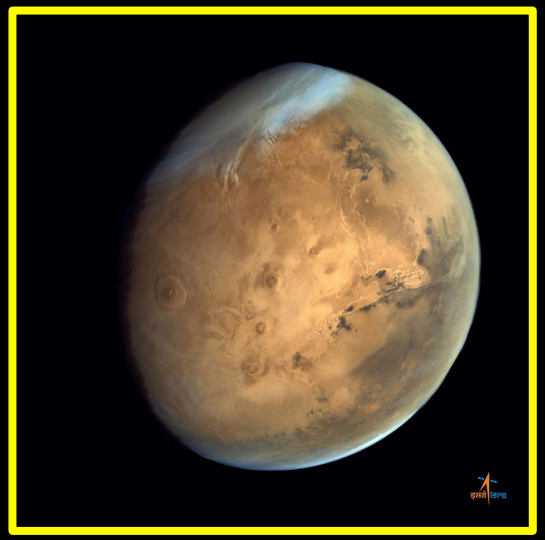
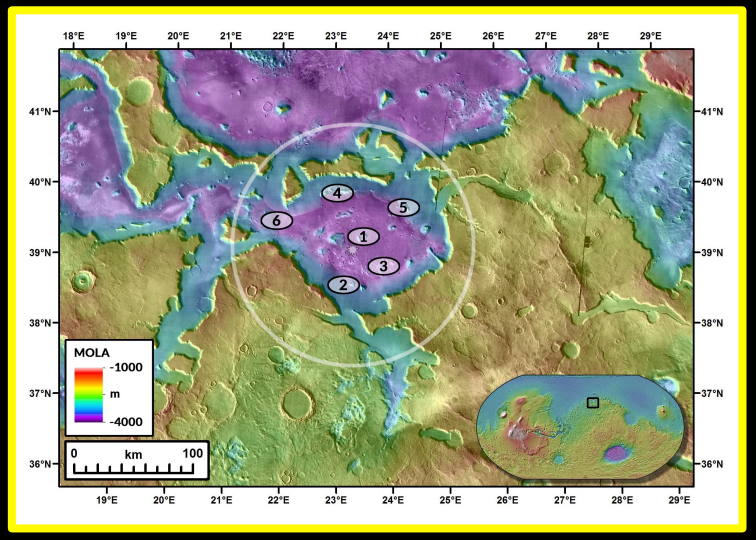
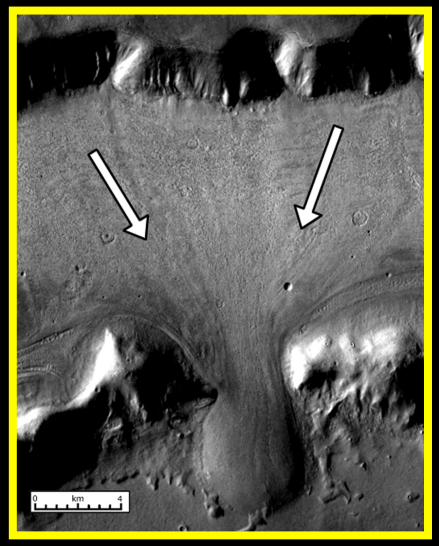
MARS HUMAN SCIENCE EXPLORATION AND RESOURCE UTILIZATION: THE DICHOTOMY BOUNDARY DEUTERONILUS MENSAE EXPLORATION ZONE

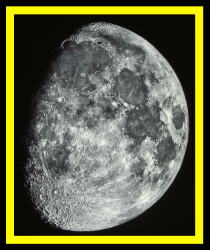






James Head[1], James Dickson[1], John Mustard[1], Ralph Milliken[1], David Scott[1], Brandon Johnson[1], David Marchant[2], Joseph Levy[3], Kjartan Kinch[4], Christine Hvidberg[4], Francois Forget[5], Dale Boucher[6], Jill Mikucki[7], James Fastook[8], Kurt Klaus[9].

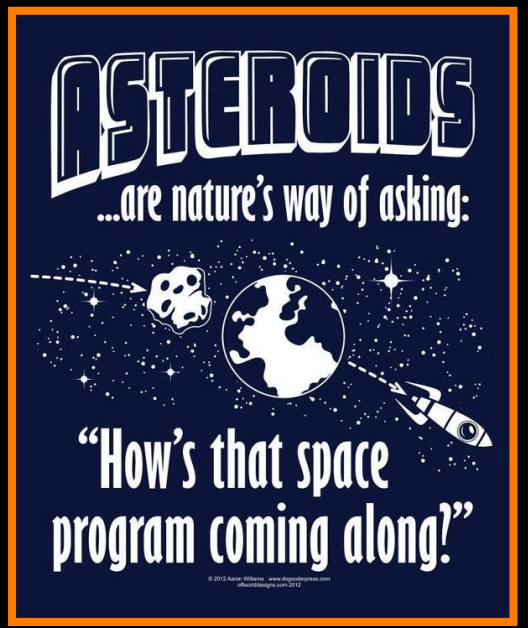
#1033
(39.11° N, 23.199° E)
Elevation -3750



[1]Brown University, Providence, RI USA; [2]Boston University, Boston, MA USA; [3]University of Texas Institute for Geophysics, Austin, TX USA; [4]Nils Bohr Institute, University of Copenhagen, Copenhagen, Denmark; [5]Laboratoire de Météorologie Dynamique, Université Pierre et Marie Curie, Paris, France; [6]Deltion Innovations, Capreol, Ontario CA; [7]Middlebury College, Middlebury, VT USA; [8]University of Maine, Orono, ME USA; [9]Boeing Company, Houston, TX USA.

The Goal: A Philosophy and Long-Term Strategy

- Goal: Living *off of* Mars.
- We live on Earth: We are actually living *off of* Earth.
- A16 CDR John Young: "Single-planet species don't survive."
- We first need to live *off-Earth*, not *off-of-the Earth*
  - ISS is a step in that direction: 15 years on November 2.
- Mars is the most hospitable environment in this Solar System.
- Short-term Goal: Living *on* Mars.
  - 225 million km-long umbilical.
- Long-term Goal: Living *off of Mars*.
  - This requires a hugely different attitude toward planning/exploration. Cut the cord.



Objectives: (S^3) *Science, Survival, Sustainability!!*

- **Science: Why Science first!**
  - **Learn to Live off of Mars. Look at "The Martian".**
  - **Russian colleagues: You'd be 'fooked'.**
  - **Need Rationale: Scientific exploration leading to sustainability!**
  - **Need logical reason for SES activities: Science is the driver.**
  - **Need Legacy: It is not just "flags and footprints".**

- **Survival: (ISRU) In-situ resource utilization experimentation.**
  - **The umbilical is very thin!!!**
  - **Water resources and mineral extraction.**
  - **Civil Engineering experimentation.**
  - **Synthetic biology: Biobricks.**

- **Sustainability: Living off of Mars!**
  - **The umbilical is cut. (ISRU) In-situ resource utilization required. Very abundant water resources. Civil Engineering dominates.**

The Team: Expertise in Key Areas

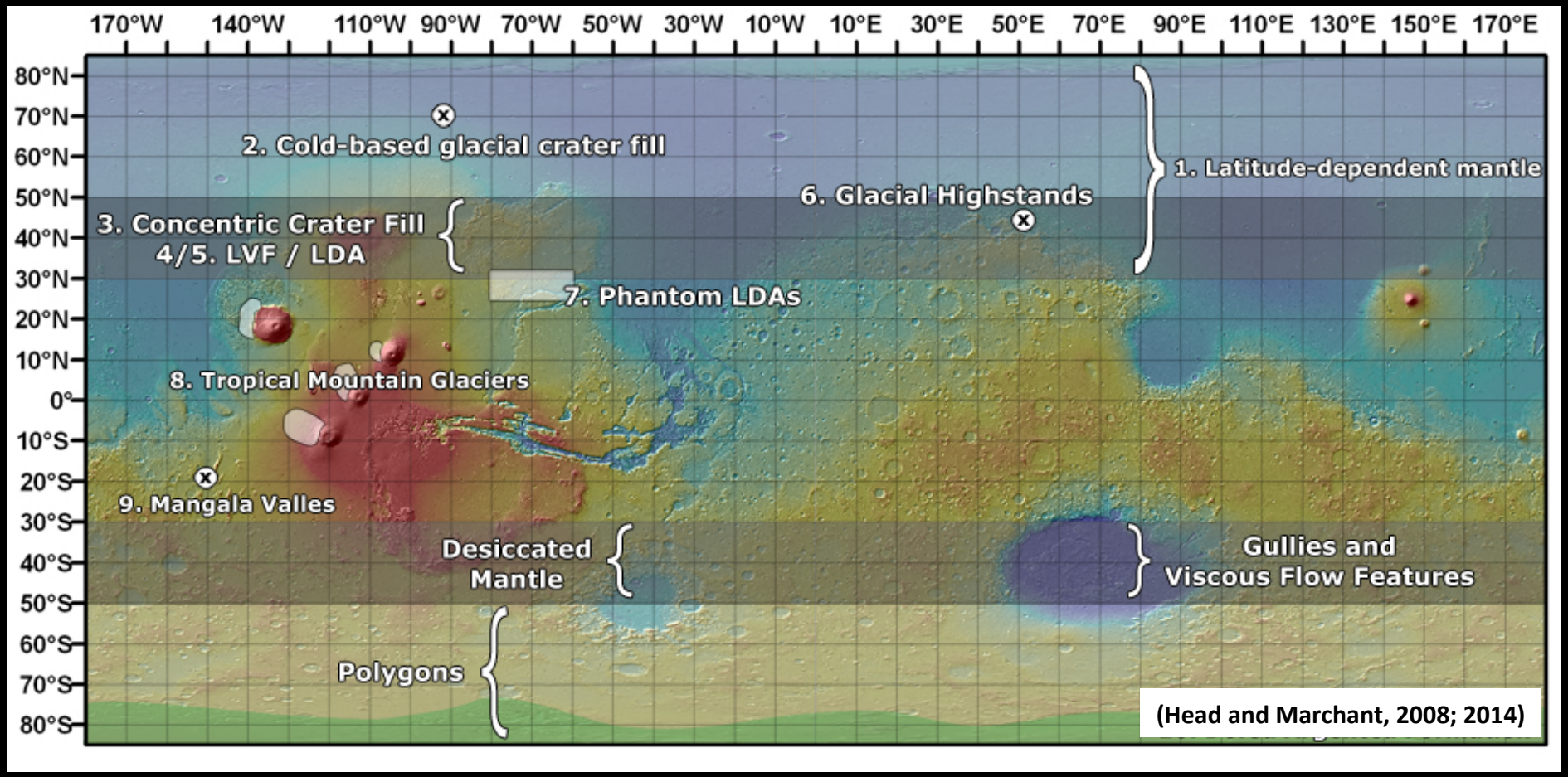
- **Mars Geology, Mineralogy, Glaciation, Hydrology, Cratering:**
  - James Head[1], John Mustard[1], Ralph Milliken[1], Brandon Johnson[1].
- **Antarctic Dry Valley Glacial Geology and Operations:**
  - David Marchant[2], Joseph Levy[3], James Dickson[1], Jill Mikucki[7].
- **Earth Climate History and Arctic Ice Sheet Operations:**
  - Christine Hvidberg[4], Kjartan Kinch[4],
- **Mars Meteorology, Climate History, Glacial Flow Modeling:**
  - Francois Forget[5], James Fastook[8].
- **ISRU, Civil Engineering and Industry Experience:**
  - Dale Boucher[6], Kurt Klaus[9].
- **Human Off-Earth Surface Exploration Planning, Operations:**
  - Apollo 15 Commander David Scott[1], James Head[1].

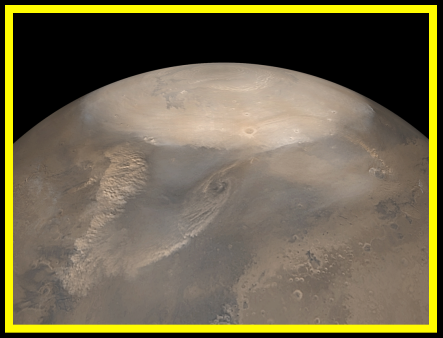
[1]Brown University; [2]Boston University; [3]University of Texas Institute for Geophysics; [4]University of Copenhagen; [5]Laboratoire de Météorologie Dynamique; [6]Deltion Innovations, Canada; [7]Middlebury College; [8]University of Maine; [9]Boeing Company.

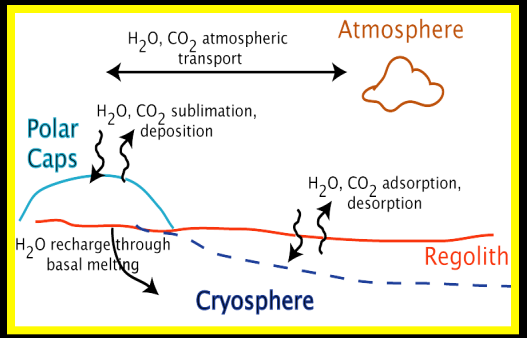
The Optimal Exploration Zone (EZ)

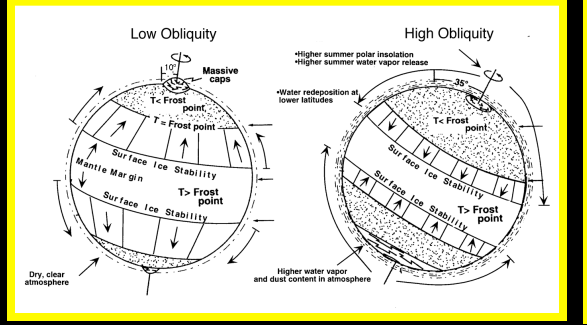
- Identify Candidate EZs as part of the process of determining *where and how we would like to explore Mars with humans*.
- Near-term this process includes:
  - (a) identifying locations that would *maximize the potential science return from future human exploration missions*,
  - (b) identifying locations with the *potential for resources required to support humans*,
  - (c) *developing concepts and engineering systems* needed by future human crews to conduct operations within an EZ, and
  - (d) identifying key characteristics of the proposed candidate EZs that cannot be evaluated using existing data sets, thus helping to define precursor measurements needed in advance of human missions (*Identify SKGs to guide future robotic exploration*).
- Existing and future robotic spacecraft will be tasked to *gather data from specific Mars surface sites* within representative EZs to support these HEOMD and SMD activities.

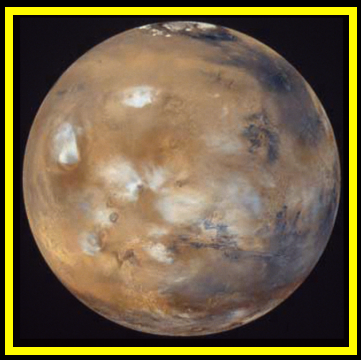
Non-Polar Latitude-Dependent Ice-Related Deposits



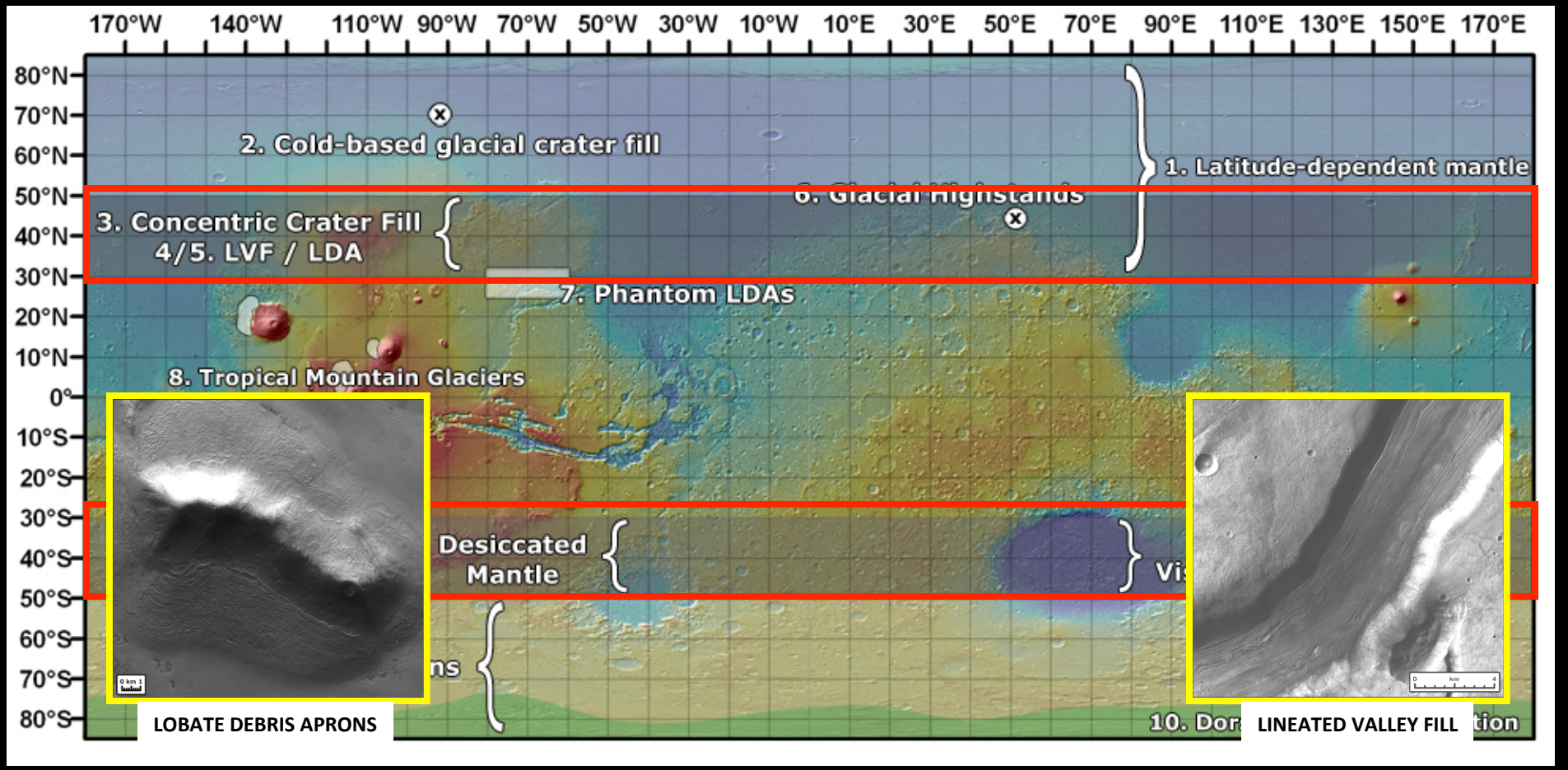






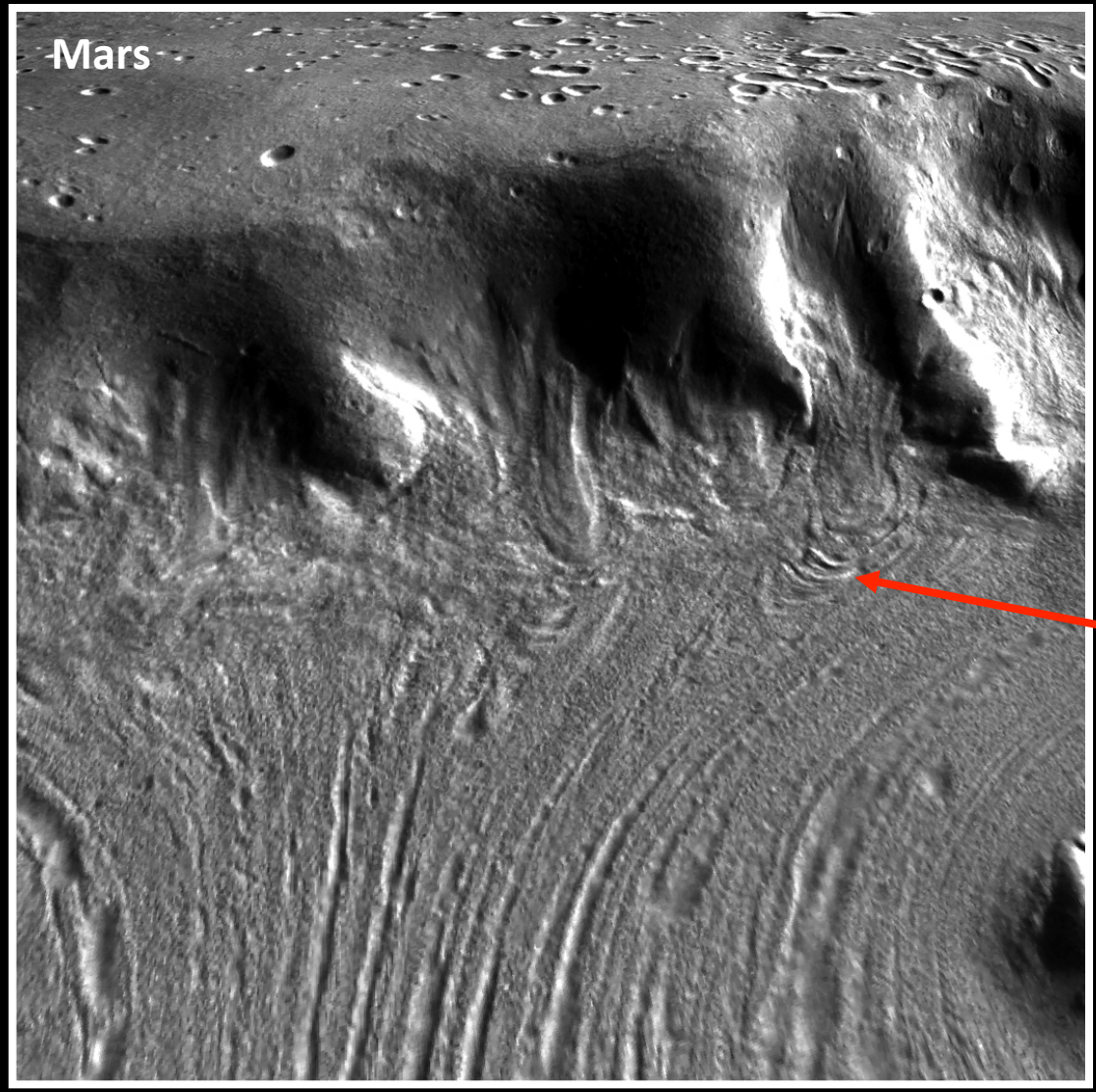


Ice Accumulation and Retention "Sweet-Spot": The Martian Mid-Latitudes

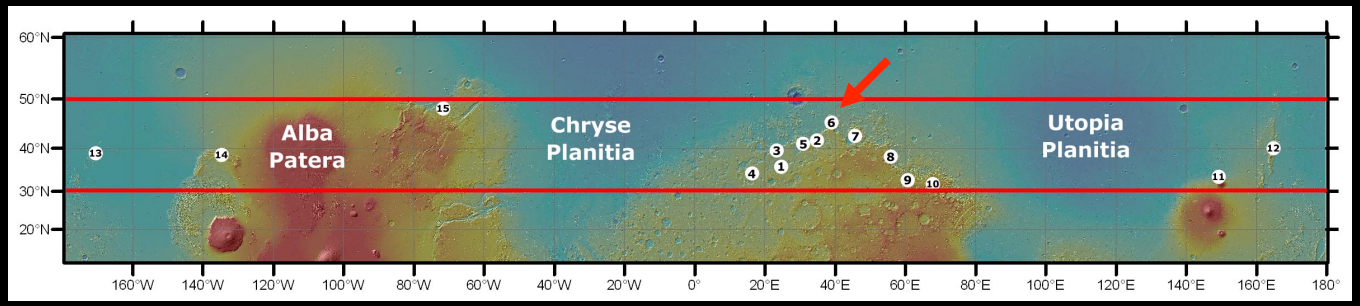


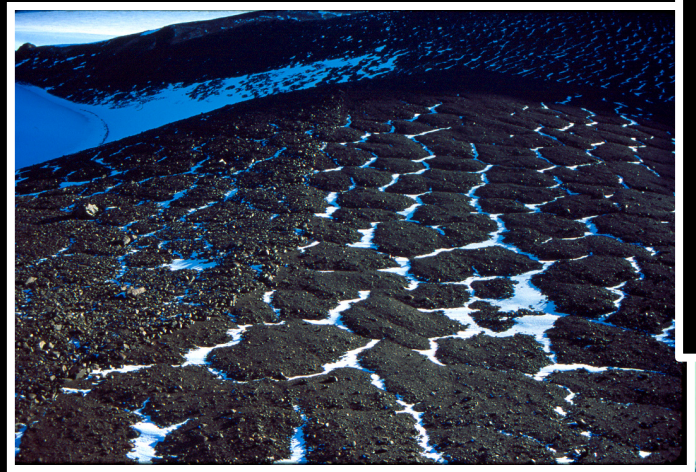
Mid-Latitude Lobate Debris Aprons and Lineated Valley Fill

