Thinking Source-to-Sink on Mars and Titan

Alan D. Howard, *University of Virginia*
John P. Grotzinger, *California Institute of Technology*

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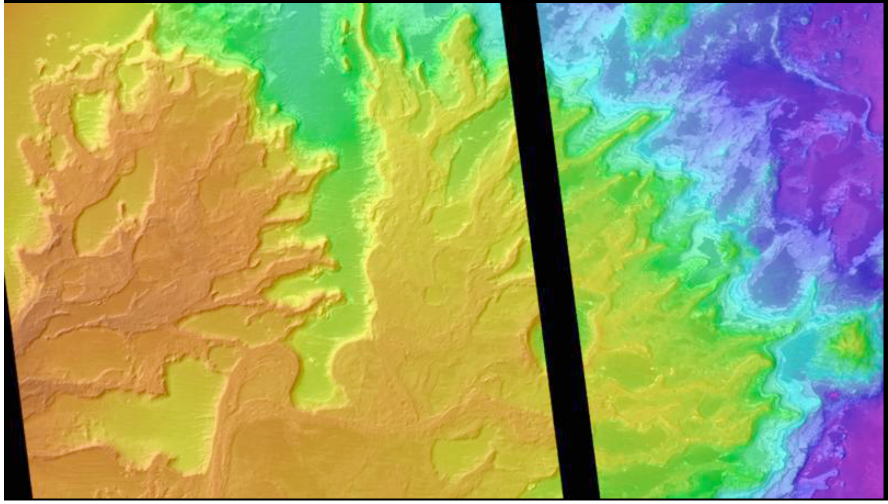
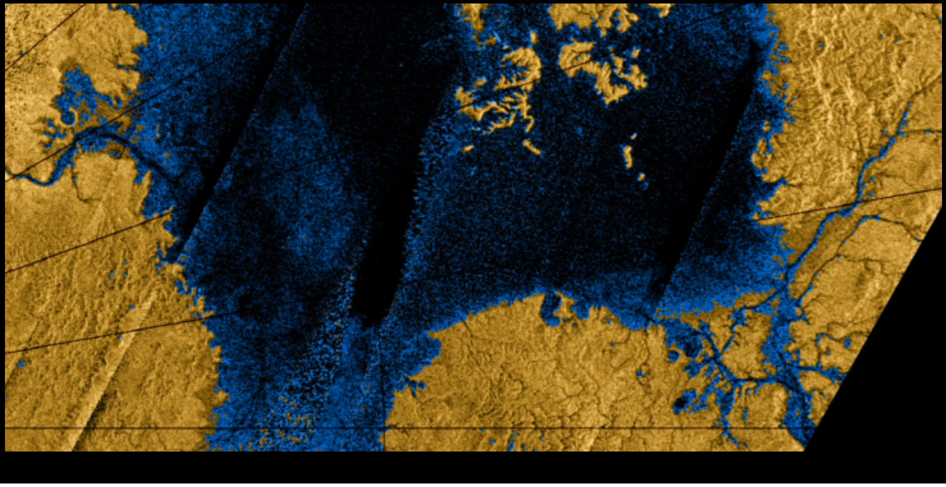


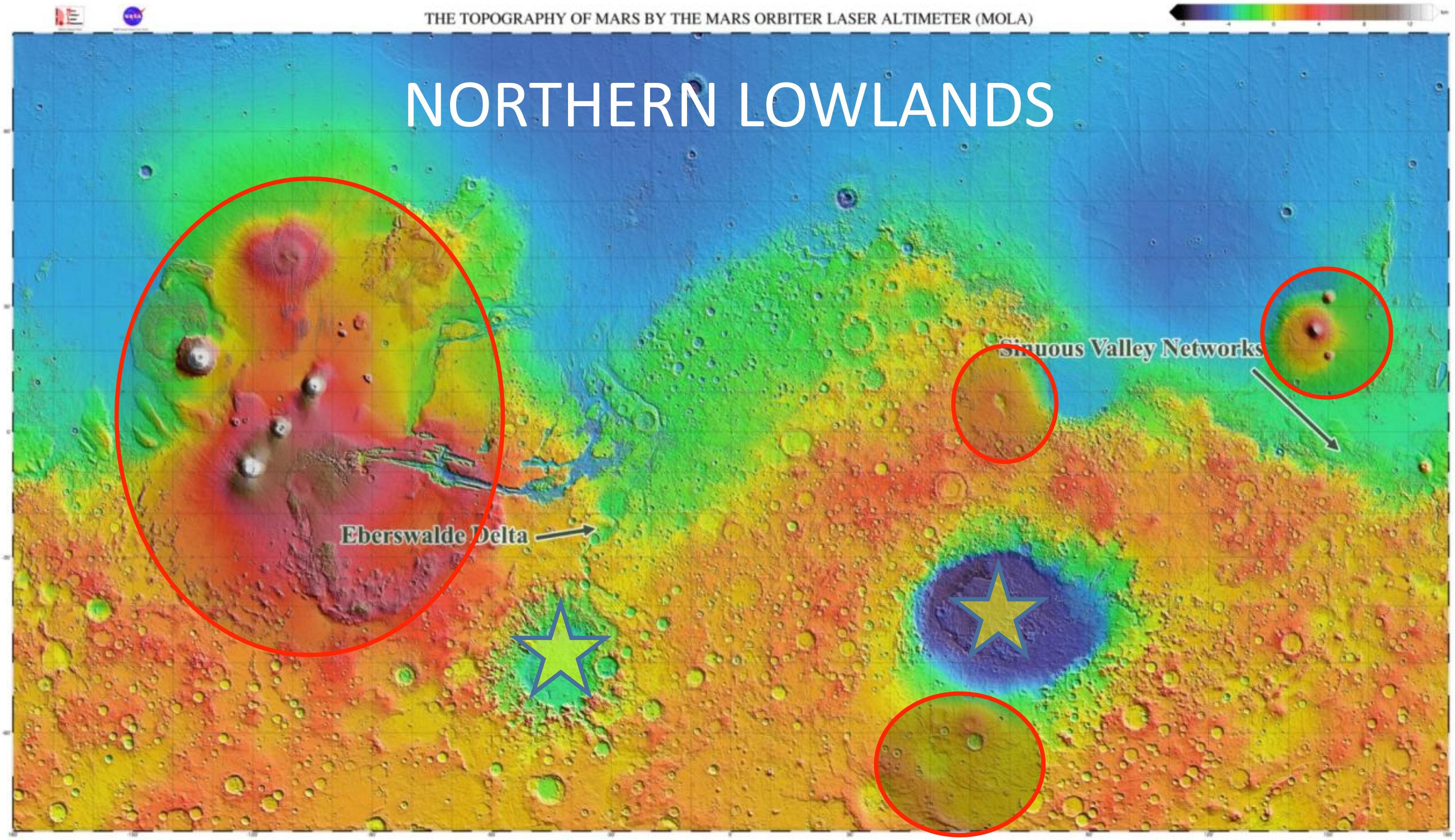


Context for S2S Meeting

- Both Mars and Titan have been extensively modified by fluvial processes *(using "fluvial" in the broad context of sediment erosion, transport, and deposition by liquids)*
- For Mars, the S2S context is an important consideration for landing site selection for the next mission: the MSL rover *(Mars Science Laboratory)*

Special Considerations for S2S on Mars

- Our information is primarily from remote sensing (visual and IR multispectral imaging, lidar topography, SAR radar, radar sounding) and a few landed missions
- Knowledge of the subsurface is very limited – near absence of tectonics limits sedimentary exposures
- On Mars wind erosion provides the best sedimentary exposures, but more often aeolian deposition obscures exposures
- An important consideration for the MSL landing site selection is the potential for hosting and preservation of microbial biosignatures.

THE TOPOGRAPHY OF MARS BY THE MARS ORBITER LASER ALTIMETER (MOLA)
NORTHERN LOWLANDS
Sinuous Valley Networks
Eberswalde Delta

S2S on Mars

- Many of the important terrestrial S2S environments have had Martian counterparts: fans, deltas, valleys, lakes, seas, meandering channels, dunes, glaciers

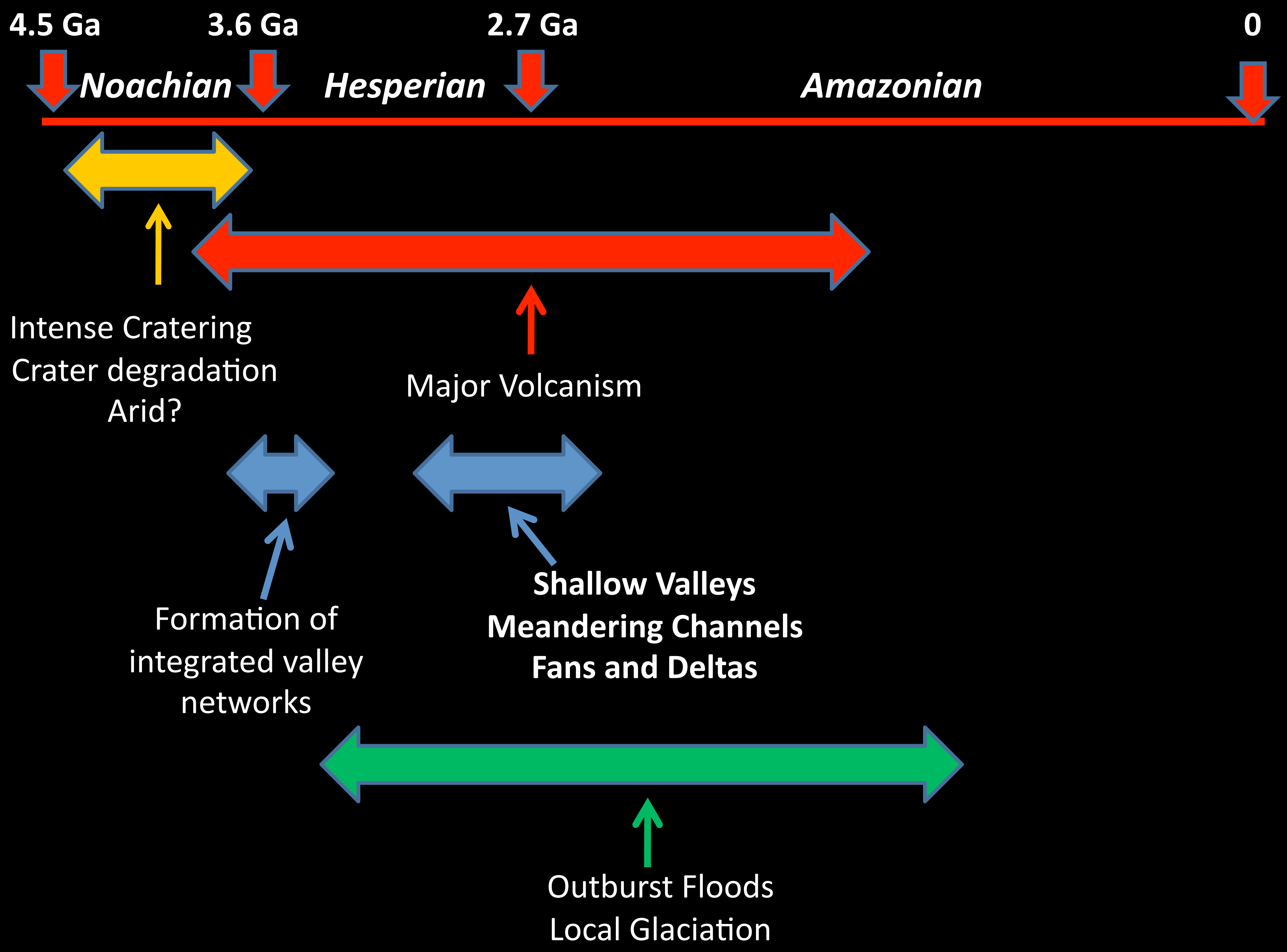
- The same main S2S issues pertain to Mars
  - *Sediment production*
  - *Transport and Deposition*
  - *Diagenesis*
  - *Exposure*

- But there are some differences in importance of processes and topographic setting

- Impact cratering was a dominant process:
  - It produced a km’s thick *megaregolith* of pulverized debris
  - The “swiss cheese” topography of the highlands generally meant short flowpaths from source to sink
- Physical weathering apparently dominated on uplands (lack of vegetation cover)
- Chemical weathering generally was limited to the subsurface in depositional basins, forming clays and other hydrated minerals
- Vast quantities of fine-grained sediment have been cycled and recycled by atmospheric deposition and erosion – volcanic ash, loess, impact ejecta.

Mars – Past and Present

- Mars is presently a desert planet with low atmospheric pressure, water limited to the poles, a cryosphere, and possibly brief, low-intensity transient water flows in gullies and from ice-rich deposits
- The features discussed here formed more than 2 Ga ago when there was a larger water inventory, a denser atmosphere , and an active hydrologic cycle
- Mars has had a rich volcanic history but little tectonic activity
- Most of the early erosional and depositional activity centered on the ancient cratered highlands of the southern hemisphere



4.5 Ga **3.6 Ga** **2.7 Ga** **0**

Noachian ***Hesperian*** ***Amazonian***

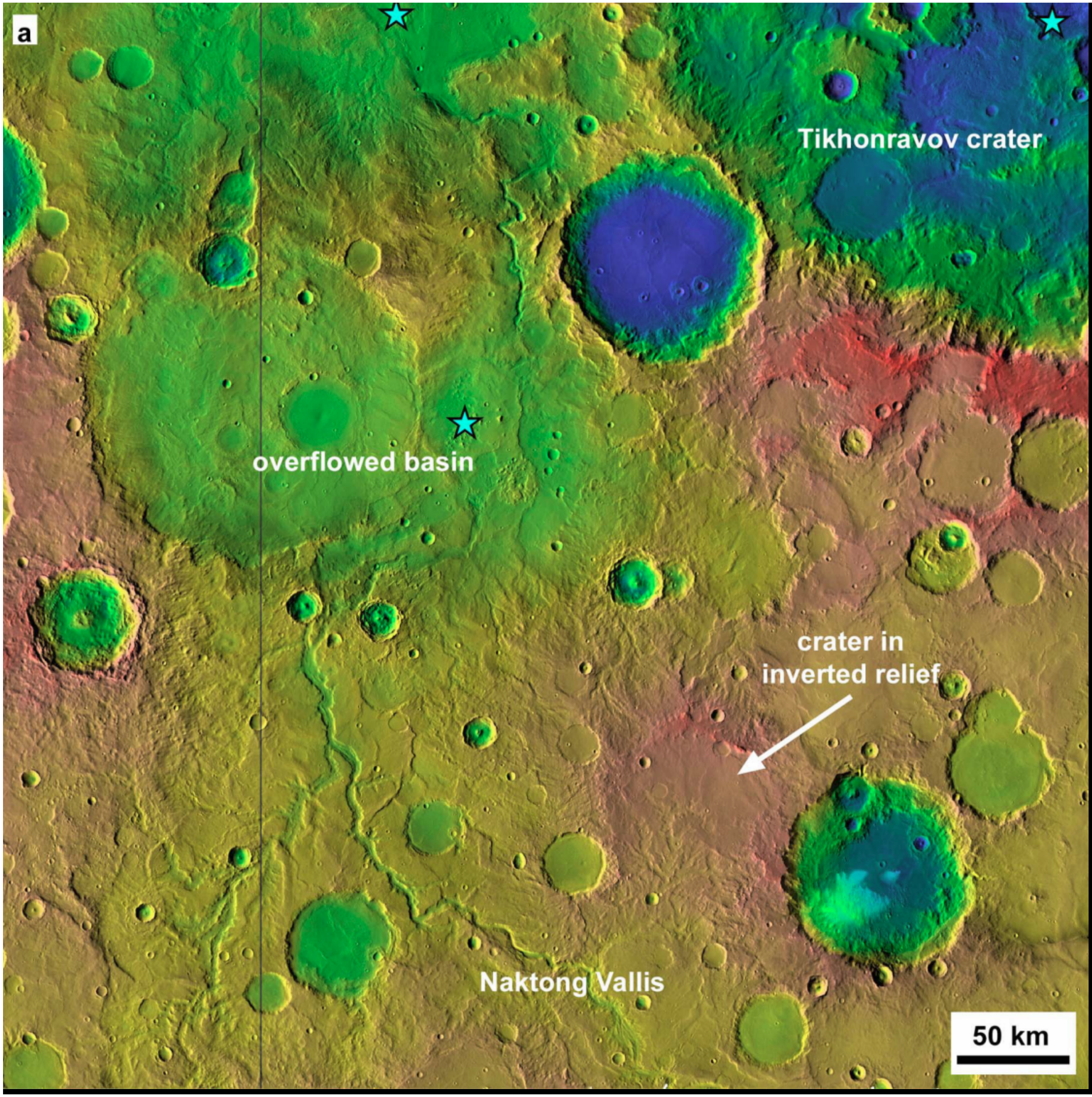
Intense Cratering
Crater degradation
Arid?

Major Volcanism

Formation of
integrated valley
networks

Shallow Valleys
Meandering Channels
Fans and Deltas

Outburst Floods
Local Glaciation



Irwin et al, *in press*

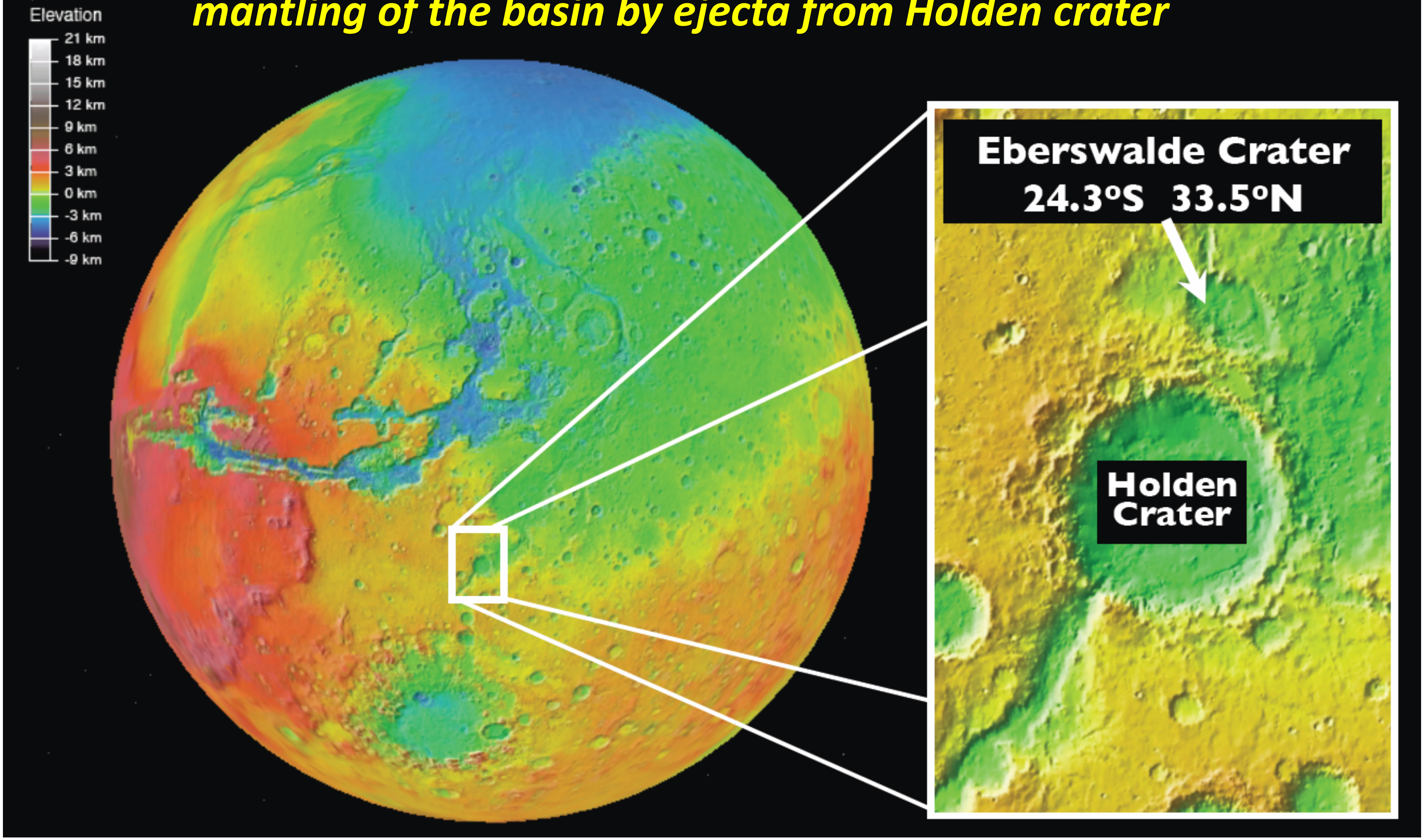
Martian S2S Examples:
1. The Eberswalde Delta

