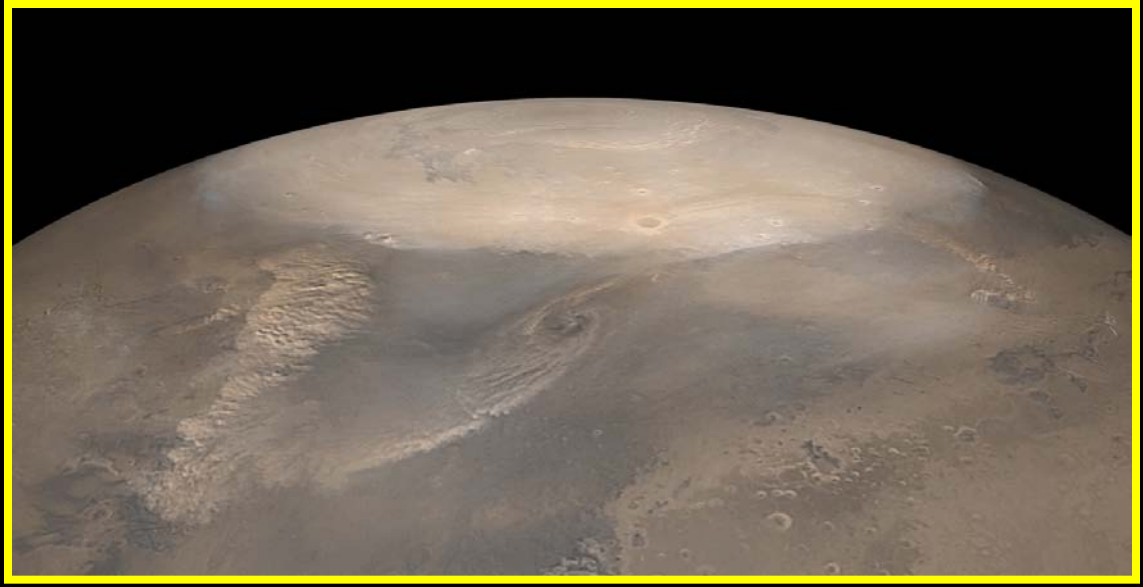
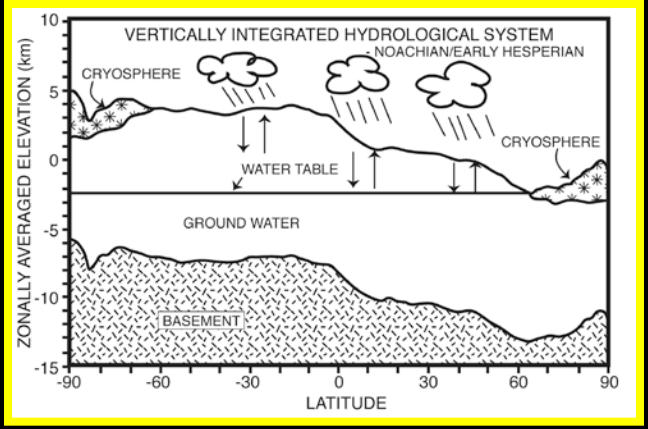
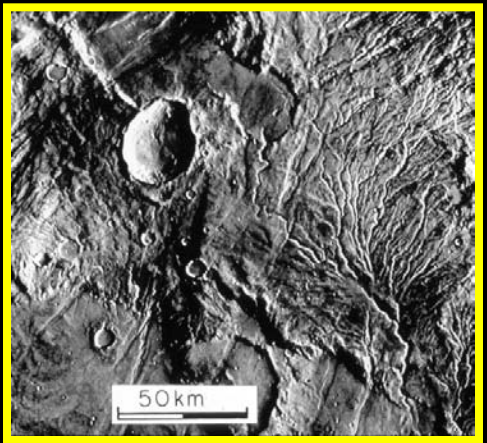
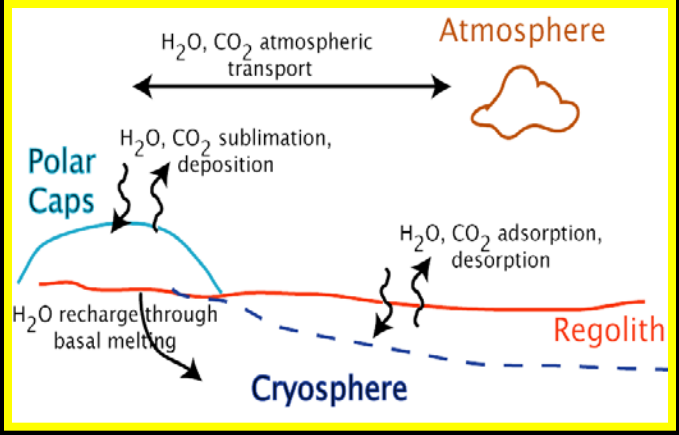
An Overview of the History of Climate on Mars: A Geological Perspective









James W. Head
Department of Geological Sciences, Brown University, Providence, RI USA
Santander Astrobiology Summer School, Universidad Internacional Menéndez Pelayo, June, 2011

Santander Astrobiology 2011 Summer School
Universidad Internacional Menéndez Pelayo

Perception:

As most humans understand it, water is a critical component of life, and liquid water appears to be a fundamental requirement for an abundant and diffuse biota.

Danger: Likely to be a terracentric, acosmic view: But let's explore it for now.

Context of This Week's Discussions: *Where do we go? What do we do?*

-Francois Poulet: Planetary Surface Formation and Evolution and Mars.

-Jim Head: The climate history of Mars; Water on Mars; Antarctic Dry Valleys.

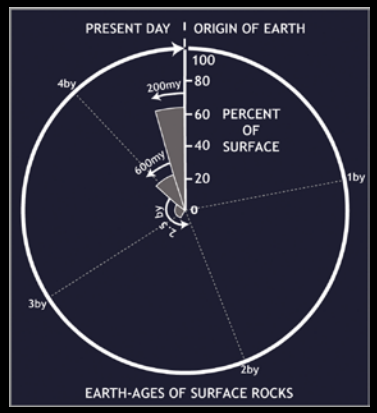
-Francois Forget: The present and past climate of Mars.

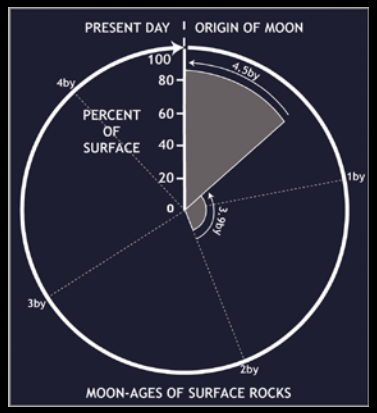
-Bethany Ehlmann: Mineralogy and chemistry of Mars: Links to life.

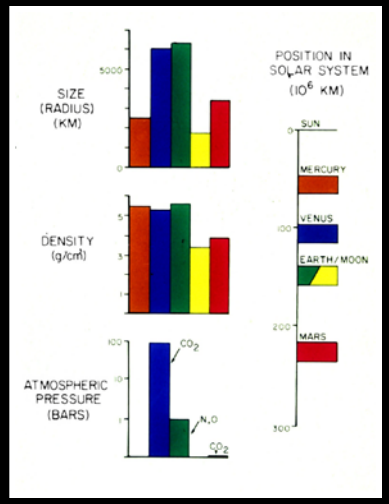
-David DesMarais: Life and the biosphere on early Earth; Exploring Mars for habitable environments and life.

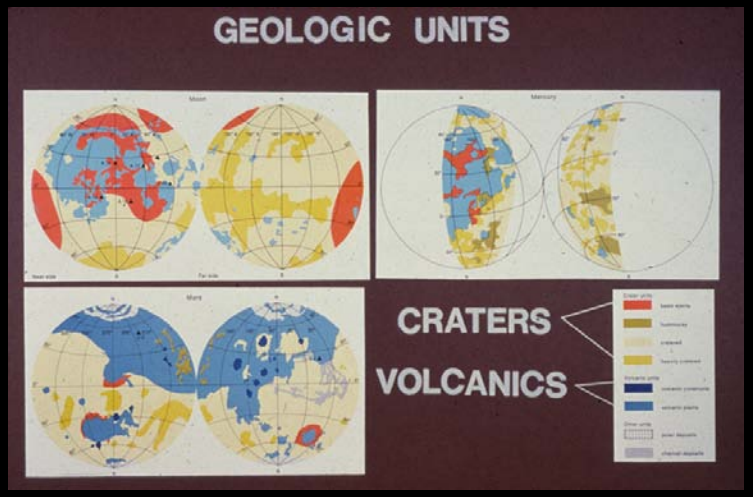
-Alvaro Gimenez: Future Mars Exploration.

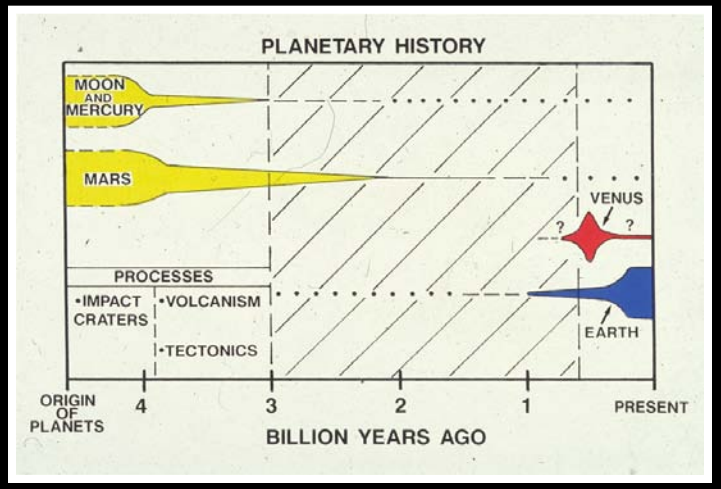
Mars in Terrestrial Planet Context

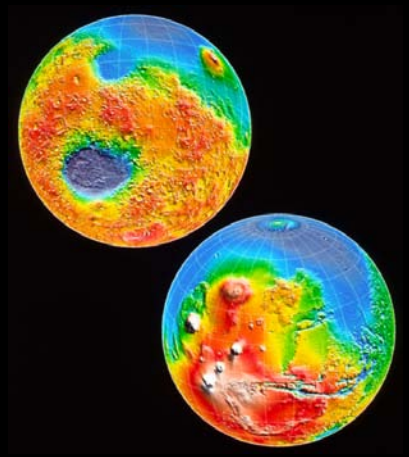




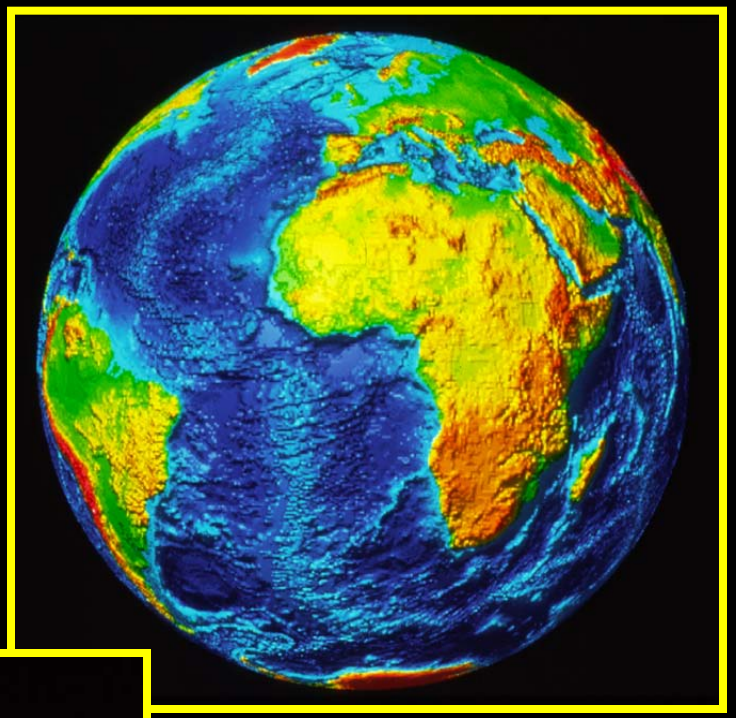




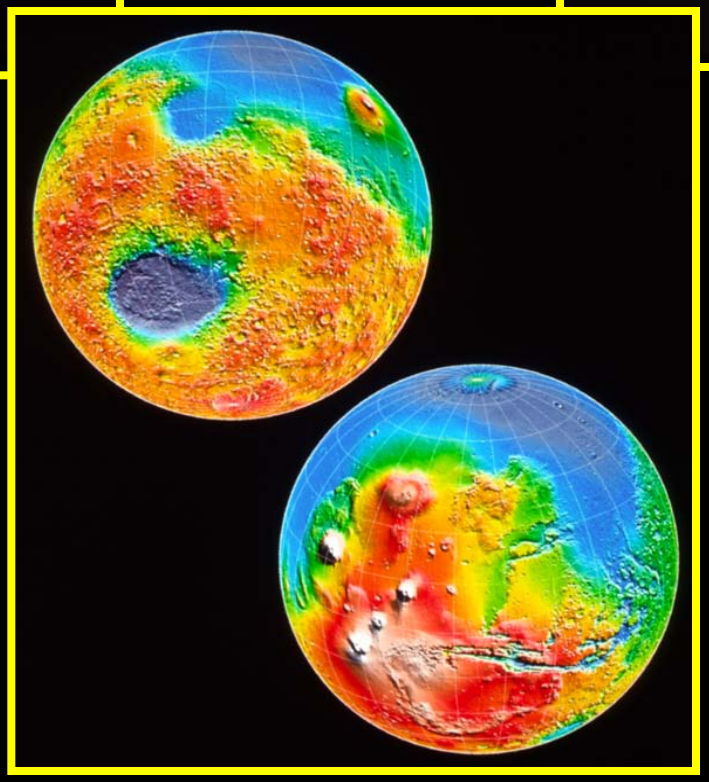




Water on Mars:
History of Climate Change and Evolution of the Water Cycle.



Climate and its Record on Earth and Mars



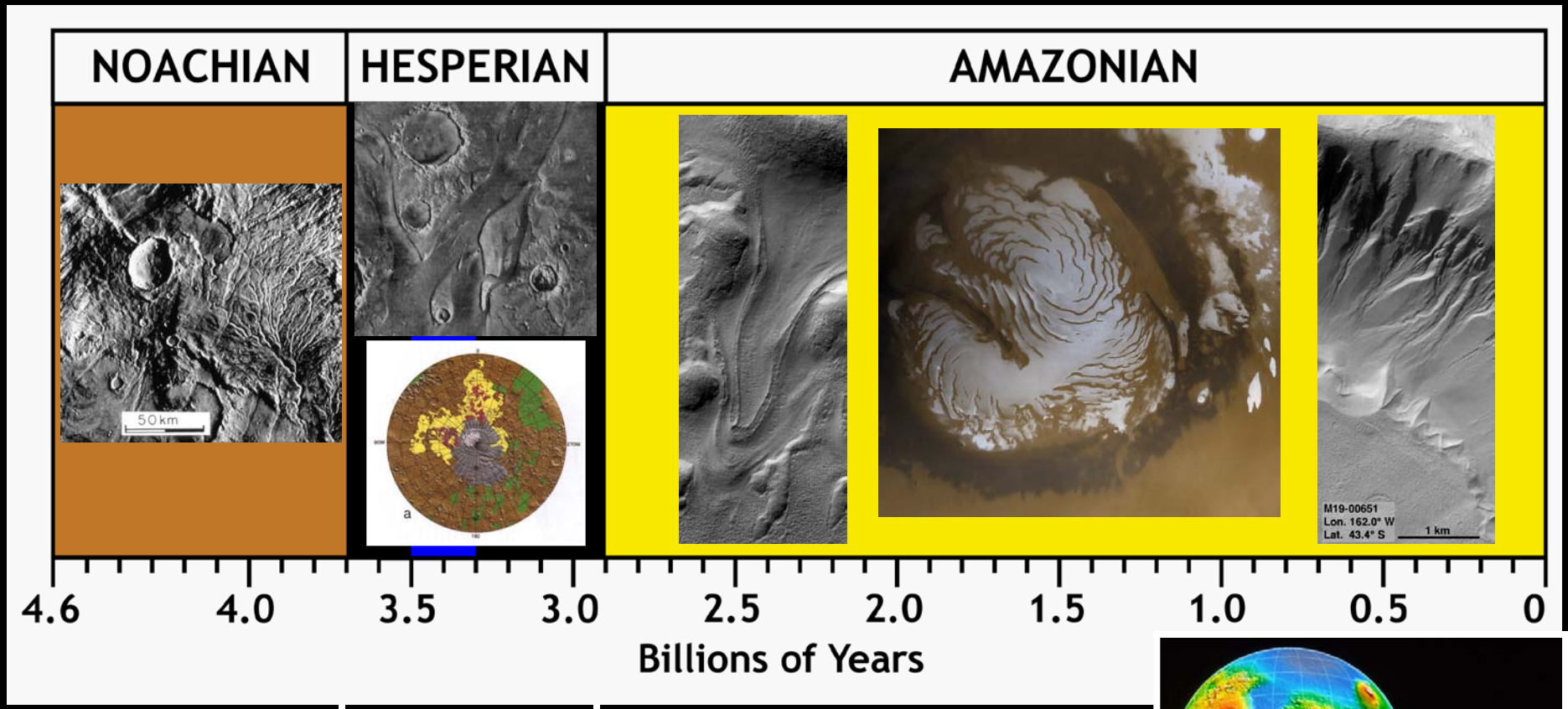
Earth

1. Active weathering.
2. Plate tectonics.
3. Oceans: buffering.

Mars

1. Ultraslow weathering.
2. No plate tectonics.
3. No oceans (?).

Climate on Mars: Relation to Geologic History



- Heavy impact bombardment.
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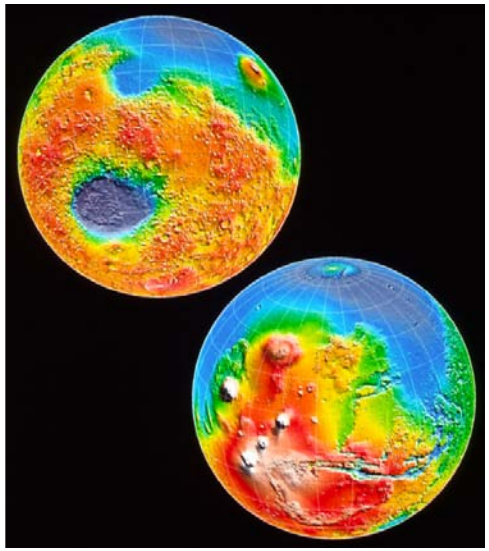

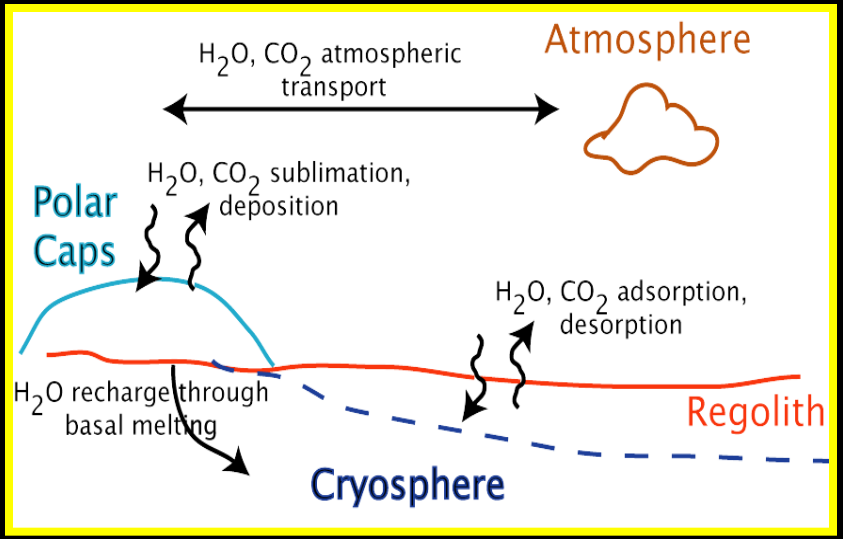

Climate on Mars Today

-CO_2, a few millibars.
-Hyperarid, hypothermal polar desert.

Climate Change Analysis: New Developments

- New spacecraft data.
- New understanding of water/ice reservoirs: where it resides, how and when it is mobilized.
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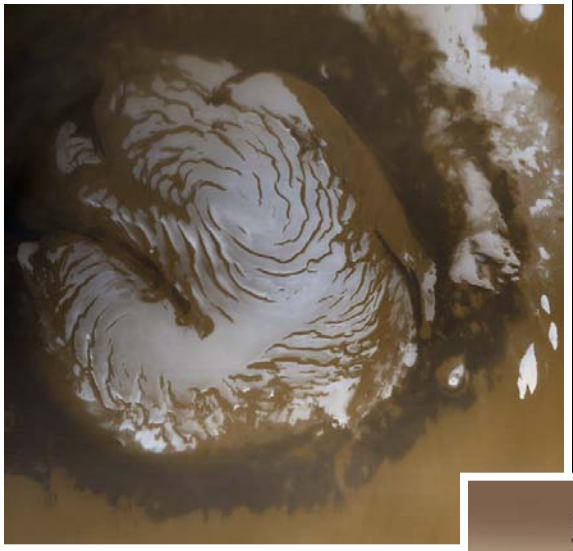
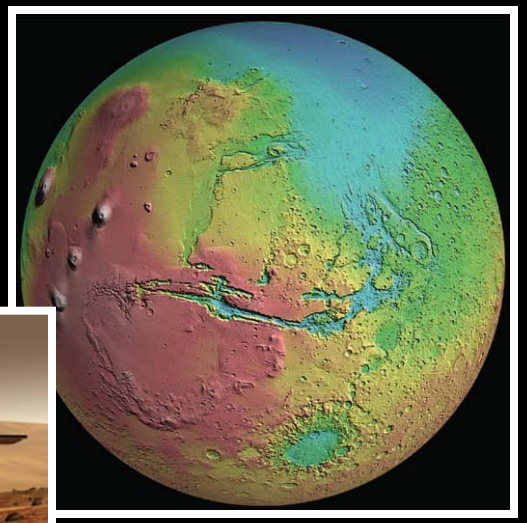
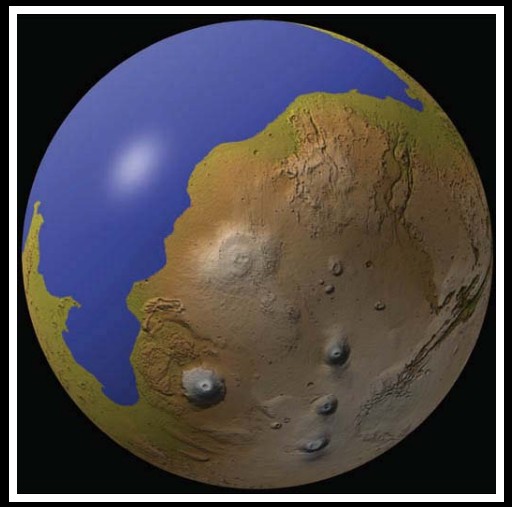
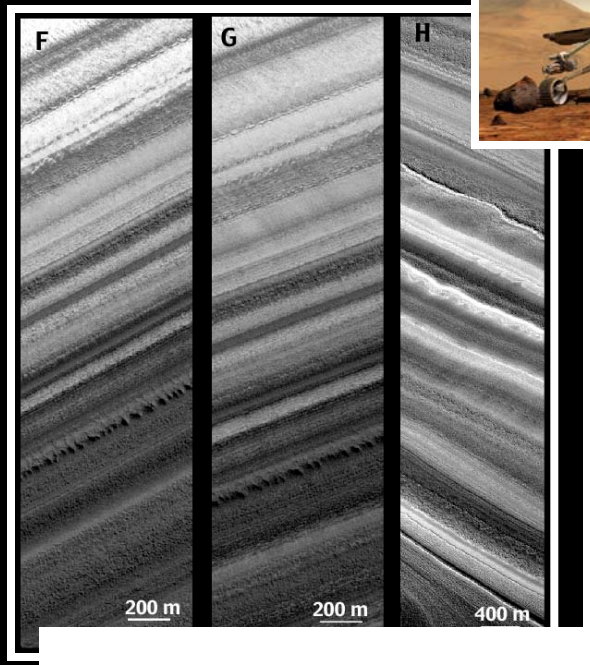
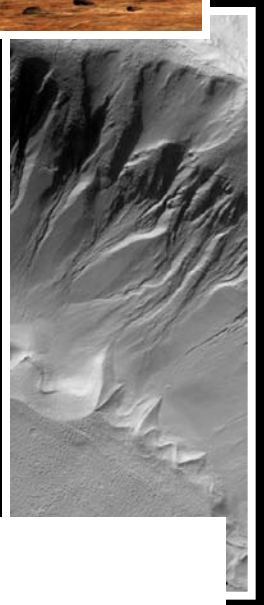
The Geological Record Of Climate Change

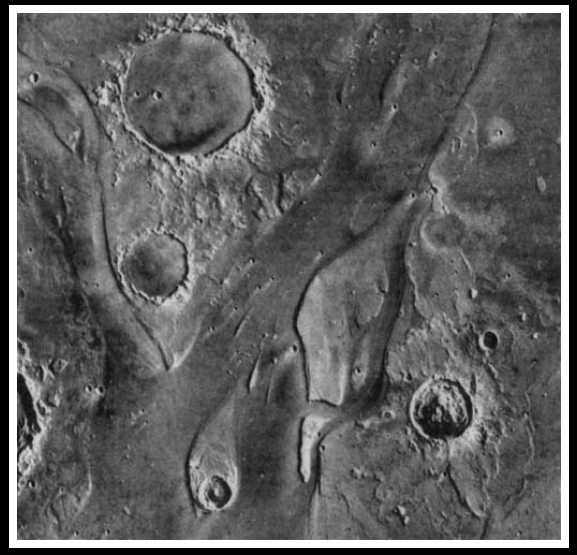


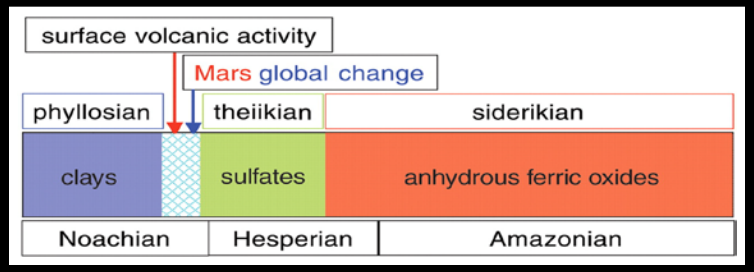












QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

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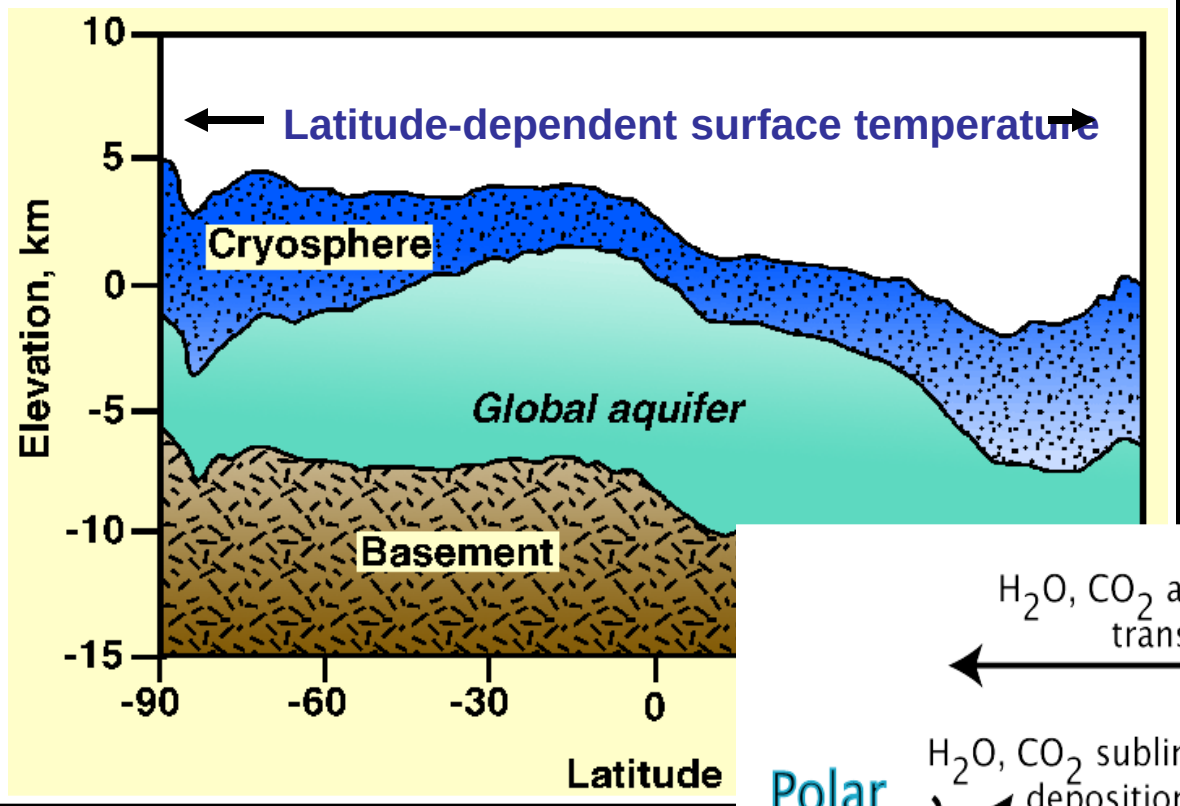
Hydrological Cycle and System

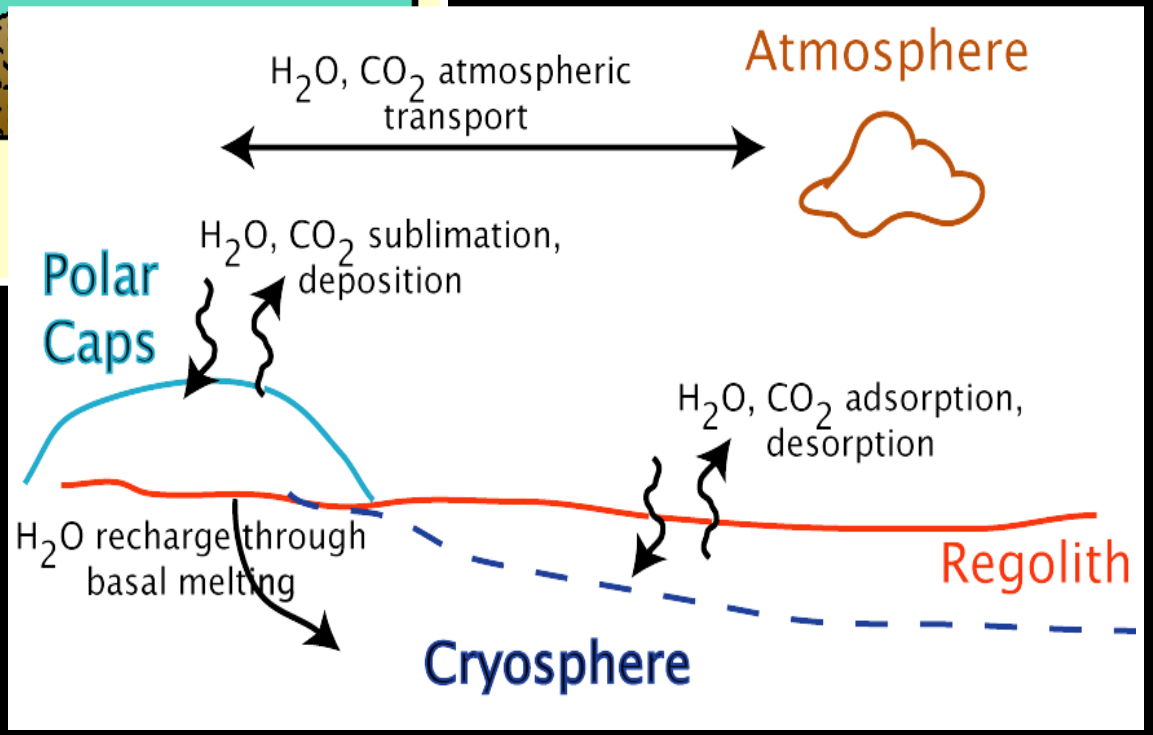


-Amazonian: Horizontally stratified.

-Noachian: Vertically integrated?

Geothermal gradient

Surface and Near-Surface Reservoirs



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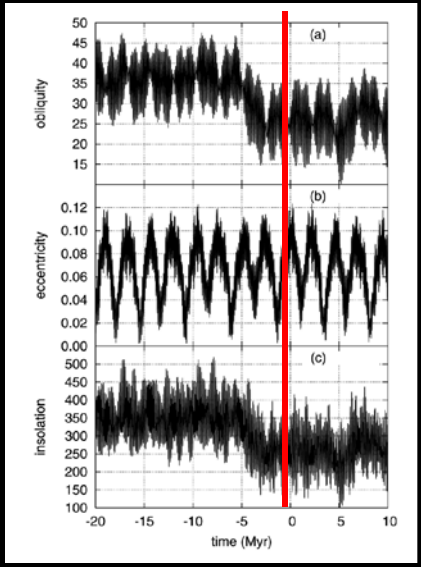
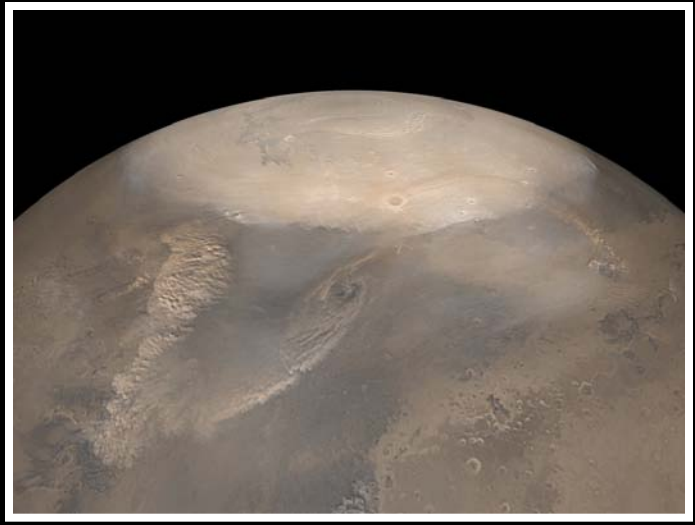
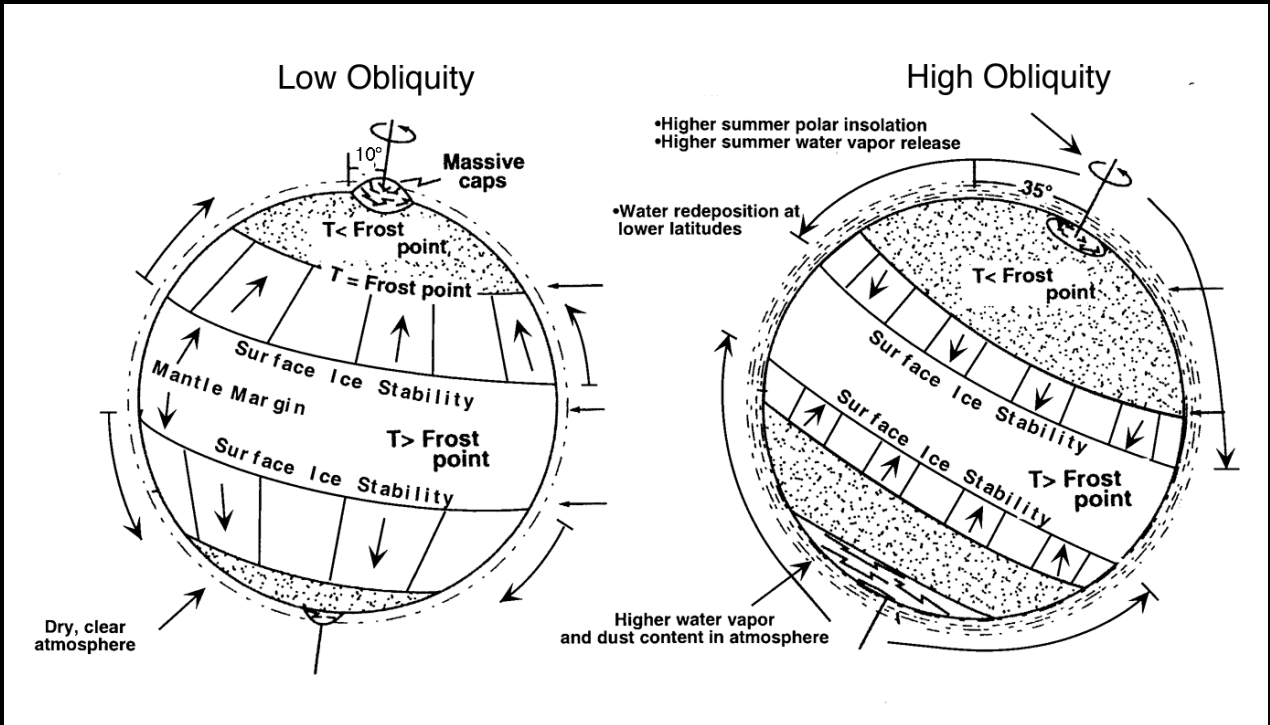
New Developments

- **Range of recent astronomical climate forcing values.**
- **Recent climate modeling (high obliquity).**
- **-> Significant amounts of polar water ice can be mobilized and transported equatorward during periods of high obliquity.**



(Laskar et al. 2004)





(Richardson and Wilson, 2002; Haberle et al.., 2003; Mischna et al., 2004; Forget et al., 2006)

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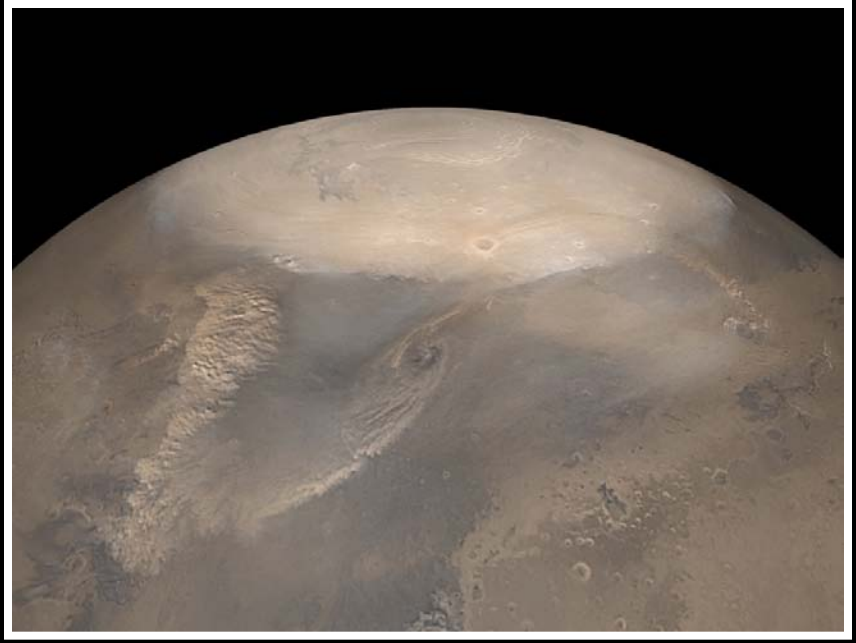
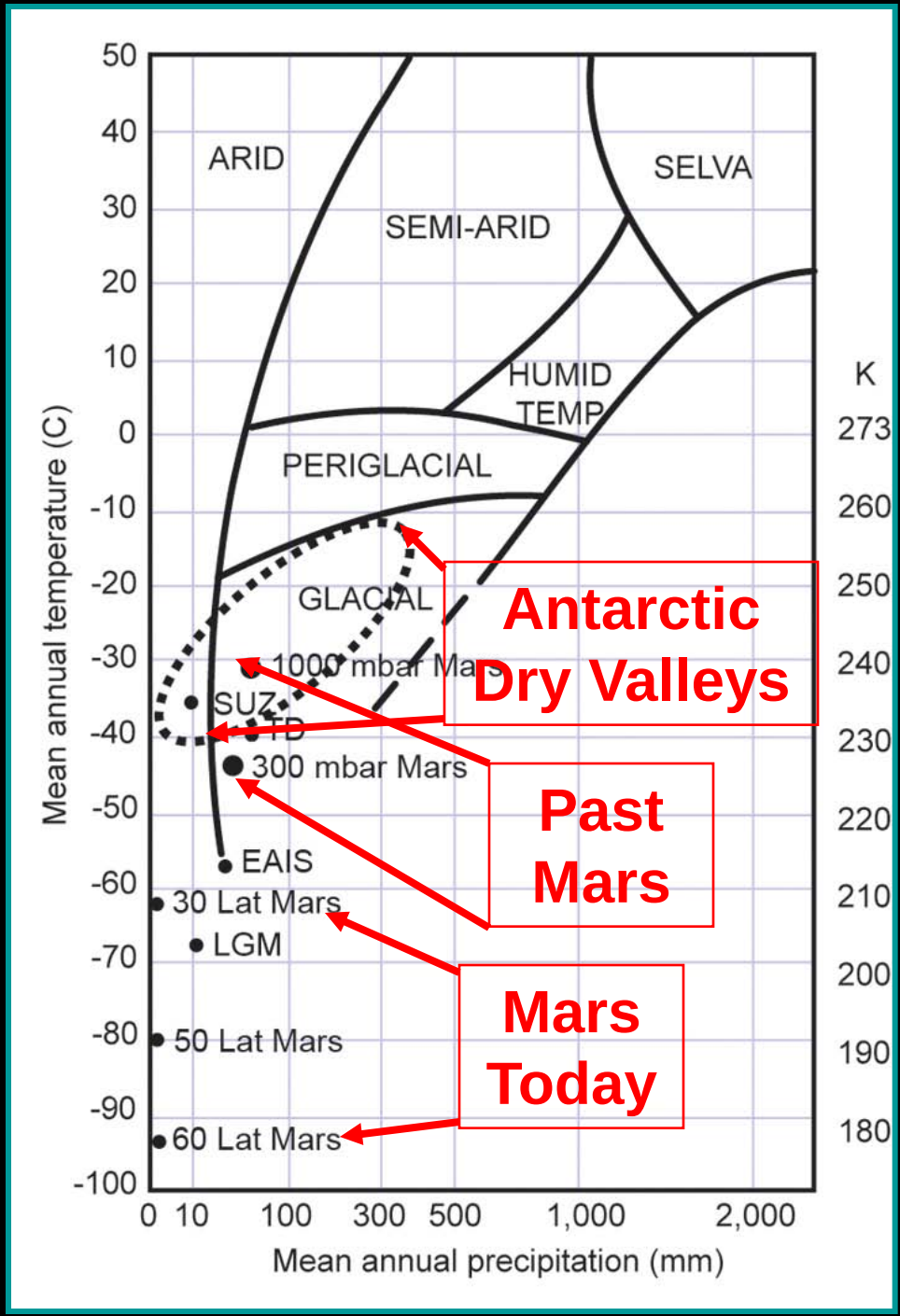


Mars is Currently a Cold Hyper-arid Desert



Antarctic Dry Valleys: Hyperarid Hypothermal Polar Desert -Cold-Based Glaciation-

Climate Change Analysis: New Developments

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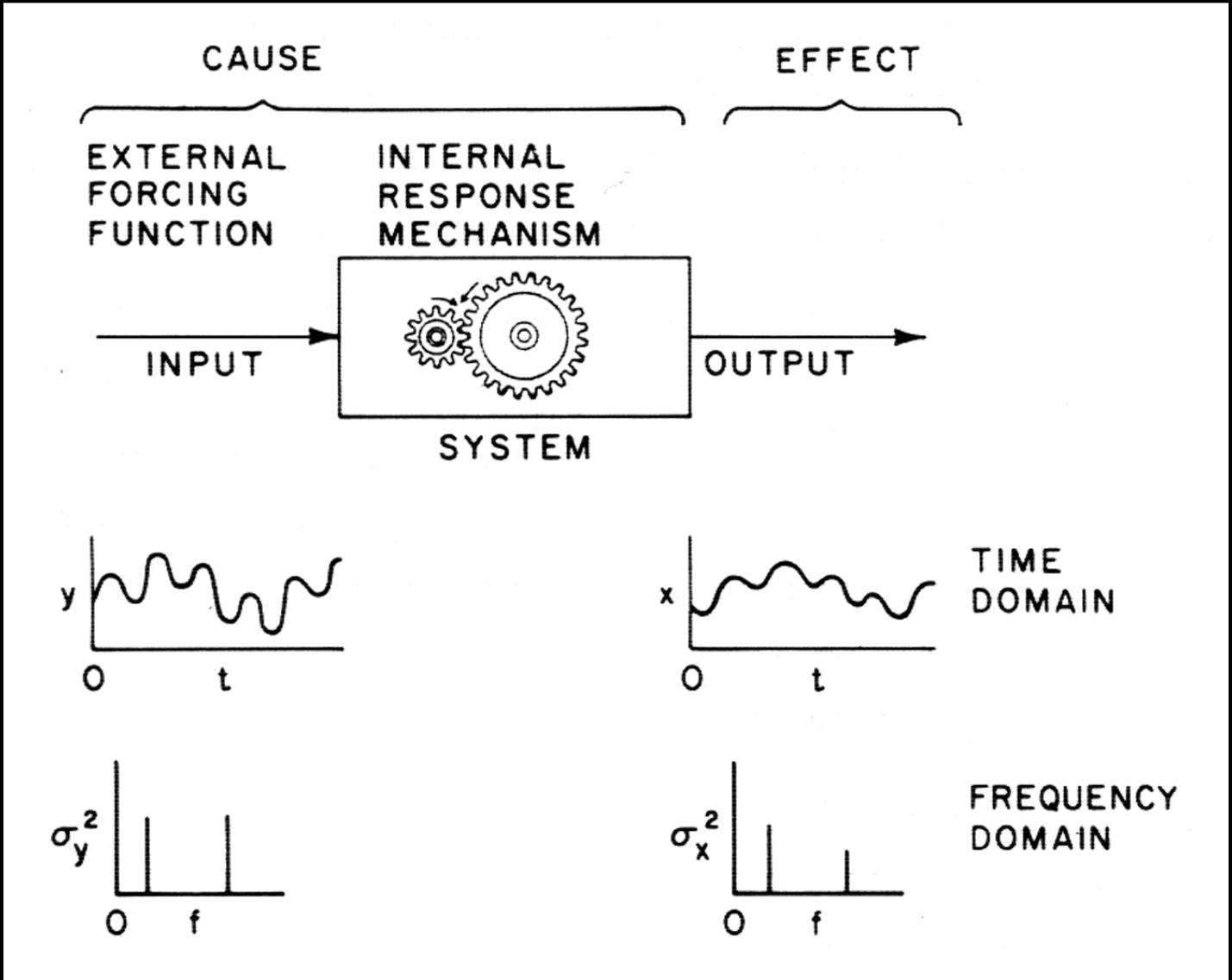
Understanding Climate Dynamics and the Climate Record



Orbital Parameters | **Climate System** | **Geological Record**

(Imbrie, 1982)

Ingredients to Decipher Mars Water & Climate History:

1) The Cause: External Forcing Function:

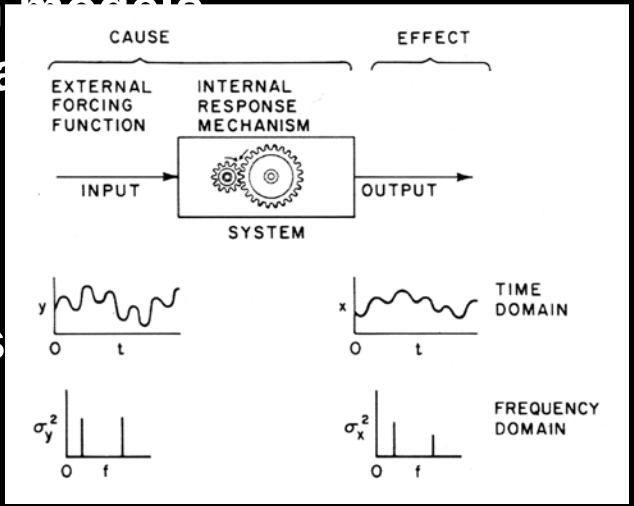
- -Very strong orbital parameter signals relative to Earth.
- -Precise solution of evolution of Mars' spin over 10-20 Ma.
- -Statistical study of its possible evolution over 250 Ma and beyond.
- -Obliquity: Maximum: 82 º; Average 37.62º.
- -Probability of obliquity >60 º in past 1 Ga is 63.0%; 89% in past 3 Ga.

