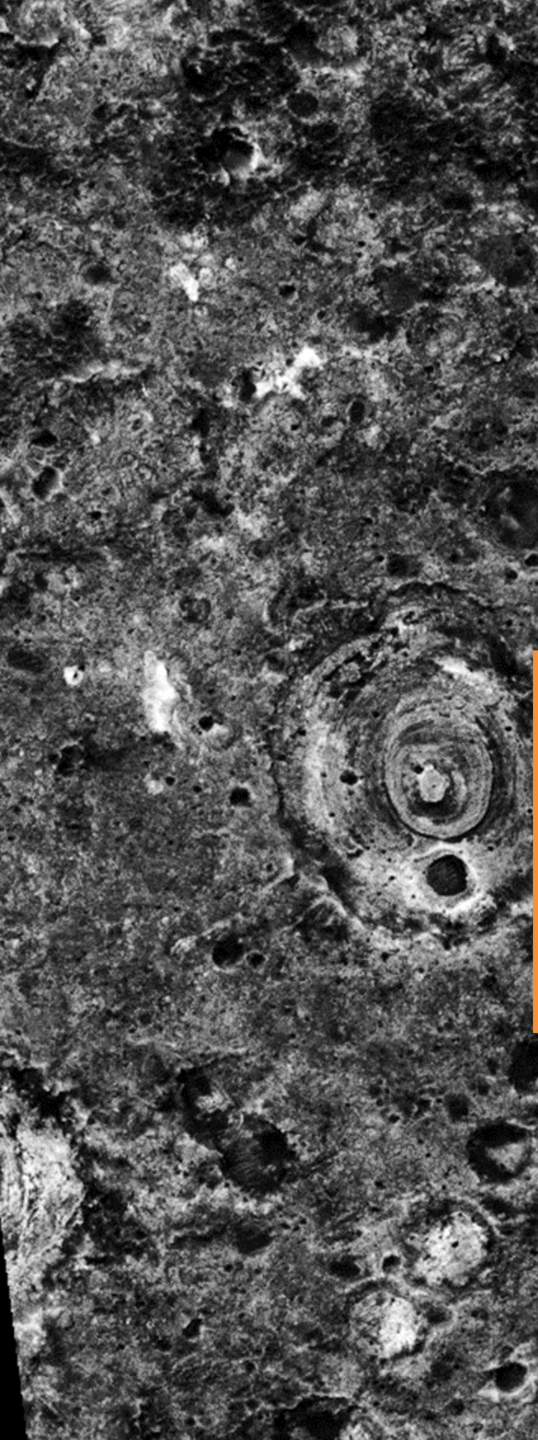

Multi-Gyr History of Mars' CO_2-Dominated Atmosphere: New Data and a New Synthesis

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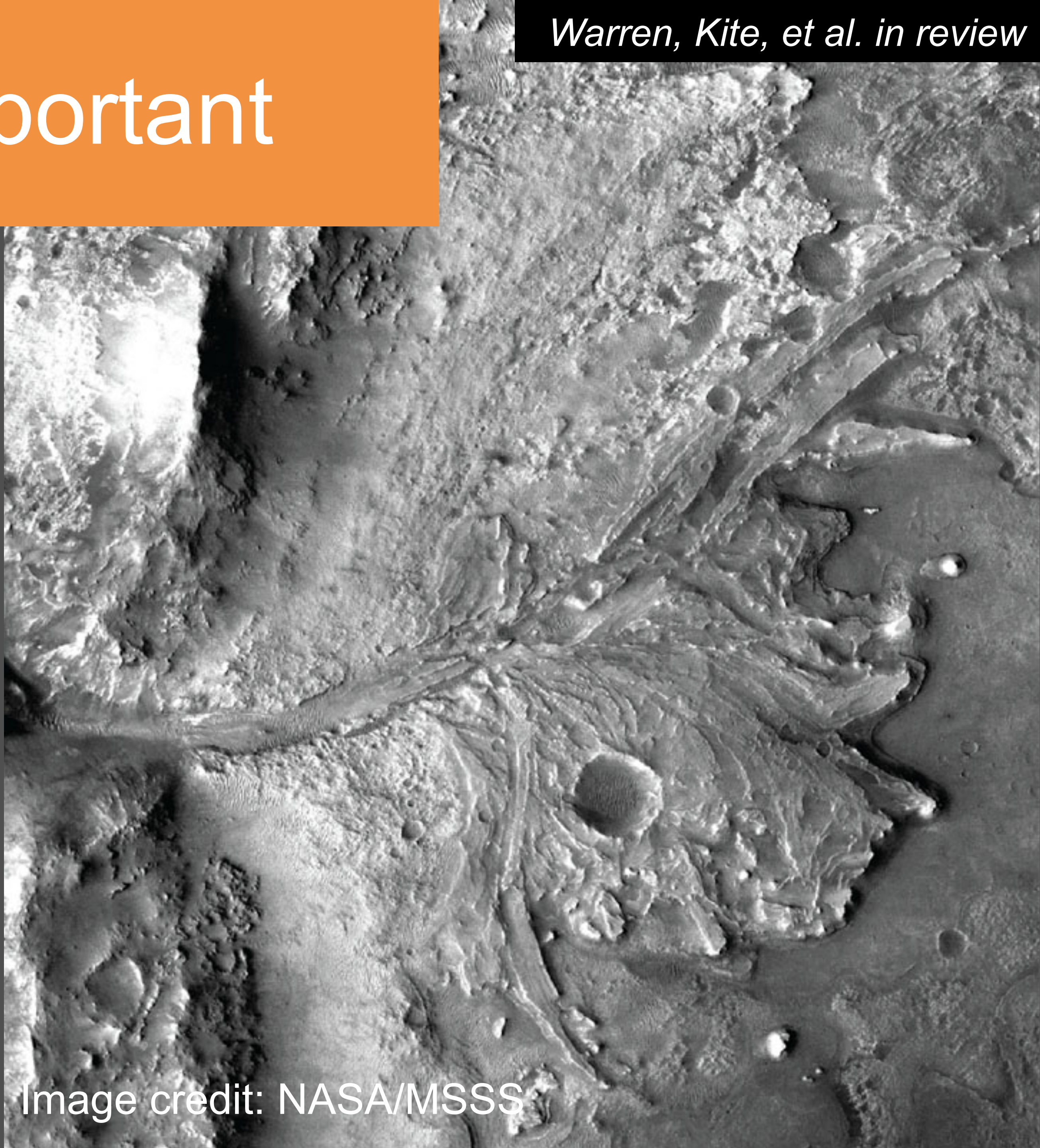
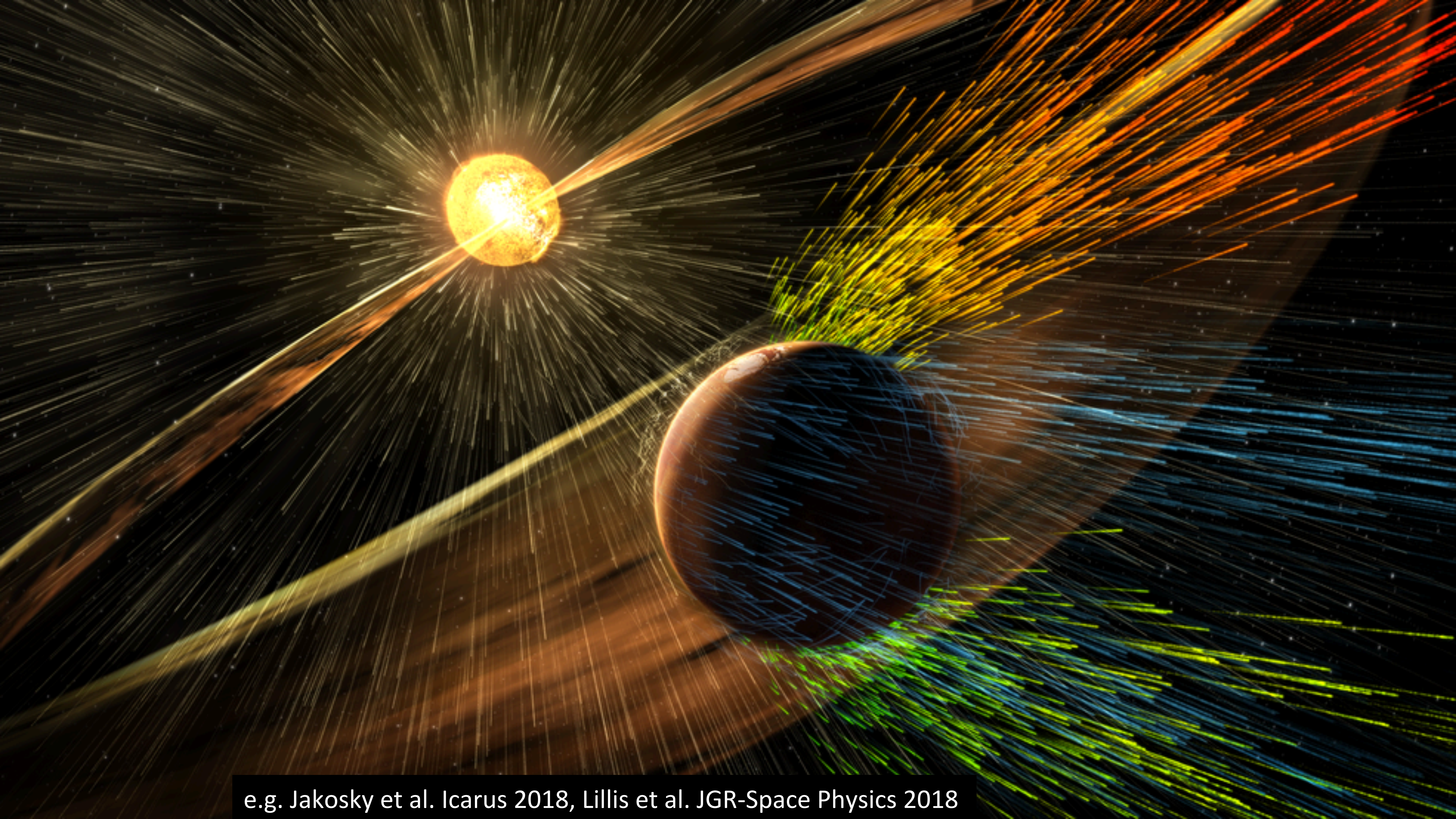
Mars paleo-pCO_2 is important

Warren, Kite, et al. in review

- Early Mars climate allowed rivers and lakes
- Paleopressure → max. CO_2 available for greenhouse warming:

  Pure CO_2?
  CO_2 + H_2O clouds?
  CO_2 + H_2/CH_4?





