Pervasive Ice-Related Erosion of Mid-latitude Martian Craters

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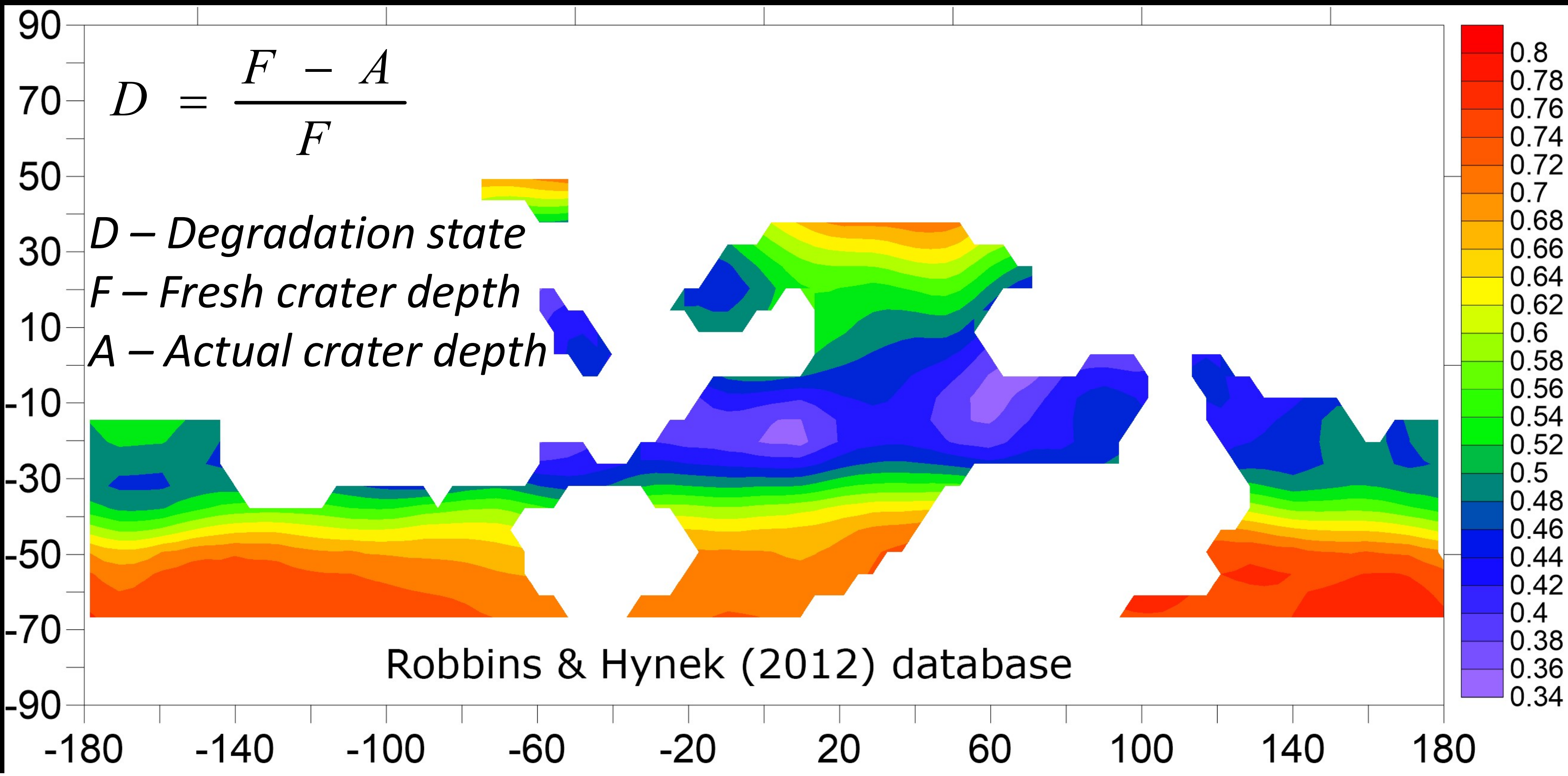
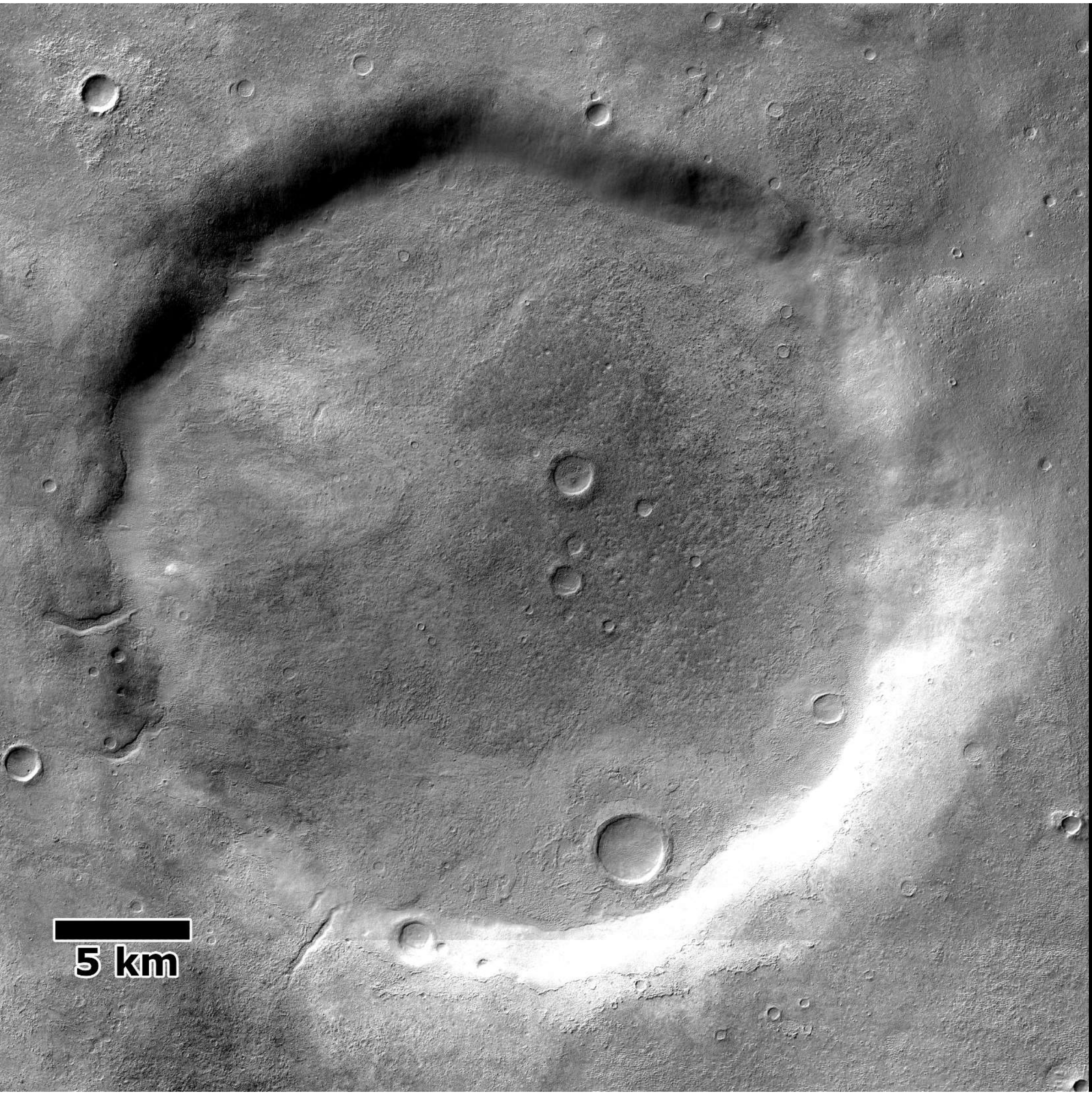
Major Points

- Multiple episodes of ice-rich mantle emplacement, sublimation, and glacial flow occurred during the Hesperian and Amazonian in the mid-latitudes.
- The glacial flows have been accompanied by lateral erosion of crater rims.
- Exterior crater ejecta slopes have likewise developed scarps and pits due to ice-related erosion.
- In the 38-45° latitude band episodes of fluvial activity modified the mantled craters.
- Terrain south of 45° has a deep mid-latitude mantle.
- The evolution of this landscape can be modeled as a combination of mantling, glacial and solifluction flows, weathering, and glacial erosion, and fluvial erosion.

The degradation state of 4-10 km craters in Noachian terrain increases systematically with latitude



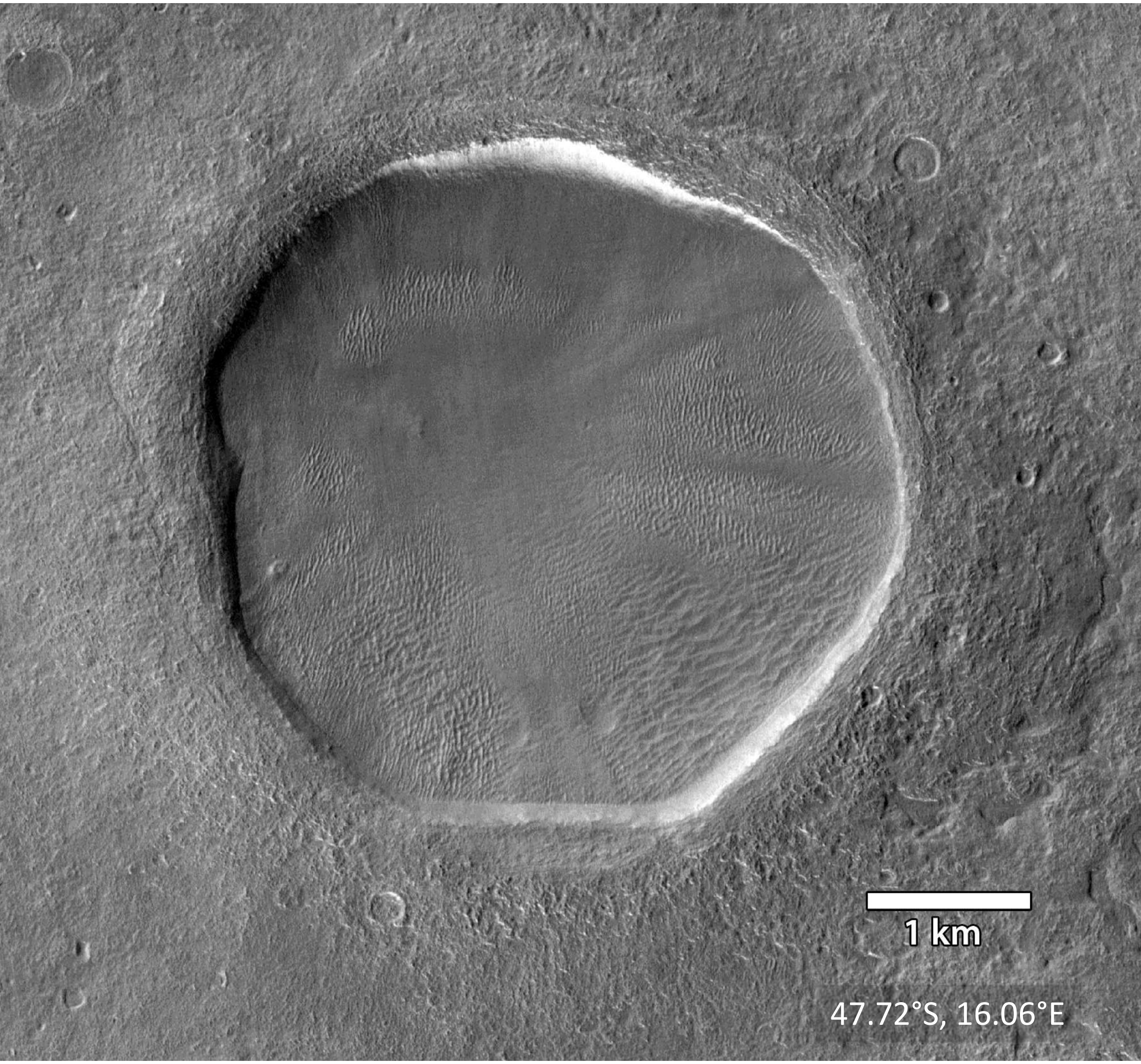


In craters where degradation by mid-latitude mantling dominates over other processes crater rims are broadly-rounded, generally accompanied by preferential infilling of crater interiors and a smoothing of intercrater plains. Mantling was accompanied by diffusive smoothing, either by glacial flow or solifluction.

Some inward flow of ice on the crater floor has also probably occurred.

