Underground Ice on Mars: Characterization Activities, Potential as an In Situ Resource, and Possible Destination for Human Explorers

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Abstract

One of the next giant leaps for humanity—inhabiting our neighbor planet Mars—requires enough water to support multi-year human survival and to create rocket fuel for the nearly 150-million-mile return trip to Earth. Water that is already on Mars, in the form of ice, is one of the leading in situ resources being considered in preparation for human exploration. Human missions will need to land in locations with relatively warm temperatures and consistent sunlight. But in these locations, ice (if present) is buried underground. Much of the ice known to exist in mid-latitude locations was likely emplaced under climate conditions (and orbital parameters) different from today. So in addition to providing an in-situ resource for human exploration, Martian ice also provides a crucial record of planetary climate change and the effects of orbital forcing.This presentation will highlight techniques and recent activities to characterize Mars' underground ice, such as the Subsurface Water Ice Mapping (SWIM) Project (Morgan et al. 2021, Nature Astro.; Putzig et al. In Press, Handbook of Space Resources; Putzig et al. this AGU; Morgan et al. this AGU). We present outstanding questions that will be vital to address in the context of ISRU (in situ resource utilization) and connections between these questions and the climate in which the ice was emplaced and evolved (e.g., Bramson et al. 2020, Decadal White Paper). Lastly, we discuss how these science activities intersect with future exploration, particularly that enabled by collaborations between space agencies as well as industry partners (Heldmann et al. 2020, Decadal White Paper; Golombek et al. 2021, LPSC).High-priority future work includes better orbital characterization of shallow ice deposits, such as radar sounding at shallower scales (<˜10m) than that of SHARAD, as proposed for the International Mars Ice Mapper. Also needed are detailed studies of the engineering required to build potential settlements at specific candidate locations; this includes characterization of the nature of the overburden above the ice, which will inform future resource extraction technology development efforts. Ideally, initial landing sites would be chosen with a long-term vision which includes preparation and development of the basic technologies and designs needed for human landing on Mars.

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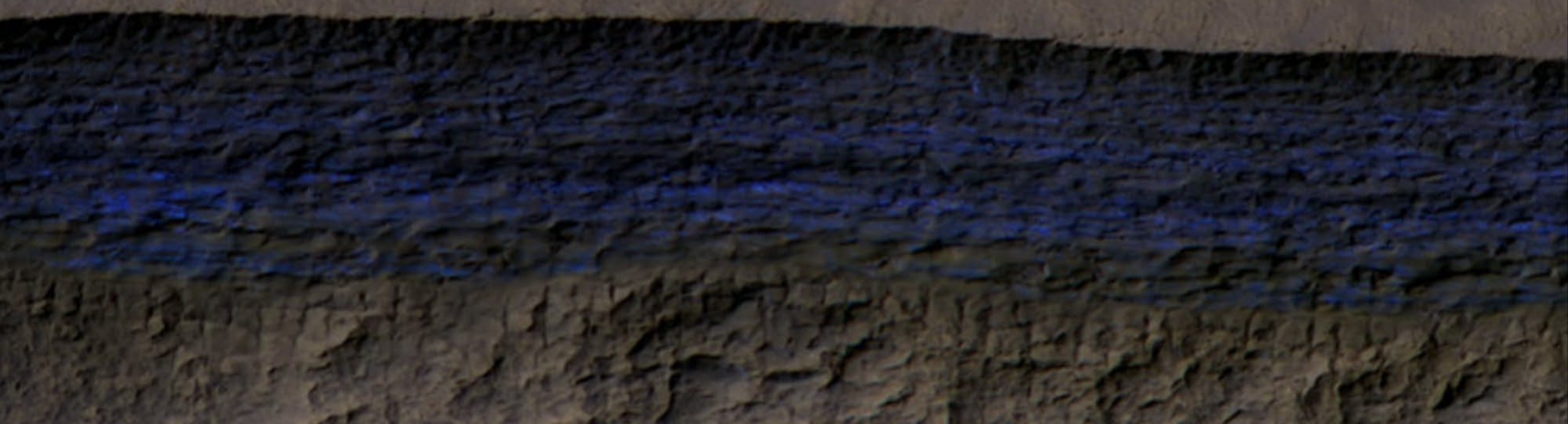