2) The Climate System: The Internal Response Mechanism:

- -Know how input signals linked to insolation.
- -Increasingly sophisticated general circulation models
- -Full 3-D simulations, include water vapor beha

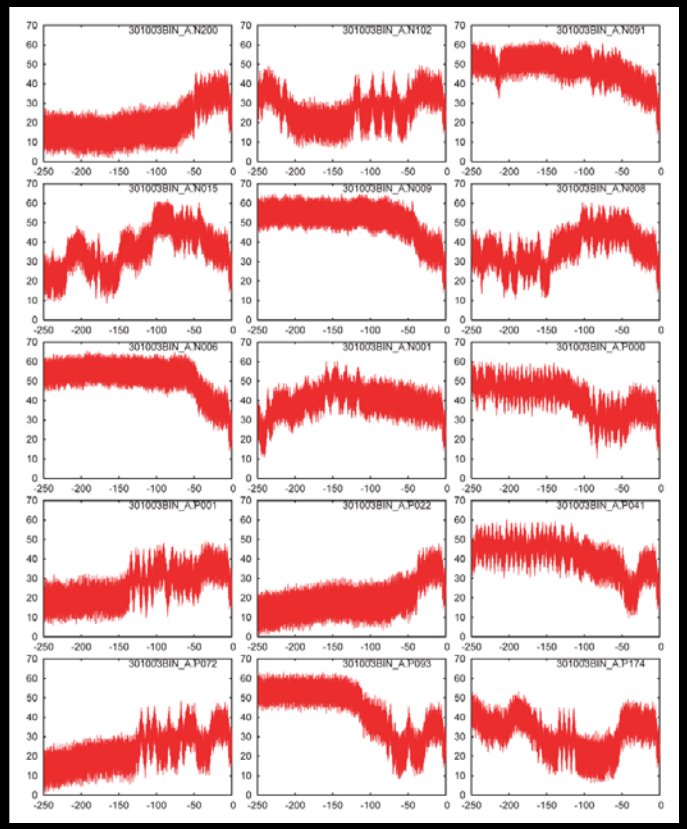
3) The Effect: The Geological Record:

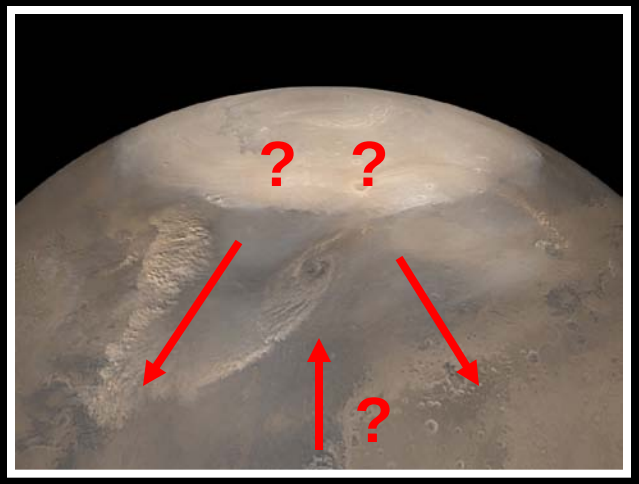
- -Rich geological record spanning >4 Ga.
- -Polar caps: 3 km thick, layered, CO_2, H_2O, dus
- -International Mars Exploration Program.



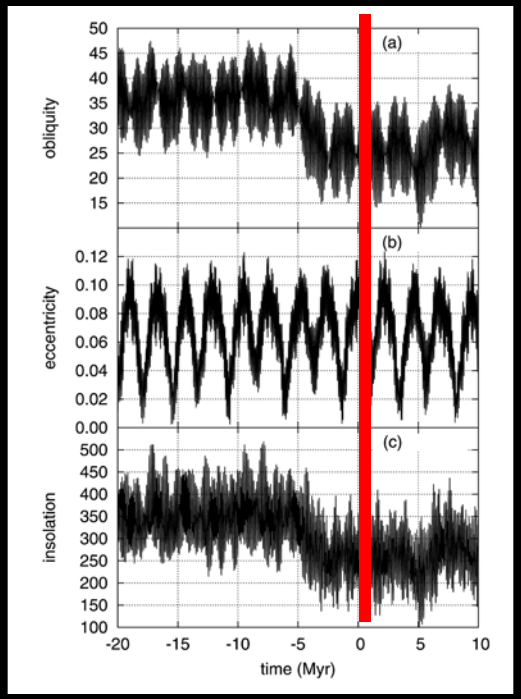
Major Uncertainties Remain

- History of obliquity prior to 10-20 Ma?
- Transit paths of polar water vapor?
- Localities of its ultimate deposition?
- Predicted maximum accumulation?

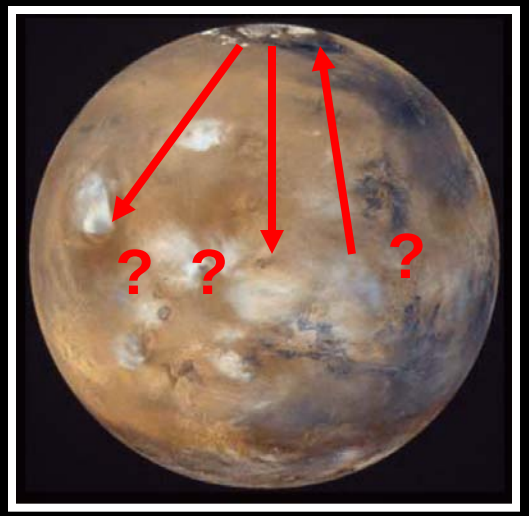




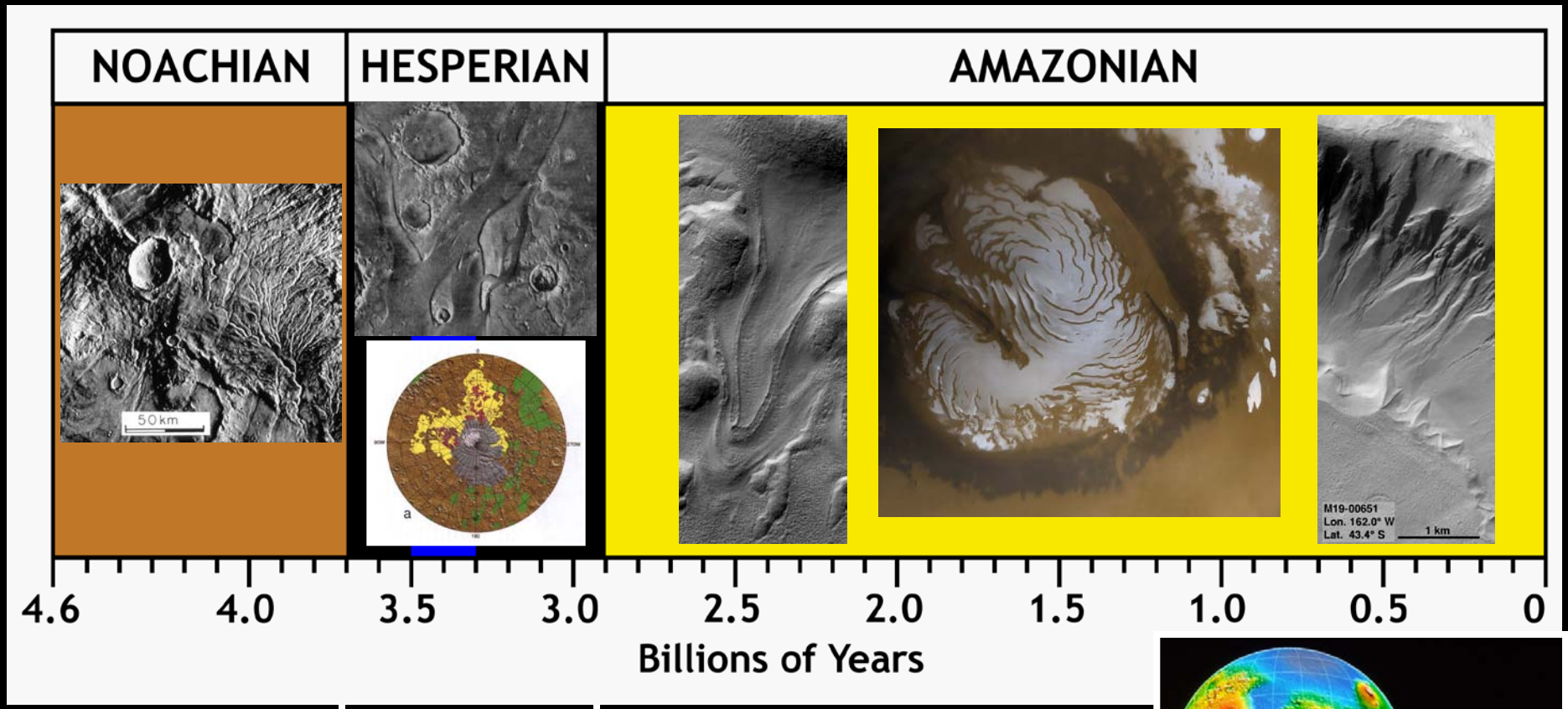
Transit Paths



Deposition and Accumulation



Water and Climate on Mars: Relation to Geologic History



- Heavy impact bombardment.
- Valley networks.
- "Warm/Wet" early Mars?

-Volcanism.
- Outflow channels.
- Oceans?
- South circumpolar deposits.

- Low impact rates.
- Tharsis volcanism continues.
- Outflow channels continue.
- Late-stage polar caps.
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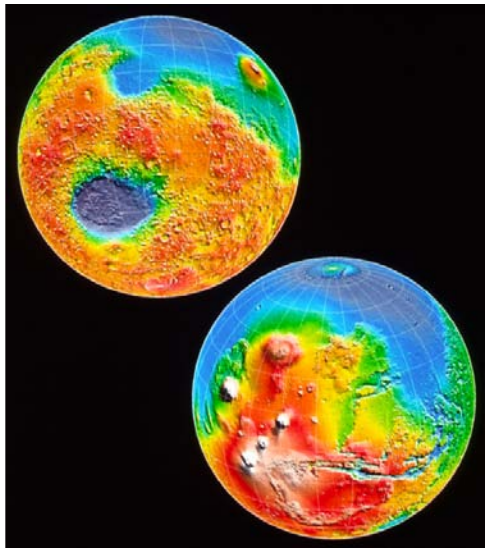

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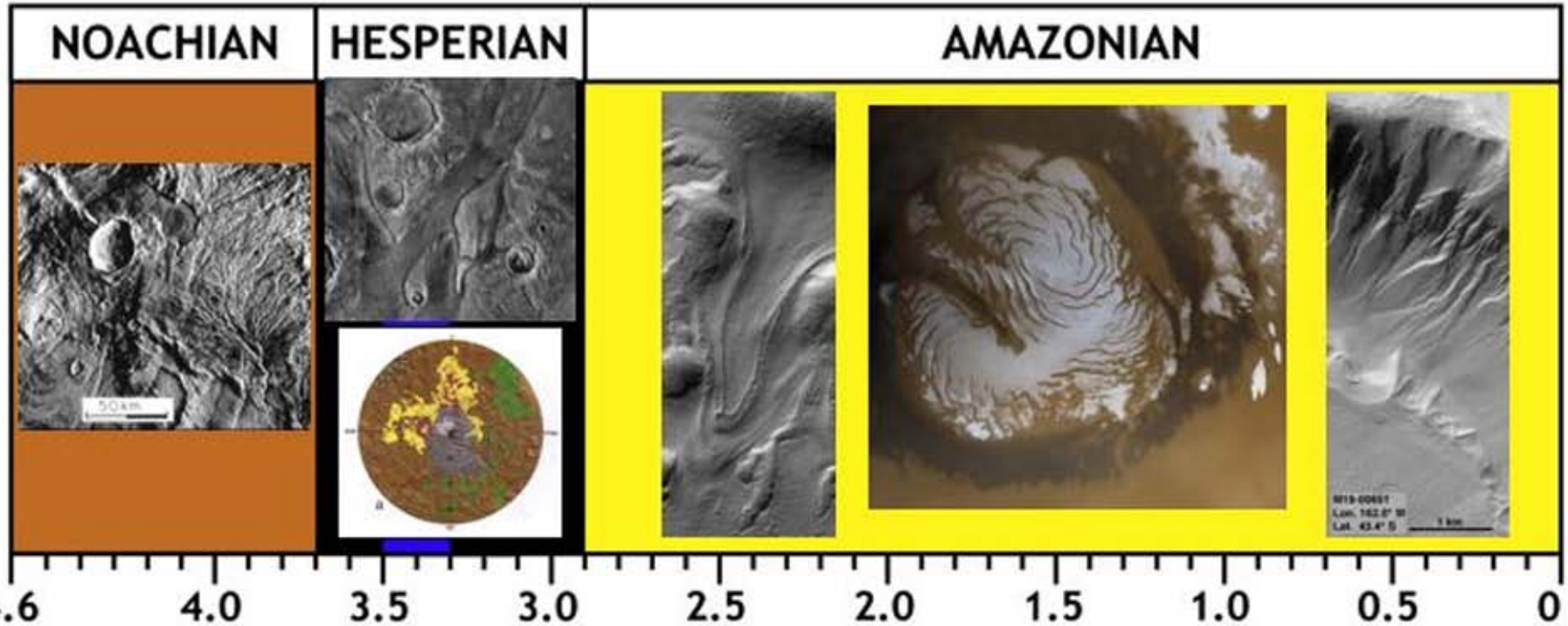

- Heavy impact bombardment, volcanism.
- Valley networks.
- Open-basin lakes.
- "Warm/Wet" early Mars?

- Volcanism.
- Outflow channels.
- Oceans?
- South circumpolar glacial deposits.

- Low impact rates.
- Tharsis volcanism continues.
- Outflow channels continue at much lower rate.
- Tropical and mid-latitude glaciation.
- Late-stage latitude dependent mid-high latitude layers.
- Late-stage polar caps.
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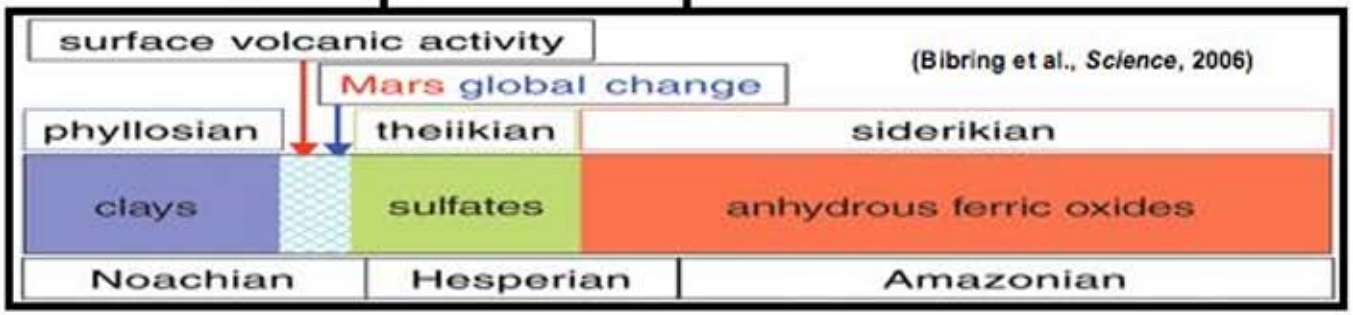
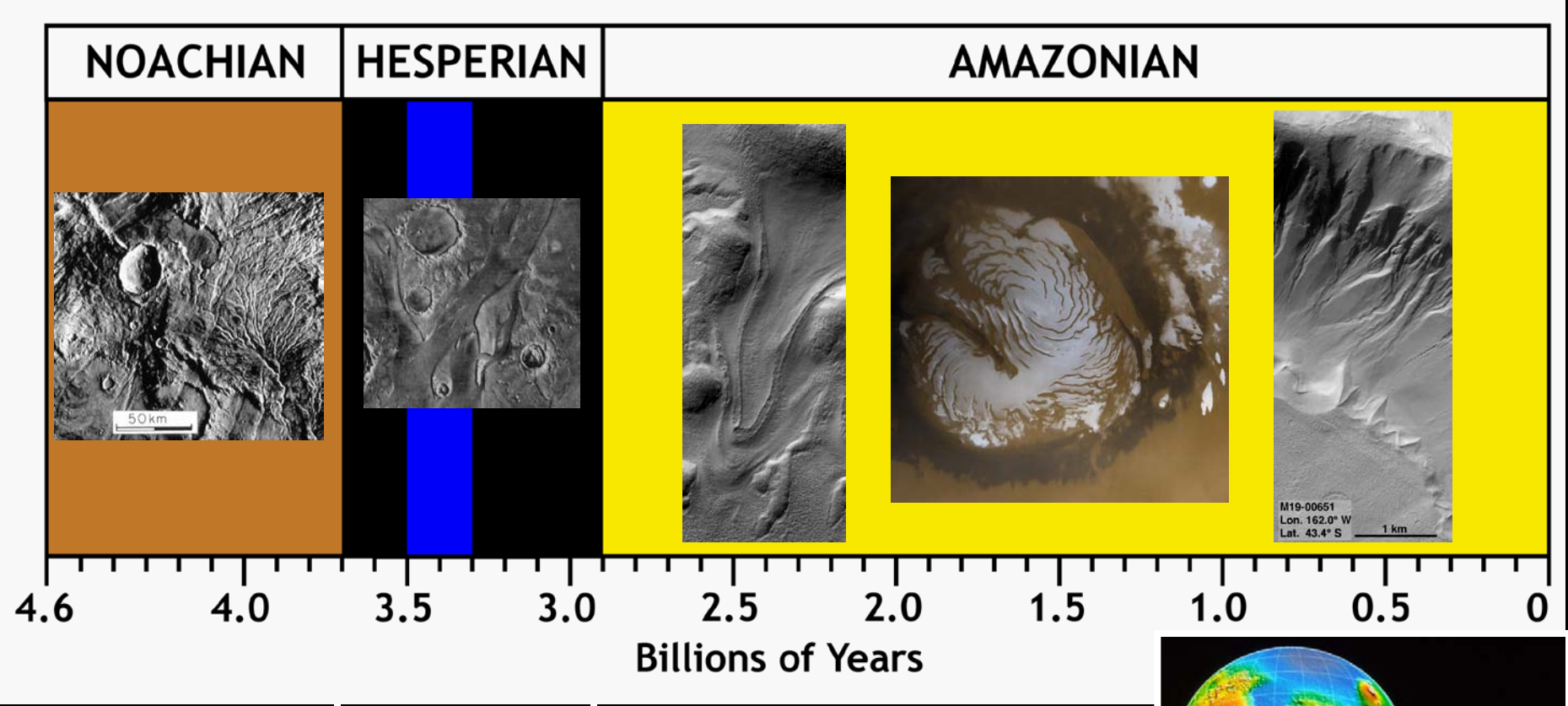


(Bibring et al., *Science*, 2006)

Water on Mars: Relation to Geologic History



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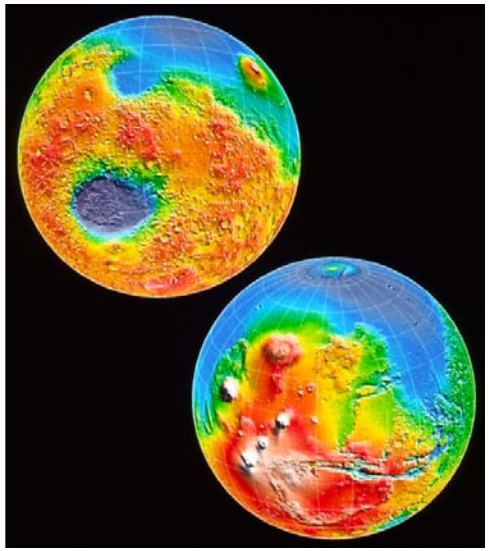

Current conditions at the surface:

- Mean atmospheric pressure is ~ 6 mbar (Earth: 1000 mbar).
- Mean temperature is ~ -40°C (Earth: +17°C).
- Under present conditions, liquid water unstable on the surface of Mars.
- Mars currently a very cold hyperarid polar desert.

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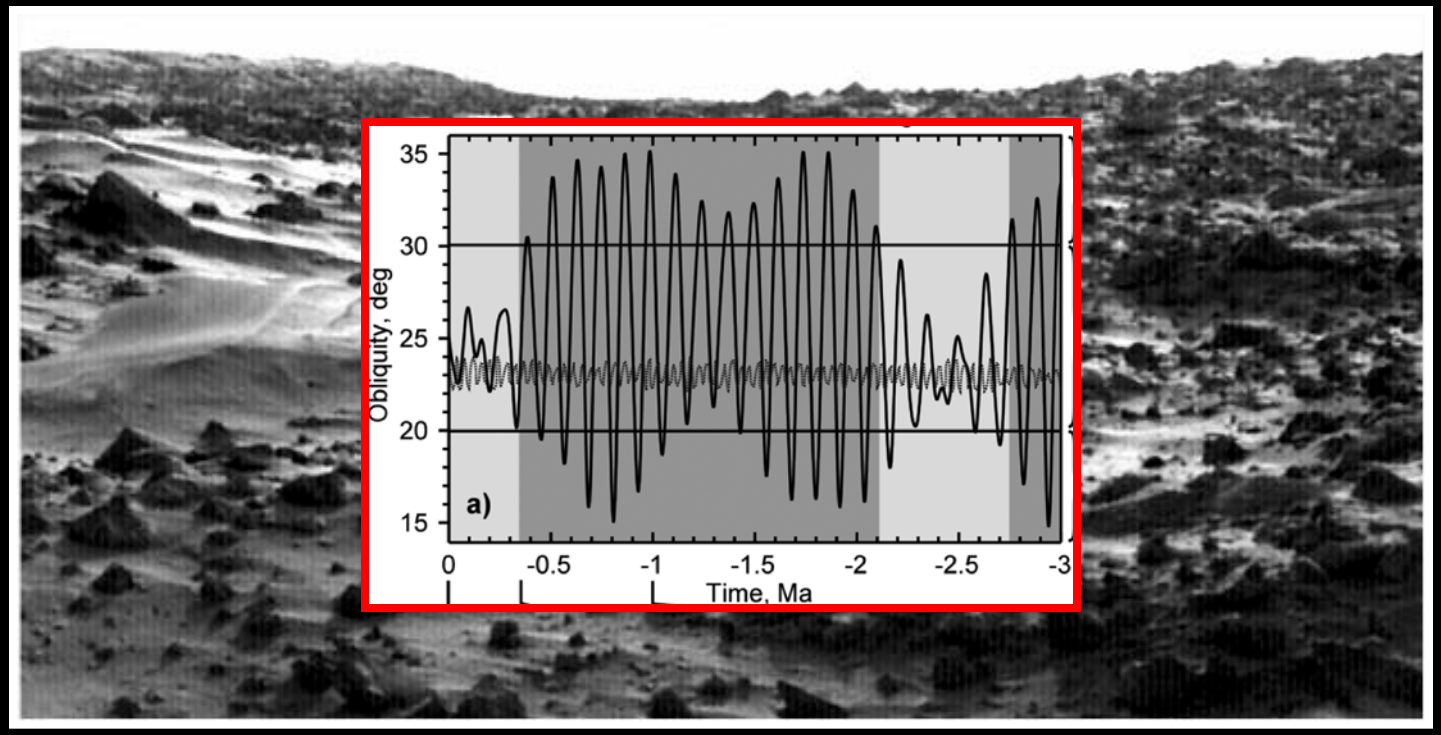

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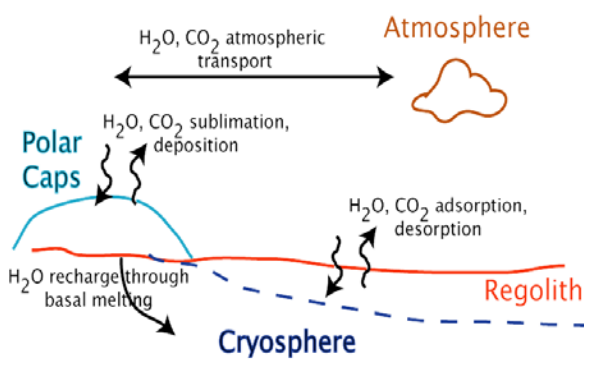
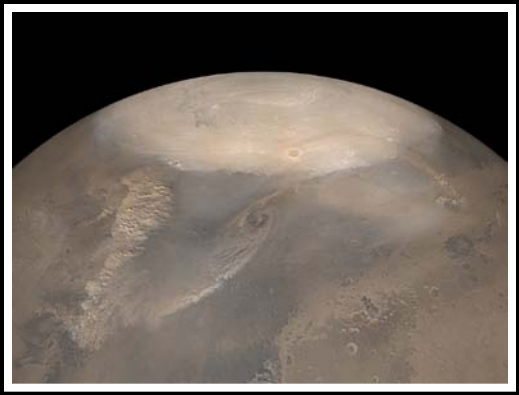
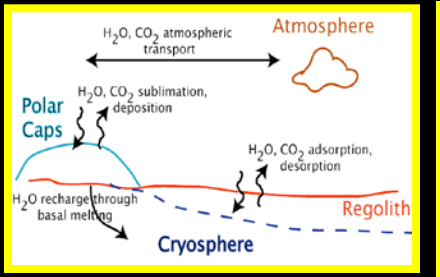
Evidence for Non-Polar Ice Deposits in the Past History of Mars

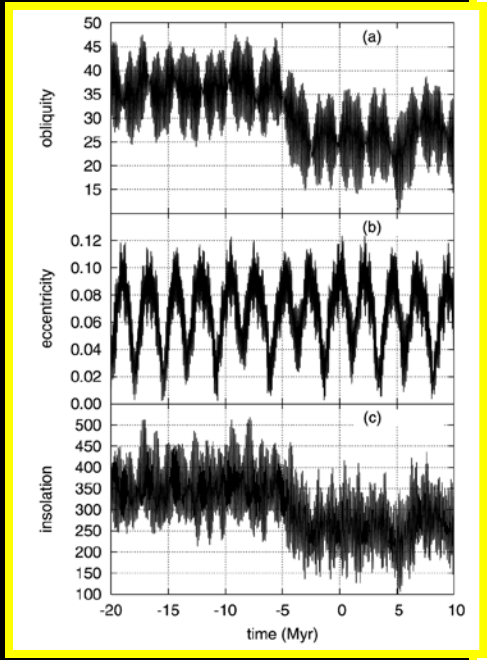
- What is the structure and history of the polar caps?
- What is the geological evidence for non-polar ice deposition?
- Where and when was non-polar ice deposited?
- Was there any sequestration of non-polar ice?
- Is there evidence of any non-polar ice deposits accessible at the present?
- What is the inventory of ice movement and sequestration through time?
- How do these deposits inform us about Mars' climate history?



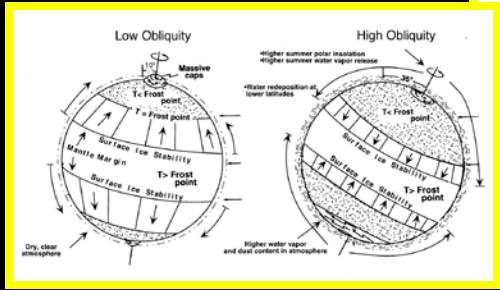


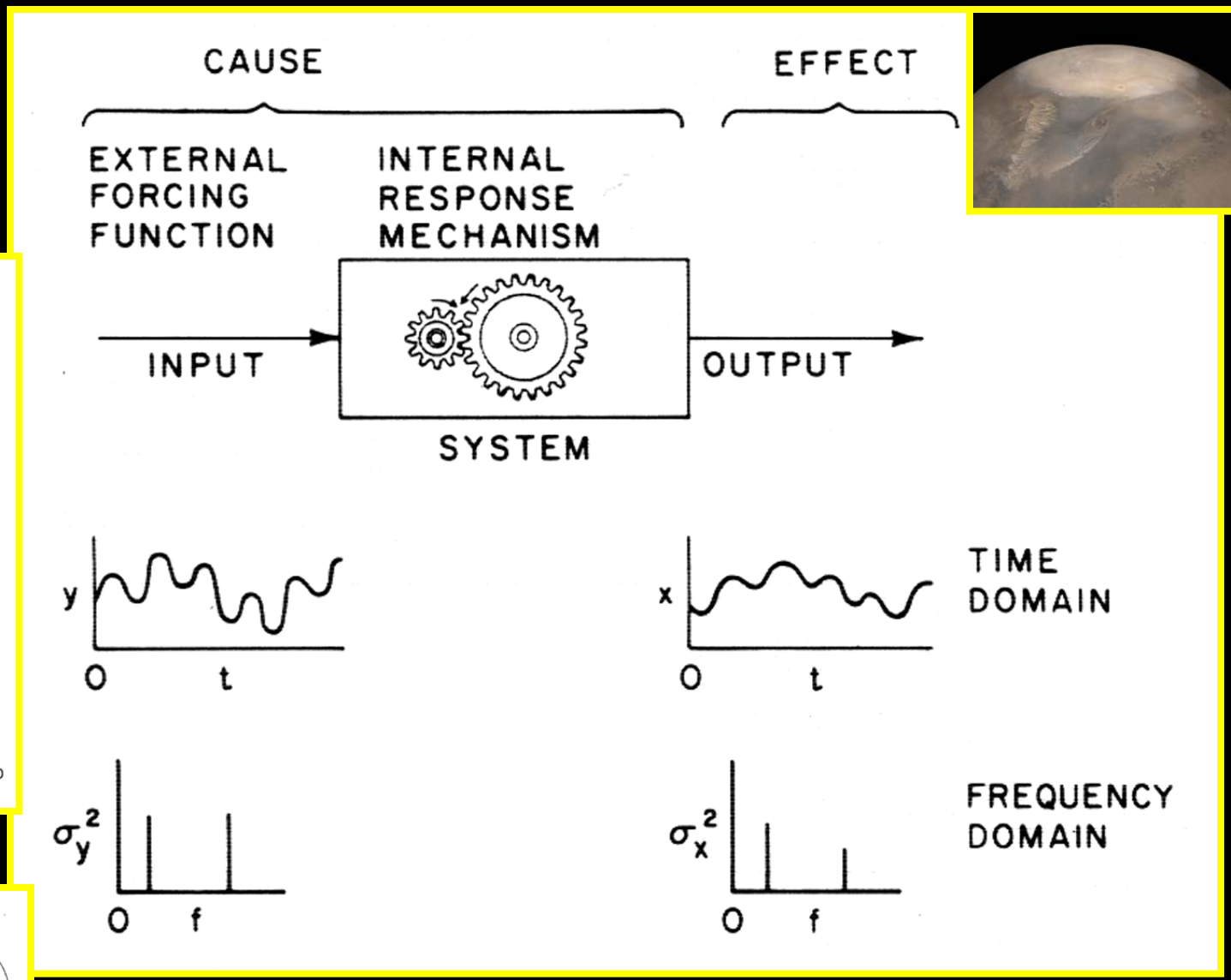
Understanding Climate Dynamics and the Climate Record





(Laskar et al., 2004)

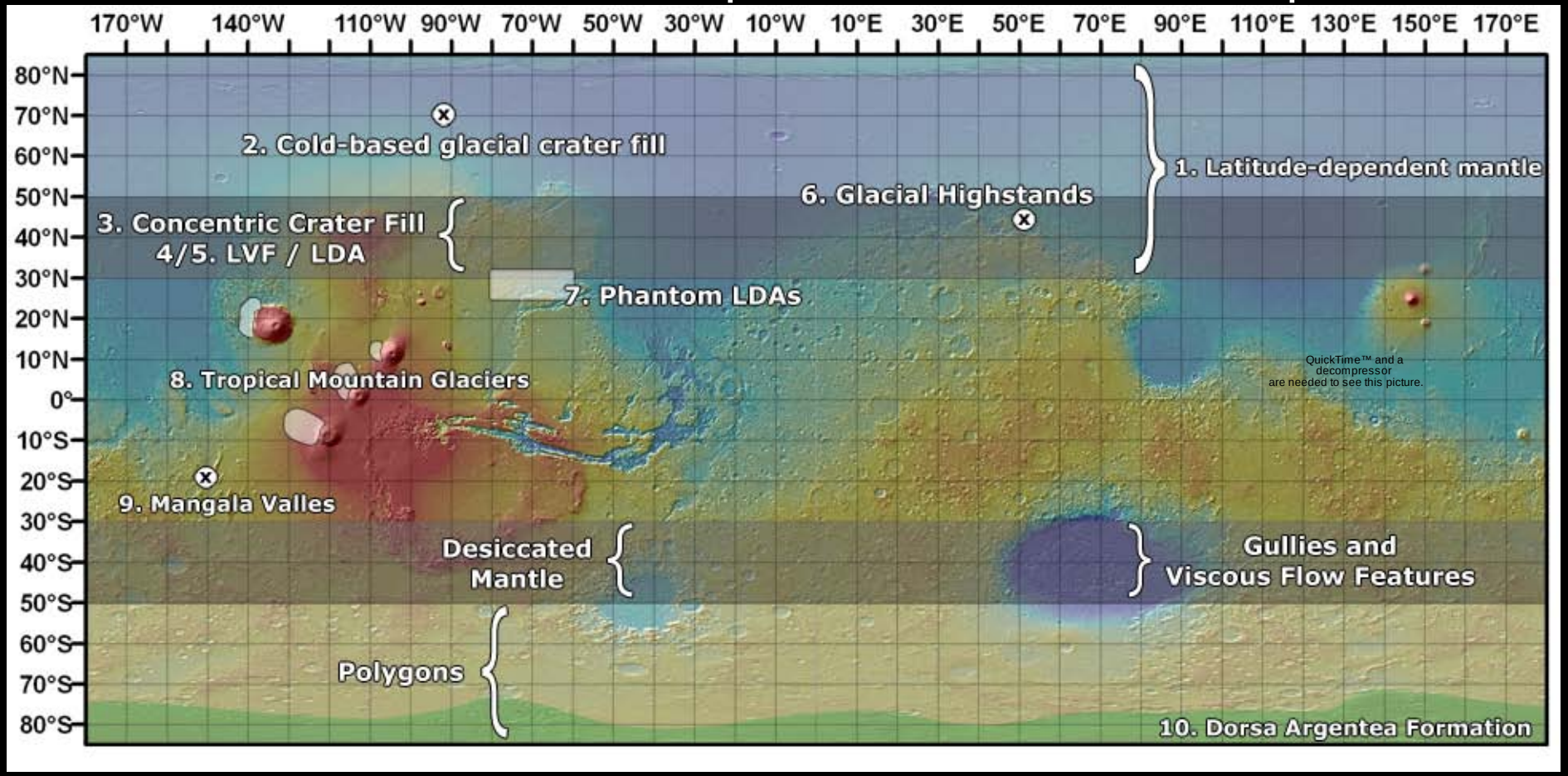


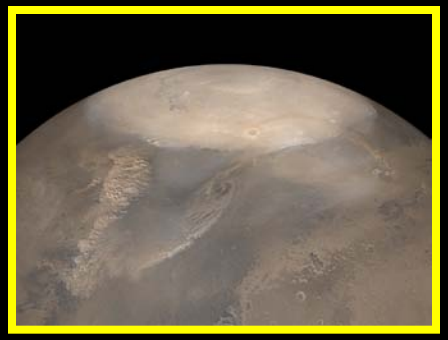


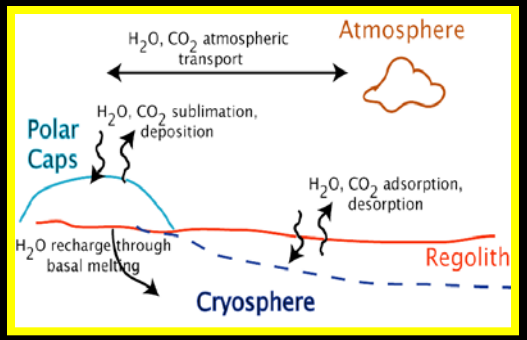
Orbital Parameters | **Climate System** | **Geological Record**

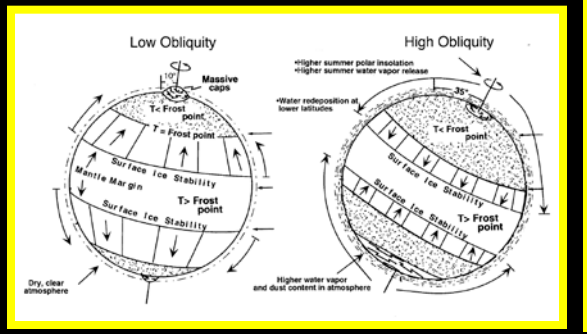
(Imbrie,

Non-Polar Latitude-Dependent Ice-Related Deposits









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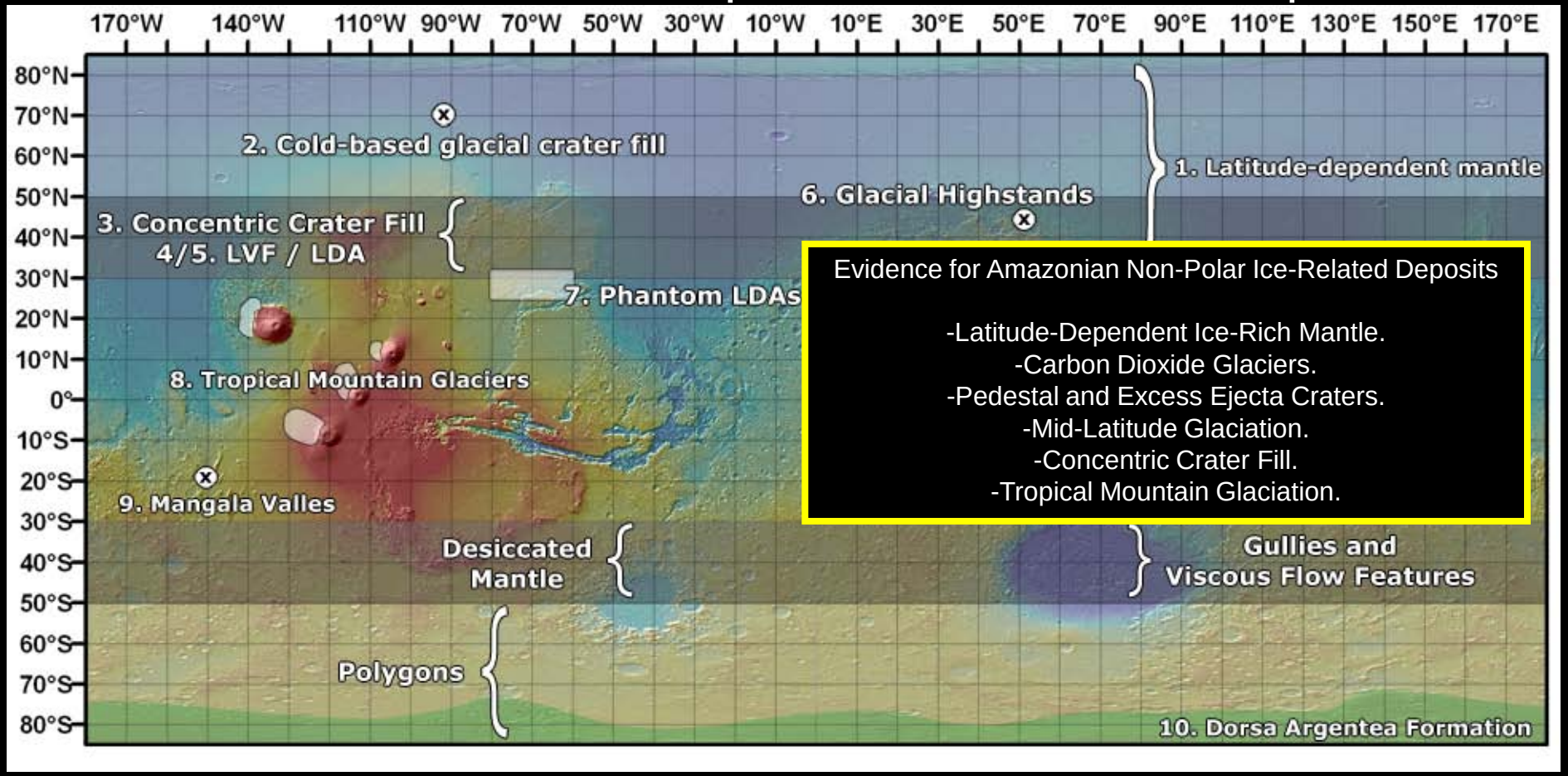
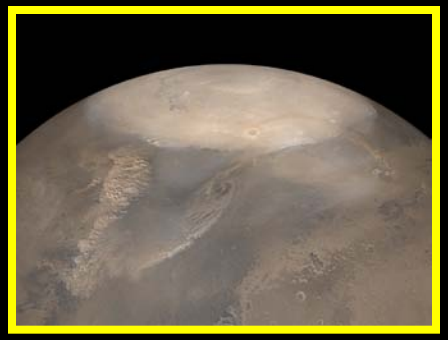
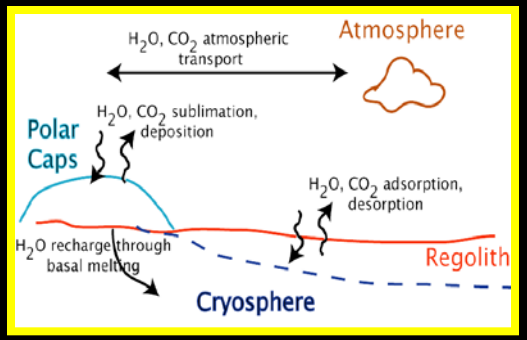
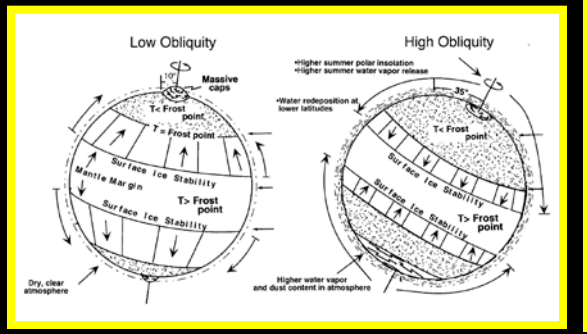


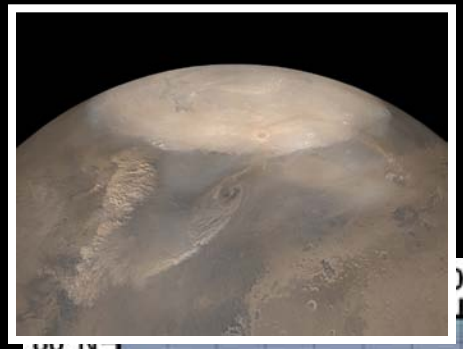
Evidence for Amazonian Non-Polar Ice-Related Deposits

-Latitude-Dependent Ice-Rich Mantle.
-Carbon Dioxide Glaciers.
-Pedestal and Excess Ejecta Craters.
-Mid-Latitude Glaciation.
-Concentric Crater Fill.
-Tropical Mountain Glaciation.









