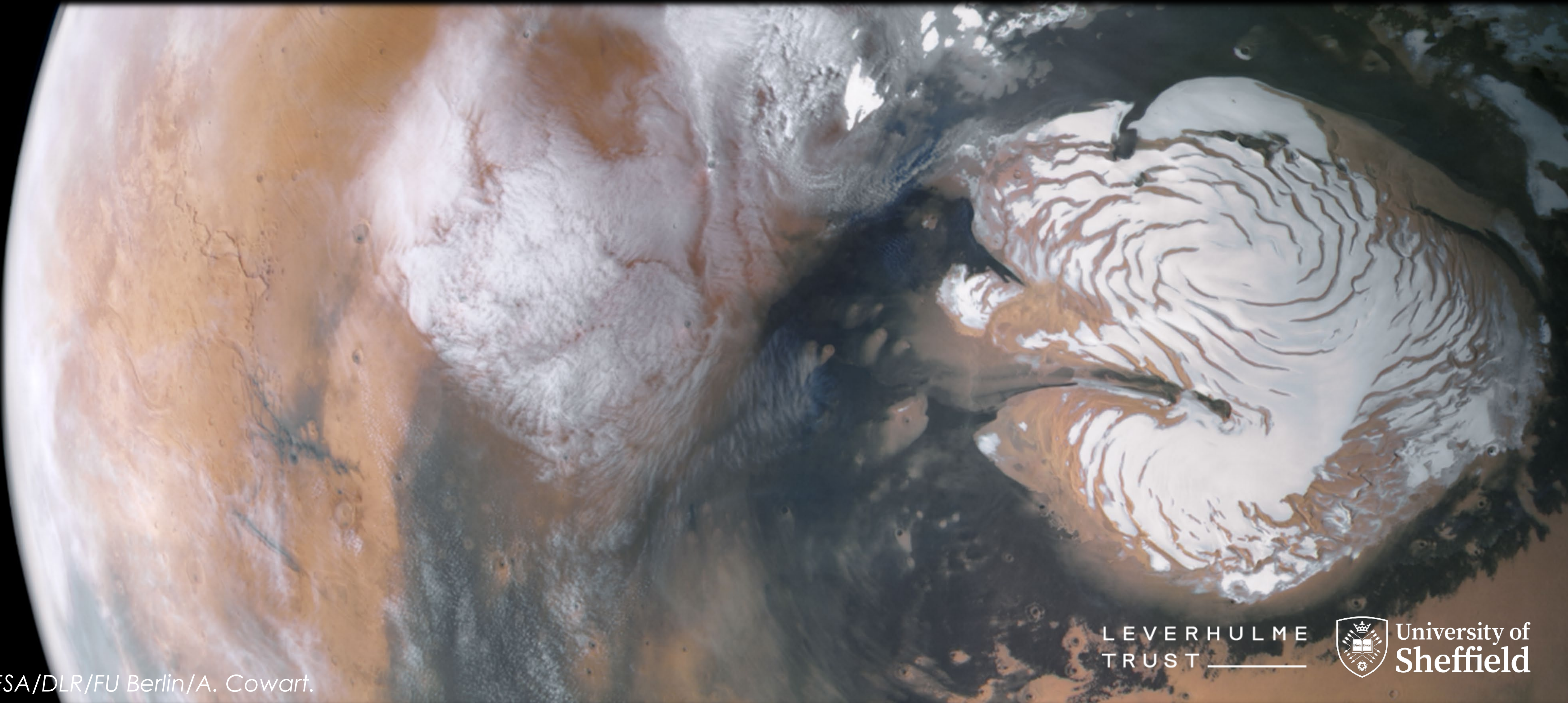
Ice on Mars: Where to find it and what science we could do with it

Frances Butcher

University of Sheffield, UK



ESA/DLR/FU Berlin/A. Cowart.

LEVERHULME TRUST

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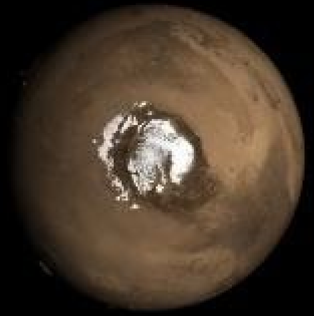
The Martian cryosphere

- Most deposits are **water ice**, with influence of **carbon dioxide** ice at poles and in frosts

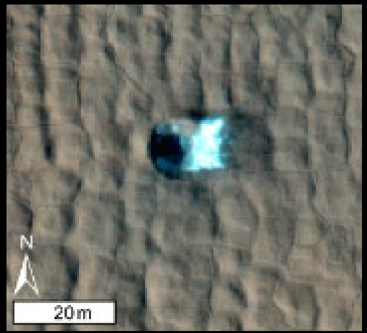
Polar layered deposits



Seasonal polar 'caps'

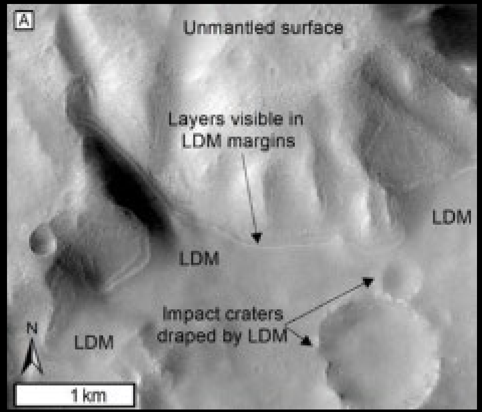
Diurnal/seasonal frosts

Mid-to-high latitude perennial ground ice

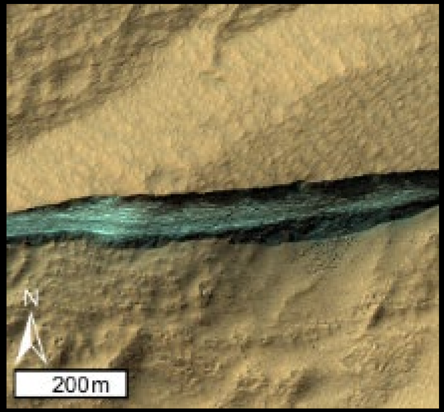


Mid-to-high latitude 'plains ice' (sheets)

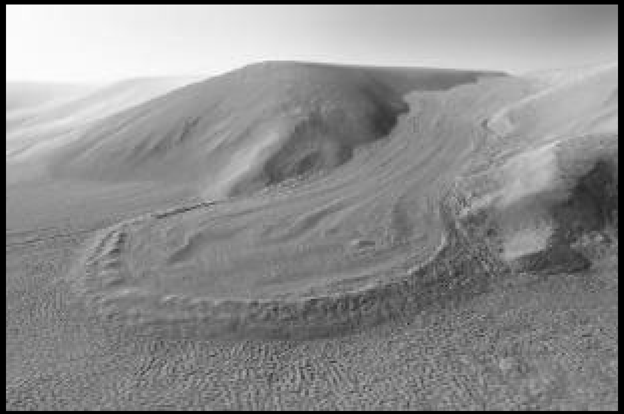
'Latitude-dependent mantle' (icy dusty drape)



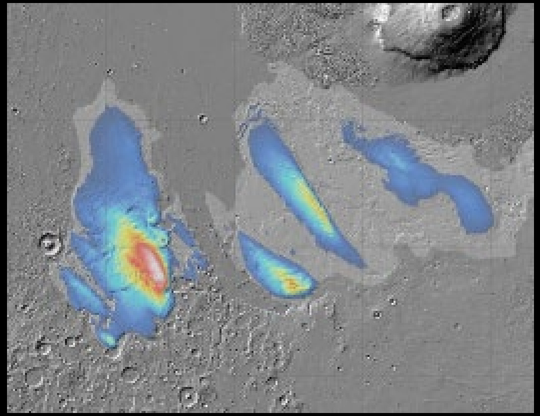
Buried mid-latitude ice slabs



Mid-latitude debris-covered glaciers

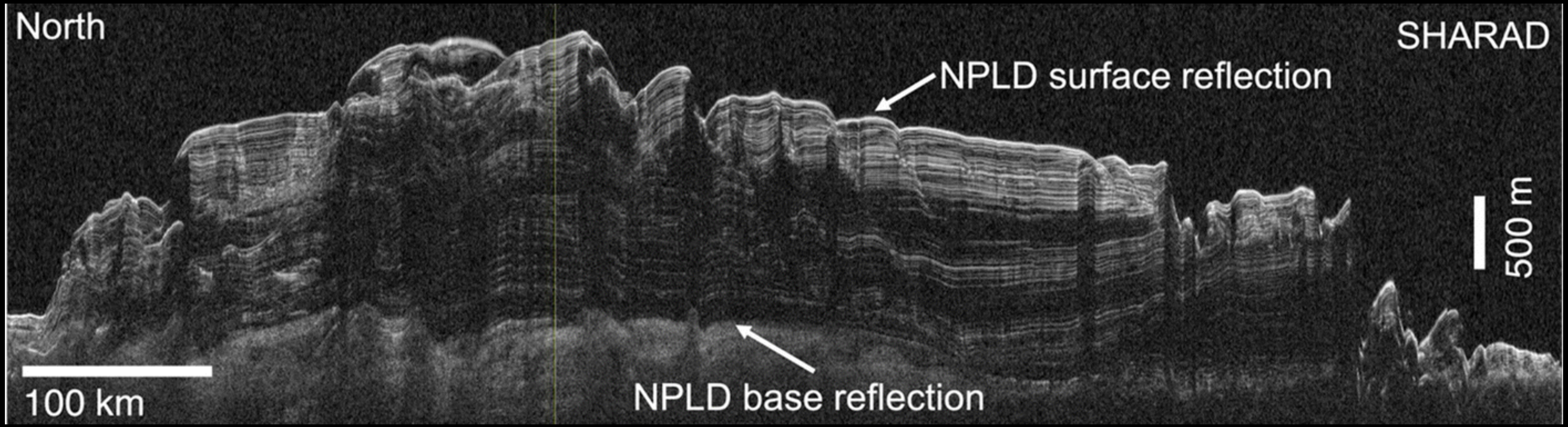


Deep equatorial ice?
(Watters et al. 2024, GRL)

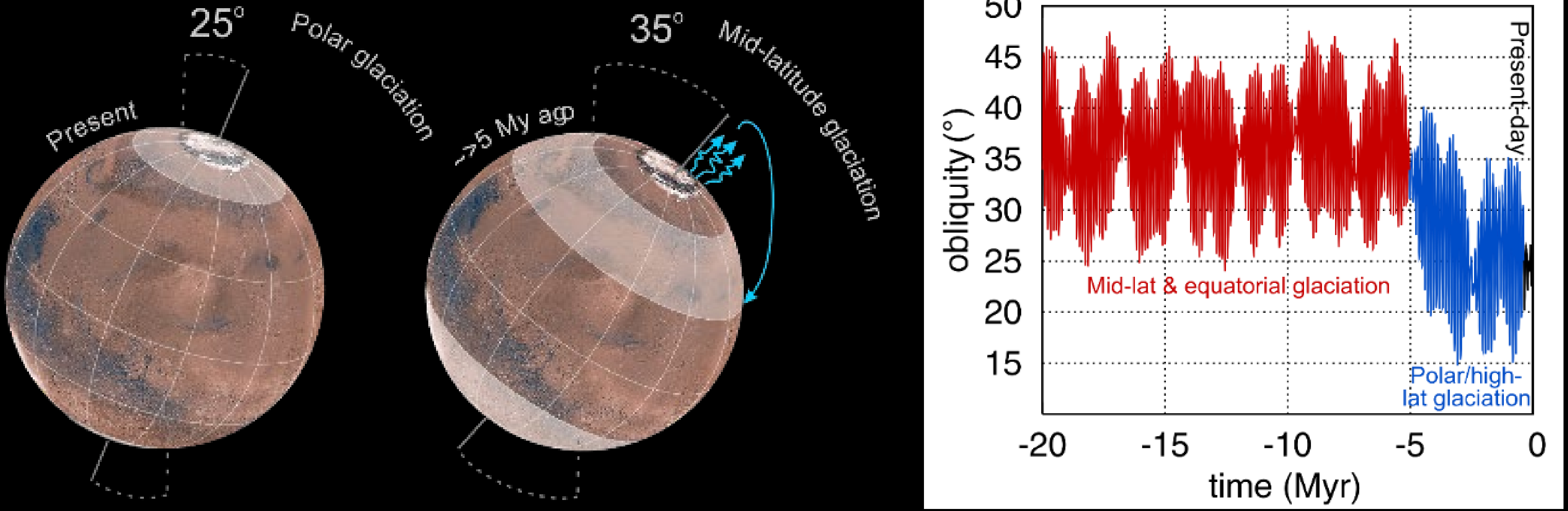


TL-BR (1) NASA/Goddard SFC; (2) Hubble/P. James/S. Lee; (3-5,6-7): HiRISE NASA/JPL/Caltech/UofA; (6) CTX NASA/JPL/MSSS; (7) HiRISE/Sean Doran; (9) Mars Express/PSI/Smithsonian/ESA

Mars' polar caps record millions of years of dynamic climate change



Orbital Shallow Radar profile through Mars' north polar cap. (from Thomas et al. 2022. Exp. Astron.)



