2. Recent erosional landforms: A cold desert

2.1 Eolian activity *(quick summary)*

- 2.1.1 Dunes on Mars
- 2.1.2 Wind erosion
- 2.1.3 Wind streaks and atmospheric dust deposition

2.2 Polar caps

- 2.2.1 Polar layered deposits and obliquity variations
- 2.2.2 The south polar cap features and composition
- 2.2.3 Ancient polar caps
- 2.2.4 Glaciers at equatorial latitude?

2.3 Ground ice related features at permafrost scale (> 10 m thick)

- 2.3.1 Lobate debris aprons and lineated features
- 2.3.2 Terrain softening
- 2.3.3 Lobate ejecta craters

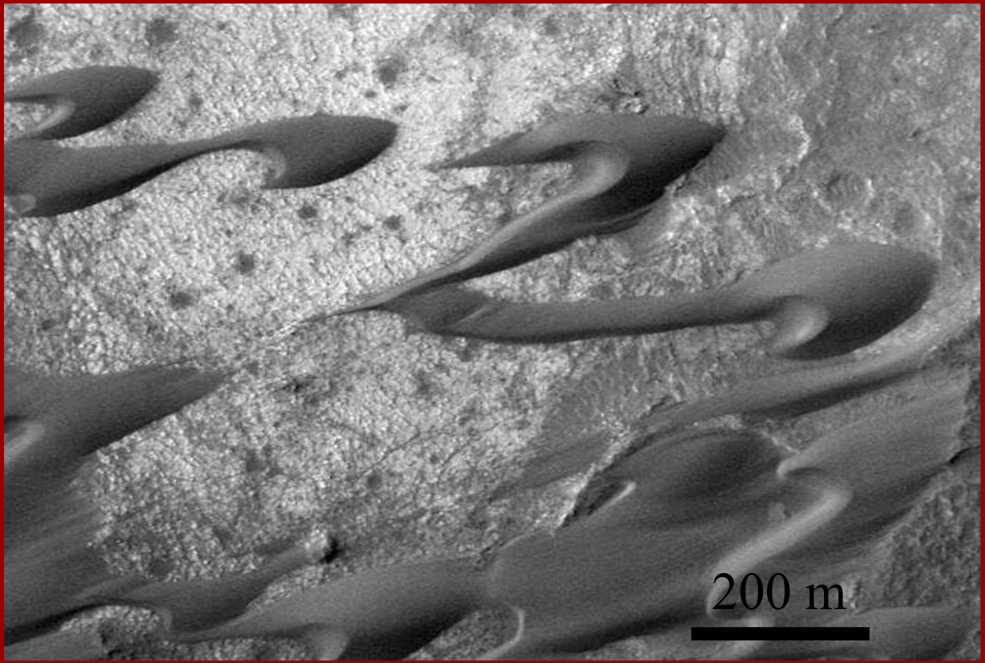
2.4 Small scale ground ice related features (< 10 m thick)

- 2.4.1 Dissected terrains and ice sublimation
- 2.4.2 Polygons, frost cracks and near surface ground ice
- 2.4.3 Recent gullies

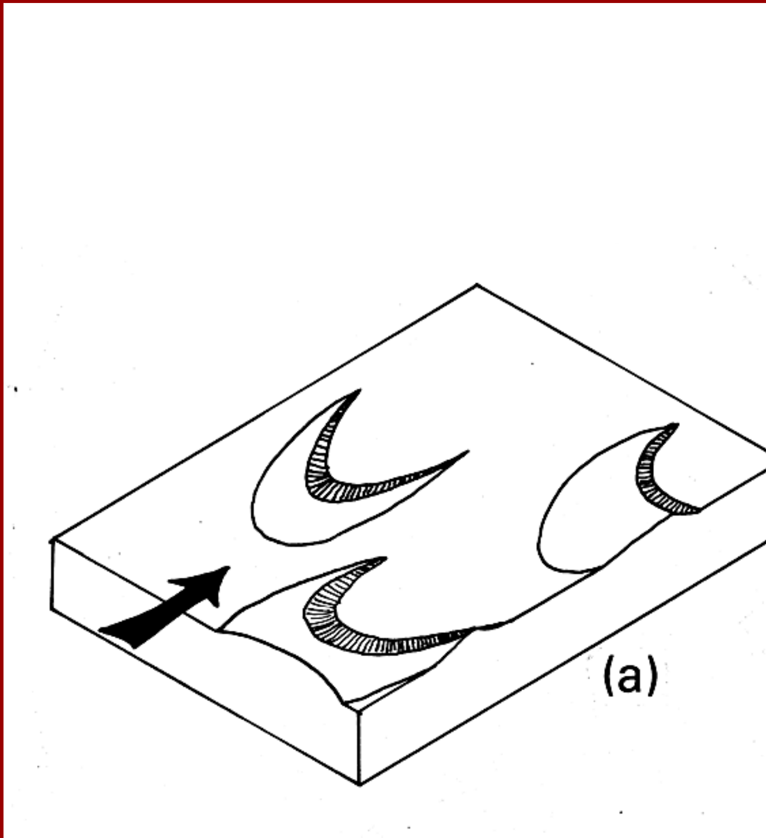
2.1 Eolian activity

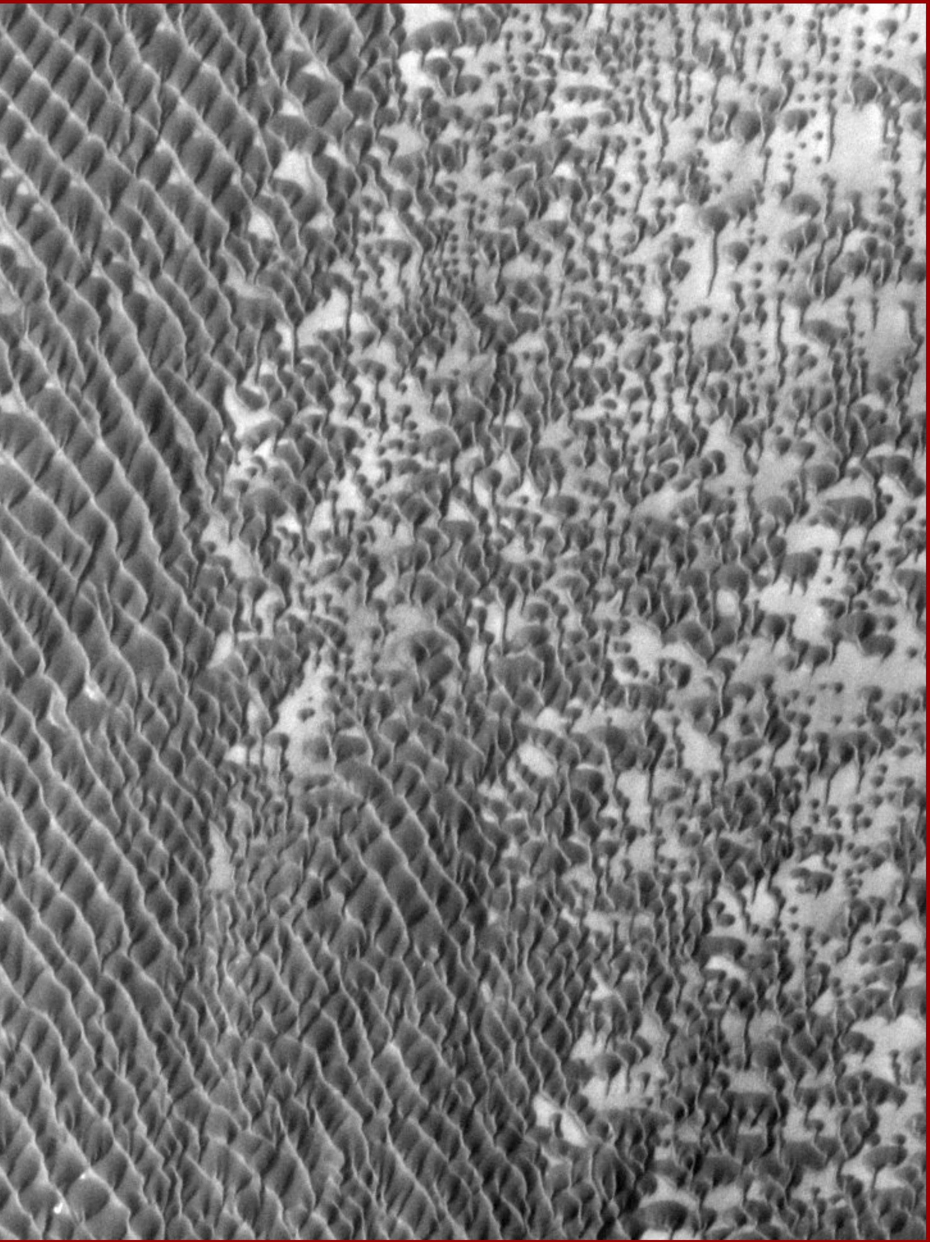
2.1.1 Dunes on Mars

- Dunes are very common at the surface
- Dark dunes on crater floors and polar regions are from several meters to > 100 m high
- Volcanic sand most likely origin for dark dunes



Typical barkhanes (wind from right to left)





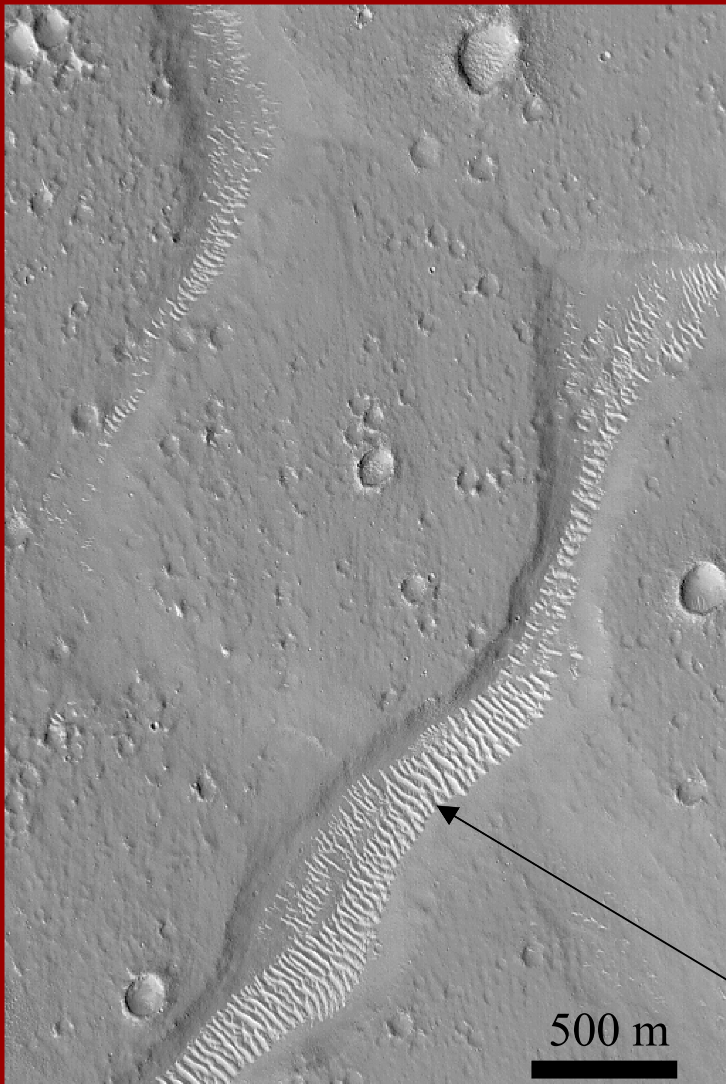
Earth
(Sahara

* Large dune fields (> 10 km long)
exist like on Earth

* No clear evidence of current activity
(no movement of dunes since Viking mission

Mars

- Bright dunes often appear as small ripples
- Material can be feldspaths or assemblages of dust particles
- They often fill depressions like ancient valleys or craters

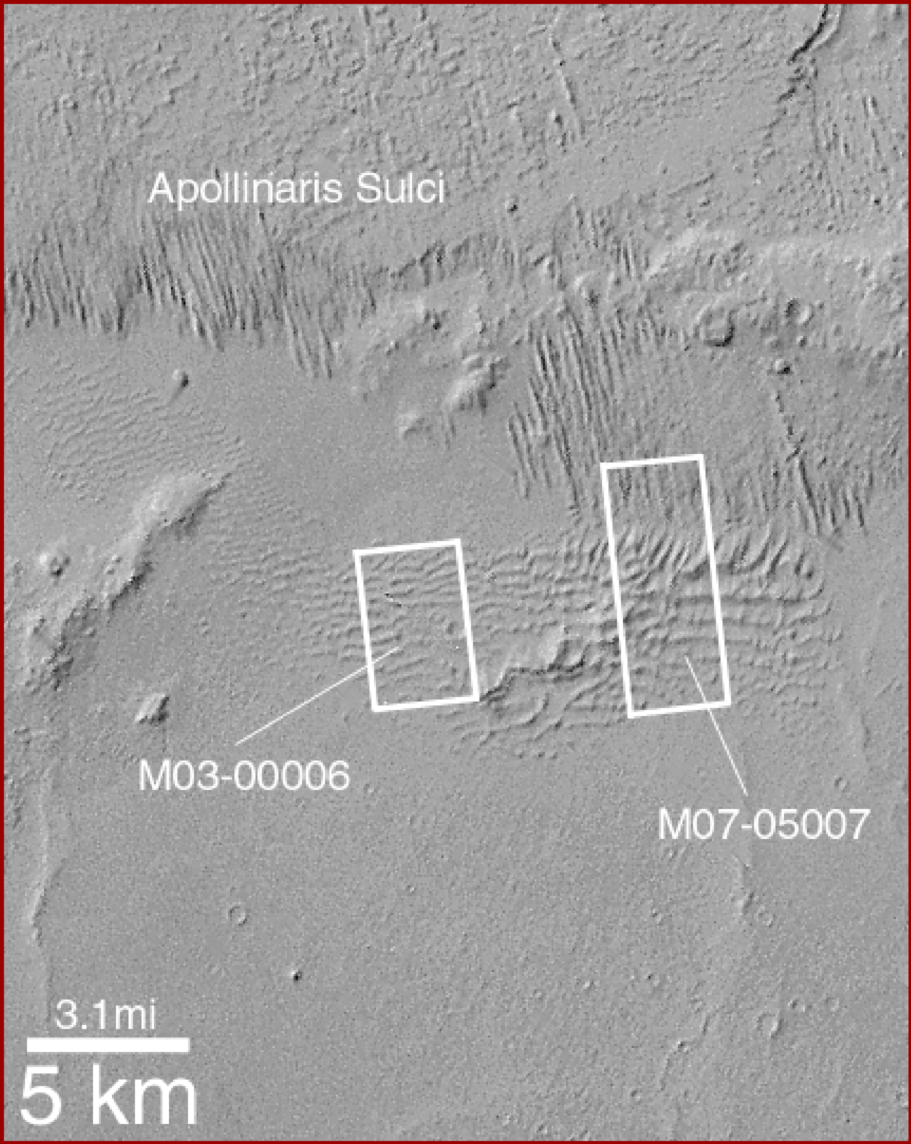


Ripples
(small dunes)

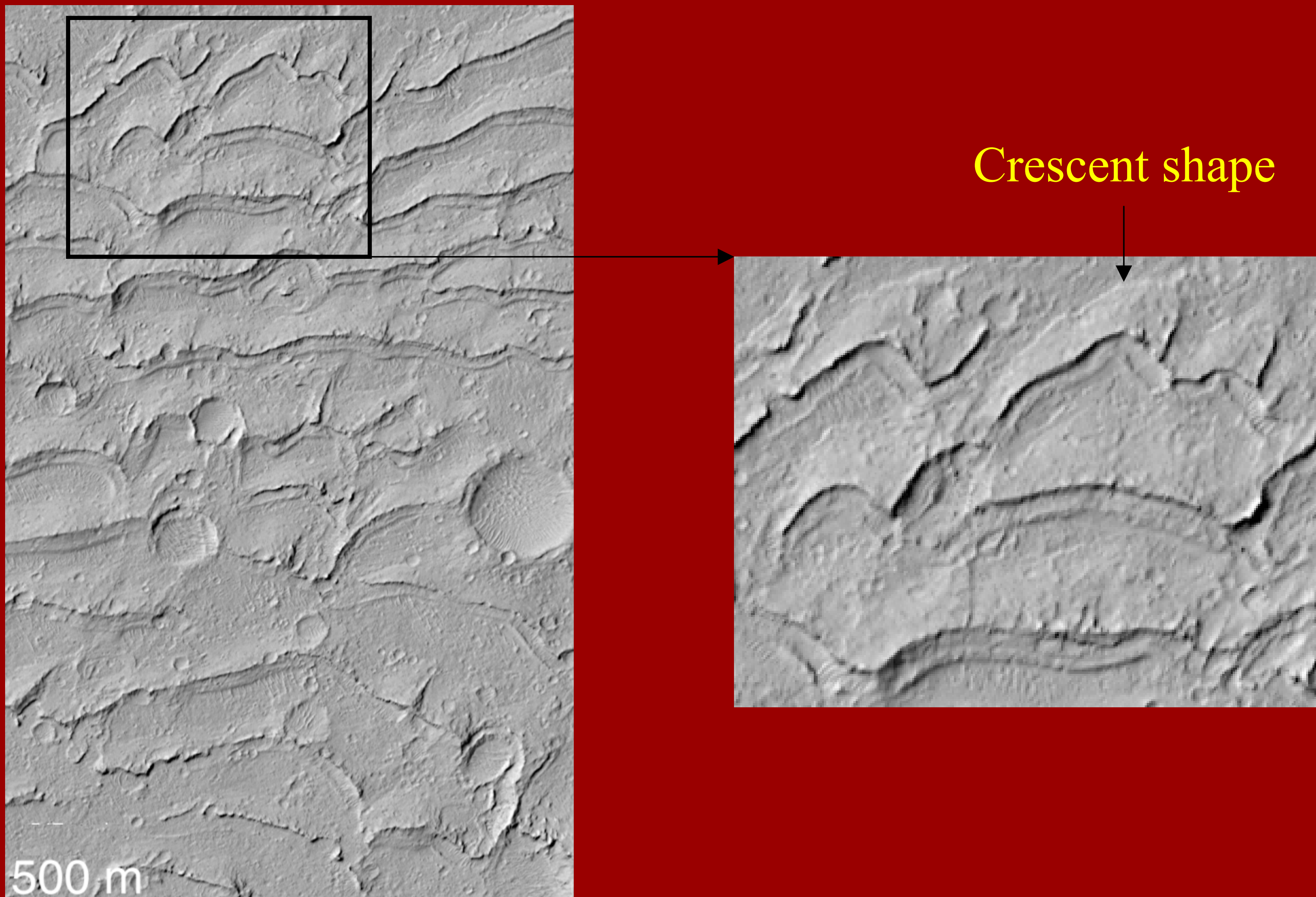
MOC images

- Ancient paleodunes are consolidated indurated dunes (sandstone)
- Presence of erosional grooves and craters

- Ancient paleodunes are consolidated indurated dunes (sandstone)
- Presence of erosional grooves and craters

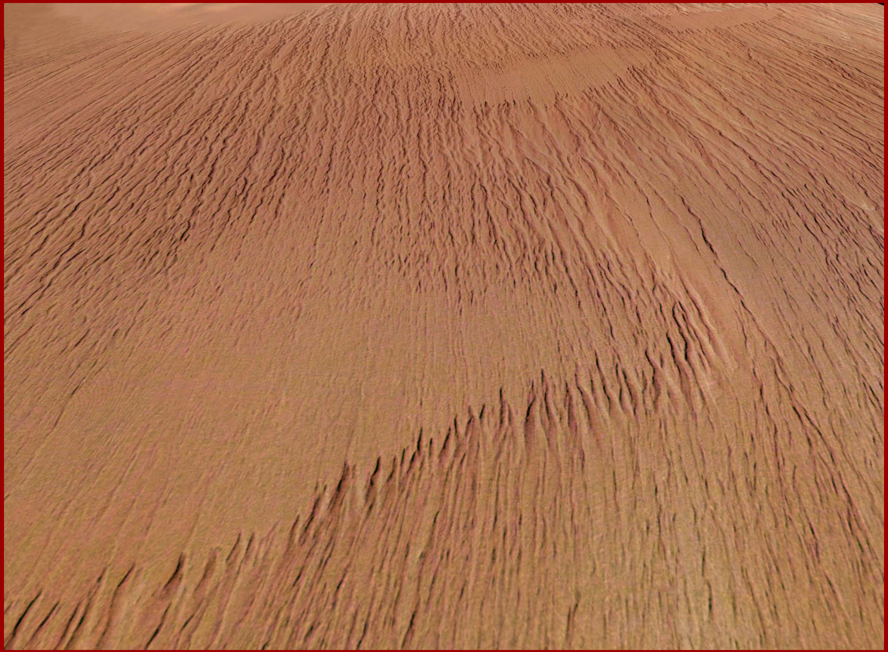


- Ancient paleodunes are consolidated indurated dunes (sandstone)
- Presence of erosional grooves and craters

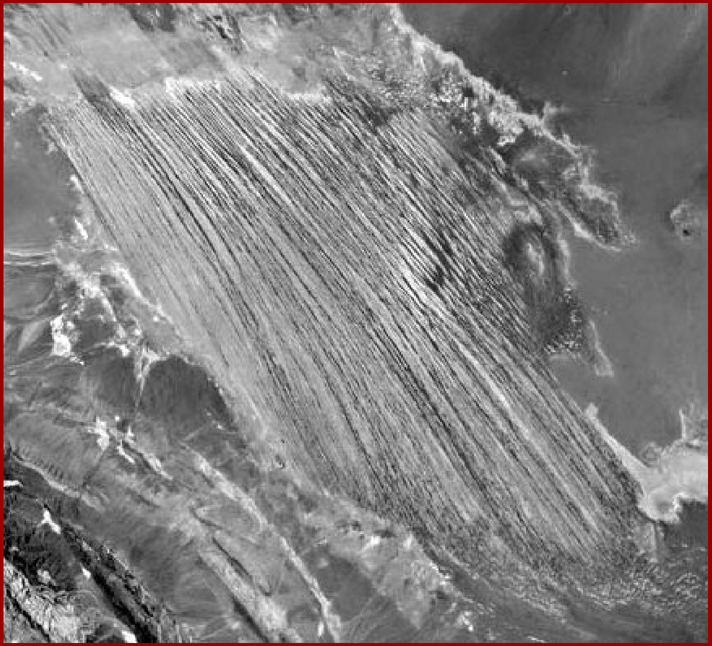


2.1.2 Wind erosion

- Yardangs are linear features formed by wind erosion on weak deposits like ash or fine sediments (especially clay)
- Eolian deflation are common

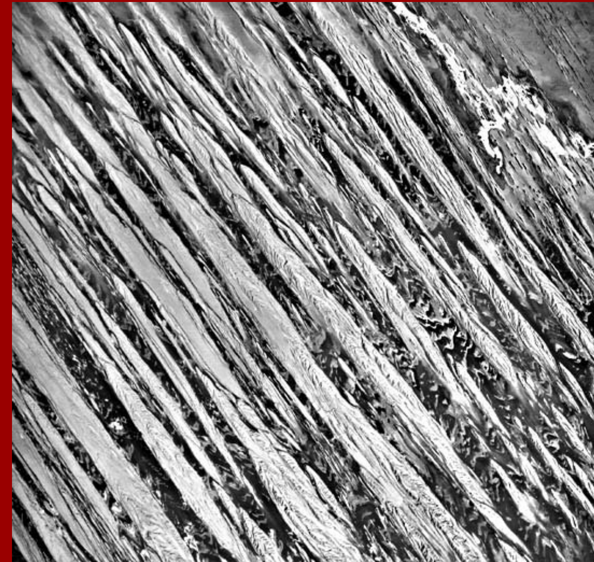


MOC wide angle

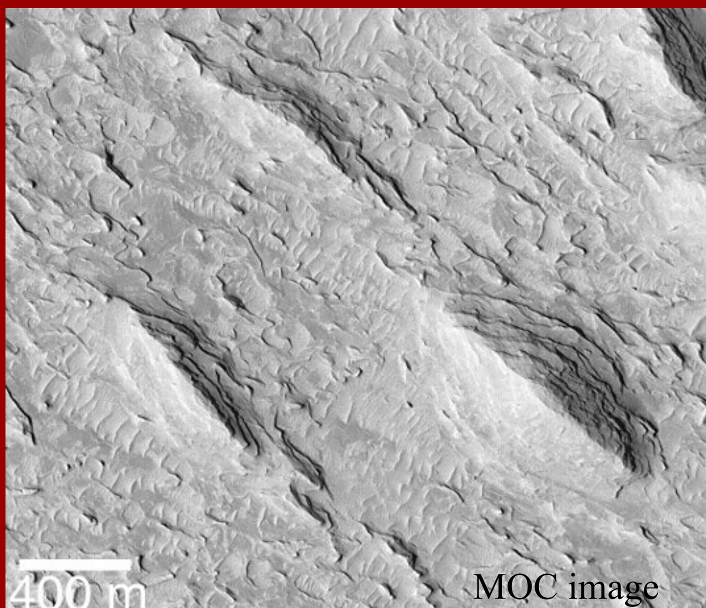


Lut, Iran

Yardangs (chinese word for lineated features due to wind erosion)

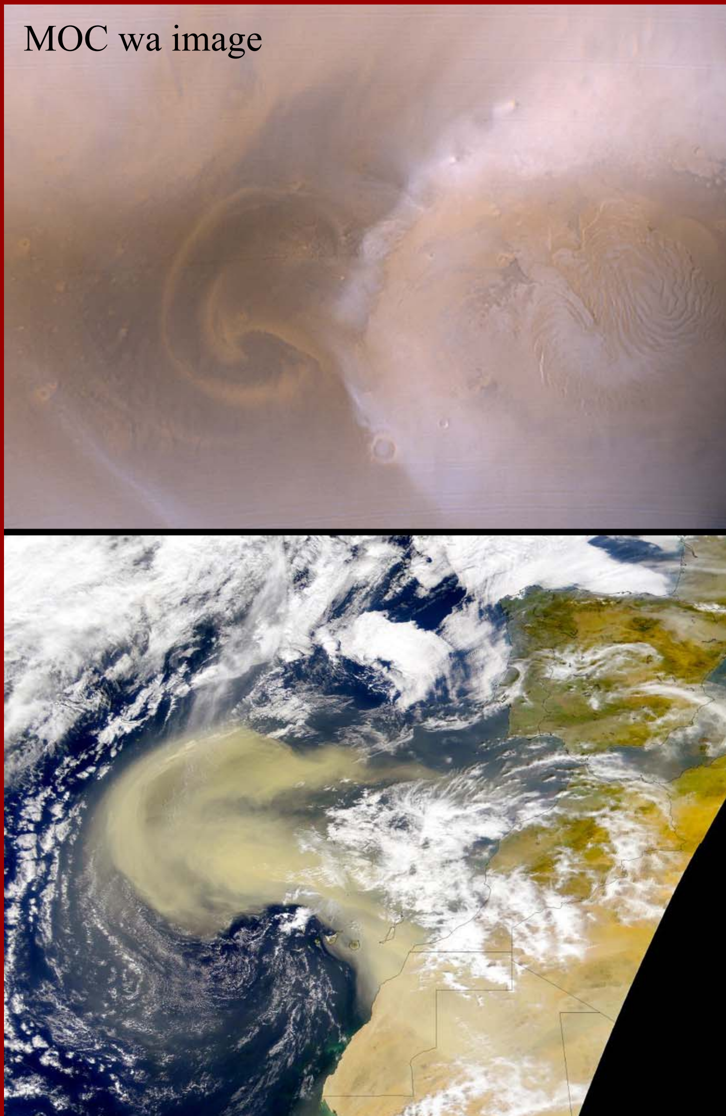


Lut unit
(Iran desert)