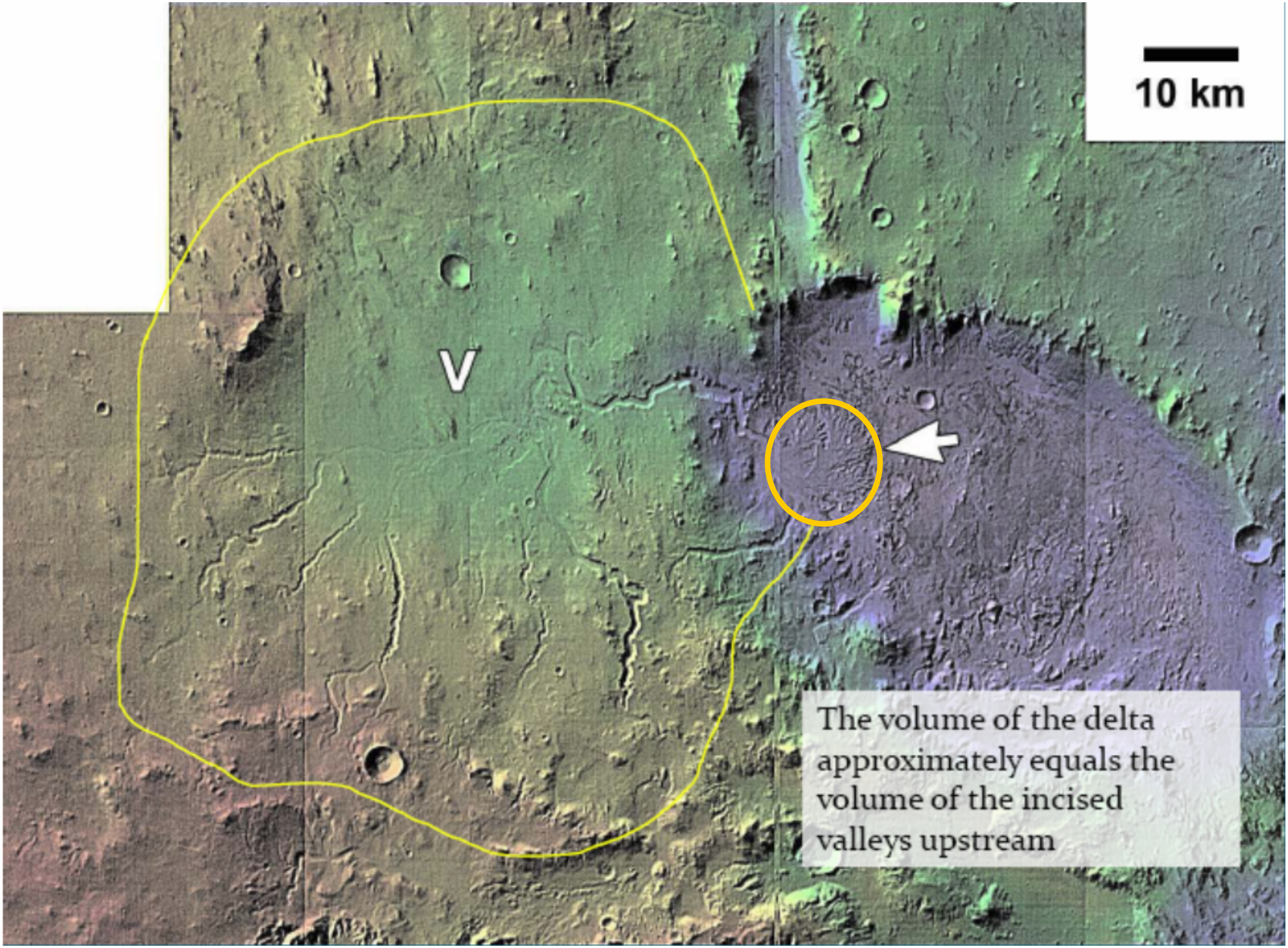
- In considering fluvio-lacustrine systems the ideal circumstance is being able to
  - *Define the drainage area*
  - *Identify and characterize the processes of sediment production, transport and deposition*
  - *Characterize the deposited sediments by grain size, stratigraphy, and geochemistry*
  - *Use the above to define the controlling geologic, geomorphic, and climatologic environment*

- The Eberswalde Delta comes closest to providing such context, but significant differences in interpretation remain. It is one of the candidate MSL sites. It is the best exposed of a number of Martian deltas

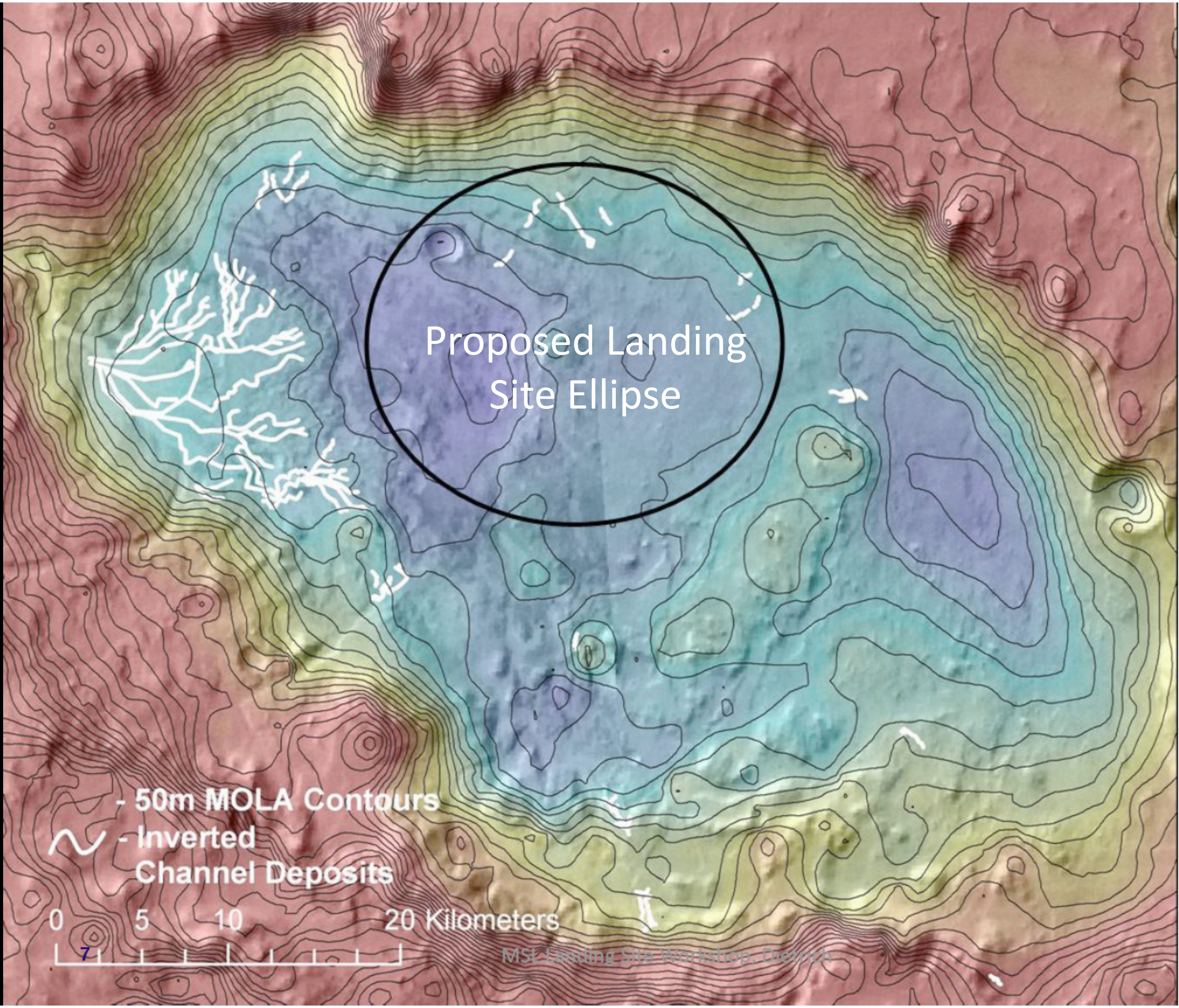
Eberswalde Crater Location

The delta is in a degraded crater and post-dates the mantling of the basin by ejecta from Holden crater





The volume of the delta approximately equals the volume of the incised valleys upstream


Proposed Landing Site Ellipse
- 50m MOLA Contours
- Inverted Channel Deposits
0
5
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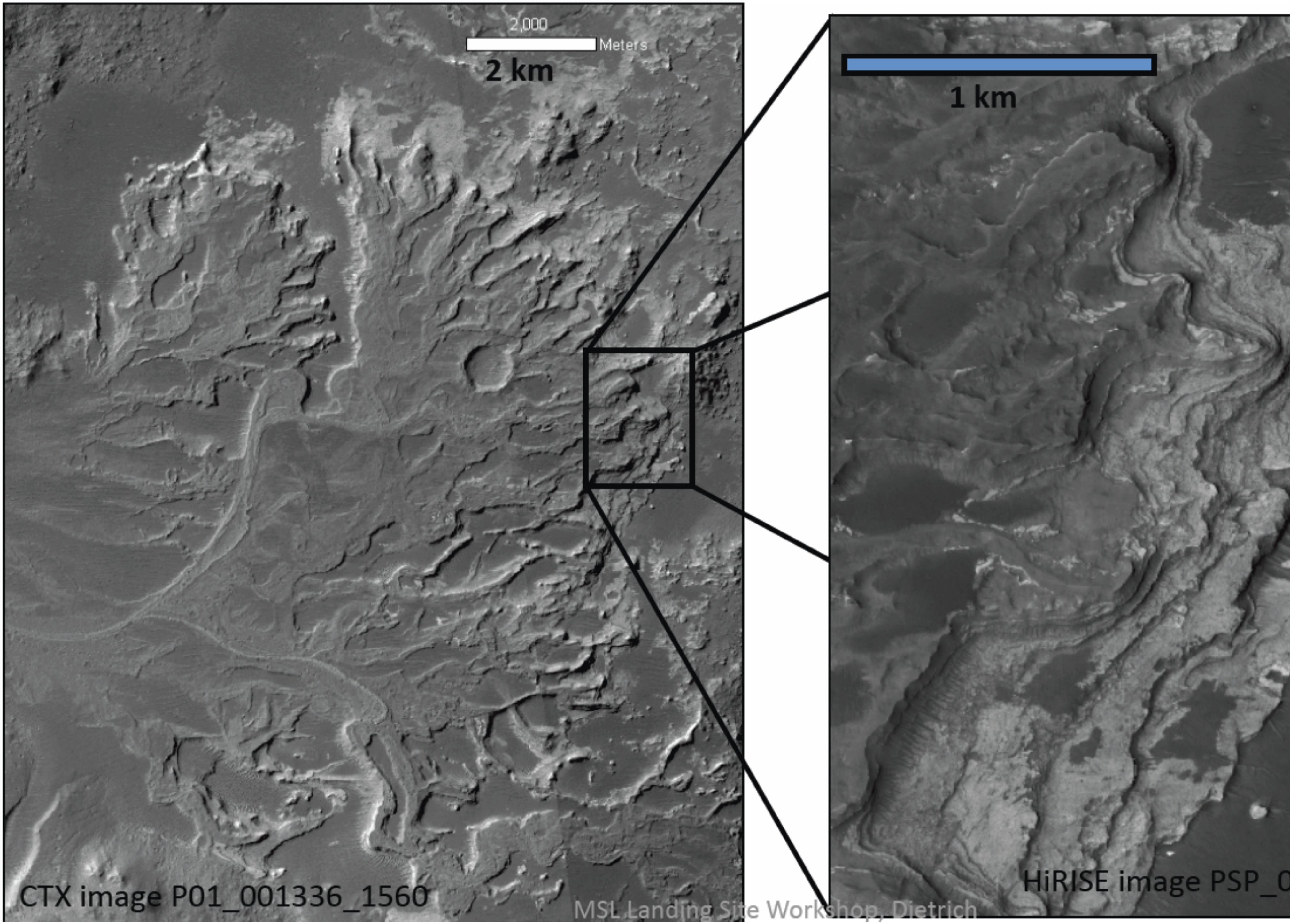
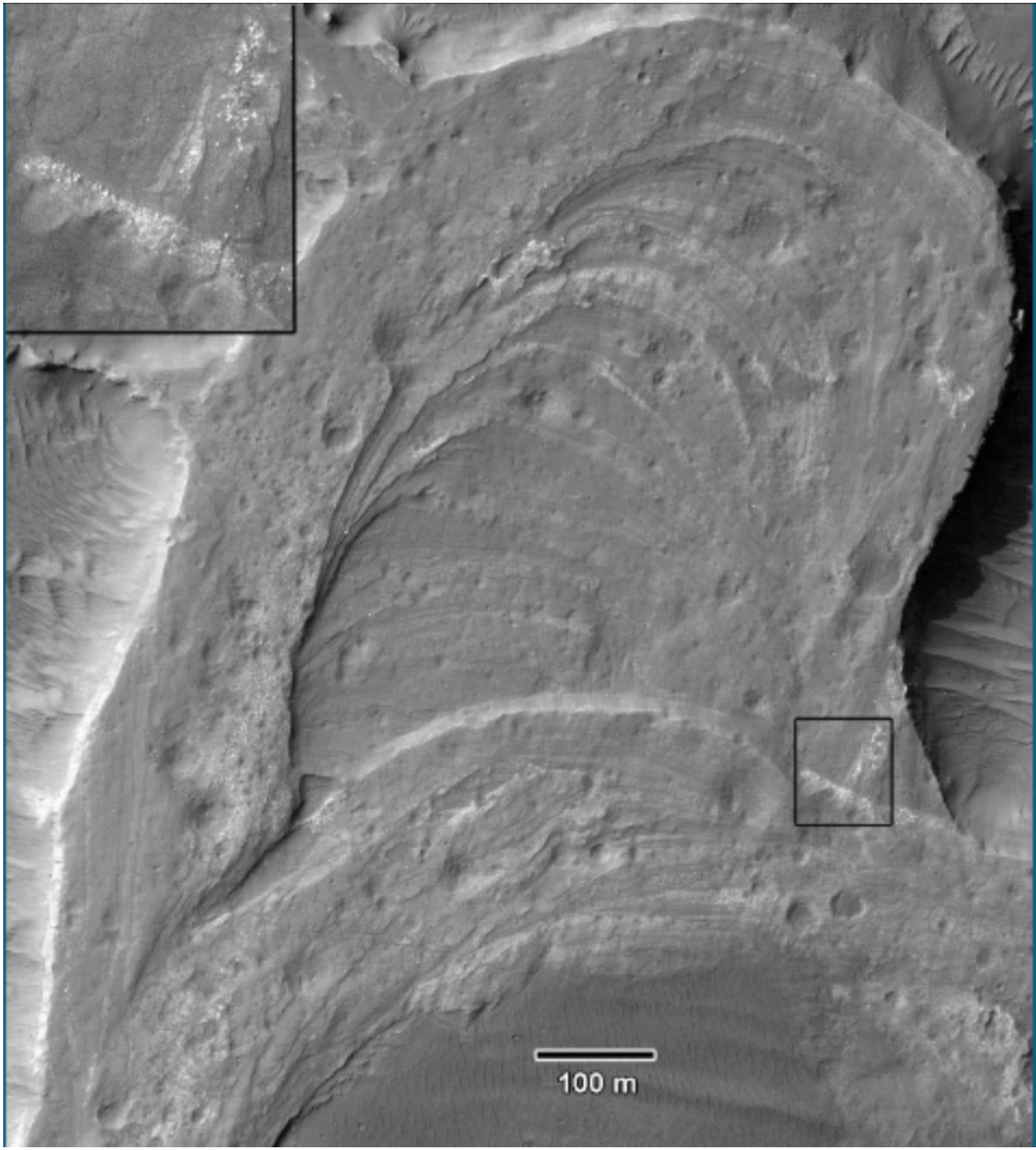
20 Kilometers