Adapted from Butcher 2019. PhD thesis (with data from Laskar et al. 2004, Icarus).

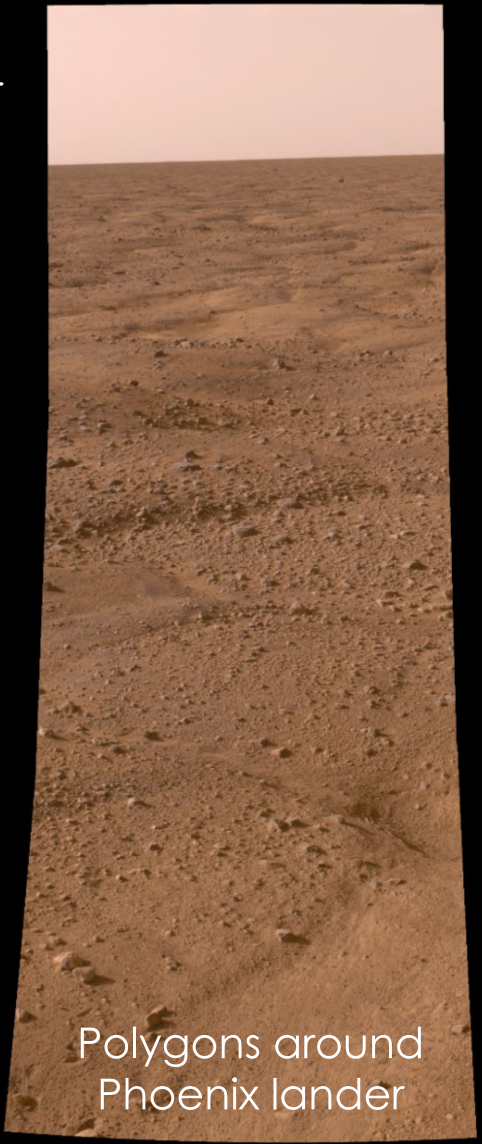
Non-polar ice has been preserved – buried in the ground

Polygonal patterned ground extends over vast swathes of Mars' high latitudes >~55°N/S

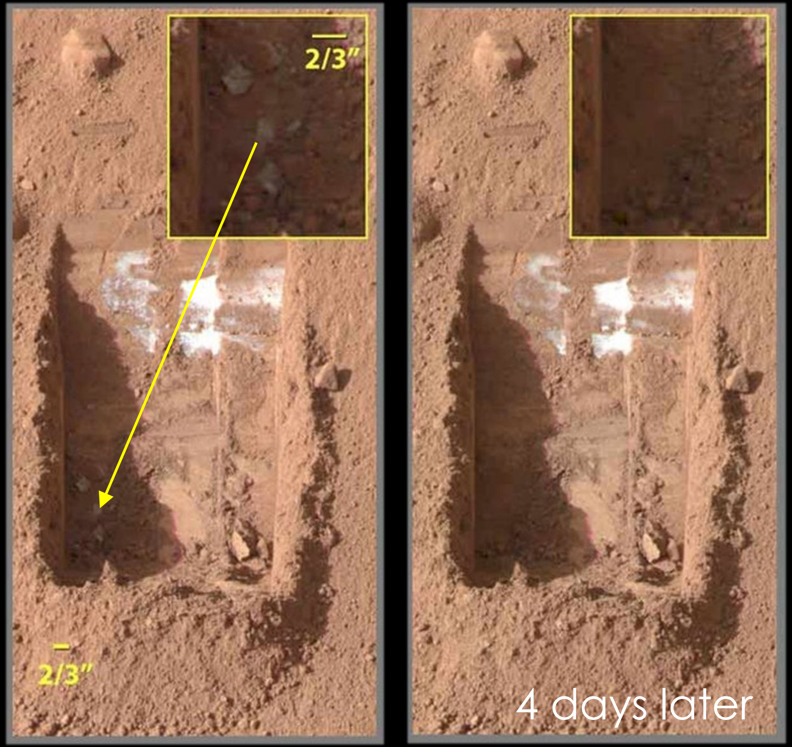
(e.g. Mangold et al. 2005, Icarus)

High-arctic polygonal patterned ground on Earth

Credit: Dennis Cowals (Wikimedia commons)

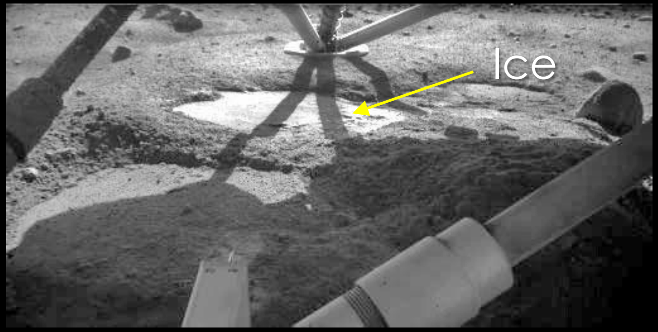


Credit: NASA/JPL/University of Arizona/Texas A&M University



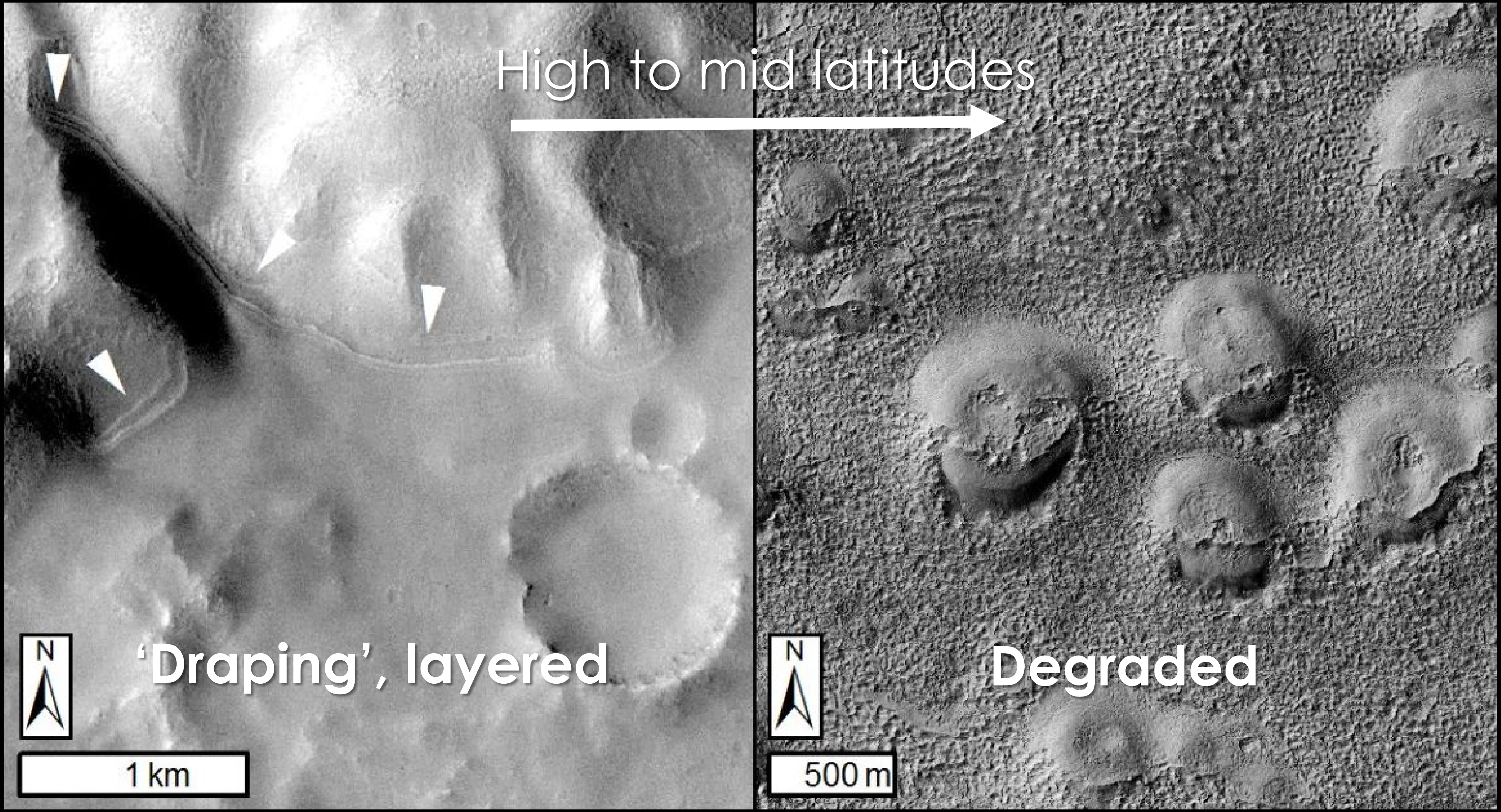
Credit: NASA/JPL-Caltech/University of Arizona/Texas A&M University

Phoenix Lander, 69°N (2009)



Credit: NASA/JPL-Caltech/University of Arizona/Max Planck Institute

Layered 'mantling deposits' at high latitudes (degrading equatorward)

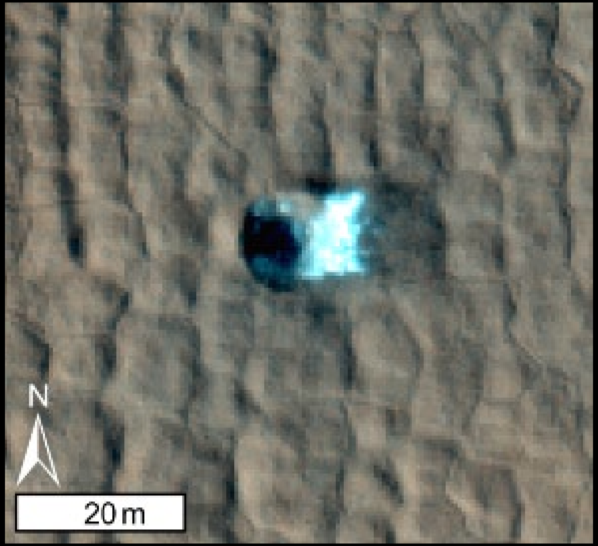


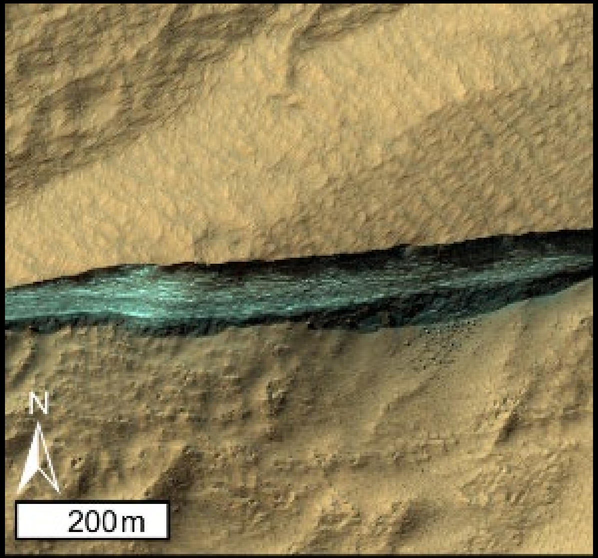
Butcher 2019, after Head et al. (2003) Nature

