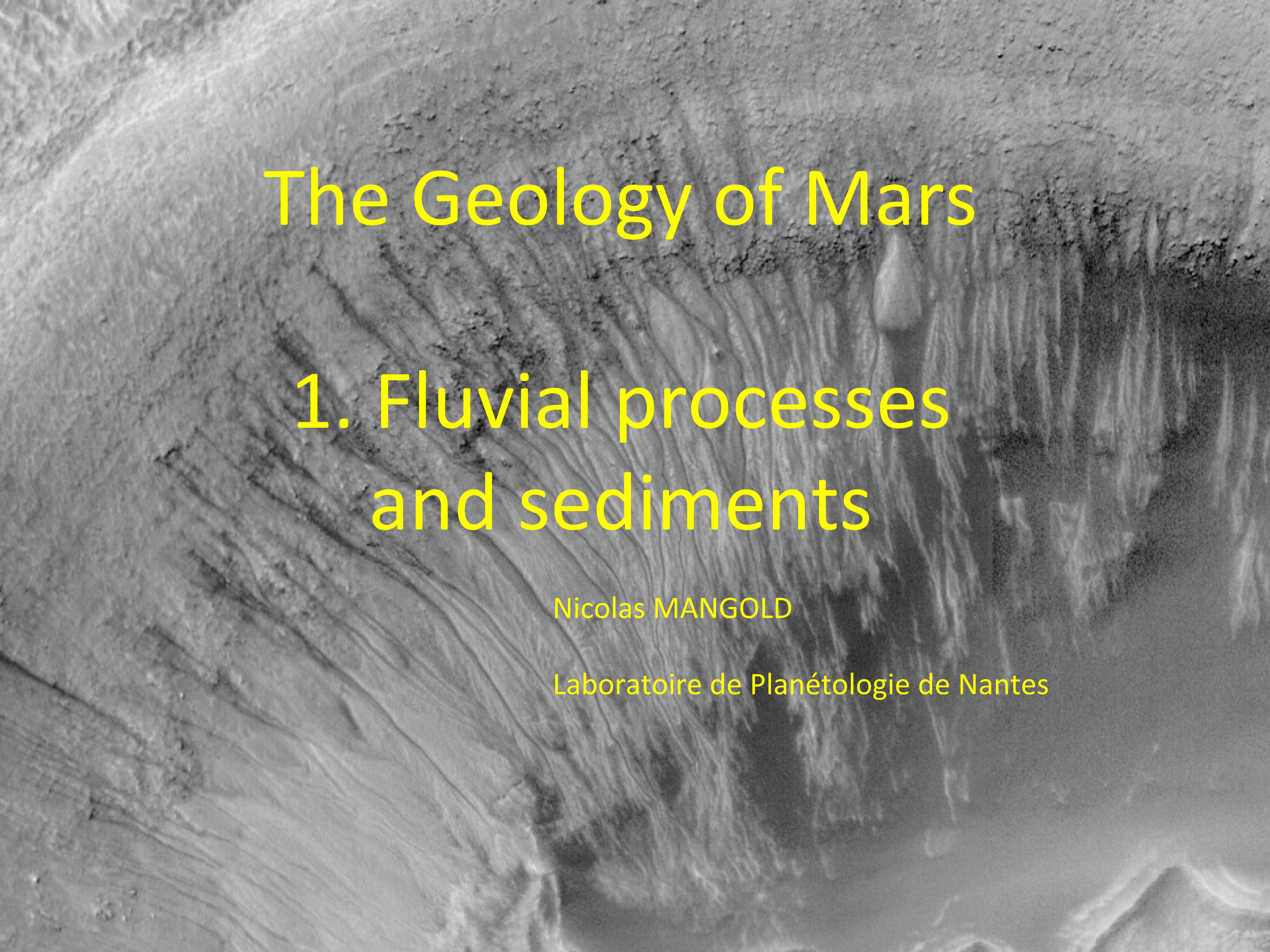


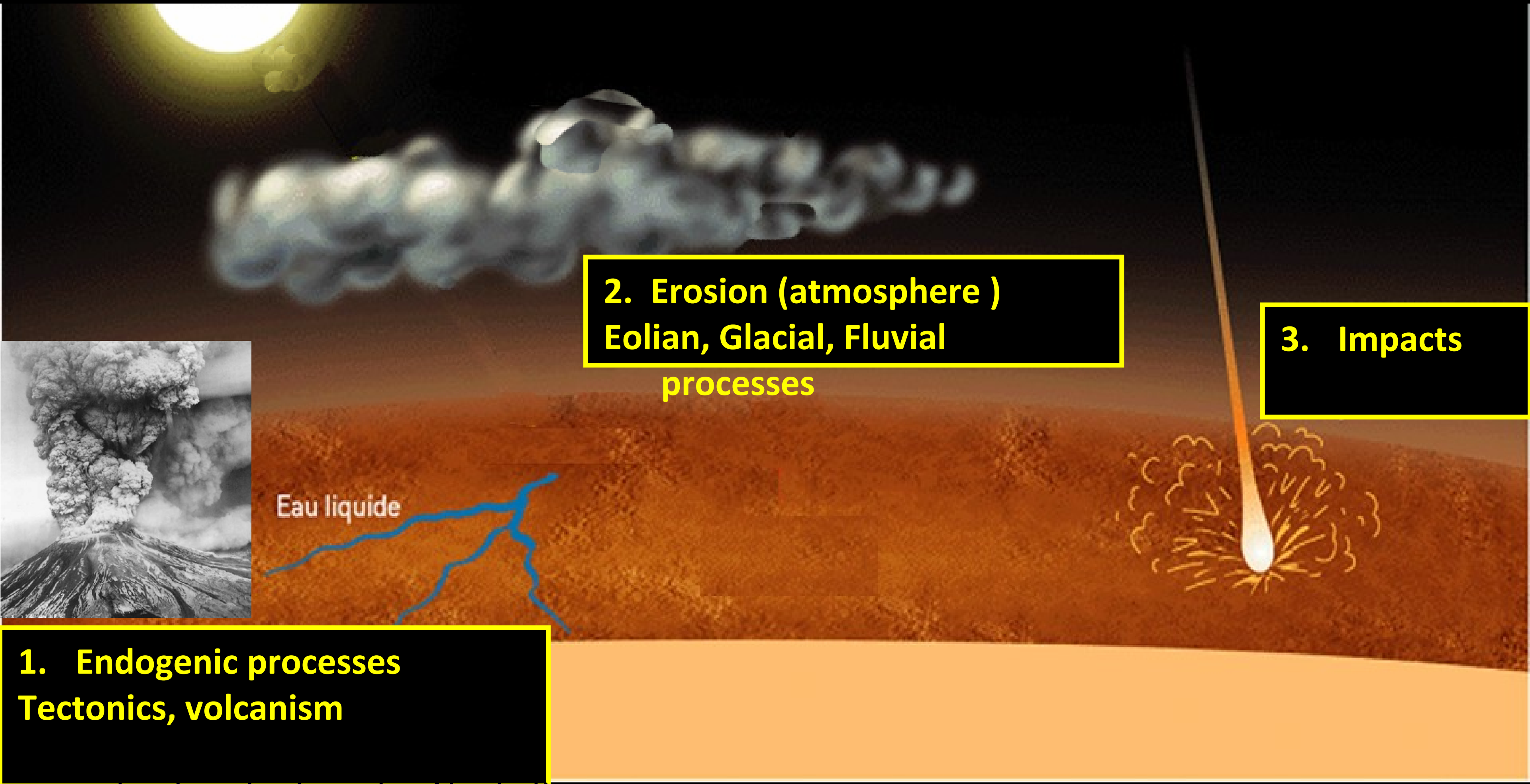
The Geology of Mars

1. Fluvial processes and sediments

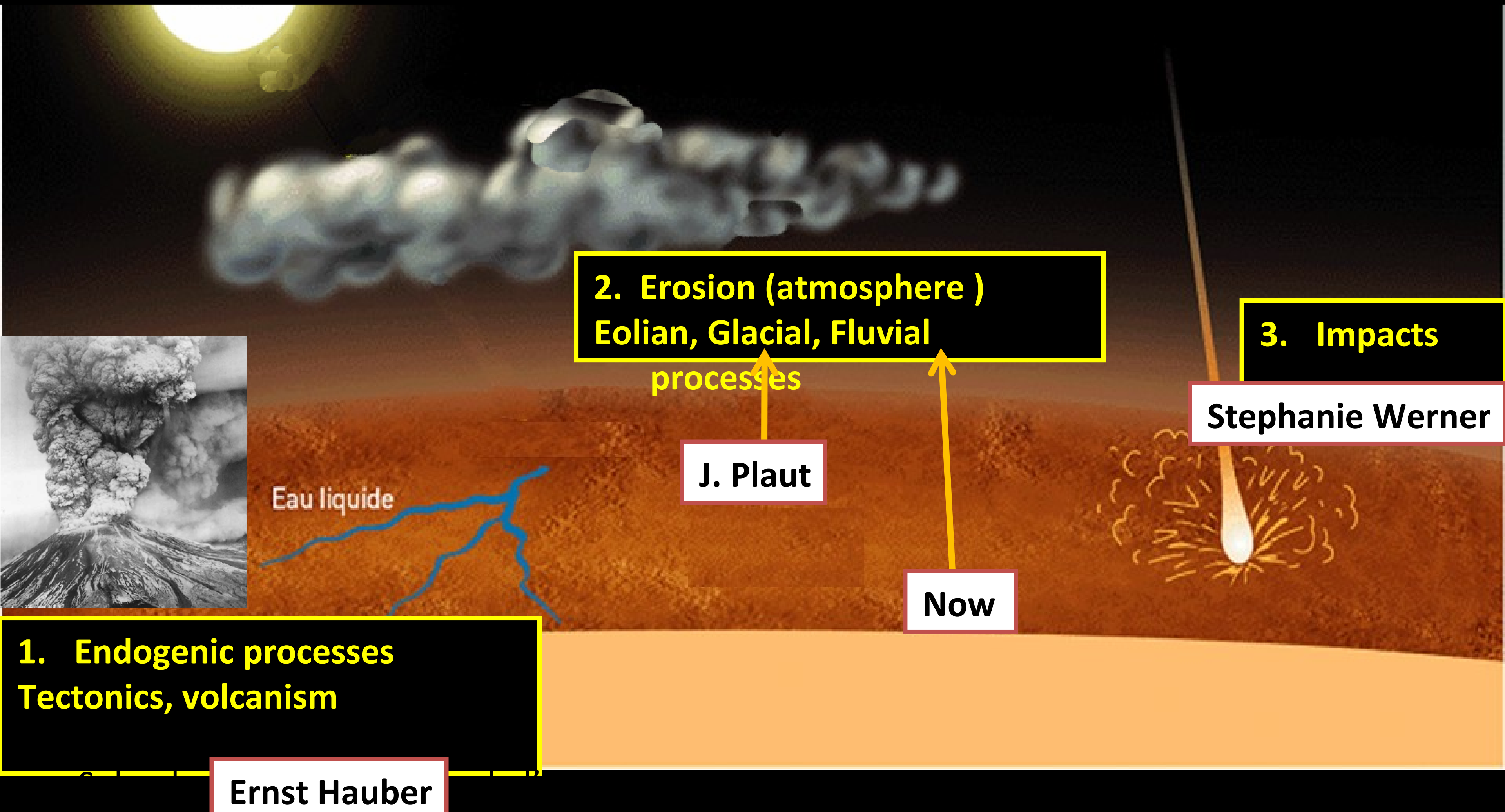
Nicolas MANGOLD

Laboratoire de Planétologie de Nantes

Planetary surfaces are shaped by the interaction of three types of processes:



Planetary surfaces are shaped by the interaction of three types of processes:



1. Valley networks

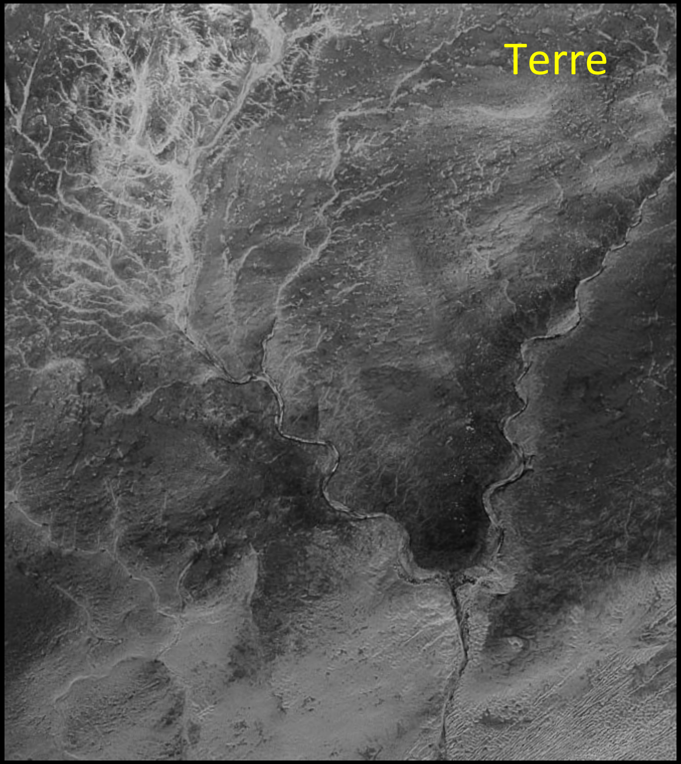
2. Sediments

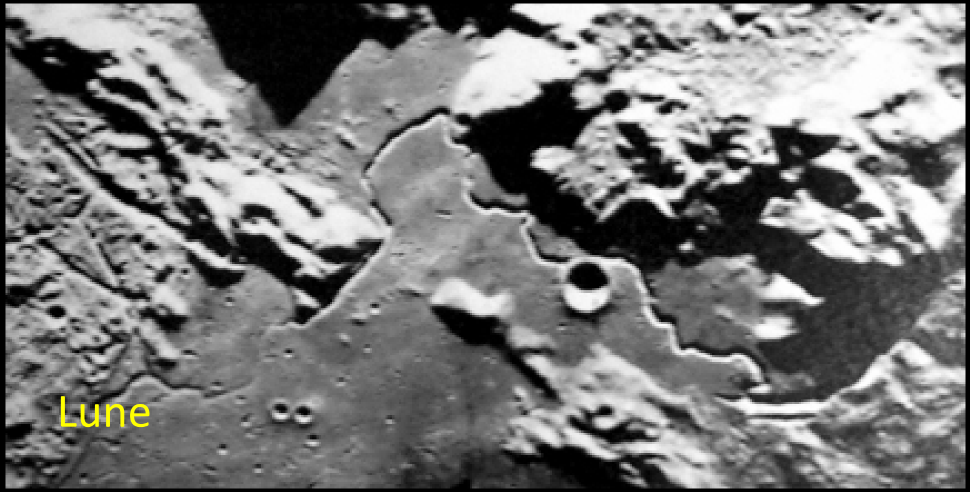
3. Outflow channels

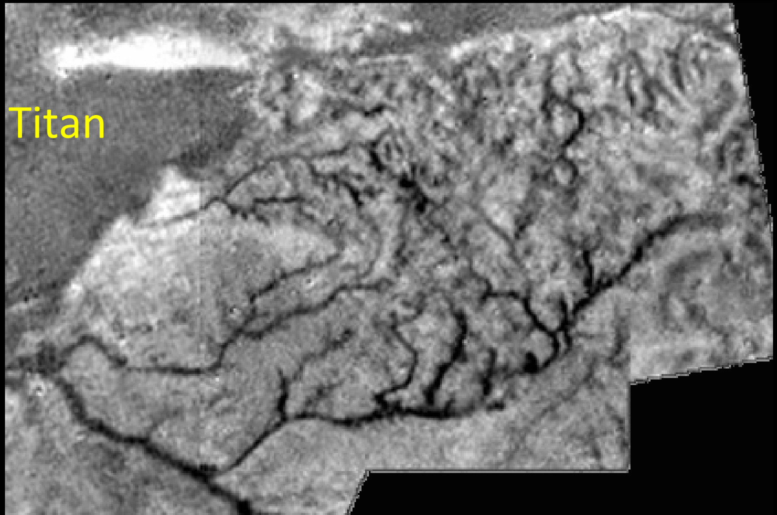
4. Recent Gullies

Summary

0. Fluid flows on planets: They can form by a variety of processes



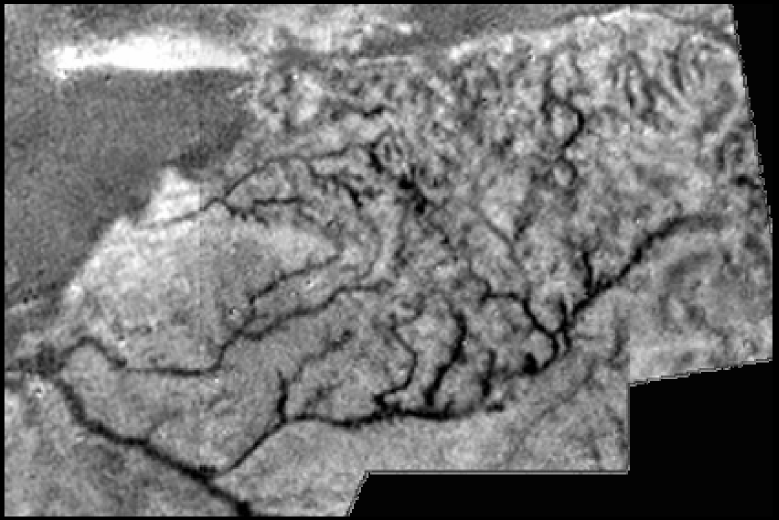


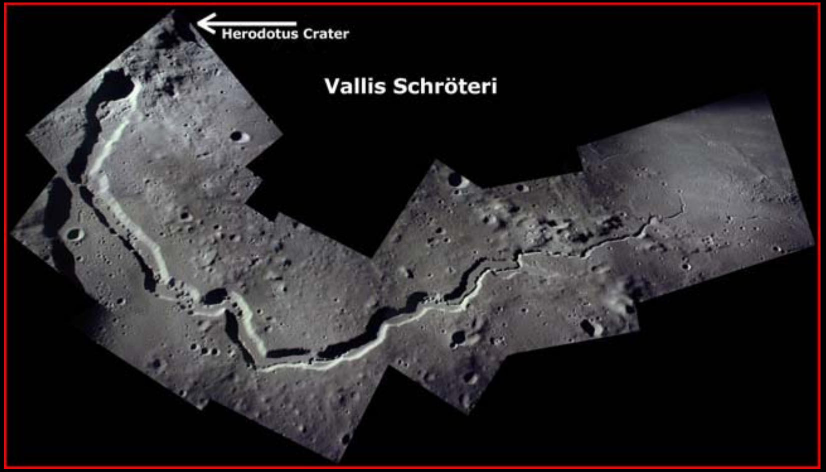


0. Fluid flows on planets: A variety of fluids can be involved

Liquid water on Mars (?)

