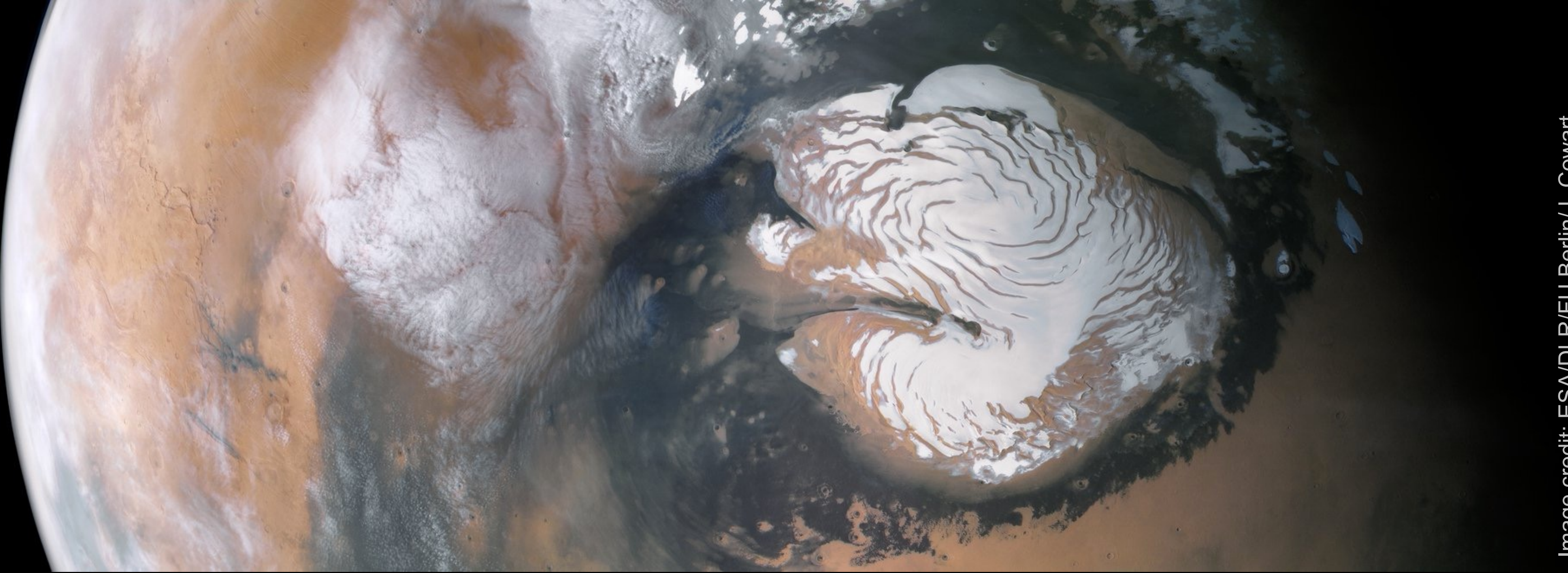


Image credit: ESA/DLR/FU Berlin/J. Cowart

Geophysical observations of ice and climate on Mars

A Short Course Talk for Planetary Geodesy KISS Workshop

Prof. Ali M. Bramson
Purdue University

Earth Atmospheric Planetary Sciences

In this talk:

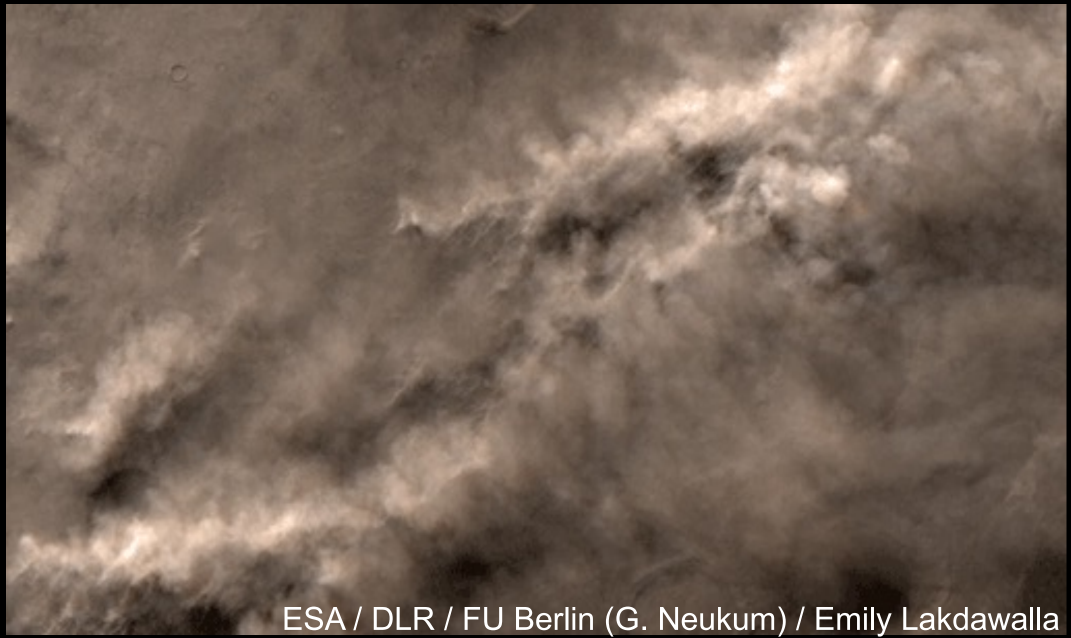
- Primer on Mars climate history
- Gravity, topography, and radar observations of the polar deposits
- Radar observations and the debate on mid-latitude ice
- Prospects for future:
  - static gravity fields to search for ice and elucidate climate history
  - time-variable topography and gravity fields to detect active climate processes

1. Mars Climate History

Present-Day Mars Climate 101

- Mars is a cold, dusty desert
- Temperatures: -225°F to 70°F
- Atmosphere ≤ 1% of Earth's (mostly CO_2)
- Liquid water not stable, but lots of ice!
- Ice is stable at the surface only at the poles
- Dynamic world, with dust storms,
  water and CO_2 clouds and snow and frost

50% further away from the Sun
½ the diameter of Earth
Day = 24.6 hours
Year = 687 days



Mars has 3 main periods of geologic history.

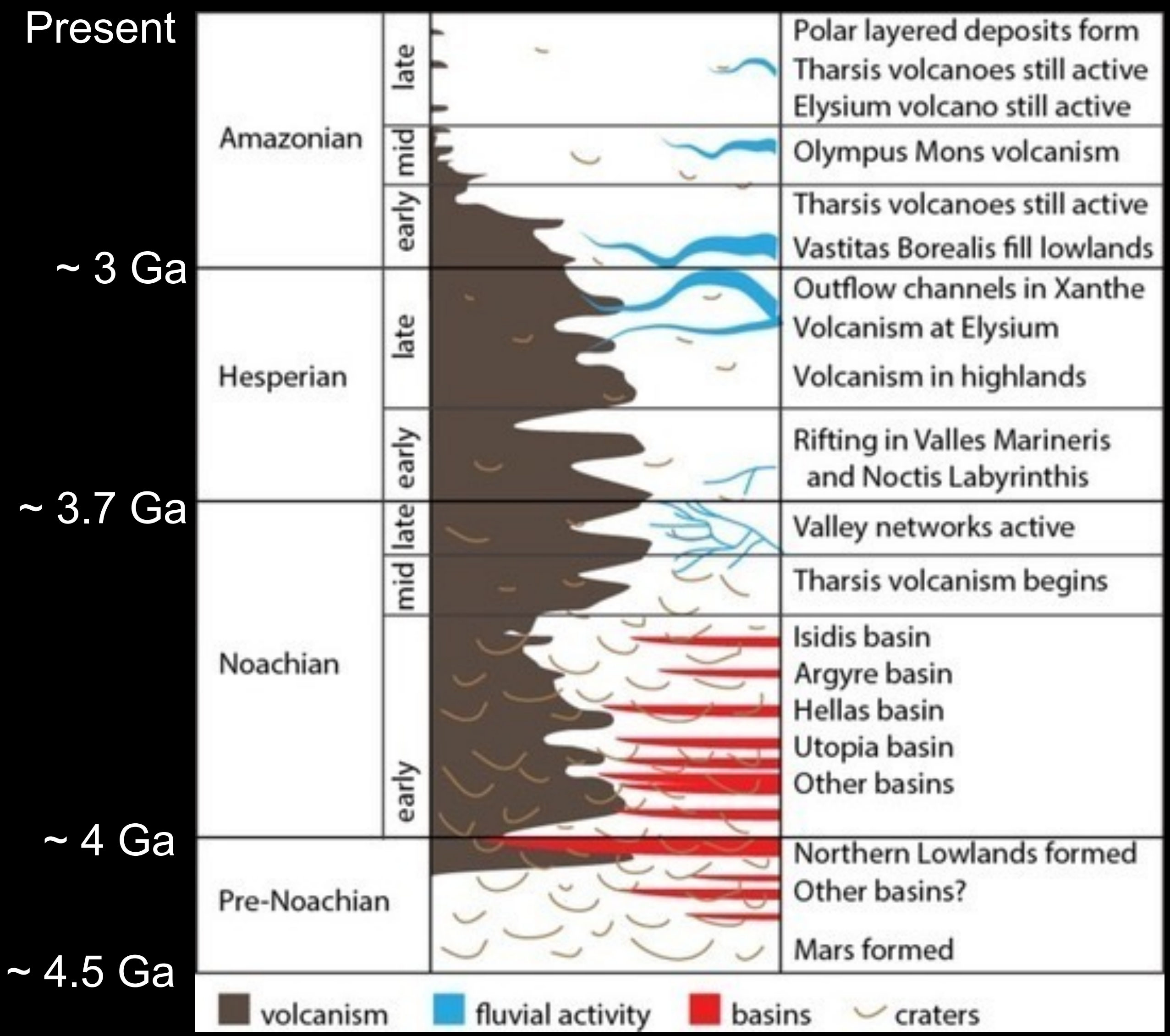


Figure Credit: Emily Lakdawalla after *Tanaka & Hartmann 2012*

The Amazonian:

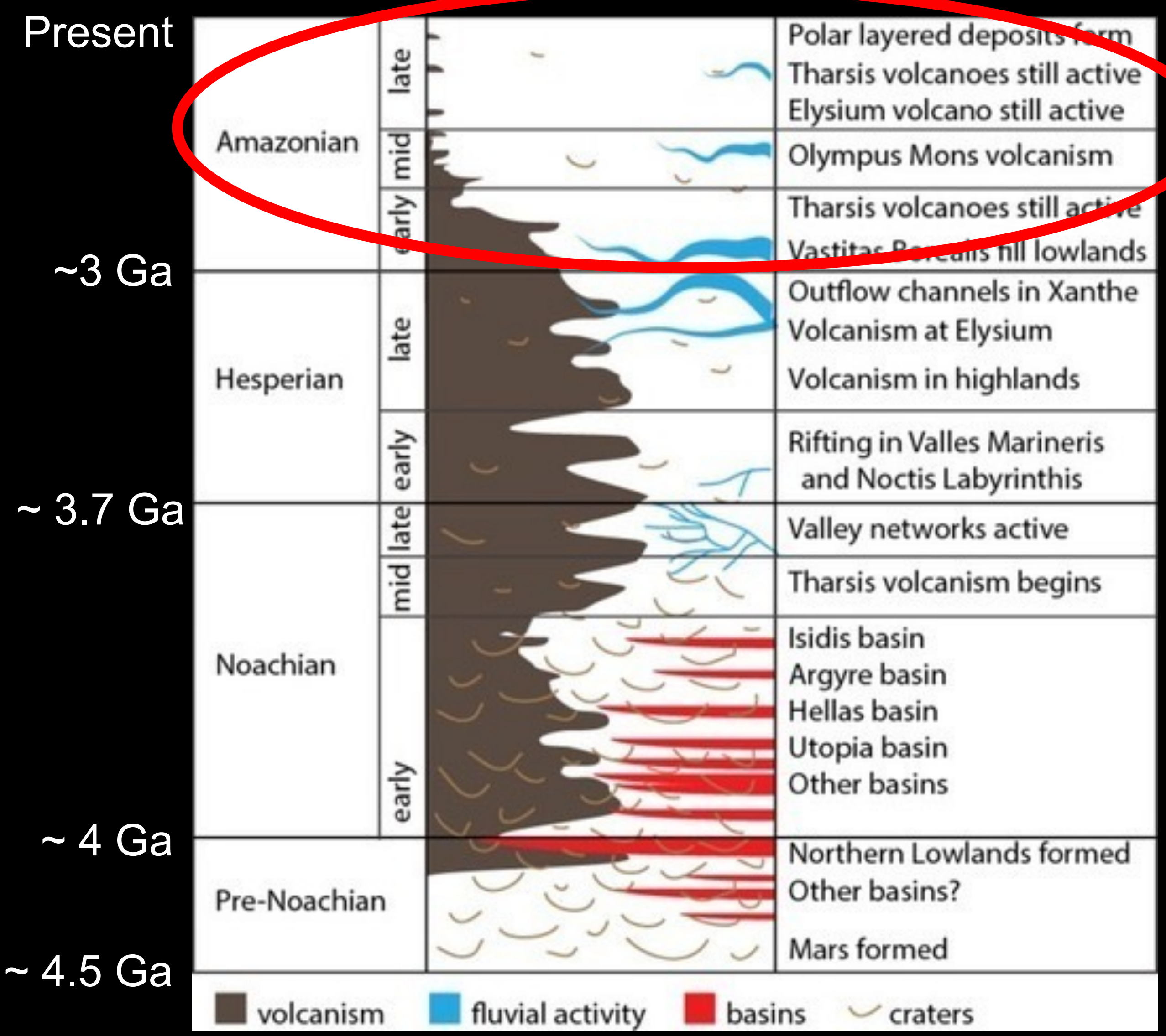


Figure Credit: Emily Lakdawalla after *Tanaka & Hartmann 2012*

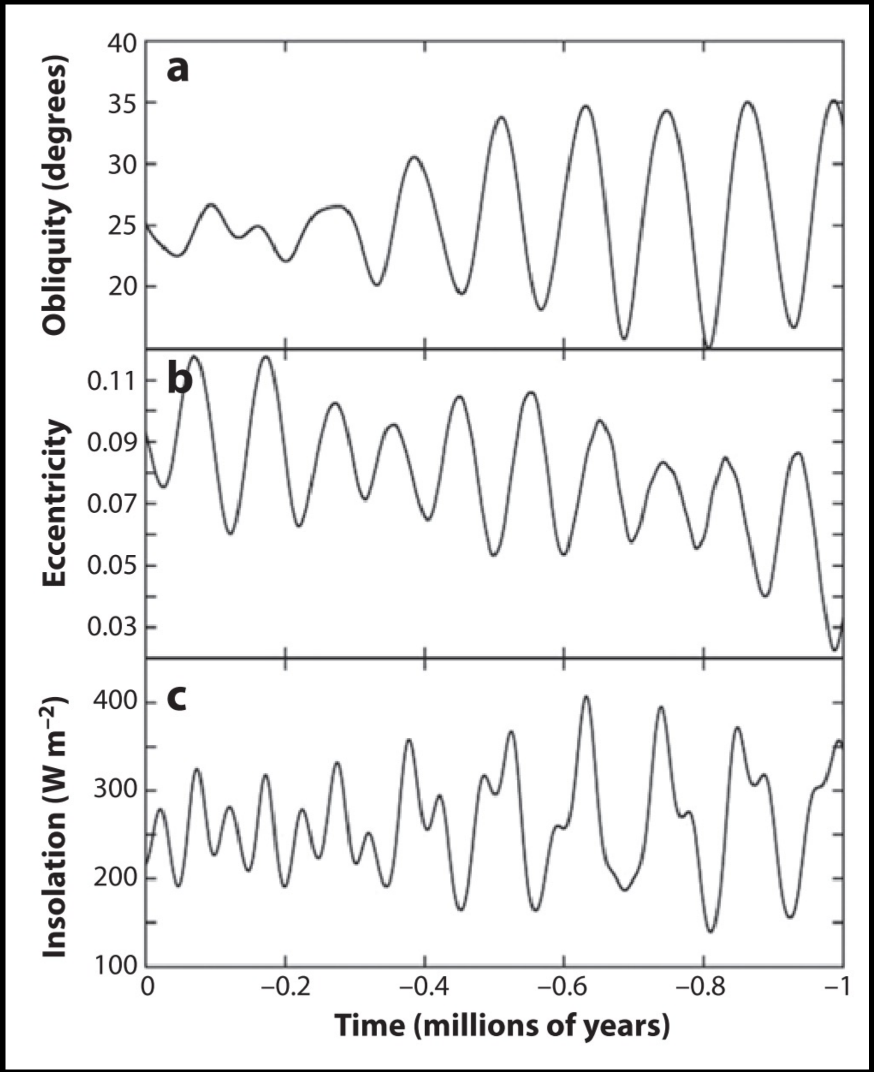
hyperarid
little liquid water?
ice/vapor
processes

Orbital Variations Analogous to Milanković Cycles Drive Mars' Amazonian Climate

Laskar et al. 2004 calculated solutions for ~20 Myr of Mars' history

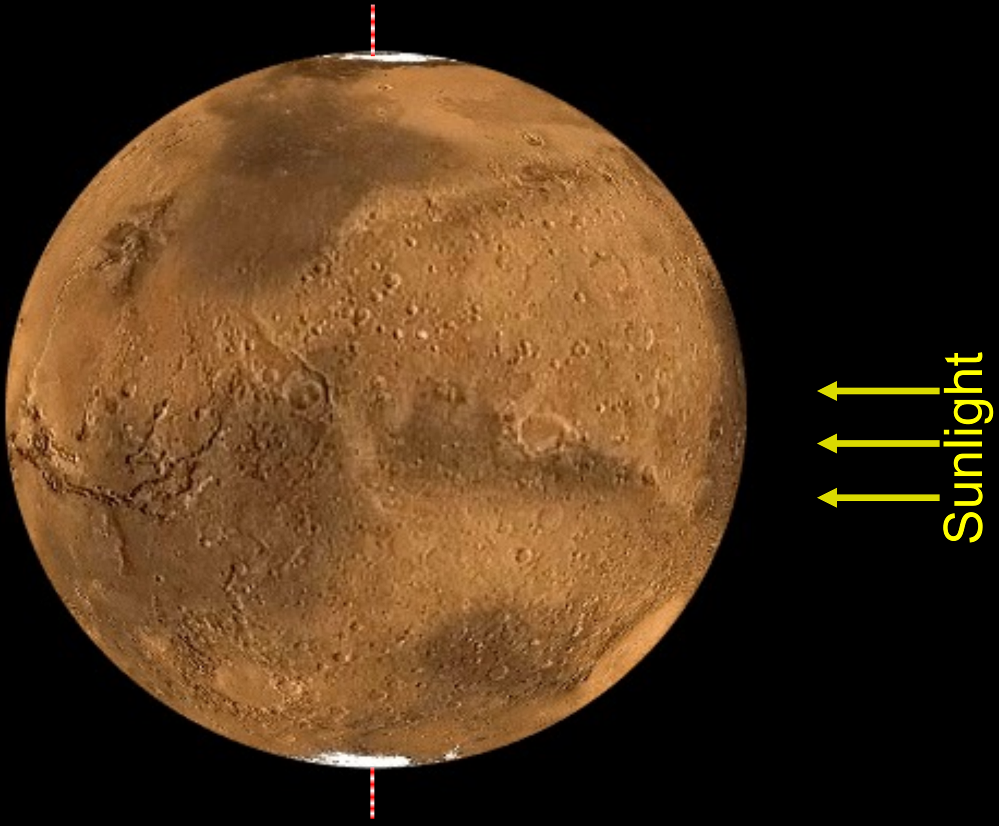
Beyond that solutions are chaotic, but statistically suggest:

- Max obliquity may be as high as 82°
- ~100% chance obliquity >60° in Mars' history

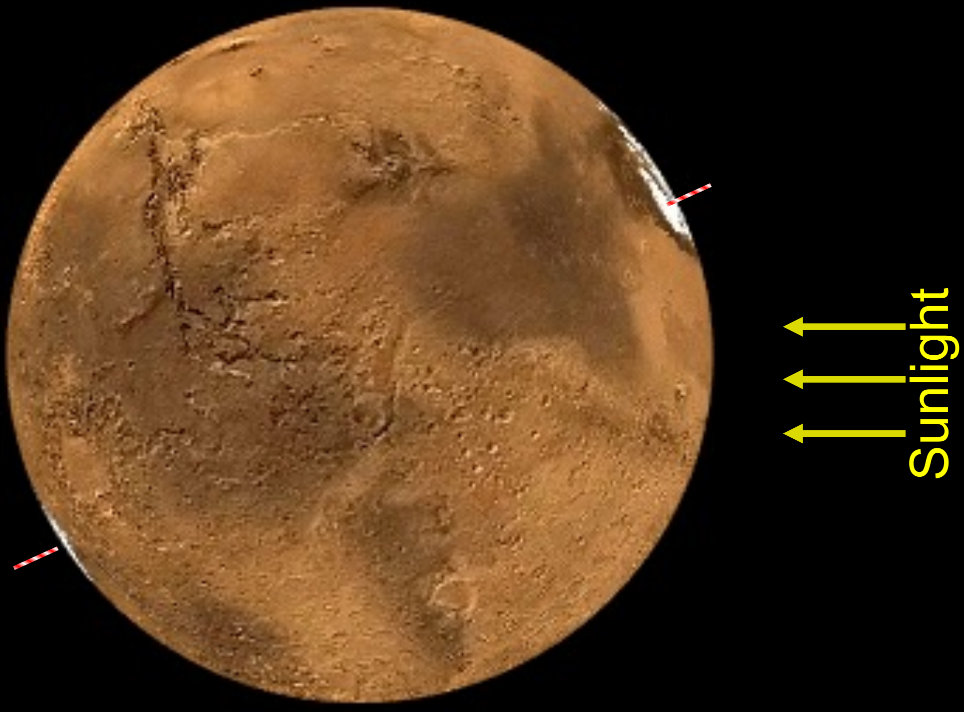


Laskar et al. 2004

Obliquity is extremely important for the distribution of ice/volatiles.

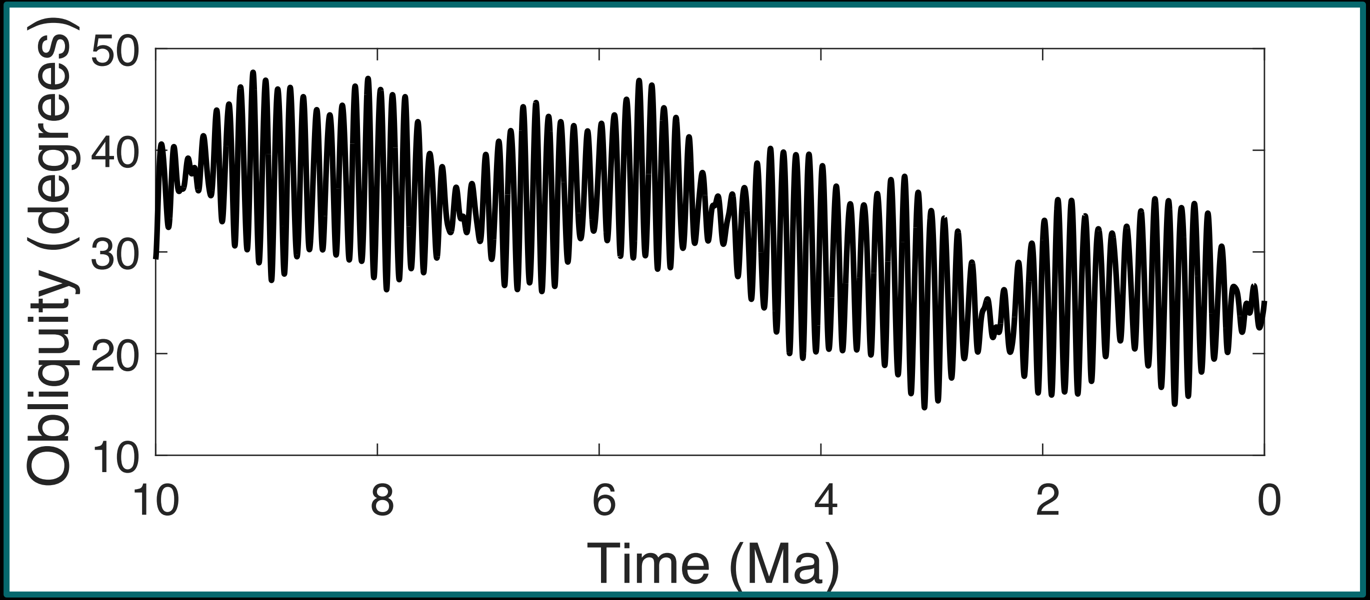


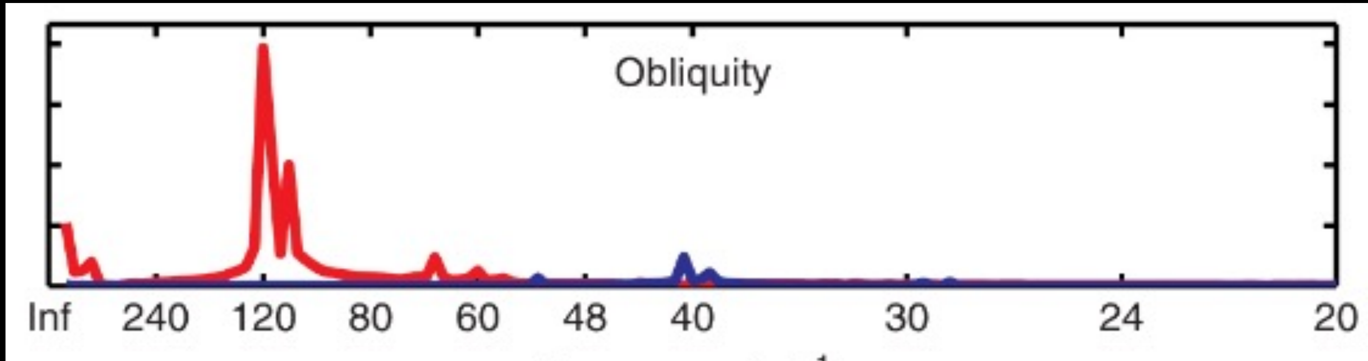
Obliquity = 0°



Obliquity = 60°

Obliquity variations have primary periodicity of 120 kyr.





Schorghofer 2008

Obliquity:

- 120,000 years

Argument of perihelion:

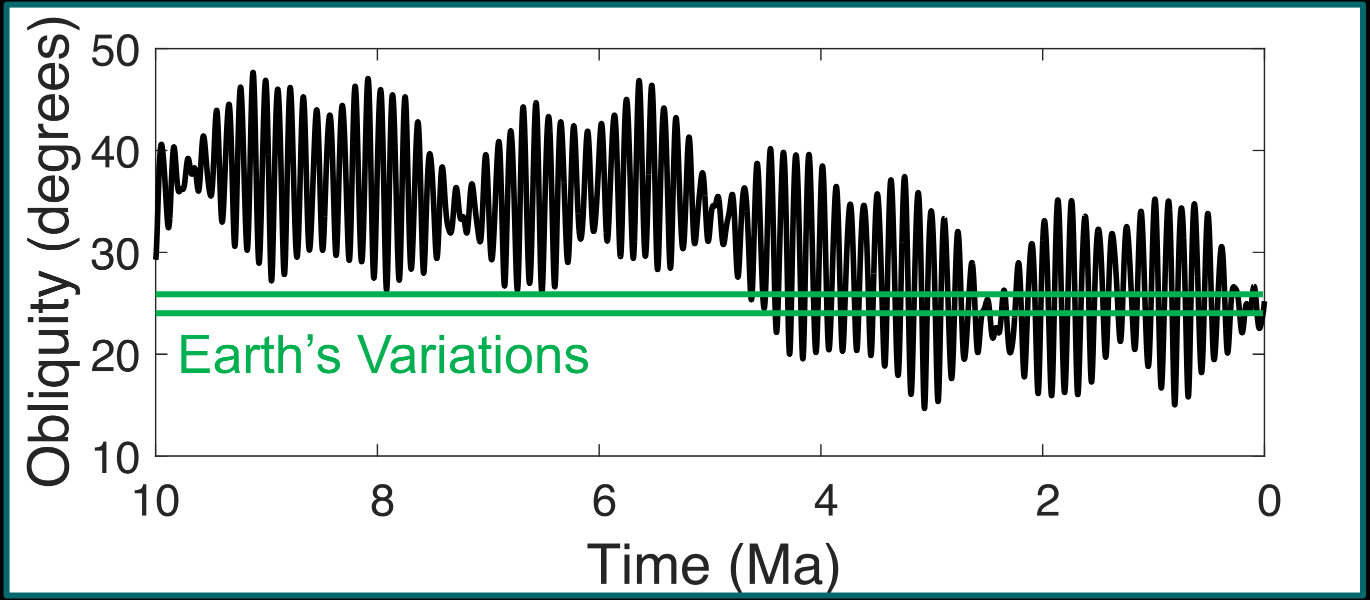
- 51,000 years

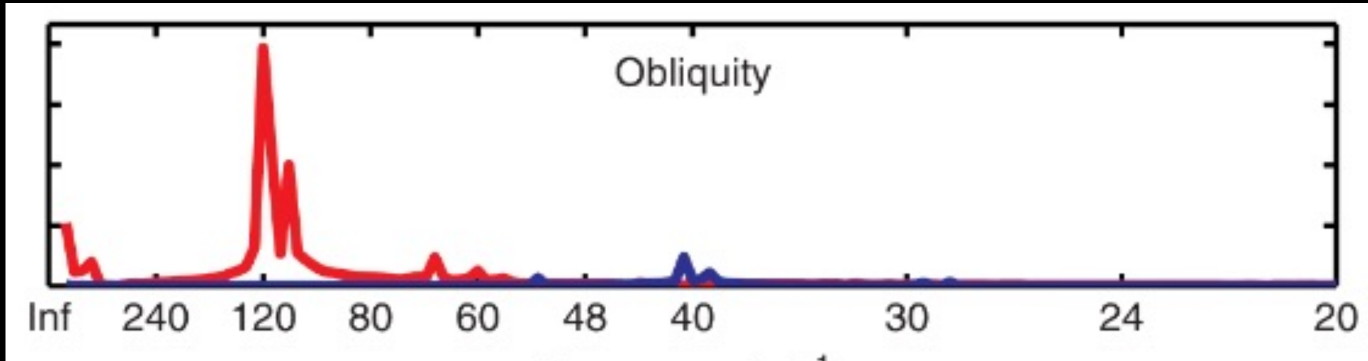
Eccentricity:

- 95,000 – 99,000 years
- and 2.4 Myr

Laskar et al. 2004

Obliquity variations have primary periodicity of 120 kyr.

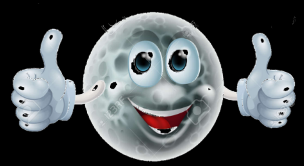




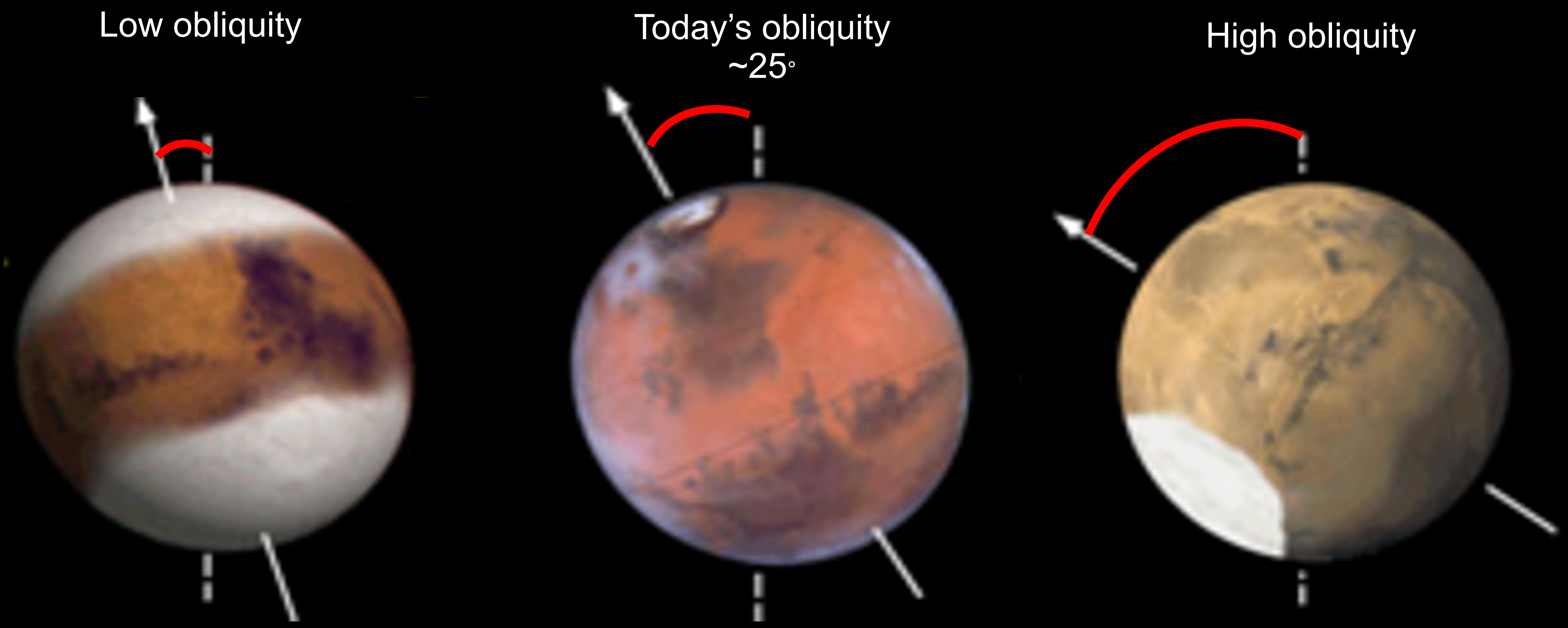
Schorghofer 2008

Note the amplitude of Mars' obliquity variations compared to Earth!

Thanks, Moon.



Ice Stability Mainly Controlled by Obliquity

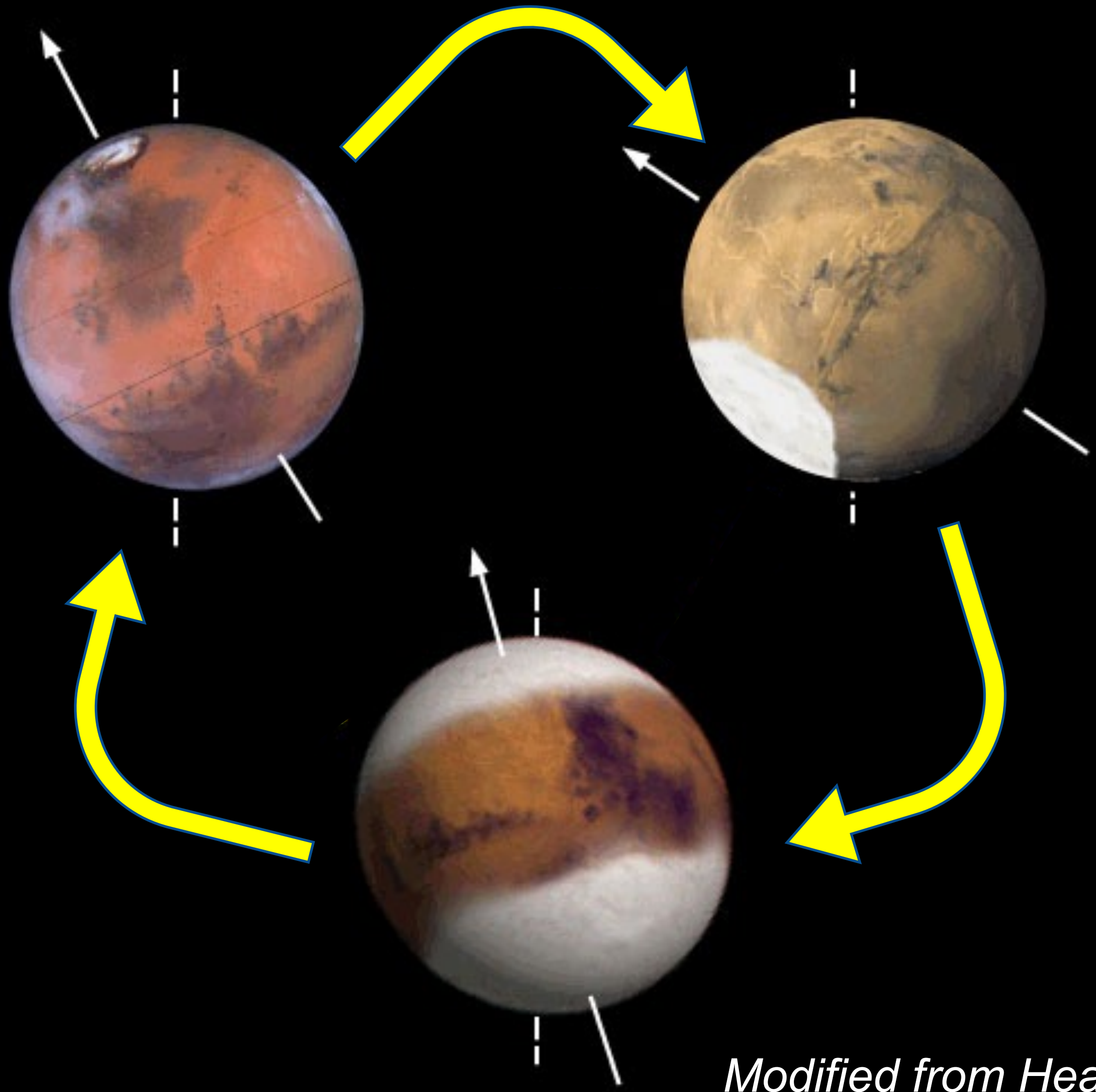


e.g. Laskar et al. 2002; Head et al. 2003

Ice Stability Mainly Controlled by Obliquity

Mars is an excellent laboratory for how orbital forcing affects planetary climates!