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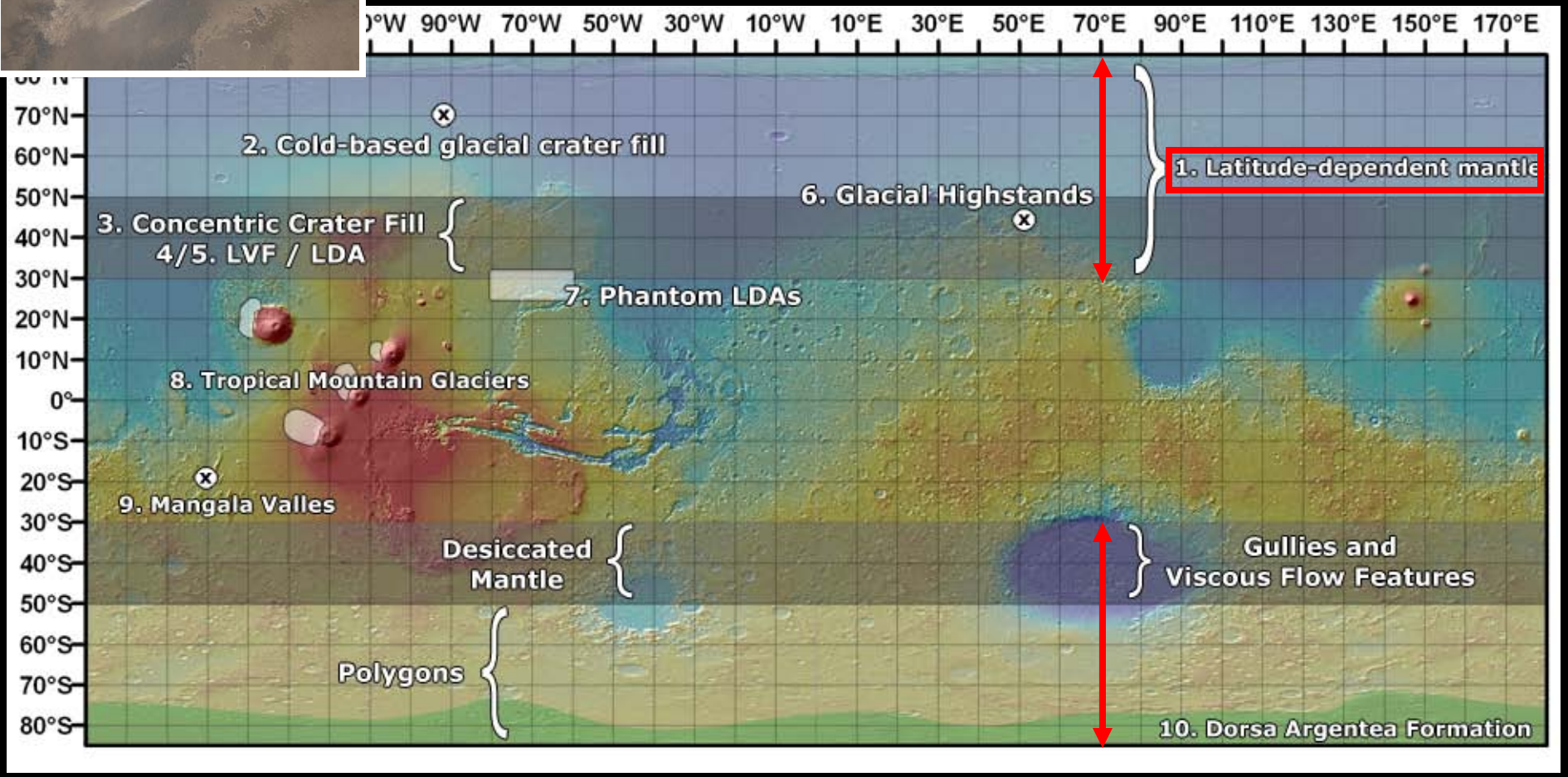
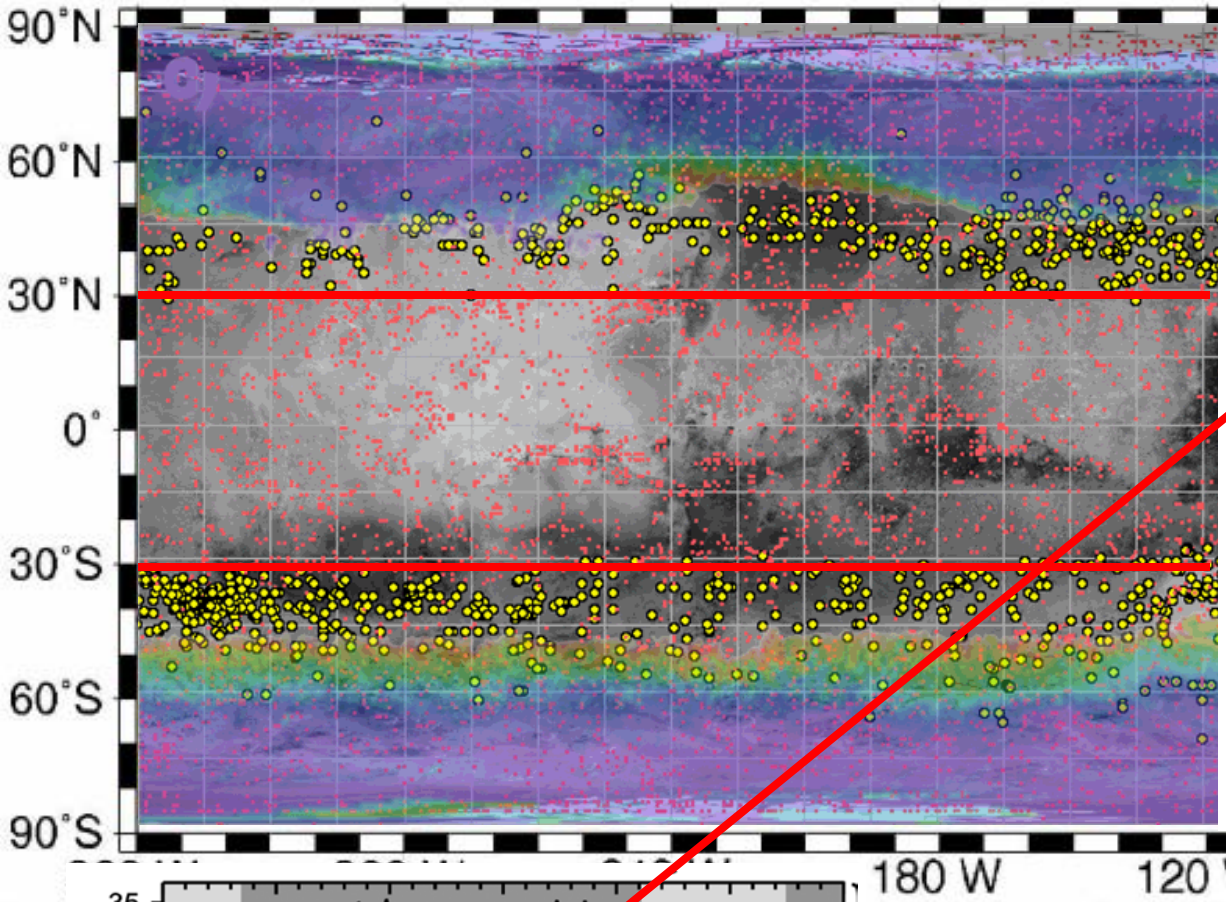
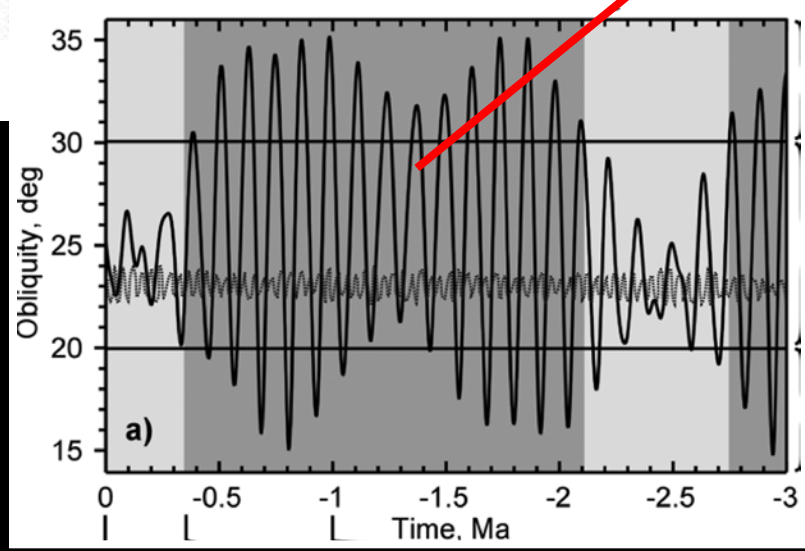


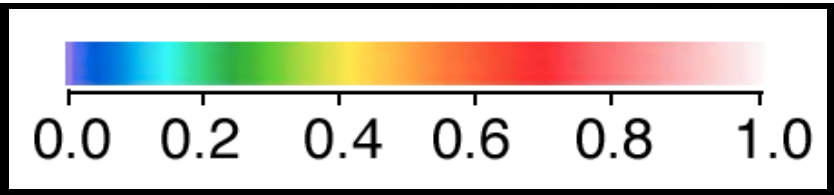
Latitude-dependent layer found above 30º North and South latitude.

(Mustard et al., 2001; Kreslavsky and Head, 2000, 2002; Milliken et al., 2003; Head et al., 2003)

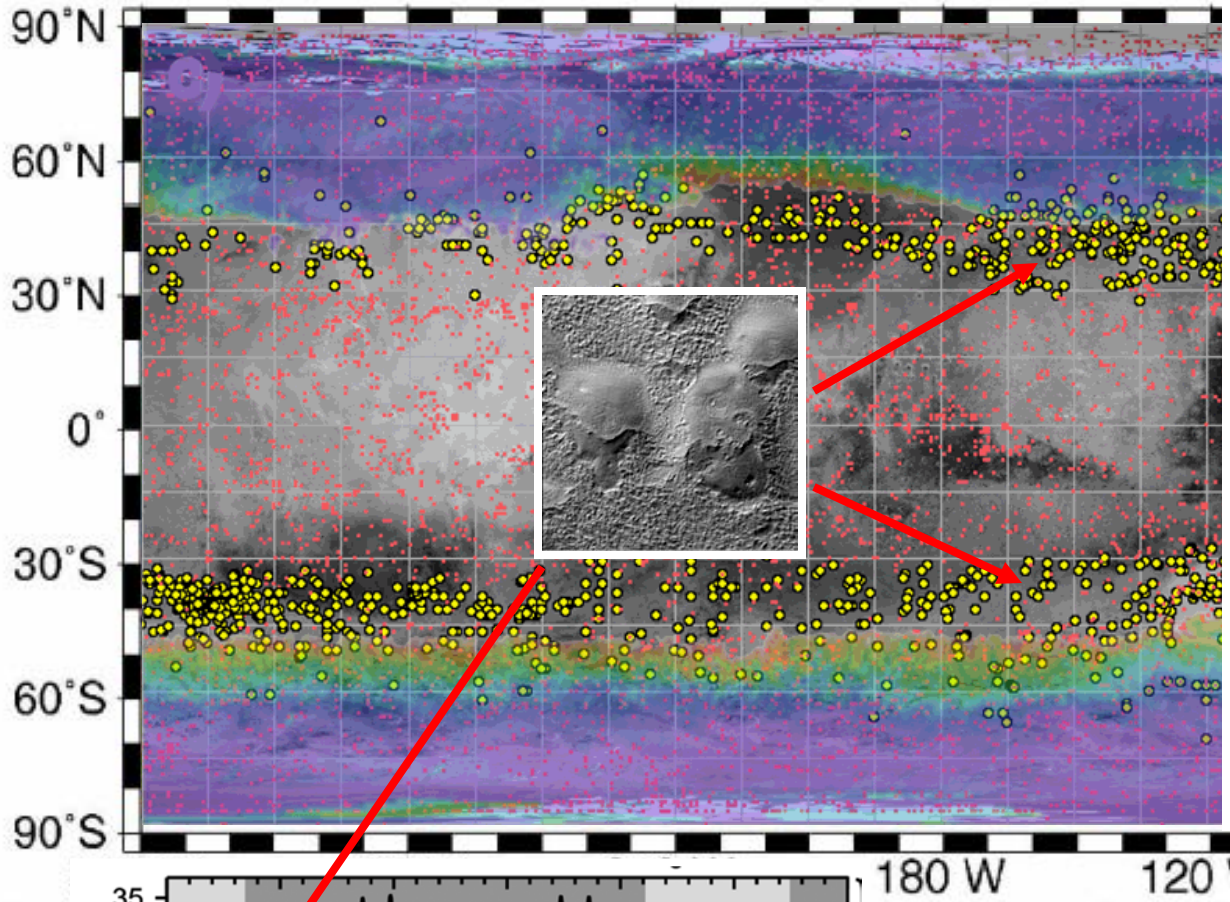


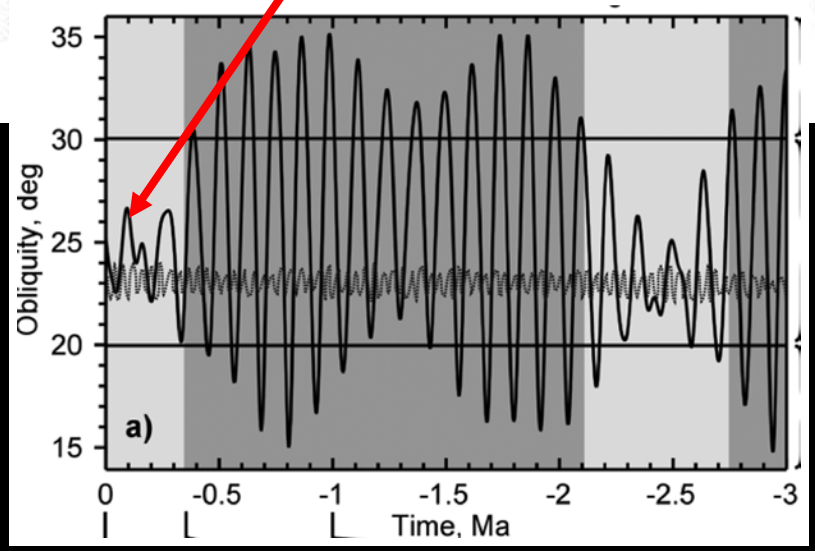
(Head et al., 2003)

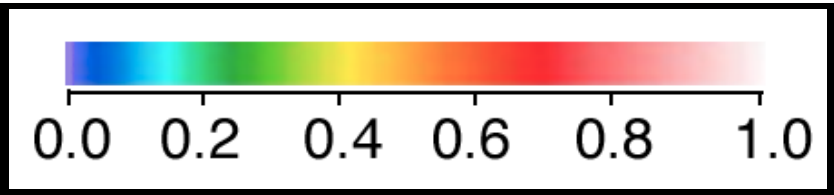




Ice Table Depth [m]
Mellon, LPSC 34







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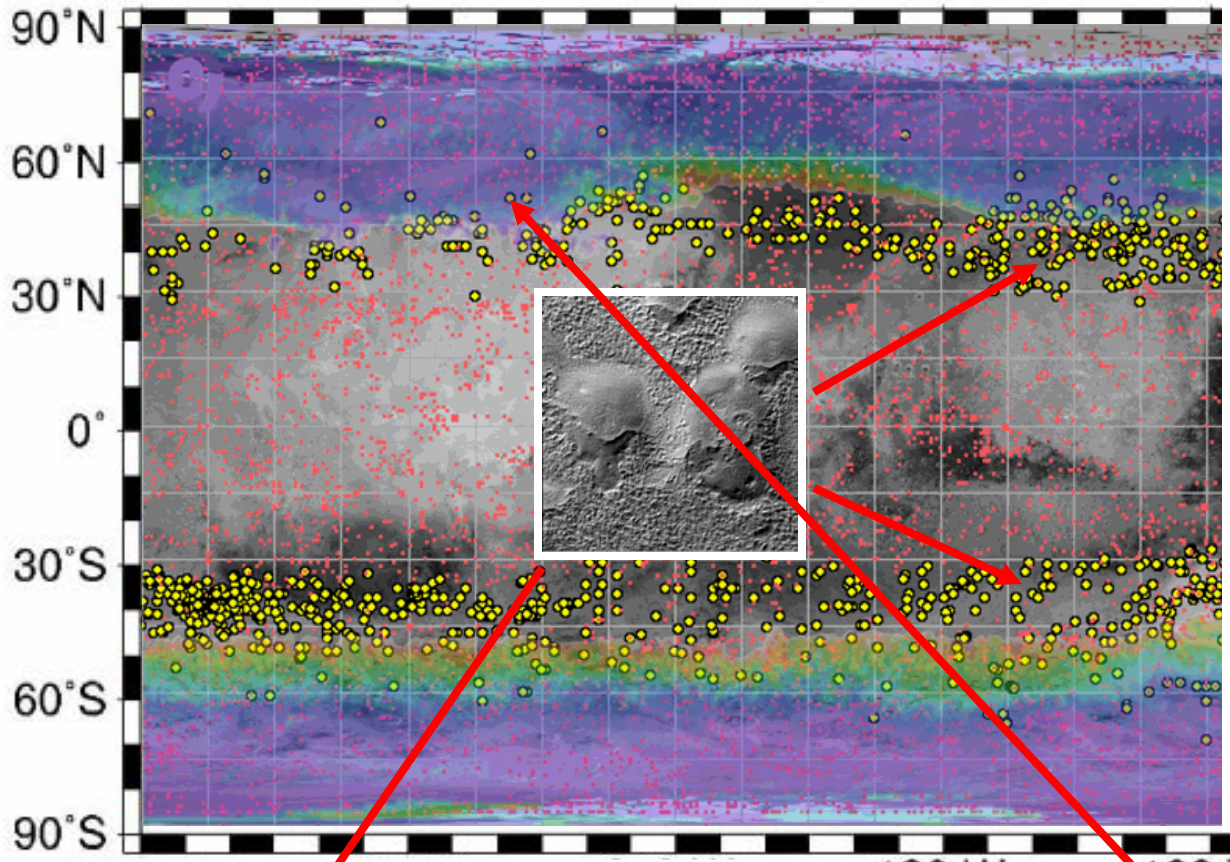

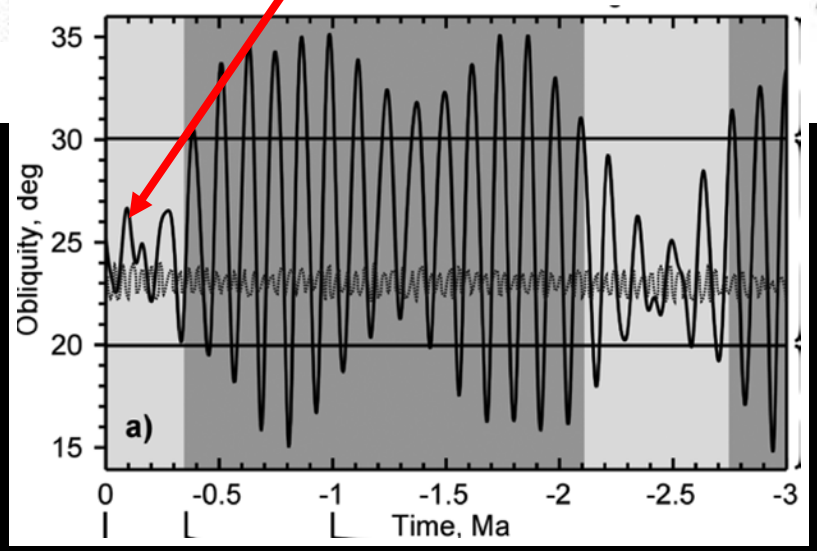

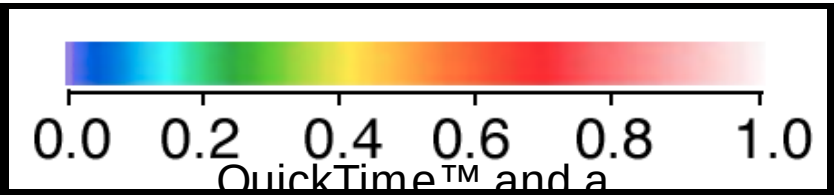

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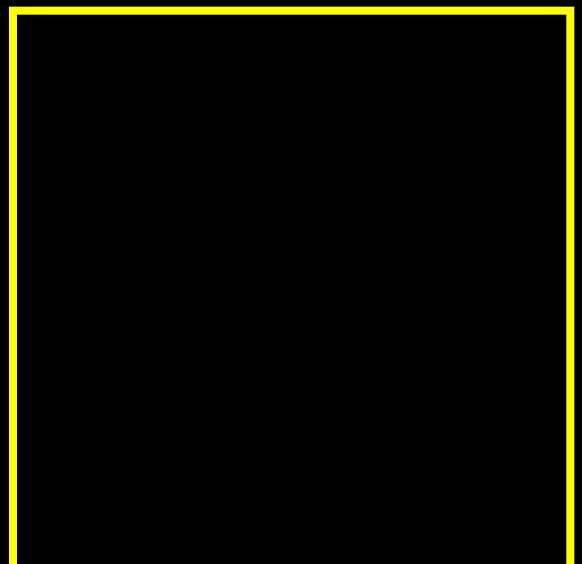
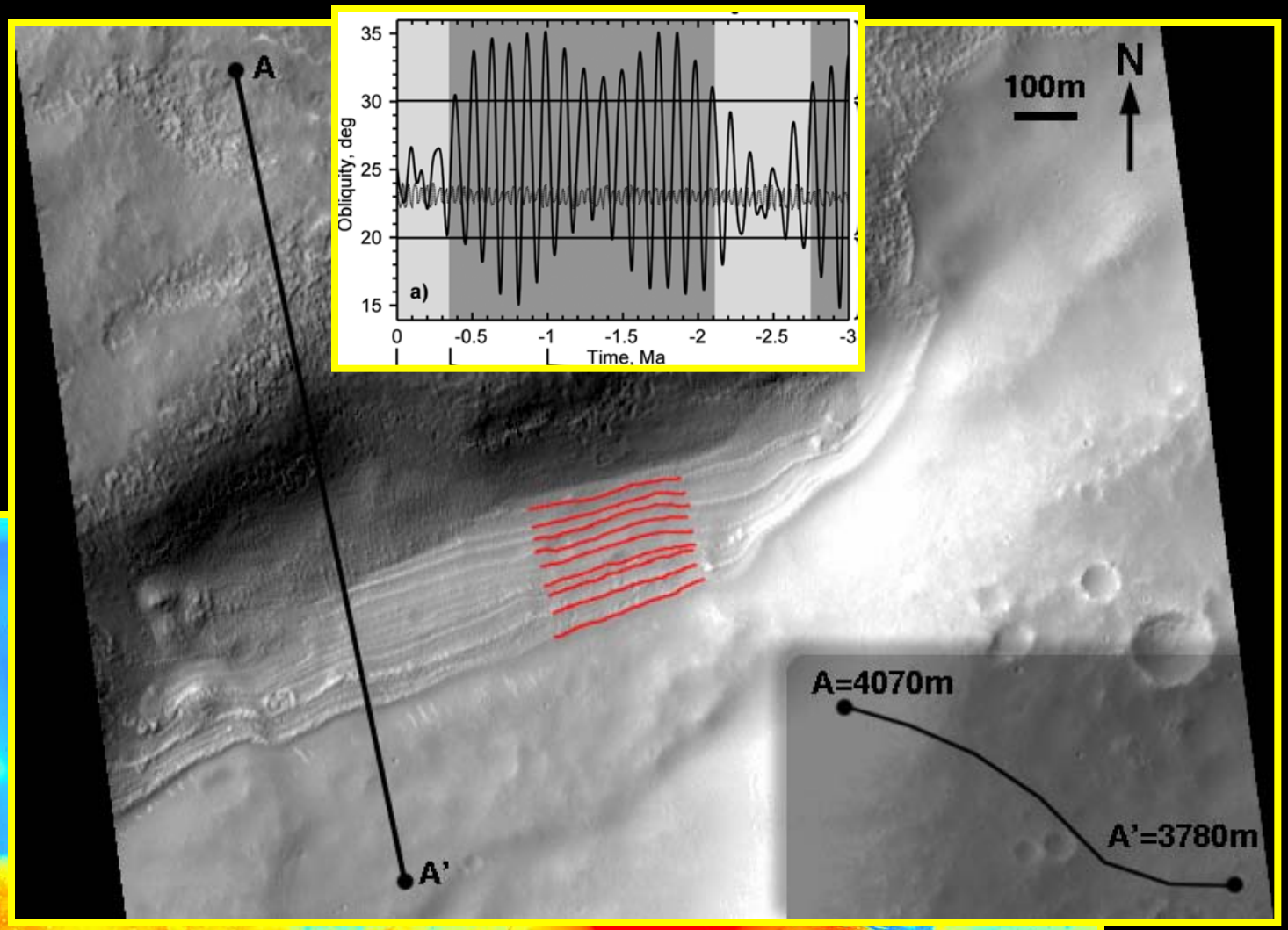
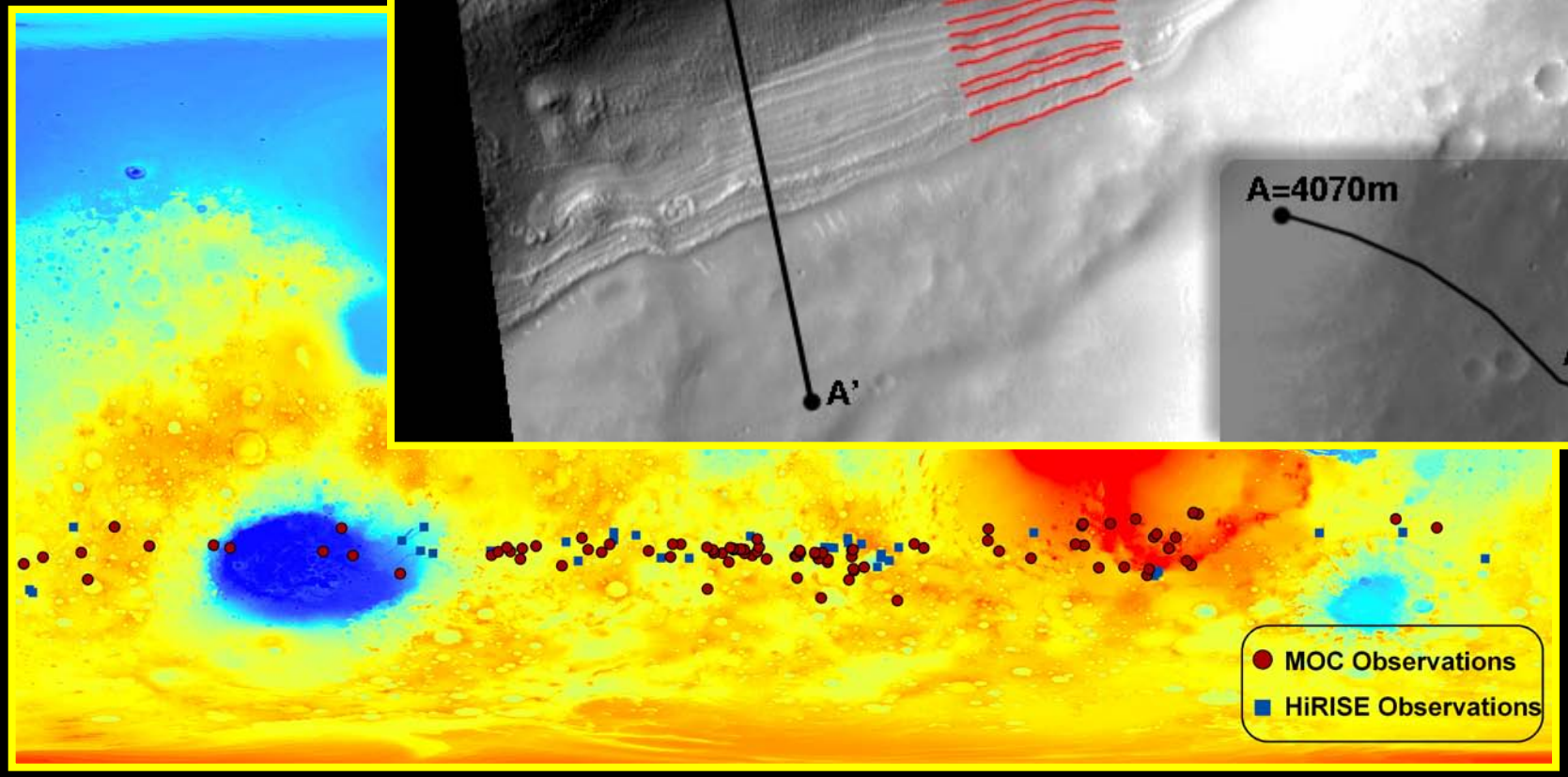


Observation of Buried Ice at Very Shallow Depth

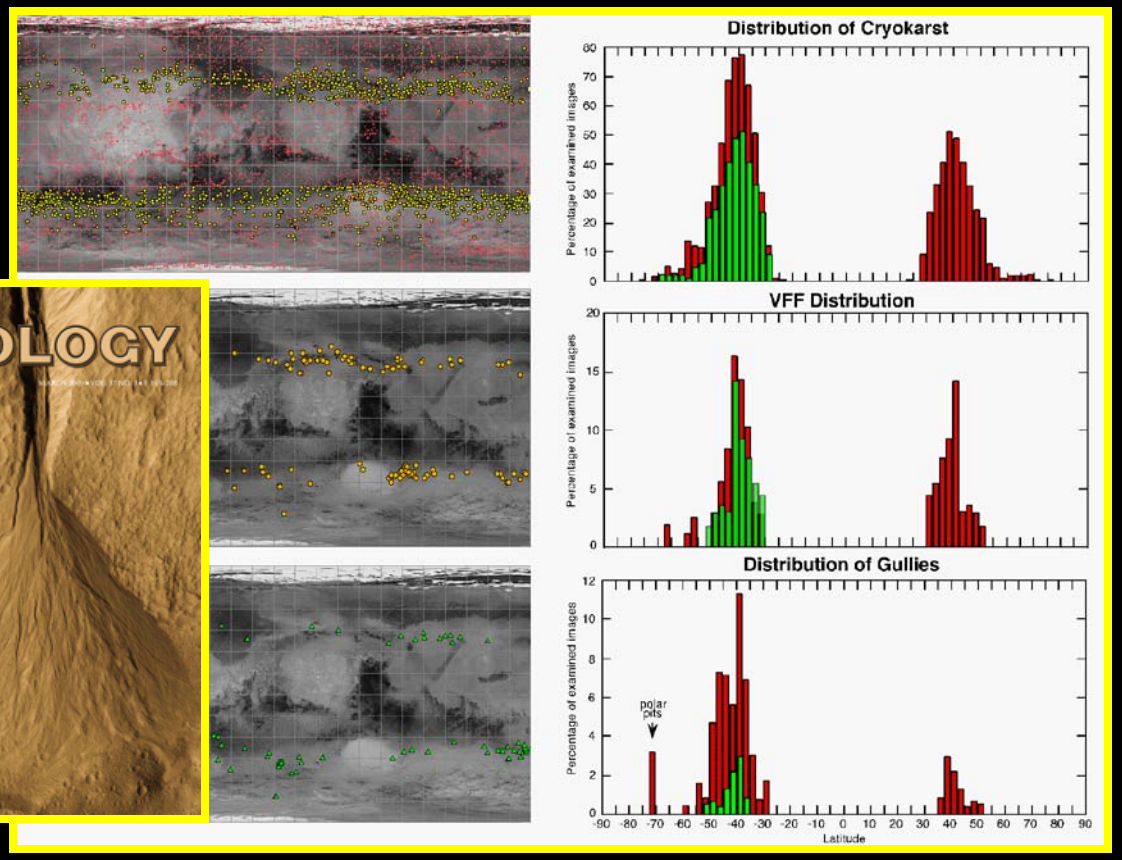
Multiple Layers in Mantle - Correlated with Obliquity Cycles.

(Schon and Head, 2009)





What is Relation of Mars Gullies to Regional Mantling Deposit?

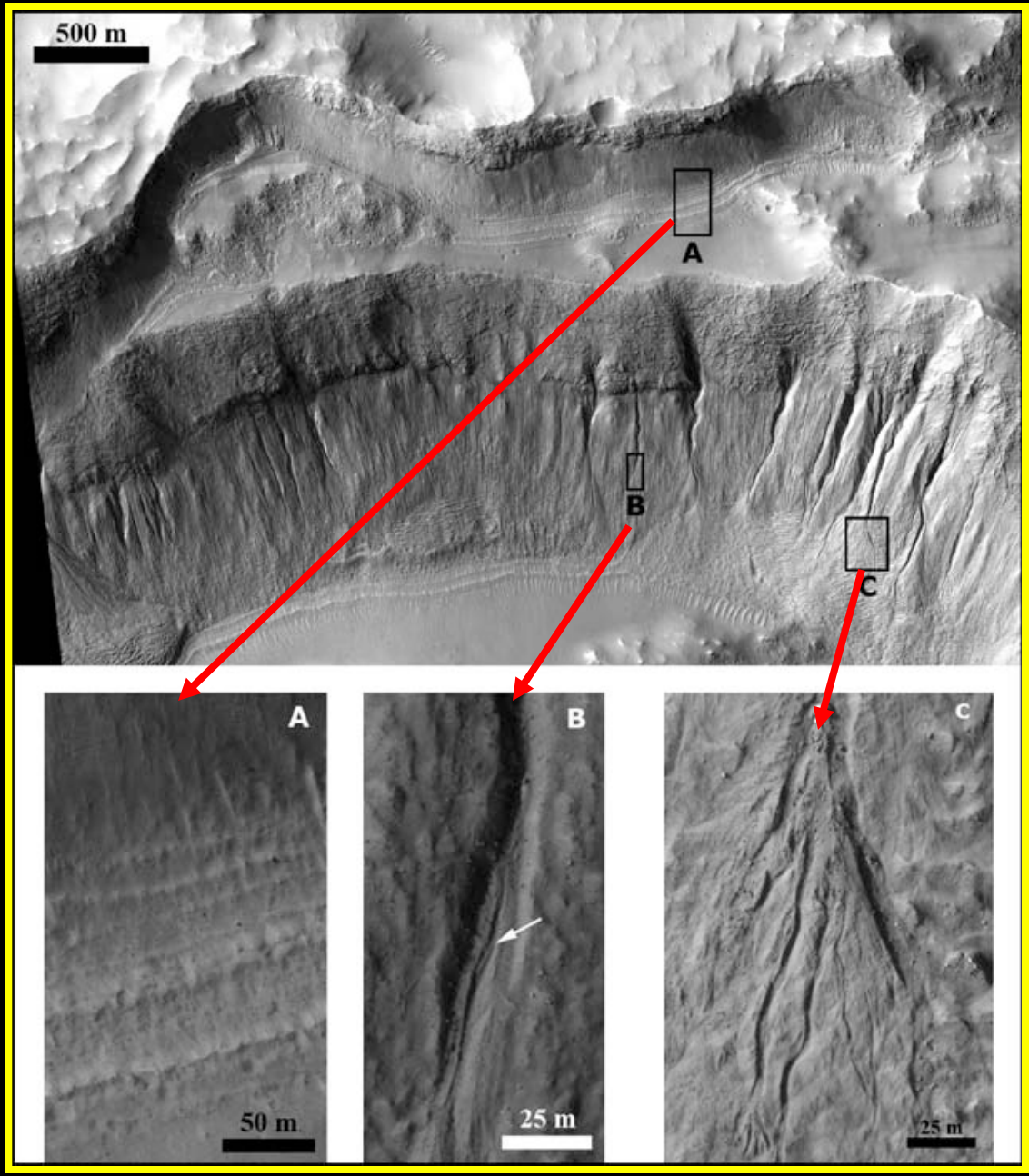


Mustard et al., 2000; Milliken et al., 2003; Head et al., 2003.

-What is the association of the recent ice-rich latitude-dependent climate-related mantle deposits and correlative features and structures?

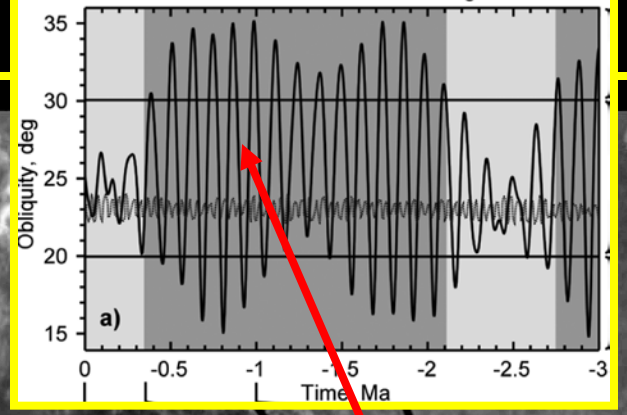
- **Gullies.**
- **Dissected Terrain (cryokarst) and Mantle Layering**

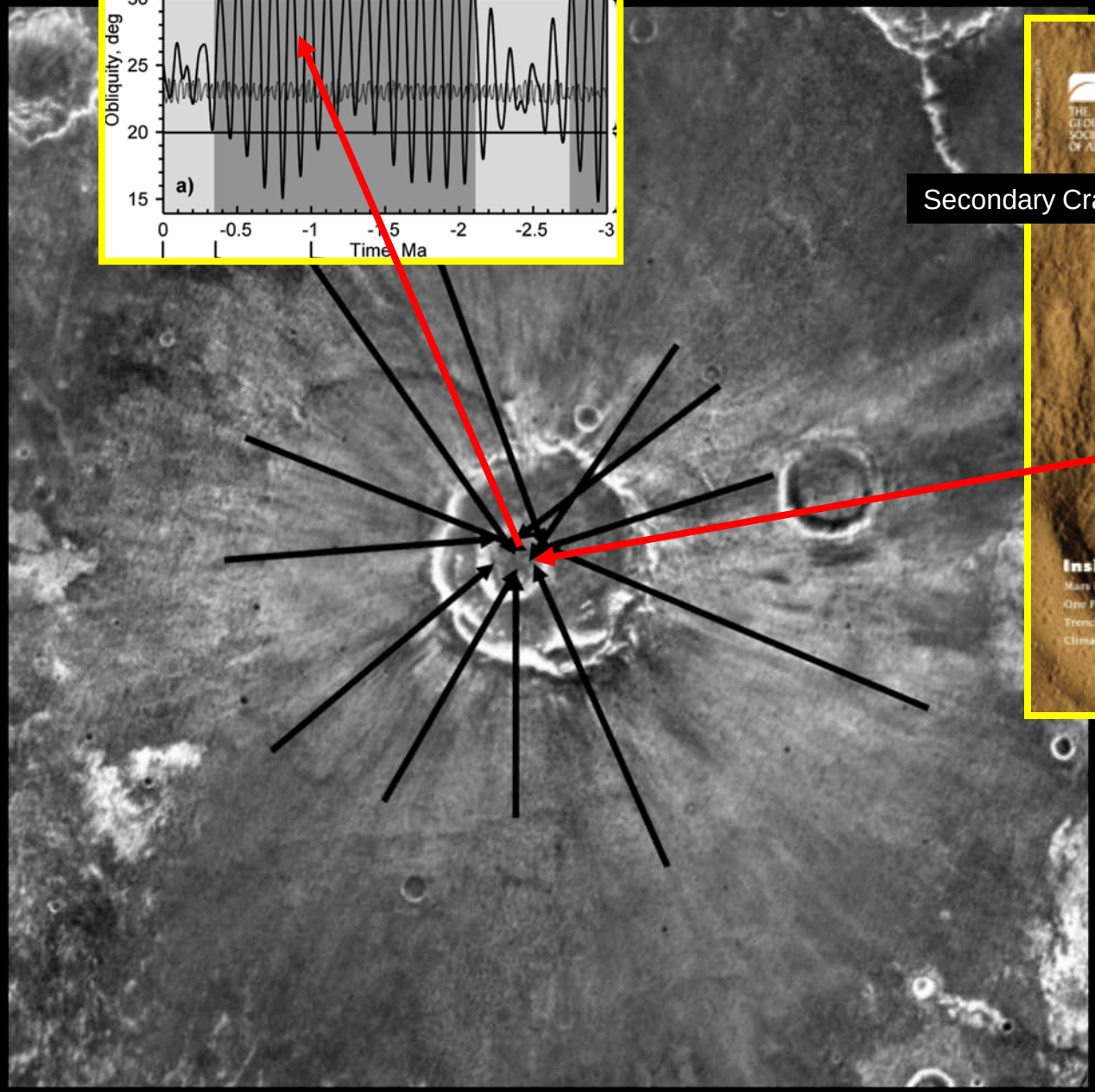
Correlation of Ice-Rich Latitude-Dependent Mantle and Related Gully Features.