e.g. Jakosky et al. Icarus 2018, Lillis et al. JGR-Space Physics 2018

e.g. Cassata et al. 2012, Cassata 2017, Kurokawa et al. 2018


e.g. Van Berk et al. 2012, Van Berk et al. 2013

Mars paleopressure constraints

1[c] - Cosmochemical estimate

2[c], 3[c] – Models of atmosphere isotopic composition

4[c], 5[c], 9*[c] - Mineral stability/thermodynamic models

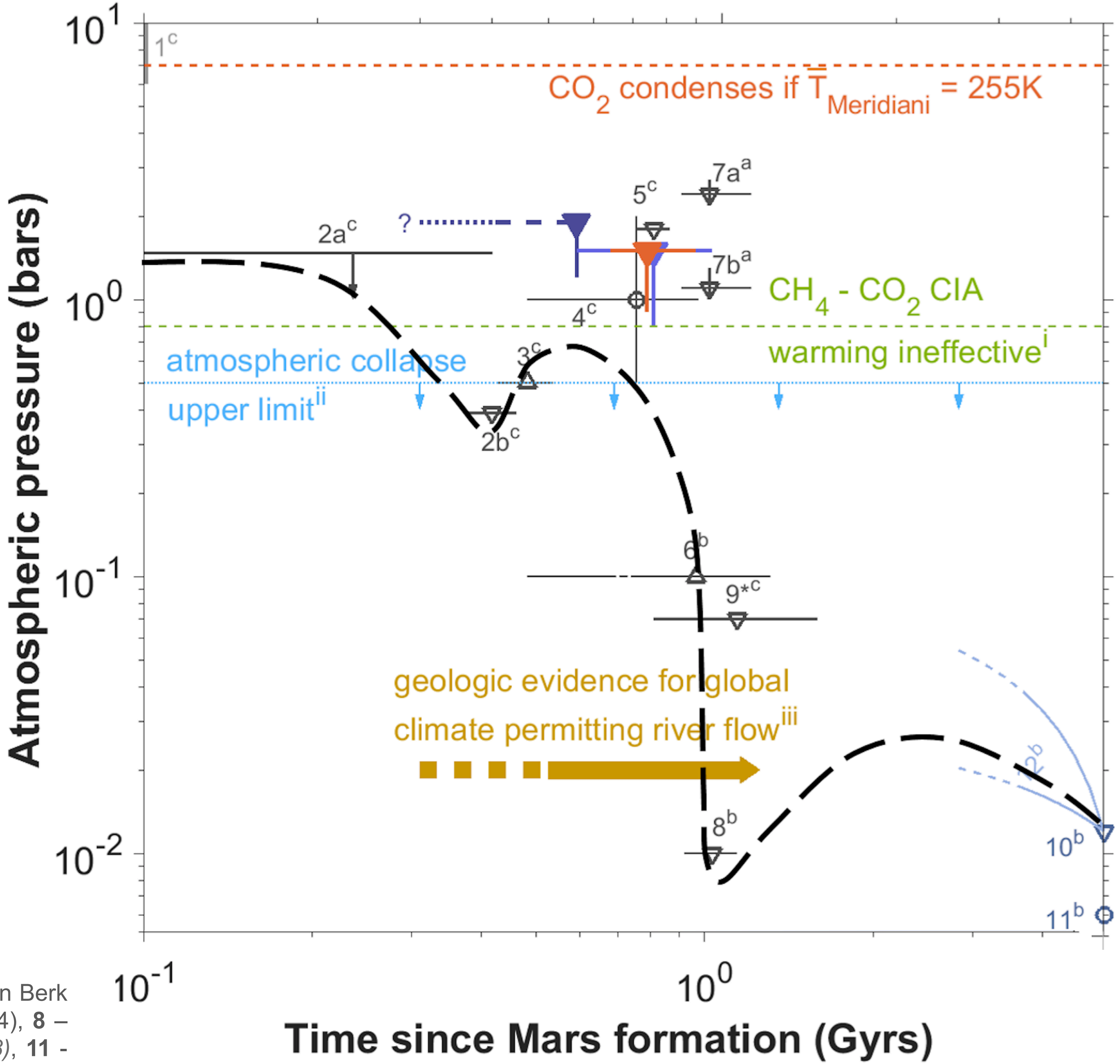
6[b], 8[b] - Sedimentary features

7[a] - Ancient craters preserved in sedimentary rocks (updated from Kite et al. 2014)

10[b], 11[b] - Present day atmosphere (± ice caps)

12[b] – MAVEN loss rate

1 - Lammer et al. (2013), **2** – Cassata (2012), **3** – Kurokawa et al. (2017), **4** – Van Berk et al. (2012), **5** – Hu et al. (2015), **6** – Manga et al. (2012), **7** – Kite et al. (2014), **8** – Lapotre et al. (2016), **9*** - Bristow et al. (2017) *but see also Tosca et al. (2018)*, **11** - Bierson et al. (2016), **12** – Lillis et al. (2015), **i** – Turbet et al. (2019), **ii** – Soto et al. (2015), Forget et al. (2013), **iii** – Kite (2019)

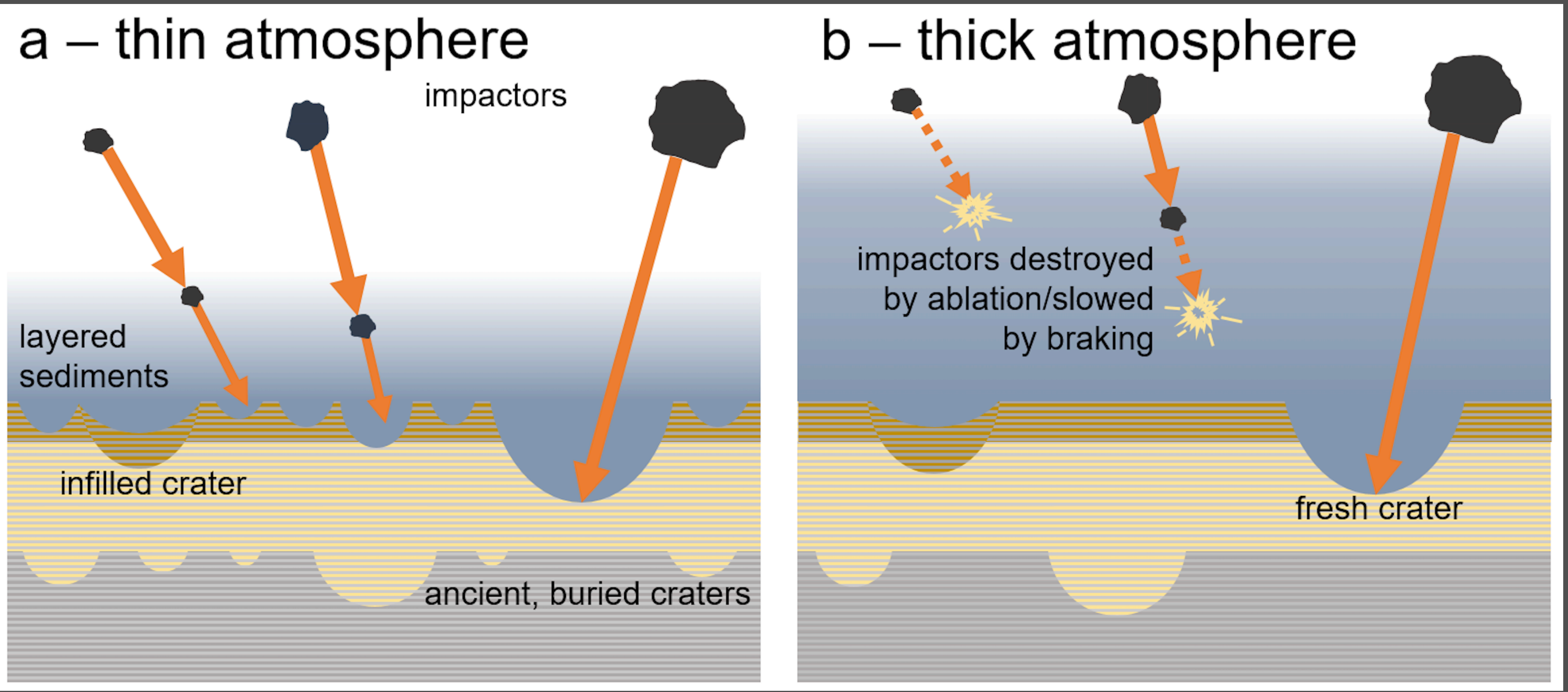


Warren, Kite, et al., in review.

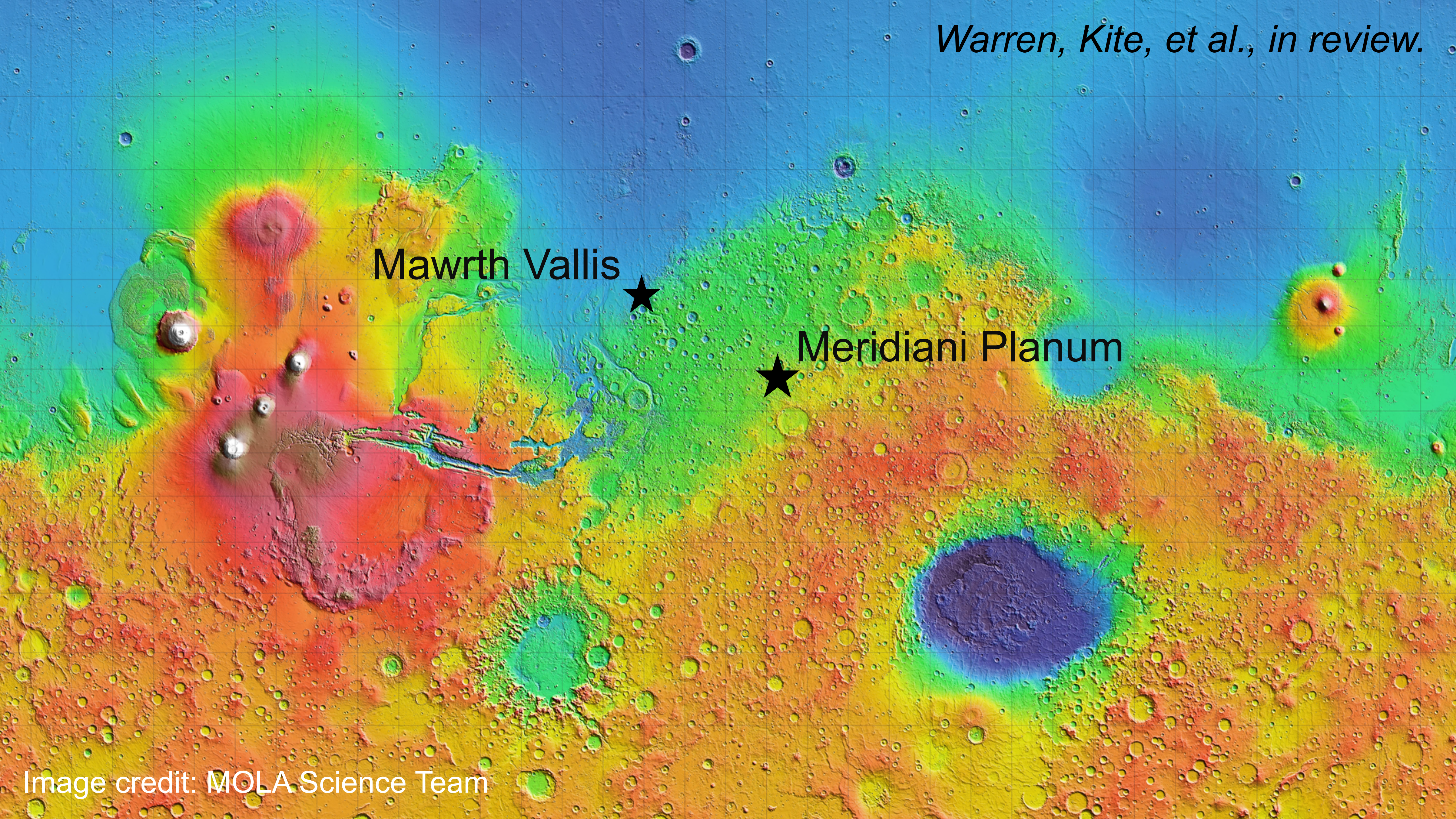
Small ancient craters: a direct constraint on paleo-atmospheric pressure