- Amplified forcing
- No oceans, humans, etc.

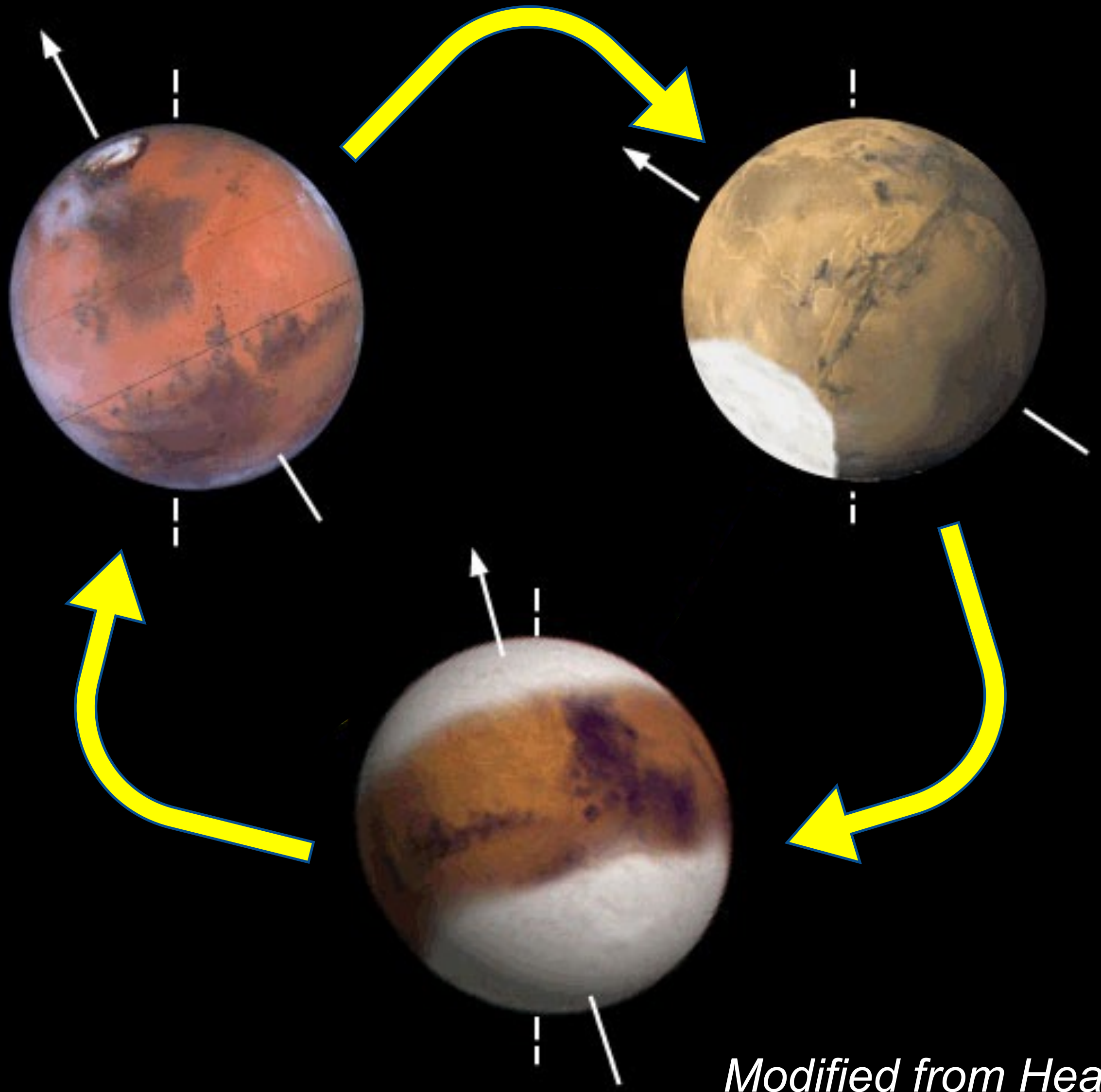


Modified from Head et al. 2003

Ice Stability Mainly Controlled by Obliquity

Mars is an excellent laboratory for how orbital forcing affects planetary climates!

Need to know where the ice is and characterize its properties.



Modified from Head et al. 2003

2. Gravity, topography, and radar observations of the polar deposits

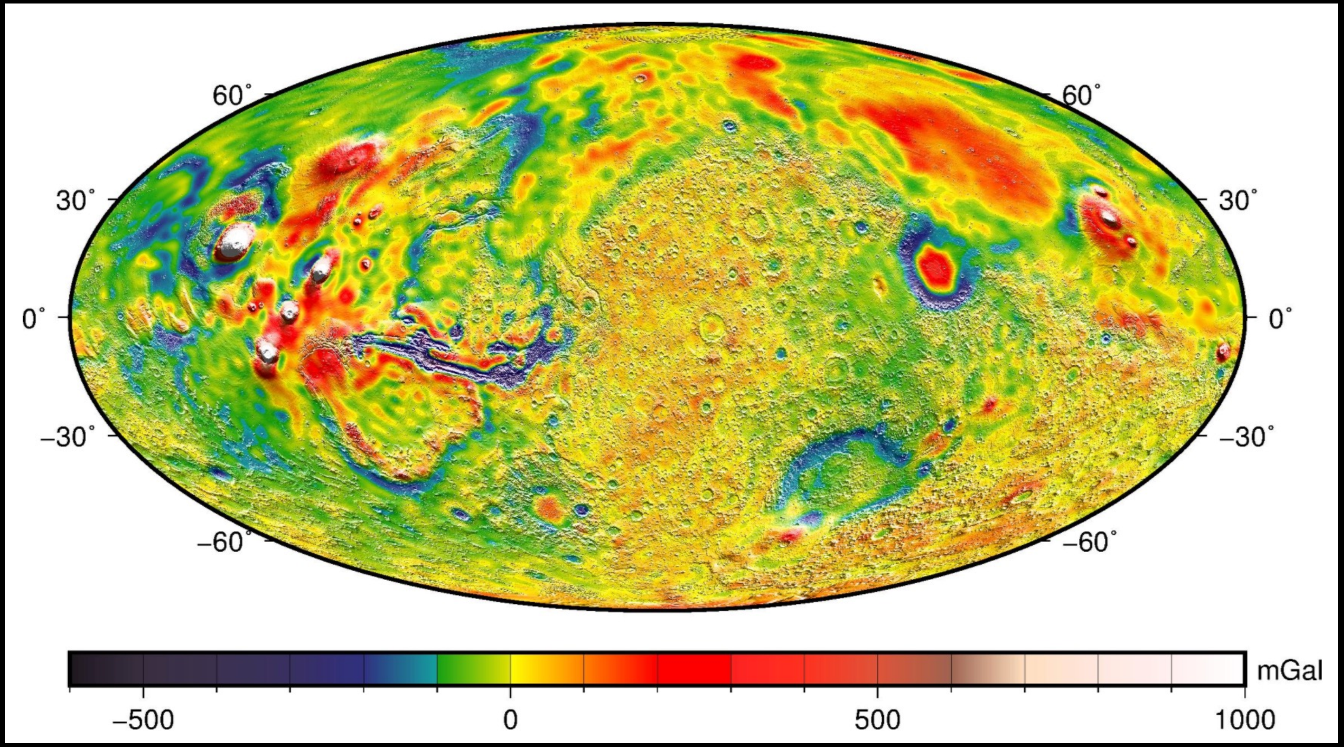
Key instruments for Mars' gravity, topography, and radar observations:

Radio tracking by the Deep Space Network of

- Mars Global Surveyor (MGS)
  Smith et al. 1999
- Mars Odyssey (ODY)
  Konopliv et al. 2006; Marty et al. 2009
- Mars Reconnaissance Orbiter (MRO)
  Zuber et al. 2007

Goddard Mars Model-3 (GMM-3)

- static gravity field of Mars in spherical harmonics to degree and order 120
  Genova et al. 2016



GMM-3 free-air gravity anomaly map
Genova et al. 2016

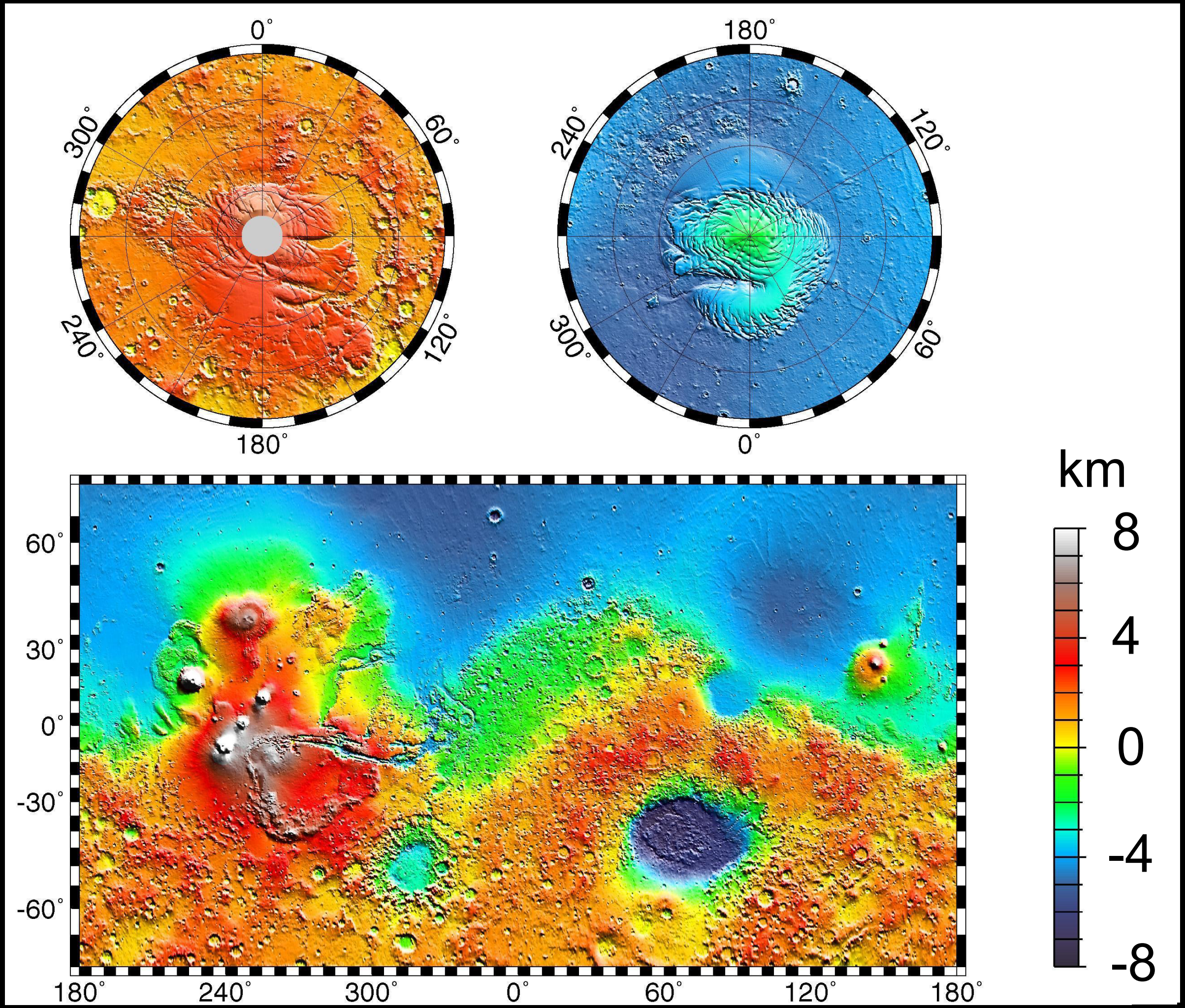
Key instruments for Mars' gravity, topography, and radar observations:

Mars Orbiter Laser Altimeter (MOLA)

Smith et al. 2001

- Onboard Mars Global Surveyor
- Collected over 600 million altimetry measurements
  - Precision of range measurements: 10s of cm (smooth, level surfaces) to meters (sloped surfaces)

Elevation map horizontal resolution: 463 m/pixel or better

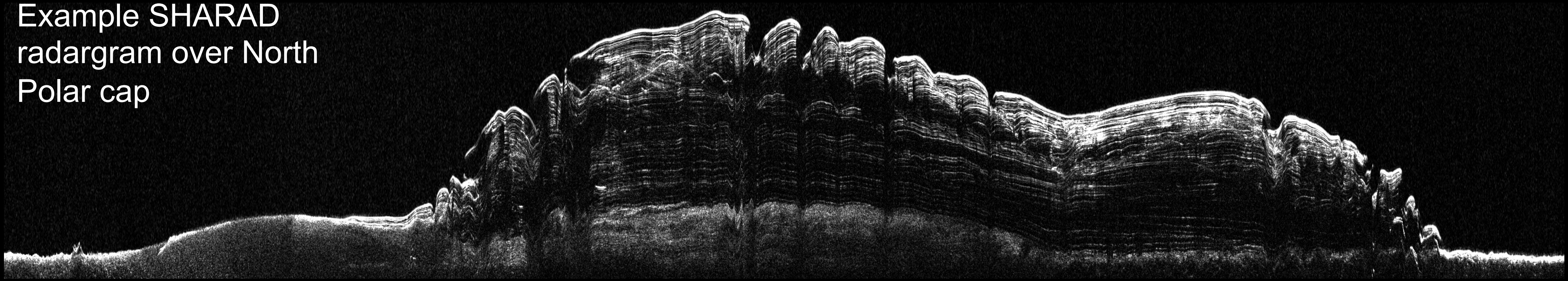


Smith et al. 2001

Key instruments for Mars' gravity, topography, and radar observations:

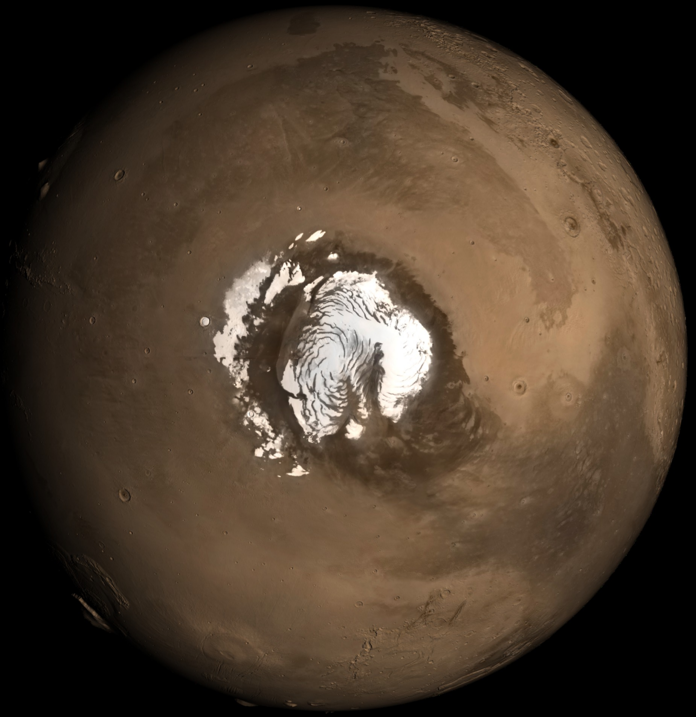
	SHARAD	MARSIS
Spacecraft Onboard	Mars Reconnaissance Orbiter	Mars Express
Center Frequency	20 MHz	1.8, 3.0, 4.0 and 5.0 MHz
Bandwidth	10 MHz	1 MHz
Vertical resolution, in free space	15 m moderate penetration depth	150 m deep penetration depth
Horizontal resolution (along track)	0.3–1 km	5–10 km
Horizontal resolution (cross track)	3–6 km	10–30 km
	Seu et al. 2007	*Picardi et al. 2005*

Example SHARAD radargram over North Polar cap

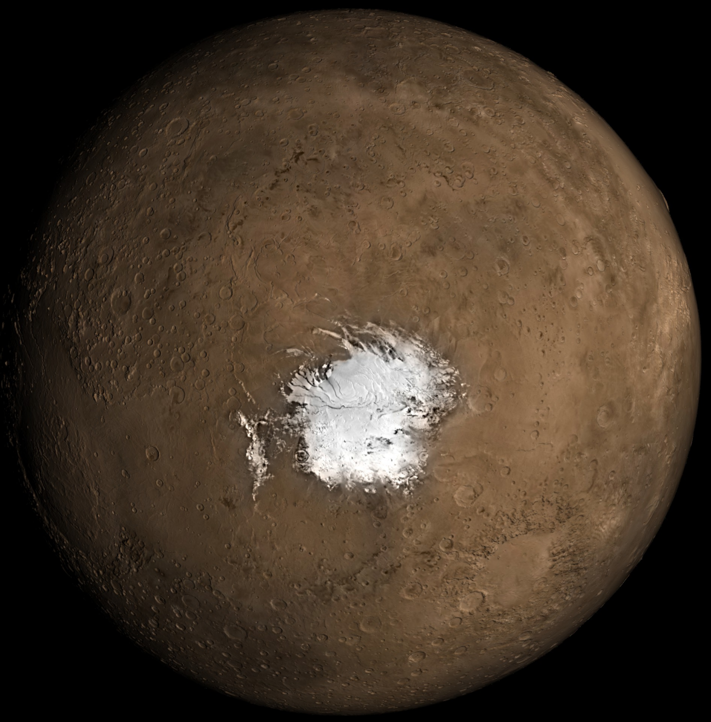


Mars’ poles have kilometers-thick ice caps.