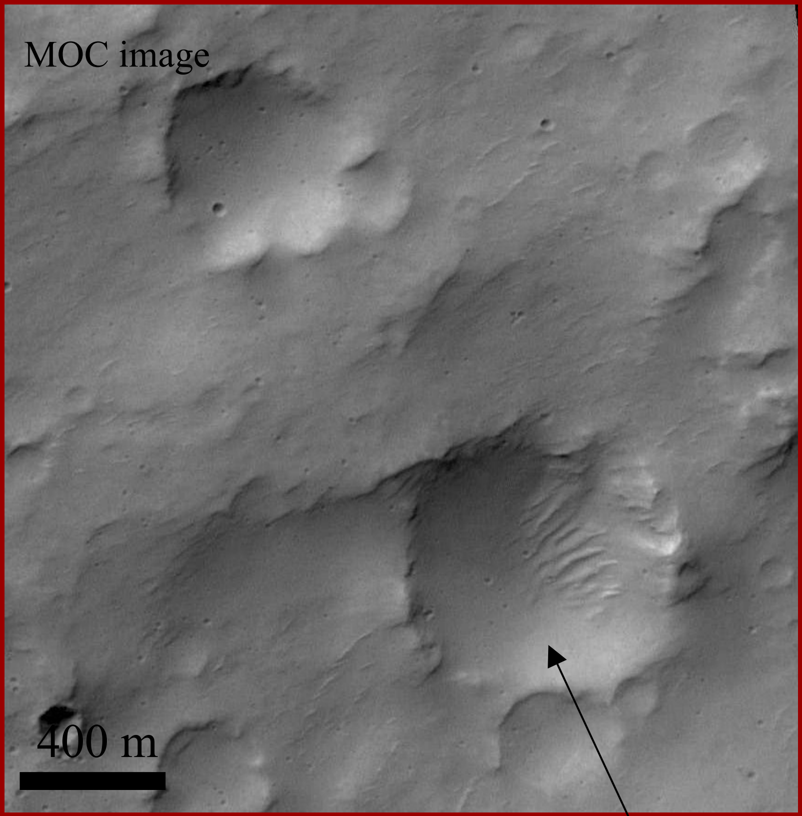
=> wind erosion has been underestimated previously,
erosion by wind can be > 100 meters

2.1.3 Dust deposits, wind streaks and other dust related streaks



- Dust storms are observed for long time by astronomers
- Mars has a very dusty atmosphere with particle size of dust < 5 microns
- Dust on Mars can accumulate over important thicknesses (> 10 m) over geologic duration
- These deposits are similar to loess on Earth

2.1.3 Dust deposits, wind streaks and other dust related streaks

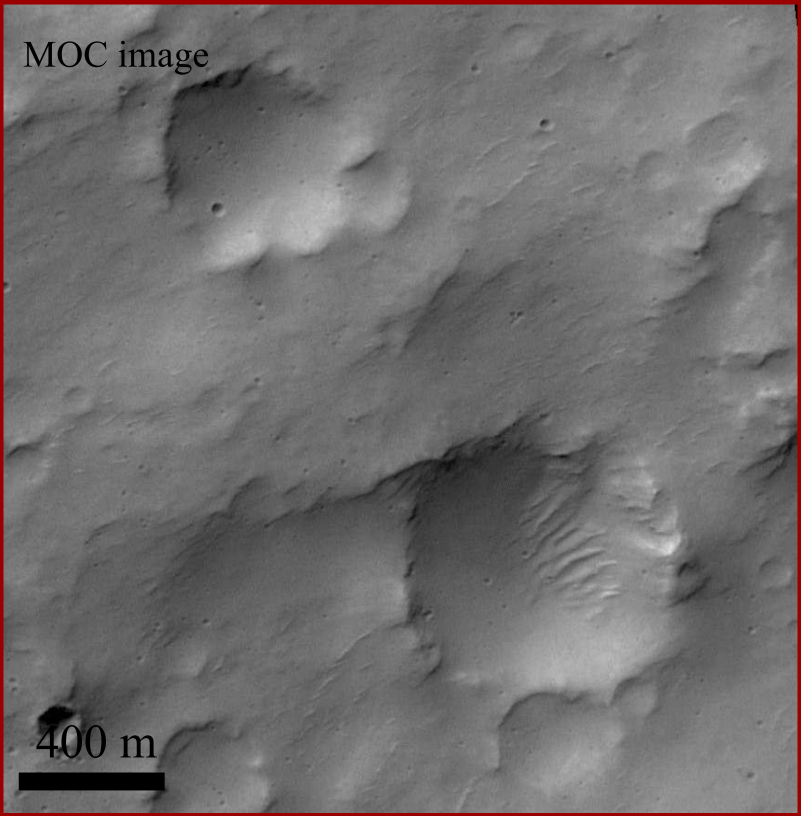


Cratered uplands in Arabia Terra

- Dust storms are observed for a long time by astronomers
- Mars a very dusty atmosphere with particle size of dust < 5 microns
- Dust on Mars can accumulate over important thicknesses (> 10 m) over geologic duration
- These deposits are similar to loess on Earth
- These deposits are problematic for **understanding buried landforms** and for **dating surfaces** from small impact craters

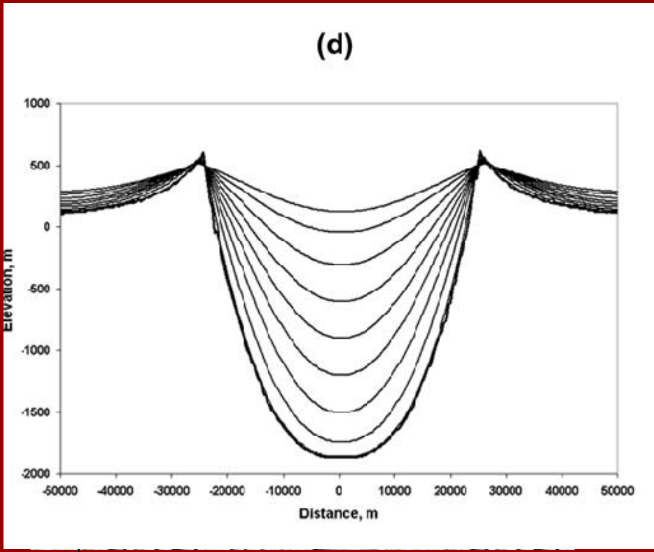
Craters are partially or completely filled by dust

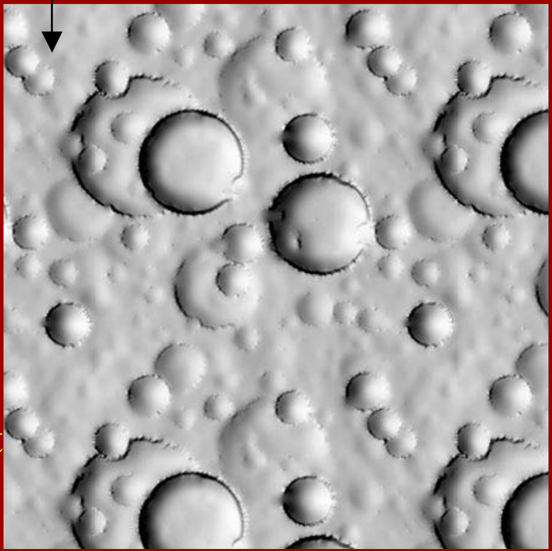
2.1.3 Dust deposits, wind streaks and other dust related streaks



Cratered uplands in Arabia Terra

Arabia Terra buried under > 50 m from
MOC crater count (Vincendon et al., LPSC, 2002)

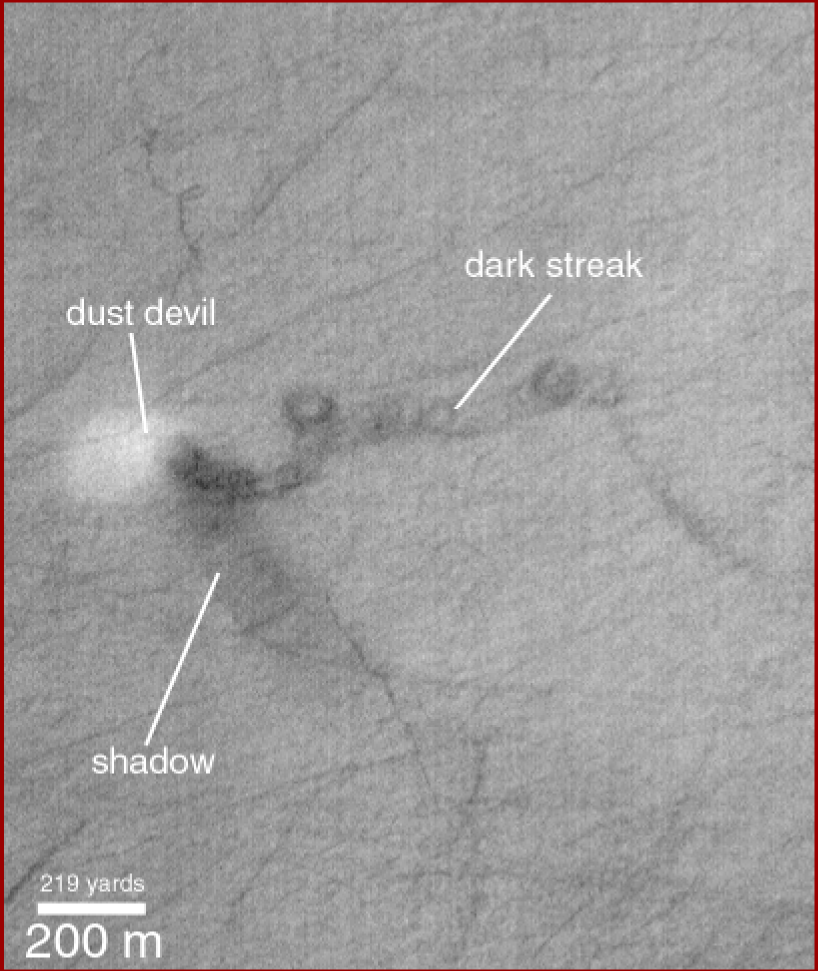




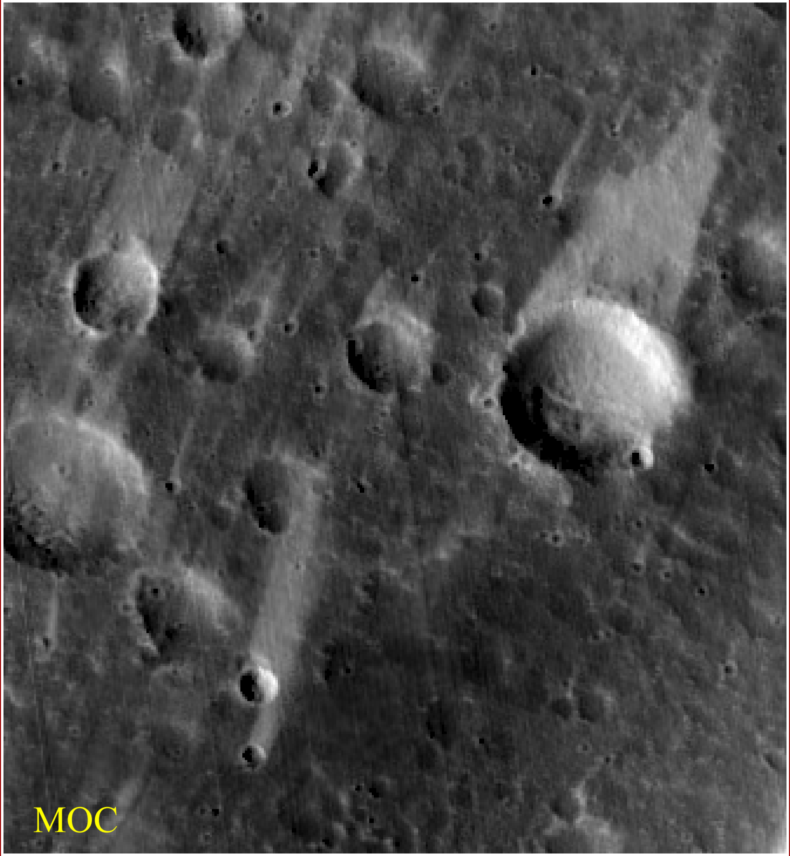
Model of dust deposit
on impact craters
(Howard et al., 2004
Forsbergh-Taylor et al., 2004)

t=er

- Patterns of dark or bright lines are the result of dust devil activity
- They usually remove dust from darker surface

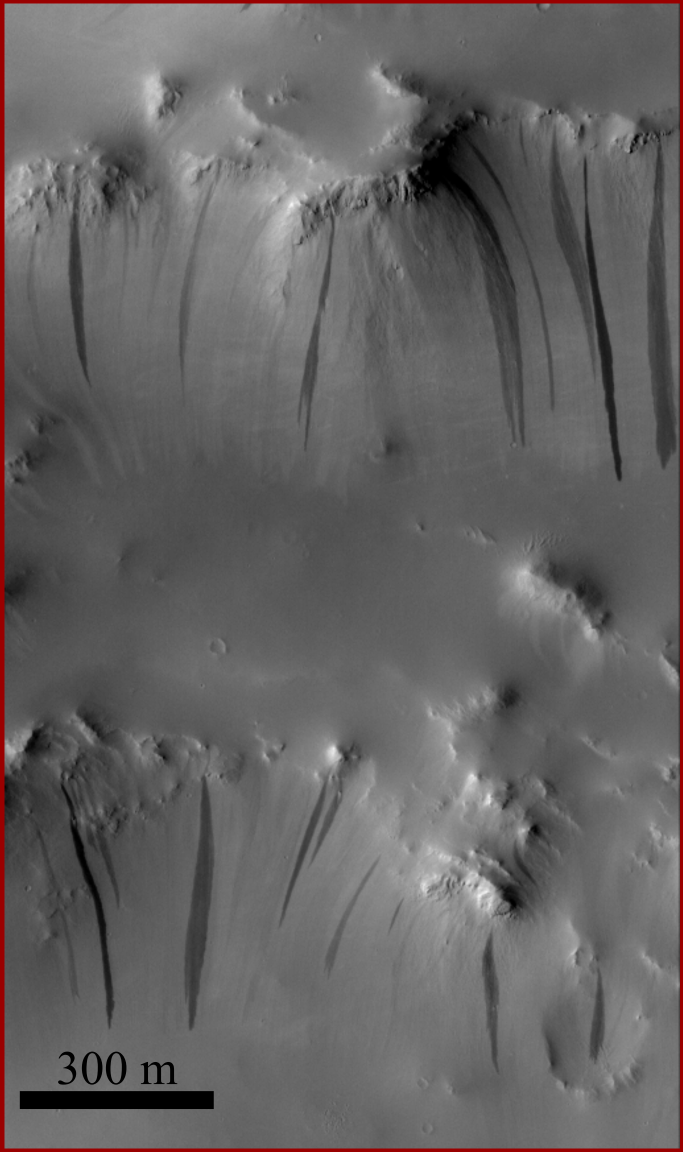


- Wind streaks are due to the effect of wind stopped by obstacles (usually crater rims)
- Wind streaks indicate the wind direction
- Changes are currently observed from one year to another



- Streaks can be dark or bright, and result of deposition or non-deposition (4 cases)
- Example: bright depositional streak o deposition behind crater rim
- Dark streaks can be a non-deposition of bright material in the lee of the crater or a deposition of dark material on a brighter surface

- Slope streaks: Dark or bright streaks associated to hillslopes



Slope streaks in Arabia Terra

- Slope streaks: Dark or bright streaks associated to hillslopes

Slope streaks are correlated with low thermal inertia regions (means dust rich regions)

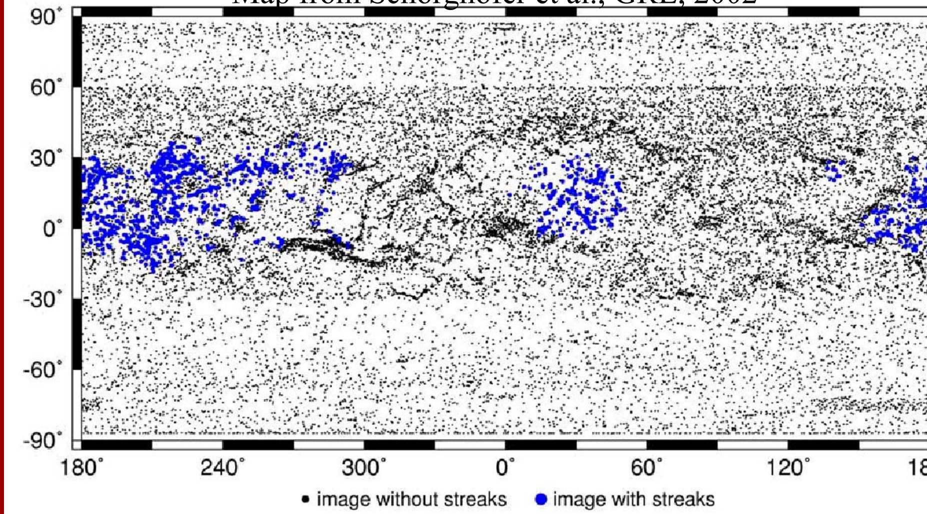
The origin of these features is debated:

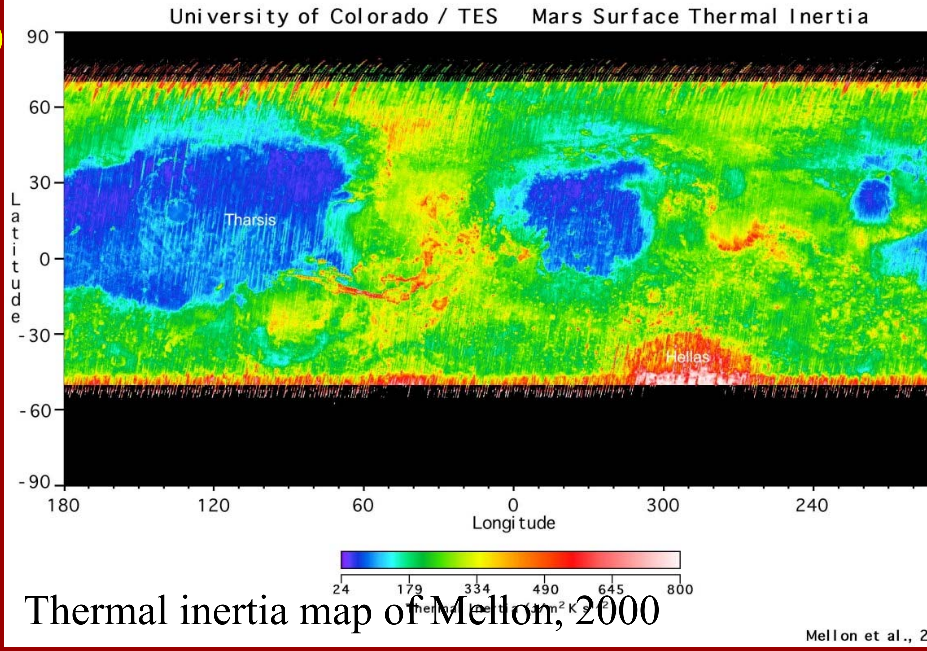
* Pure dry mass wasting hypotheses
(Sullivan, JGR, 2001)
Analogue to snow avalanches

* Downslope water flow
(Motazedian, LPSC, 2003, Miyamoto et al., 2004)

But equatorial features occur where liquid water is strongly instable

Map from Schorghofer et al., GRL, 2002

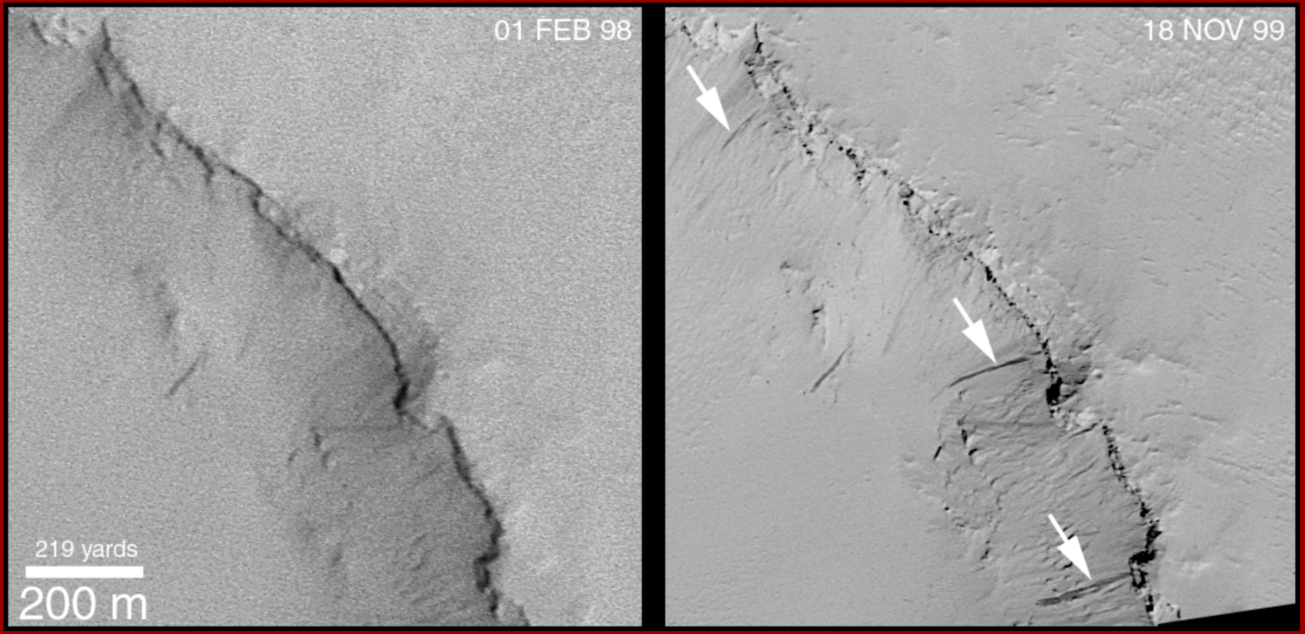




Thermal inertia map of Mellon, 2000

- Slope streaks: Dark or bright streaks associated to hillslopes

What is certain: They are active currently at surface



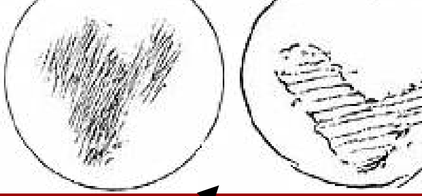
New ones have been discovered on MOC (Malin and Edgett, JGR, 2000)

Current formation rate: 7% new streaks/per Martian year/per existing streaks (Aharonson, JGR, 2003)

2.2 Polar caps

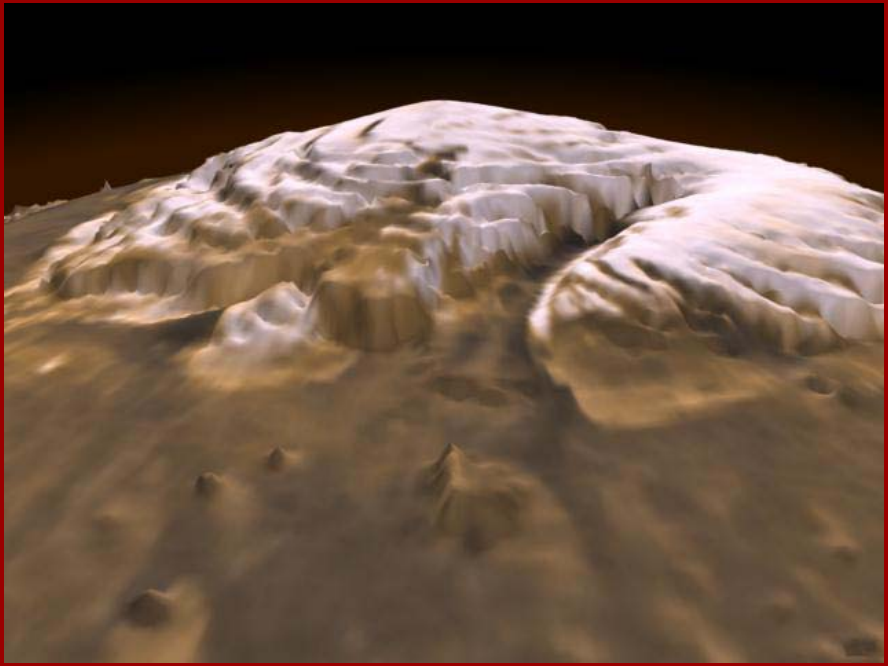
(only permanent cap, for seasonal cap see the lecture about meteorology of Mars)

2.2.1 Polar layered deposits and obliquity variations



Huygens (167

- Polar caps (seasonal) are observed for two centuries by telescopes
- Composition by water ice or CO2 ice? If water=30 m equivalent layer (important reservoir of water)
- Polar deposits are kilometer thick deposits observed on Viking images



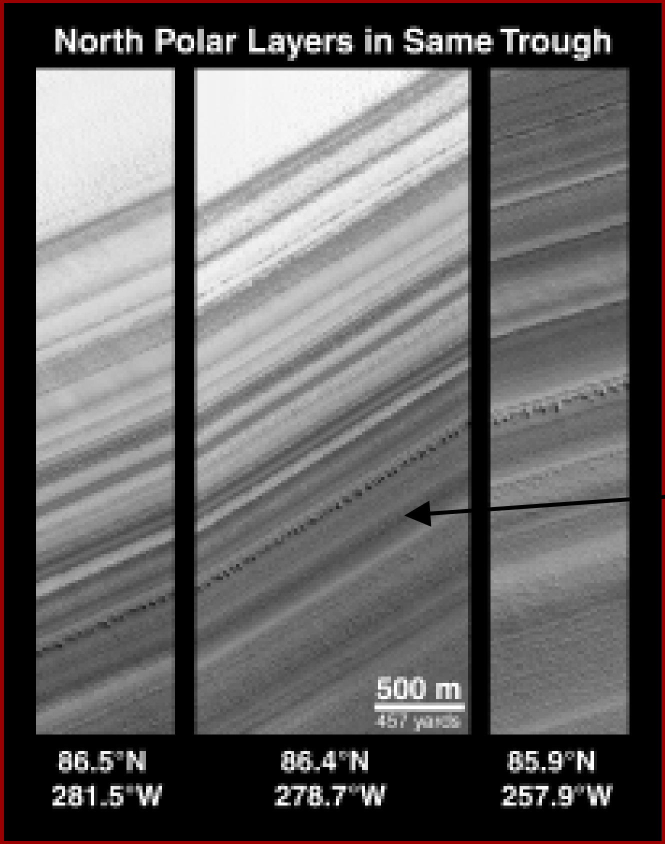
North Polar cap

MOLA+MOC color wide angle

2.2 Polar caps

2.2.1 Polar layered deposits and obliquity variations

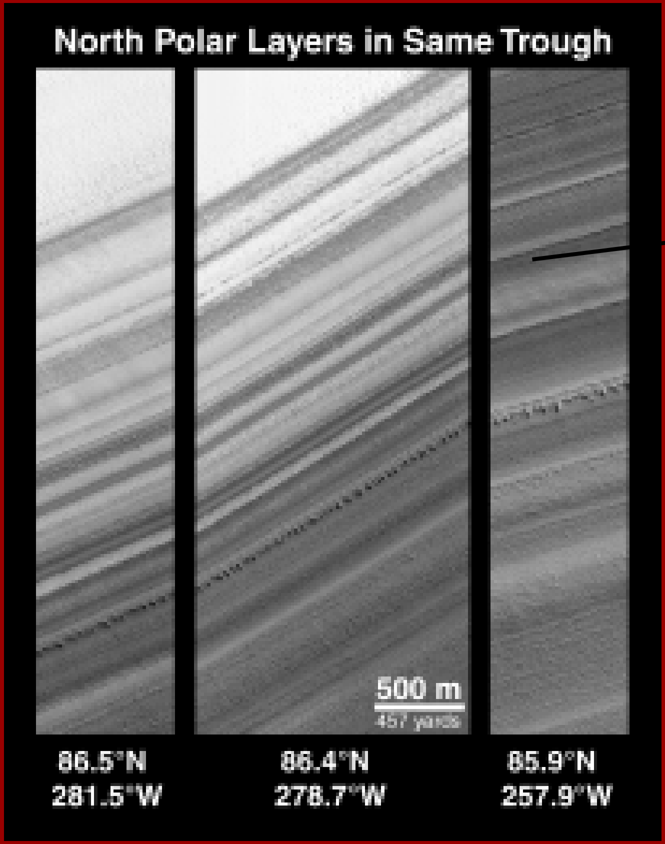
- Layered terrains are dust+ice accumulations through time
- Periodicity of layers gives a view from past astronomical cycles, especially obliquity cycles (Laskar et al., Nature, 2002).