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

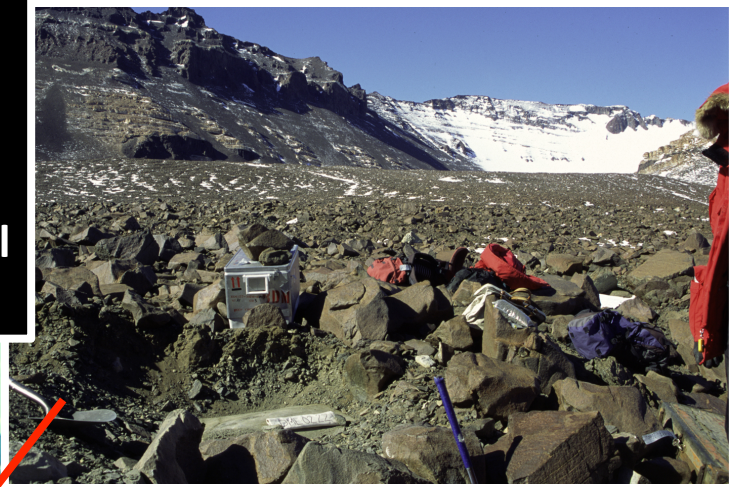


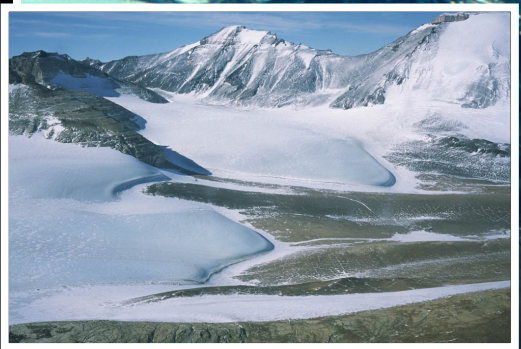
Lineated Valley Fill: Debris-Covered Valley Glacier Systems.



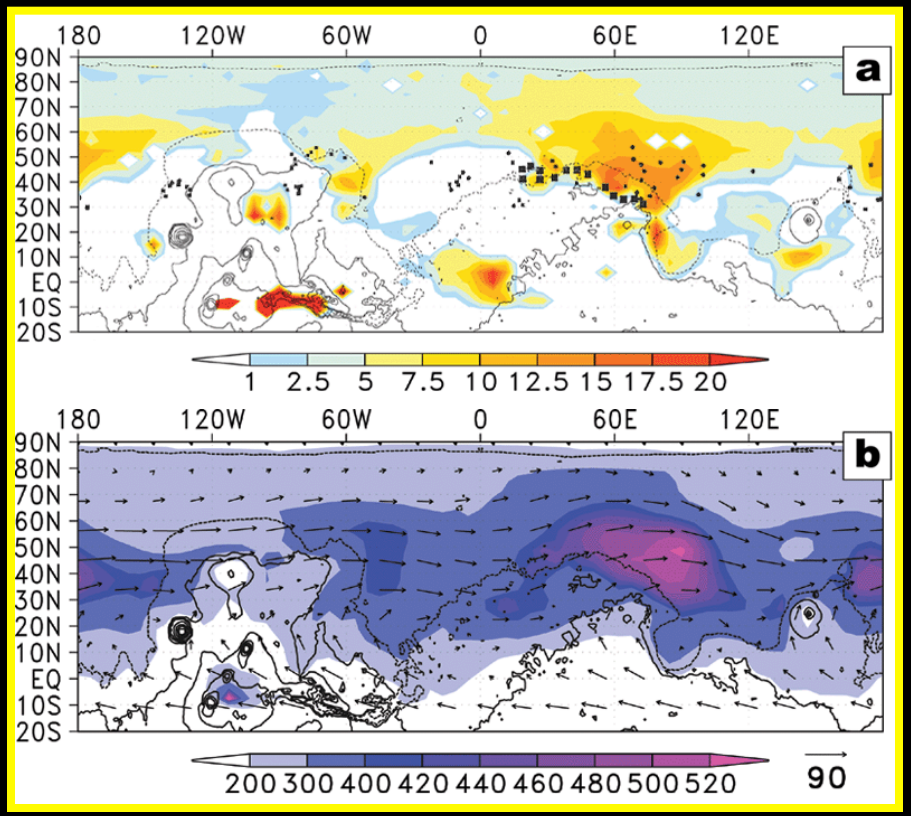


Field Research And Climate Monitoring in a Mars-Like Hyperarid-Hypothermal Environment

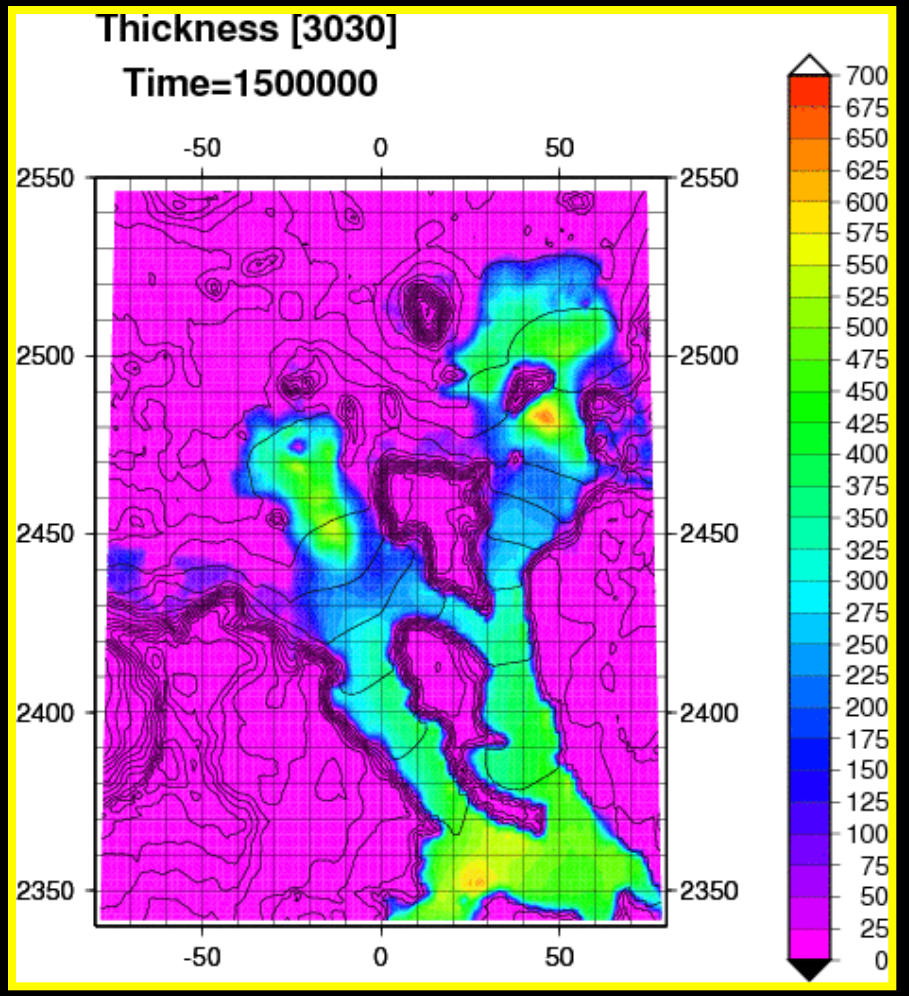




Cold-Based Glaciation-Beacon Valley, Antarctica (Marchant and Head, 2007; Mackay et al. , 2015)



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

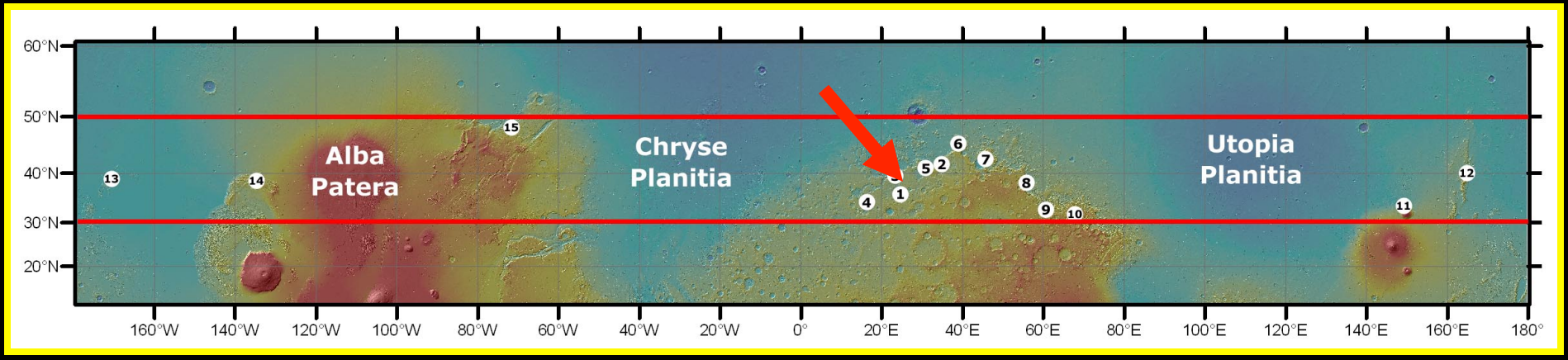


GCM Analyses:
35° obliquity with moderate dust loading.
(J.-B. Madeleine et al., 2009)

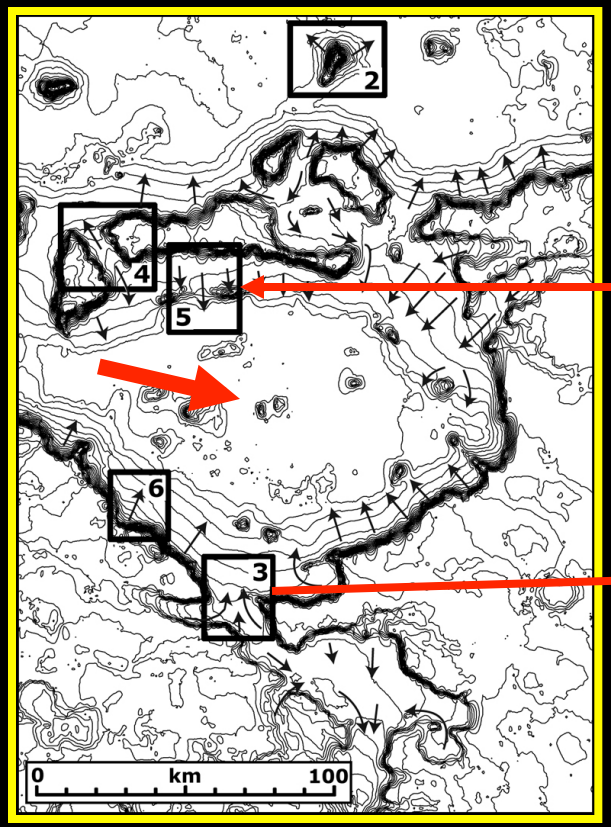
Glacial Flow Modeling:
Plateau Glaciation-Alpine Glaciers.
(J. Fastook et al., 2009; 2011)

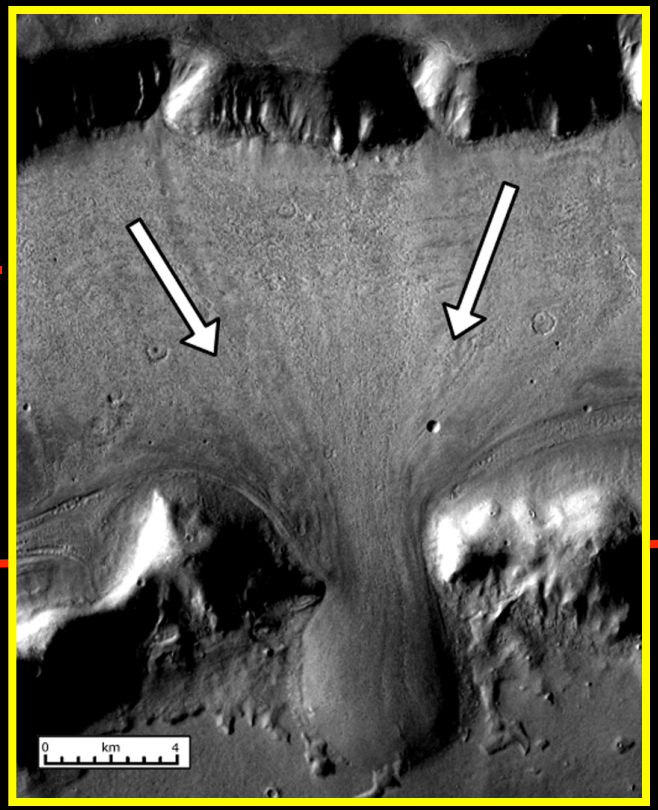
Synthesis:
Alpine valley glaciation *and* regional mid-latitude plateau glacial landsystems.

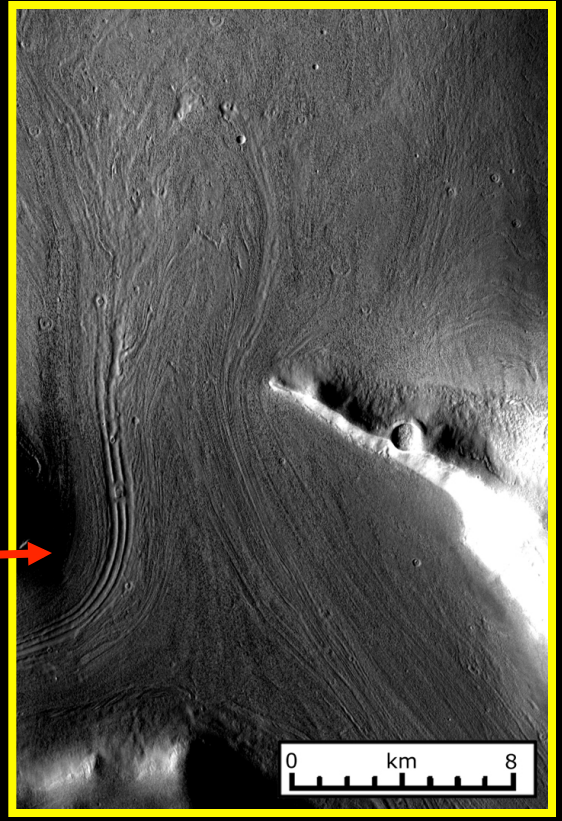
Noachian-Aged Crater at the Dichotomy Boundary



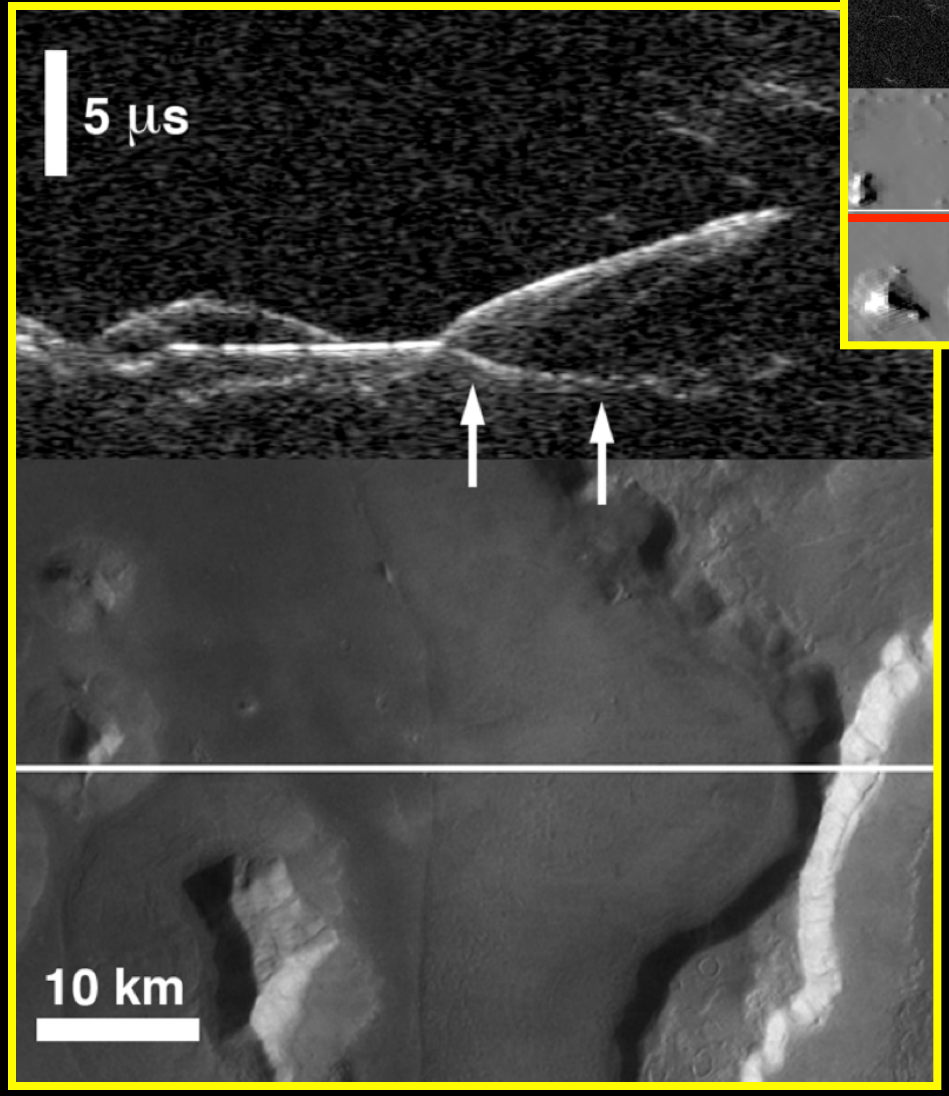
(Head and Marchant, 2006)

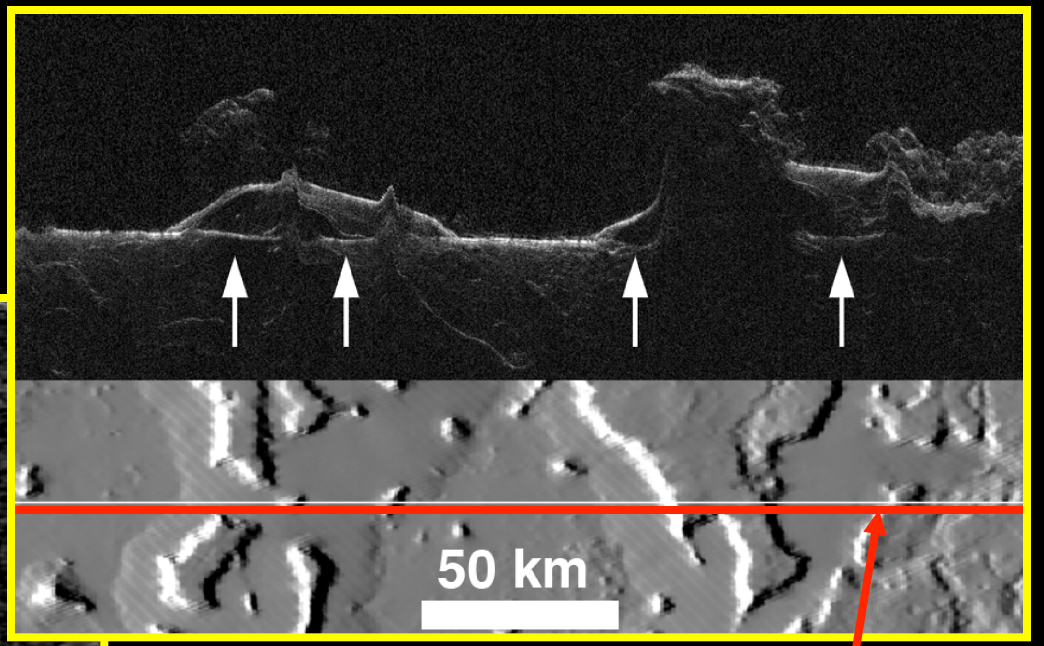


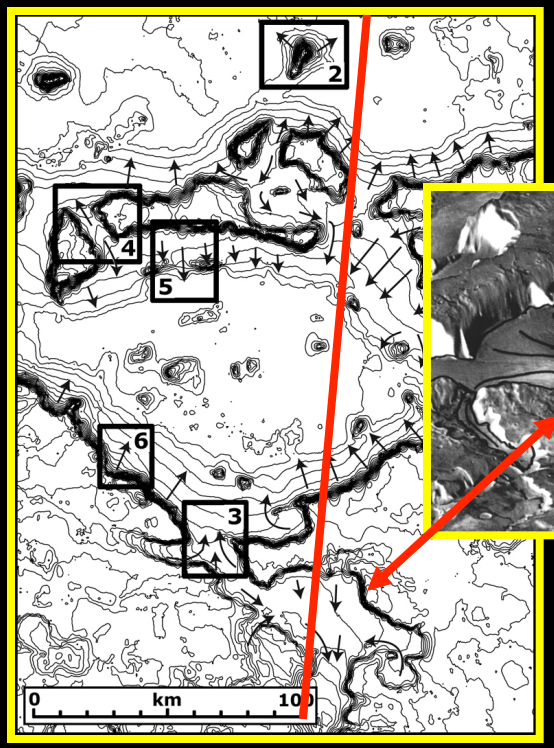


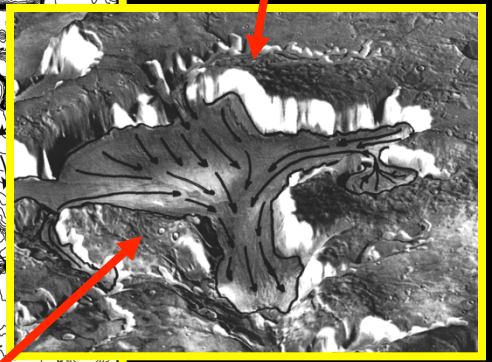


SHARAD Data on Lobate Debris Aprons / Lineated Valley Fill Show Presence of Nearly Pure Ice Buried Beneath Debris-Rich Sublimation Residue Layer.