Some of the Noachian age craters in the high mid-latitudes exemplify this style of degradation

45.83°S -9.10°E

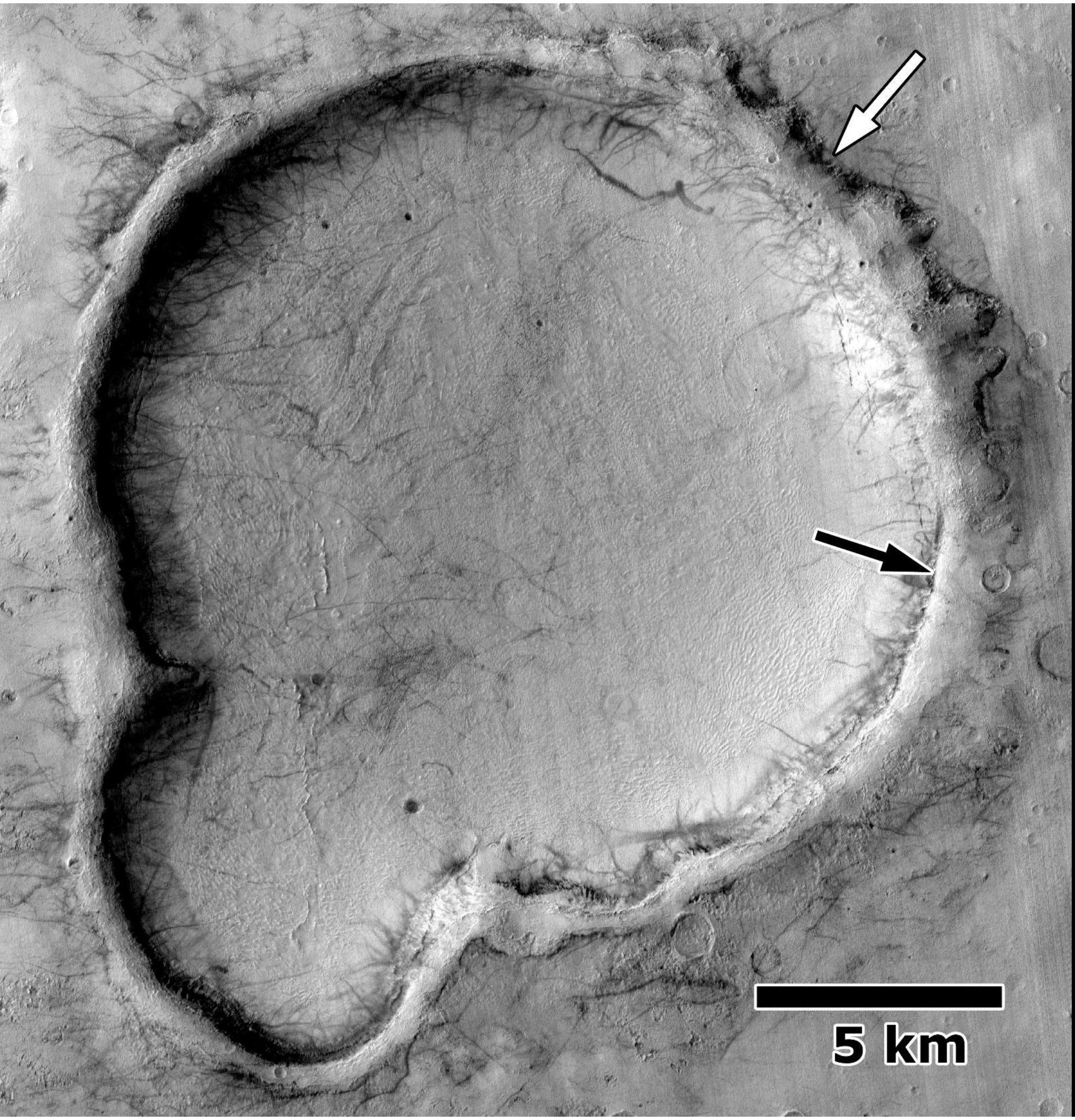


This small crater exemplifies crater interior wall erosion associated with concentric crater fill (CCF).

The interior crater walls are steep, probably close to being at the angle of repose, and the walls define a smooth curve around the central peak.

Up to a few hundred meters of crater wall retreat has occurred.

The rim and exterior of this crater are deeply mantled, but show little evidence of degradation or erosion.



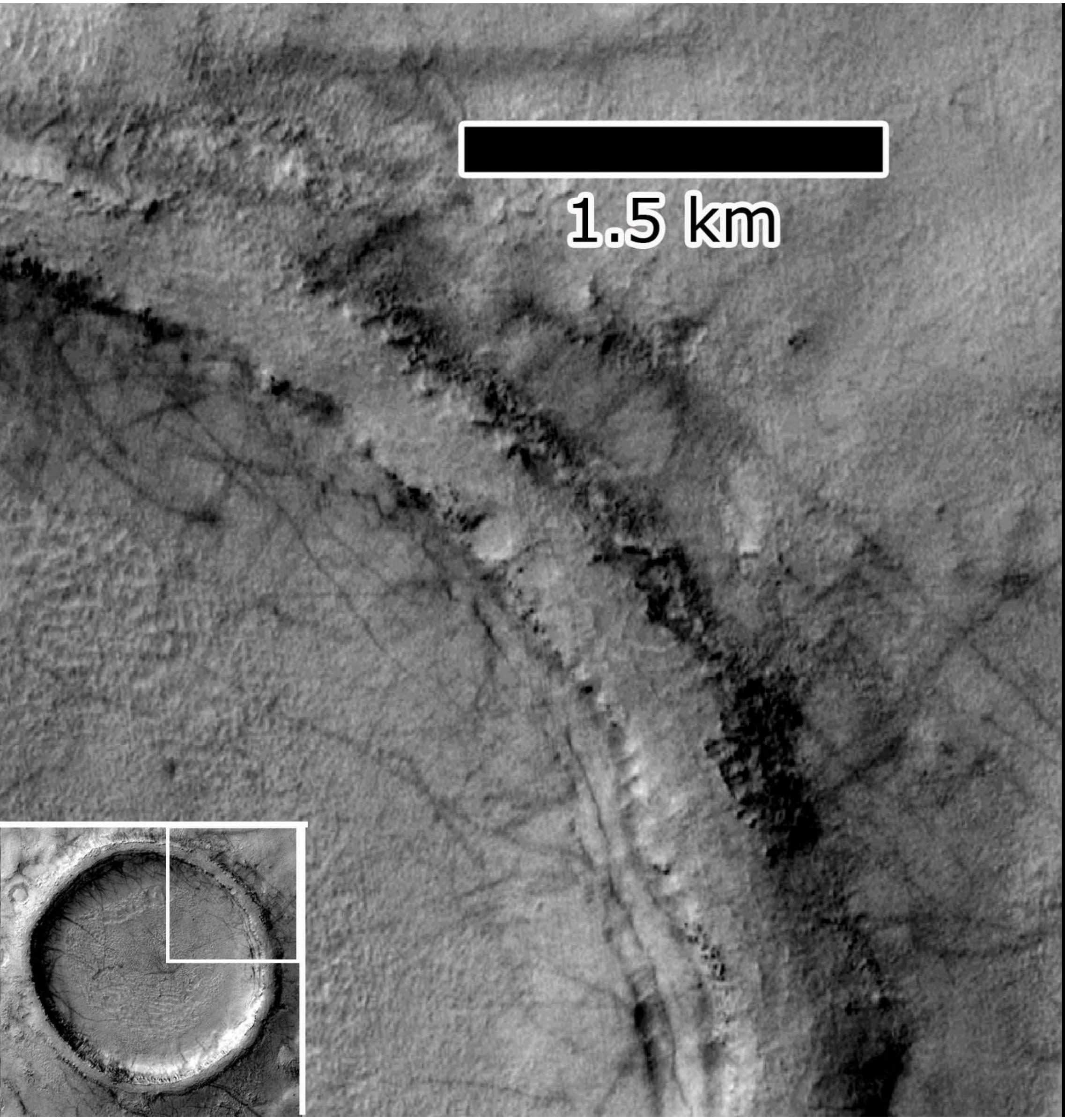
More commonly, however, mid-latitude crater degradation involves multiple processes, including:

- Inward glacial flow (CCF).
- Erosional attack and steepening of interior crater walls (black arrow).
- Ice-related attack of the exterior crater rim (white arrow).

This results in a skeletal rim, or “donut” morphology.

The smooth texture of the inter-crater plains at kilometer scales suggests deep mantling.

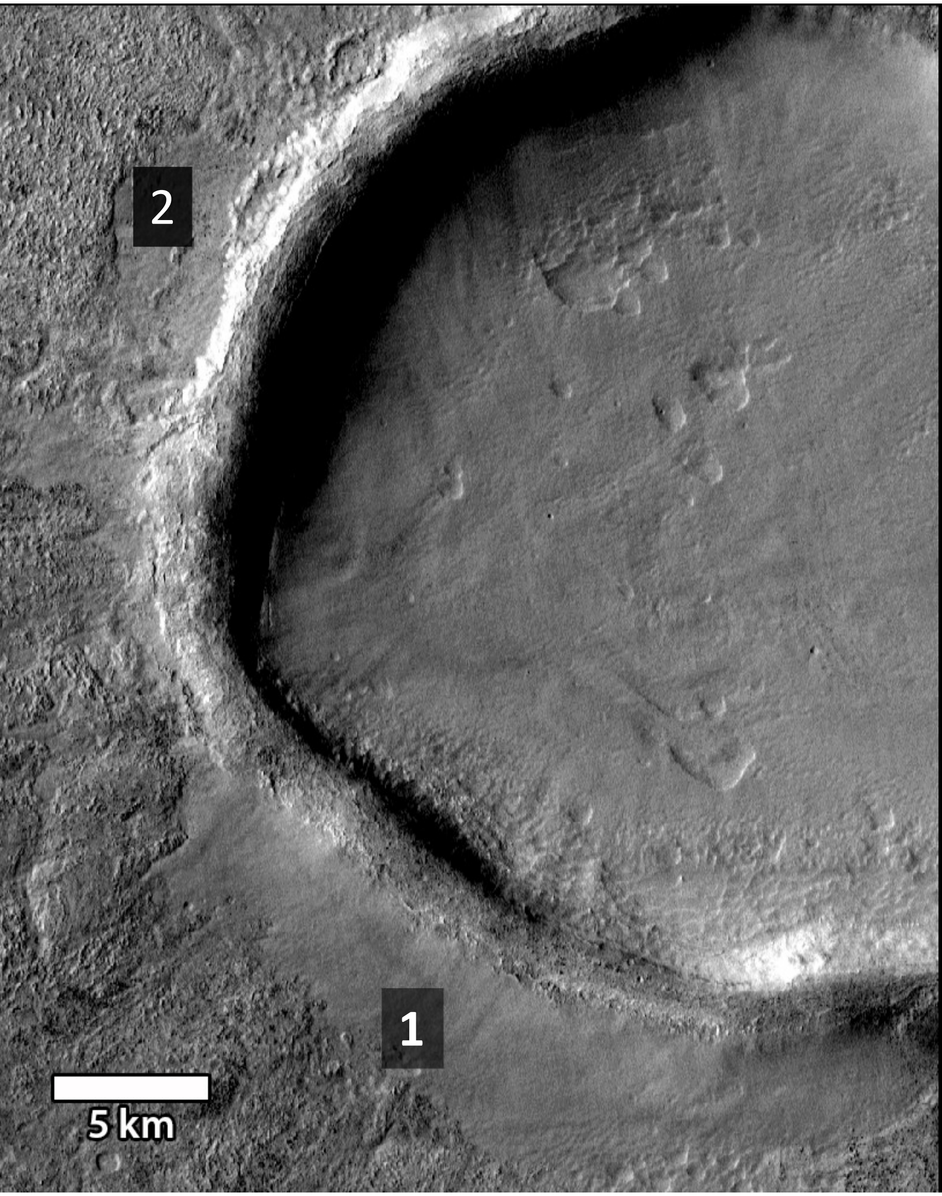
47.02°S, -130.38°E



This northeast quadrant of a skeletal crater illustrates the smoothly rounded character of the remnant crater rim,

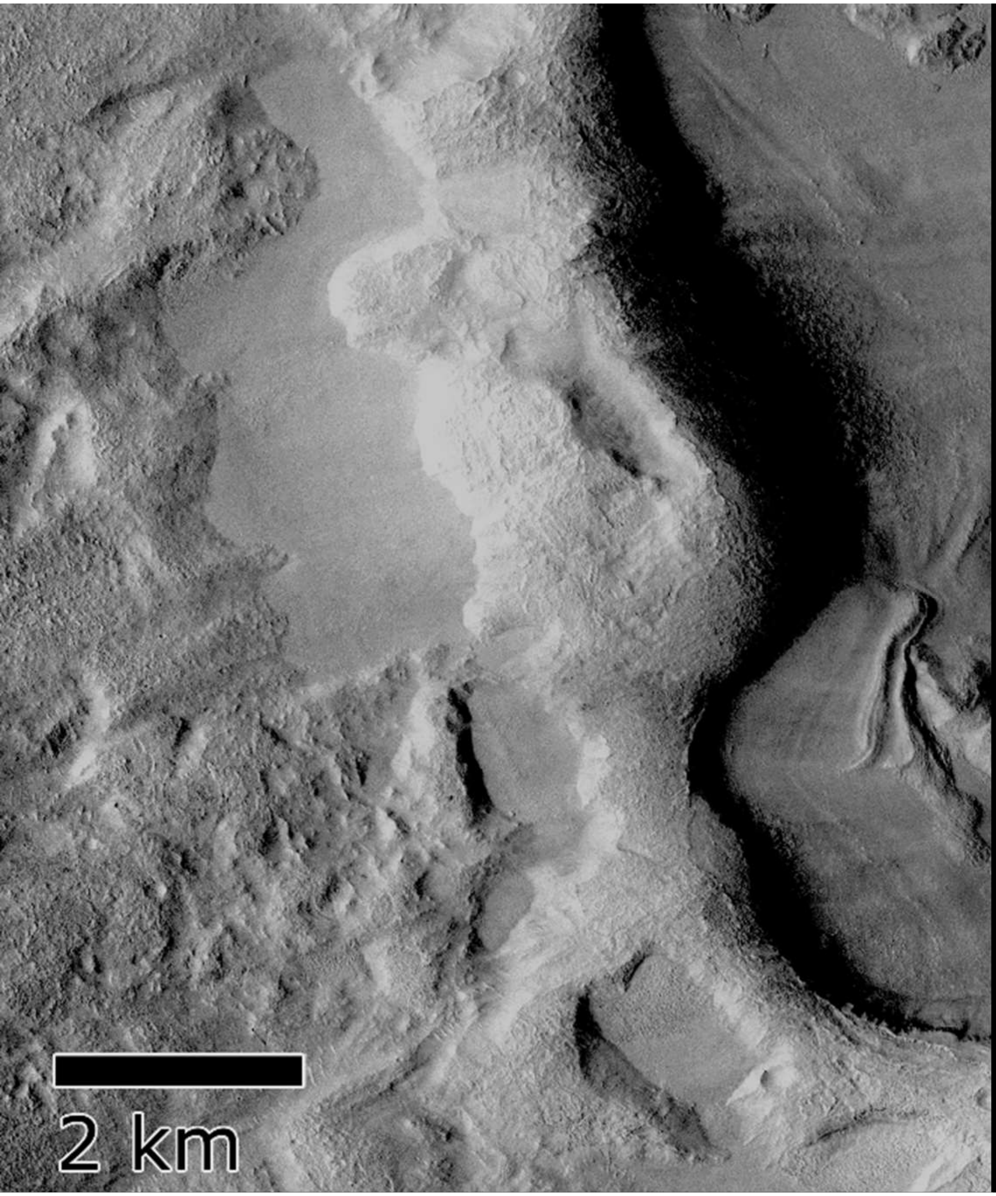
This rim is being narrowed by both inward and outward directed undercutting.