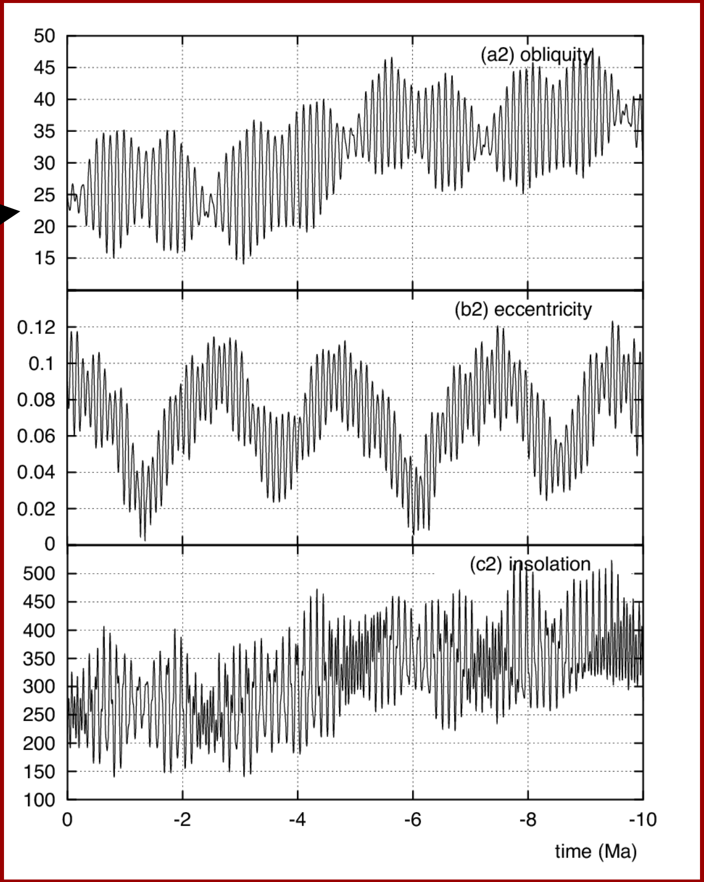


2.2 Polar caps

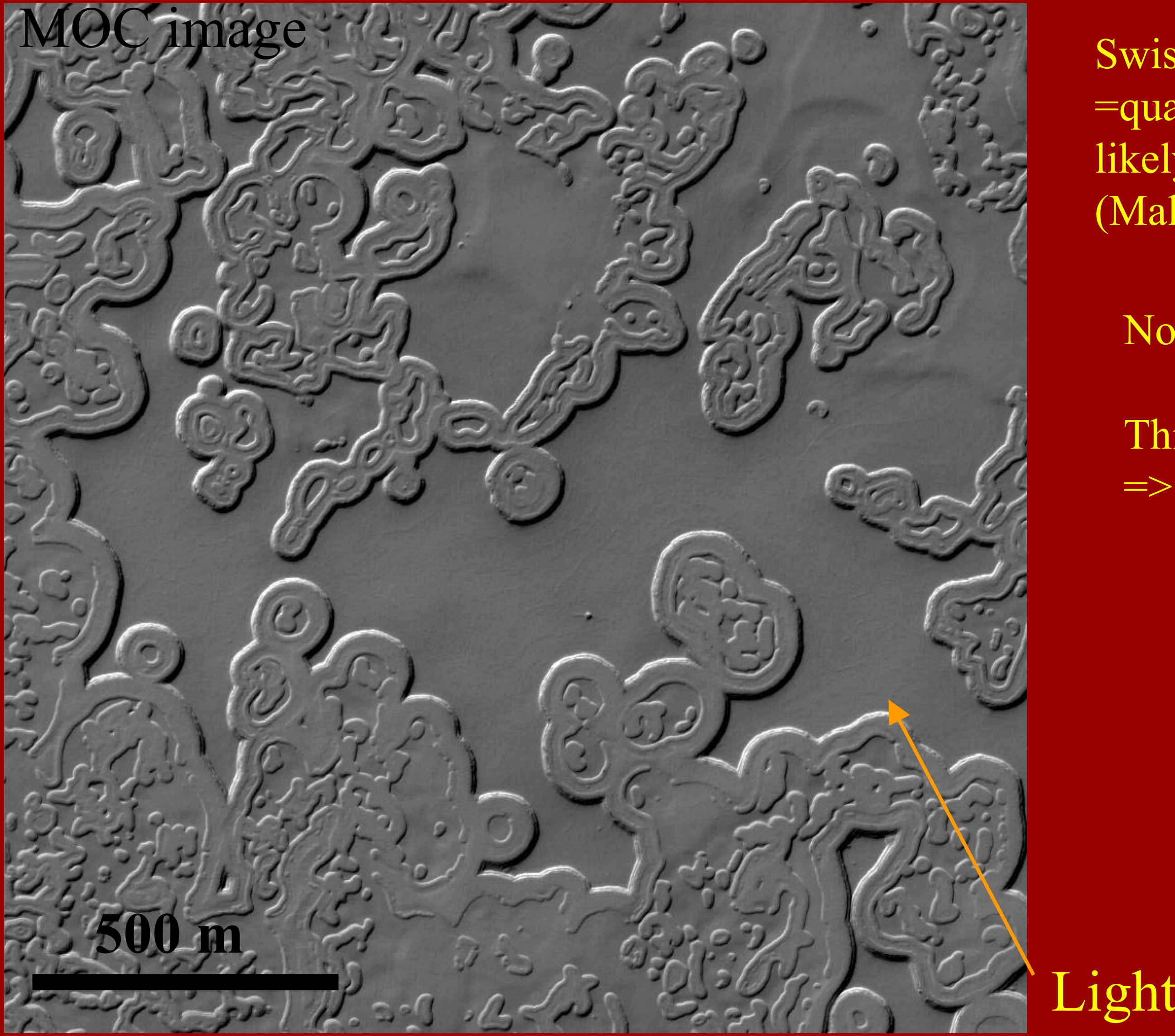
2.2.1 Polar layered deposits and obliquity variations

- Layered terrains are dust+ice accumulations through time
- Periodicity of layers gives a view from past astronomical cycles, especially obliquity cycles (Laskar et al., Nature, 2002).





2.2.2 The south polar cap features and composition

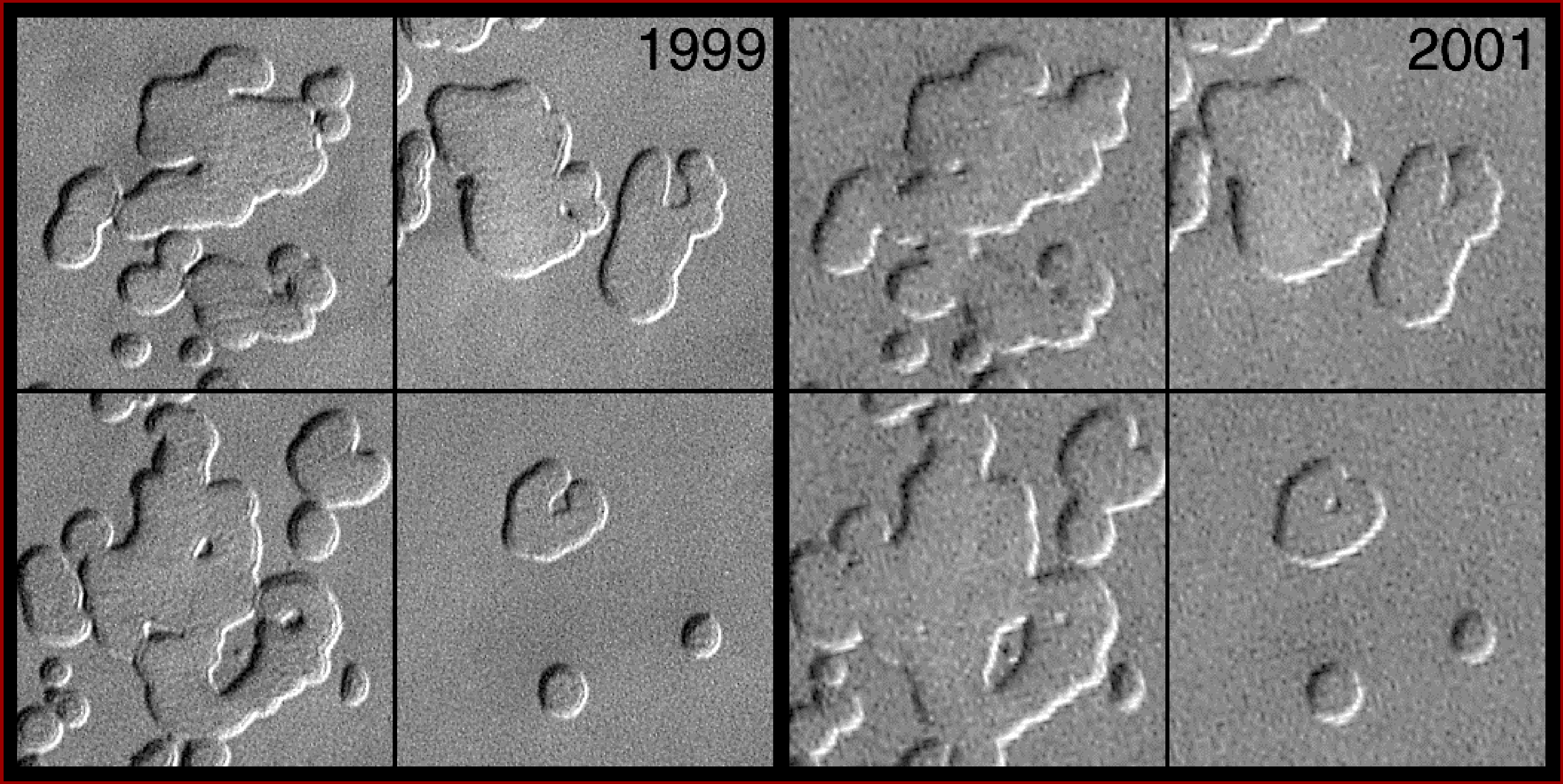


Swiss cheese terrains
=quasi circular depressions
likely due to CO_2 sublimation
(Malin et al., Science, 1999)

No apparent water ice

Thickness of CO_2 ice?
=>Several meters

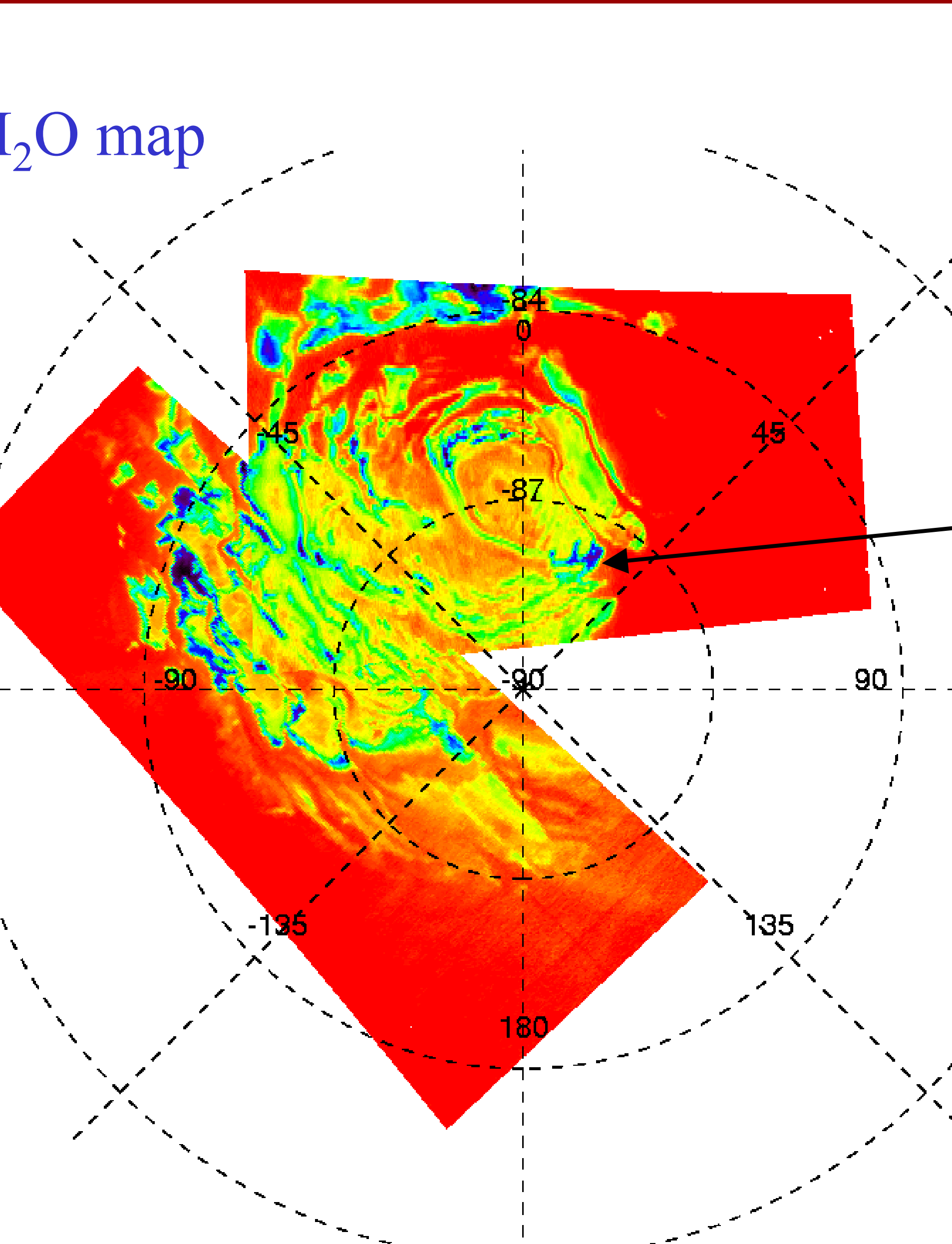
2.2.2 The south polar cap features and composition



Malin et al., Science, 2001

A currently active process:
loss of about 2m/year at the scarp edge

2.2.2 The south polar cap features and composition

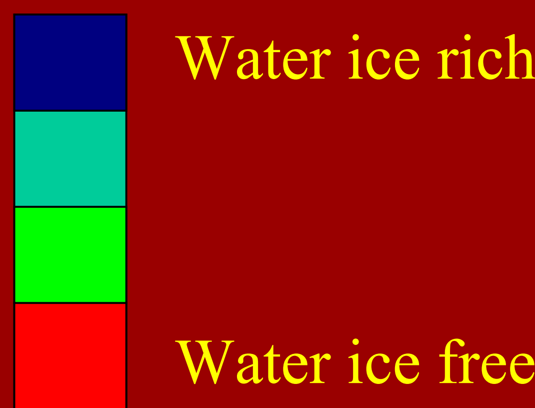


OMEGA data
(onboard Mars Express)

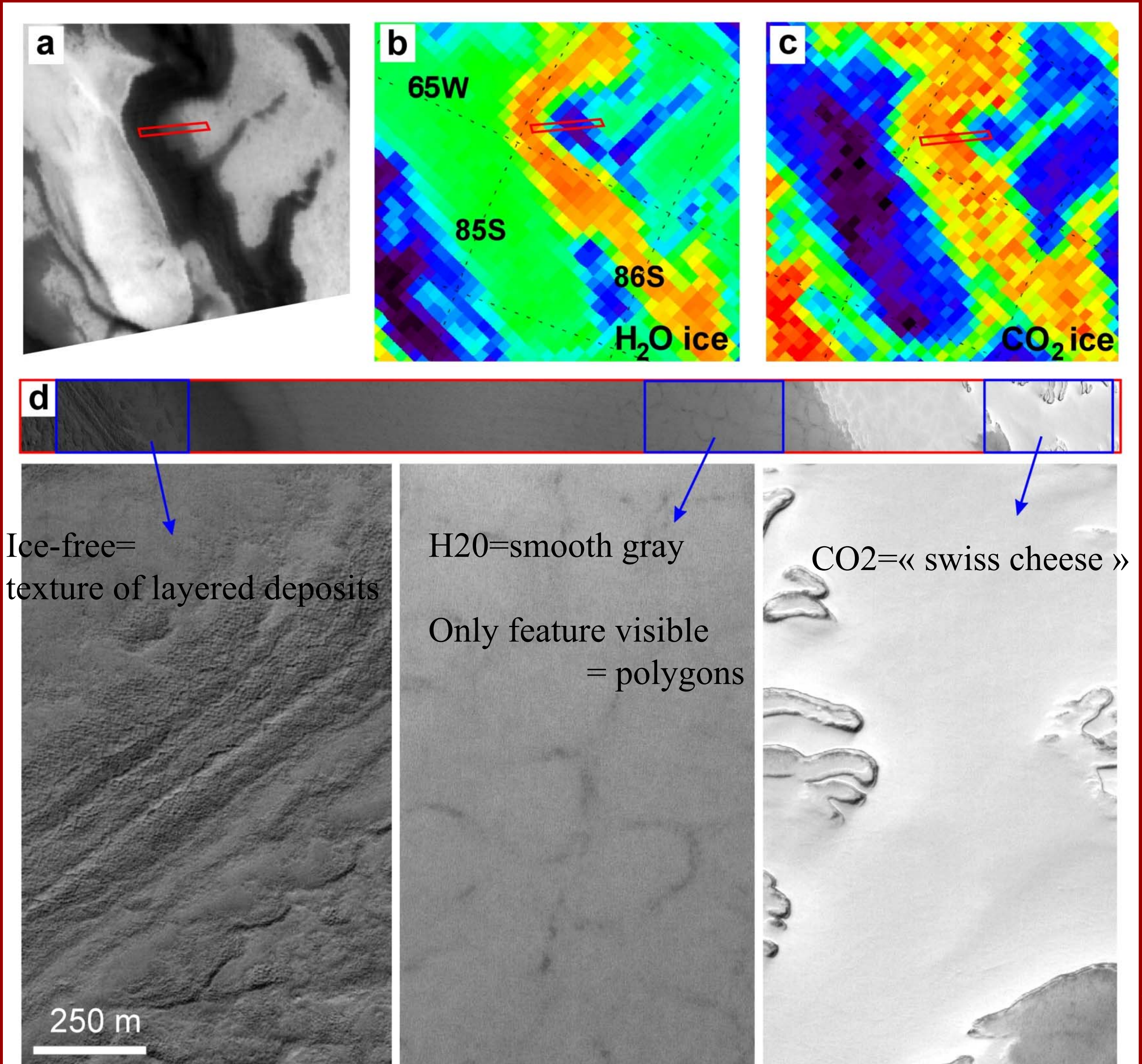
Bibring et al., Nature, 2004

* CO_2 ice at the top of the south cap (confirms MOC interpretation)

* H20 ice on the edge of the cap and locally surrounding the cap



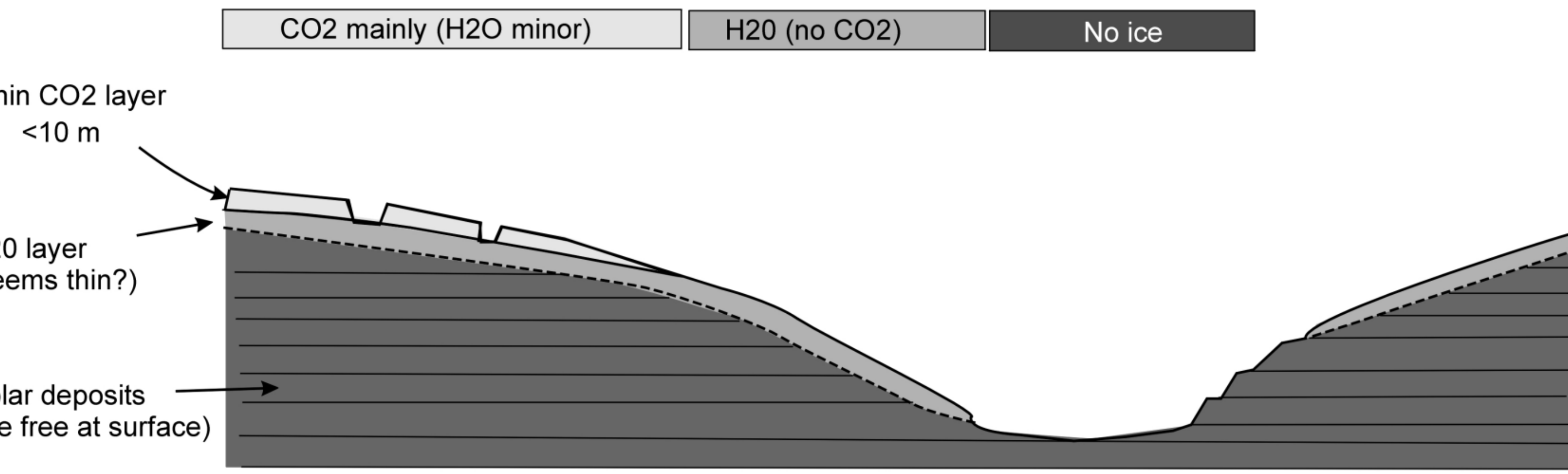
Comparison OMEGA/MOC



Water ice is present on a smooth unit which lies underneath the CO2 cap

MOC image
Ls=325°

Current views : thin CO_2 layer (10 m) in sublimation over a water ice layer of unknown thickness

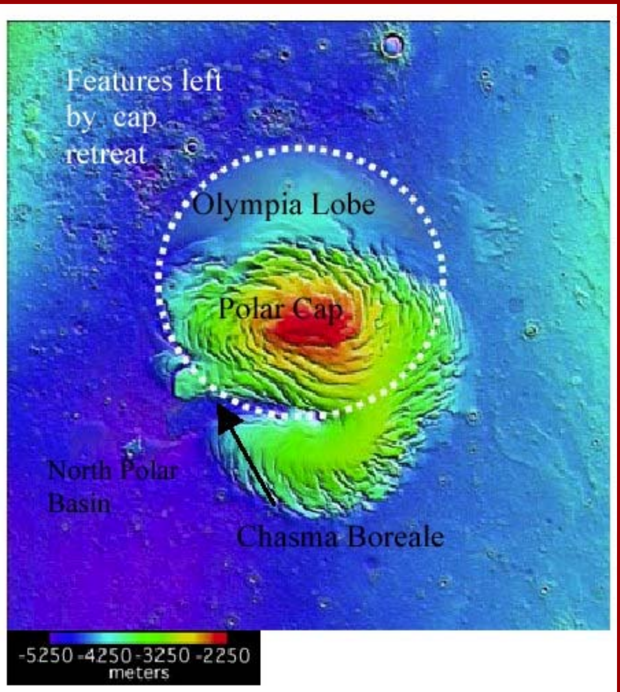


Mangold et al., COSPAR abstracts, 20

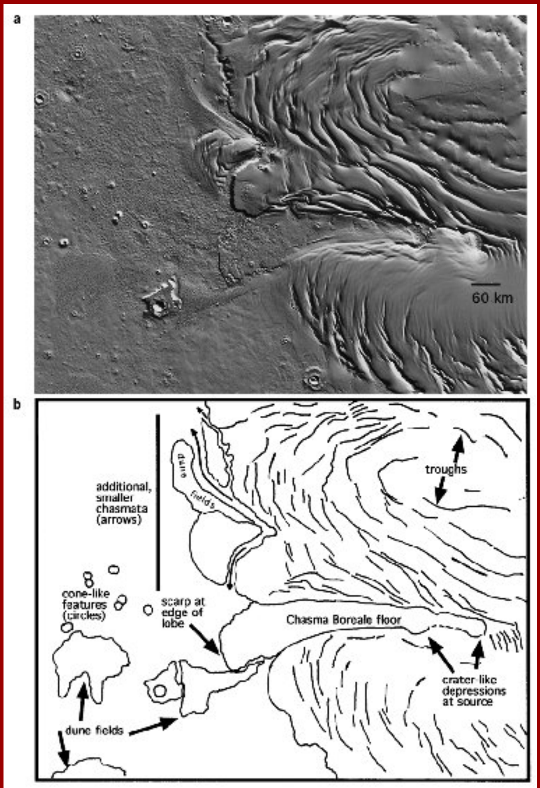
Need radar data such as MARSIS (Mars Express) or SHARAD (MRO mission) to establish the thickness and proportion of the ice layer.

2.2.3 Ancient polar caps

- Glaciers form features such as grooves, moraines, eskers which most are due to the basal sliding and subglacial melting
- Polar caps are currently cold and devoid of subglacial melting (Greve et al., PSS, 2002)
- Do we have evidence of past subglacial melting?