Liquid methan (or other organics) on Titan

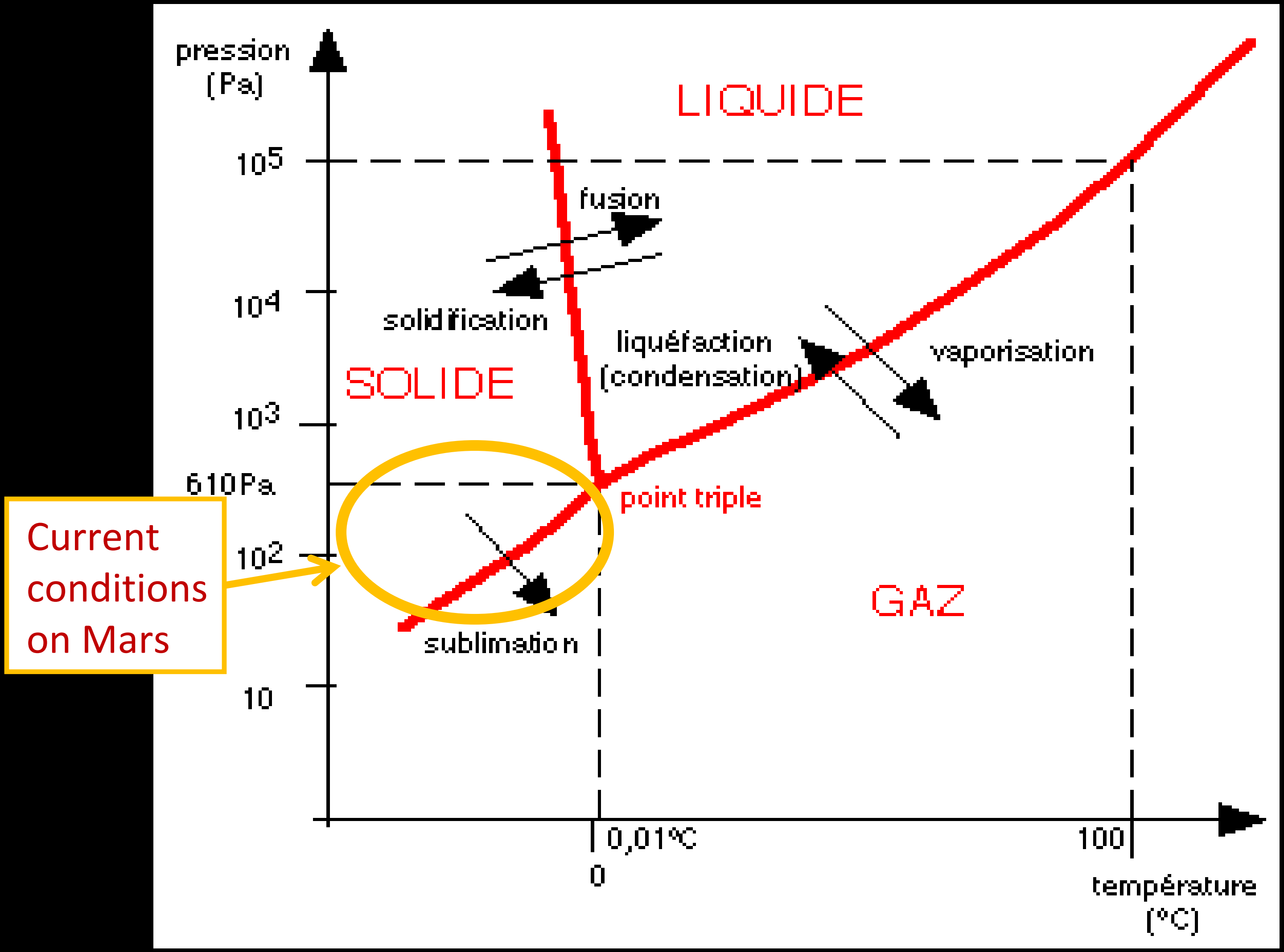




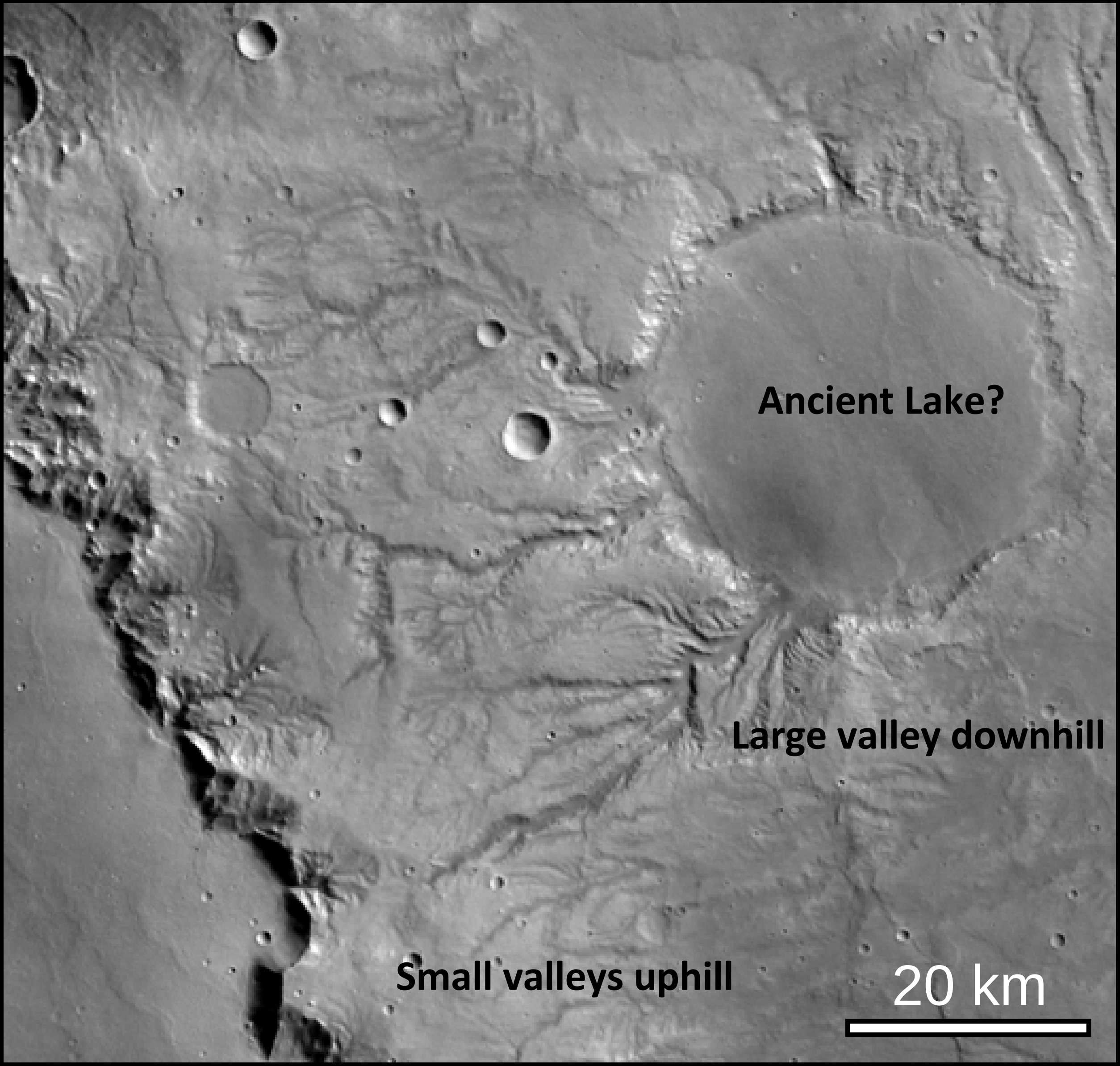
Volcanic lava flows on the moon

0. Fluid flows on planets: A variety of fluids can be involved

Liquid water is the most likely fluid on Mars



1. Valley networks: Geometry



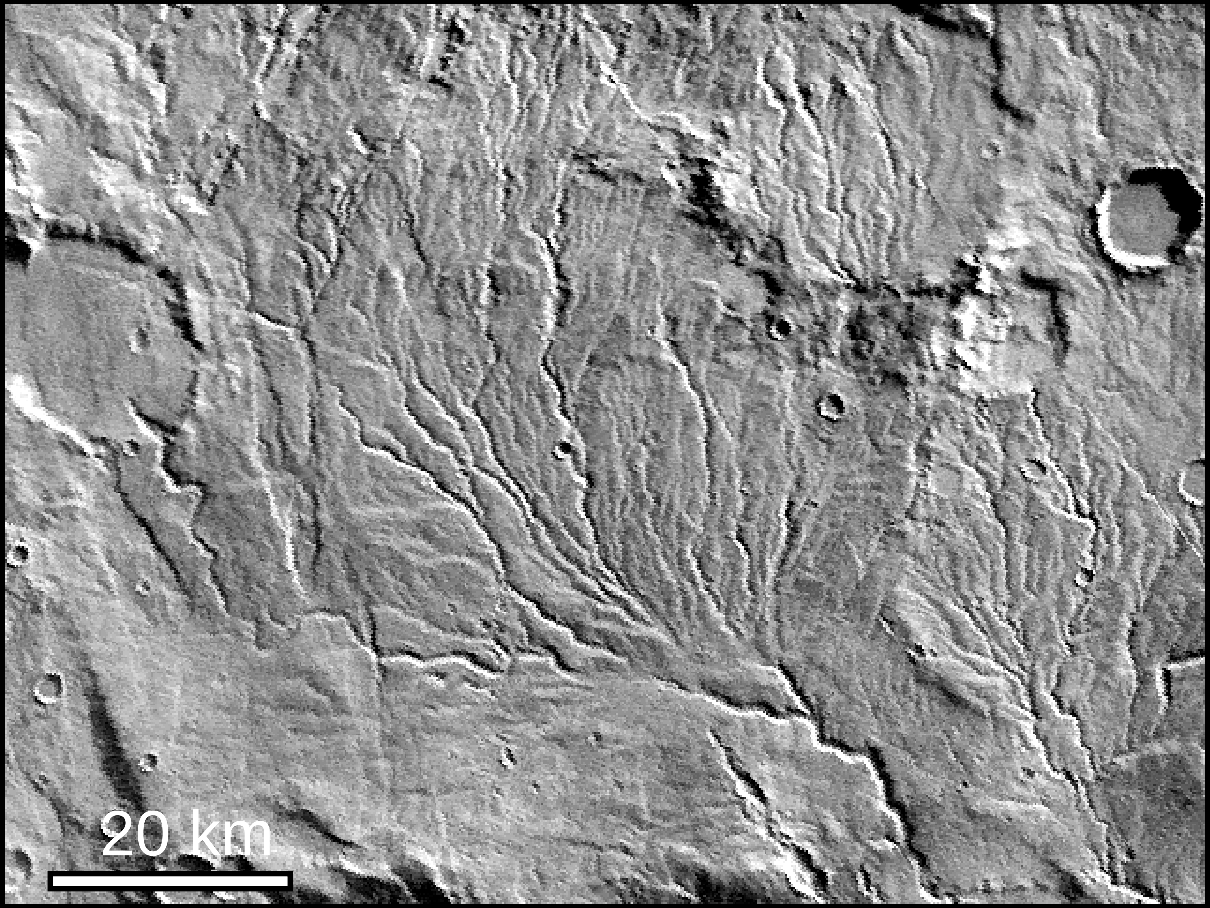
Dendritic geometry:

Small valleys connect
⇒ to wider valleys
⇒ to an outlet

1. Valley networks: Geometry

Valley networks different from single valleys

=> Requires a coeval plays of tens of valleys

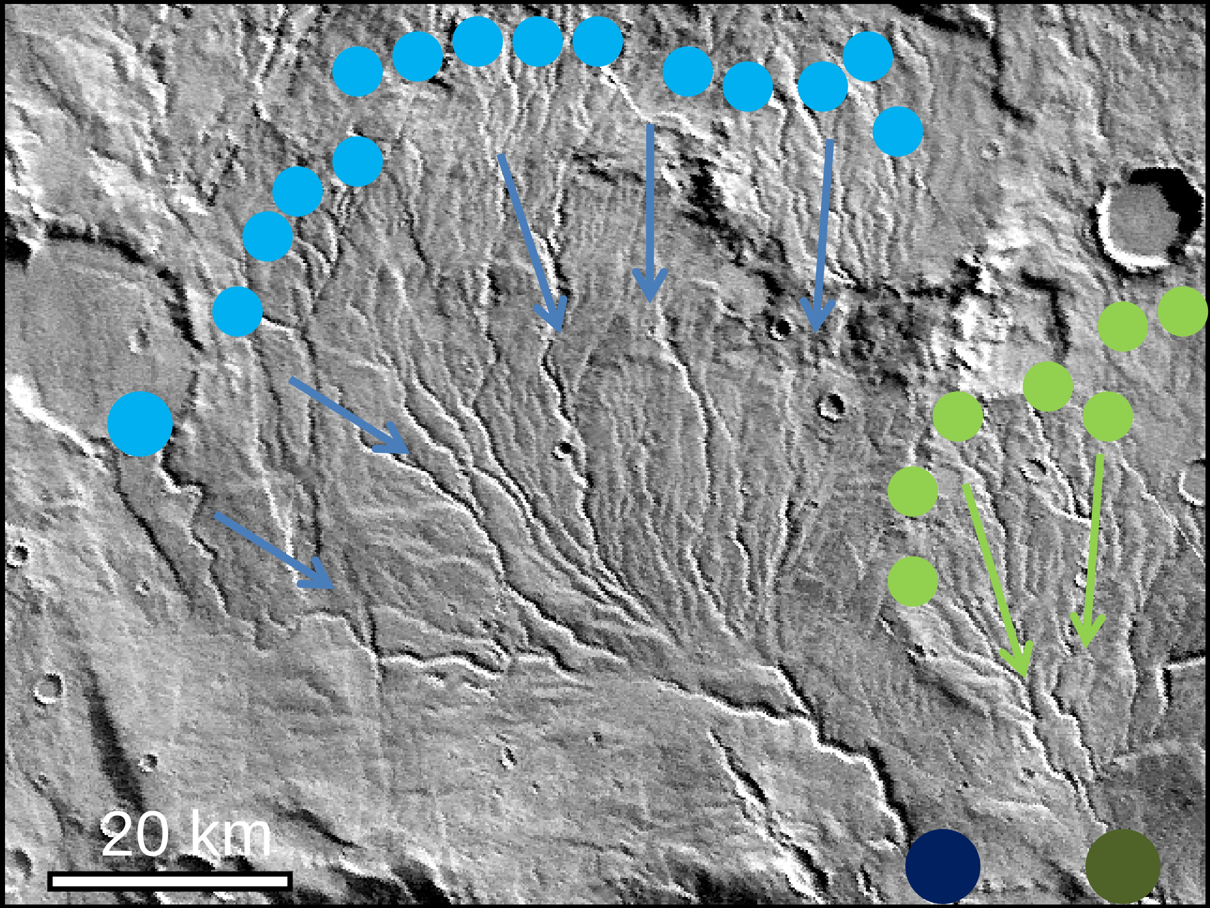


Warrego Vallis: A typical valley network

Single valleys (unbranched)

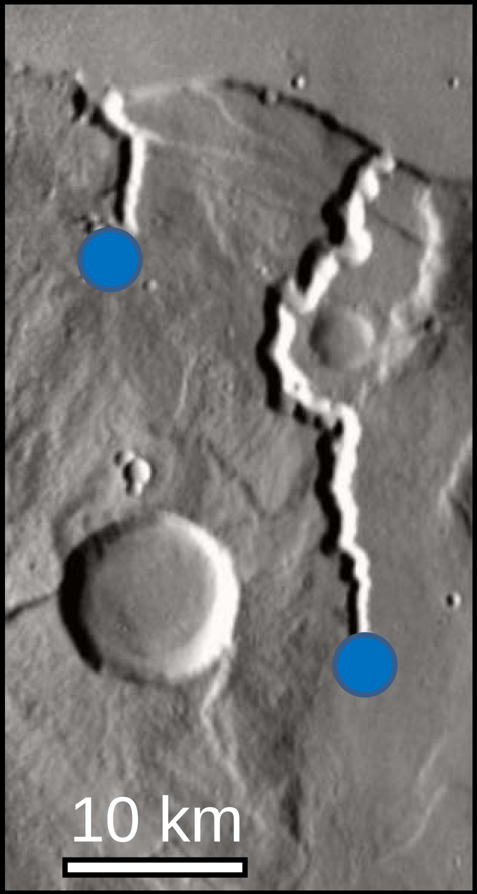
1. Valley networks: Geometry

Multiple valley heads + A single outlet
=> Define a watershed



Warrego Vallis: A typical valley network

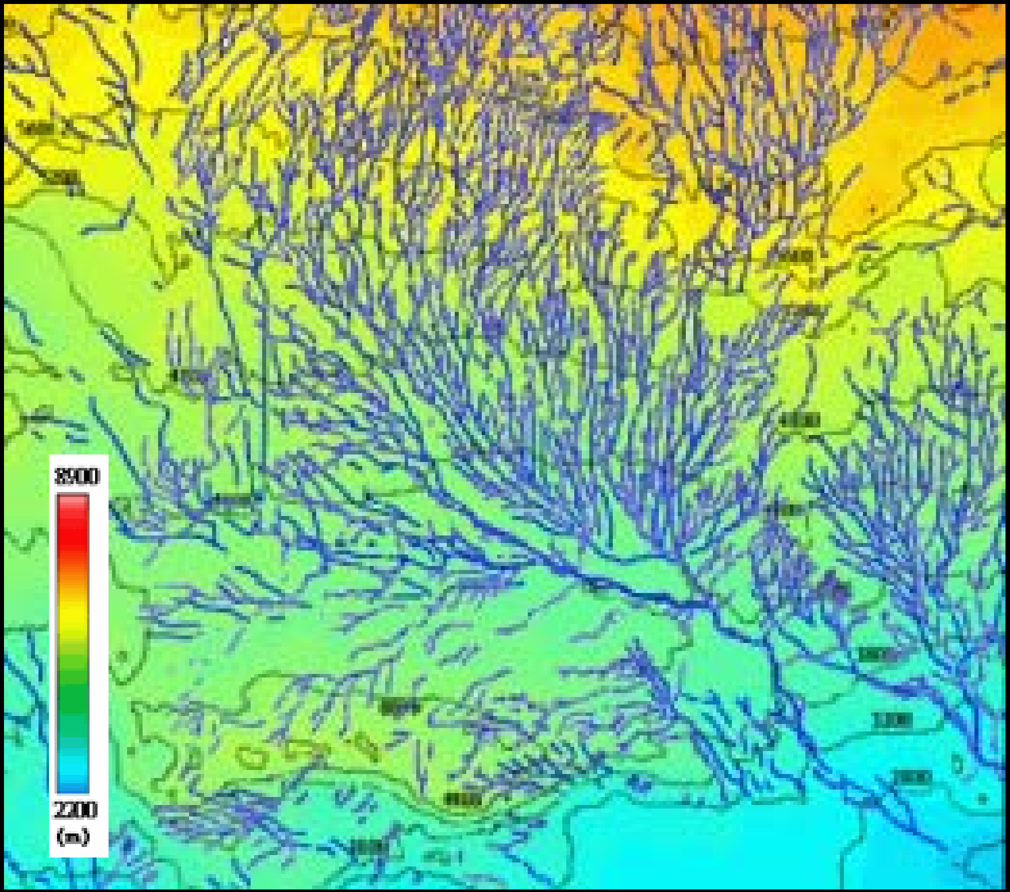
Point source discharge:
Process uncertain



Single valleys (unbranched)

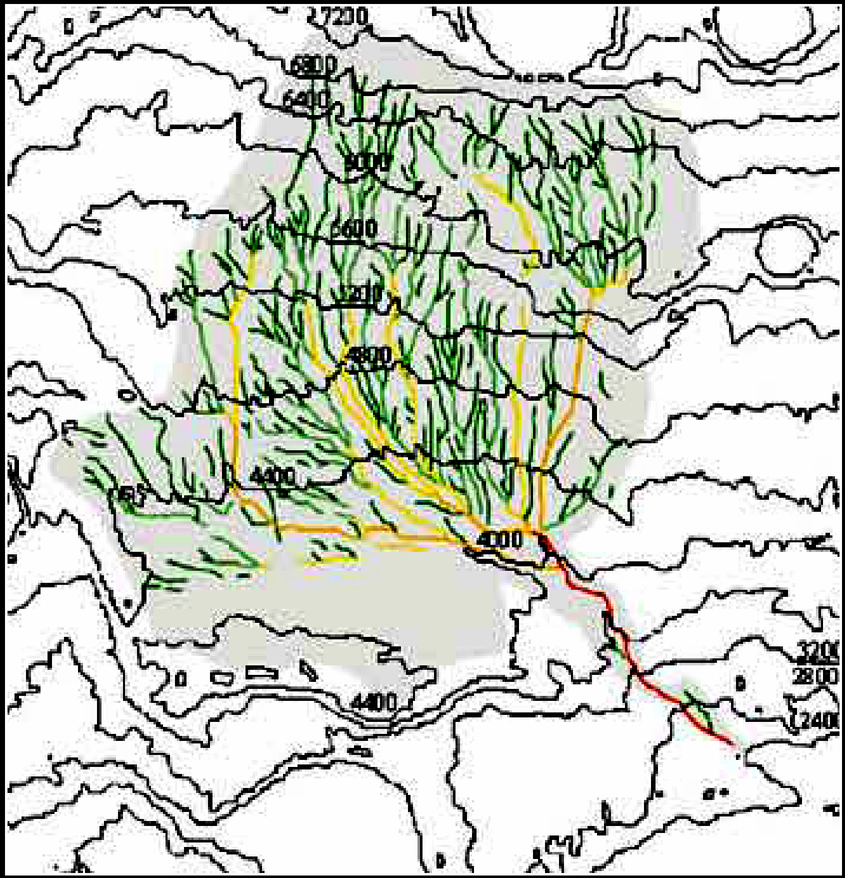
1. Valley networks: Geometry

Valleys follow the topography



Ansan and Mangold, PSS, 2006

Automatic extraction of valleys
Define watershed with topography

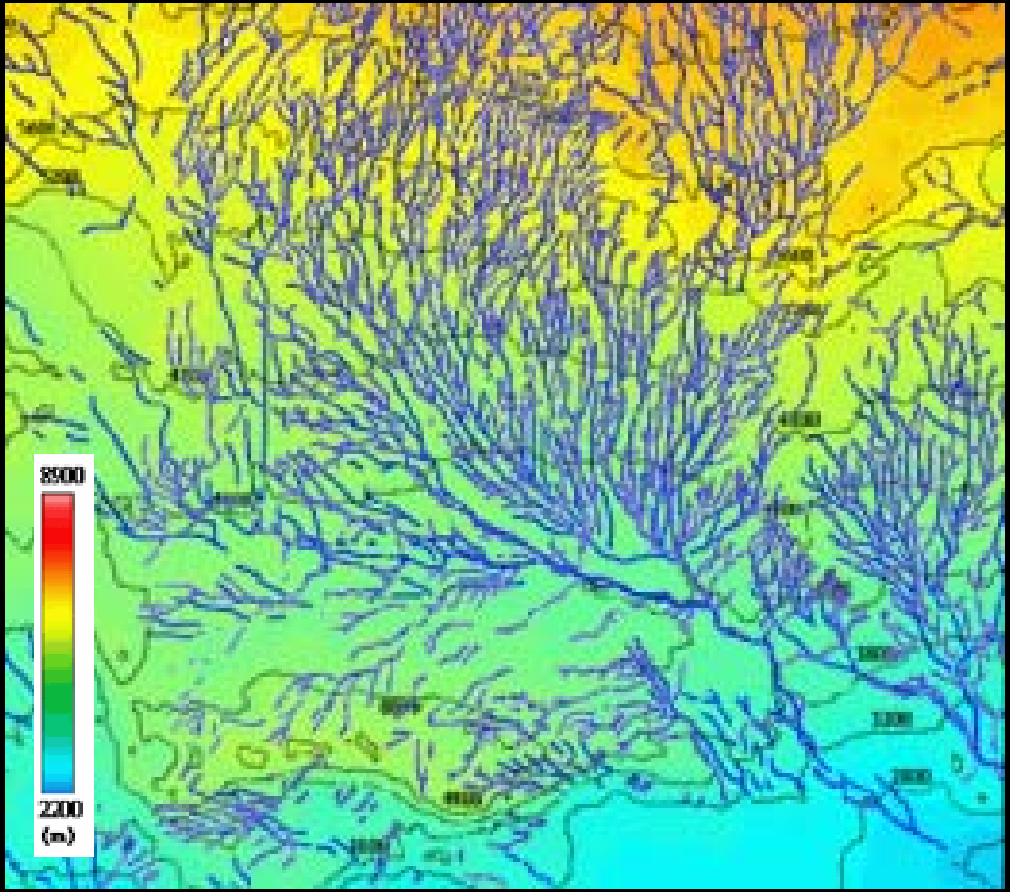


Automatic detection of valleys fits those observed on images

1. Valley networks: 3D Geometry

Valleys follow the topography

Warrego basin displays slopes >2°

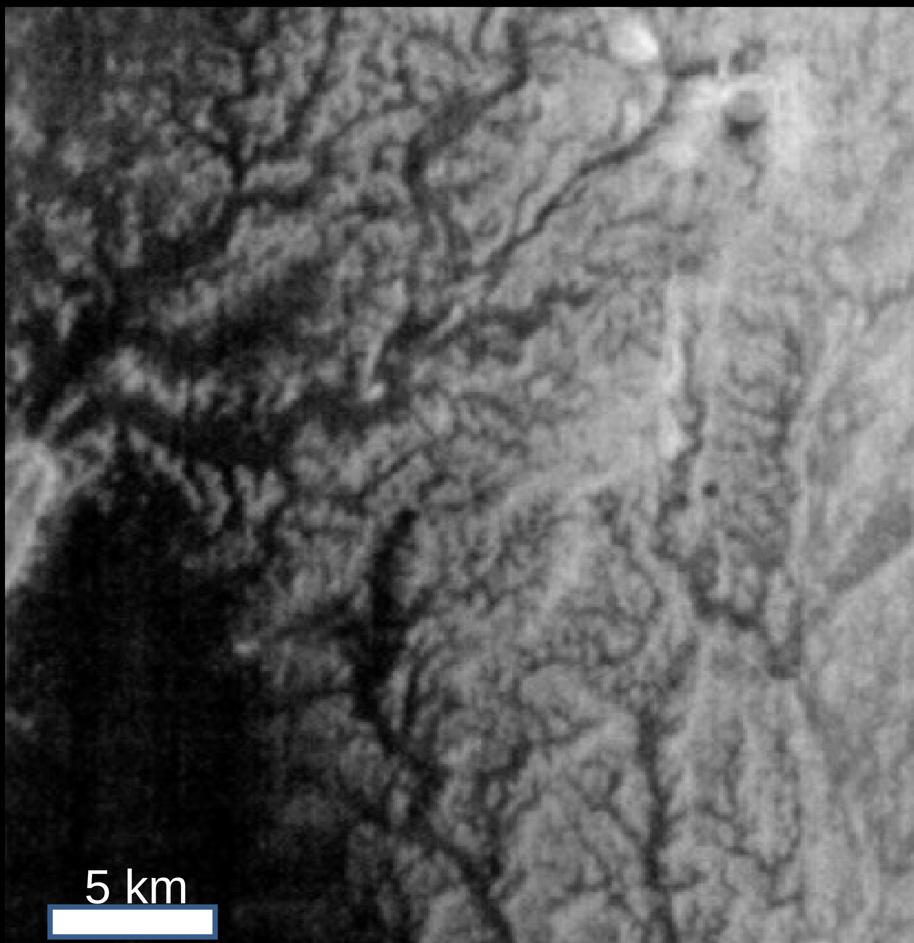


Subparallel network in Chile on slopes >2°

Subparallel networks occur on slopes > 1.5° on Earth, as well as on Earth

1. Valley networks: Geometry

Dendritic pattern on Echus plateau (slope<1°)