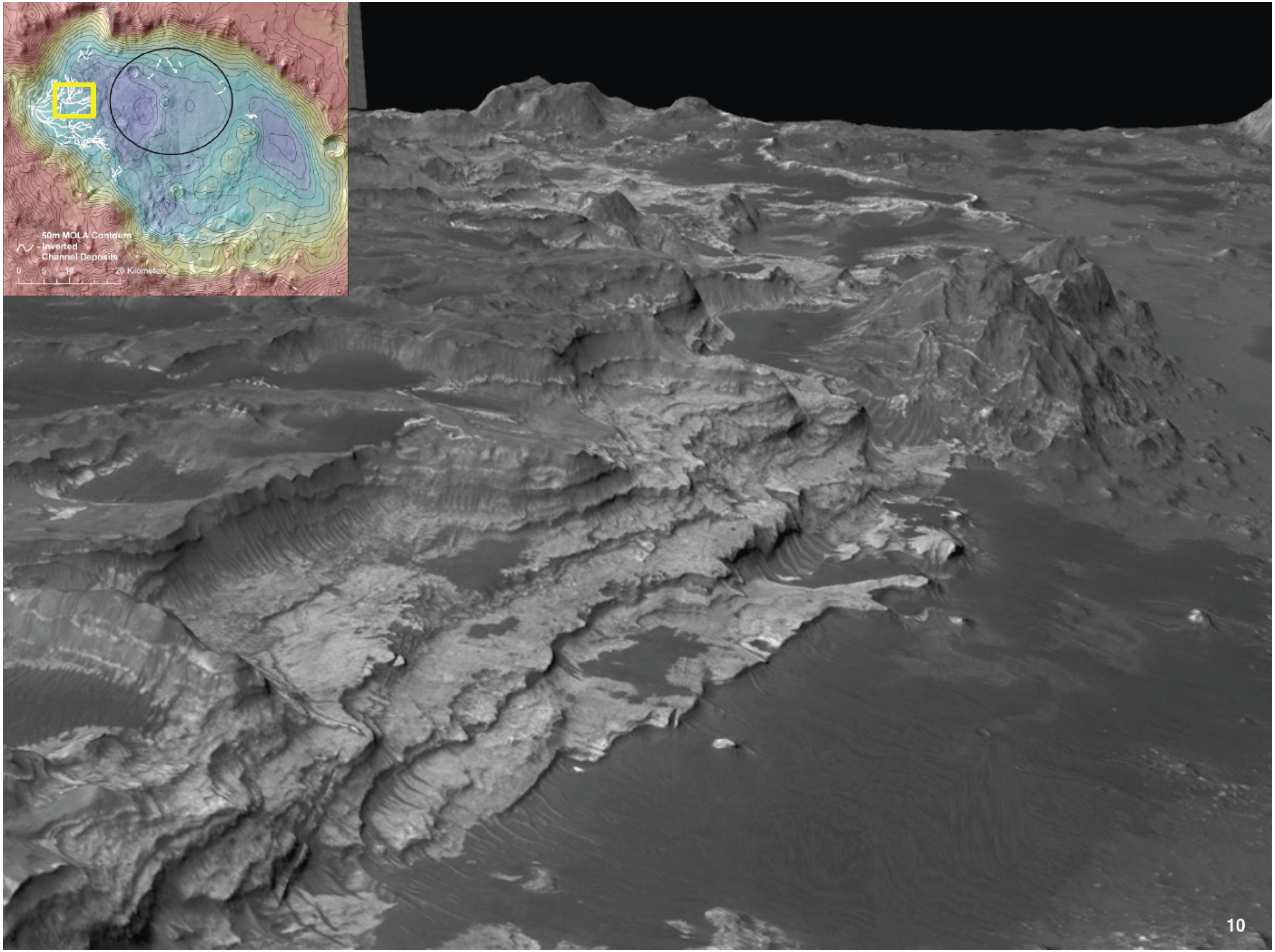
MSL Landing Site Workshop, Dietrich

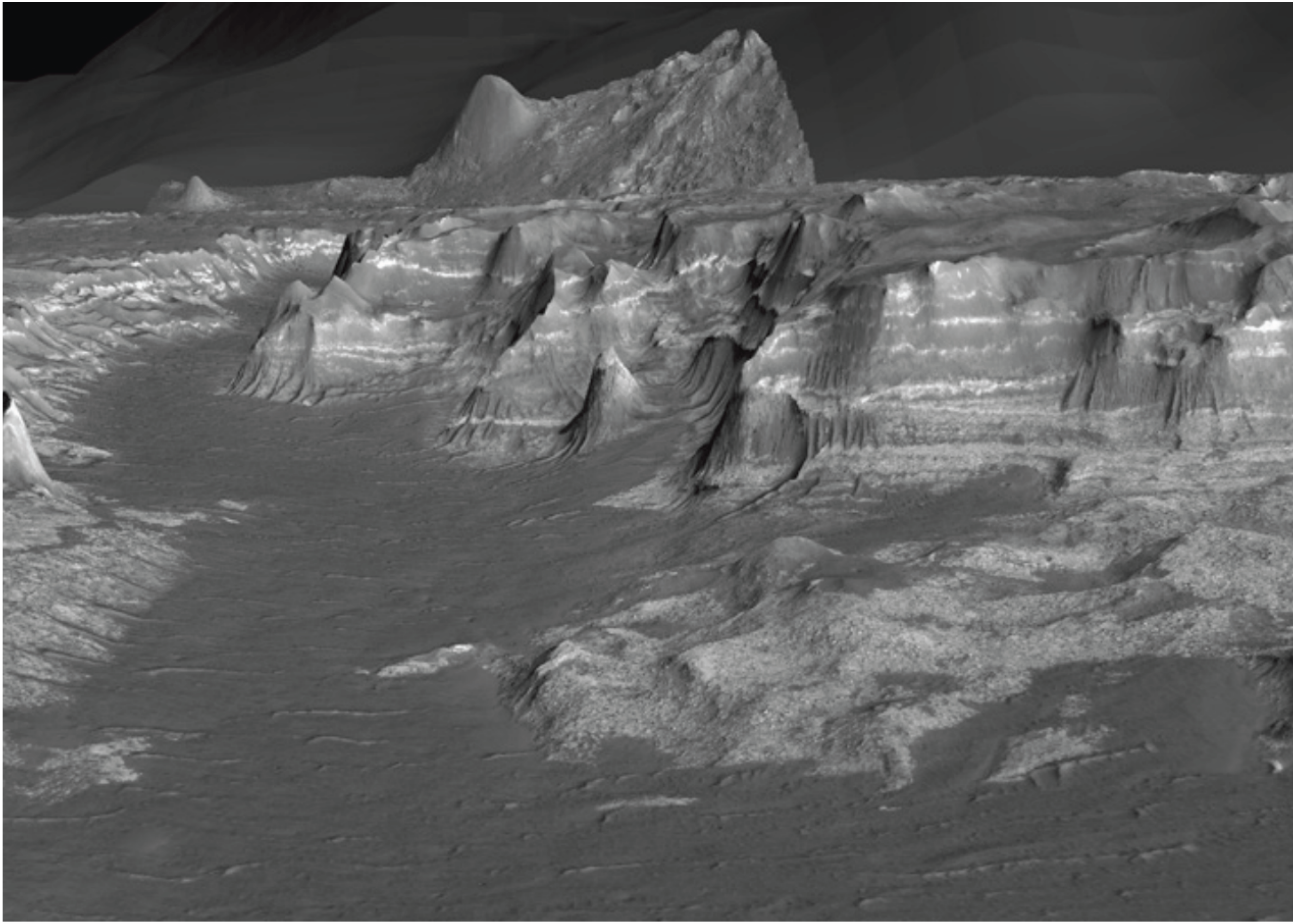


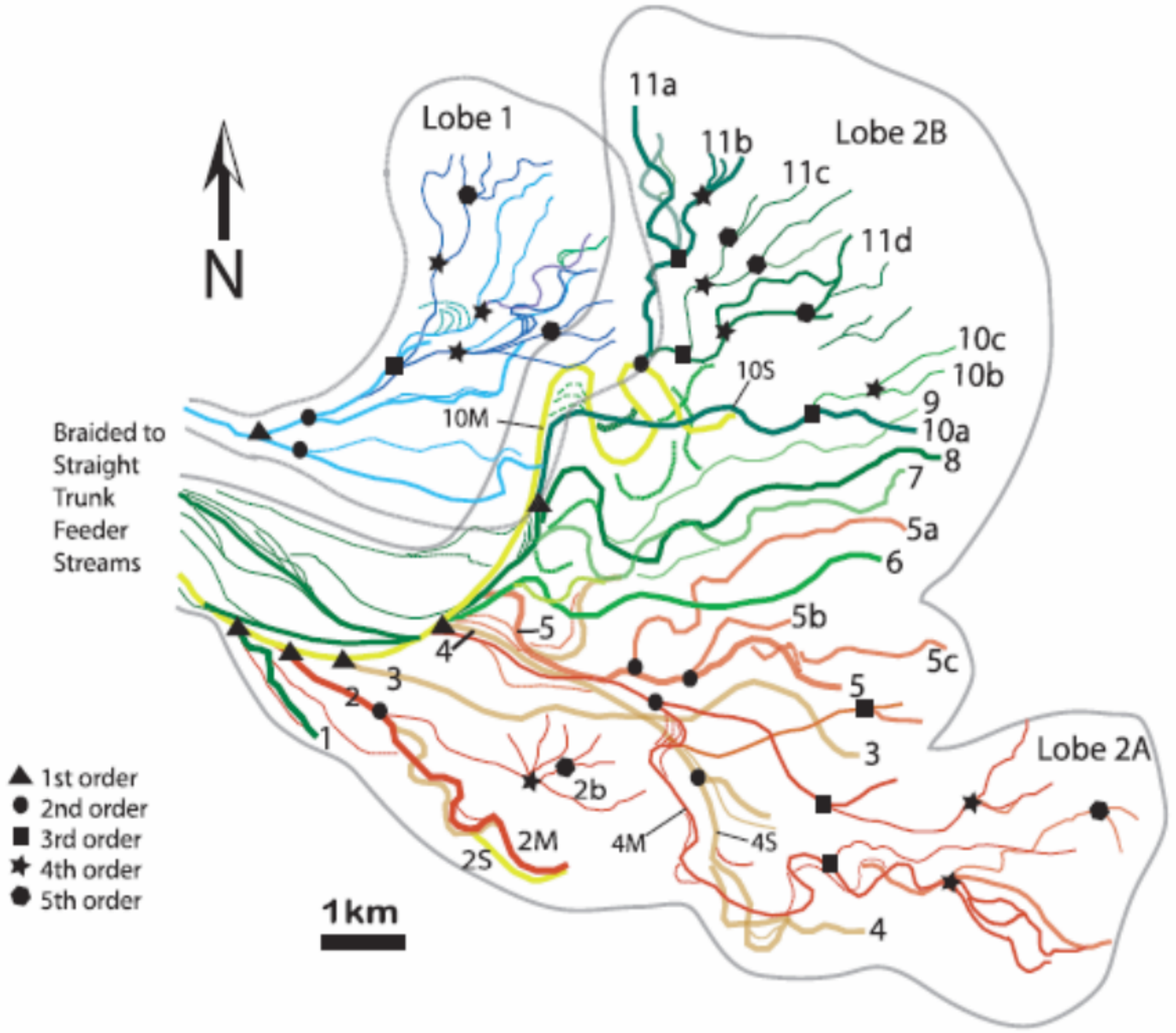
A HiRISE image of a meander loop that enlarged while aggrading, followed by cutoff of the loop.

The parallel scars are not point bars, but successive channel beds exposed by eolian erosion of finer point bar and overbank sediments.

The inset shows meter-scale boulders transported across the delta.


- 50m MOLA Contours
- Inverted Channel Deposits
0 5 10 20 Kilometers





The delta is compose of several distinct lobes.

Bhattacharya et al. 2005

Flow Magnitude

- Discharge estimates for Eberswalde main channel based on channel dimensions, meander wavelength, and fan models scaled to Martian gravity. “Bankfull” discharge (m^3/s):
  - 700 (300-1600) Moore et al. 2003
  - 410 (240-950) Jerolmack et al. 2004
  - 550 Irwin et al. 2005

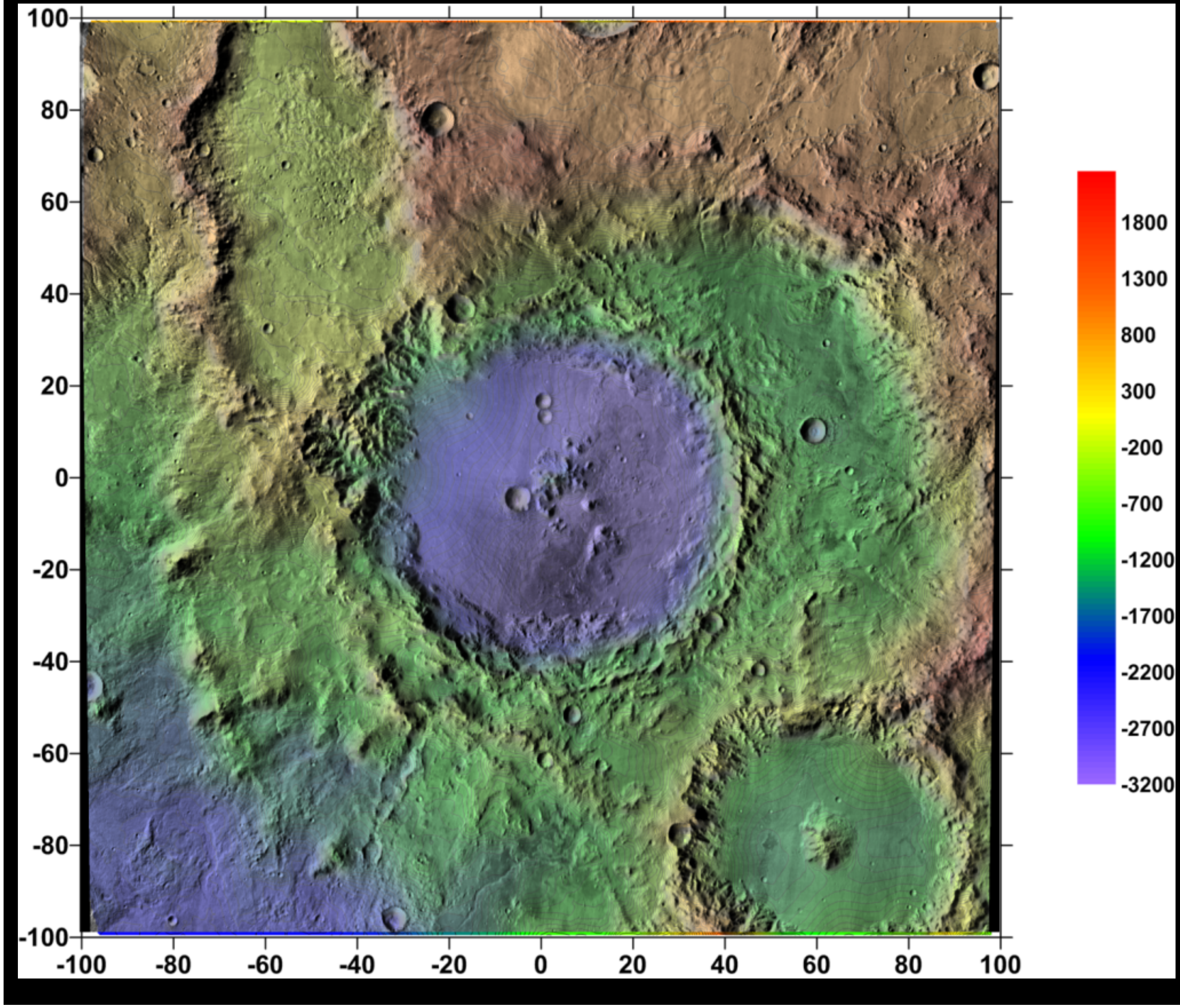
Uncertainties and Ongoing Debates

- Were flows due to 1) precipitation (snow or rain) and runoff or 2) due to melting of surface or subsurface ice and snow by Holden Crater ejecta?

- If flows due to precipitation, was it a short-duration but continuous flow (perhaps due to effects of a large impact somewhere on Mars) or a more terrestrial climate of episodic flows?

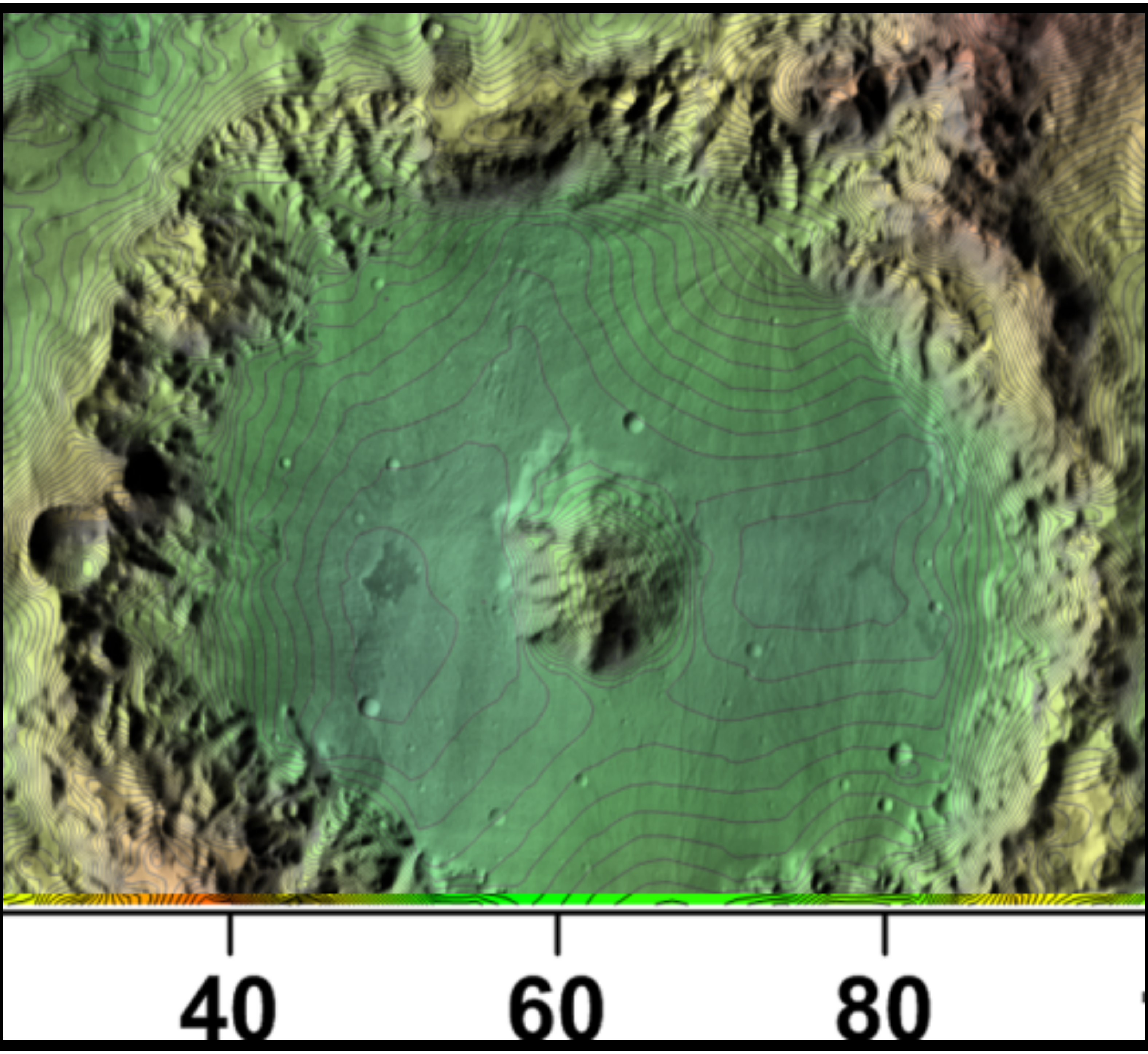
- Because of the relative youth of the delta (Hesperian) would it have afforded a suitable environment for support and preservation of biosignatures?

2. Alluvial Fans on Mars



Two craters hosting large alluvial fans (Saheki and a smaller crater to the southeast.

These large alluvial fans are limited to late-Noachian to early Hesperian craters larger than 40 km diameter and the sediment is derived from deeply dissected interior crater rims.


40
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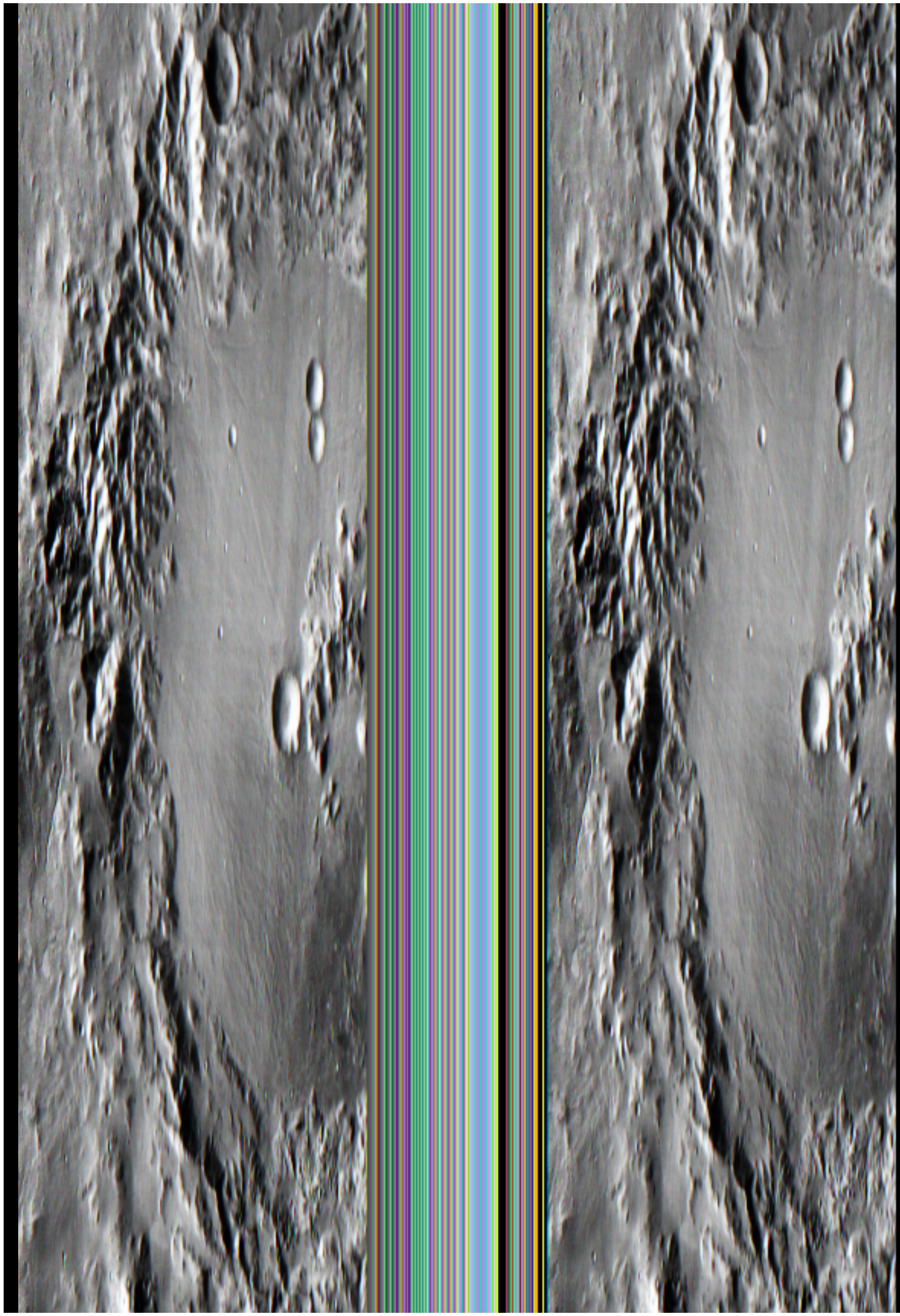
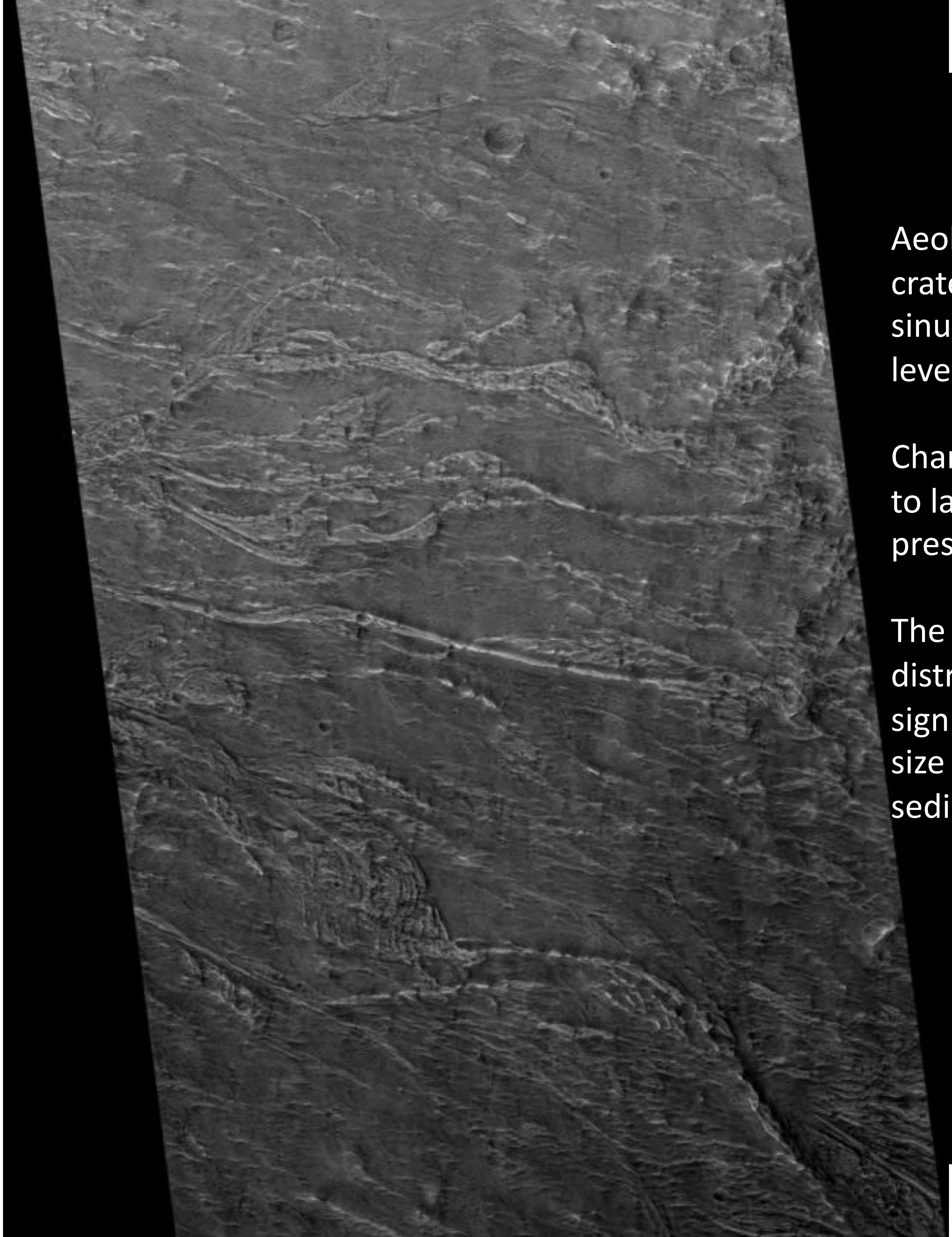


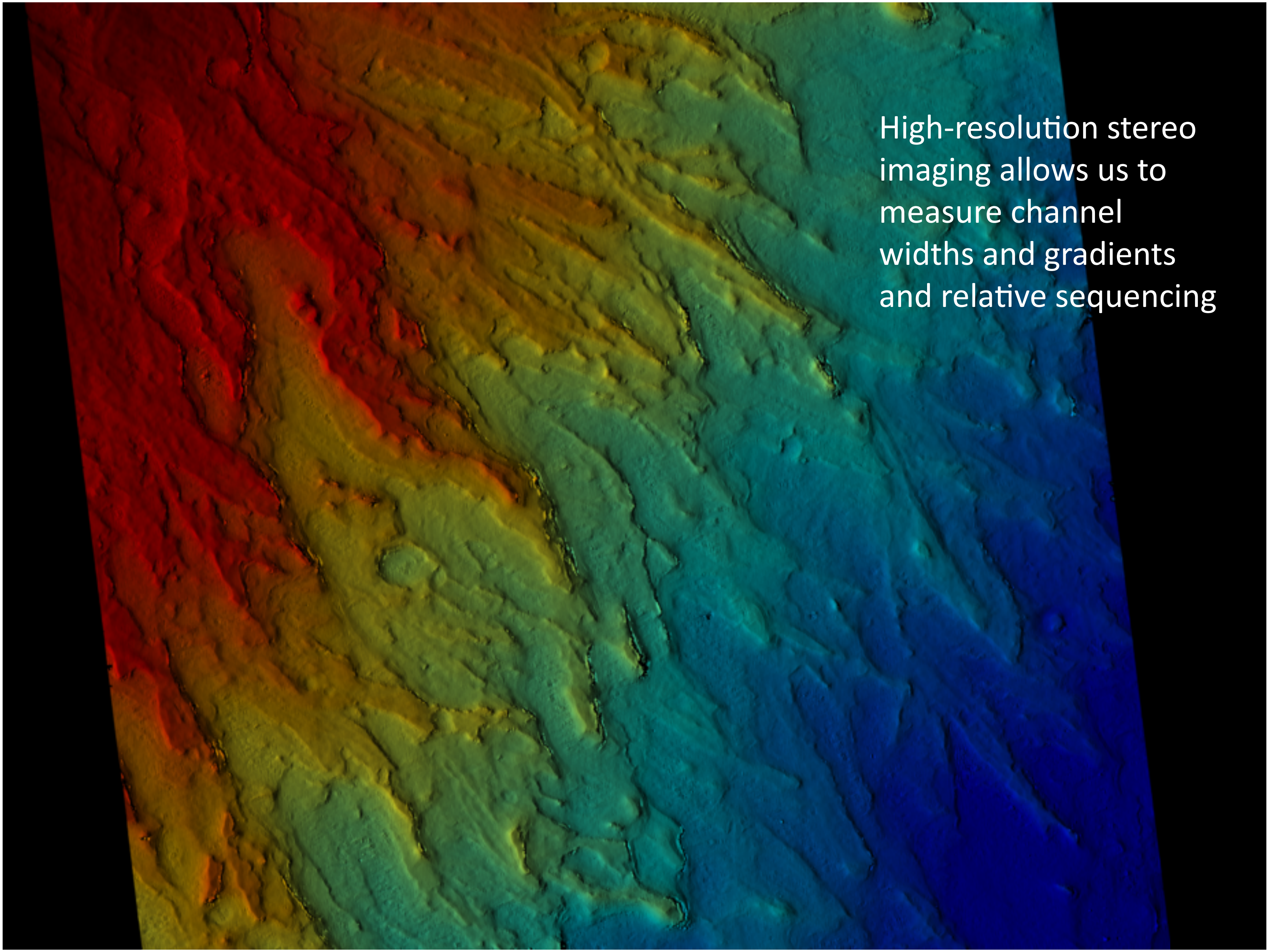
The Saheki Crater fans.