- Each roughly dome-shaped, ~1000 km across, 3–4 km topographic relief compared to surroundings (from MOLA data)
- Total volume of ice similar to Greenland on Earth
- Are a record of processes on multiple spatial and temporal scales



North



South

Image Credit: NASA/GSFC Scientific Visualization Studio

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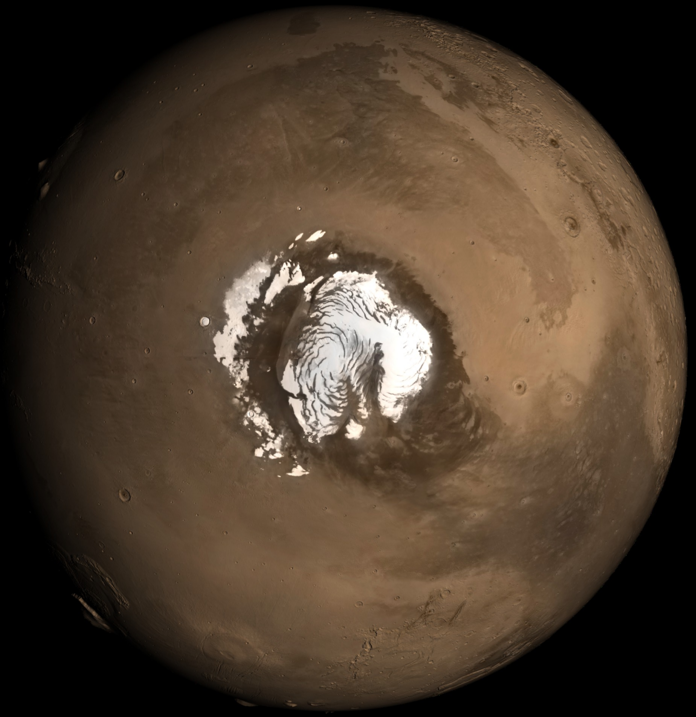
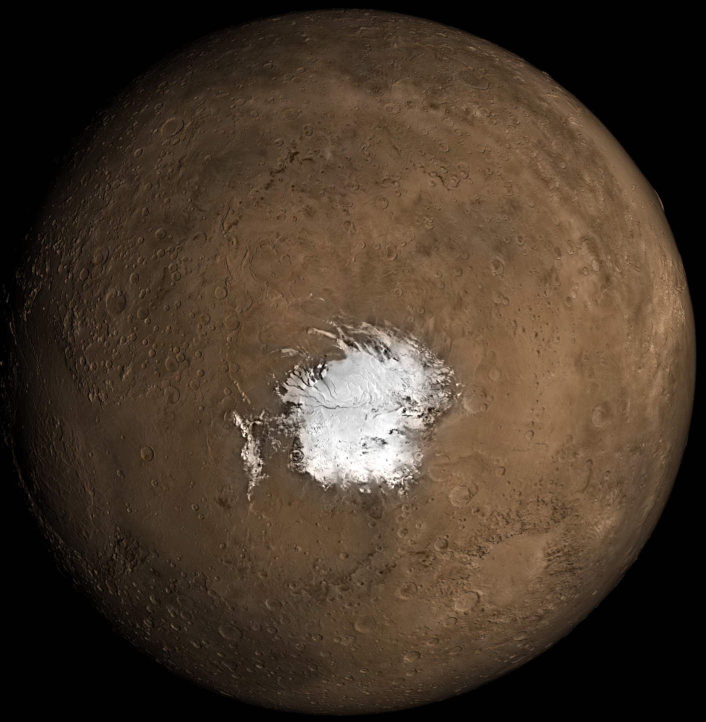


North



South

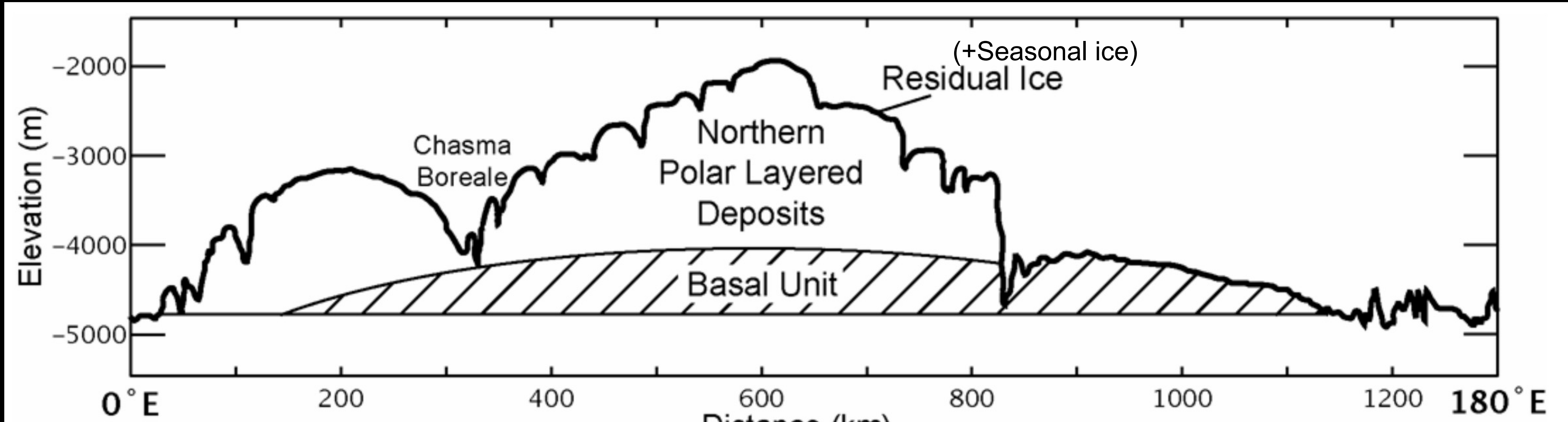
Image Credit: NASA/GSFC Scientific Visualization Studio

Mars' poles have kilometers-thick ice caps.

- Are a record of processes on multiple spatial and temporal scales

Seasonal ice cap
Residual ice cap
Polar layered deposits
Basal unit
Underlying/Surrounding Terrain

Youngest
Oldest

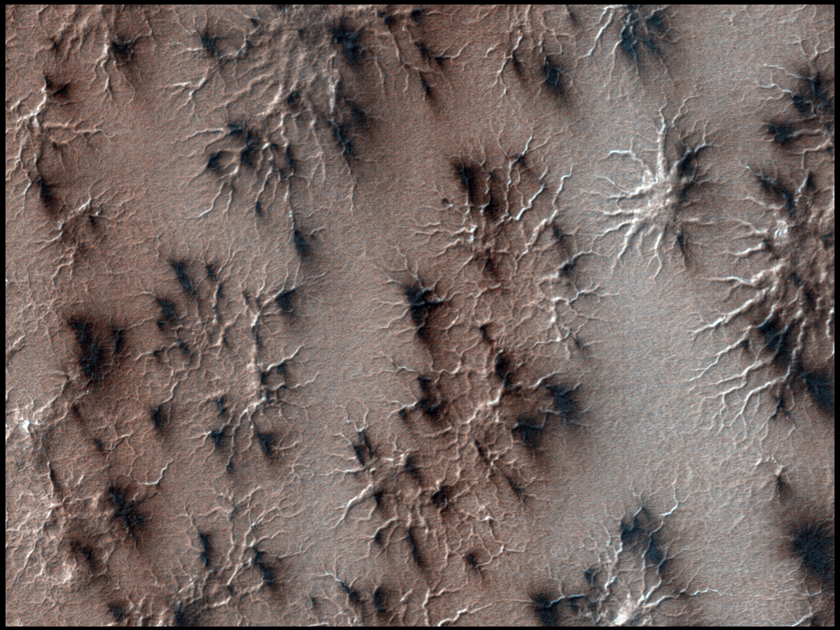


Milkovitch and Head 2006

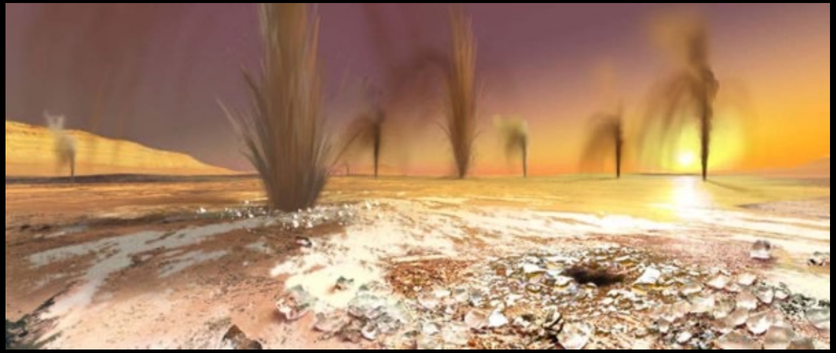
Seasonal ice caps: Up to ⅓ of the atmosphere condenses out in winter.

- Seasonally deposited dusty, porous CO_2 ice
  - In the North, also an annulus of water frost
- Sinters into transparent solid CO_2 slab
- In Spring (particularly in the South):
  - Bottom of slab heats up
  - Sublimates → Pressurized CO_2 jets
  - Fans of dust
  - Radial channels called araneiforms ("spiders")

e.g. Kieffer et al. 2006



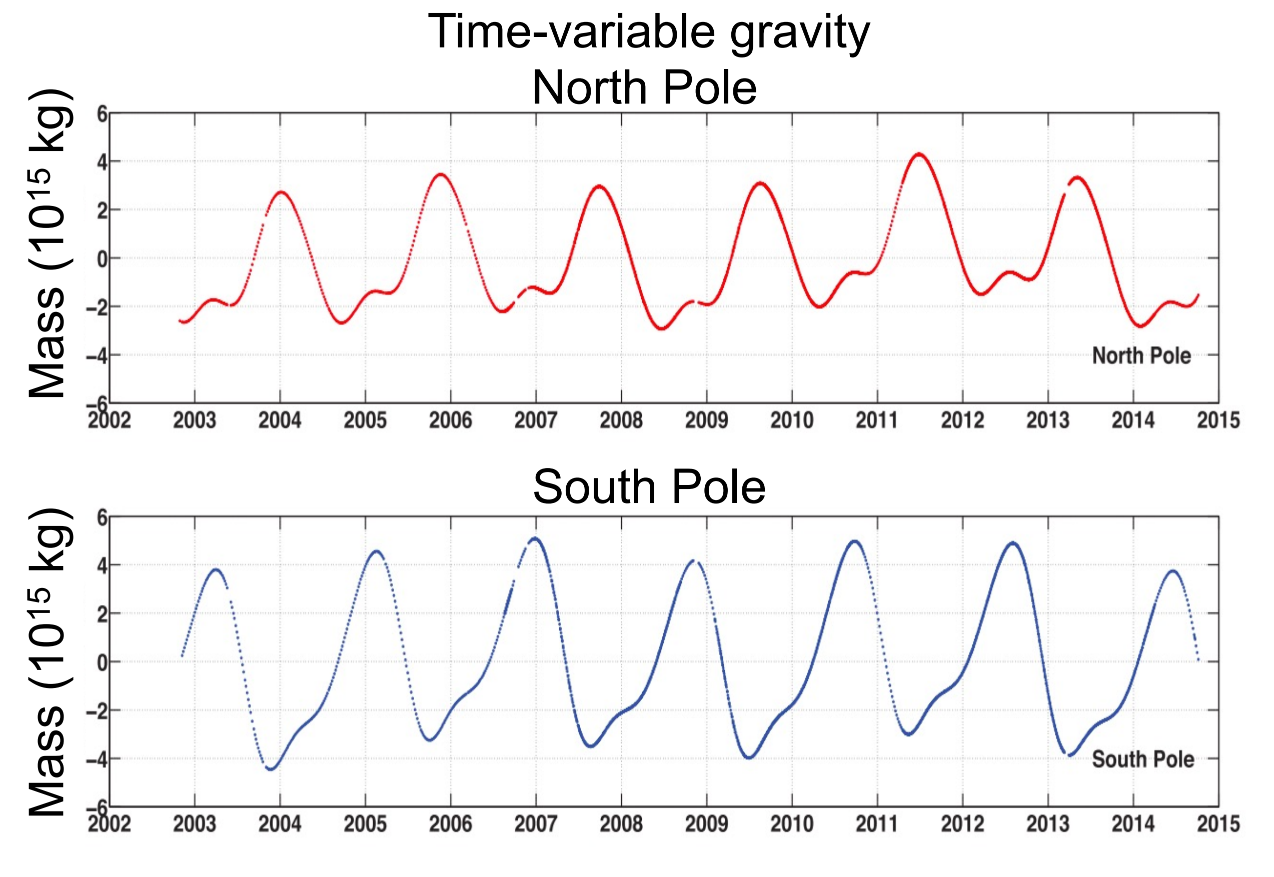
HiRISE image of Southern "spiders"



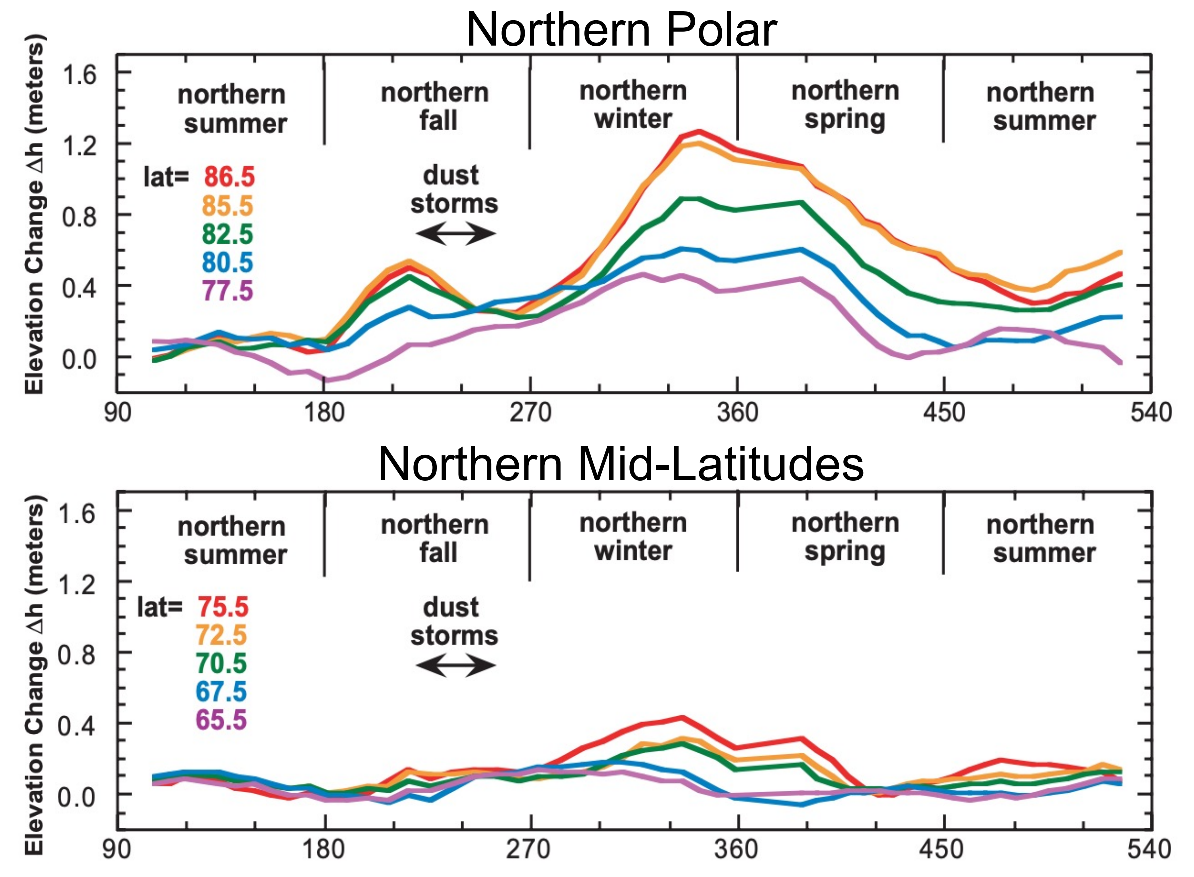
Artist's conception of seasonal CO_2 jets
Image Credit: Ron Miller/ASU

Seasonal changes in gravity combined with MOLA elevation changes constrain bulk density of seasonal CO_2 to 910 ± 230 kg/m^3.