Chasma Borealis:
large valley (80 km large, 300 km long)



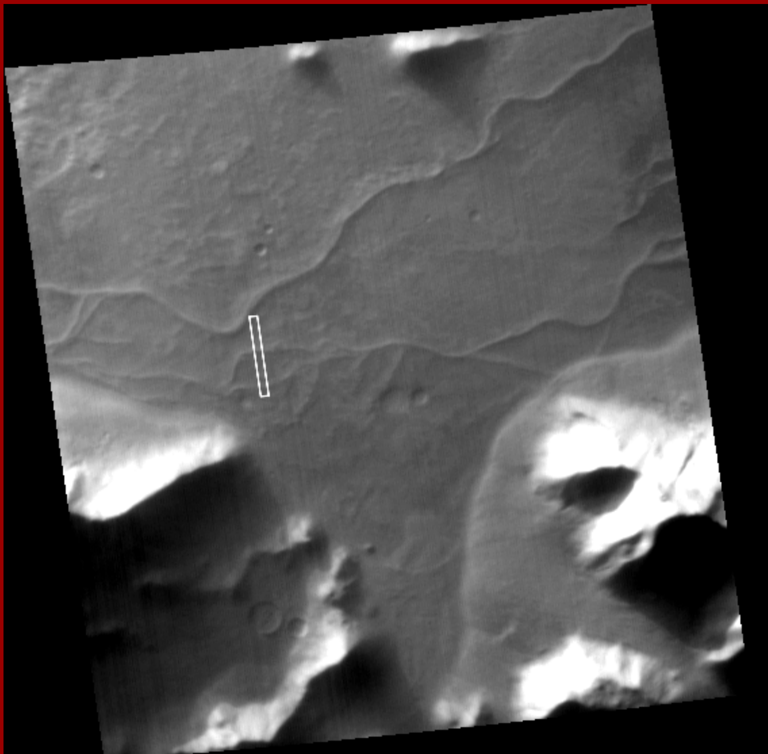
From Fishbaugh et al., JGR, 2001

Possible outflow from the North polar cap, in the Amazonian epoch

(still debated if water comes from climate modifications or volcanic activity)

2.2.3 Ancient polar caps

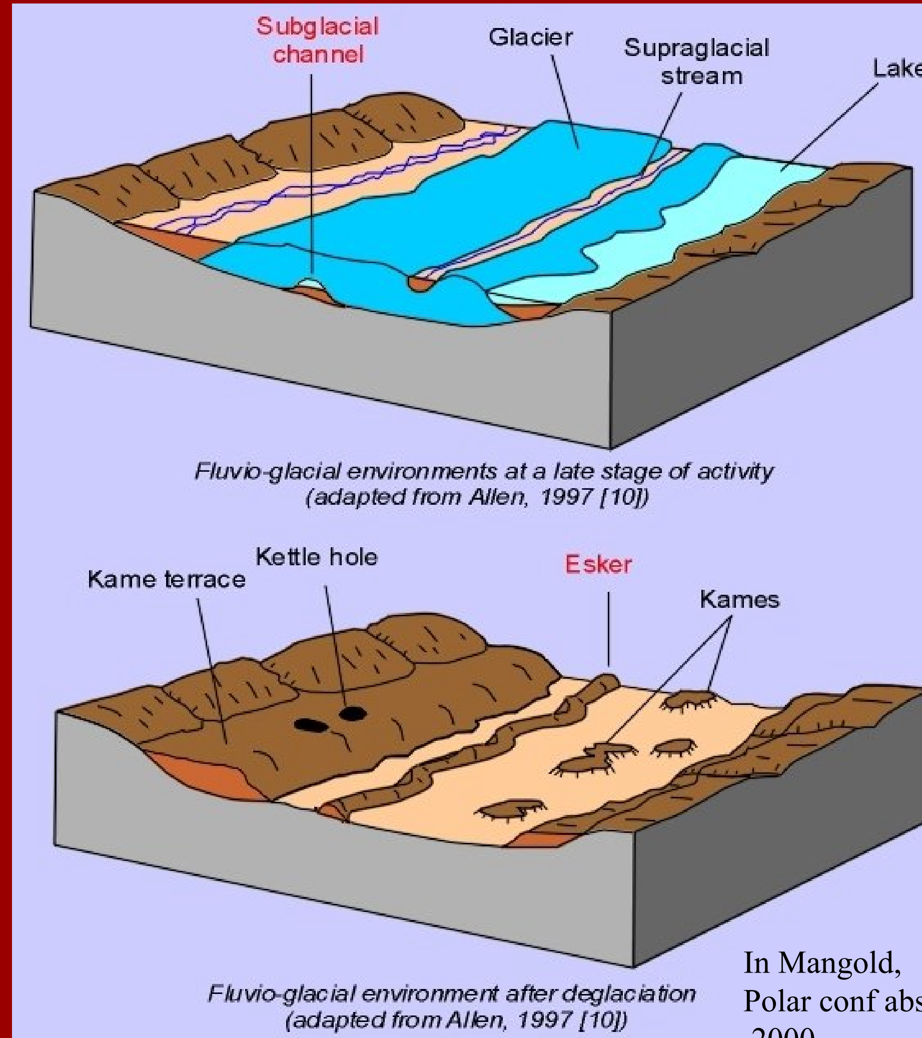
Evidence of ancient polar caps from eskers



Sinuous ridges in Argyre, MOC wa

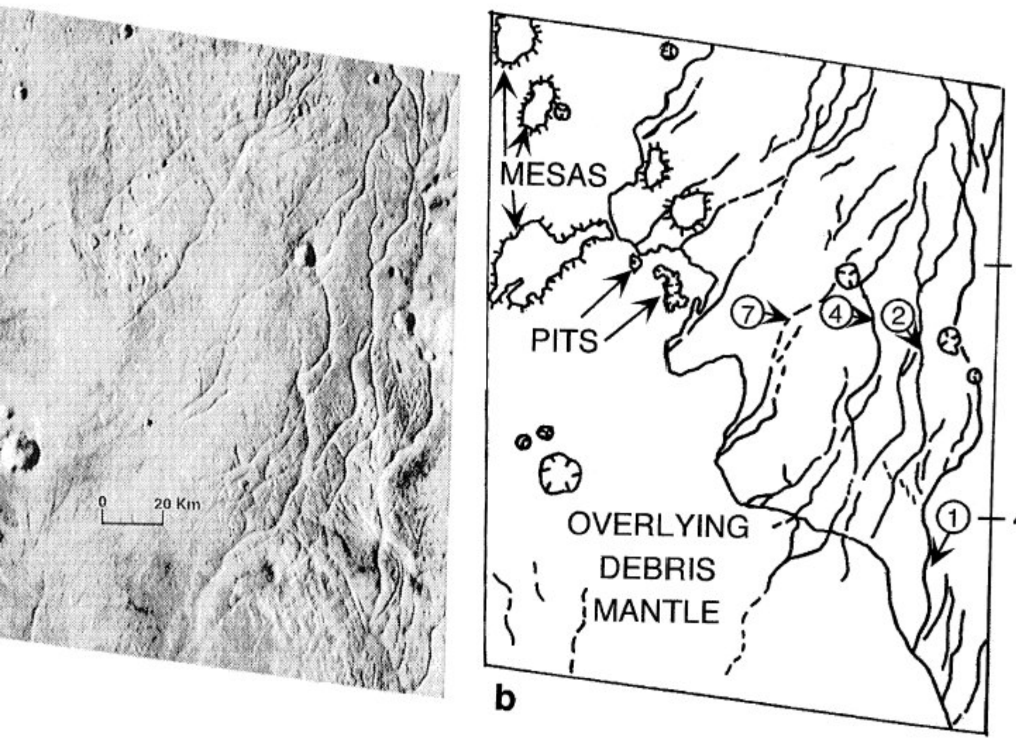
Eskers are formed by deposition in subglacial channels

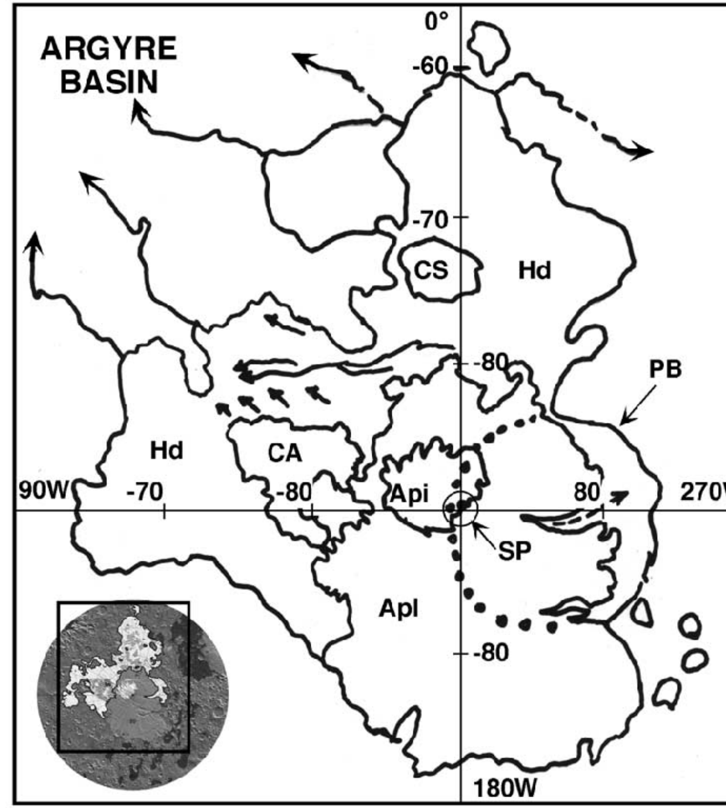
Eskers in Canada



In Mangold, Polar conf abs 2000

The Late Hesperian South polar cap





Milkovich et al., JGR, 20

Identification of eskers, sedimentary layers and meltwater channels at the front of the south cap.
Craters counts give an age into the Late Hesperian epoch.

2.2.4 Glaciers at equatorial latitude?

From Head and Merchant, Geology, 2003

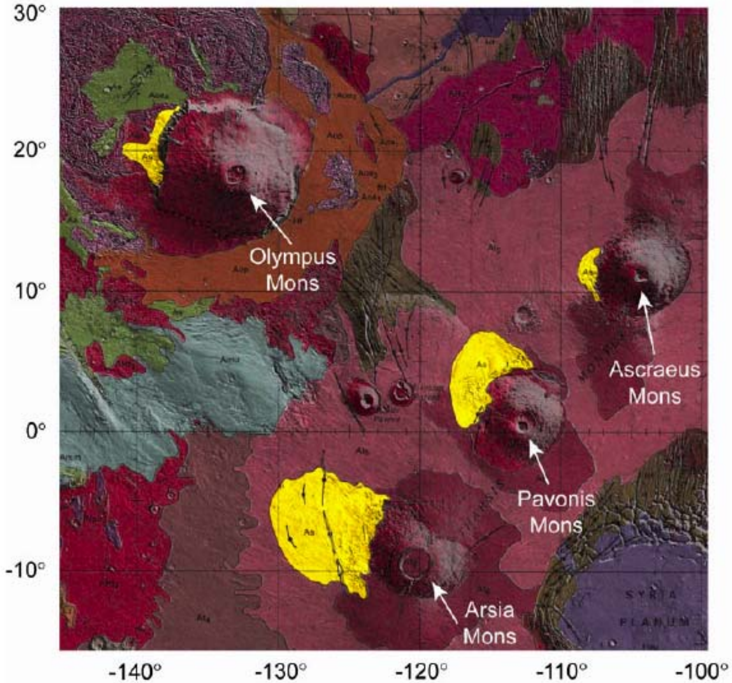


Figure 1. Geologic map of Mars showing the fan-shaped deposits (yellow, unit As) associated with the northwest flanks of the Tharsis Montes and Olympus Mons [8].

Head et al., Polar conf. abstract, 2003

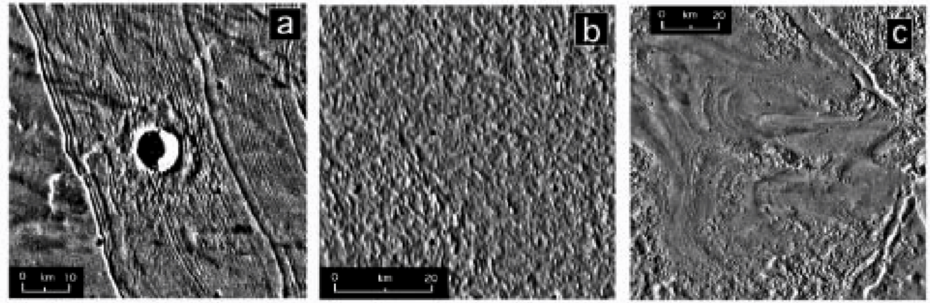


Figure 2. Facies of the fan-shaped deposit. a) Ridged facies, interpreted as drop moraines; b) Knobby facies, interpreted as sublimation tills; c) Smooth facies, interpreted as rock glaciers; (Viking Orbiter images)

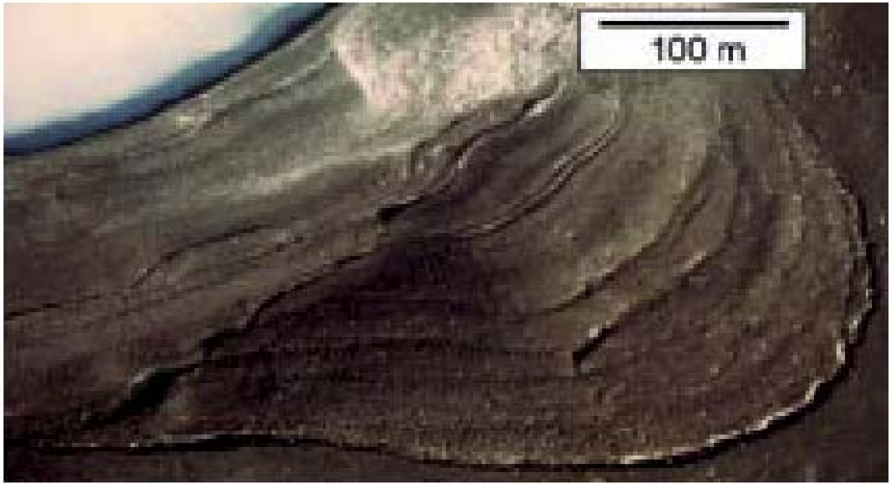


Figure 1b. Close-up view of drop moraines in lower Arena Valley (Taylor Glacier in upper right-hand corner). The outermost moraine stands 3 m above the surrounding valley floor.

Lobate features of controversial origin
(volcanic, mass wasting?)
=> could be drop moraines of cold based glaciers
(no basal melting means no eskers or erosion grooves but drop moraines)

Equatorial glaciers could exist due to high obliquity (>45°) when equatorial are cold with increasing water vapor

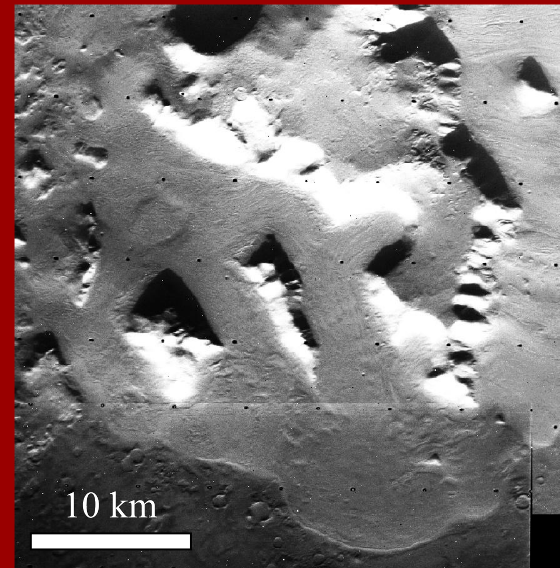
2.3 Ground ice related features at permafrost scale (> 10 m thick)

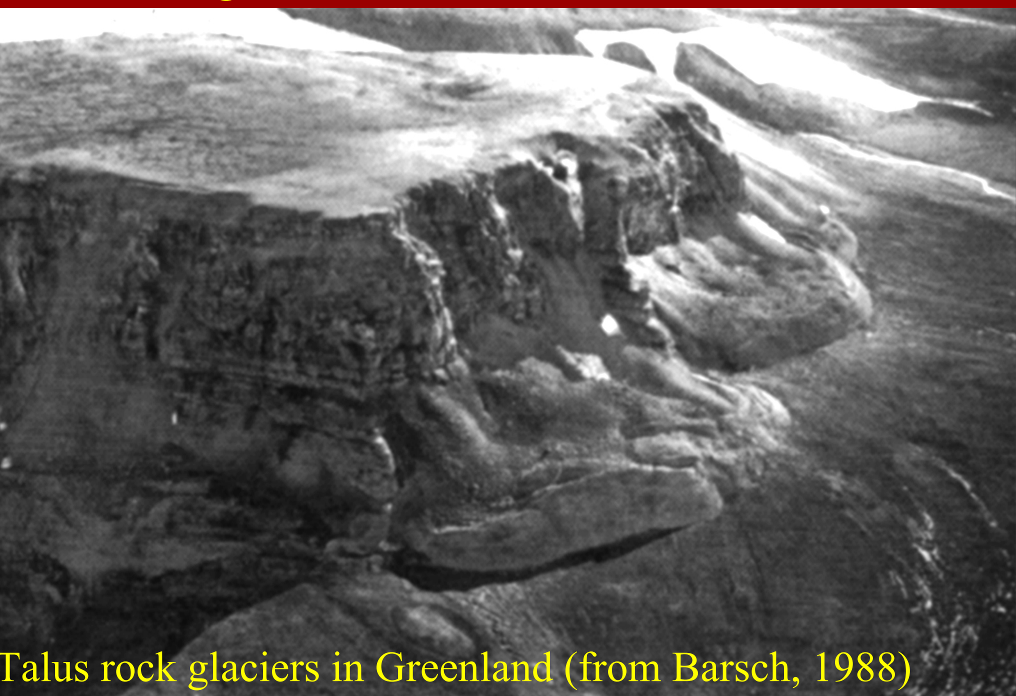
2.3.1 Lobate debris aprons and lineated features

Lobate debris aprons (Squyres, 1979):
10-20 km long
Widespread in 30 to 50° latitude
especially at the dichotomy boundary

~ Rock glaciers 100-800 m thick

LDA in Deuteronilus Mensae

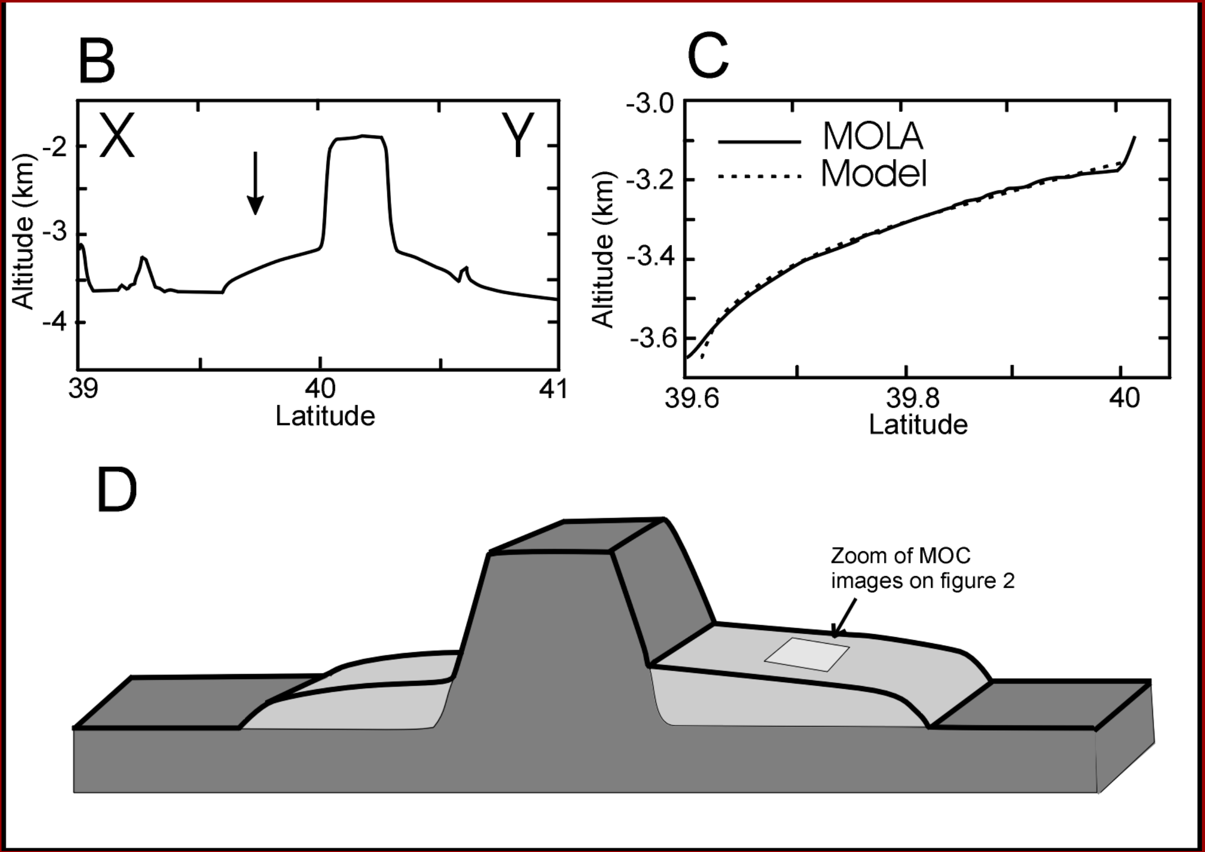




Talus rock glaciers in Greenland (from Barsch, 1988)

Viking images

Topography of lobate debris aprons confirms the occurrence of ice



At plastic stage:
the profile follows a parabol

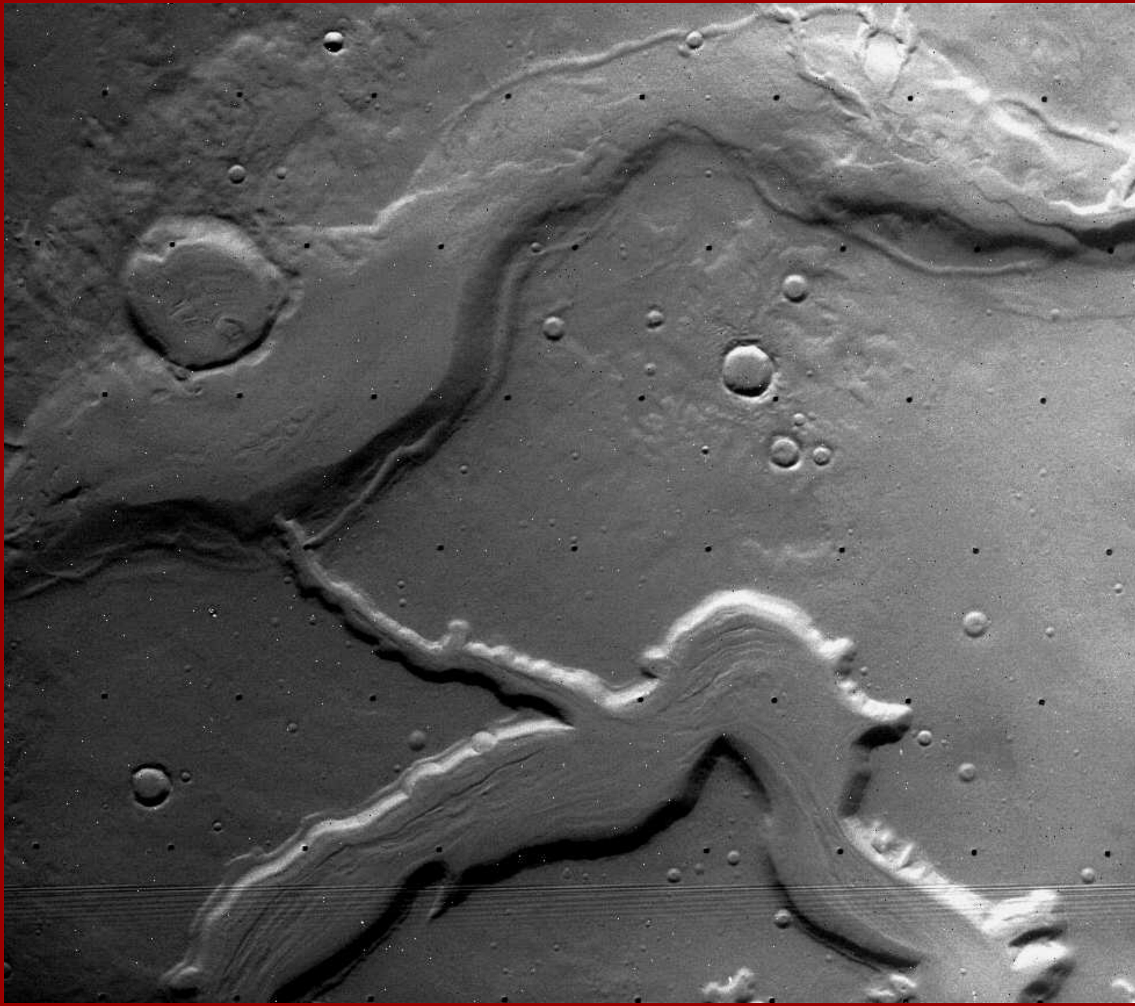
Mangold, JGR, 2003
Mangold & Allemand,
GRL, 2001

Calcul of basal stress of 50 to 100 kPa (that of glacier ice)

* Rock glaciers are mixtures of ice and rock

* They can comes from :
  1. Accumulation of debris filled by atmospheric snow and refreezing of water
  2. Creep of the whole permafrost (ice in porosity)
  3. Burial of pure ice glacier by debris or moraines (ice-core rock glaciers)

Lineated valley fills (e.g. Squyres, Icarus, 1989)



* Valleys are filled by same material as lobate aprons

* The viscous material is younger than the formation of valleys in which they form

* These valleys are « fretted channels » which occur close to the dichotom
but not clear if related to liquid water flows or mass wasting processes.

2.3.2 Terrain softening

* Especially visible on softened craters
* Exist in the same region than those affected by lobate and lineated features (Squyres, 1989)

* Softened craters are often filled by concentric crater fill a geomorphic equivalent to the lineated valley fills
* Interpreted as a viscous deformation of the entire ground due to the viscous deformation of ice

* Estimation of the thickness from modeling: Jankowski and Squyres (1993) estimate at 1 km the thickness over which the viscous deformation occurs to provide the topography of softened craters observed

* Concurrent hypotheses: Dust mantling can also explain the smoothing (Zimbelman, 1994)

* MOC and THEMIS images suggest deposition of ice+dust that could agree with both hypotheses (in progress!)

Themis
57 km x 28 km

Features related to the viscous deformation of ground ice:

* Lobate debris aprons, lineated valley fills, concentric crater fills, softened craters (Squyres, Icarus, 1989)

* All of these features are located between 35-55° latitude in both hemisphere (Squyres and Carr, Science,1986)

* The estimation of the ice proportion from experimental deformation of ice-rock mixtures: Viscous creep requires % of ice > 30% (Mangold et al, PSS, 2002)

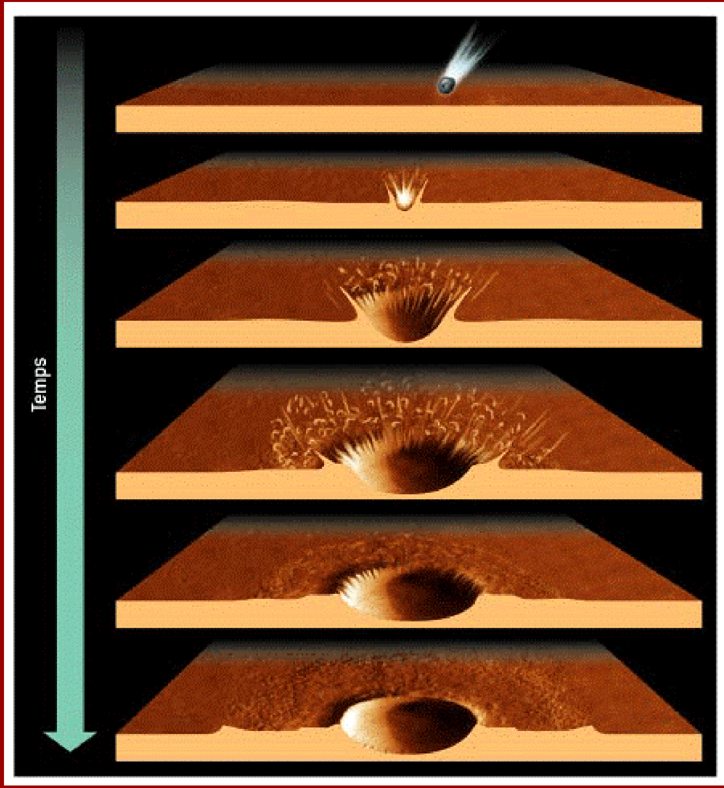
* Widespread features: A high proportion of water ice could be stored in lobate debris aprons and similar features (Squyres and Carr, Science,1986)
Possibly an equivalent layer of ocean of 50-100 meters.