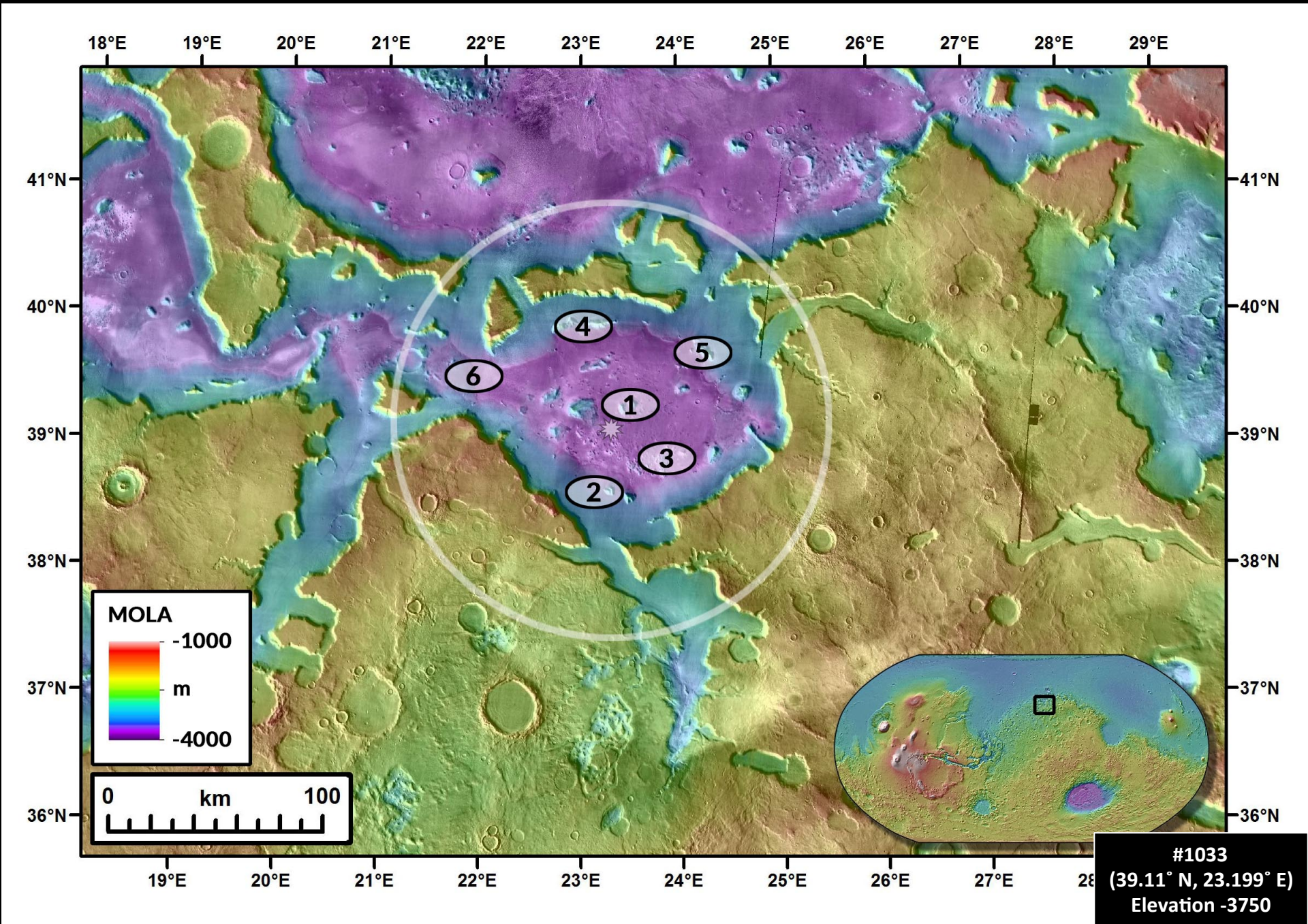


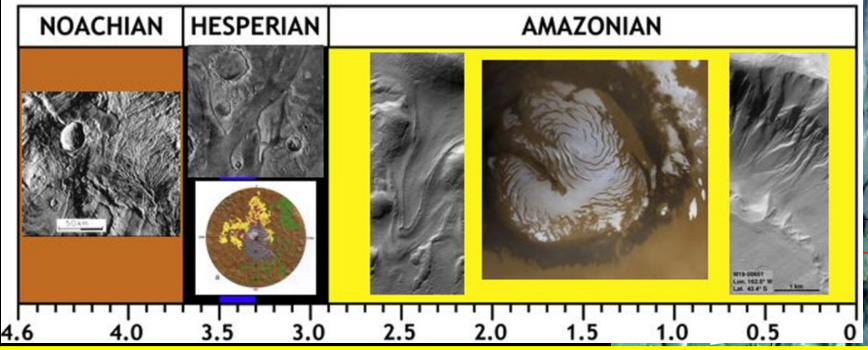


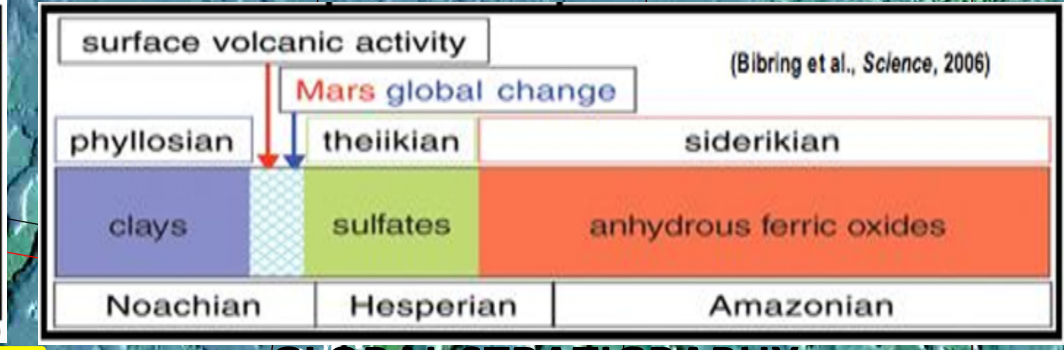
(Plaut et al., 2008)
(Holt et al, 2007)

(Head and Marchant, 2006)

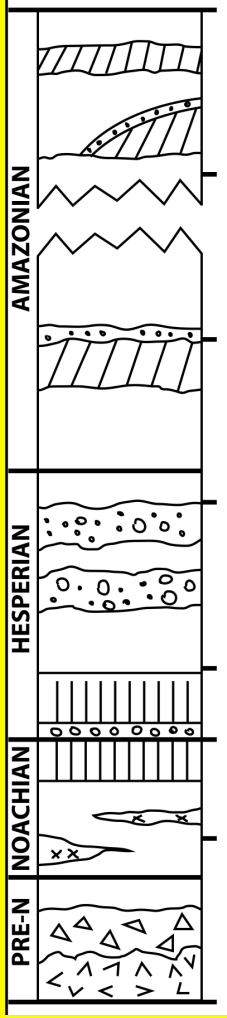
THE DICHOTOMY BOUNDARY DEUTERONILUS MENSAE EXPLORATION ZONE







GEOLOGICAL HISTORY - DEUTERONILUS MENSAE REGION



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NATURE OF COLD AND ICY MARS
- RECENT ICE AGES
- GLACIATION
  - ROOT CAUSES
  - CHRONOLOGY
  - THERMAL STRUCTURE
  - DEBRIS COVER
  - PRESERVED ICE/ATMOSPHERE
  - AREAL EXTENT
  - PRESERVED ICE/BIOSIGNATURES
  - ICE INVENTORY
- COLD AND ICY MARS TRANSITION

0.5

2.5

3.0

- NATURE OF HYDROLOGIC SYSTEM
- OUTFLOW CHANNEL FORMATION
- NORTHERN OCEAN?

3.5

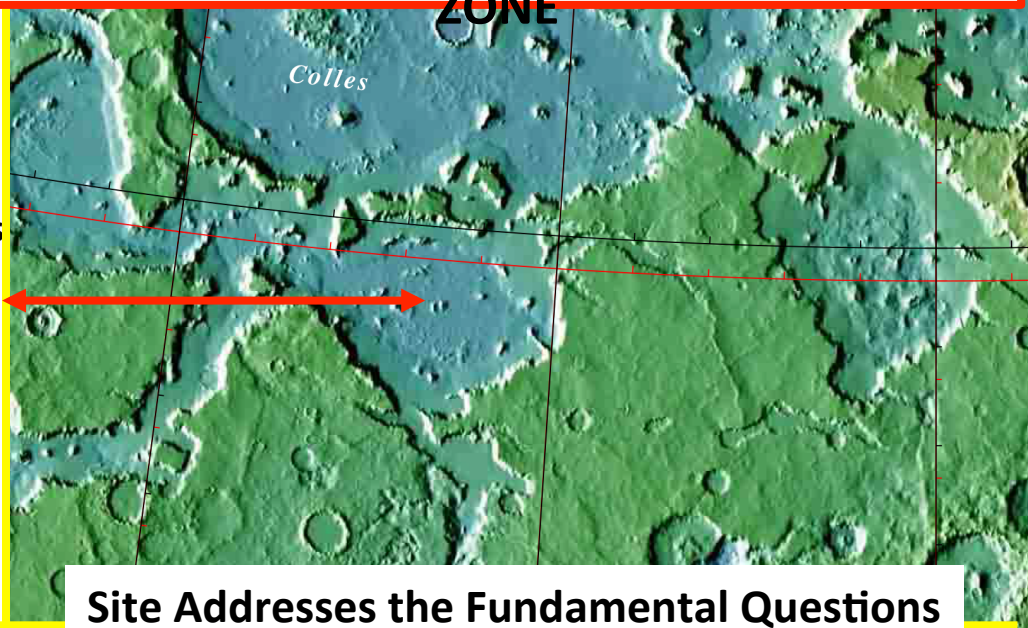
- MINERALOGIC AND CLIMATE TRANSITION
- VALLEY NETWORKS, OPEN-BASIN LAKES
- NORTHERN OCEAN?
- REGIONAL VOLCANIC PLAINS
- CORE DYNAMO CEASES?

4.0

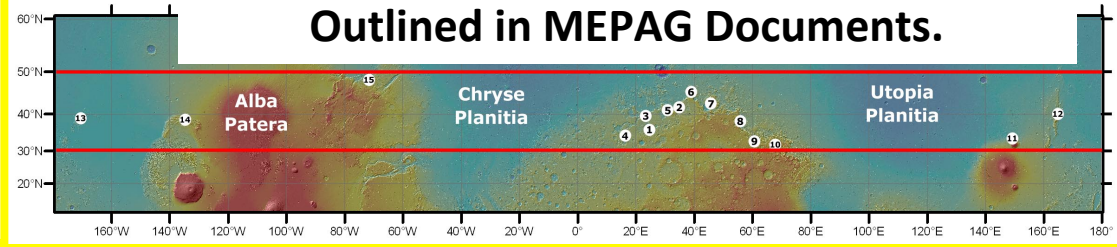
HELLAS/ISIDIS/ARGYRE FORMATION
- BOREALIS BASIN FORMATION
- CRUSTAL FORMATION

4.5 Ga

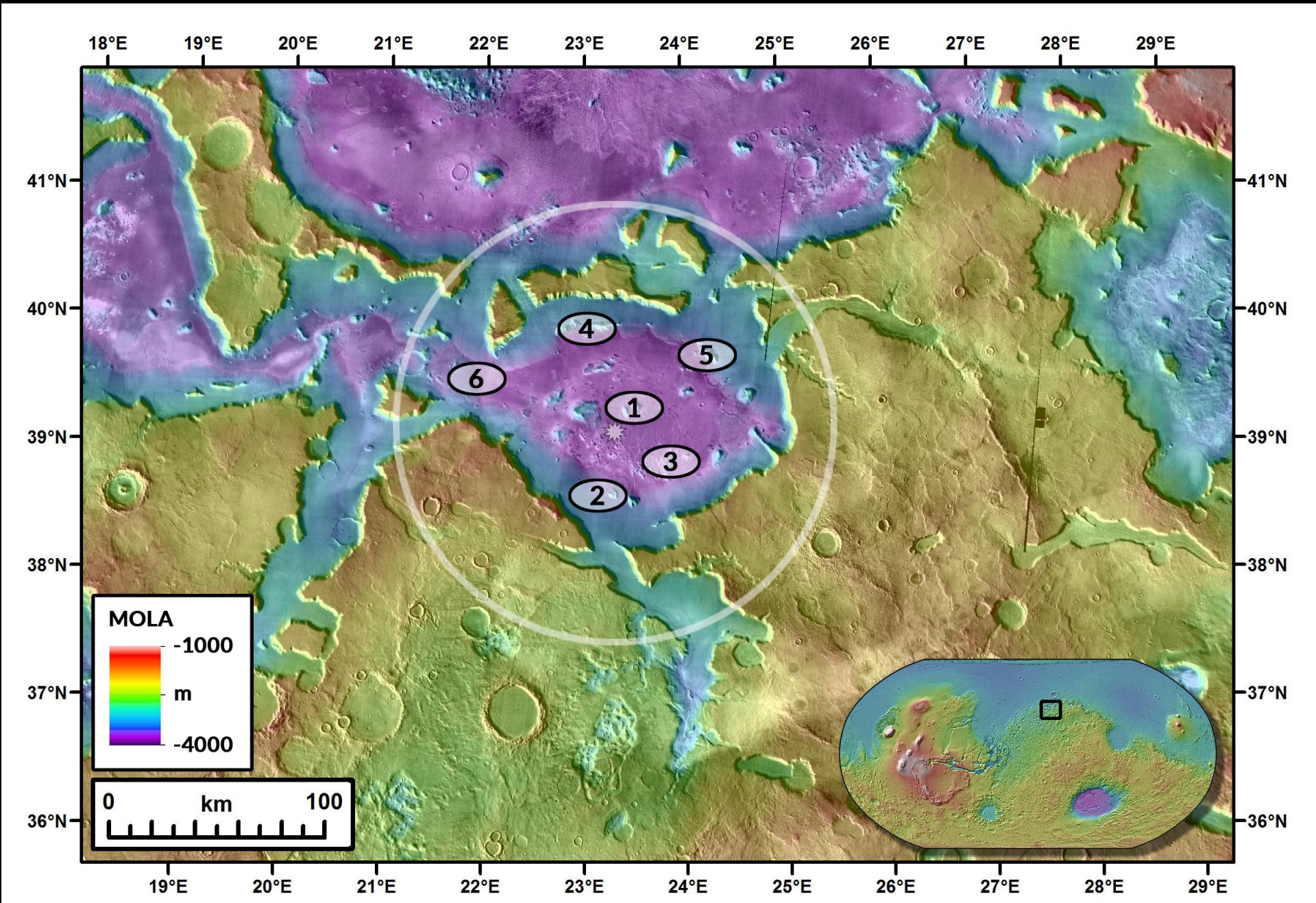
GLOBAL STRATIGRAPHY AT THE DICHOTOMY BOUNDARY DEUTERONILUS MENSAE EXPLORATION ZONE



Site Addresses the Fundamental Questions Outlined in MEPAG Documents.



THE DICHOTOMY BOUNDARY DEUTERONILUS MENSAE EXPLORATION ZONE



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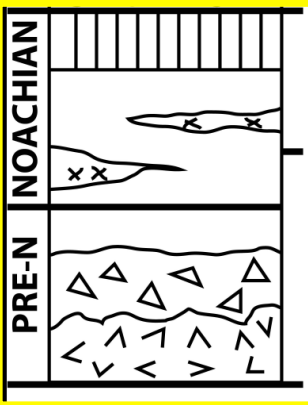


- NORTHERN OCEAN?
- REGIONAL VOLCANIC PLAINS
- CORE DYNAMO CEASES?

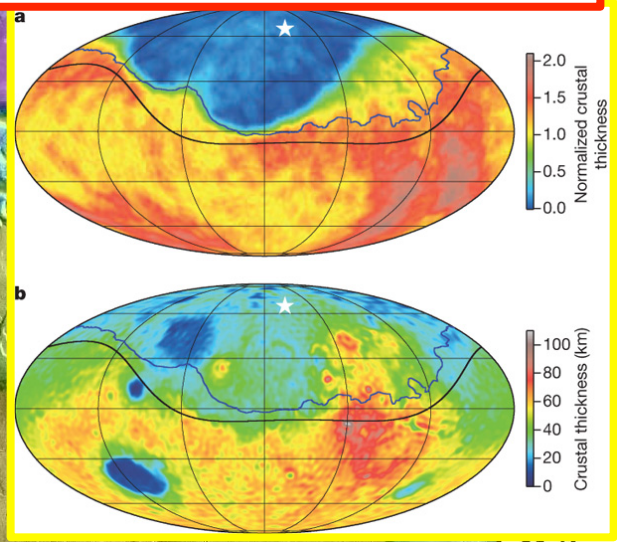
4.0

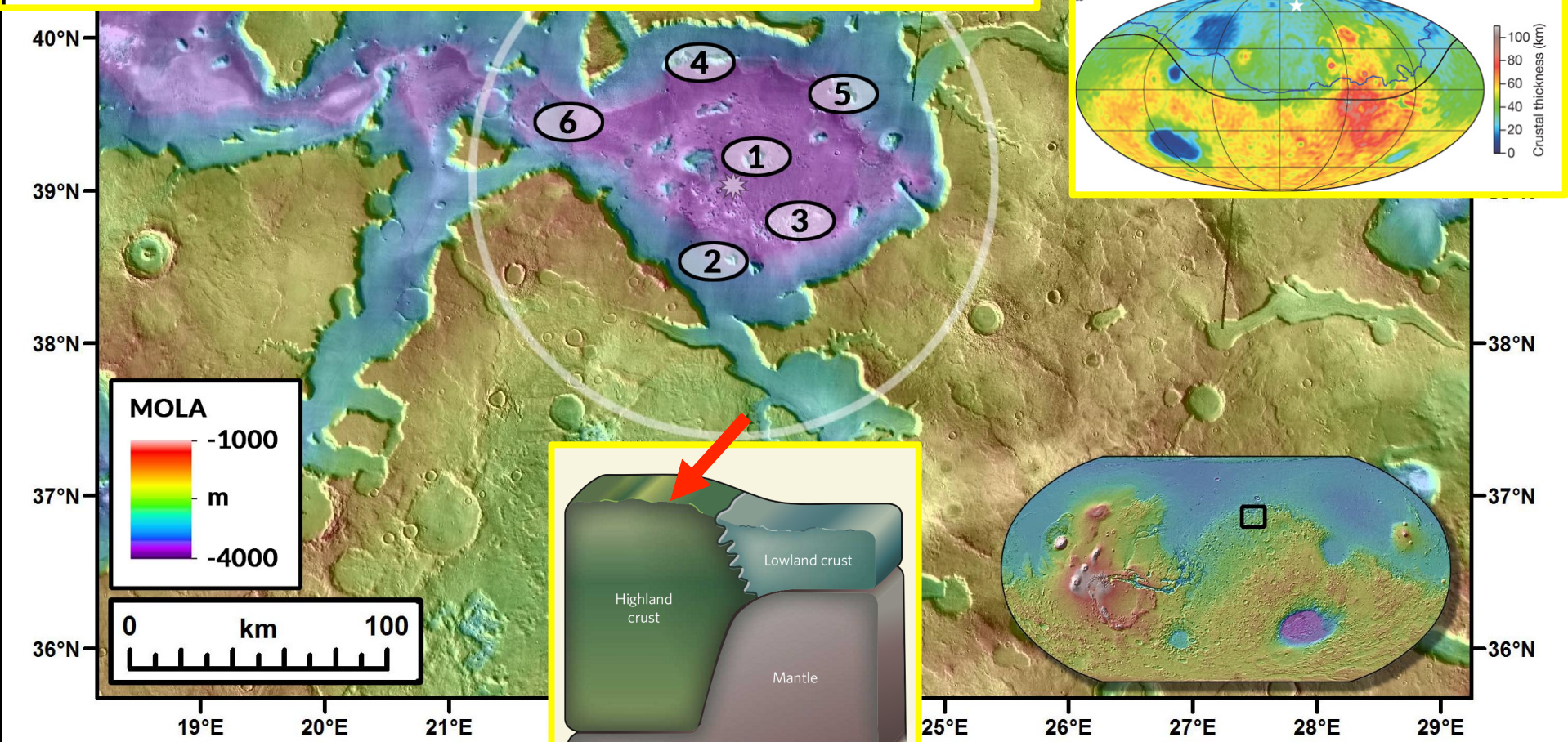
HELLAS/ISIDIS/ARGYRE FORMATION

- BOREALIS BASIN FORMATION
- CRUSTAL FORMATION

4.5 Ga

PreNoachian-Noachian Era

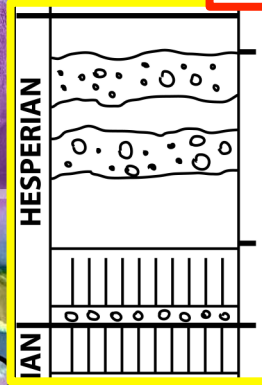




THE DICHOTOMY BOUNDARY DEUTERONILUS MENSAE EXPLORATION ZONE

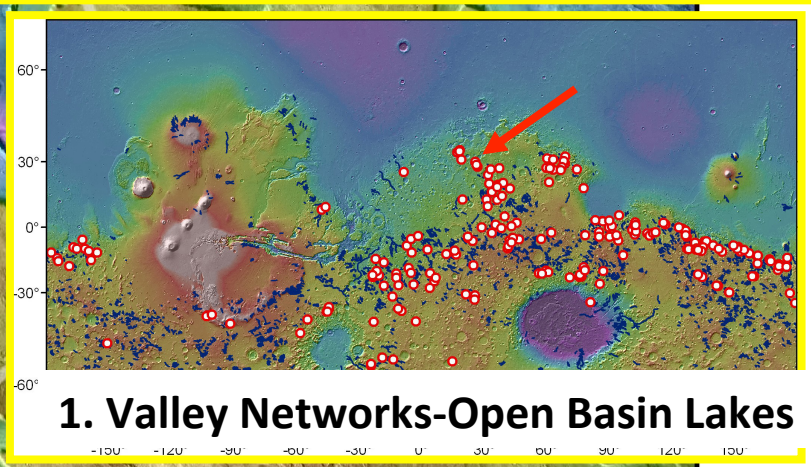
Late Noachian-Hesperian Era

4. Outflow Channels

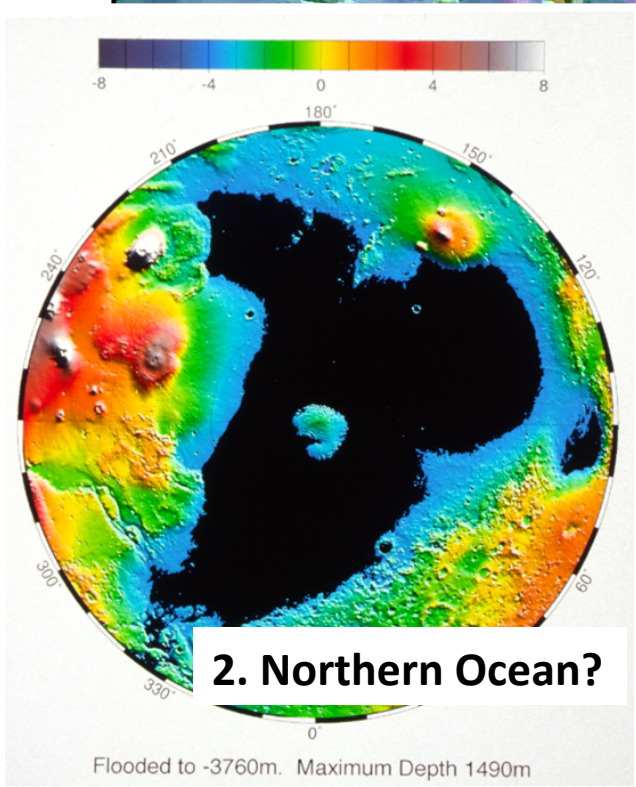


- NATURE OF HYDROLOGIC SYSTEM
- OUTFLOW CHANNEL FORMATION
- NORTHERN OCEAN?

