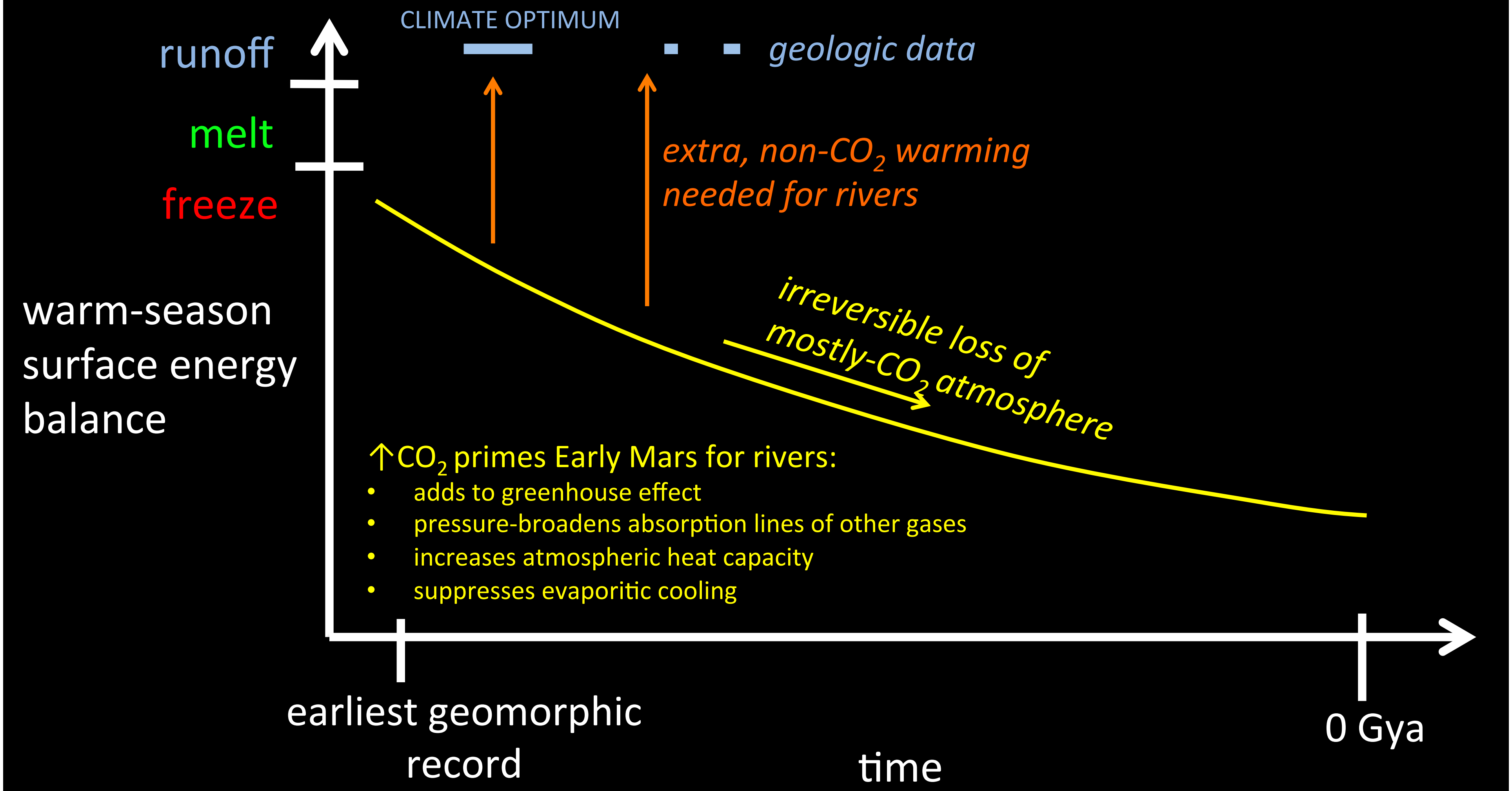
NEW MODEL

Atmospheric-collapse trigger hypothesis

Climate optimum on Mars triggered by atmospheric loss?

Mars atmospheric loss and river-forming climates: the standard view



CLIMATE OPTIMUM

geologic data

runoff

melt

freeze

warm-season surface energy balance

extra, non-CO_2 warming needed for rivers

irreversible loss of mostly-CO_2 atmosphere

↑CO_2 primes Early Mars for rivers:

- adds to greenhouse effect
- pressure-broadens absorption lines of other gases
- increases atmospheric heat capacity
- suppresses evaporitic cooling

earliest geomorphic record

time

0 Gya

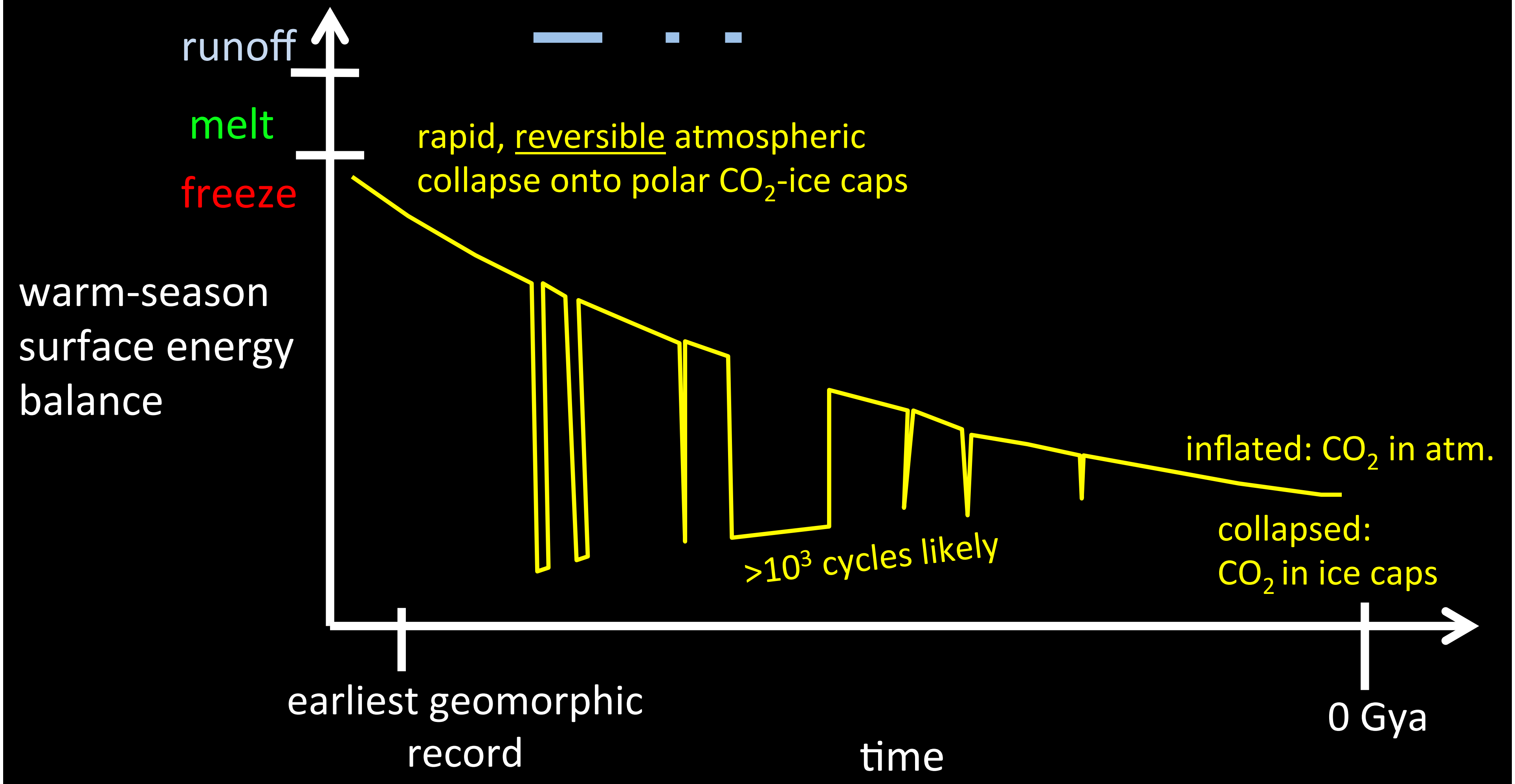
e.g. Irwin et al. in "Lakes on Mars" 2008, Howard et al. JGRE 2005, Irwin et al. JGRE 2013, Goudge et al. Geology 2016, Kite et al. EPSL 2015

e.g. Mahaffy et al. Science 2013, Hu et al. Nat. Comm. 2015, Barabash et al. Science 2007, Kite et al. Nature Geoscience 2014, **Jakosky et al. this session**

e.g. Ozak et al. JGR 2016, Forget et al. Icarus 2013, Mischna et al. JGR 2013, Kite et al. Icarus 2013

Alternative views: Tian+ GRL 2009; Richardson & Mischna JGR-E 2005

Mars atmospheric loss and river-forming climates: atmospheric collapse

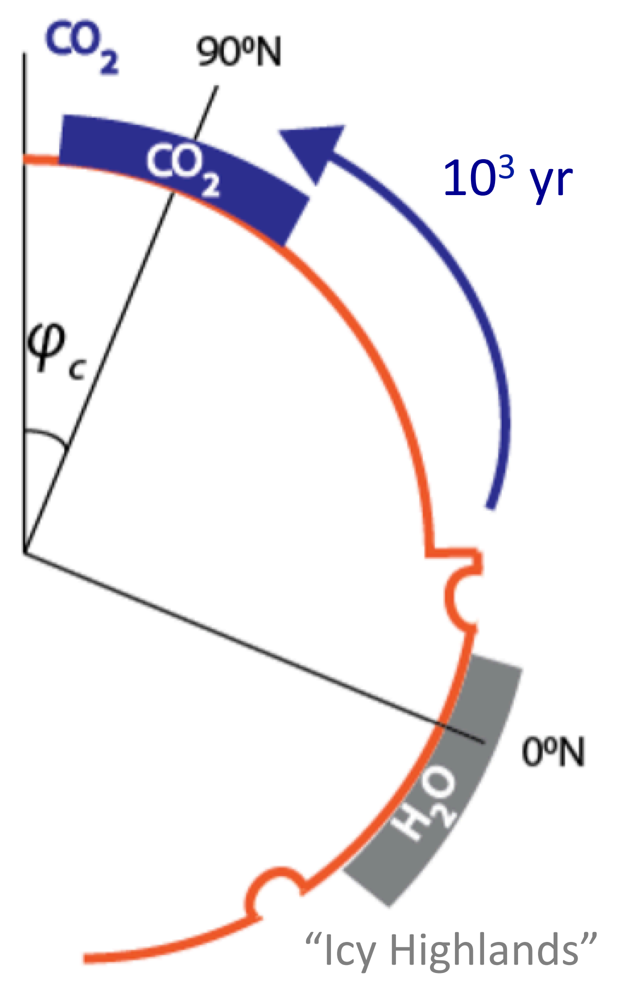


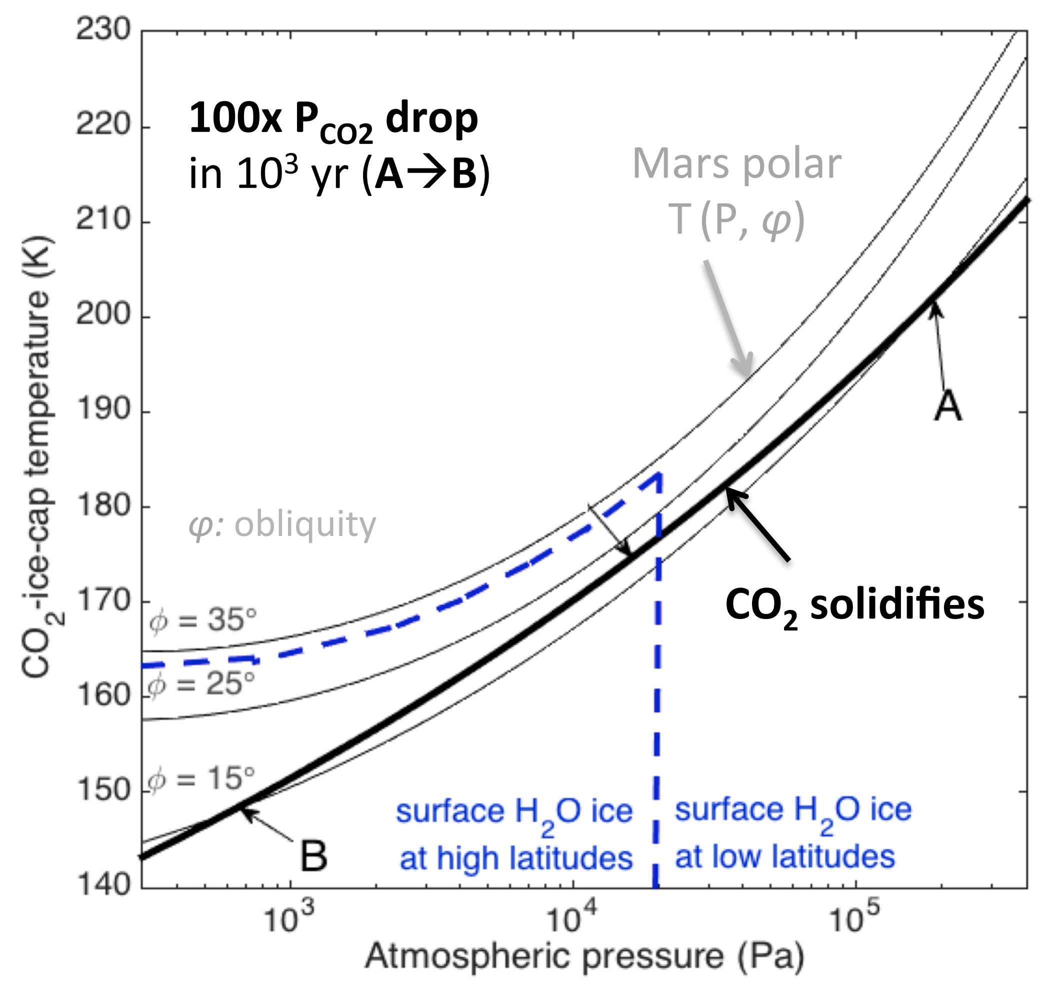
e.g. Sagan et al. 1973, Gierasch & Toon 1973, Nakamura & Tajika 2002, Wordsworth et al. 2013, Soto et al. 2015, Lapotre et al. 2016, Bristow et al. 2017

Collapse-trigger climate optimum scenario

Kite et al., in prep.

Step 1: Mars' first atmospheric collapse





Sagan et al. 1973, Gierasch & Toon 1973, Nakamura & Tajika 2002,
Wordsworth et al. 2013, Soto et al. 2015

Collapse-trigger climate optimum scenario

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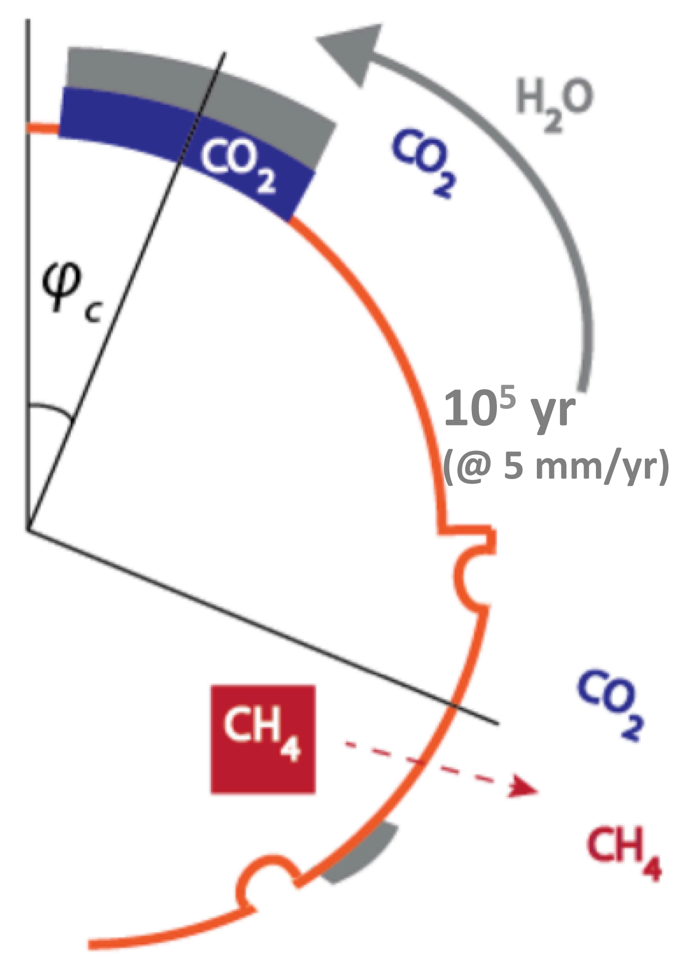
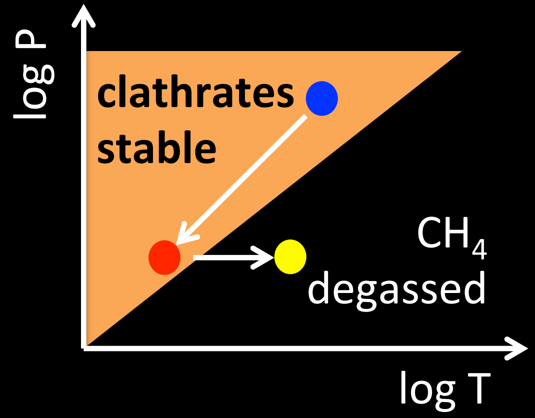
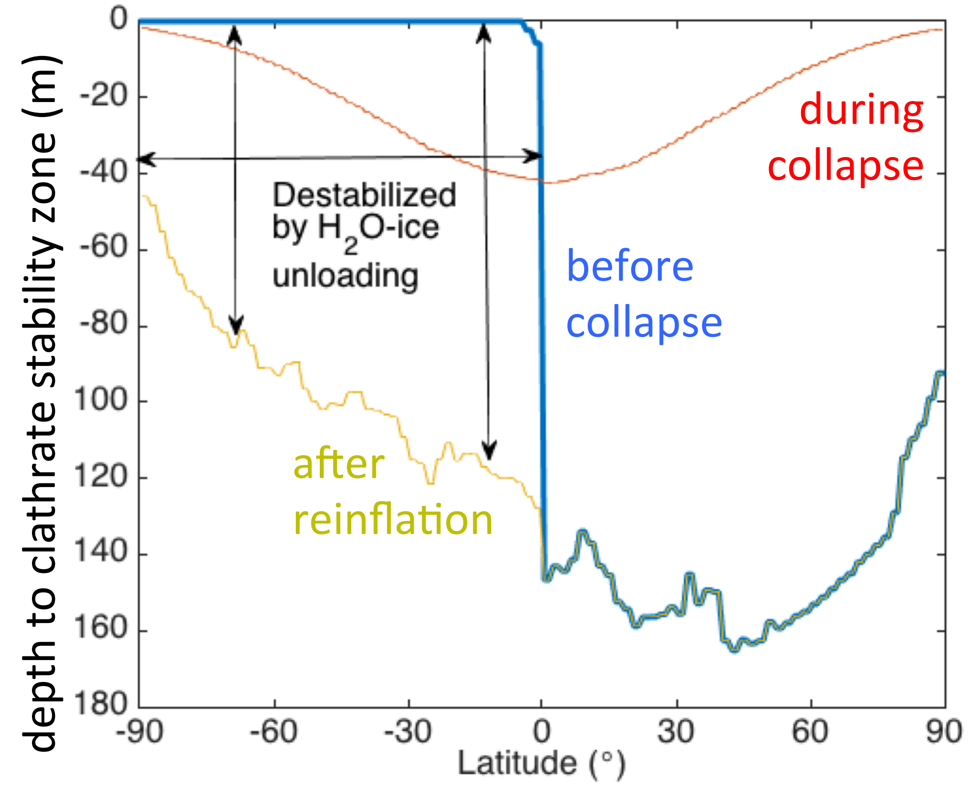
Step 2: H_2O-ice unloading destabilizes CH_4 clathrate





We drove a 3D model of CH_4 clathrate stability using realistic orbital forcing, MOLA topography, and T(pCO2, pCH4, φ, latitude, elevation) from previously published models.