2.3.3 Lobate ejecta craters

* Also called « Rampart craters »
(Barlow et al., 1992 Mouginis-Mark, 1979)

* Continuous lobate ejecta boundary
= different from usual dry ballistic ejecta
which are not continuous

* Suggest fluidization of the material
=> water involved (Carr, 1977)

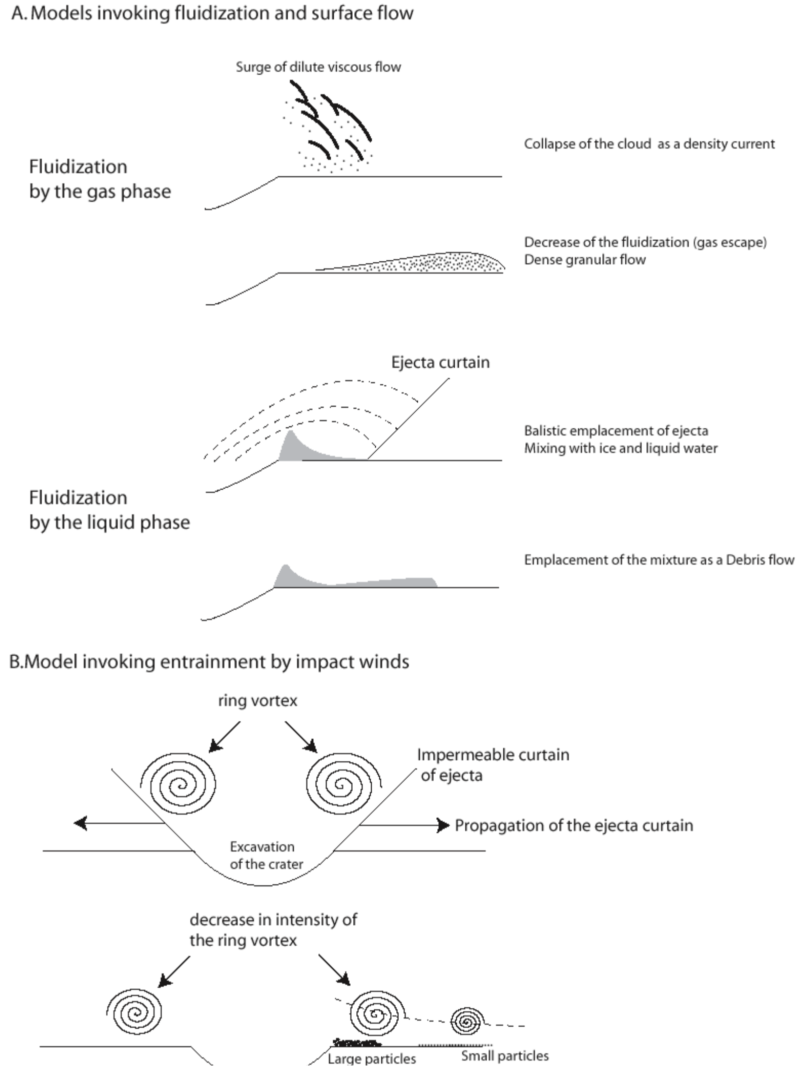


Formation of lobate ejecta

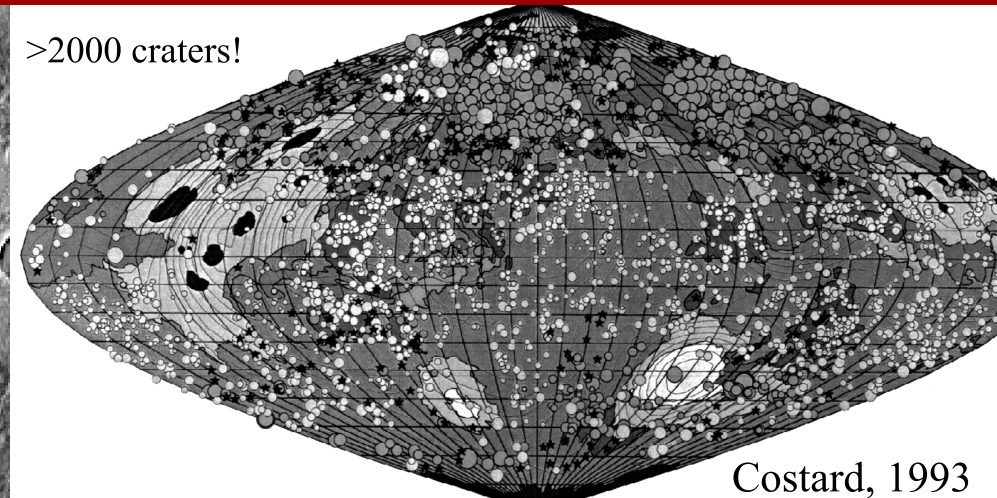
* Usual model: debris flow like pyroclastic flows= water vapor fluidization (Wohletz and Sheridan, 1983)

* Concurrent hypothesis: wind deposition of ejecta (Schultz), but does not explain some characteristics
(model which work for lobate ejecta on Venus, Patm=90 bars)

* Not known if water vapor comes from ground water or ground ice



* Strong diversity of ejecta (double lobate, circular, very sinous , etc.)
Still not explained

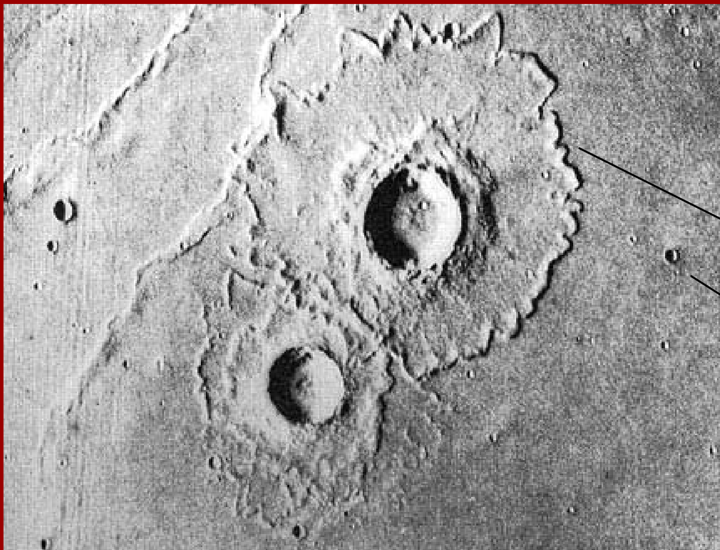


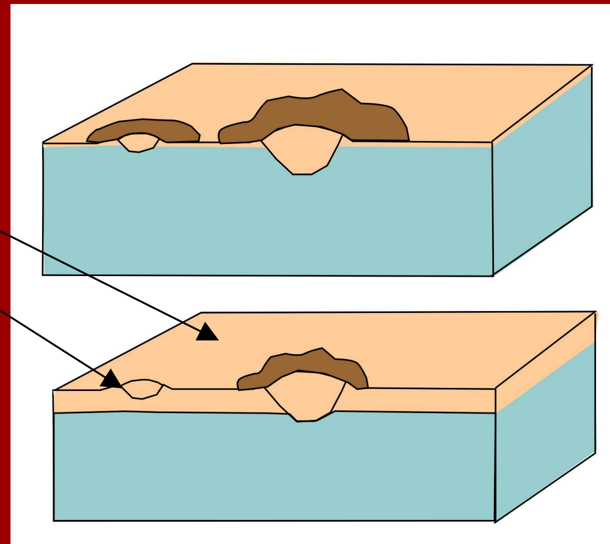
* Widespread occurrence of such impacts

* Lobate ejecta craters are a tool to understand the subsurface distribution of water (Kuzmin et al., Costard et al.)

Where water is shallow, all craters ejecta are lobate

Where water is deeper, small craters ejecta are not lobate





* Depth of the ground ice table

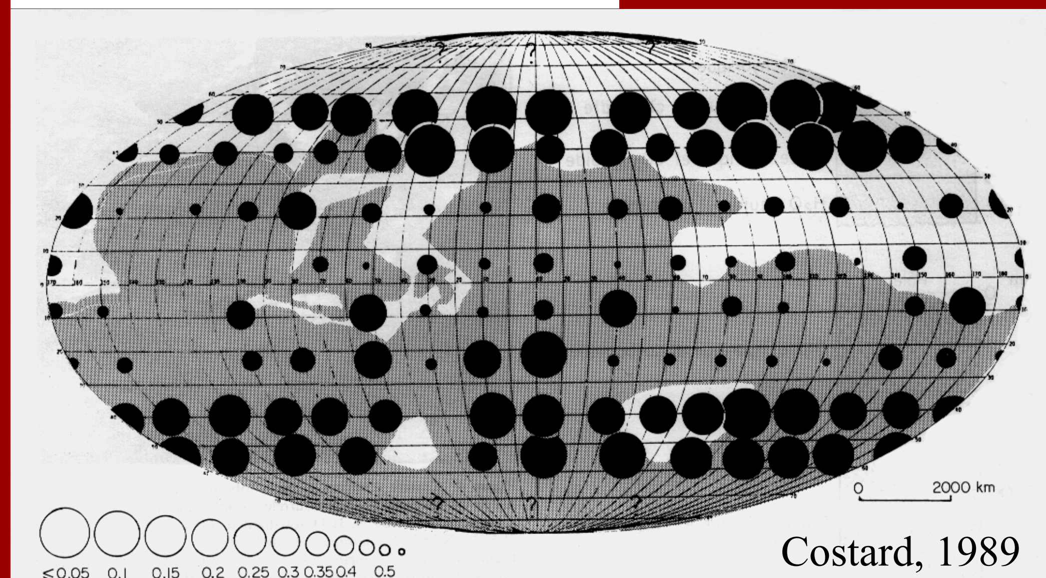
Equatorial regions:

between 500 m to 1 km depth

High latitudes:

between 30 m to 300 m

(at the time of impact event)



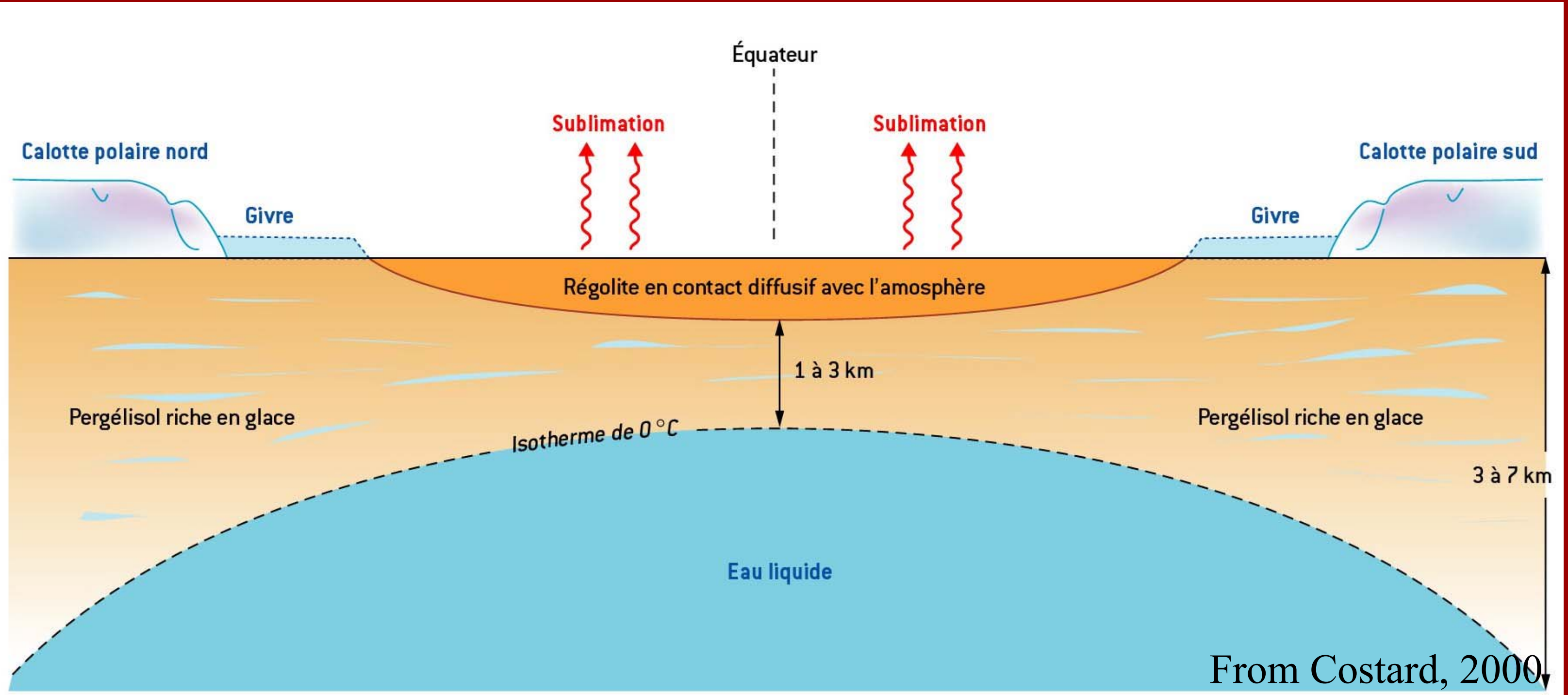
Costard, 1989

Theoretical distribution of the Martian permafrost consistent with the results from lobate ejecta craters:

At low pressure (6 mbar), ice is not stable above 200 K at the surface due to low P_{H2O}

At latitudes > 40° -50° , mean annual t° is below the frost point, permitting stable ice.

At depth: The thermal gradient controls the thickness frozen
Average thermal gradient:
0° isotherm : 1 to 3 km depth (equator) versus 3 to 7 km depth (polar regions)

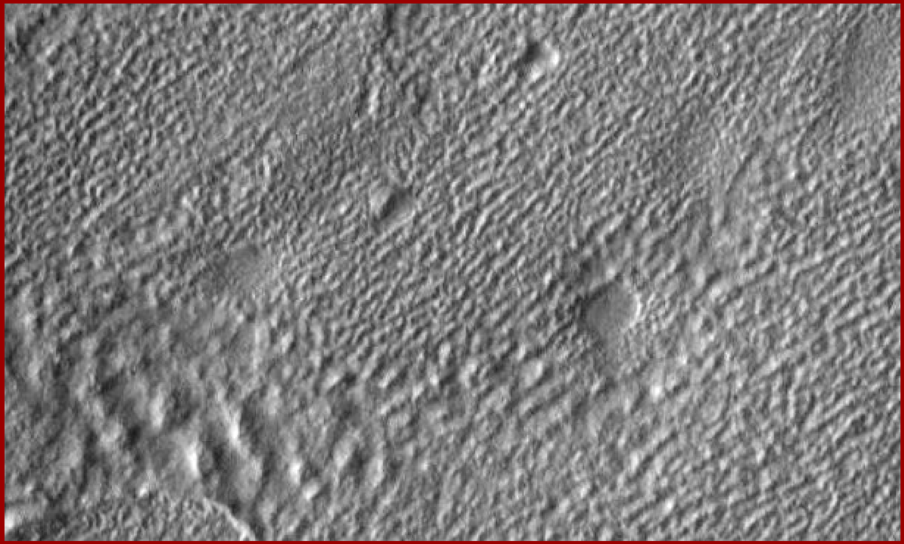


From Costard, 2000

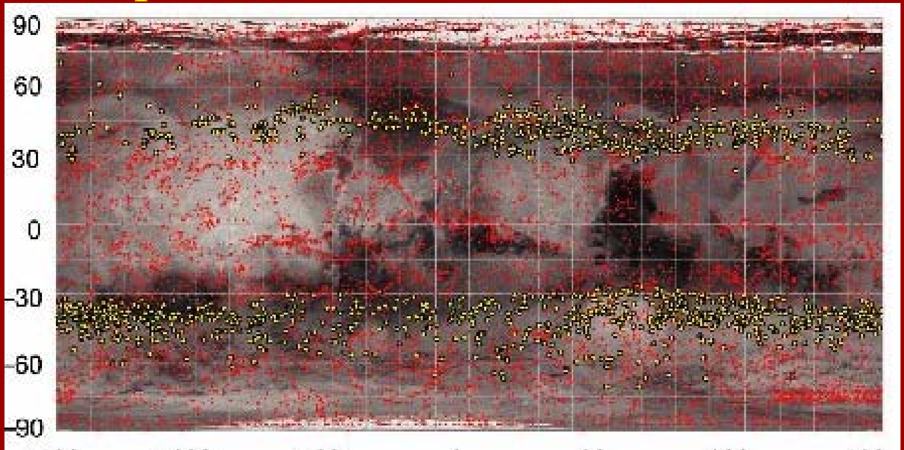
2.4 Small scale ground ice related features (< 10 m thick)

2.4.1 Dissected terrains and ice sublimation

New observations from MOC images:
Other ice related features than at Viking scale



* Map of Mustard et al., Nature, 2001



* Latitude range: 30-60°

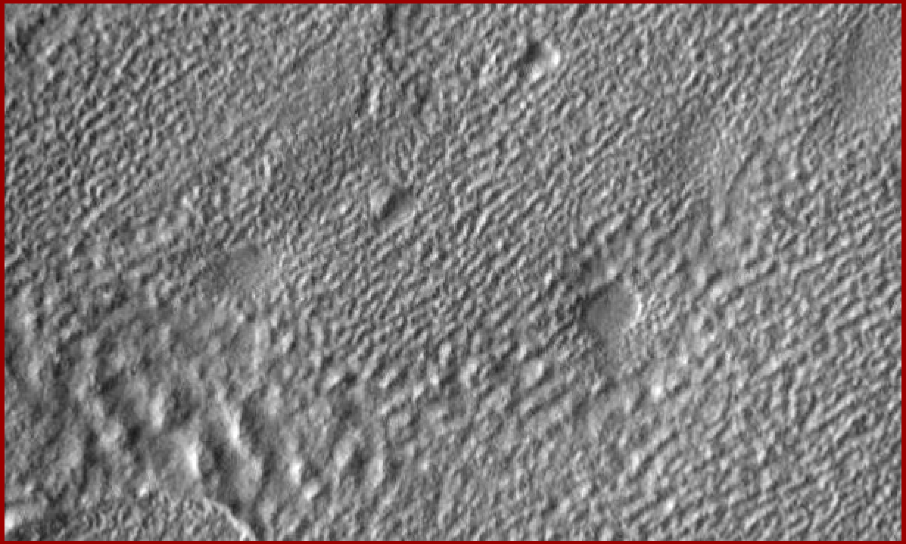
* Typical thickness affected by dissection: 10 mete

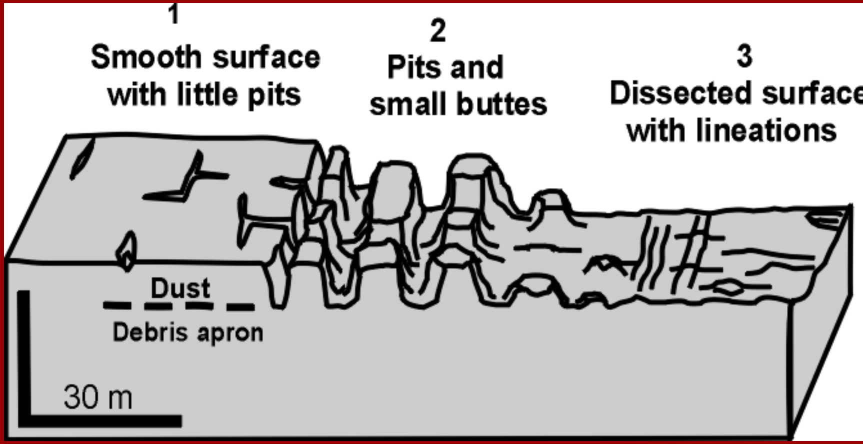
* Can be attributed to sublimation of ice rich depos
of probably dust and wind blown material

2.4 Small scale ground ice related features (< 10 m thick)

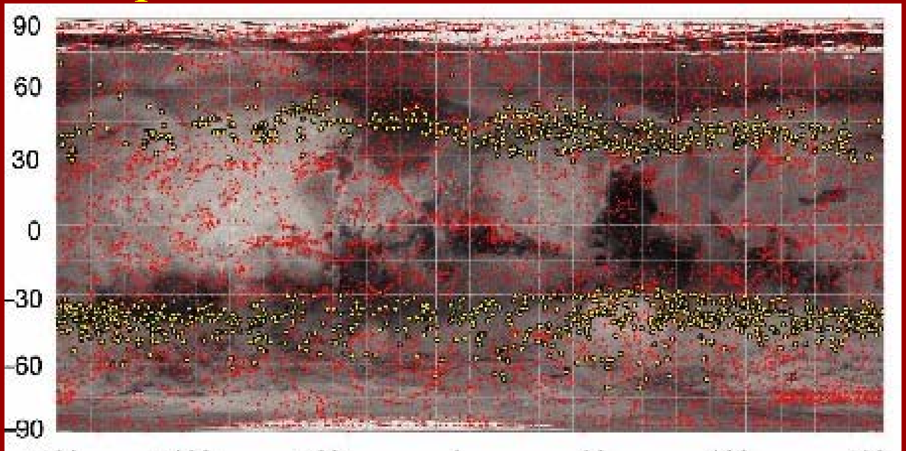
2.4.1 Dissected terrains and ice sublimation

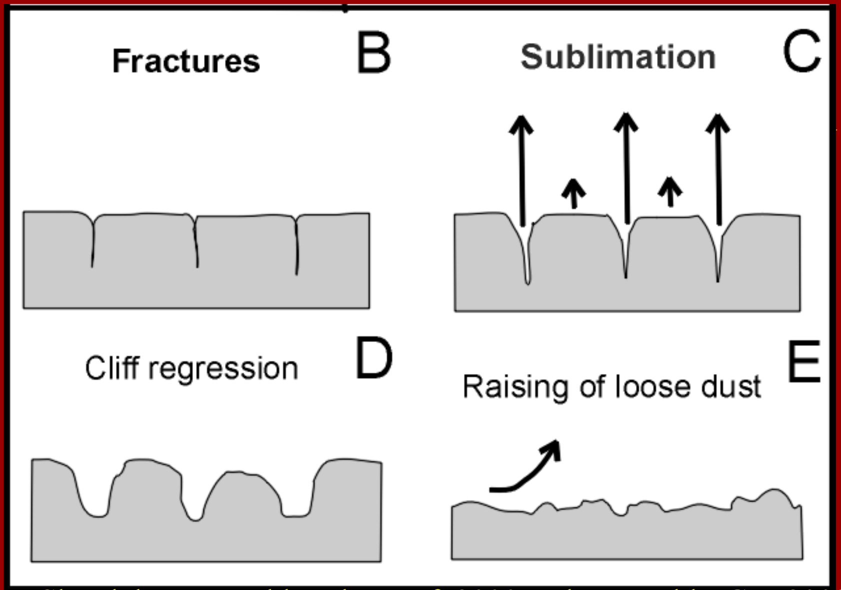
New observations from MOC images:
Other ice related features than at Viking scale



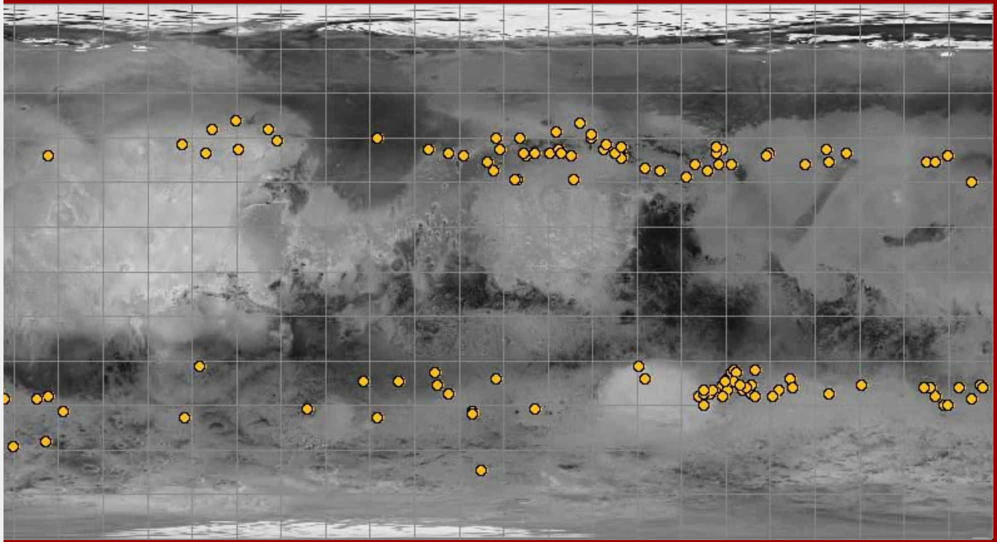


* Map of Mustard et al., Nature, 2001





Viscous features at MOC scale



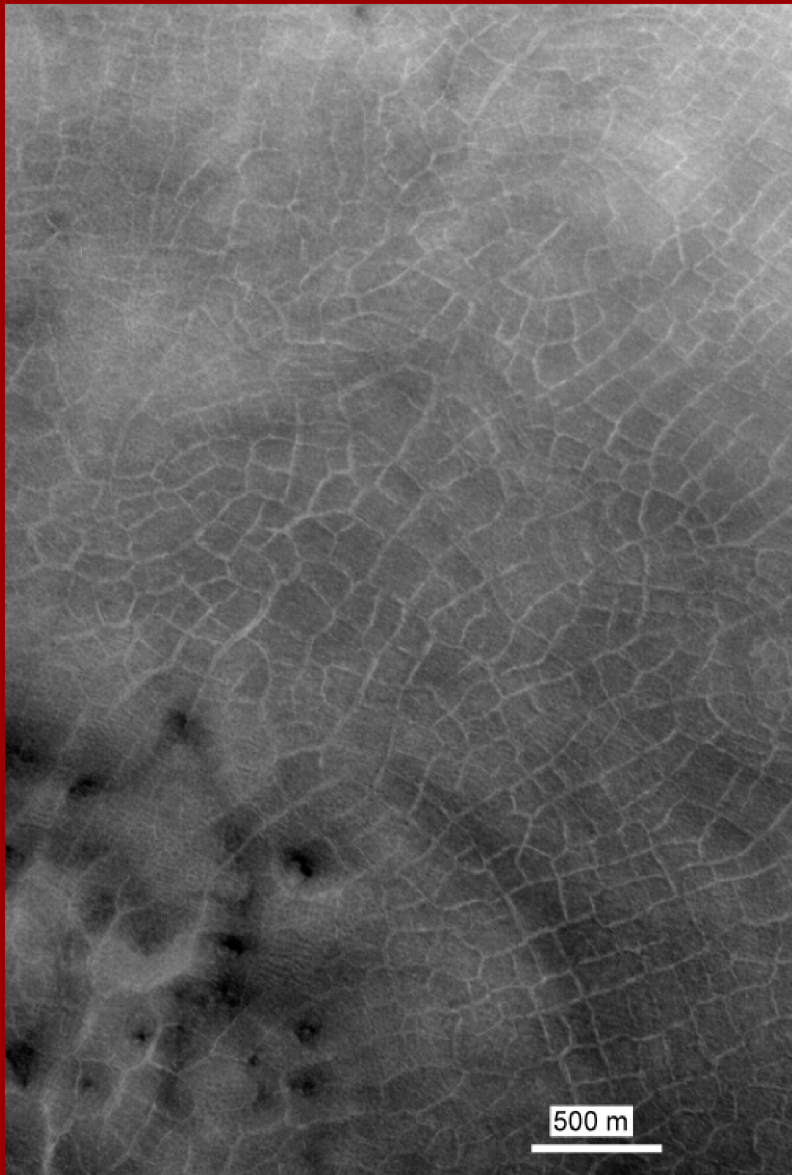
R. Milliken et al. (JGR, 2003)