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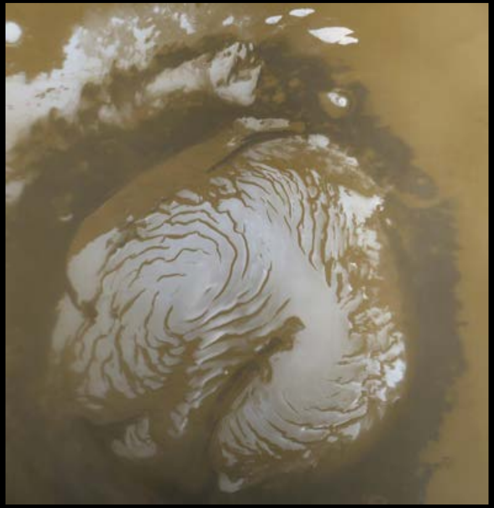
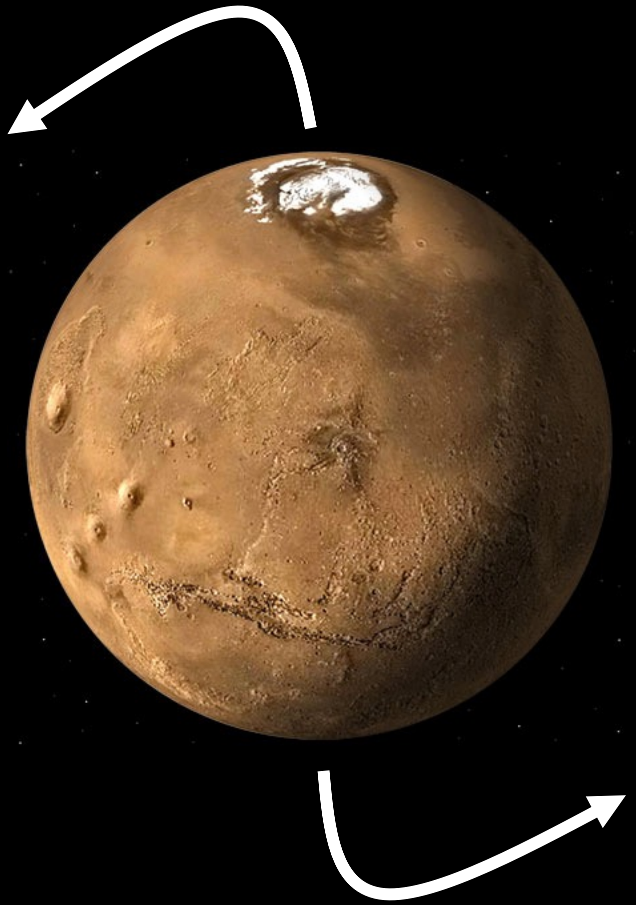
Sam Courville (ASU), James W. Head (Brown University), David W. Beaty (JPL/Caltech), Paul Wooster (SpaceX)

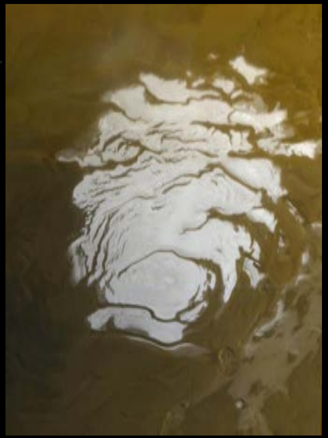
Human missions will need to land in locations with relatively warm temperatures and consistent sunlight and near accessible water ice deposits.





Both poles of Mars feature km-thick ice caps.

But poles are not great for human exploration (months of cold, dark winters)



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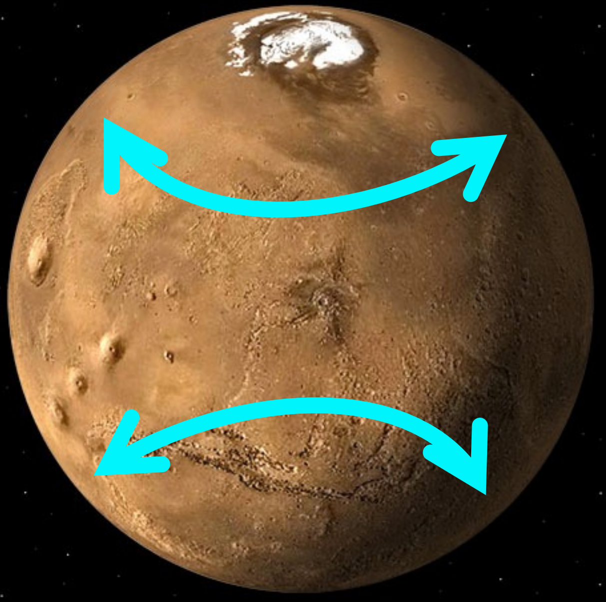
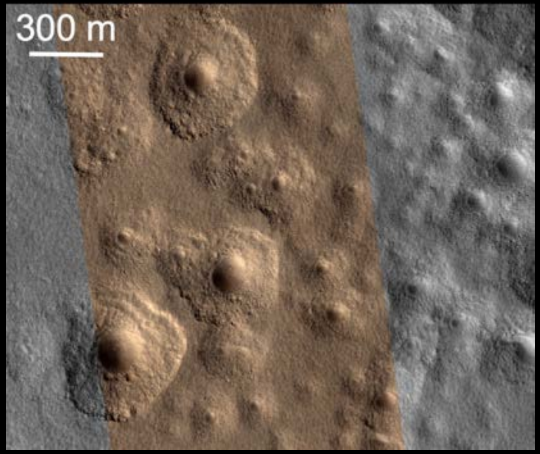
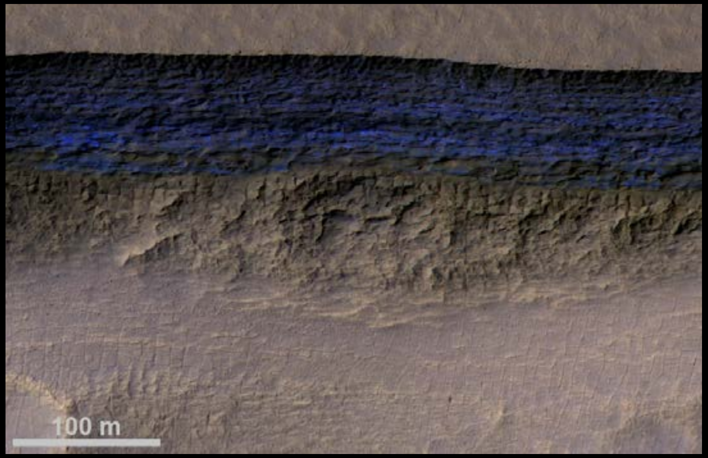


There is ice closer to the equator (warmer), but in these locations, ice (if present) is buried underground.