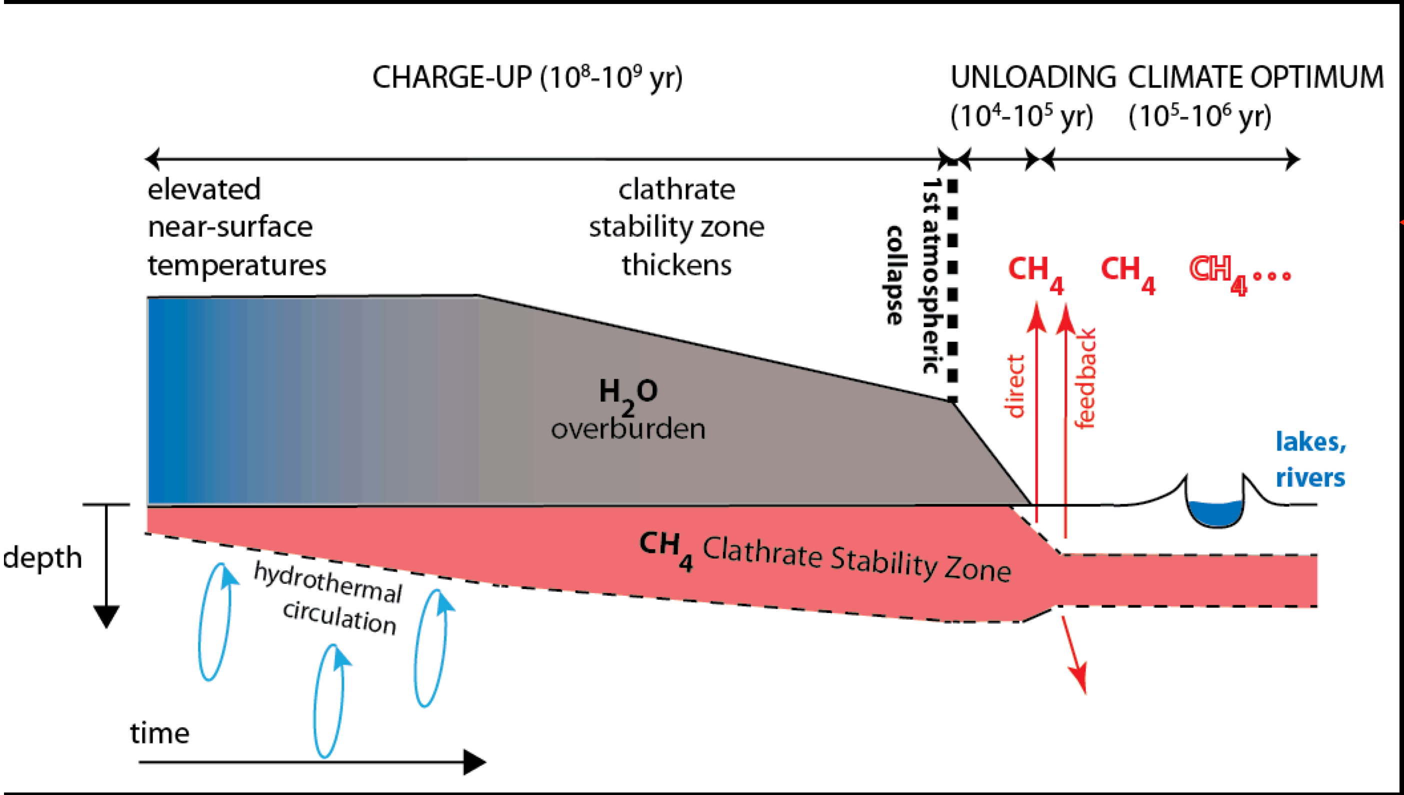


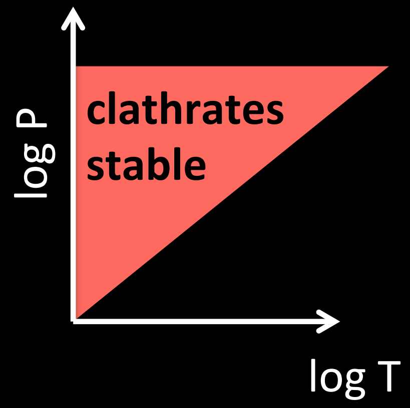
CH_4 production and release

Kite et al., in prep.

abiotic

store-up by clathrates
infrequent release due to
shifts in P, obliquity



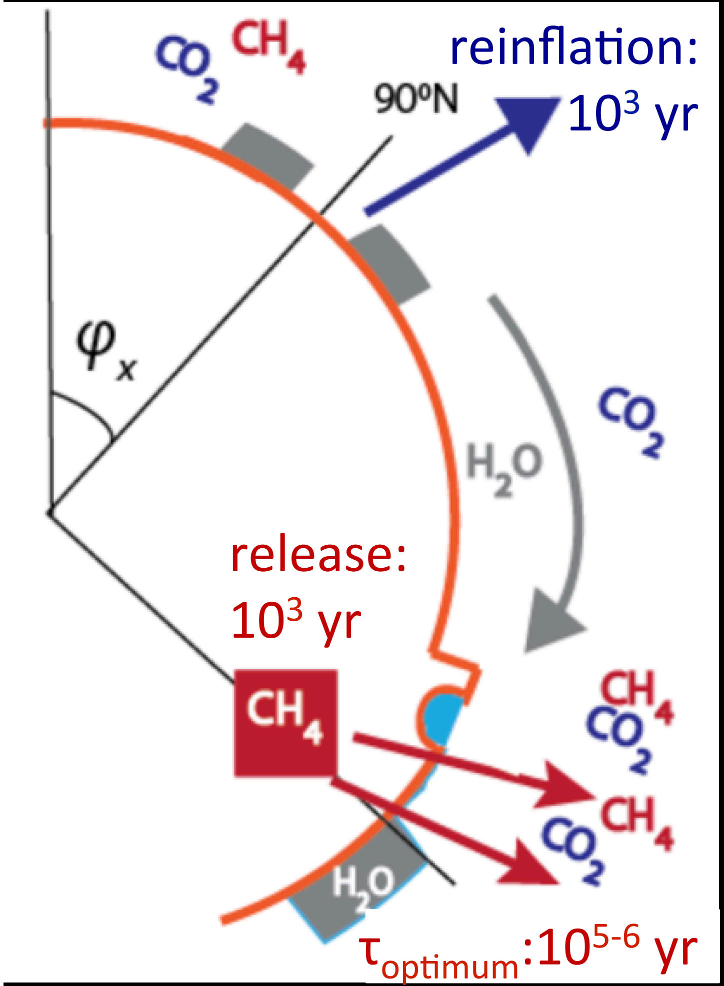


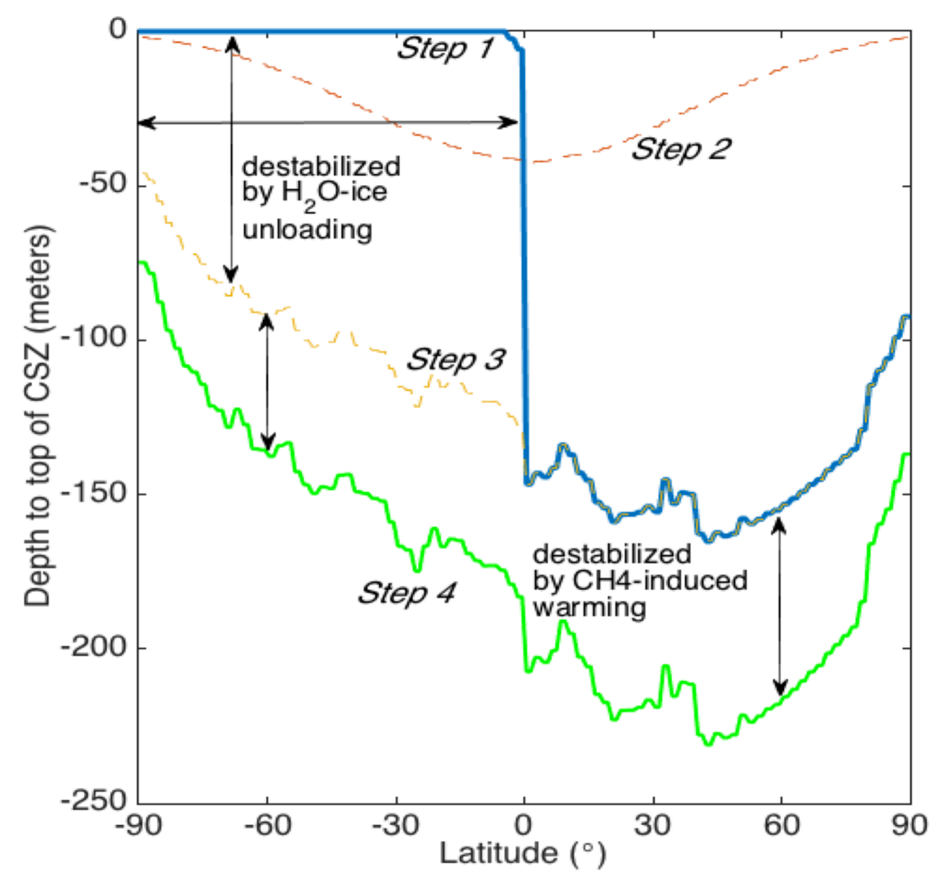
Crustal hydrothermal circulation very early in Mars history would yield CH_4 that could be incorporated into clathrate on approach to the cold surface. See e.g. Prieto-Ballesteros et al. 2006, Etiope & Sherwood Lollar 2013, Mousis et al. 2013, Chassefiere et al. 2016. For an Earth analog, see MacAyeal & Lindstrom 1990.

Collapse-trigger climate optimum scenario

Kite et al., in prep

Step 3: Reinflation → 10^5-10^6 yr Mars climate optimum





━ = direct CH_4-warming-induced CH_4 release using $\Delta T = \Delta T(pCO_2, fCH_4)$ from Wordsworth+ GRL 2017

Plots show results for volume fraction of clathrate stability zone occupied by clathrate = 0.03

Collapse-trigger climate optimum scenario

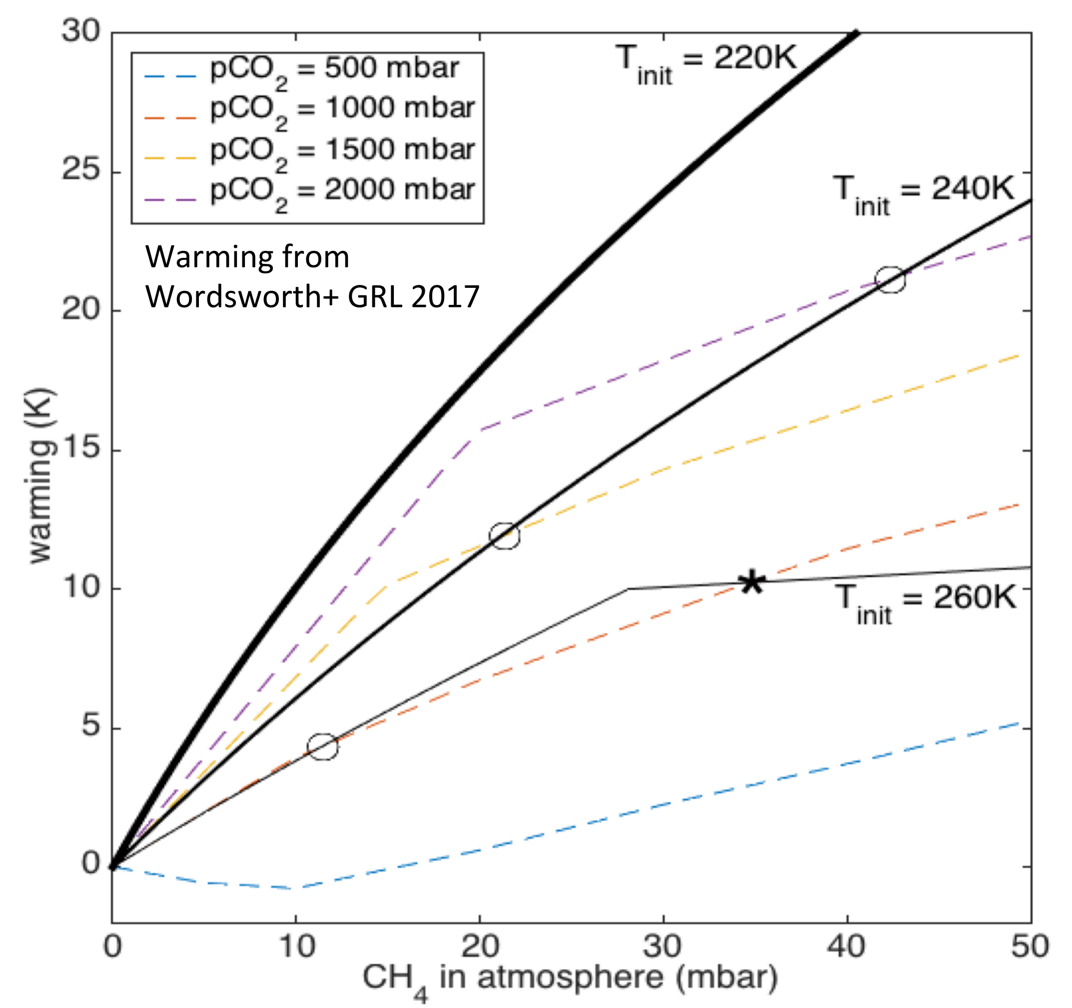
Kite et al., in prep

Step 4: Climate optimum – low latitude rivers and lakes

stronger +ve feedback for :

↑ clathrate abundance
↑ pCO_2
↑ initial T

--- = Warming given imposed pCH_4
— = pCH_4 released given imposed warming
○ = selected stable equilibria
★ = an unstable fixed point



Warming from Wordsworth+ GRL 2017

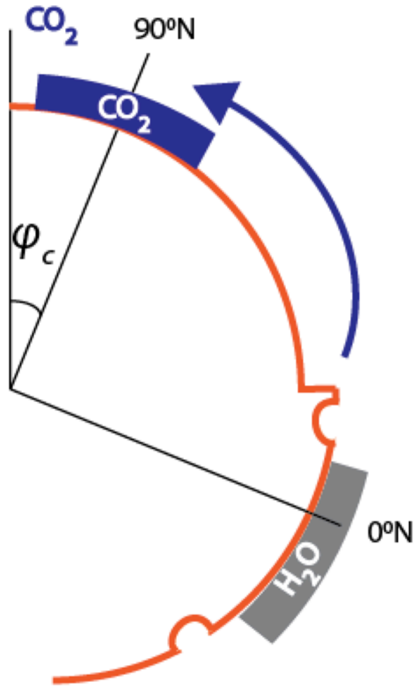
Plots show results for volume fraction of clathrate stability zone occupied by clathrate = 0.03

Sub-talik CH_4 release not included

Atmospheric-collapse-triggered Mars climate optimum

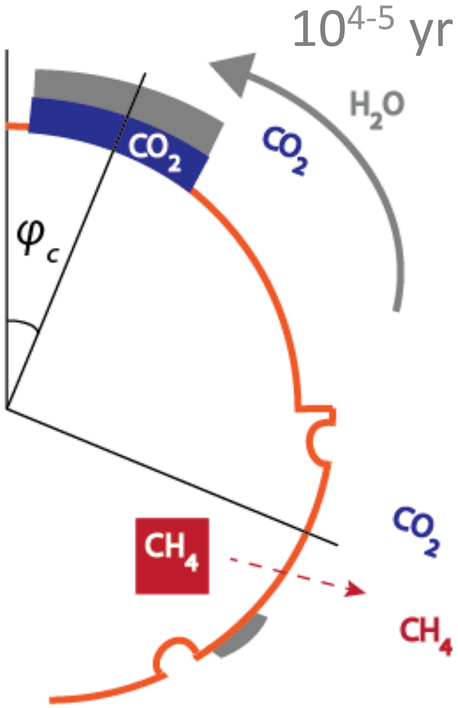
Kite et al., in prep.

Step 1. Collapse of CO_2 atmosphere
(~1 Kyr)



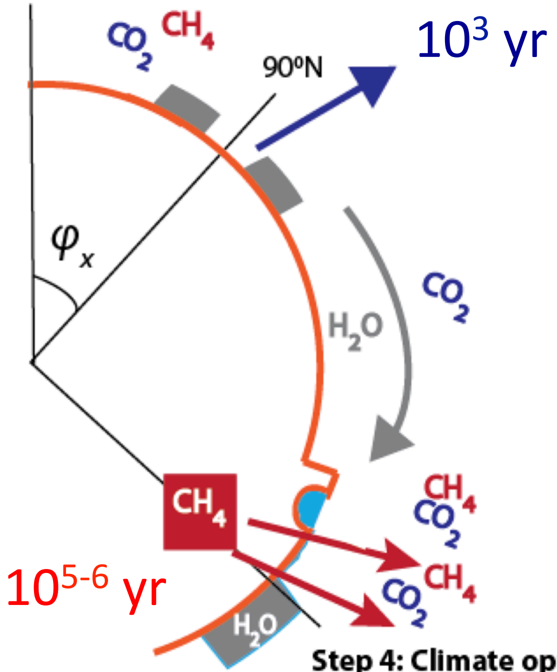
pCO$_2$: 2 bar → 0.005 bar
Teq ~ 250K → 210K

Step 2. H_2O-ice unloading, CH_4 release
(10-50 Kyr)



$_2$ 5 bar → 0.2 bar
fCH_4: 0 → 0.01
Teq ~ 210K

Step 3. Initiation of Mars climate optimum
(CO_2-atmosphere reinflates,
CH_4 release, CO_2+CH_4 warming).



Step 4: Climate optimum
valley network incision
lake overspill
snowmelt (0.1 - 1 Myr)

pCO$_2$: 0.2 bar → 2 bar
fCH_4: 0.01 → 0.05
Teq ~ 210K → >260K

Collapse trigger hypothesis matches data & makes novel testable predictions

Mars' first-ever atmospheric collapse shifts H_2O ice from high ground to poles, releasing CH_4 from sub-ice clathrate. For >1% clathrate stability zone volume occupancy fraction, strong warming results.

(1) Zero *D*<25 m pre-valley network craters
(2) Few or no *D*>1 km craters during valley network incision
(3) Zero pre-valley-network perchlorates
(4) Abiotic soots at base of Jezero delta
(5) Present day diffusive release of CH4-clathrate

Climate optimum - inferences from data:

Duration $>10^5$ yr, but relatively brief	Ly-α limited CH_4 photolysis (Kite et al. arXiv 2016)
Intensity	Strong CIA-induced warming (Wordsworth+ 2017)
Uniqueness	Clathrate reservoir recharges slowly, if at all
Transient surface-(deep hydrosphere) connection	Sub-lake taliks
Shift from phyllosilicates → sulfates	S outgasses at low P_{atm} (Gaillard & Scaillet 2009)
Hesperian perchlorates	Thin atmosphere permits GCR → ClO_4
Brief, intense surface weathering	"CH4-warming-induced CH_4 release" fe

Conclusions

CONSTRAINTS

What do we know about ancient Mars climate?