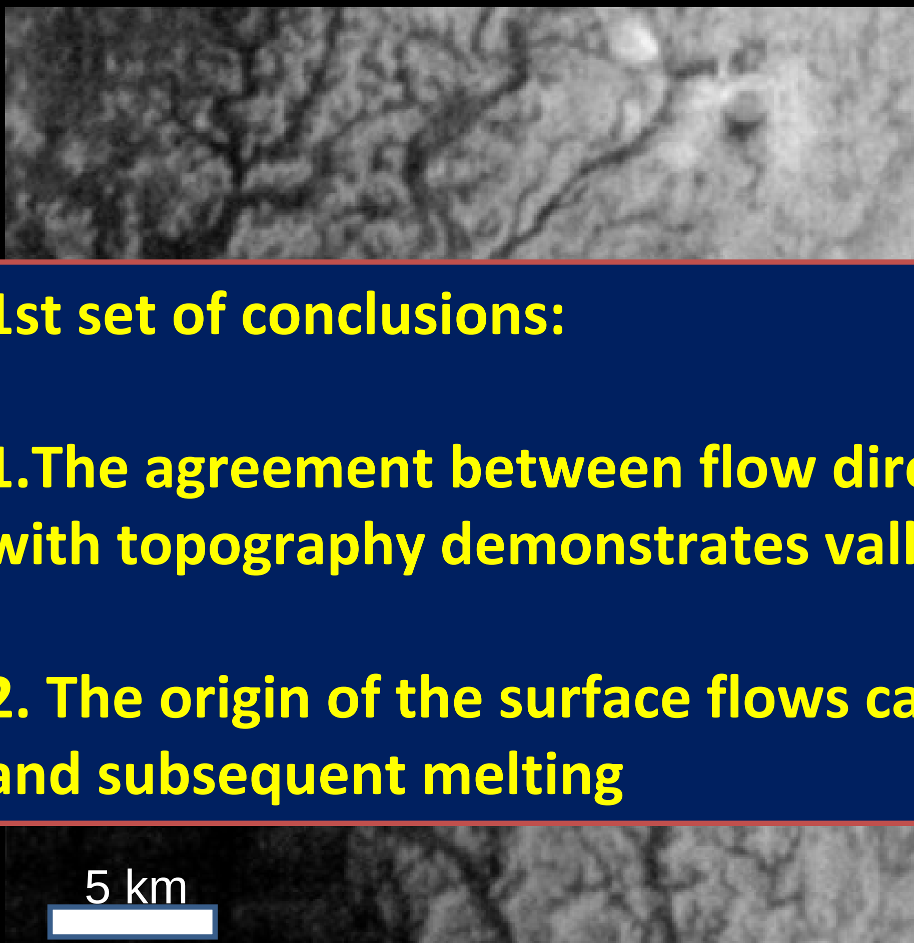


Dendritic pattern in Yemen (slope<1°)

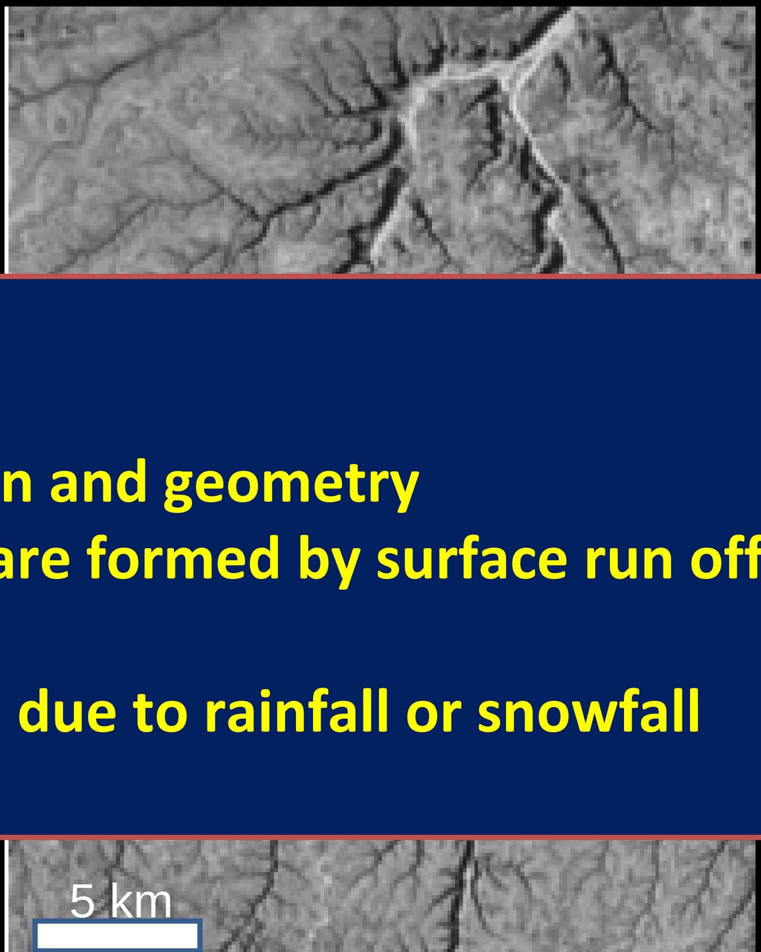
Dendritic pattern with orthogonal junctions are due to flows on slopes <1.5°

1. Valley networks: Geometry

Dendritic pattern on Echus plateau (slope<1°)



Dendritic pattern in Yemen (slope<1°)



1st set of conclusions:

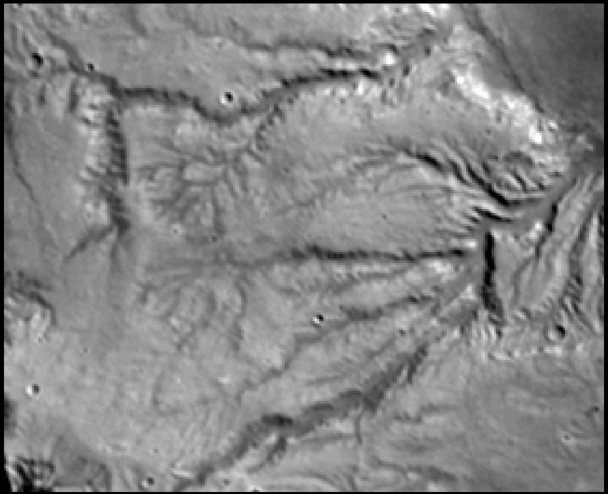
1.The agreement between flow direction and geometry with topography demonstrates valleys are formed by surface run off.

2. The origin of the surface flows can be due to rainfall or snowfall and subsequent melting

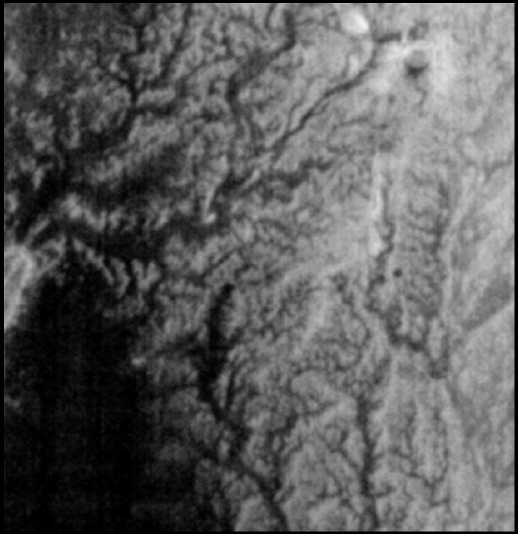
Dendritic pattern with orthogonal junctions are due to flows on slopes <1.5°

1. Valley networks: Drainage density

Drainage density (km^{-1})
= Total Valley length (km)/Basin area (km^2)

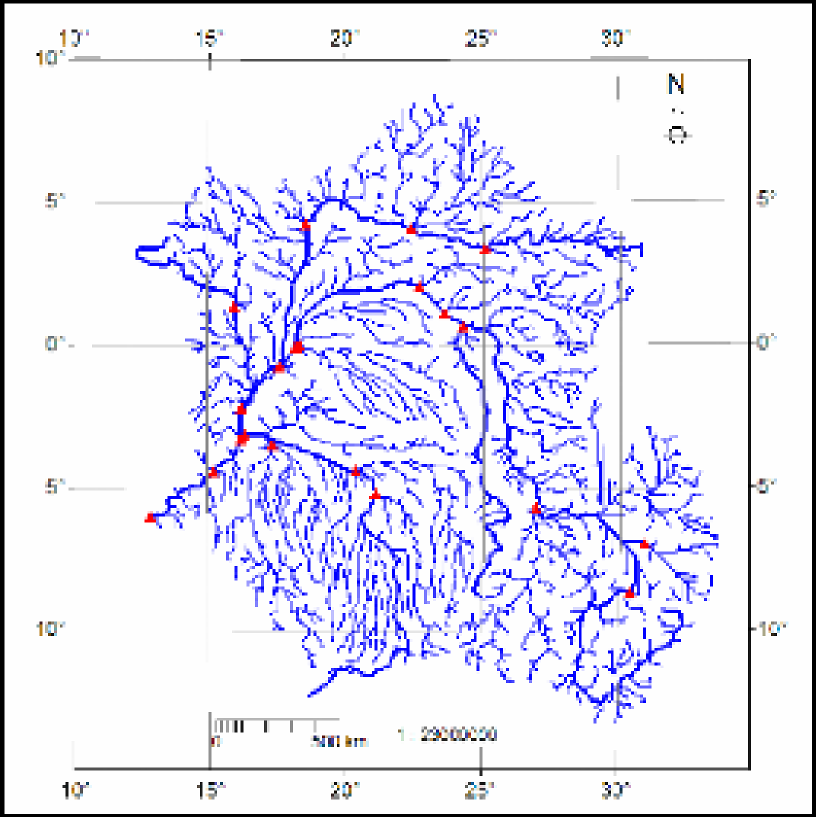


Huygens crater
0.2 km^{-1}



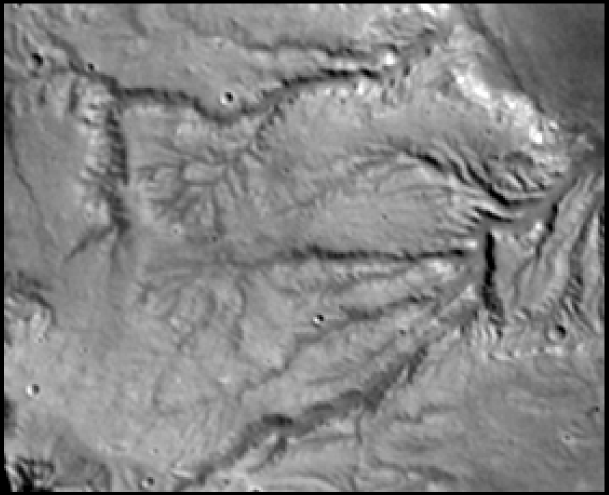
Echus plateau
1.0 km^{-1}

On Earth: Current Terrestrial river > 5 km^{-1}

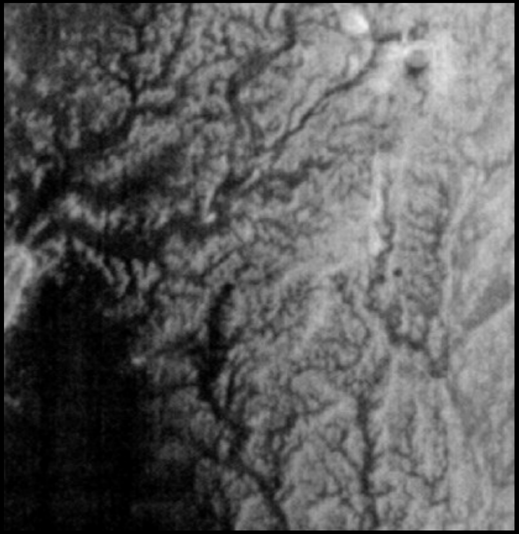


Congo river basin

1. Valley networks: Drainage density



Huygens crater
0.2 km^{-1}



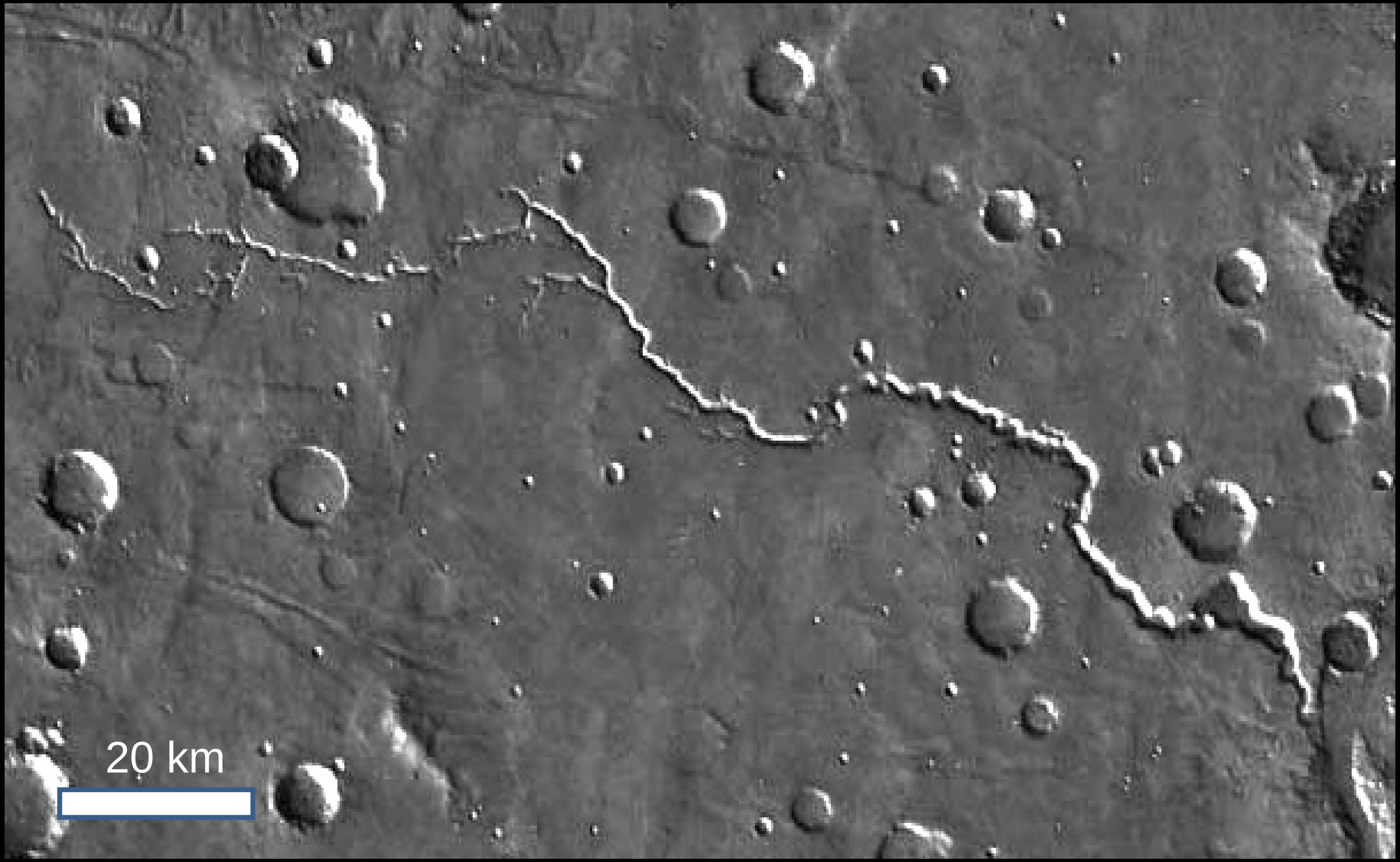
Echus plateau
1.0 km^{-1}

Drainage density (km^{-1})
=Valley length (km)/Basin area (km^2)

Past river basin in Sahara: 0.1-1 km-1

1. Valley networks: Subsurface flows?

Poorly branching valleys: Frequently named sapping valleys
Formed by groundwater flows?
=> Do Martian valleys really require overland flows/role of geothermal heating?



Nirgal Vallis

1. Valley networks: Subsurface flows?

Poorly branching valleys: Frequently named sapping valleys
Formed by groundwater flows?

But sapping requires the water to be stable at the surface
+ Sapping requires a recharge of the aquifer
$\Rightarrow$ Groundwater and surface flows occur in concert

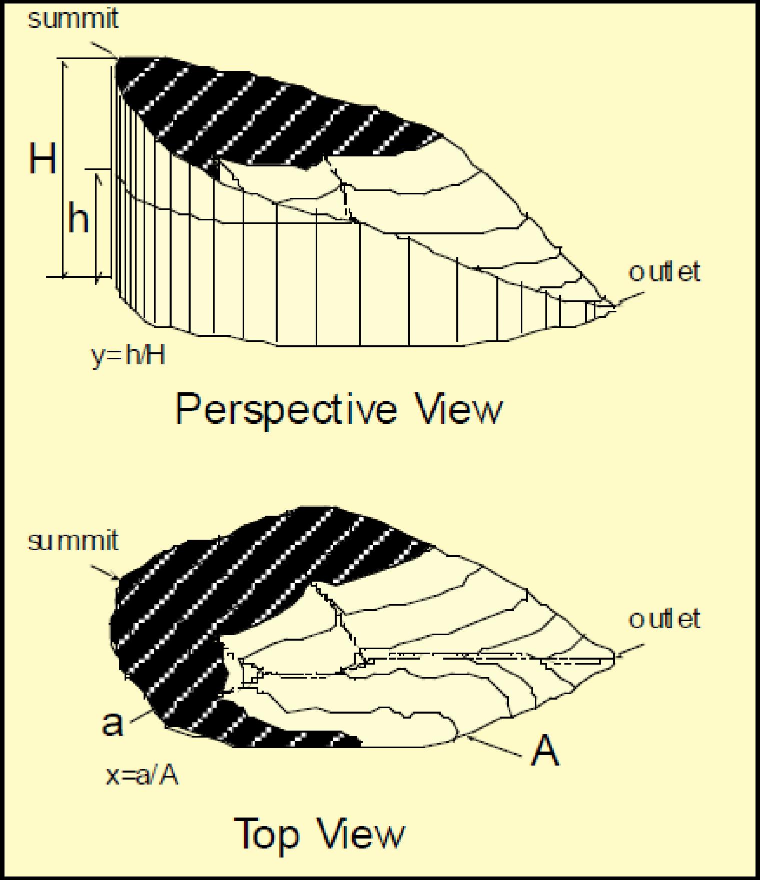
1. Valley networks: Subsurface flows?

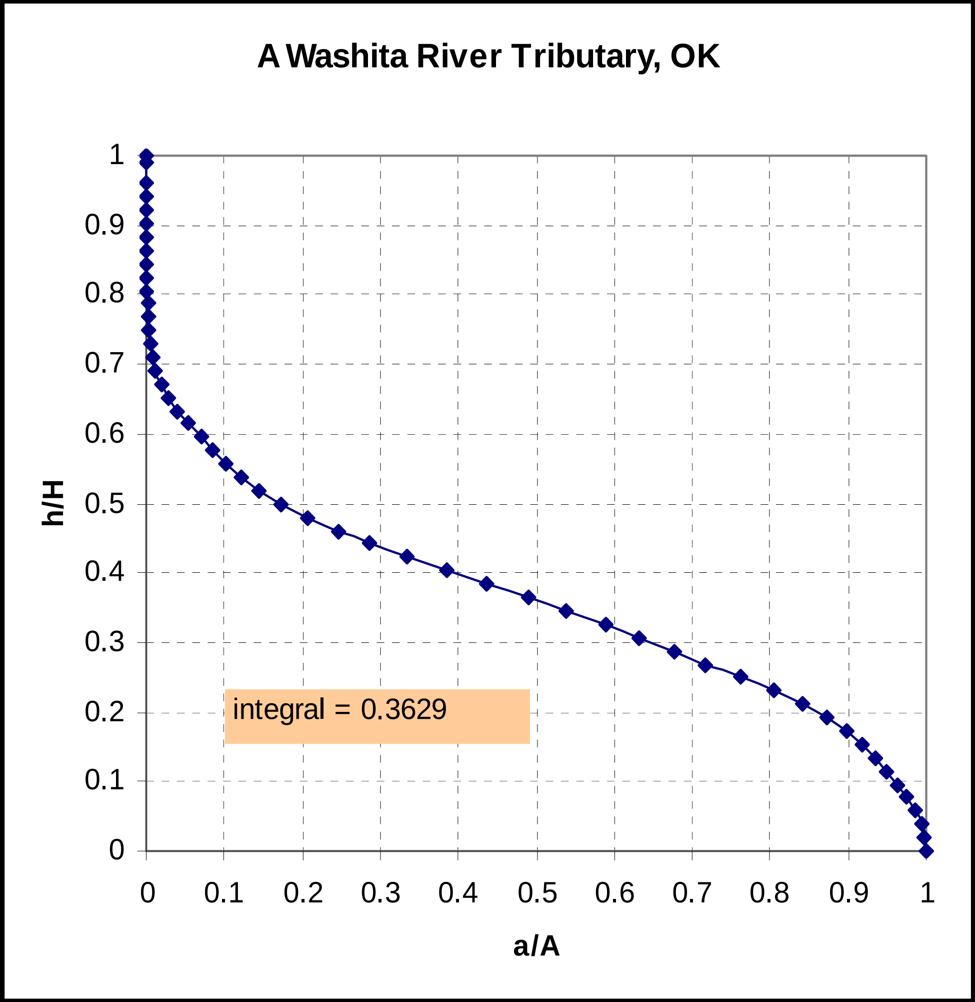
Typical terrestrial network

Colorado sapping like system

1. Valley networks: Subsurface flows?

Hypsometric curve (Strahler, 1952)

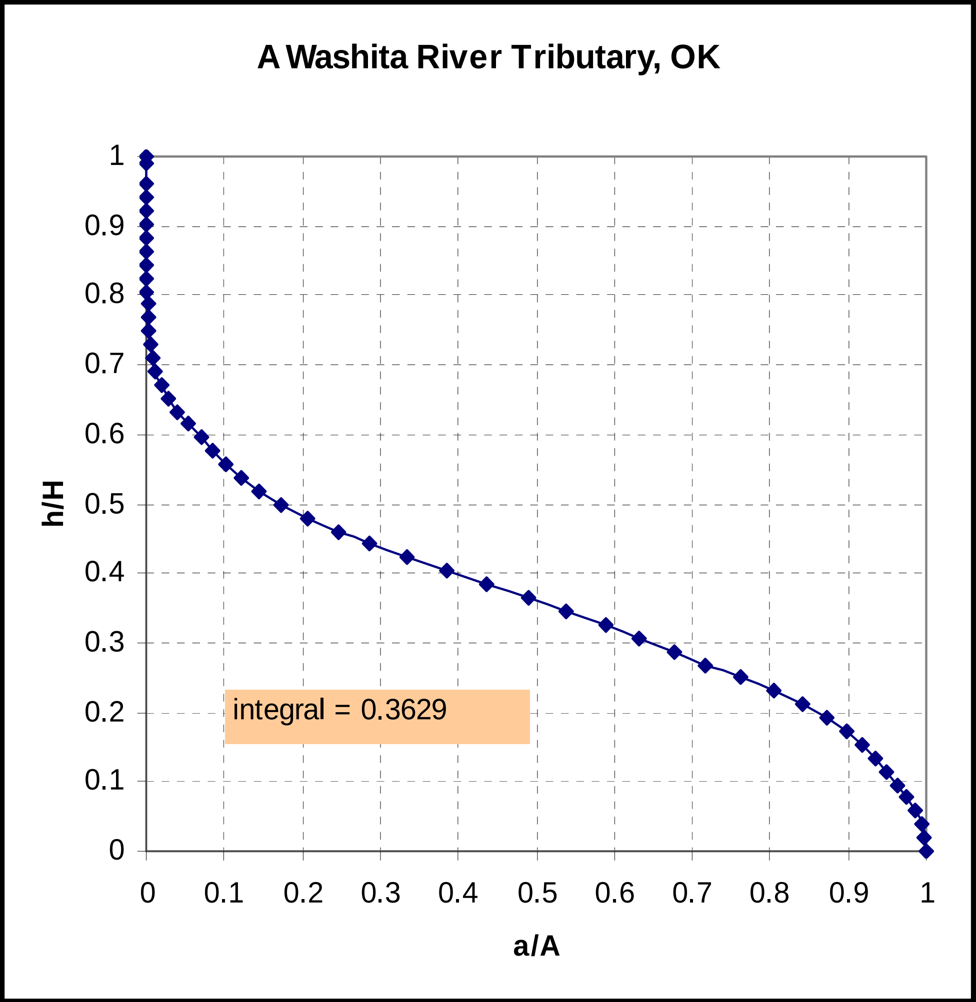




The y-axis is the elevation at a particular point divided by the total elevation.
The x-axis is the area at that point divided by the total area.