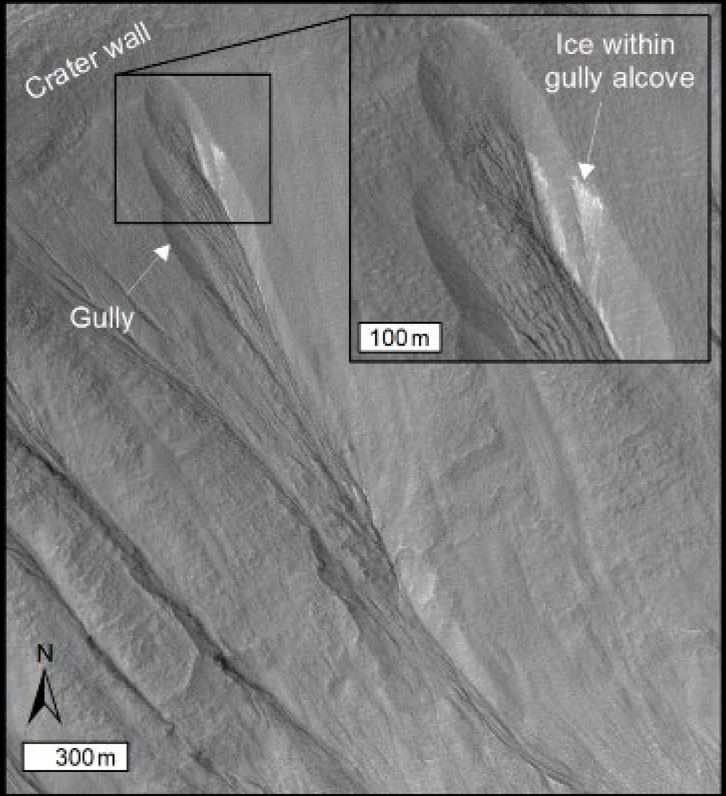
Direct images of non-polar ice from orbit

e.g., Dundas et al. 2021, J. Geophys. Res. Planets 126

- **Natural exposures** of non-polar ice are rare, but growing number of observations from orbit.
- **Small, fresh impacts** can exhume ice. *(Byrne et al. 2009, Science 325)*
- Retreating **~100m high ice cliffs** - exposure mechanism unknown. *(Dundas et al. 2017 Science 359).*
- Possible ice exposures by **mass movements in gullies.** *(Khuller and Christensen 2021, J. Geophys. Res. Planets 126)*

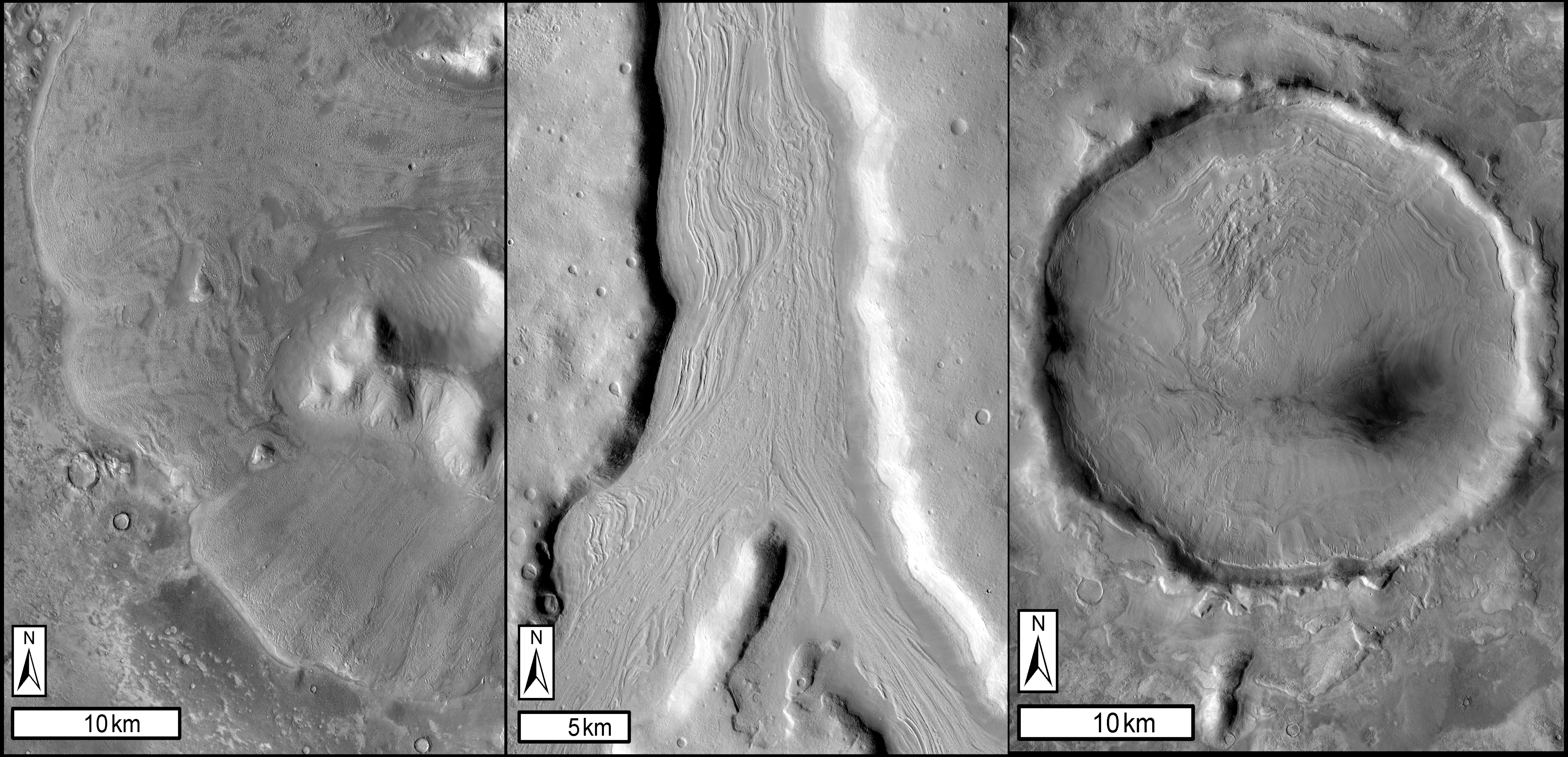






HiRISE images. Credit: NASA/JPL/University of Arizona/F. Butcher

‘Viscous flow features’ – putative debris-covered glaciers

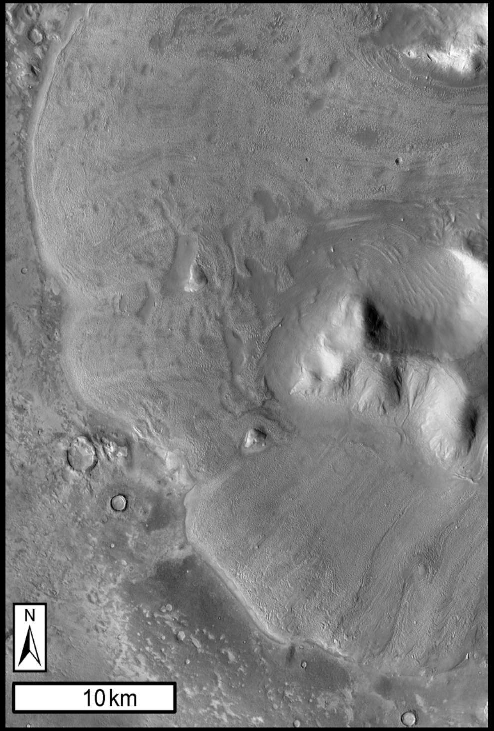


CTX images. Credit: NASA/JPL-Caltech/MSSS/F. Butcher

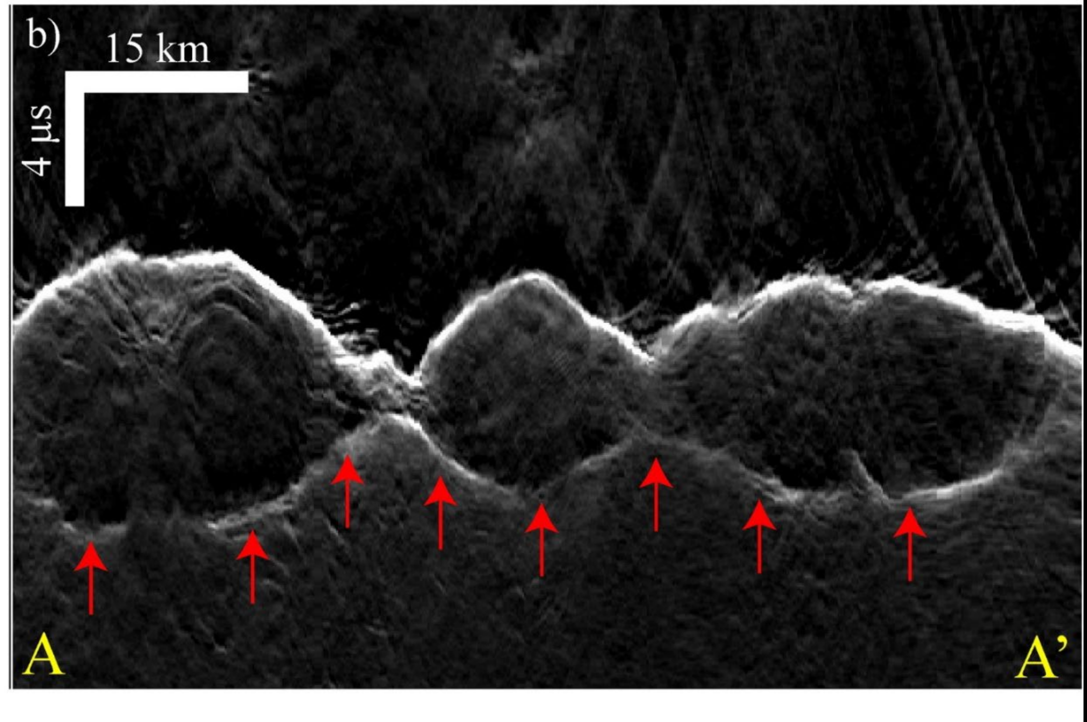
Peering beneath the surface with orbital radar

- Large viscous flow features contain up to **90% ice by volume**
  i.e. they are analogous to **debris-covered glaciers** *(e.g. Holt et al. 2008, Plaut et al. 2009)*

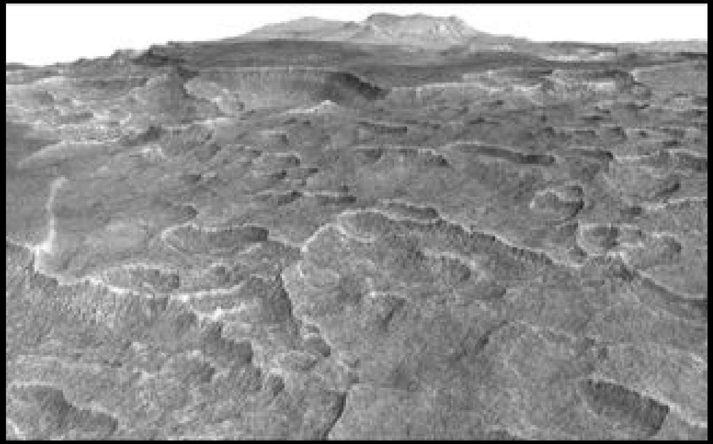
- High ice content also inferred for **plains deposits** in Arcadia/Utopia Planitiae, but **some debate** over % ice content *(e.g. Bramson et al. 2015, Campbell and Morgan 2018)*



CTX images. Credit: NASA/JPL-Caltech/MSSS/F. Butcher



SHARAD 3D radargram through a complex of glaciers (Perry et al. 2023. Icarus). CC BY 4.0 DEED