46.61°S, 140.05°W



- The pattern of ice accumulation and ice-related erosion often varies with azimuthal orientation.
    - At “1” a sloping ramp of surface ice has accumulated – the degree of exterior crater rim erosion below that ice is uncertain.
    - At “2” ice is limited to flooring depressions, and extensive exterior crater rim erosion is revealed.
- Both interior and exterior crater rims are favored sites for ice accumulation and erosion.

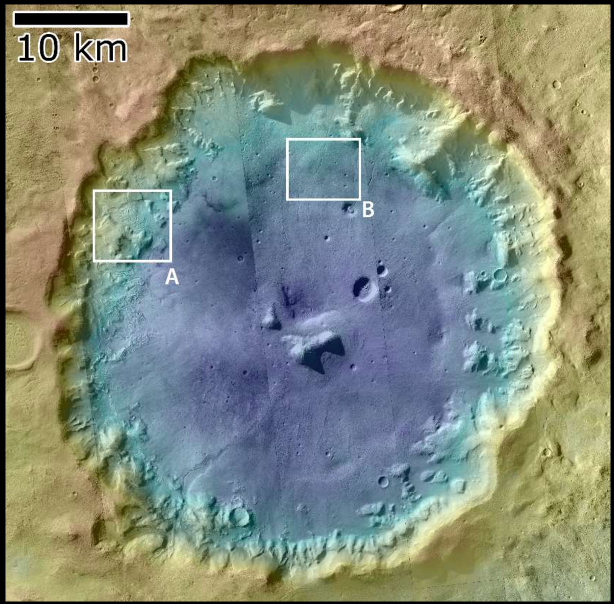
46.84°S, 24.87°E

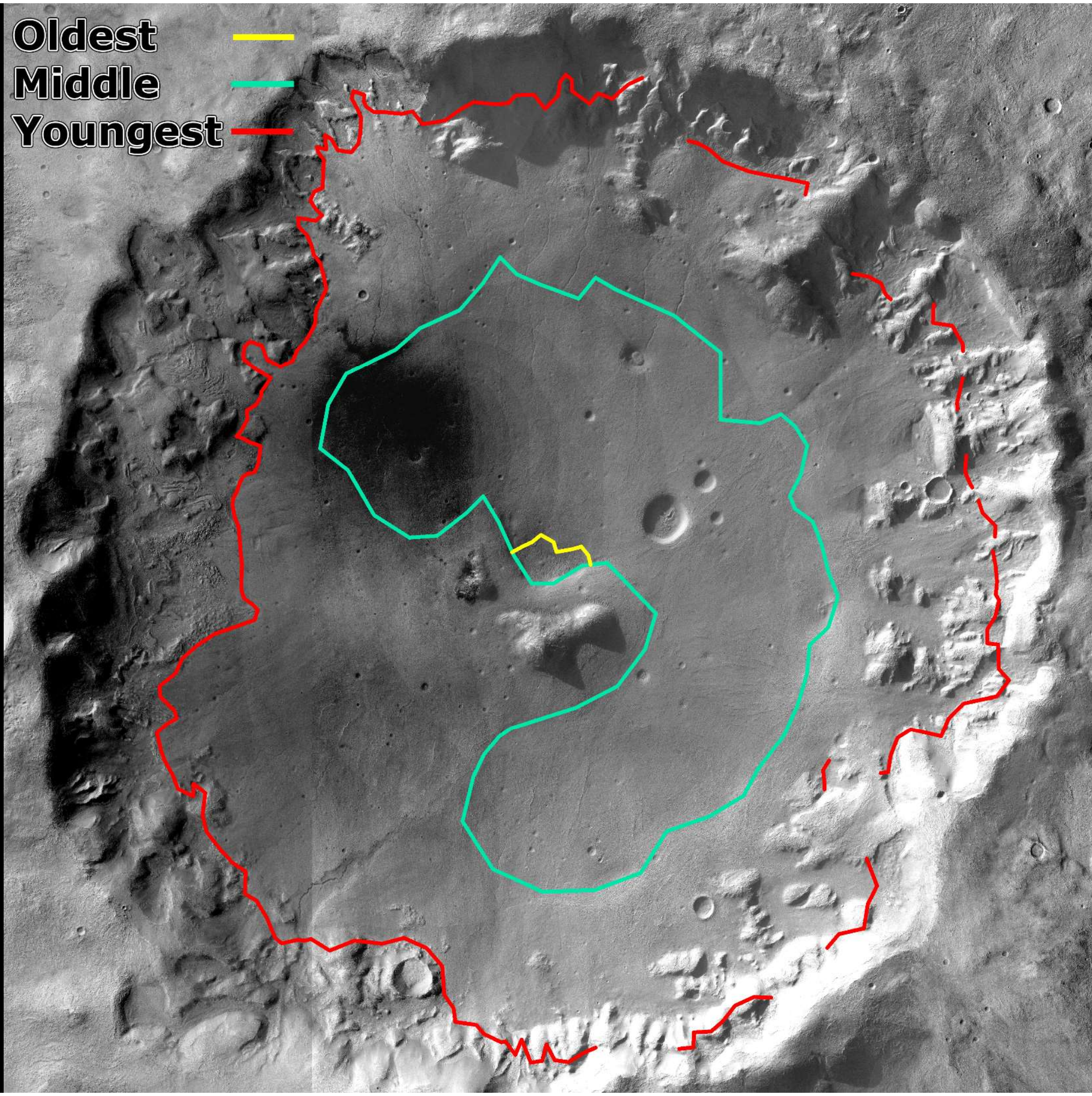


- The southwestern exterior rim of this 23 km diameter crater has experienced extensive pit development accompanied by lateral erosion of the crater rim and ejecta.
- The vertical and lateral erosion forming the pits may involve:
  - **Incision into thick mid-latitude mantle deposits on top of crater rim and ejecta**. If this is the case the implied missing material may be largely layered ice and dusty sediment that could be exported by eolian transport.
  - **Erosion of crater rim and ejecta materials**. If this case dominates erosion then export of the eroded debris becomes problematic.
- The present smooth floor of the pits is likely ice-rich and may or may not represent conditions and depth of ice cover representative of those during lateral erosion.

39.10°S, 16.86°E

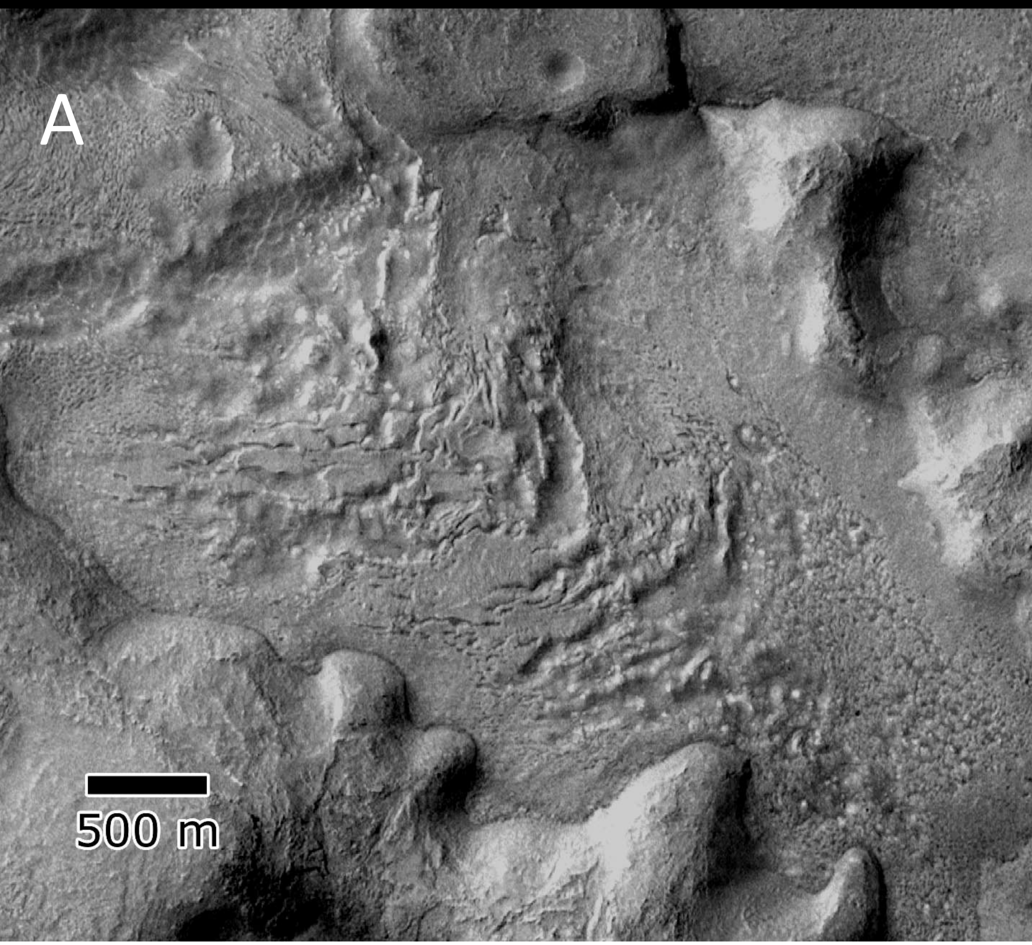
- This crater at 43.4°S, 75.8°W illustrates a variety of glacial phenomena.
- The most recent glacial advances have been less extensive than earlier ones.
- Almost all of the crater interior was covered by the oldest visible glacial complex.
- The central peak also sourced outward-directed glacial flows.

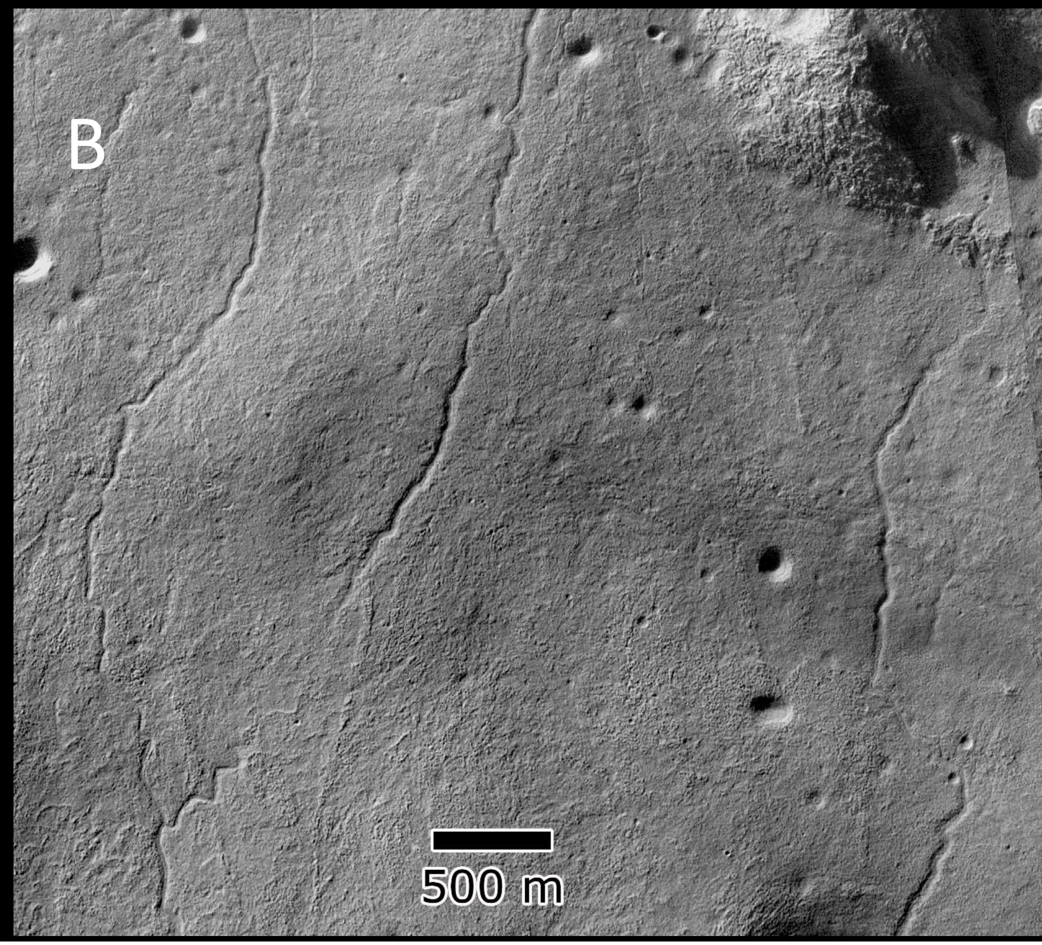




- The most recent glaciers have been deeply sublimated, indicating a high ice/particulates ratio.