Gravity detects seasonal changes



MOLA topography detects seasonal changes



Genova et al. 2016

Smith et al. 2001

Northern residual ice cap: meters-thick water ice

- Water ice of large ice grains
  - Indicate old ice is being exposed in summer, undergoing net loss

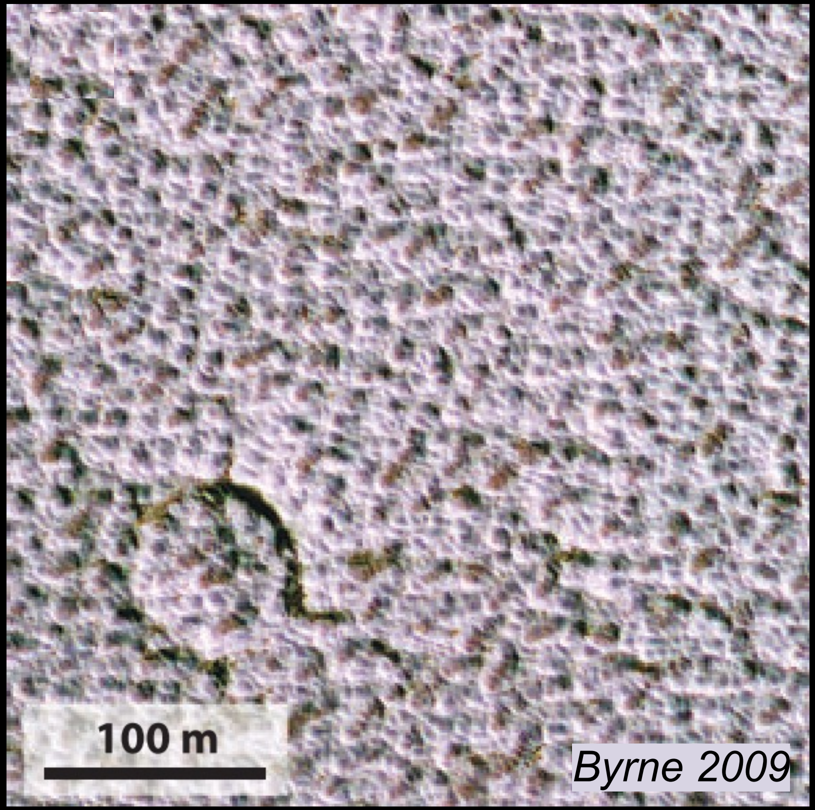
  Langevin et al. 2005

- ...But other areas retain seasonal frost and are accumulating
- Temporally and spatially variable

  e.g. Calvin & Titus 2008

- Very young surface age (kyr)

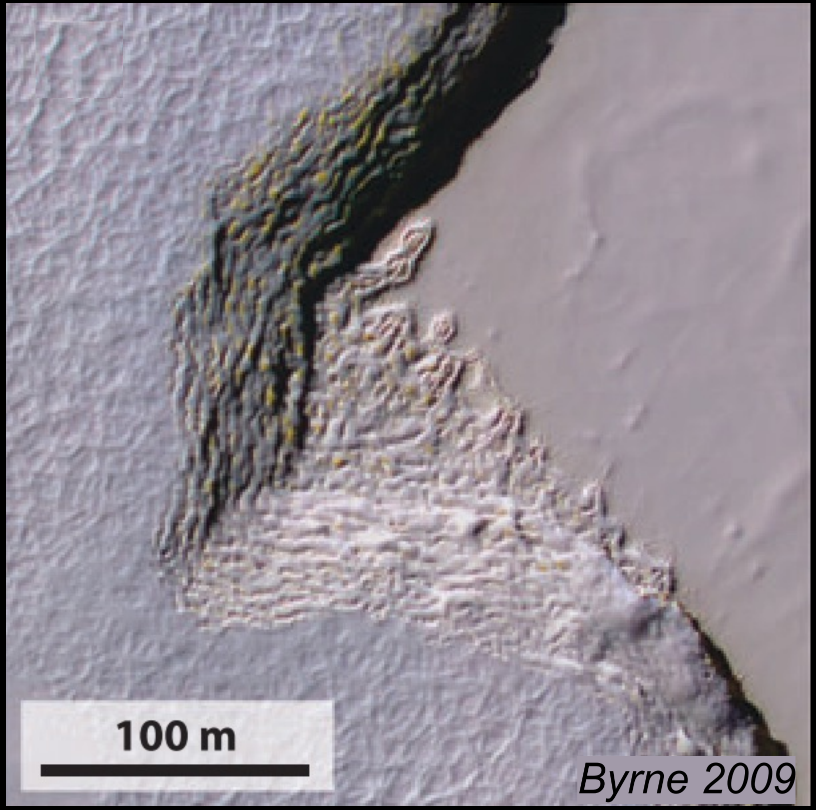
  e.g. Landis et al. 2016, Wilcoski & Hayne 2021



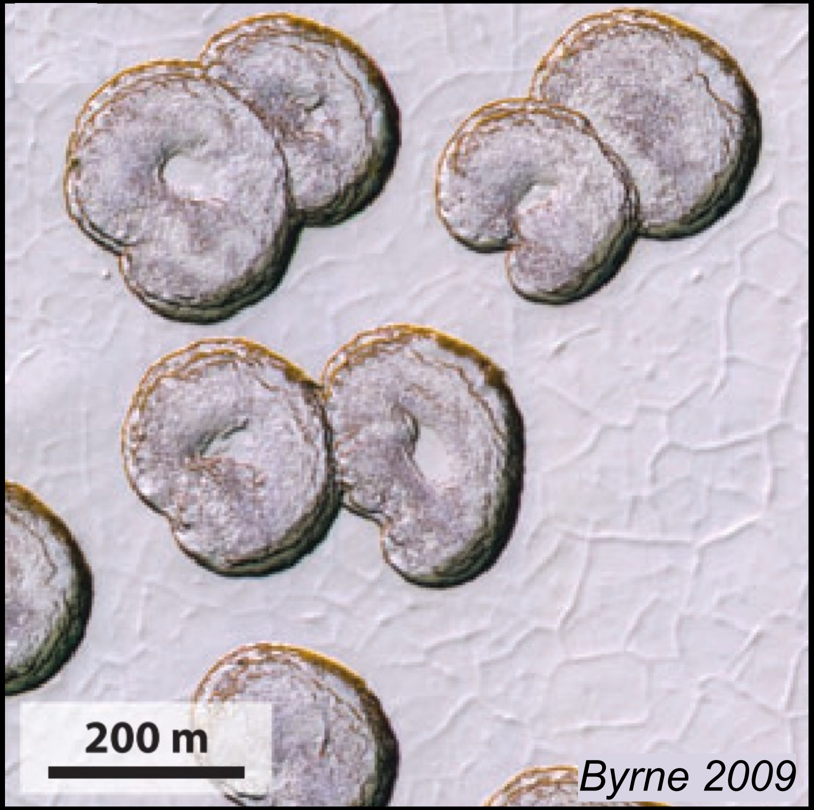
Typical surface texture of North residual cap

Southern residual ice cap: meters-thick CO_2 ice slab

- Layers indicate deposited in discrete events
- Pits and surface texture show active erosion
- …But annual mass balance unknown (evidence of both accumulation and ablation)
    - Cycling of the cap proposed to occur in 10s–100s years *(e.g. Thomas et al. 2016)*



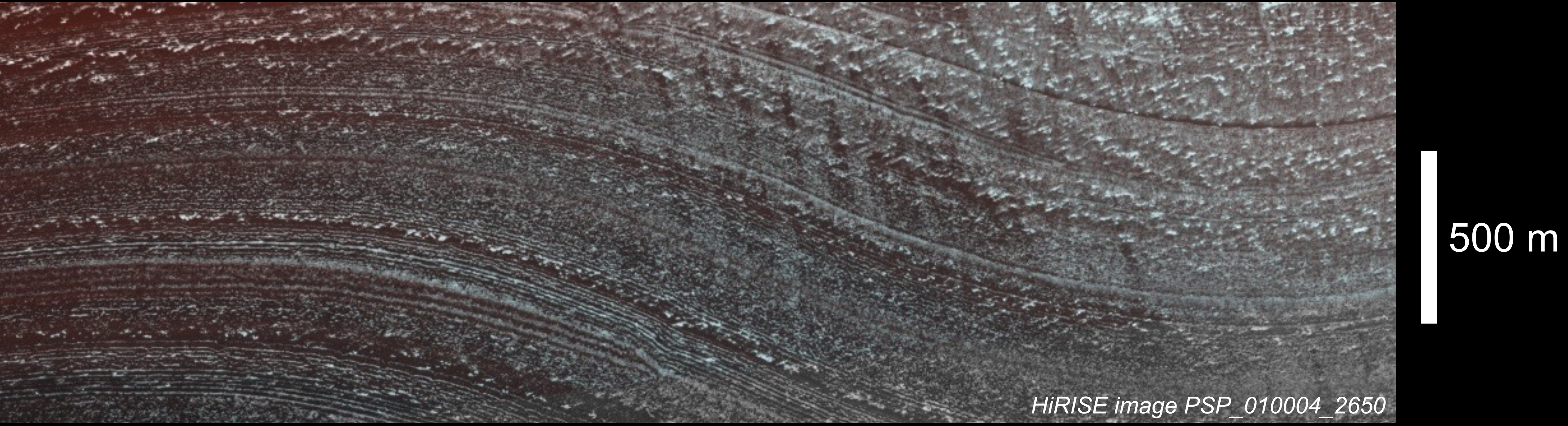
Layering in the residual cap



"Swiss cheese" ablation pits

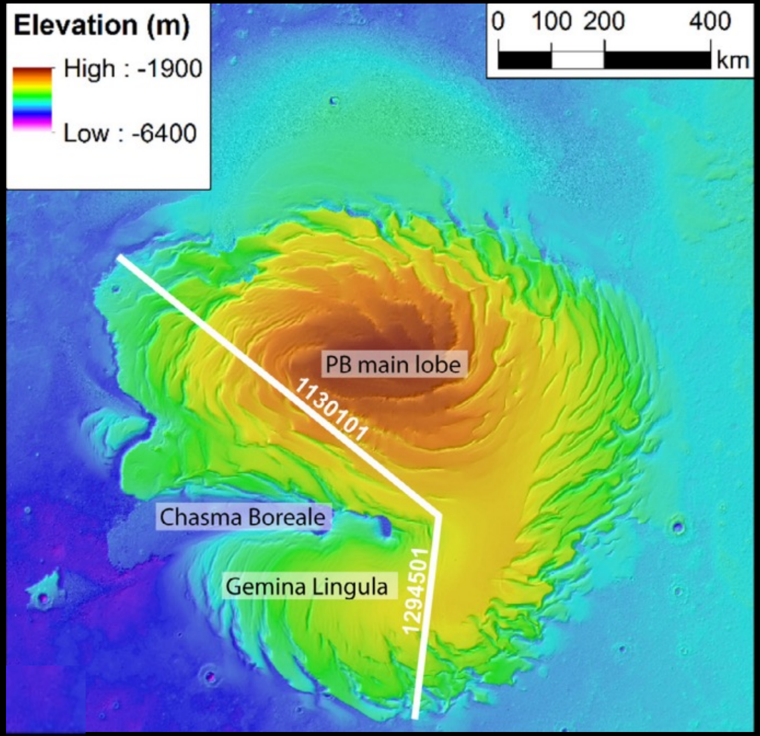
Polar Layered Deposits (PLD): kilometers-thick deposit of water/dust layers

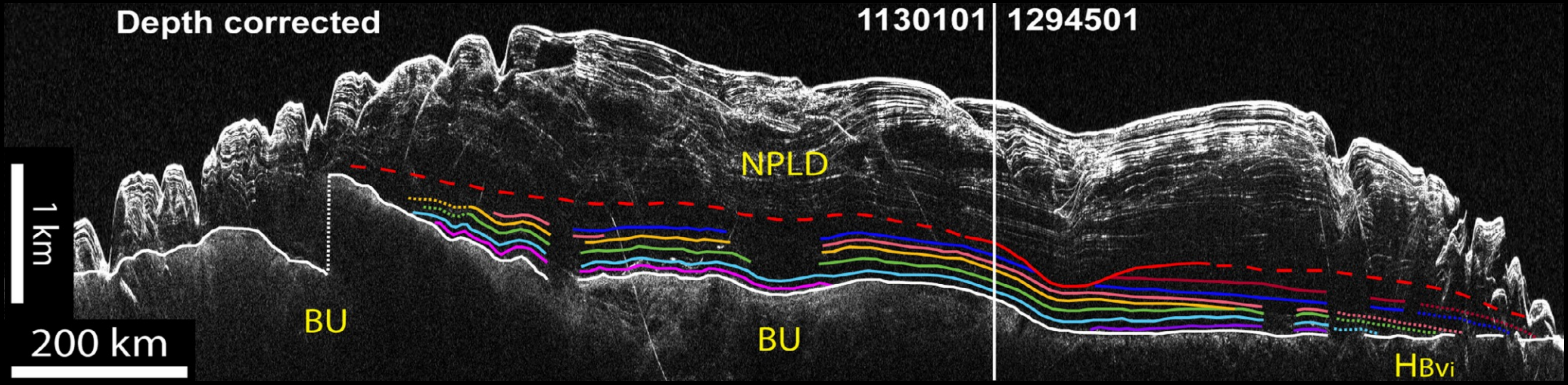
- PLD are made up of 1000s of layers, exposed at trough/scarp faces
  - Layer thicknesses: decimeter (North) to meters (South)
- Laterally continuous – indicates homogenous formation processes, but under variable ice/dust conditions
- North expected to be ~4–5 Myr old (*Levrard et al. 2007*)
- South older, 10s Myr (*Herkenhoff & Plaut 2000, Koutnik et al. 2002*)



Radar indicates bulk of PLD is nearly pure water ice.

- Contrasts in layers/layer packets cause radar reflections
- Lack of attenuation of radar signal with depth indicates nearly pure water ice
  - North: <5% dust *(Grima et al. 2009; Picardi et al. 2005)*
  - South: <10% dust *(Plaut et al. 2007)*



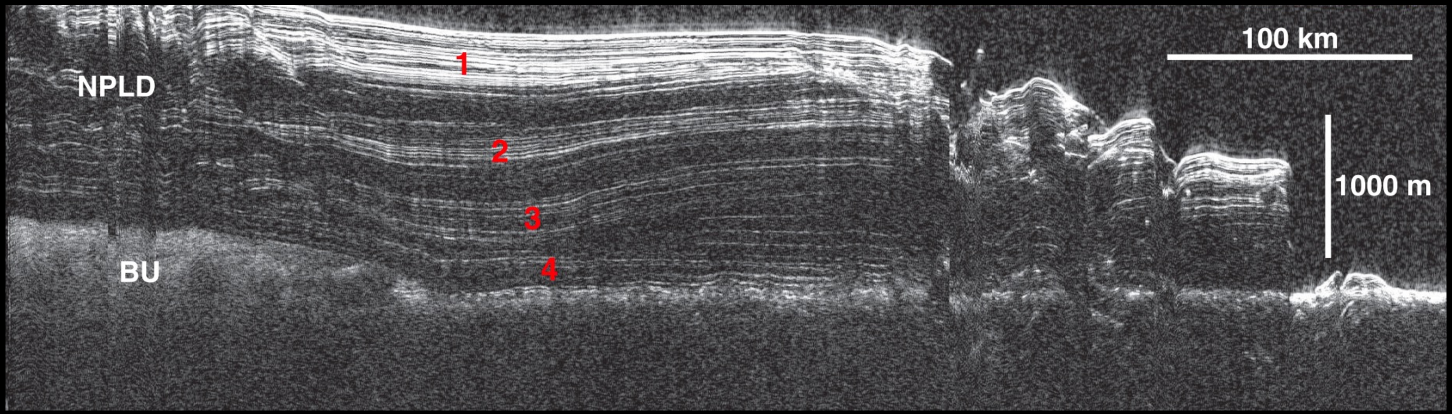


Nerozzi & Holt 2018

Radar data also show flat basal topography under North and South polar caps.

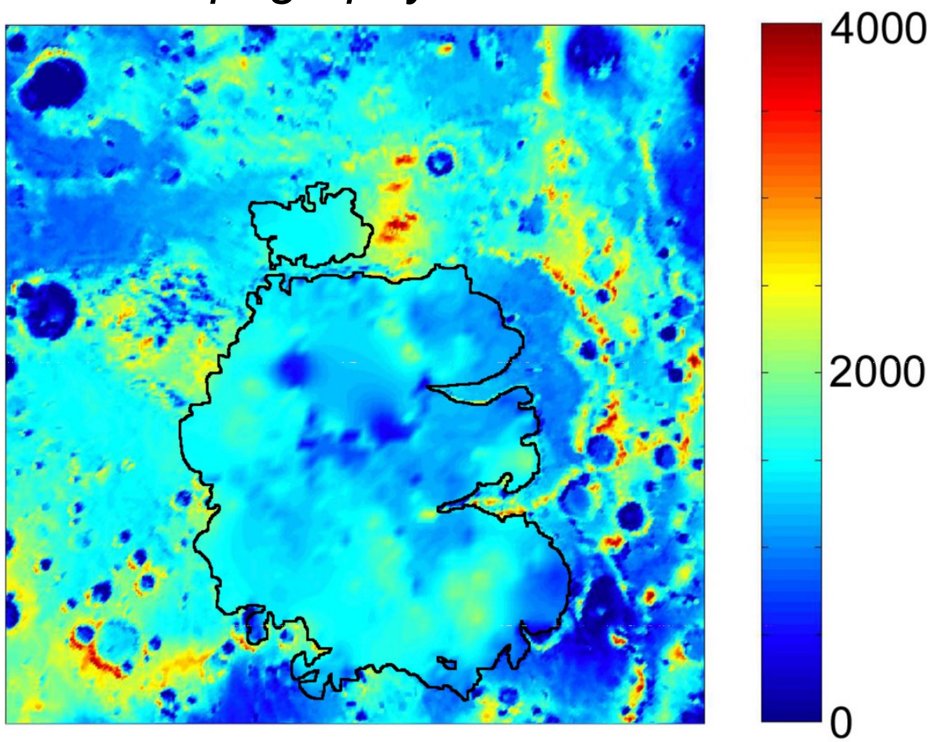
- No downward flexure observed (radar constrains <100 m deflection)
  - Indicates thick elastic lithosphere (>300 km) (*Phillips et al. 2008*)

SHARAD Radargram at North Pole



Phillips et al. 2008

Basal Topography at South Pole



Zuber et al. 2007

Gravity, topography, and radar used in concert to constrain the density of PLD.