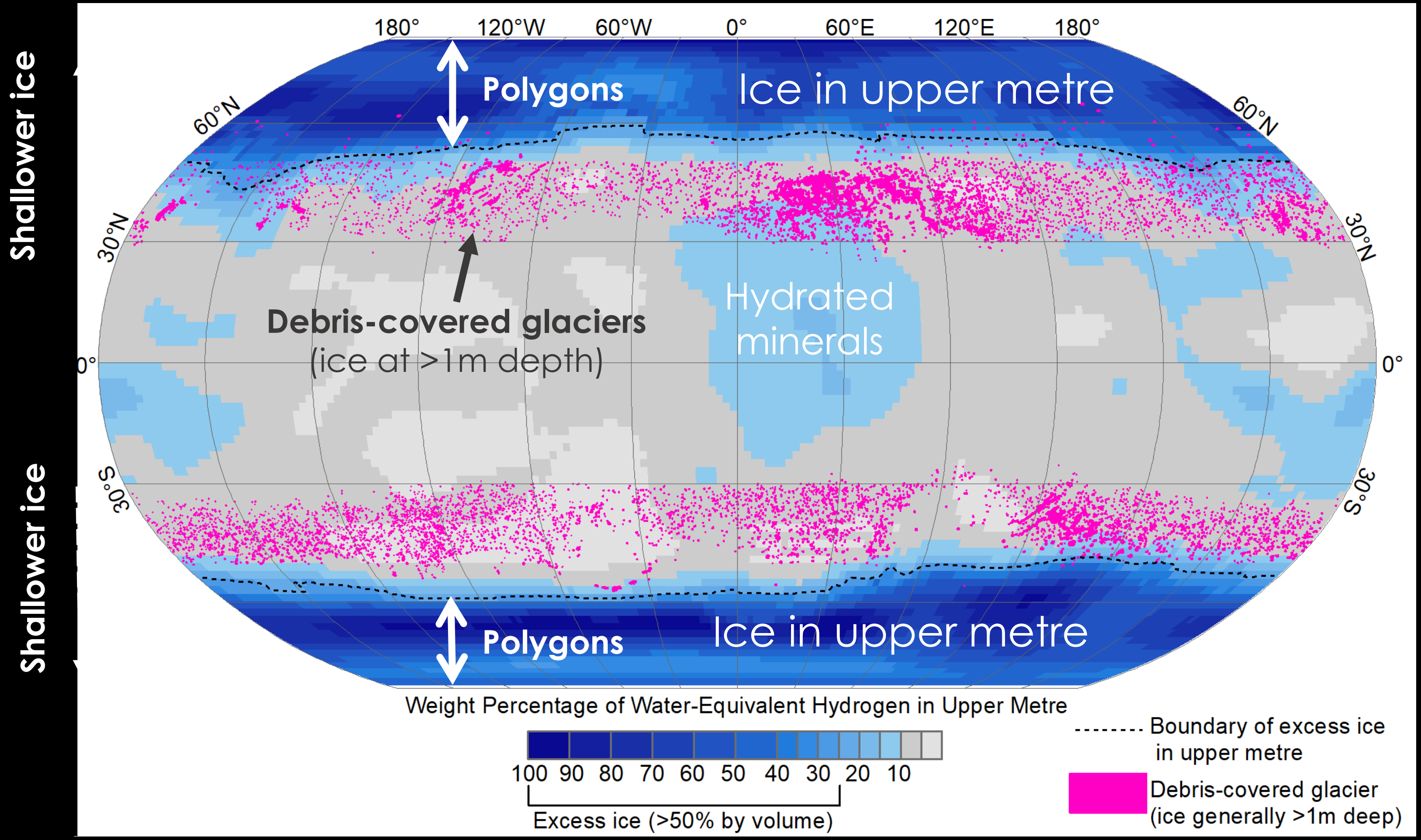


Morphologies of <u>ice degradation</u> in plains where ice % is less certain

NASA/JPL-Caltech/Univ. of Arizona

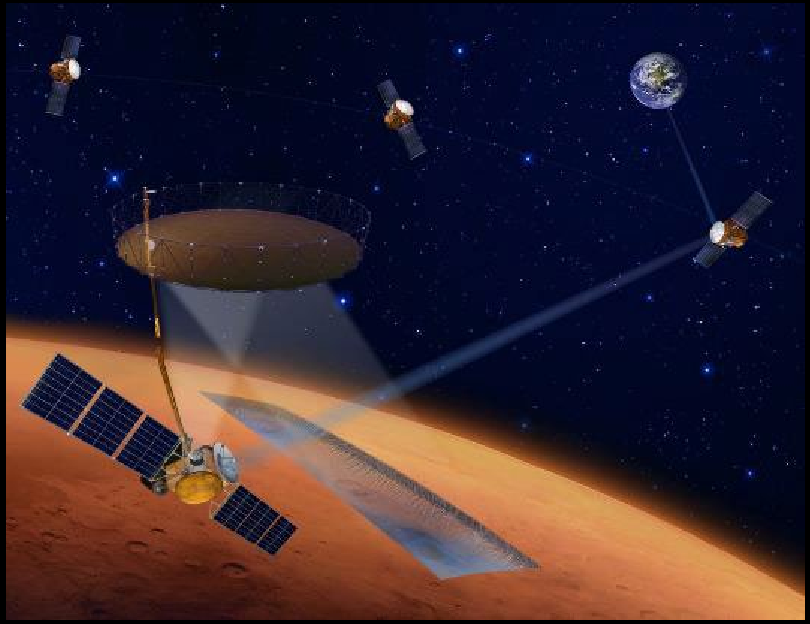
~1/3 of Mars is affected by perennial ice

- Massive ice in upper metre across latitudes >~55°N/S
- Massive ice between 1-10m depth >~30°N/S



Redrawn and adapted from Butcher, 2022, Ox. Res. Encyclopedia, with data from Pathare et al. 2018, Icarus.

International Mars Ice Mapper aims to map ice in 1-10m 'detection gap'

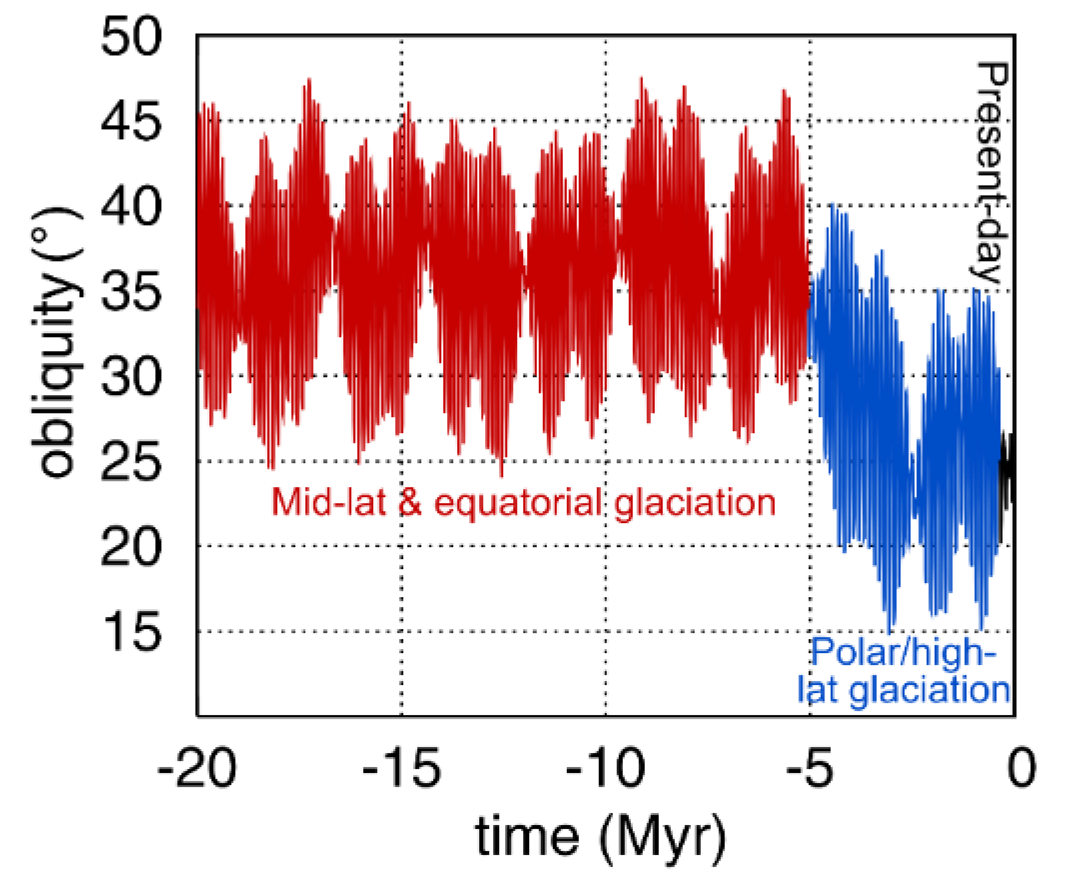


Artist Impression of I-MIM. Credit: NASA

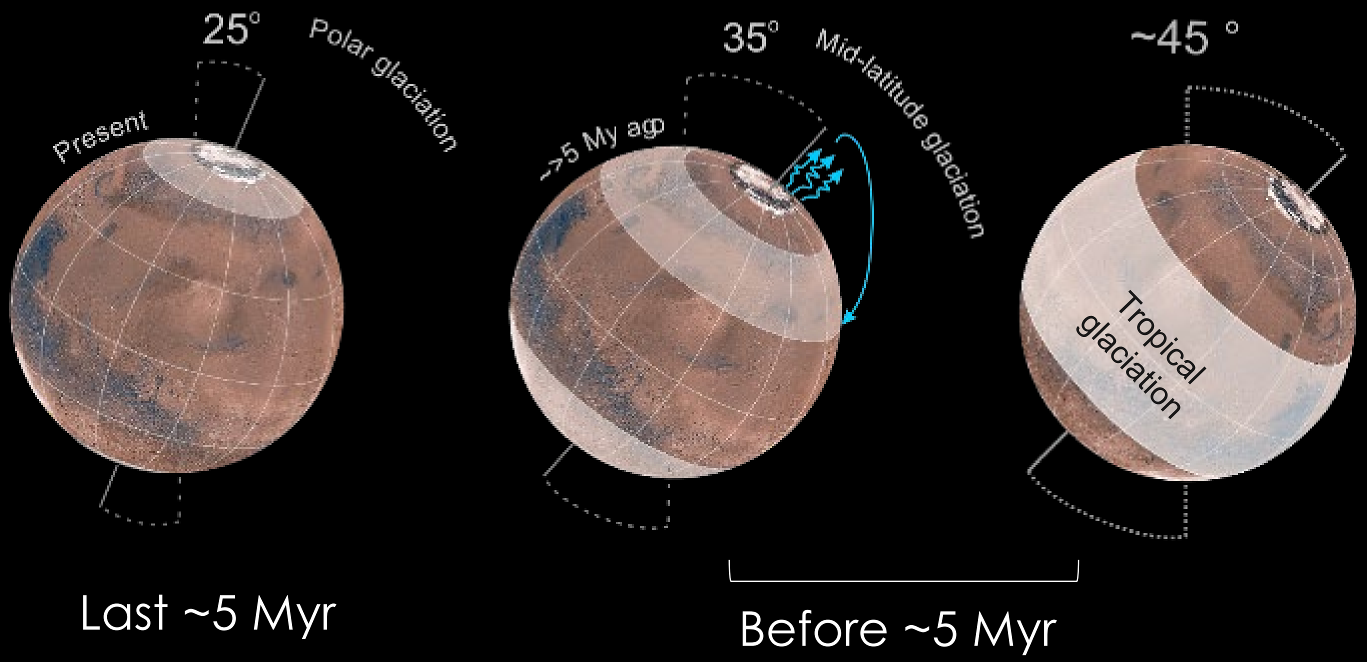
The global influence of the cryosphere through time

- Over geologic time, **low-latitude glaciation may have been more common** than polar.
- **Mars typical obliquity over 4 Gyr: ~ 42°**

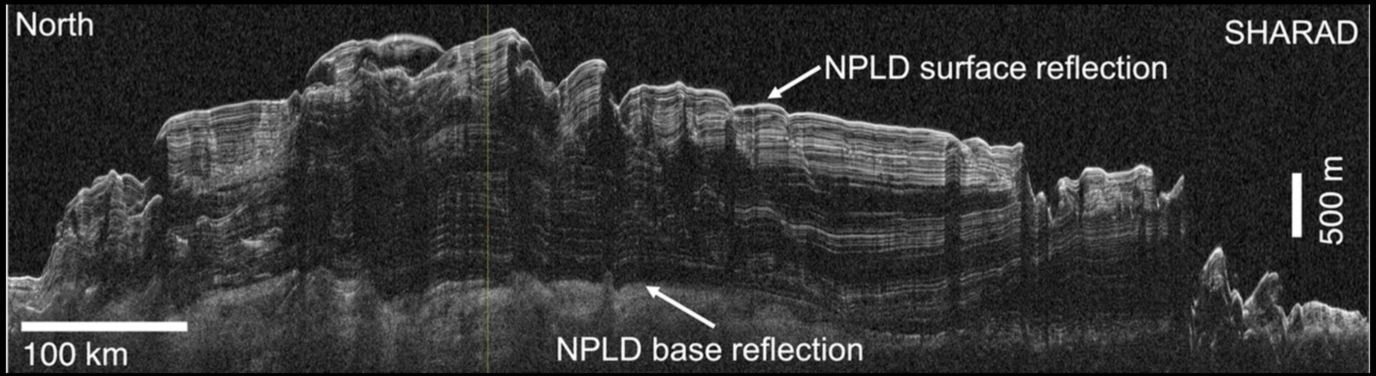
Laskar et al. 2004, Icarus



Adapted from Butcher 2019. PhD thesis (with data from Laskar et al. 2004, Icarus).