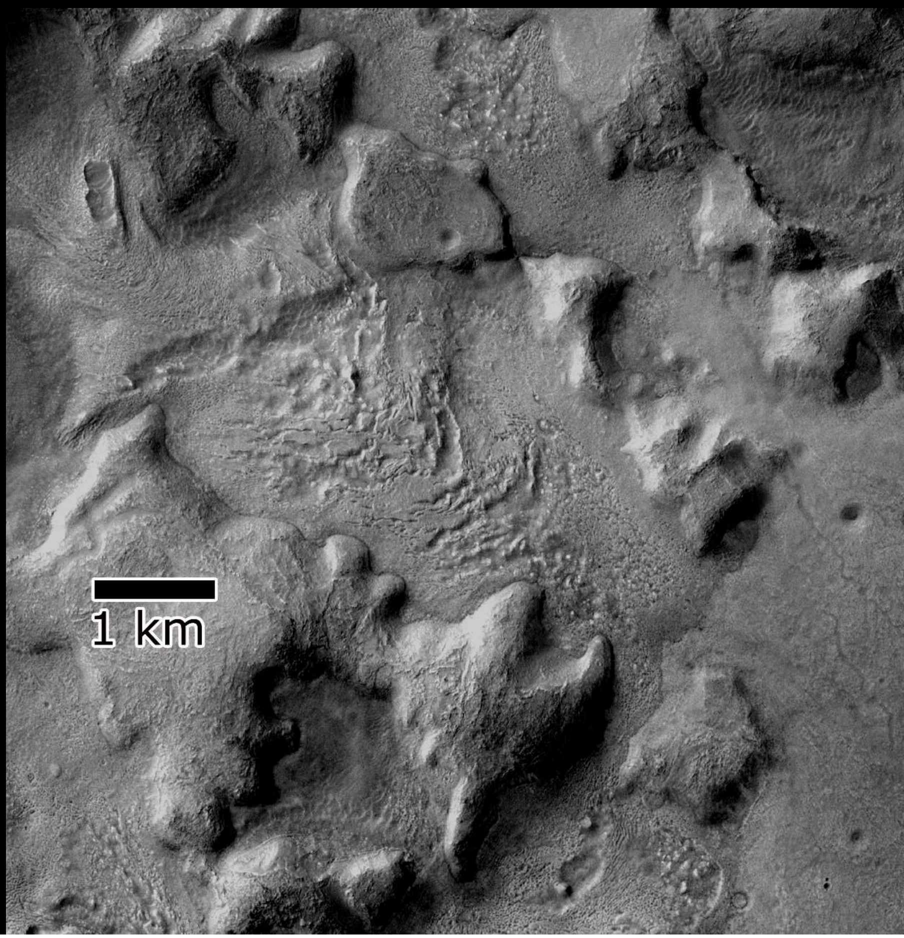
- The older glaciers are smoother, with supraglacial runoff valleys, which in some cases are inverted.
- The lesser sublimation suggest a higher particulate content, albeit with expanded craters.

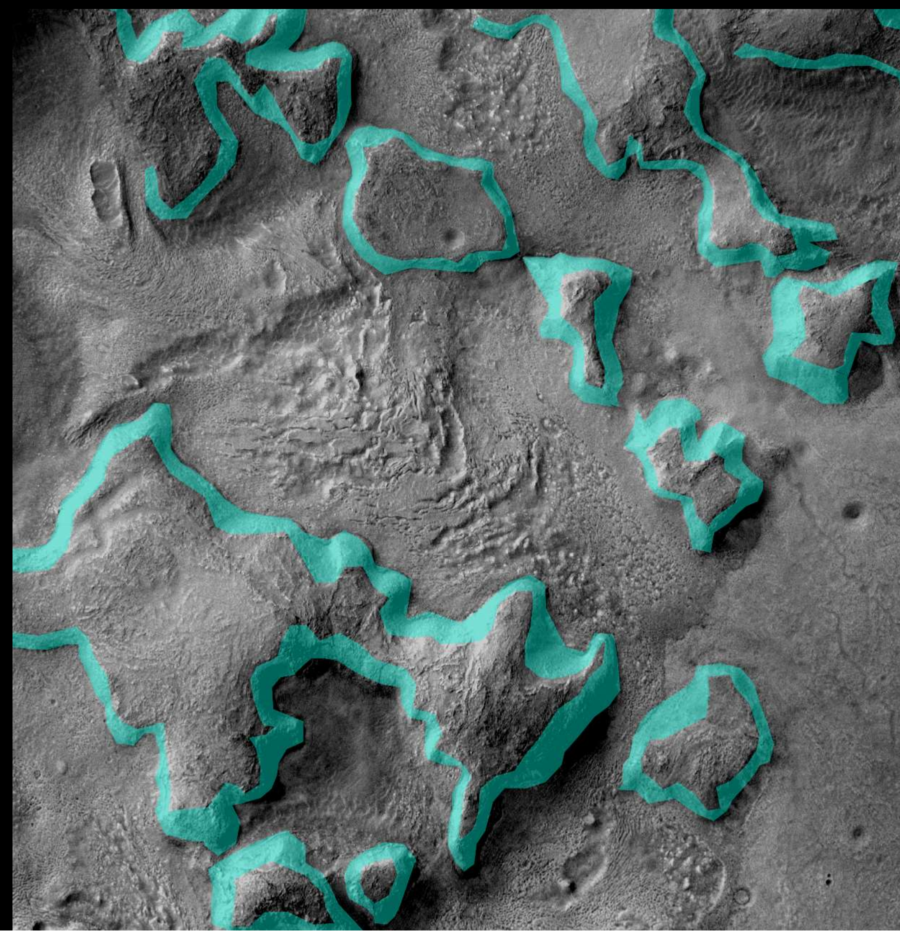


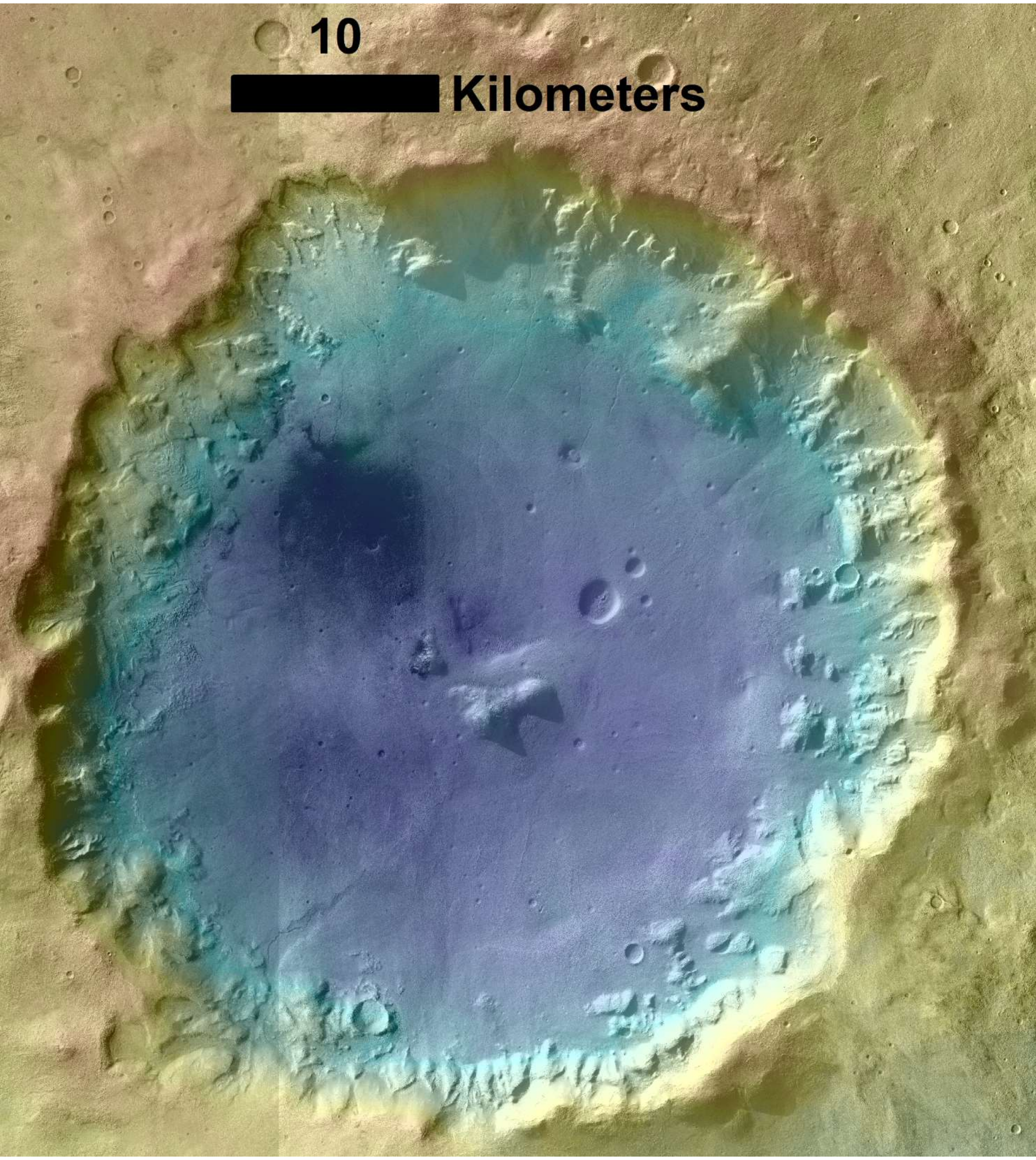


- Glaciers within this mid-latitude crater eroded laterally and probably basally as well.

- The blue overlay on the image to the right shows interior crater wall slopes steepened by lateral glacial erosion.



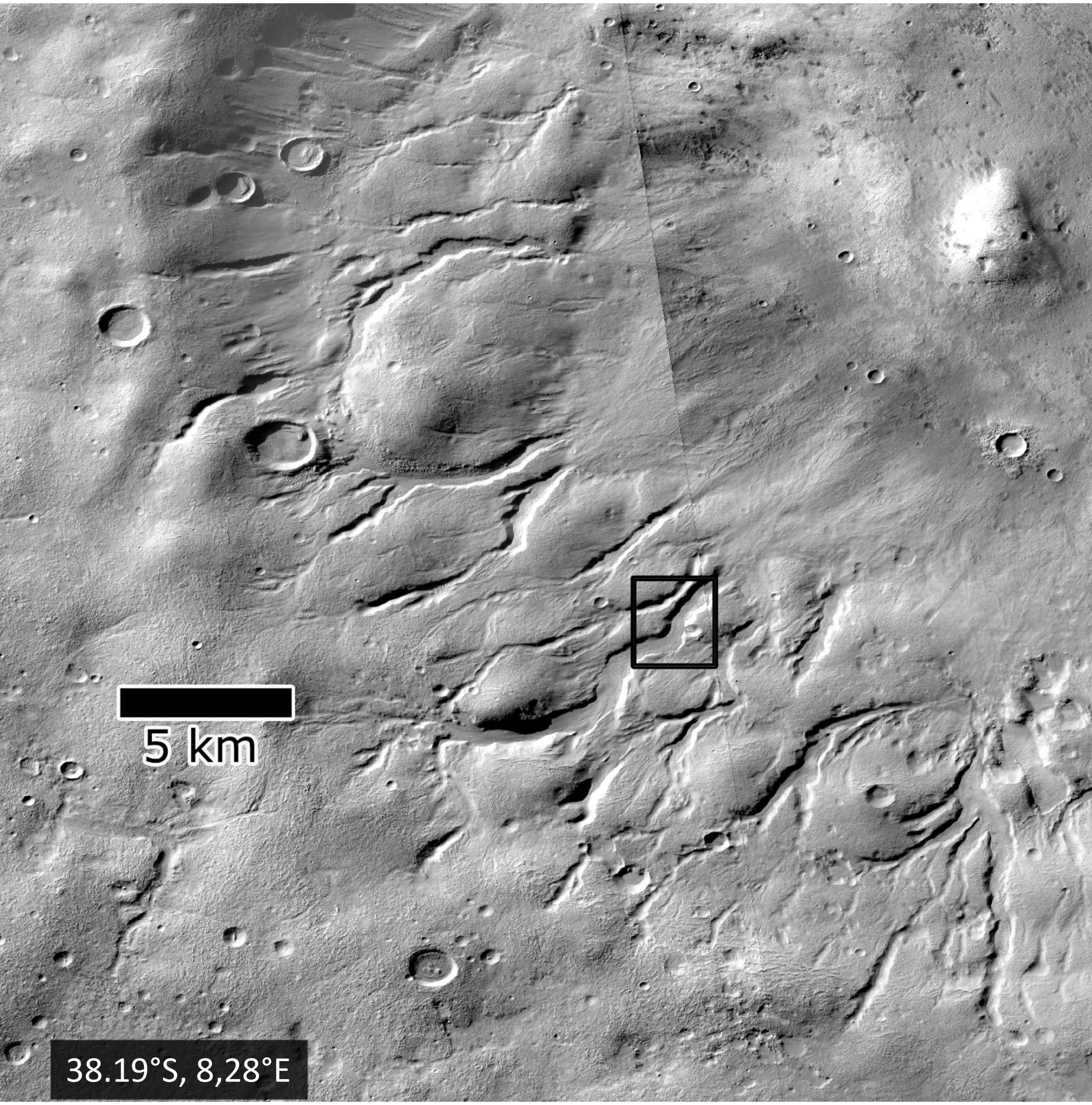




The “scalloped” interior rim of the crater, particularly in the western and northern quadrants, probably implies lateral glacier-related rim erosion on the scale of 1 to 3 kilometers of rim retreat.