Rivers and lakes = greatest challenge for models.
Many of Mars' rivers and lakes were rain- or snowmelt-fed.
Individual lakes lasted >10^3 yr. Lake-forming climates *span* >10^9 yr; minor weathering suggests intermittency. A relatively brief (but $\gtrsim 10^5$ yr) climate optimum started >3 x 10^8 yr after Mars formed.
$P_{atm} \lesssim 1$ bar by 3.6 Ga.

EXISTING MODELS

CO_2-driven models and their extensions

↑CO_2(± H_2O_v) is necessary, but insufficient.
Volcanism and impacts underpredict lake lifetimes.
Metastable wet climates and cirrus clouds require fine-tuning.
(CH_4/H_2)-CO_2 collision-induced absorption (CIA) may provide an intermittent boost to CO_2-only warming.

NEW MODEL

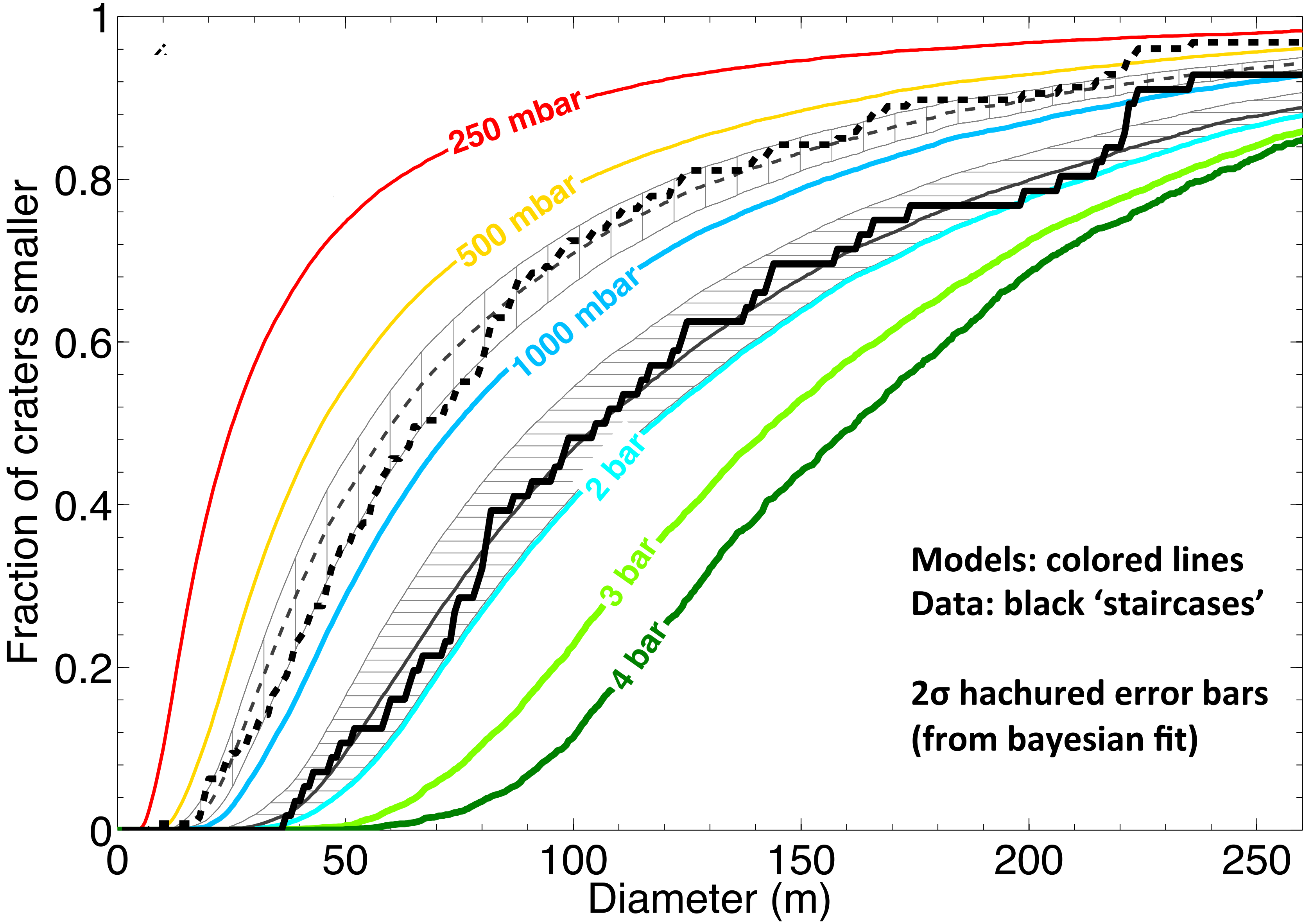
Atmospheric-collapse trigger hypothesis

A new model in which CH_4-clathrate degasses consequent to Mars' first atmospheric collapse may explain the duration, intensity and uniqueness of the Mars climate optimum. This model makes novel testable predictions.

Bonus slides

[redacted]

Kite, Williams, Lucas & Aharonson, Nature Geoscience, 2014



CH_4 : strong warming for 10^4-10^6 yr bursts

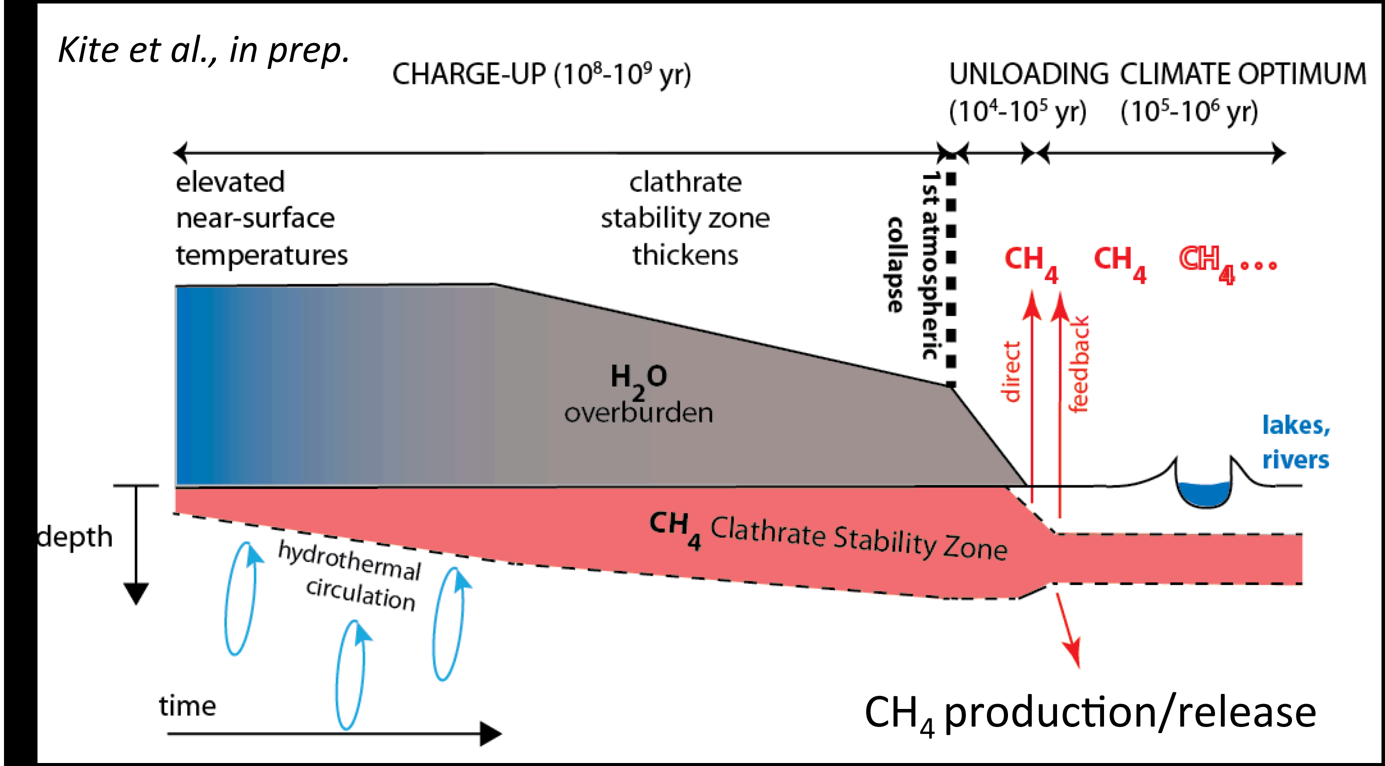
abiotic

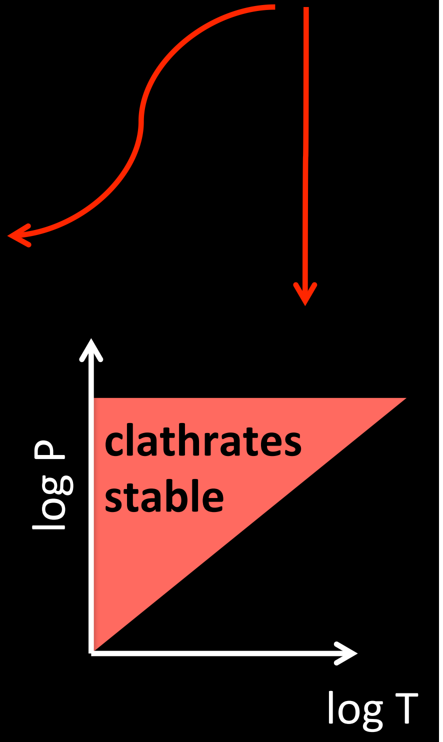
Collision-Induced Absorption

Wordsworth et al., arXiv:1610.09697

photon-limited destruction of CH_4

store-up by clathrates infrequent release due to shifts in P, obliquity





Crustal hydrothermal circulation very early in Mars history would yield CH_4 that could be incorporated into clathrate on approach to the cold surface. See e.g. Prieto-Ballesteros et al. 2006, Mousis et al. 2013, Chassefiere et al. 2016.

For an Earth analog, see MacAyeal & Lindstrom 1990.

Individual lake-forming climates lasted >1 Kyr

- Deep, persistent lakes fed by seasonal melt are consistent with T_{ave} = 254K (Doran et al. JGR 2002).
  - Sedimentological arguments for/against low ancient temperatures are inconclusive.
- Number of lake-forming events ≥3
  - Palucis et al. 2016, Gabasova & Kite in prep.
- Lake depth and areal coverage are hard to relate to climate

A problem for:
volcanic eruptions (Halevy & Head 2014)
impacts (Segura et al. 2008)

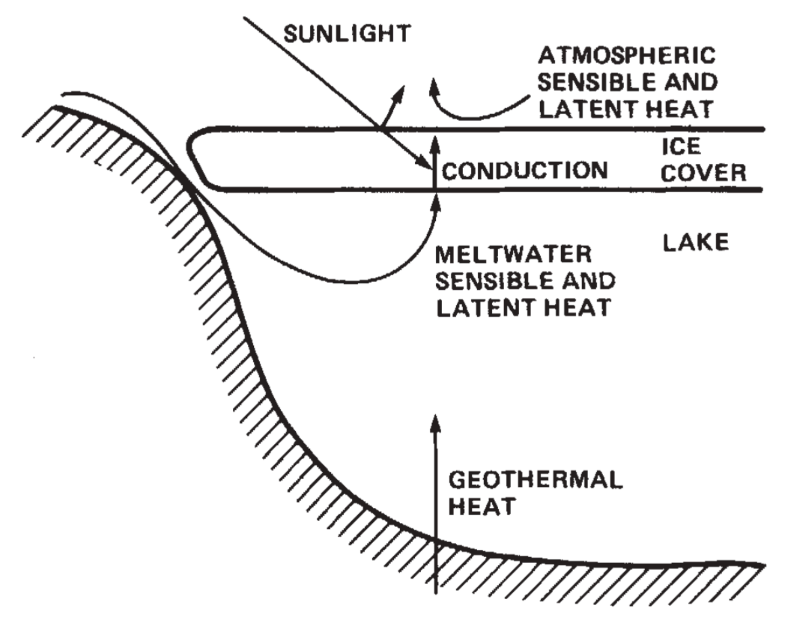
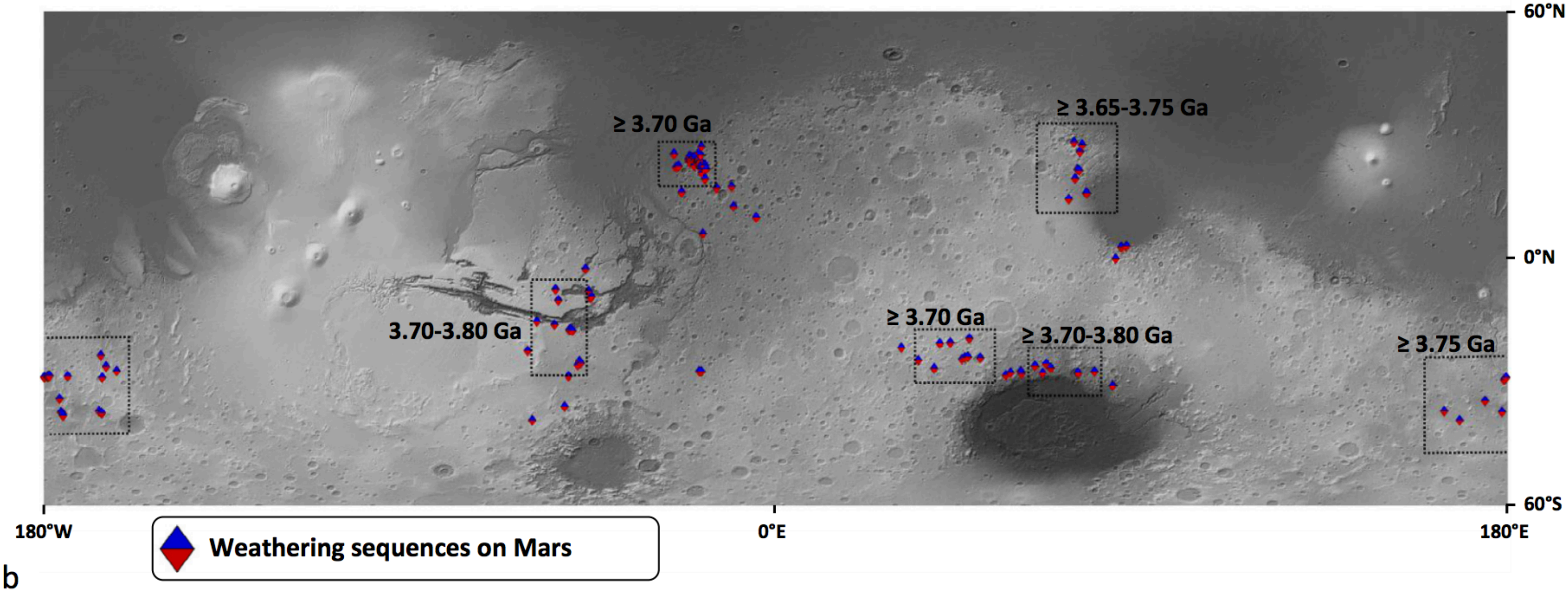


Fig. 1 Energy sources and sinks for perennially ice-covered lakes.

McKay et al. Nature 1985

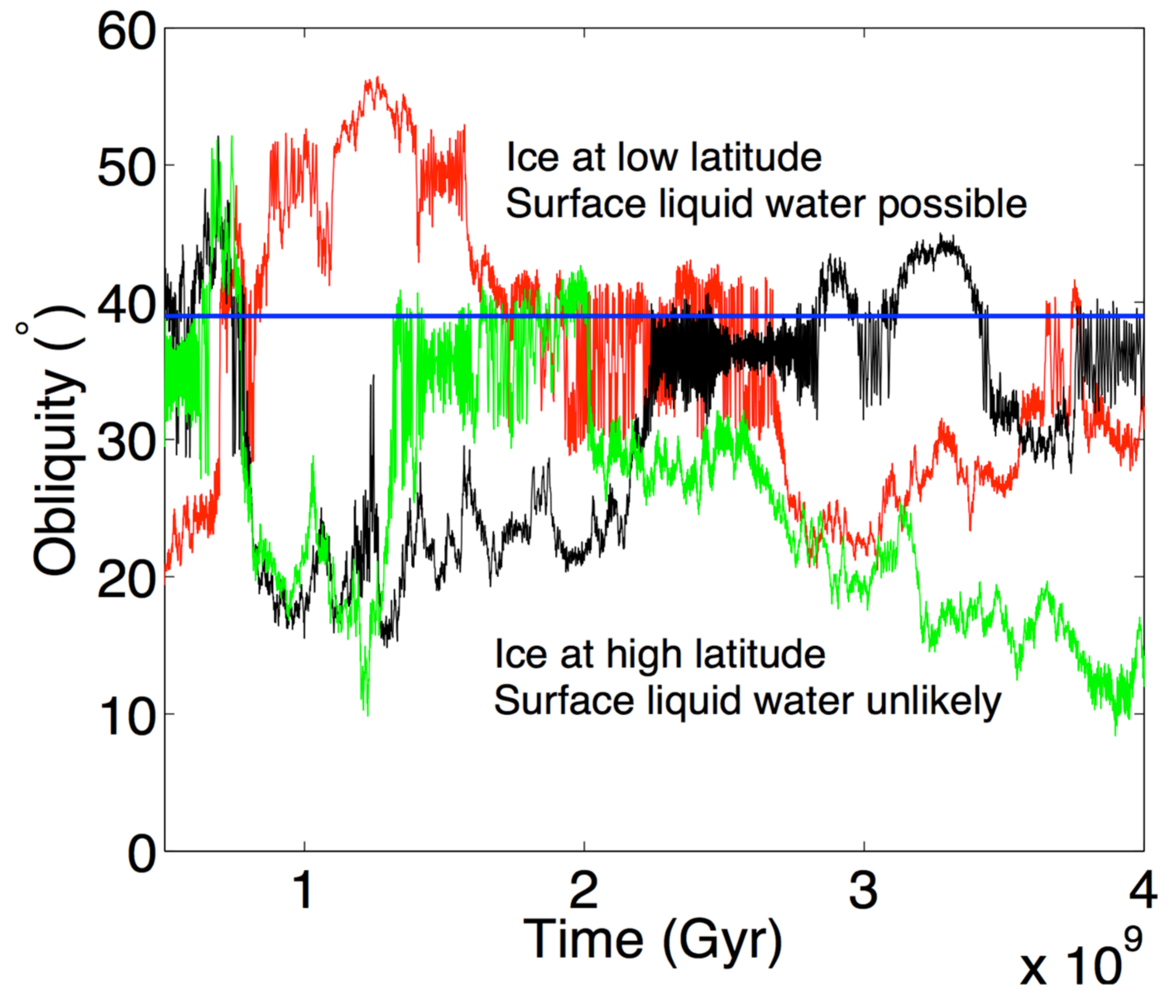
Matsubara et al. 2013

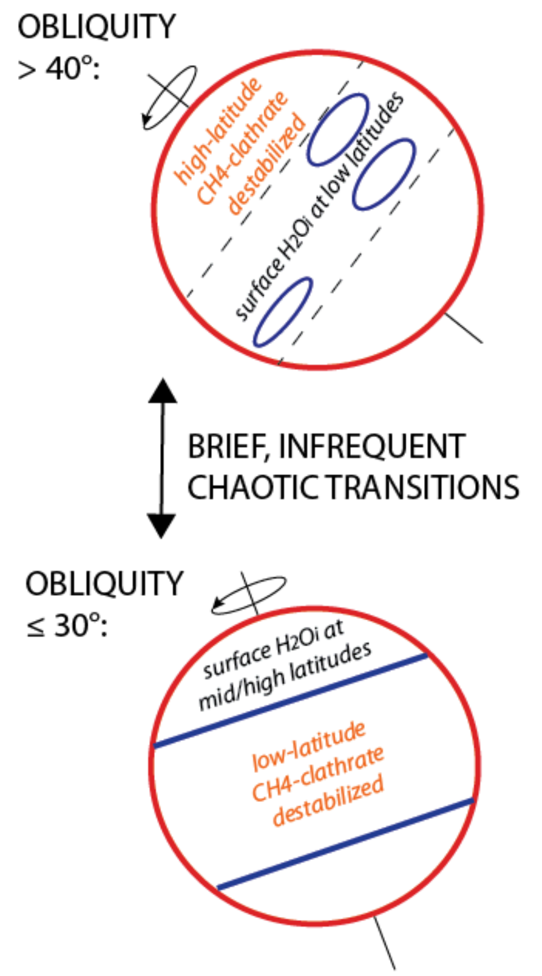
Globally distributed near-surface Al-clay layer



Carter et al. Icarus 2015

Also: Zolotov & Mironenko Icarus 2016


Ice at low latitude
Surface liquid water possible
Ice at high latitude
Surface liquid water unlikely
Obliquity (°)
60
50
40
30
20
10
0
1
2
3
4
Time (Gyr)
x 10^9


OBLIQUITY
> 40°:
high-latitude
CH4-clathrate
destabilized
surface H2Oi at low latitudes
BRIEF, INFREQUENT
CHAOTIC TRANSITIONS
OBLIQUITY
≤ 30°:
surface H2Oi at
mid/high latitudes
low-latitude
CH4-clathrate
destabilized

CH_4-burst / collapse trigger summary

Kite et al. in prep

SUCCESSES:

- Explains duration and rapid shutdown of lake-forming climates
- Explains late climate optimum (see also Tian et al. GRL 2009)

WEAKNESSES AND FAILURES:

- Invokes CH_4-clathrate reservoir for which there is no independent evidence
- Wet climate(s) too short-lived to explain sedimentary rock mounds

IMPLICATIONS:

- Surface sterilized immediately before climate optimum
- Contrasts between Noachian versus Hesperian climate-sensitive deposits correspond to a transition from a never-collapsed atmosphere to a collapse-prone climate, ultimately driven by slow loss of CO_2 to space (link to MAVEN).
- Sulfate-rich light-toned layered deposits postdate the VNs.