1. Valley networks: Subsurface flows?

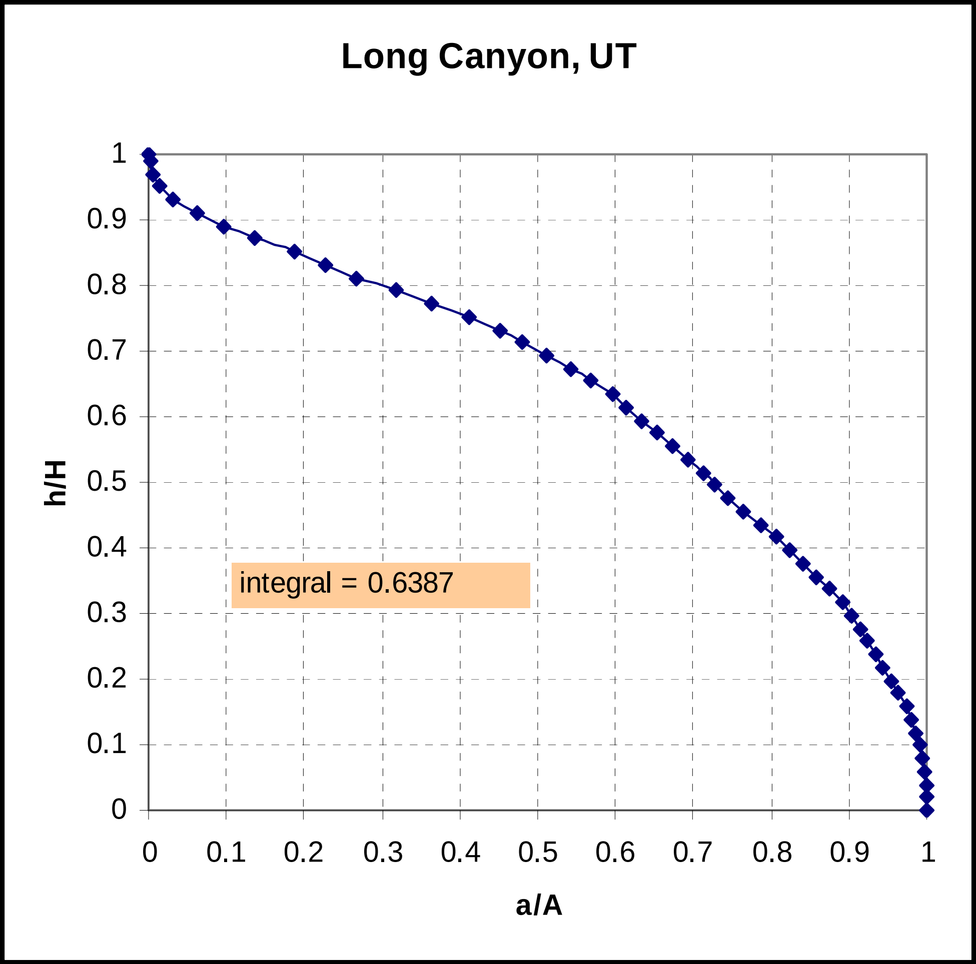
Hypsometric curve



Run off dominated system (Integral<0.5)
(Empirical law)

1. Valley networks: Subsurface flows?

Hypsometric curve

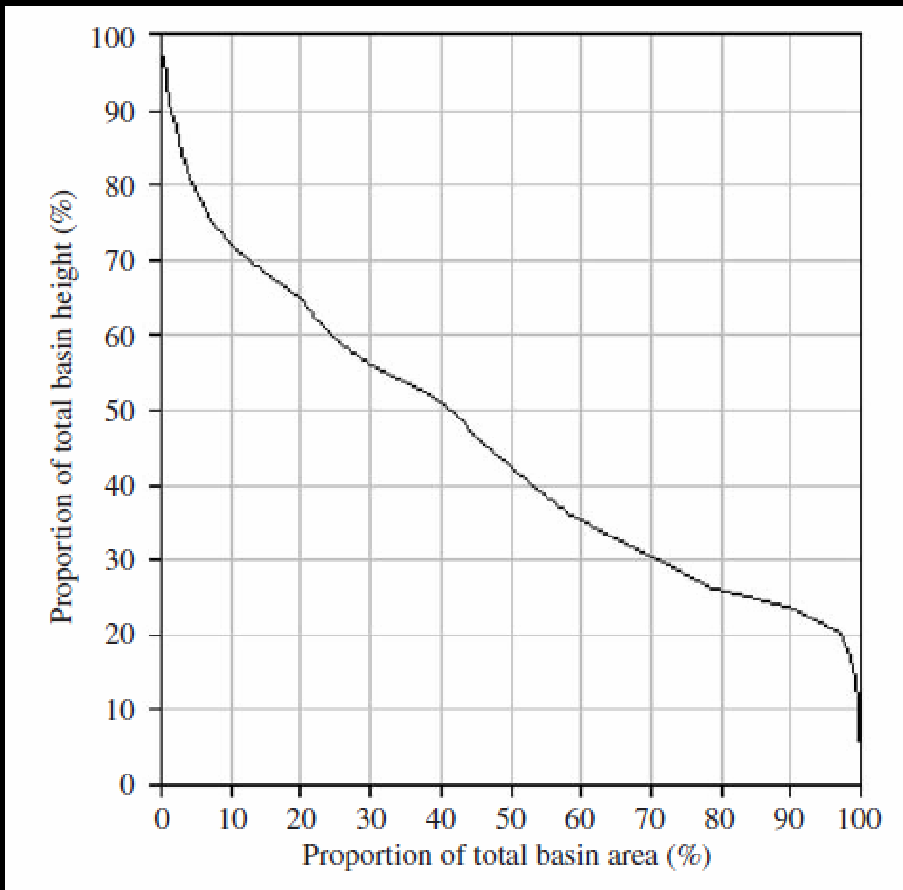


Sapping dominated system (Integral>0.5)

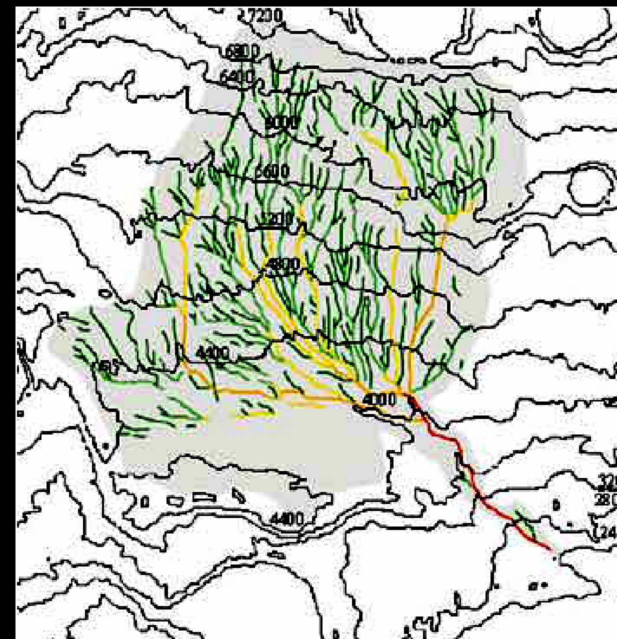
Sapping canyon

1. Valley networks: Subsurface flows?

Hypsometric curve: Results on Mars

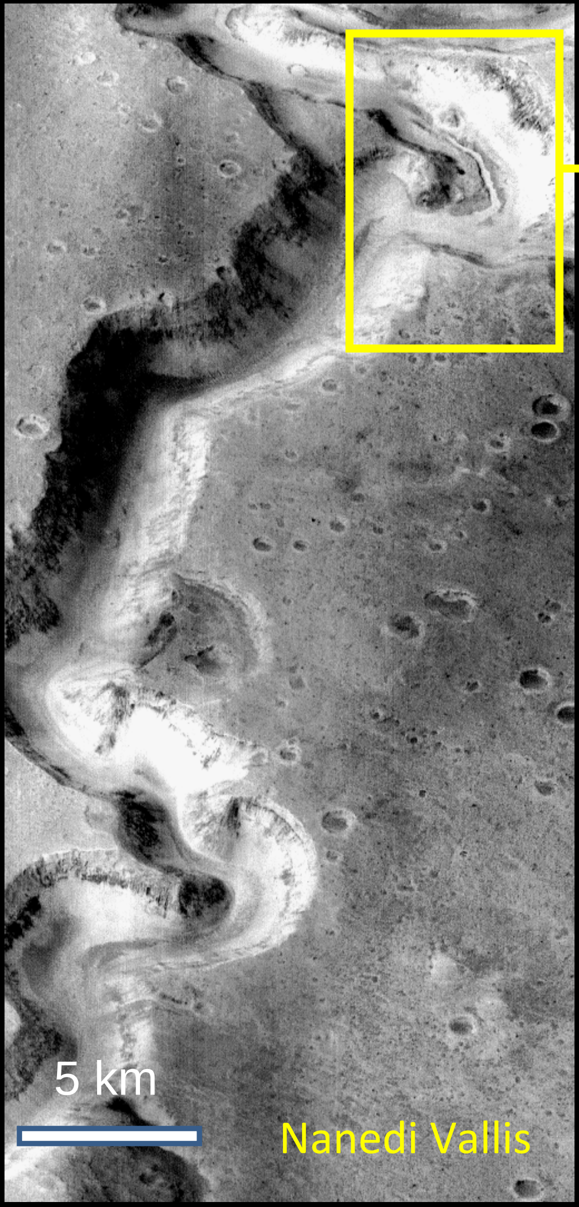


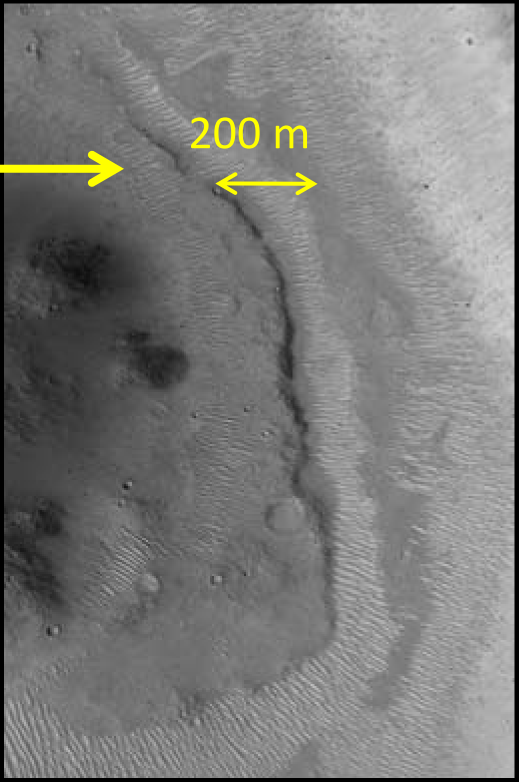
Warrego Vallis Integral=0.46
Run off dominated



In general, Martian networks are predominantly run off,
but sapping exists,
or poorly incised valleys

1. Valley networks: Interior channels

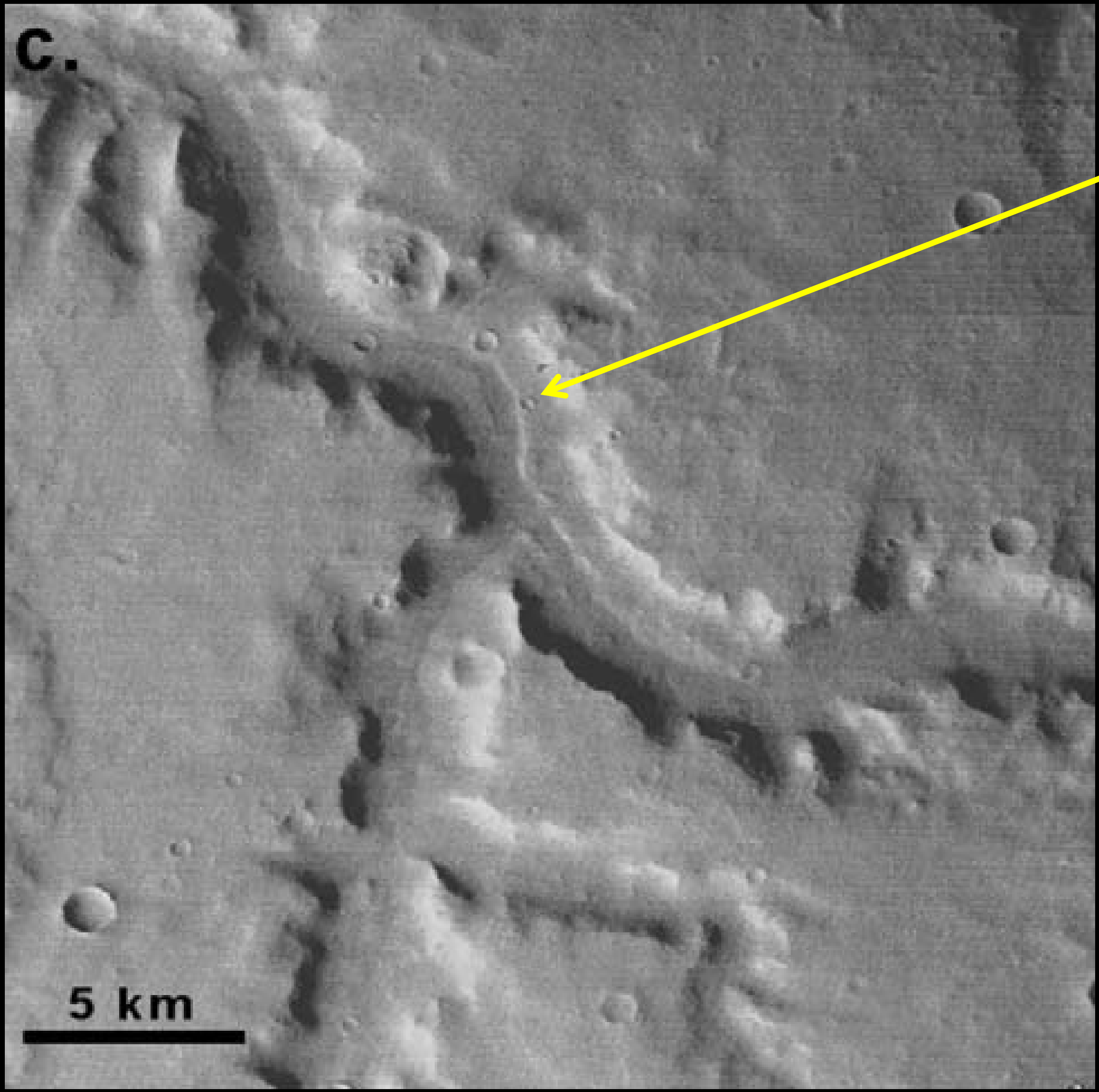




The channel inside the valley corresponds to the former river stream

NB: The valley is 4 km wide, 1 km deep.
It has been carved by a flow which is much smaller:
< 200 m wide and <20 m deep

1. Valley networks: Interior channels



Naktong Vallis

Interior channel
300 m in width

The channel inside the valley corresponds to the former river stream

Problem:
Valleys are filled by eolian material
Channels are not frequent

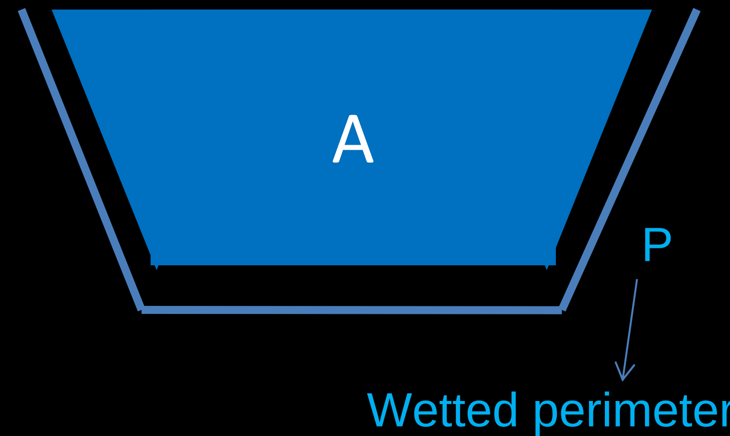
1. Valley networks: Interior channels

Estimating discharge rates Q:

- Using meander wavelength
- Using channel width and depth:

Manning equation (1890) empirical relation

modified by Komar (1979) for Mars



Velocity (m/s)

$$Q = A(g_m s R^{4/3} / g_e n^2)^{1/2}$$

Discharge rate (m^3/s)

Cross section area (m^2)

Mars gravity

Channel Slope

Hydraulic radius R=A/P

Earth gravity

Manning coefficient empirical (0.01 to 0.07) Usually 0.04 for rough gravely surfaces

1. Valley networks: Interior channels

Channel discharge from interior channels

Valley, quadrangle	Channel width (m)	Discharge (m^3/s)
Samara Vallis, Margaritifer Sinus	400	2200
Nanedi Vallis,	530	3,000
Nirgal Vallis,	770	4,800
Licus Vallis,	380	2000
Unnamed,	90	350
“Eberswalde” Crater,	130	550
Unnamed,	180	800
Unnamed,	140	600
Unnamed,	140	600
Unnamed,	130	550
Durius Vallis,	460	2600

Irwin et al., Geology, 2005

<u>On Mars:</u>

Values from 300 to 5,000 m3/s

<u>On Earth:</u>

Loire River: 500-1000 m3/s
Danube: 5,000 m3/s
Amazon: 100,000 m3/s

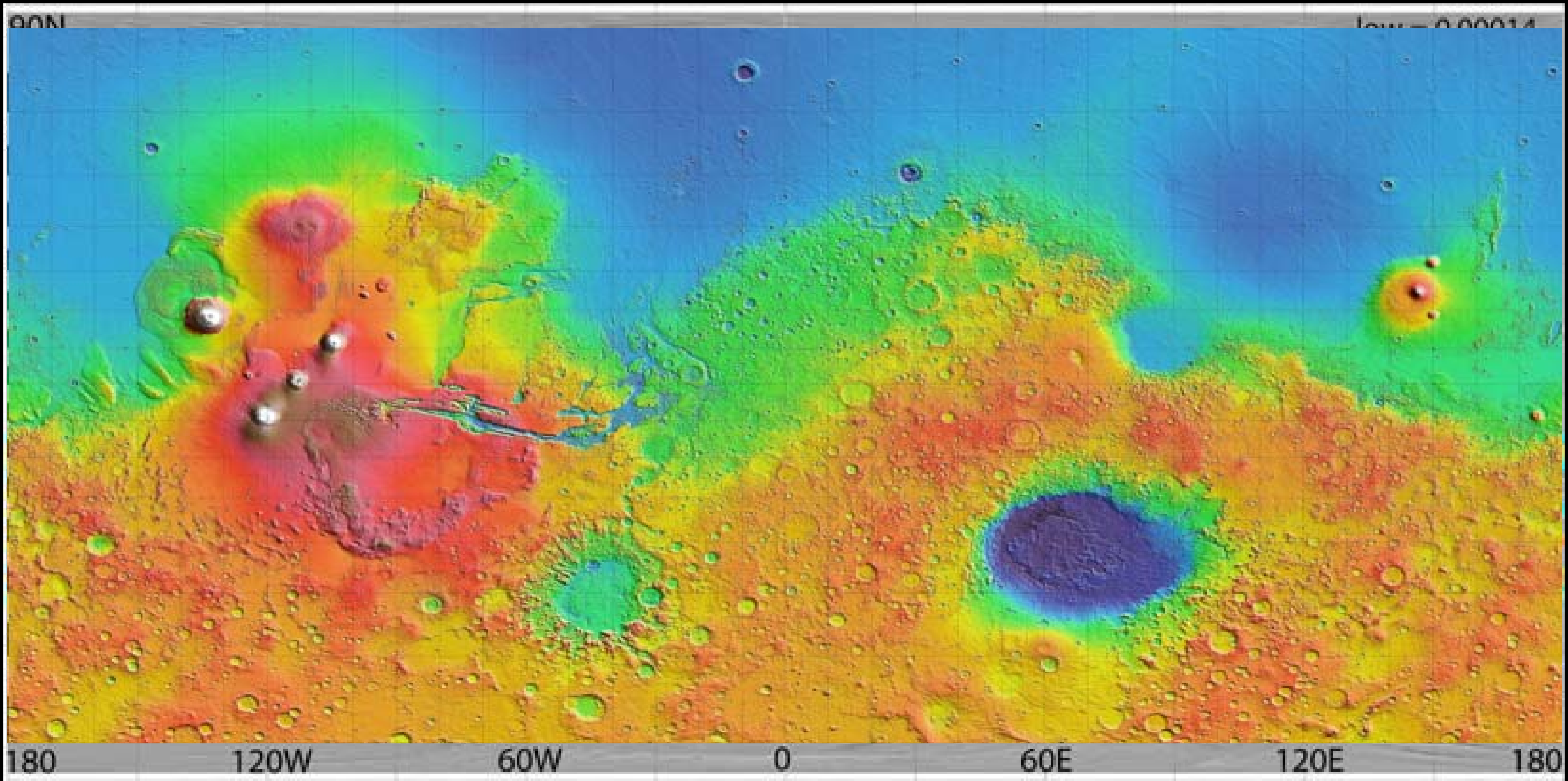
Problem:

Channels preserved correspond to the last fluvial activity

⇒ May not be representative of early Mars activity

1. Valley networks: Geographic Distribution

Valley networks limited to highland terrains => Old landforms

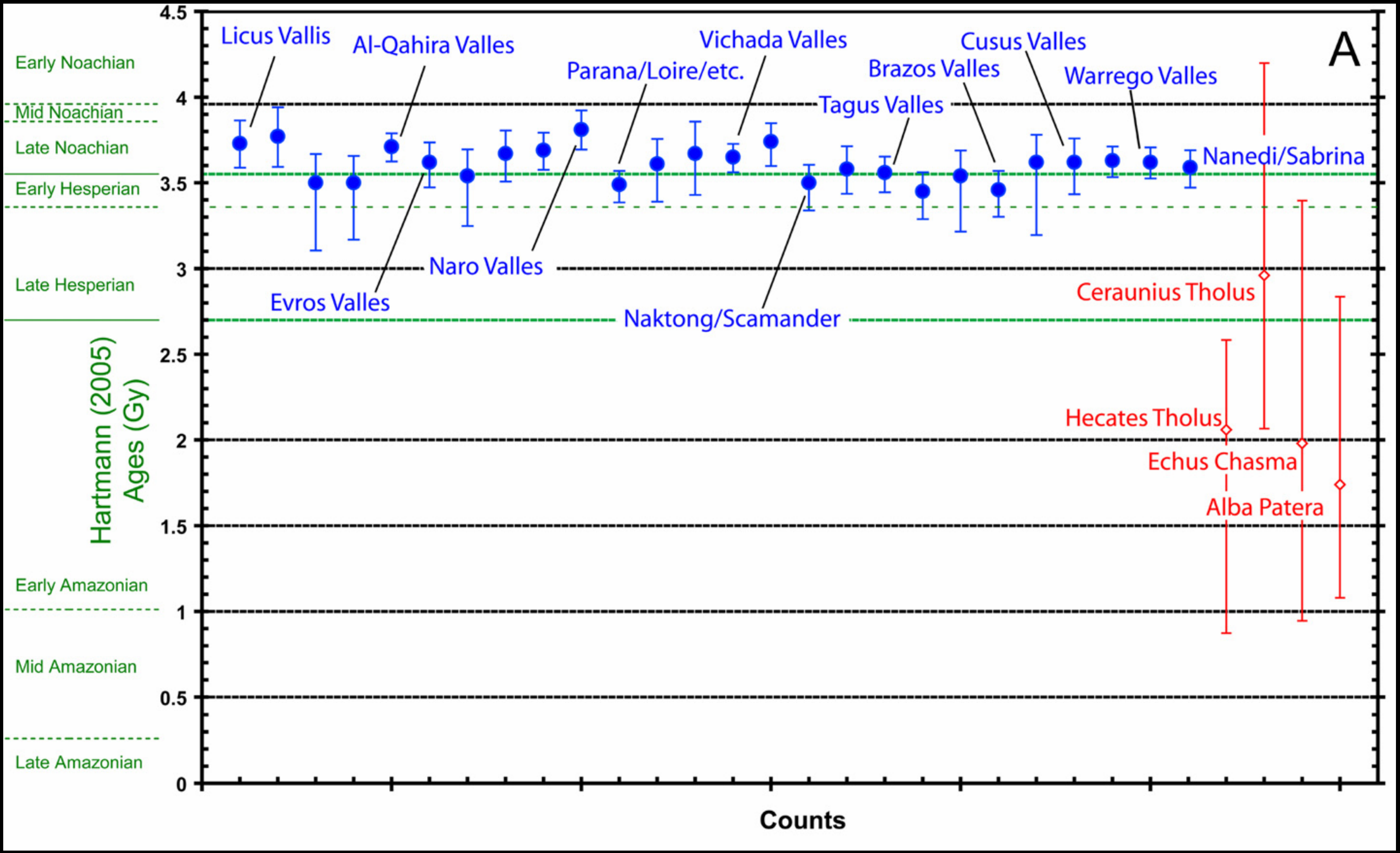


Luo and Stepinski, JGR, 2009

Valley networks postdates the main Martian topography: Dichotomy+Tharsis+Hellas

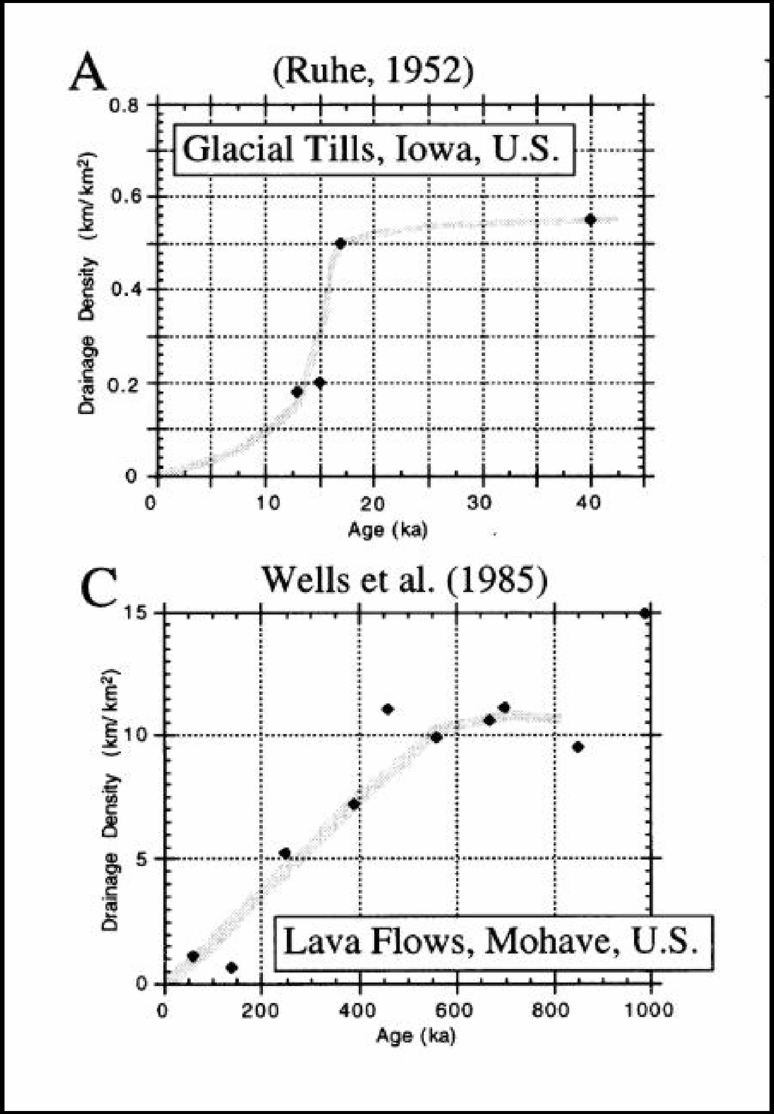
1. Valley networks: Chronology

Age: Late Noachian - Early Hesperian

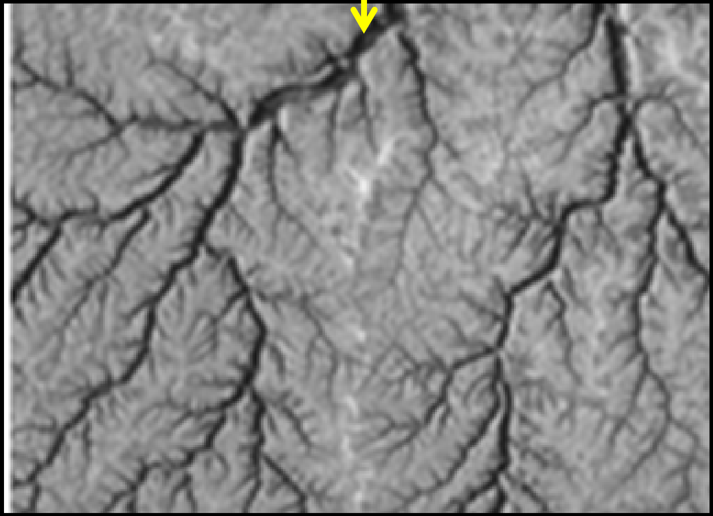


Fassett and Head, JGR, 2008

1. Valley networks: Duration

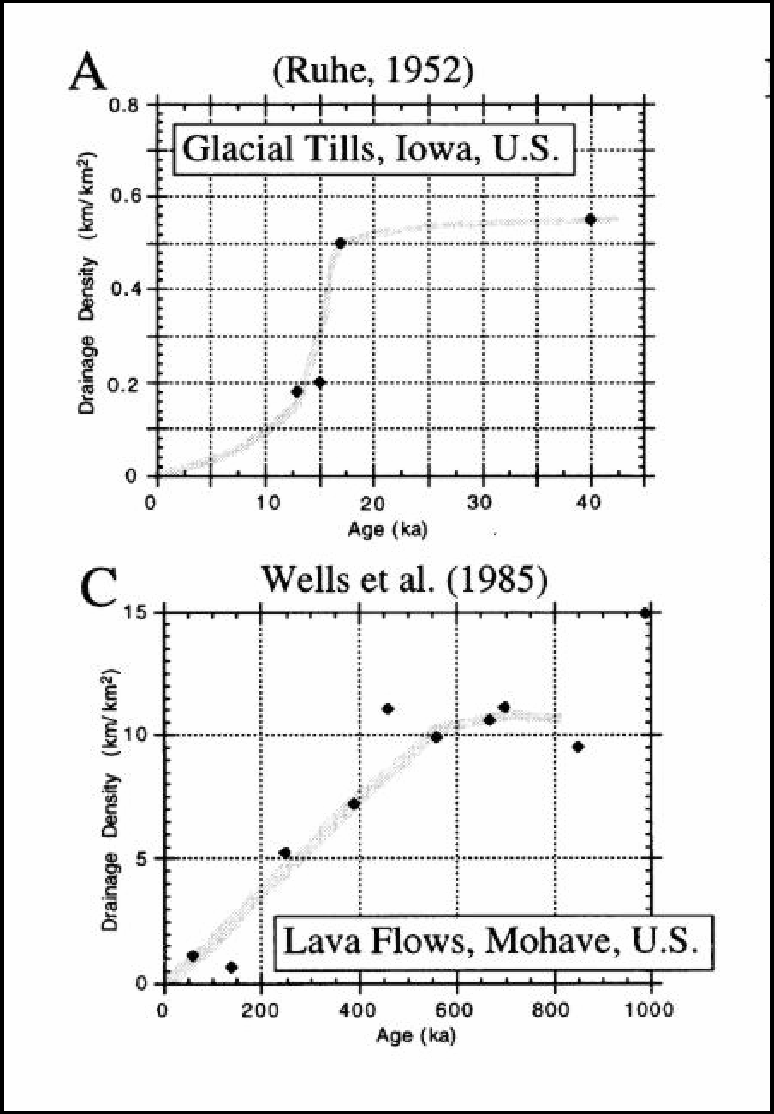


Initial drainage system



Final drainage system

1. Valley networks: Duration



* Depending on rocks eroded the drainage density observed on Mars required about >1,000 - 100,000 years

⇒ Requires a sustained activity not possible under current environment

* Drainage density does not increase after the network has reached a stability

⇒ The total duration can not be established using these parameters

* Observed valley networks do not require 100s My of fluvial activity

1. Valley networks: Summary

<u>What we know:</u>

1. 2D and 3D geometry as terrestrial networks formed by run off

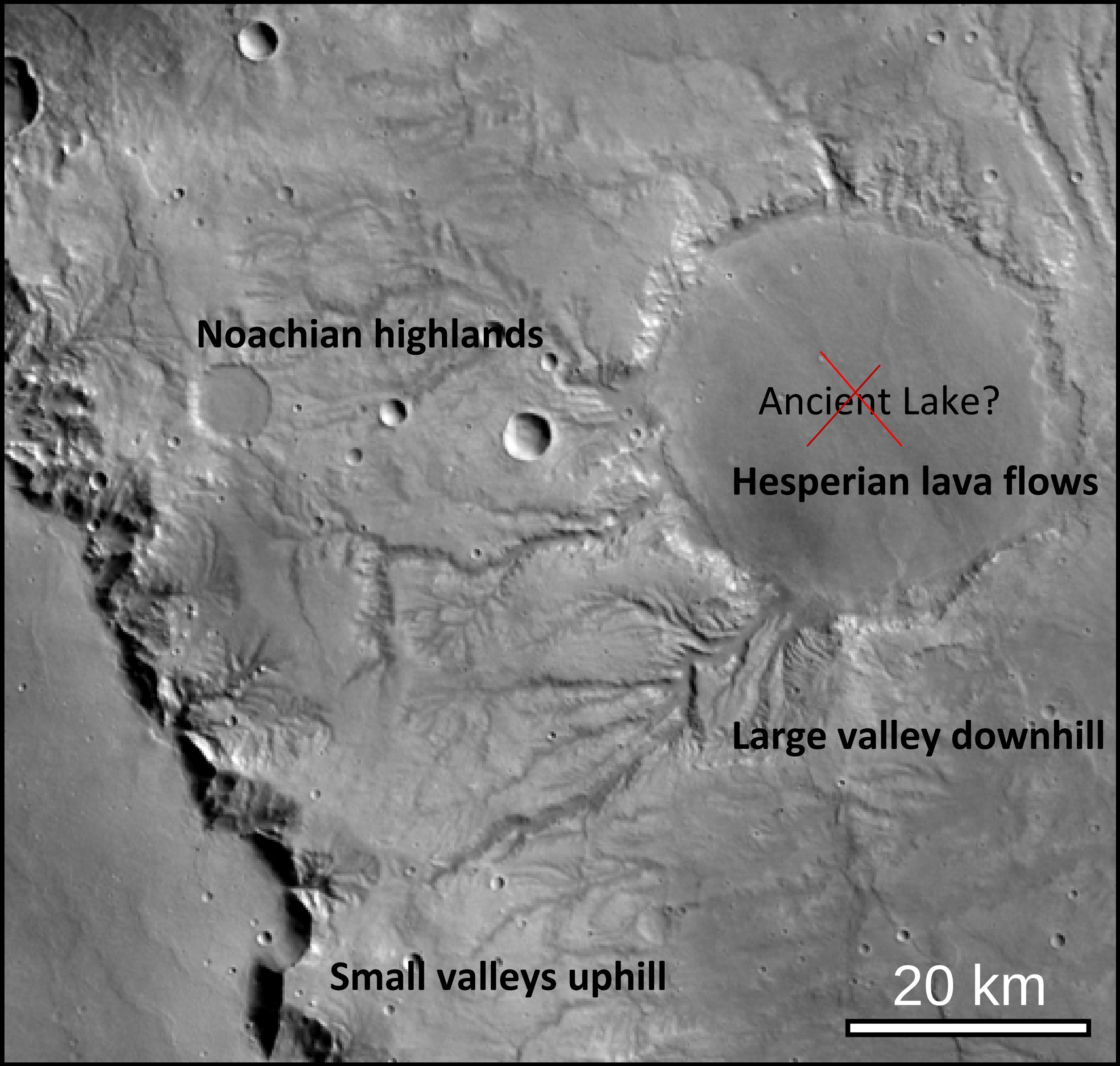
2. Interior channels with discharge rates similar to Earth (few 100s to 1000s m^3/s)

3. Require sustained liquid water to form

<u>What we want to know:</u>

- Climate (periglacial, arid)? Duration of activity (last fluvial episodes recorded)?
- Role of impact heating and high geothermal flux?

2. Sediments: Old landforms => Buried deposits

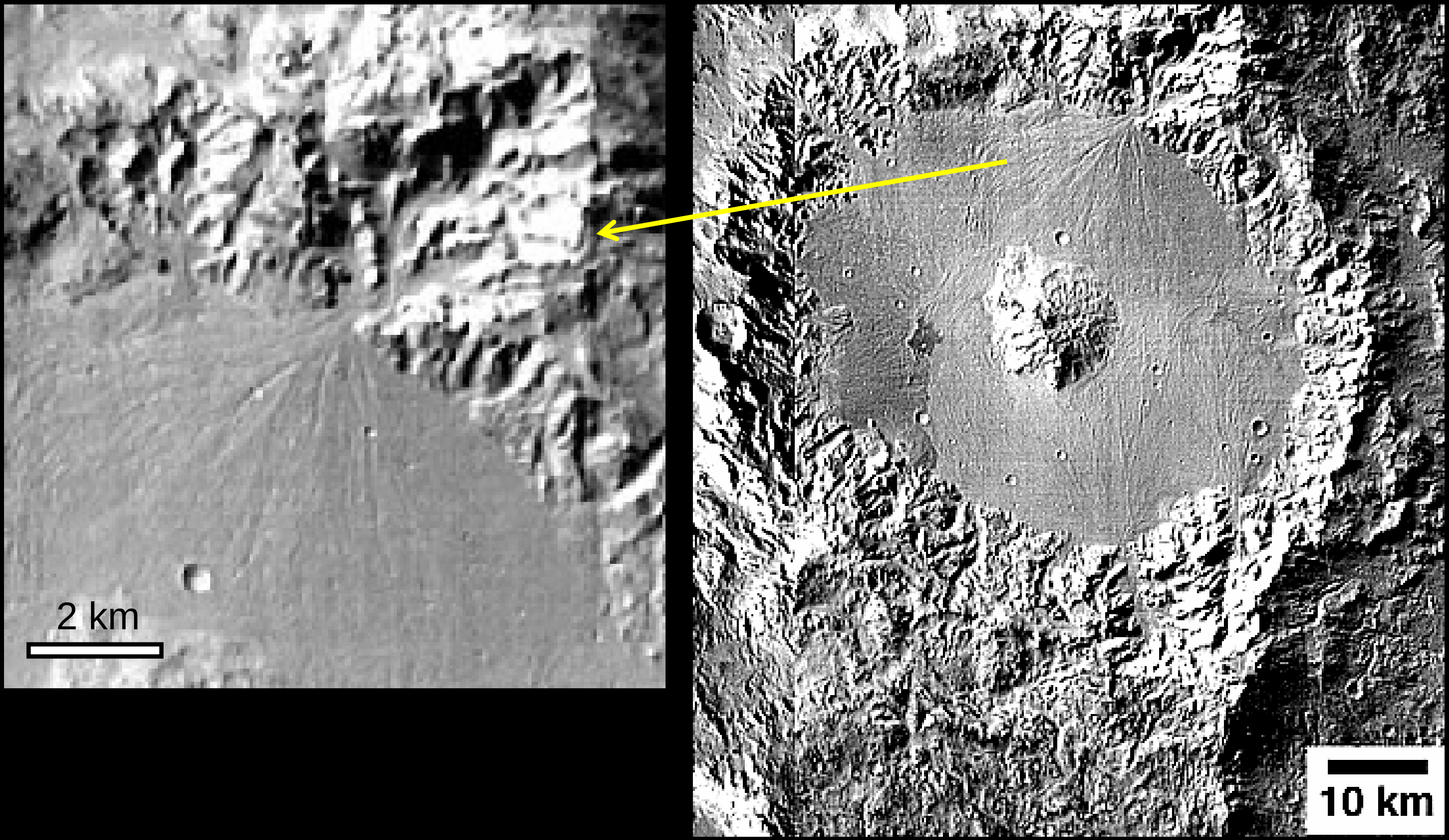


Lot of sediments eroded by fluvial activity are buried beneath subsequent volcanic flows

Most valley networks do not link into paleolakes

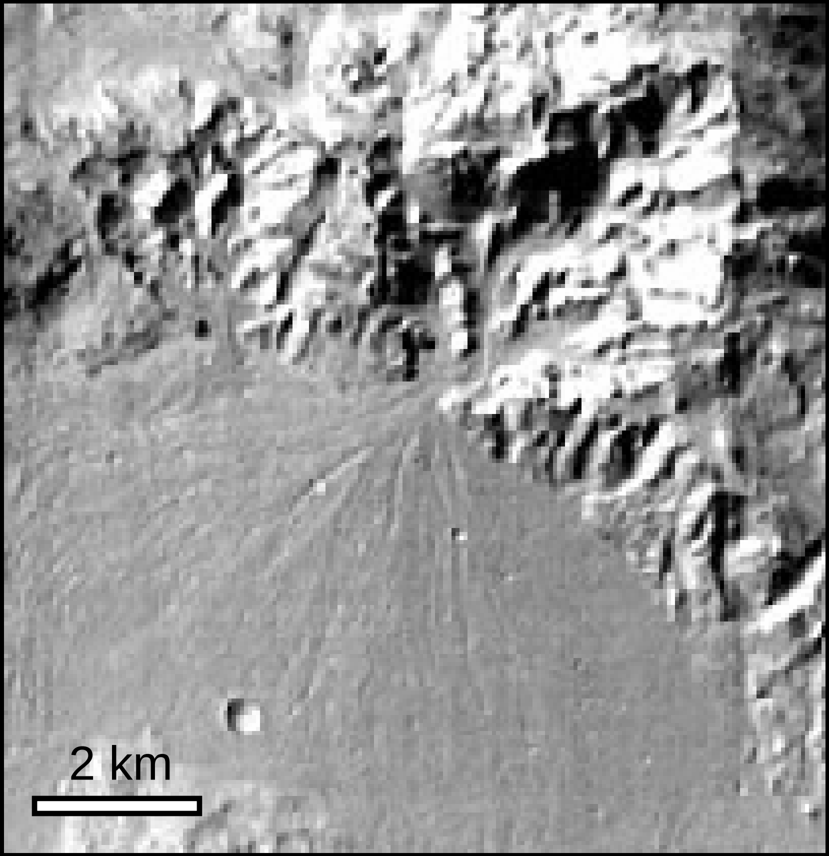
2. Sediments: Alluvial fans observations

Do fans involved paleolakes?