Layers in the polar caps likely reflect orbital cycles

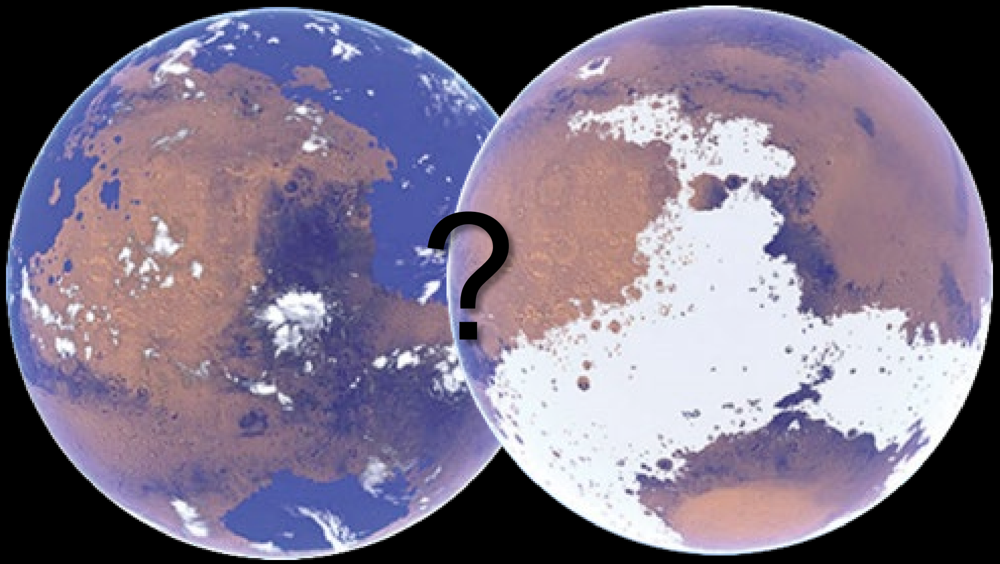


Orbital Shallow Radar profile through Mars' north polar cap. (from Thomas et al. 2022. Exp. Astron.)

Ice was probably an important agent on ancient Mars

- Much debate over whether ancient Mars hosted a **cold/dry**, or **warm/wet** climate, something **in-between**, or **both at different times**.

e.g., Wordsworth et al. 2016. Ann. Rev. Earth. Planet. Sci. ; Kite and Conway 2024. Nat. Geosci.



Wordsworth et al. 2016. Ann. Rev. Earth. Planet. Sci.

Earth is a 'warm and wet' planet, with great oceans AND great ice sheets and mountain glaciers.

↓

Ice & glaciation is not exclusive to cold climate scenarios.

Ice as a key target for human exploration

e.g., ICE-SAG Report (2012); First Ice Cores from Mars Report (2021); I-MIM MDT Final Report (2022)

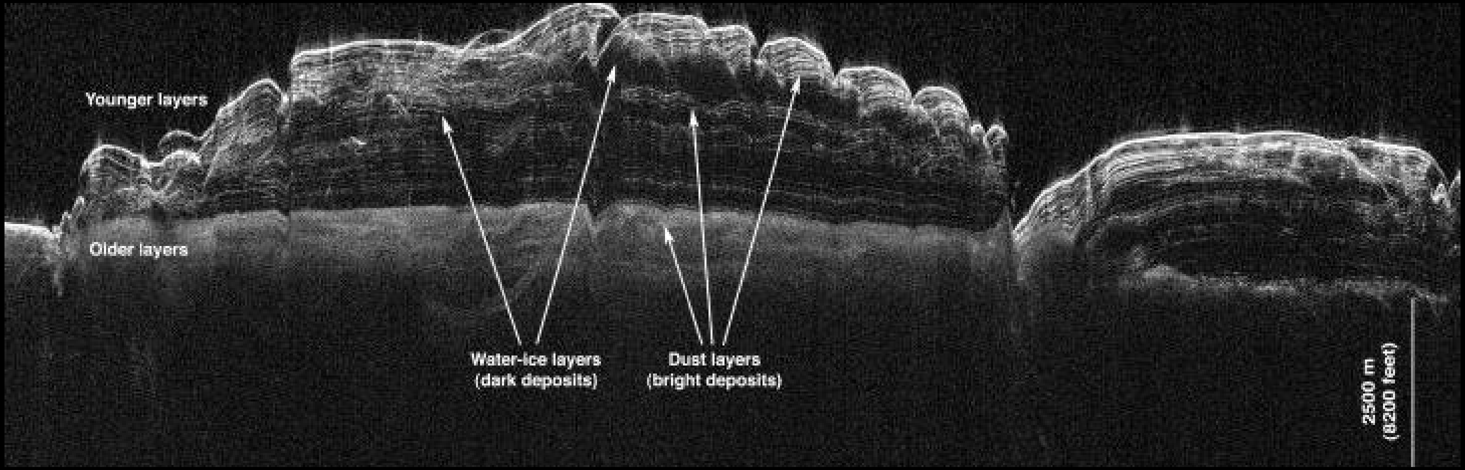
- Critical **in situ resource** (e.g. for radiation protection, fuel production)
- Significant opportunities for **holistic science**: advances to be made on **cryospheric, atmospheric, climatological, geologic, atmospheric, and exogenous** processes.
- Ice a **key target for life-searching**. On Earth ice hosts abundant life, even at subfreezing temperatures.

NASA

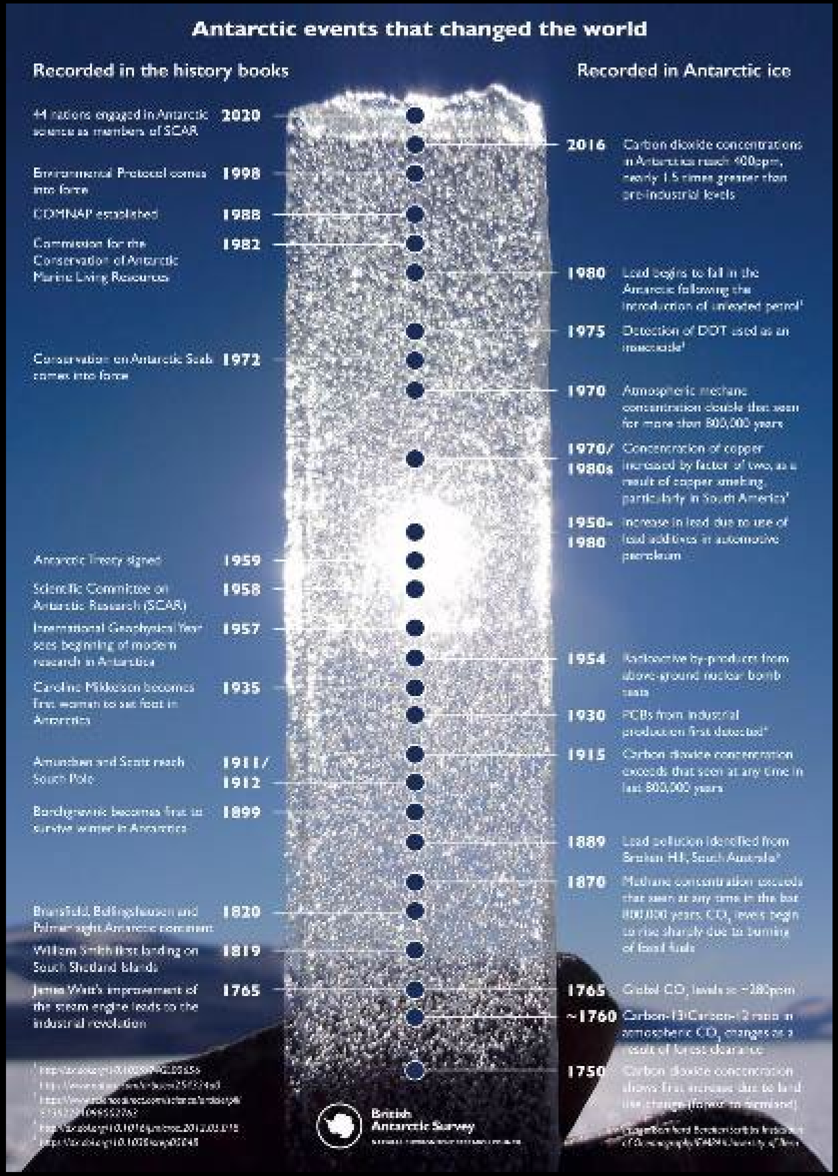
What's in an ice core?

Climate archives

- **'History books'** of atmospheric, geological, biological, anthropogenic, exogenous processes
- e.g., changes in **temperature**, **global ice volume, water sources, solar activity (^{10}Be, δ^2H)**[2] etc.
- Trapped **samples of past atmosphere**e.g. [1,3]
- Indicators of past **melt events** & variations in **snow crystal properties**[4]



Credit: NASA/ESA/JPL-Caltech/ASI/U. Rome/U. Washington St. Louis



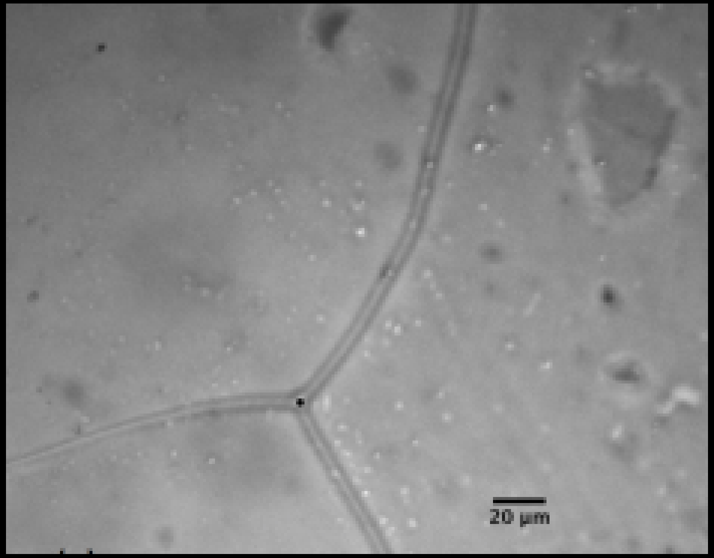
Credit: British Antarctic Survey

[1] Jouzel J. and Masson-Delmotte V. (2010) WIREs Climate Change 1, 621–763; [2] Raisbeck G.M. et al. (1990) Phil. Trans. Royal. Soc. A 330, 463–470
[3] First Ice Cores from Mars report (2021); [4] Moser D.E. et al. (2023) EGUsphere (Preprint).

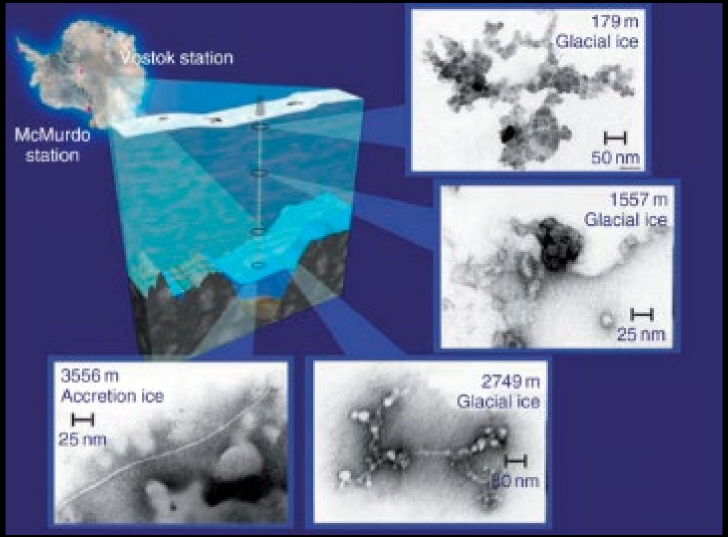
What's in an ice core?

Micro-scale meltwater environments, and life.

- Glacial ice hosts **micro-scale meltwater veins**[1] at crystal boundaries. Liquid can exist down to **−30°C**[2].
- Microbial life **even in cold polar desert** environments (e.g. Antarctic Dry Valleys)[e.g., 3].
- Cryosphere a highly **significant component of Earth's biosphere** *(e.g., mass of prokaryotic cells in Greenland & Antarctica* ***approaches bacterial carbon contained in all surface freshwater*** *on Earth[4])*
- **Impurities/entrained lithics increase ice habitability** - energy sources, & encourage melt & solute release.[5]



Ice crystal junctions from Greenland ice core (146m depth) – liquid veins, lithic particles, and cells observed. Chemical composition of liquid from Micro-raman. Barletta et al. 2012, J. Glaciol.