TESTABLE PREDICTIONS:

- Zero pre-valley-network perchlorates
- Zero $D < 50$ m pre-valley network craters
- No meter-wavelength wind-drag ripples (Lapôtre et al. 2016) pre-valley-networks
- Abiotic soots just before the climate optimum (high CH_4/CO_2)

What climate allowed sedimentary rocks to form on Mars?

Why did that climate end?

What makes the mound in Gale Crater special?

Thanks to NASA and U. Chicago for funding:

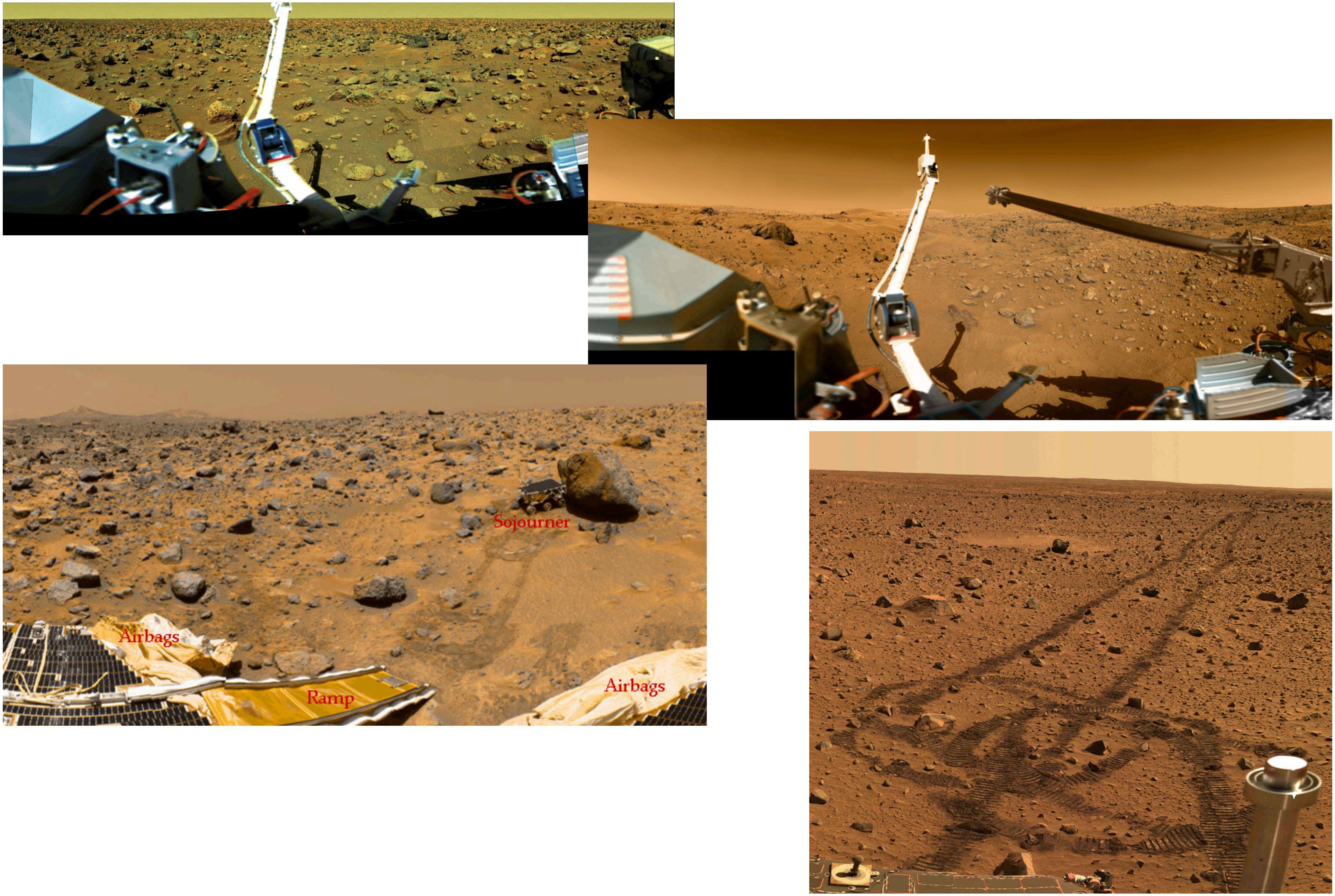
NASA

THE UNIVERSITY OF CHICAGO

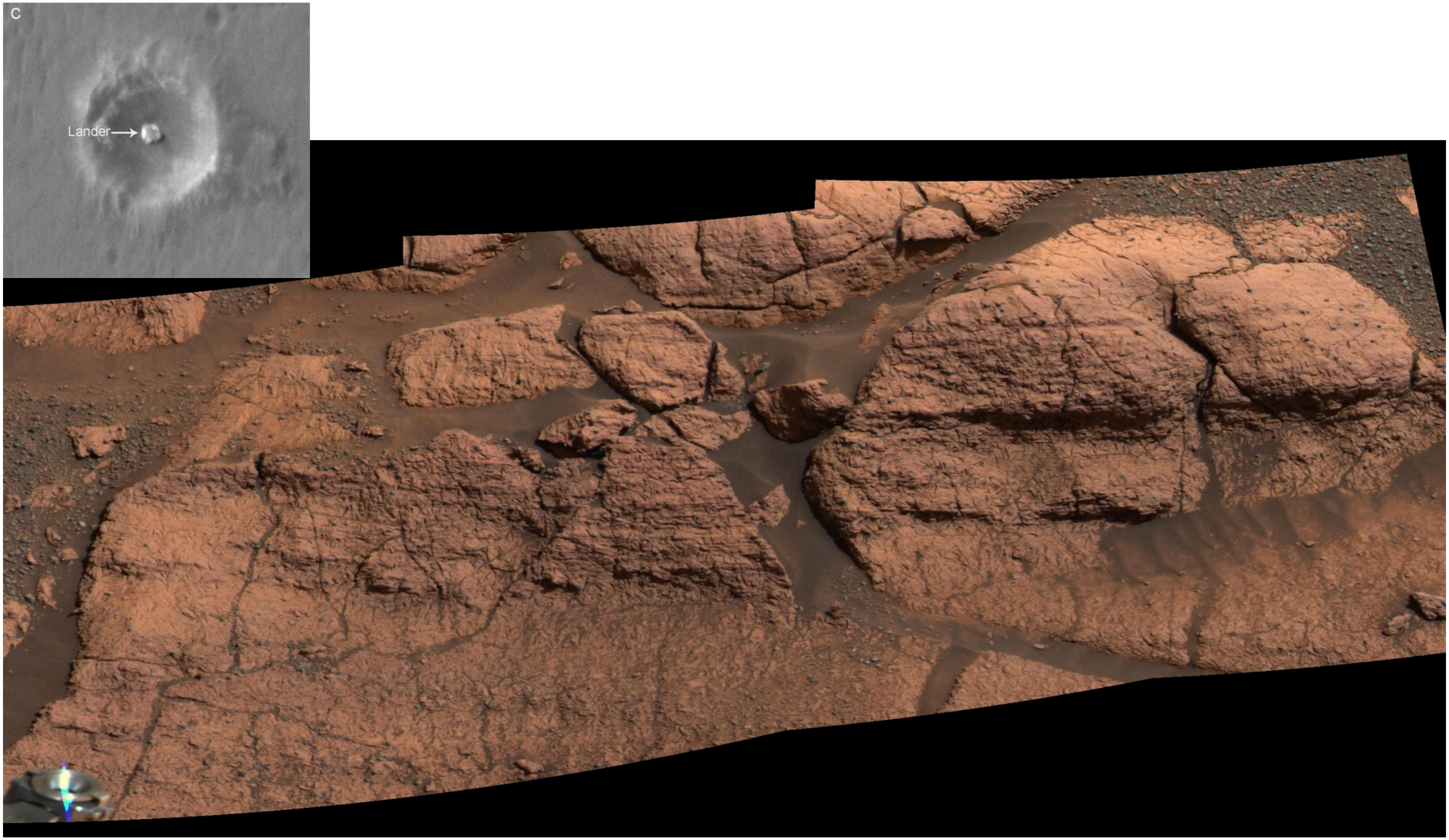
And thanks to you for listening!

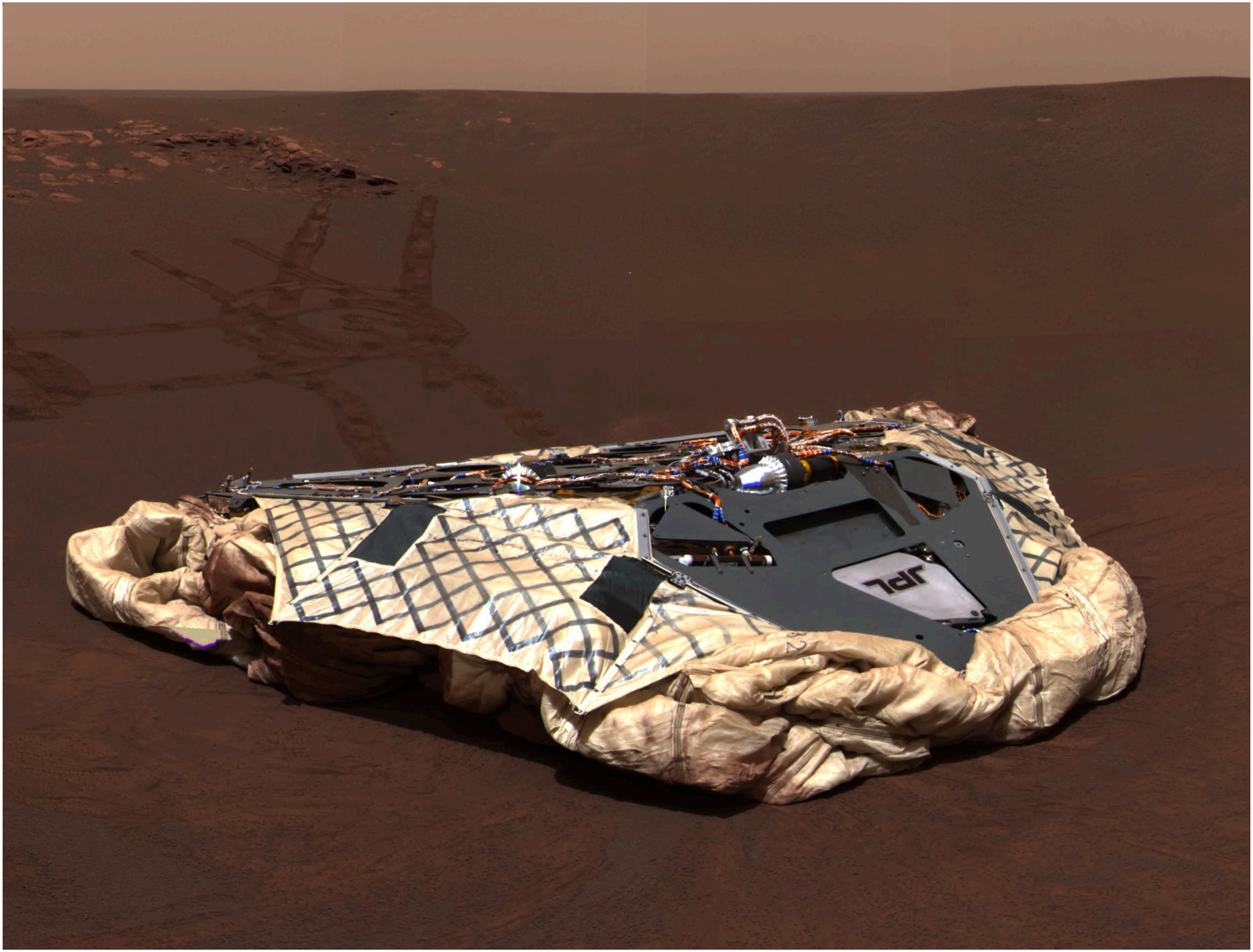
Bonus slides

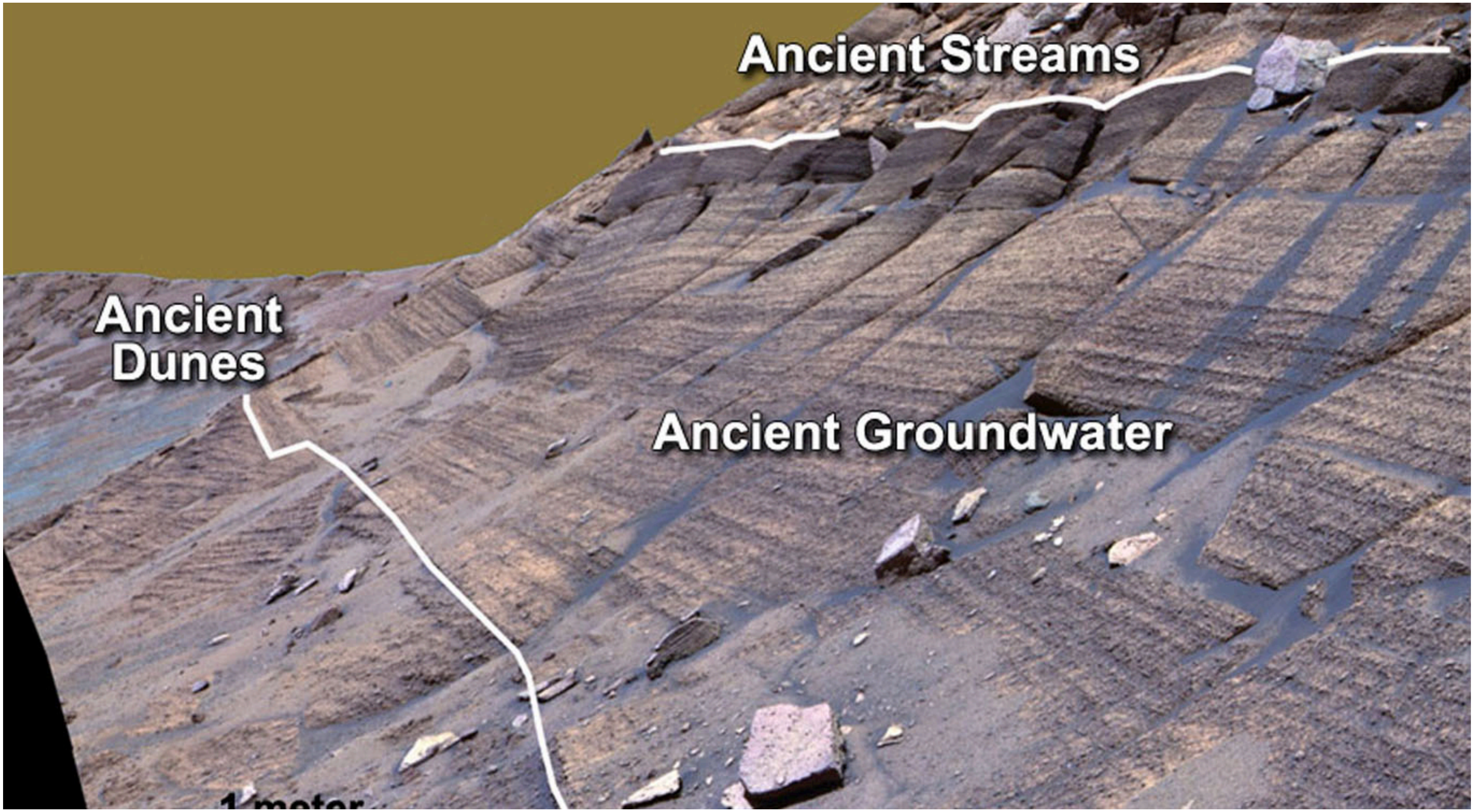
The first four landings: “basalt prisons”