- Assuming surface topography from MOLA and basal topography from radar:
  - model gravity anomalies for different PLD densities
  - Find best fit to observations

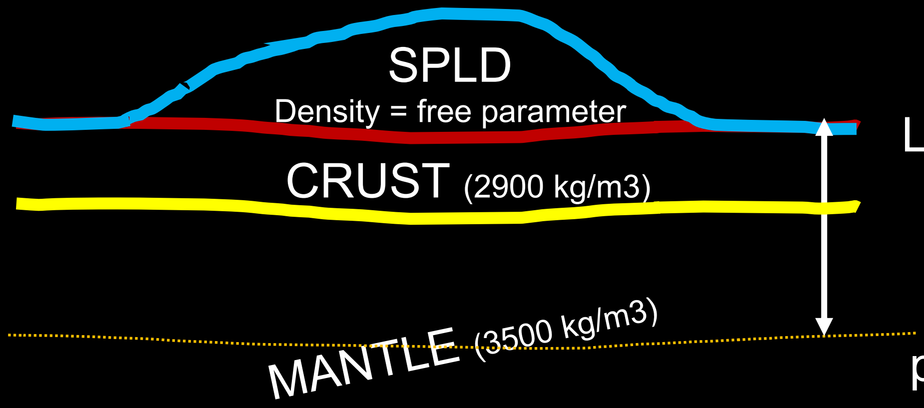
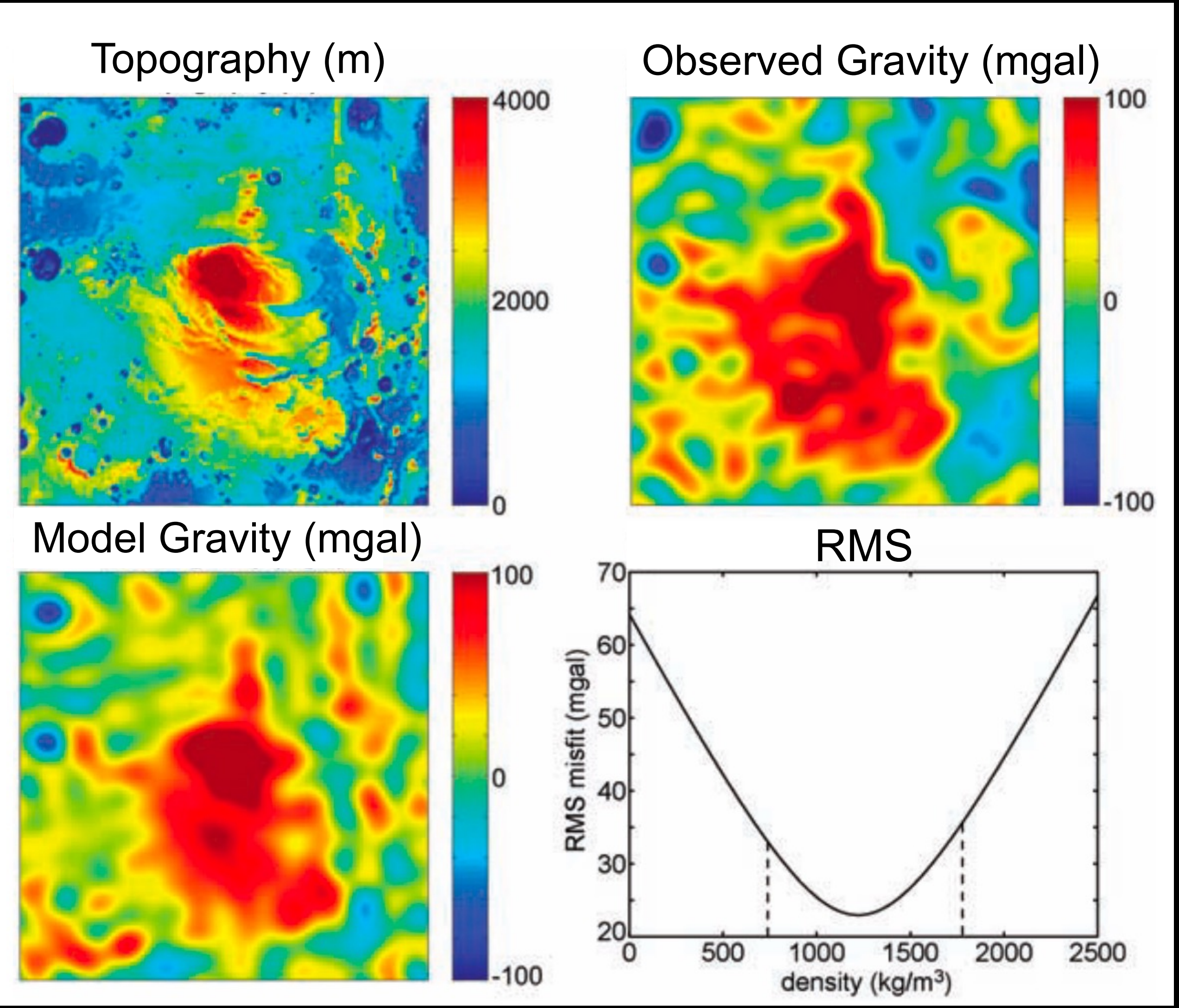


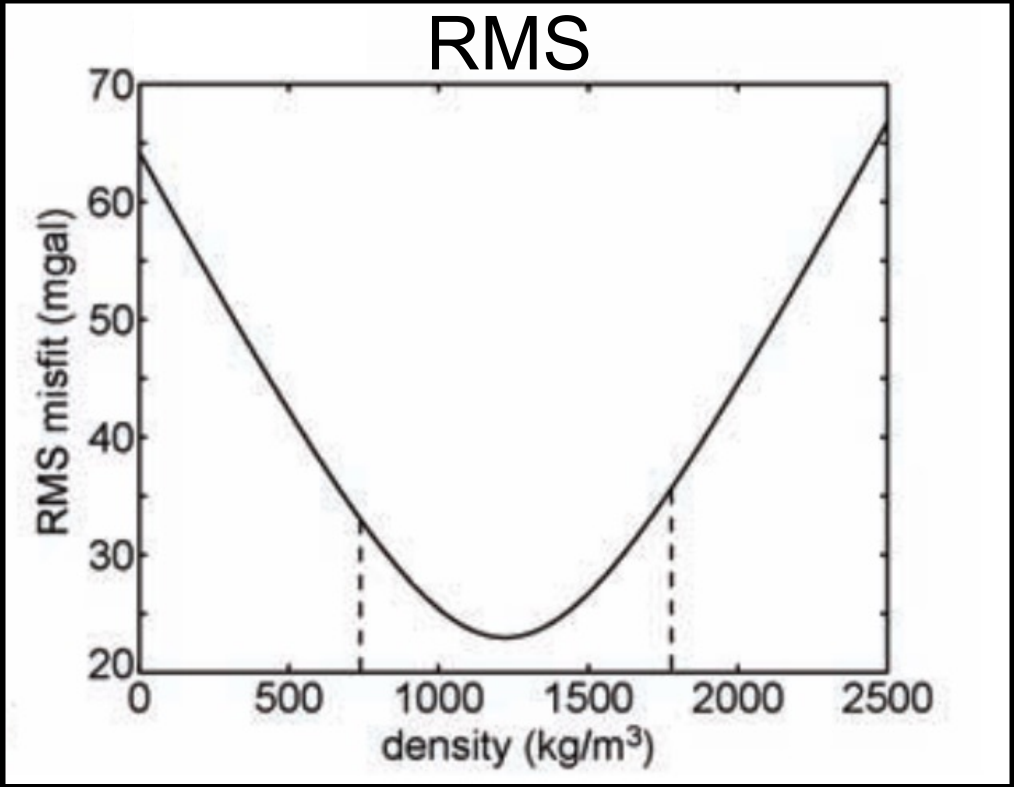
*Diagram not to scale



Zuber et al. 2007

Gravity, topography, and radar used in concert to constrain the density of PLD.

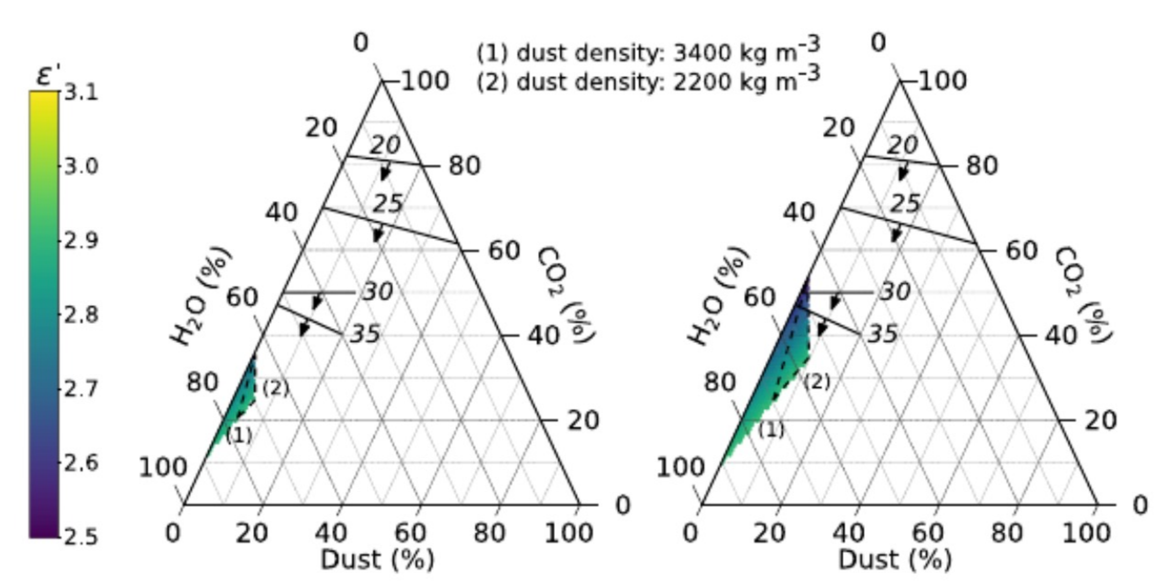
- SPLD density estimates:
  - Wieczorek 2008: 1271 kg/m^3
  - Zuber et al. 2007: 1220 kg/m^3
- NPLD density estimates:
  - Ojha et al. 2019: 1126 kg /m^3
- Density indicates mostly water ice (not denser CO_2 ice), and <15% dust



Zuber et al. 2007

Gravity, topography, and radar used in concert to constrain the composition of PLD.

- Radar and gravity are the two tools for understanding the subsurface
- Each individually provides constraints on composition
  - Dielectric properties (radar)
  - Density (gravity)
- Translation to compositions non-unique for each technique, so powerful to consider both together



Broquet et al. 2020

The Basal Unit under NPLD is composed of two units: cavi and rupes.

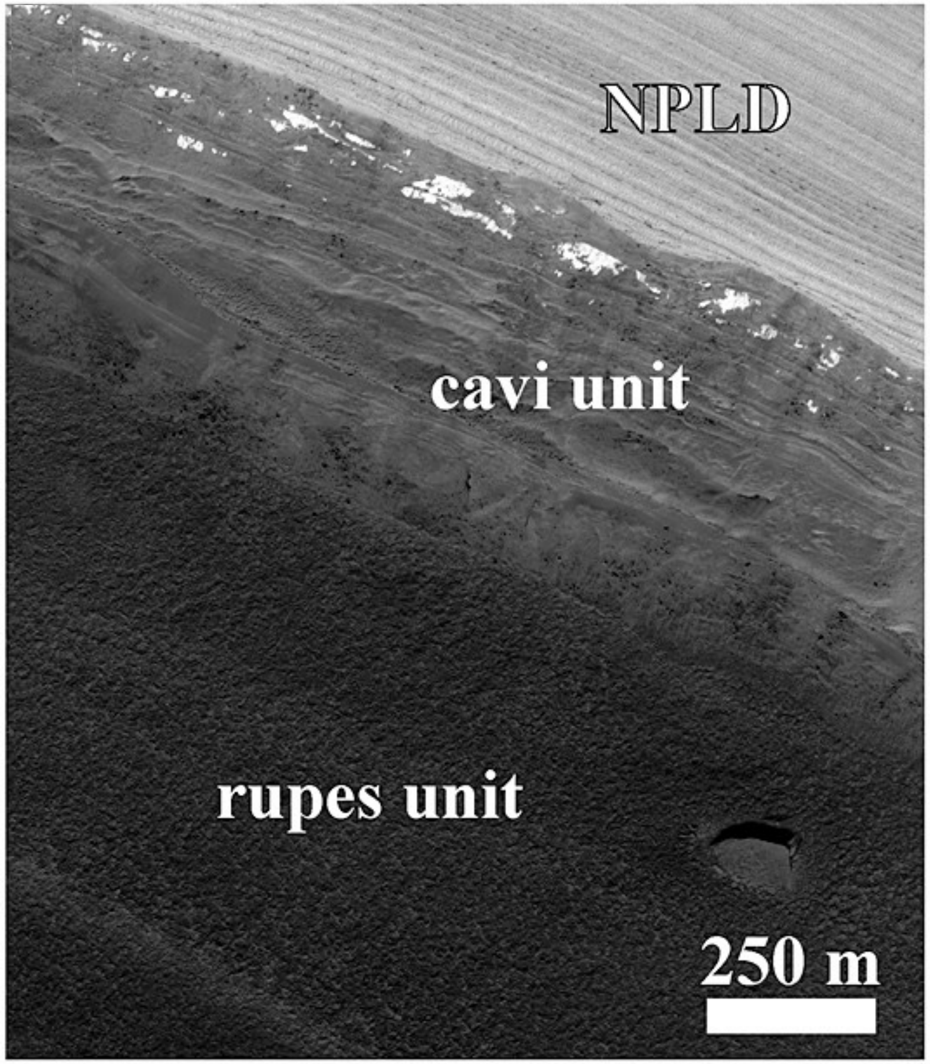
<u>Provides a record of older climates</u>

- Cavi: sandy, aeolian cross-strata weakly cemented by water ice, and interbedded with purer ice layers
  (middle Amazonian)
- Rupes Tenuis - lithic-rich
  (early Amazonian)

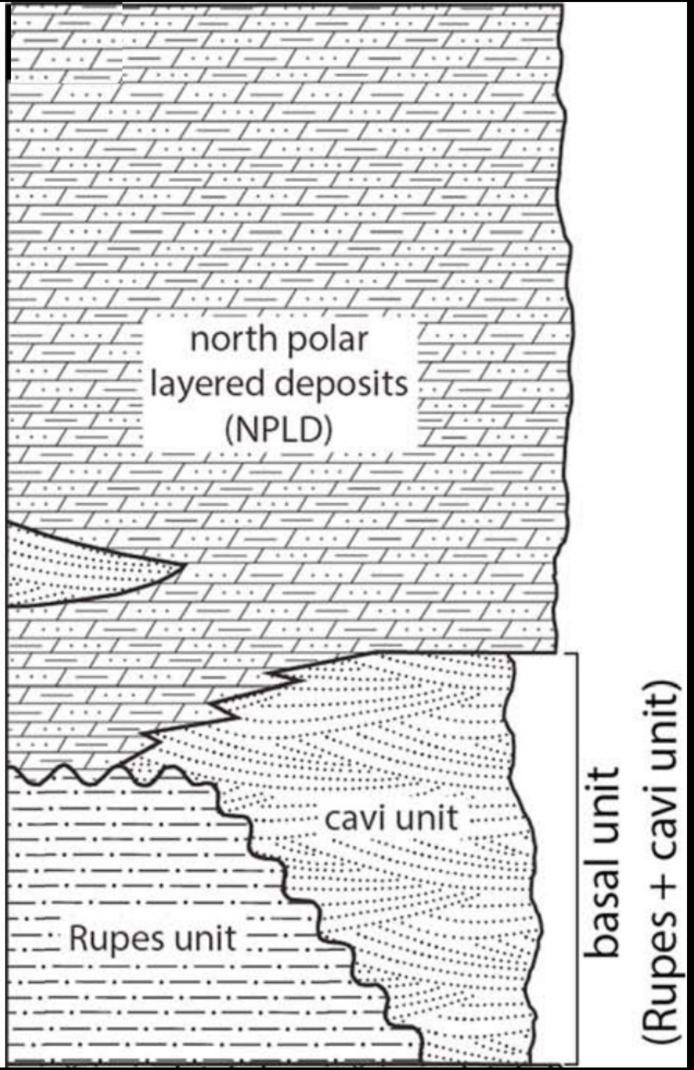
Bulk BU density from gravity: 2007 kg/m^3

- 55 ± 25% water ice

Ojha et al. 2019



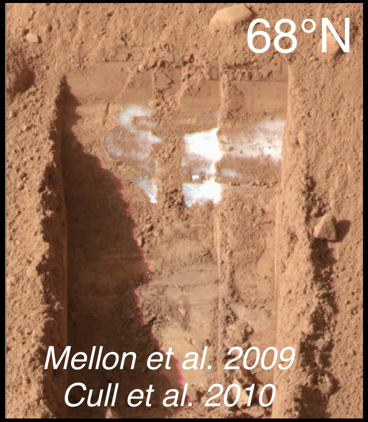
Brothers et al. 2015



Nerozzi & Holt 2019

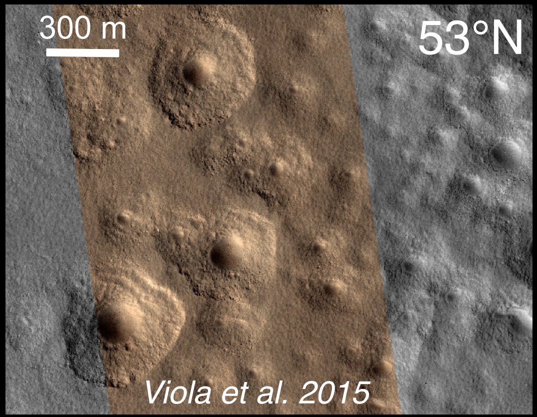
3. Radar observations and the debate on mid-latitude ice

Evidence for massive water ice in the mid-latitudes:



Phoenix excavation

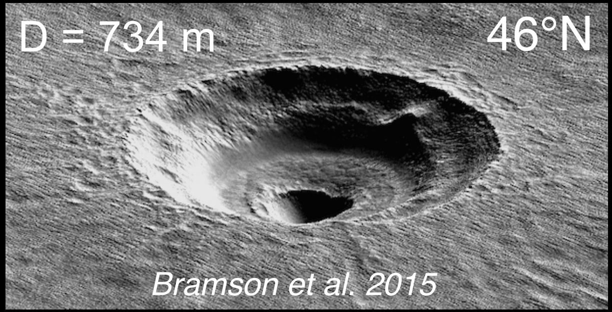
Icy impact craters



Expanded craters

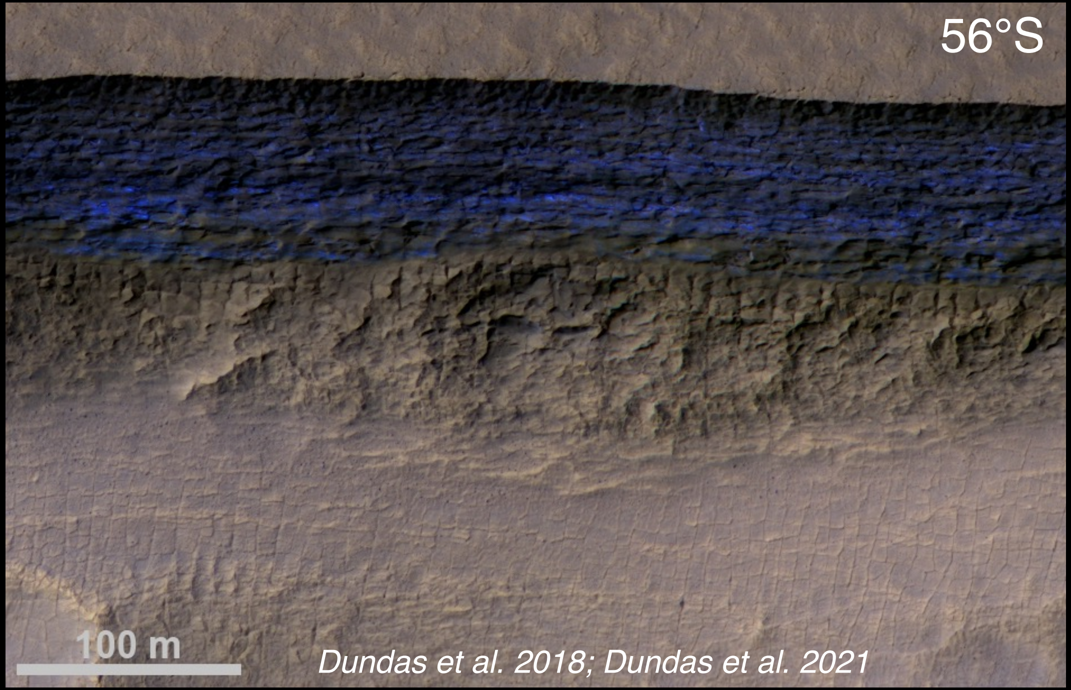
Scalloped Terrain

Viscous Flow Morphologies



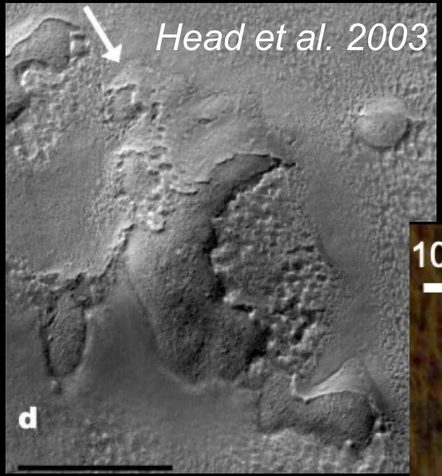
Terraced Craters

Debris Covered Glaciers



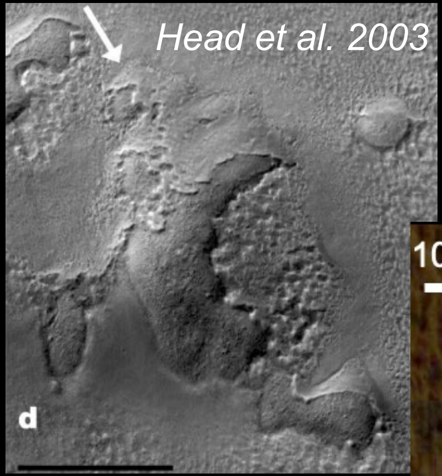
Icy Scarps

Mid-latitude ice also 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 is most relevant to geodesy, important for human exploration, and also where the most debate exists.