Moore and Howard, JGR, 2005

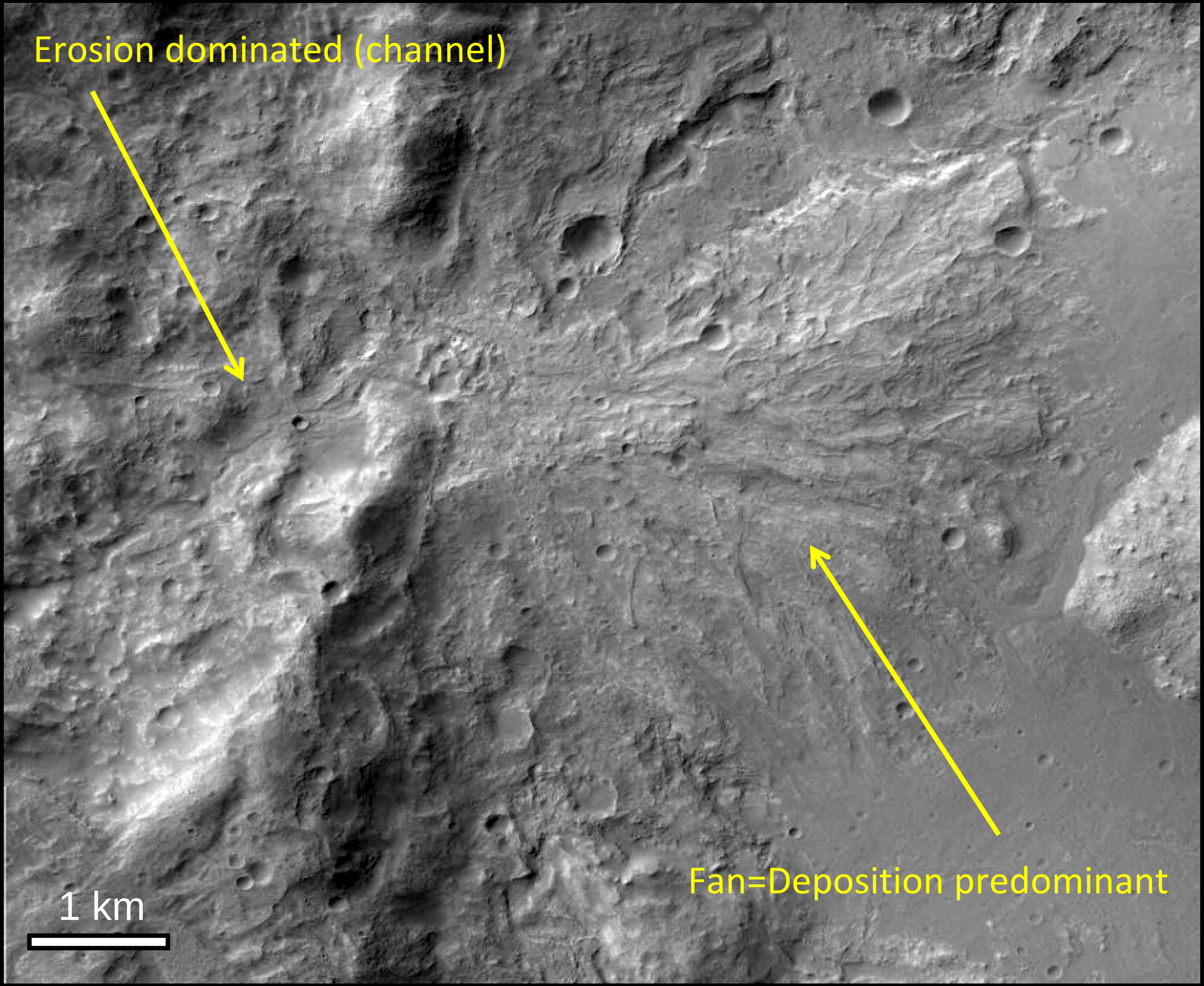
2. Sediments: Alluvial fans observations



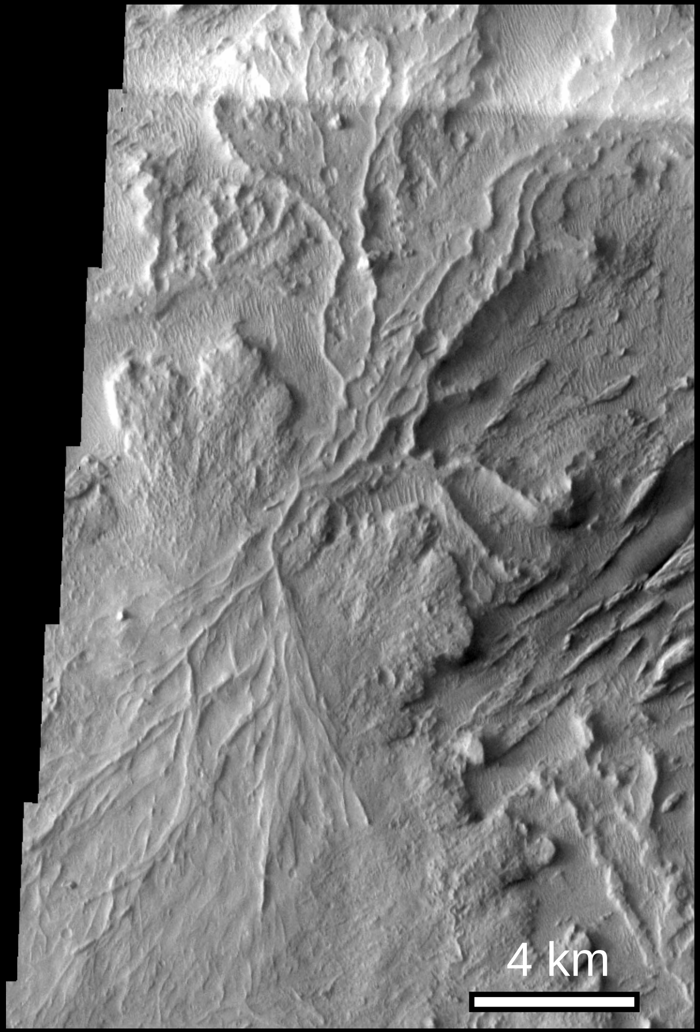
Mars

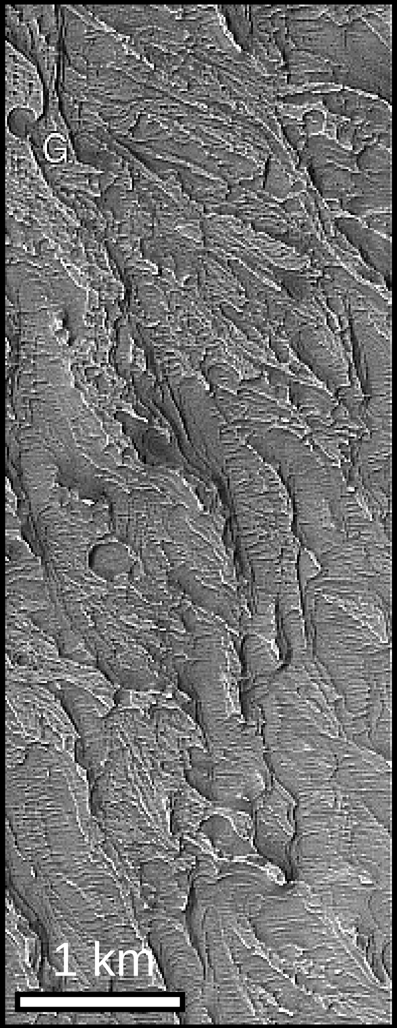
Terre (Death Valley)

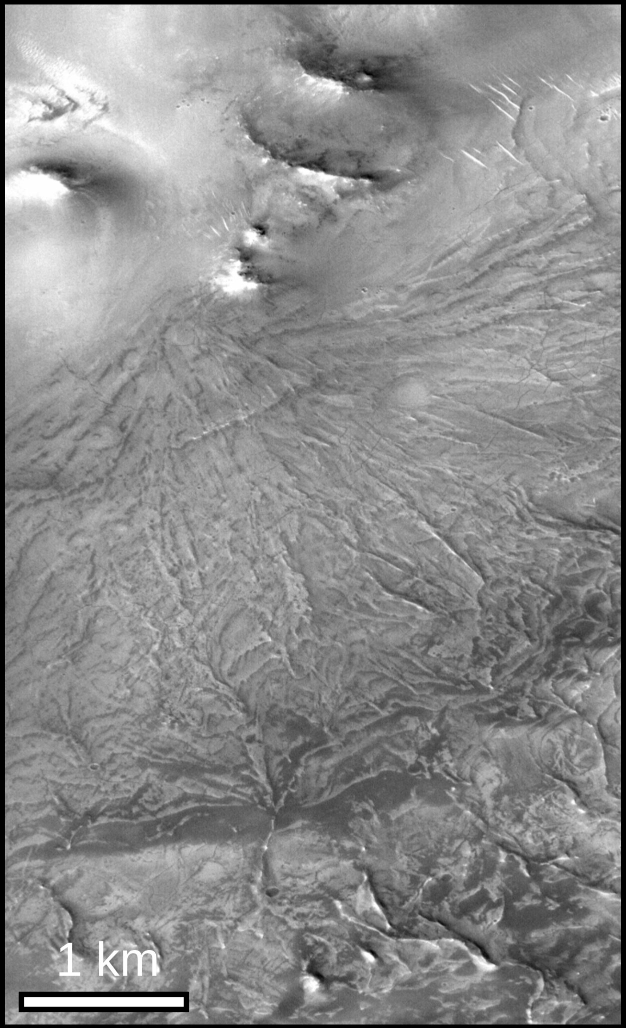
2. Sediments: Alluvial fans observations



2. Sediments: Alluvial fans observations

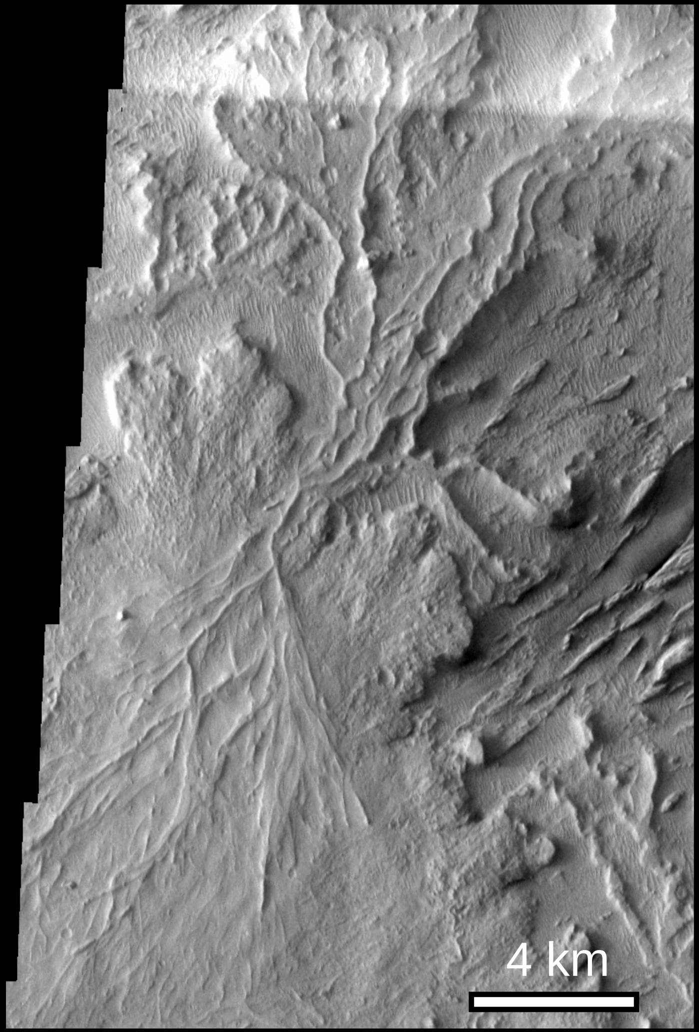


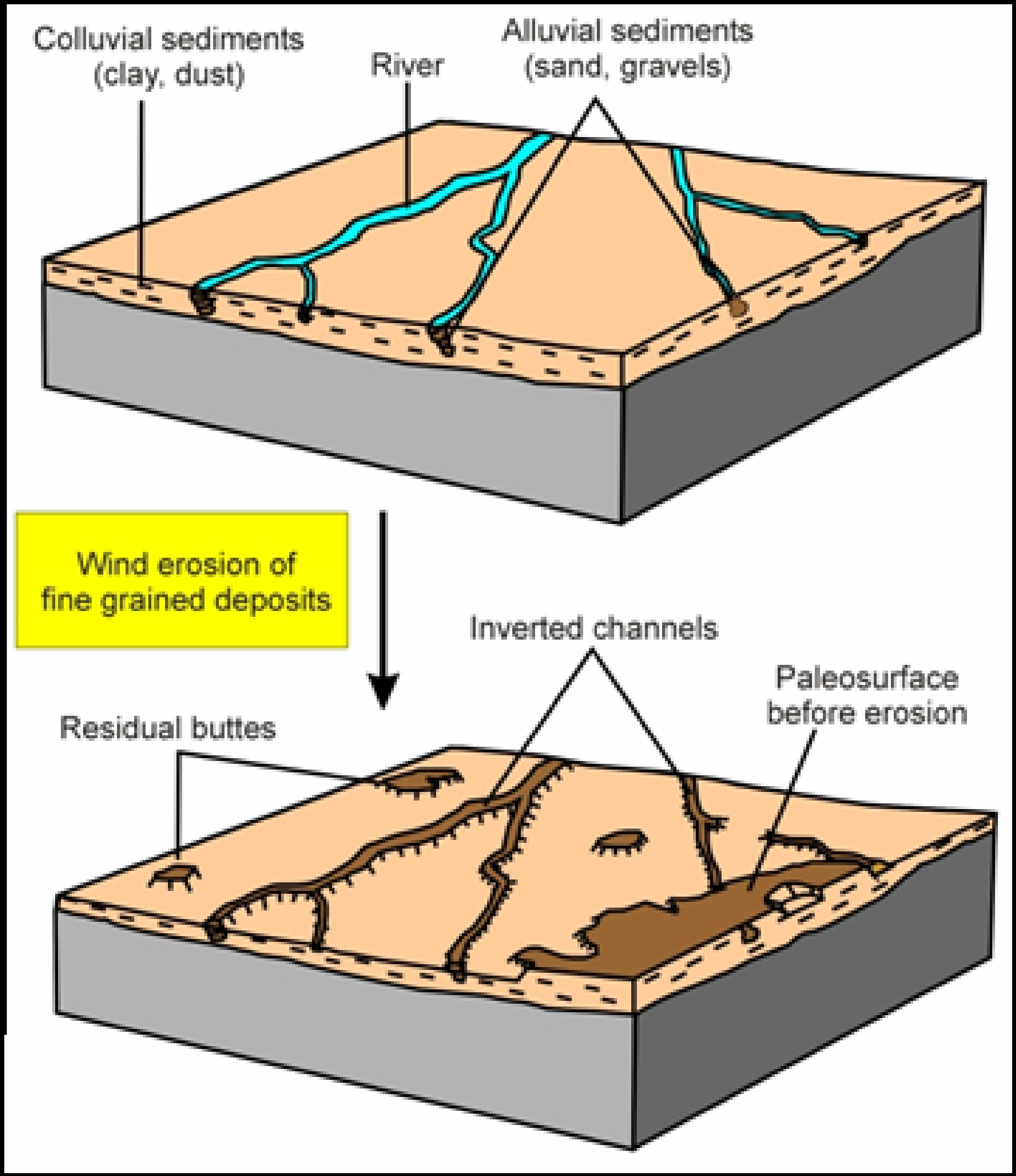




Morphology of fans: Inverted channels

2. Sediments: Alluvial fans observations

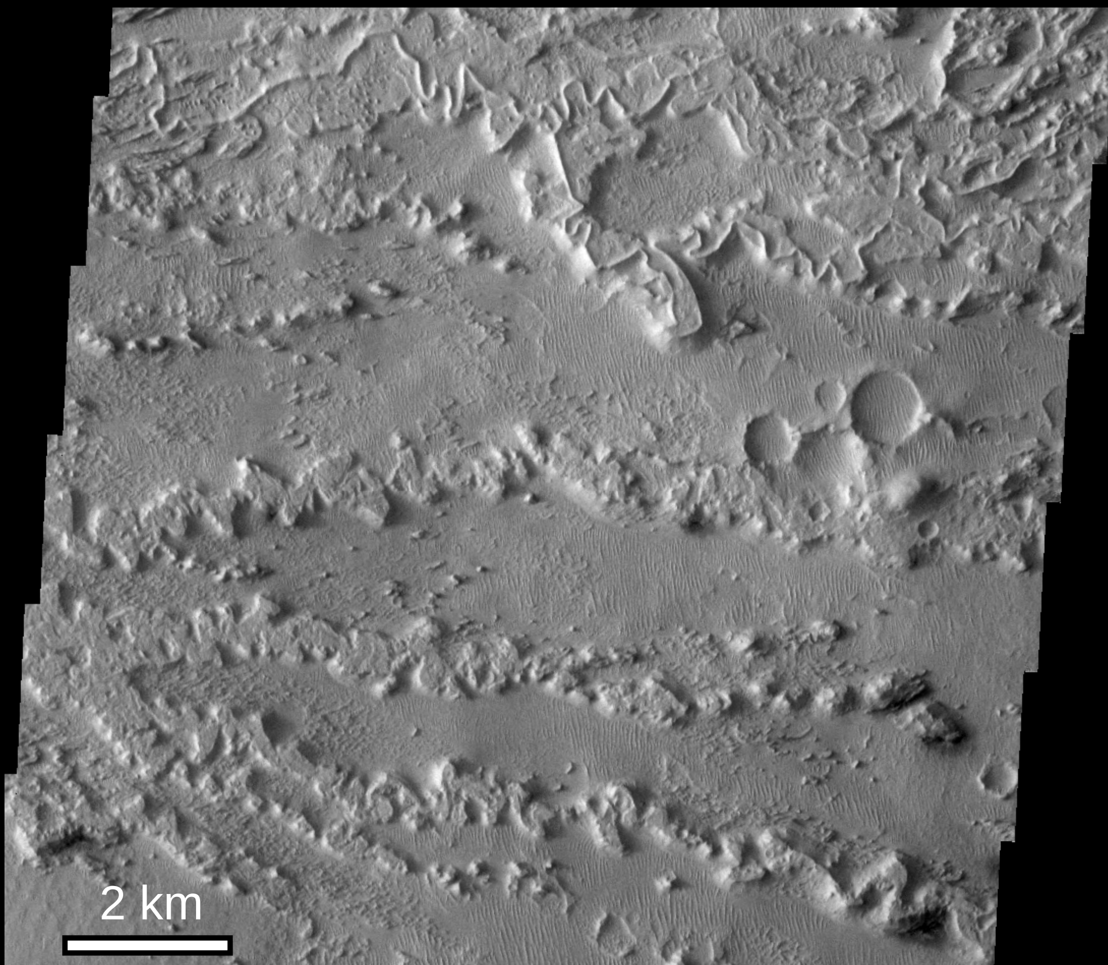




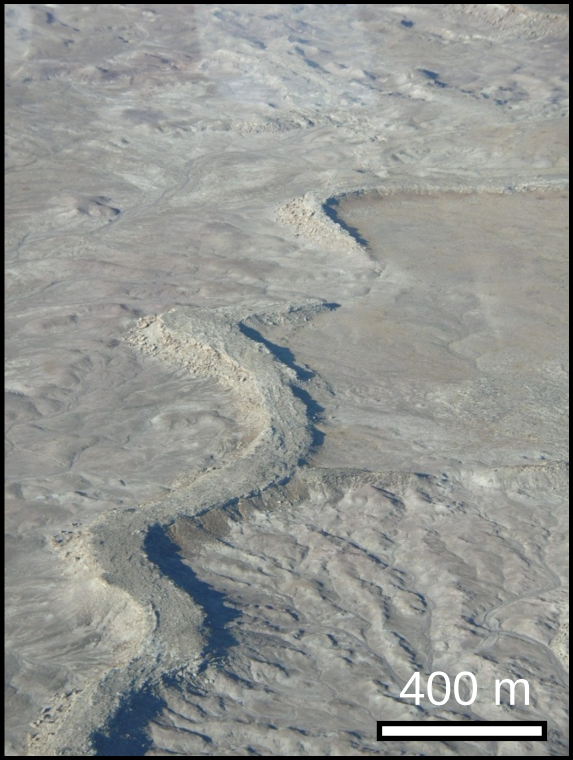
Formation of inverted channels

2. Sediments: Alluvial fans observations

Zephyria ragion
(Williams et al., 2009)