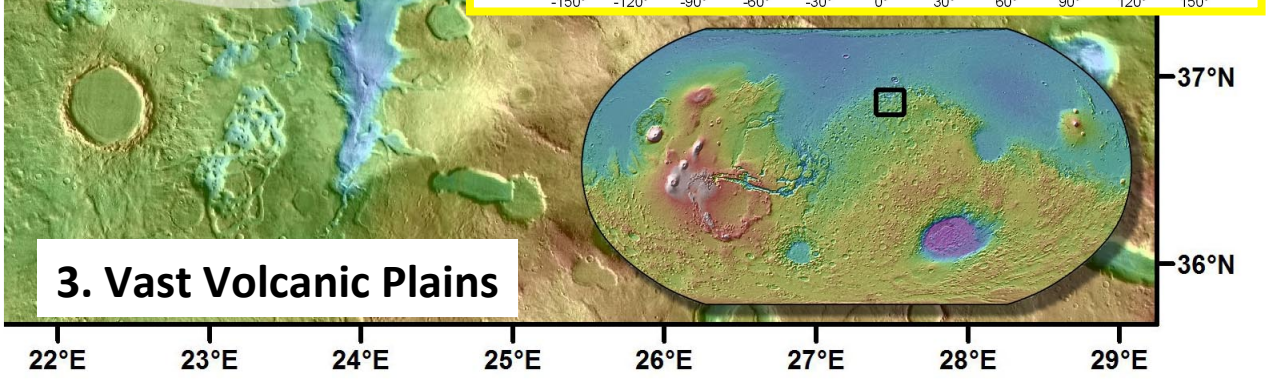
- MINERALOGIC AND CLIMATE TRANSITION
- VALLEY NETWORKS, OPEN-BASIN LAKES
- NORTHERN OCEAN?



1. Valley Networks-Open Basin Lakes

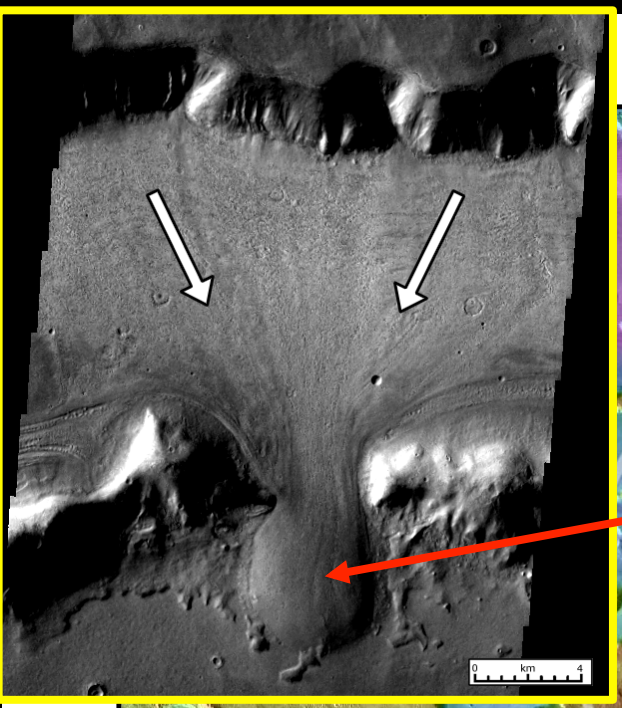


2. Northern Ocean?



3. Vast Volcanic Plains

THE DICHOTOMY BOUNDARY DEUTERONILUS MENSAE EXPLORATION ZONE



- RECENT ICE AGES
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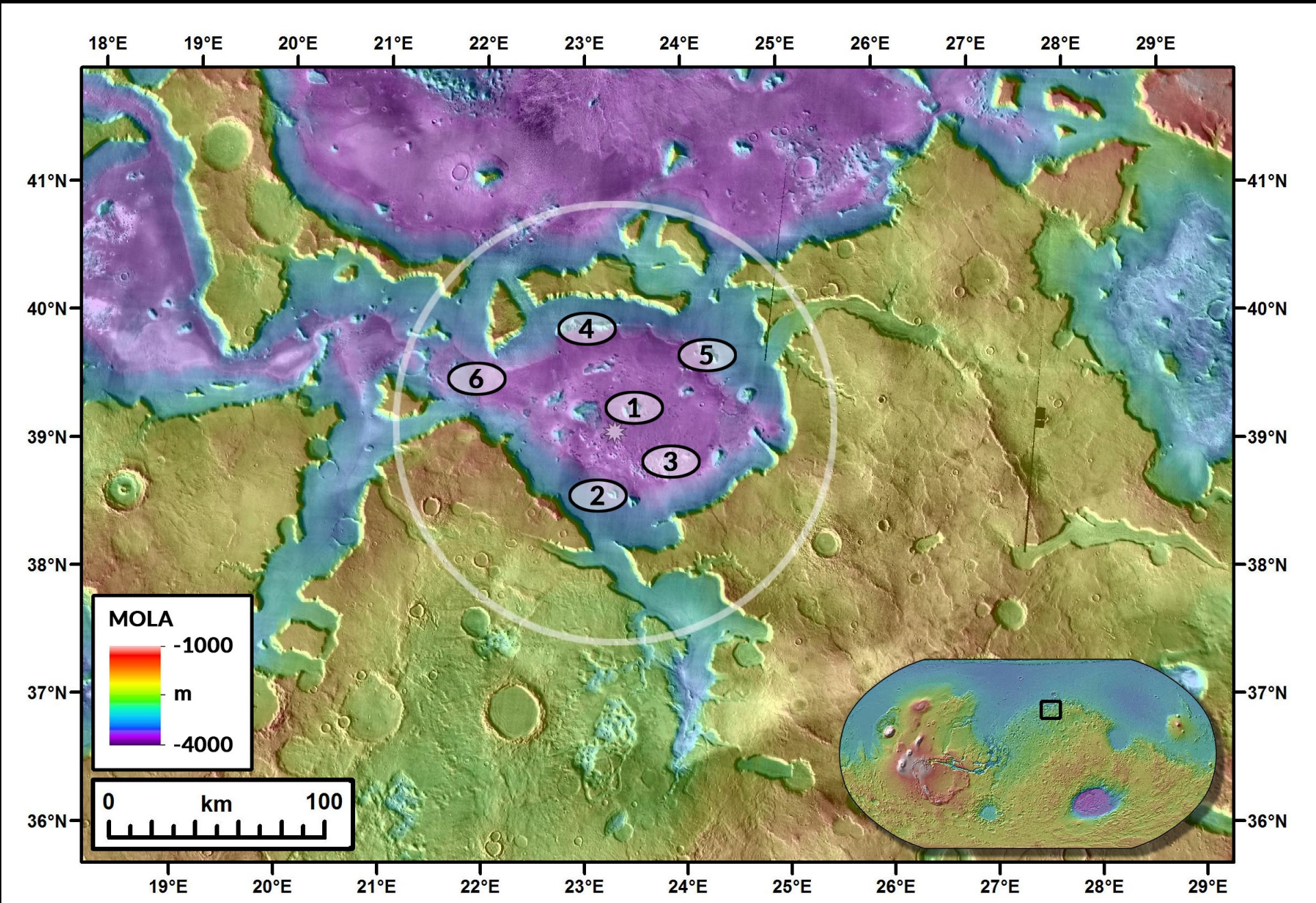
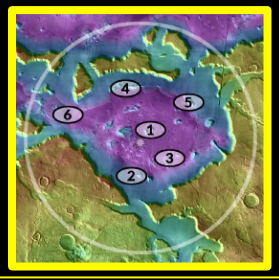
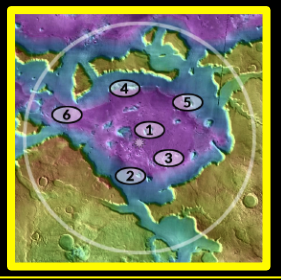
THE DICHOTOMY BOUNDARY DEUTERONILUS MENSAE EXPLORATION ZONE

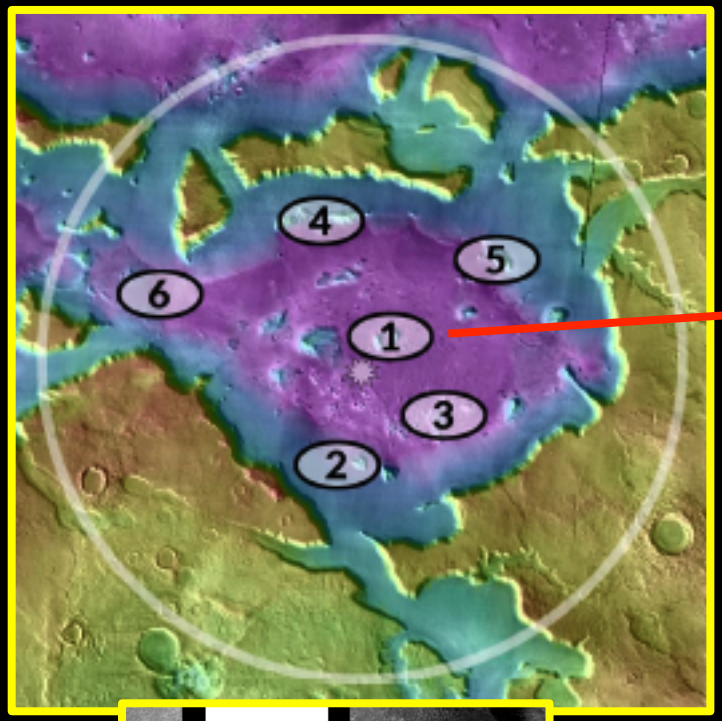




Deuteronilus Exploration Zone Science-Resource ROIs



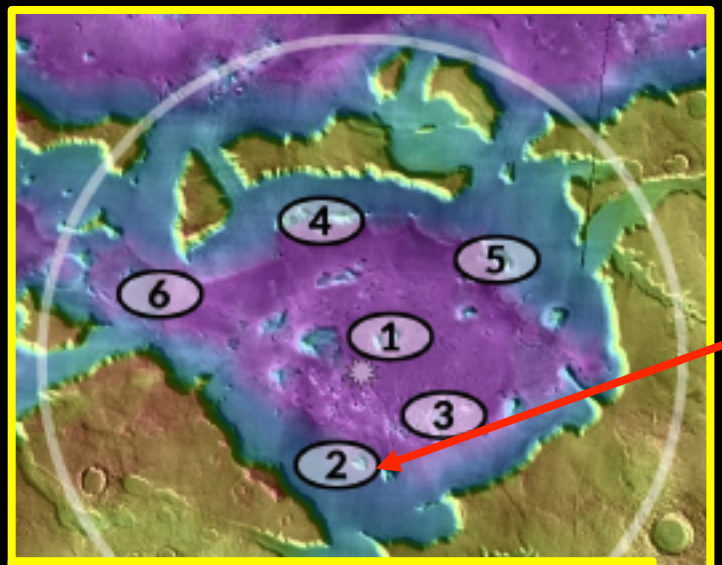
- **Science-Resource ROI 1:** Located nearby the landing site, this ROI is represented by the Noachian-aged crater central peak, uplifting and exposing deeper crustal material, and by LDM fragments that expose the climate record and are a potential water resource.
- **Science-Resource ROI 2:** Base of the LDA with water ice resources at shallow depths and a rock material suite that will include samples brought from the broader region to the south.
- **Science-Resource ROI 3:** Extensive flat-lying LDM several tens of meters thick, containing an Amazonian climate record and nearly pure ice intercalated with ice-cemented debris.
- **Science-Resource ROI 4:** Distinctive LDA protruding through ridge representing potential peak ring of Noachian-aged crater. Access to water ice in near subsurface and suite of samples from terrain to the north.
- **Science-Resource ROI 5:** Ridge representing potential peak ring of Noachian-aged crater; LDA banked behind with LDA lobes on both sides of the outcrop of ancient crustal material.
- **Science-Resource ROI 6:** Outlet from Noachian-aged crater floor to west provides access to additional LDA and wrinkle-ridge-like structure that may mark the location of ancient lavas.

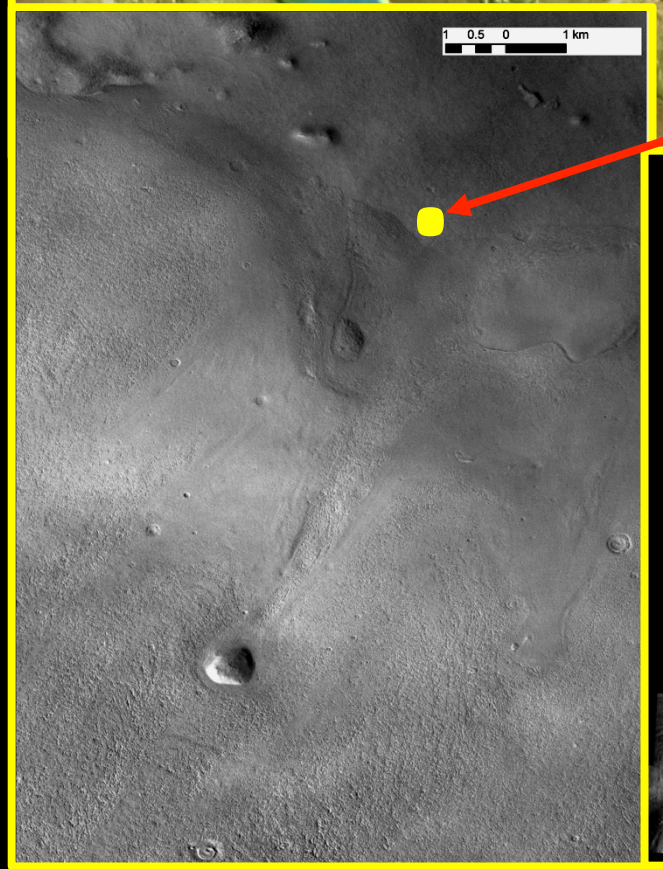


Science-Resource ROI 1:

- Located nearby the landing site, this ROI is represented by the 1) Noachian-aged crater central peak, uplifting and exposing deeper crustal material, and by 2) LDM fragments that expose the climate record and are a very high-potential water resource.

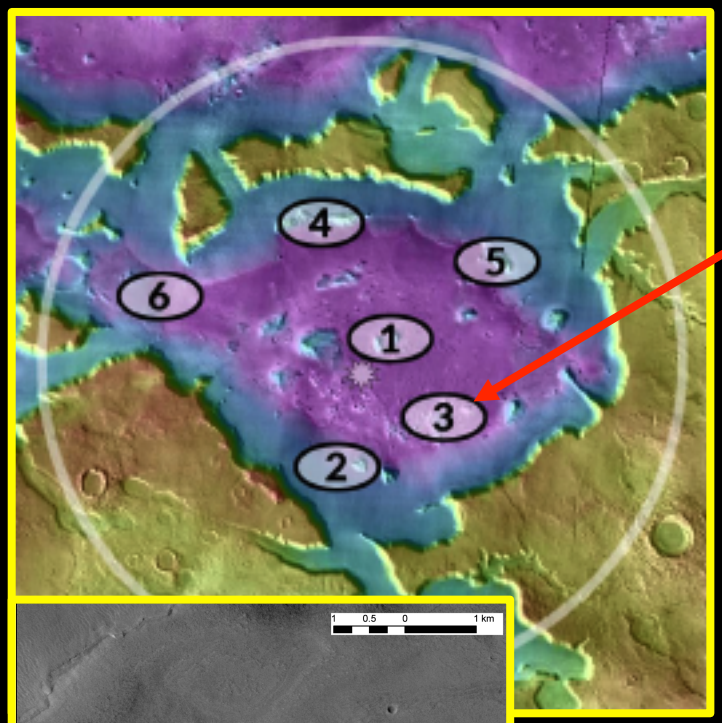
Science-Resource ROI 2:

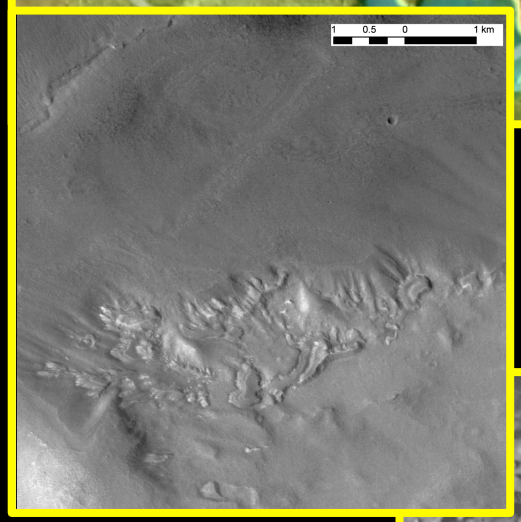


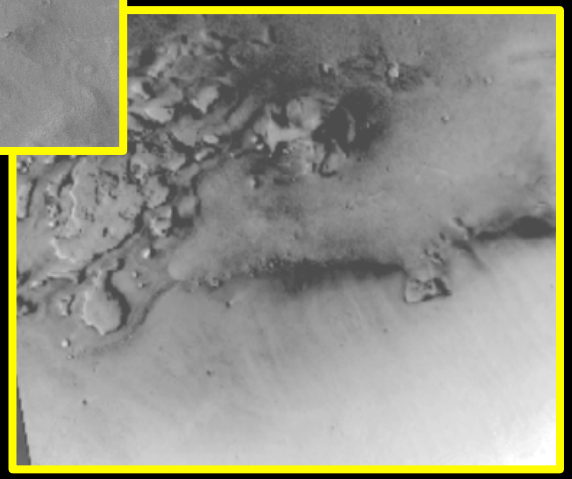


- 1) Base of the LDA with water ice climate history and resources at shallow depths, and 2) a rock material suite that will include Noachian and Hesperian volcanic and impact ejecta samples brought from the broader region to the south and 3) km-scale cliff outcrops.