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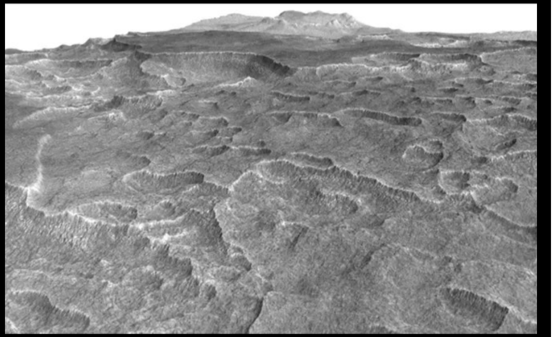
Glacial Landforms	100s Myr	10^5 km^3 (2.6 m GEL) *Levy et al. 2014*	100s m – km

Widespread radar reflections have been attributed to ice sheets across the Northern plains.



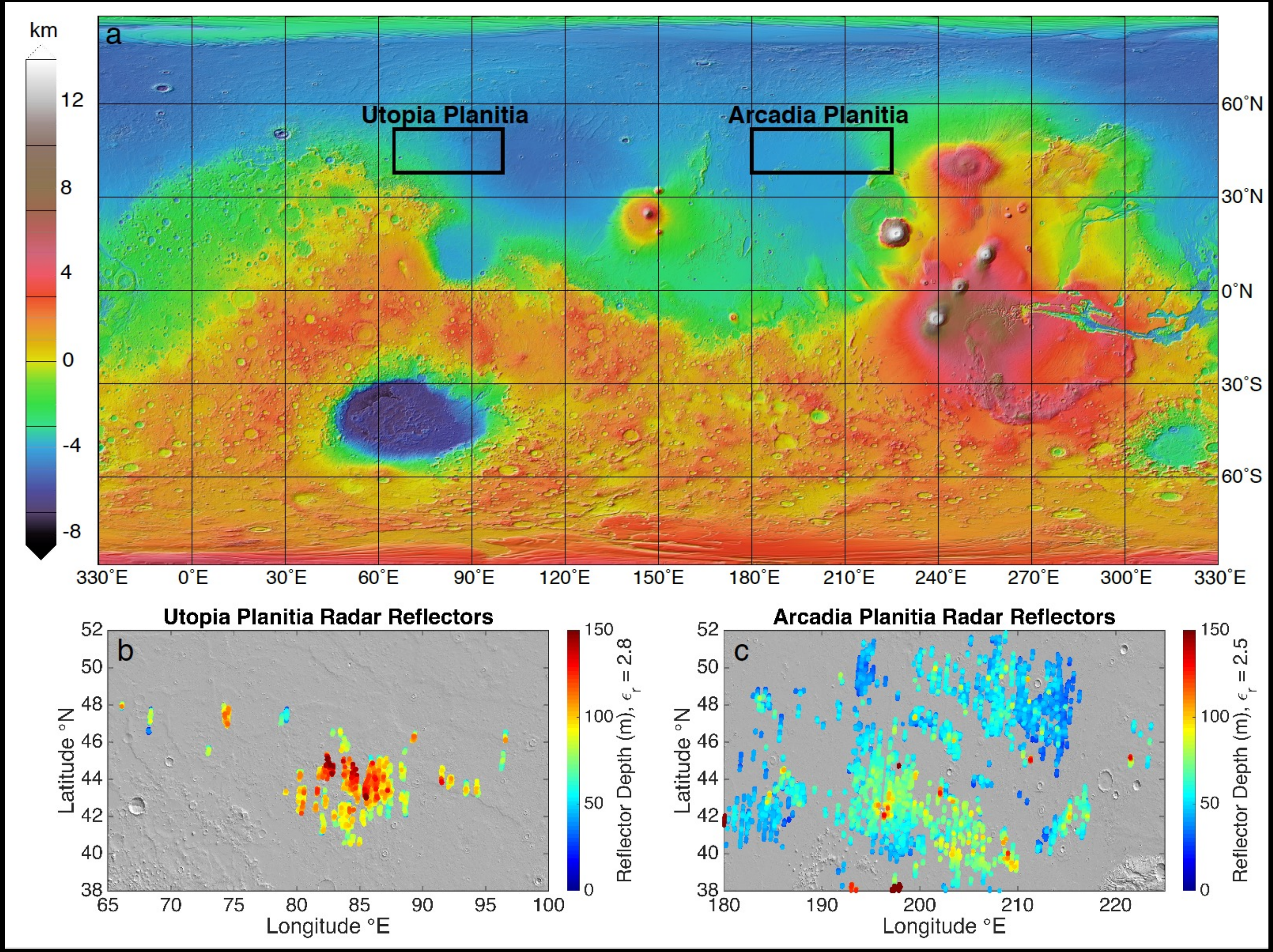
Utopia Planitia

Stuurman et al. 2016

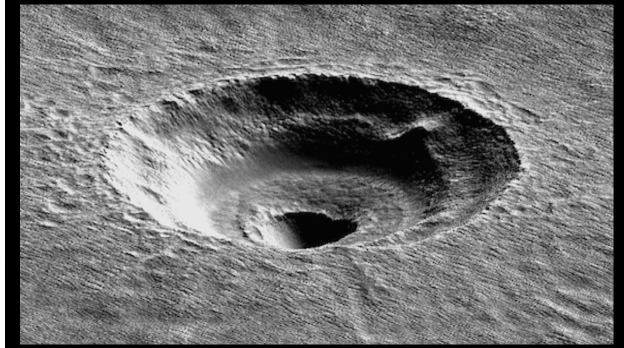
~10^4 km^3

~80–170 m thick

ε_r = 2.8 ± 0.8



Bramson et al. 2017



Arcadia Planitia

Bramson et al. 2015

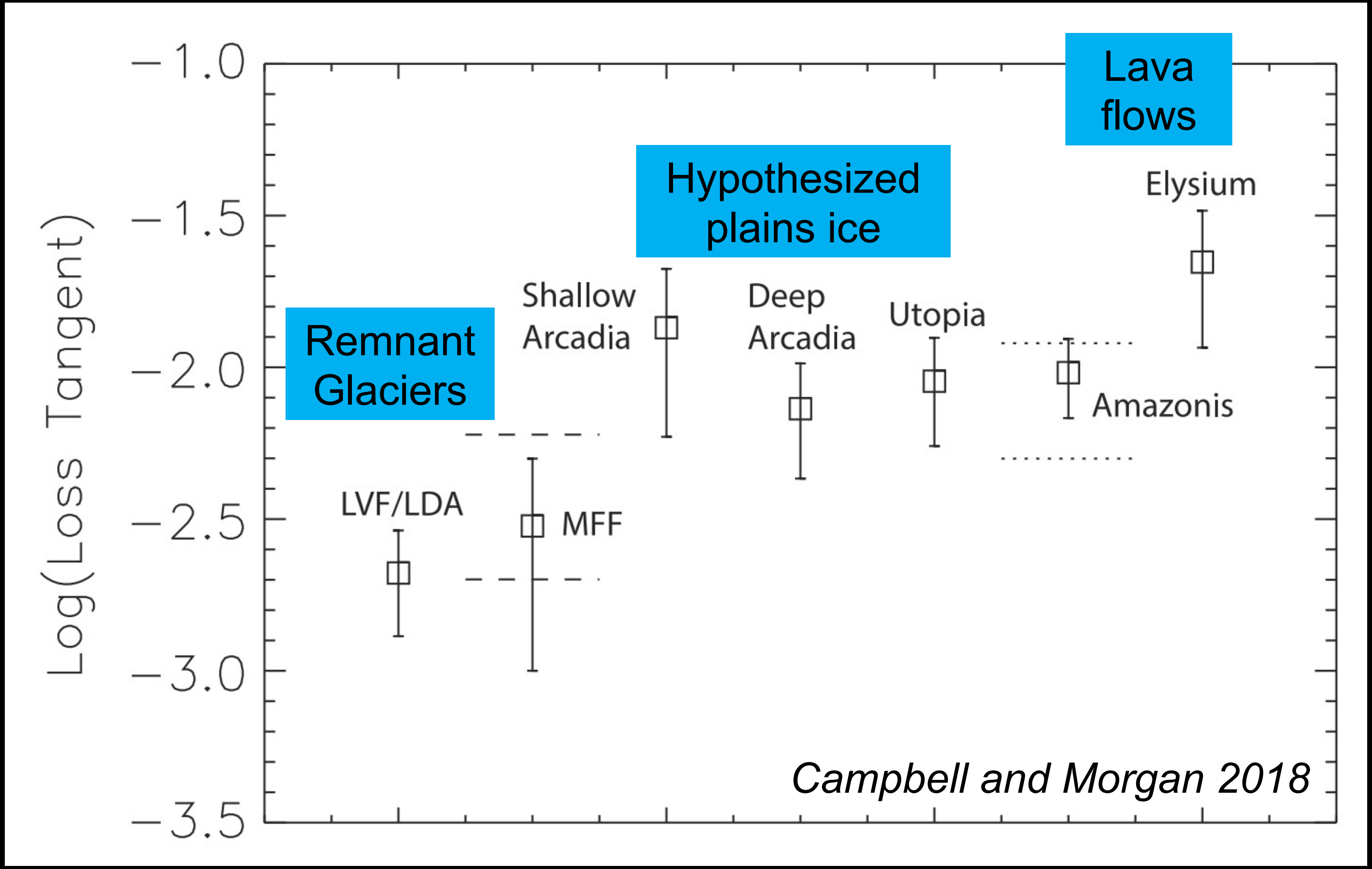
~10^4 km^3

~25–80 m thick

ε_r = 2.5 ± 0.28

But… the radar signal is being attenuated more than expected for pure ice…

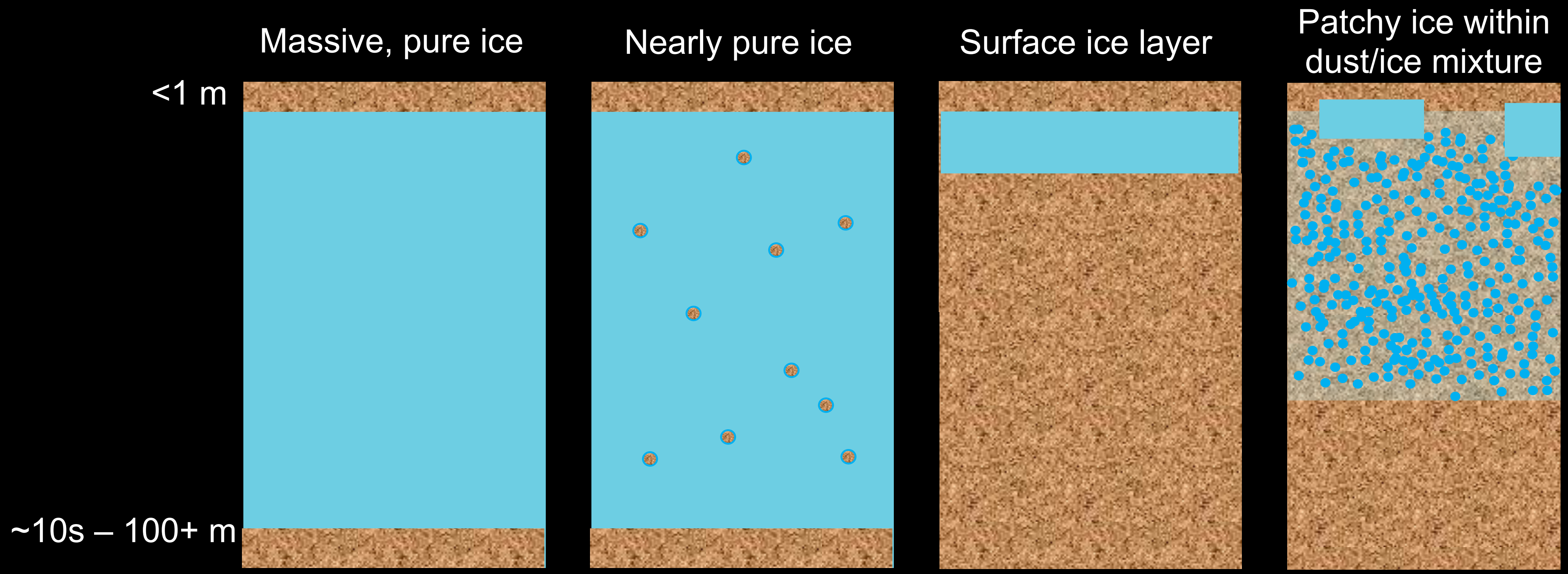
- Requires higher lithic content in the subsurface
- So debate exists regarding the presence of thick, massive ice deposits at these locations



Ultimately, we lack instruments that can resolve the debate on decameters thick mid-latitude ice.

How laterally and vertically extensive is the shallow plains ice?

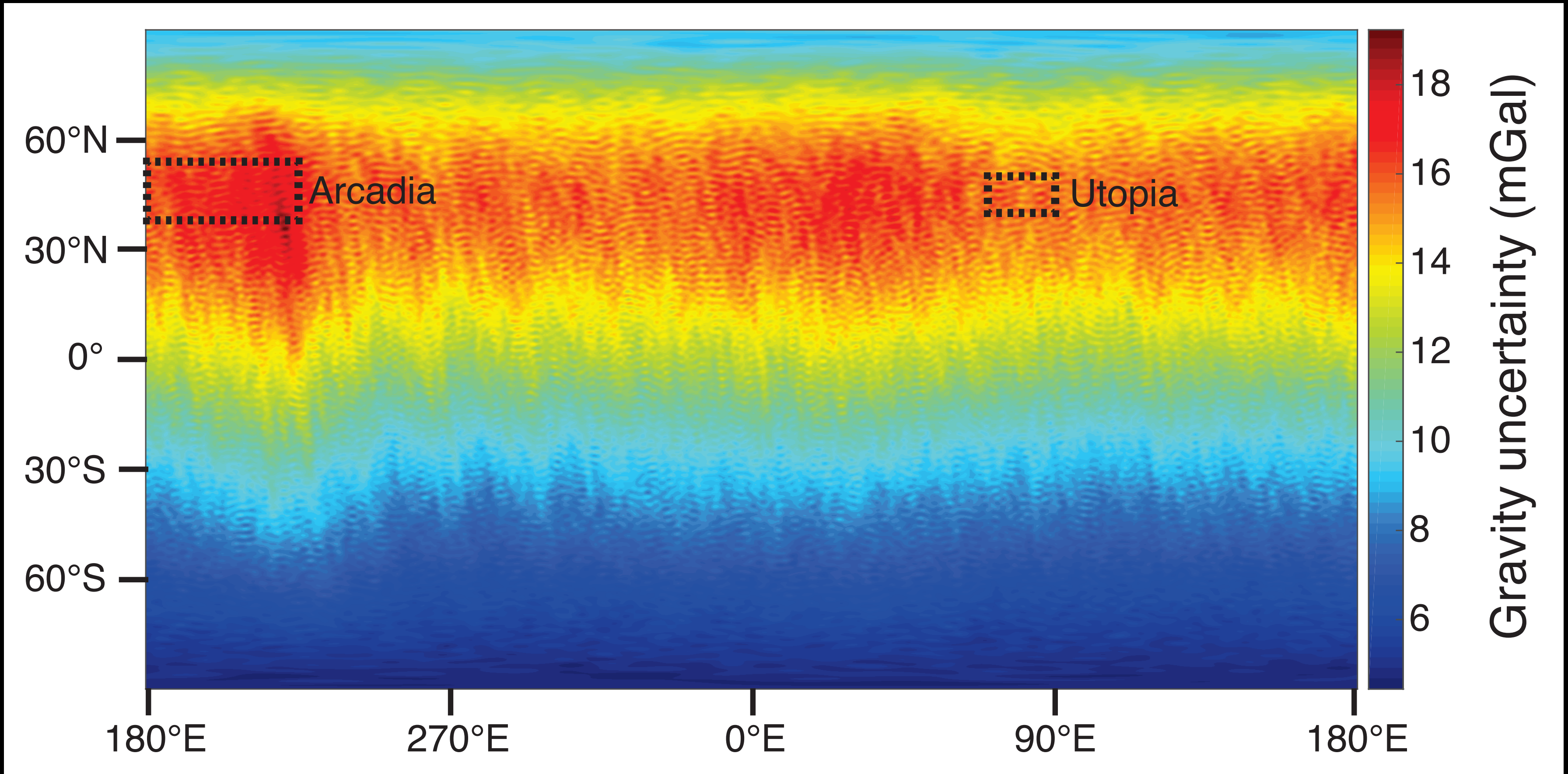
Hugely important for human exploration and formation mechanism of the ice!