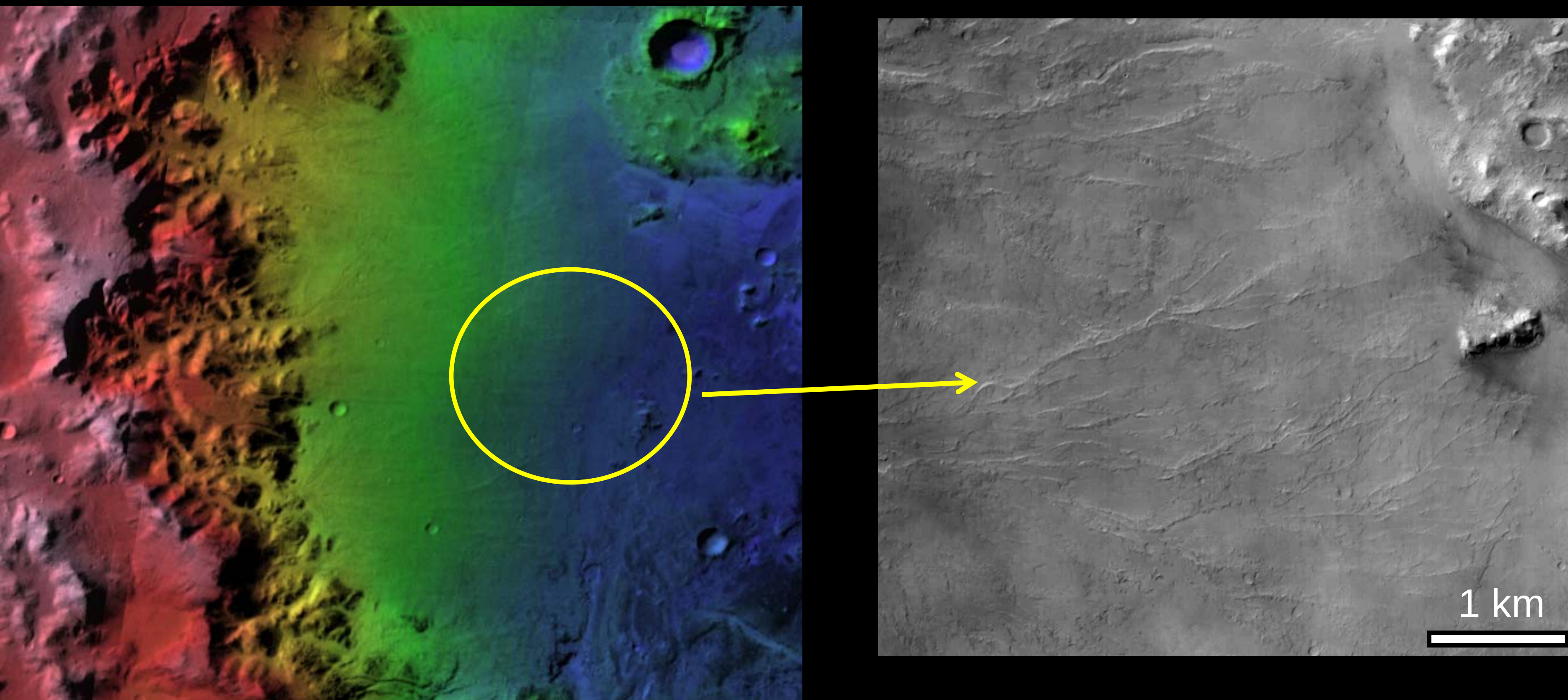
Utah



Sinuous inverted channels related to exhumed fluvial sediments

2. Sediments: Alluvial fans geometry

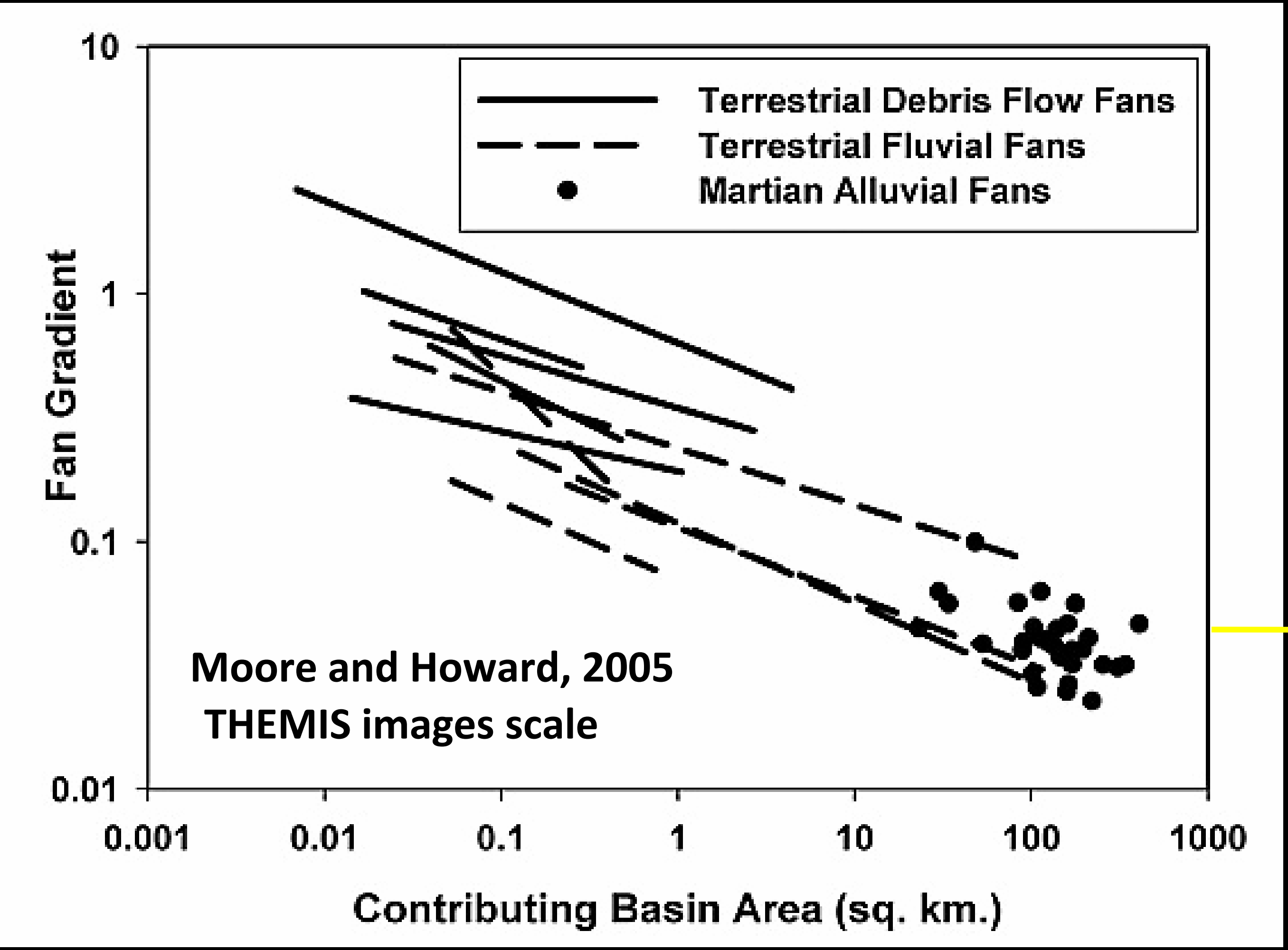
Holden crater MSL Landing site



Irwin et al., 2008, Grant et al., 2008

Alluvial fans form regular slopes

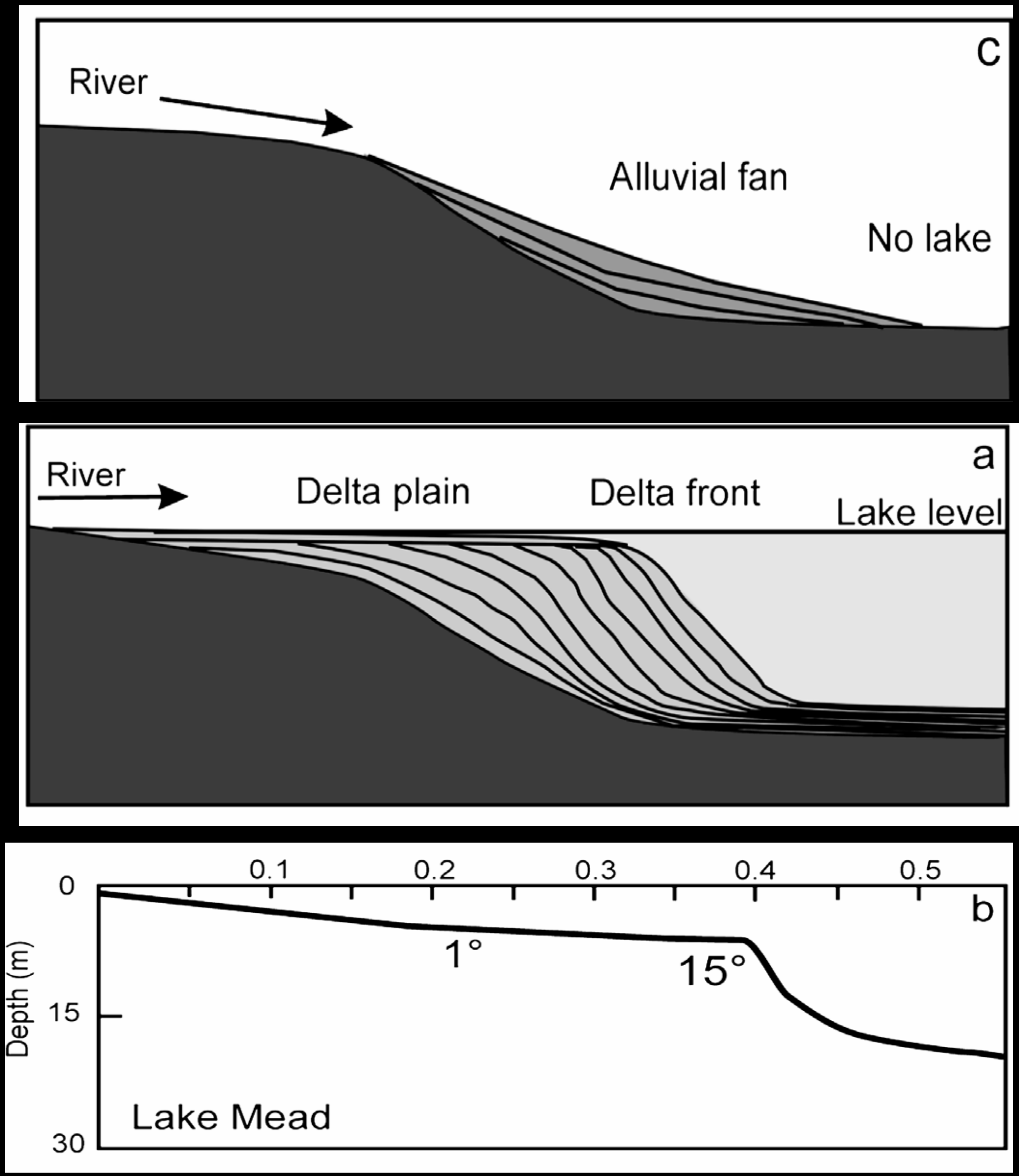
2. Sediments: Alluvial fans geometry



Slopes 2-6°

Martian fans are formed by fluvial deposition without lakes
They require fluvial activity (not transient flows)

2. Sediments: Alluvial fans vs delta fans topography

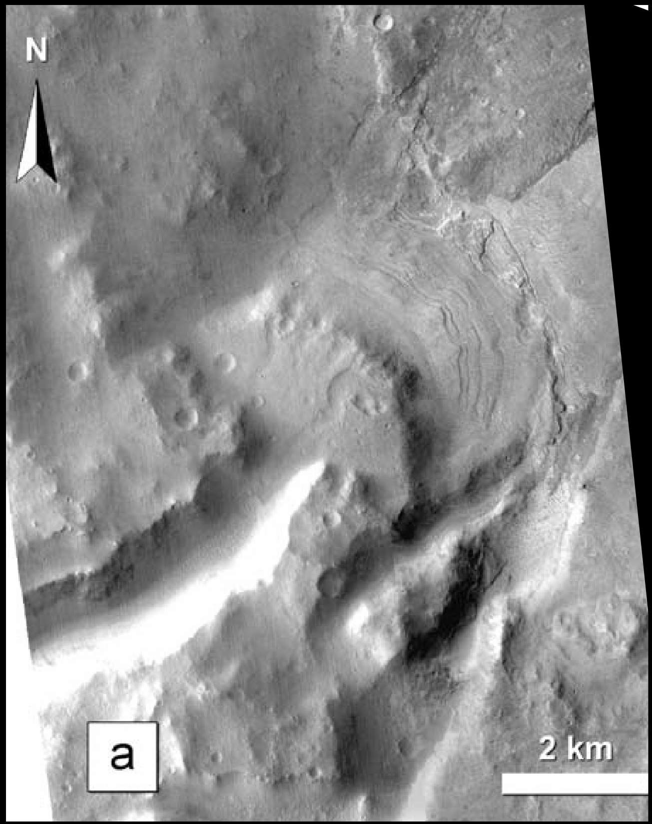


Regular slopes about 5° in average

Delta fans characterized by a flat plain slope with steep front

Critical difference to distinguish alluvial fans from delta fans

2. Sediments: Delta fans observations

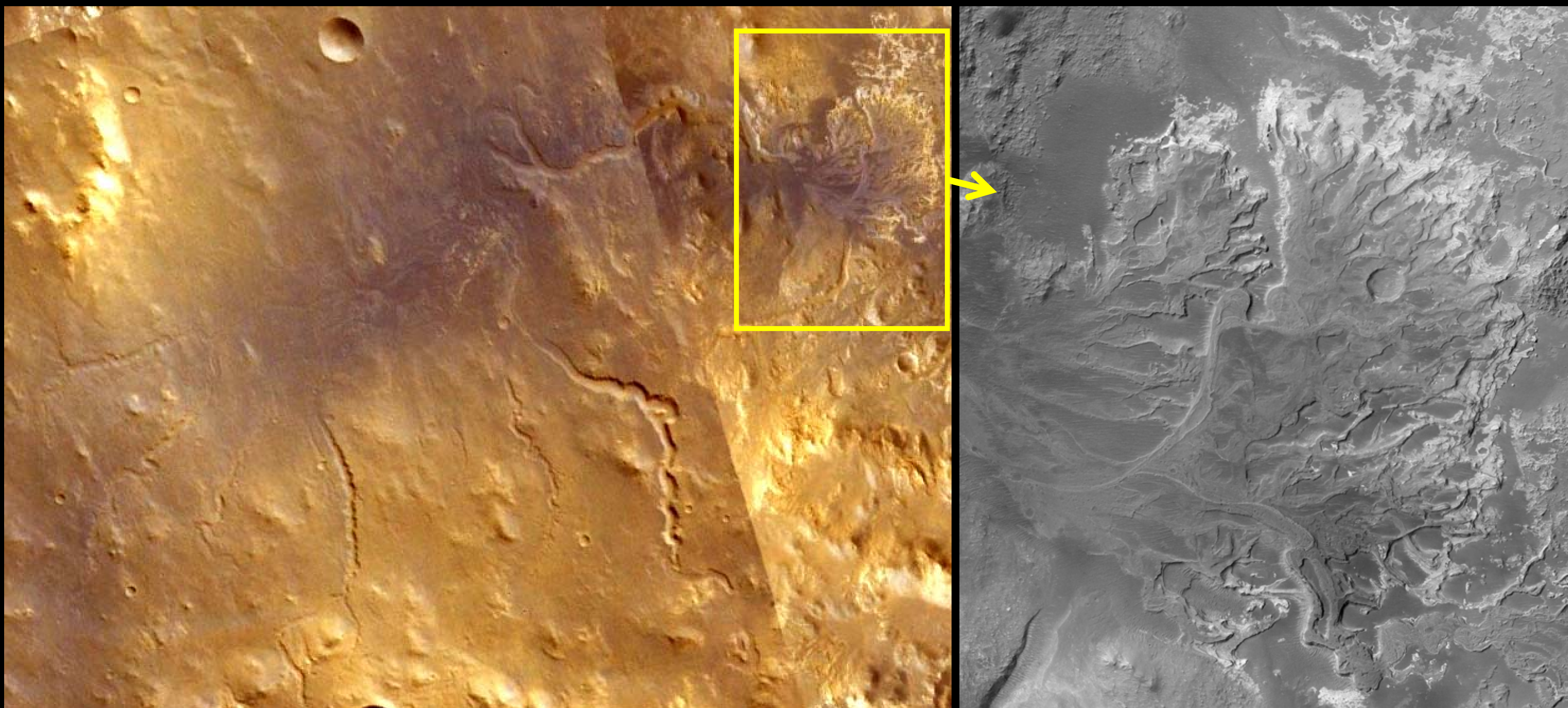


Subur Vallis
(Irwin et al., 2005, Hauber et al., 2008)

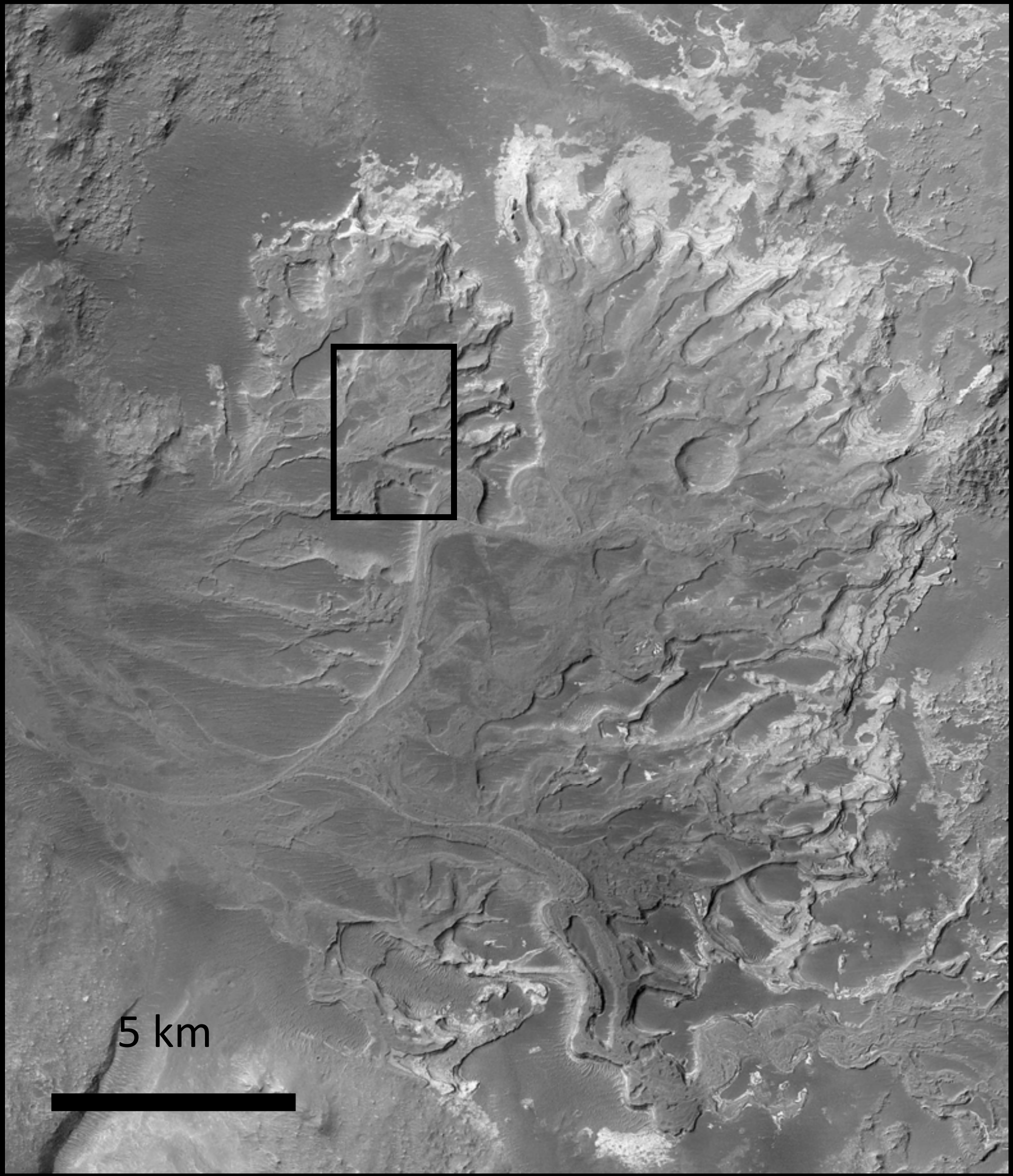

Nepenthes Vallis (Irwin et al., 2005, Kleihans et al., 2010)

2. Sediments: Delta fans observations

Eberwalde crater and fan (Malin and Edgett, Science, 2003)

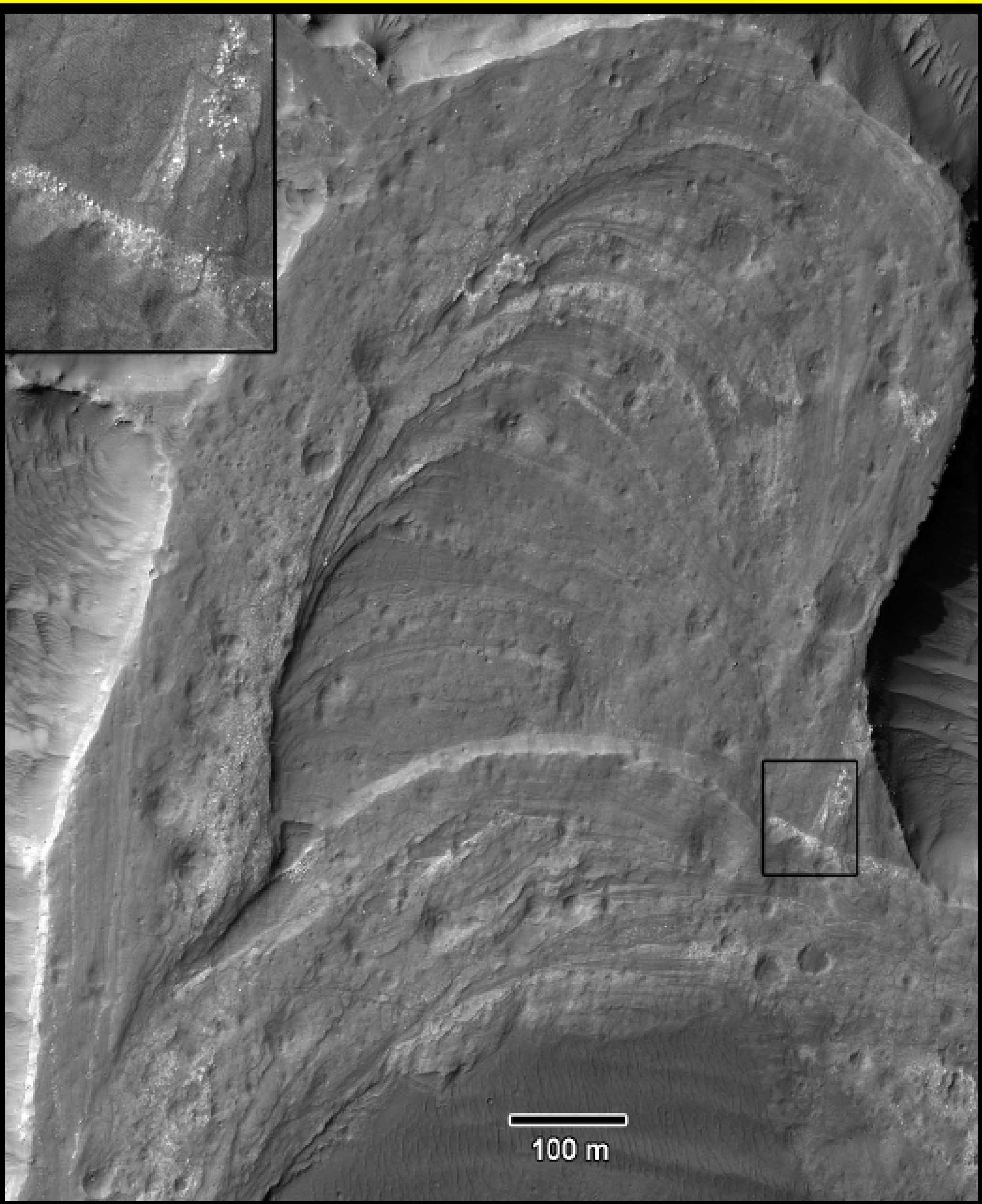


2. Sediments: Delta fans observations



Delta du Mississippi

1.2. Sediments: Delta fans observations



Meanders on Earth

1.2. Sediments: Delta fans formation process

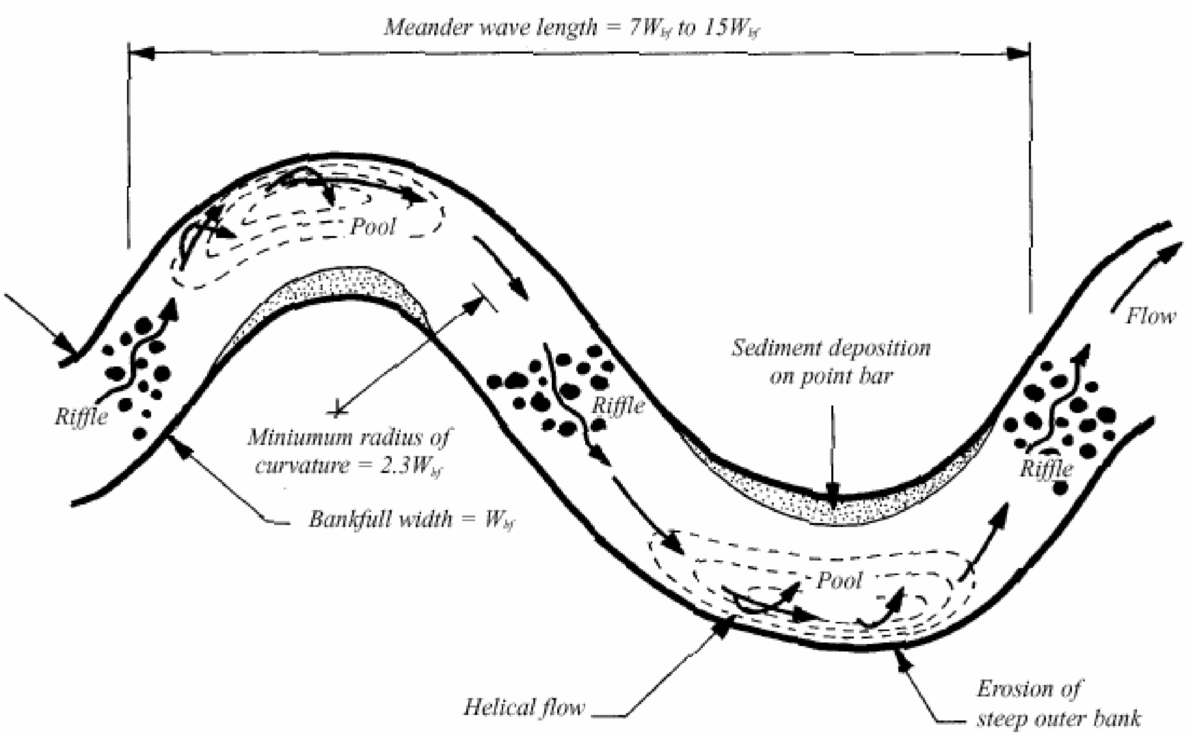
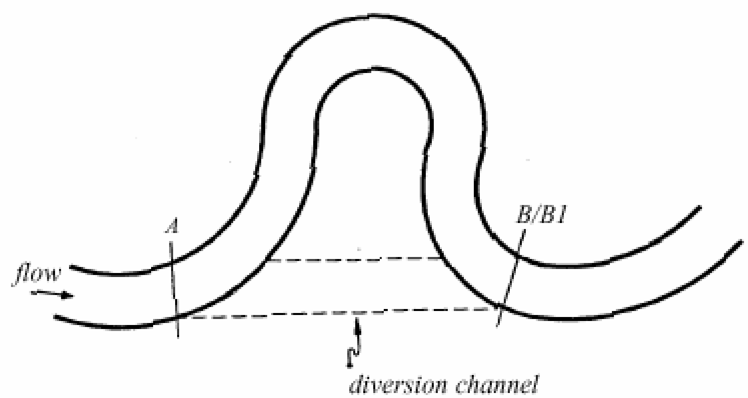