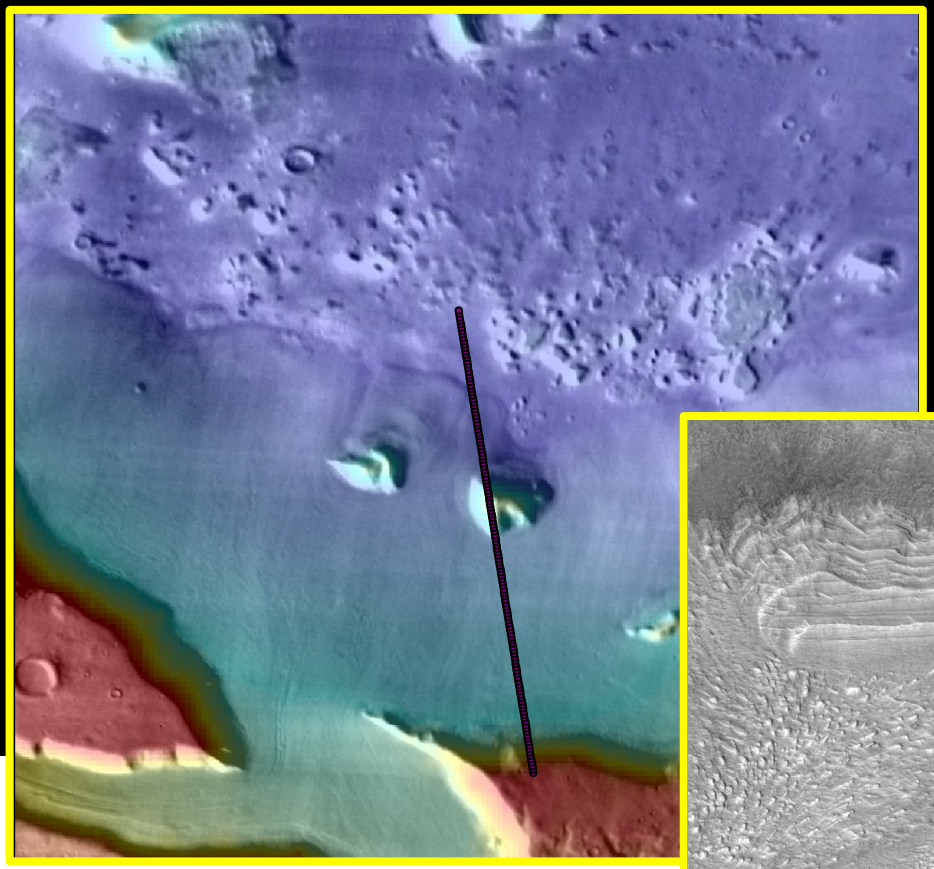
Science-Resource ROI 3:

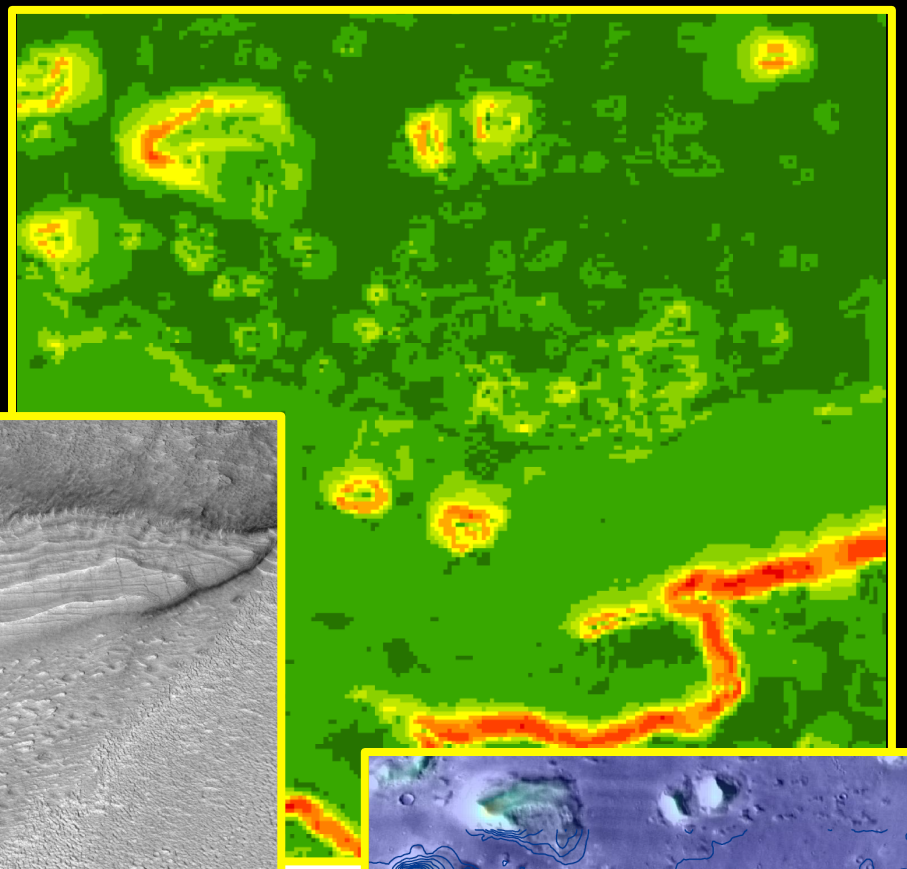


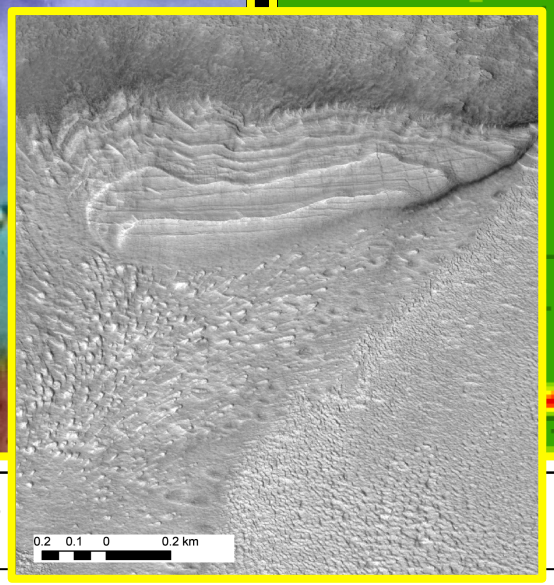


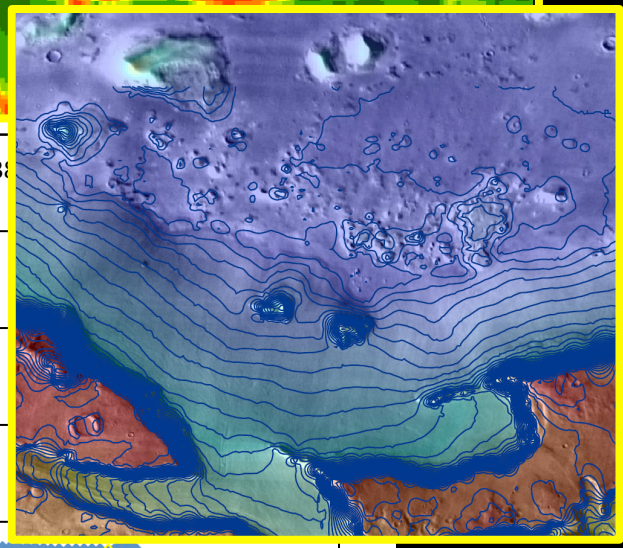


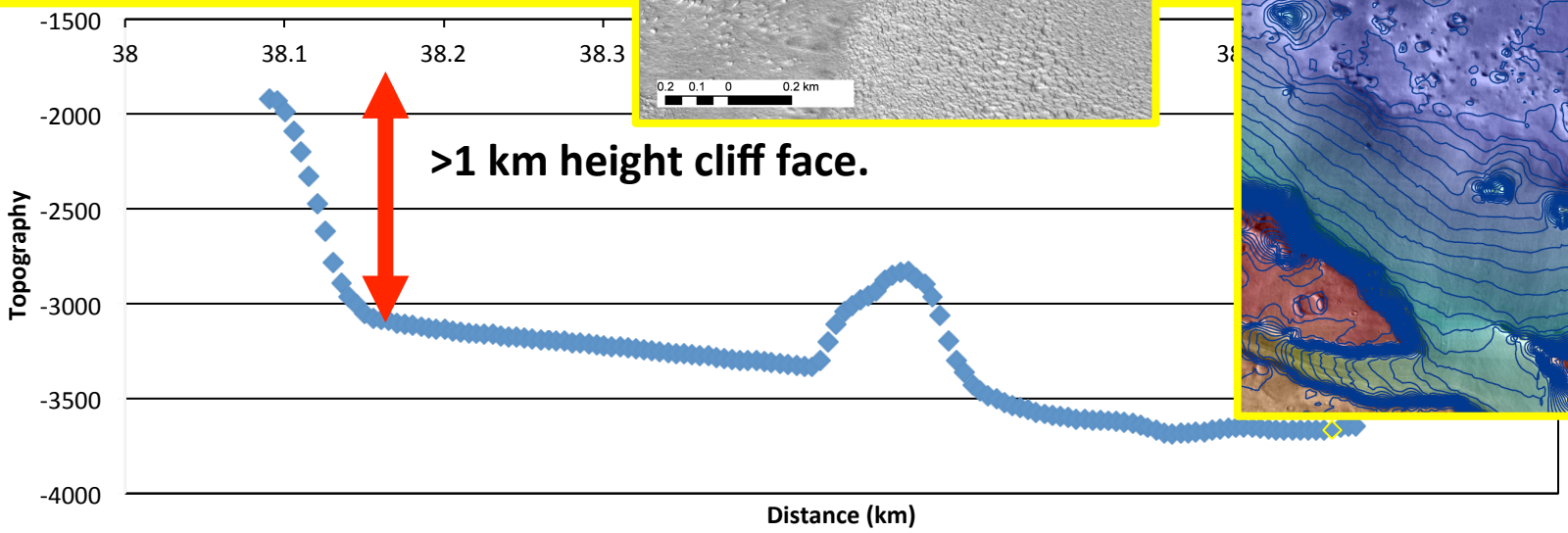
- Extensive flat-lying/tilted 1) LDM several tens of meters thick, containing an Amazonian climate record and nearly pure ice intercalated with ice-cemented debris; 2) >1 km cliff face for Noachian-Hesperian volcanic stratigraphic contex.

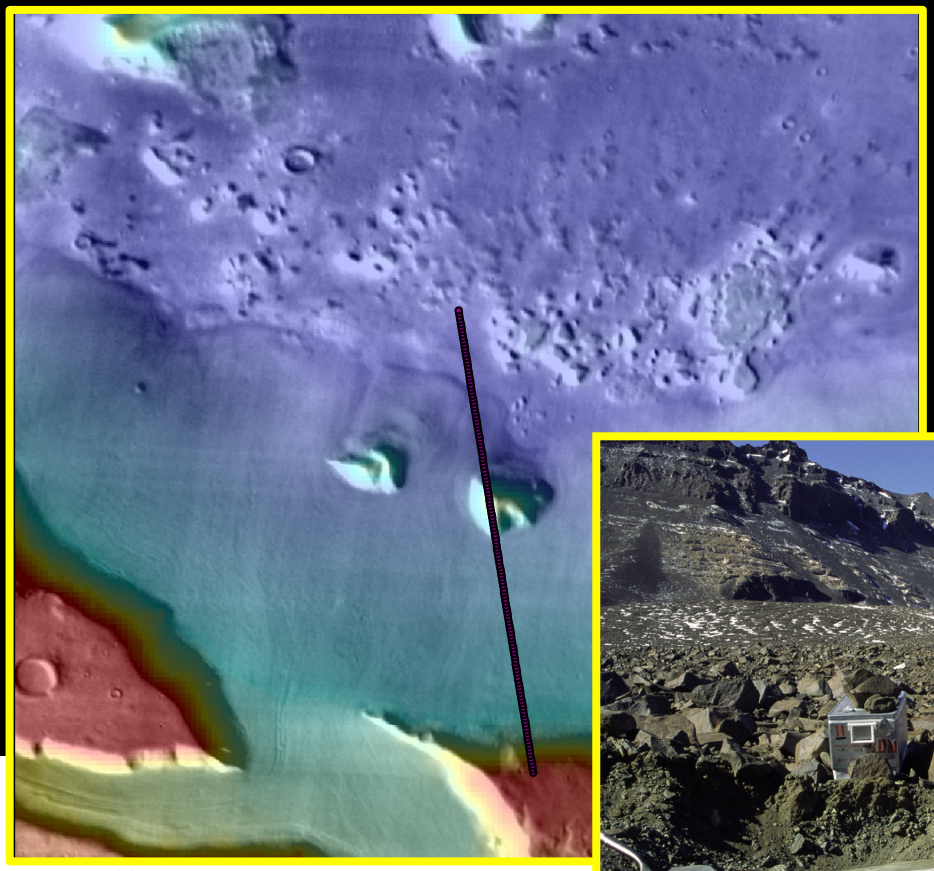


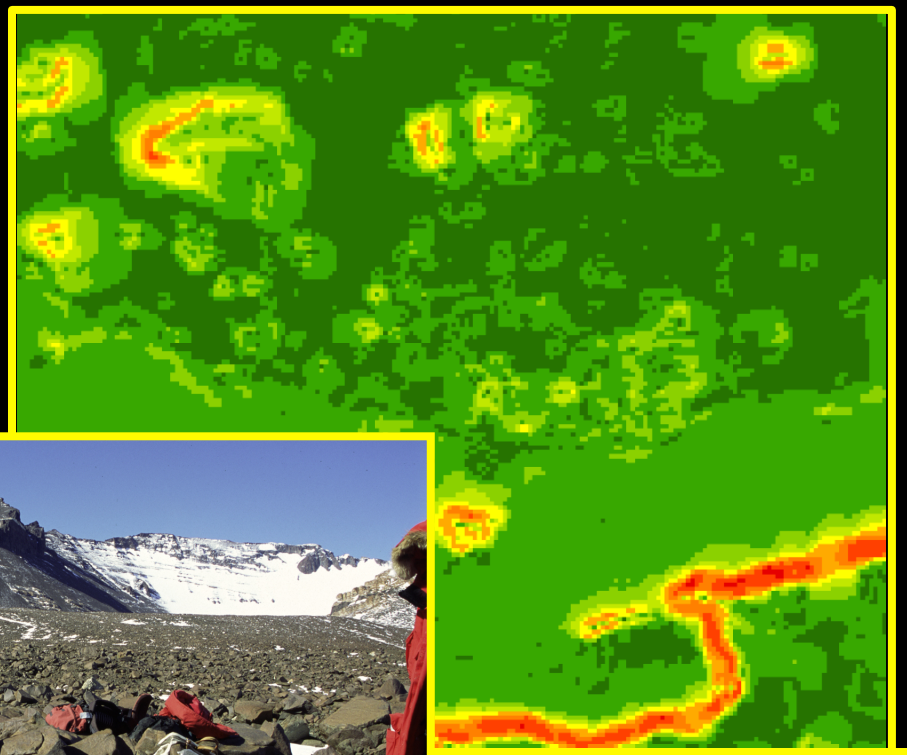


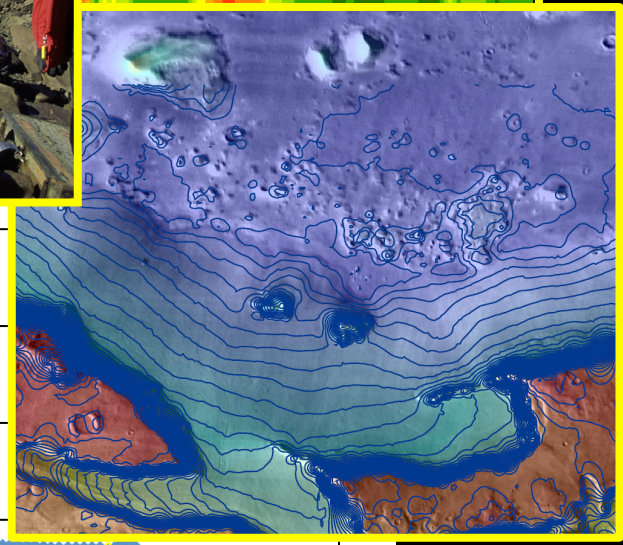

0.2 0.1 0 0.2 km

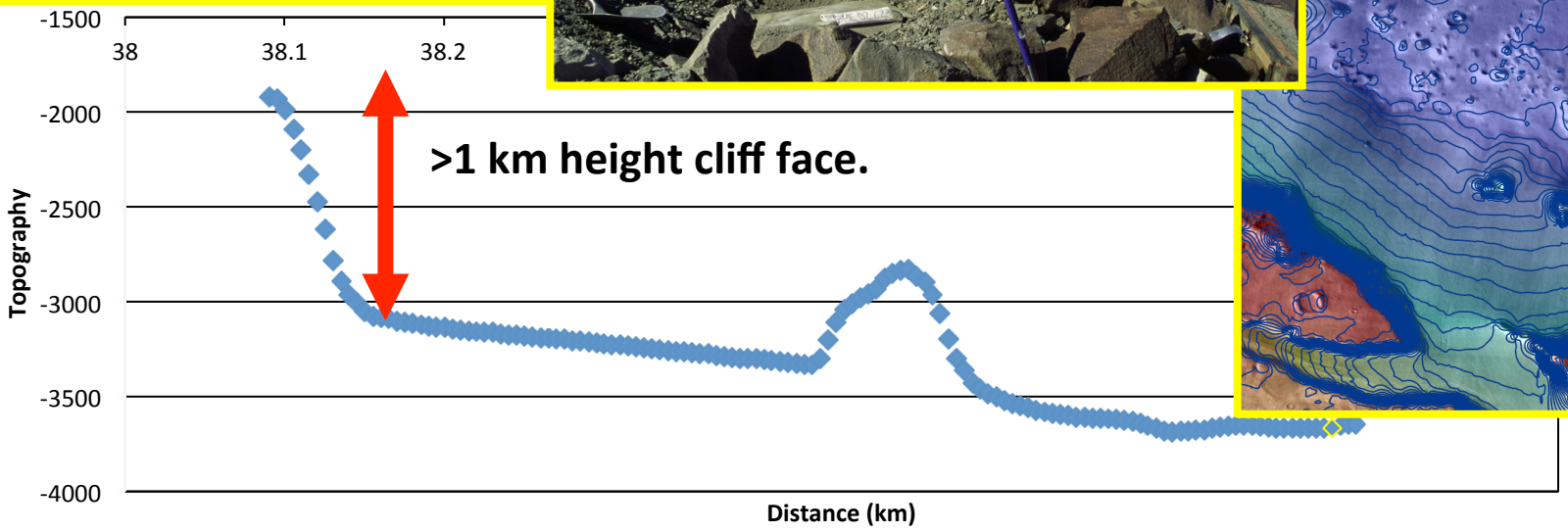



-1500
38
38.1
38.2
38.3
-2000
-2500
-3000
-3500
-4000
Topography
Distance (km)
>1 km height cliff face.

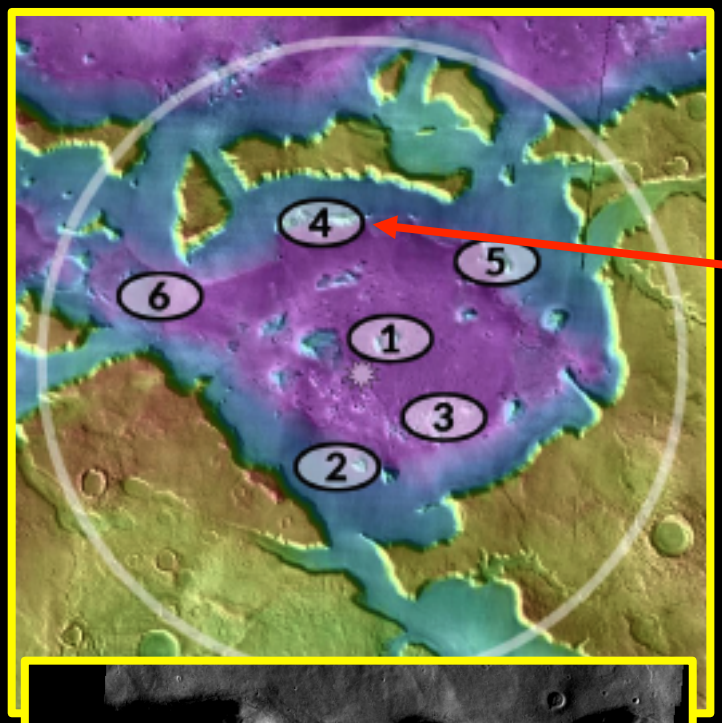


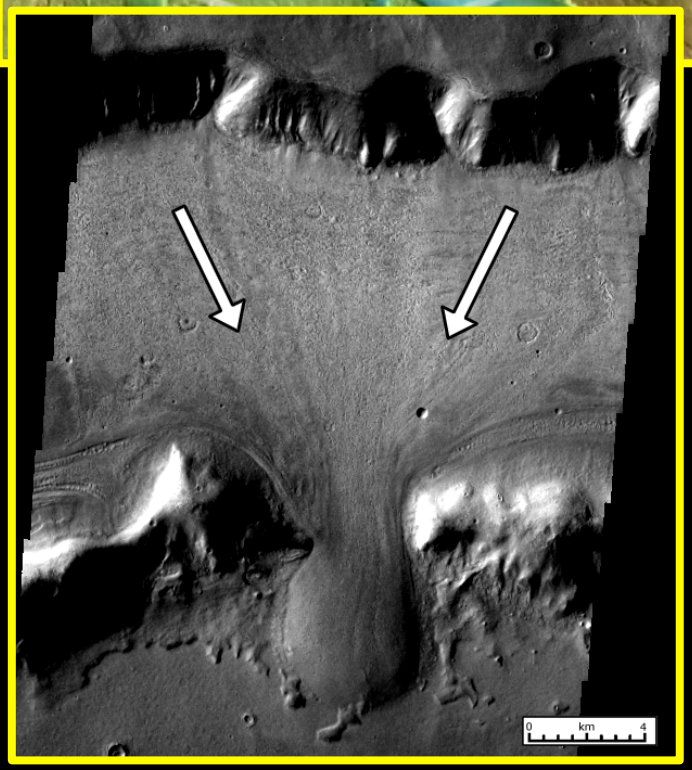




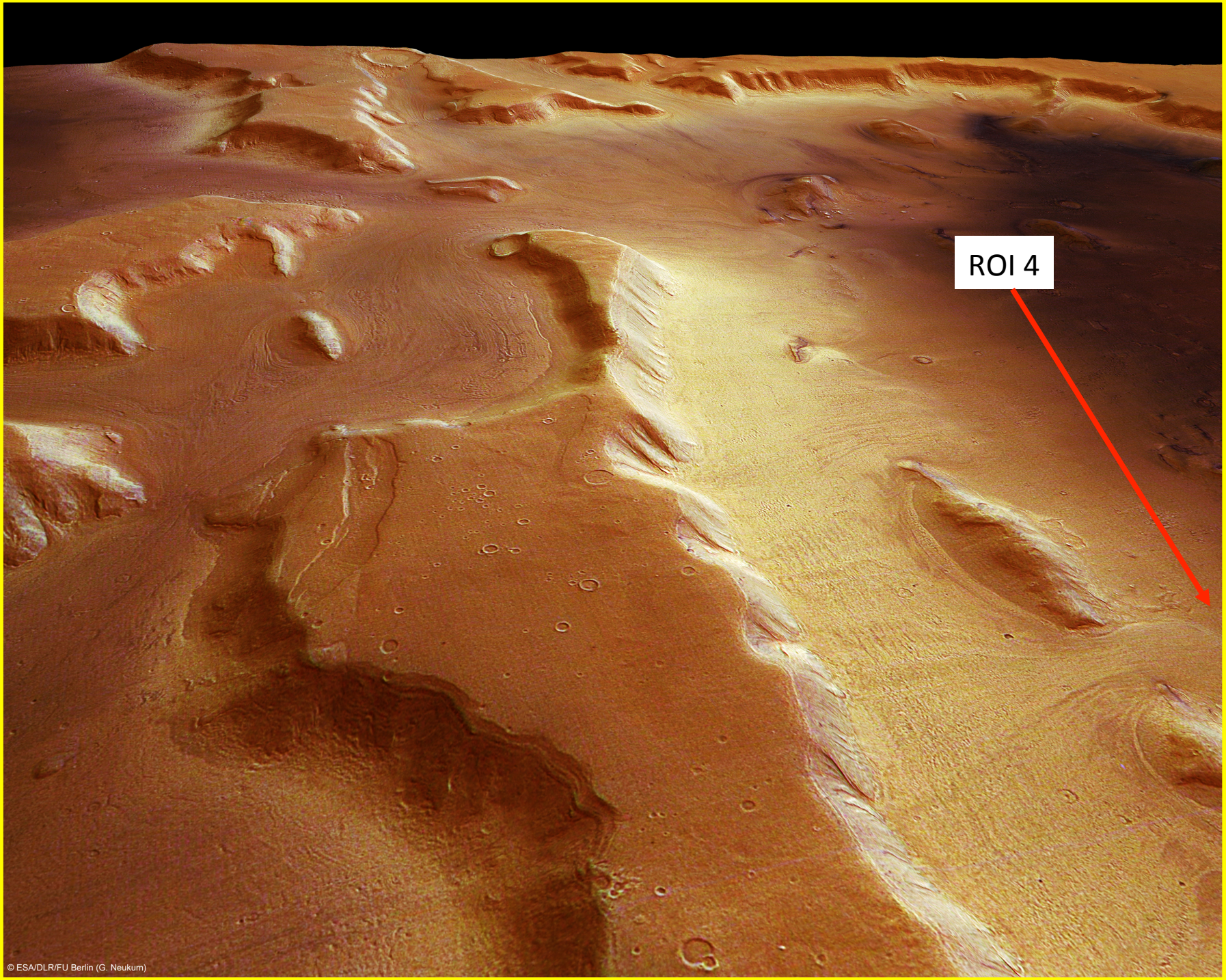

-1500
38
38.1
38.2
-2000
-2500
-3000
-3500
-4000
Topography
>1 km height cliff face.
Distance (km)