Viral particles in Vostok ice core (transmission electron microscopy). Priscu et al. (2007) Encyc. Quat. Sci. Vol. 2

[1] Barletta et al. 2017 J. Glaciol. [2] Dash et al. 1995, Reports on Prog. In Phys. [3] Montross et al., 2014, Geomicrobio. J. [4] First ice cores from Mars report 2021. [5] Priscu et al. 2007, Encyc. Quat. Sci. V2

What's in an ice core?

Impurities

- Record **geologic, atmospheric**, **oceanographic**, and **biological** processes at local, regional, and global scales.[e.g., 1,2]
- On Mars: e.g., **dust, volcanic/impact tephra, aerosols, salts**.
- Info on atmospheric connections & changes in source regions of water/impurities
- Help with **dating,** and **age correlation.**[see e.g., 3]
- **Energy sources** for microbial life.[4]

Credit: Heidi Roop, NSF

Valuable e.g., for constraining **recent impact/volcanism/outgassing rates**, **dust cycles** and **ice-climate coupling,** and **atmospheric connections between regions**.

[1] Jouzel J. and Masson-Delmotte V. 2010 WIREs Climate Change 1, [2] First Ice Cores from Mars Report, 2021 [3] Smith et al. 2020, Planet. Space. Sci., [4] Priscu et al. 2007, Encyc. Quat. Sci. V2.

What's in an ice core?

Rocks in/on ice

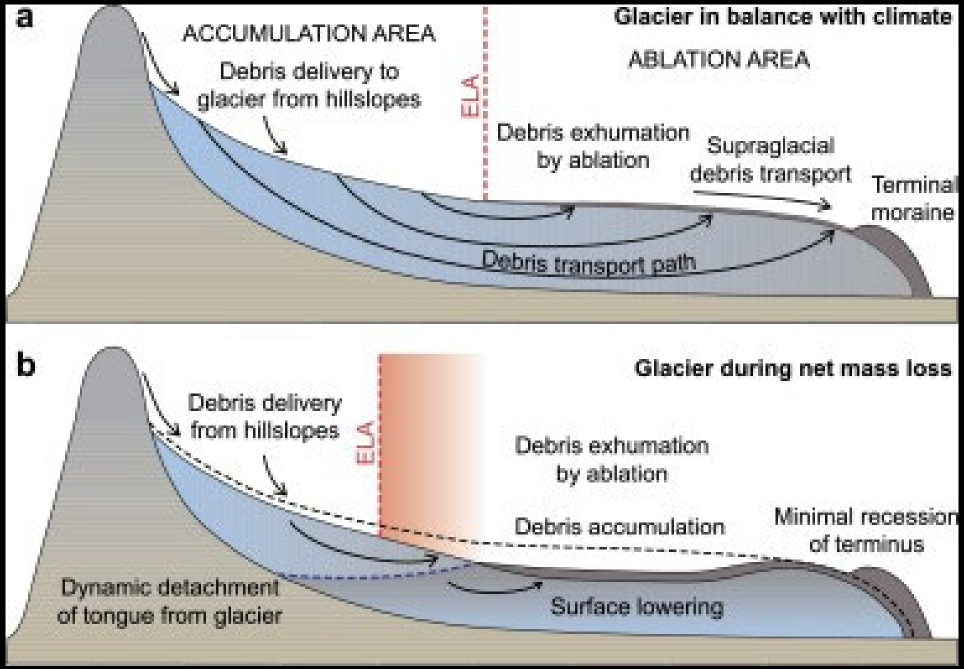
Can be **transported from geologically-interesting sites**, including e.g. **gullies** and **ancient strata**[1]

Can be transported from **bed/basal ice**

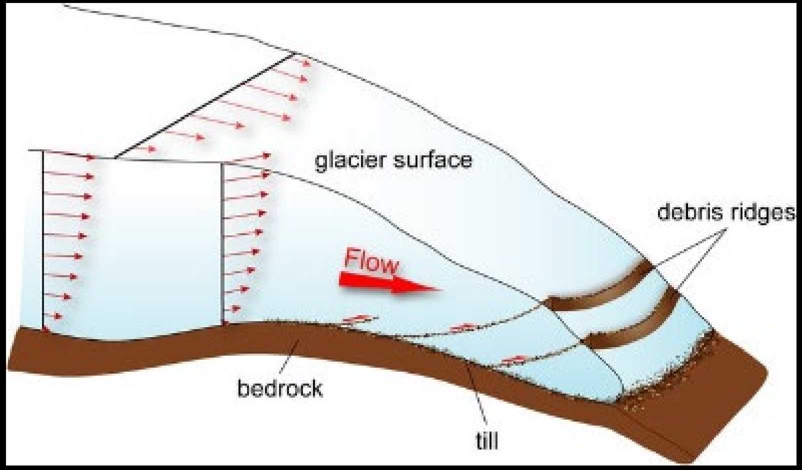
Varied pathways: **over, through, beneath ice** - record different conditions e.g., **water activities** through system[2].

More rarely, can be **meteorites**[3]. Mars' glaciers may also include **impact ejecta.**

[1] See extensive review of glacier debris transport in Benn and Evans 2010, Glaciers and Glaciation. [2] Tranter et al. 2002, Hydrol. Process. [3] Joy et al. 2024, Meteor. Planet. Sci.



Rowan et al. 2015, Earth Planet Sci. Lett.



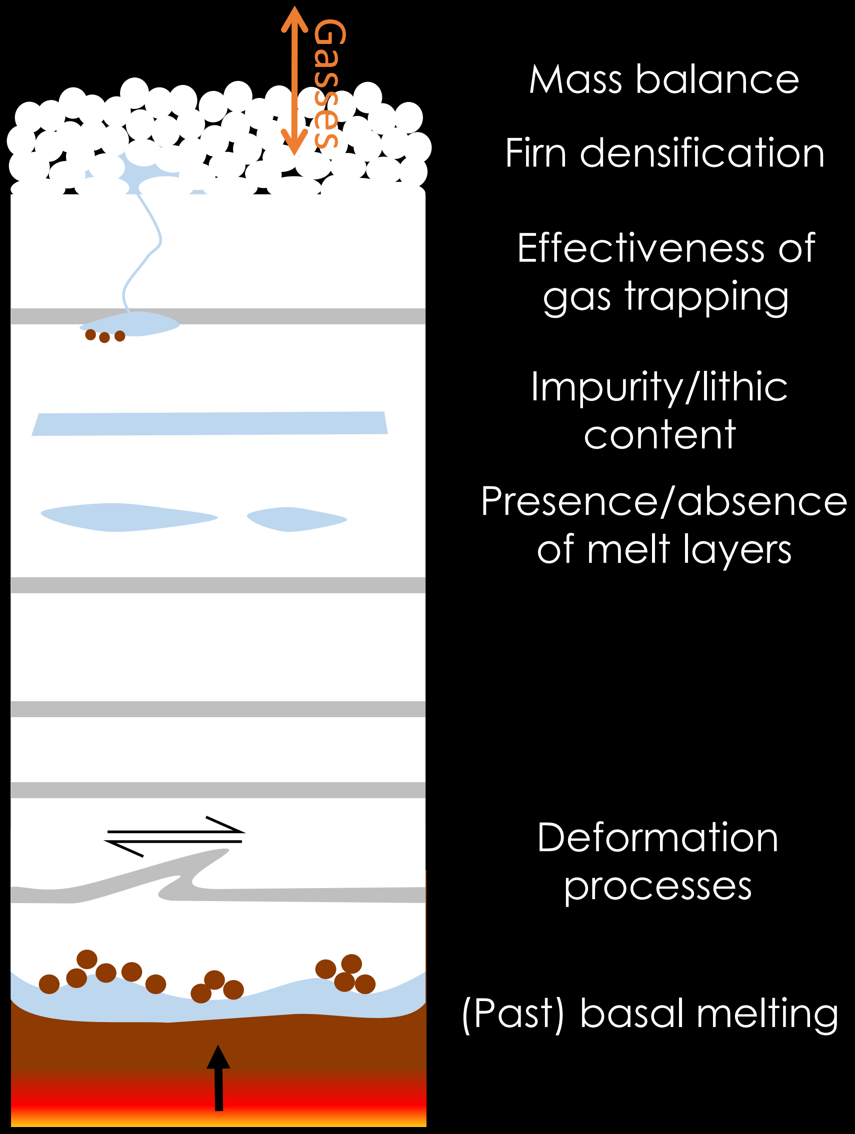
Monz et al. 2021, Boreas

Where is the 'best ice' for science?

- **Objective-dependent.**
- Potentially **more restrictive than for ISRU**.
- **Will vary spatially** even within a given landing region.
  - **E.g. Trapped gasses**: cold ice, preserved layering, high accumulation rate (or rapid sealing off from atmosphere), minimal melt*.

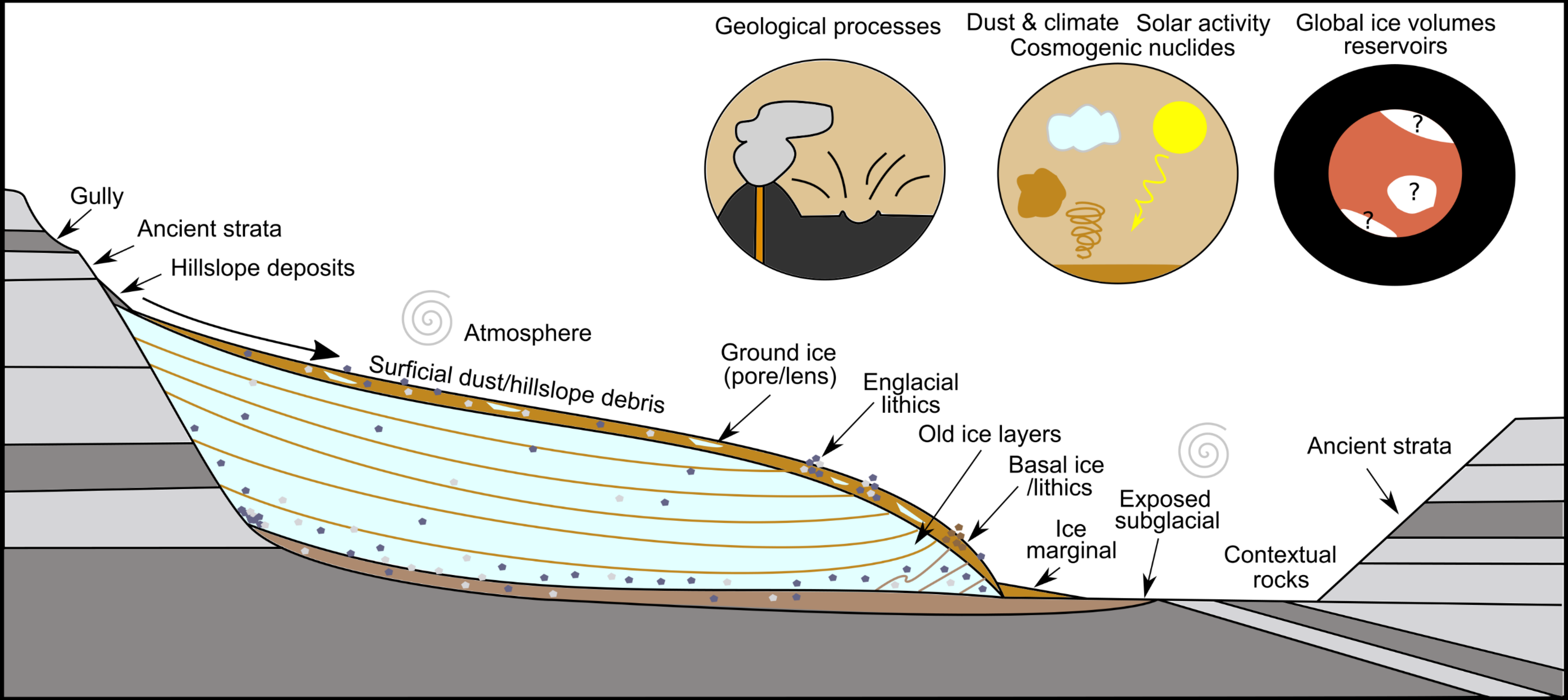
    **Melt layers interesting climate records in themselves*
    (e.g. Moser et al. 2024, The Cryosphere)

  - **Habitability**: some melt, relatively dirty ice, energy inputs from ice flow/glacial erosion.