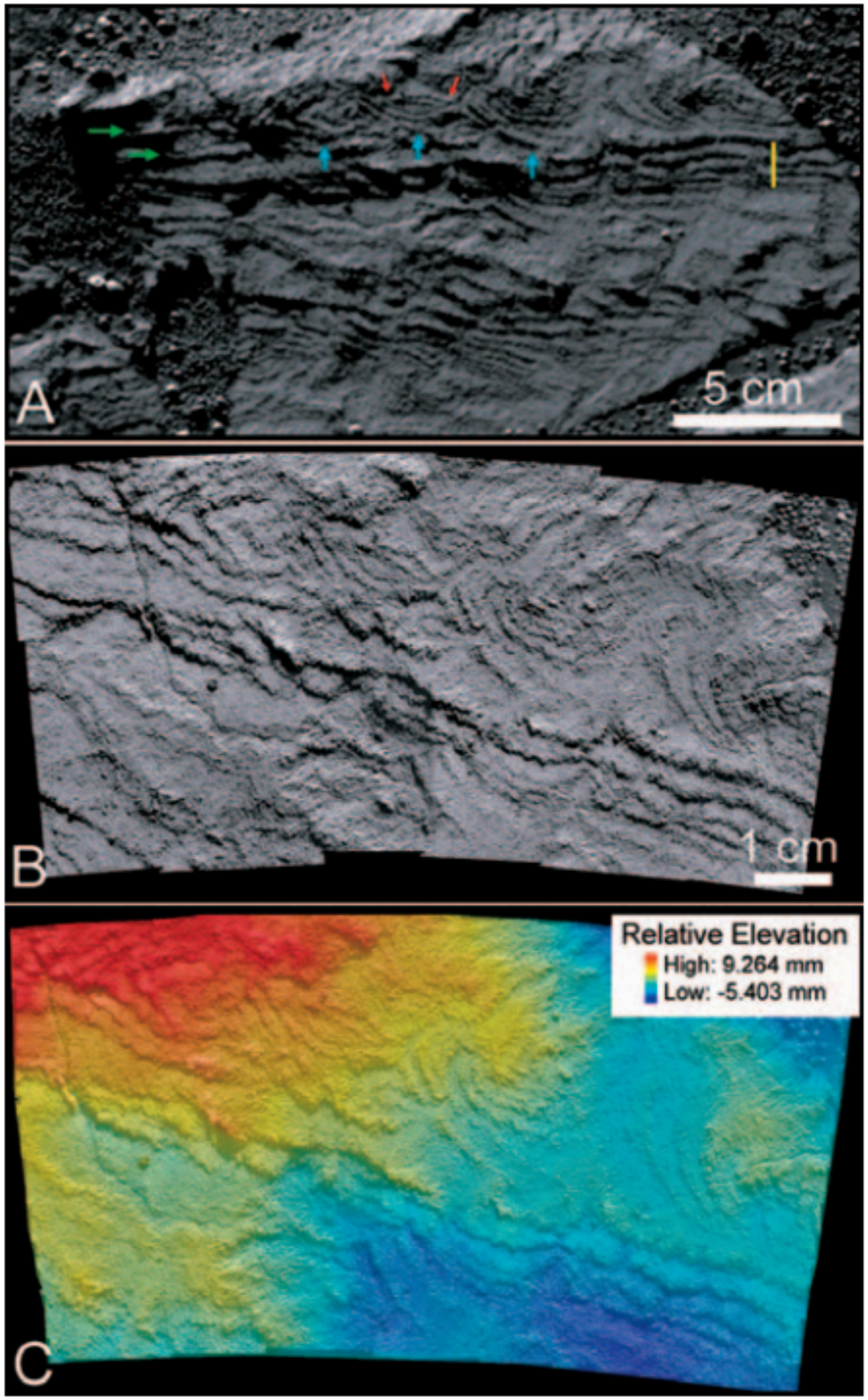


The fifth landing (Feb. 2004): sedimentary-rock **outcrops**

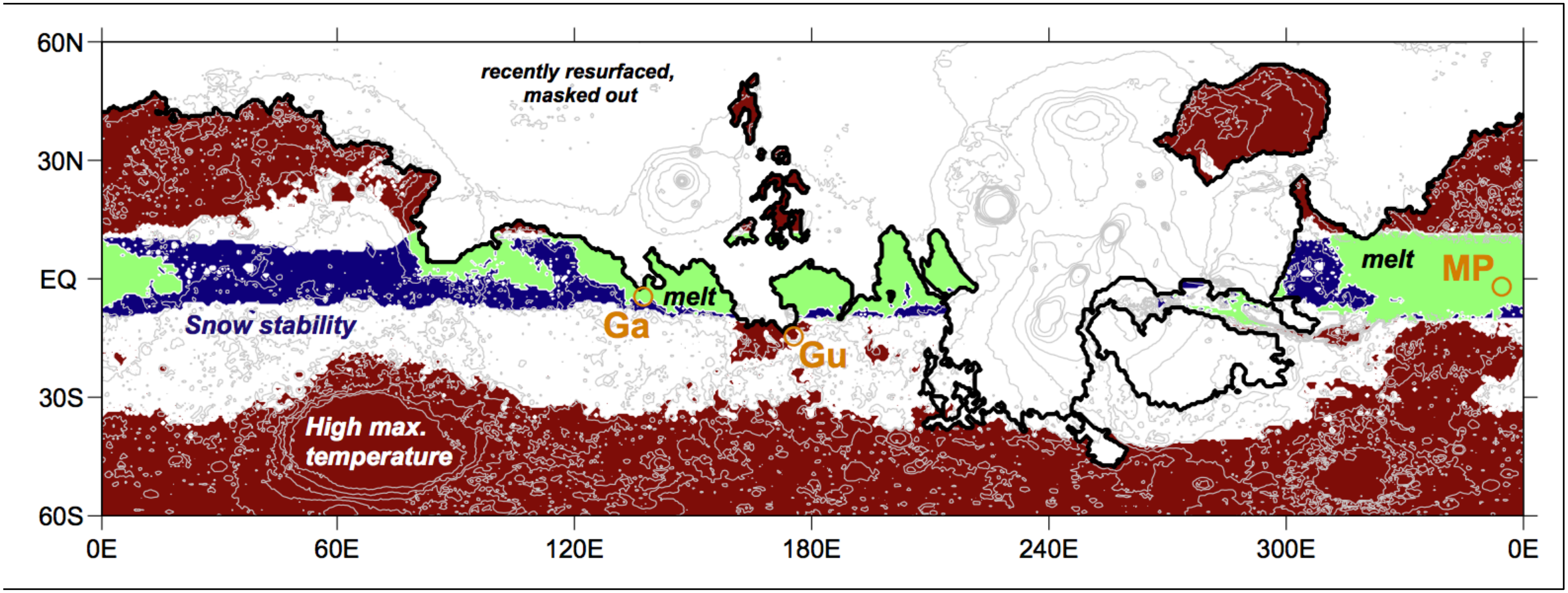



JPL

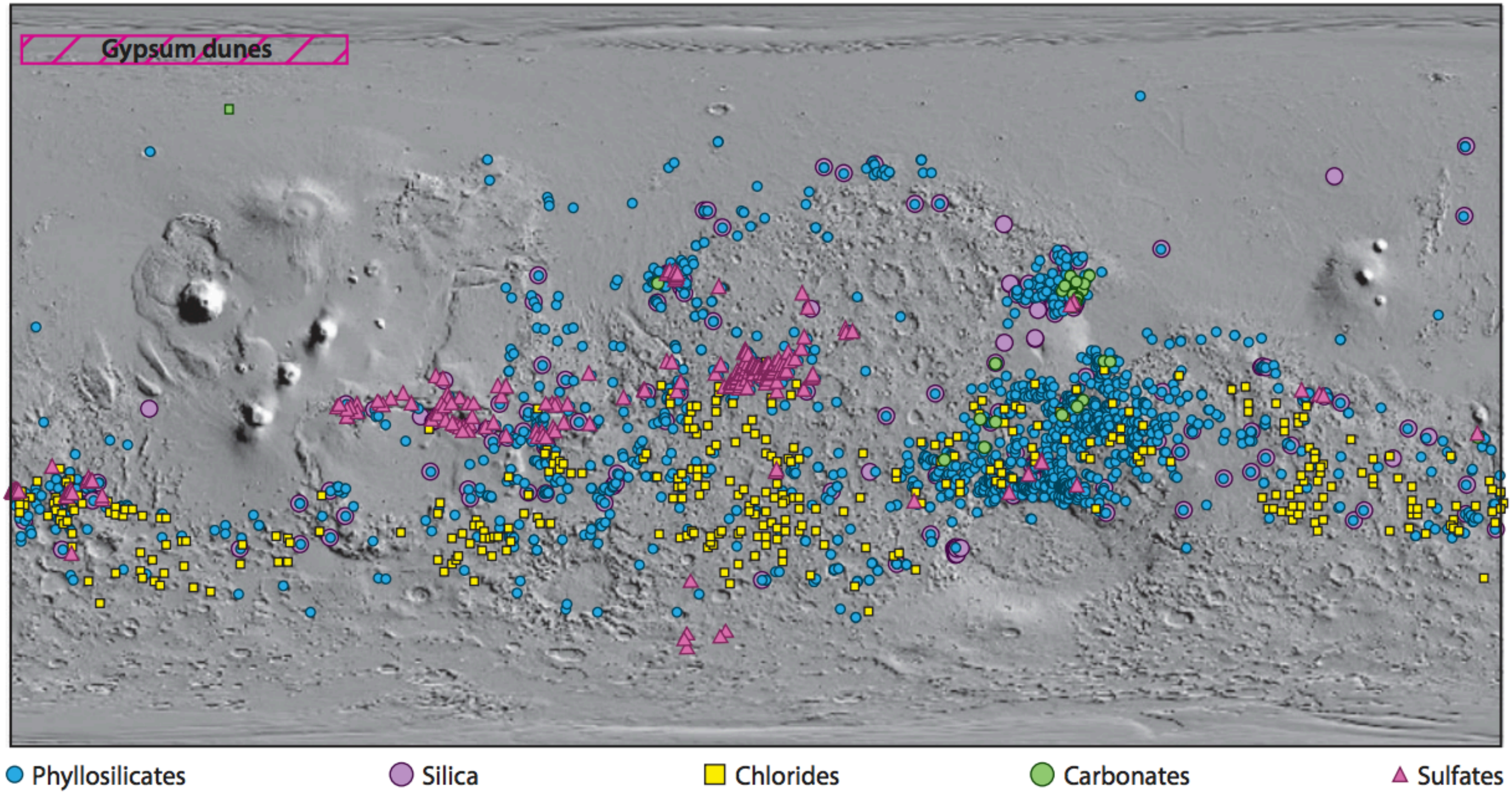

Ancient Streams
Ancient Dunes
Ancient Groundwater
1 meter



Grotzinger et al., Geology, 2006


60N
30N
EQ
30S
60S
0E
60E
120E
180E
240E
300E
0E
recently resurfaced, masked out
melt
melt
MP
Ga
Gu
Snow stability
High max. temperature

2005-: Orbiters confirm planet-wide association between sedimentary rocks and liquid water.



Ehlmann & Edwards, Annual Reviews, 2014

Mars Global Surveyor Project

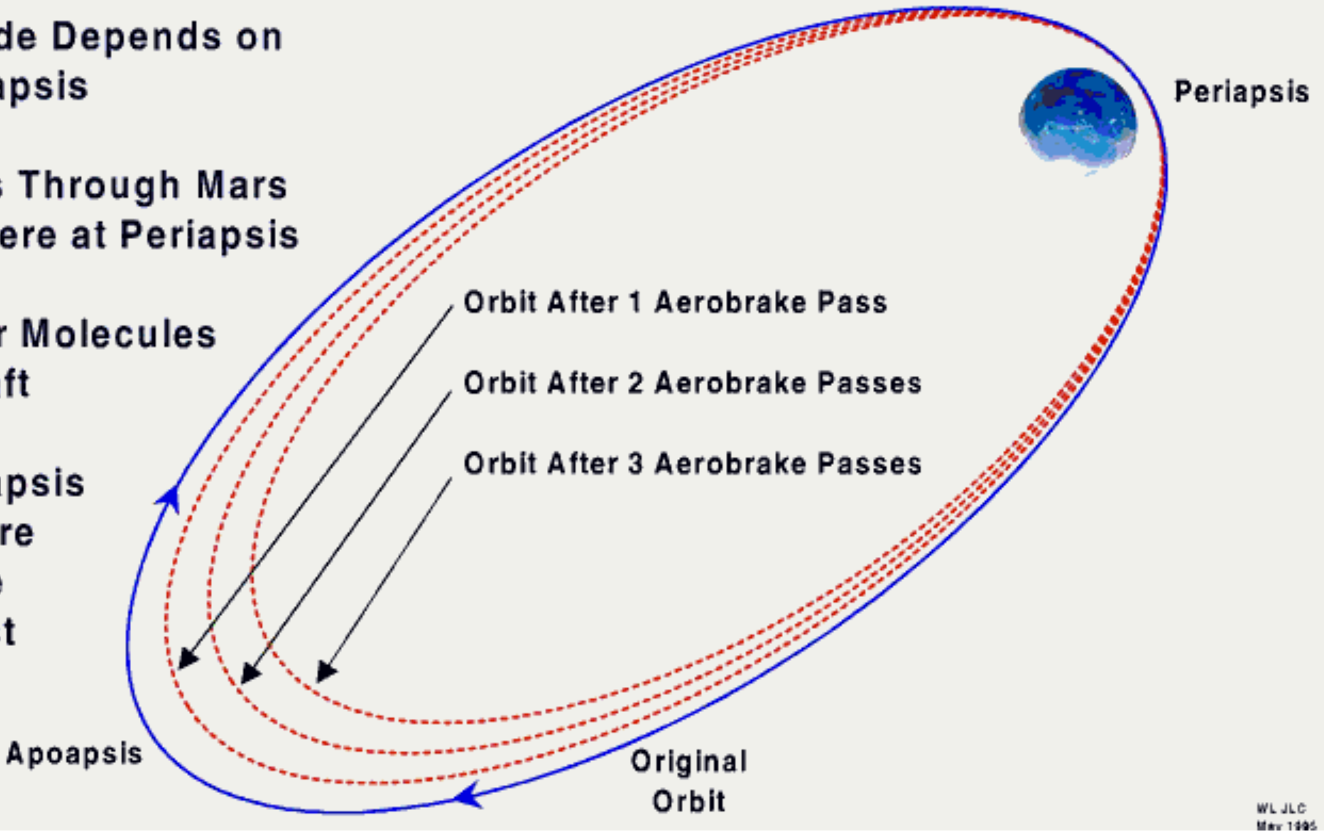
How Aerobraking Lowers the Orbit

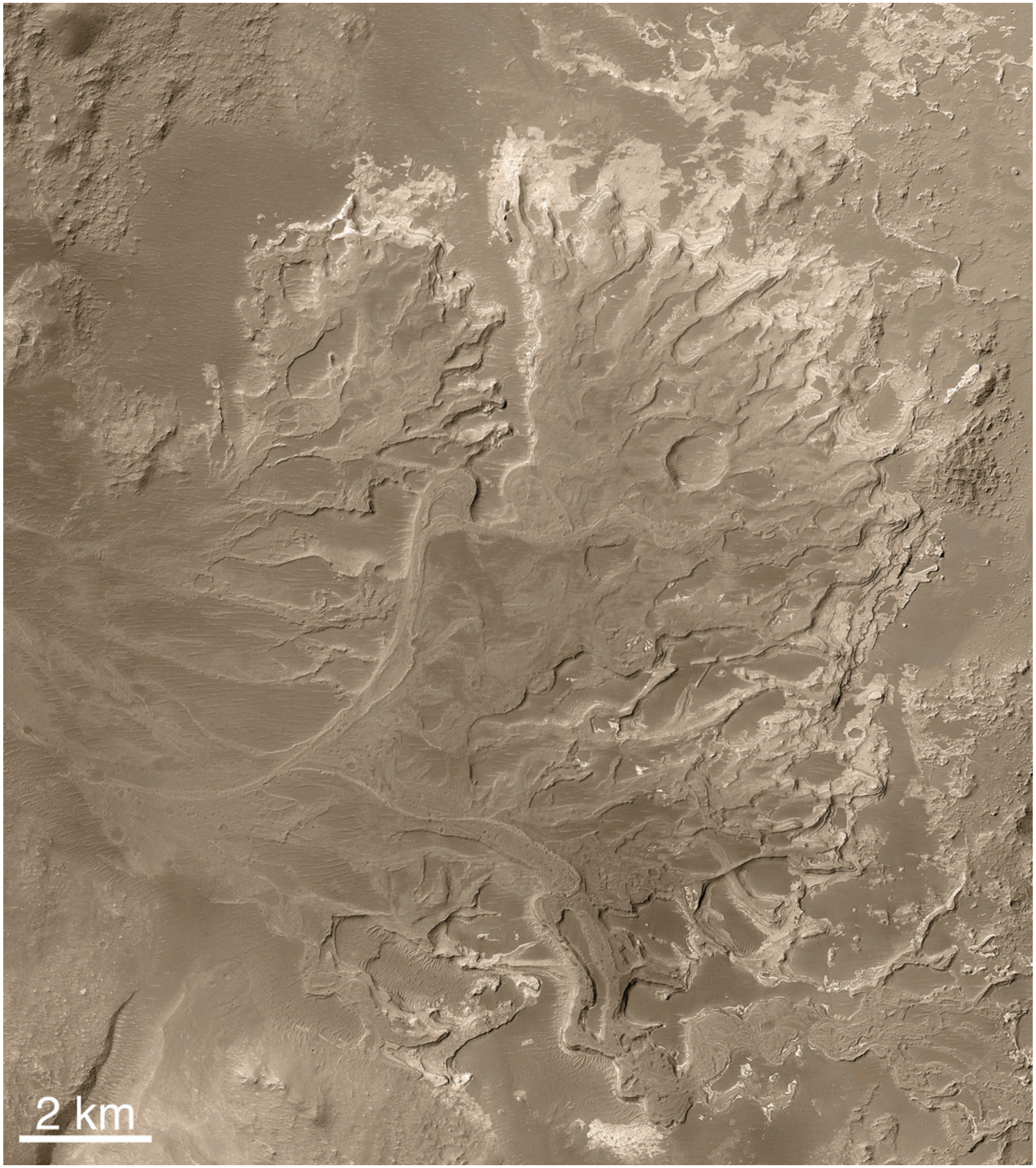
Apoapsis Altitude Depends on Velocity at Periapsis