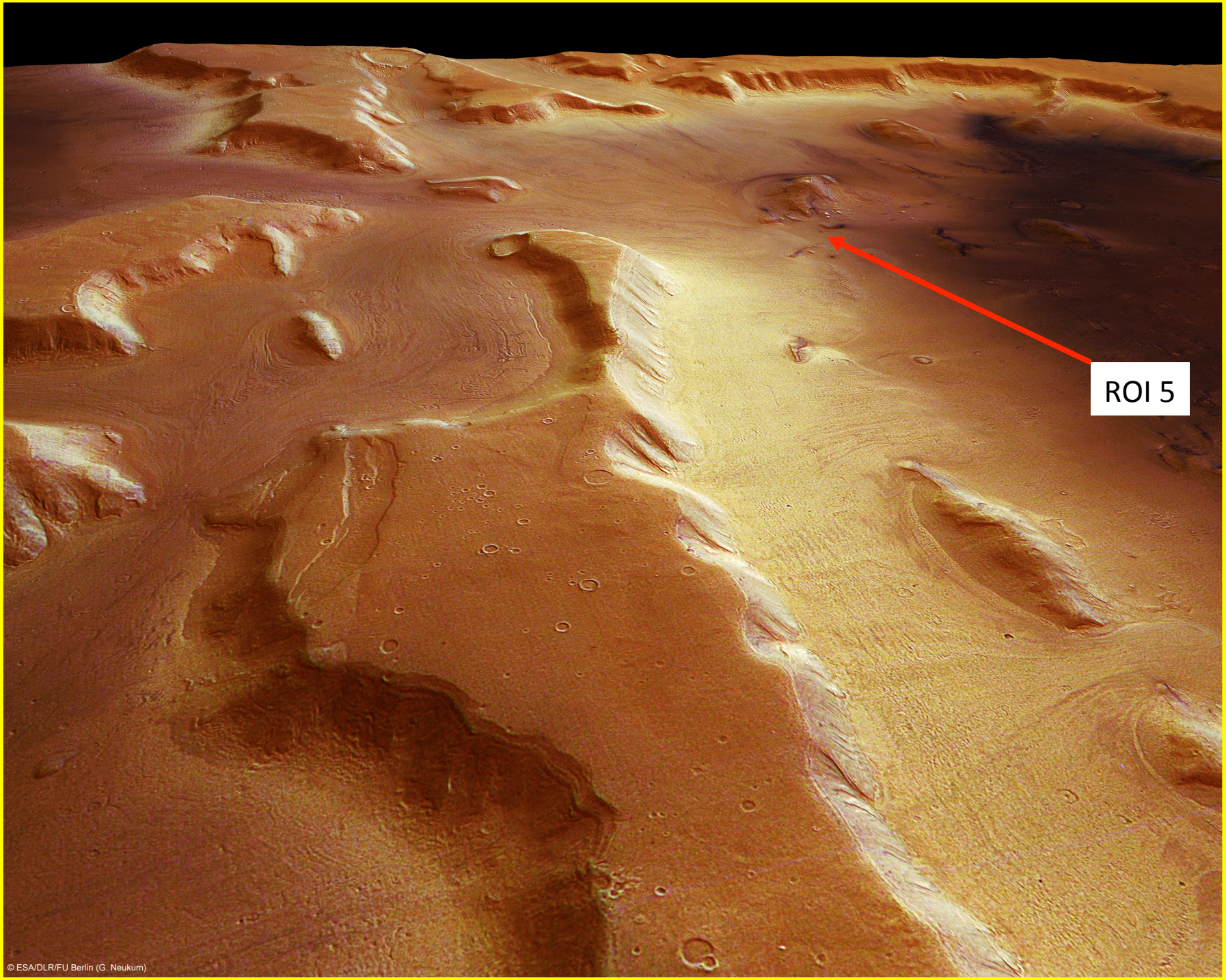
Science-Resource ROI 4:



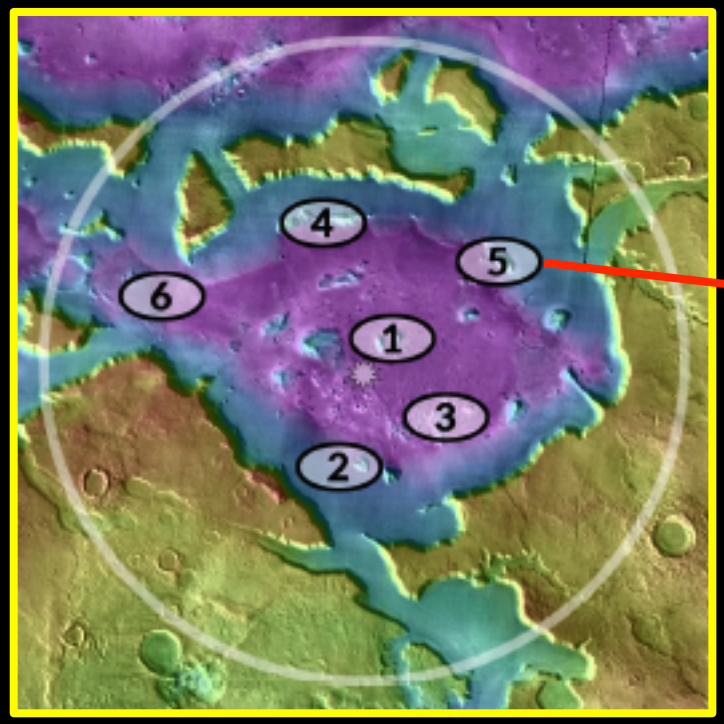


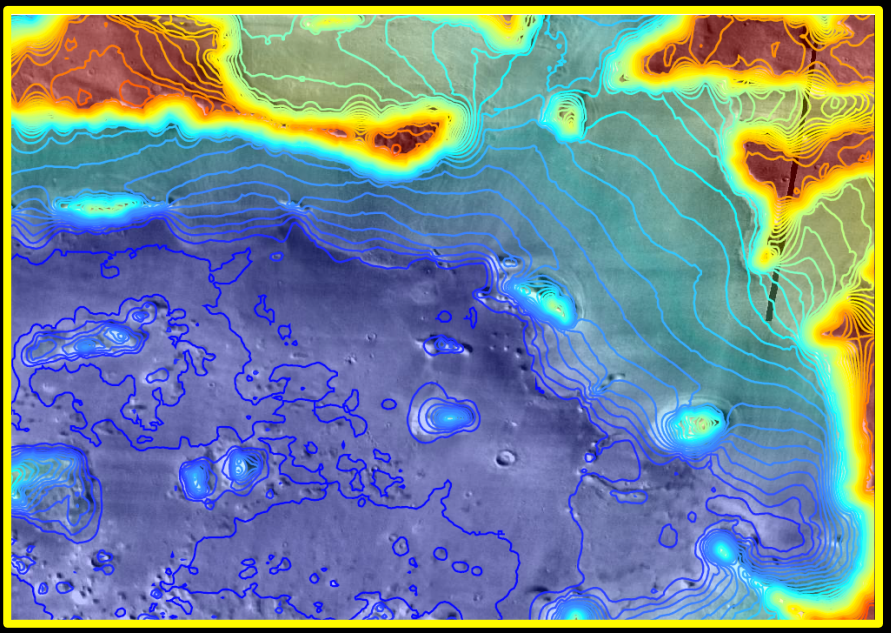
- 1) Distinctive **LDA glacial ice record** protruding through 2) ridge representing **peak ring of Noachian-aged crater**, and 3) Noachian-Hesperian volcanics. Access to water ice in near subsurface and suite of samples from terrain to the north.




ROI 5
© ESA/DLR/FU Berlin (G. Neukum)

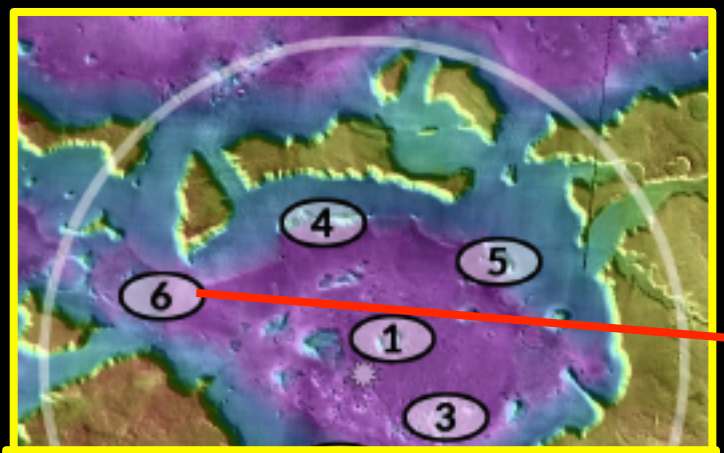
Science-Resource ROI 5:

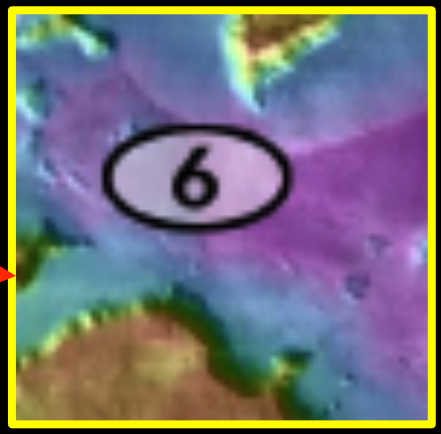


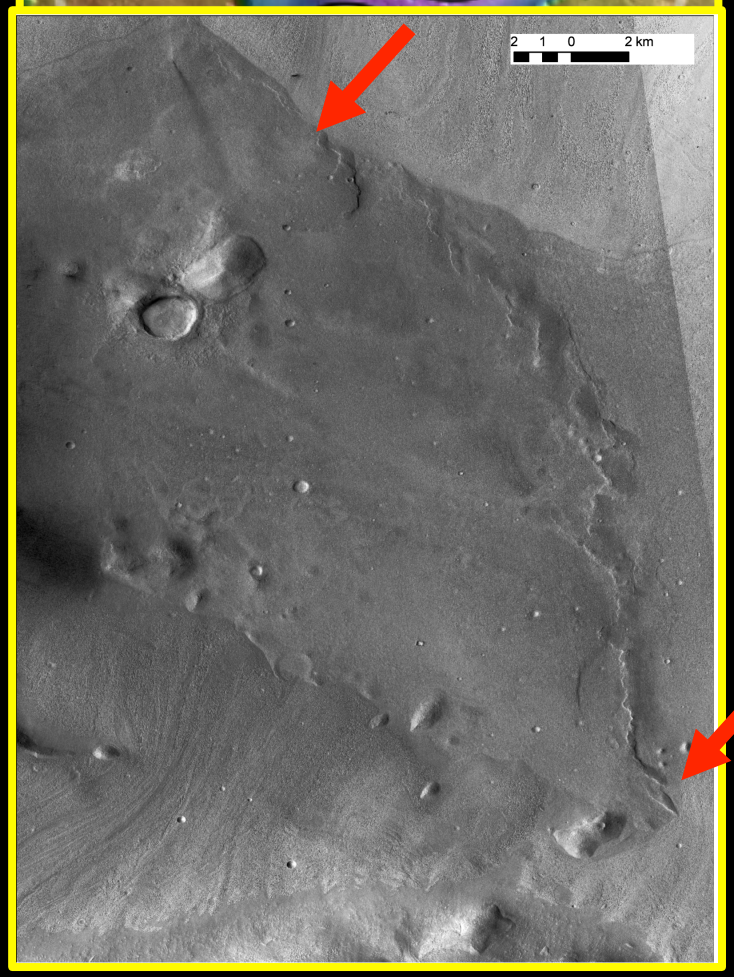


- 1) Ridge representing peak ring of Noachian-aged crater; 2) LDA banked behind with LDA ice lobe on both sides of the outcrop of ancient crustal material; 3) Noachian-Hesperian volcanics. Access to water ice in near subsurface and suite of samples from terrain to the north.

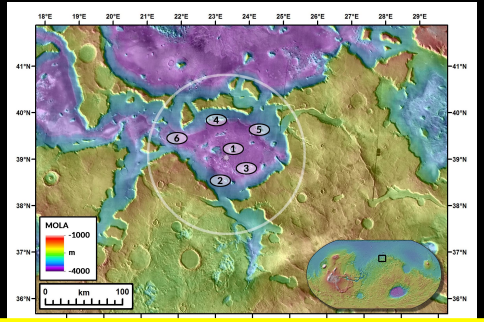
Science-Resource ROI 6:







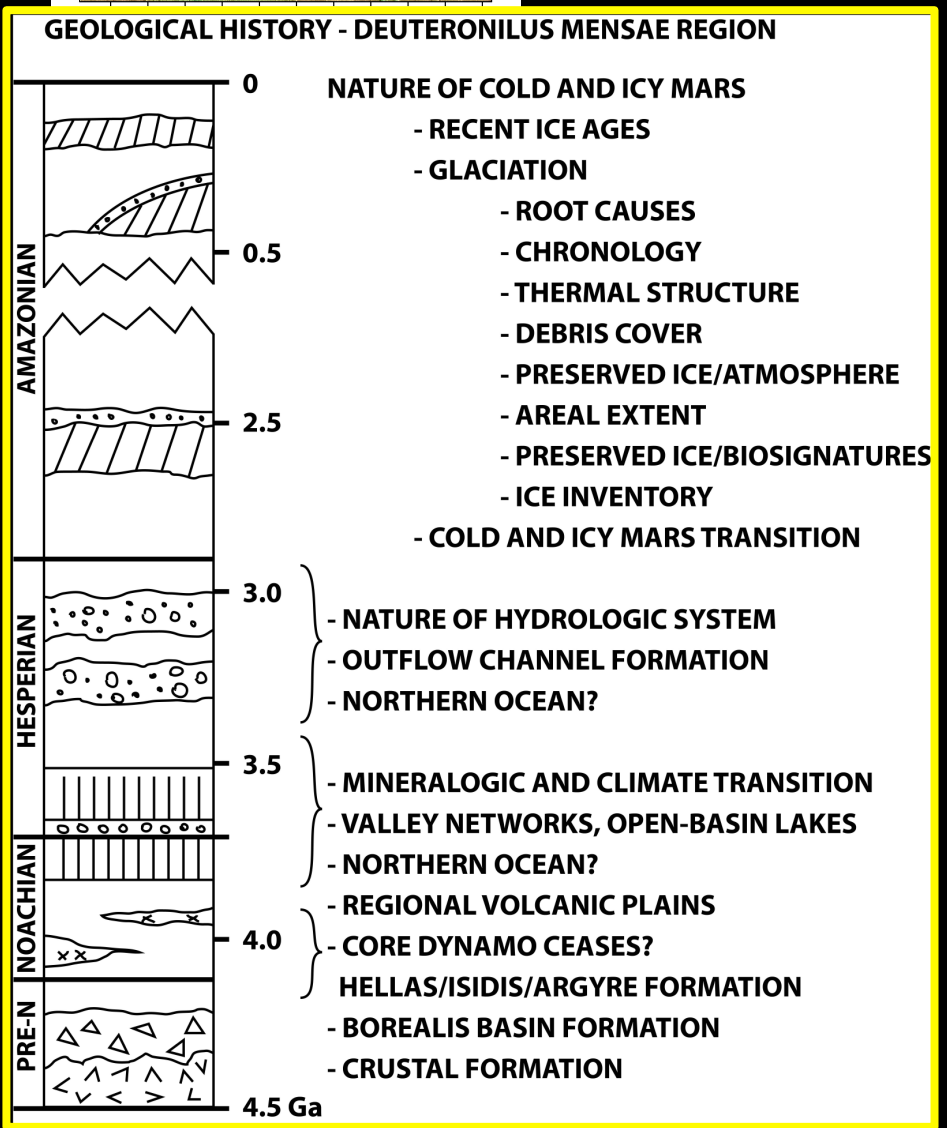
- Outlet from Noachian-aged crater floor to west provides access to additional 1) LDA ice and climate history, and 2) wrinkle-ridge structure with stratigraphic relations, may mark location of ancient lavas; 3) Noachian, Hesperian and Amazonian samples and processes.

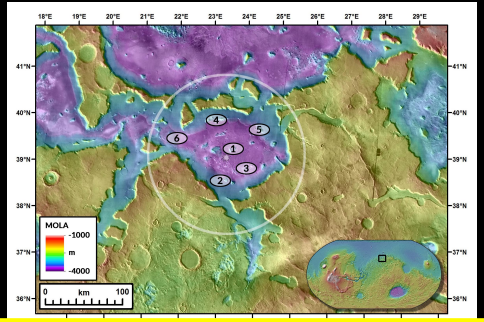


HSO-SAG Mars Human Landing Site Criteria

- HSO-SAG determined that potential landing sites on Mars should have access to the following:
  - 1) Deposits with a high preservation potential for evidence of past habitability and/or sites that are promising for present habitability;
  - 2) Noachian and/or Hesperian rocks that can be used to understand past atmospheres;
  - 3) Exposures of at least two crustal units that are suitable for radiometric dating;
  - 4) Access to outcrops with signatures indicative of aqueous processes;
  - 5) Identifiable stratigraphic contacts and cross-cutting relationships from which relative ages can be determined.

Scientific ROIs within this exploration zone can be considered candidate sites for human exploration.





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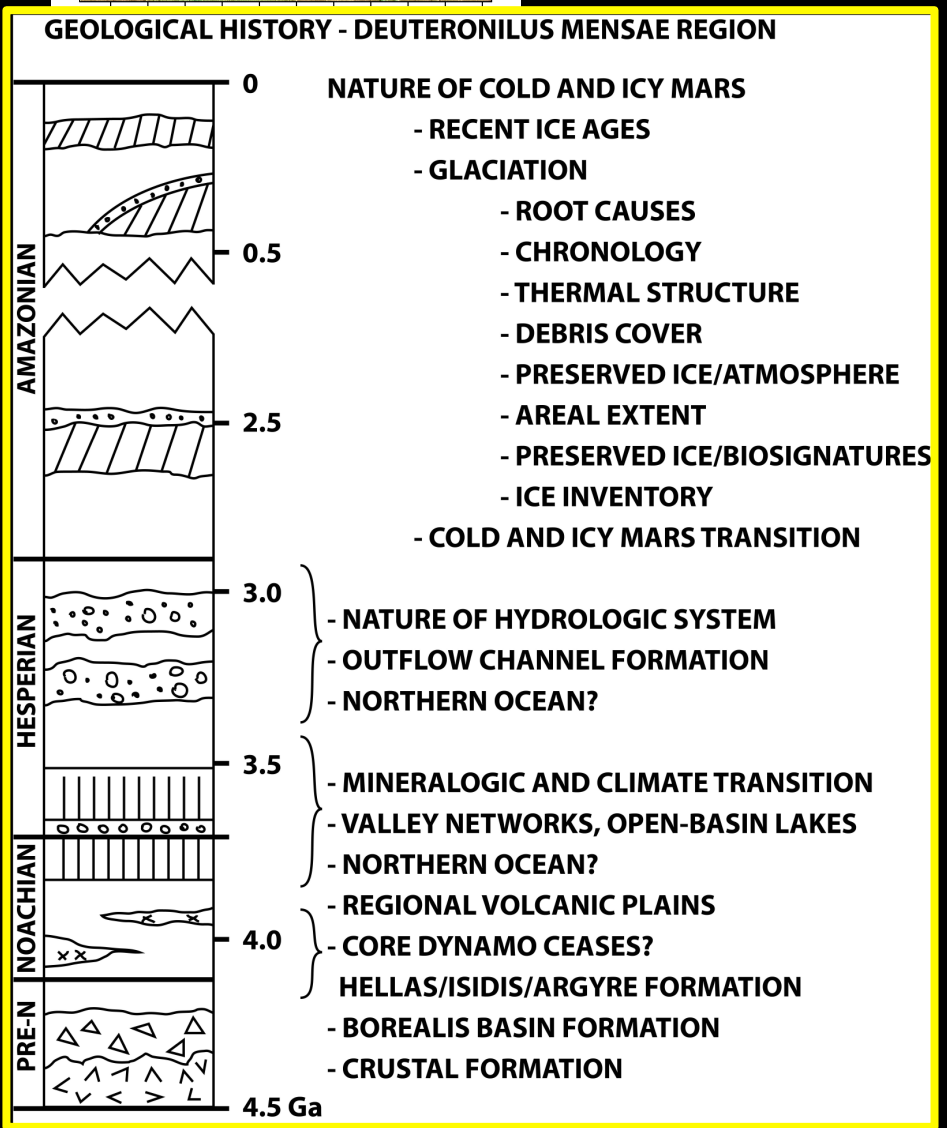