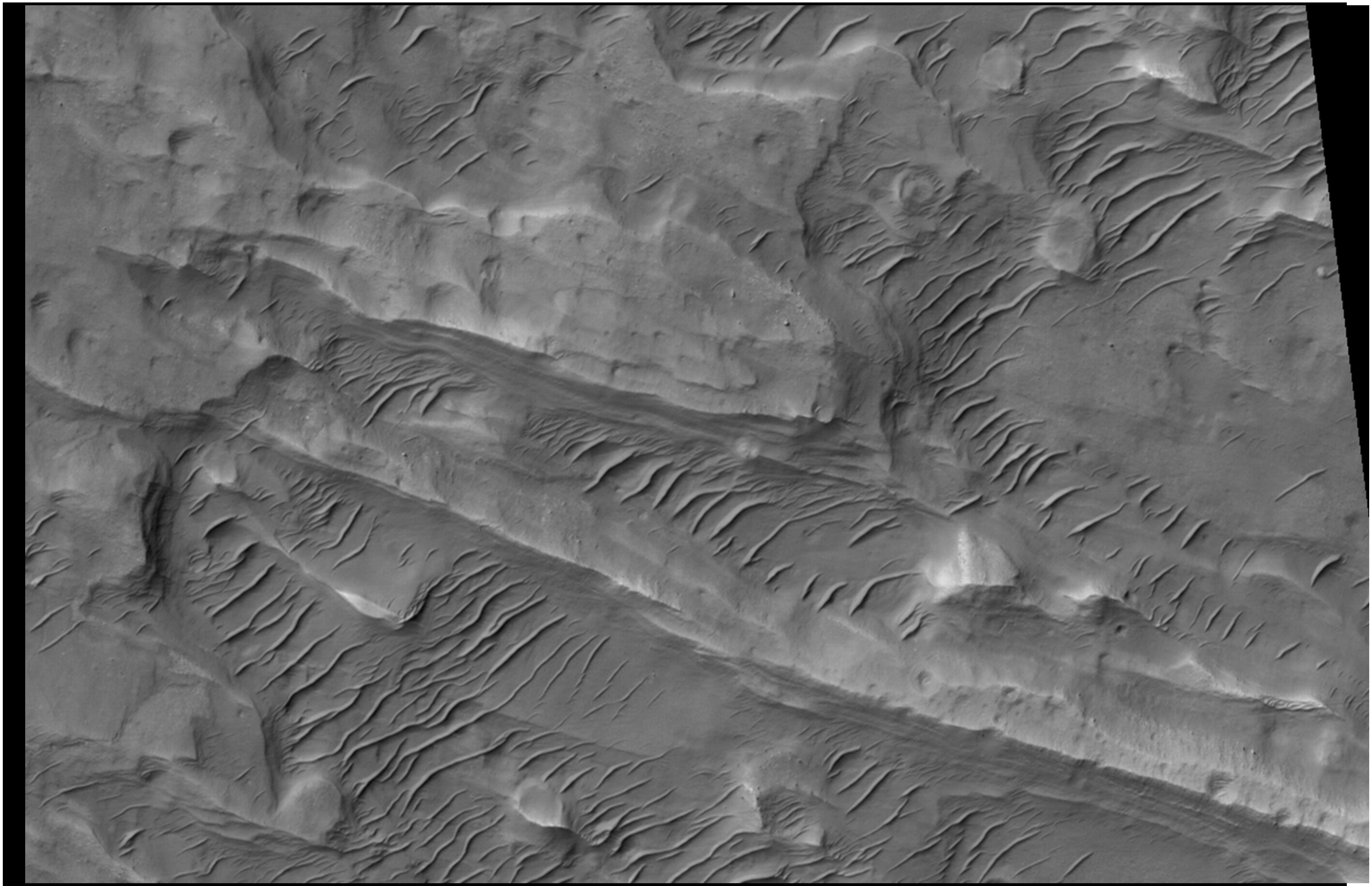
Aeolian erosion of the Saheki crater fans reveals long, modestly sinuous distributaries at multiple levels.

Channels are in positive relief due to large grain size plus, presumably, some cementation.

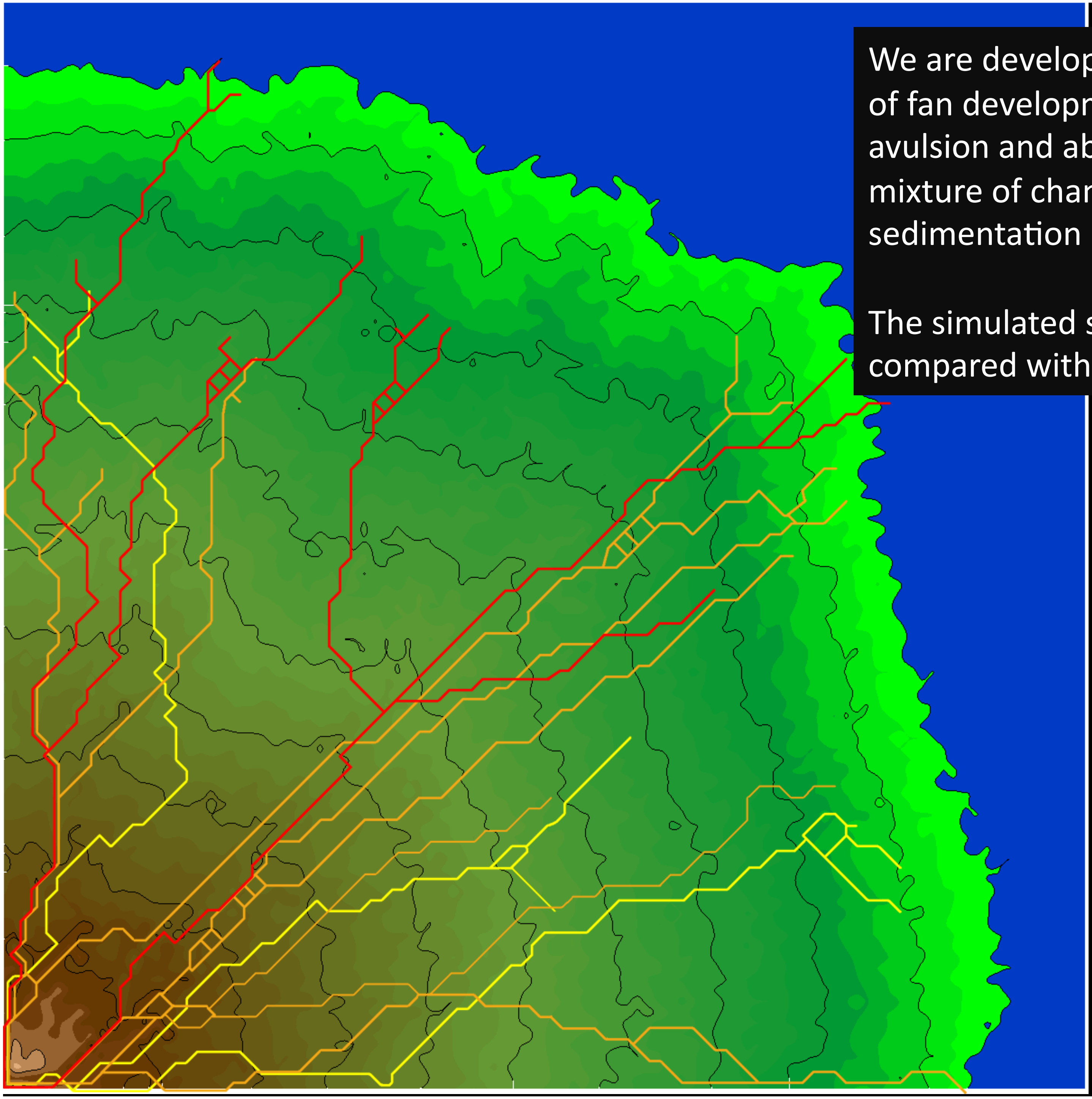
The wind-stripping between distributaries suggests a significant component of sand-size or smaller overbank sedimentation



High-resolution stereo imaging allows us to measure channel widths and gradients and relative sequencing



HiRISE imaging reveals a few meter-scale boulders and weak layering in distributaries



We are developing a simulation model of fan development incorporating avulsion and abandonment and a mixture of channel and overbank sedimentation

The simulated stratigraphy will be compared with the Martian fans

Questions about Mars Fans

- Why do they occur only on large, relatively young (Hesperian) craters? -- Need relief and steep slopes to encourage erosion?

- Why is erosion limited to localized alcoves?
  - Microclimate control?
  - Particularly erodible wallrock?

- Why do we not see examples of such fans in older (Noachian) craters?

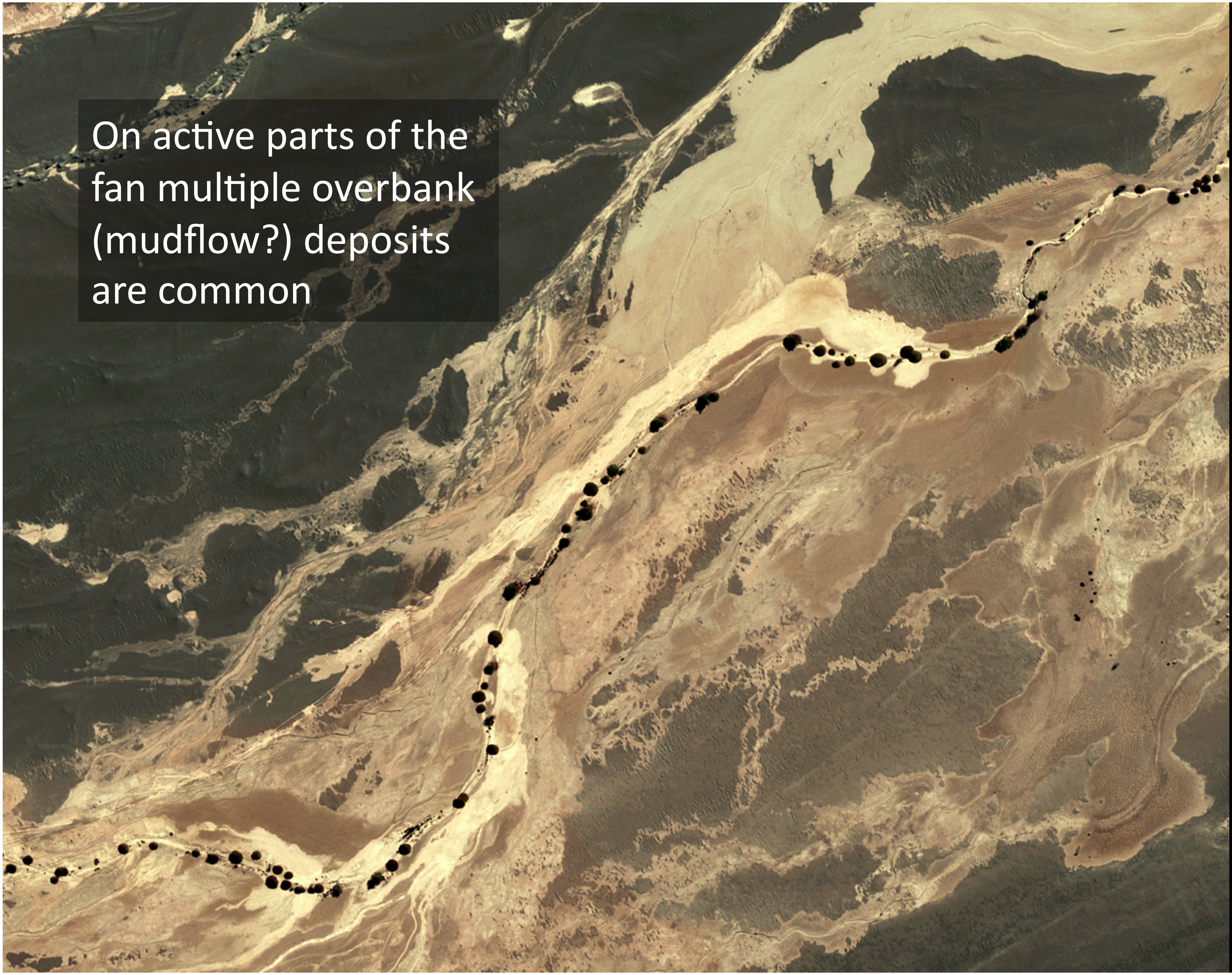
- What is the source of the fine sediment in the fans?

- Formed by normal stream flow, mudflows, or a combination?

A possible terrestrial partial analog in the Atacama Desert of Chile

Inactive parts of the fan develop inverted relief of distributaries due to wind erosion

Channel gravels are dark, overbank deposits are lighter



On active parts of the fan multiple overbank (mudflow?) deposits are common

Relief on inverted channels is modest: 1-2 m

Gravel is loose on surface, with subsurface hardpan.

Evidence of post-depositional weathering

Aeolian deflation of inter-channel fine sediment creates yardangs

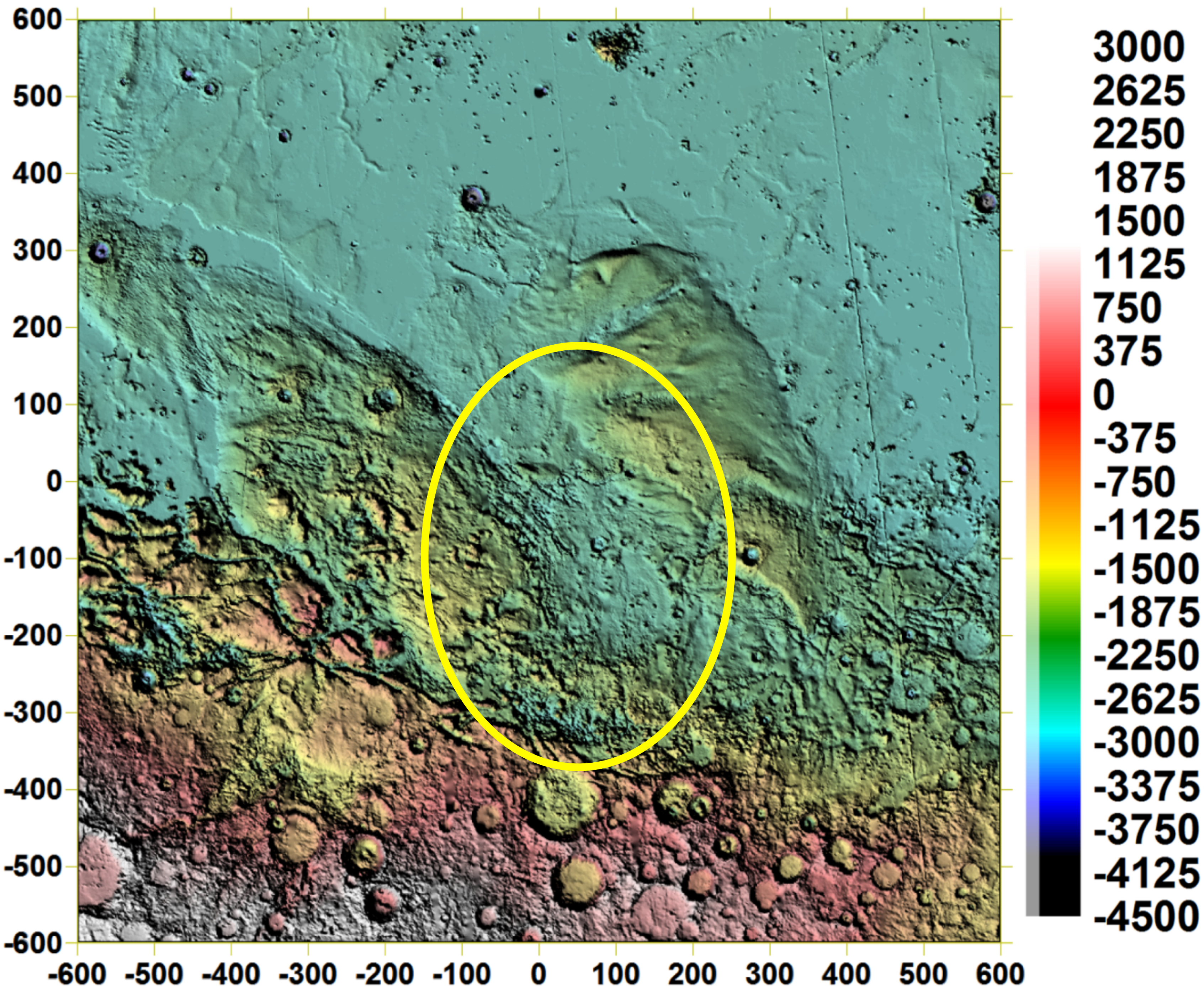
3. Highly Sinuous Channel and Floodplain System

- These are dendritic valley systems with highly sinuous channels

- They are developed in fine-grained airfall deposits (loess? volcanic ash?)

- They were buried to some degree after formation and later exposed by aeolian erosion