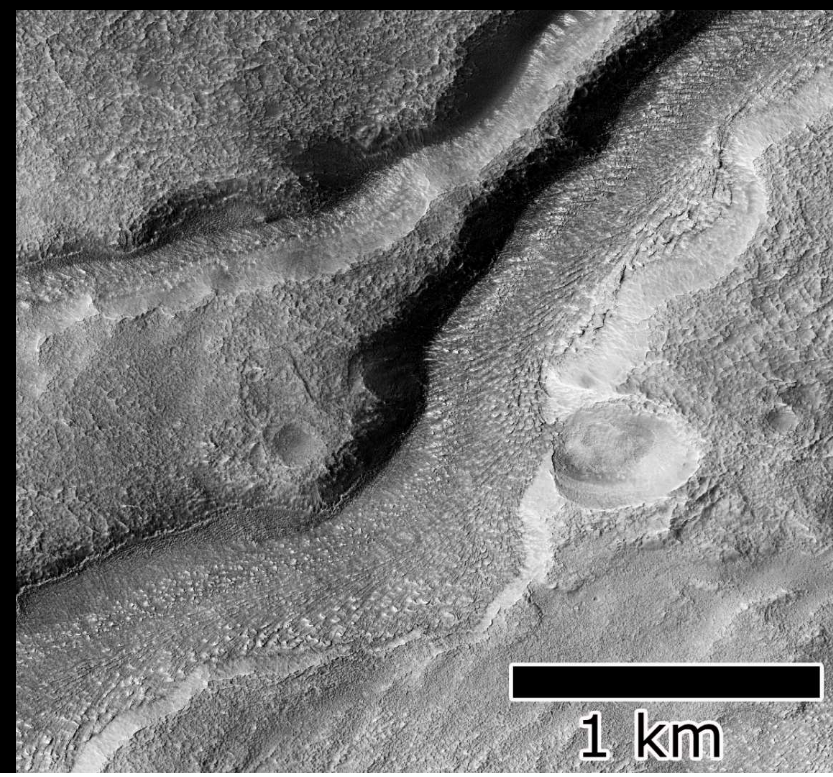
Processes of Erosion

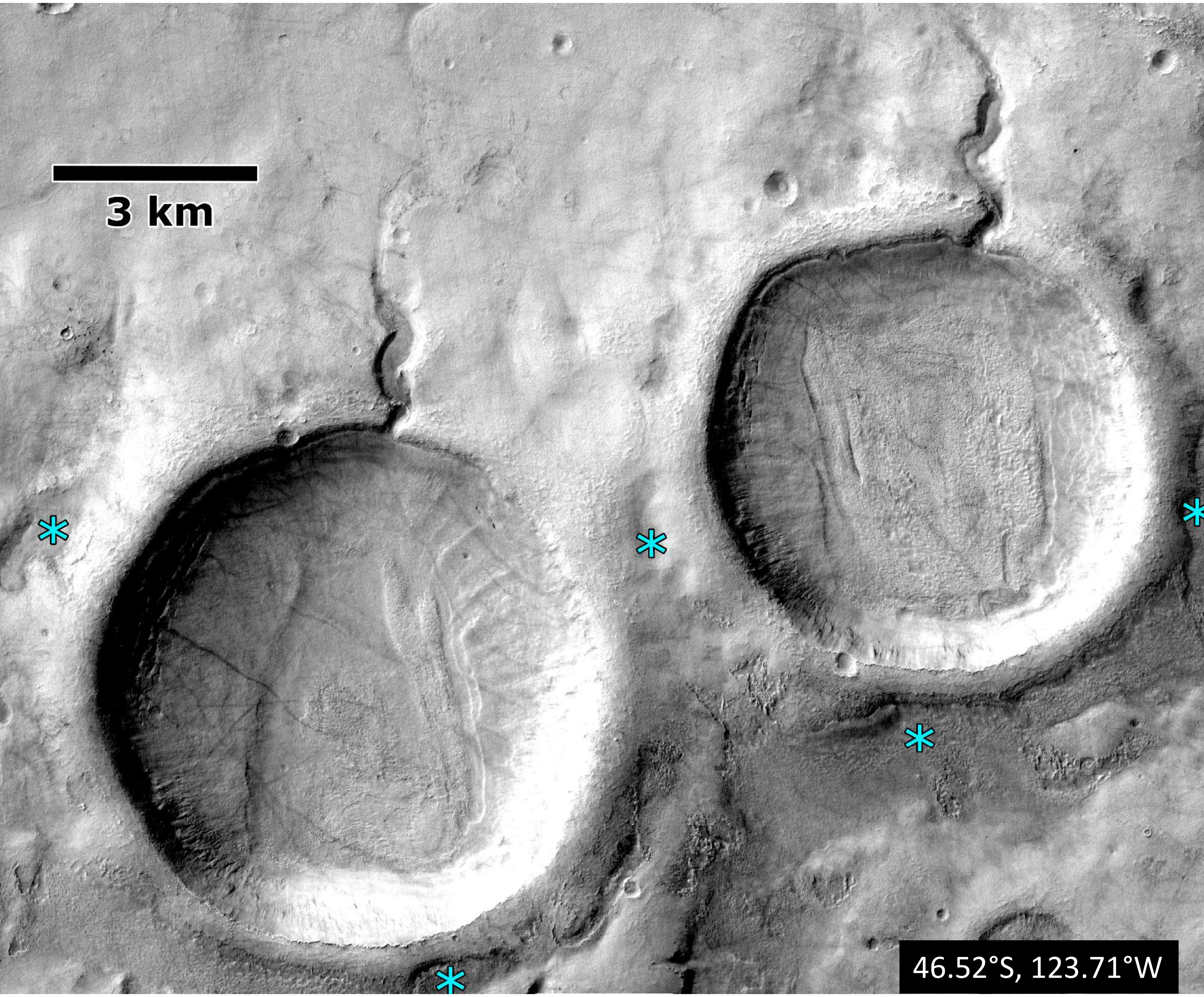
- Erosion is concentrated at the contact between ice and crater interior walls or ejecta.
- The eroding ice may be flowing as glaciers in crater interiors or relatively fixed as in exterior wall pits.
- The depth of erosion extending beneath extant ice is uncertain.
- The mechanics of erosion are uncertain – shear, tensional fracturing, and ice melting and freezing are possible. Evidence for episodic liquid water is abundant for mid-latitude craters in the 38-50° N and S latitude range.
- The present inventory of ice as CCF or as ice within pits on ejecta may not be the primary agent of erosion. Cycles of ice accumulation, flow, and sublimation are likely to have occurred.
- In many cases it is unclear whether erosion is attacking thick mid-latitude mantle deposits or crater wall and ejecta deposits.
- In the case of enclosed depressions material is missing – possibly due to sublimation if erosion primarily attacked ice-rich mantles (e.g., Dundas et al., 2021), or erosion was aided by eolian deflation.



In the 35-45° latitude range glacial and mantling processes have often alternated with fluvial incision, as shown here.

The inset shows former fluvial valleys now occupied by, and widened by, glacial ice.

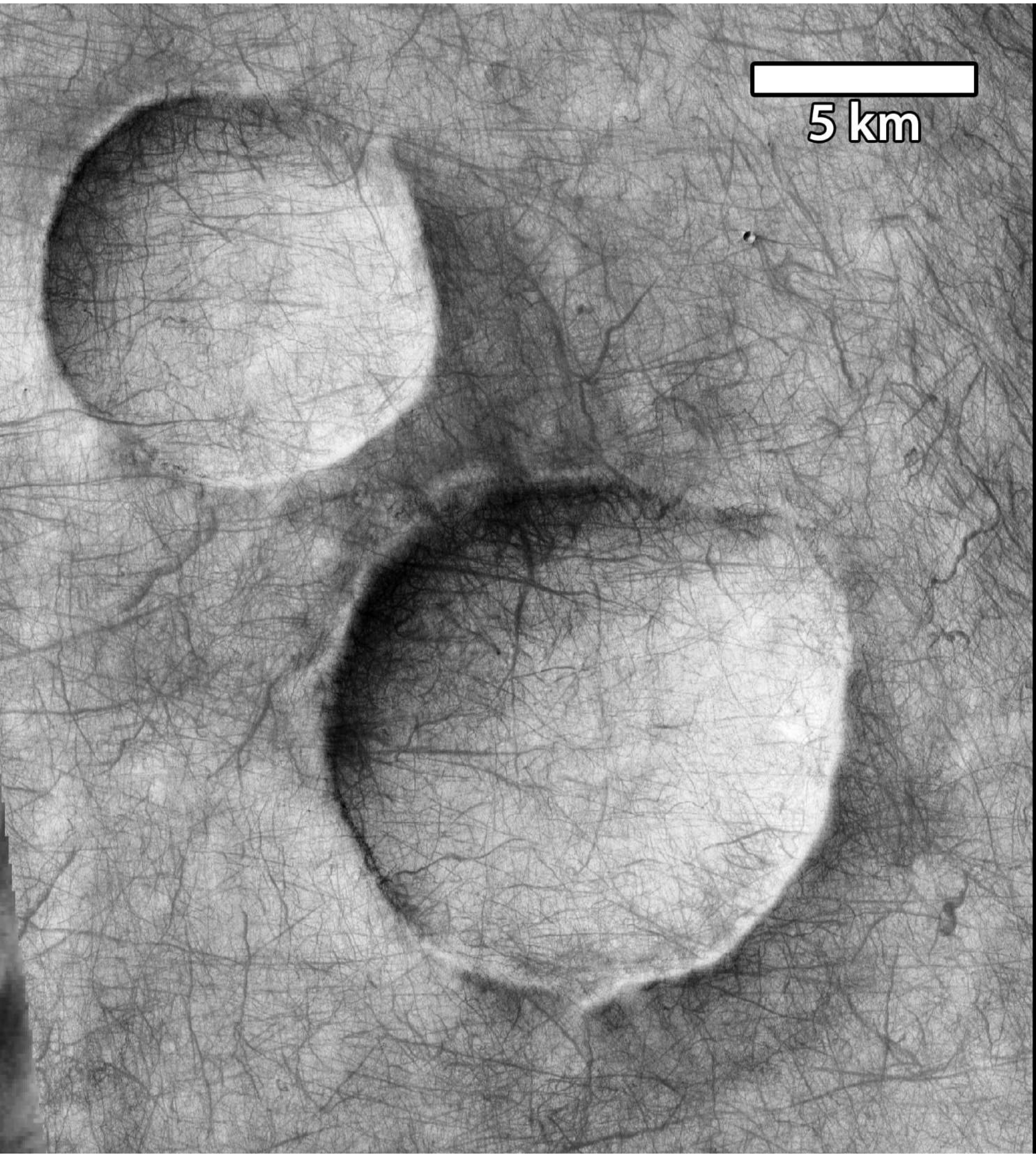




These exit-breach, or pollywog craters indicate that an ice/water infilling once reached sufficient depth to cause overflow and erosion of the crater rim.

Asterisks mark locations along the craters' exterior where depressions are associated with exterior rim backwasting.

Both the pollywog craters and fluvial incisions indicate liquid water was episodically abundant in the mid-latitudes.

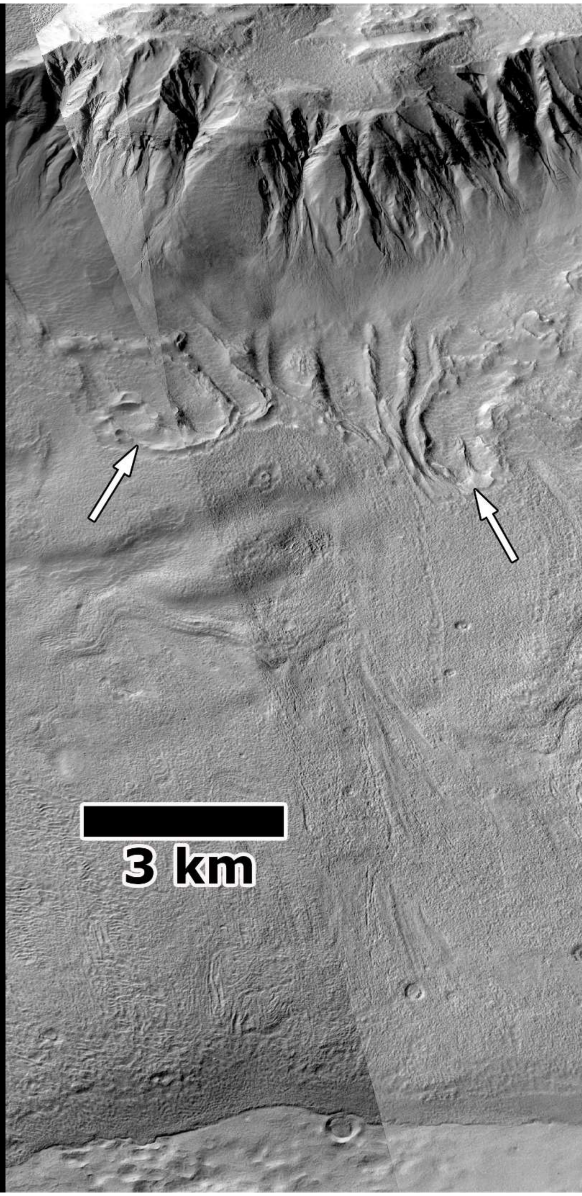


At latitudes poleward of 50° degradation of craters and intercrater plains is dominated by mantling and glacial flow.

Evidence for fluvial activity or ice-related erosion is generally absent, although evidence for past activity might be buried beneath the hundreds of meters of mantling.