Dundas et al., 2014



Viola et al., 2015



Dundas et al., 2018

The Martian underground therefore is crucially important as an in situ resource to enable future human exploration.

"The objectives for the first mission will be to <u>confirm water resources</u>, identify hazards, and put in place initial power, mining, and life support infrastructure." – *SpaceX Website; Elon Musk, IAC, 2017*

Image Credit: NASA Langley Advanced Concepts Lab/Analytical Mechanics Associates

SPACEX

Science activities to characterize the ice intersect with planning for future human exploration.

- Outstanding questions about the ice are vital for understanding:
  - Connections between the ice and the climate in which the ice was emplaced and evolved – how planetary climate systems operate
    e.g., *Bramson et al., 2020, Decadal White Paper*
  - ISRU (in situ resource utilization)
- Collaborations between space agencies as well as industry partners
  - Statement of intent to develop an International Mars Ice Mapper concept (NASA Press Release, Feb. 3, 2021)
  - Utility of the SpaceX architecture for enabling human presence:
    e.g., *Heldmann et al., 2020, Decadal White Paper;*
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  - Possible Starship Landing Sites
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Image Credit: NASA

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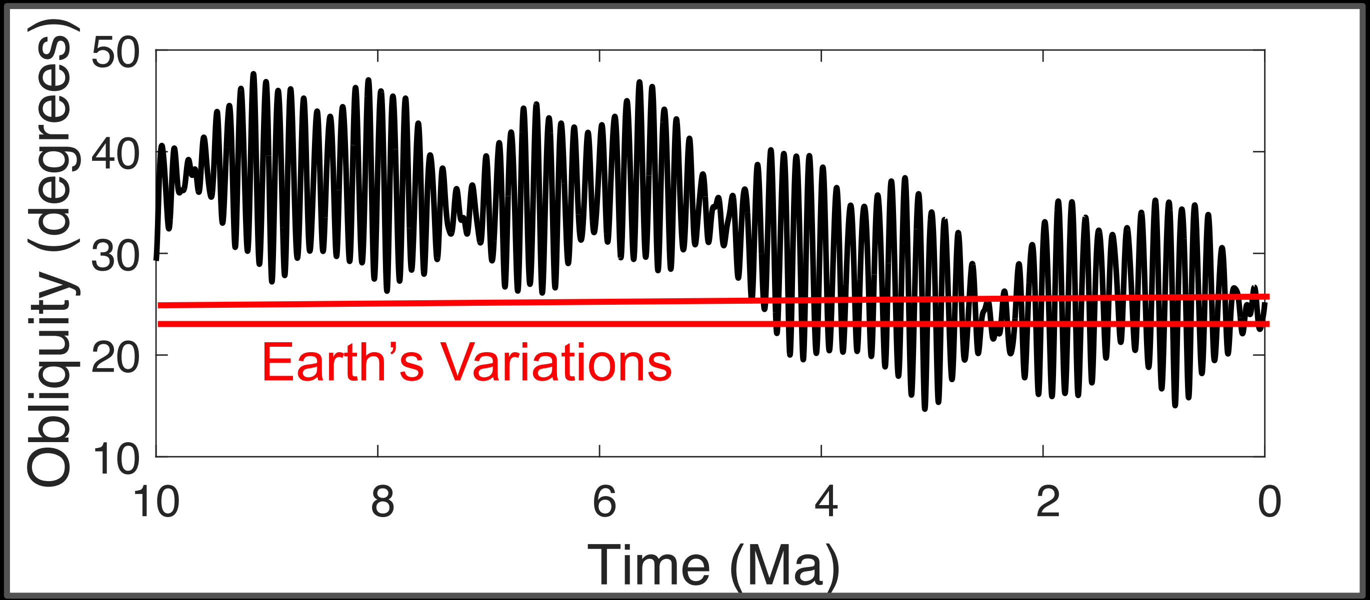
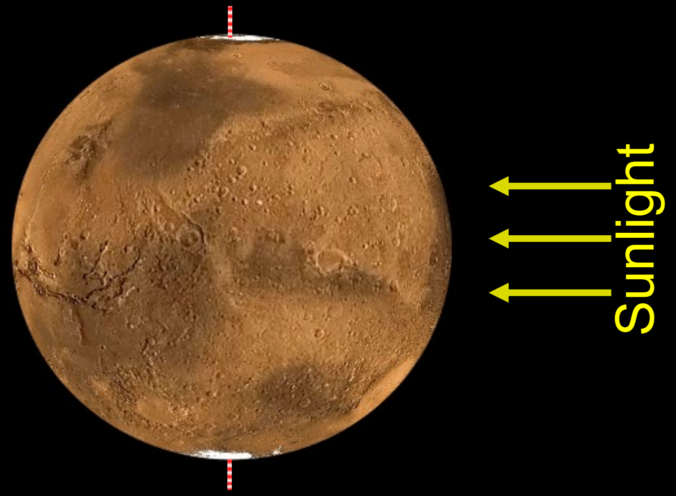
Image Credit: NASA