Exposed Layered mantle = A
Gully alcoves and channels = B
Gully channels and fans = C

Dickson et al., 2007, 2009;
Schon and Head, 2007



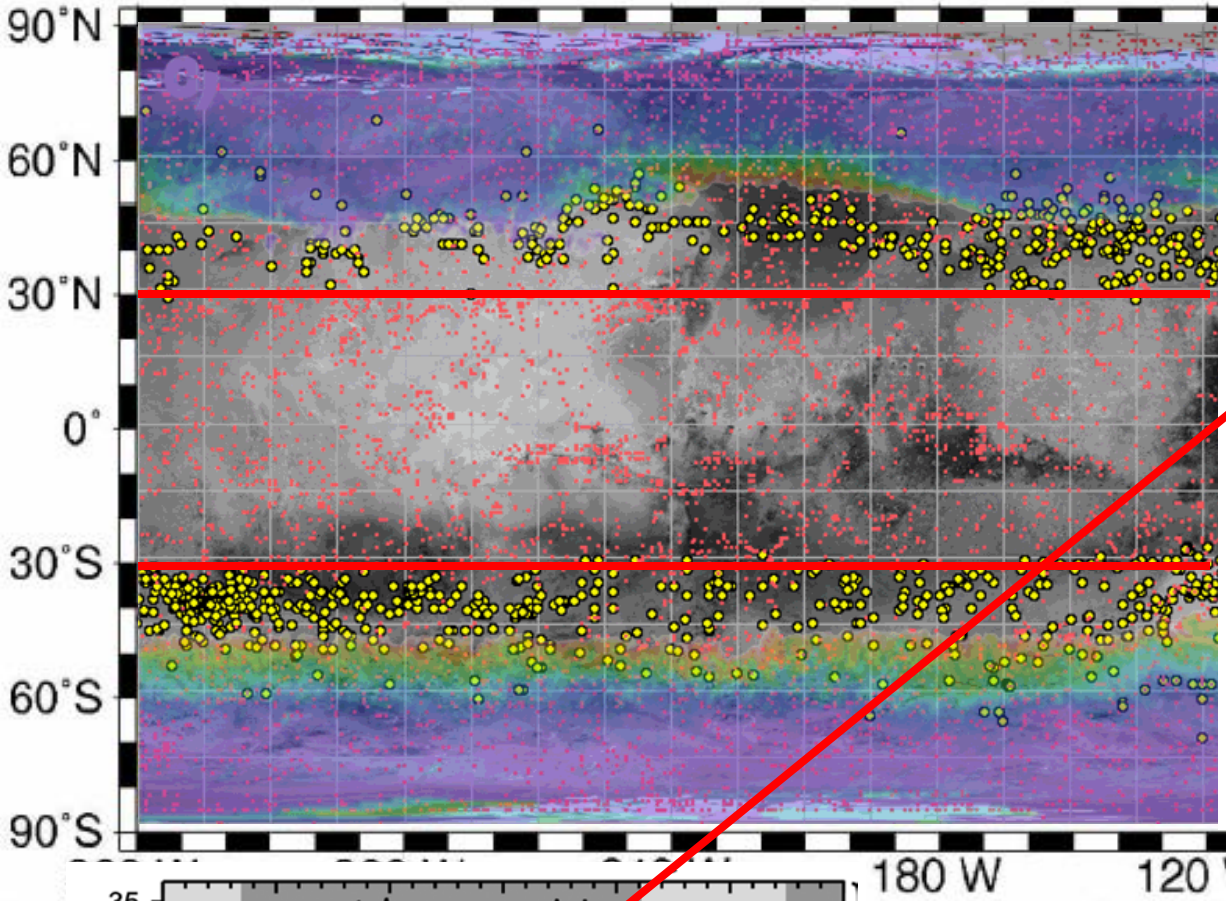


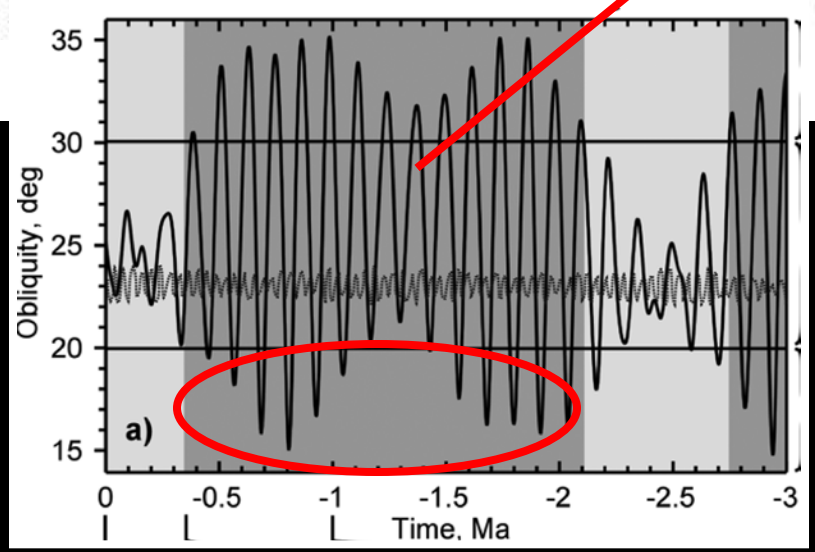
Secondary Crater Clusters

Trace
secondary crater cluster
back to parent crater
and date the crater.

Recent Liquid Water!

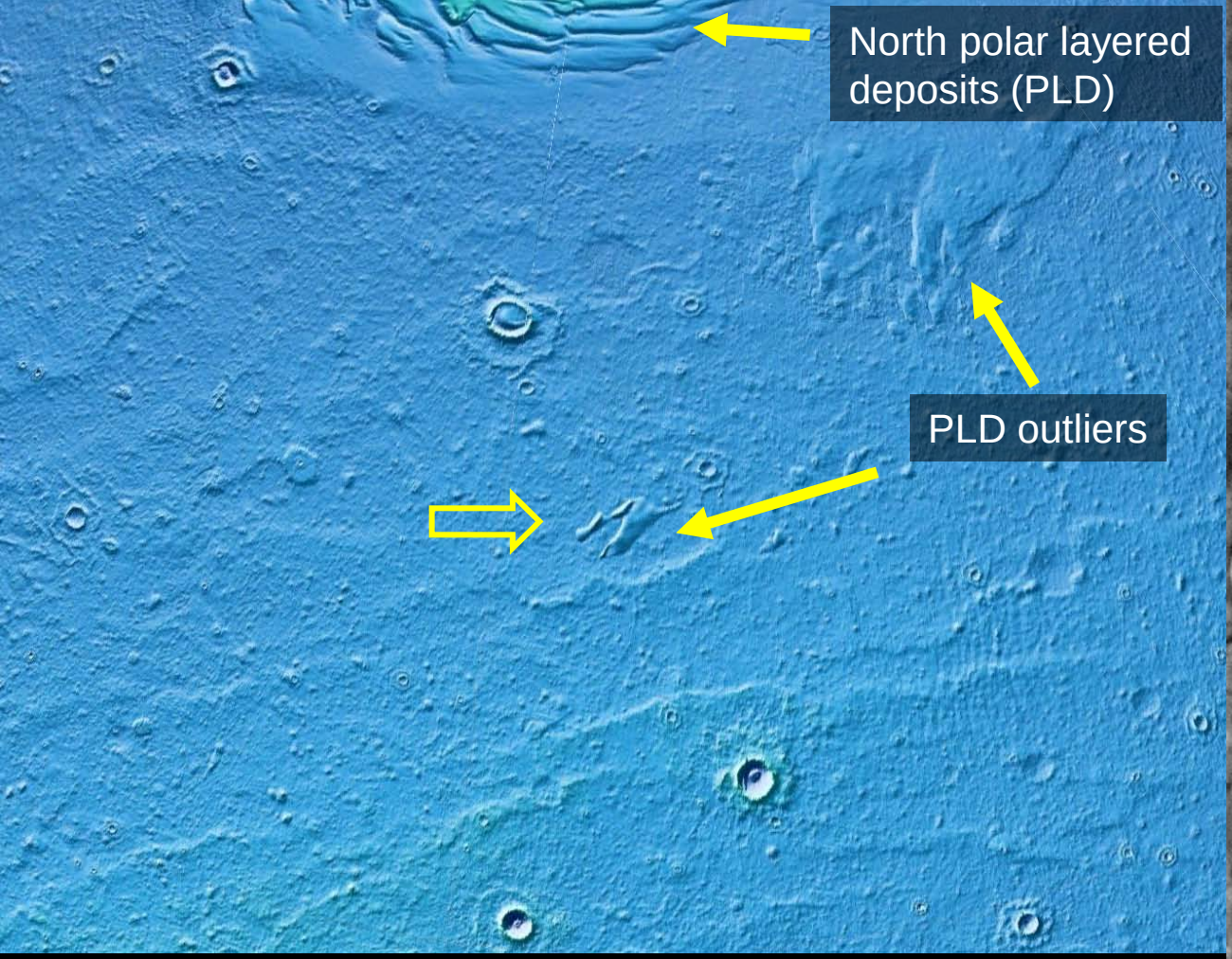
(Schon and Head, 2008)

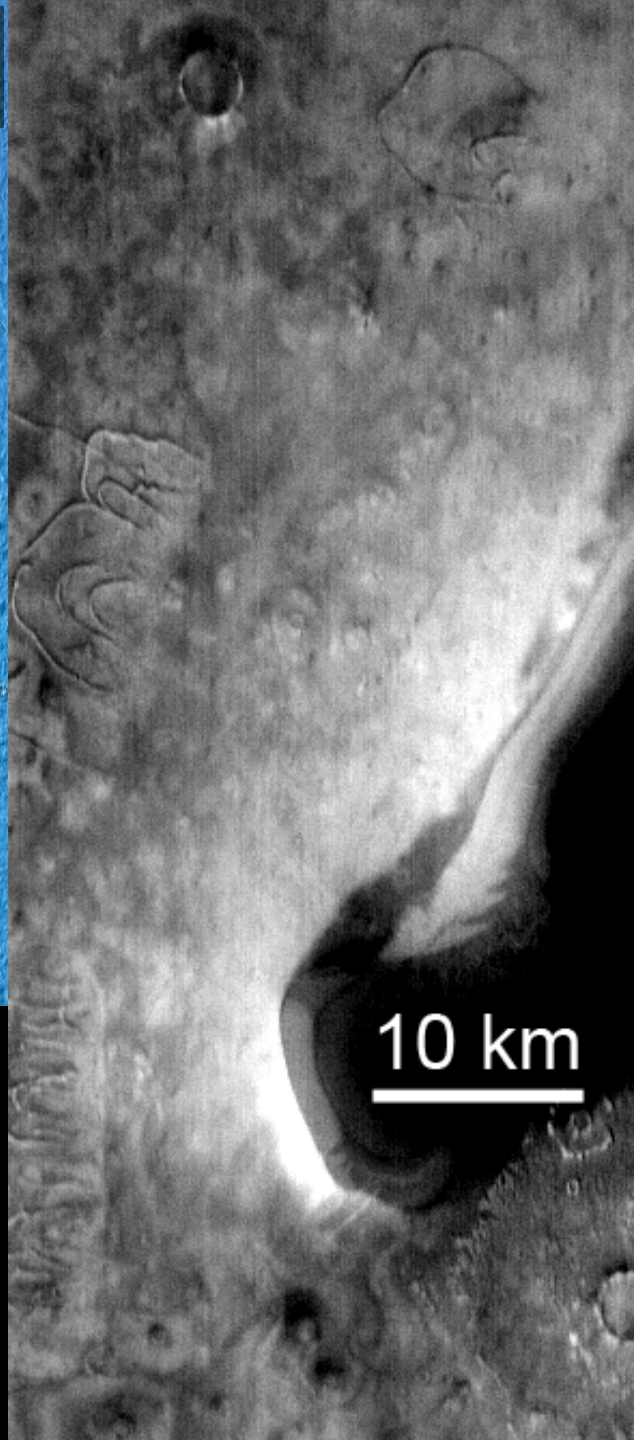




-What happens at very low obliquity (<20º)?

-Collapse of CO_2 atmosphere, deposition near poles (Kreslavsky and Head, 2006).





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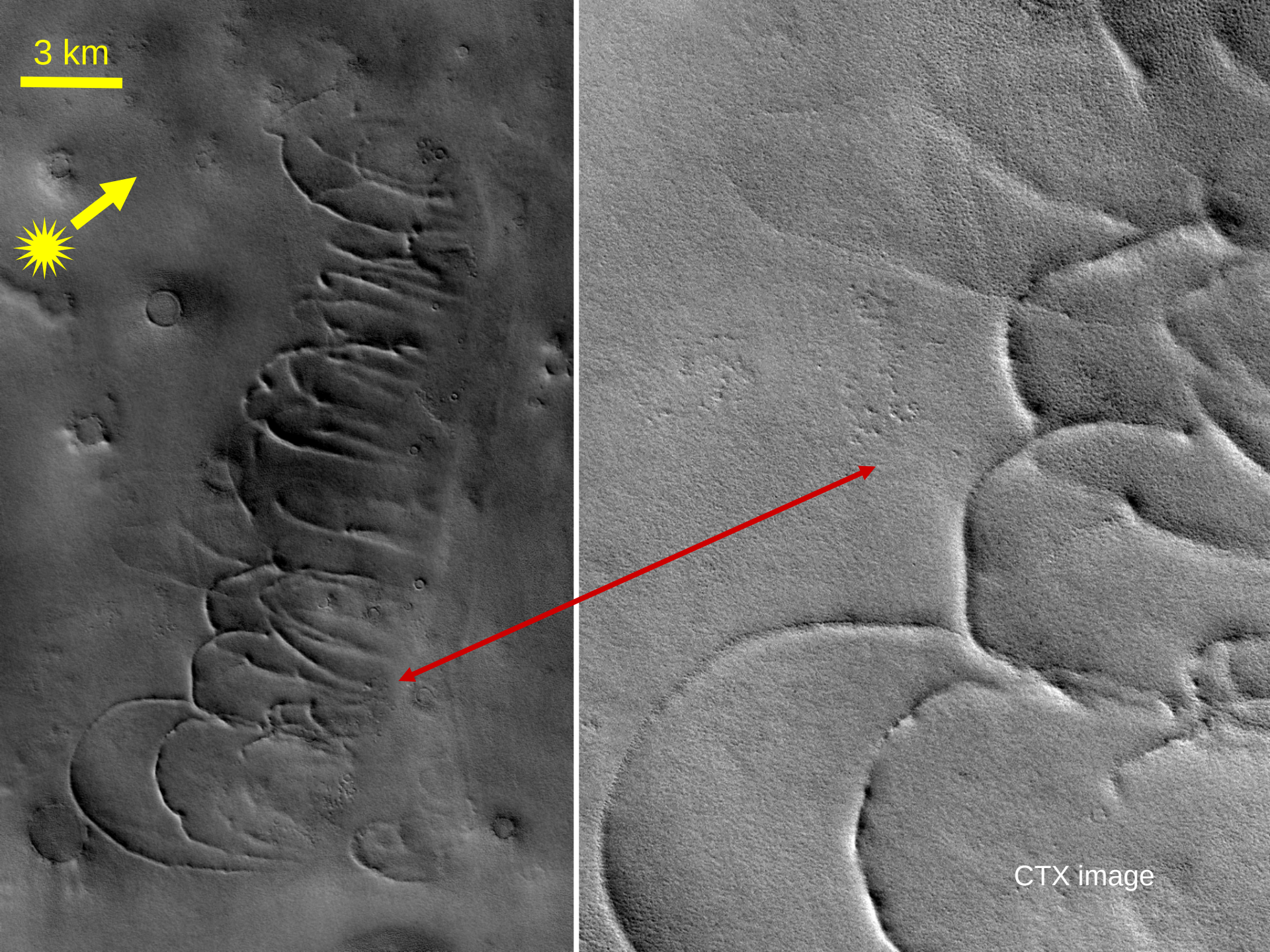
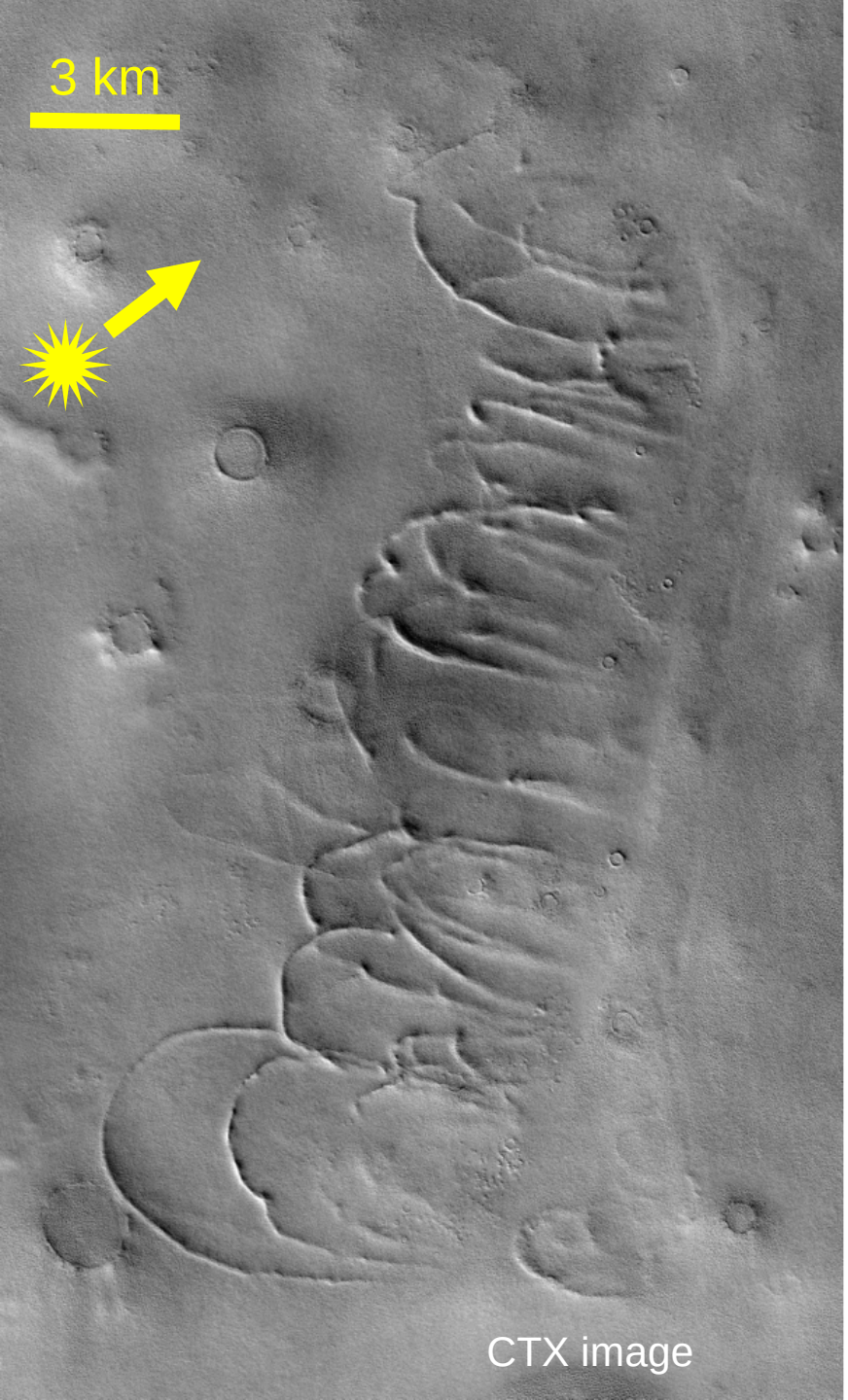

3 km
CTX image



Interpretation:

Drop moraines left by cold-based glaciers

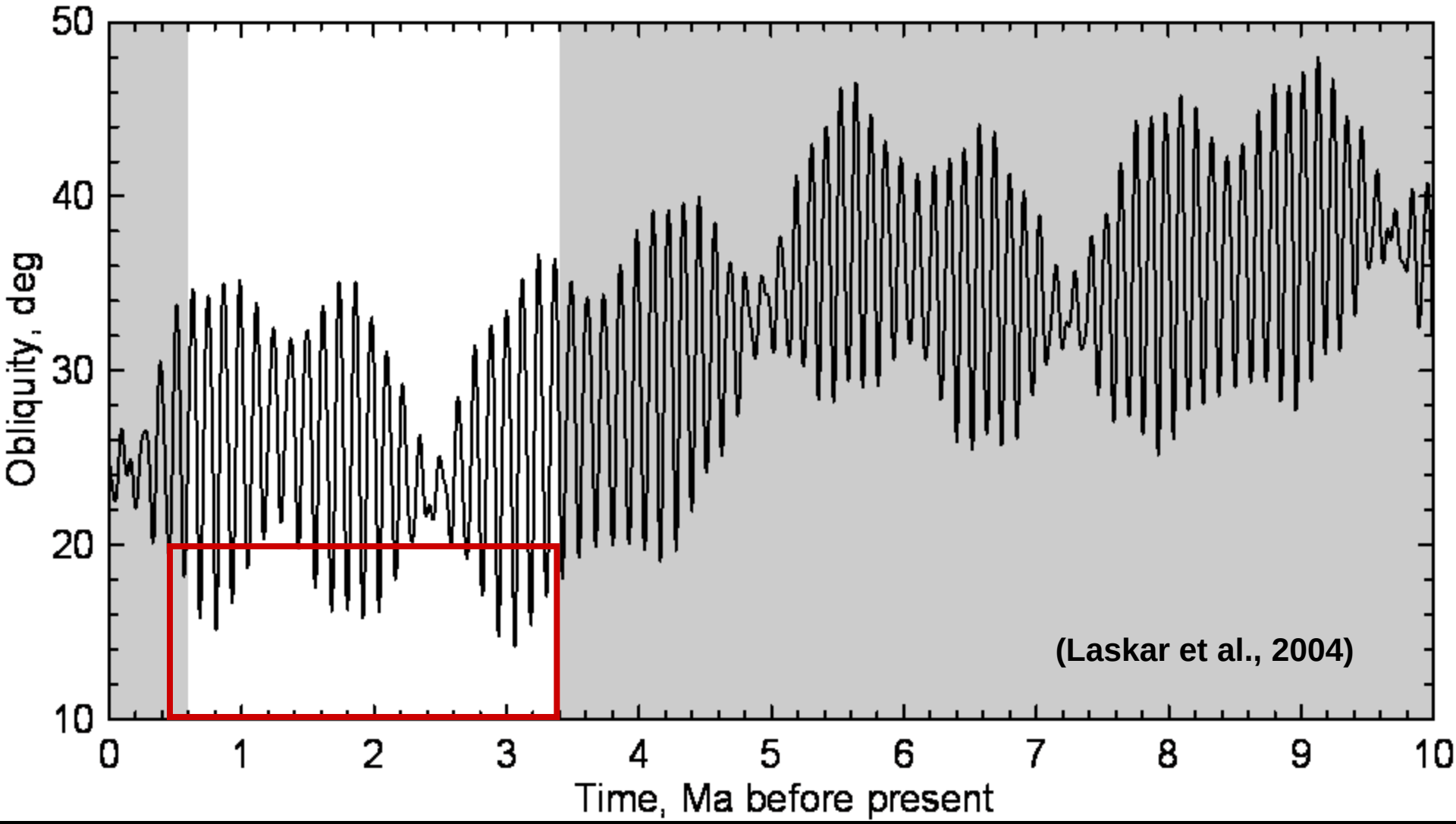
…but…

Flowing material is much softer than H_2O ice.

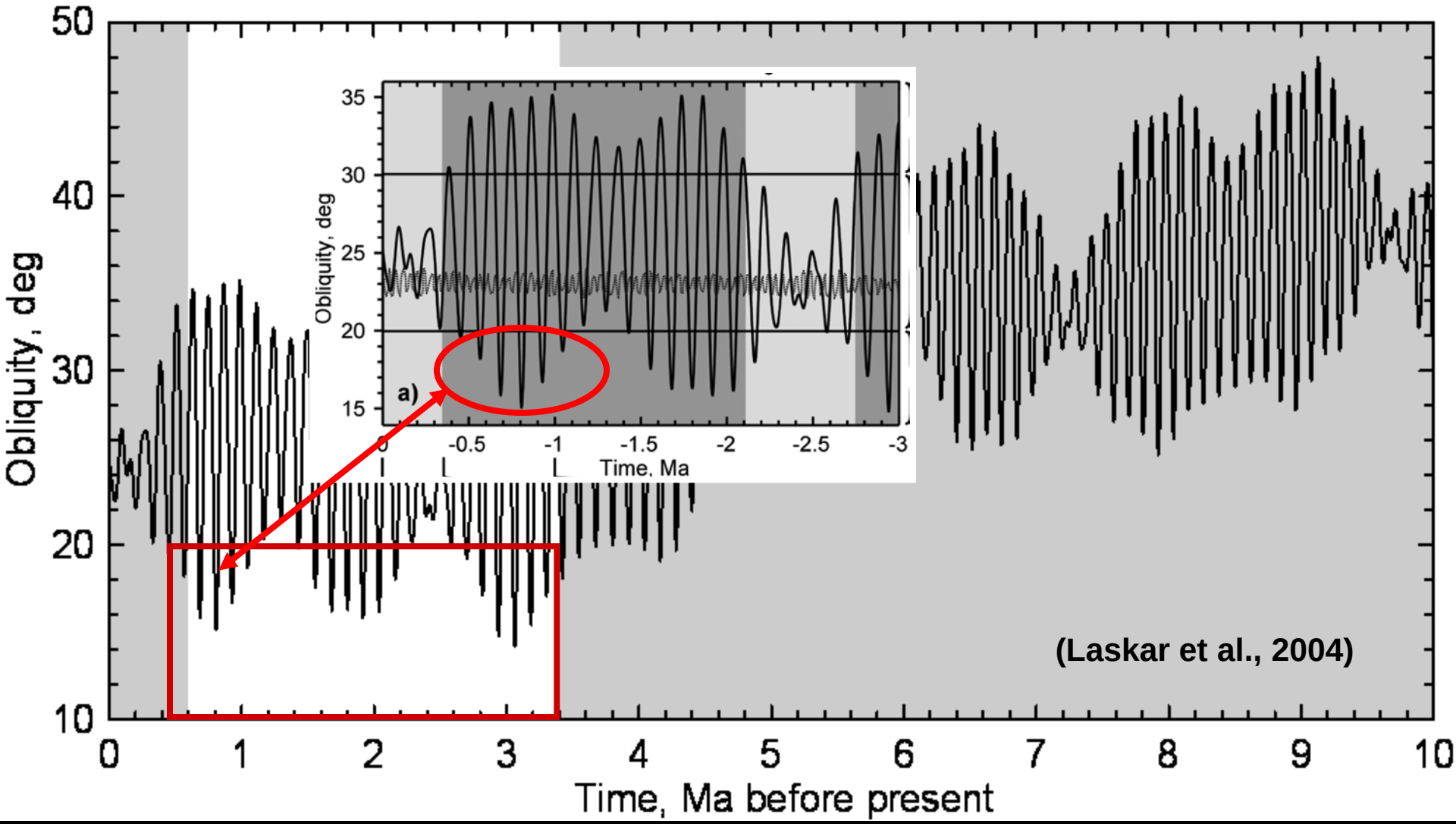
CO_2 ice?

-At low obliquity (<~18-20º), there is perennial accumulation of CO_2 on steep slopes.

[*Kreslavsky and Head, 2006*]



-There are three suitable low obliquity periods 3.4 – 0.6 Ma ago.
-No low obliquity periods earlier.
-Most likely youngest, based on stratigraphy (craters and mantle).



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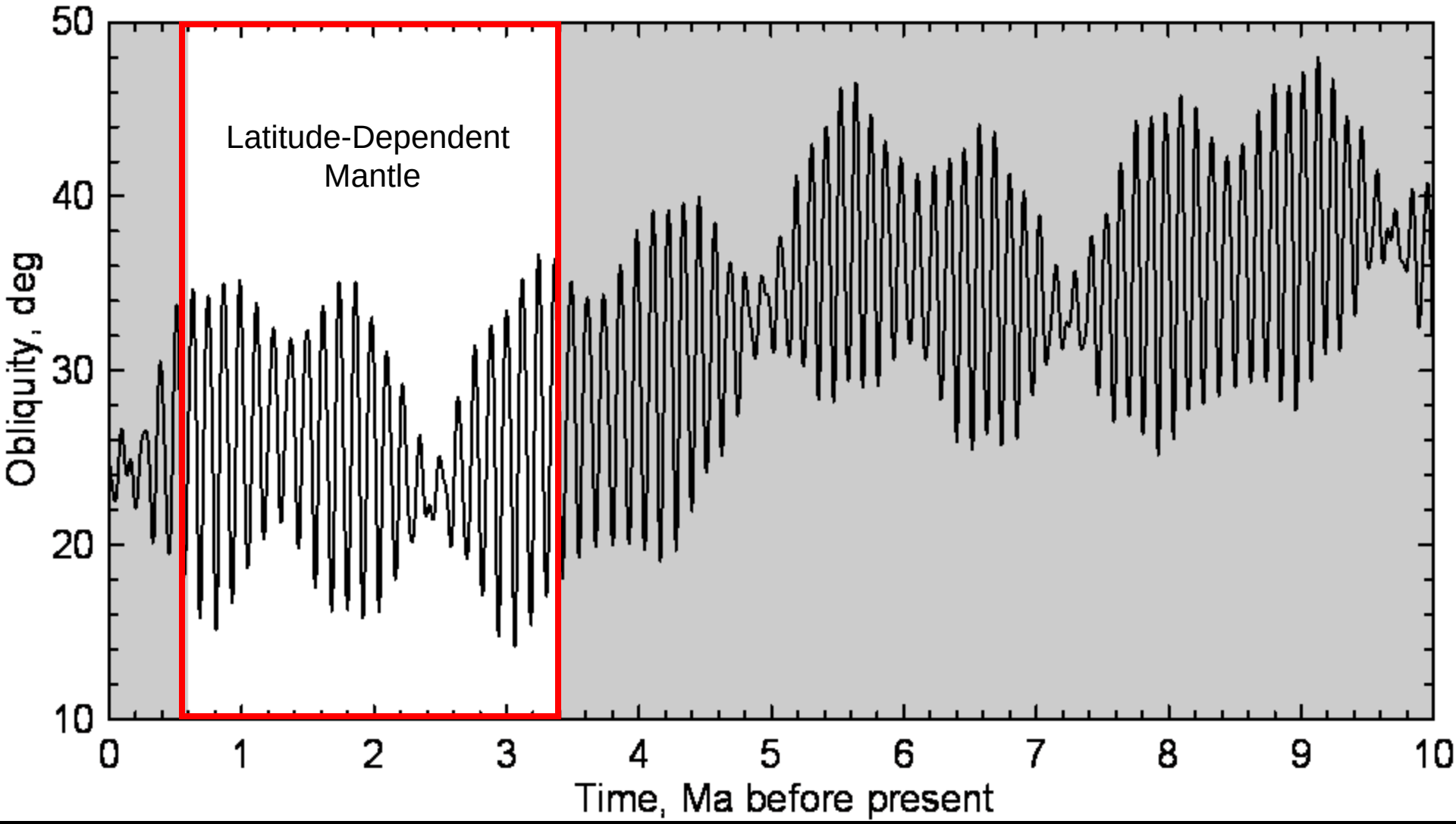
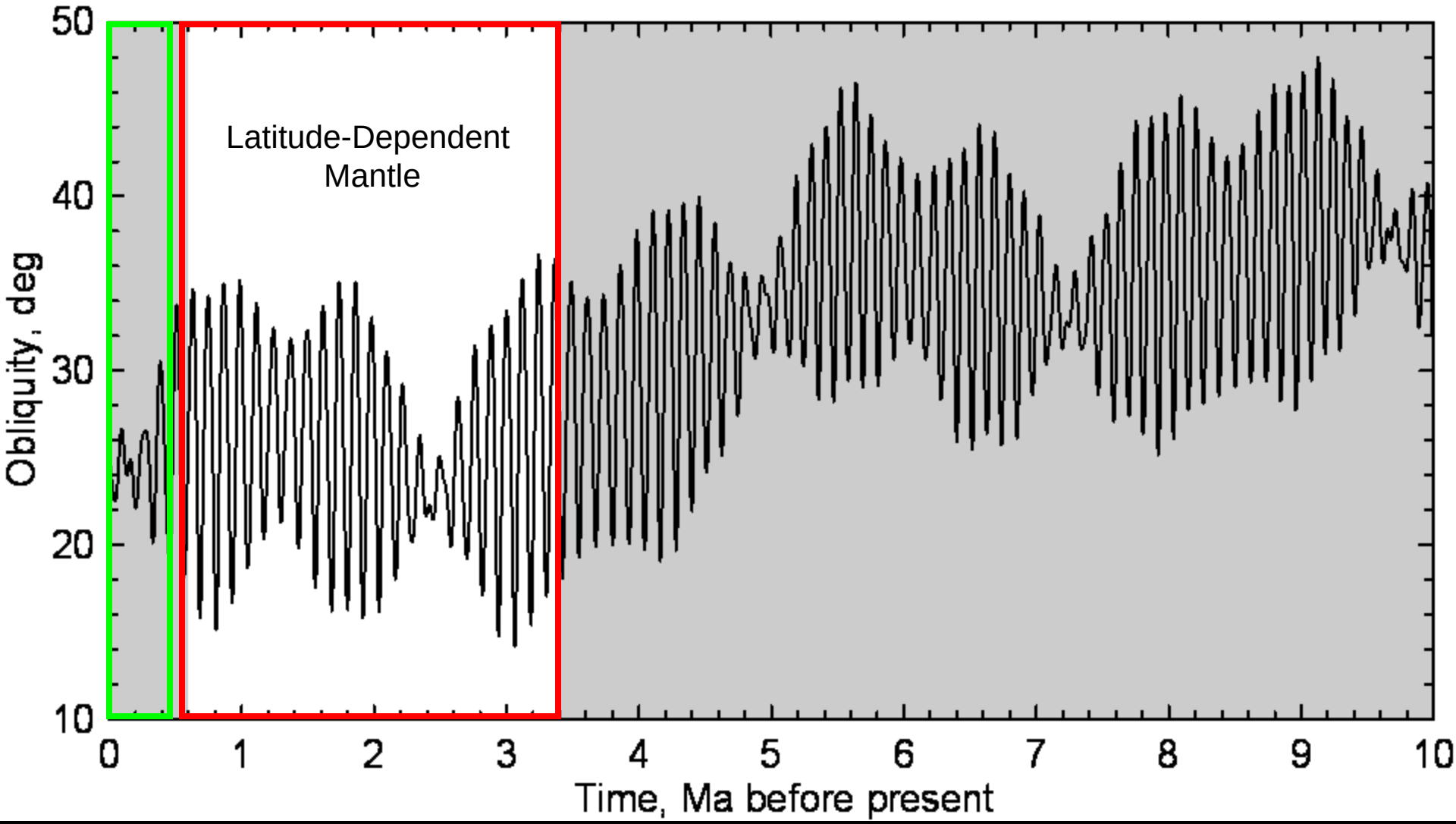


-If the latitude-dependent mantle was emplaced in the last 3 million years, and is now undergoing loss at 30º-50º N and S latitude, were similar mantles deposited earlier in the Amazonian?



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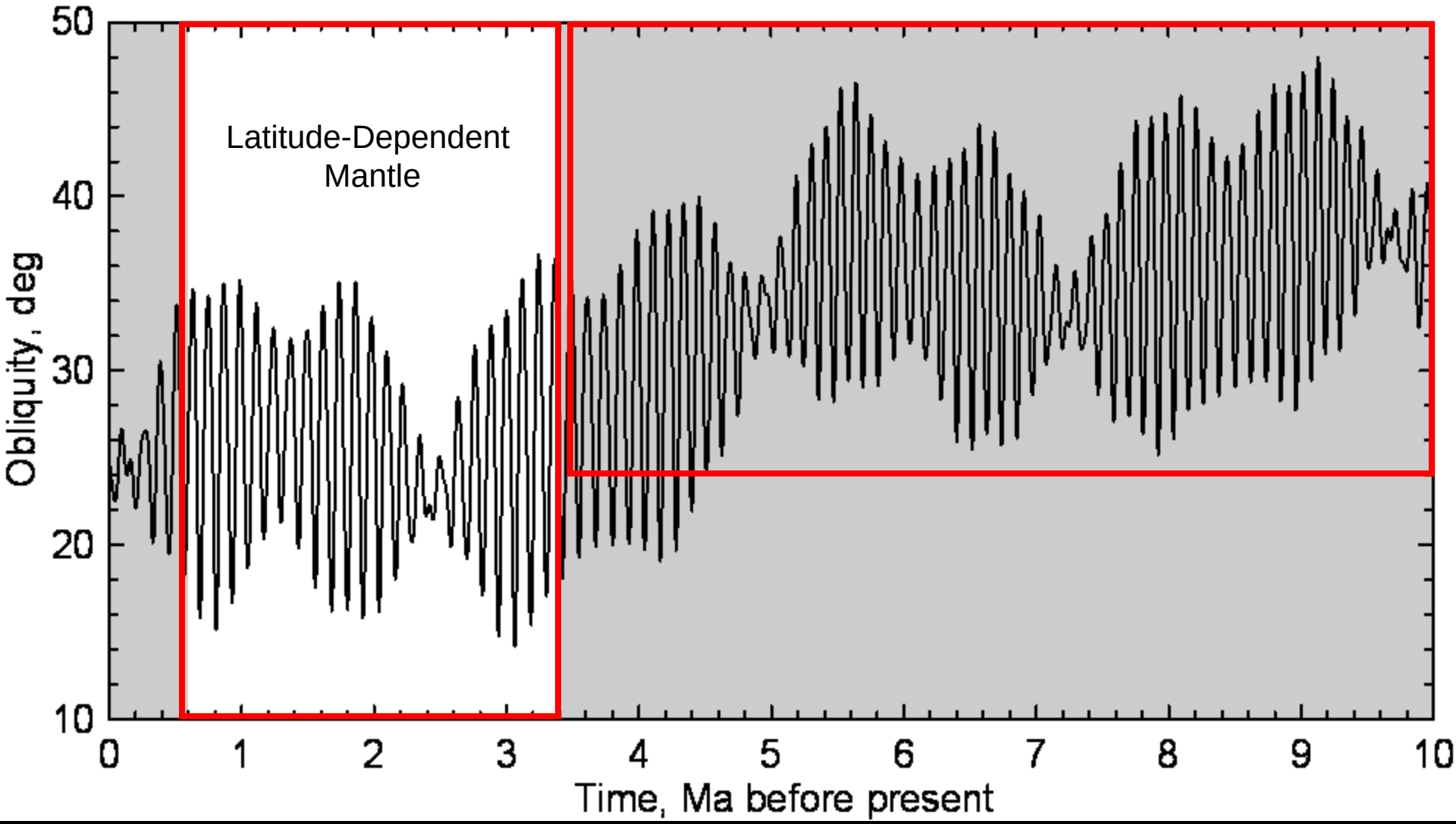

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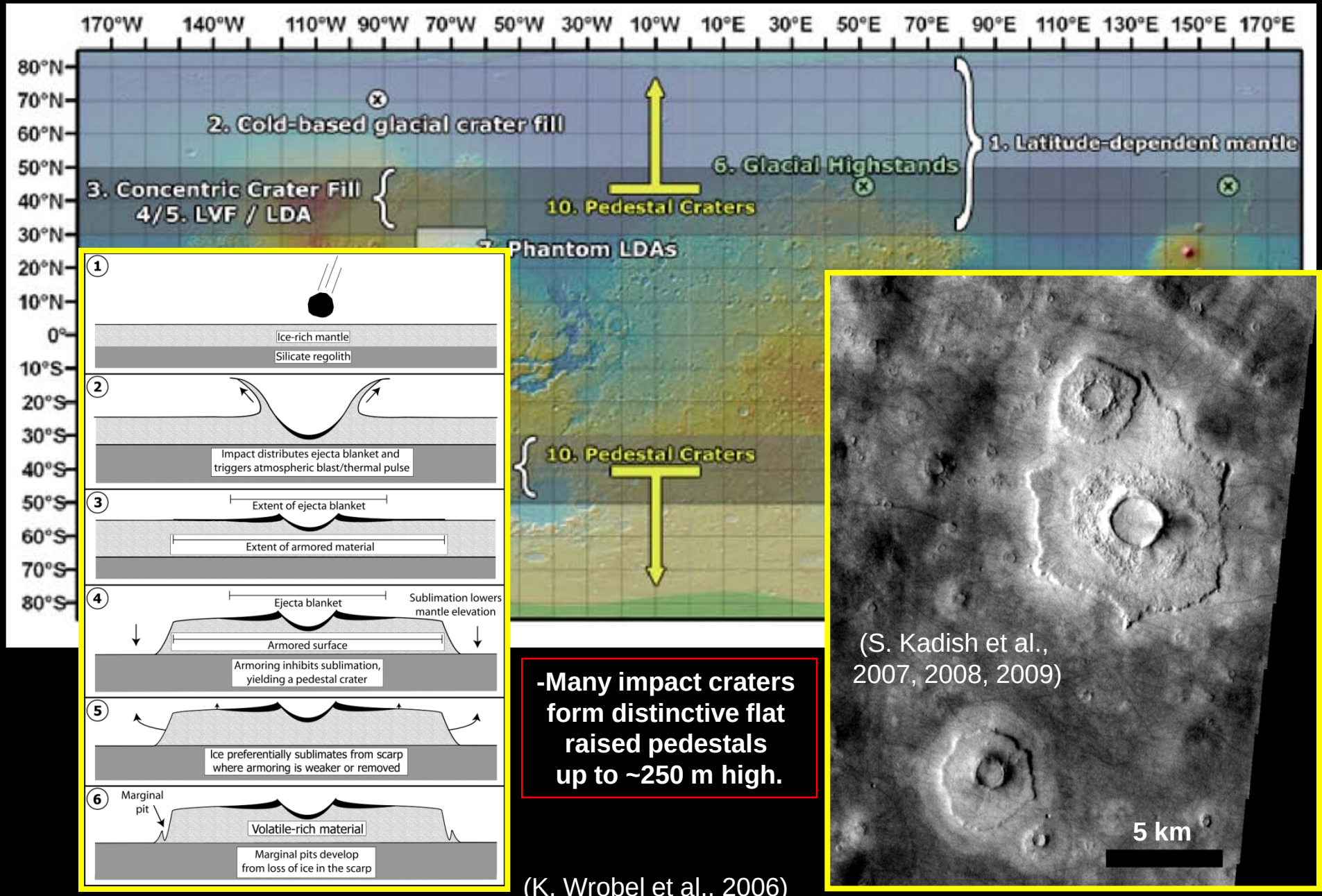
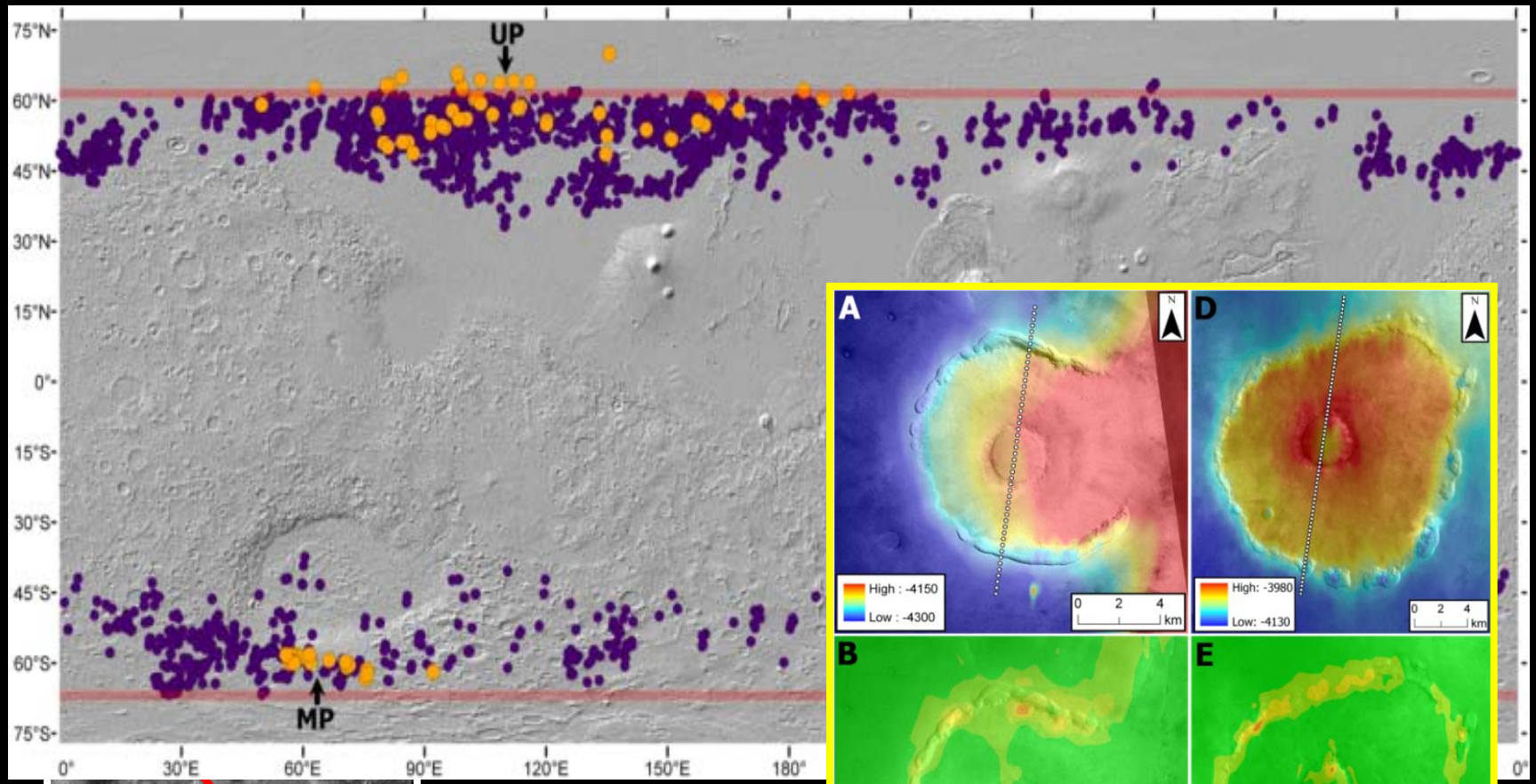
Pedestal Craters - A Record of Ancient Ice Deposits?