Holistic sampling opportunities

- Ice-sampling missions bring many opportunities beyond ice cores



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Holistic sampling opportunities

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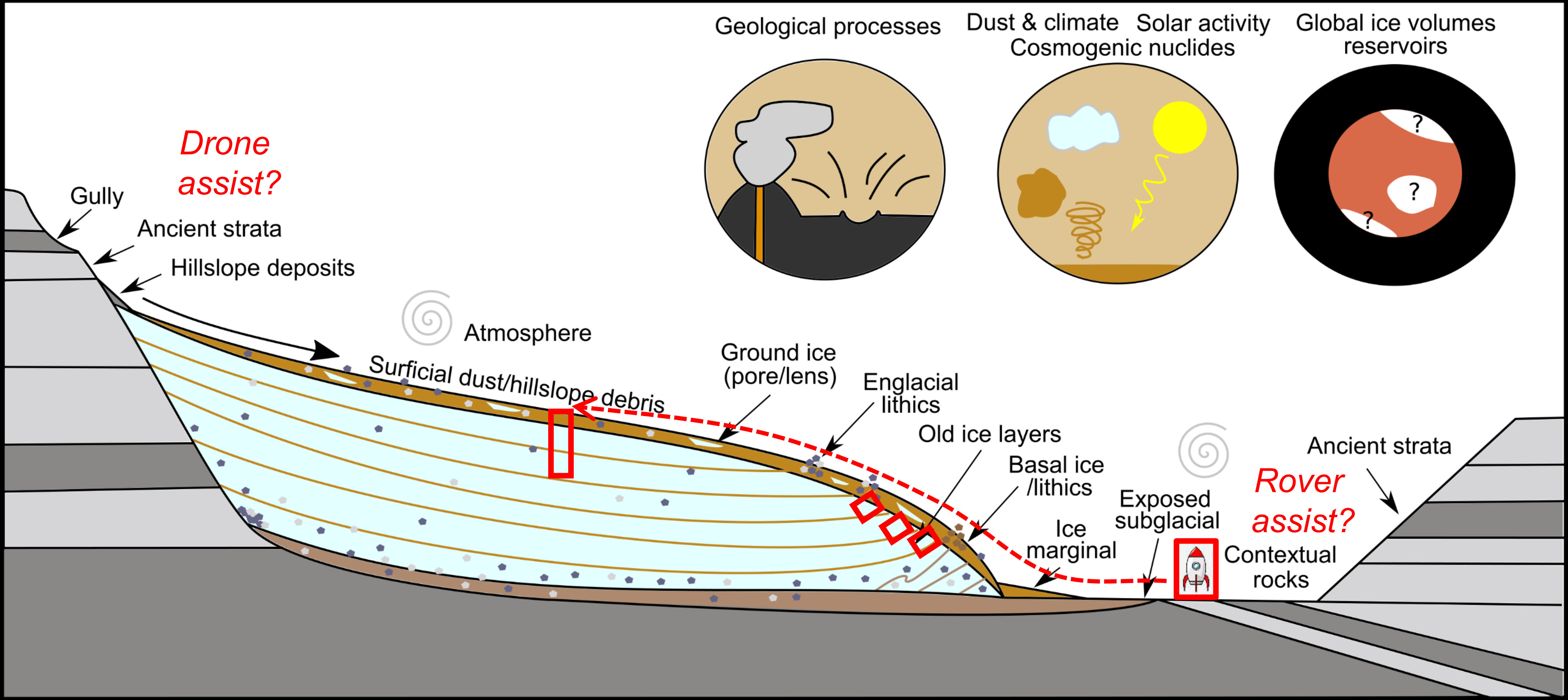

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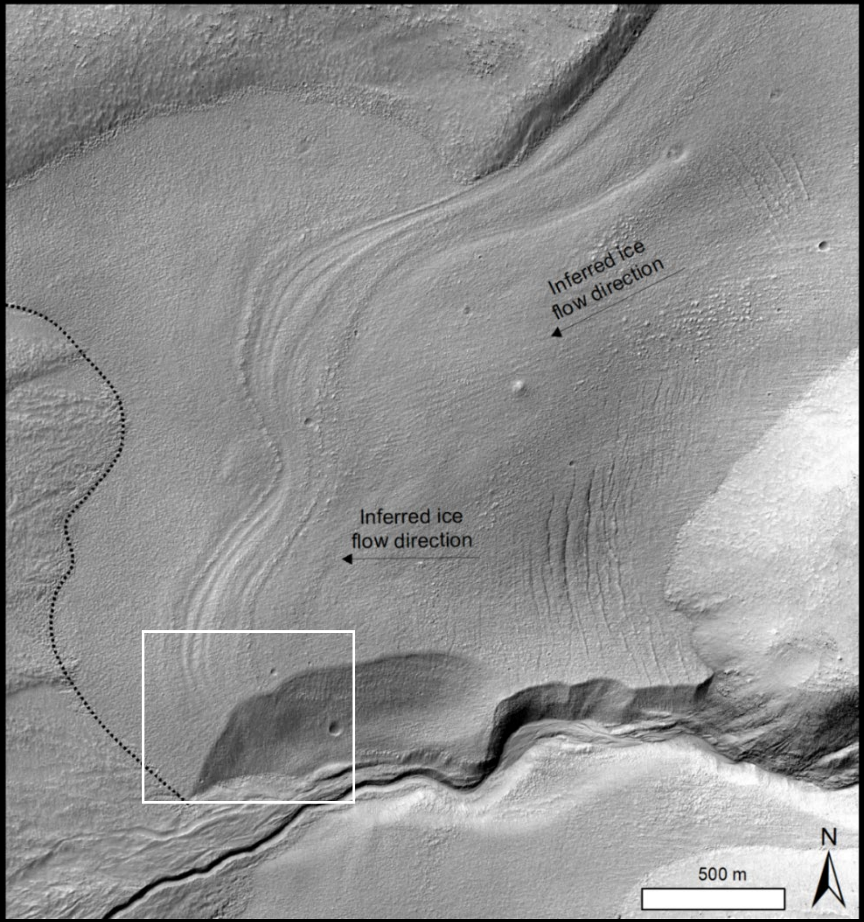
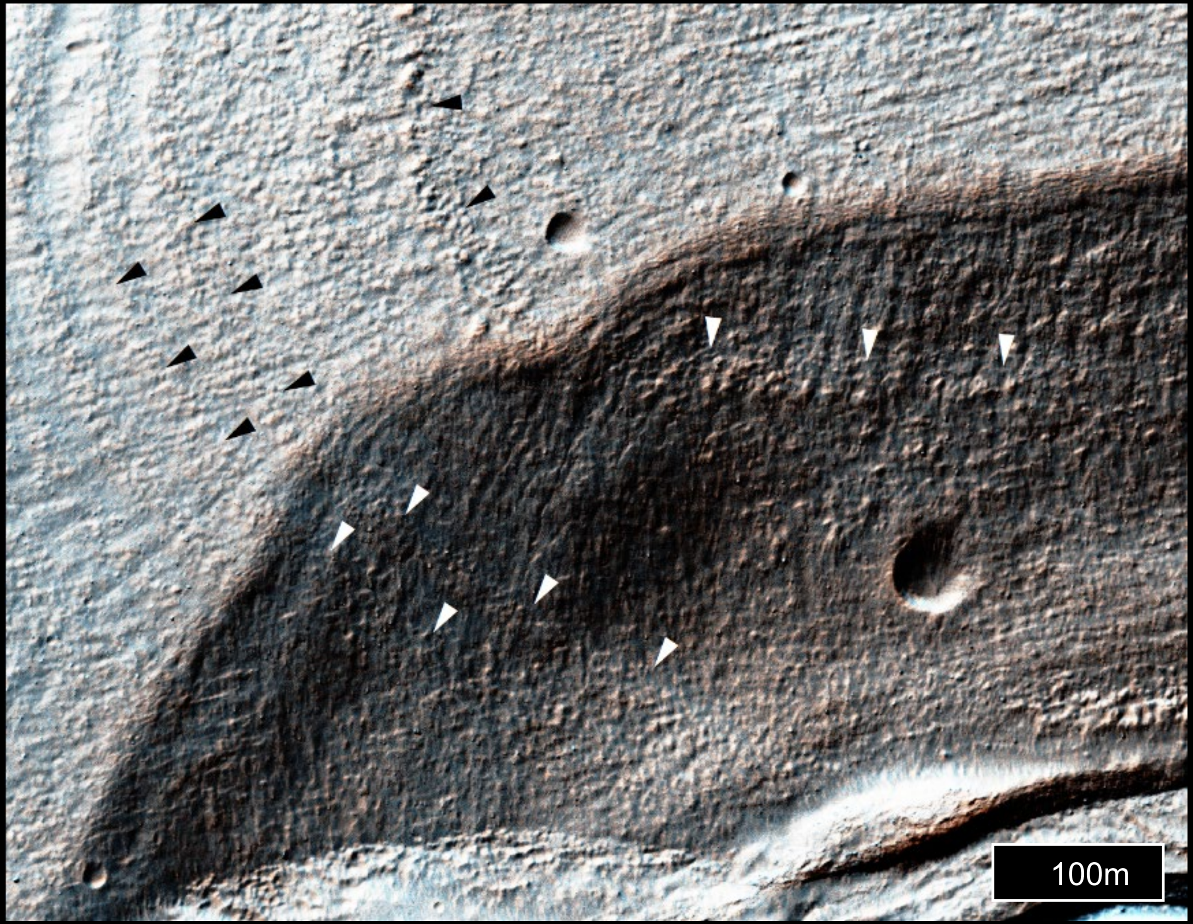
Could ice flow hold the key to accessing old ice on Mars?

Butcher et al. (2023), Icarus, Arnold and Butcher (2024), Int. Conf. Mars Polar. Sci. & Exploration.

- Ice-internal layering observed connecting to flow-related structures on the surface of a mid-latitude debris-covered glacier



CTX image (6 m/pixel). Credit: NASA/JPL-Caltech/MSSS/F. Butcher



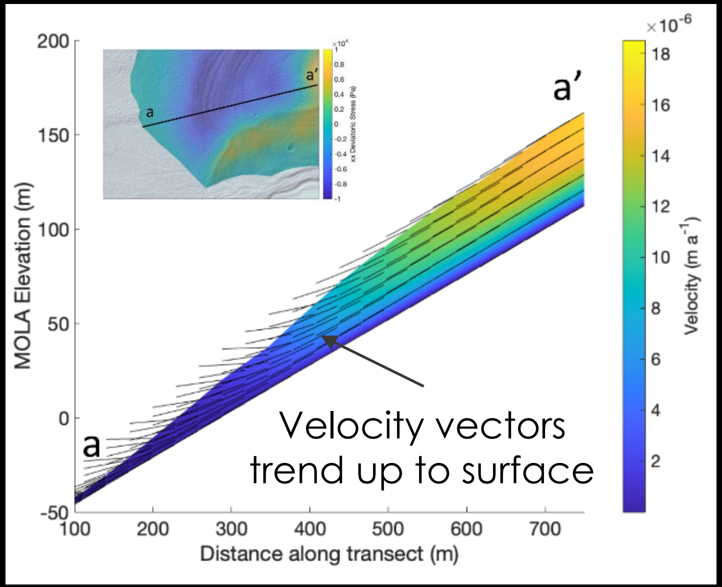
HiRISE false-colour image (25 cm/pixel). Credit: NASA/JPL/U of Arizona/F. Butcher

Could ice flow hold the key to accessing old ice?