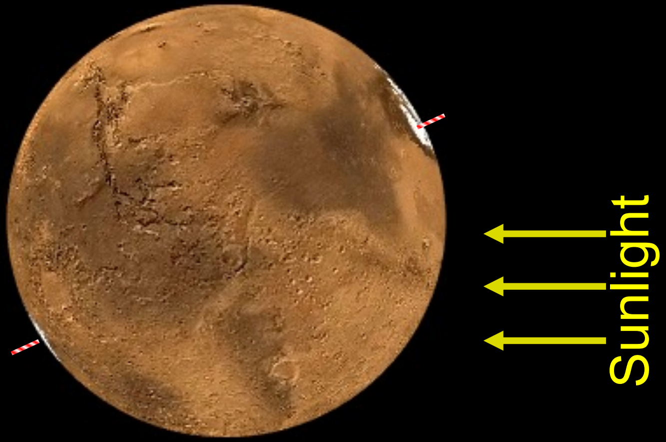
Changes in axial tilt and the orbit causes volatile stability on Mars to change over time.



Solutions from Laskar et al., 2004

Obliquity = 0°

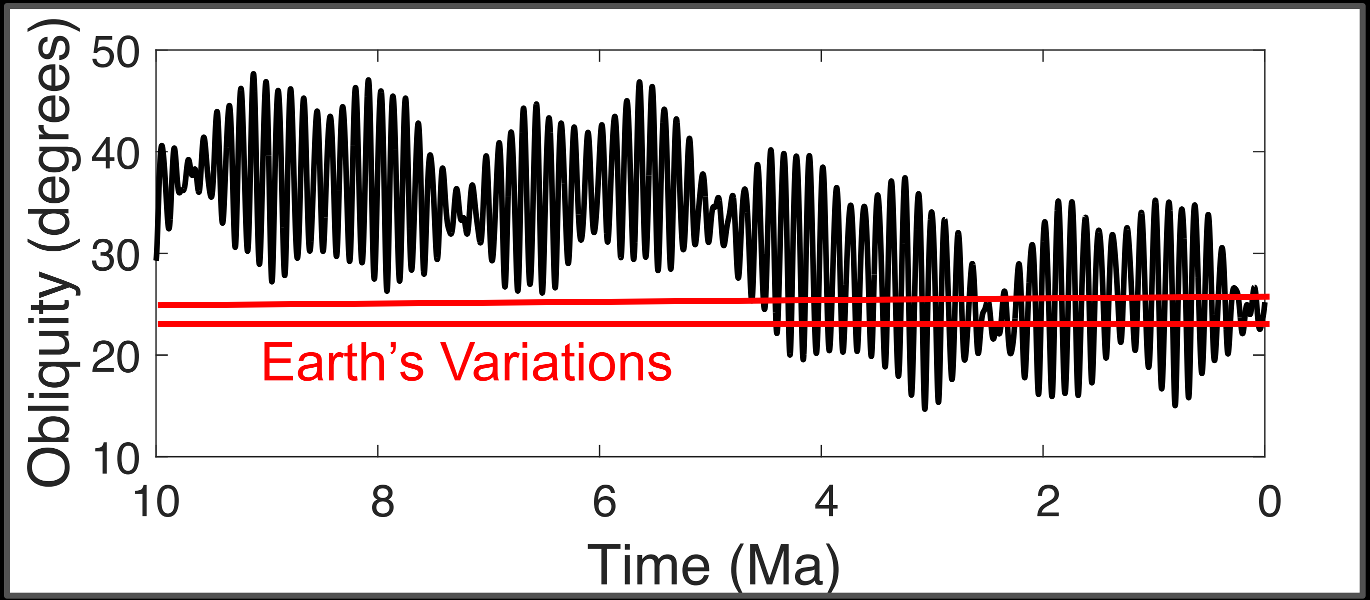




Obliquity = 60°

Analogous to Milankovitch cycles on Earth – but more extreme!

Changes in axial tilt and the orbit causes volatile stability on Mars to change over time.