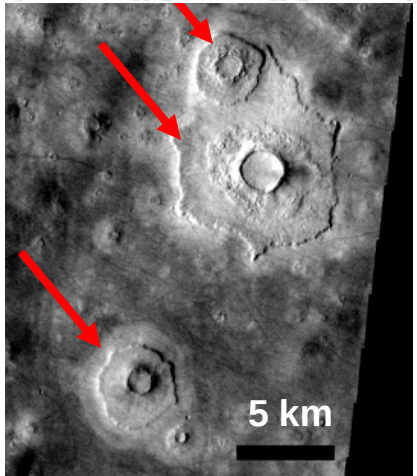


-Many impact craters form distinctive flat raised pedestals up to ~250 m high.

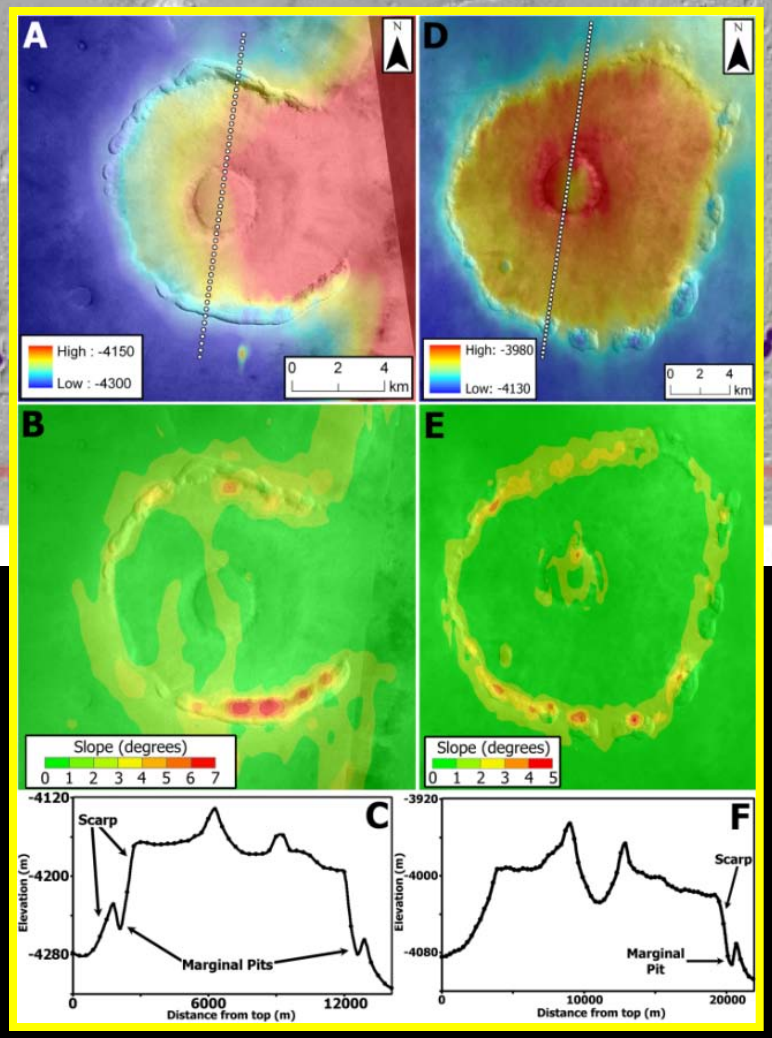
(K. Wrobel et al., 2006)

Global Distribution of >6,000 Pedestal Craters on Mars





Kadish et al., 2007



Pedestal Heights

N = 2,300

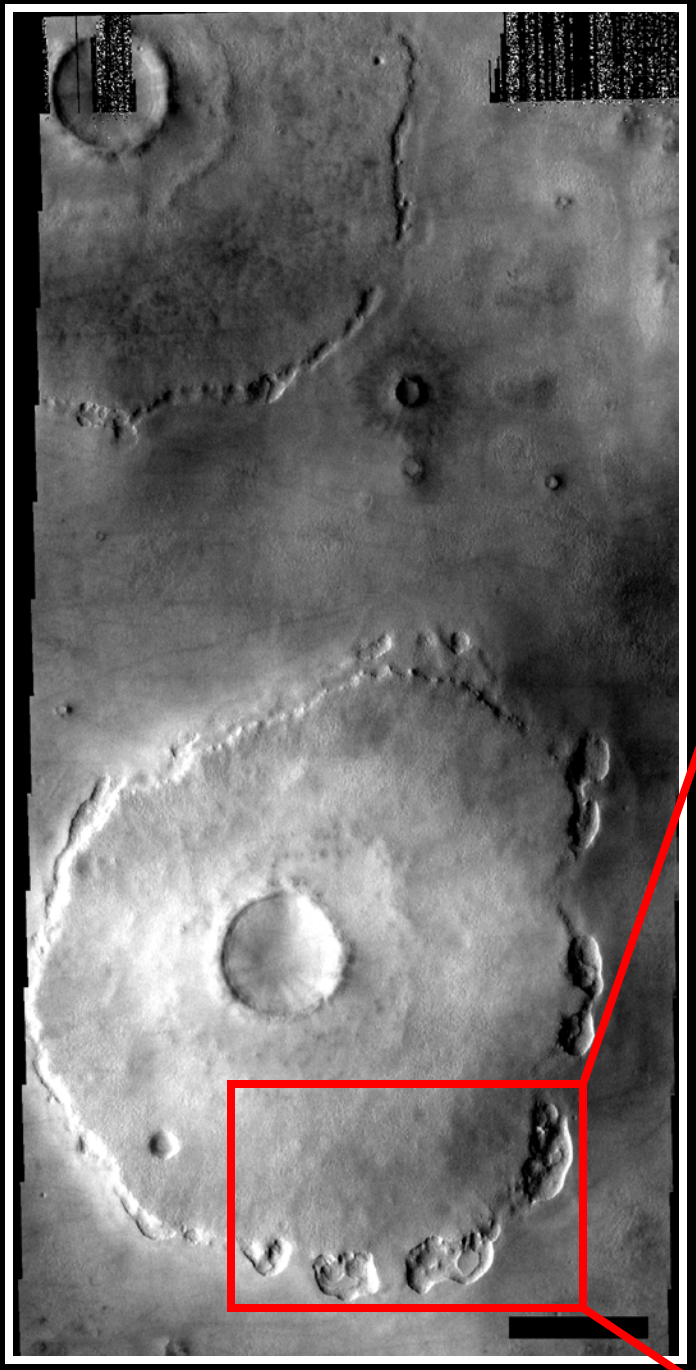
Range = 20-256 m

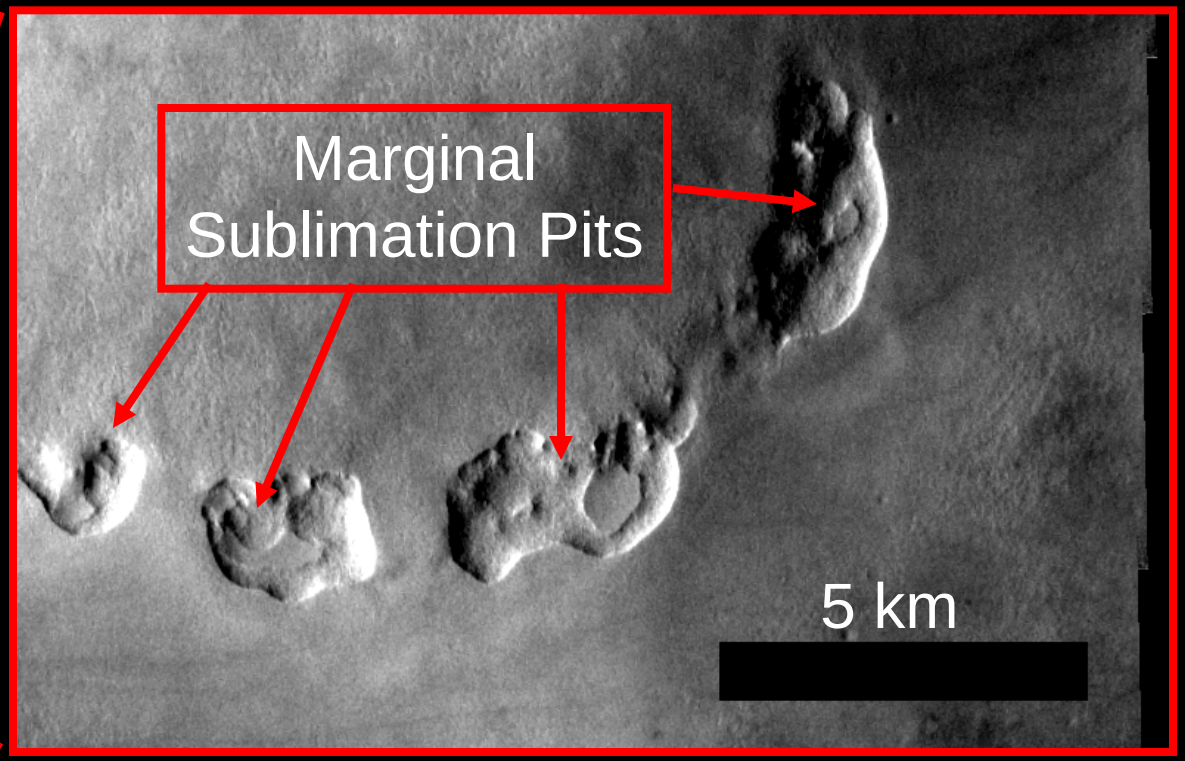
Mean ≈ 50 m

Pitted Pedestal Craters

-Evidence for Sublimation Pits around the Margins of Pedestal Craters

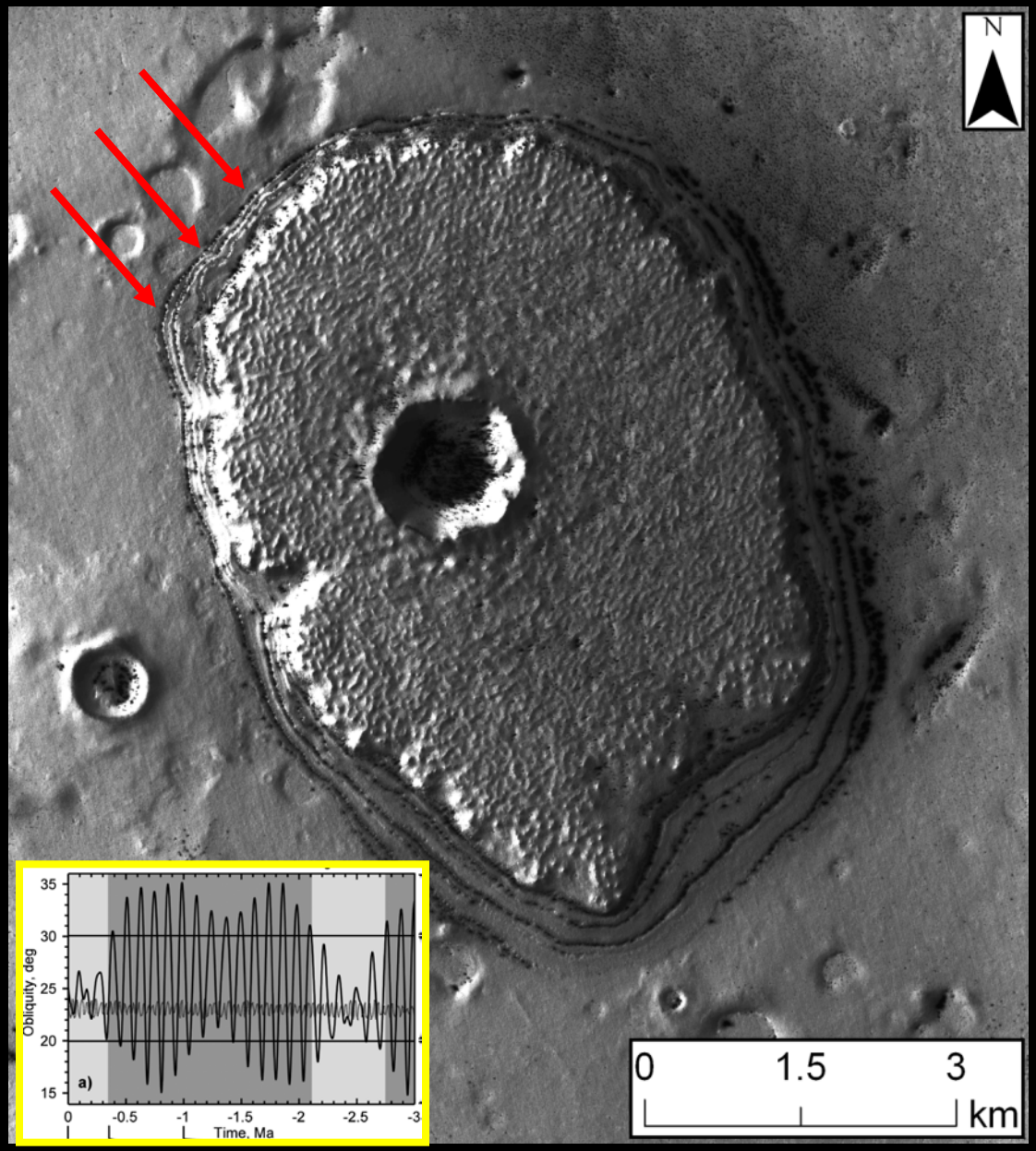
-Interpreted to be thick buried ice below pedestal crater summit.

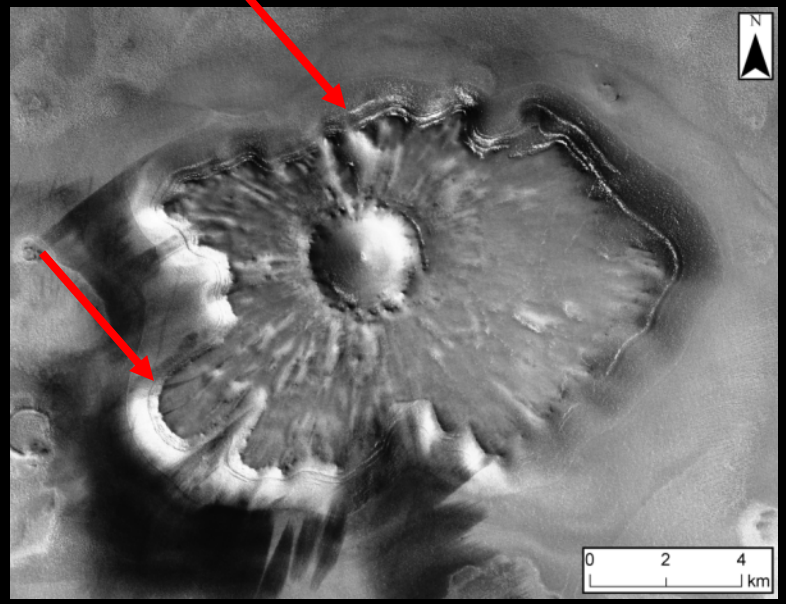


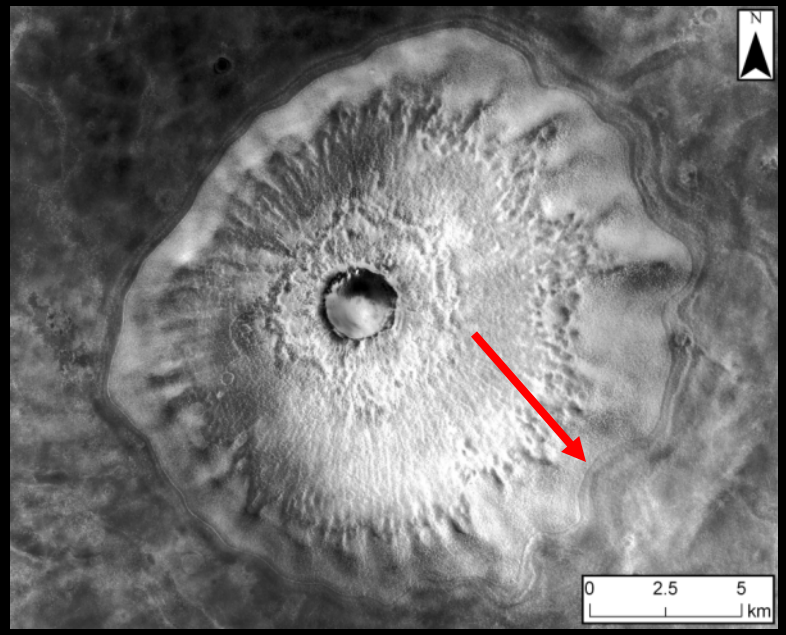


Kadish et al. GRL, 2008

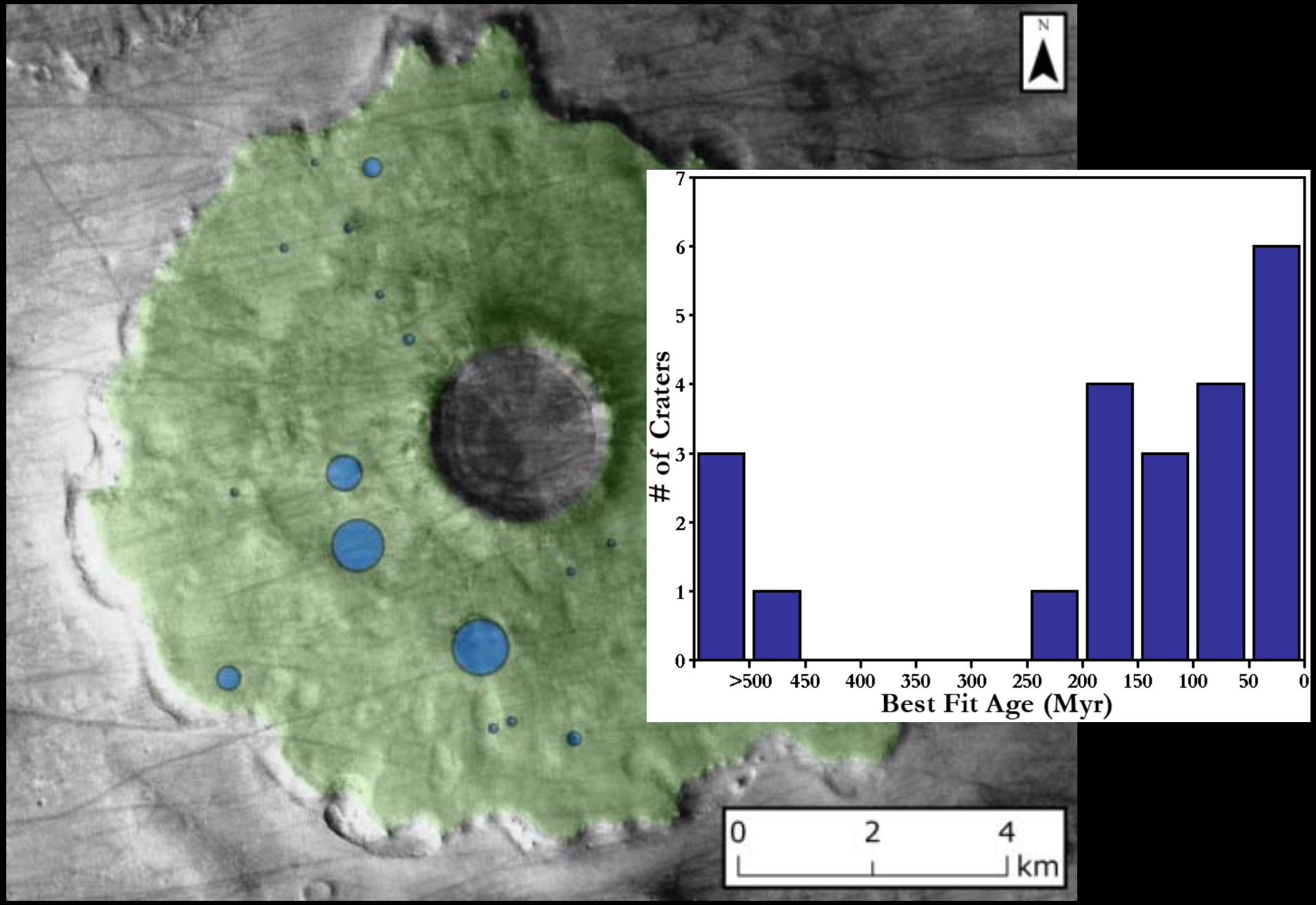
Layers in Pedestal Craters





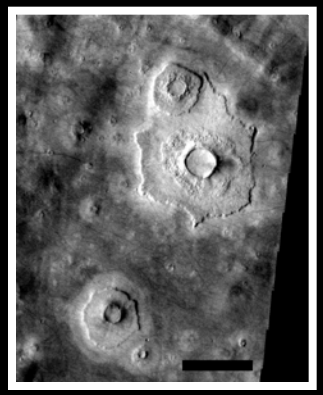


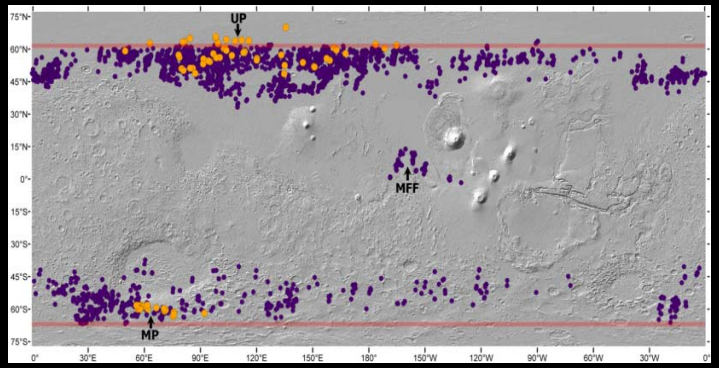
When Did the Mantles Occur? - Ages of Pedestal Craters

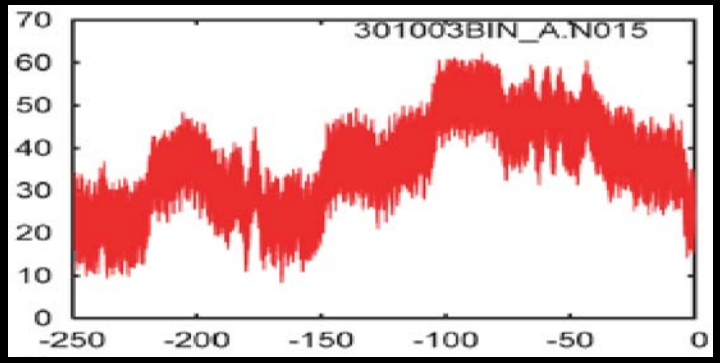


Pedestal Crater Synthesis: Previous Presence of Extensive Volatile-Rich Layer

- Pedestals widespread in mid-high northern and southern latitudes.
- Pedestals layered and volatile rich; show preferential thickness (Utopia).
- Ages show that they formed over a wide range in the Late Amazonian.
- Indicate that polar volatiles were transported to mid-high latitudes in large volume and often, to create widespread mantling deposits.
- How much volume?
  - Average pedestal height in Northern Hemisphere is ~50 m, so volume is: 1.1 x 10^6 km^3 (North Polar cap = 1.14 x 10^6 km^3)
  - Average pedestal height in Southern Hemisphere is ~40 m, so volume is: 8.5 x 10^5 km^3 (South Polar cap = 1.6 x 10^6 km^3)
- Correlate with Laskar orbital parameter predictions for Late Amazonian.

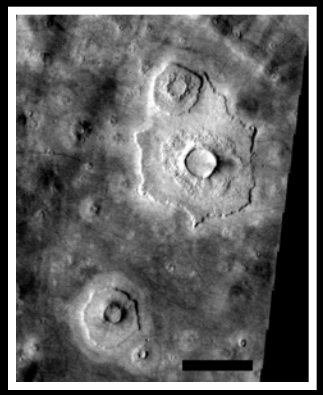


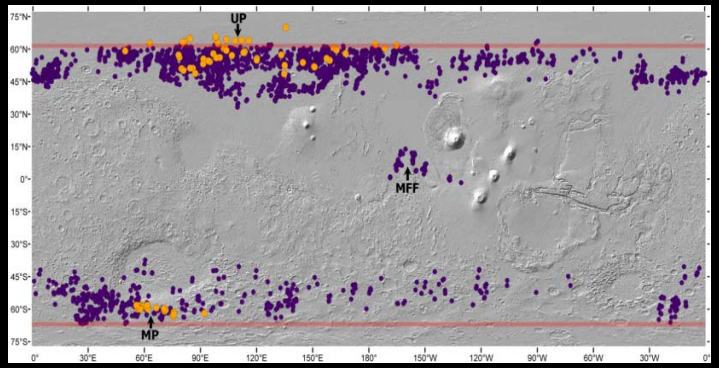


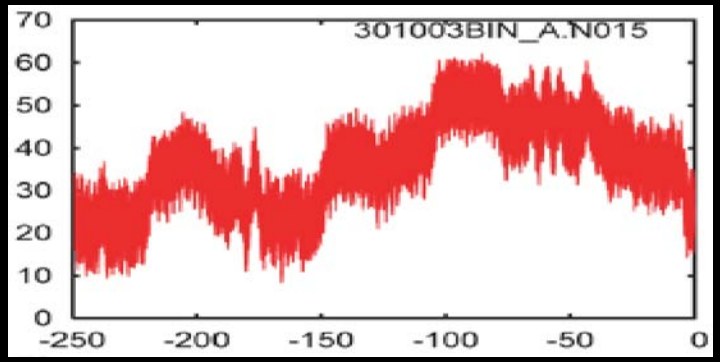


Pedestal Crater Synthesis: Previous Presence of Extensive Volatile-Rich Layer

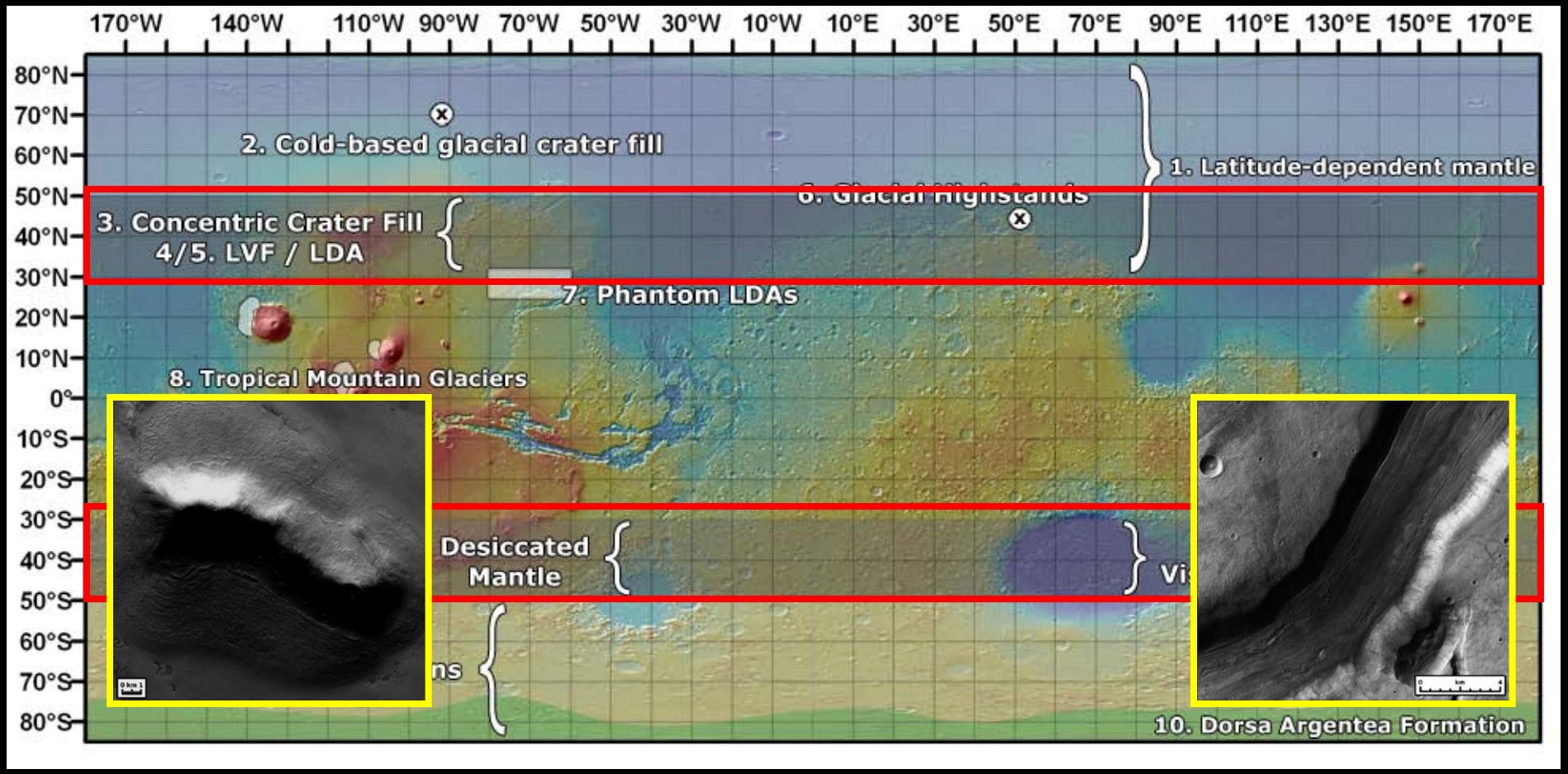
- Pedestals widespread in mid-high northern and southern latitudes.
- Pedestals layered and volatile rich; show preferential thickness (Utopia).
- Ages show that they formed over a wide range in the Late Amazonian.
- Indicate that polar volatiles were transported to mid-high latitudes in large volume and often, to create widespread mantling deposits.
- How much volume?
  - Average pedestal height in Northern Hemisphere is ~50 m, so volume is: 1.1 x 10^6 km^3 (North Polar cap = 1.14 x 10^6 km^3)
  - Average pedestal height in Southern Hemisphere is ~40 m, so volume is: 8.5 x 10^5 km^3 (South Polar cap = 1.6 x 10^6 km^3)
- Correlate with Laskar orbital parameter predictions for Late Amazonian.
- MARS NOT LIKE TODAY IN THE VERY RECENT PAST!!





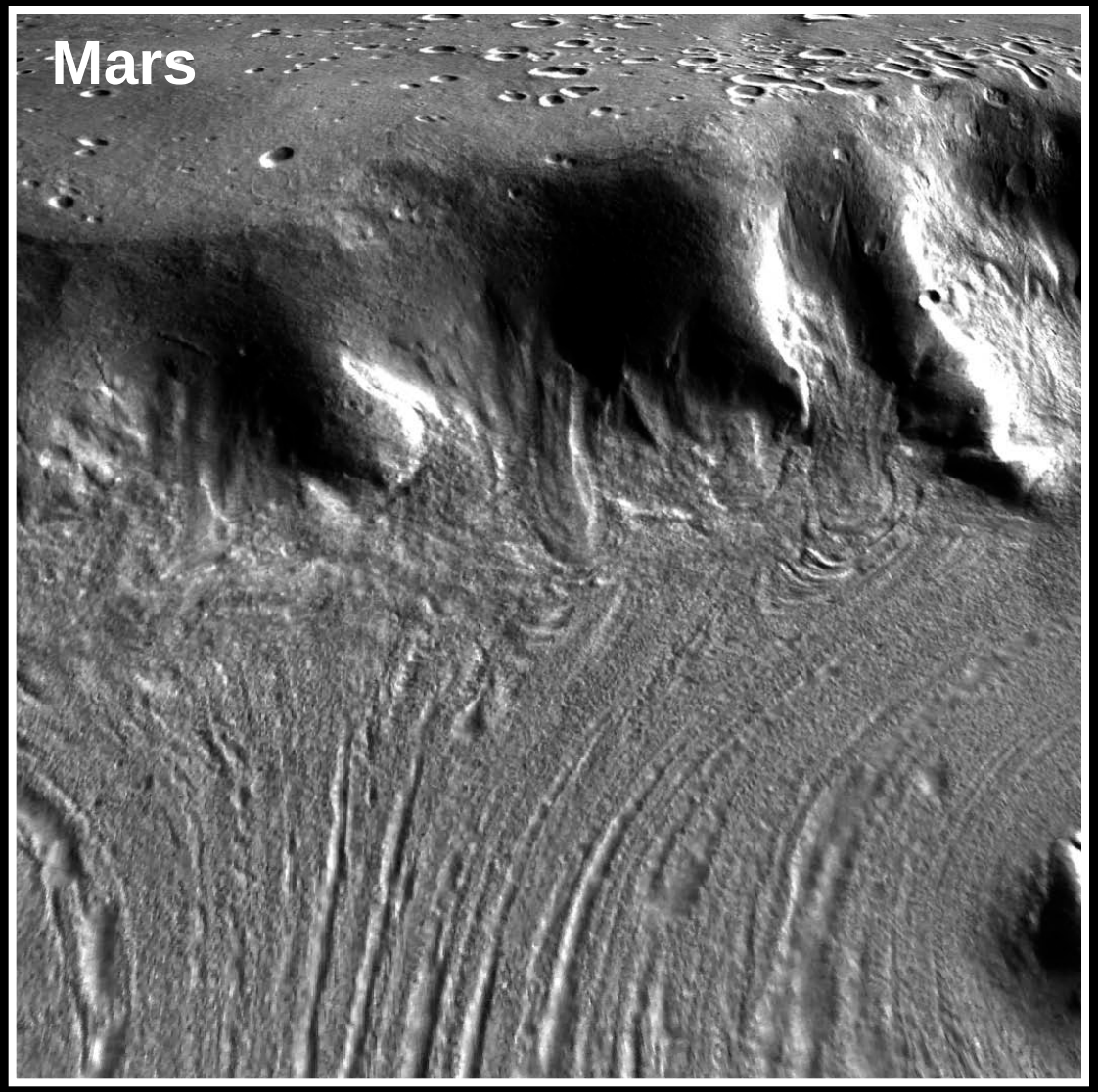


Non-Polar Latitude-Dependent Ice-Related Deposits



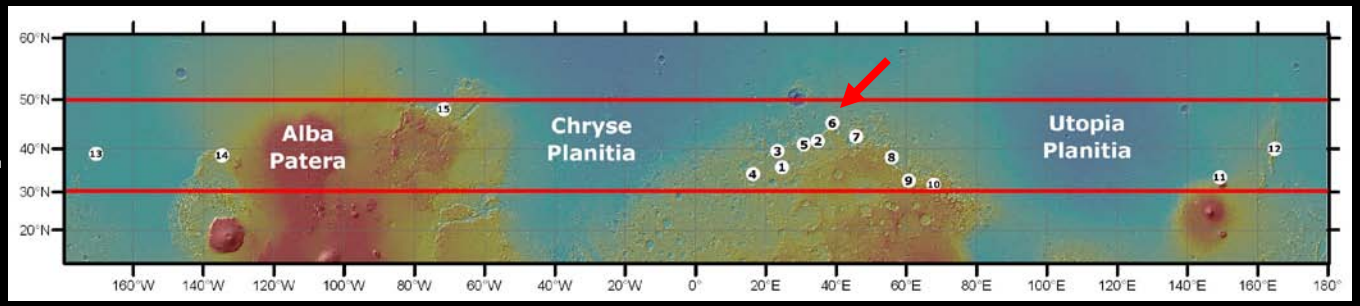
Mid-Latitude Lobate Debris Aprons and Lineated Valley Fill

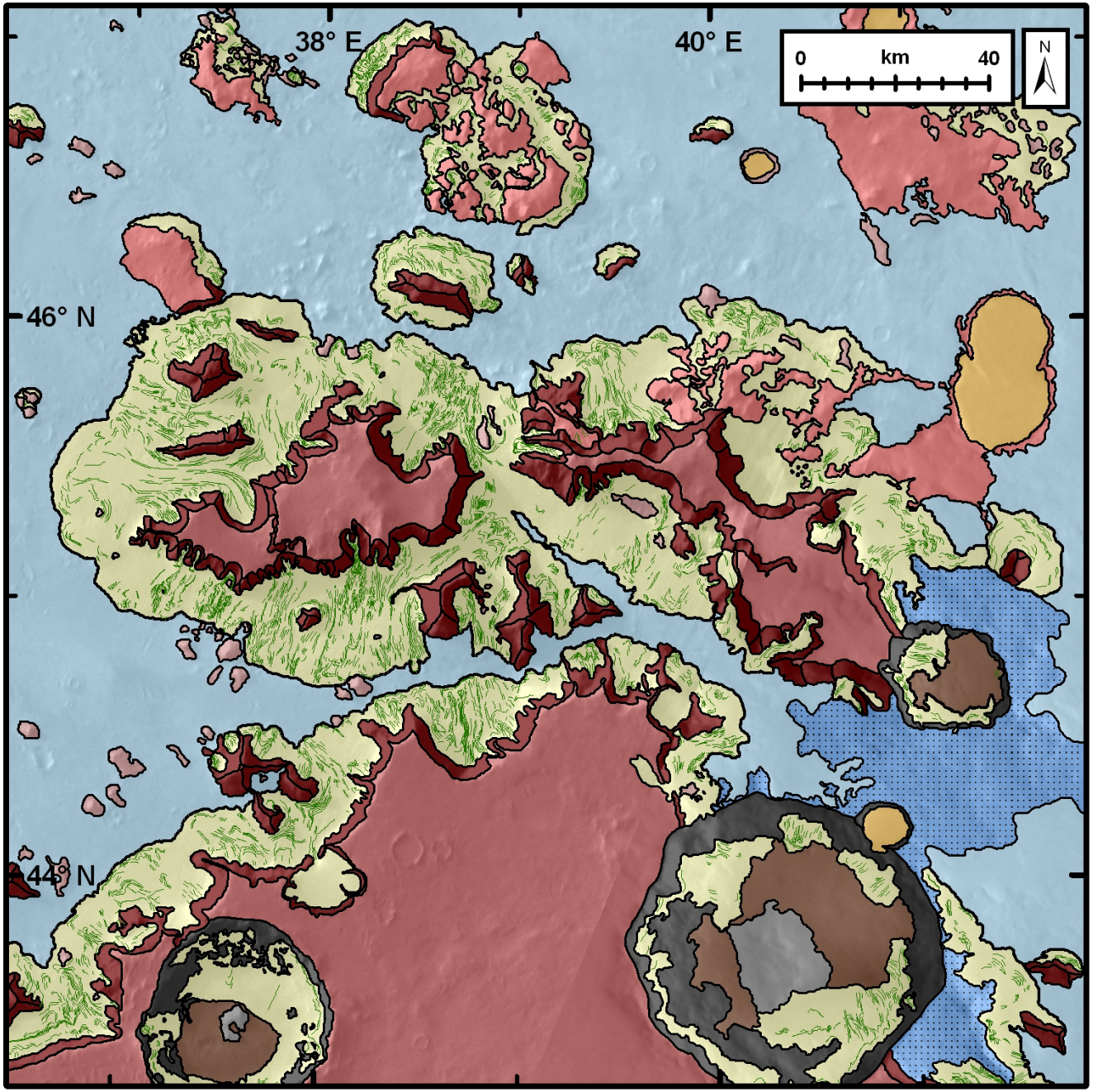
(Baker et al., Dickson et al., Morgan et al., Levy et al., Kress et al., Ostrach et al., Head et al.)