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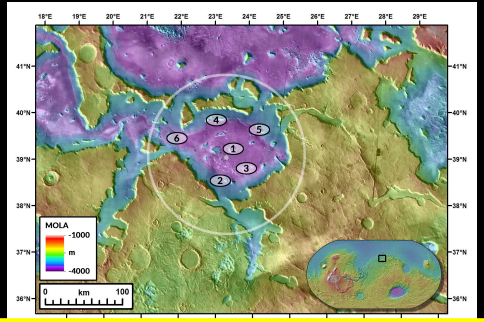

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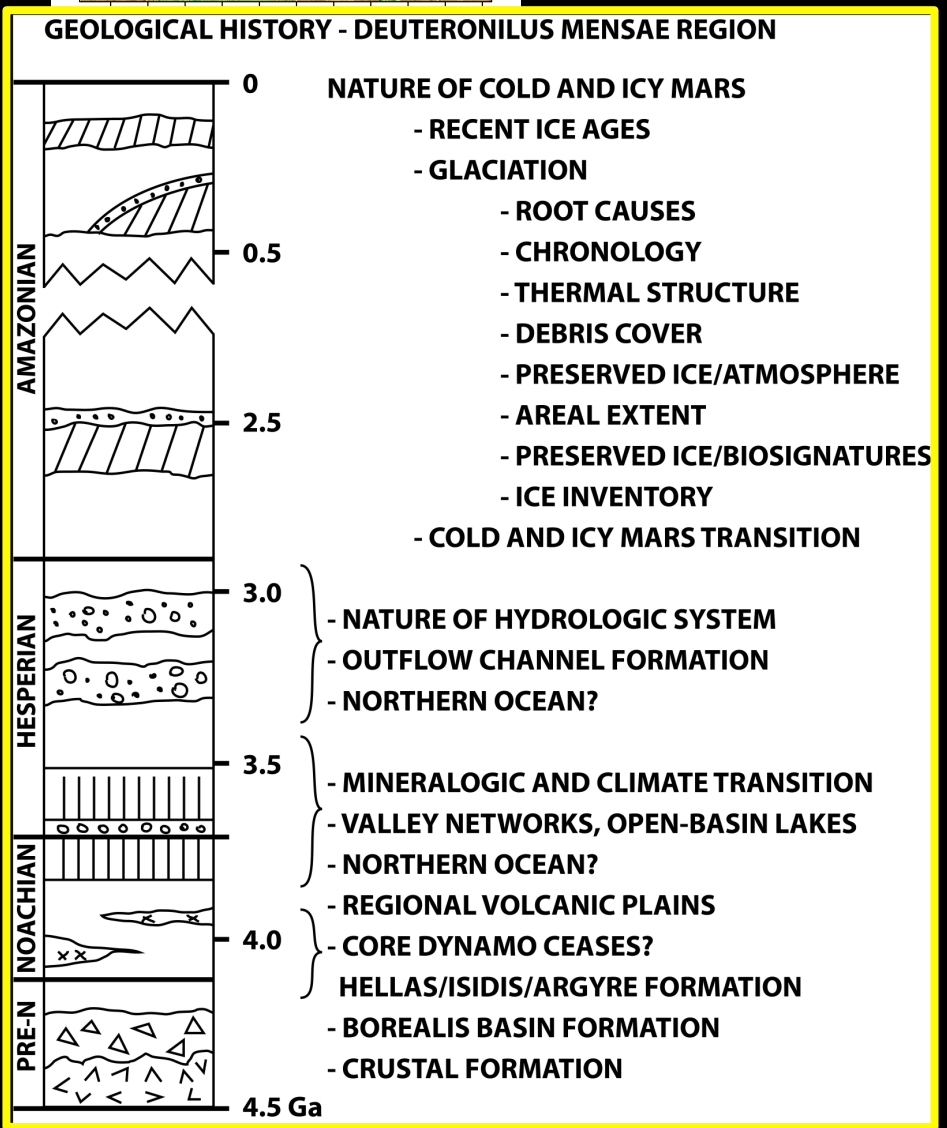

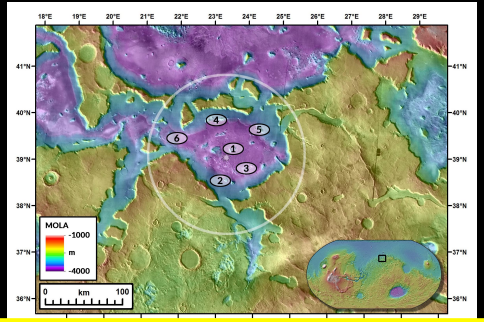

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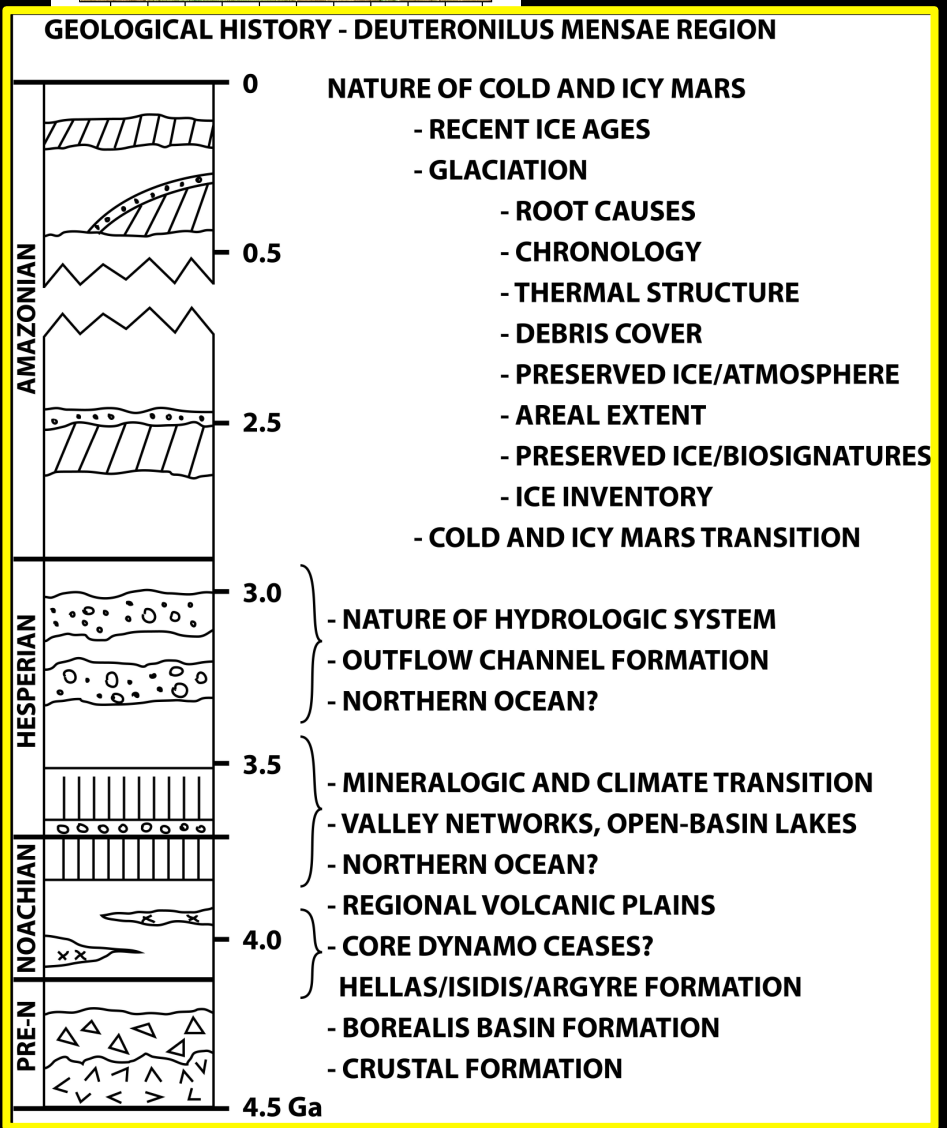

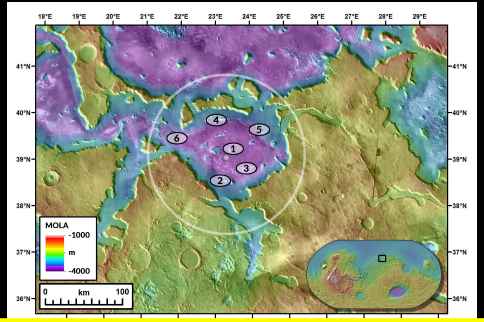

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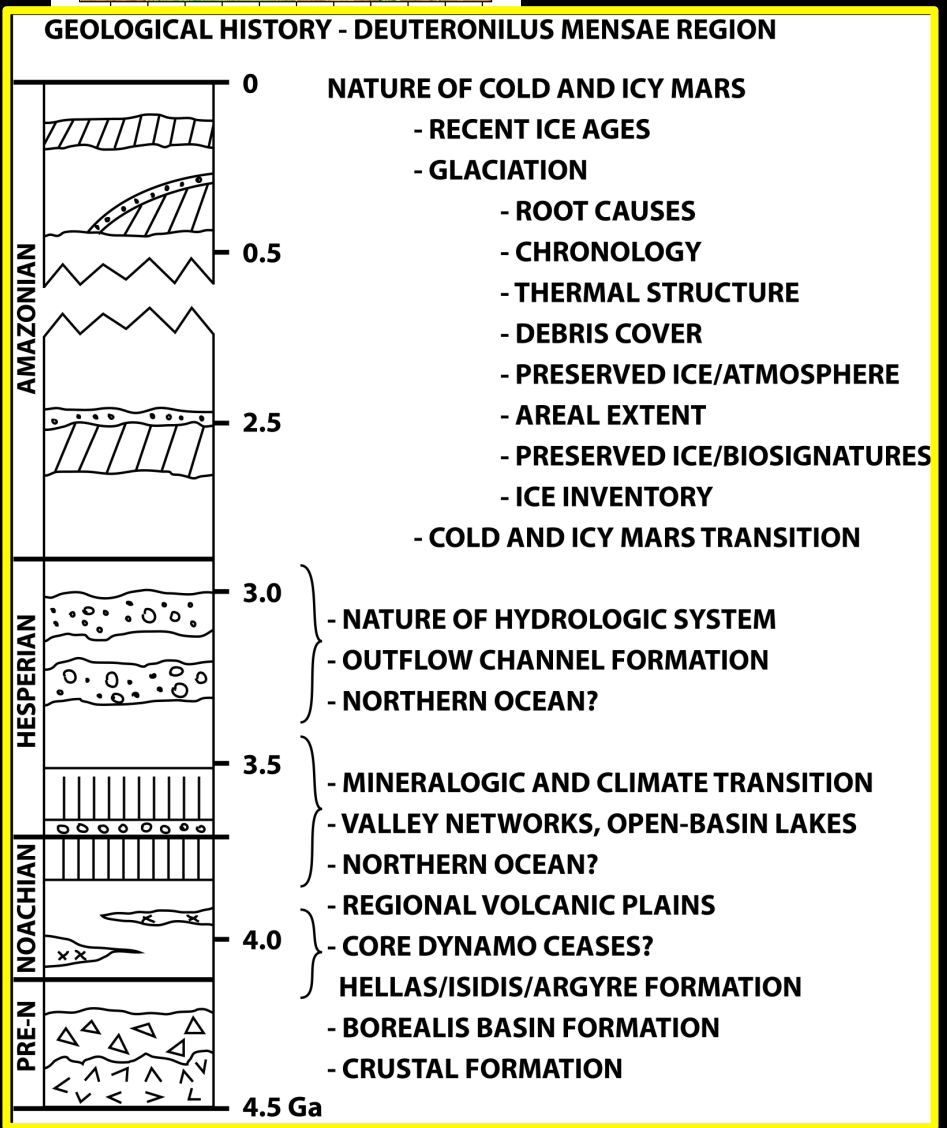

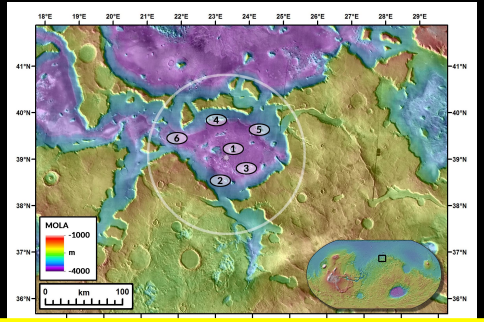

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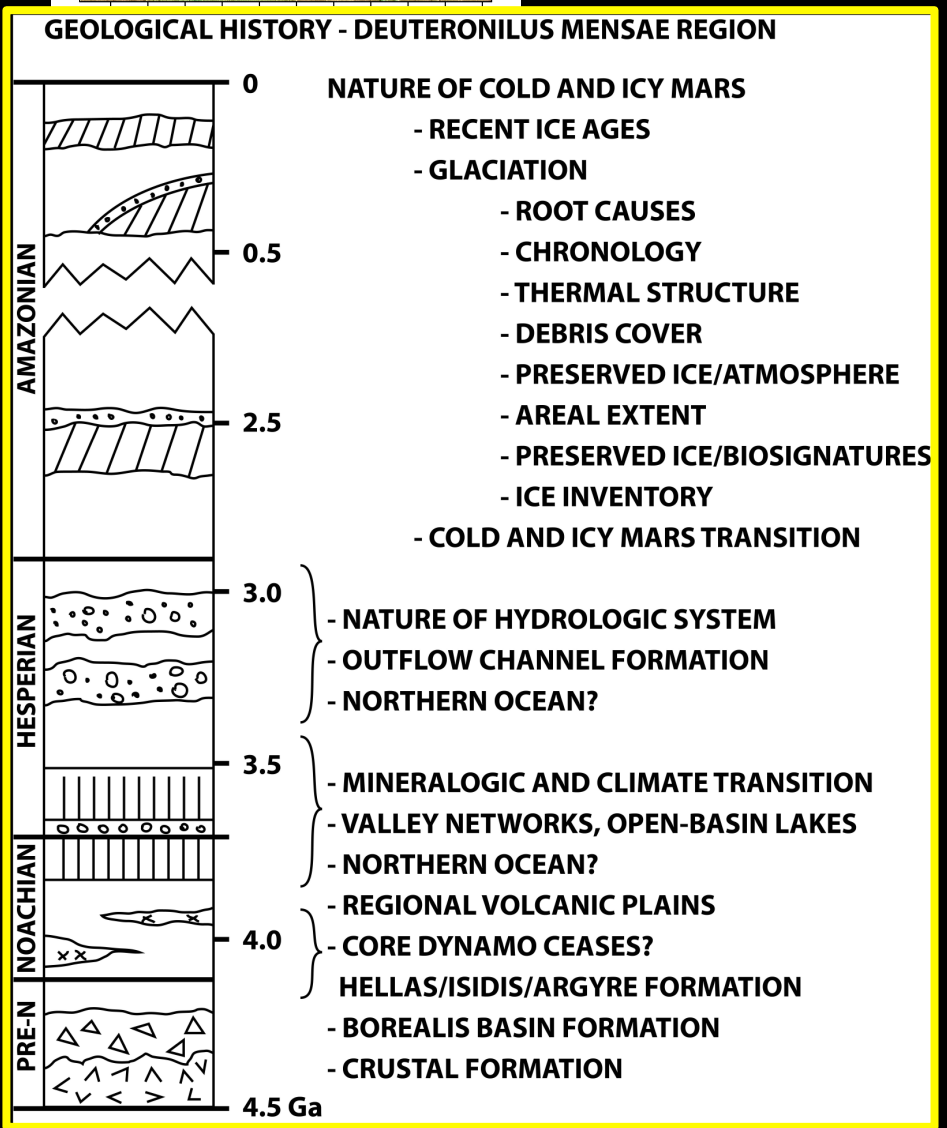
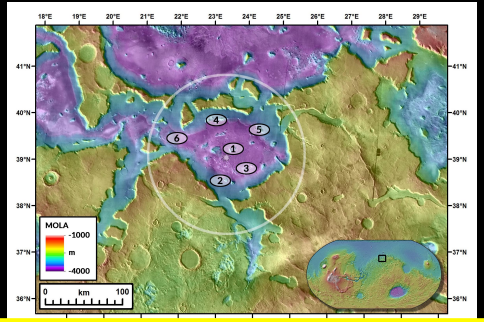
Scientific ROIs within this exploration zone can be considered candidate sites for human exploration.





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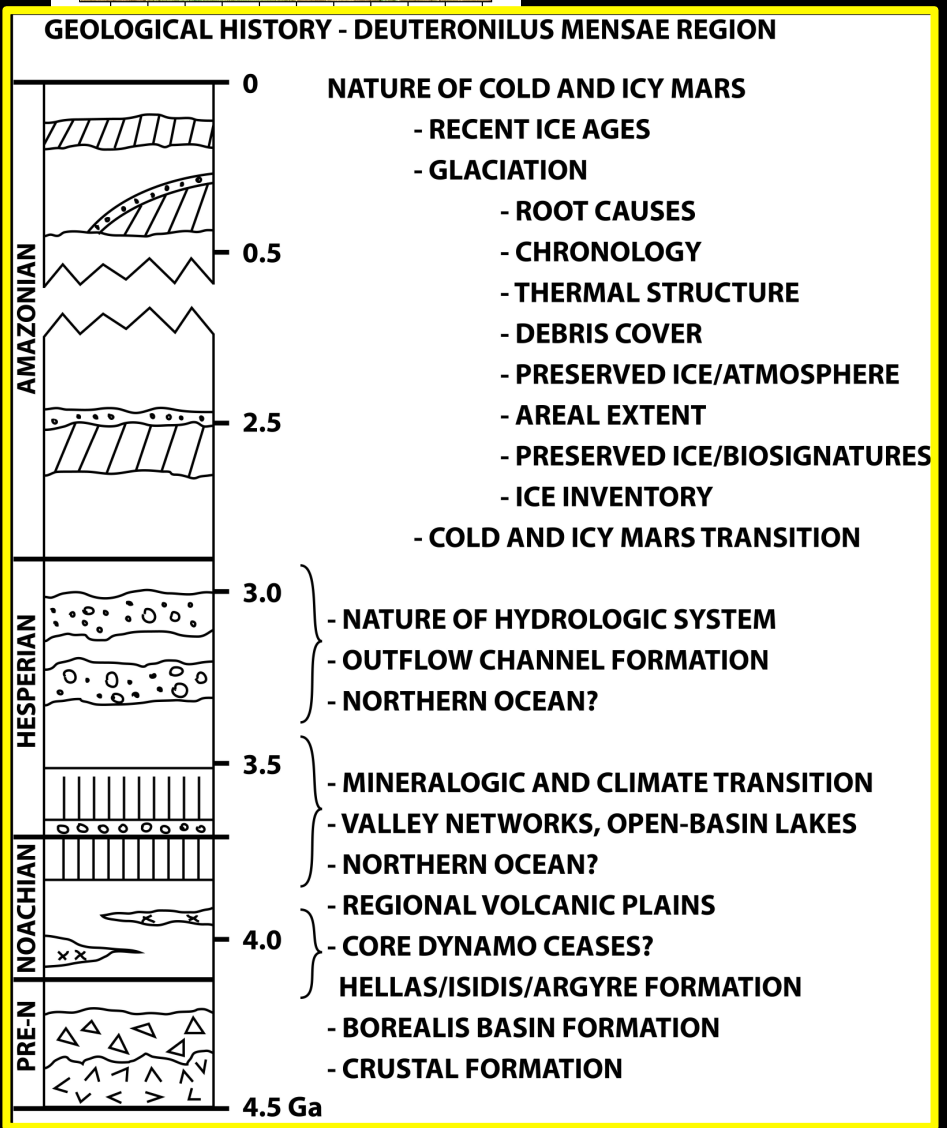
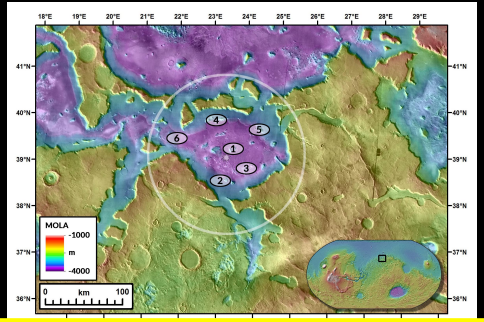
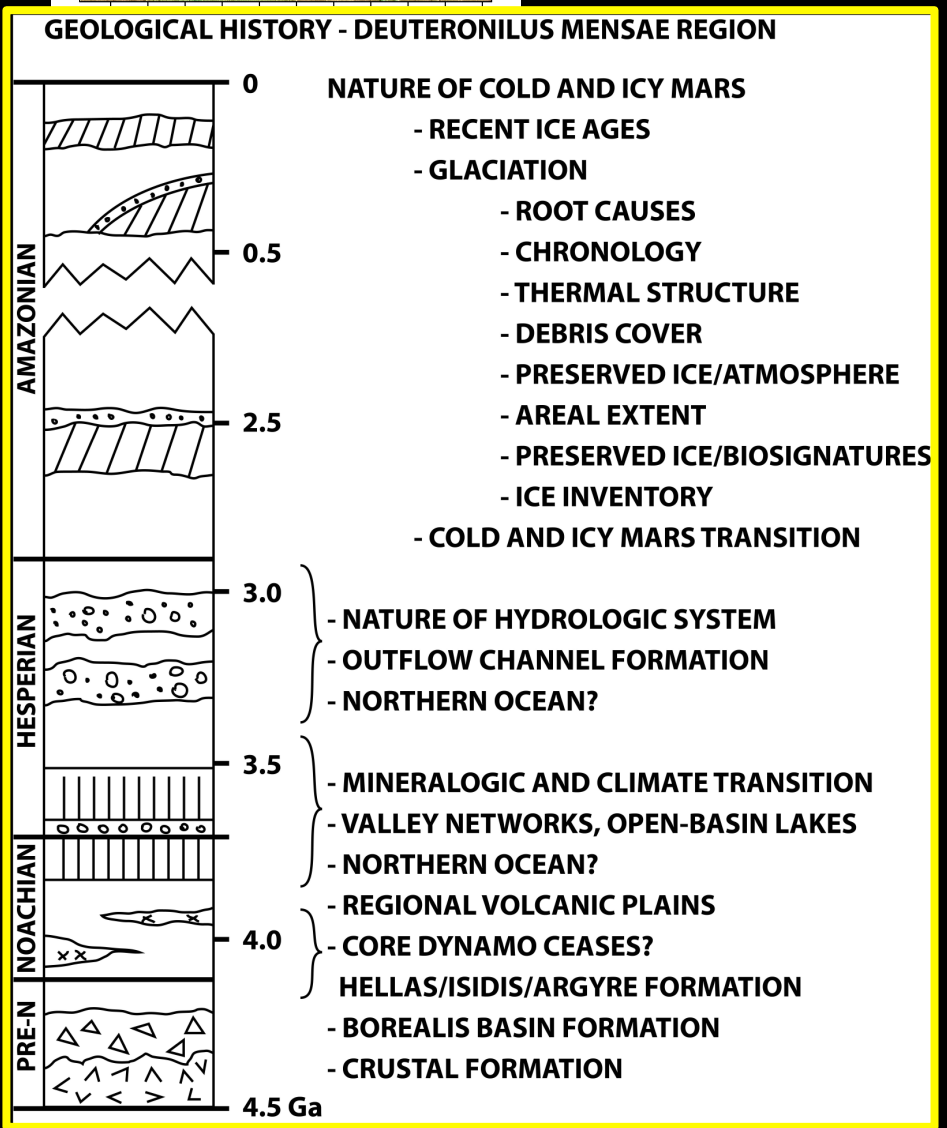
Scientific ROIs within this Exploration Zone are candidate sites for human exploration +ISRU/CE.