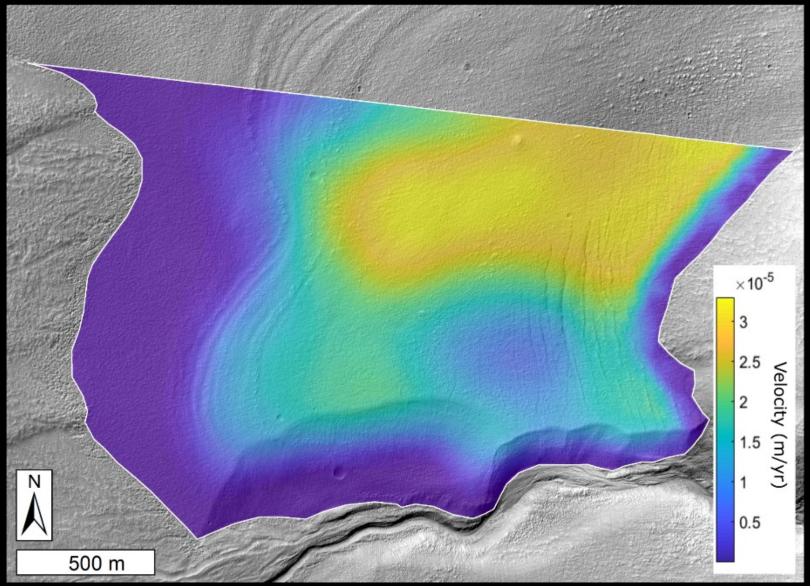
Butcher et al. (2023), Icarus

- Structures correspond with **ice flow deceleration** & horizontal **flow compression**, where **layers are forced up to the surface**.
- Potential **transport of old ice to the near-surface** from depth.
- Work ongoing *(e.g. Arnold and Butcher, 2024 Int. Conf. Mars. Polar. Sci. & Exp.)*

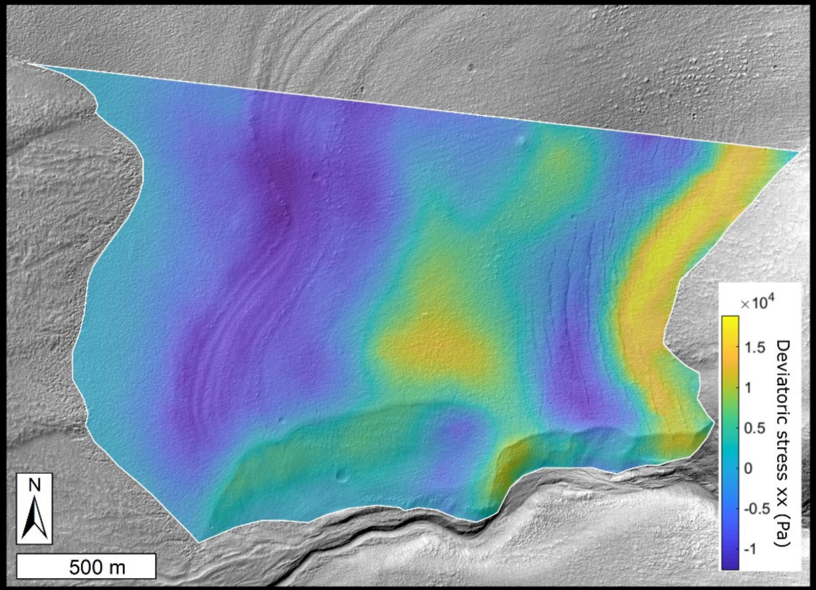
3D velocity



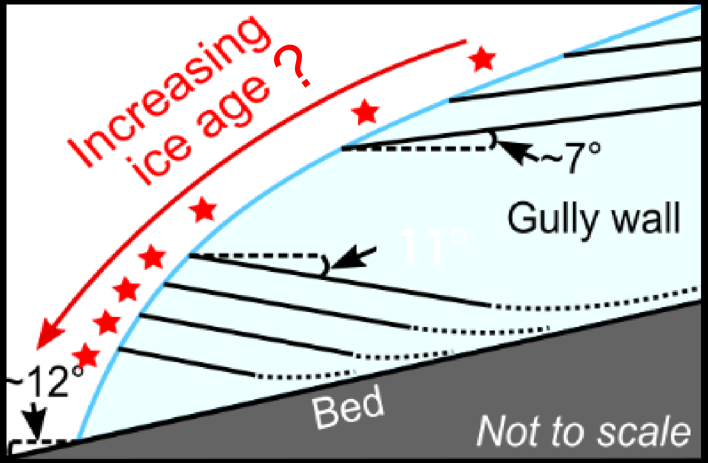
Horizontal velocity



Deviatoric stress xx (Horizontal)

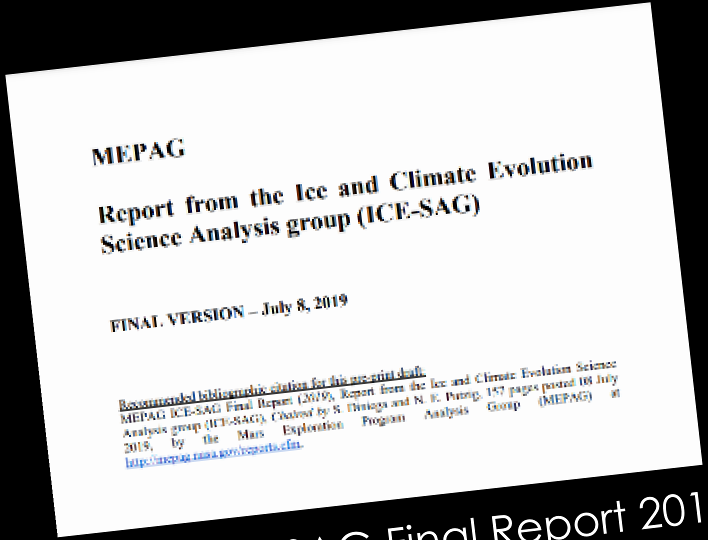


Blue is compressional



Adapted from Butcher et al. (2023), Icarus (CC BY 4.0 DEED)

Some key papers/reports

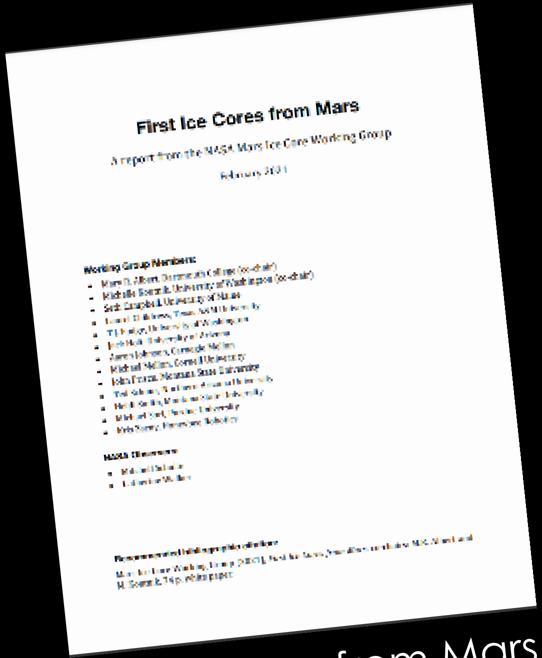

MEPAG

Report from the Ice and Climate Evolution Science Analysis group (ICE-SAG)

FINAL VERSION – July 8, 2019

Recommended bibliographic citation for this pre-print draft: MEPAG ICE-SAG Final Report (2019), Report from the Ice and Climate Evolution Science Analysis group (ICE-SAG), Chaired by S. Diniega and N. E. Putzig, 157 pages posted 18 July 2019, by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.nasa.gov/reports.cfm.

MEPAG ICE-SAG Final Report 2019


First Ice Cores from Mars

A report from the NASA Mars Ice Core Working Group

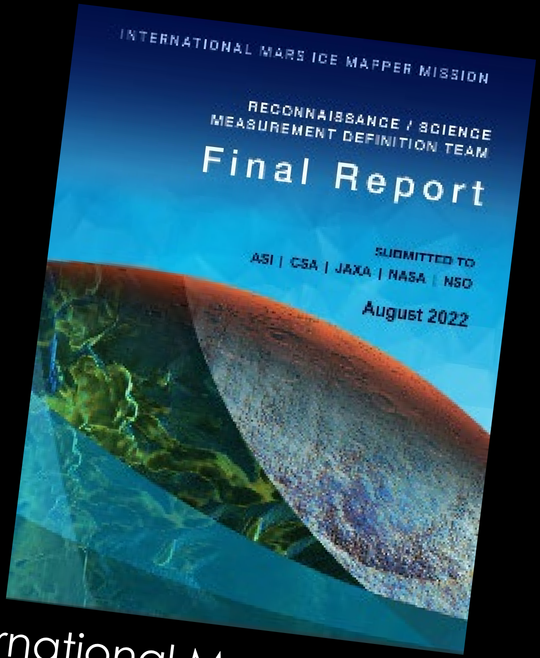
Working Group Members:

First Ice Cores from Mars Report 2021

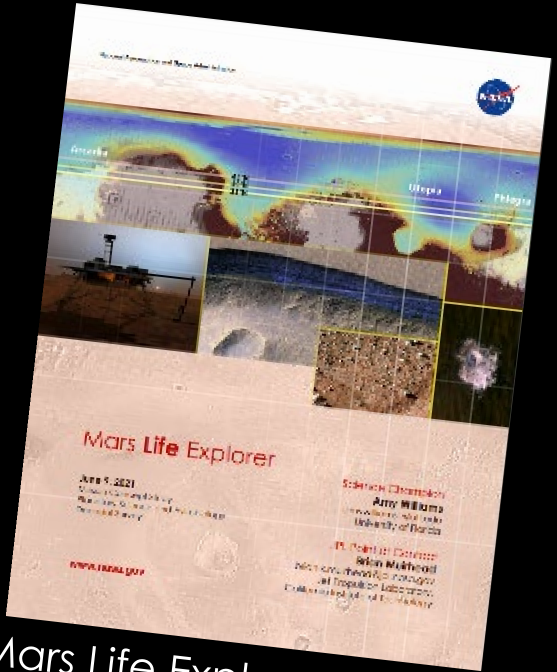

Planetary and Space Science

The Holy Grail: A road map for unlocking the climate record stored within Mars' polar layered deposits

Smith et al. (2020). PSS 184. Roadmap for unlocking polar climate records



International Mars Ice Mapper MDT Final Report 2022



Mars Life Explorer Lander Concept 2021

Examples of hypotheses we could test with ice

See e.g., NASA first ice cores from Mars report 2021; ICE-SAG report 2019, and references therein

- Mars' ice deposits contain records of recent climate evolution.
- Recent climate cycles on Mars were driven by orbital variations (predominantly obliquity).
- Mars' ice deposits contain records of atmospheric composition through time.
- Mars' glacial and dust cycles are coupled.
- Mars' layered ice deposits contain records of variations in impact rates over time.

e.g., Smith et al. (2020). PSS 184; Madeleine et al . 2009. Icarus; Levrard et al. 2007 JGR

- Mars' mid latitude glaciers host ice from 100s Myr ago (much older than Earth's ice).
- Mars' mid latitude glaciers formed over multiple climate cycles.

e.g., Baker and Carter 2019b Icarus; Hepburn et al. 2020 JGR Planets

- Volcanic activity has occurred since Mars' mid latitude ice was deposited. *e.g., Hauber et al. 2011 GRL*

- Mars' ice deposits host, or recently hosted habitable environments (e.g. interfacial meltwater lenses, debris-rich basal ice) *e.g., Montross et al., 2014, Geomicrobio. J.*
- Mars' ice deposits produced liquid water in the past *e.g., Butcher et al. 2017, Icarus, 2023 Annals Glaciol.*
- Mars' ice deposits host microbial life *e.g., ICE-SAG report 2019, and references therein.*

And many, many (many) more…

Decadal questions relevant to ice on Mars

Q4: Impacts & dynamics

4.2: Impact bombardment & its variations

Q5: Solid body interiors & surfaces

5.4 & 5.5: Surface modification records/processes
5.6: Drivers of active processes

Q6: Solid body atmo/exo/magneto spheres & climate evolution

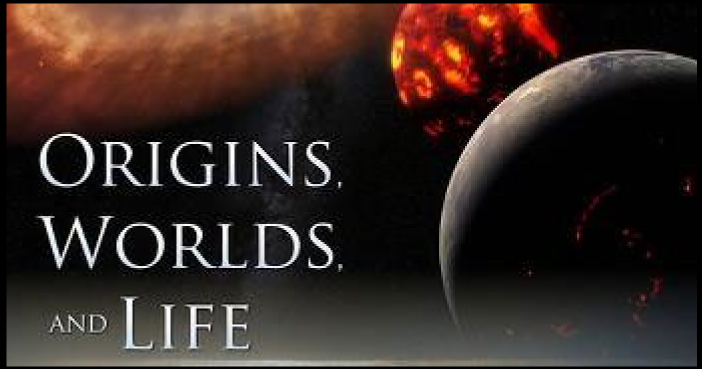
6.2: Planetary atmospheres and climate evolution

6.3: Dynamics & energetics of atmospheres

6.4: Surfaces/interiors interactions with atmospheres

6.5 Processes governing atmospheric loss to space

6.6: Clouds, chemistry, composition of atmospheres



Q10: Dynamic habitability

10.2: Where are/were habitable environments?
10.3: Water availability & controls over time
10.5: Nutrient/inorganic ingredient availability for life
10.6: Controls on energy available for life
10.7: Habitability continuity/sustainability

Q11: Search for life

11.2: Biosignature potential in habitable environments
11.3: Is/was there life elsewhere?
11.4: Nature of life elsewhere, if it exists?