Lineated Valley Fill: Debris-Covered Valley Glacier Systems.

Plateau Icefields?





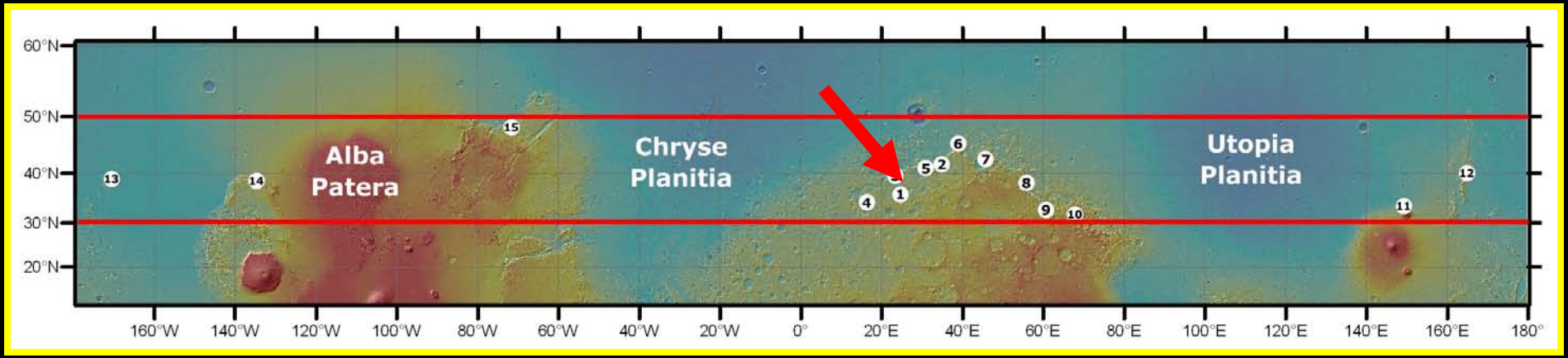
Deuteronilus Mensae Region

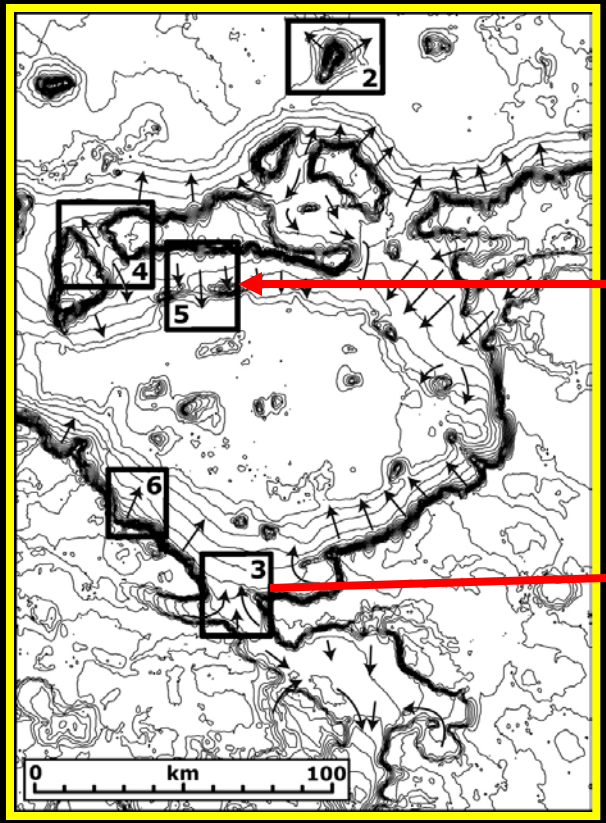
Units

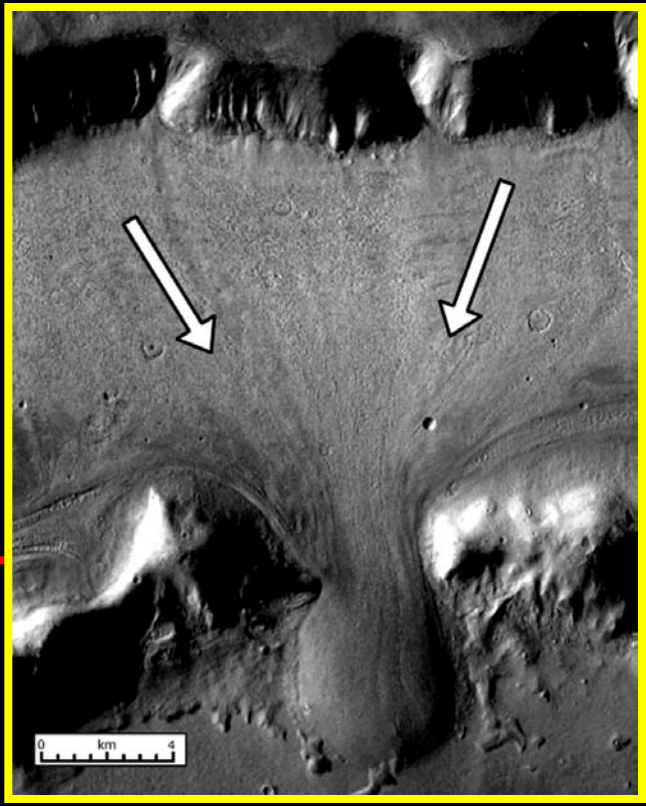
- plateau top tier
- plateau middle tier
- plateau wall
- massif
- blocks
- plains
- hummocky plains
- main apron material
- concentric crater fill
- crater wall material
- crater floor material
- crater peak

(Baker et al., 2009)

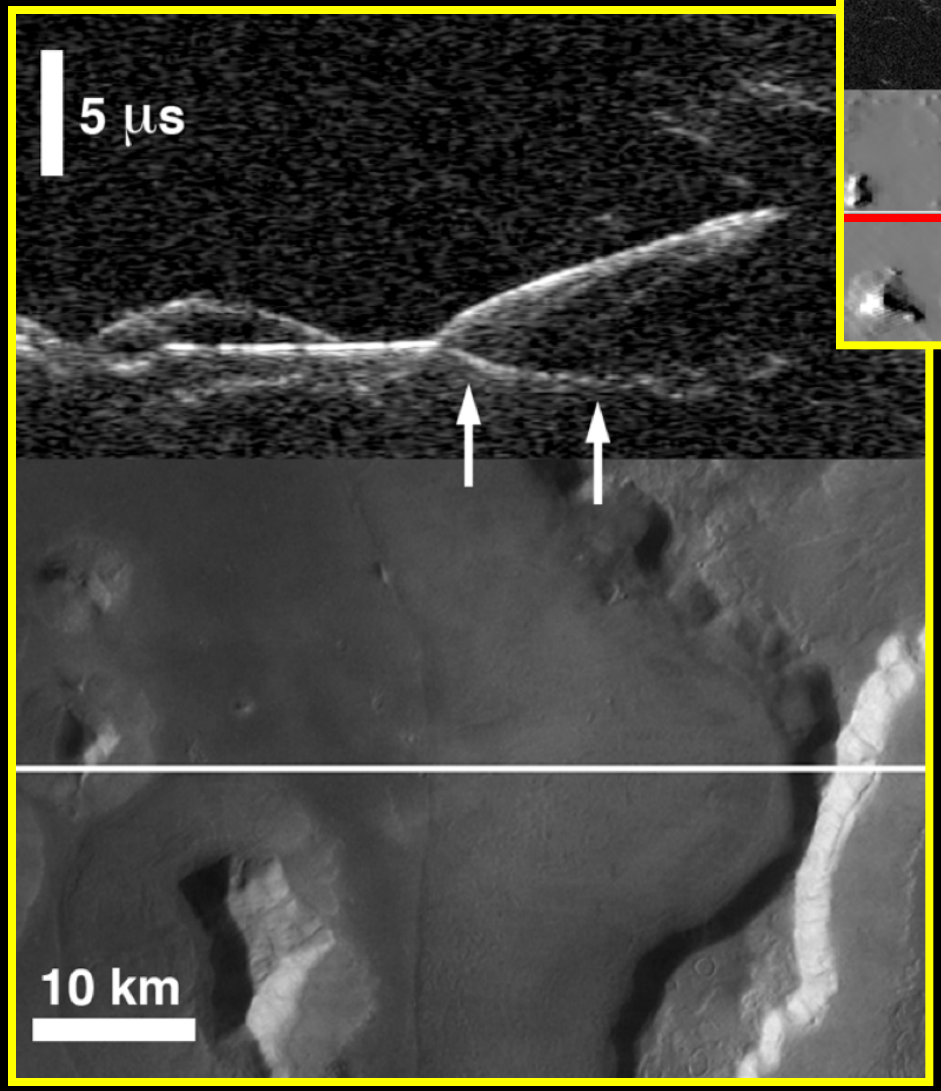
Noachian Crater at the Dichotomy Boundary

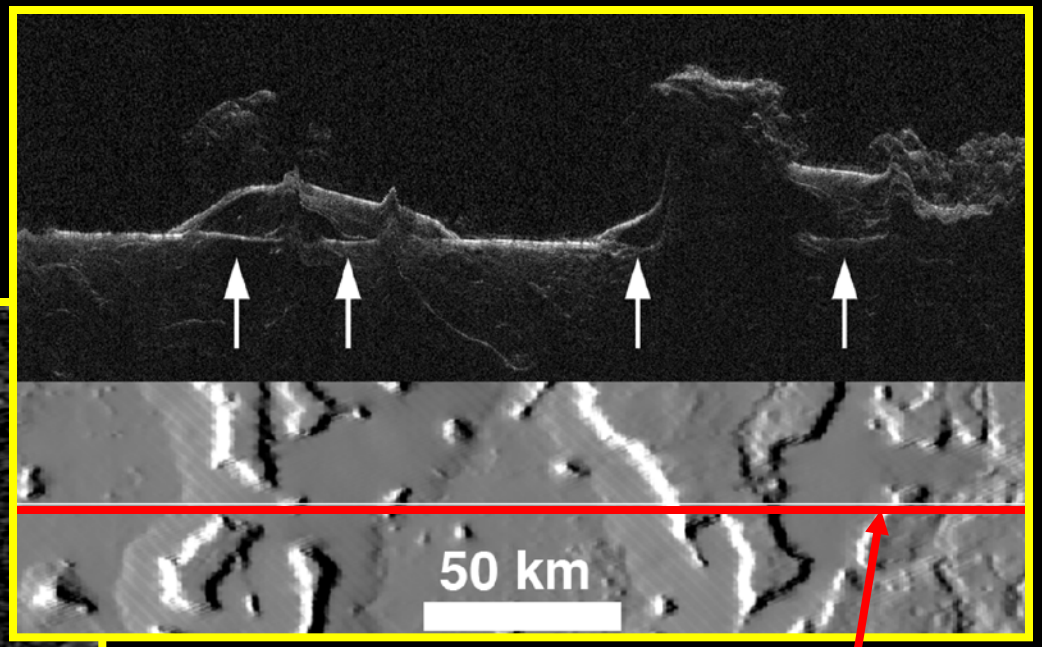


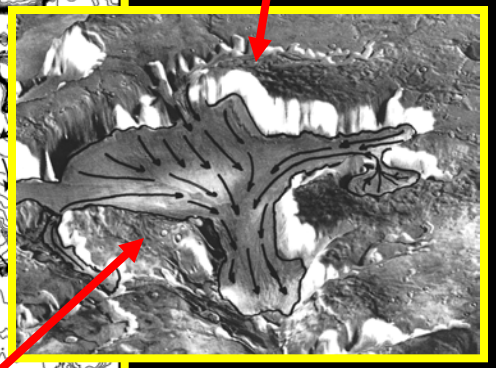




SHARAD Data of
Lobate Debris Aprons / Lineated Valley Fill
Show Presence of
Nearly Pure Ice Buried Beneath
Debris-Rich Sublimation Residue Layer.

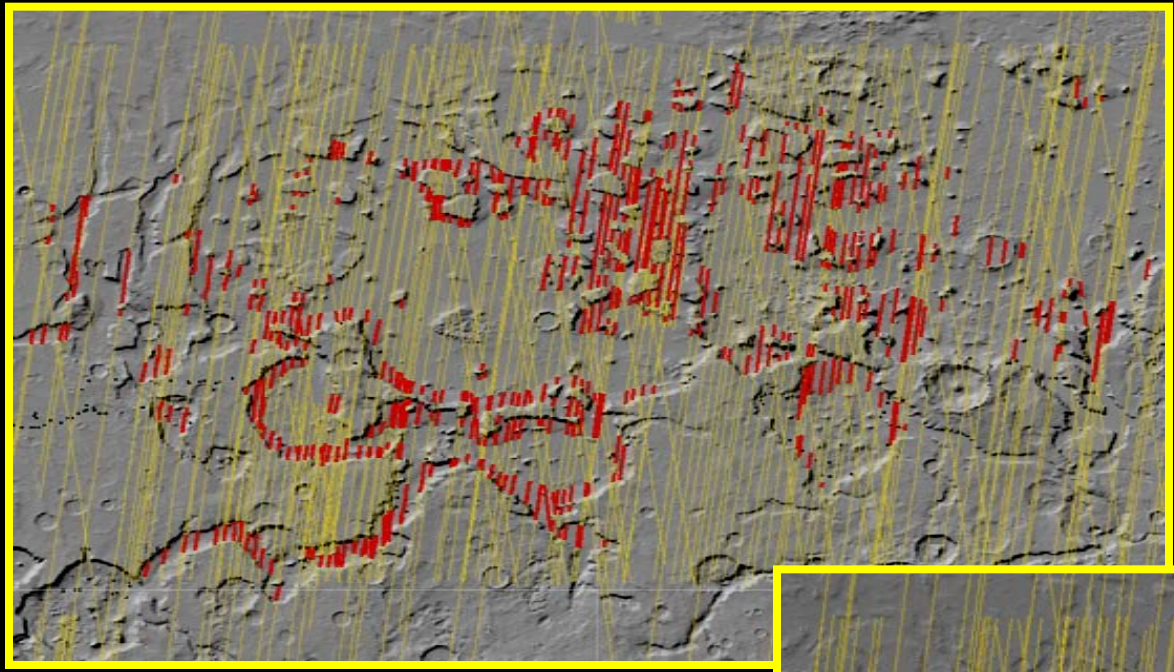


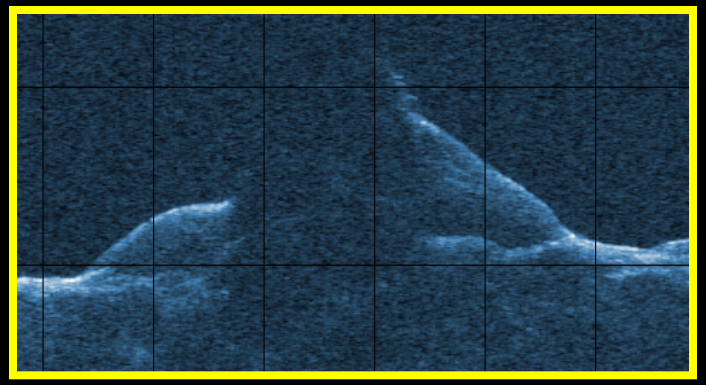




(Plaut et al., 2008)
(Holt et al, 2007)

Synthesis of SHARAD Data in Deuteronilus Mensae





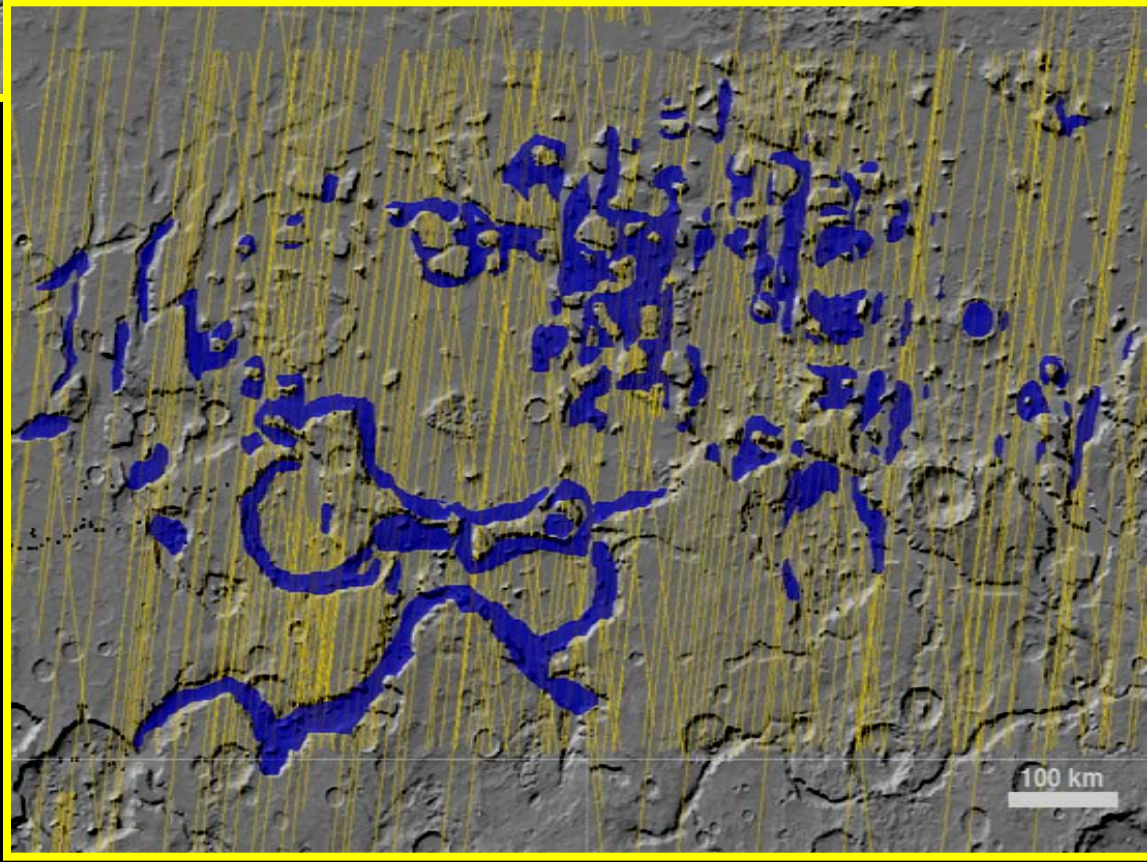
(Plaut et al., 2010)

-SHARAD signals penetrate lobate debris aprons to ~1 km depth.

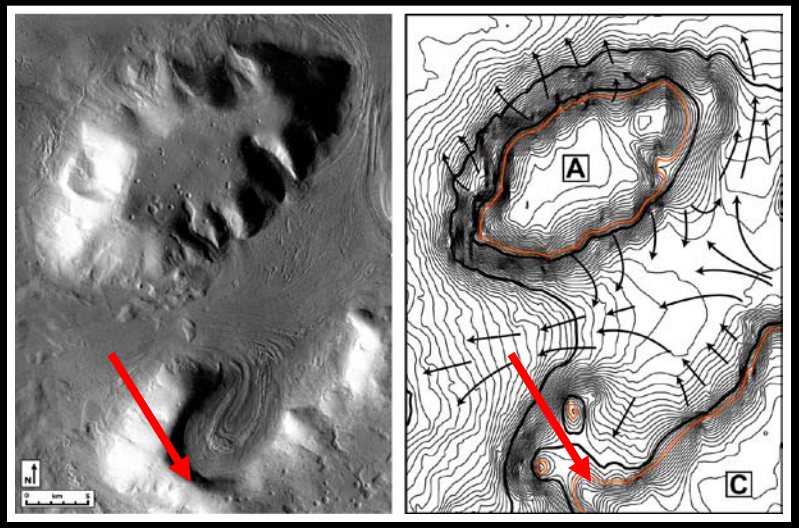
-Ice is widespread in Deuteronilus Mensae; most “classic” aprons show an ice signature.
-Lobate aprons, lineated valley fill, concentric crater fill all show the same signature.

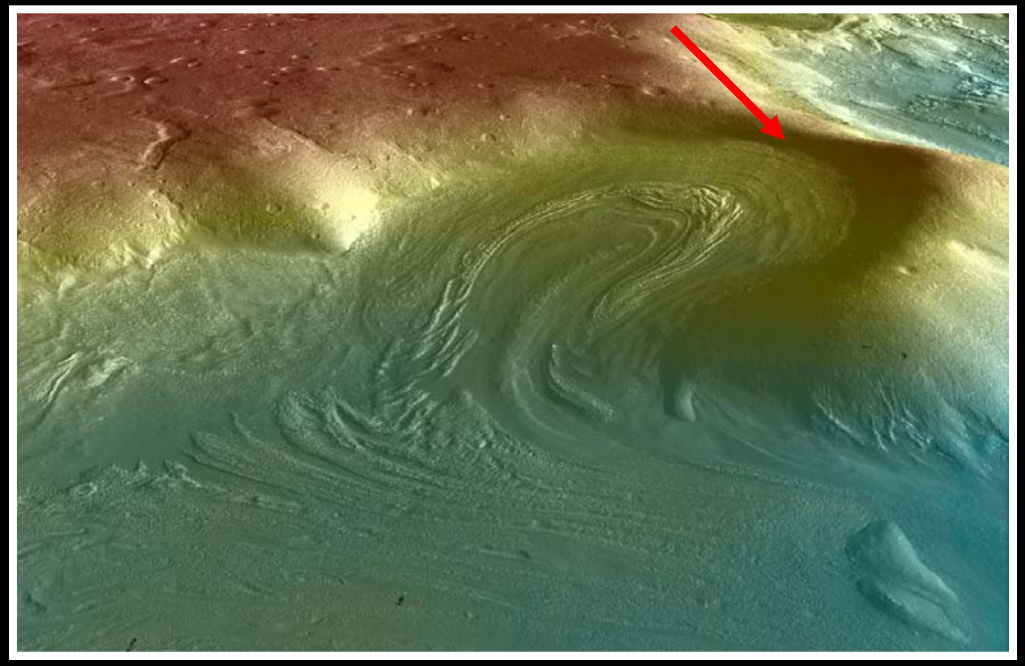
-Surface area of observed ice masses = 21,100 km^2
-Volume (assuming average thickness of 300 m) = 6325 km^3
~ 5 cm global equivalent layer
(compare to PLD: ~ 20 m)

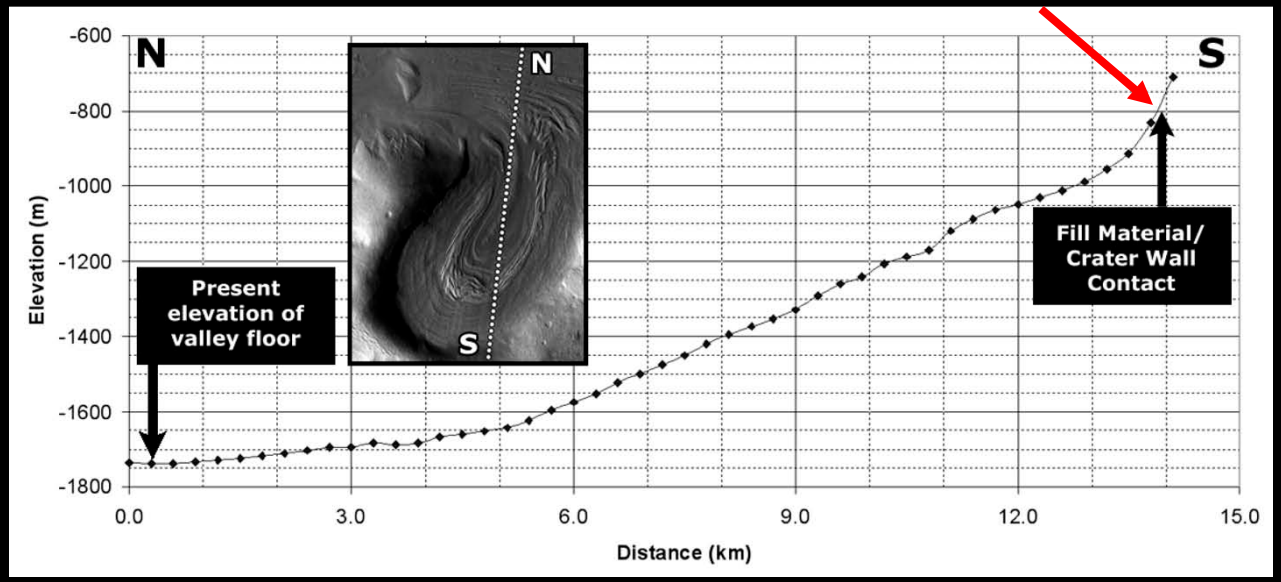
-ICE SEQUESTRATION + THERMOMETER!



Evidence for Glacial Highstands Up to ~1 Km Above Current Deposits



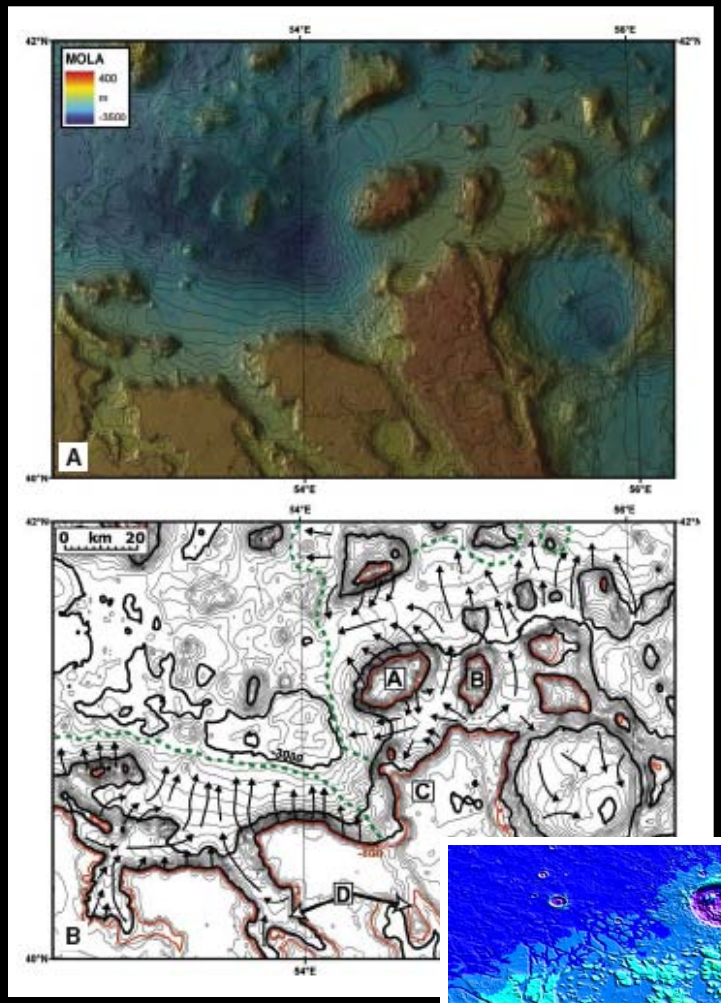




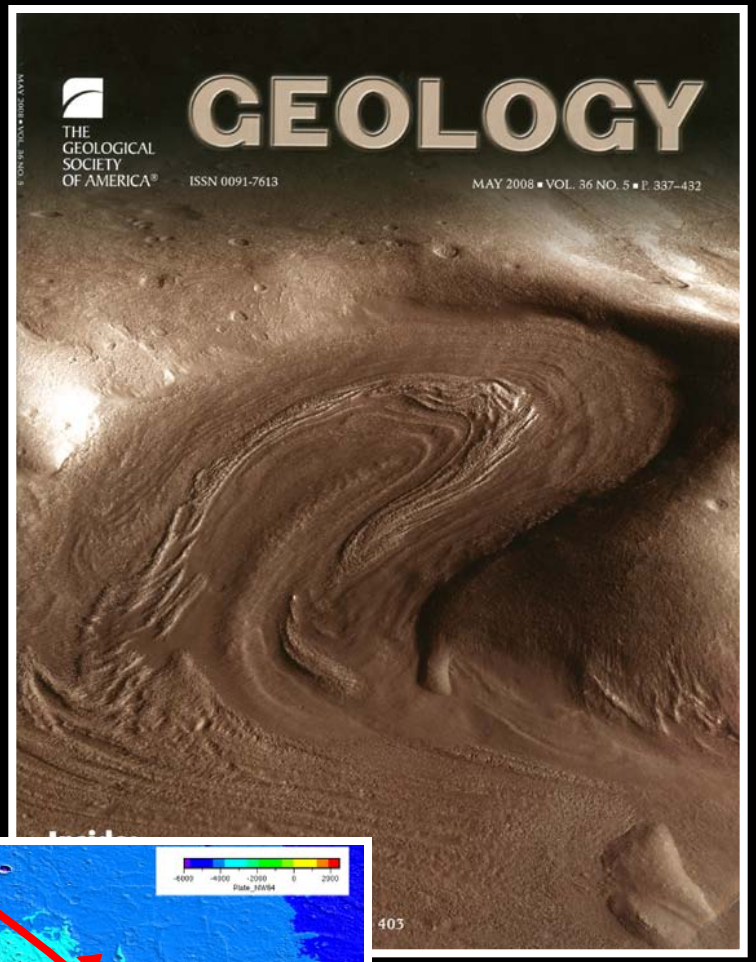
Coloe Fossae Region

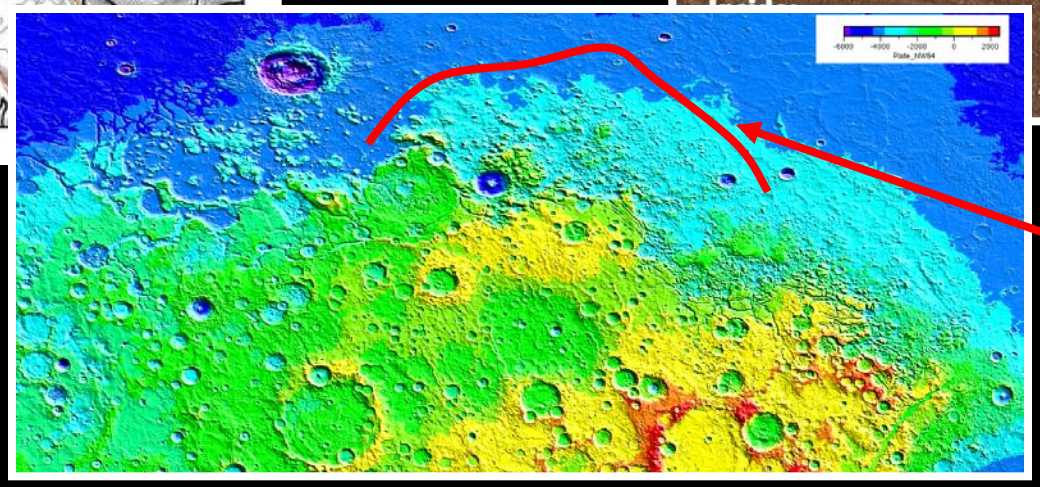
(Dickson et al. 2008)

Mars: Amazonian Mid-Latitude Glaciation

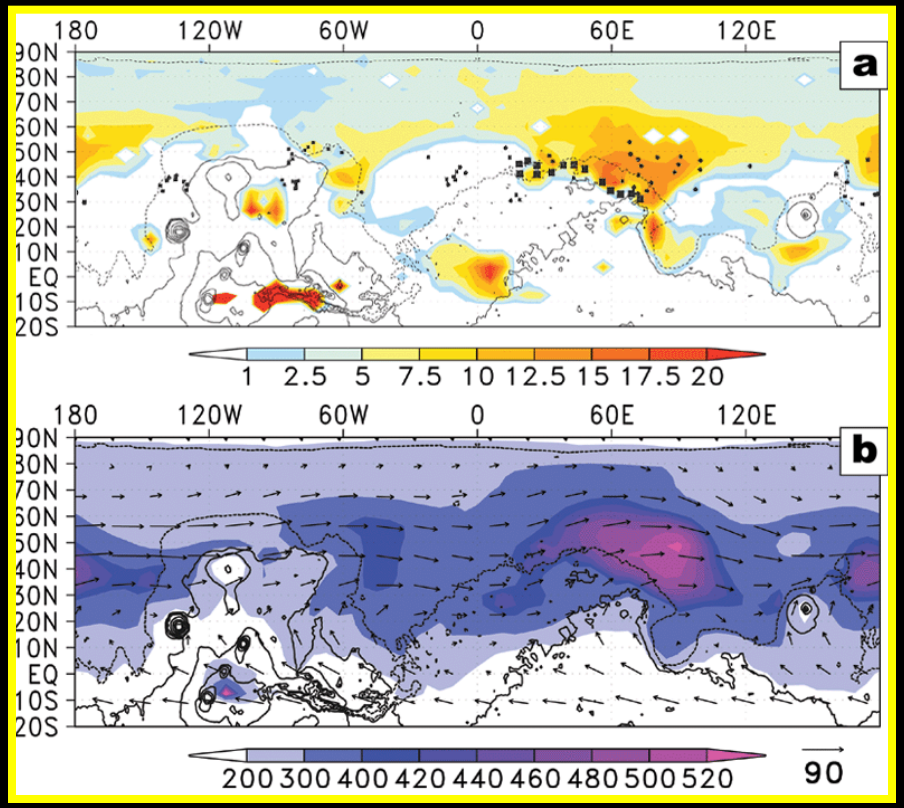


(Dickson et al. 2008)

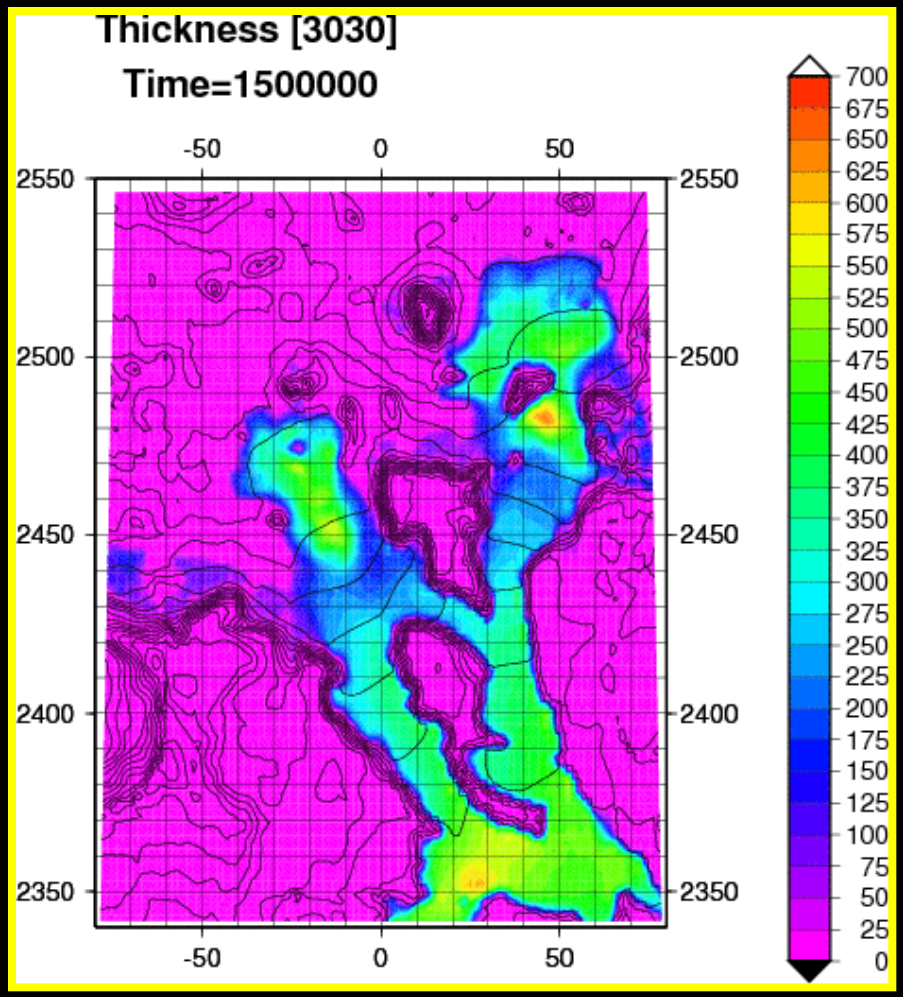




Previous extent of glaciation?



a) Predicted ice accumulation (mm/yr).
b) Average cloud ice content (pr-µm) and 24 km winds for Ls = 270-300°.

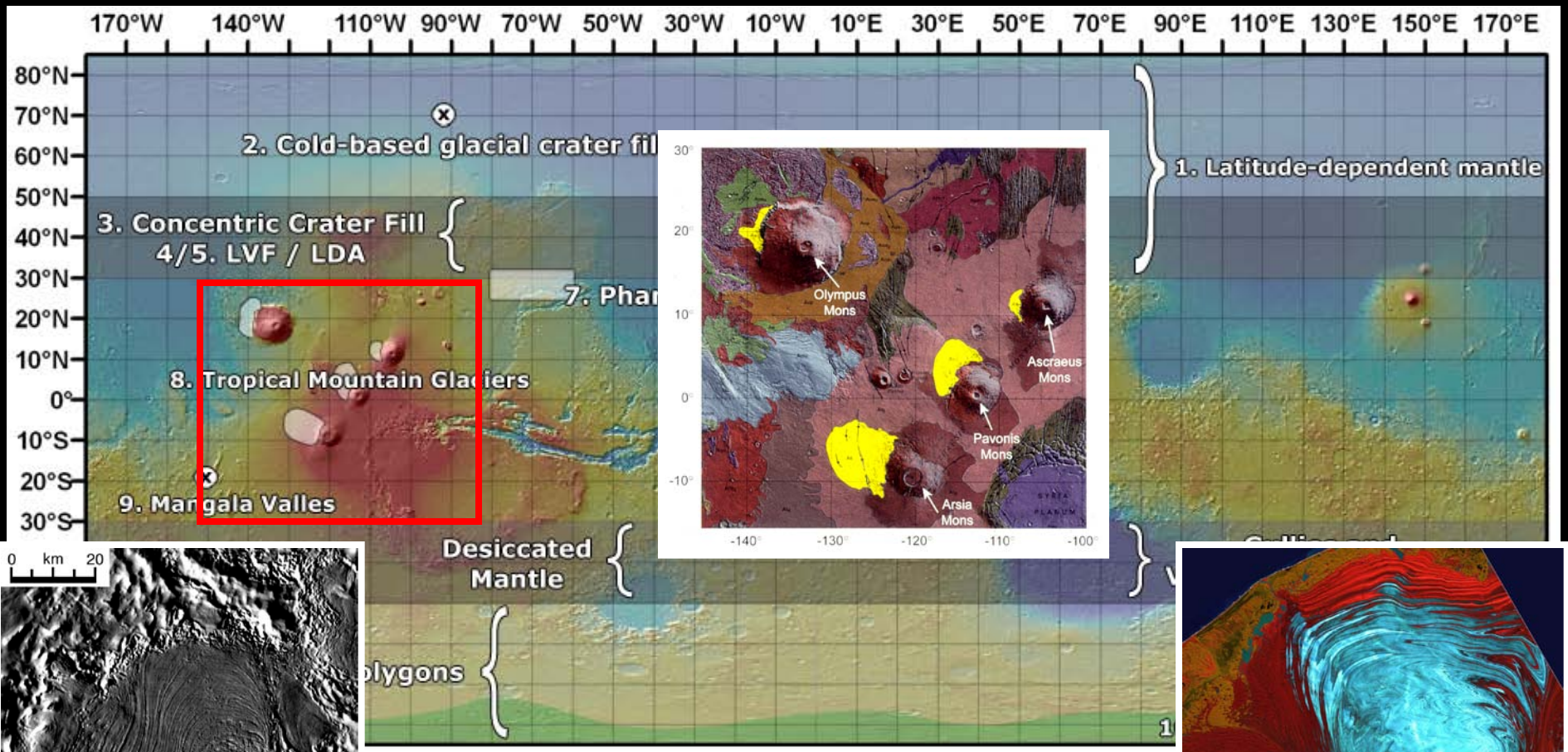


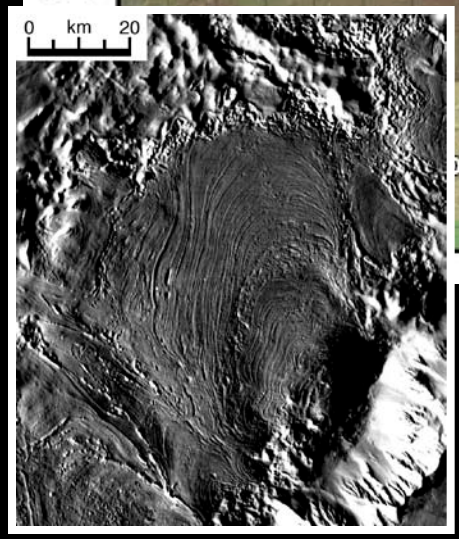
GCM Analyses:
(J.-B. Madeleine et al., 2009)

Glacial Flow Modeling:
(Fastook et al., 2009)

Synthesis: Alpine valley glaciation *or* regional mid-latitude plateau glacial landsystems?