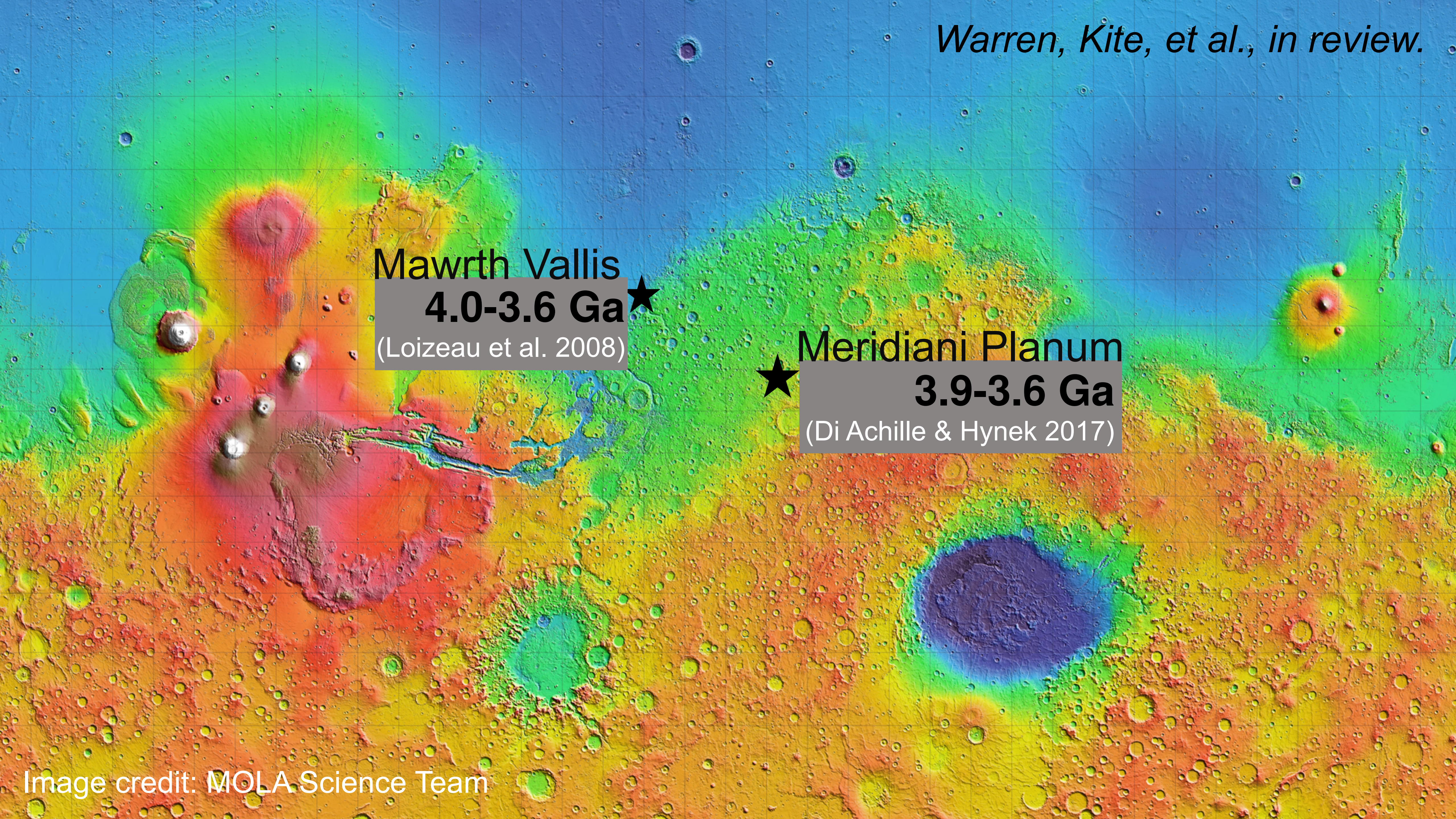
Kite et al. Nature Geoscience 2014

Warren, Kite, et al., in review.



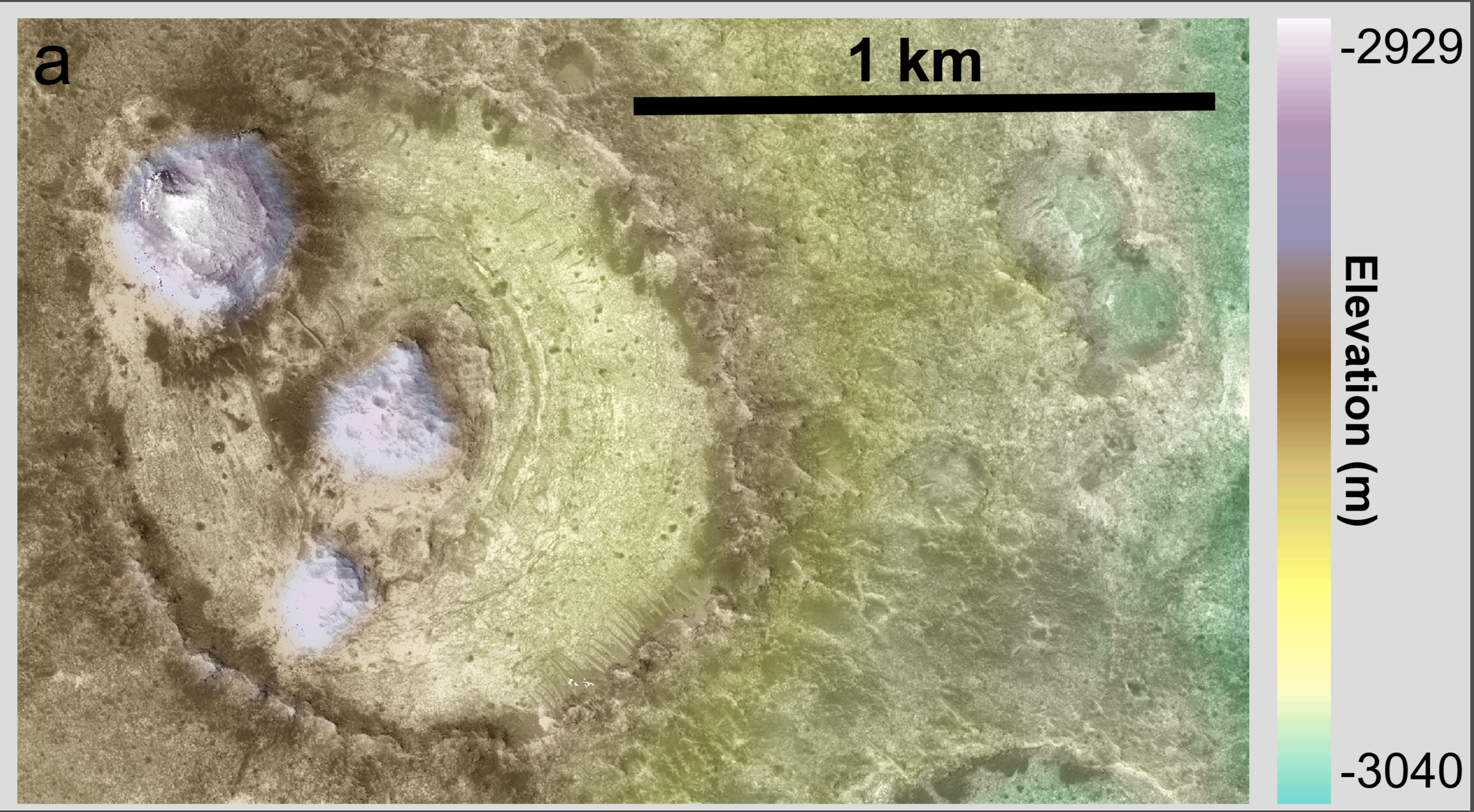
- Thick atmospheres brake, ablate, and fragment small impactors
- Must reach surface with at ≥ 500 ms^{-1} to form a hypervelocity crater
- Our forward-model impactor population is based on terrestrial fireball observations


Warren, Kite, et al., in review.
Mawrth Vallis
Meridiani Planum
Image credit: MOLA Science Team


Warren, Kite, et al., in review.
Mawrth Vallis
4.0-3.6 Ga
(Loizeau et al. 2008)
Meridiani Planum
3.9-3.6 Ga
(Di Achille & Hynek 2017)
Image credit: MOLA Science Team

Ancient craters are common at Mawrth

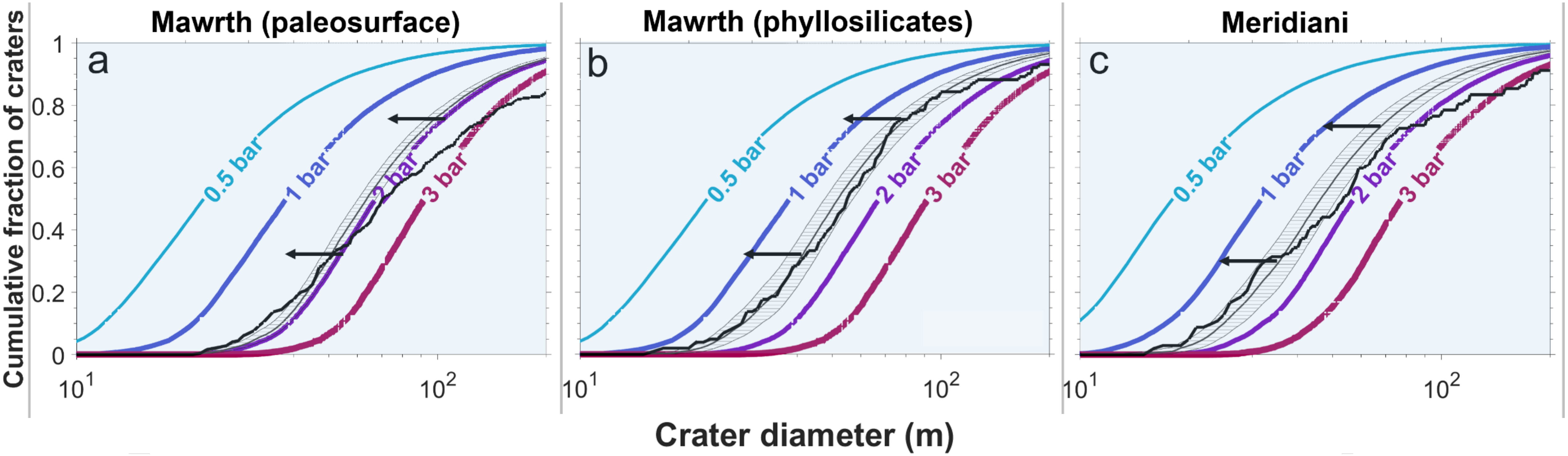
Warren, Kite, et al, in review
Loizeau et al. 2010



This an unusually large example

Warren, Kite, et al., in review.