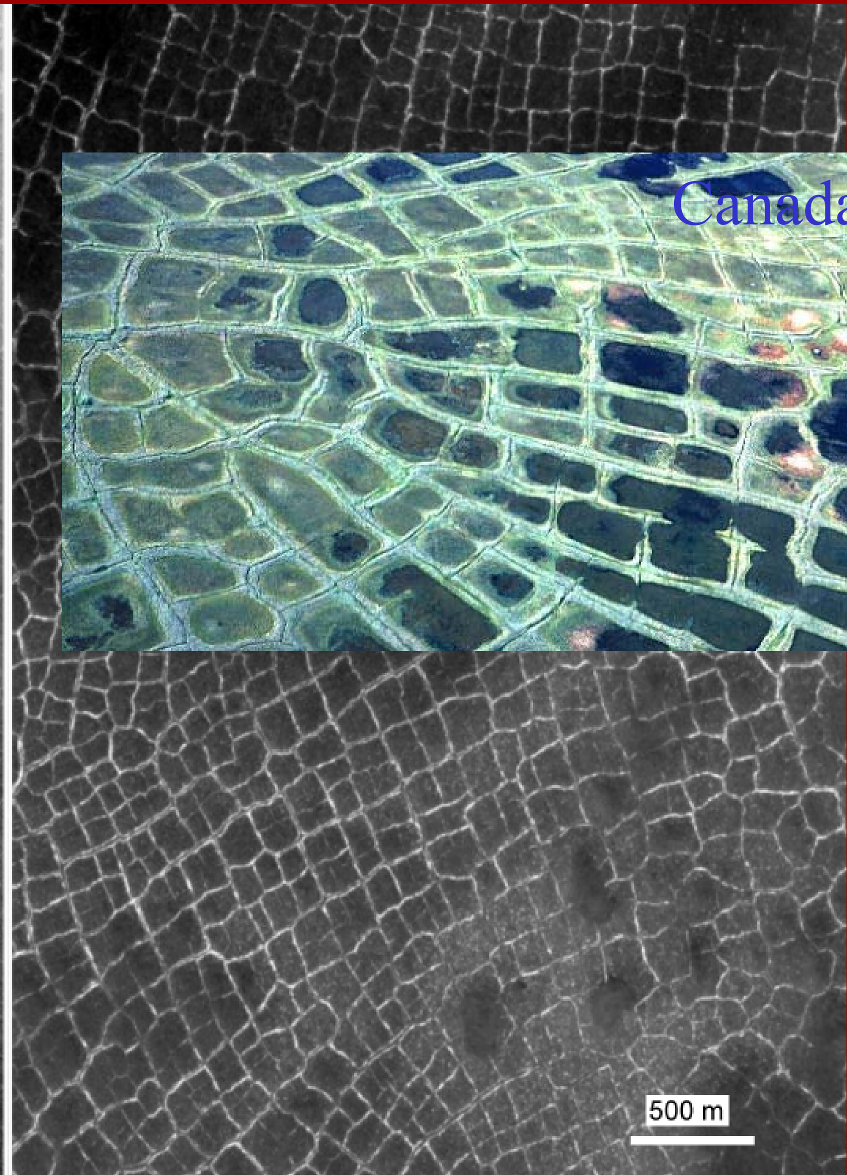
Connection between MOC scale features and Viking features: same latitude 30-50°

Here ice seems to be atmospheric (sliding blanket)

2.4.2 Polygons and frost cracks

Periglacial polygons





MOC images (Mangold, Icarus, submitted)

Small scale patterned grounds on Mars:

* Size polygons 10 to 300 meters

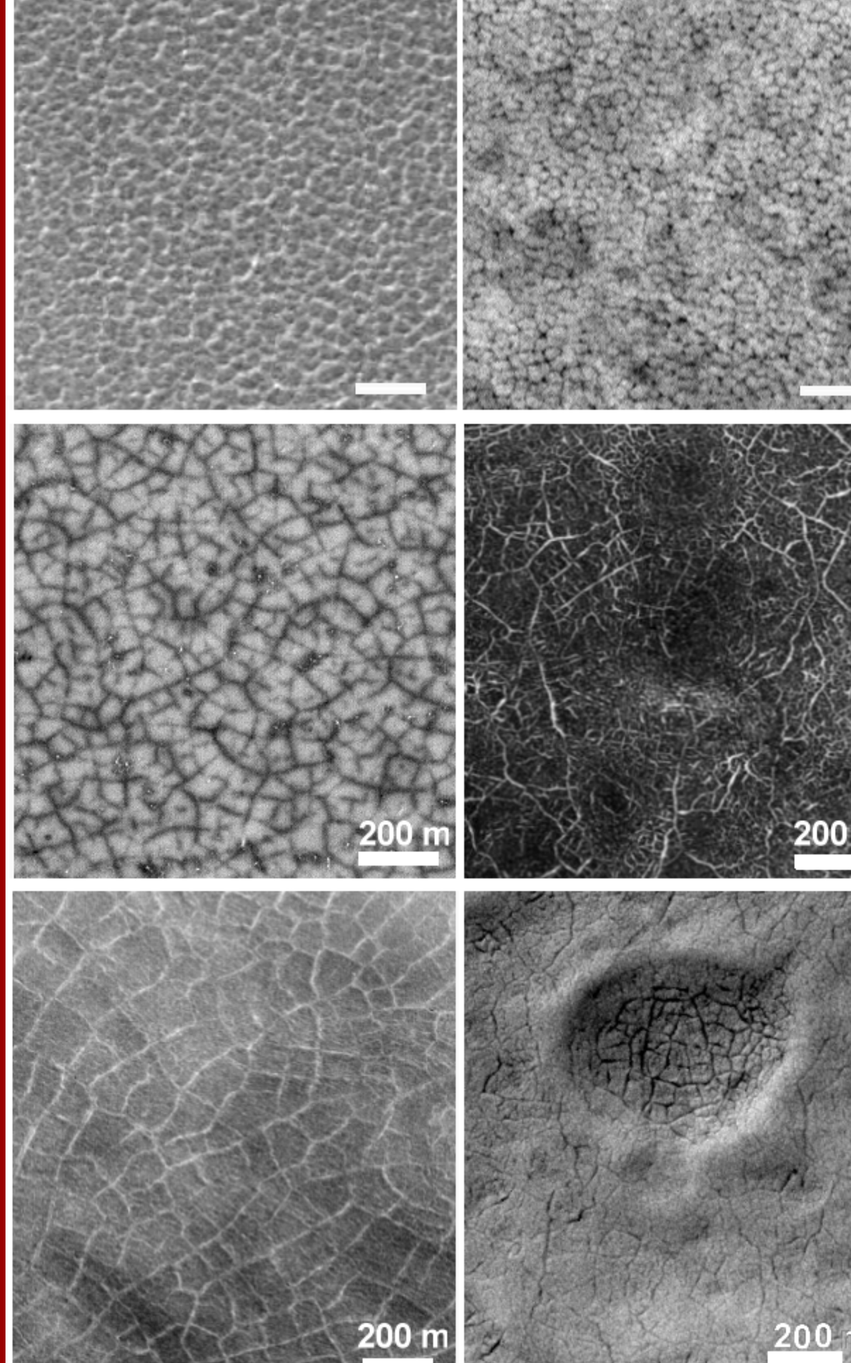
* Periglacial origin likely
=> indicate the presence of ground ice

* Cracks due to thermal contraction due to seasonal temperature variations
=> main process on Earth

* Very recent features (no impact craters)

* Strong diversity => no single process

* Possibility of **seasonal thaw** in their formation (ice wedge polygons)
=> debated issue



Small scale patterned grounds on Mars:

* Size polygons 10 to 300 meters

* Periglacial origin likely
=> indicate the presence of ground ice

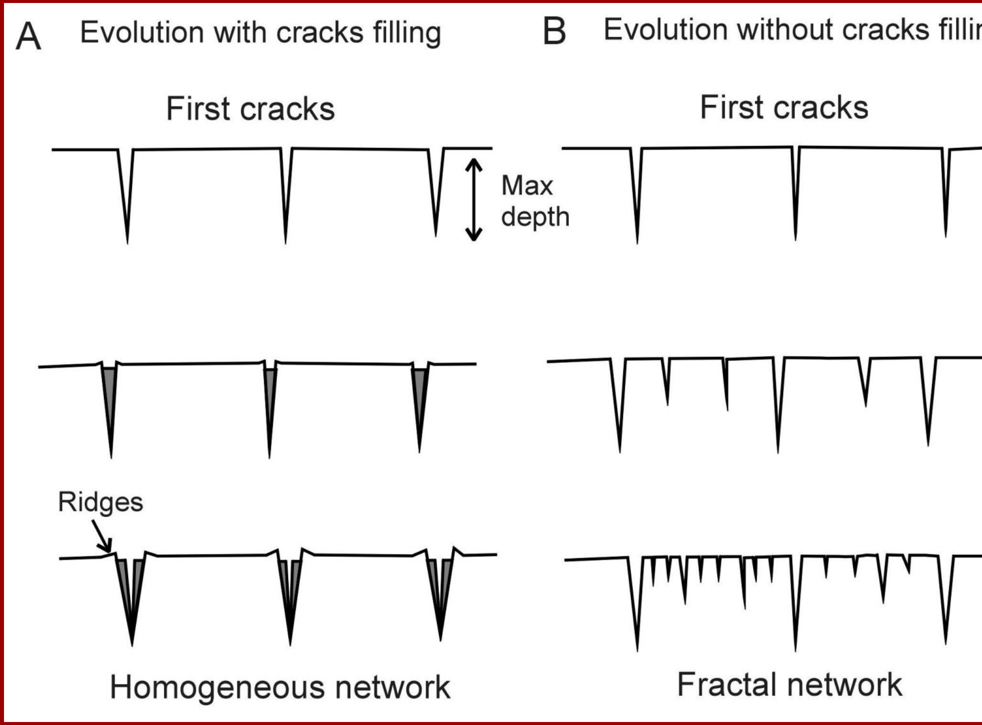
* Cracks due to thermal contraction due to seasonal temperature variations
=> main process on Earth

* Very recent features (no impact craters)

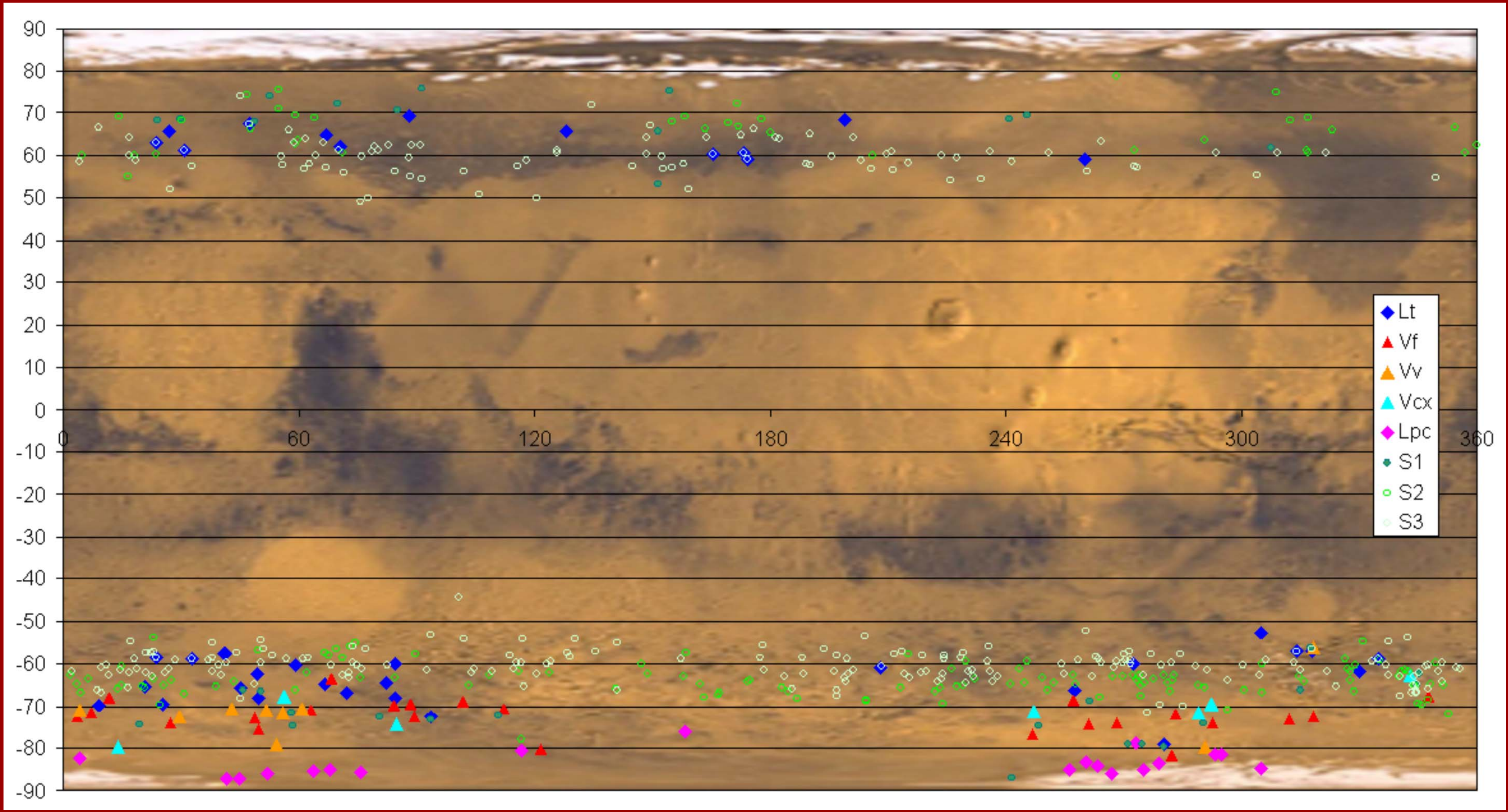
* Strong diversity => no single process

* Possibility of **seasonal thaw** in their formation (ice wedge polygons)
=> debated issue

Ice wedge in Canada



Distribution of patterned ground on Mars

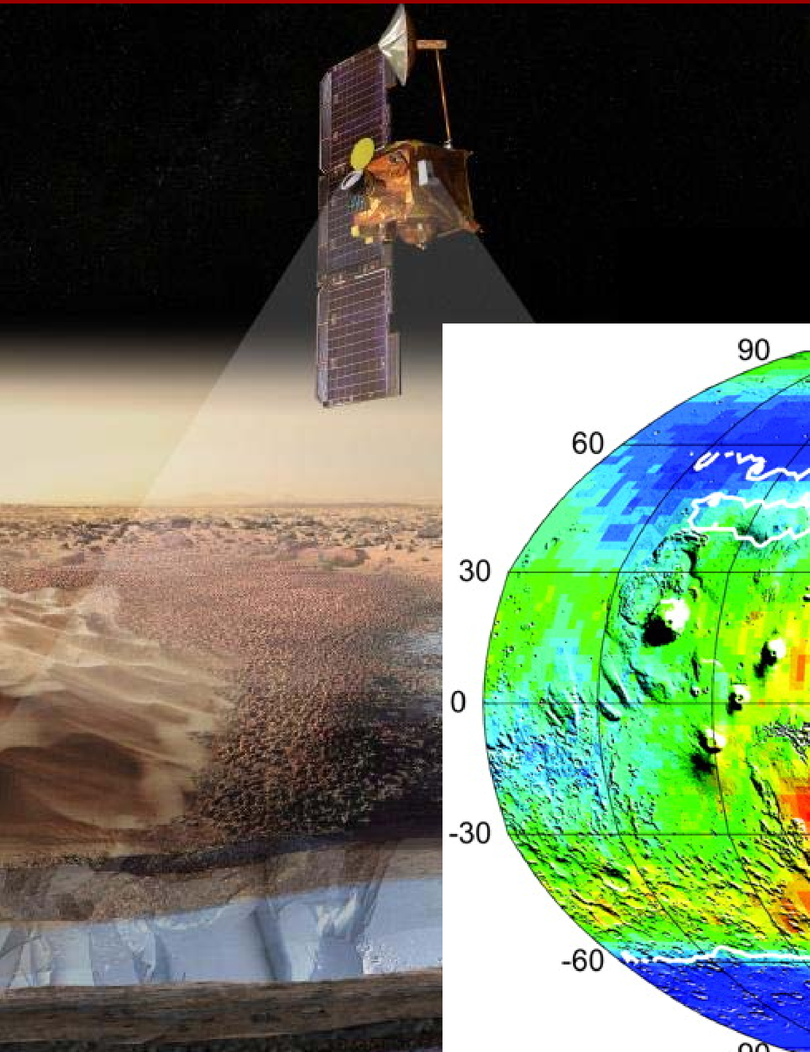


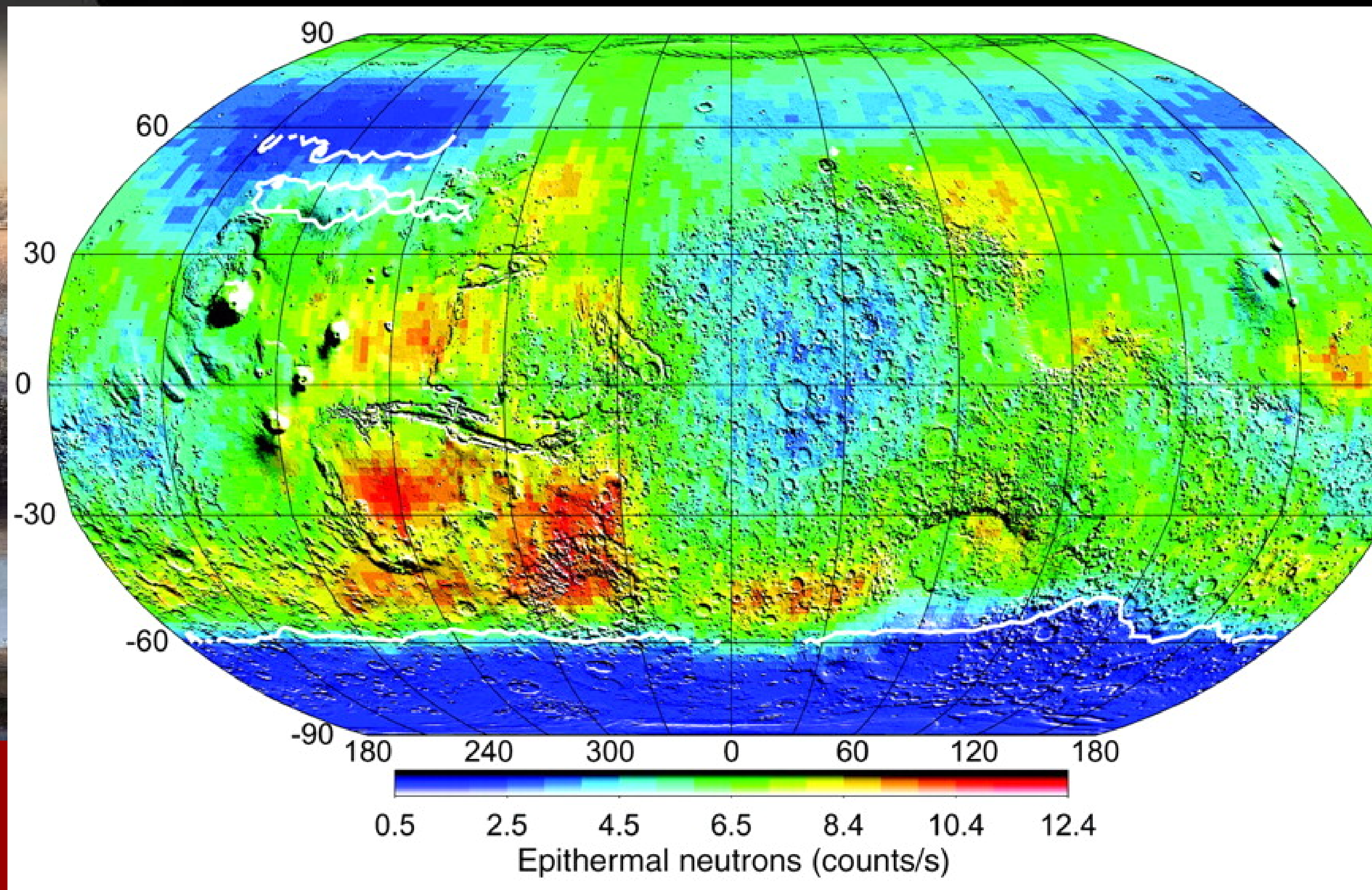
Seasonal thermal contraction affect 1-3 meters of ground

Distribution of ground ice from Mars Odyssey data

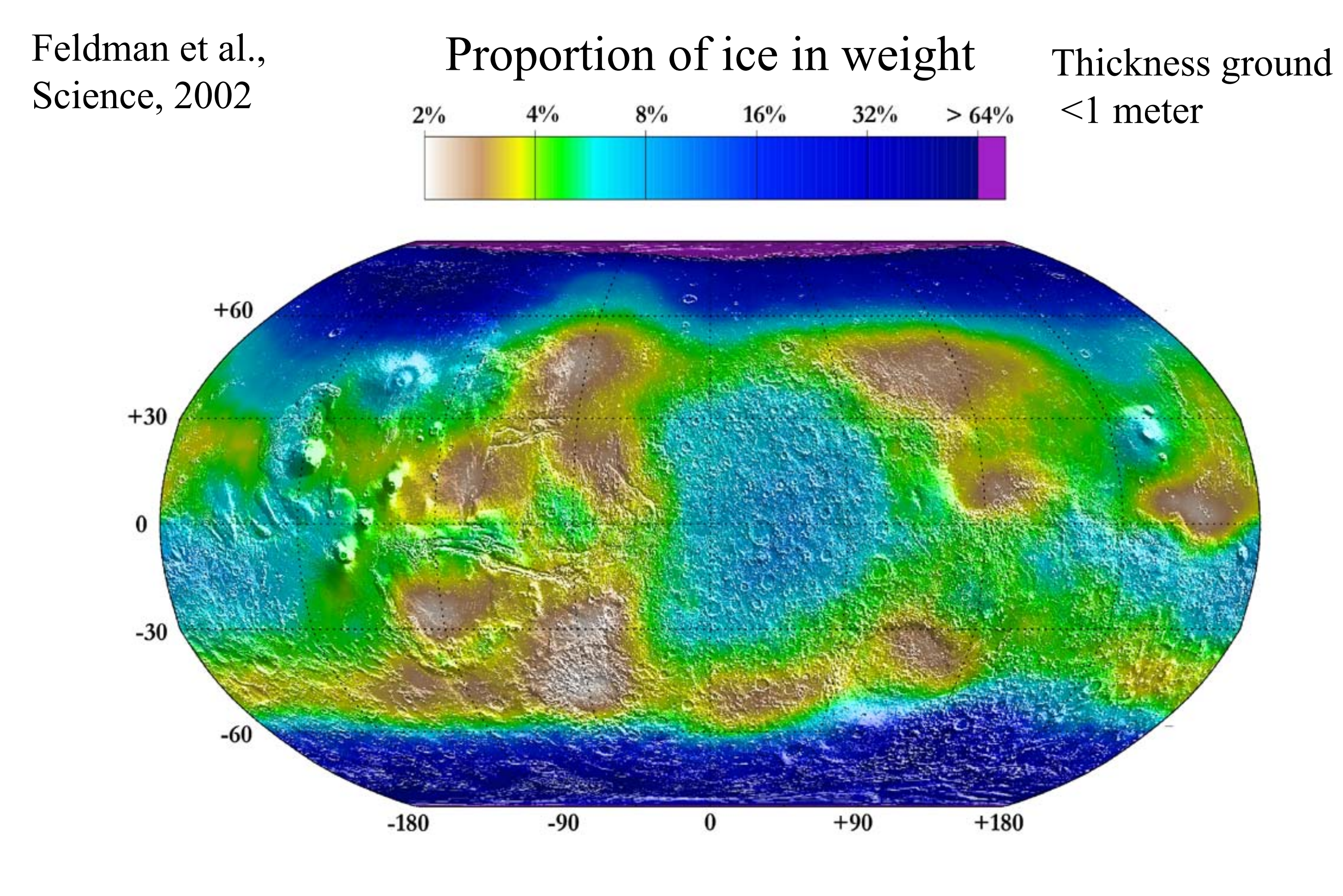
Neutron Spectrometer
onboard Mars Odyssey
(Feldman et al., Science, 2002)

Indirect detection of ground ice (Hydrogen





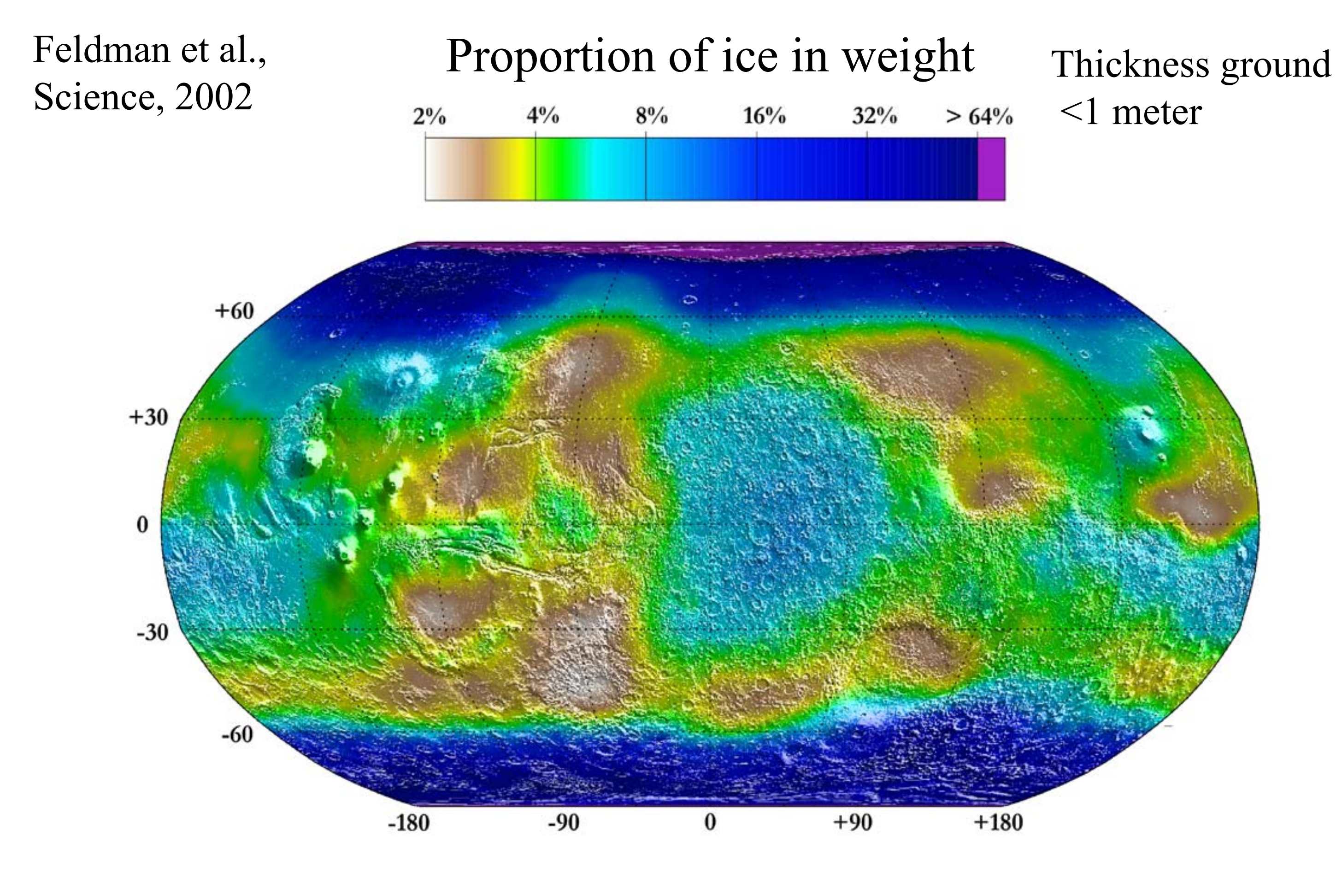
Distribution of ground ice from Mars Odyssey data