The abundant dust-devil tracks suggest eolian processes also might be important in sediment redistribution

60.23°S, 161.67°W

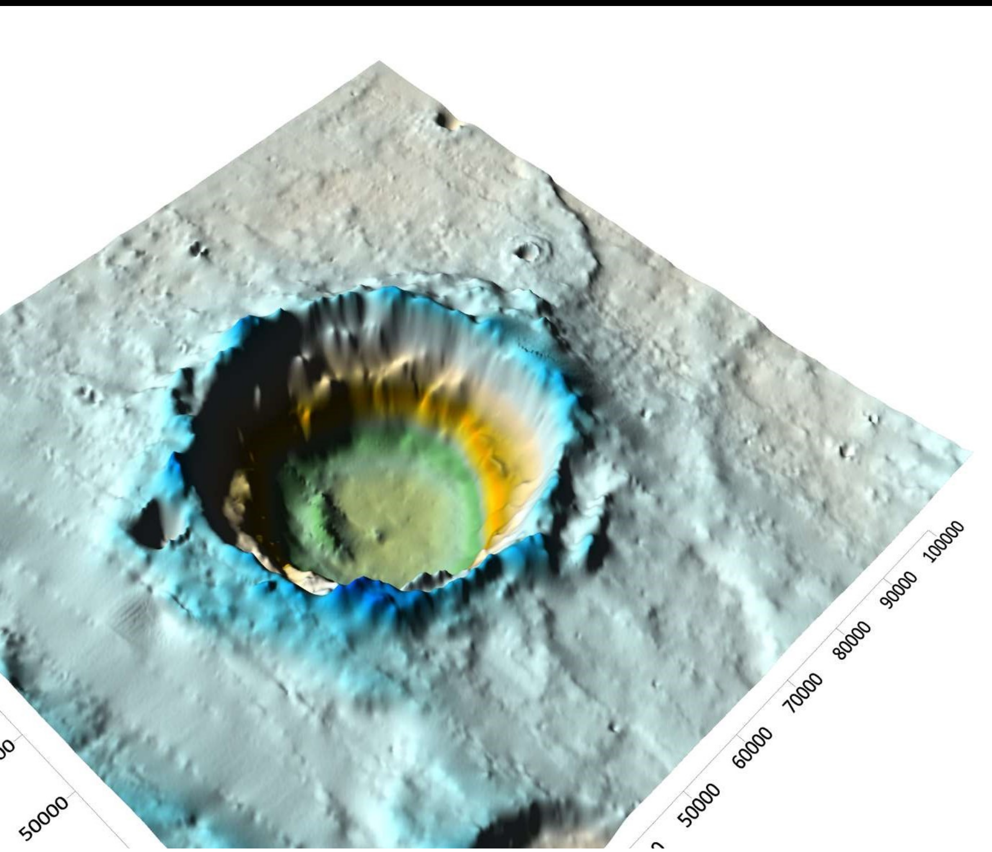


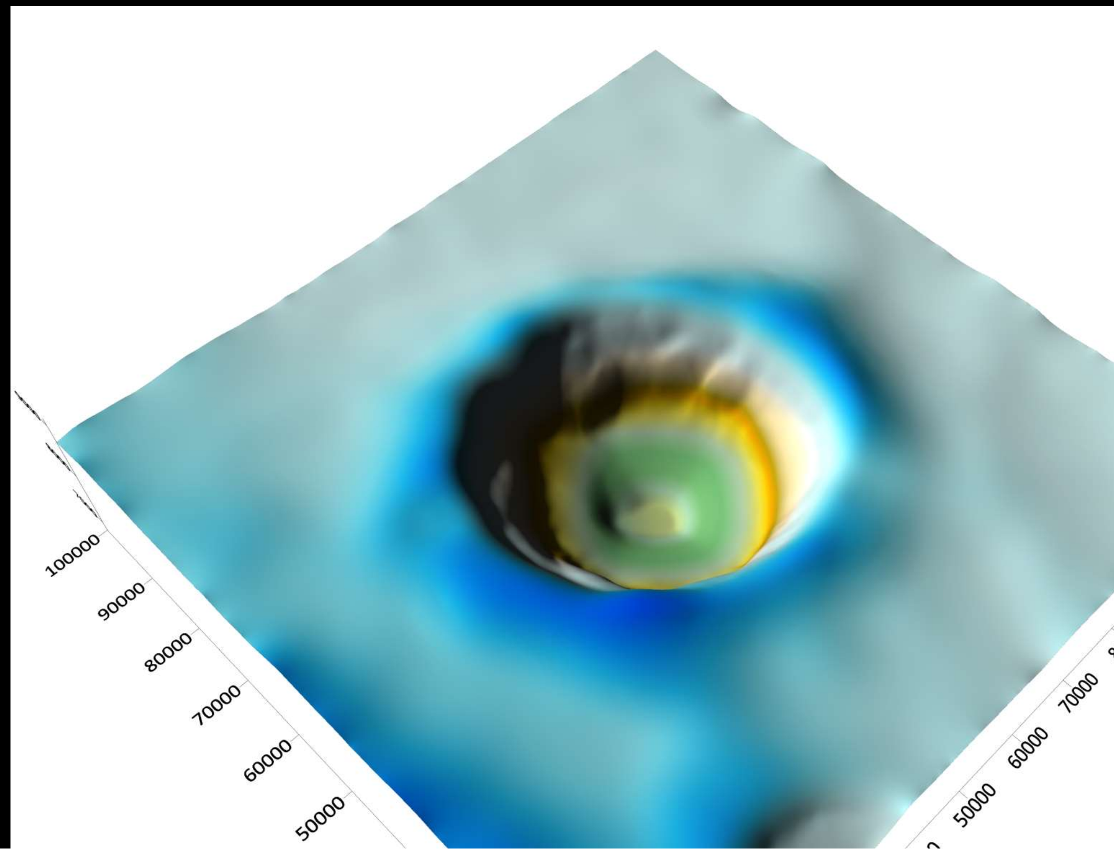
The spatulate ridges (white arrows) are remnants of relatively recent glaciers sourced from the crater rim (top) now almost completely sublimated away.

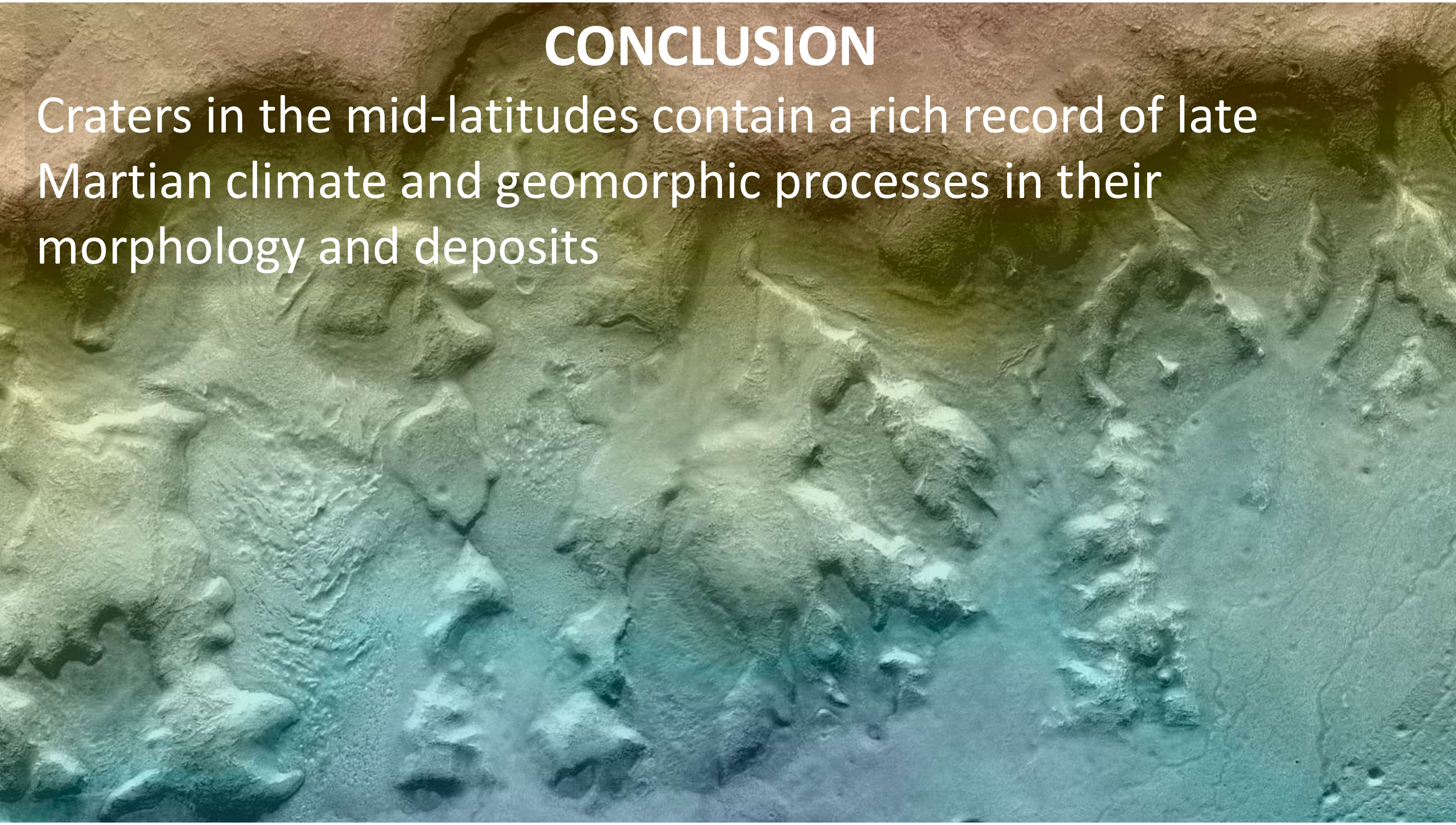
The more extensive earlier glacial flows in the crater interior are much less sublimated, suggesting a higher dust/particulate content

Preliminary simulation modeling of mid-latitude landscapes

- The crater on the left is a fresh martian crater
- The crater on the right has been modified by a combination of atmospheric ice deposition, weathering of the crater rim, diffusive mass wasting, and glacial flow. Glacial erosion is not modeled, however. Although the ice deposition is areally uniform, an inward-directed flow front develops because of the steep crater walls and the radial symmetry







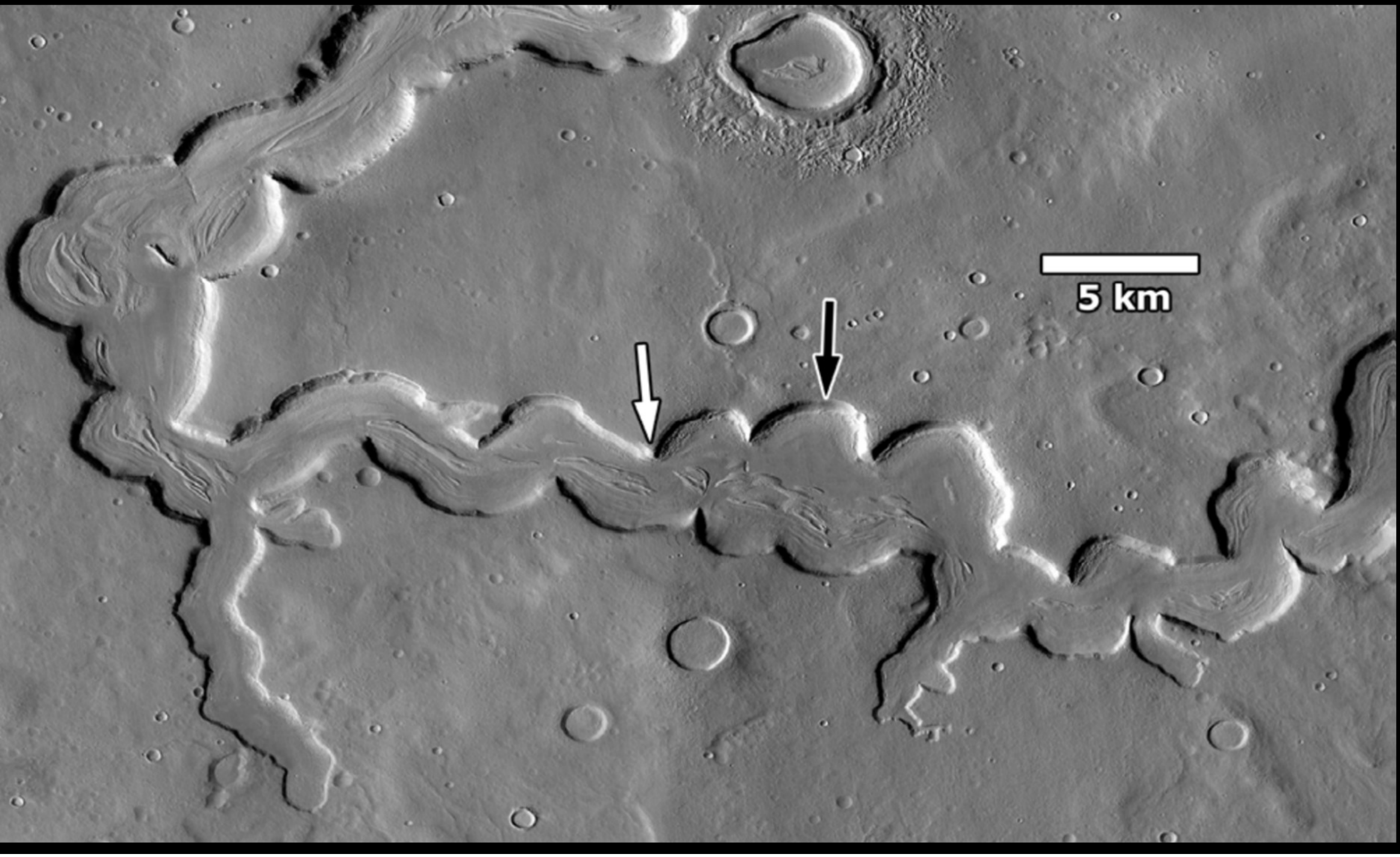
CONCLUSION

Craters in the mid-latitudes contain a rich record of late Martian climate and geomorphic processes in their morphology and deposits