Abundant small ancient craters imply pCO_2 < (1.5-1.9) bars

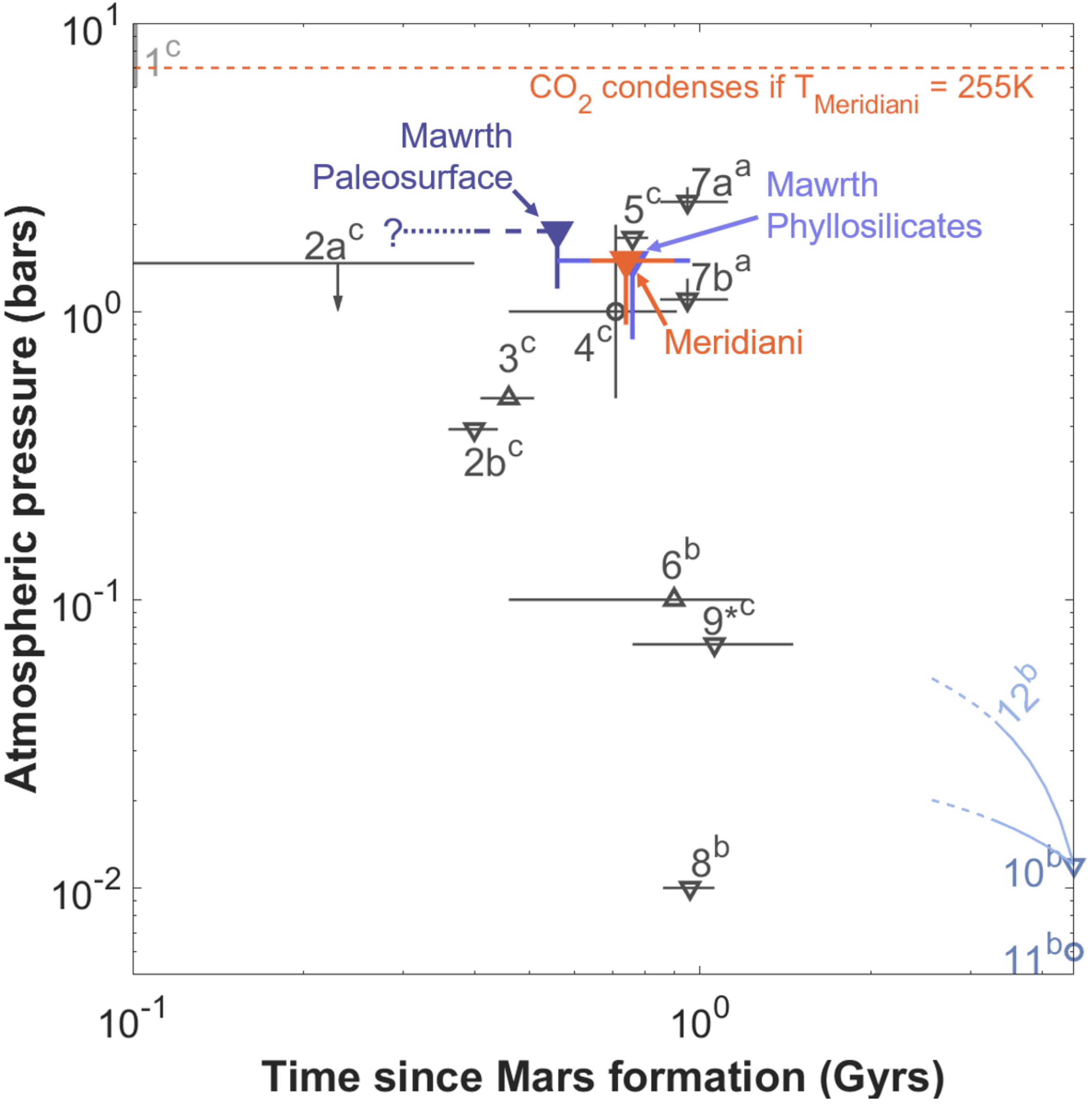


We found that atmospheric pressure was

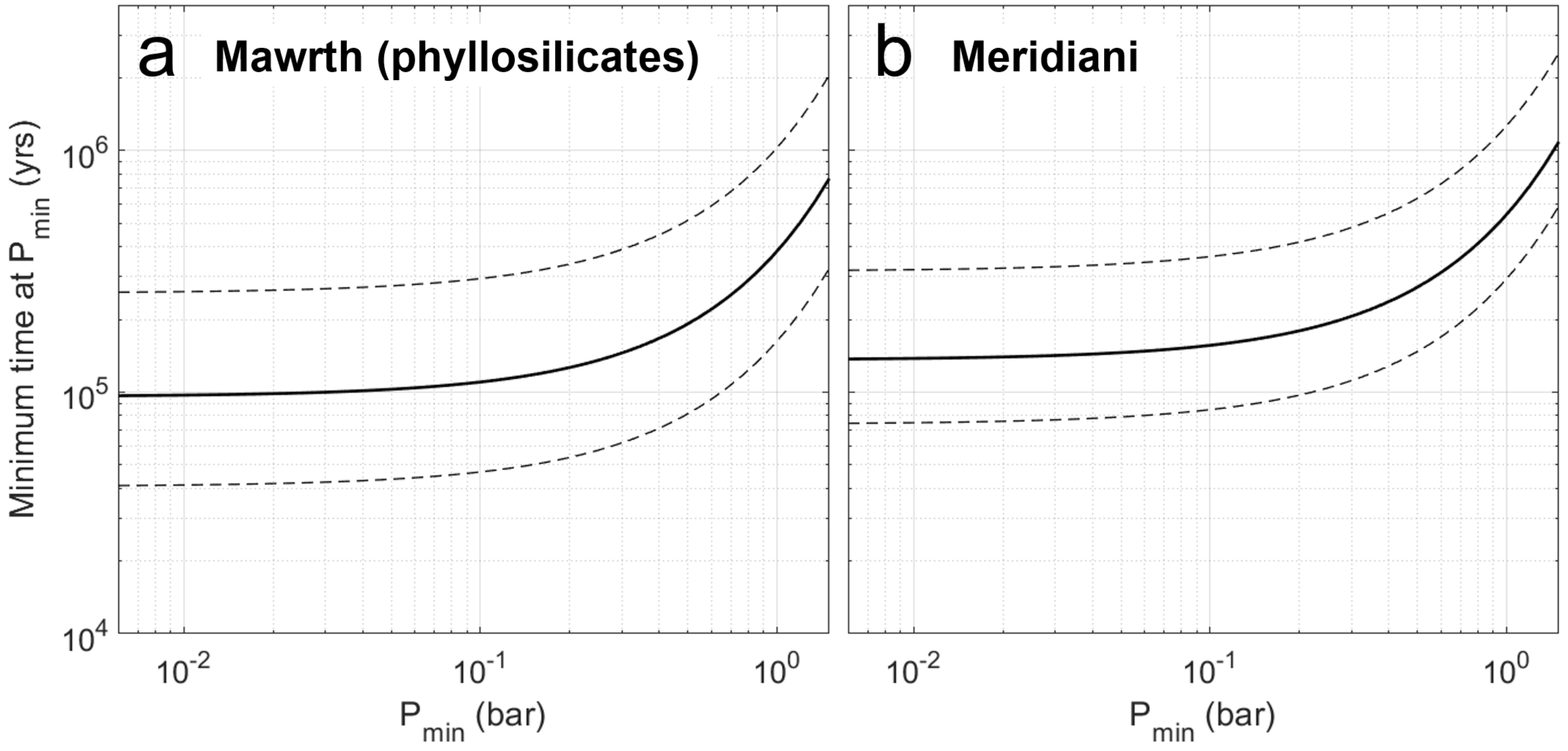
<1.9±0.1 bar (for >10^4 yr) @ 4 Ga

<1.5±0.1 bar (for >10^5 yr) @ 3.8 Ga

Warren, Kite, et al., in review.



Our sites record only a small fraction of Mars' history



A Range of Atmospheric Pressure Histories Are Consistent With The New Data

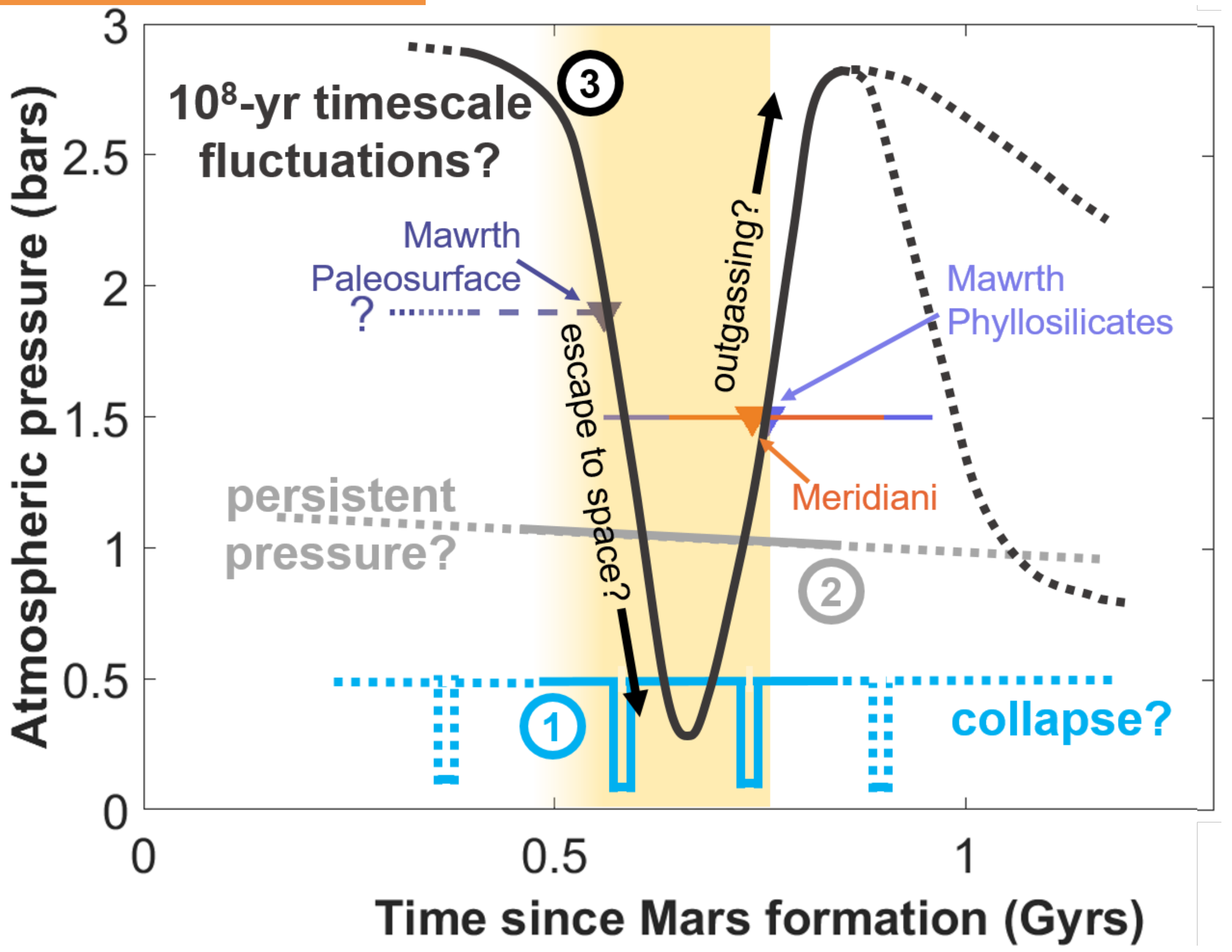
Warren, Kite, et al., in review.