Non-Polar Latitude-Dependent Ice-Related Deposits

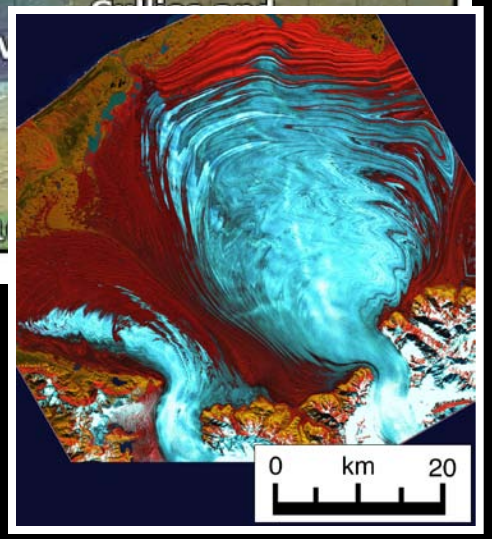




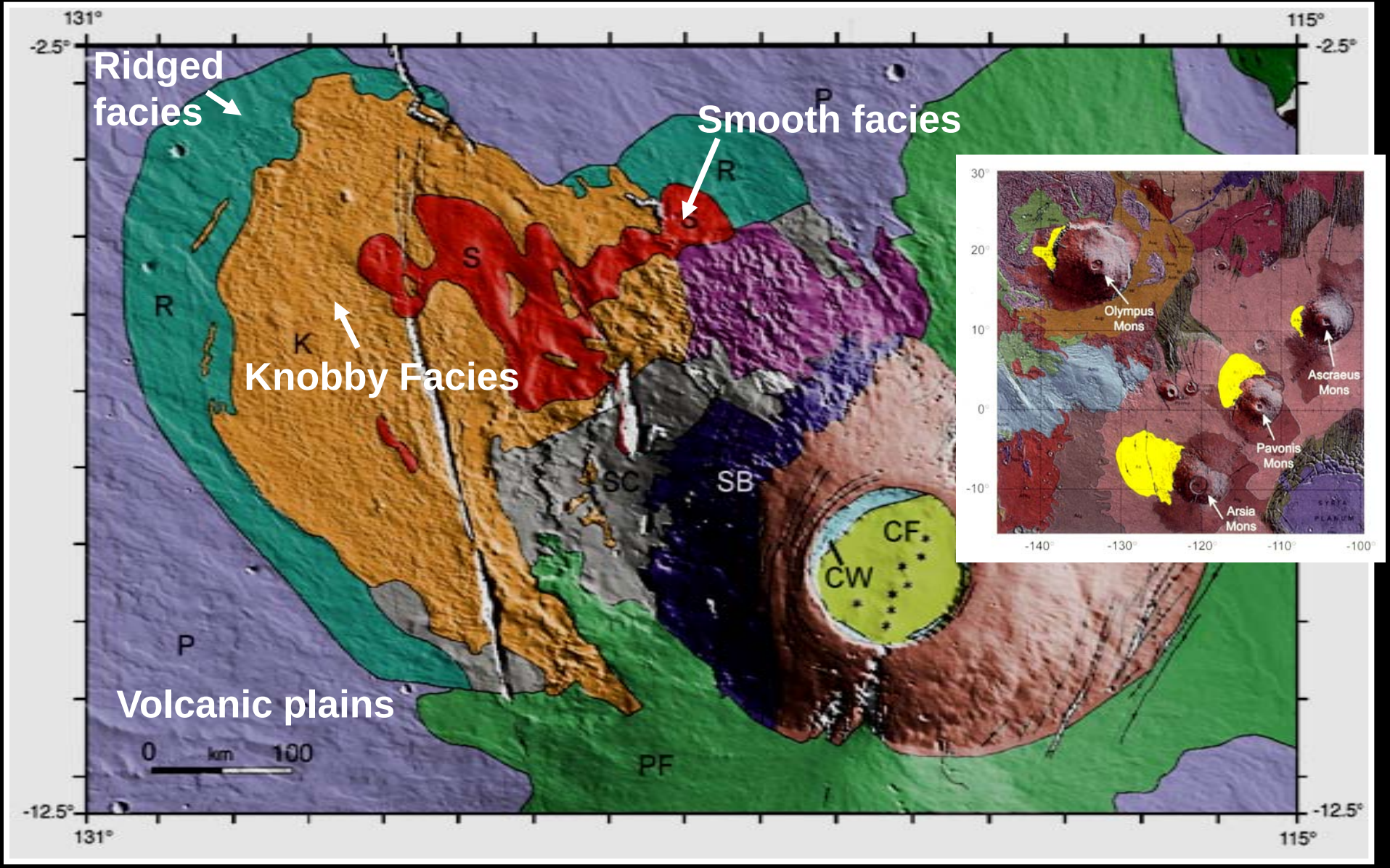
Tropical Mountain Glaciers

Mars-Olympus

Earth-Alaska

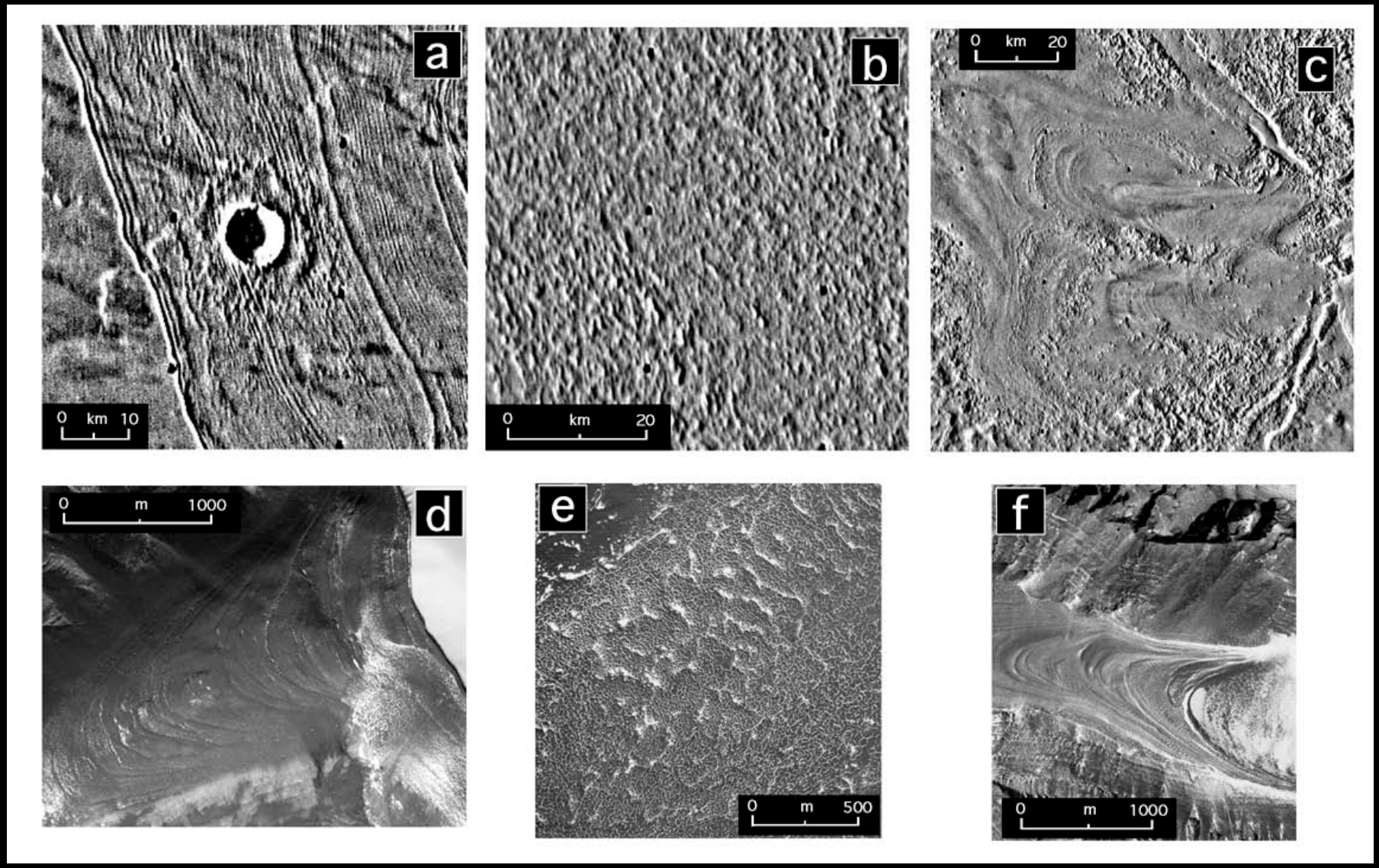


Arsia Mons Fan-Shaped Deposit



After Zimbelman and Edgett (1992)

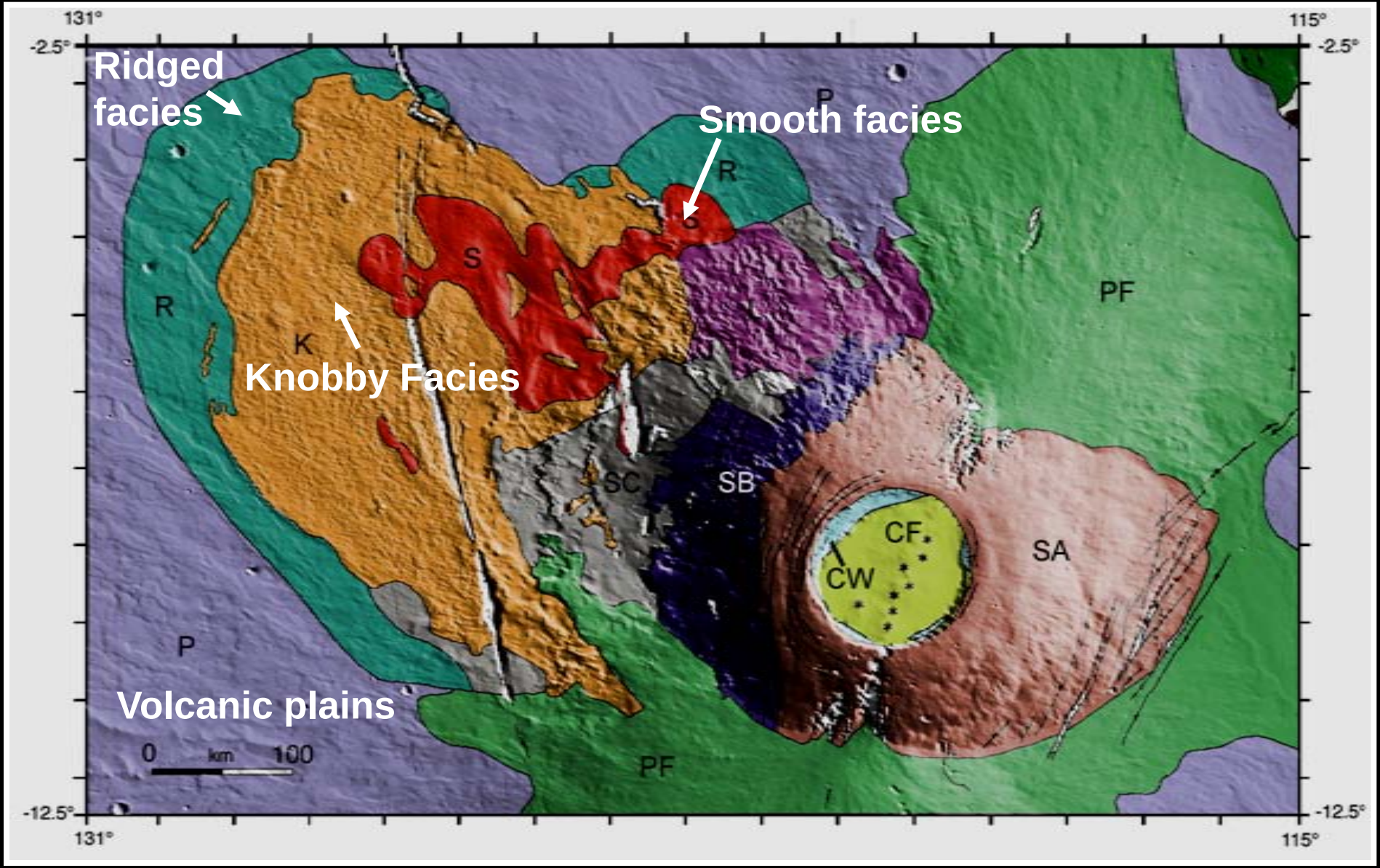
Ridged Facies **Knobby Facies** **Smooth Facies**



Drop Moraines **Sublimation Till** **Debris-Covered Glaciers**

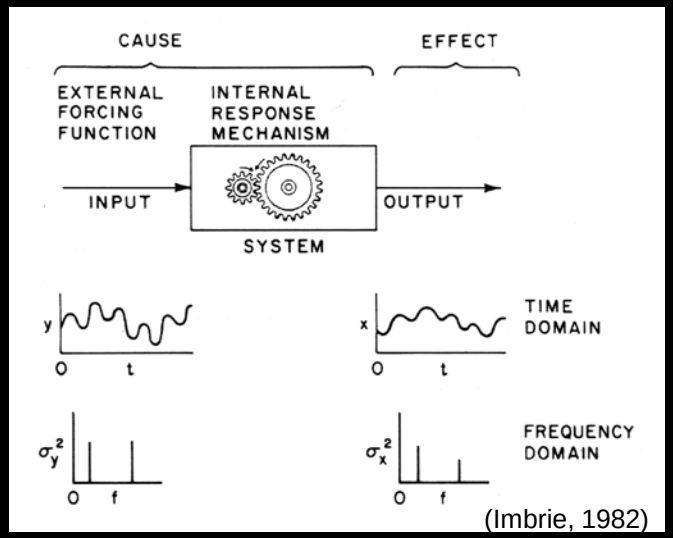
-Cold-based glacier facies- Head and Marchant, 2003,

Arsia Mons Fan-Shaped Deposit



After Zimbelman and Edgett (1992)

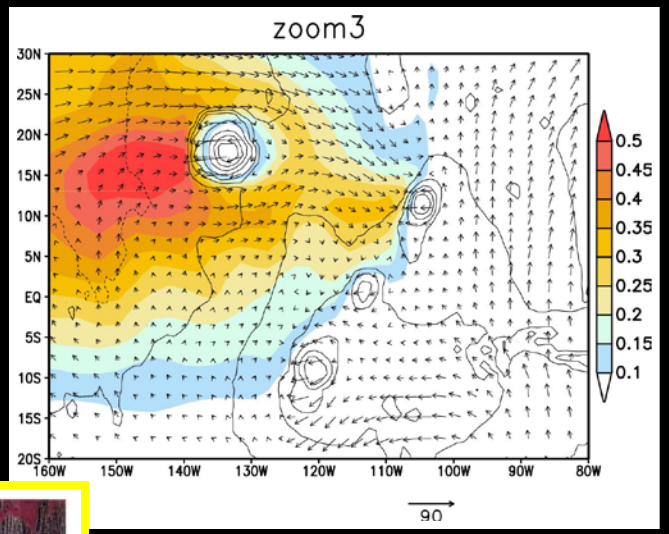
How Do We Get Tropical Mountain Glaciers?



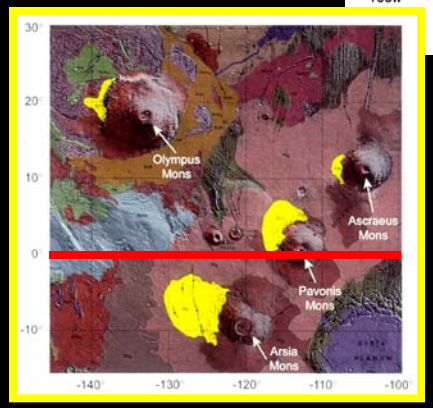
(Imbrie, 1982)

Orbital Parameters | **Climate System** | **Geological Record**

Westerly winds dominate in the Tharsis region in N. Summer (and other seasons). The abundant water vapor is strongly adiabatically cooled in the updraft near the volcanoes and other slopes. Ice accumulates and forms glaciers.



Cloud thickness (kg/m^2) and mean winds at 1km above the surface during Northern summer.



-Moderate mean Obliquity ~45°.

-No water ice polar caps.

-Equatorial water ice reservoir dominates.

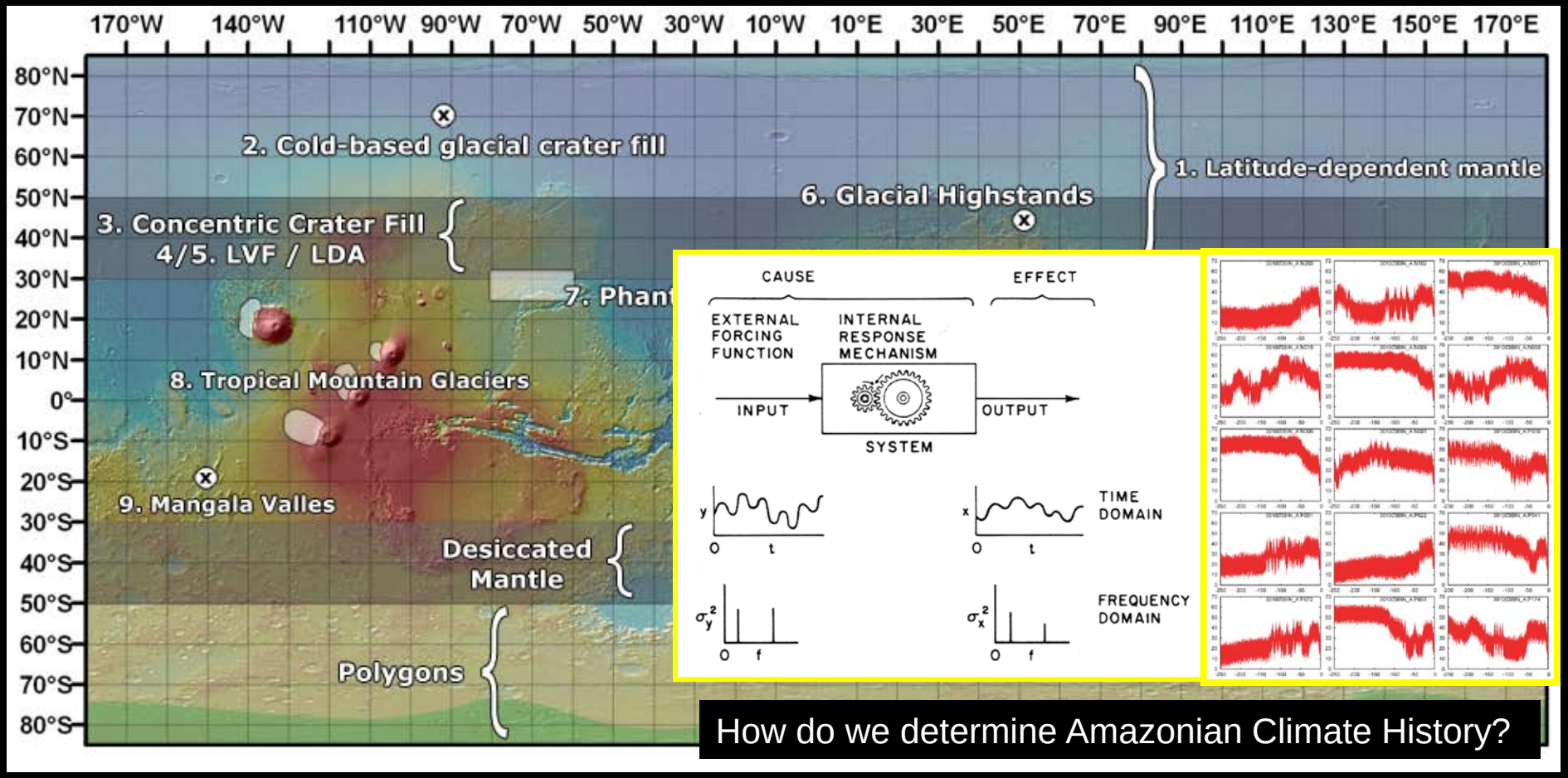
-Robust tropical mountain glaciers.

Why do glaciers form?

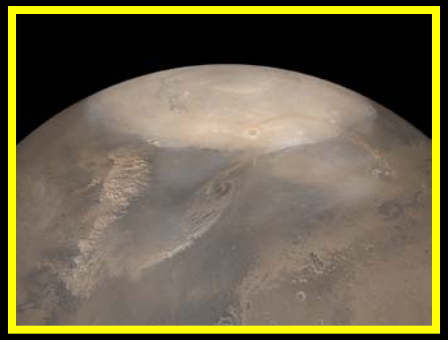
Precipitation on windward slope.

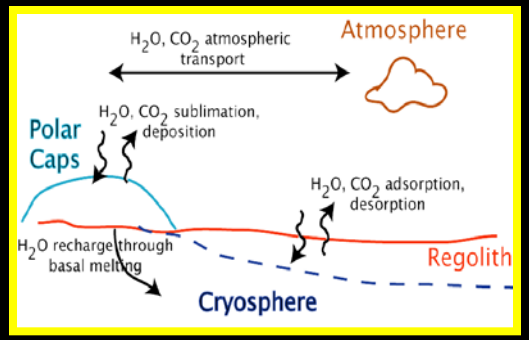
(Forget et al. 2006)

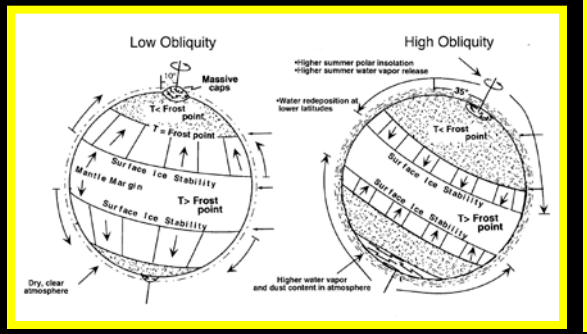
Inventory: Non-Polar Latitude-Dependent Ice-Related Deposits



How do we determine Amazonian Climate History?

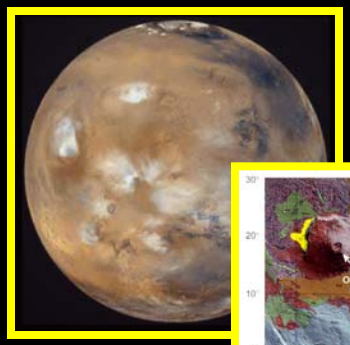


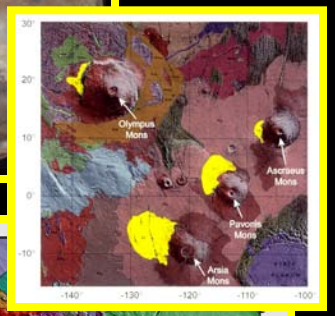




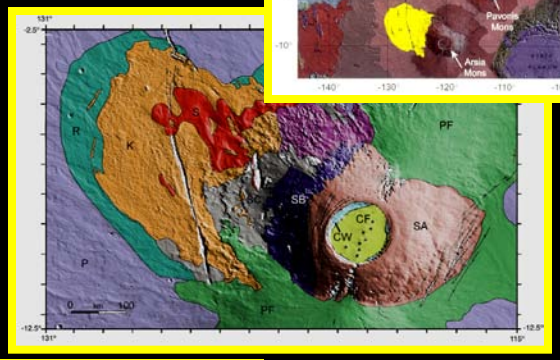
Amazonian Climate History

1) Determining Obliquity History: Analysis of the geological record of non-polar ice deposits can help significantly in distinguishing among candidate Late Amazonian obliquity histories.



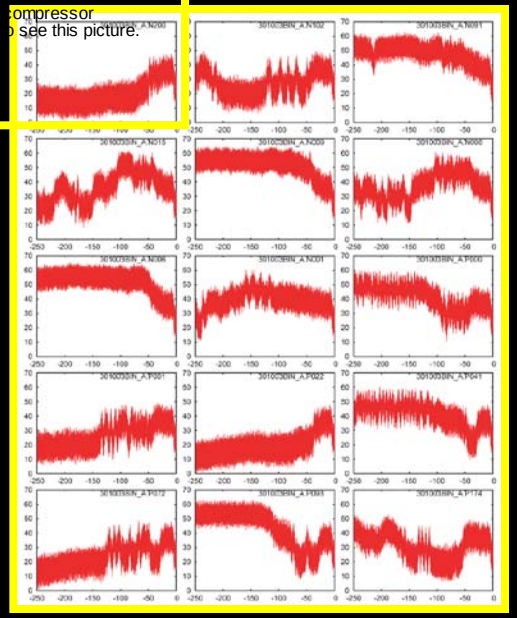


2) The selected scenarios are not necessarily the correct ones, but these give significant guidance to major segments of climate history.

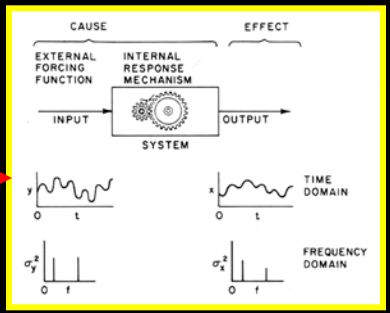


3) The ability to reject the vast majority of the candidate scenarios underlines the usefulness of the approach.

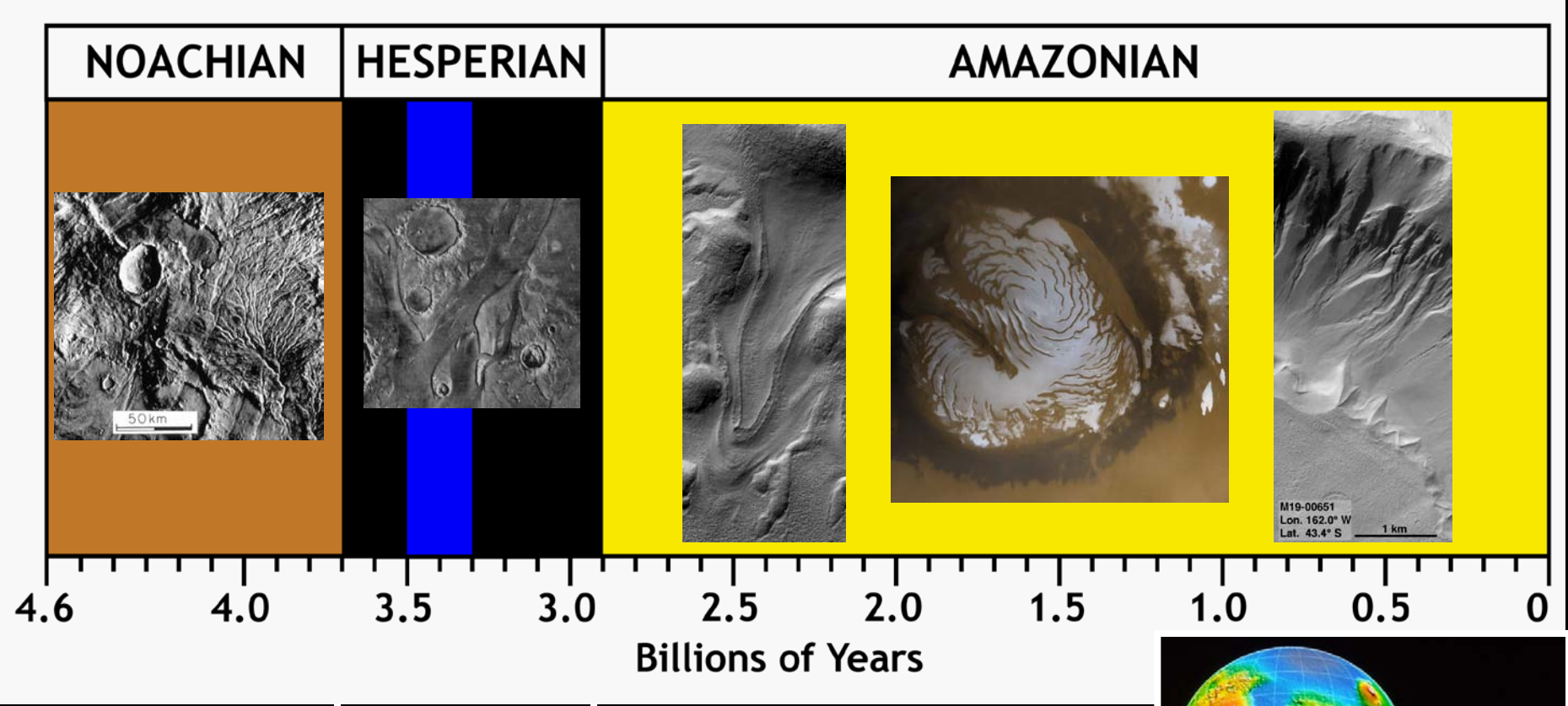
4) Preliminary results suggest that actual obliquity history was not characterized by long-term (>150 Ma) periods at extreme values; also, <u>not likely to have been like today</u>!



5) The <u>geological record</u> provides the basis to analyze and reconstruct <u>previous climate history</u>.



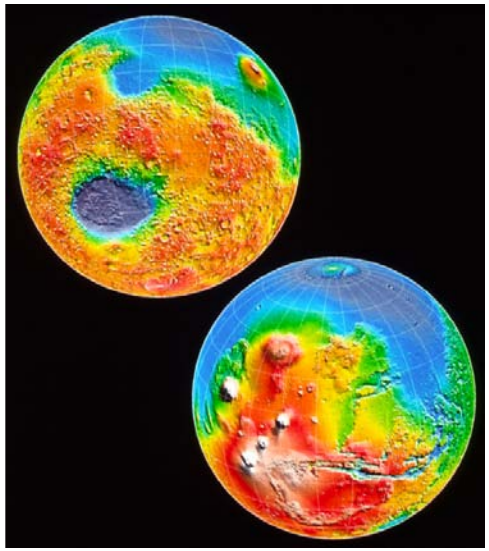
Water on Mars: Relation to Geologic History



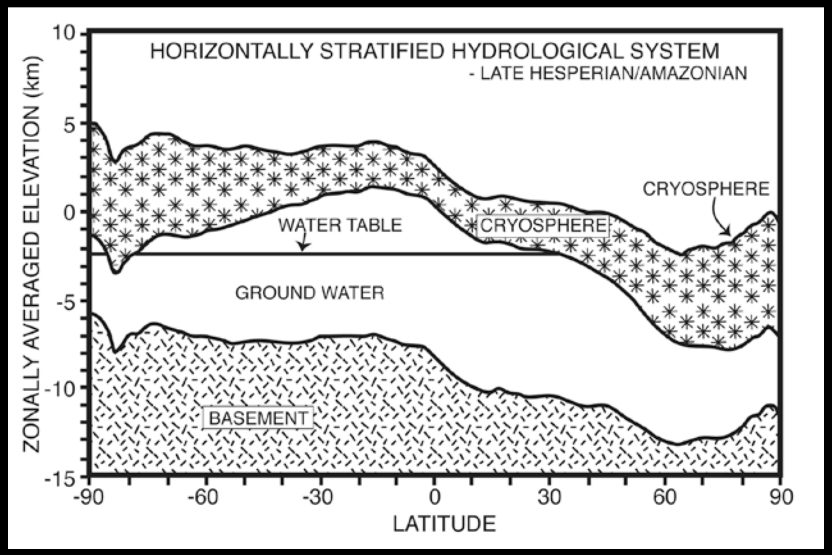
- Heavy impact bombardment.
- Valley networks.
- "Warm/Wet" early Mars?

-Volcanism.
- Outflow channels.
- Oceans?
- South circumpolar deposits.

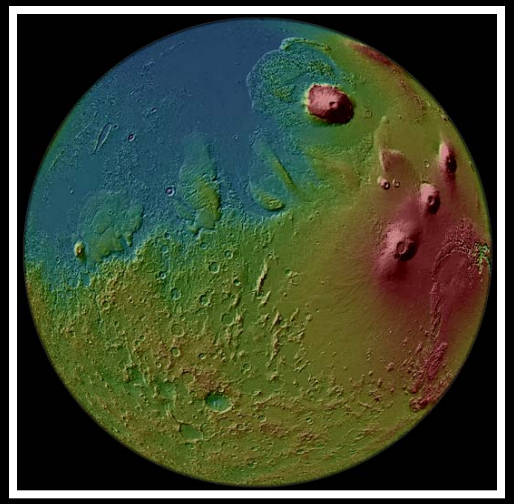
- Low impact rates.
- Tharsis volcanism continues.
- Outflow channels continue.
- Late-stage polar caps.
- "Cold/Dry" late Mars.



Mangala Valles:
Dike-Induced Cryospheric Cracking, Phreatomagmatic Eruption, Massive Groundwater Release from Aquifer Under Hydrostatic Pressure.

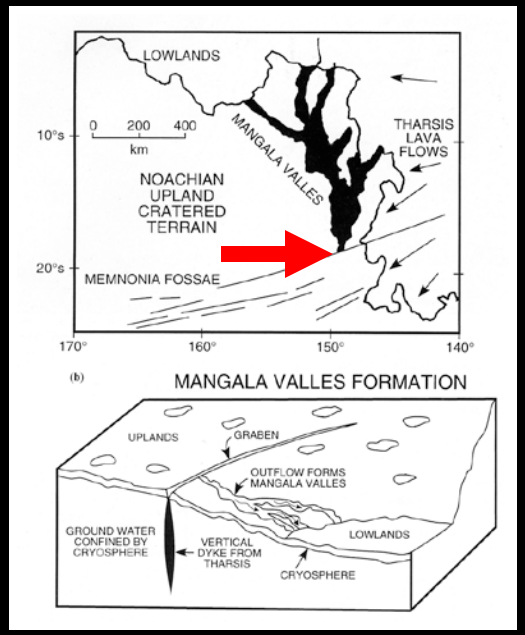


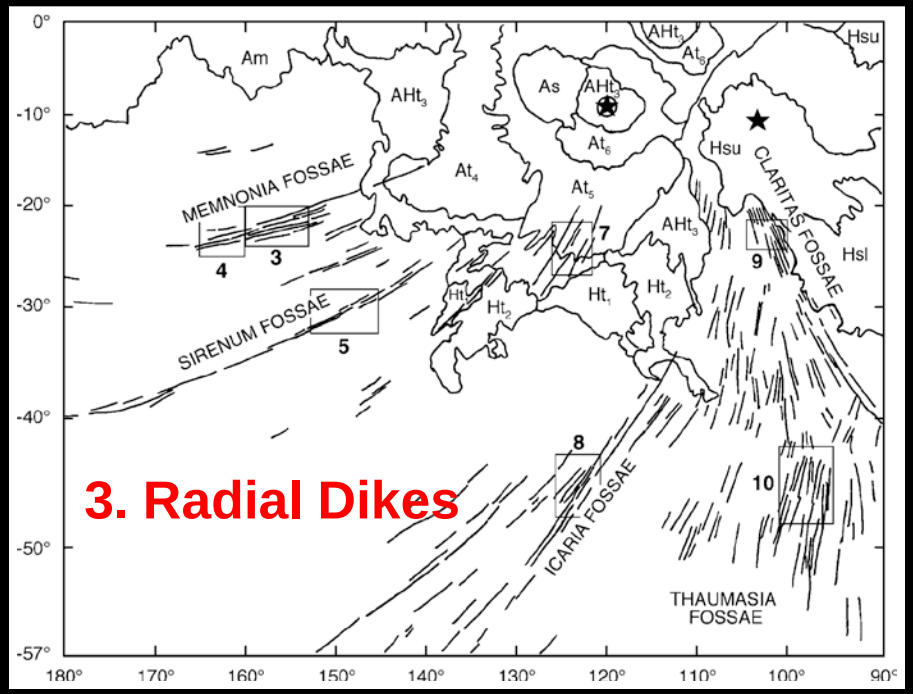
1. Global Confined Aquifer



2. Tharsis Volcanic Province

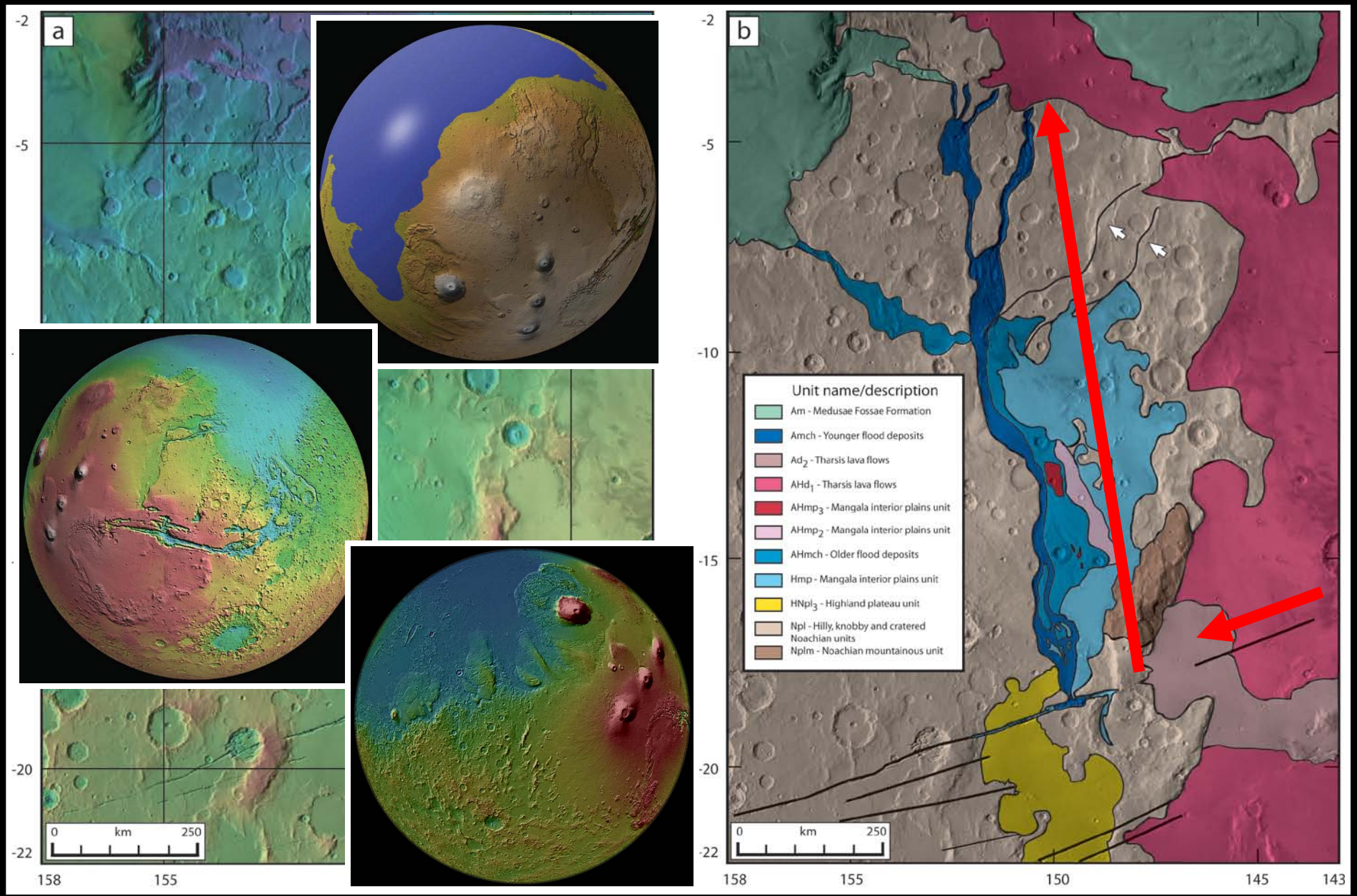
4. Dikes Crack, Heat Cryosphere, Release Pressurized Groundwater.