Spacecraft Flies Through Mars Upper Atmosphere at Periapsis

Friction With Air Molecules Slows Spacecraft

Altitude at Apoapsis After Atmosphere Passage Will Be Lower Than Last Orbit

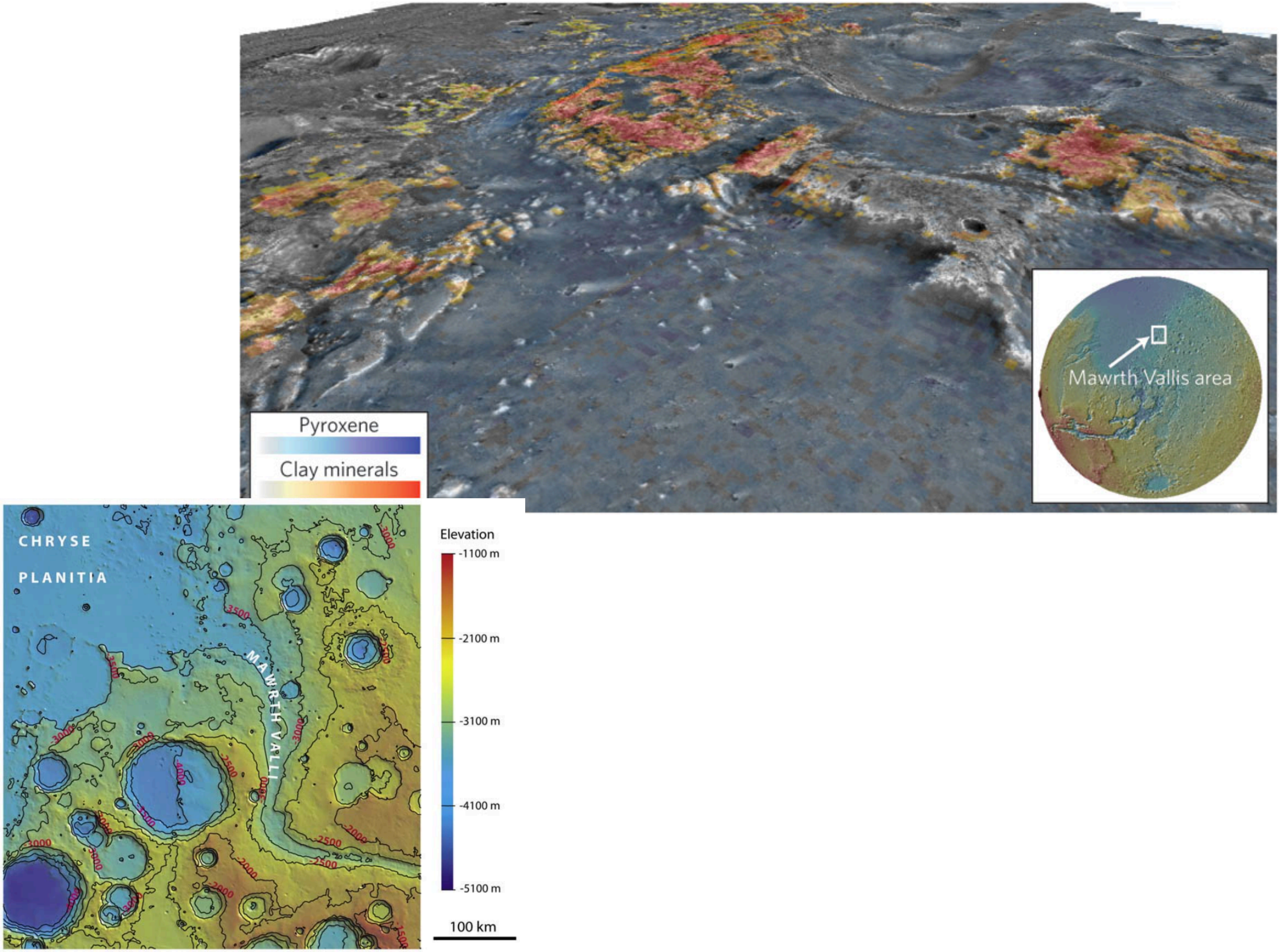




Irwin et al.,
Geomorphology 2015

0.01 – 1 Myr

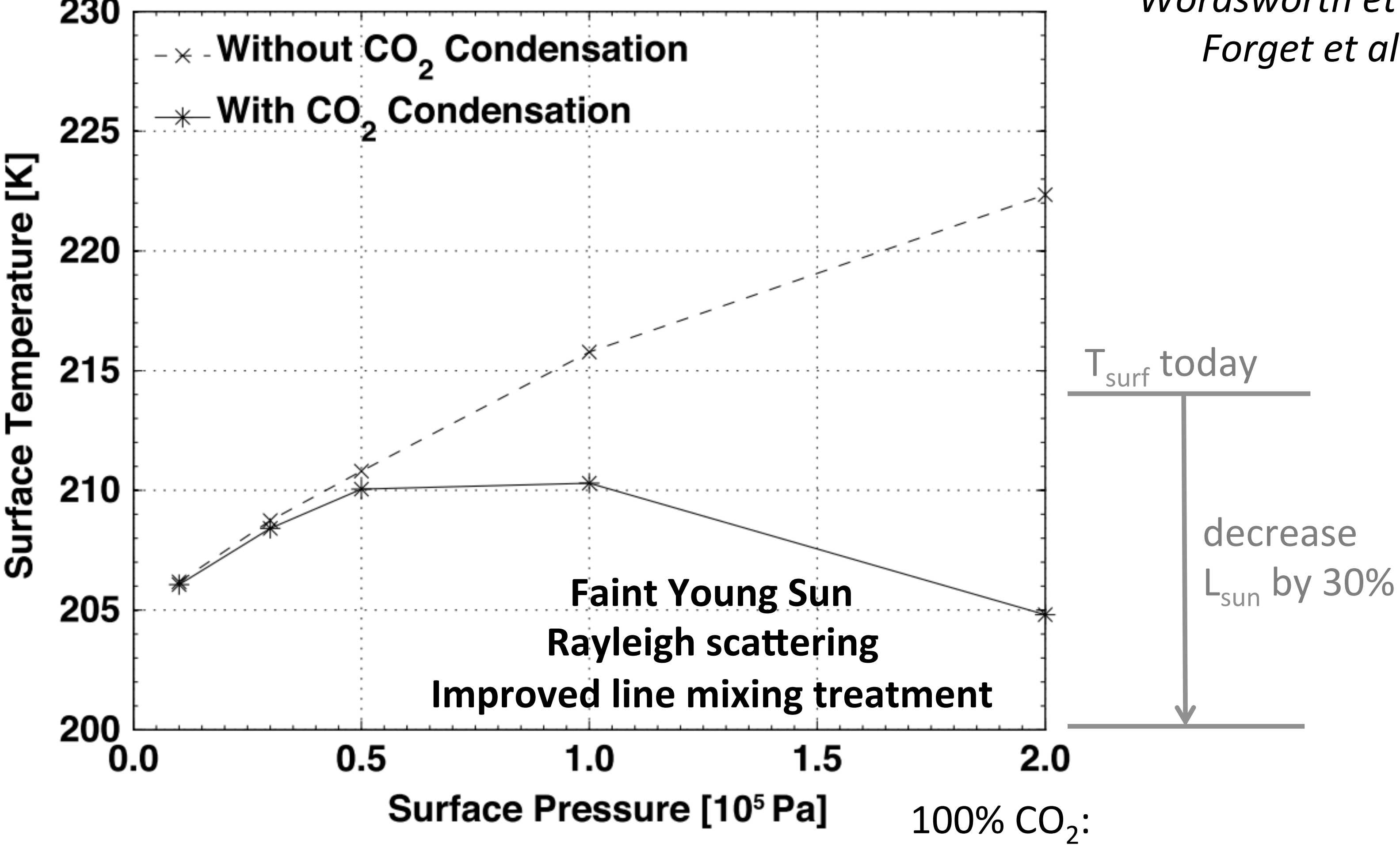
1 cm/day rainfall or
snowmelt


Pyroxene
Clay minerals
Mawrth Vallis area
CHRYSE
PLANITIA
MAWRTH VALLIS
Elevation
-1100 m
-2100 m
-3100 m
-4100 m
-5100 m
100 km

More CO_2 → necessary but insufficient for lake-forming climates on Mars

Ozak et al. JGR 2016
Haberle et al. JGR 1998
Wordsworth et al. JGR 2015
Forget et al. Icarus 2013

Results from steady-state 1D radiative-convective code

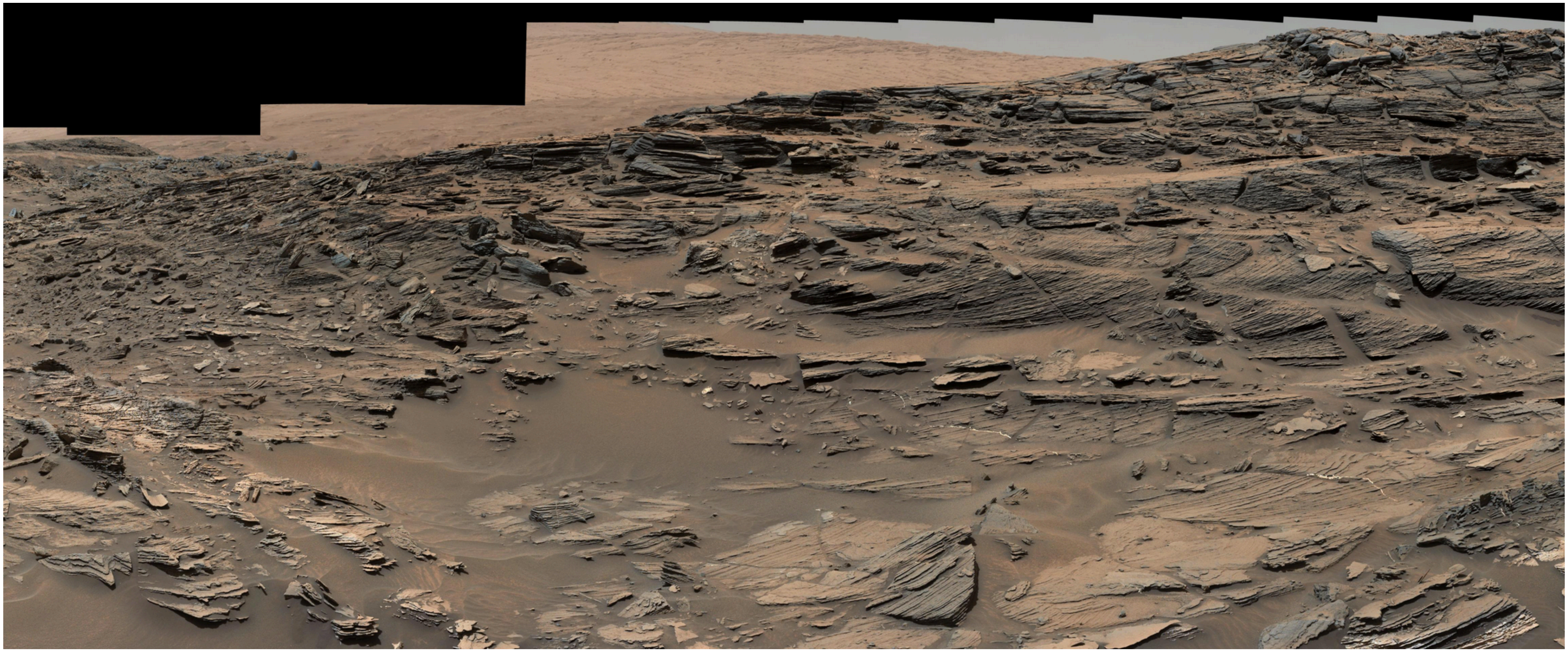


Faint Young Sun
Rayleigh scattering
Improved line mixing treatment

T_{surf} today

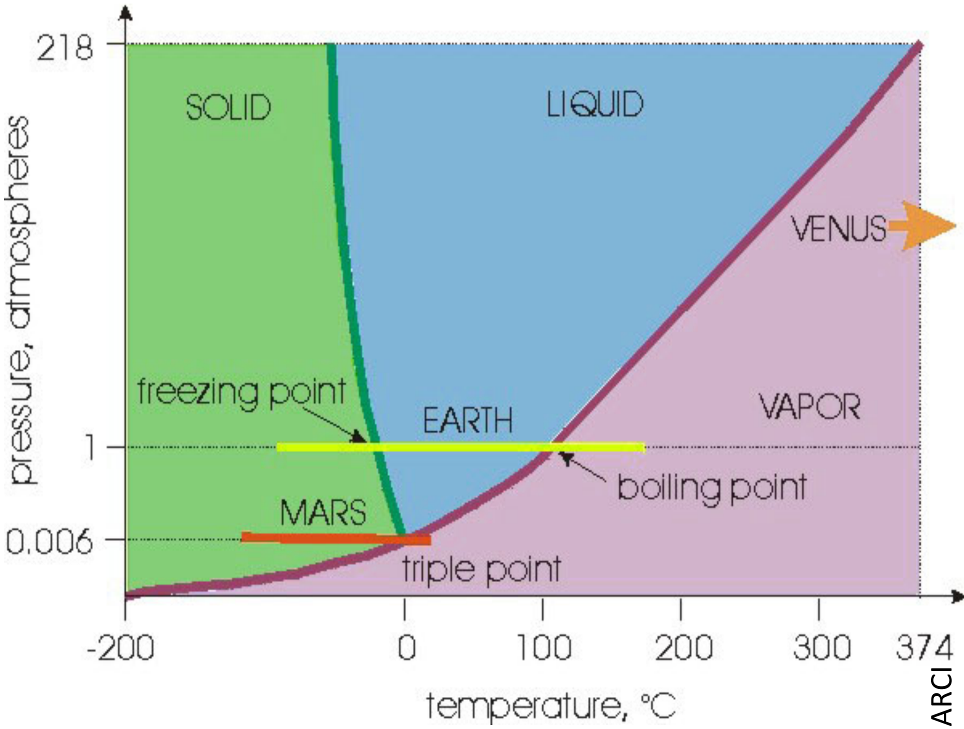
decrease
L_{sun} by 30%

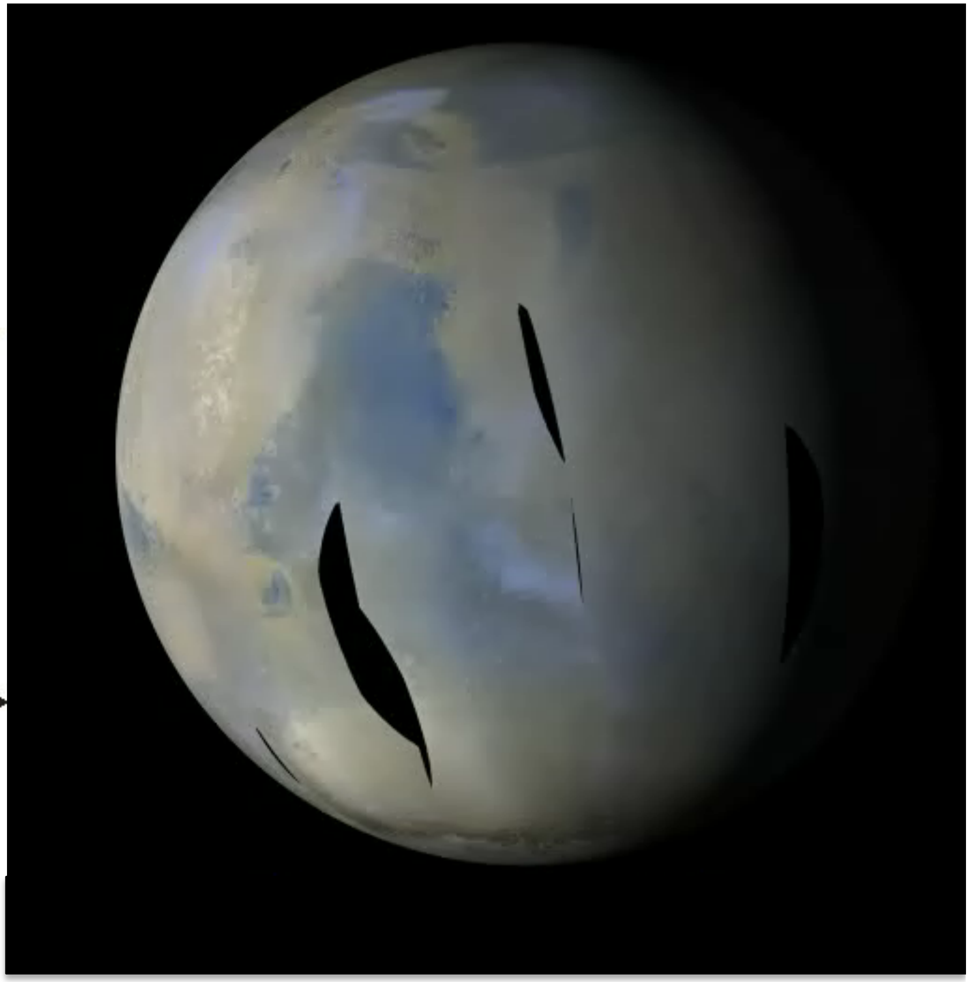
100% CO_2:
adding H_2O_v has little effect



Main discoveries by *Curiosity* rover so far:
Lacustrine, circumneutral ancient environment
Methane bursts
Ancient organic matter (?)

Mars today is hostile to life





MSSS/MARCI

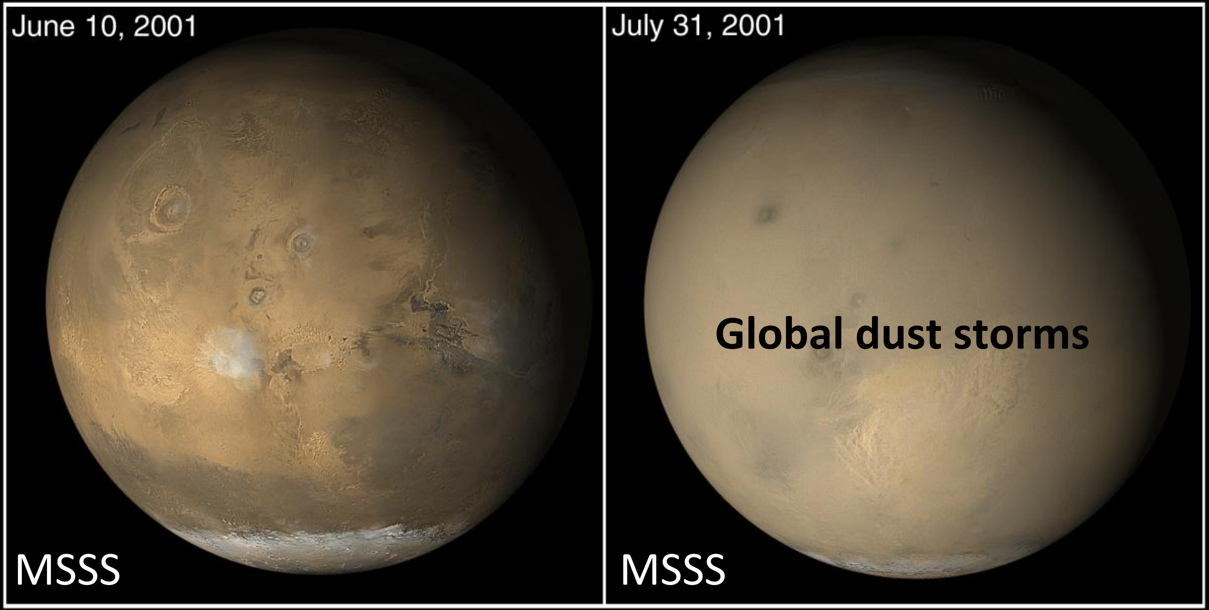
- Sunlight 0.4 × Earth
- 6 mbar CO_2 atmosphere
- Sterilizing surface conditions
- No active hot-springs or volcanoes
- Mean rock erosion rate < 10^{-5} × Earth

- **Active cycles of water ice/vapor (~1km^3/yr); dust (~10 km^3/yr); CO_2 (2 x 10^3 km/yr)**
- Milankovitch cycles 10-100 × Earth
- Evidence for limited `wet patches' < 100 Ma

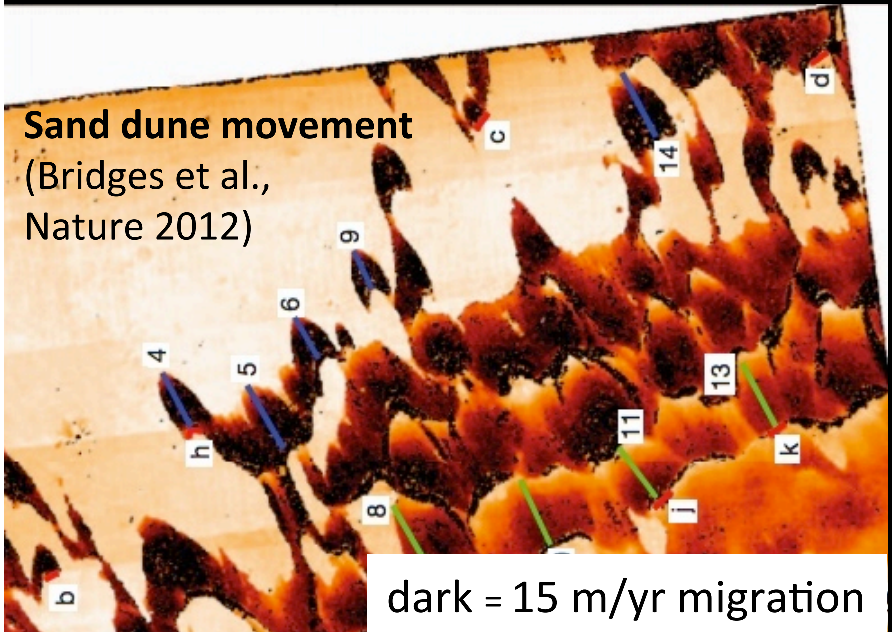
Martian sedimentary rocks: just add (liquid) water?