Results consistent with variety of atmospheric pressure histories >4.1 – 3.8±0.2 Ga:

① Persistently **<0.5** bar with atmospheric collapse

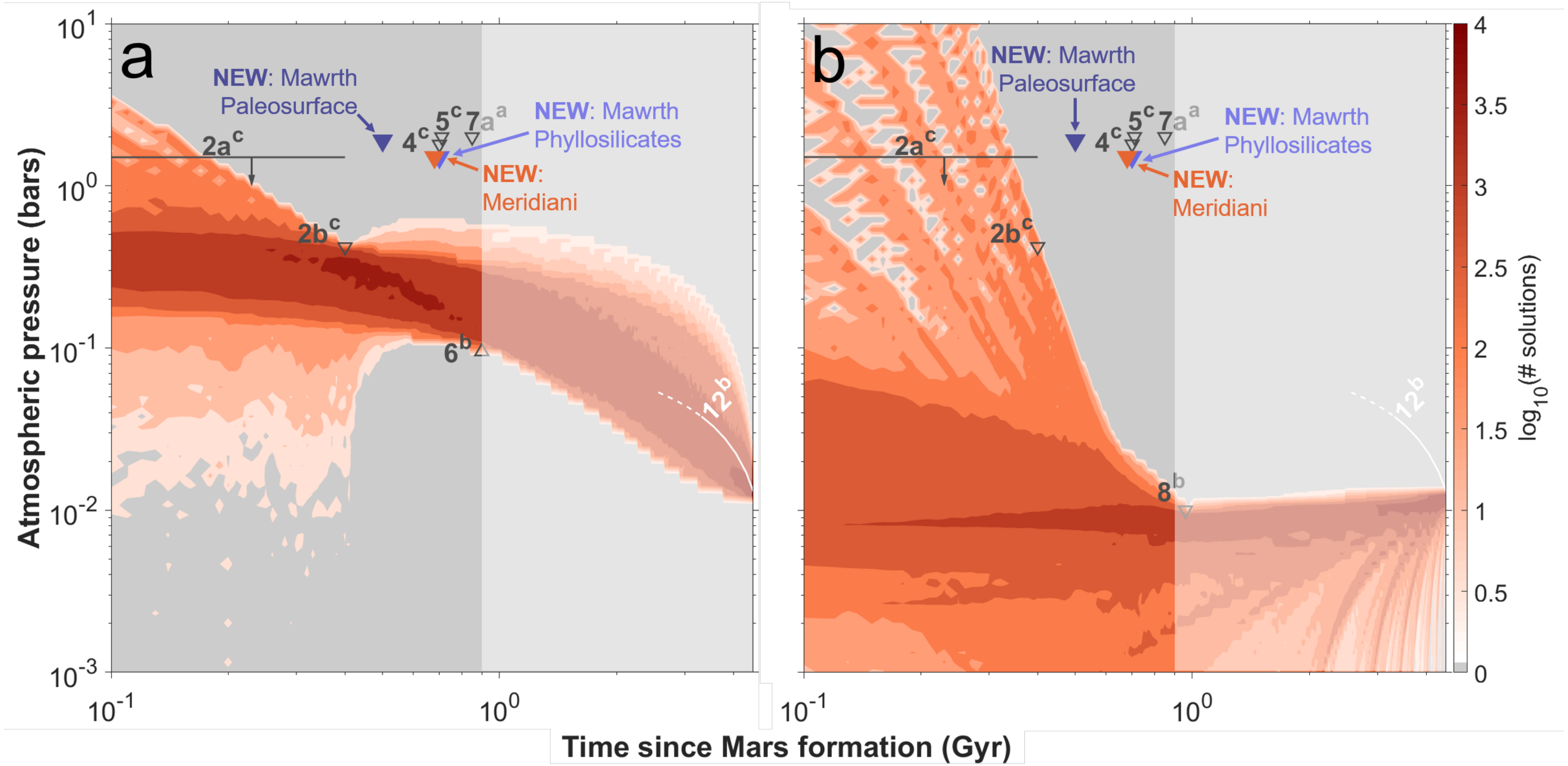
② Persistently **at** continuous pressure upper limits

③ Variations of several bar on 10^8-yr timescales



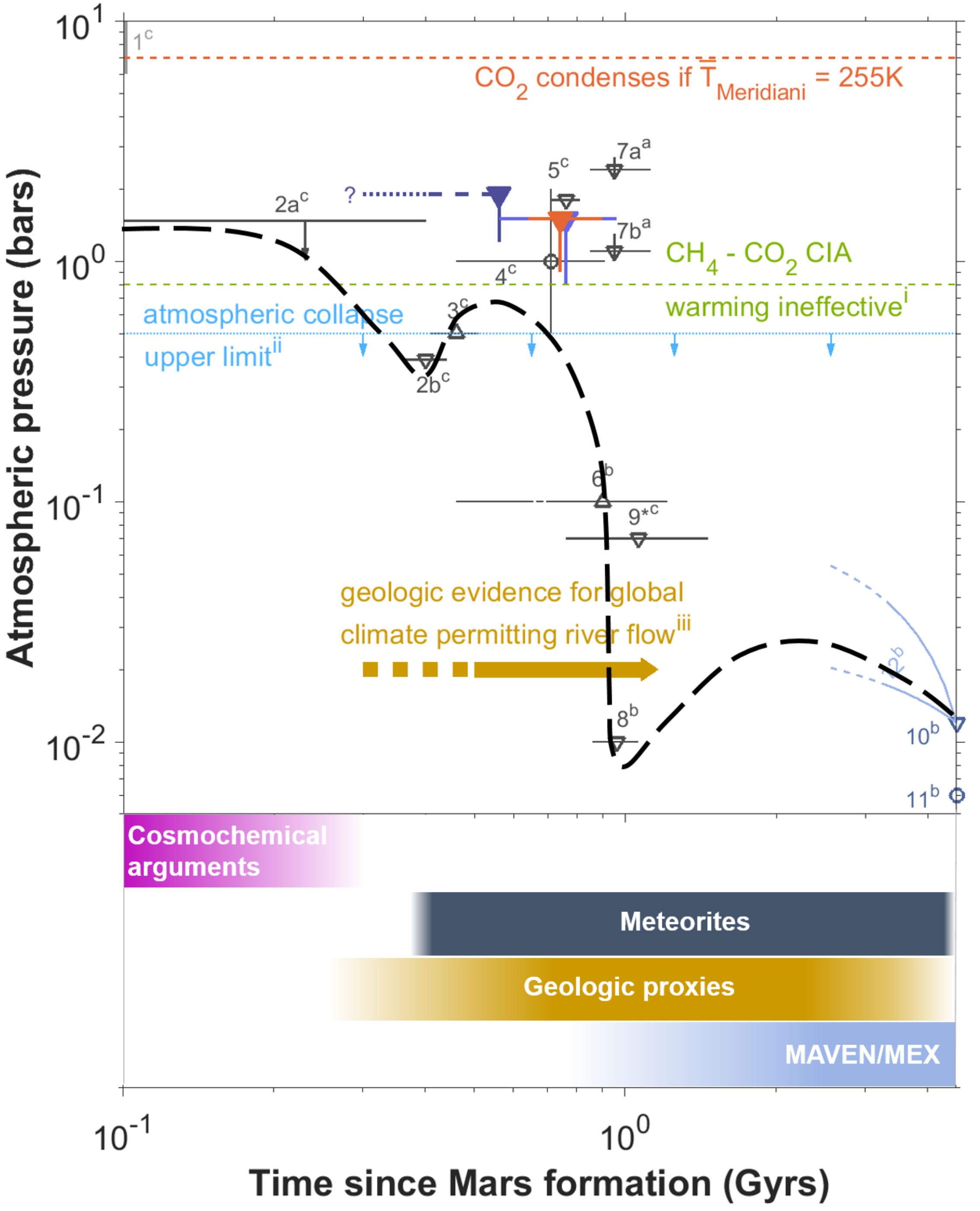
Simple model combining all paleo-data suggests low **(<1 bar)** atmospheric pressure on early Mars

Warren, Kite, et al., in review.



More Post-3.6-Ga Constraints Are Needed

Warren, Kite, et al., in review.



Data are (just) consistent with both CH_4-CO_2 and H_2-CO_2 Collision-Induced Absorption warming.

Conclusions

Warren, Kite, et al., in review.

- Small ancient craters are a **direct** probe of Mars paleo-atmospheric pressure (Kite et al. Nature Geoscience 2014).
- New results: atmospheric pressure 3.8±0.2 Ga was below 1.5-1.9 bars for >(10^4-10^5) yr on at least two occasions
  - Consistent with persistently low pCO_2
- Simple model combining all paleo-data suggests low **(<1 bar)** atmospheric pressure on early Mars, but is (just) consistent with both CH_4-CO_2 and H_2-CO_2 Collision-Induced Absorption warming.

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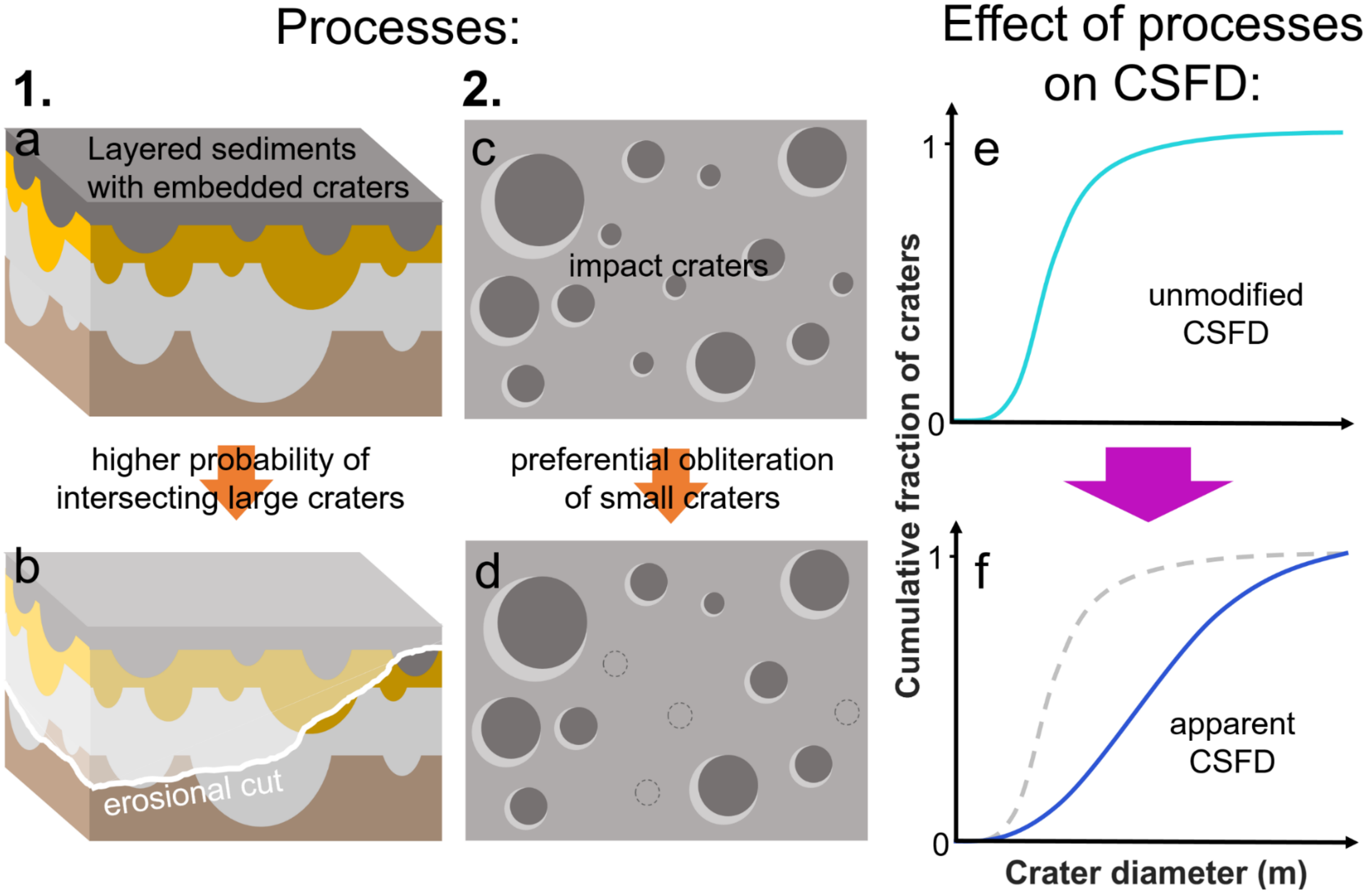
Bonus Slides

CSFD Modification

Warren, Kite, et al., in review.