Decrescent Scarps on Mars

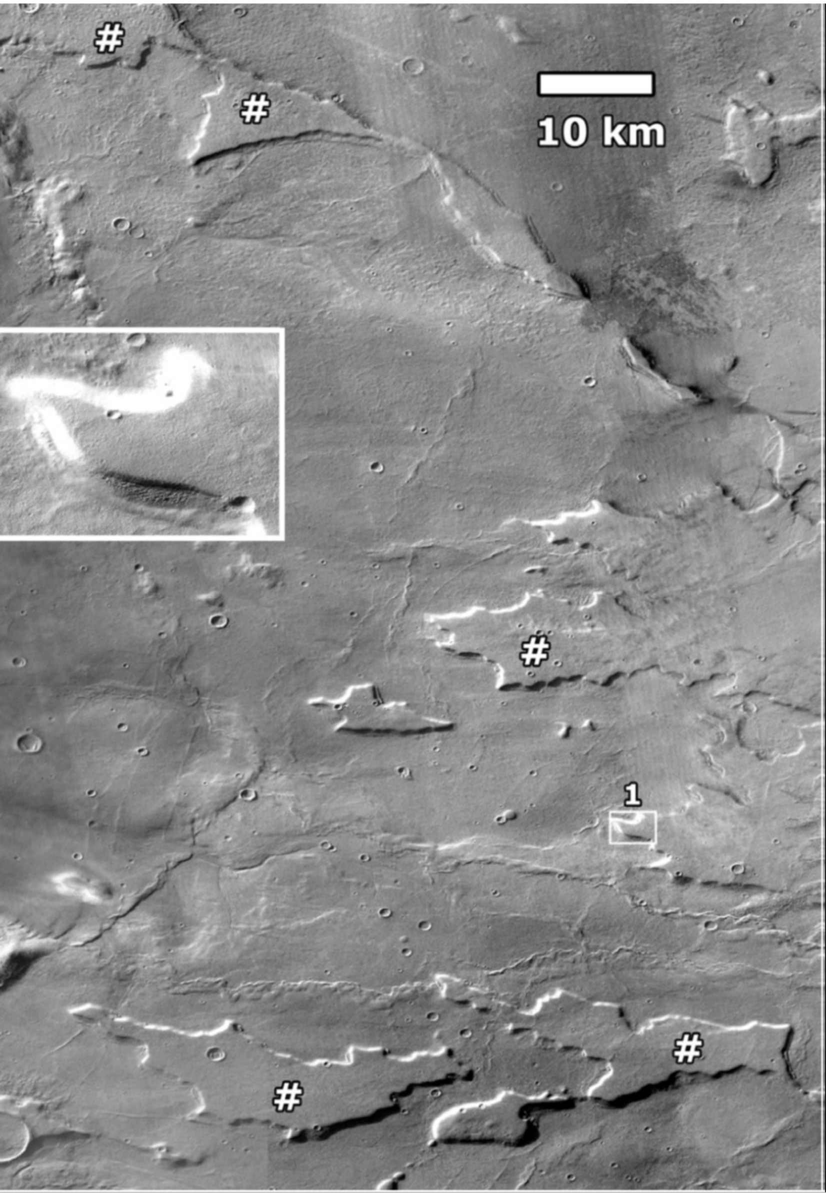
- Where the rate of retreat of scarps at the edge of plateaus is nearly spatially uniform (quasi-uniform decrescence) their planform evolves into pointed projections and broad embayments
- Three rate laws permit long-distance scarp retreat.
  - Case A, applicable, for instance, to polar scarps on Mars, is a threshold between ablation of steep slopes and non-erosion or accumulation on slopes below that threshold.
  - Case B is where a indurated caprock creates steep slopes, while continued erosion of the subjacent slopes episodically undermines the caprock, as happens in the southwestern United States.
  - Case C is where erosional attack is concentrated at the base of the slope, such as by running water, groundwater sapping, or, as suggested here, erosion by glacial ice accumulated at the base of scarps.

Decrescent widening of valleys at 36.7° N by lineated valley fill

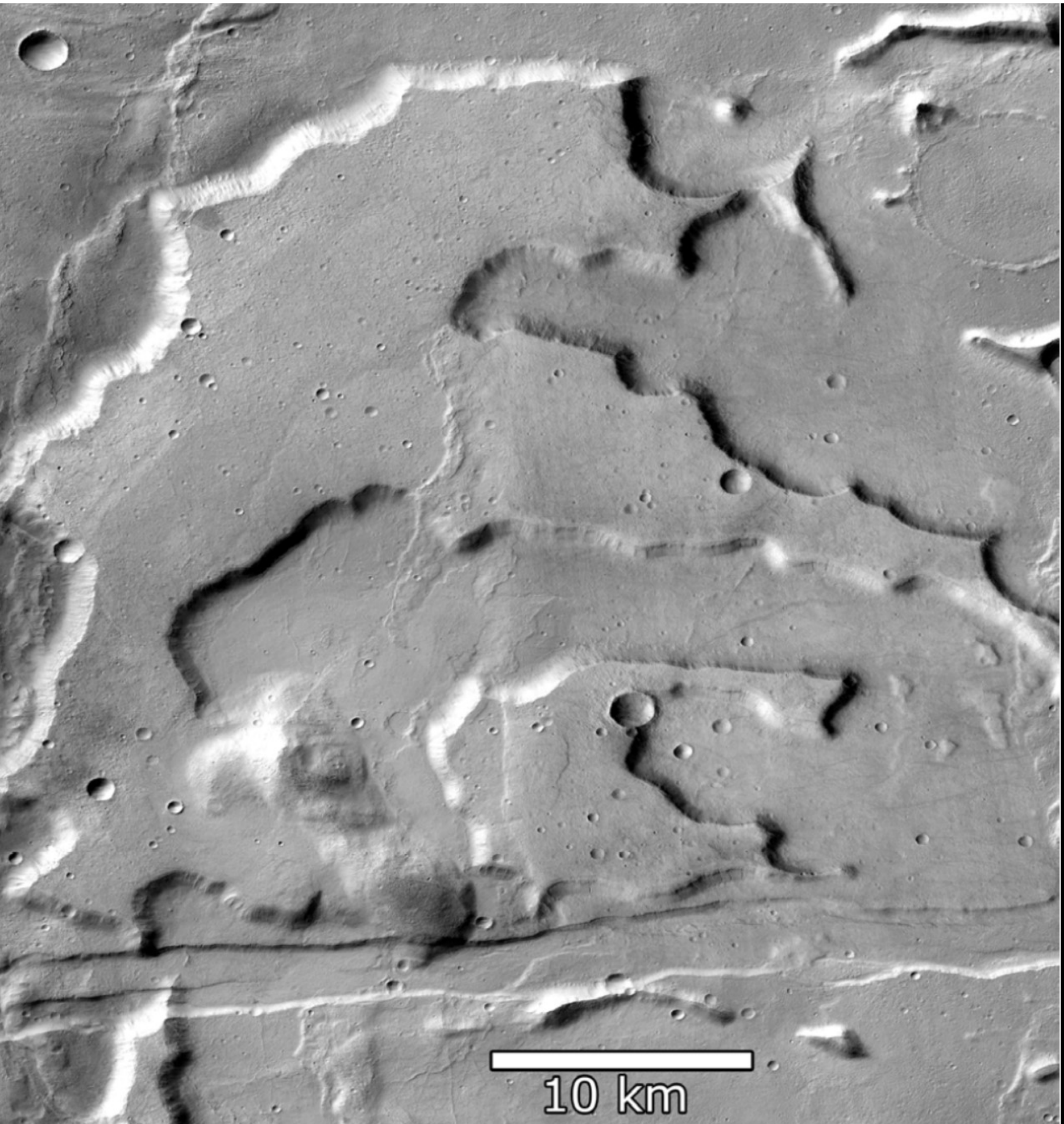


White Arrow: Pointed projections

Black Arrow: Concave embayments

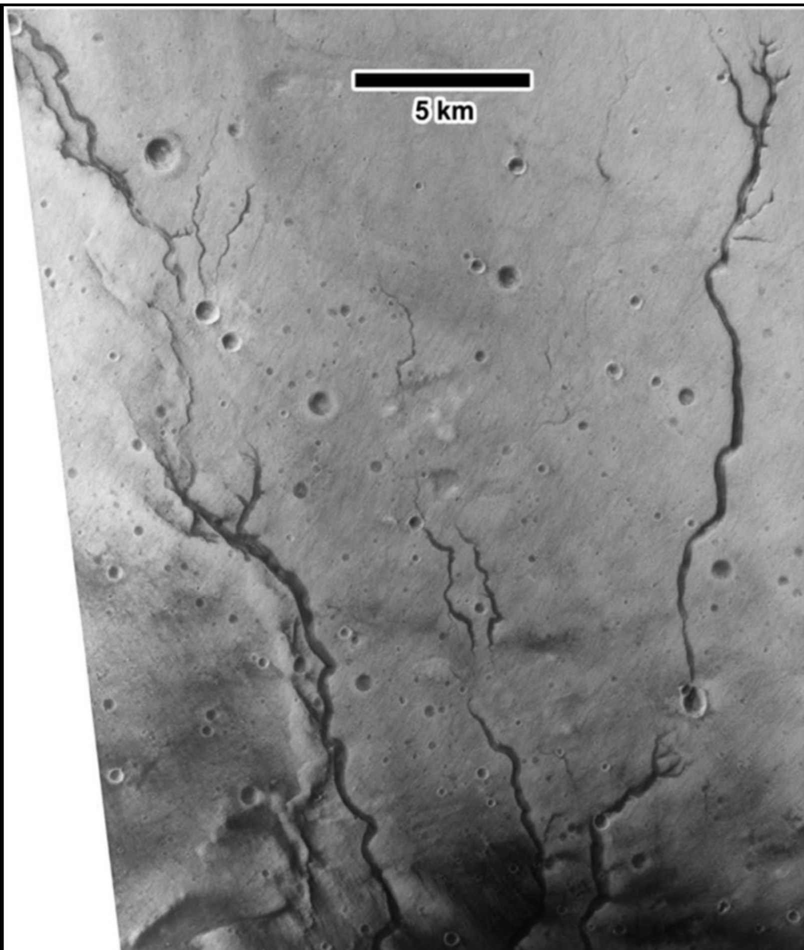


- Decrescent mesas on the eastern slopes of Hellas basin at 98.12°E, 41.29°S, with example mesas shown by "#"s.
- The inset from the scarp at "1" shows sublimation-decaying LDA on the southwest-facing mesa scarps