Modern: Active redistribution of sand and dust (10-100 µm/yr)

Very little aqueous cementation

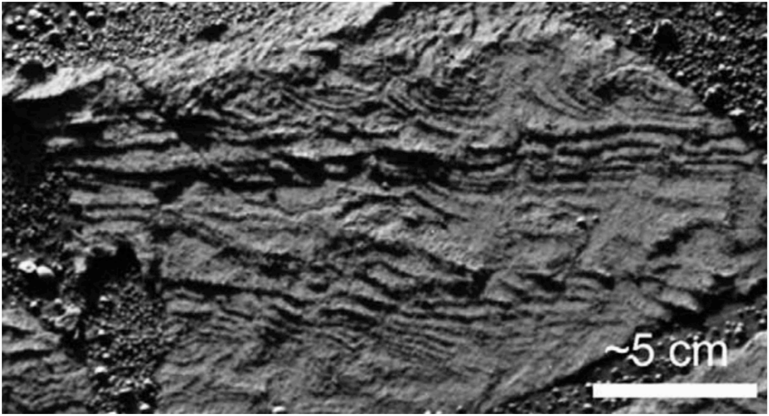


Global dust storms



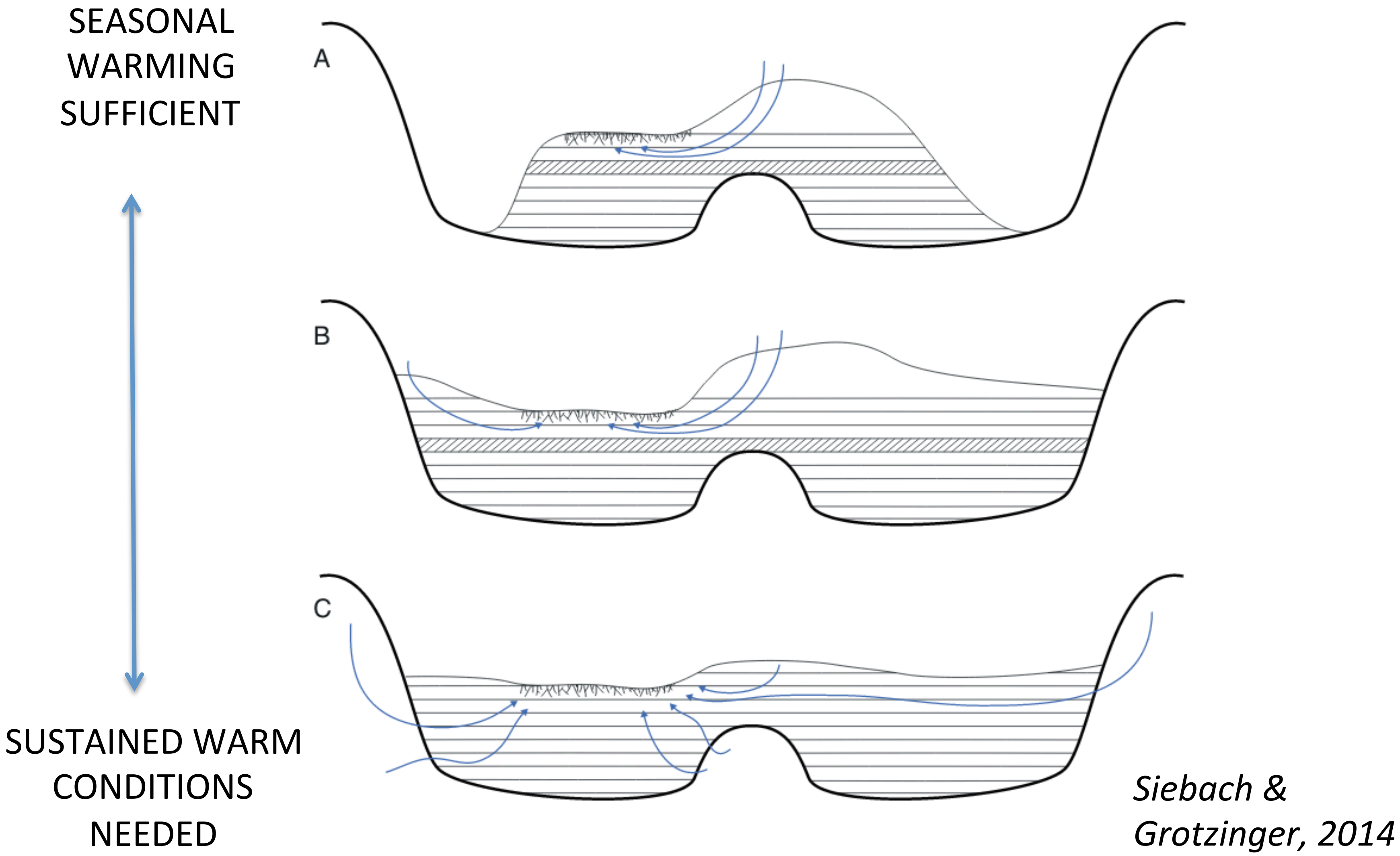
Sand dune movement (Bridges et al., Nature 2012)

dark = 15 m/yr migration



Some surface runoff (Grotzinger et al., Geology 2006; Metz et al., J. Sed. Res. 2009; Grotzinger & Milliken, SEPM Sp. Pub., 2012)

What was the water source for the sedimentary rocks?

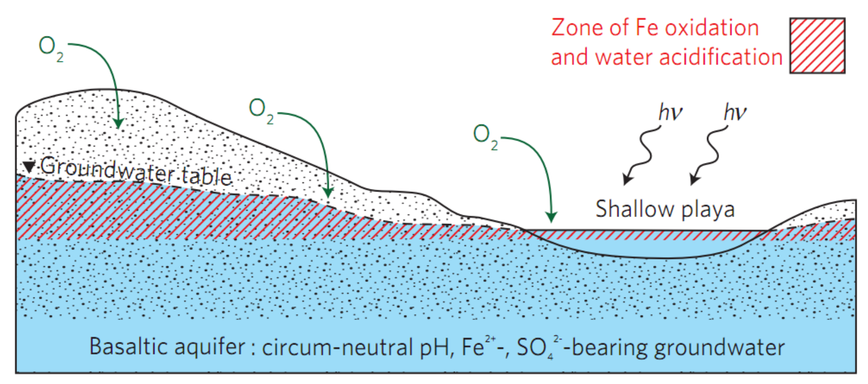

SEASONAL WARMING SUFFICIENT

SUSTAINED WARM CONDITIONS NEEDED

Siebach & Grotzinger, 2014

Water source: Bottom-up or top-down?

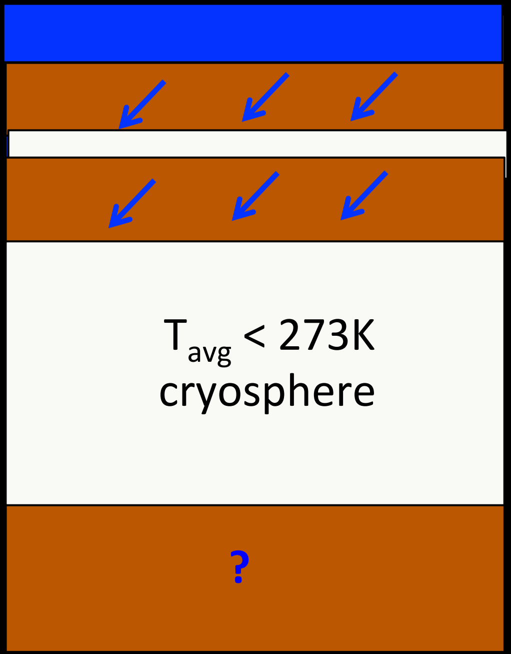
The prevailing view:
globally-integrated groundwater
warm ($T_{avg} > 273K$)



Depositional scenario (Hurowitz et al., 2010)
(Andrews-Hanna et al., Nature 2007)

Alternative: seasonal melting

"top-down" cool



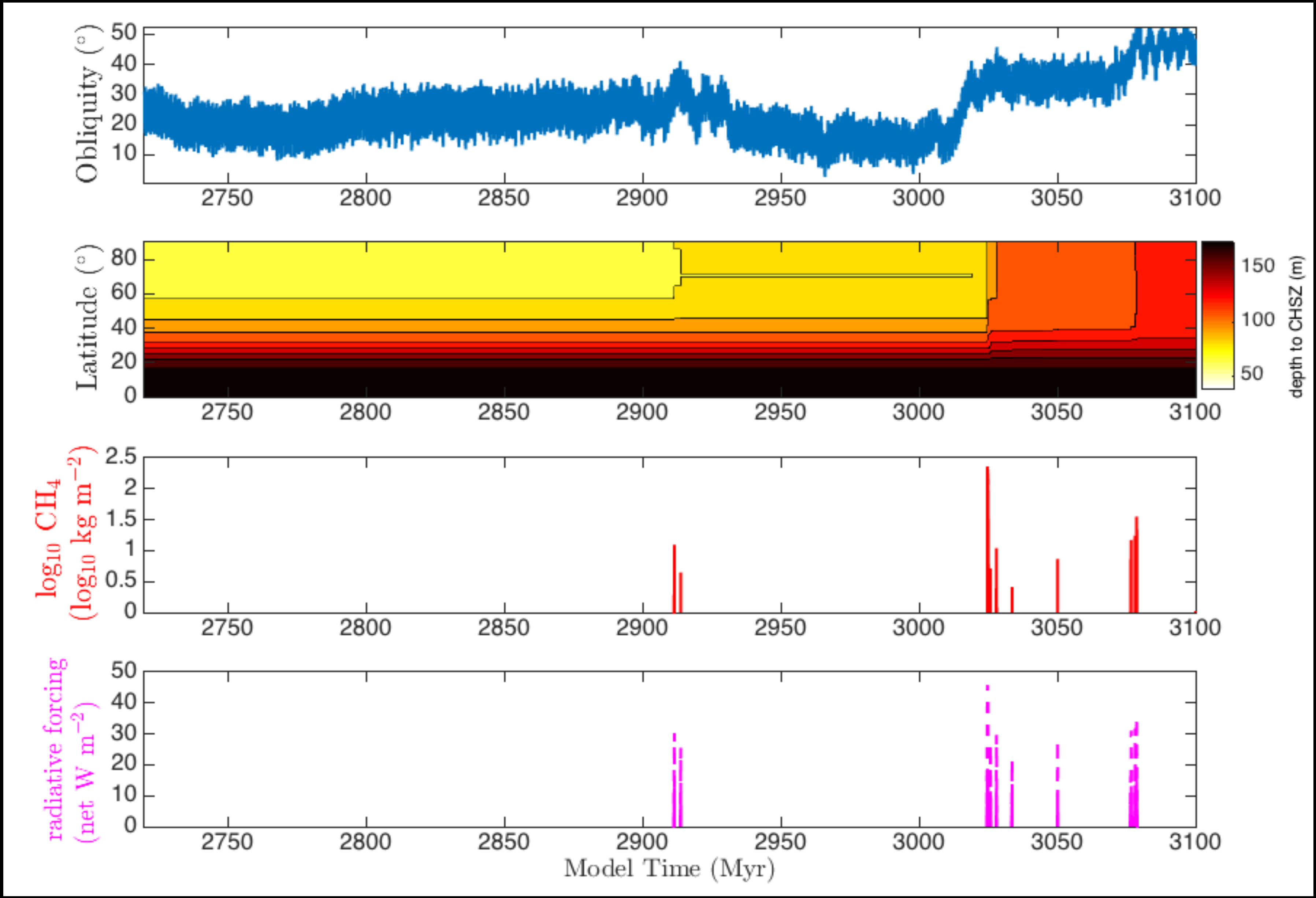
e.g. Clow, Icarus, 1987;
Amundson et al., GCA, 2008,
Niles & Michalski, Nat. Geo., 2009

Bottom-up model requires T_{avg} > 273K

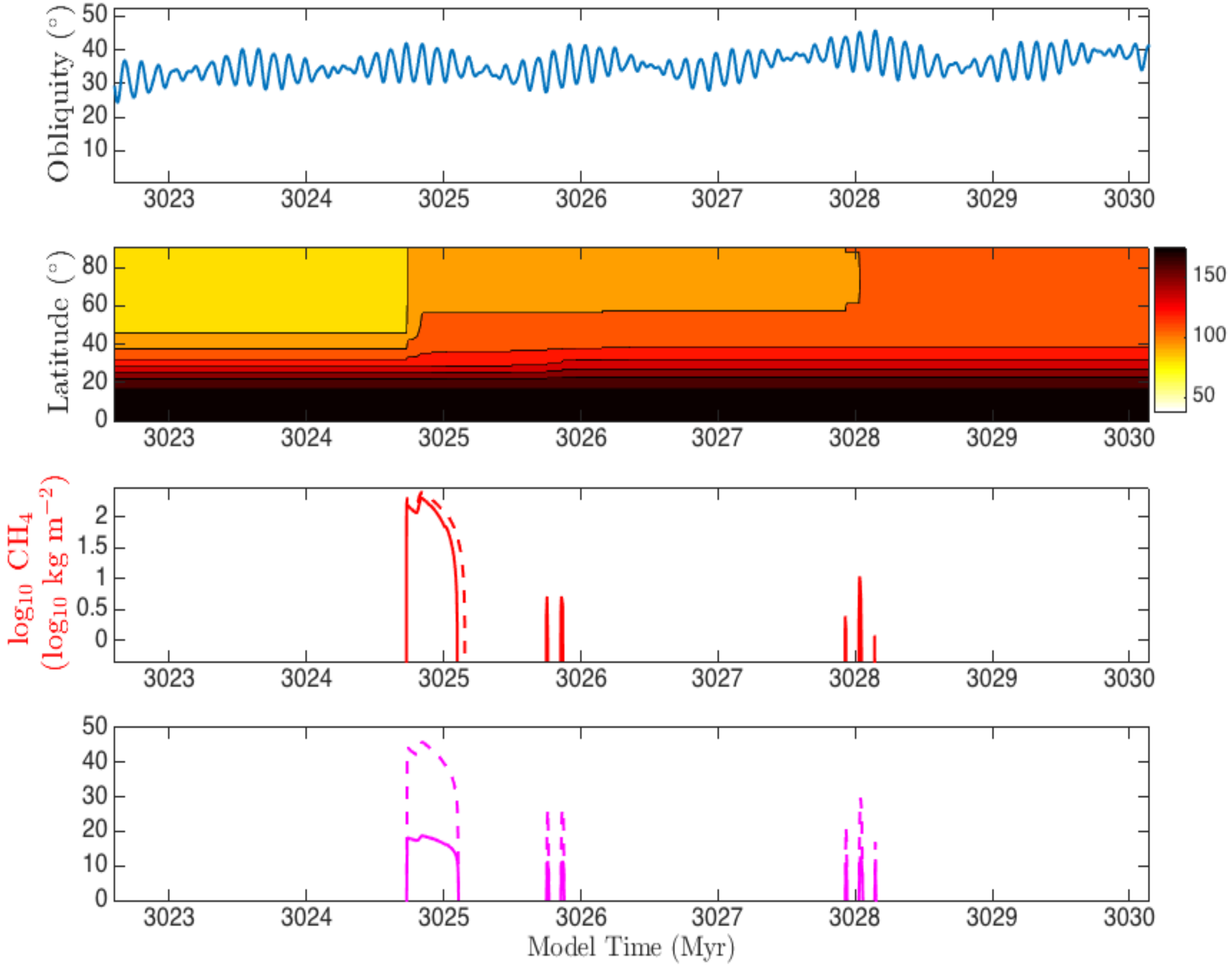
- impossible with a CO_2/H_2O atmosphere

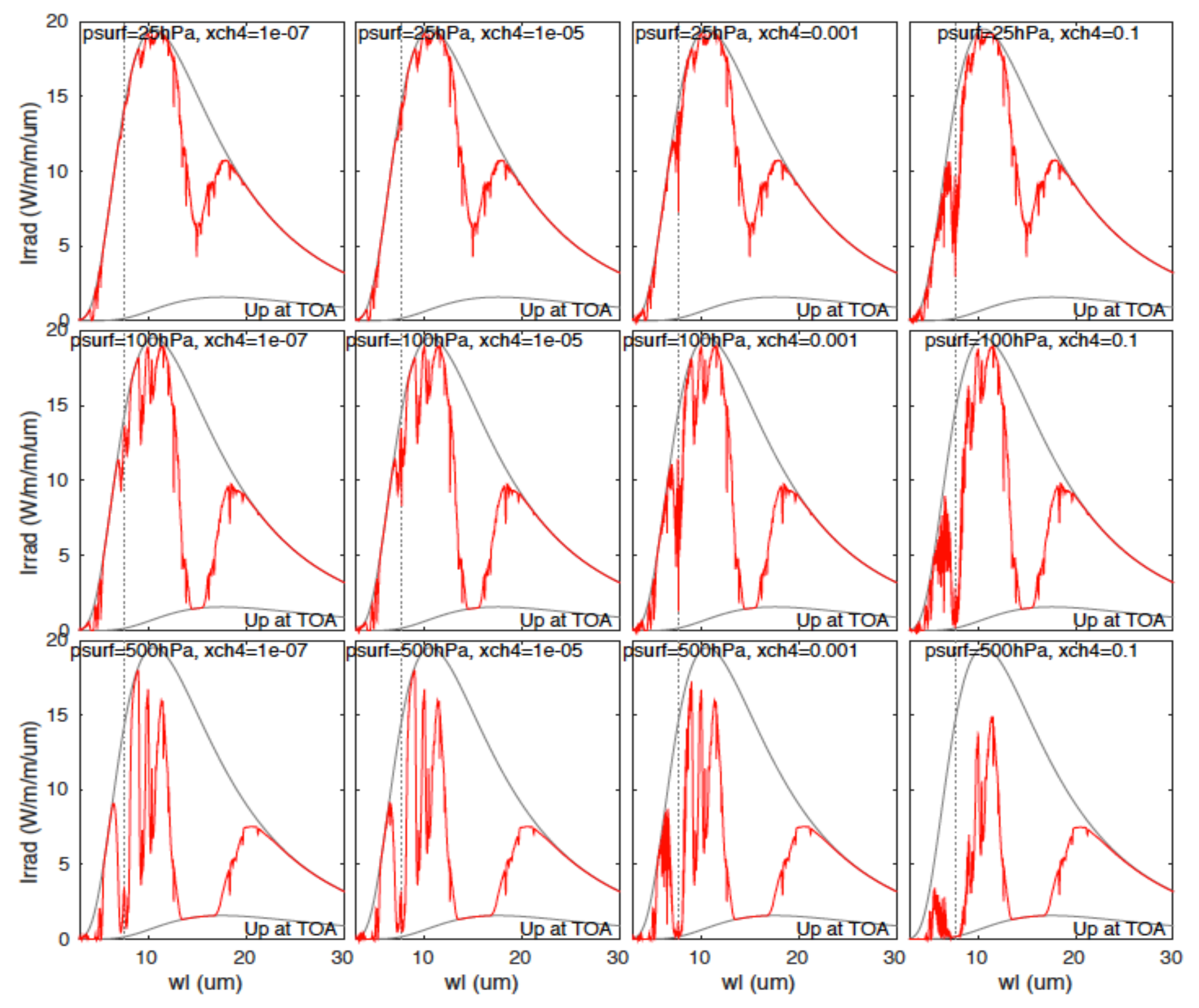
  e.g. Forget et al., Icarus, 2012; Wordsworth, Icarus, 2010.
- other greenhouse gases (e.g. SO_2) have short lifetimes; high salinity can't help (sulfates).
- is there a water source that will work with reasonable atmospheric parameters?