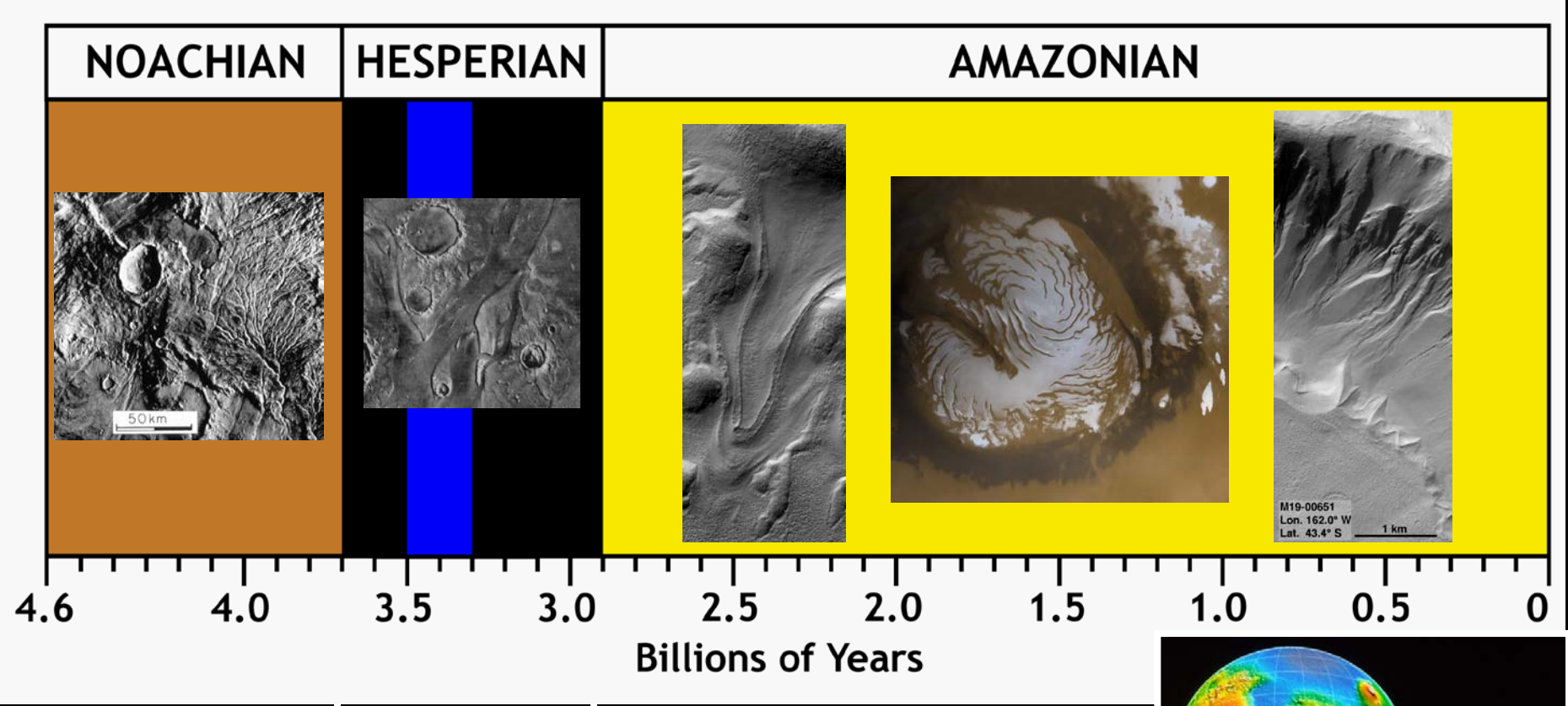


(Wilson and Head, 2002)
(Head and Wilson, 2003)

Mangala Valles:
“Pressurized Groundwater-Release Jokulhlaup”



Water on Mars: Relation to Geologic History



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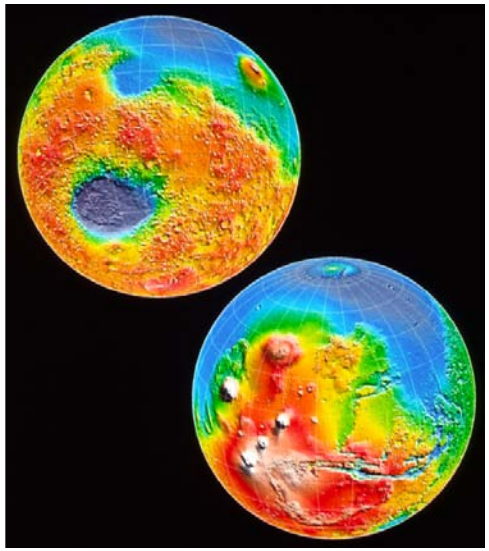
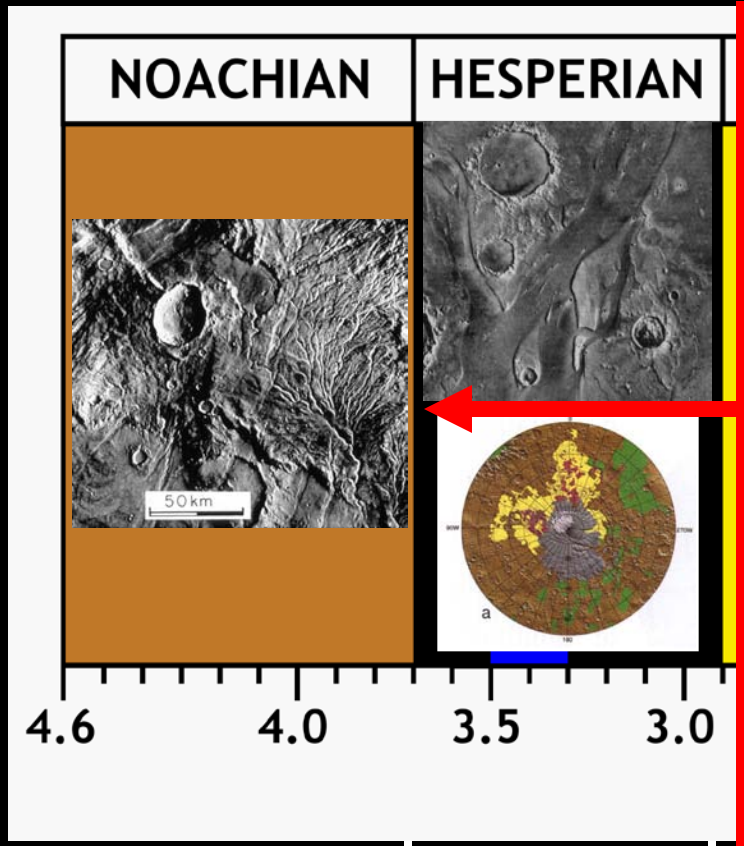
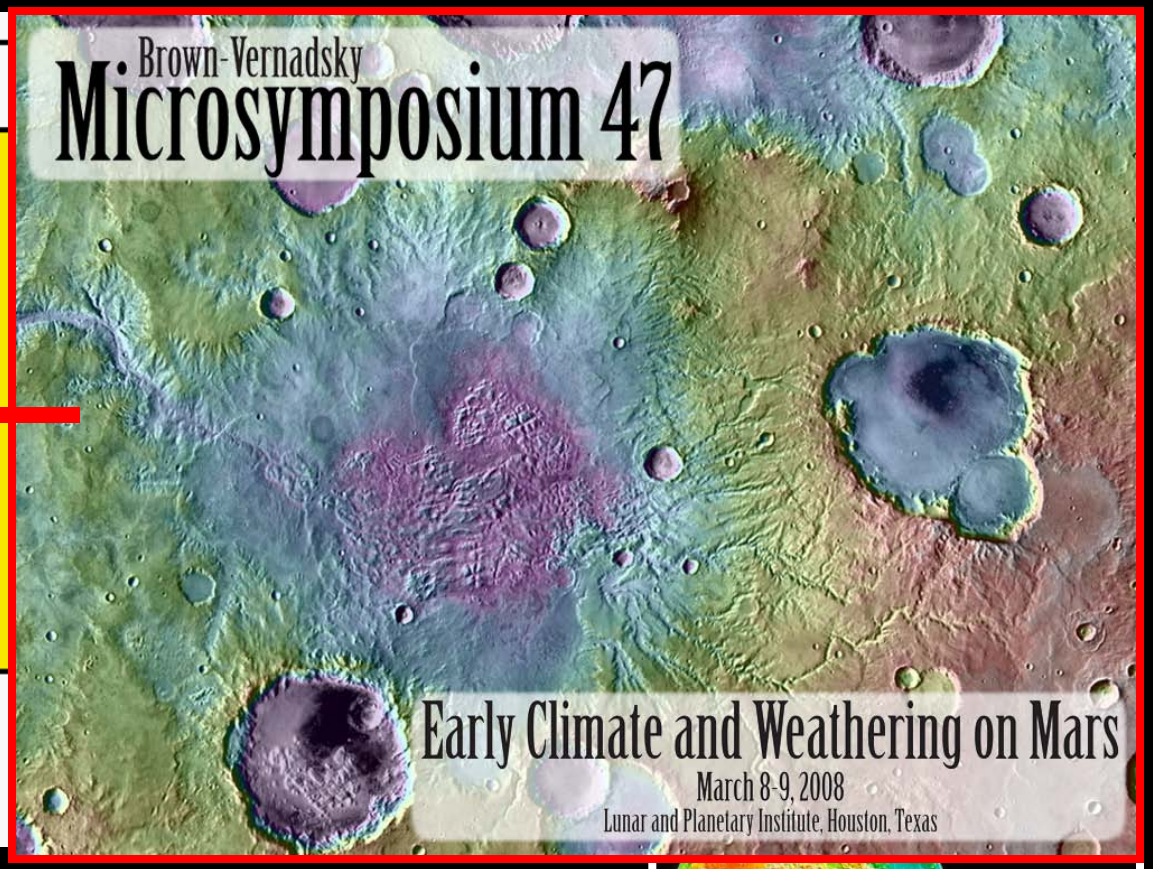


Water and Climate on Mars: Relation to Geologic History





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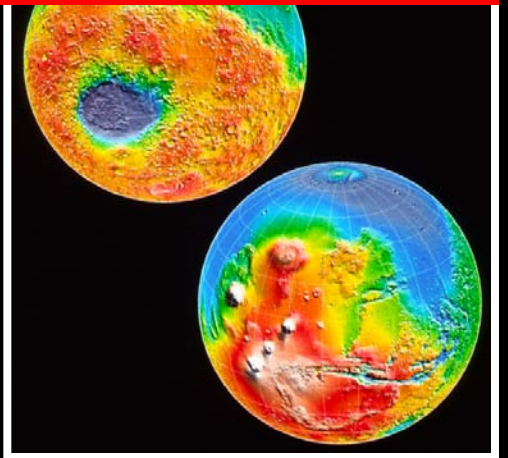
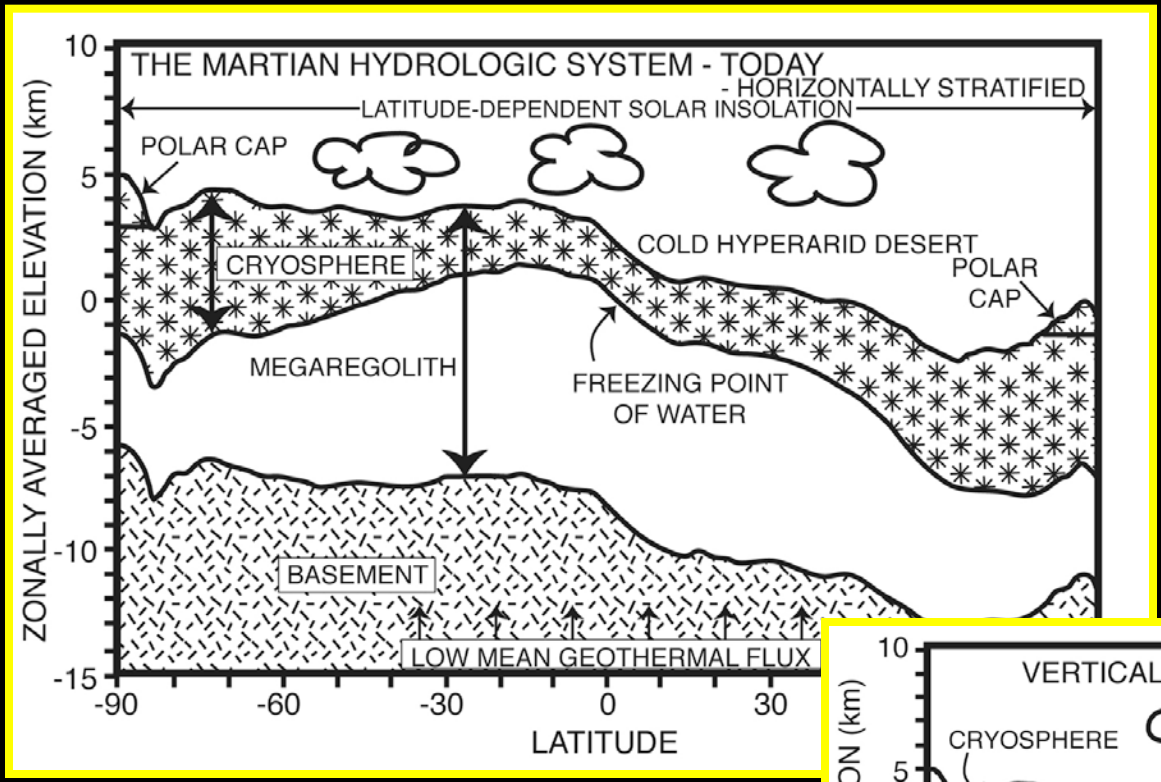


What is the Nature of the Hydrological Cycle on Mars?



TODAY:
-Cold, Hyperarid Desert.
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-Global Cryosphere.
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NOACHIAN:
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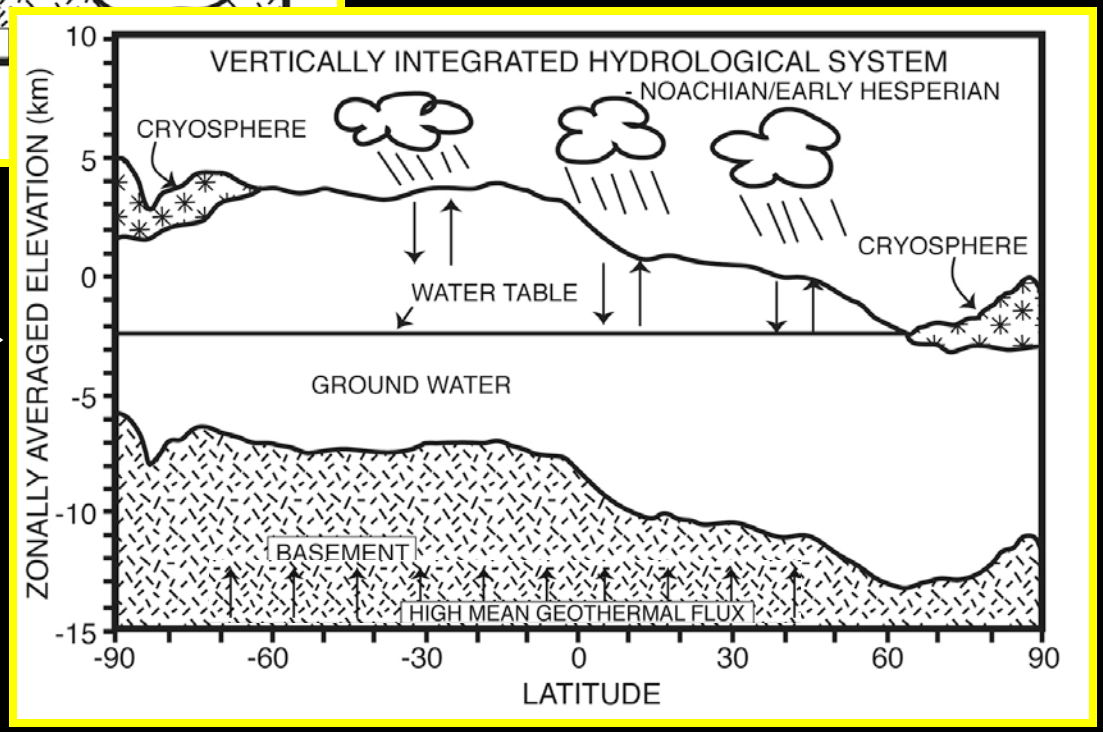
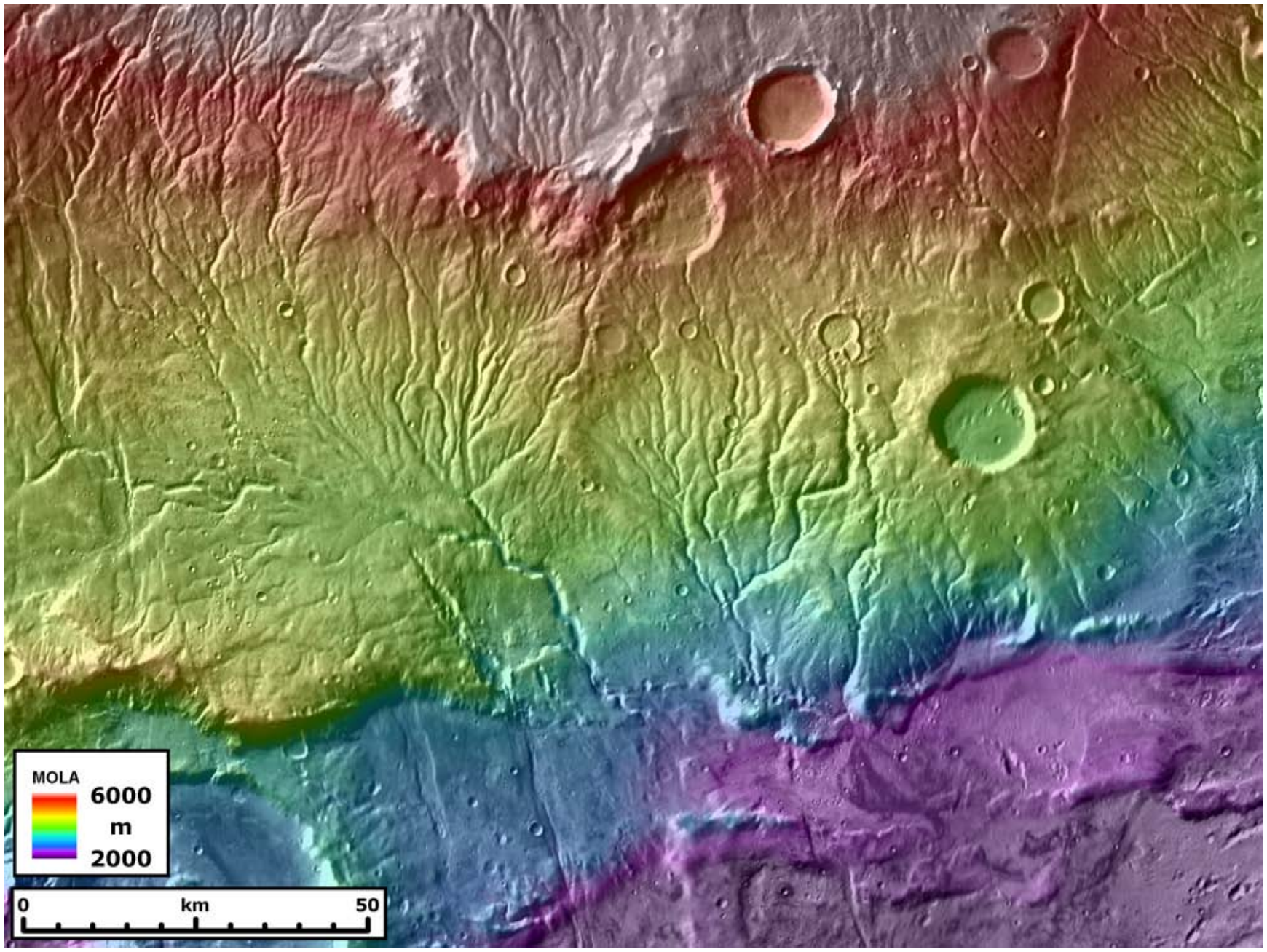
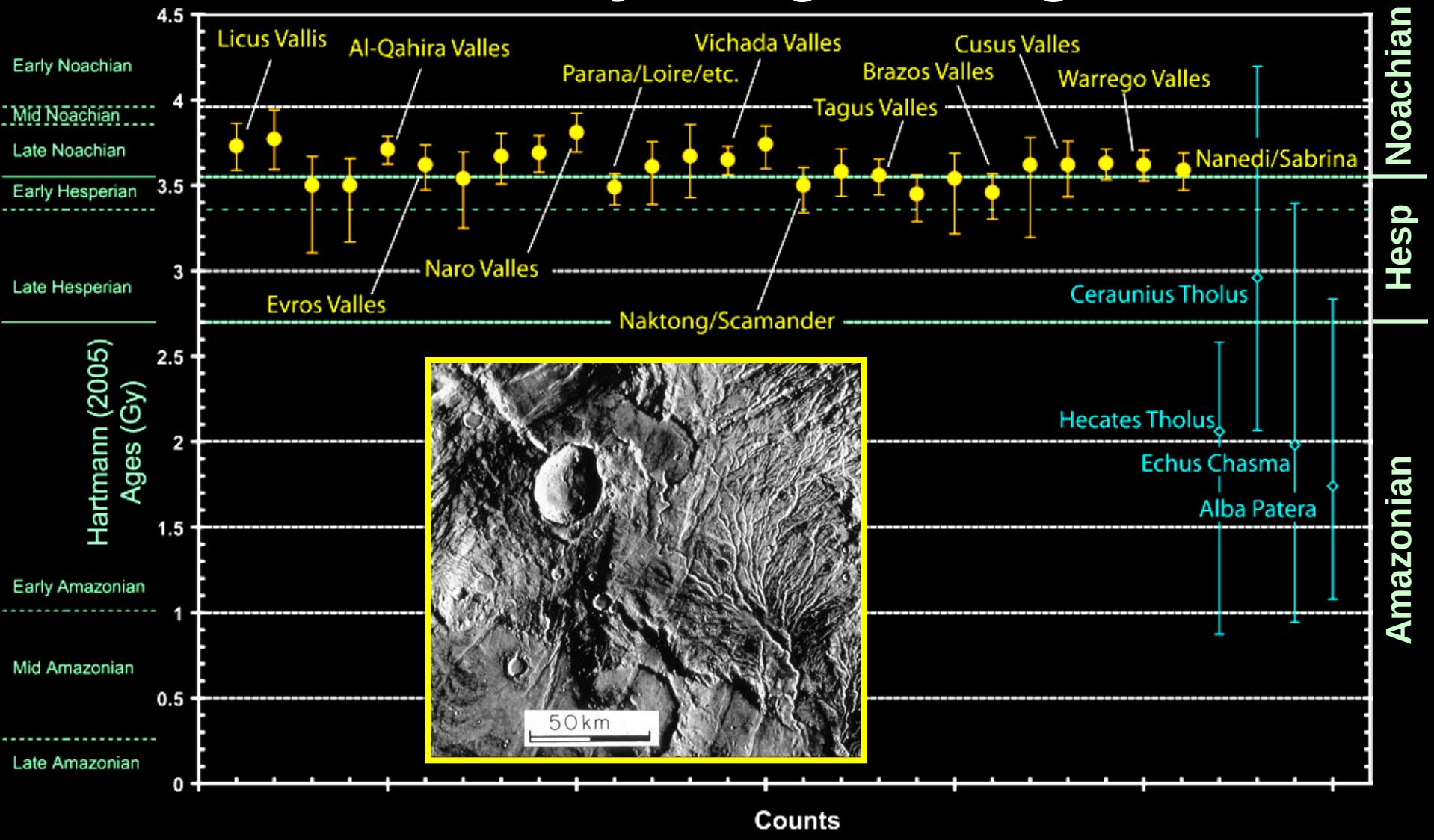
-Warmer and Wetter (?).
-Vertically Integrated Cycle (?).



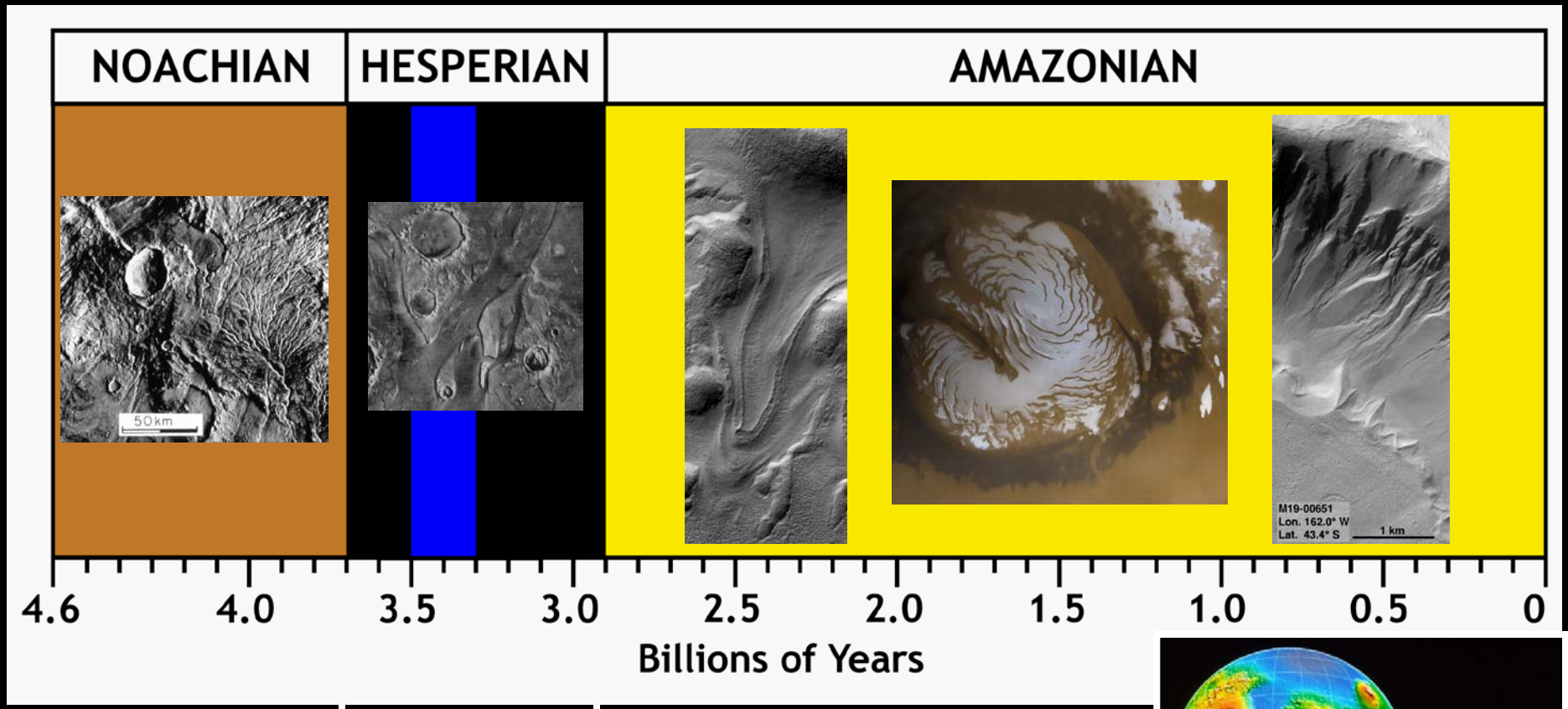

MOLA
6000
m
2000
0
km
50

Valley Networks: Summary of Age Dating



Fassett and Head, 2008, Icarus.

Water and Climate on Mars: Relation to Geologic History



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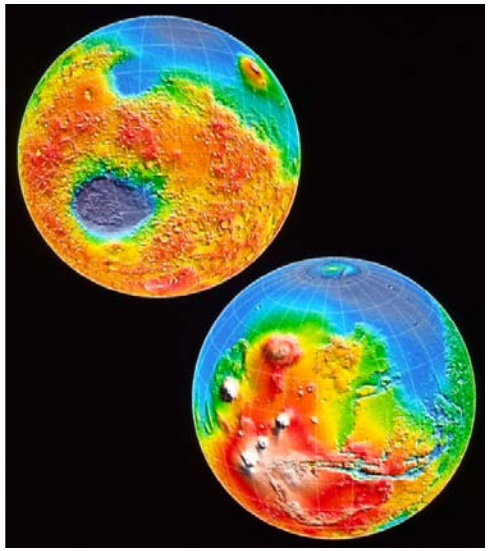
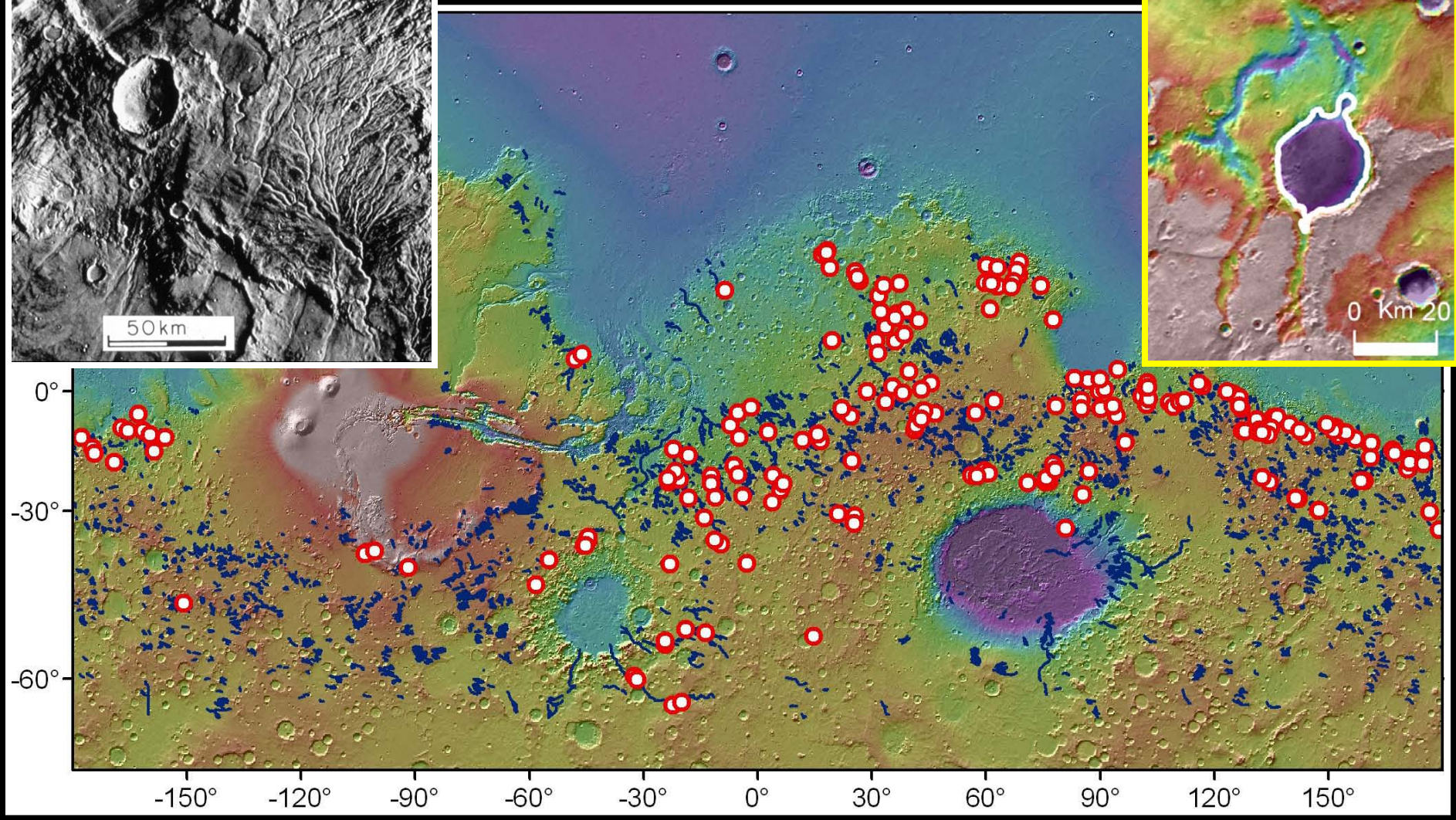


Noachian Valley Networks and Open Basin Lakes



Fassett and Head, 2008a,b

Open Basin Lakes
N=>210 (~65% newly recognized)

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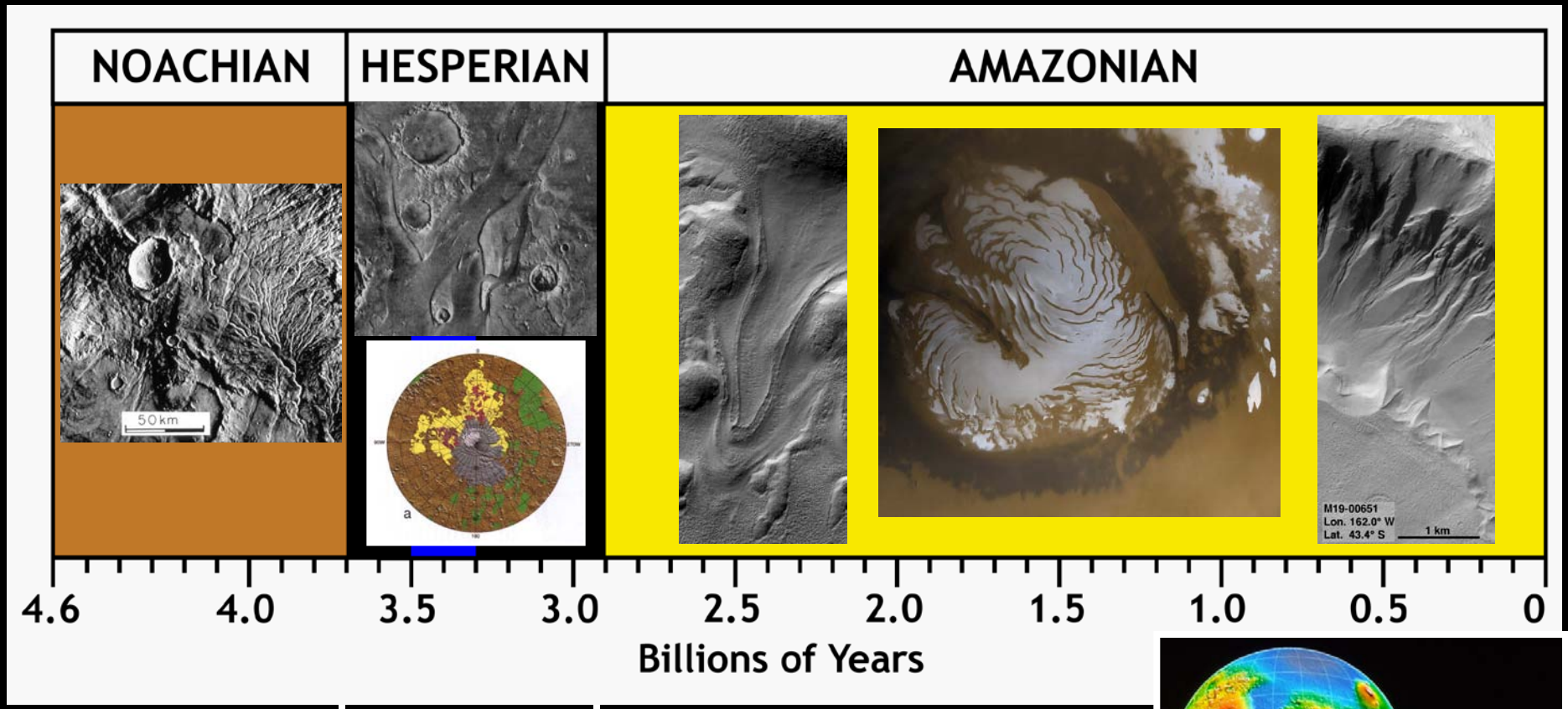
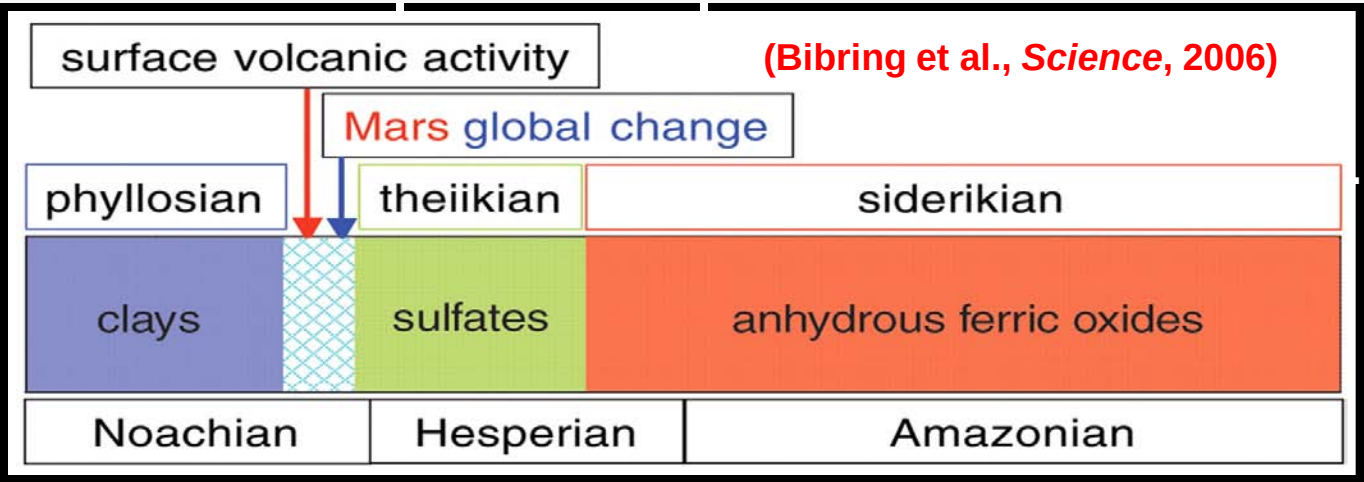
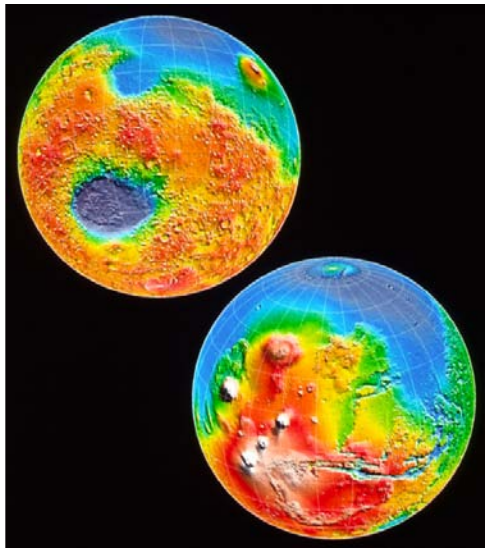
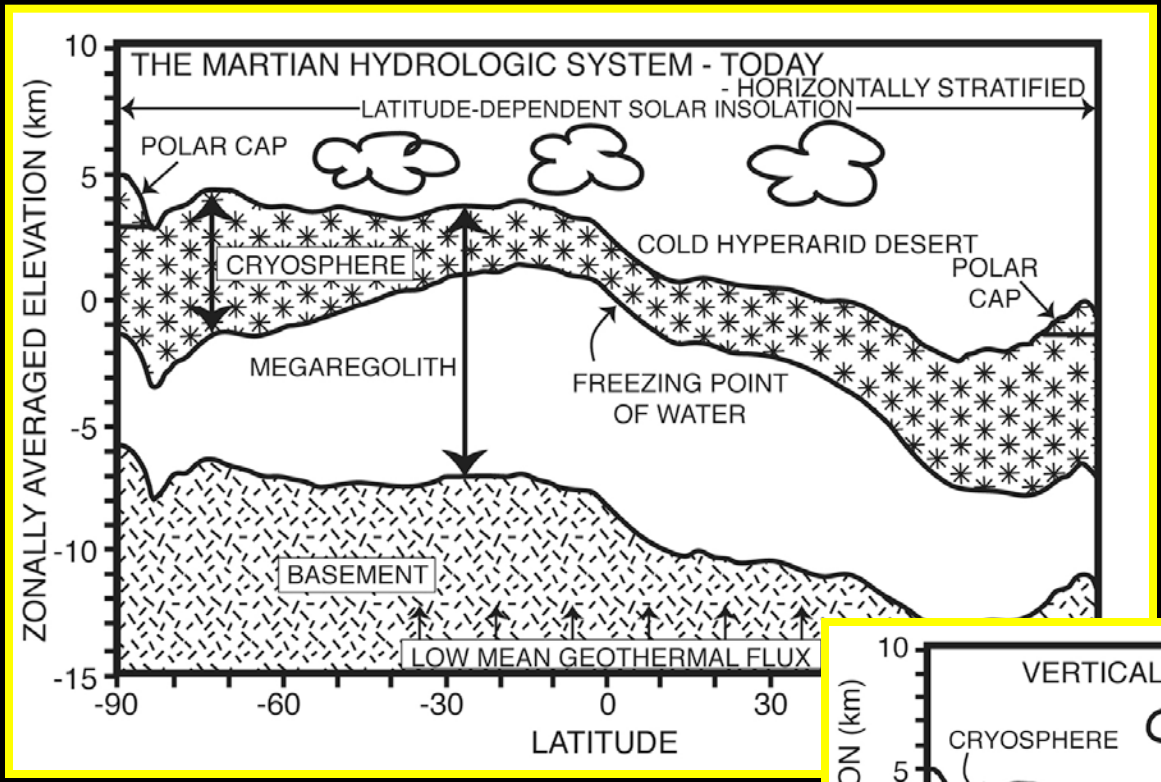




(Bibring et al., *Science*, 2006)



Nature of the Hydrological Cycle on Mars: Implications for Life



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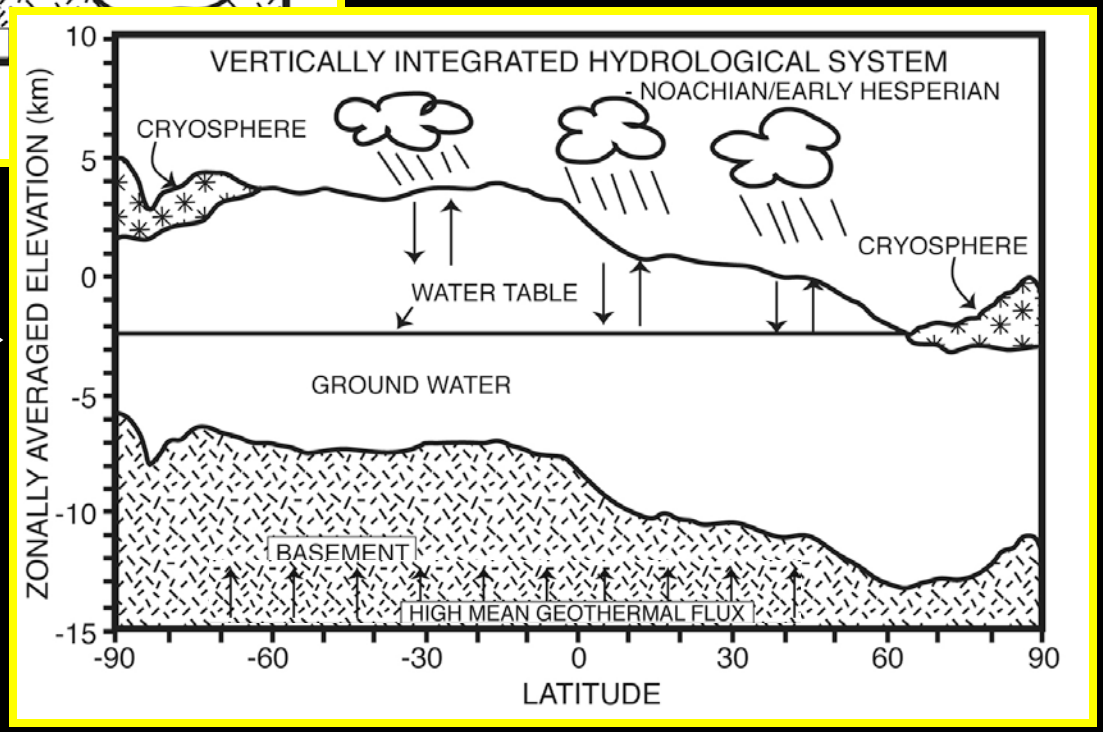
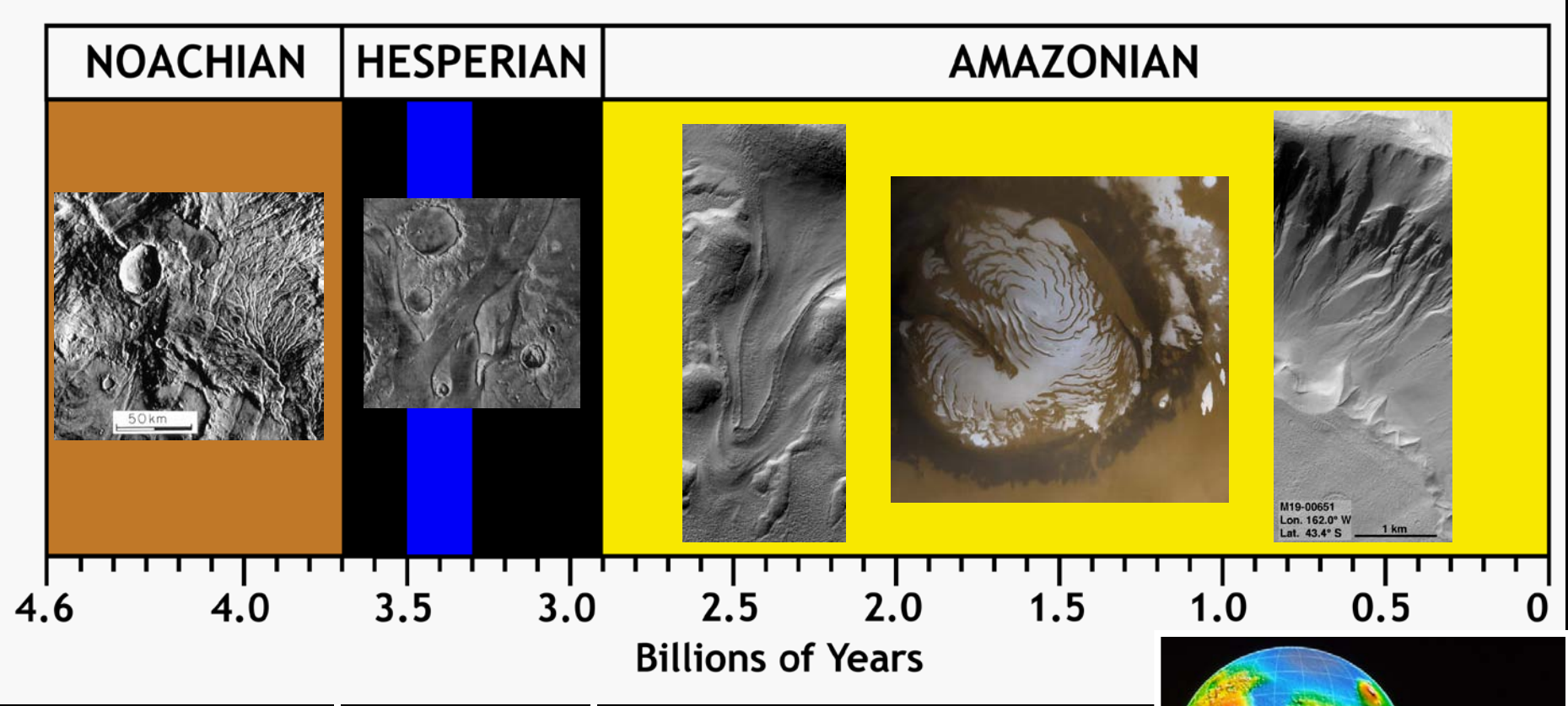


Water on Mars: Relation to Habitable Environments



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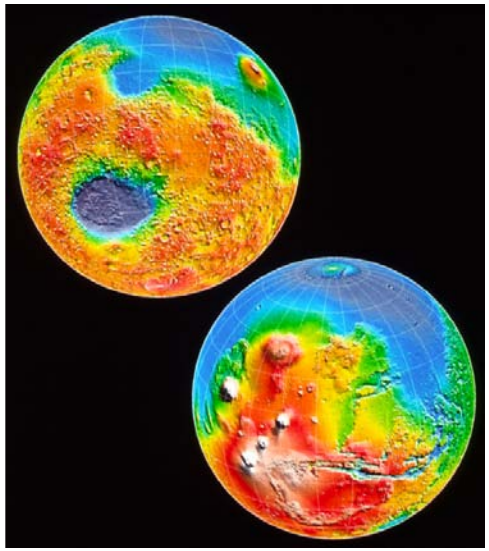

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http:www/planetary.brown.edu

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