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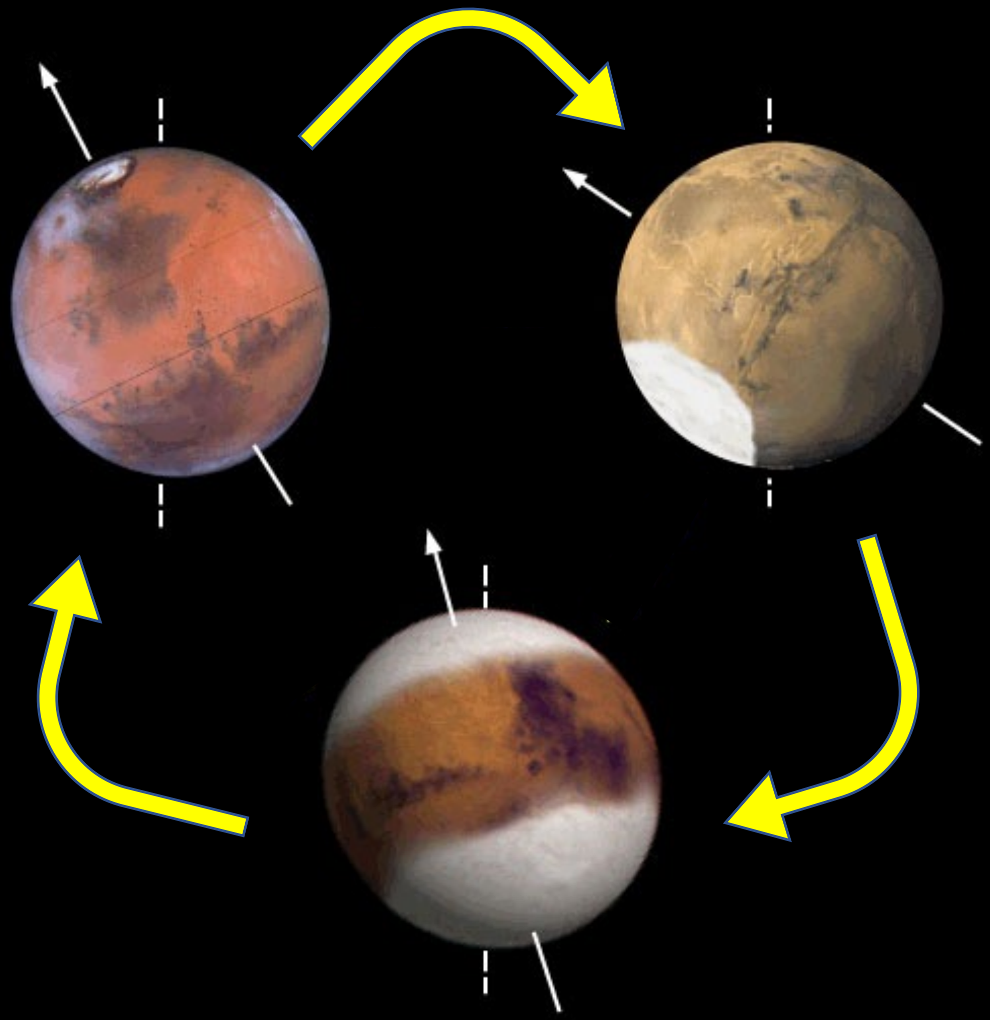
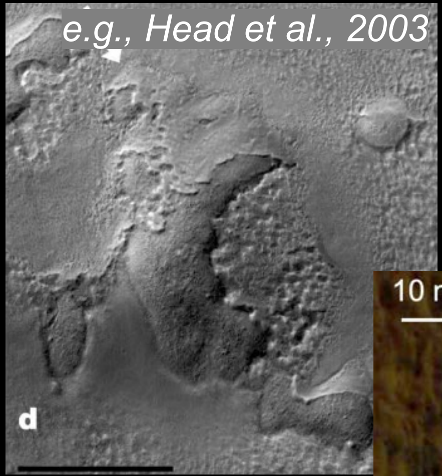
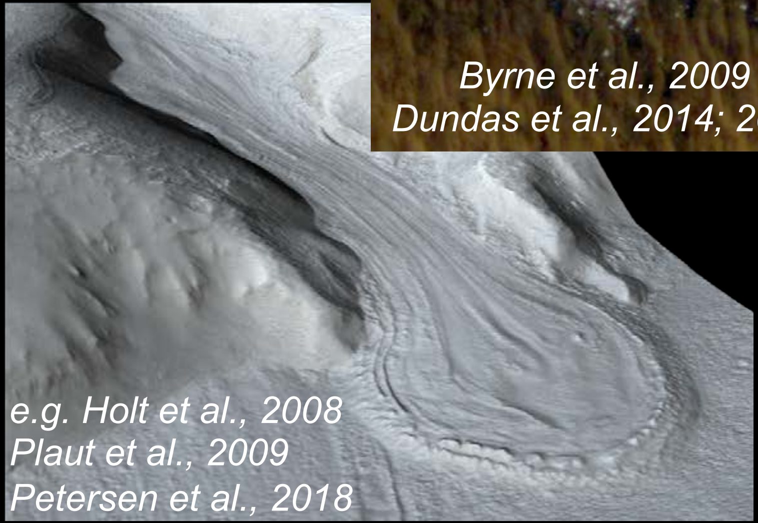


Analogous to Milankovitch cycles on Earth – but more extreme!

Modified from Head et al., 2003

Buried mid-latitude ice records climate processes on multiple spatial and temporal scales.