At present obliquity ice is stable at all latitudes >50° below few 10s cm (upper tens of cm are dessicated) (Mellon and Jakosky, 1995)

=> Direct correlation of data with current models

Distribution of ground ice from Mars Odyssey data



But: 1. Proportion higher than previously assumed

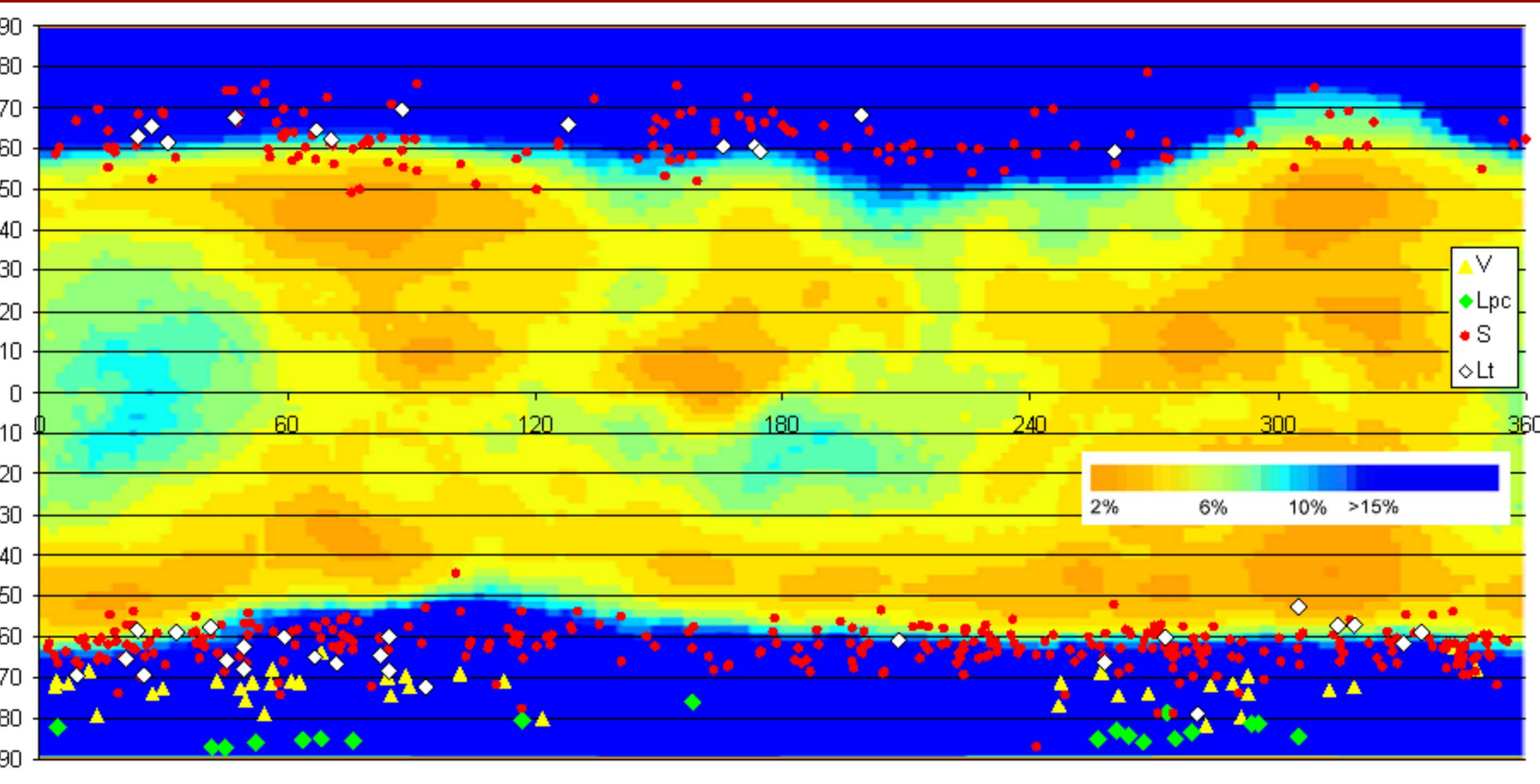
=> possible ice layers directly condensed at surface (Mischna et al., 2003)

2. Equatorial ice unpredicted

=> still debated if real ice, adsorbed water or mineral clays (-OH, -H20 in molecule)

Comparison Neutron Spectrometer/Patterned ground

Mangold et al, JGR (2004)



Good correlation

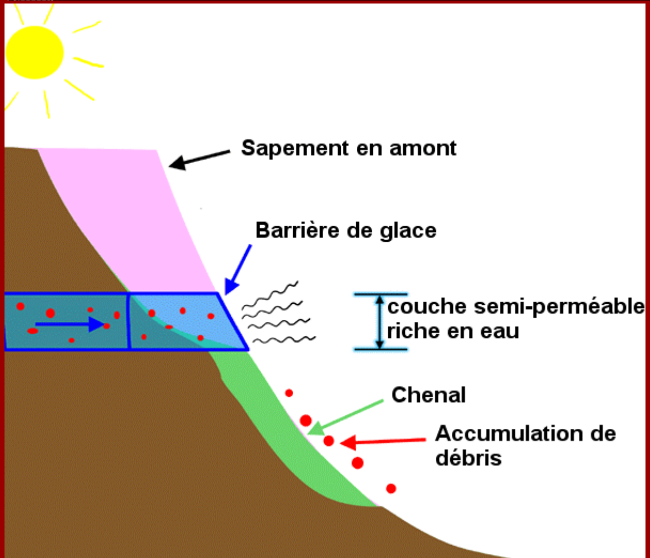
=> Patterns are young and still associated to the current ice distribution

=> Patterns are formed by processes in the uppermost meters of the ground

2.3.4 Recent gullies

First interpretation:
Malin and Edgett (Science, 2000):

Seepage of water from aquifers

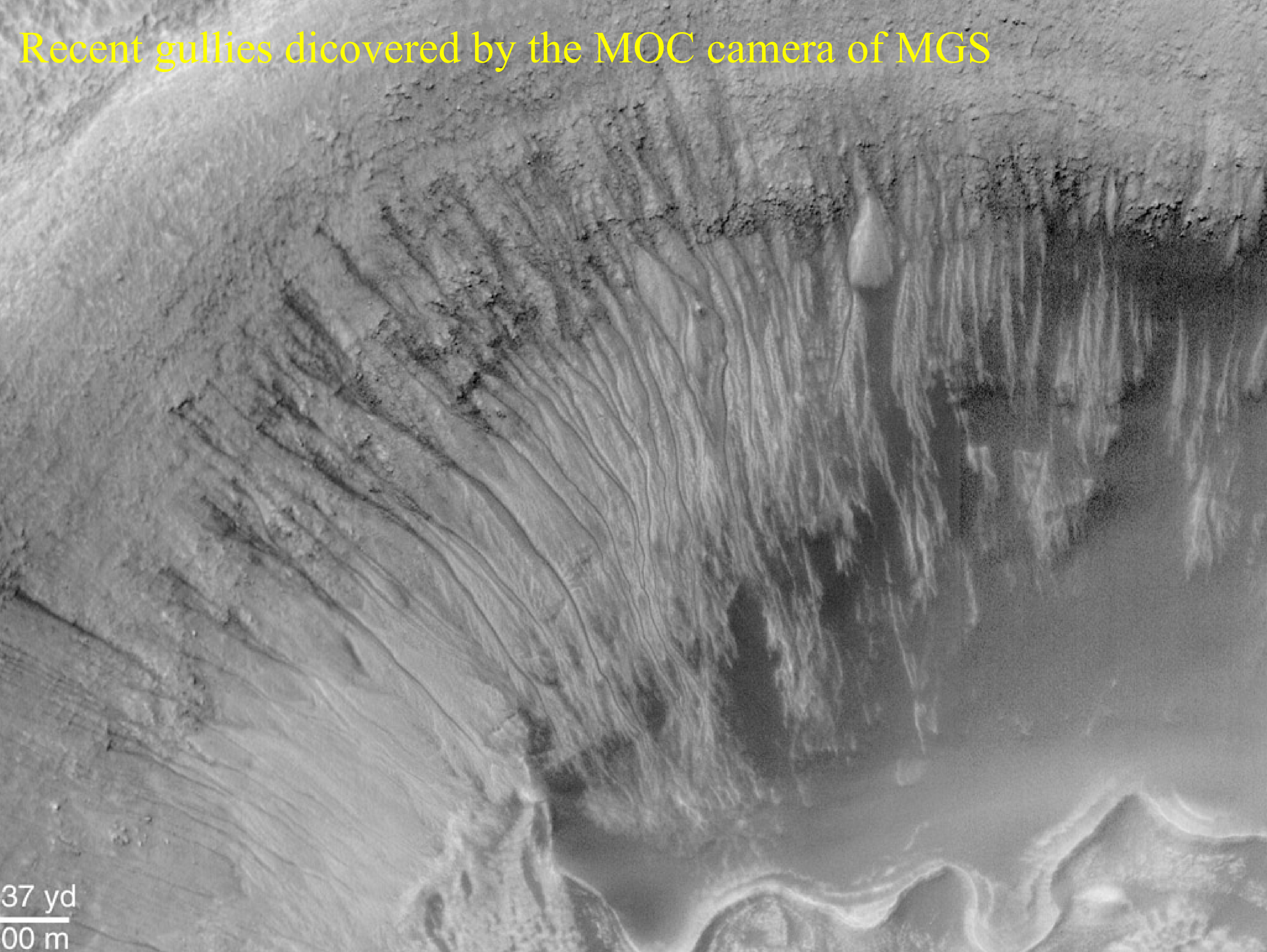


Malin and Edgett (Science, 2000):
Subsurface water exist at 100 meters deep

They propose the water to be expulsed quickly due to ice plugs which stops permanent water flow

Problem: Temperature -70° C at the surface
Should be still -65° C at 100 m deep

Recent gullies dicovered by the MOC camera of MGS



Different other hypothesis have been proposed:

Mellon and Phillips, JGR, 2000: Thermal conductivity of loose material could permit liquid water at 100 m deep
(but we see scarps fromed by rocks)

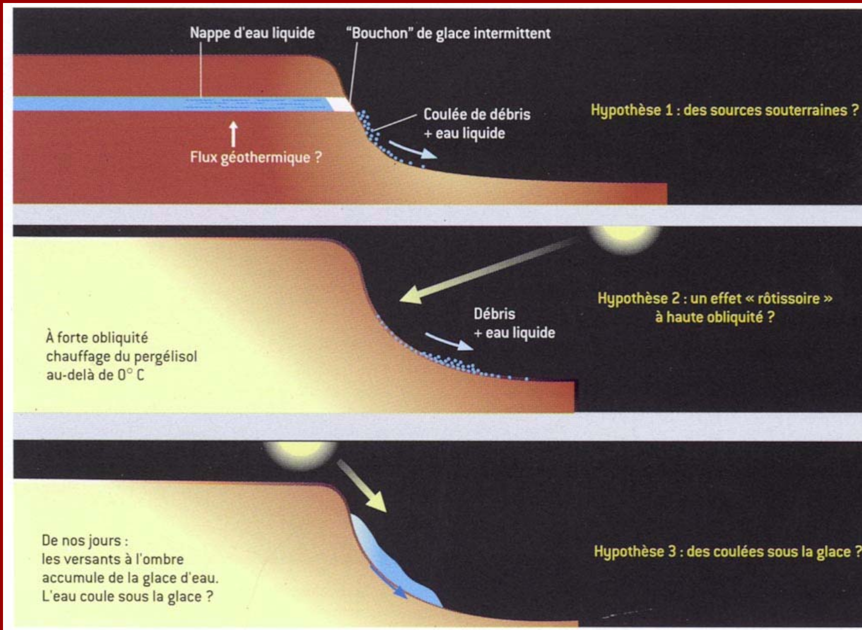
Musselwhite et al., GRL, 2001: Clathrates or salt rich material in the ground (lower melting point than water ice)
(but no evidence of exotic materials)

Hoffman, Icarus, 2001: liquid CO2 flows
(but highly unstable at atmospheric pressure)

Costard et al., LPSC, 2001,
Costard et al., Science, 2002: Formation by external heating due to obliquity change

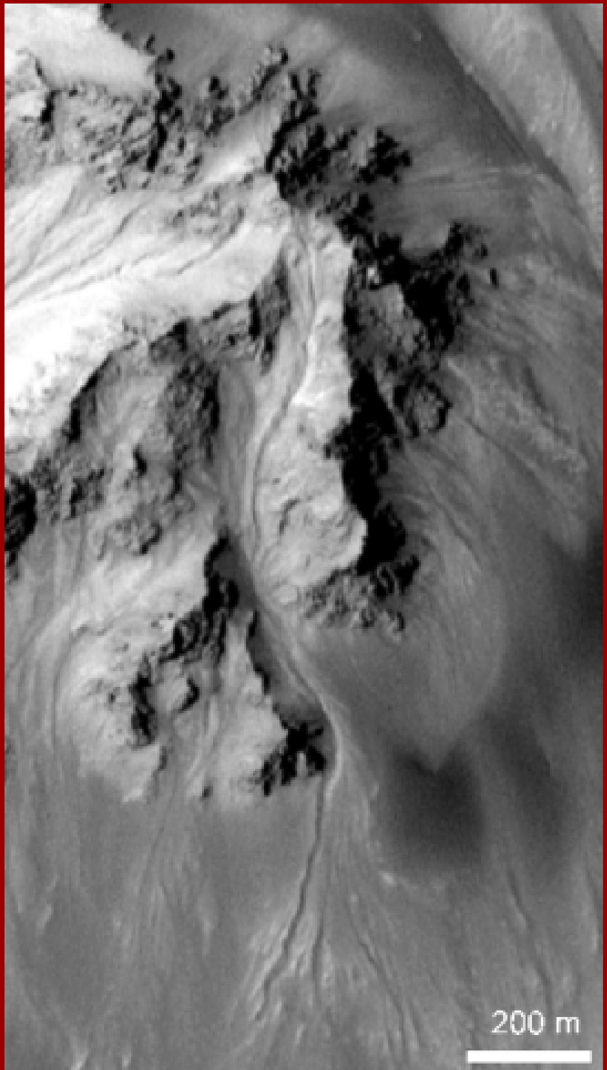
Lee et al, LPSC, 2001,
Christensen, Nature, 2003: Snow accumulation and melting

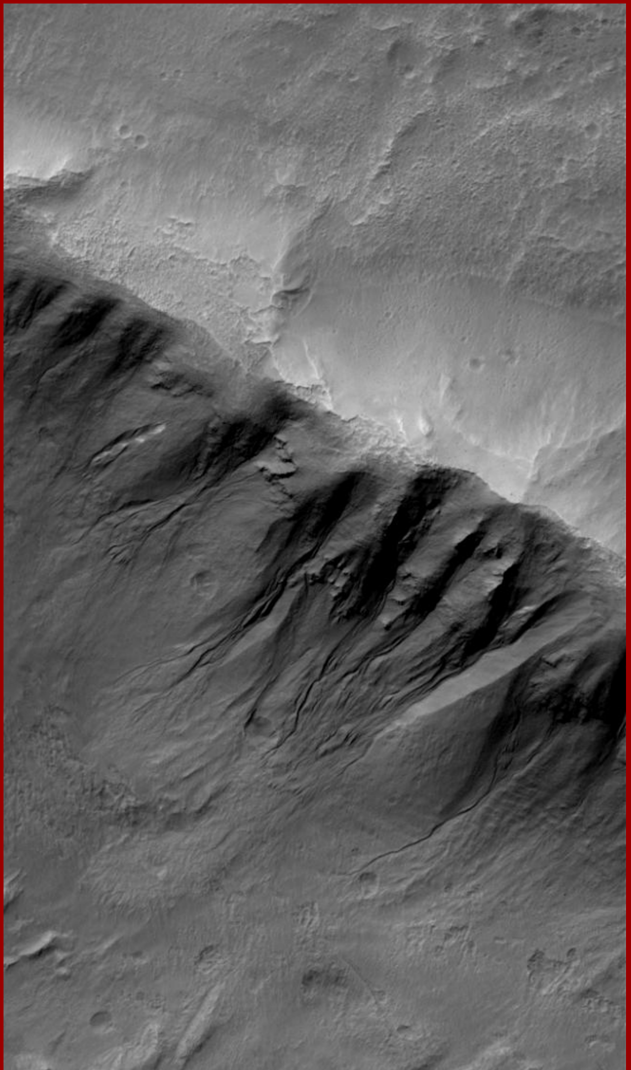
In summary:
Current subsurface aquifers
or
current snow melting (external process)
or
past obliquity melting (external process)



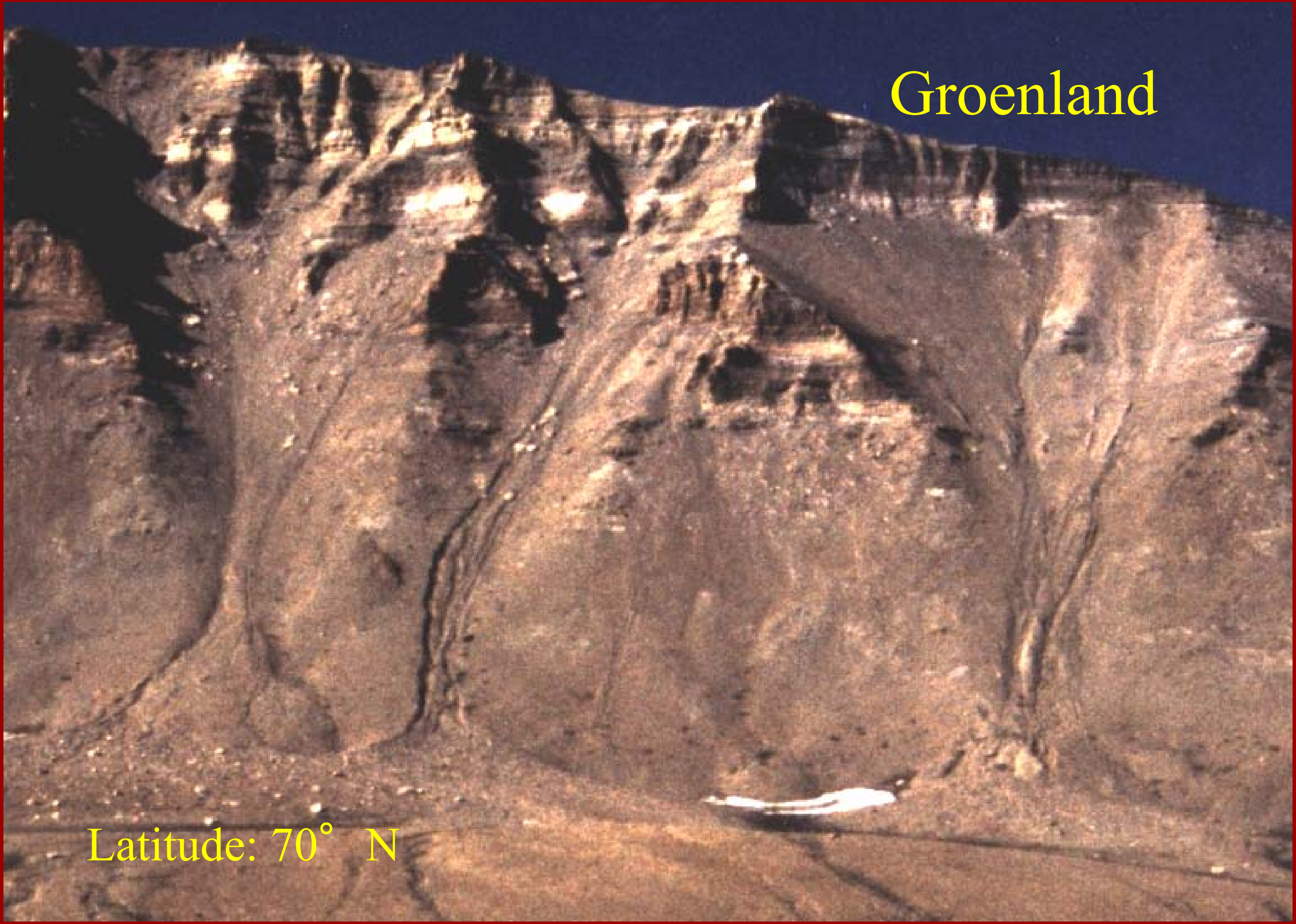
In 2001, we proposed these gullies are formed by external heating, why?

1. Gullies exist over isolated hills (no relation with aquifers)





2. Gullies are similar to terrestrial debris flows
which form by snow/near surface ground ice melting

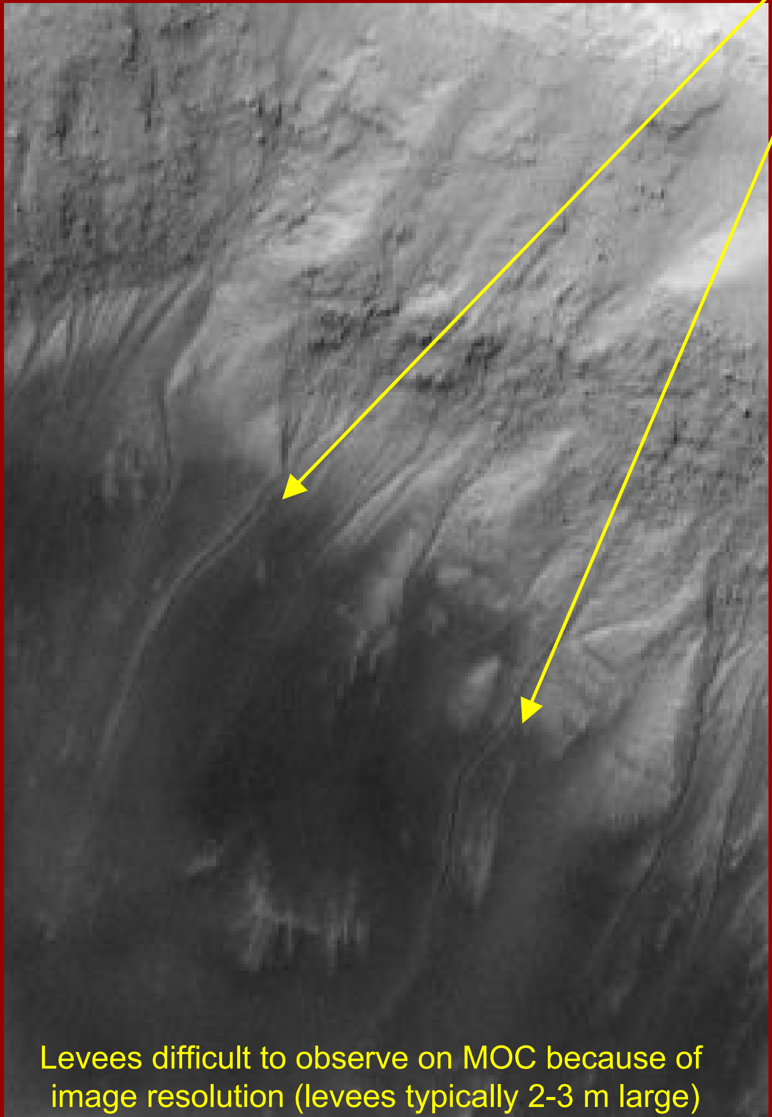


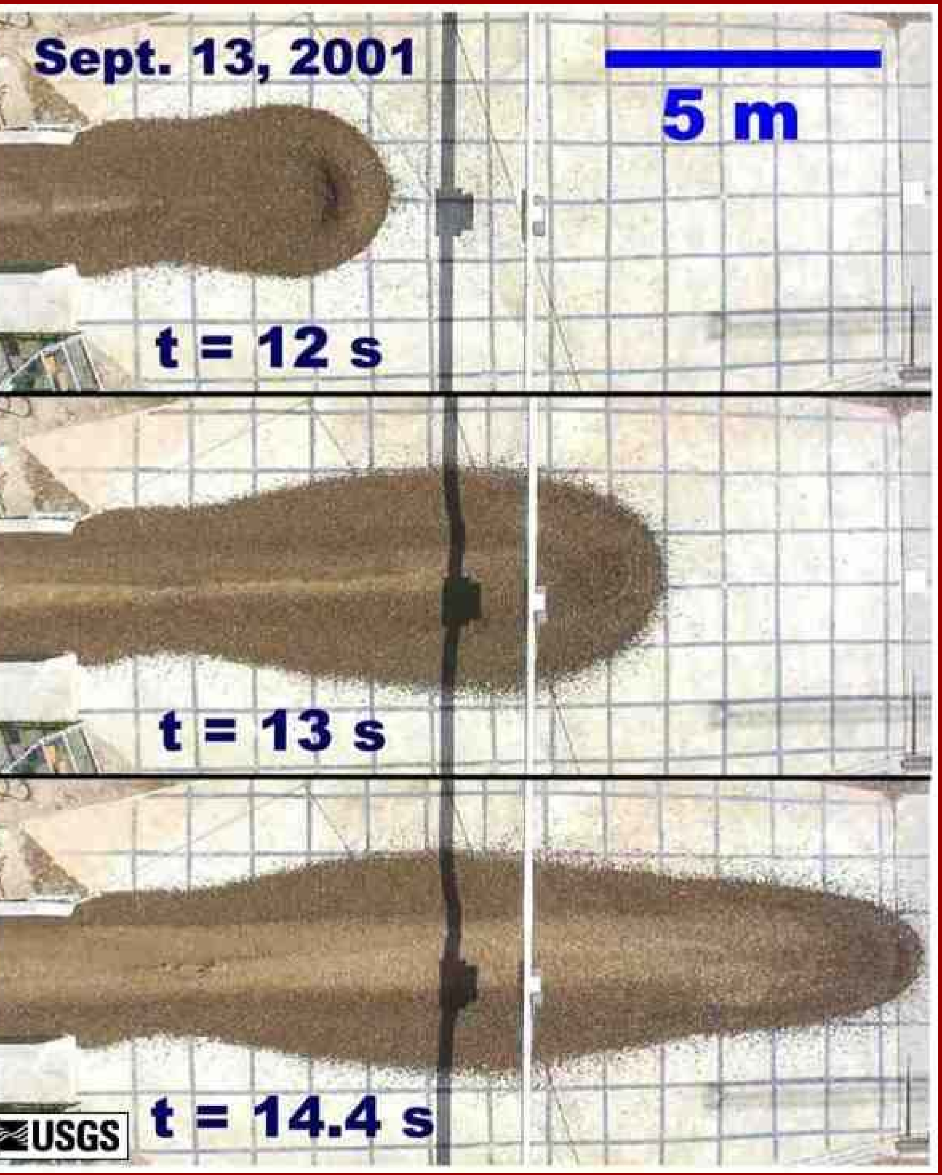
Debris flows: Seasonal melting

3. Like on the Earth, channels are bordered by levees

=> with water + rock in proportion >50%

=> mass flow, not progressive erosion (in agreement with Malin and Edgett interpretation)