Acknowledgements

Warren, Kite, et al., in review.

- J. Sneed produced the HiRISE Digital Terrain Models using the pipeline of Mayer & Kite (2016. *LPSC*)
- Grants: NASA (NNX16AJ38G)

Atmospheric pressure model - setup

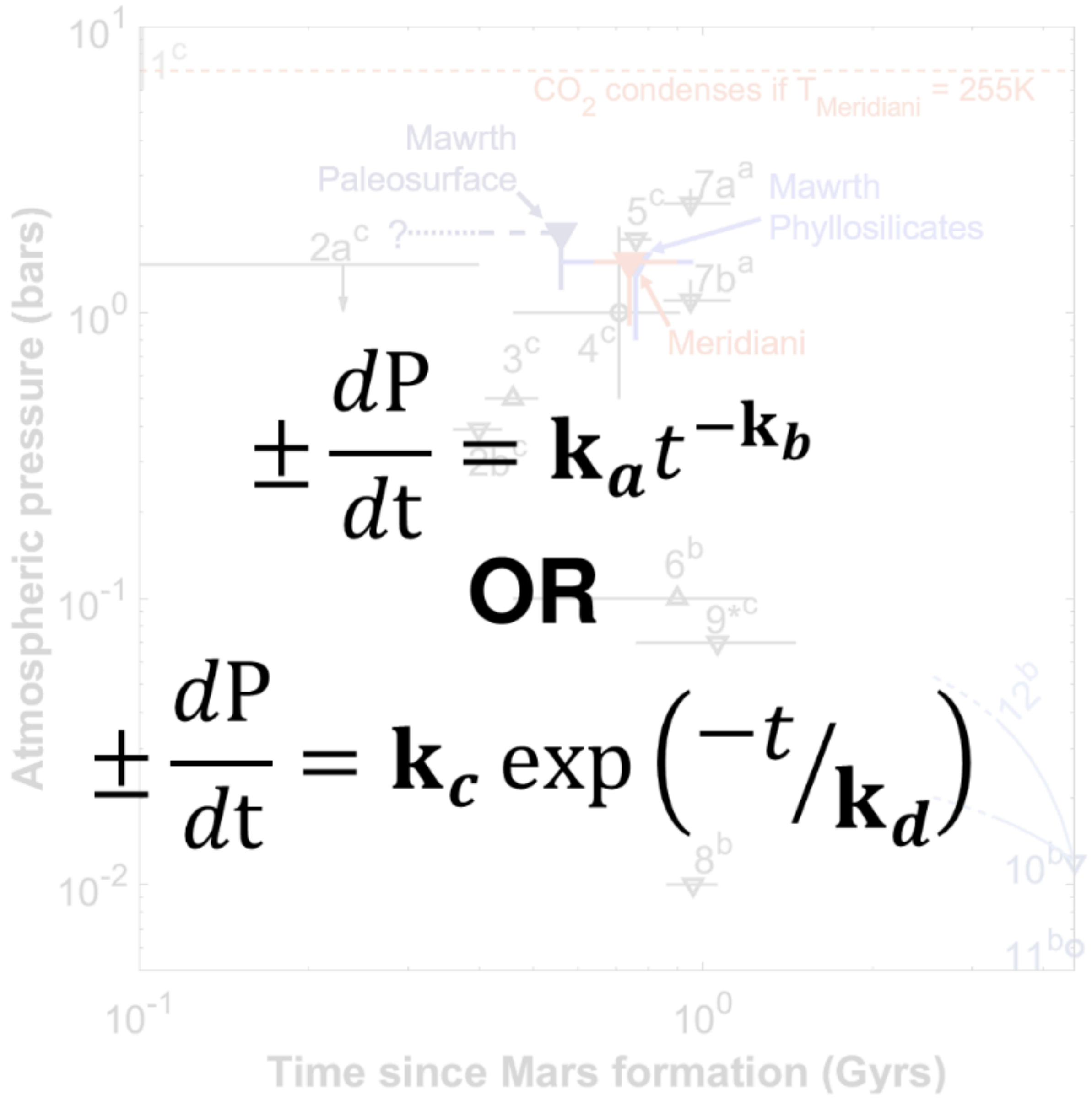
Warren, Kite, et al., in review.

Sources

- Outgassing
- Impact delivery of volatiles
- Thermal decomposition of carbonates

Sinks

- Loss to space
- Impact erosion
- CO_2 ice caps
- Carbonates



$$\pm\frac{dP}{dt} = \mathbf{k}_a t^{-\mathbf{k}_b}$$

OR

$$\pm\frac{dP}{dt} = \mathbf{k}_c \exp\left(-t/\mathbf{k}_d\right)$$

Identifying ancient craters

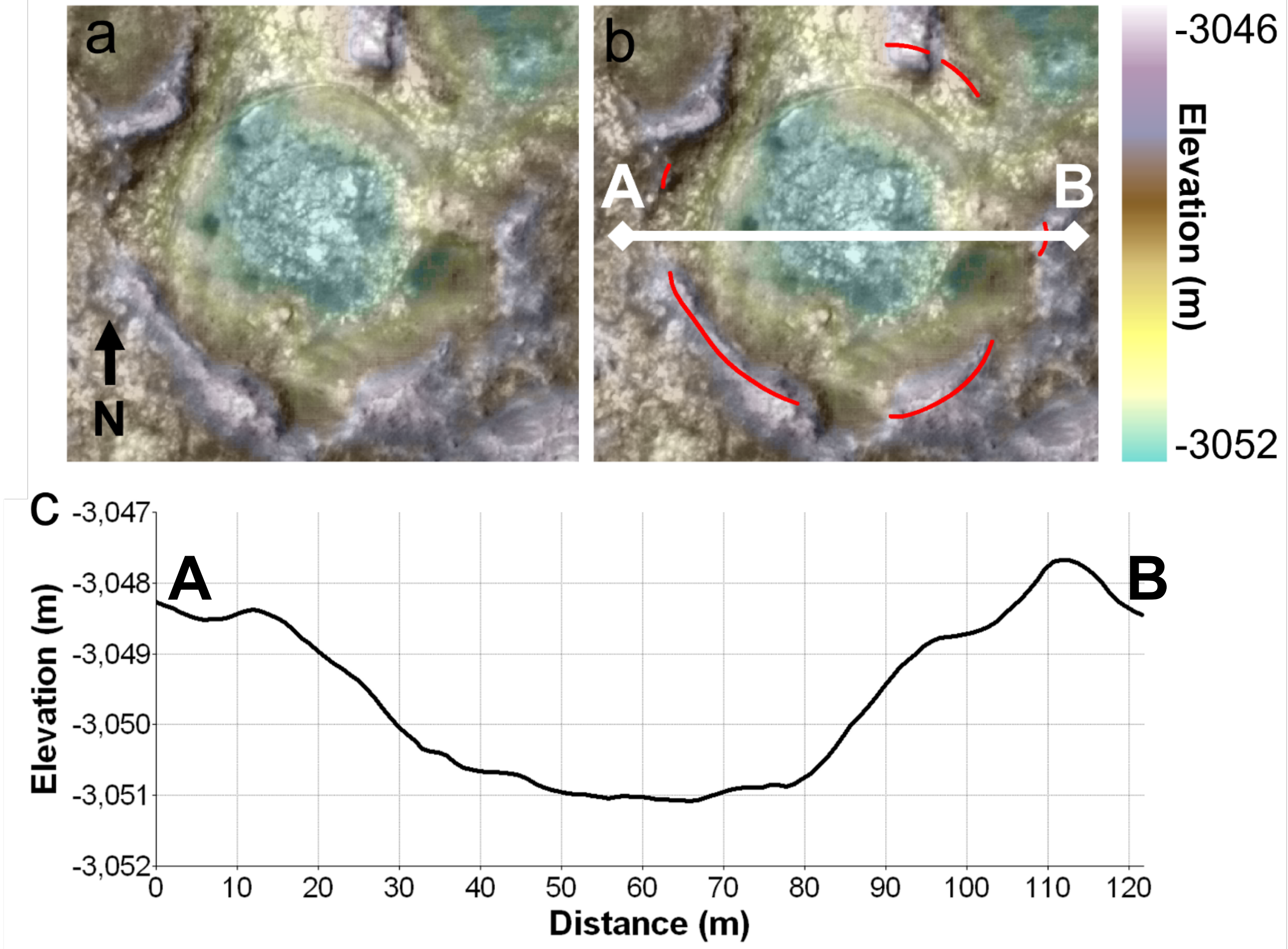
Warren, Kite, et al., in review.

Crater if…

1. Circular topographic depression
2. Concave-up in anaglyph
3. >150° arc of rim preserved

Ancient if…

1. Embedded in sedimentary units
2. Depth << 0.2 × diameter
3. Sand/dust-free center
4. <50% obscured by dust/sand



Local Pressure Variations

Warren, Kite, et al., in review.