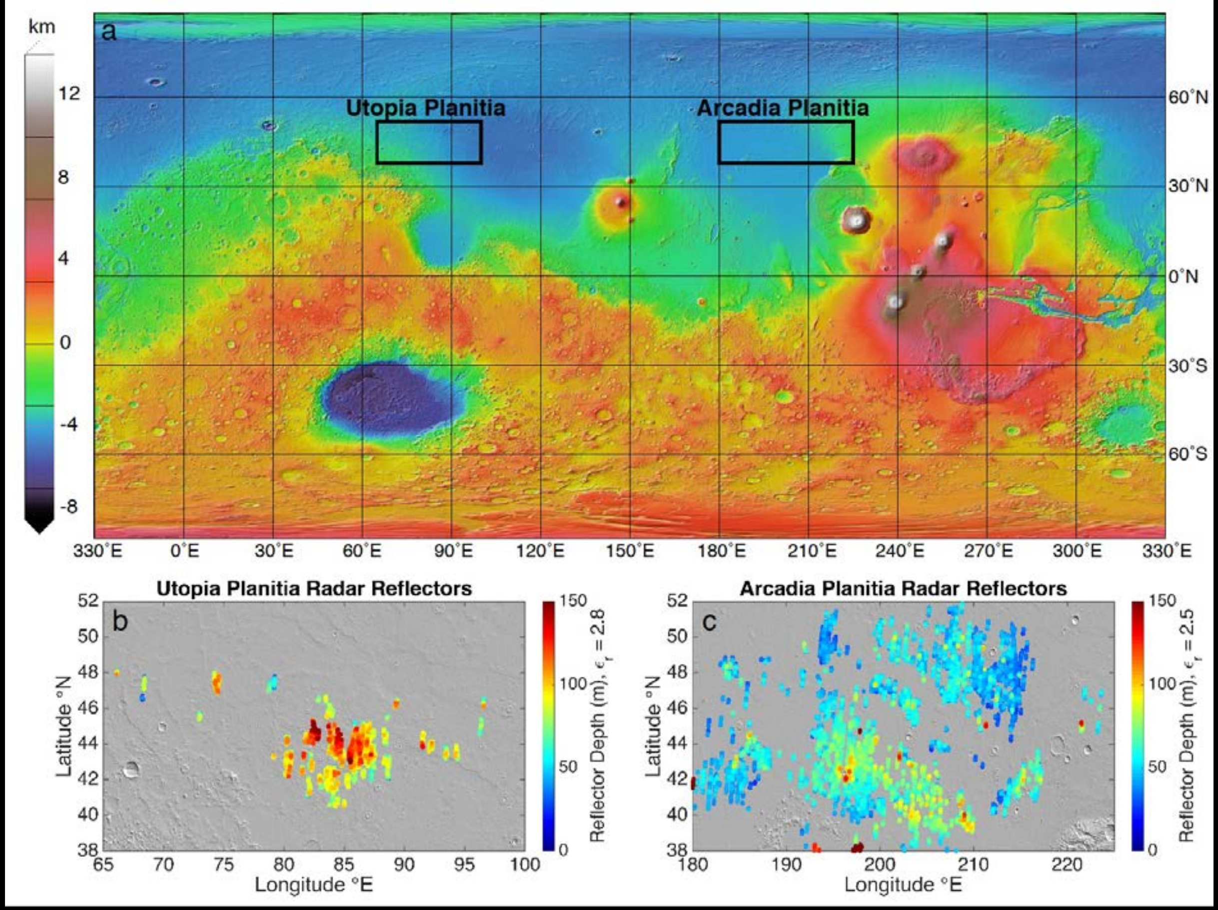




Landform	Age	Volume Estimate	Thickness
Latitude Dependent Mantle	kyr to Myr	10^5 km^3 (1 m GEL) *Head et al., 2003*	Meters
Plains Ice	10s Myr	10^4 km^3 (40 cm GEL Arcadia, 10 cm GRL Utopia) *Bramson et al., 2015; Stuurman et al., 2016*	10s – 100 m
Glacial Landforms	100s Myr	10^5 km^3 (2.6 m GEL) *Levy et al., 2014*	100s m – km

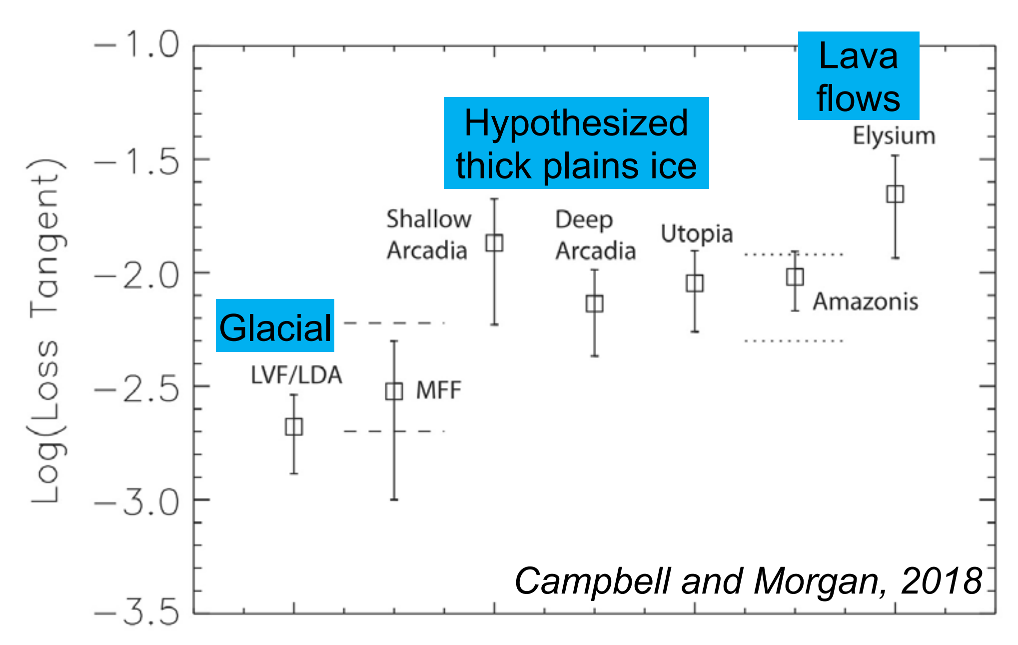
Regional plains ice highly relevant for ISRU and climate studies, but confounding radar evidence.

Low dielectric permittivities (real component) have been proposed to be due to massive ice in subsurface.



Bramson et al., 2017; Bramson et al., 2015; Stuurman et al., 2016

But radar attenuations (imaginary component) are greater than expected for massive ice.



- Recent updates increase real dielectric constant (*Morgan et al., 2021*) in Arcadia. Suggests more lithic content -- Reconciles radar differences? But not geomorphology.
- So how pure and thick is the ice? What is the relationship to shallower pure ice? (Icy cliff sites suggest connected)

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Image Credit: NASA

And ISRU preparation activities intersect with science questions.