- They required distributed precipitation and runoff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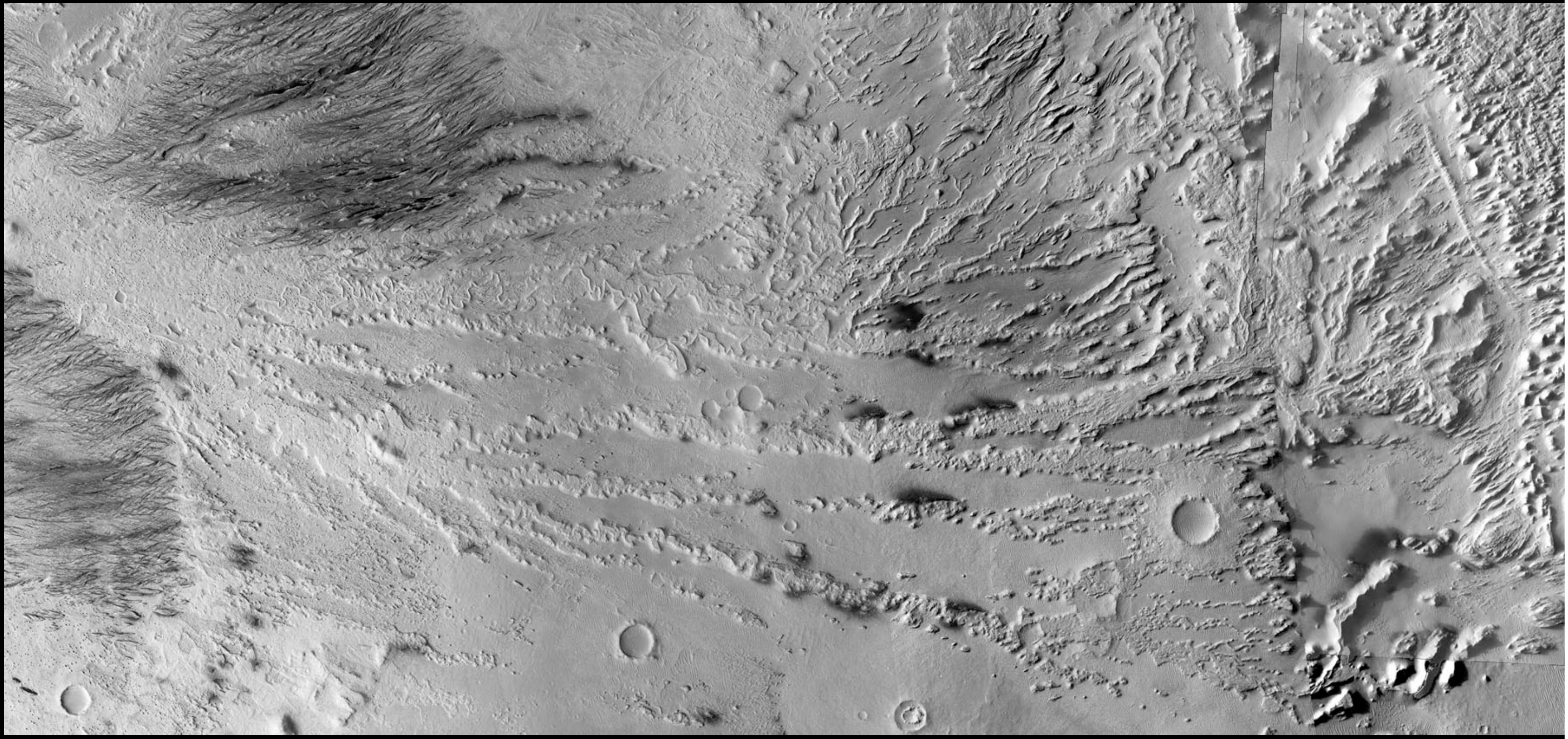
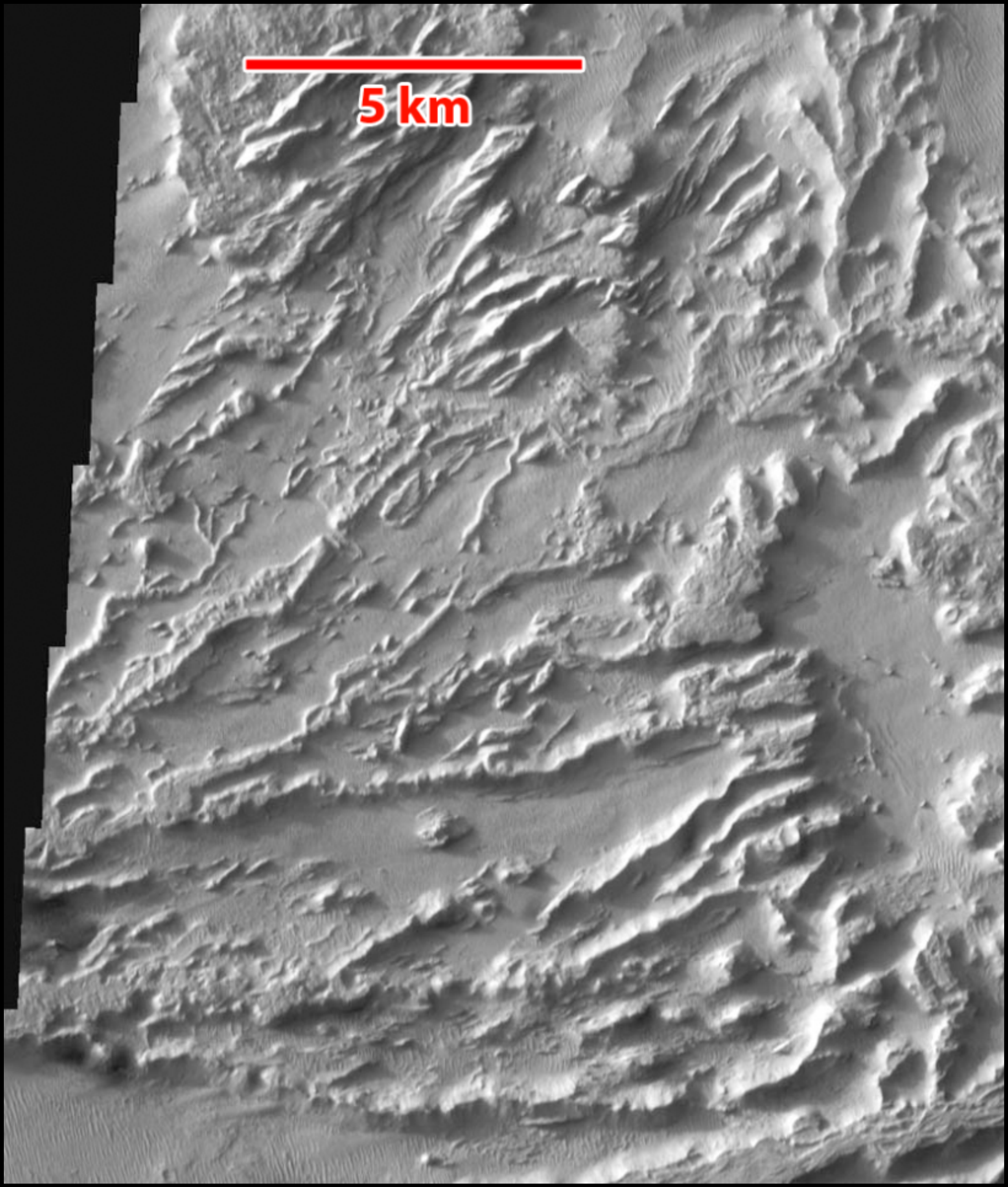
600
3000
2625
2250
1875
1500
1125
750
375
0
-375
-750
-1125
-1500
-1875
-2250
-2625
-3000
-3375
-3750
-4125
-4500

These are inverted floodplains and channels in the Medusa Fossae Formation. They comprise a dendritic network here flowing and converging to the left



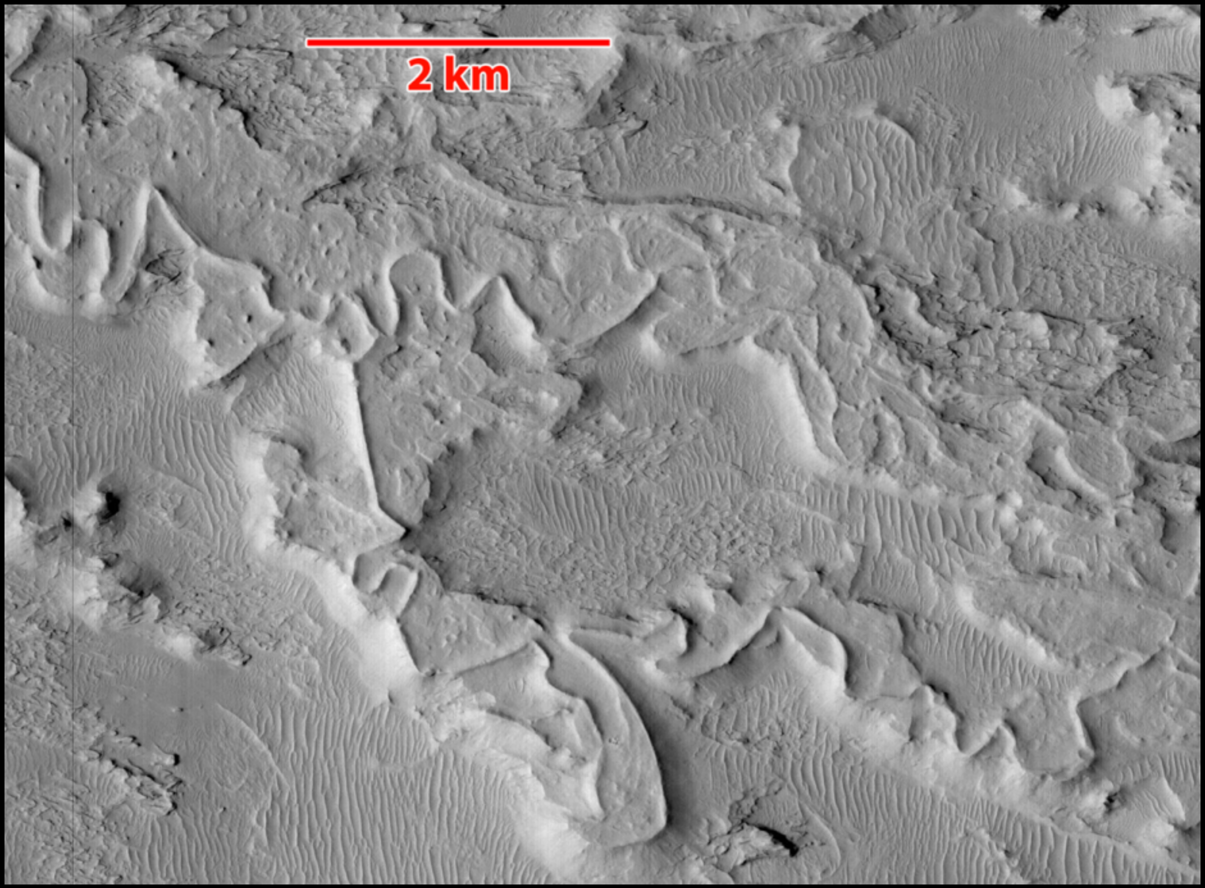


These ridges are remnants of a dendritic drainage system now etched into positive relief by wind erosion.

The channels and floodplains have resisted erosion presumably because of being coarser sediment or having been cemented.

The channel system formed by spatially distributed runoff (over a considerably larger area than shown here).

They are enigmatic because they formed fairly late in Martian history, well after widespread rainfall and runoff ceased. This is based on the apparent Hesperian to Amazonian age of the hosting deposits.



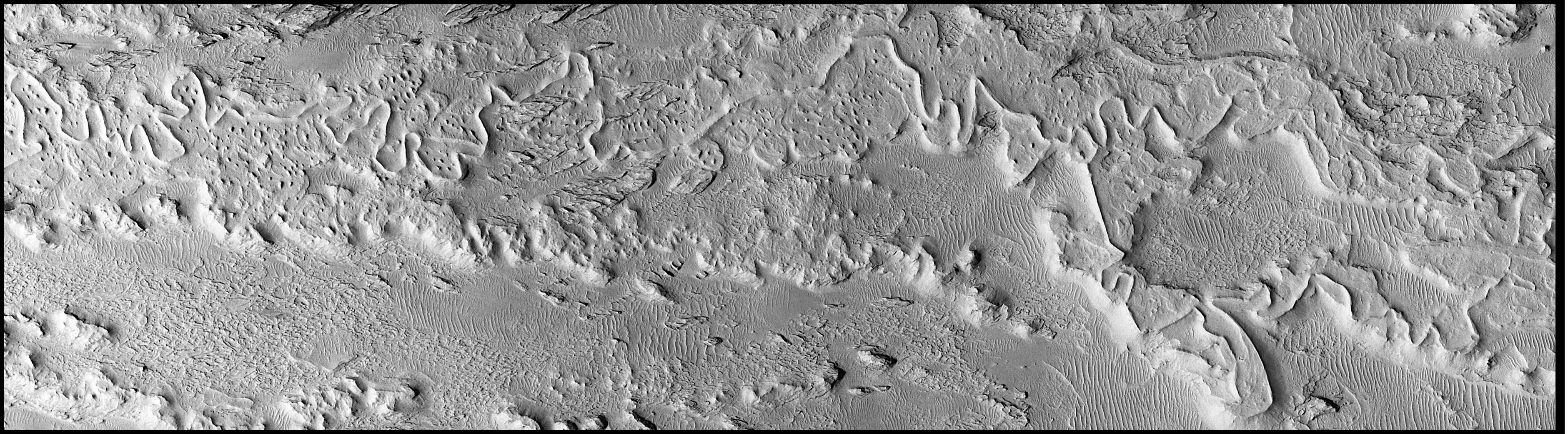
A closer look at some of the raised features reveals highly sinuous channel remnants in inverted relief.

The surrounding flat-topped ridges exhibit scroll bars and cutoff loops.

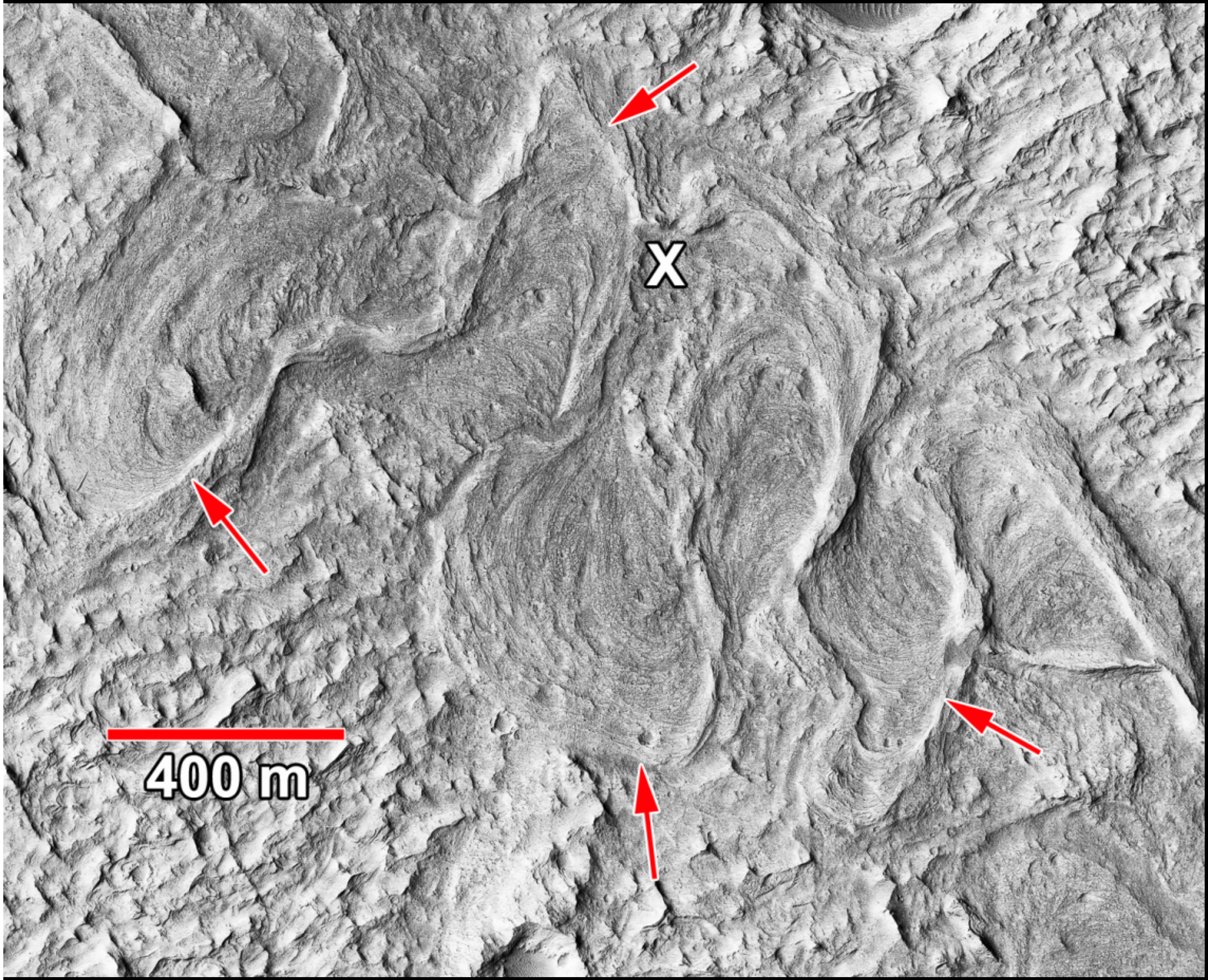
This implies the channels formed by sustained or repeated discharges that allowed extensive channel migration.

Highly sinuous meanders require channels with low width to depth ratio to discourage braiding. This is difficult to achieve unless banks are cohesive or vegetated.

The “bedrock” is silty, friable loess or volcanic ash



The “bedrock” is fine-grained (silty) deposits – either loess or volcanic ash that is easily stripped by the wind leaving the slightly more indurated or coarser grained channel and floodplains in positive relief.

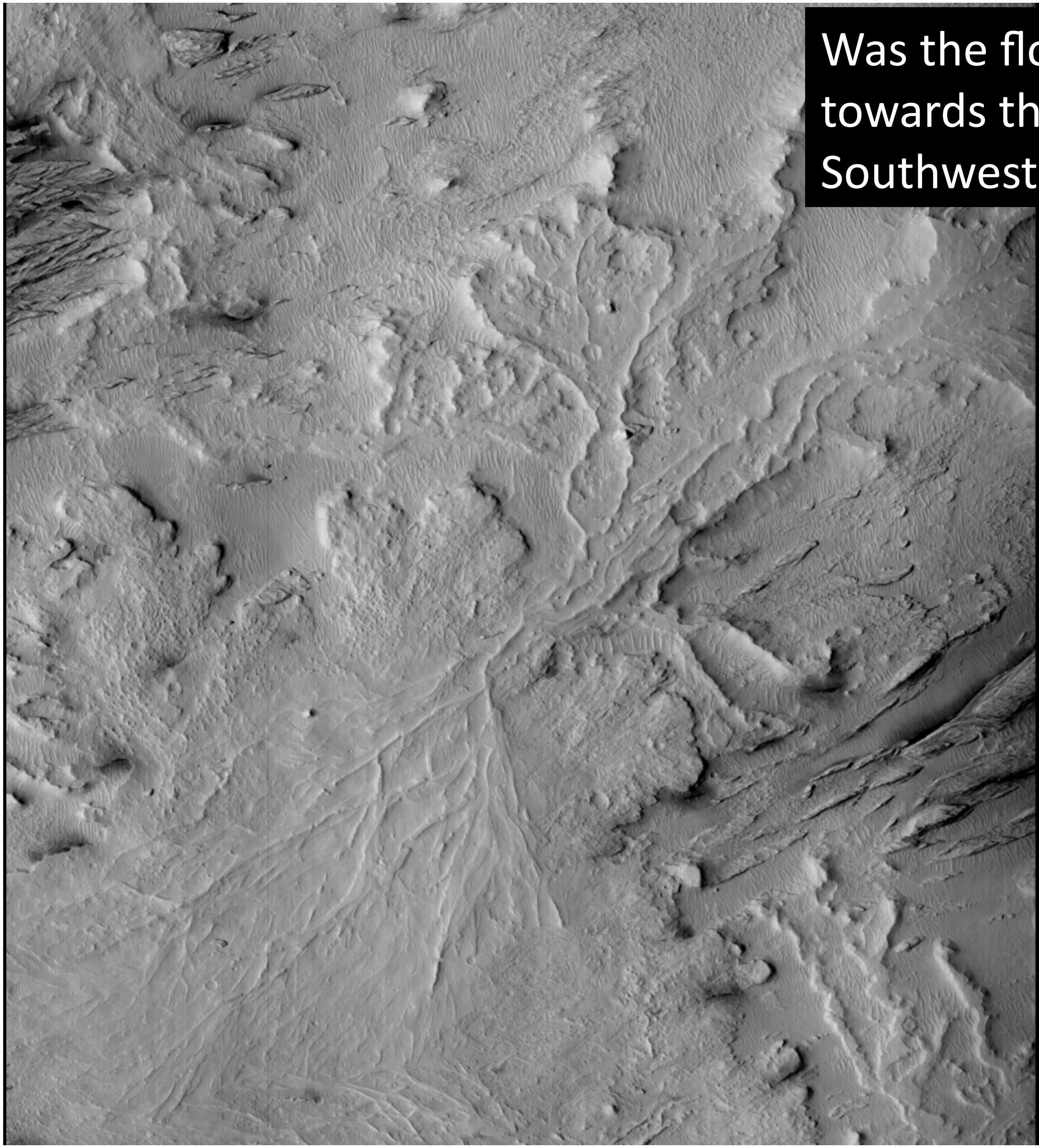


This is an image by the HiRISE orbital camera.

Wind scour has inverted channels and scoured surrounding terrain.

Meanders have enlarged with probable cutoff near the end of active flow above “X” abandoning loop below “X”

Parallel lines interior to bends are probably channel bed deposits, not point bars



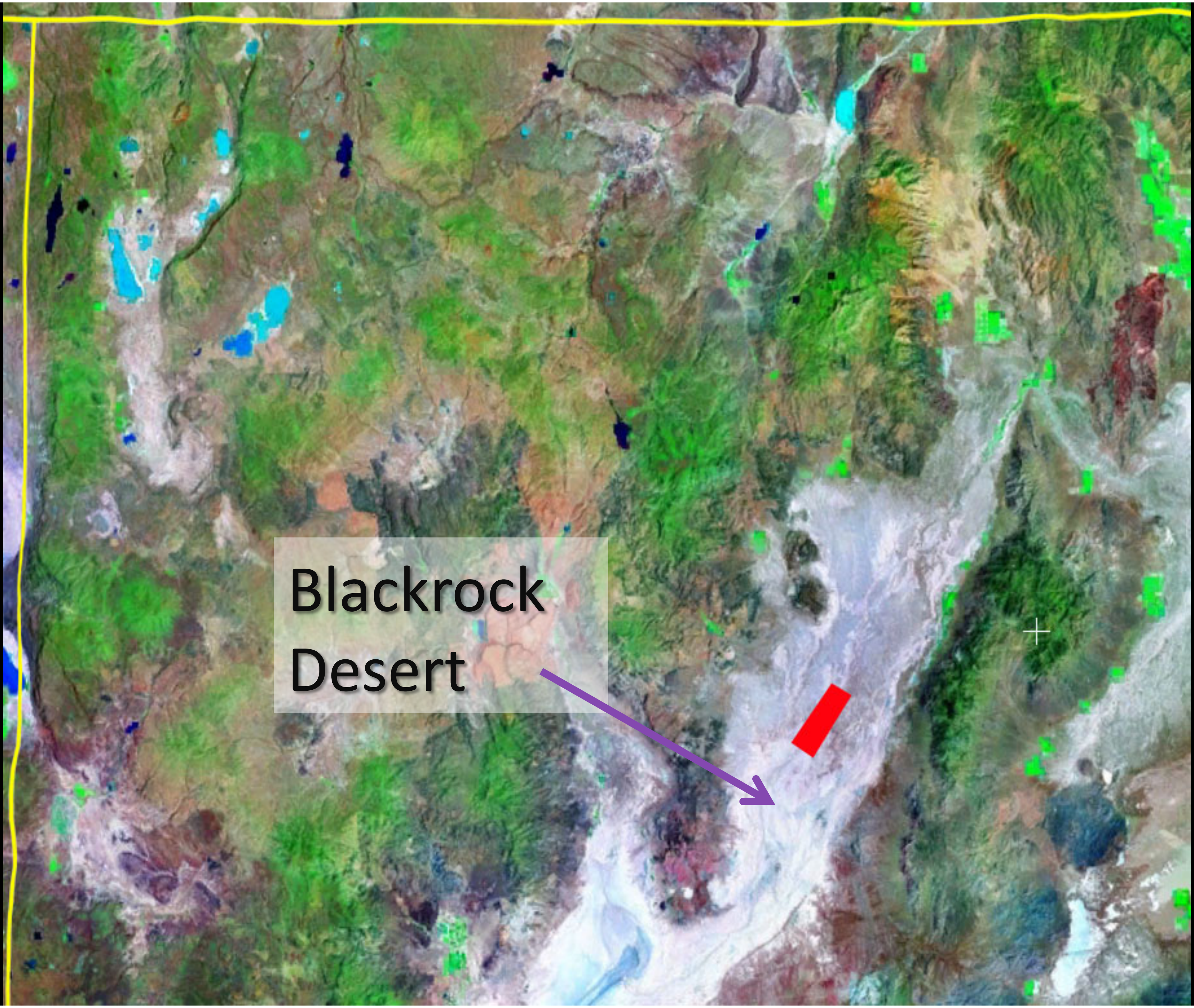
Was the flow in this system towards the Northeast or the Southwest?