- Pressure variations on Earth due to Hadley circulation of order 1% atmospheric pressure
  - Well below error on paleopressure estimates
- From geostrophic balance, maintaining a hemispheric pressure difference of $0.2p_{atm}$ with a background surface temperature of 300K would require ½ of Mars' surface to be at ~420K

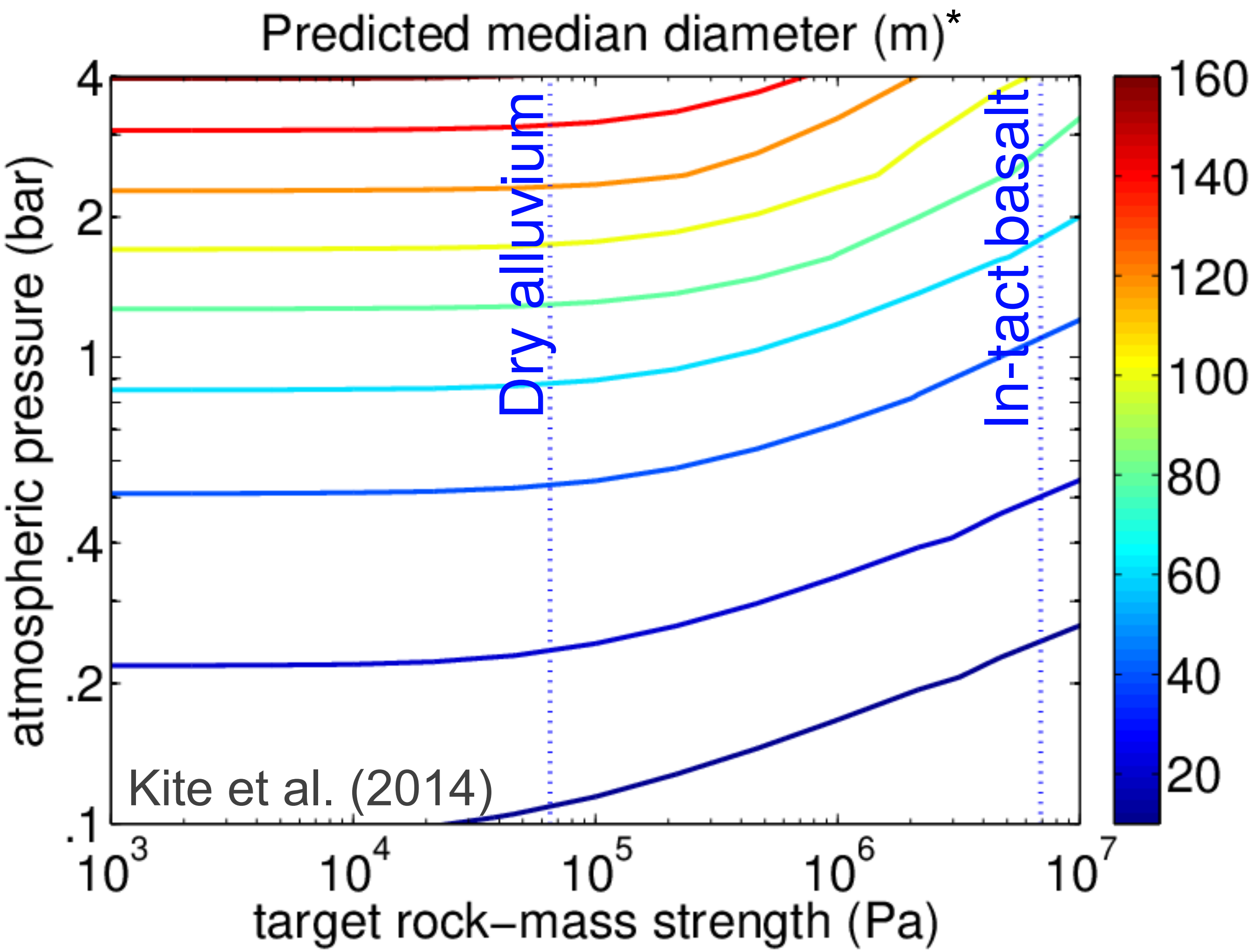
Secondary craters

- Small craters formed by primary crater ejecta (e.g. Zunil crater)
- Do not observe secondary craters in geologic record on Earth
- Williams et al. 2014 model reproduces crater SFDs for modern Mars – **secondary craters do not have a major effect**

Additional factors

Warren, Kite, et al., in review.

- Target properties
  - Dry desert alluvium
  - In-tact basalt
- Modification of SFDs to higher apparent pressures
  - More large impactors (e.g. Late Heavy Bombardment) – flatten SFDs

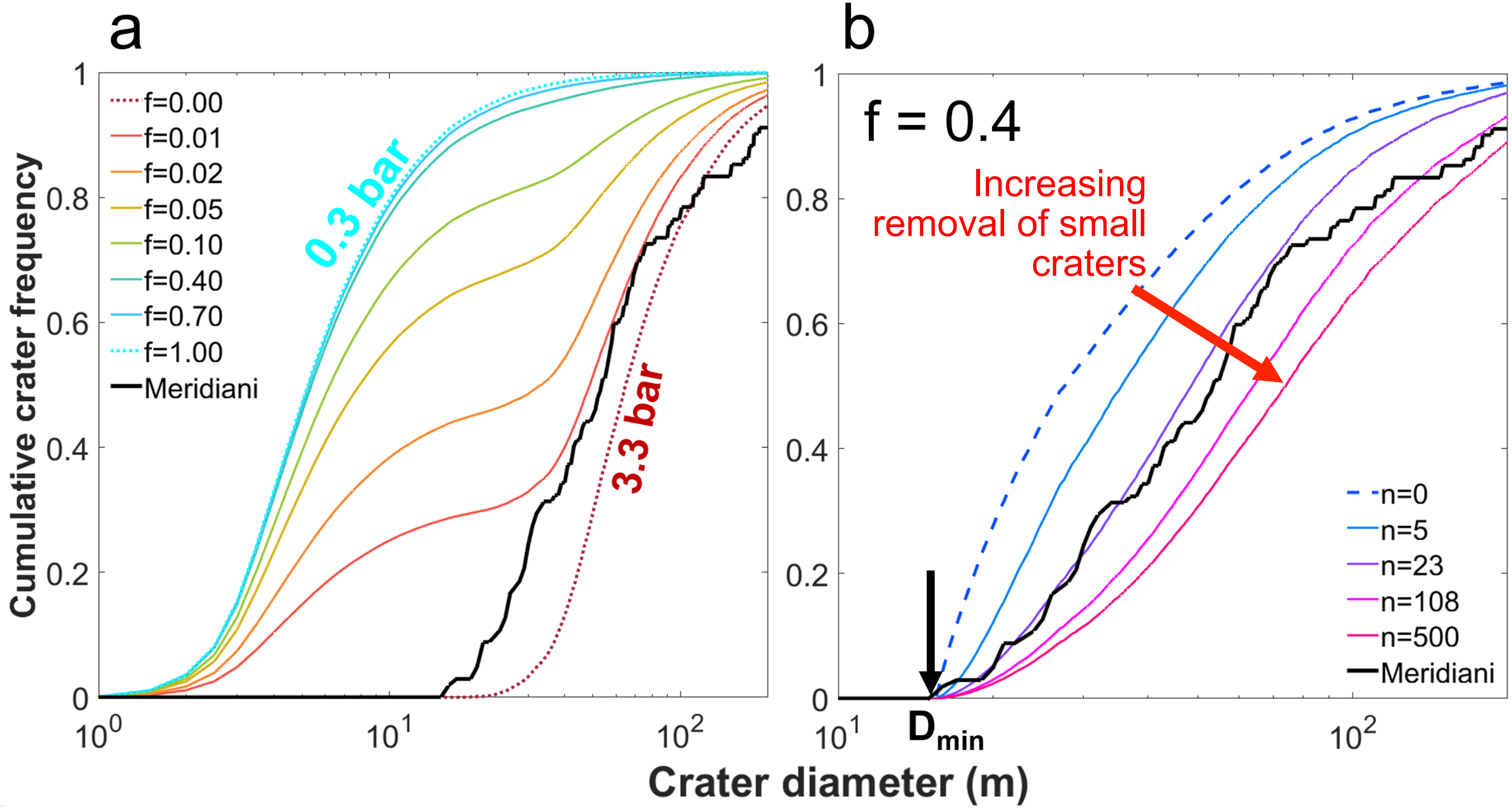


*for constant μ = 0.41

Time-varying pressure & crater removal

Warren, Kite, et al., in review.

Low pressure = 0.3 bar, high pressure = 3.3 bar



*f – fraction of time spent at low pressure

Comparison to data

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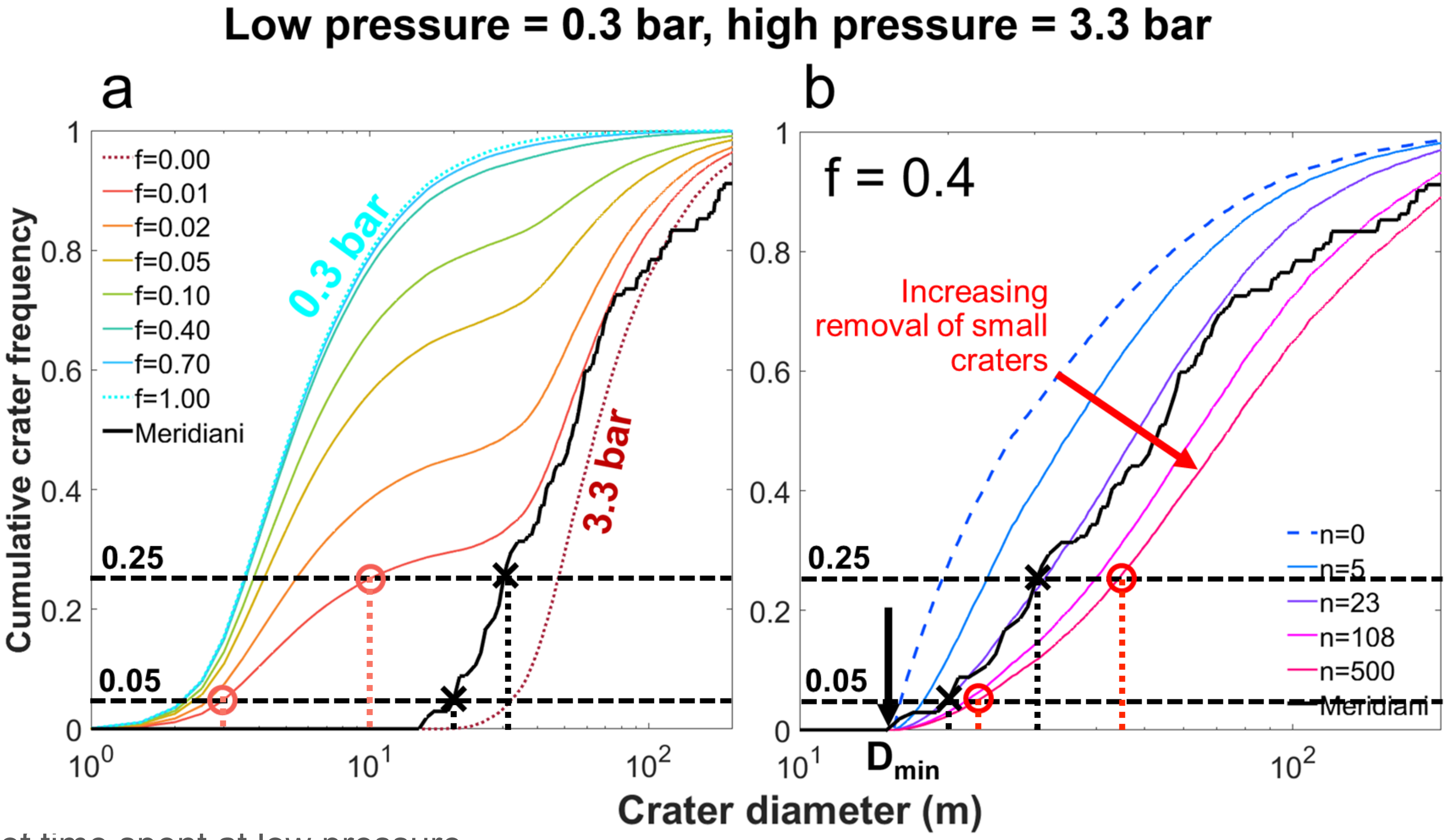