Step 1: Characterize ice (resource exploration and prospecting)
- Understand the overburden burying the ice
- Understand the local geologic setting (purity and history of ice)

Step 2: Acquisition of Water Ice
- Rodriguez Well – melt the ice at depth and pump it to the surface
  - Used at the U.S. South Pole Station in Antarctica since 1995
- Mechanically remove (e.g., shovel, jackhammer)
- Controlled explosives to remove debris on top and expose the ice

Step 3: Distribution of water
- Prevent from rapidly boiling away into the atmosphere

Step 4: Purification and processing
- Contaminants (e.g., perchlorates, dust content)

Step 5: Storage and use

Image Credit: NASA

Mellon et al., 2009
Cull et al., 2010

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Image Credit: NASA

Landing sites considered for SpaceX Starship:

Golombek et al. 2021, LPSC

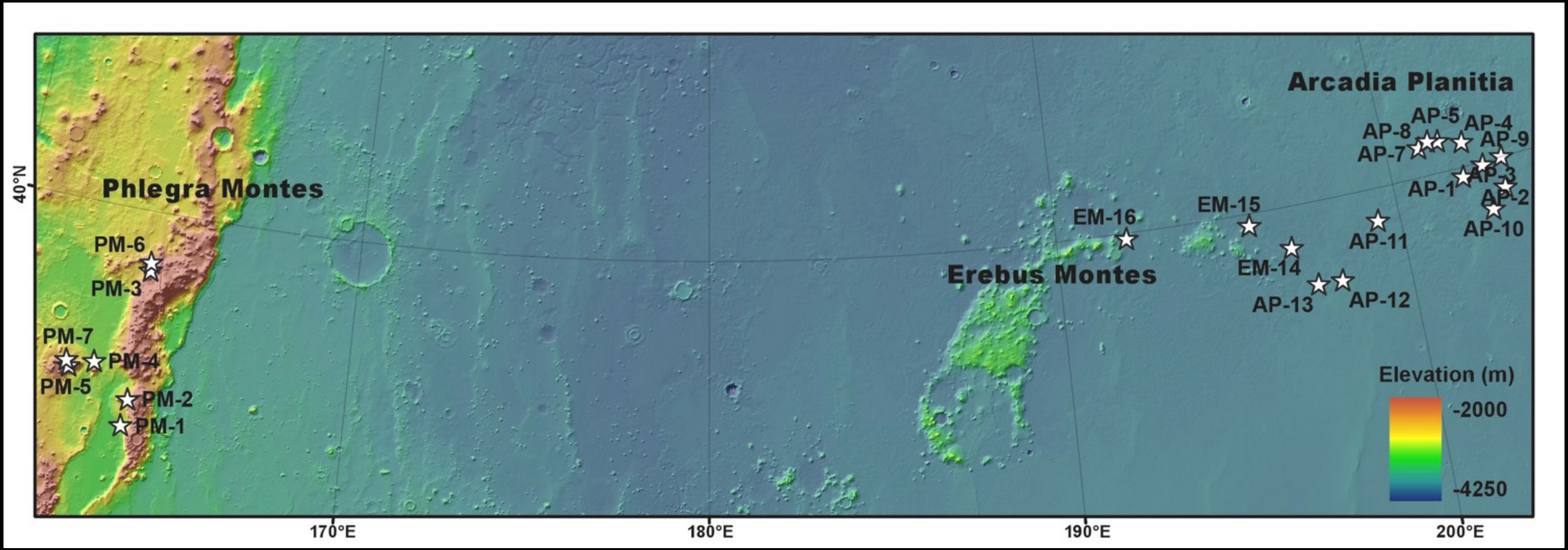
Properties of the prospective landing sites that were evaluated include:

- Elevation (need <-2 km for landing; <-3 km ideal)
- Latitude (≤40° for solar power and thermal management)
- Rocks (<5% chance of impacting a rock greater than 0.5 m high)
- Slopes (<5° over a 10 m length scale)
- Roughness
- Thermal inertia
- Albedo
- Dustiness
- Evidence for ice:
  - Polygons
  - Expanded secondary craters
  - Nearby lobate debris aprons (LDAs)
  - Assessments of subsurface ice based on SWIM results (neutron, thermal, shallow radar, dielectric, and geomorphic analyses)

Landing sites considered for SpaceX Starship:

3 different terrain types with access to different types of ice deposits

Golombek et al. 2021, LPSC



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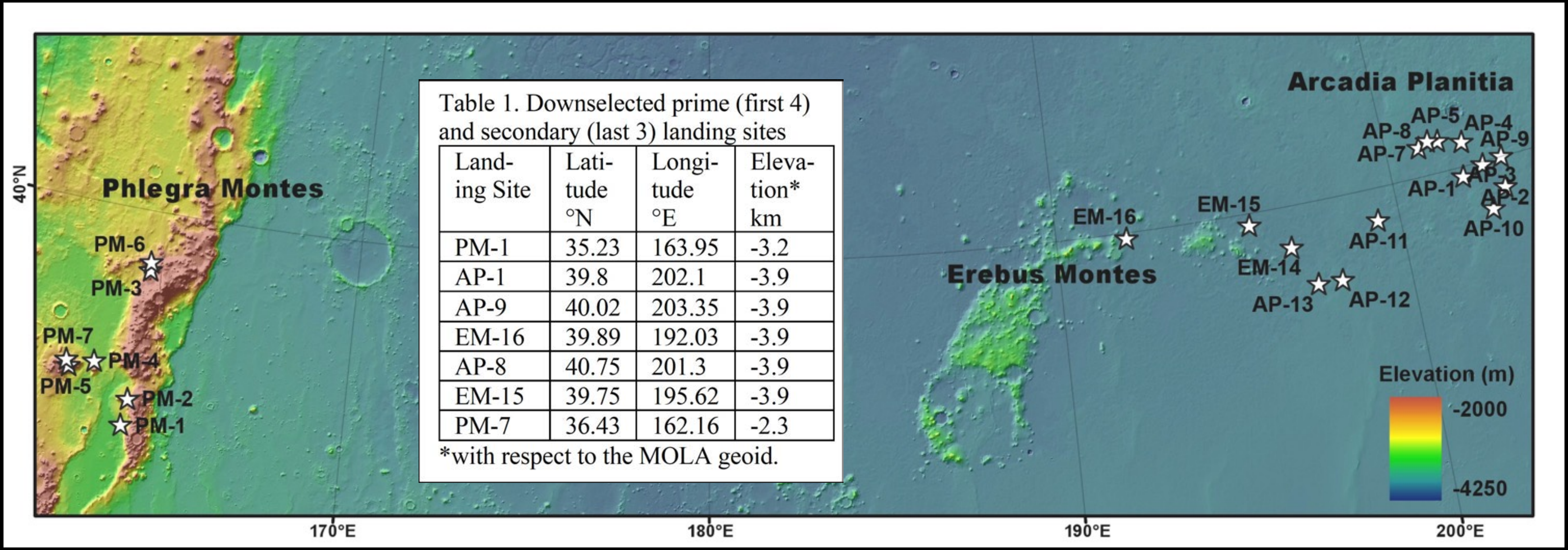


Table 1. Downselected prime (first 4) and secondary (last 3) landing sites

Landing Site	Latitude °N	Longitude °E	Elevation* km
PM-1	35.23	163.95	-3.2
AP-1	39.8	202.1	-3.9
AP-9	40.02	203.35	-3.9
EM-16	39.89	192.03	-3.9
AP-8	40.75	201.3	-3.9
EM-15	39.75	195.62	-3.9
PM-7	36.43	162.16	-2.3

*with respect to the MOLA geoid.

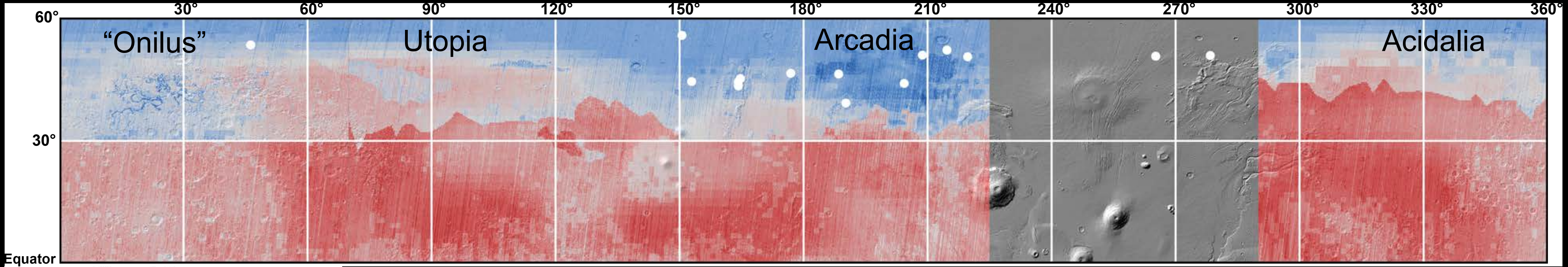
Recent undertaking to characterize Mars' underground ice: The SWIM Project

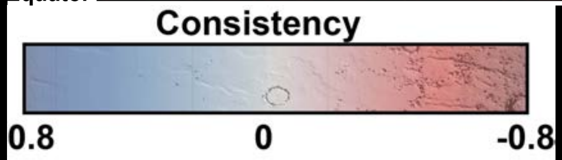
"Subsurface Water Ice Mapping" – see also:

This AGU!

- Putzig et al., Tuesday 1:15pm, NEXT TALK IN THIS SESSION
  P23B-07: Mapping Ice Resources on Mars
- Morgan et al,. Tuesday 1–1:05 pm 10 minutes before this, *Room 398-399*
  EP23C-04: Defining the Equatorial Extent of Subsurface Ice on Mars through Global Geomorphic Mapping

- *Morgan et al., 2021, Nature Astronomy*
- *Putzig et al., "Ice Resource Mapping on Mars" Chapter within Handbook of Space Resources*





- Fresh ice exposing impacts (*Dundas et al., 2014*)

Morgan et al., 2021

High-priority future work needed for the "Mars underground"

- Better orbital characterization of shallow ice deposits, such as radar sounding at shallower scales (<~10 m) than that of MRO SHARAD
- Detailed studies of the engineering required to sustain long-term presence at specific candidate locations
  - Ideally, initial landing sites would be chosen with a long-term vision
  - Characterization of the ice
    - Volumes, impurities, scales of lateral and vertical heterogeneities
  - Characterization of the nature of the overburden above the ice
    - Informs future resource extraction technology development efforts