4. Prospects for future static gravity fields to search for ice and elucidate climate history

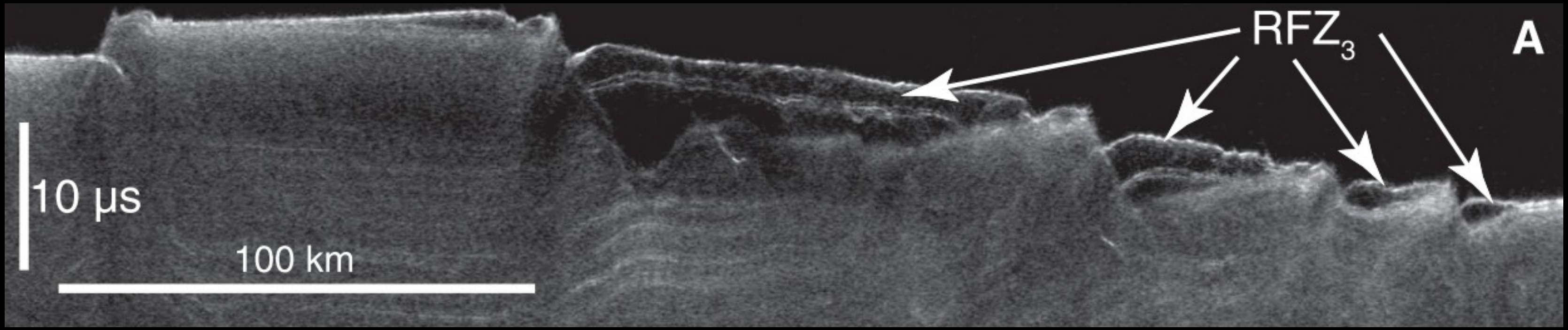
Constrain mid-latitude ice locations and purities

- Elucidate orbital forcing processes that deposit non-polar ice
- Provide critical inputs for planning for human exploration at Mars
- Current gravity field precision is weakest in northern mid-latitude plains.



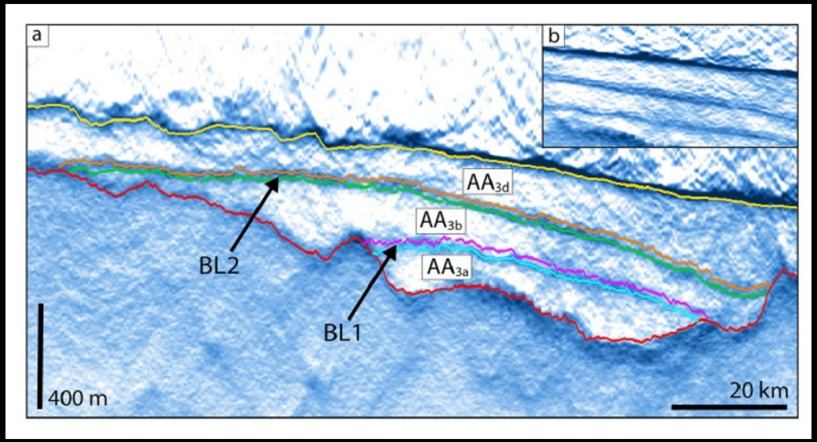
Constrain lateral density variations in the polar layered deposits, including massive CO_2.

- Elucidate past climates that form the polar caps
  - Temporal and spatial variability in past deposition of H_2O, CO_2, and dust
- Elucidate hemispheric asymmetries in Mars' dust and volatile cycles



Massive CO2 sequestered in SPLD – enough to double atmospheric pressure!
Phillips et al. 2011

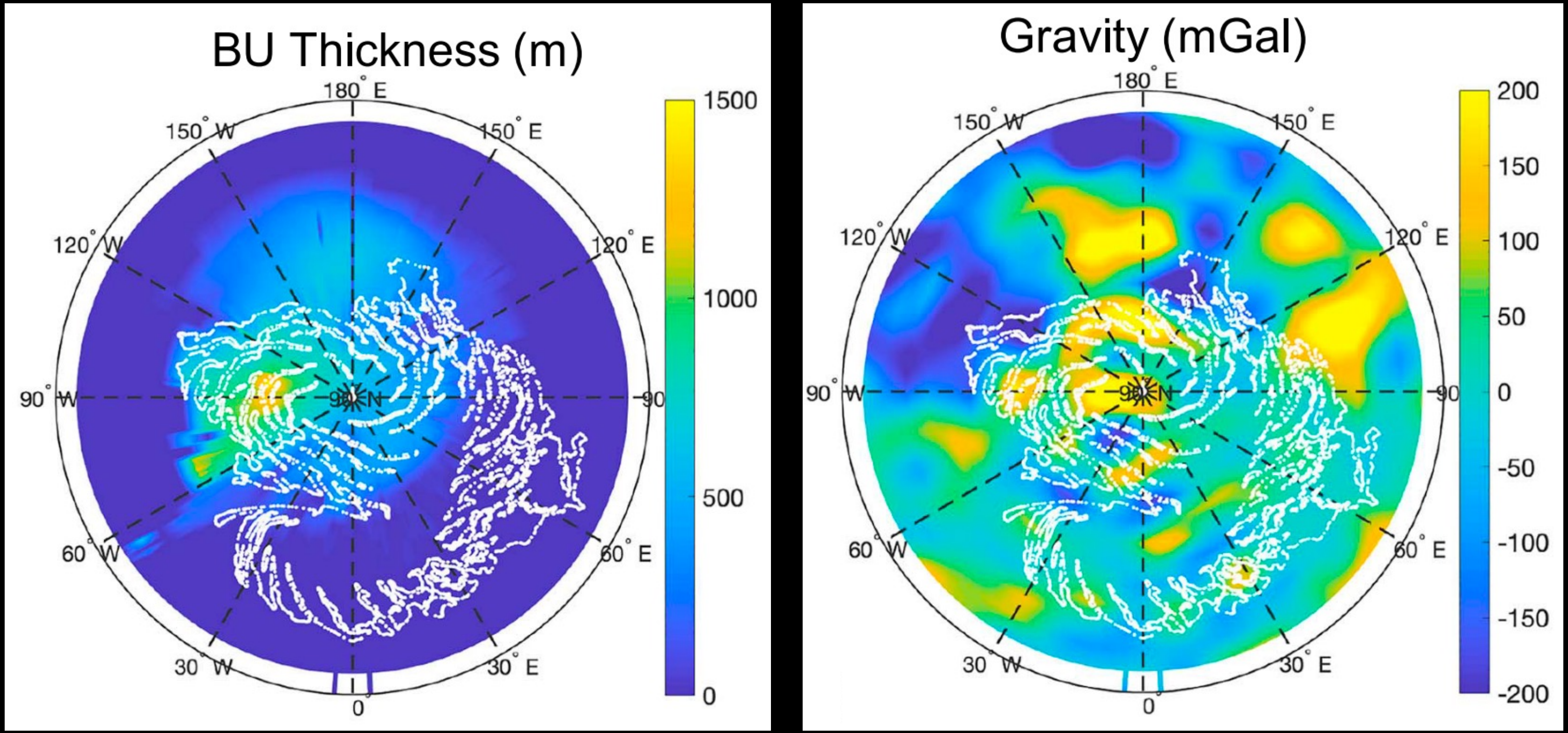
CO_2 deposits are bounded by water ice layers
e.g. Bierson et al. 2016; Alwarda & Smith 2021



No evidence for CO_2 in North PLD – only in South PLD

Determine the densities of the stratigraphically distinct Cavi and Rupes units in the North

- Elucidate climate conditions before the polar ice caps were emplaced
- Currently unresolvable



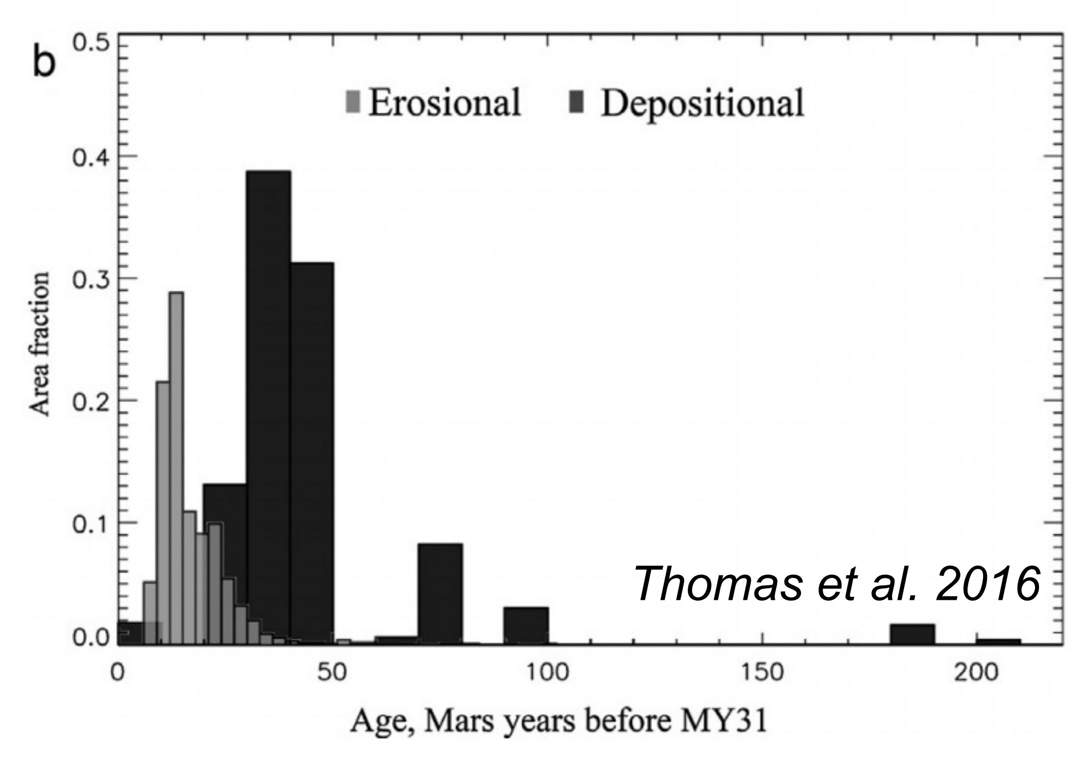
Ojha et al. 2019

5. Prospects for future time-variable topography and gravity fields to detect active climate processes

Determine if the mass balance of the residual cap is negative or positive.

- Current estimates from image data are consistent with annual mass balance of −6 to +4 km^3/Mars year *(Thomas et al. 2016)*
  - Is the cap net accumulating or ablating??
  - Informs how an individual layer of the PLD forms (residual cap is essentially the top-most recent layer of PLD)

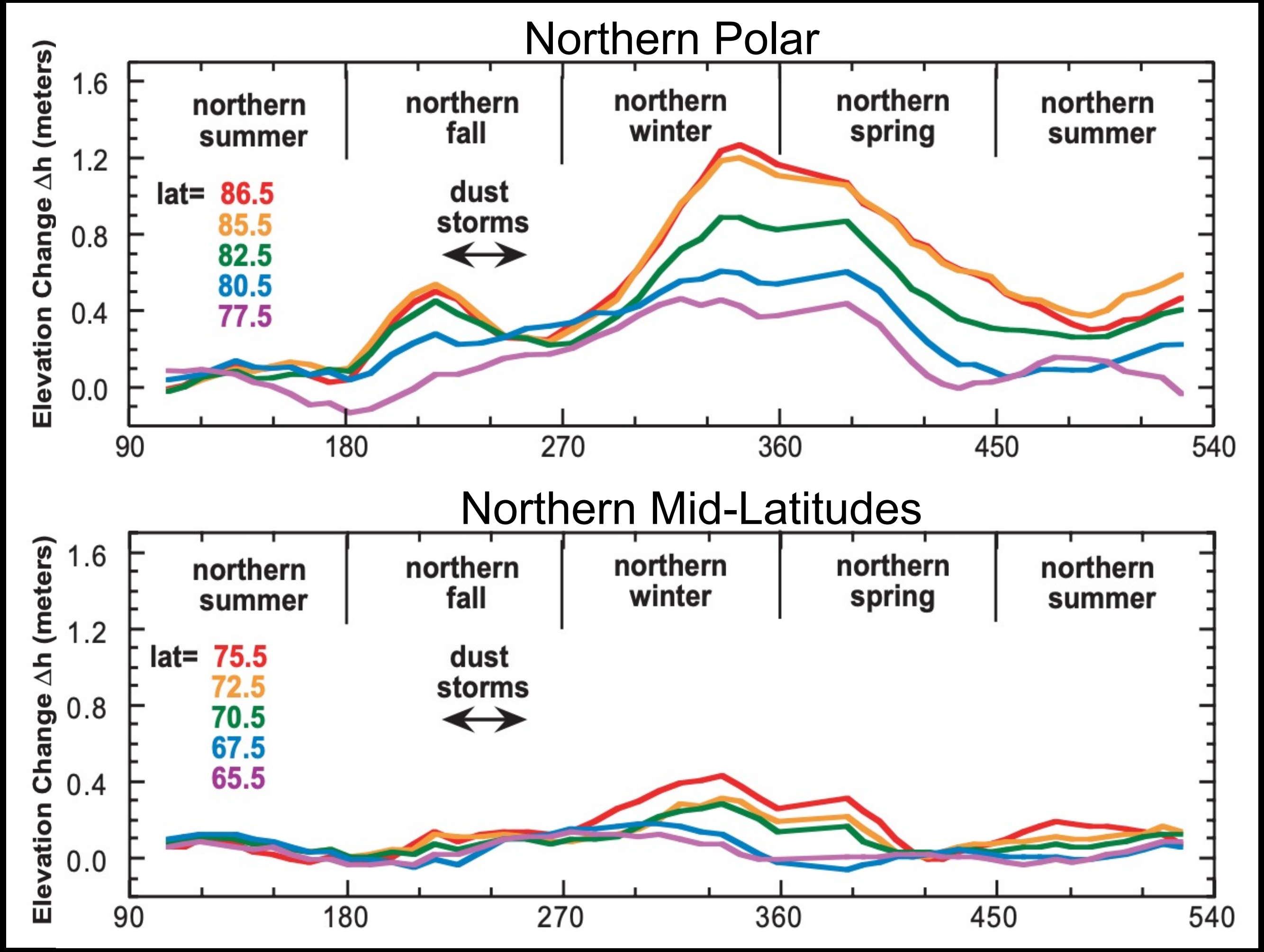
- How do these exchanges contribute to secular formation and evolution of the polar cap?
  - Higher resolution time-variable gravity and topography could address



Thomas et al. 2016

Map heterogeneities in depositional processes

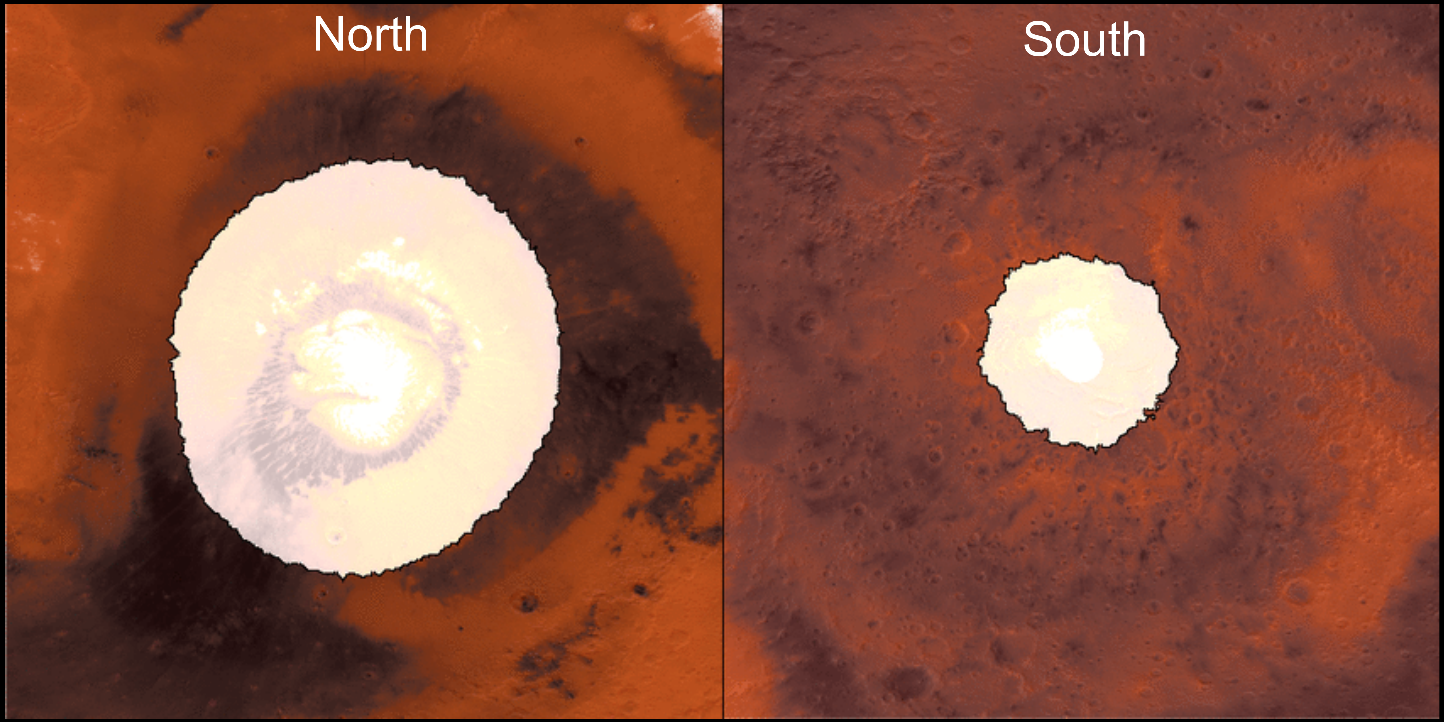
- Significant variability observed seasonally and interannually in timing and placement of deposition/ablation
- Higher resolution time-variable gravity and topography could constrain:
  - Composition (dust content, porosity) of deposits as they form and evolve
  - Spatial variability in surface density, which would shed light into local and regional scale mass balance dynamics



Smith et al. 2001

Conclusions: Geodesy provides an important tool for understanding Mars' climate and volatile cycles.

- New, higher resolution datasets would elucidate:
  - Properties of buried volatile reservoirs (including targets for human exploration)
  - Lateral and temporal variability in current mass balance across Mars
  - Keys to unlocking the climate record stored in Martian ice deposits



Distribution of seasonal CO_2 frost based on infrared data

Animation Credit: NASA/JPL-Caltech
https://photojournal.jpl.nasa.gov/catalog/PIA22546