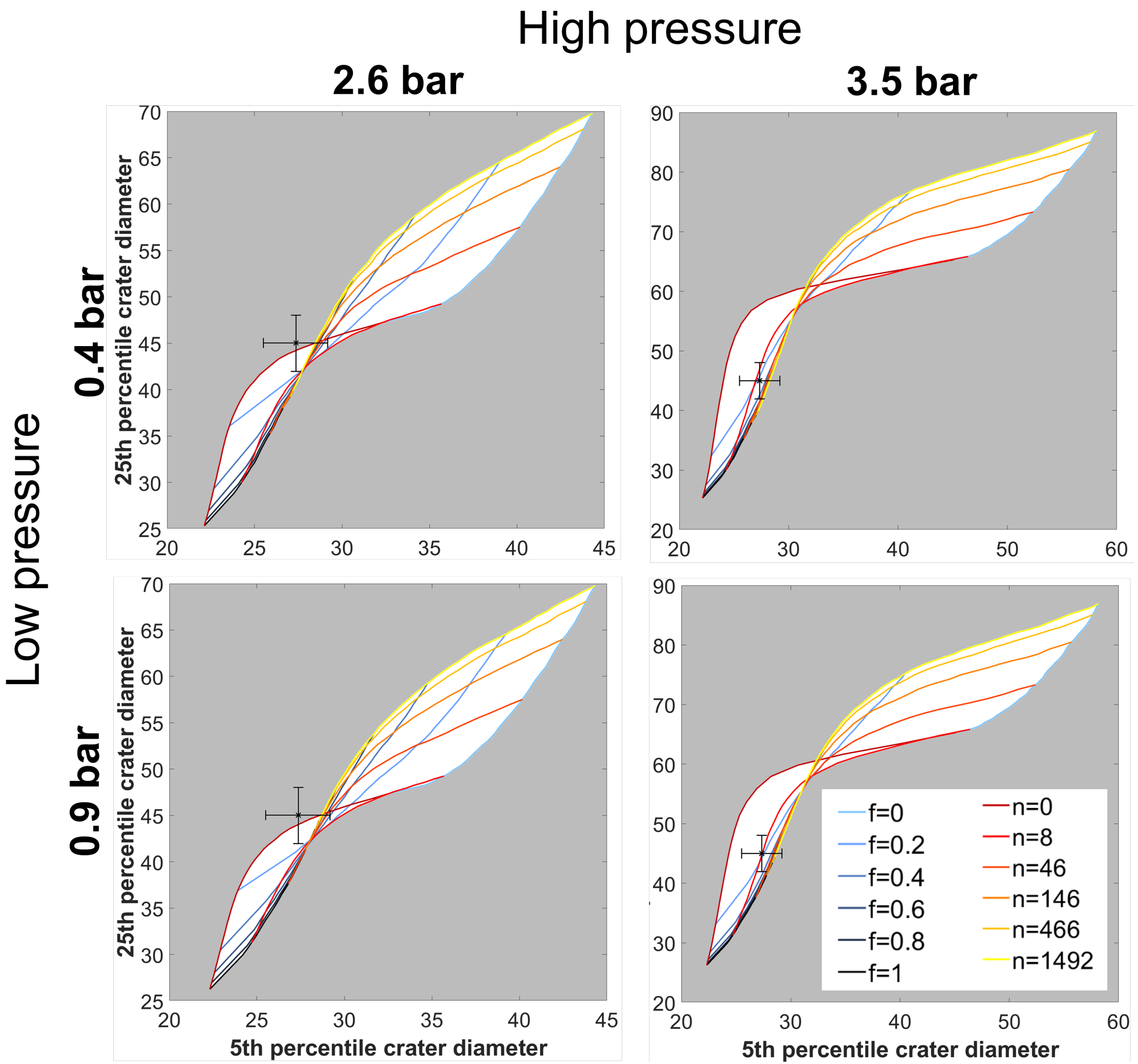
*f – fraction of time spent at low pressure

Warren, Kite, et al., in review.

Time varying pressure with minimum pressure less than continuous pressure upper limit

+

Preferential removal of small craters



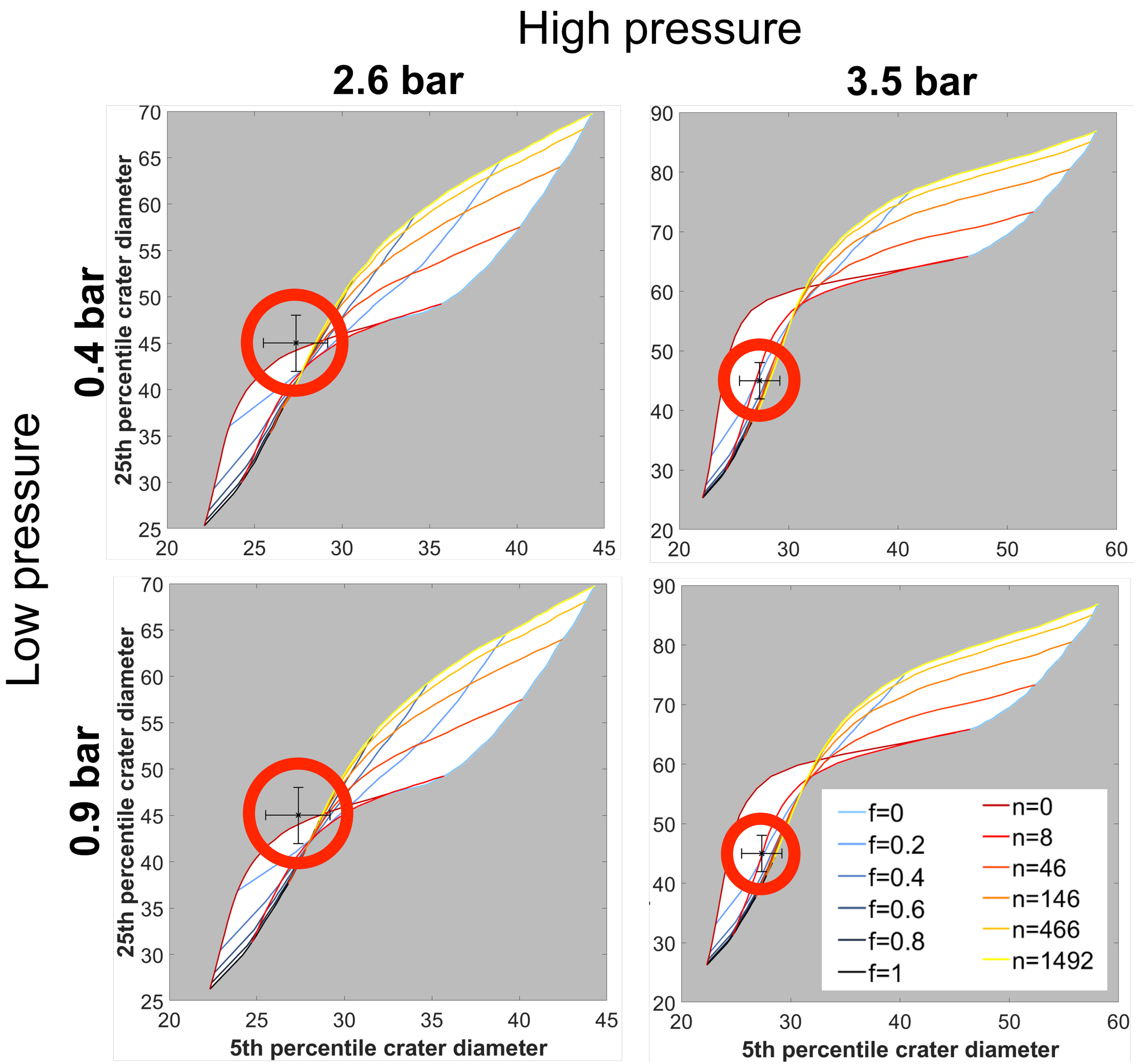
Warren, Kite, et al., in review.

Time varying pressure with minimum pressure less than continuous pressure upper limit

+

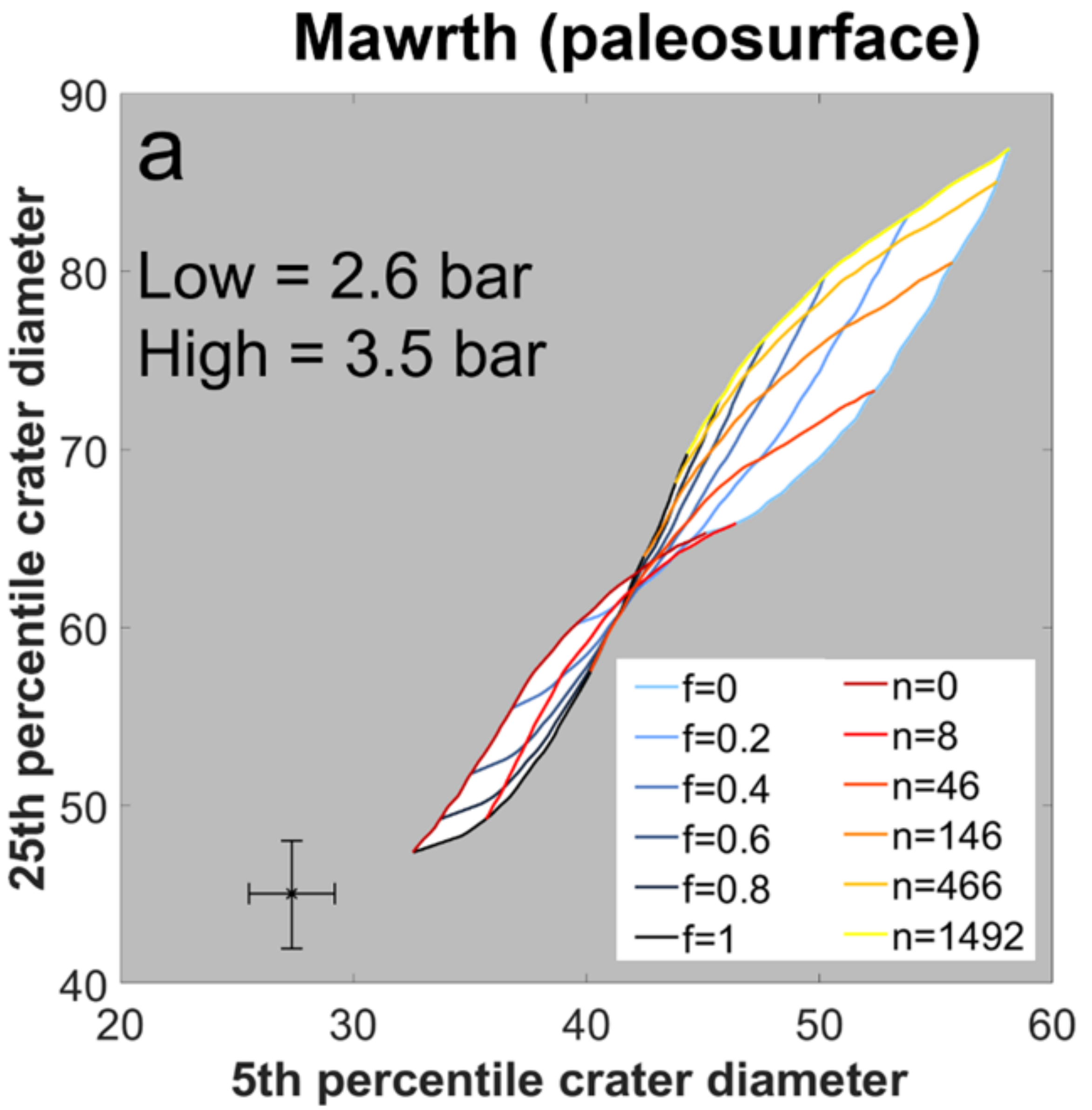
Preferential removal of small craters

✓



Warren, Kite, et al., in review.

Cannot reproduce SFDs with combinations of pressures greater than continuous pressure upper limits!



Warren, Kite, et al., in review.

Cannot reproduce SFDs with combinations of pressures greater than continuous pressure upper limits!