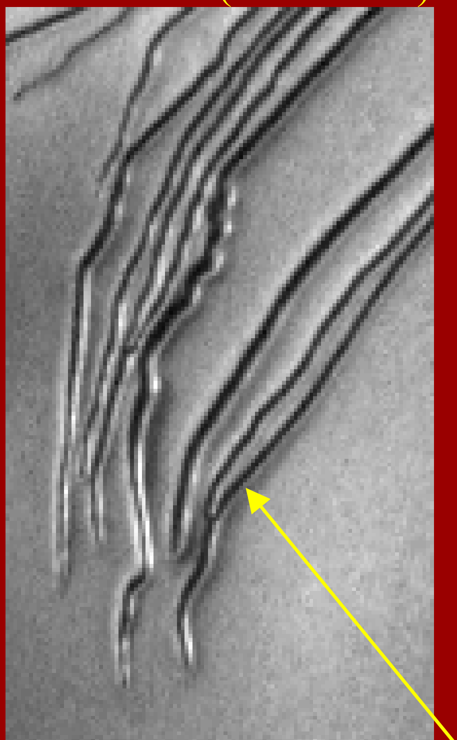


Experiment by Iverson (web page)

Hillslope debris flows in the Alps

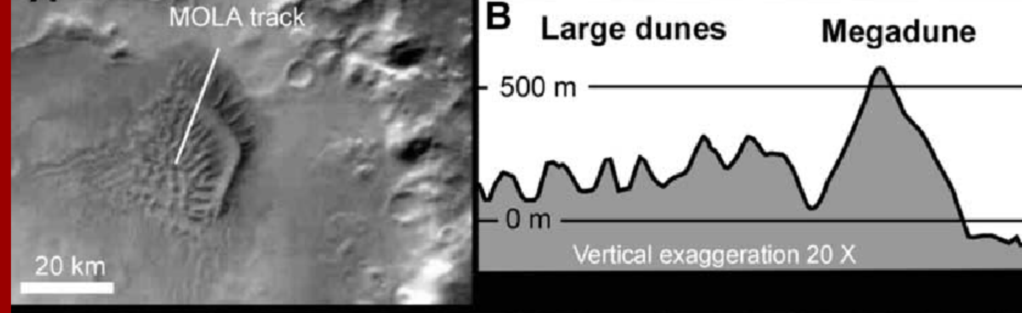
4. Gullies over sand dunes have same characteristics (aquifers unlikely)

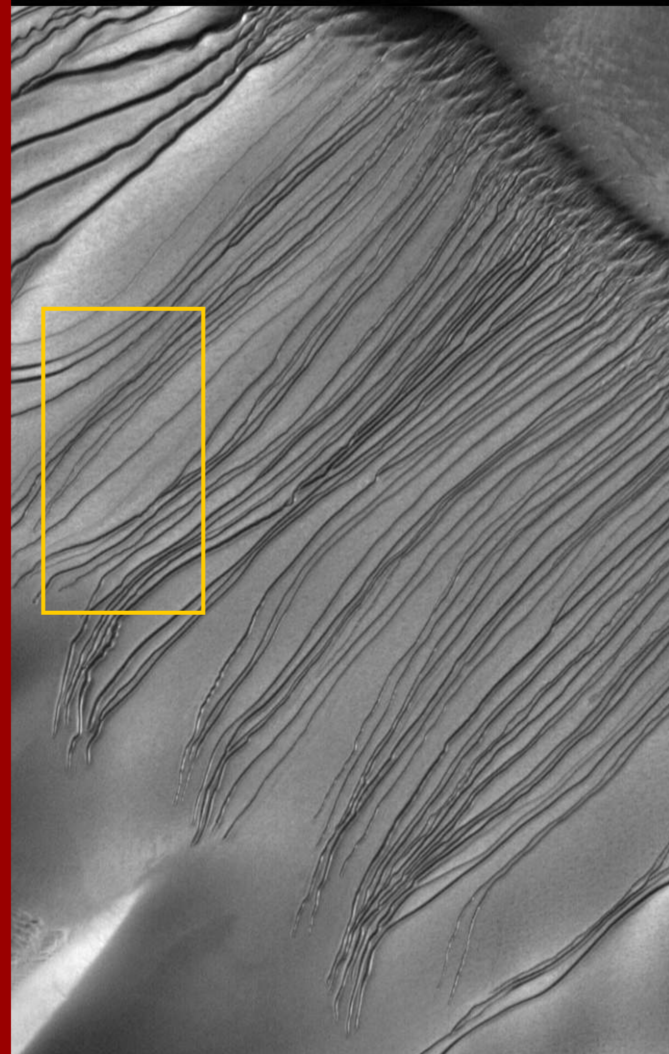
Gullies in Russell crater dune field (55° South)



(Mangold et al., JGR, 2003)

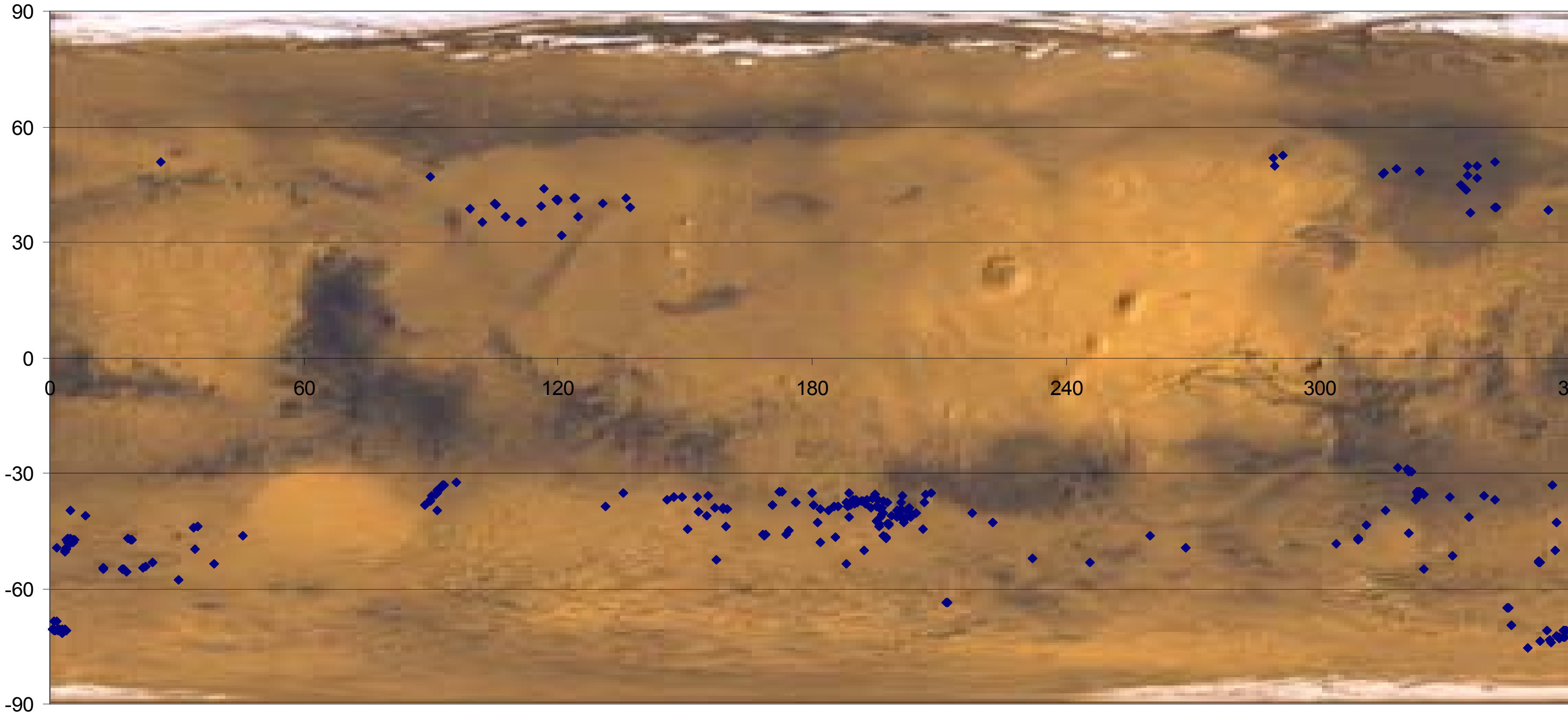
Levees





How to explain their formation by external processes?

1. Distribution latitude > 30 N and 30 S
   No equatorial flows



→ Presence in latitude range where many ice related features exis

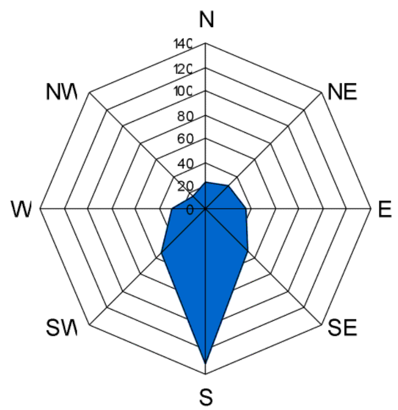
How to explain their formation by external processes?

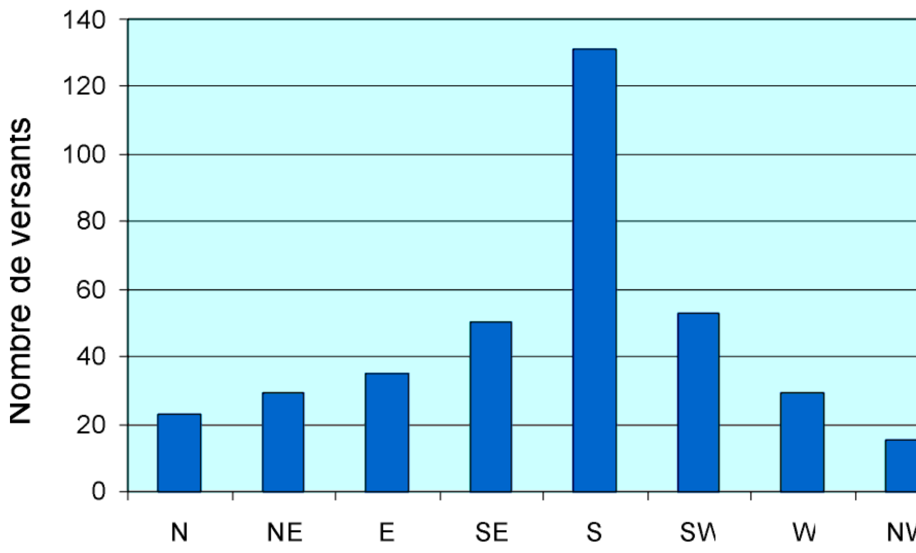
1. Distribution latitude > 30 N and 30 S
   No equatorial flows

2. Poleward facing slopes preferred

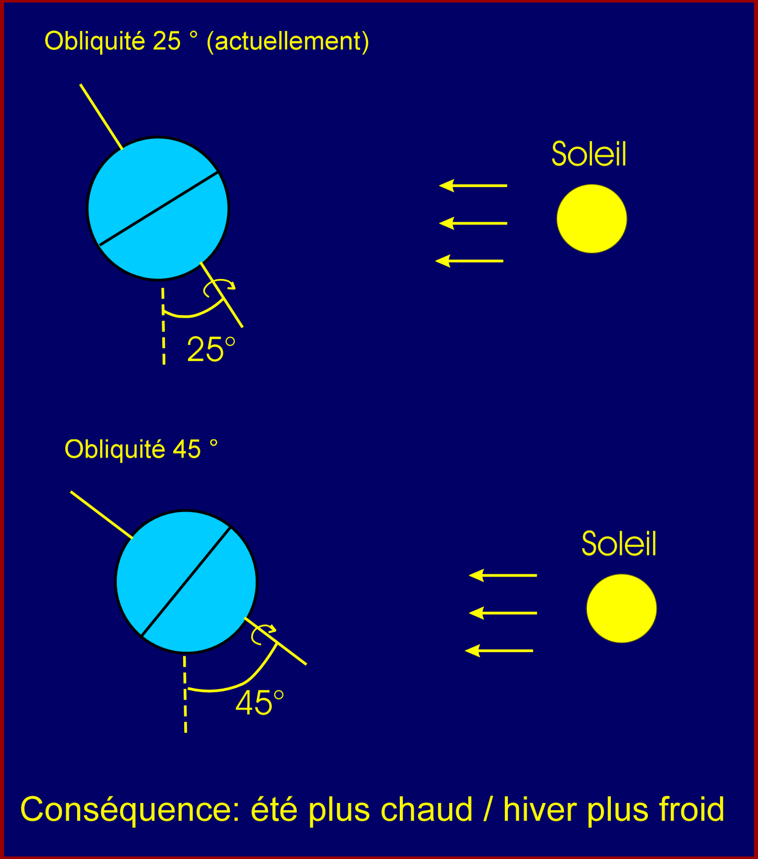
Hémisphère Sud

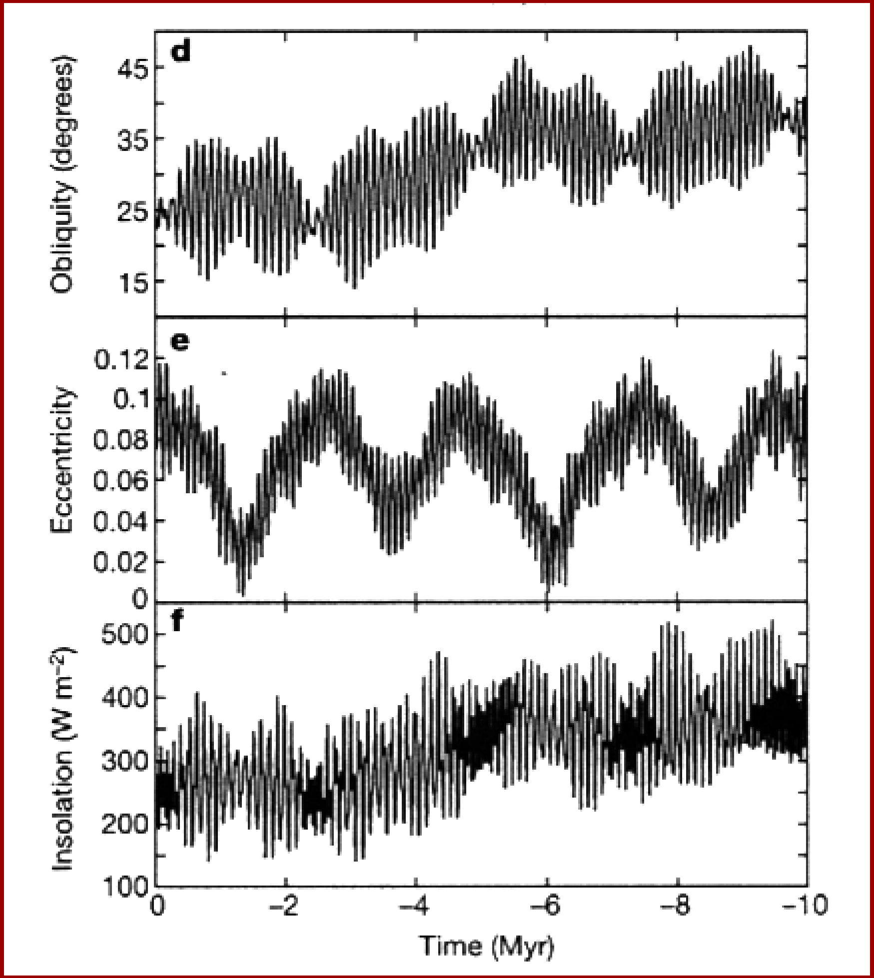
Orientation des "gullies" sur
365 versants provenant de 252 images





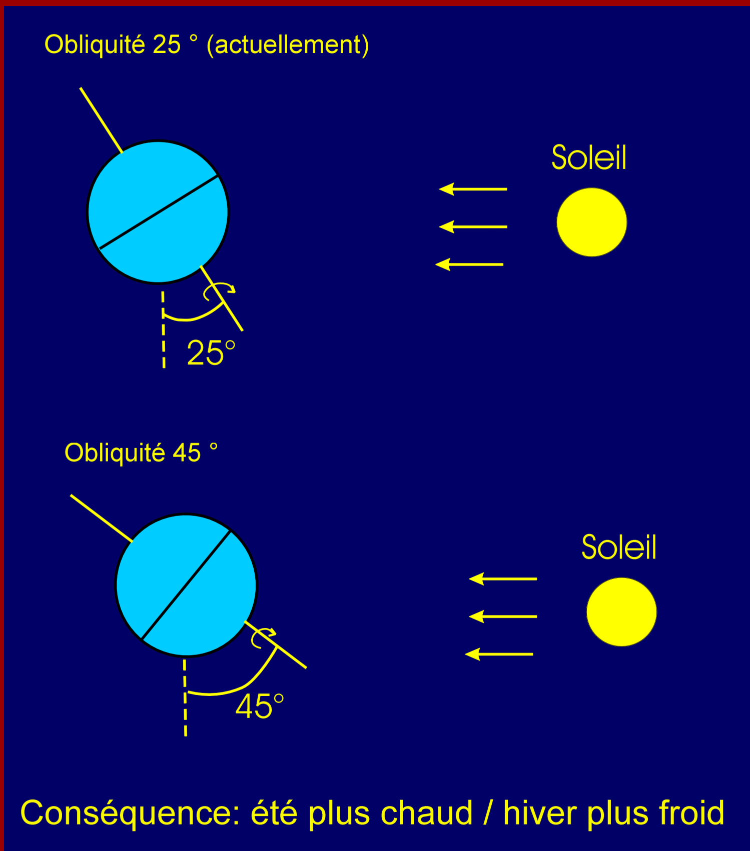
Hypothesis =
heating in polar regions
at high obliquity



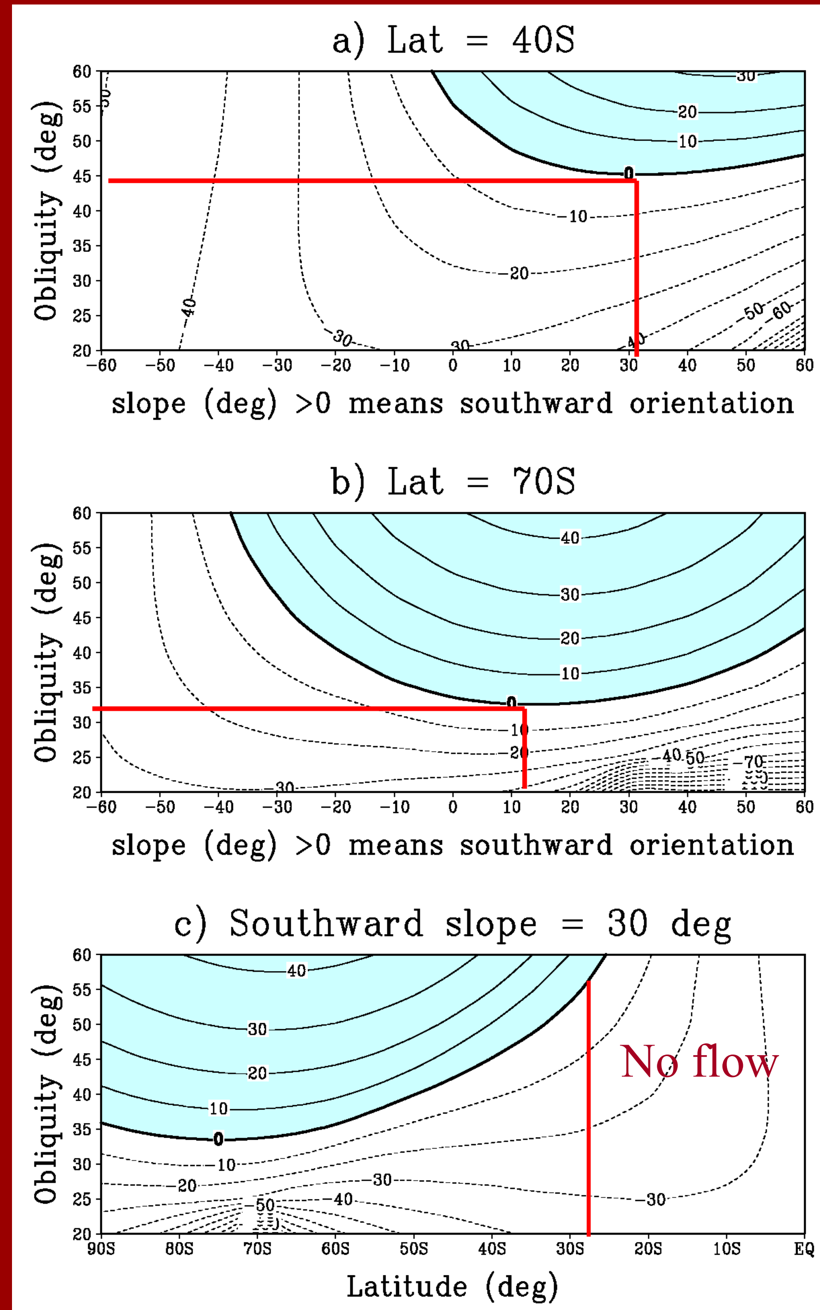


Laskar et al., Nature, 1993, 2002

Hypothesis = heating in polar regions at high obliquity



Temperature at summer solstice



- The model explains the lack of flows in equatorial regions

- Explain poleward facing slopes are preferred

Roughness of MOLA data: effect of obliquity too

High latitudes are smoother: softening (ice) (Squyres, 1989)
+ smoothing by dust/ice mixture
+ creep diffusion of slopes (Perron et al., 2003)
+ gullies formation + seasonal thaw? (Kreslavsky and Head, 200

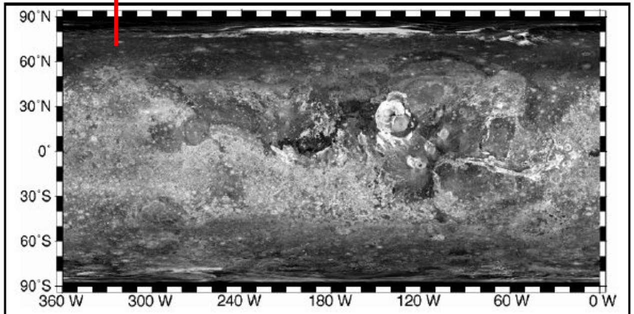


Fig. 2. Map of roughness at 0.3 km baseline. Brighter shades denote rougher surface.

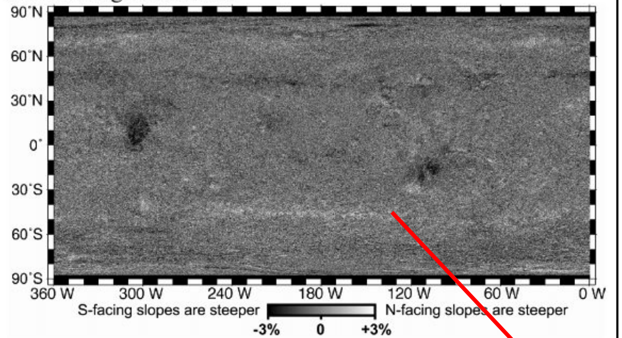


Fig. 3. Map of the north-south slope asymmetry parameter *a*. Brighter shades denote that north-facing slopes are steeper; darker shades denote that south-facing slopes are steeper.

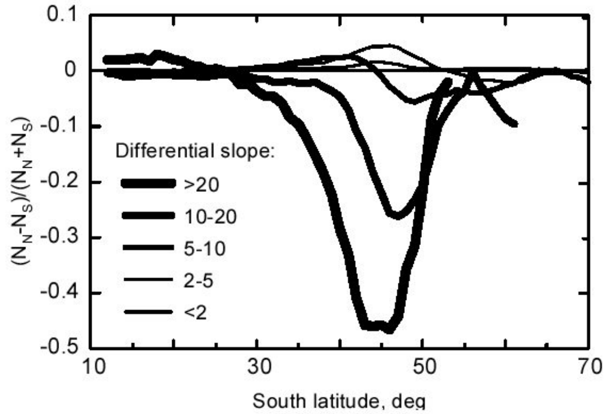


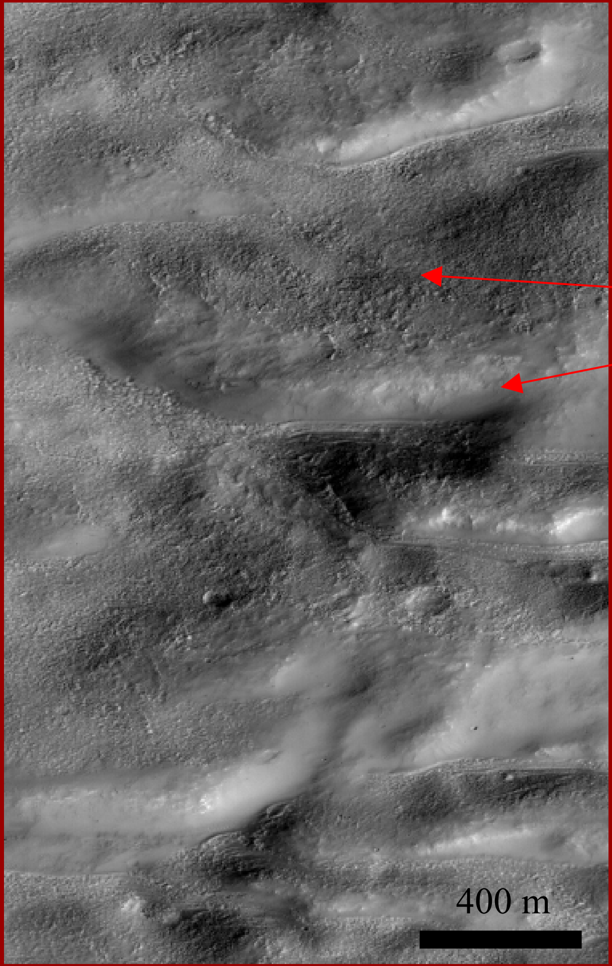
Fig. 5. Asymmetry of differential slopes calculated within 150-km wide latitudinal zones in Terra Cimmeria (180-220°W) and plotted against latitude. The measure of asymmetry is $A = (N_N - N_S) / (N_N + N_S)$, where N_N and N_S are numbers of steep N- and S-facing segments in all MOLA profiles. Different curves corresponds to different ranges of differential slopes in degrees, as shown.

Kreslavsky and Head, GRL, 2003

Dissymetry in the mid latitude slopes
=>equatorial slopes are steeper=less affected by gullies+softening

Dissymetry of mid latitude slopes on MOC and MOLA data

Dissymetry of polar facing slopes also observed on dissected terrains and ice related features on MOC images:



Dissected poleward

Smooth equatorward

Main conclusion about ice related features

All landforms are located in latitude ranges

=> climate dependency of ice stability (see lectures of tomorrow)

Pole

Most slopes<10° (smooth, no mass wasting)

Widespread icy features: Polygons, cracks + caps

Water ice rich (GRS data)

Possible seasonal thaw from polygons?

60°

Slope dissymetry

Many widespread ice related features:

Dissected terrains, lobate aprons, softening, etc.

Gullies: Transient liquid water

30°

Few or no ground ice related features (sharp slopes)

No gullies or recent water activity

Possible past equatorial glaciers very locally

Lobate ejecta craters: deep ice or ground water at which epoch?

Equator