Unresolved Issues

- Origin of the “bedrock” – volcanic or aeolian?
- Was the precipitation due to a local event (e.g., nearby volcanic eruption) or a global climate optimum?
- Probable post-depositional differential consolidation confuses interpretation of flow directions
- In S2S context source uplands are eroded, location of depositional basins uncertain, and only part of fluvial network remains

A Possible Terrestrial Analog in Nevada

- Because vegetation was probably not present during formation of the Martian sinuous channels, some mechanism for providing bank cohesion was necessary
- Some possible cohesion mechanisms include
  - High mud content
  - Chemical Cementation
  - Ice
- Cohesion needs to develop at same timescale as meandering
- We have been looking for terrestrial sites where vegetation does not provide bank cohesion for sinuous channels


Blackrock
Desert

The main stream, the Quinn River, flows from top right to center bottom with a smaller tributary entering from the top.

Note the scroll bars and past cutoffs.

The channels are incised into Pleistocene Lake Lahontan lacustrine sediment.

This is the cut bank and point bar at an actively-eroding bend. The white coloration is surficial salt accumulation, not snow. Water in the channel is frozen.

The channel is remarkably even in cross section, with steep banks in straight sections and a mud bed.

Valley gradient is about 0.0003, and channel gradient 0.00015.

The vegetation appears to be too sparse to appreciably affect either bank erosion or sediment deposition.

Both inner and outer banks are commonly covered with mud drapes.

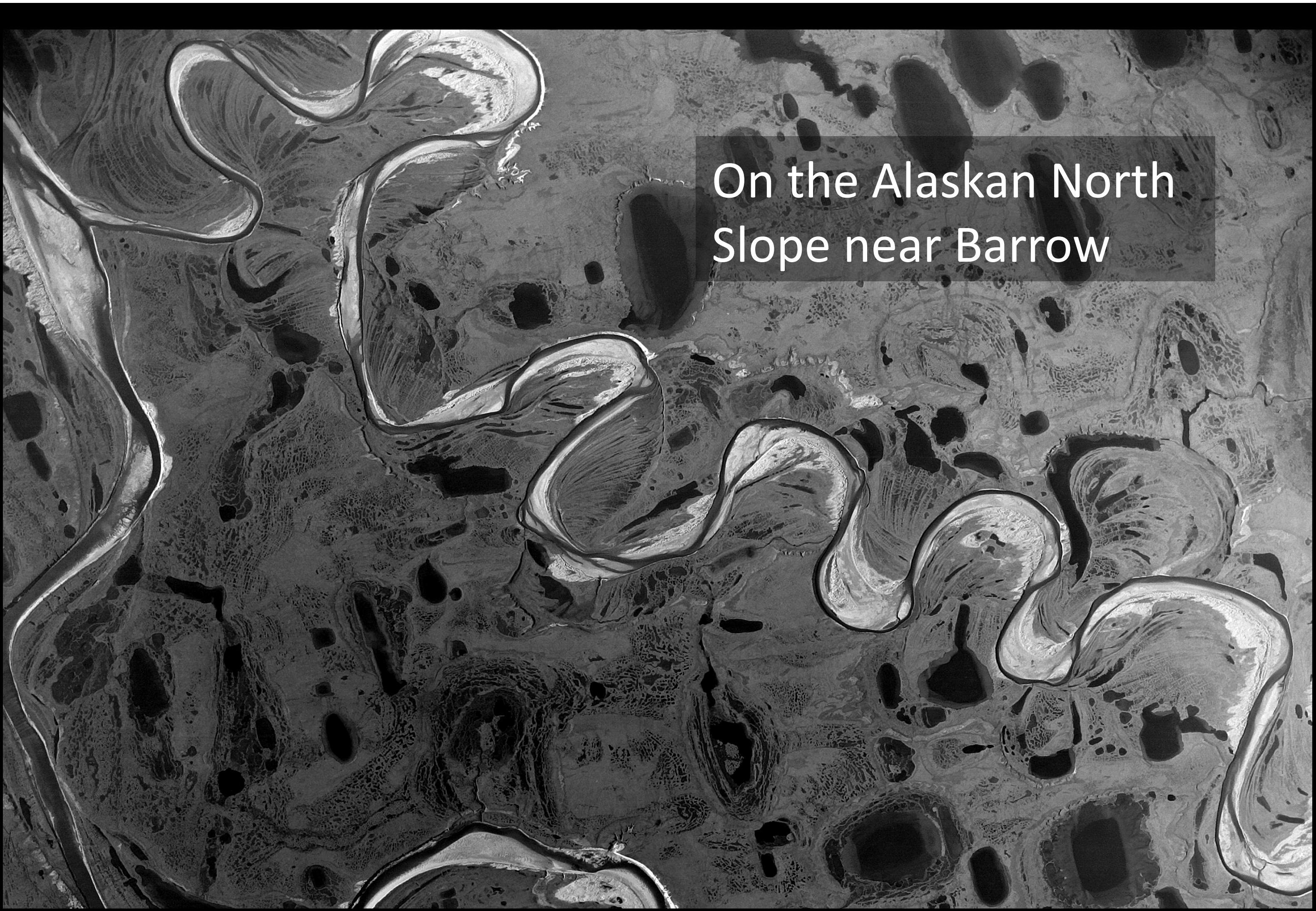
Inner bank sediments show alternating layers varying in relative sand-mud content.

Mud-draped point bar

Summary of Field Observations

- Vegetation plays a very minor role
- Mud drapes are an important factor stabilizing banks
- Almost all sediments collected fizz in acid – carbonate cementing
- Silt and clay dominate bed, bank and overbank sediments

Another Possible Analog: Arctic Channels with Frozen Banks.



Point bars and scroll bars are well developed, with occasional cutoffs.

The rate of channel migration at present seems to be very slow.

The Problem with Arctic Analogs

- All meandering arctic channels appear to be in regions with tundra vegetation – even near Barrow, Alaska

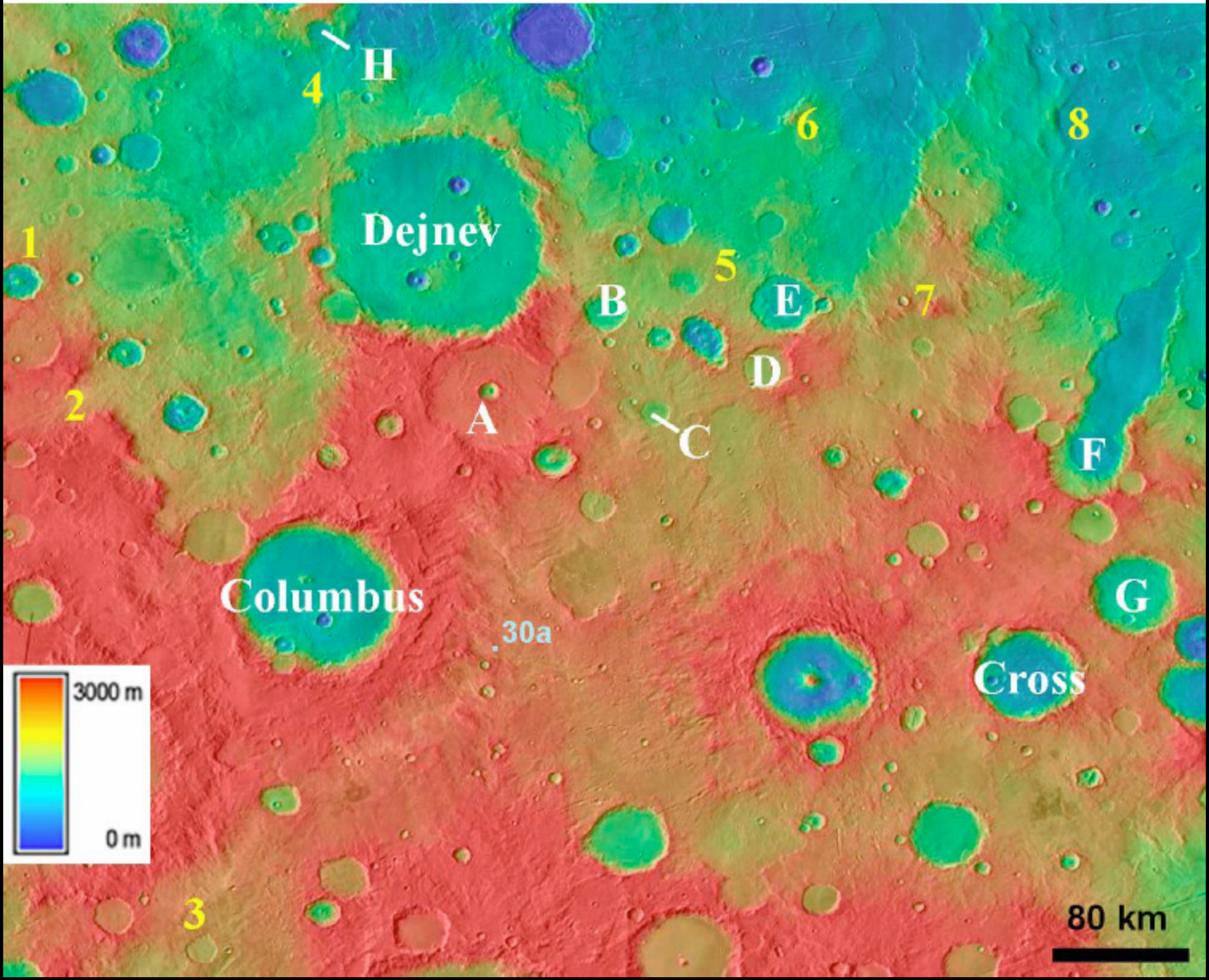
- Although thermal ice melting is an important process in these channels, vegetation may have played a dominant role in encouraging sedimentation, protecting banks after undermining, and allowing a shallow permafrost with segregated ice to develop.

5. Evaporative Chemical Lacustrine Sedimentation on Mars

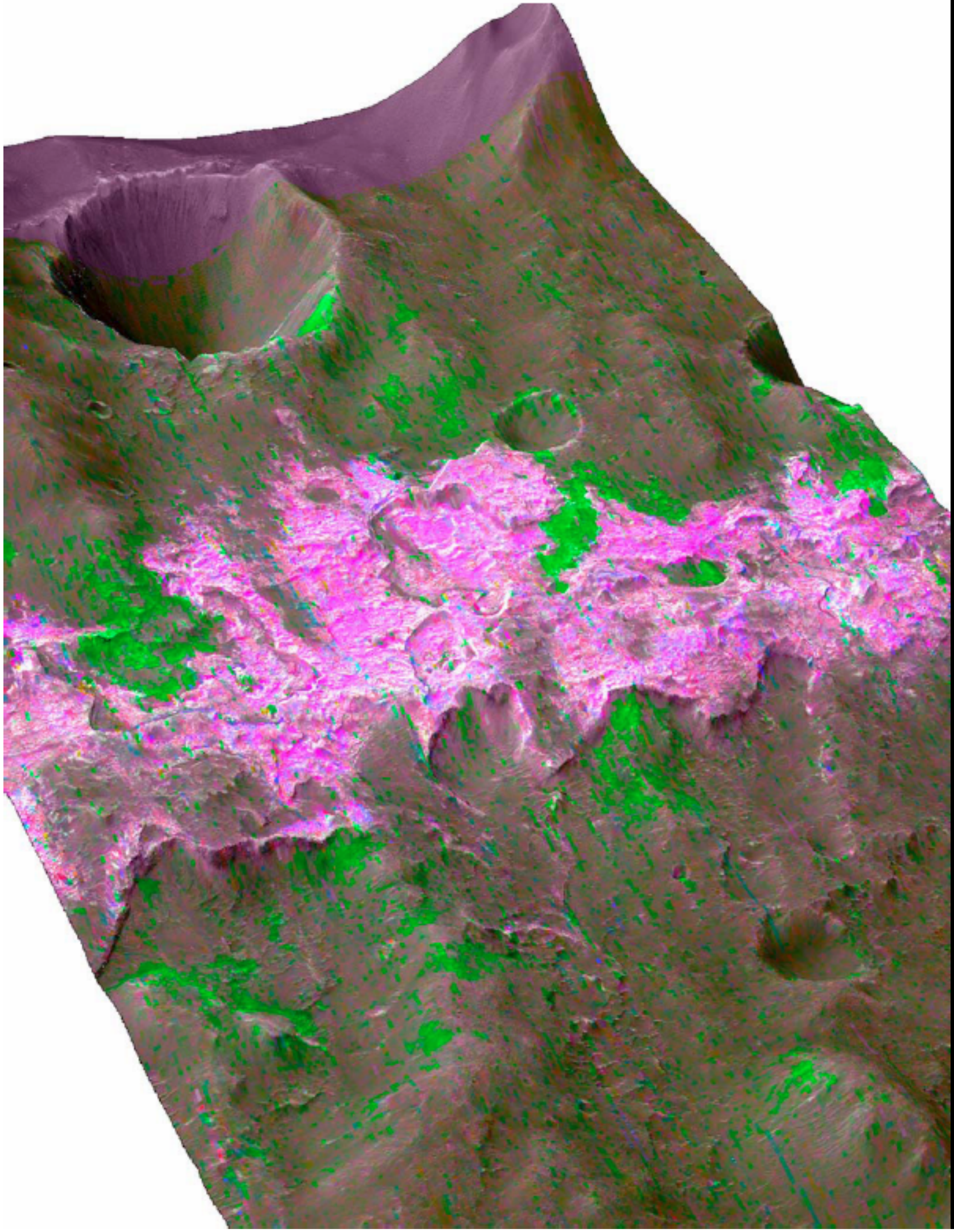
- Hyperspectral IR imaging by orbiting spacecraft (the Omega and Crism instruments) has identified hydrated minerals (primarily sulfates and phyllosilicates) and chlorides in numerous locations

- One region shows clear evidence of accumulation of evaporites and clays within craters fed by regional groundwater systems

- Illustrations are from Wray et al., 2010

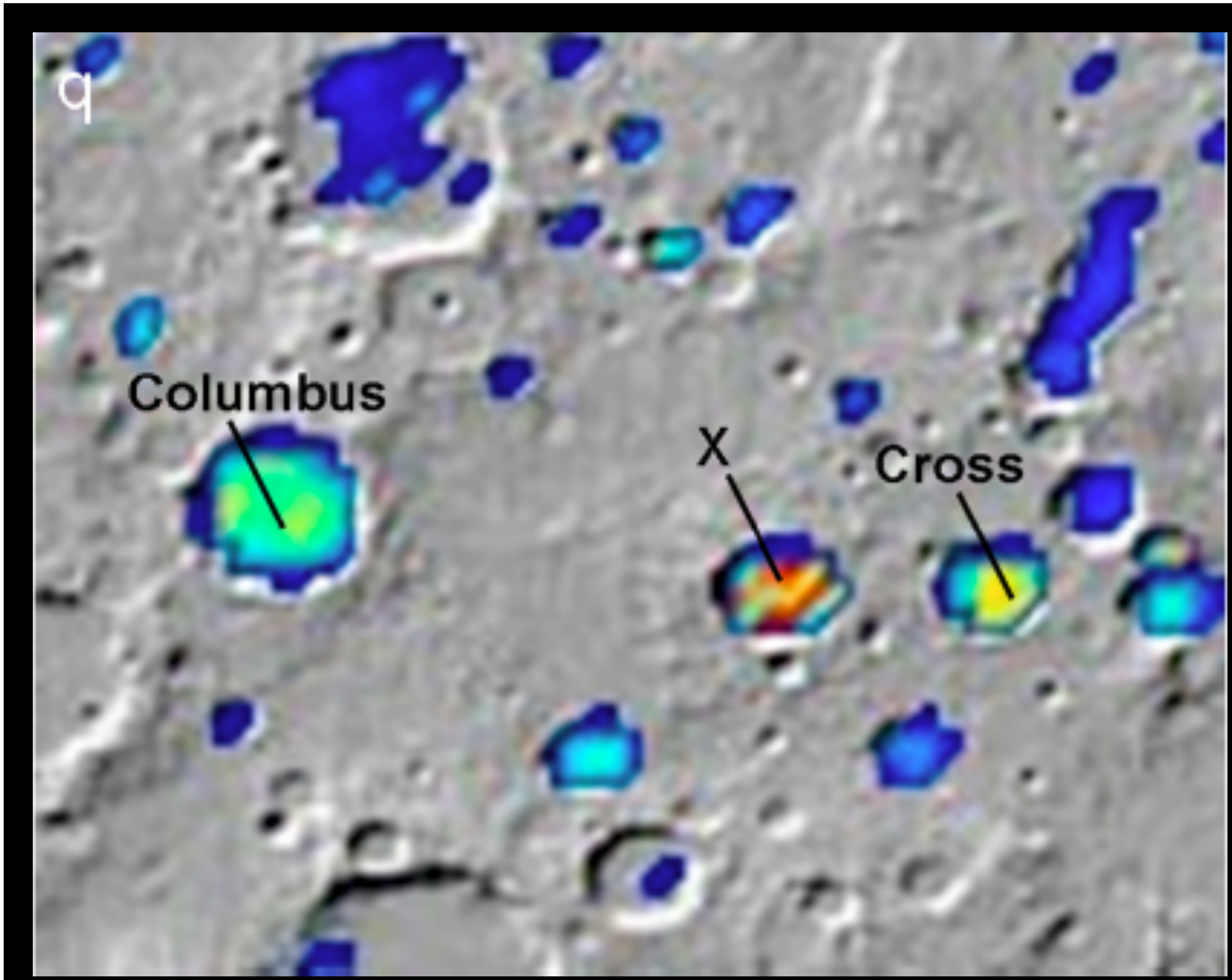


Named craters and numbered or lettered locations contain hydrated minerals or light-toned layered deposits



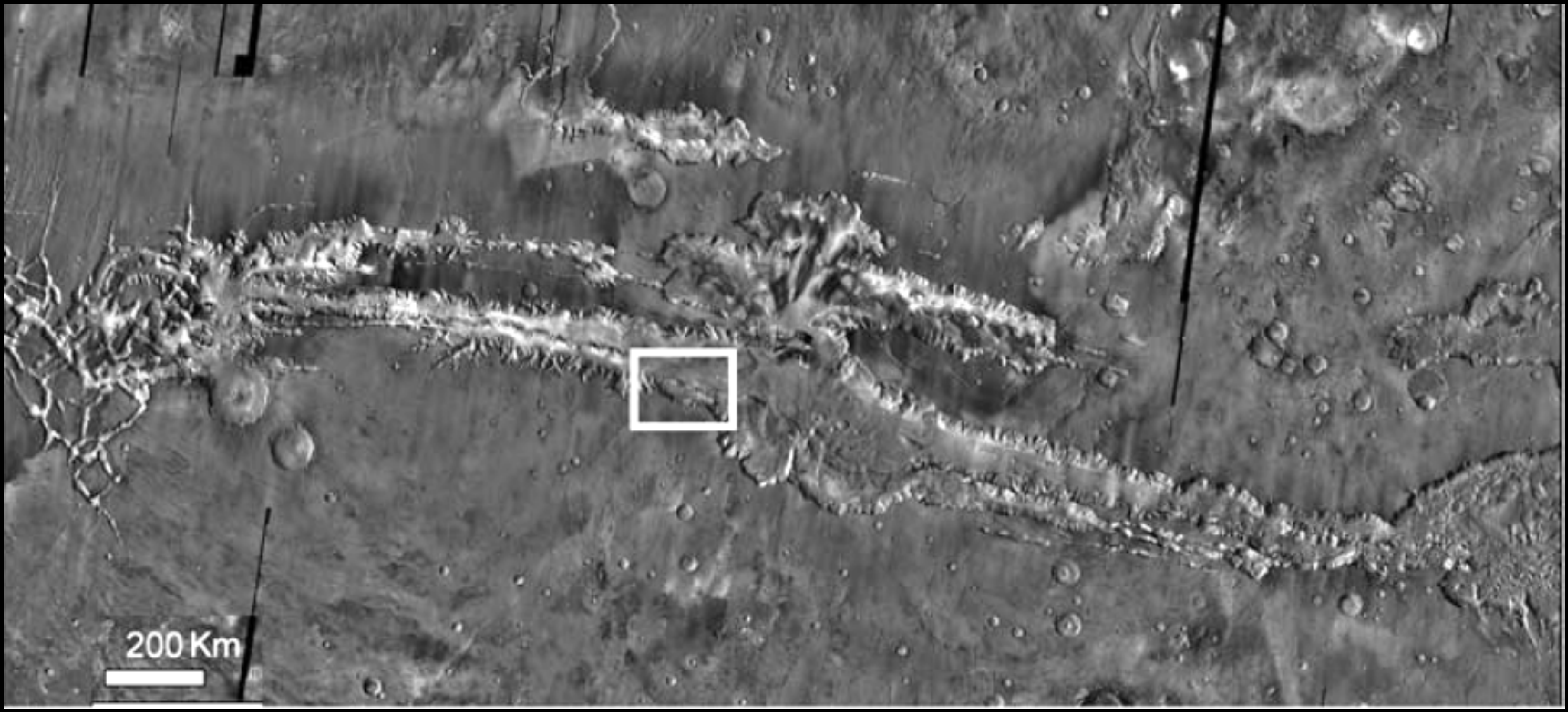
The interior wall of Columbus Crater is rimmed by a deposit of hydrated sulfate minerals (pink) and aluminum phyllosilicates (green).