Kite et al., arXiv:1611.01717

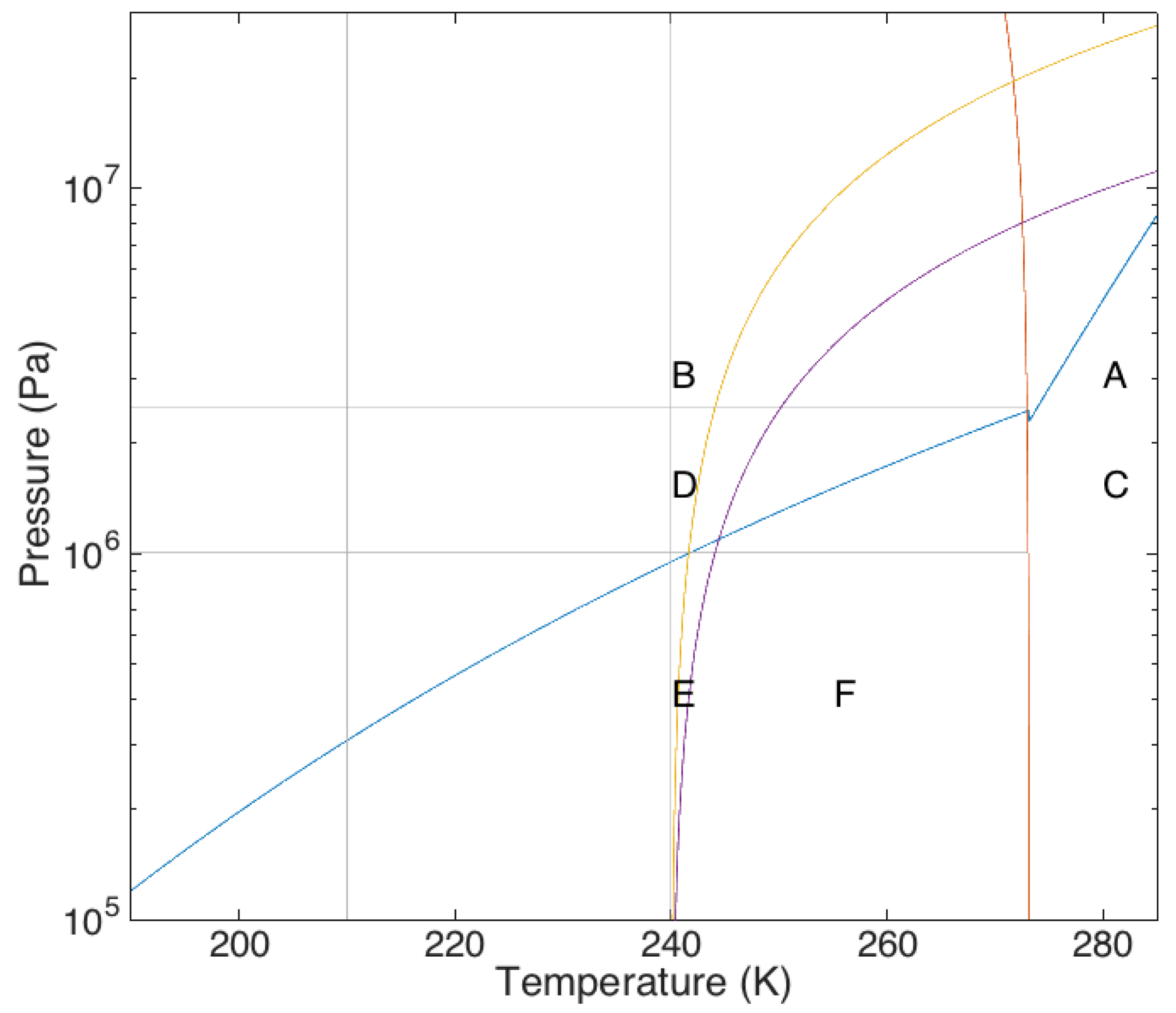


Kite et al., arXiv:1611.01717

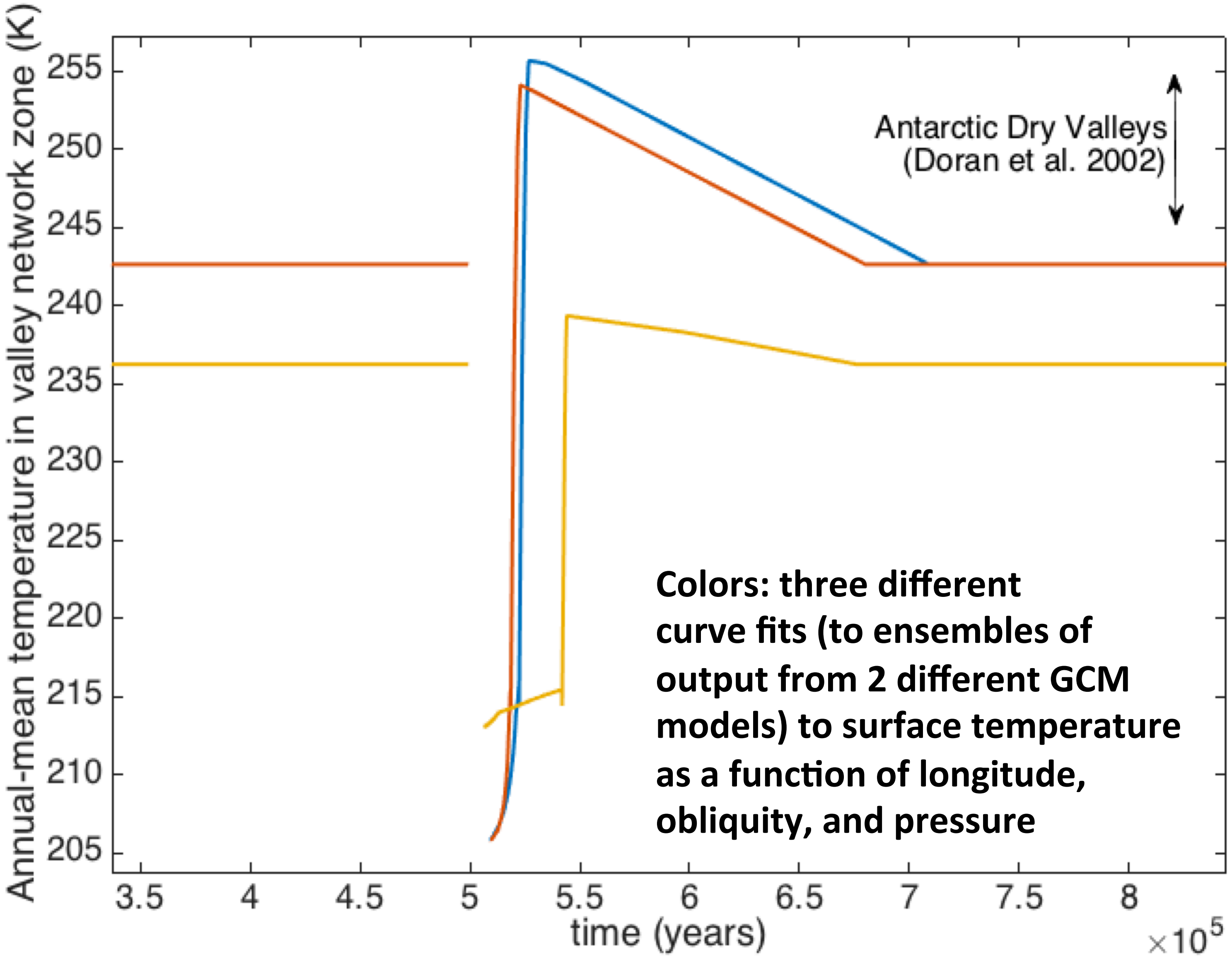



psurf=25hPa, xch4=1e-07
psurf=25hPa, xch4=1e-05
psurf=25hPa, xch4=0.001
psurf=25hPa, xch4=0.1
psurf=100hPa, xch4=1e-07
psurf=100hPa, xch4=1e-05
psurf=100hPa, xch4=0.001
psurf=100hPa, xch4=0.1
psurf=500hPa, xch4=1e-07
psurf=500hPa, xch4=1e-05
psurf=500hPa, xch4=0.001
psurf=500hPa, xch4=0.1
Up at TOA
Irrad (W/m/m/um)
wl (um)
0
5
10
15
20
10
20
30

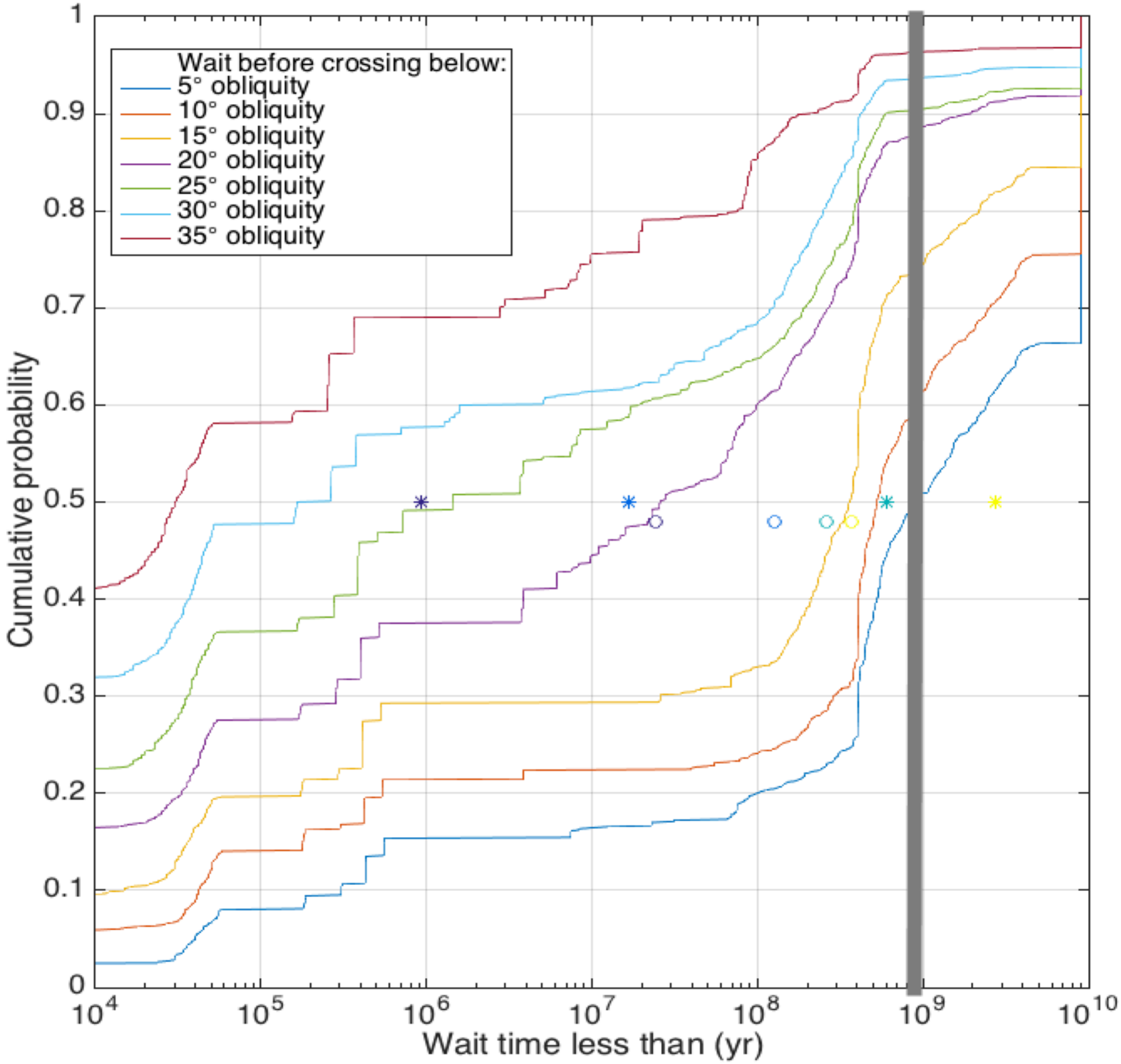
Kite et al., in prep.

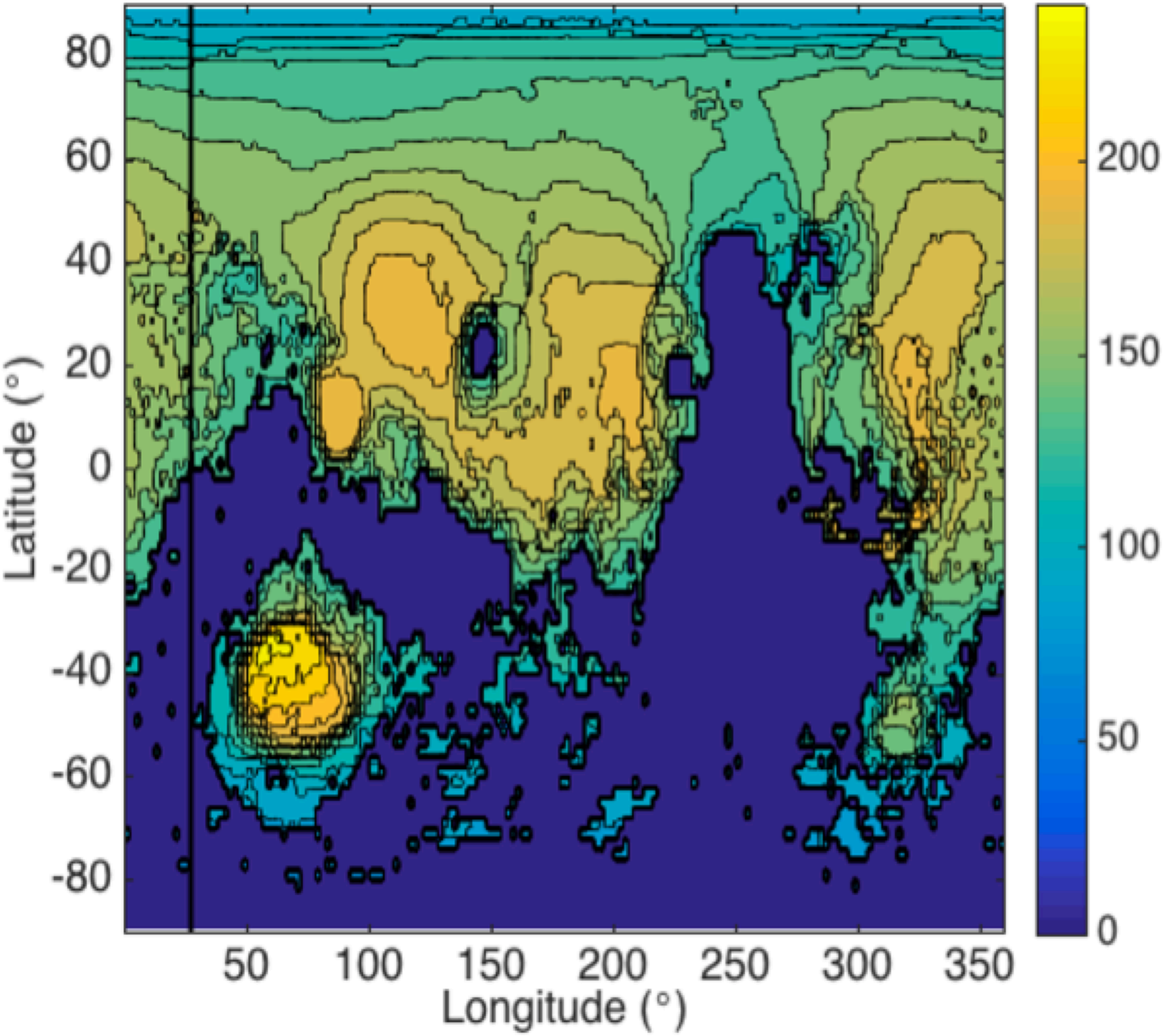


Kite et al., in prep.



Colors: three different curve fits (to ensembles of output from 2 different GCM models) to surface temperature as a function of longitude, obliquity, and pressure


Wait before crossing below:
5° obliquity
10° obliquity
15° obliquity
20° obliquity
25° obliquity
30° obliquity
35° obliquity
Cumulative probability
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
Wait time less than (yr)

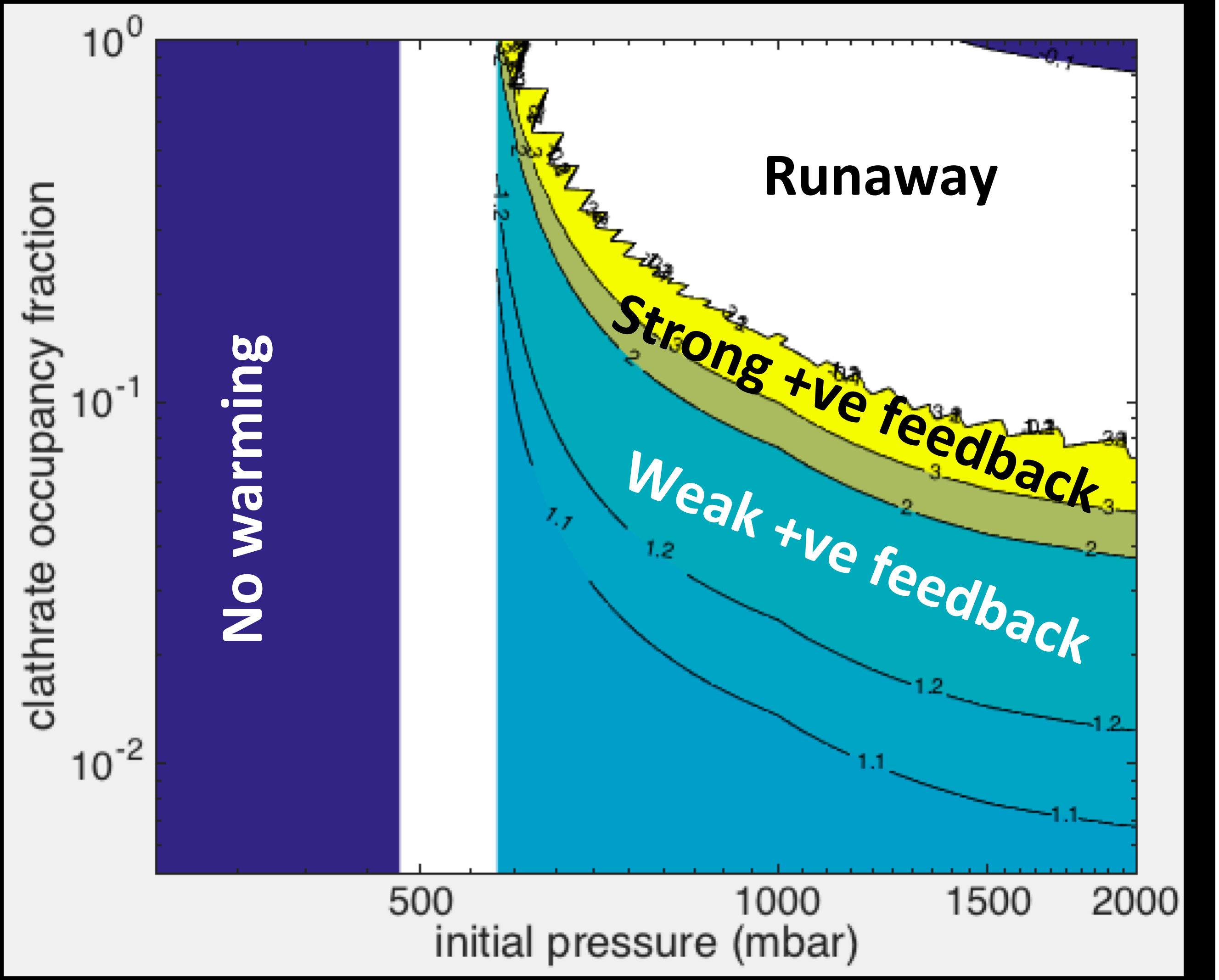


Depth to top of methane clathrate stability zone

$$G = 1/(1-F)$$

G = Gain
F = Feedback factor

fraction of **pore space** (20% porosity assumed)



Results are shown for a single-column model, but these are qualitatively representative of the response of the whole-Mars model.