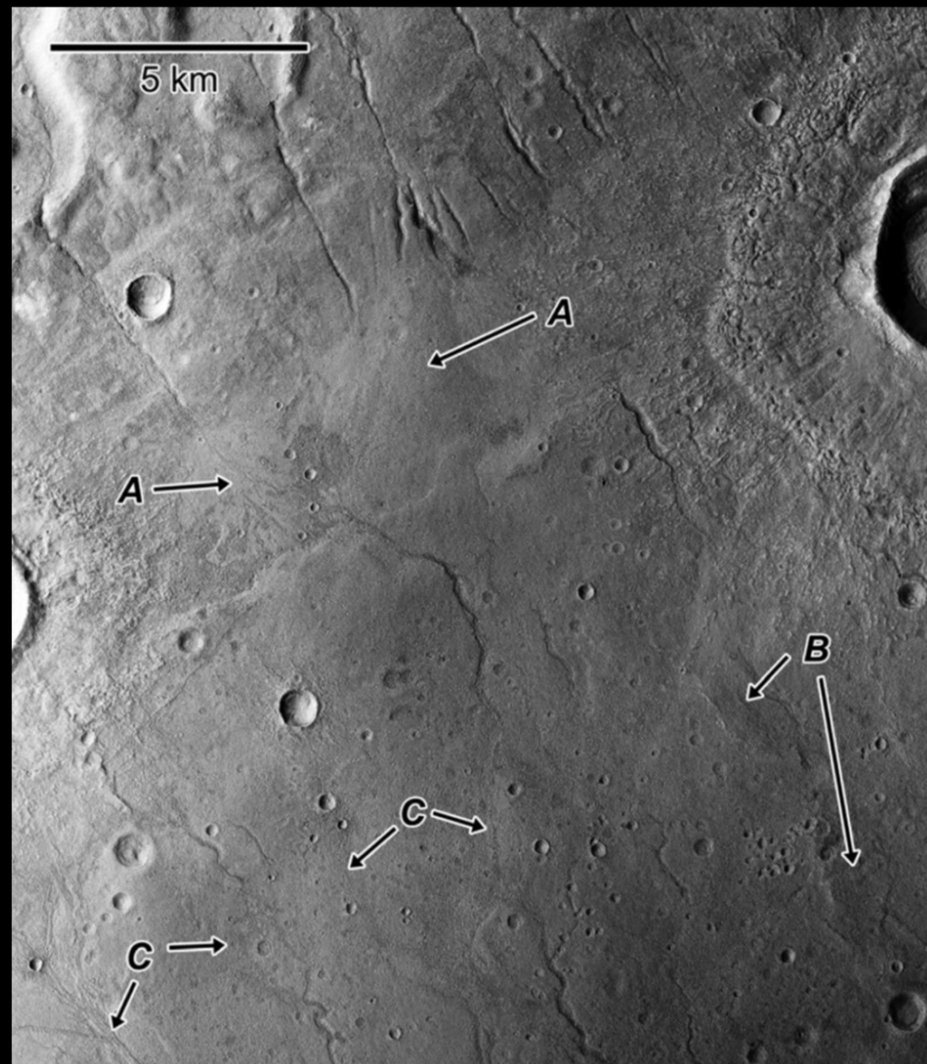


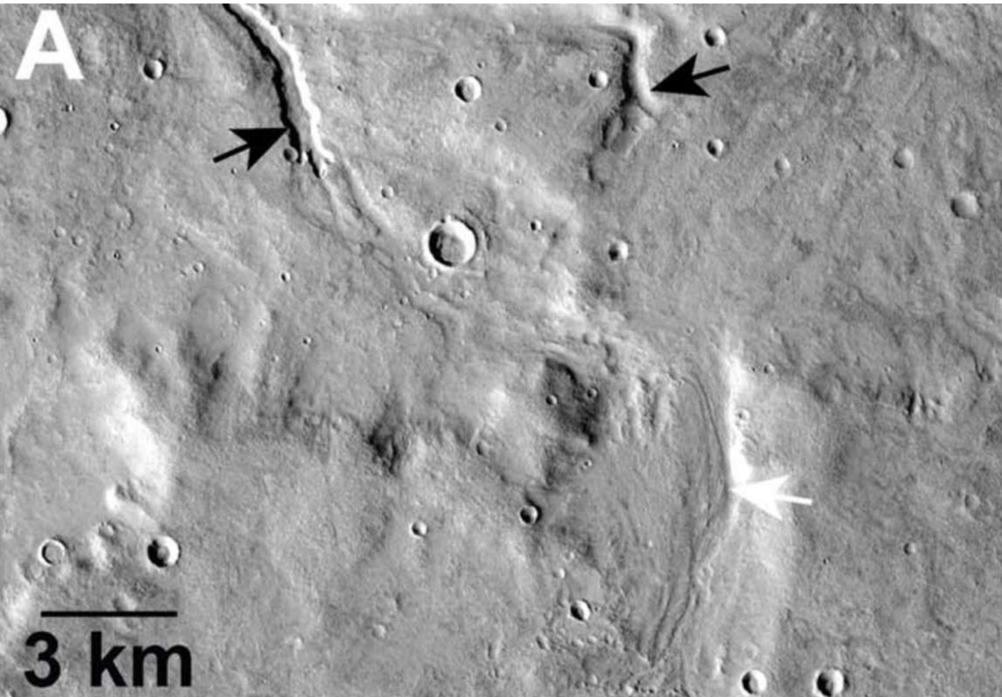
- Decrescent scarps in the Electris deposits at 177.06°E, 36.67°S in the Sirenum Fossae region
- Our hypothesis:
  - During quasi-cyclical episodes of ice accumulation in the mid-latitudes ice preferentially accumulates at the base of scarps
  - Alternatively, ice accumulation is uniform, but remains longer at the base of scarps
  - The ice attacks, disaggregates, and transports deposits at the base of the scarp from the scarp face as well as undermining and advacting the upper parts of the scarp.
  - We suggest that this process is most efficient in eroding thick deposits of poorly consolidated sediment.

Fresh, shallow valleys (FSVs) in Newton Crater

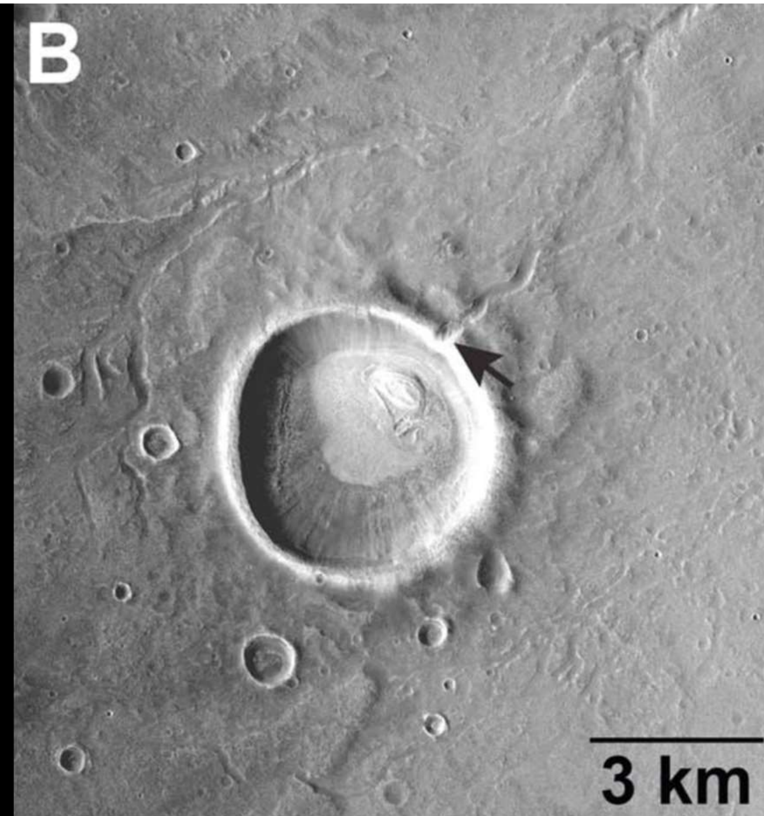


FSVs are defined by having a relatively fresh, undegraded appearance (i.e., young), and are shallowly incised into the host terrain

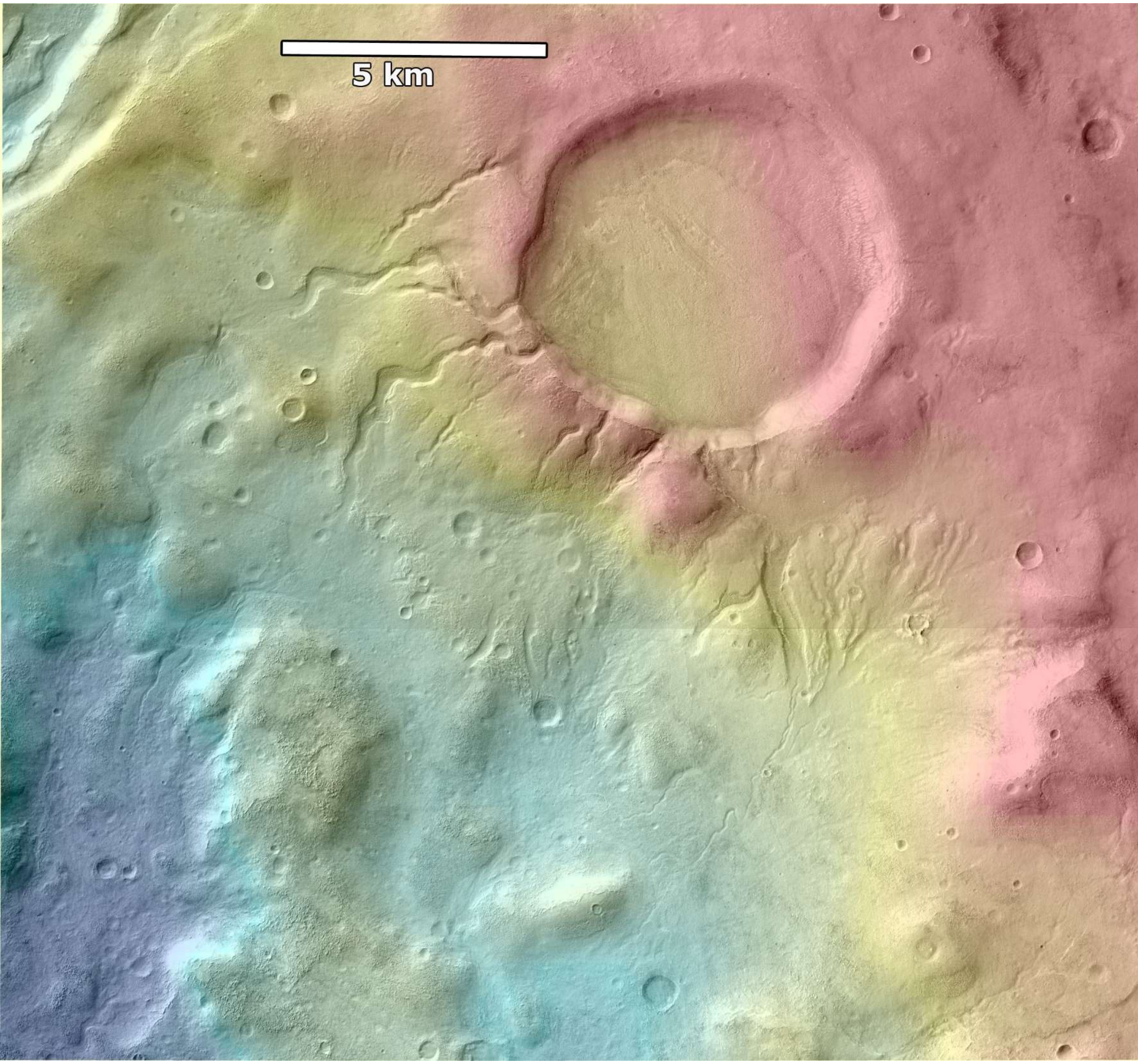




When crossing relative depressions, FSVs often widen and display bed a braided appearance



FSVs are often associated with pollywog craters, and the exit channels (tails) are, by definition FSVs



A pollywog crater with multiple exit breaches.

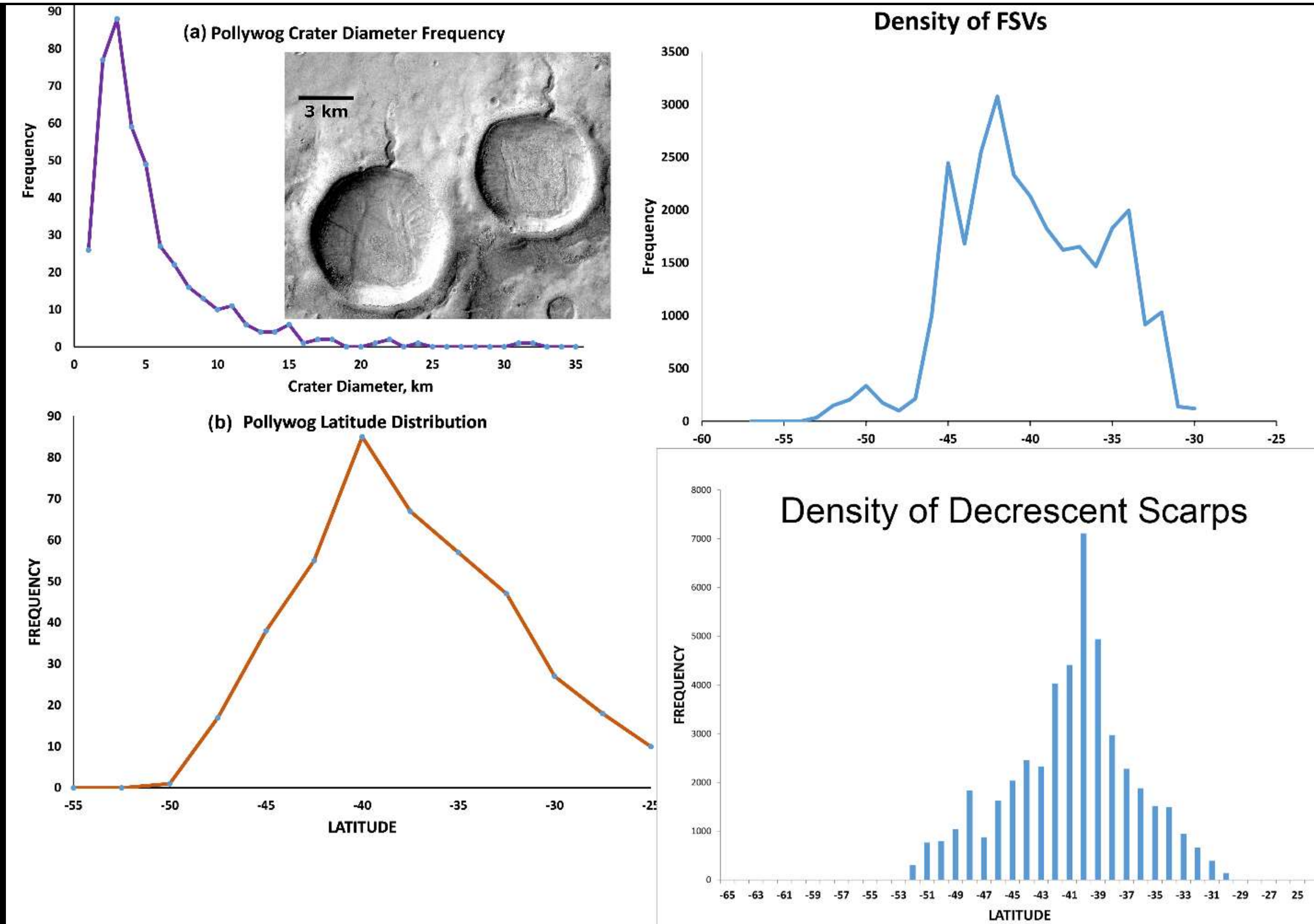
The hydrology of FSVs and Pollywog craters is an enigma.

They are mid-latitude features, and presumably form from seasonal or episodic melting of ice-rich deposits.

The multiple exit breaches of this pollywog suggest multiple runoff events.

Pollywogs formed by flow exiting from an Ice-covered lake or from a crater deeply encased in ice?

FSVs due to surface runoff or flow beneath ice?



(a) Pollywog Crater Diameter Frequency
3 km
Frequency
Crater Diameter, km
(b) Pollywog Latitude Distribution
FREQUENCY
LATITUDE
Density of FSVs
Frequency
Density of Decrescent Scarps
FREQUENCY
LATITUDE