Perspective view with overlaid spectral data



Modeling of groundwater flow and evaporative deposition indicates that the locations with identified evaporative or water related minerals are favorable locations for such accumulations

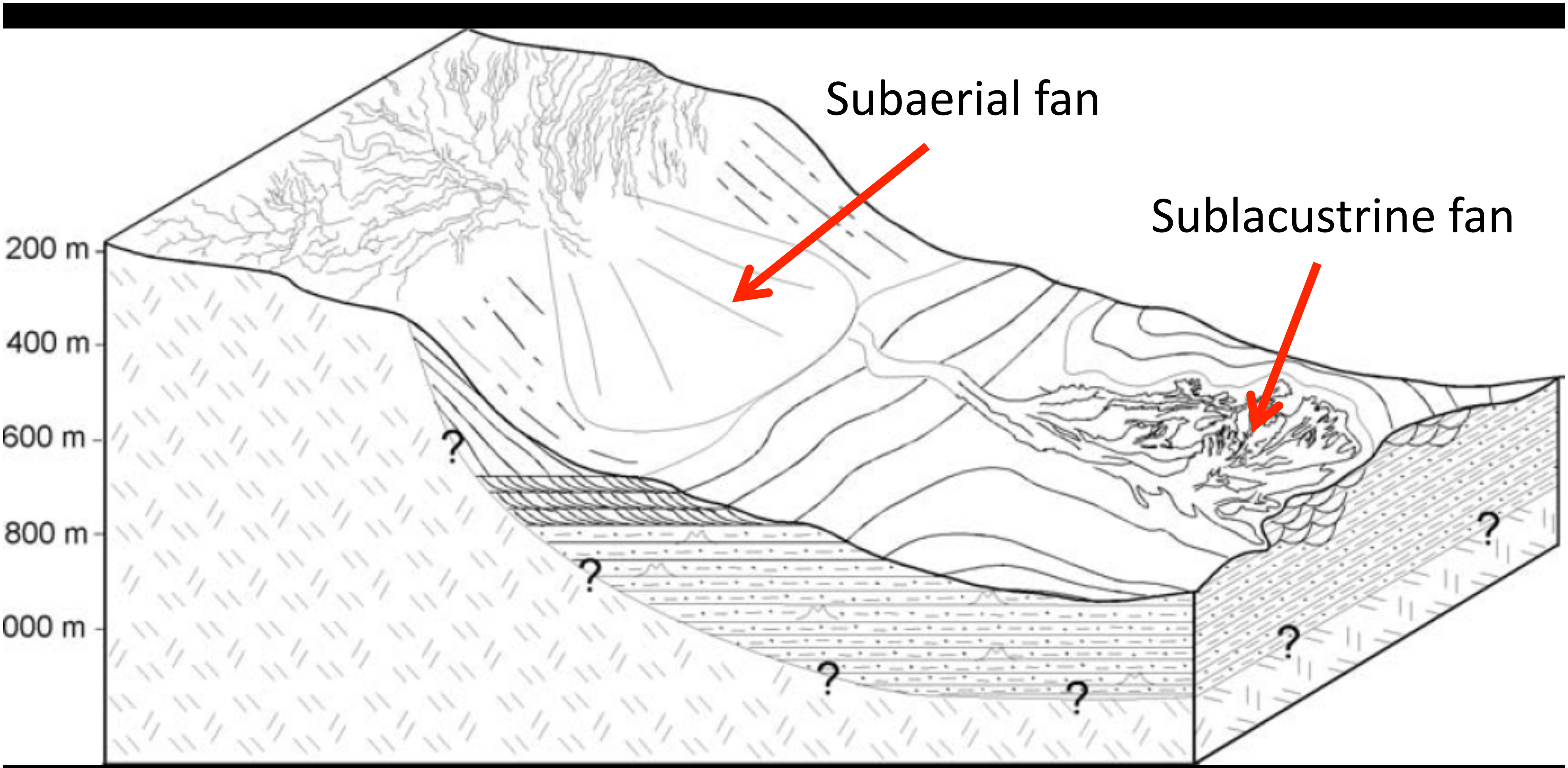
6. Submarine fans



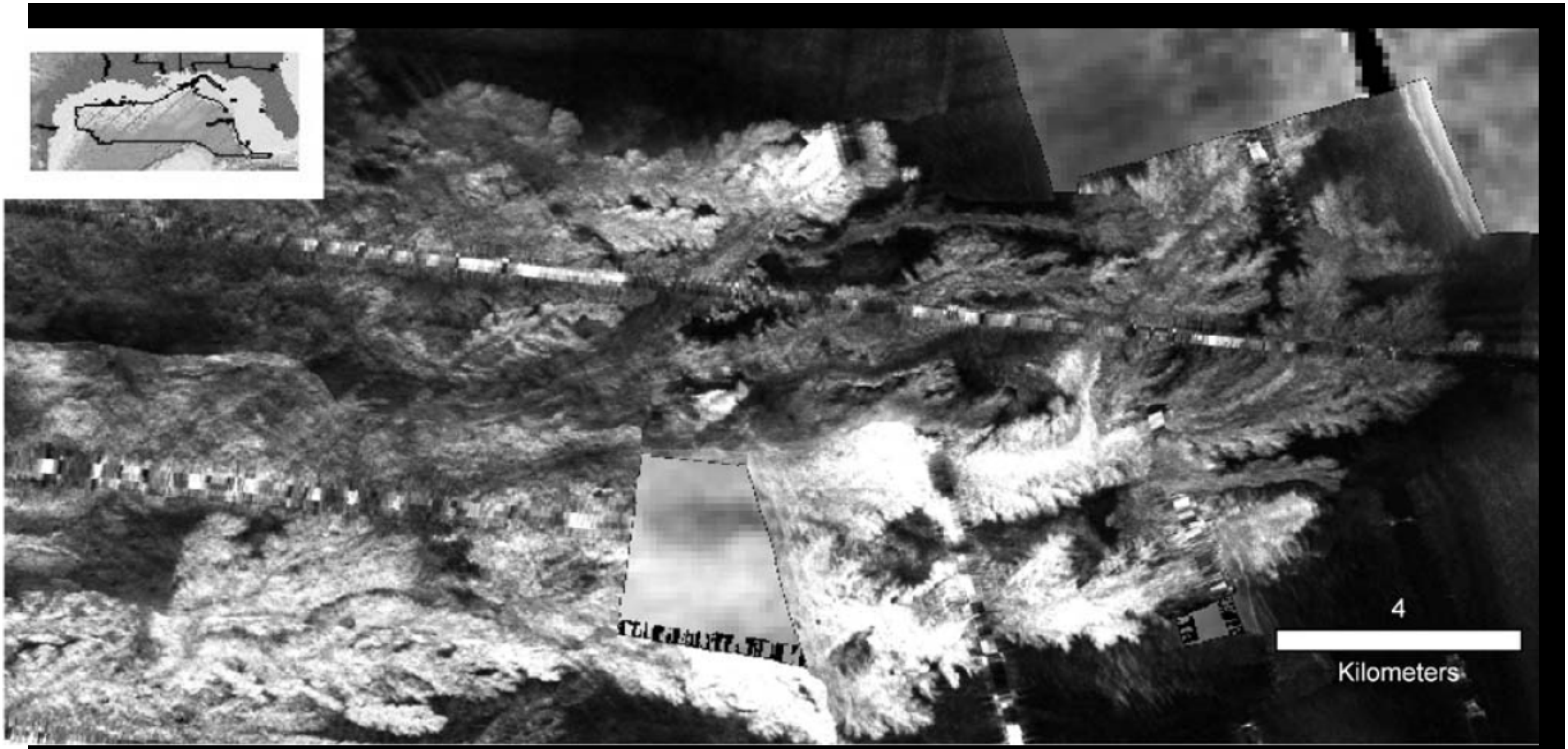
- Valles Marineris is a structural depression of Hesperian age that has apparently hosted lakes at some times and locations. The box outlines one location where possible sublacustrine fans have been identified in Melas Basin

- Illustrations from Metz et al., 2009

Depositional lobes identified as sublacustrine fans



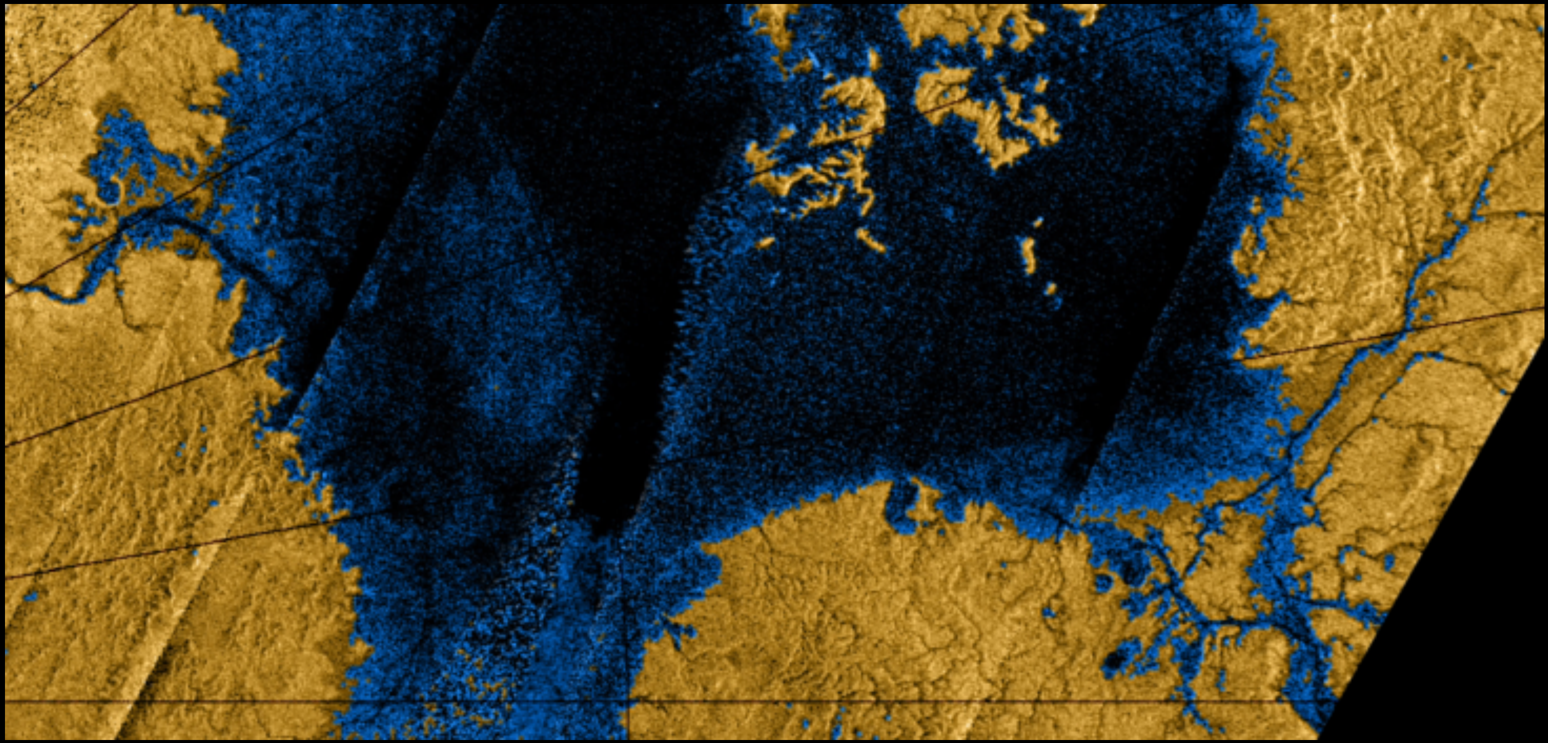
Interpretive model of Melas Basin deposits

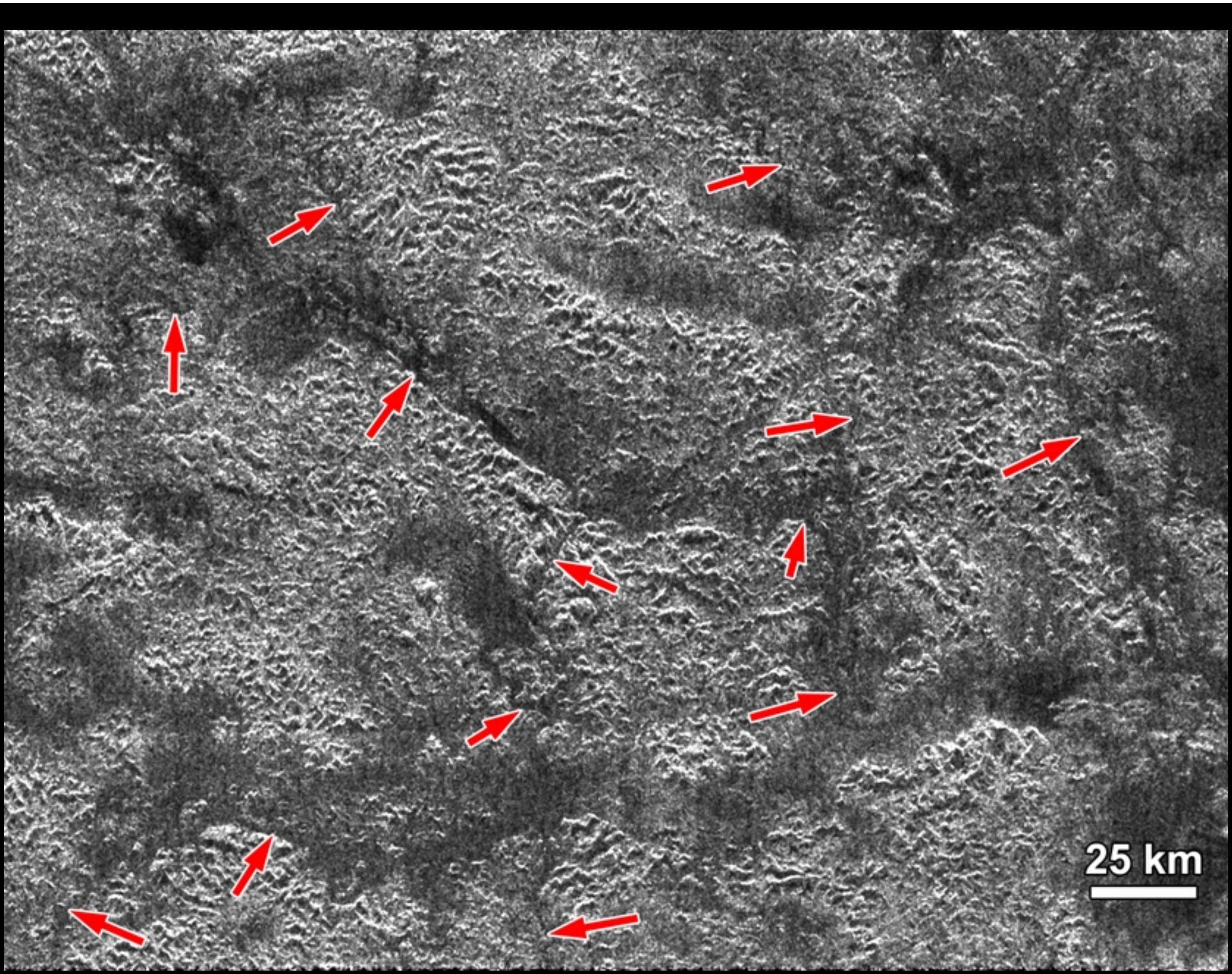


The Mississippi River submarine fan as a possible terrestrial analog

S2S on Titan

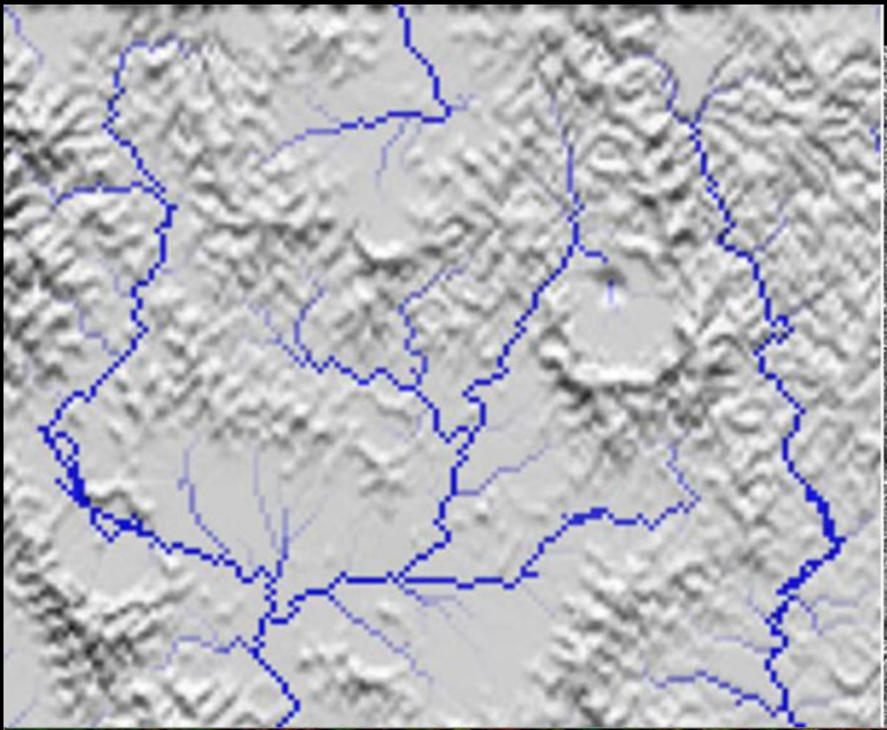
- Titan is a satellite of Saturn. It has a dense, primarily Nitrogen atmosphere with secondary Methane and other hydrocarbons.
- The surface temperature is about 100K, allowing an active hydrological cycle of methane rain, runoff, excavation of fluvial networks eroded into the water ice bedrock, and maintenance of methane lakes.

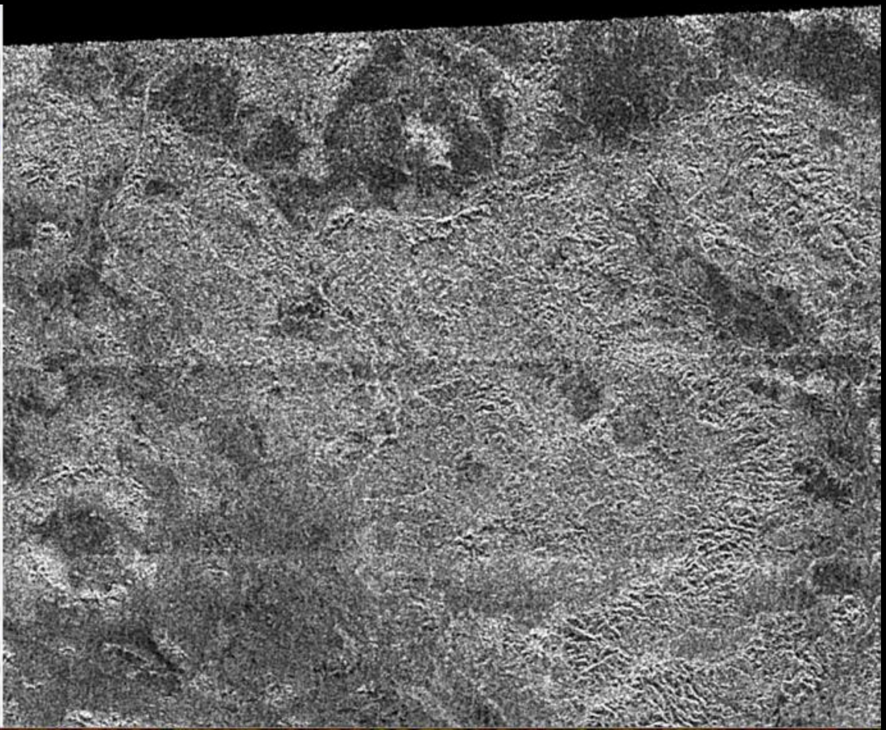


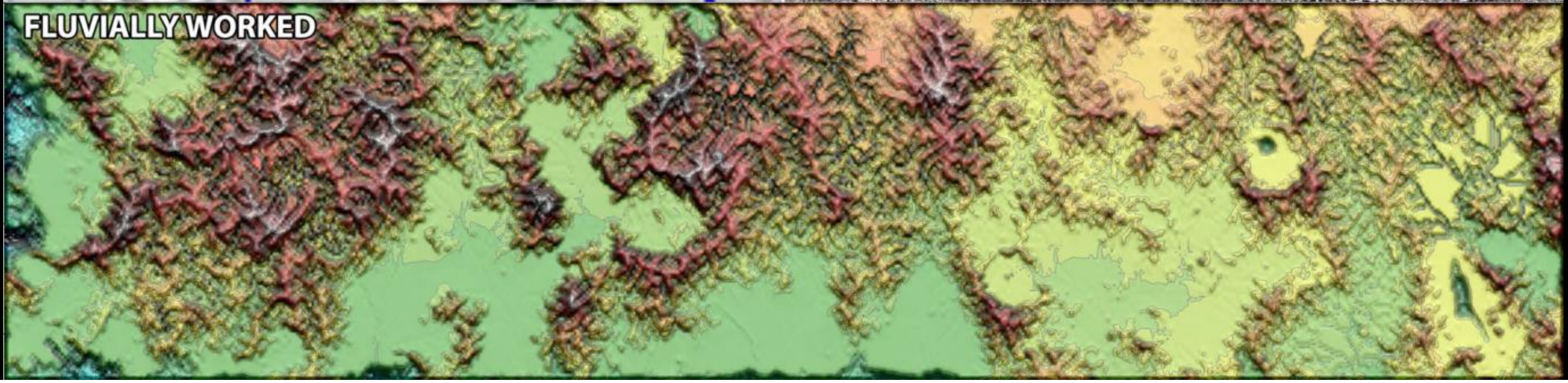


Uplands region on Titan with pronounced “banding” or “crinkling” interpreted to be ridge and valley patterns of fluvially-dissected topography. Red arrows point to trunk fluvial valleys. Smooth, dark areas are interpreted to be sedimentary basins.

Callisto’s cratered surface, which is mantled (but so is Titan’s by atmospherically derived solids) and only weakly tectonized (i.e., basin ring graben) when rained upon produces a surface where the highlands are fluvially dissected and the lowlands are broadly filled with sediment. This resembles the highlands of Titan much more than Ganymede with rain.