Resources and Civil Engineering Criteria





- -***Raw material access*** **that exhibits potential to:**
  - (a) be used as feedstock ***for water-generating In-Situ Resource Utilization (ISRU) processes*** and
  - (b) ***yield significant quantities (>100MT) of water***. Raw material can be in the form of ice, ice/regolith mix, or hydrated minerals and the top of the raw material deposit should be as close to the surface as possible'

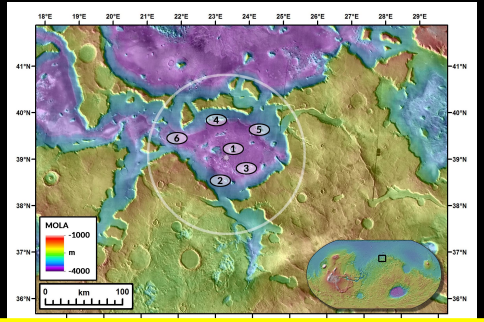
-Access to a region *where infrastructure can be emplaced or constructed*:

- Region must be less than 5 km from a central landing site and contain flat, stable terrain.
- Region should exhibit evidence for an abundant source of cobble-sized or smaller rocks and bulk, loose regolith.
- Natural terrain features that can be adapted for construction purposes (e.g., to enhance habitat radiation protection) are considered beneficial.

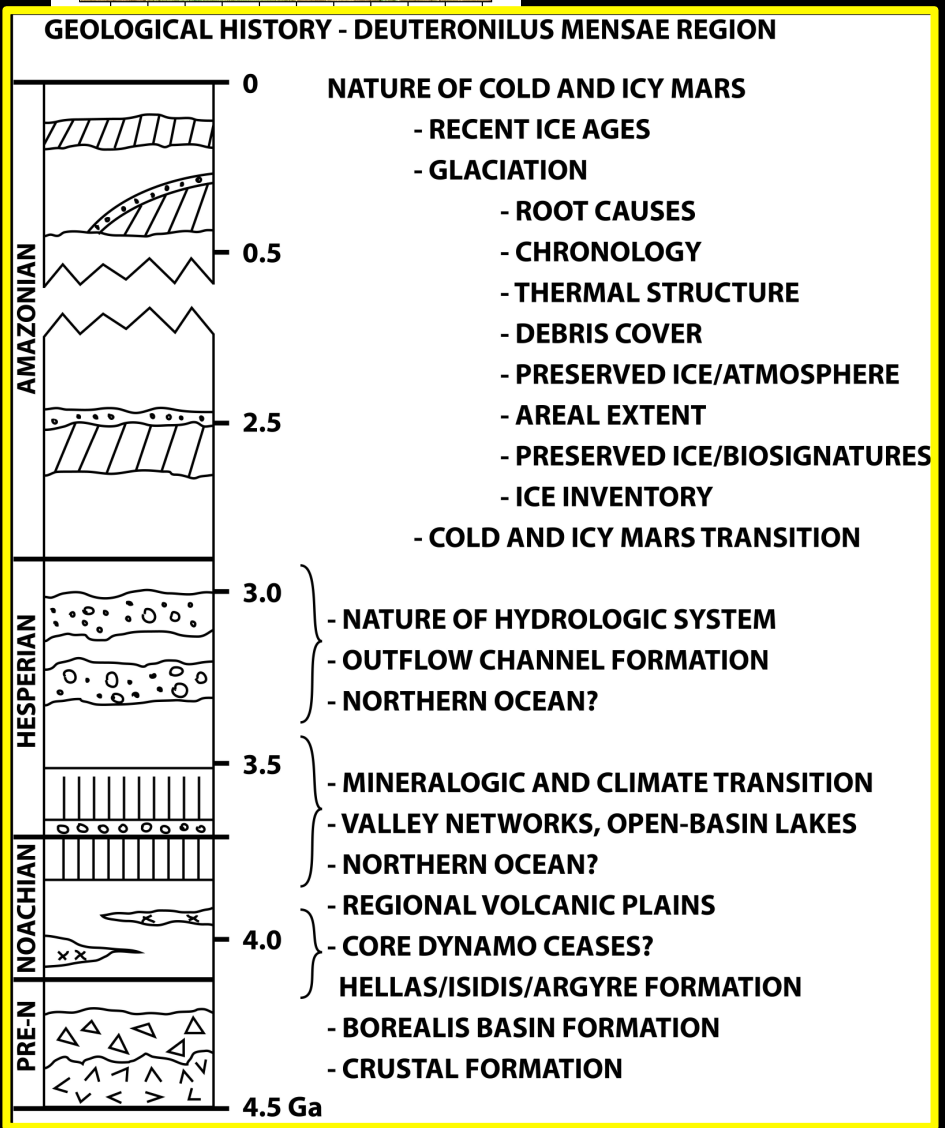
-*Access to raw material* that exhibits the potential *as metal or silicon feedstock for ISRU and construction purposes*:

- Of primary interest are iron, aluminum, and silicon; titanium and magnesium are of secondary interest.
- Raw material should be as near to the surface as possible and be in a form that can be mined by highly automated systems.

Resources and Civil Engineering Criteria



-High-Grade.
-Close Proximity.
-Two stage extraction.



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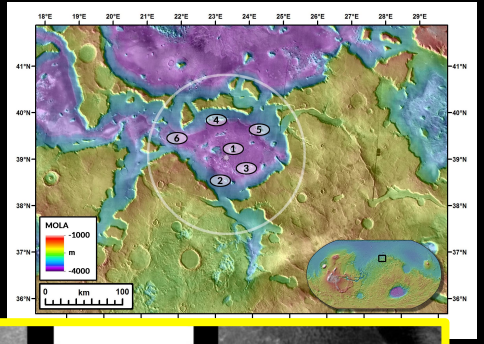
- Natural terrain features that can be adapted for construction purposes (e.g., to enhance habitat radiation protection) are considered beneficial.

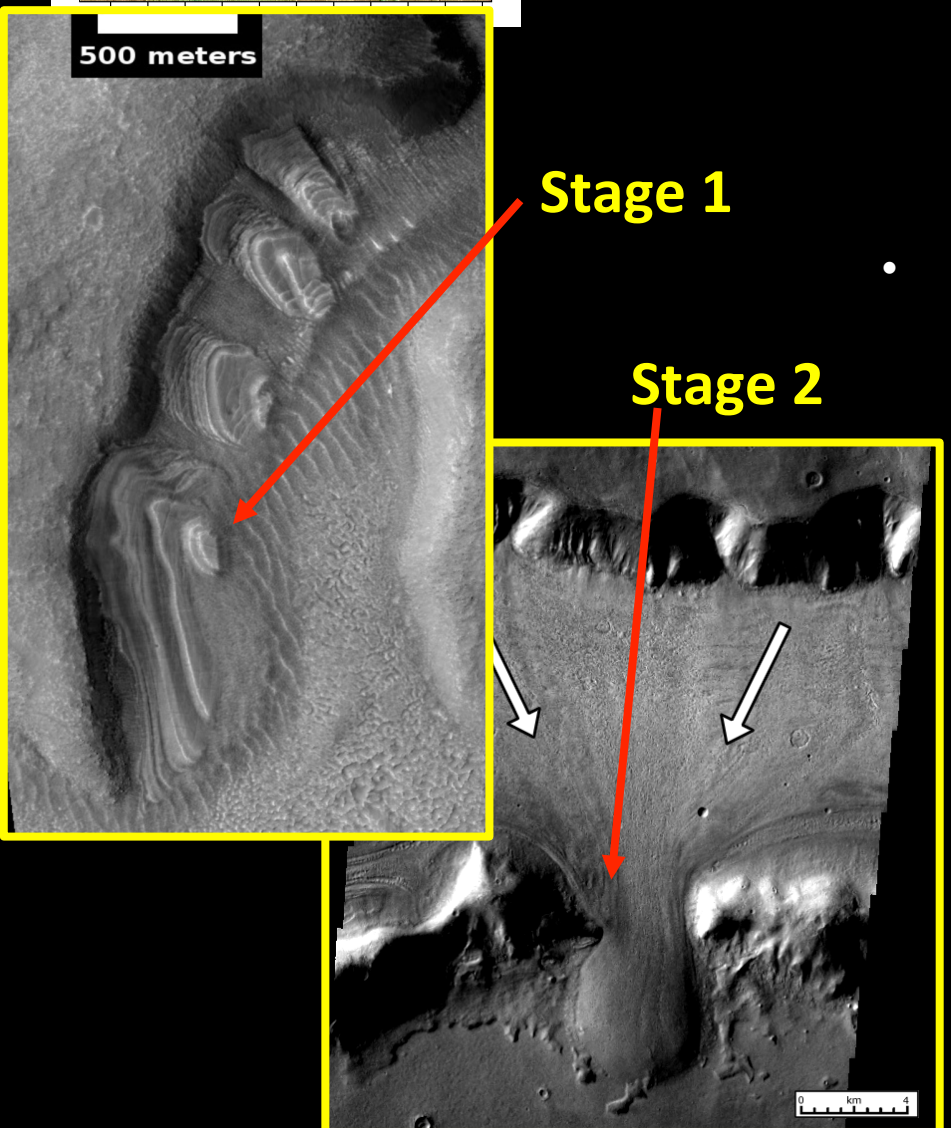
-*Access to raw material* that exhibits the potential *as metal or silicon feedstock for ISRU and construction purposes*:

- Of primary interest are iron, aluminum, and silicon; titanium and magnesium are of secondary interest.
- Raw material should be as near to the surface as possible and be in a form that can be mined by highly automated systems.

Resources and Civil Engineering Criteria



-High-Grade.
-Close Proximity.
-Two stage extraction.



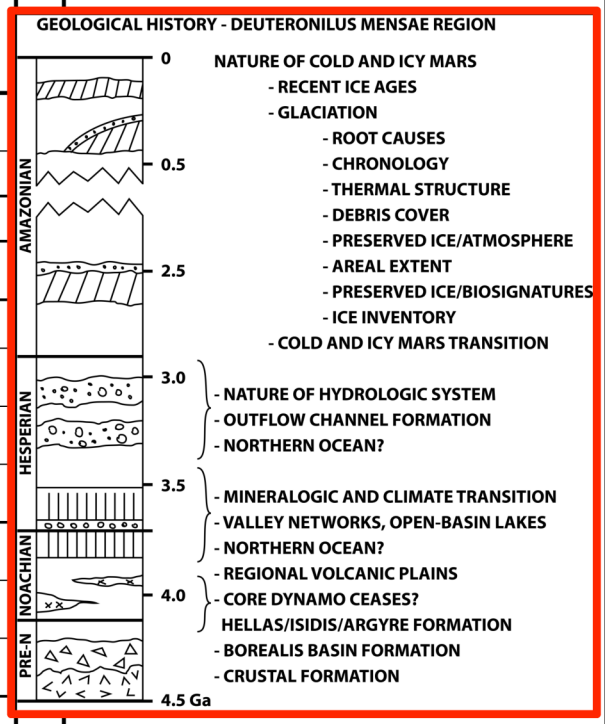
- -***Raw material access*** that exhibits potential to:
  - (a) be used as feedstock ***for water-generating In-Situ Resource Utilization (ISRU) processes*** and
  - (b) ***yield significant quantities (>100MT) of water***. Raw material can be in the form of ice, ice/regolith mix, or hydrated minerals and the top of the raw material deposit should be as close to the surface as possible'
- -Access to a region ***where infrastructure can be emplaced or constructed***:
  - Region must be less than 5 km from a central landing site and contain flat, stable terrain.
  - Region should exhibit evidence for an abundant source of cobble-sized or smaller rocks and bulk, loose regolith.
  - Natural terrain features that can be adapted for construction purposes (e.g., to enhance habitat radiation protection) are considered beneficial.

-***Access to raw material*** that exhibits the potential ***as metal or silicon feedstock for ISRU and construction purposes***:

- Of primary interest are iron, aluminum, and silicon; titanium and magnesium are of secondary interest.
- Raw material should be as near to the surface as possible and be in a form that can be mined by highly automated systems.

Science ROI(s) Rubric

Science Site Criteria				Site Factors	ROI1	ROI2	ROI3	ROI4	ROI5	ROI6	EZ SUM
	Astrobio	Threshold	AND/OR	**Potential for past habitability**	●	●	●	●	●	●	6,0
				Potential for present habitability/refugia	○	○	○	○	○	○	0,6
		Qualifying		Potential for organic matter, w/ surface exposure	○	○	○	○	○	○	0,6
	Atmospheric Science	Threshold		**Noachian/Hesperian rocks w/ trapped atmospheric gases**	●	●	●	●	●	●	6,0
		Qualifying		Meteorological diversity in space and time	●	●	●	●	●	●	6,0
				High likelihood of surface-atmosphere exchange	●	●	●	●	●	●	6,0
				Amazonian subsurface or high-latitude ice or sediment	●	●	●	●	●	●	6,0
				High likelihood of active trace gas sources	●	●	●	●	●	●	6,0
	Geoscience	Threshold		**Range of martian geologic time; datable surfaces**	●	●	●	●	●	●	6,0
				Evidence of aqueous processes	○	○	○	○	○	○	0,6
				Potential for interpreting relative ages	●	●	●	●	●	●	6,0
		Qualifying		Igneous Rocks tied to 1+ provinces or different times	●	●	●	●	●	●	6,0
				Near-surface ice, glacial or permafrost	●	●	●	●	●	●	6,0
				Noachian or pre-Noachian bedrock units	●	●	●	●	●	●	6,0
				Outcrops with remnant magnetization		●	●	●	●	●	5,0
				Primary, secondary, and basin-forming impact deposits	●	●	●	●	●	●	6,0
				Structural features with regional or global context						●	1,0
				Diversity of aeolian sediments and/or landforms	●	●	●	●	●	●	6,0

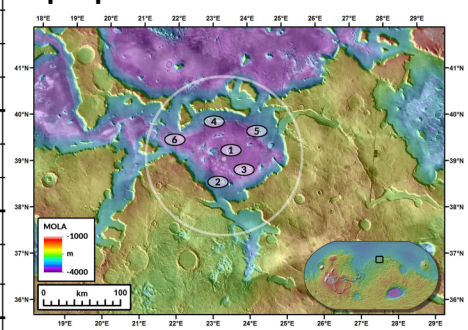


Key	
●	Yes
○	Partial Support or Debated
	No
?	Indeterminate

Resource ROI(s) Rubric

1st EZ Workshop for Human Missions to Mars

ISRU and Civil Engineering Criteria				Site Factors	ROI1	ROI2	ROI3	ROI4	ROI5	ROI6	EZ SUM
	Engineering			Meets First Order Criteria (Latitude, Elevation, Thermal Inertia)	●	●	●	●	●	●	6,0
	Water Resource	Threshold	AND/OR	**Potential for ice or ice/regolith mix**	●	●	●	●	●	●	6,0
				Potential for hydrated minerals	○	○	○	○	○	○	0.6
				Quantity for substantial production	●	●	●	●	●	●	6,0
				Potential to be minable by highly automated systems	●	●	●	●	●	●	6,0
				Located less than 3 km from processing equipment site	●		●				2,0
				Located no more than 3 meters below the surface	●		●				2,0
				Accessible by automated systems	●		●				2,0
		Qualifying		Potential for multiple sources of ice, ice/regolith mix **and** hydrated minerals	?	?	?	?	?	?	
				Distance to resource location can be >5 km		●		●	●	●	4,0
				Route to resource location must be (plausibly) traversable	●	●	●	●	●	●	6,0
	Civil Engineering	Threshold		**~50 sq km region of flat and stable terrain with sparse rock distribution**	▬	▬	▬	▬	▬	▬	6,0
				1–10 km length scale: <10°	▬	▬	▬	▬	▬	▬	6,0
				Located within 5 km of landing site location	▬	▬	▬	▬	▬	▬	6,0
		Qualifying		Located in the northern hemisphere	▬	▬	▬	▬	▬	▬	6,0
				Evidence of abundant cobble sized or smaller rocks and bulk, loose regolith	▬	▬	▬	▬	▬	▬	6,0
				Utilitarian terrain features	▬	▬	▬	▬	▬	▬	6,0
	Food Production	Qualifying		Low latitude							
				No local terrain feature(s) that could shadow light collection facilities							
				Access to water	▬	▬	▬	▬	▬	▬	6,0
				Access to dark, minimally altered basaltic sands	▬	▬	▬	▬	▬	▬	6,0
	Metal/Silicon Resource	Threshold		**Potential for metal/silicon**	▬	▬	▬	▬	▬	▬	6,0
				Potential to be minable by highly automated systems	▬	▬	▬	▬	▬	▬	6,0
				Located less than 3 km from processing equipment site	▬	▬	▬	▬	▬	▬	6,0
				Located no more than 3 meters below the surface	▬	▬	▬	▬	▬	▬	6,0
				Accessible by automated systems	▬	▬	▬	▬	▬	▬	6,0
		Qualifying		Potential for multiple sources of metals/silicon	▬	▬	▬	▬	▬	▬	6,0
				Distance to resource location can be >5 km	▬	▬	▬	▬	▬	▬	6,0
				Route to resource location must be (plausibly) traversable	▬	▬	▬	▬	▬	▬	6,0



Key	
●	Yes
○	Partial Support or Debated
	No
?	Indeterminate

Prioritization List of EZ Data Needs

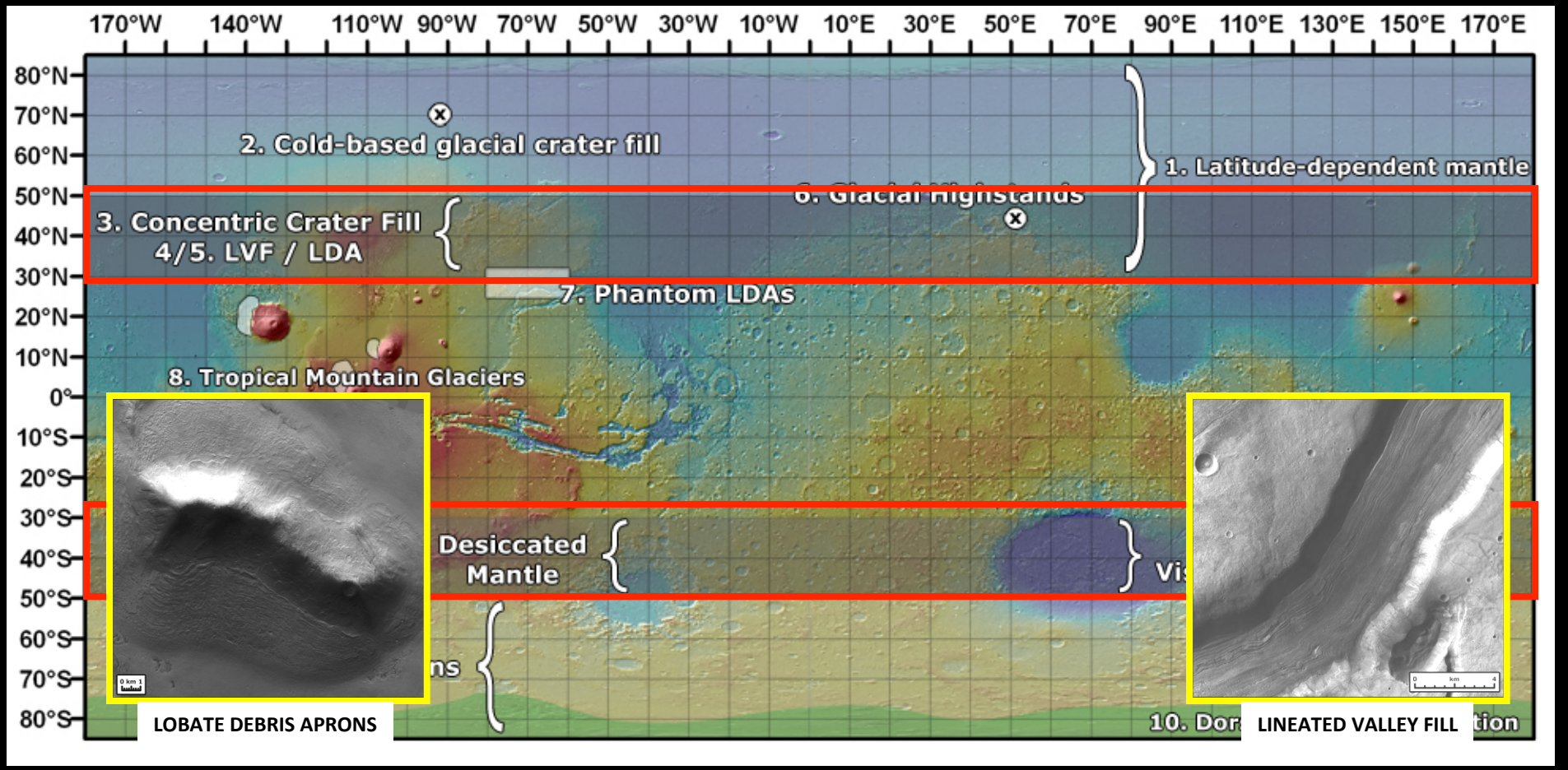
- **SCIENCE, ISRU AND CIVIL ENGINEERING DATA NEEDS**

- **ORBITER DATA:**
- HiRISE image data: Already entering targets.
- CRISM-like Imaging Spectrometer data: Very high spatial / spectral resolution.
- SHALLOW PENETRATING RADAR/NEUTRON SPECTROMETER: Map presence and geometry of shallow ice and debris cover.
- LASER ALTIMETER: Multiple-shot high spatial resolution for topography. slopes.

- **ROVER DATA:**
- *CURIOSITY*/2020-like payload.

- **PLANETARY PROTECTION: Need strategy, missions to address these issues.**

Ice Accumulation and Retention "Sweet-Spot": The Martian Mid-Latitudes



Mid-Latitude Lobate Debris Aprons and Lineated Valley Fill

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