CLIMATE HISTORY IMPLICATIONS

If Titan displays regions of degraded ancient cratered terrain, then this would have significant implications for Titan's history. Martian fluvially degraded cratered terrain still exhibits craters because fluvial activity largely ceased soon after the curtailment of heavy bombardment. For Titan to have such terrains *and* ongoing fluvial activity would imply at least three possible explanations:

(1) alkane fluvial erosion on Titan is extremely inefficient relative to that by water on the Earth and Mars, or

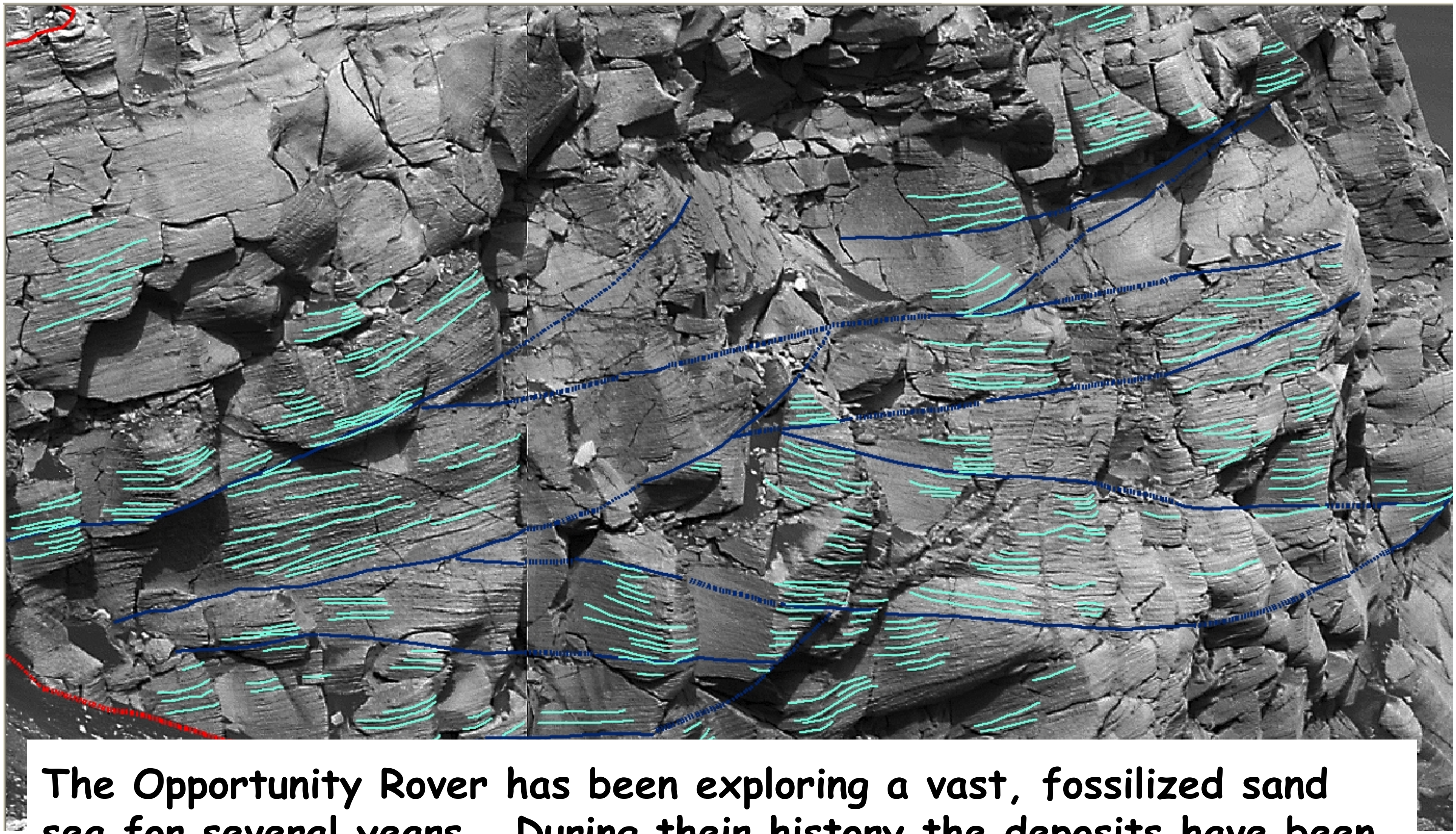
(2) fluvial erosion very rarely occurs on some regions on Titan; or

(3) it has started raining on Titan only in geologically recent times.

Martian Aeolian S2S

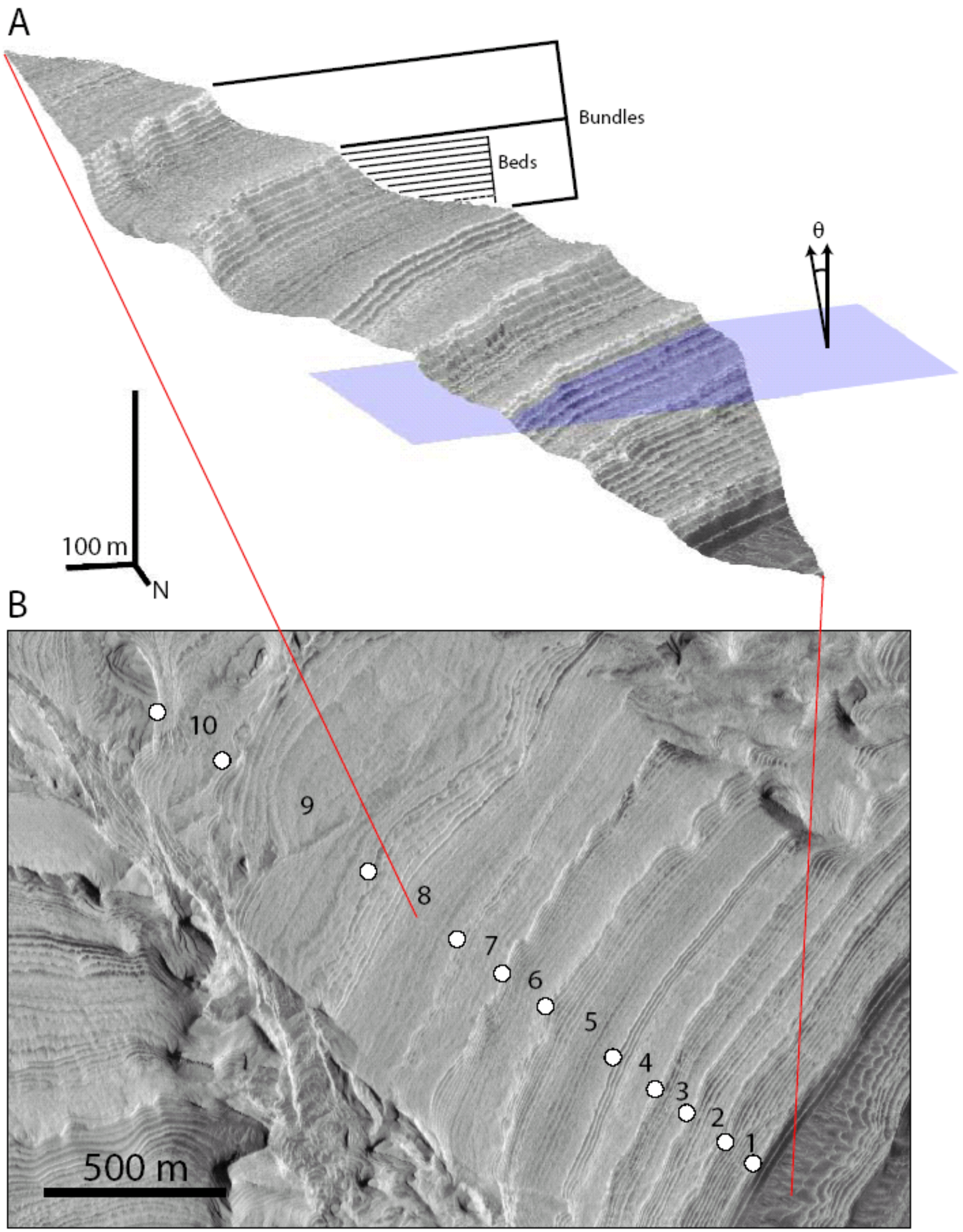
- Although aeolian processes and deposits have not been a focus of the NSF S2S, they have been a dominant factor on Mars
- In addition to modern and fossilized dune fields, vast quantities of fine, loess-like sediments have accumulated and been eroded in multiple cycles.

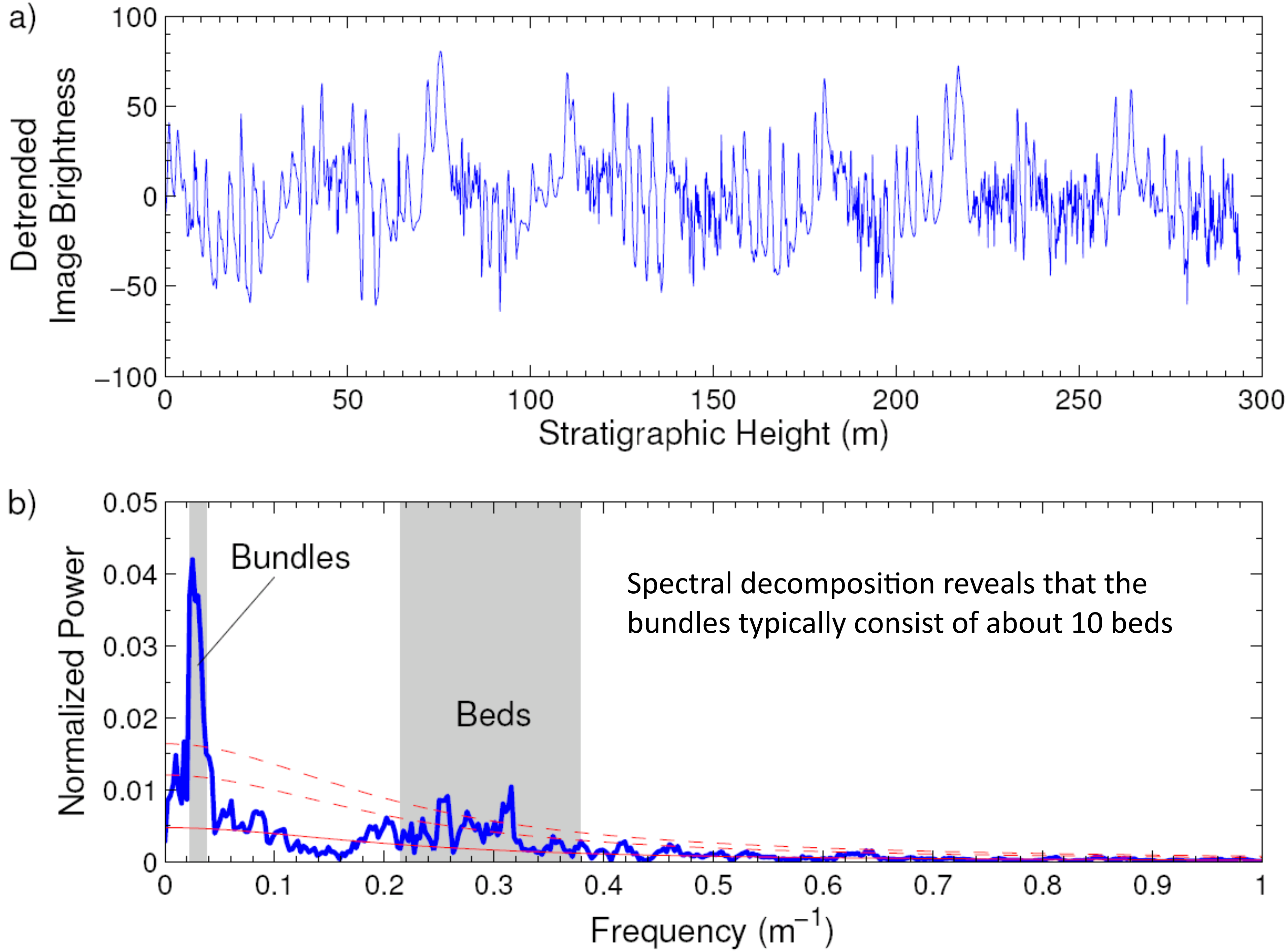
Dune-scale Cross-stratification



The Opportunity Rover has been exploring a vast, fossilized sand sea for several years. During their history the deposits have been modified by interaction with groundwater and locally reworked by water in shallow interdune playas

In several locations these airfall (or in some cases possibly playa) deposits exhibit rhythmic bedding grouped into larger sets, or bundles

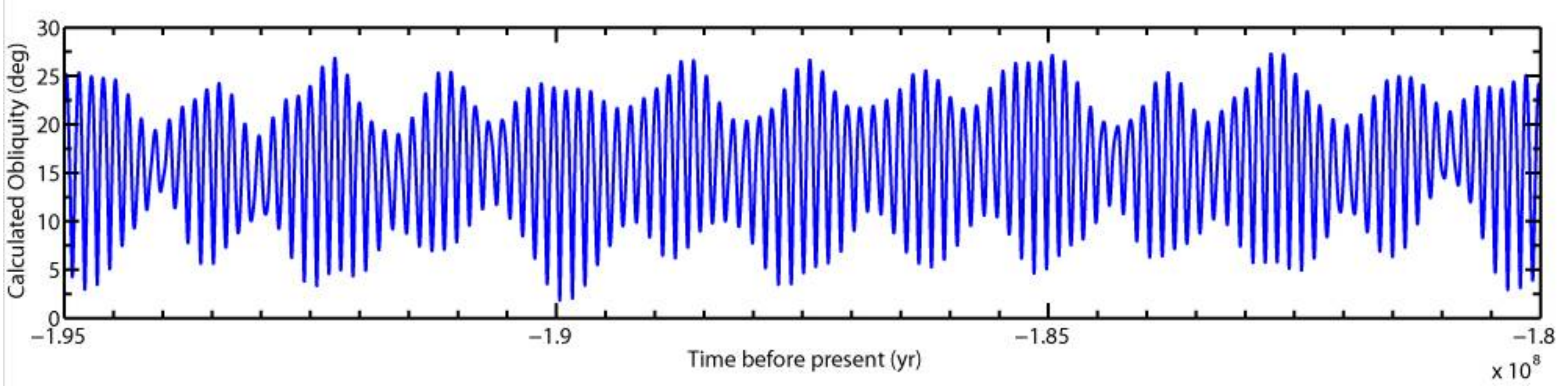




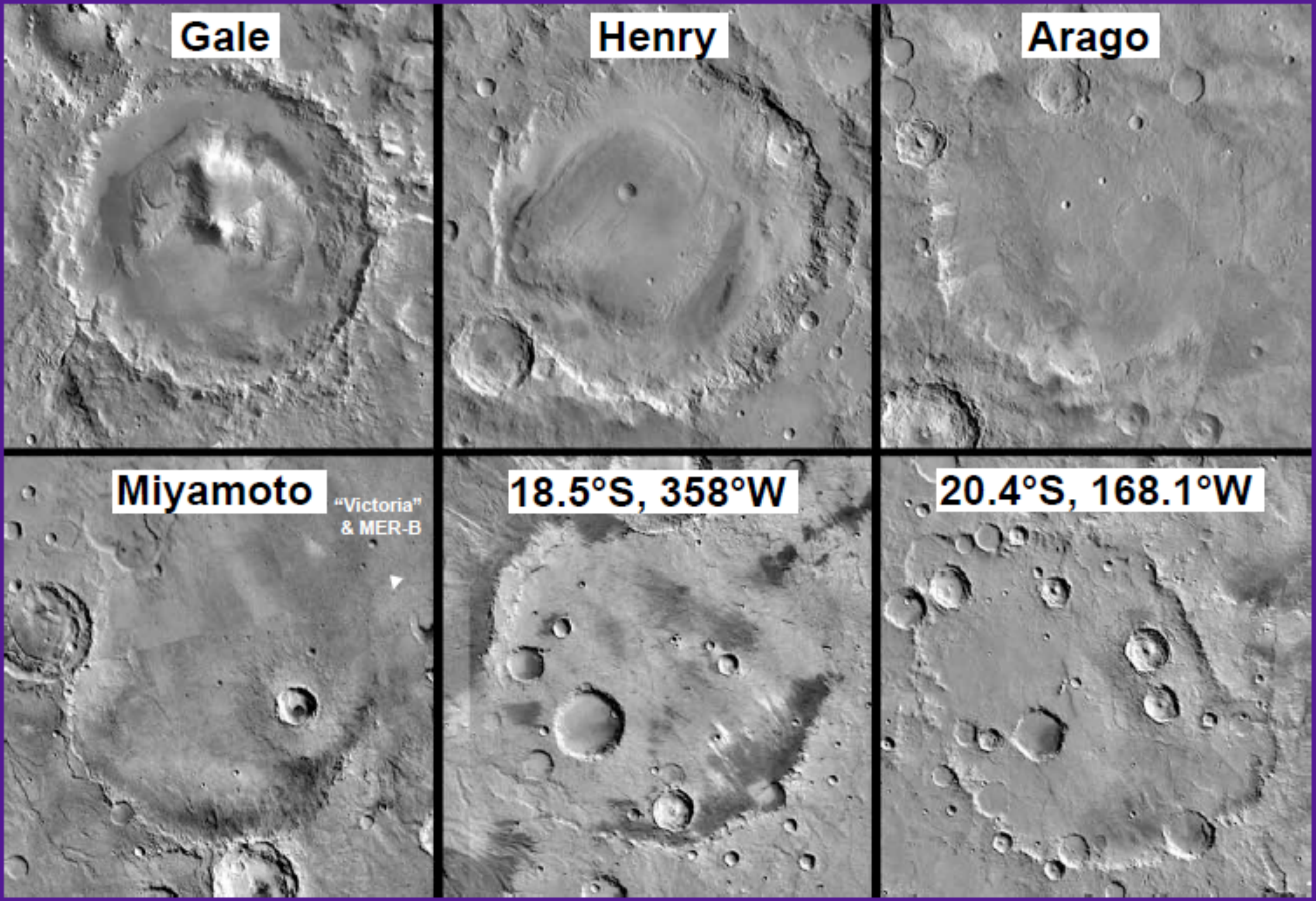
Spectral decomposition reveals that the bundles typically consist of about 10 beds

Obliquity Signal in Deposits?

- Mars undergoes much more dramatic variations in orbital properties than Earth
- 120 kyr obliquity variations are modulated on a 1.2 Myr timescale
  - Eccentricity (120 kyr) and Precession (50kyr) can not help explain the signal
  - Obliquity forcing implies a moderate deposition rate of 100 µm/yr
- Regardless of process, obliquity variations will have wide-ranging effects on climate and surface conditions, including atmospheric pressure

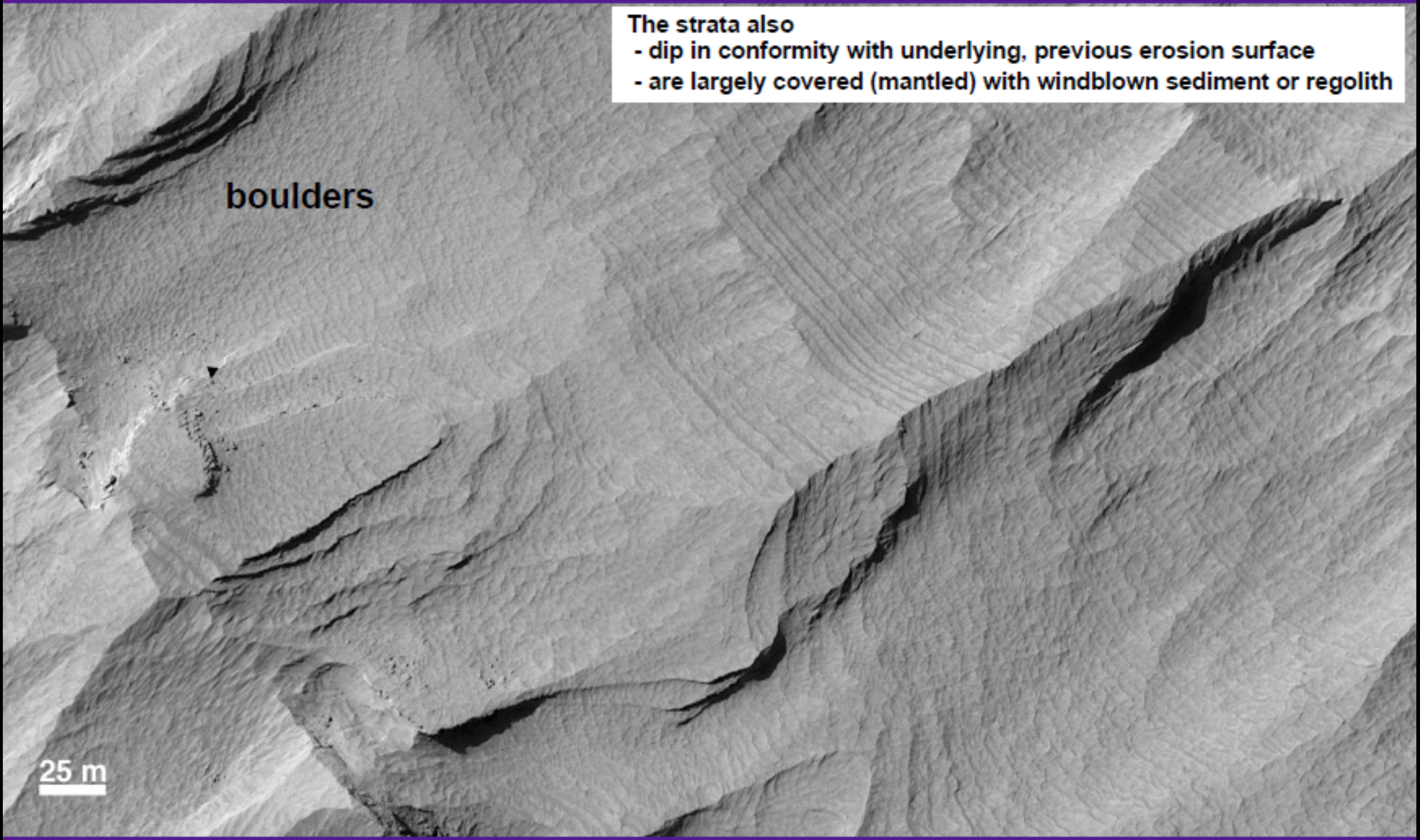


Mars Craters of Gale Size with Substantial Fill Material; Henry's fill forms a Mound; Miyamoto is Partly Exhumed



- all craters ~155 km in diameter
- USGS Viking MDIM 2.1 maps

Mound Uppermost Strata have Cliff-Bench Erosional Expression and Produce Boulders -- the Material is Rock



The strata also
- dip in conformity with underlying, previous erosion surface
- are largely covered (mantled) with windblown sediment or regolith

- sub-frame of HiRISE PSP_008002_1750
- terrain slopes downard toward upper right

End