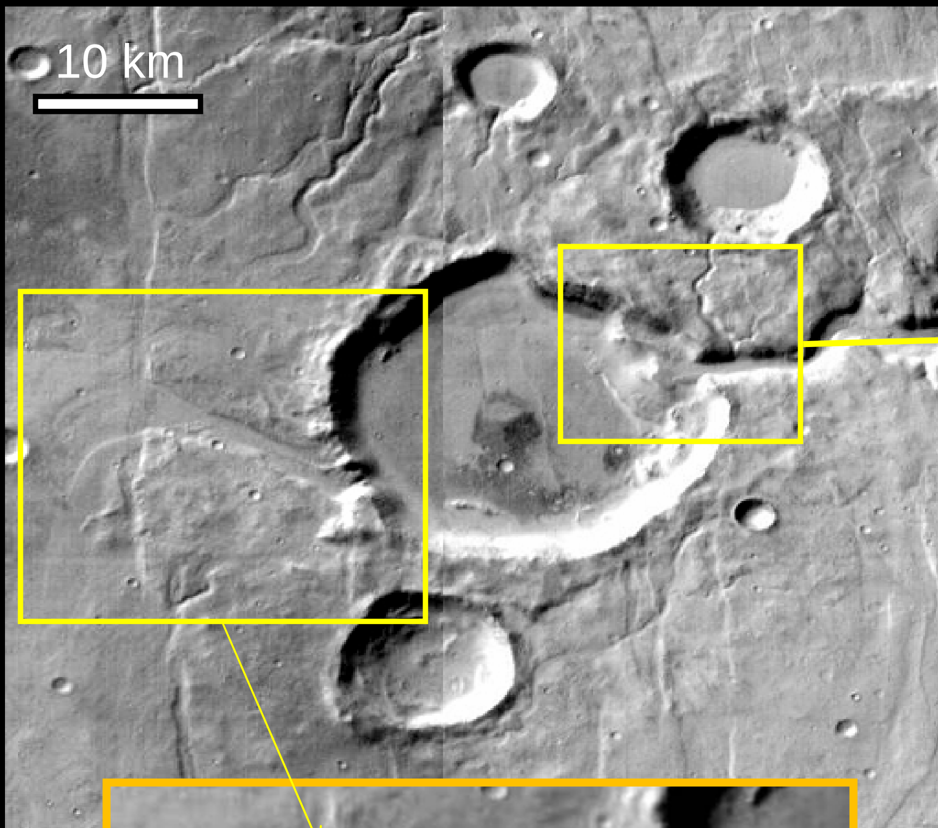
Figure 3: Meandering stream channel form.

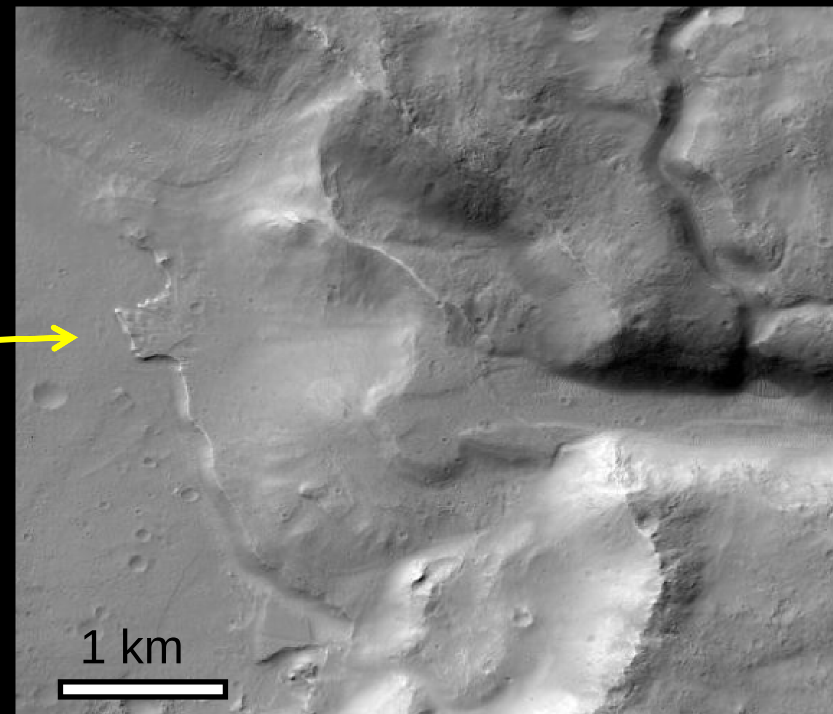
Adapted from Stream Analysis and Fish Habitat Design, Newbury & Gaboury (1993).

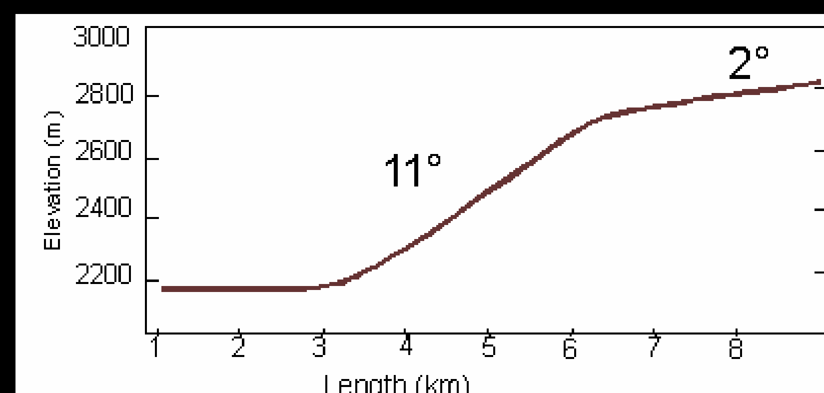


1.2. Sediments: Lacustrine activity on Mars

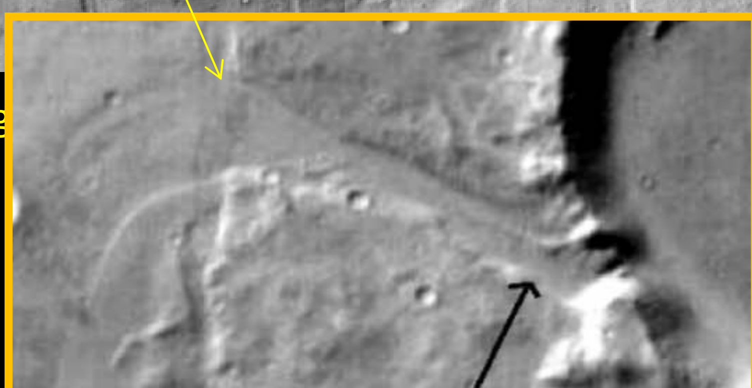
A 600 m deep paleolake in Claritas Fossae region





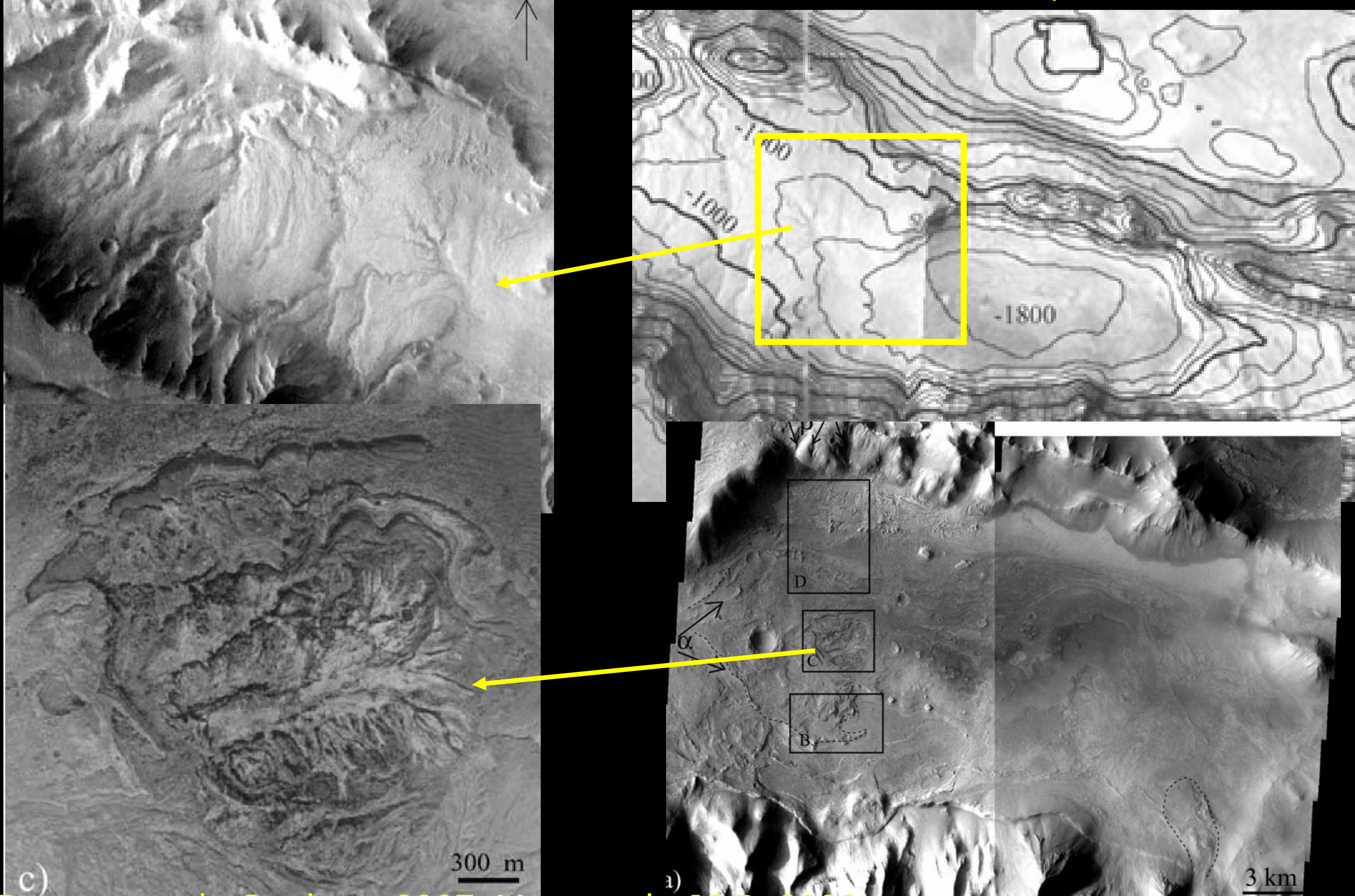


Mang



1.2. Sediments: Lacustrine activity on Mars

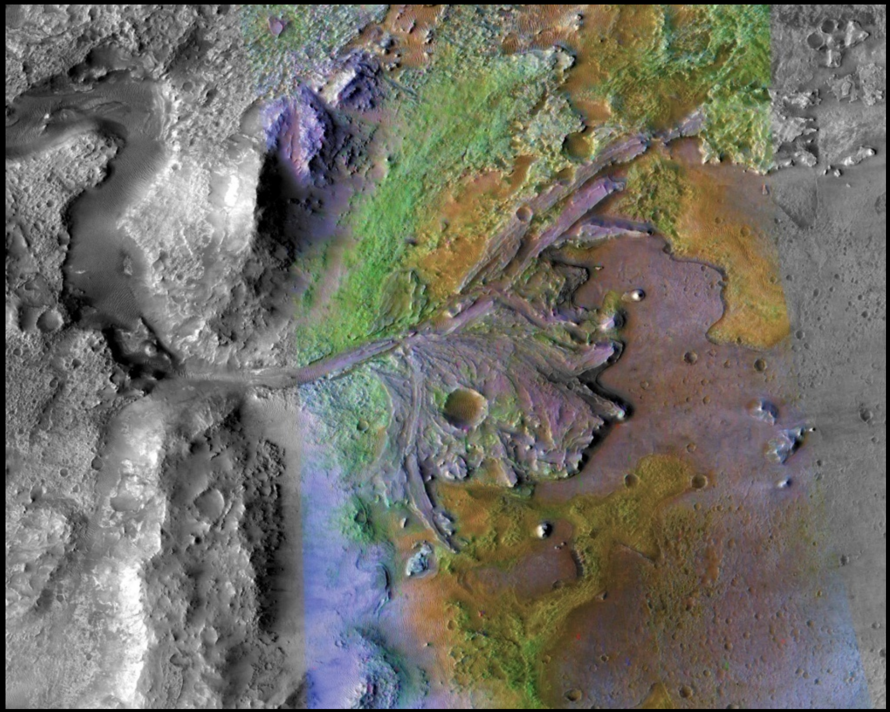
Paleolake in Melas Chasma (Quantin et al., 2005)



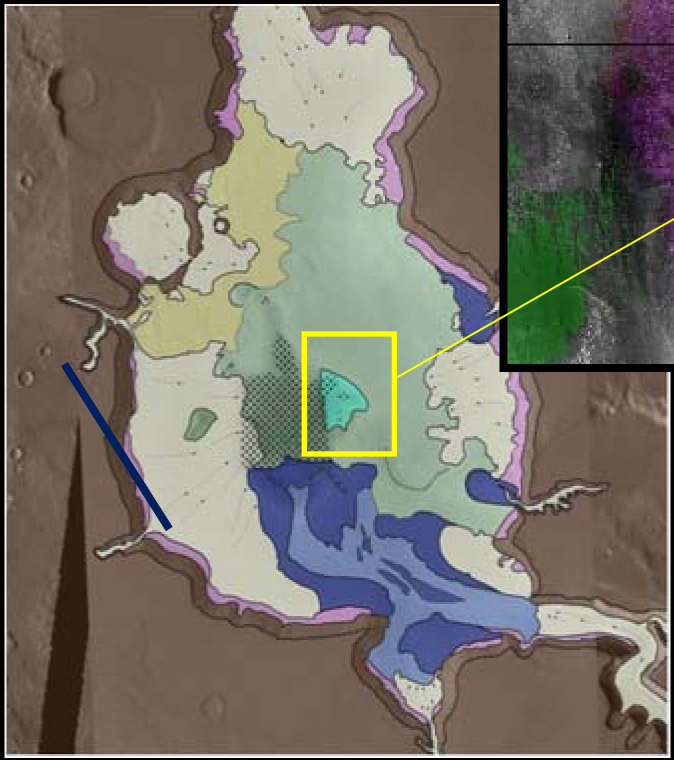
Dromart et al., Geology, 2007, Metz et al., JGR, 2009

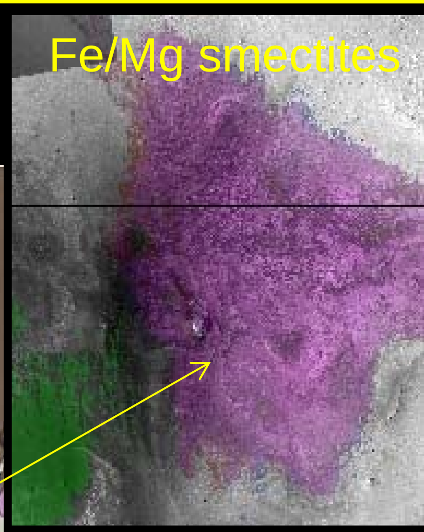
1.2. Sediments: Lacustrine activity on Mars

Delta fans often contain hydrated minerals such as phyllosilicates (formed by alteration by water)



Jezero fan with CRISM (clays in blue) (Ehlmann et al., Nature Geo., 2008)





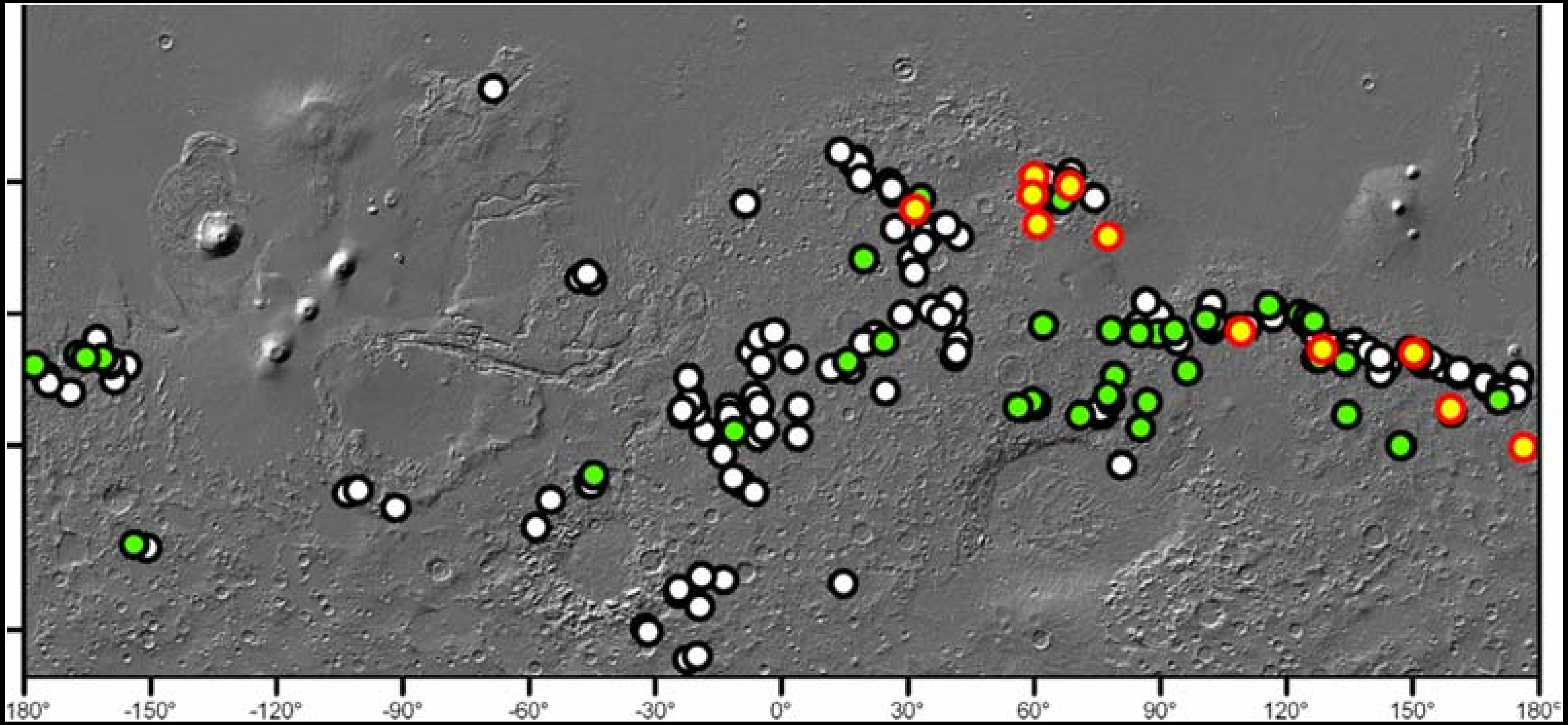
A 600 m deep paleolake in ismenius Cavus (Dehouck, PSS, 2010)

Problem: Phyllosilicates can come from transport and deposition of altered crust
=> Difficult to know if they were formed during the lacustrine activity or earlier

1.2. Sediments: Geographic distribution

No cross-checked map of paleolake published yet.
(multiple evidence of lakes as in Eberwalde are not frequent)

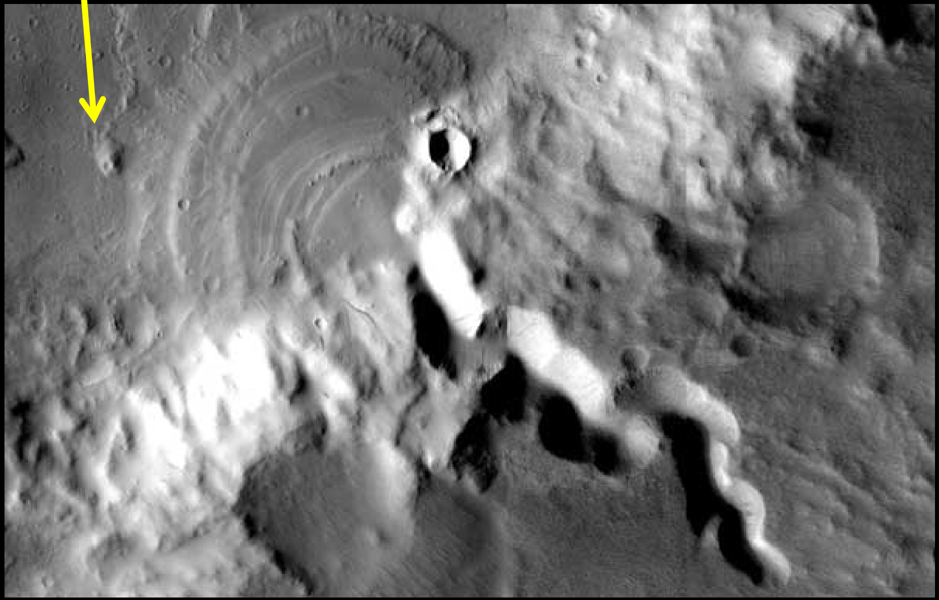
Map of open basin (valleys joining a plain with a valley exiting the plain)

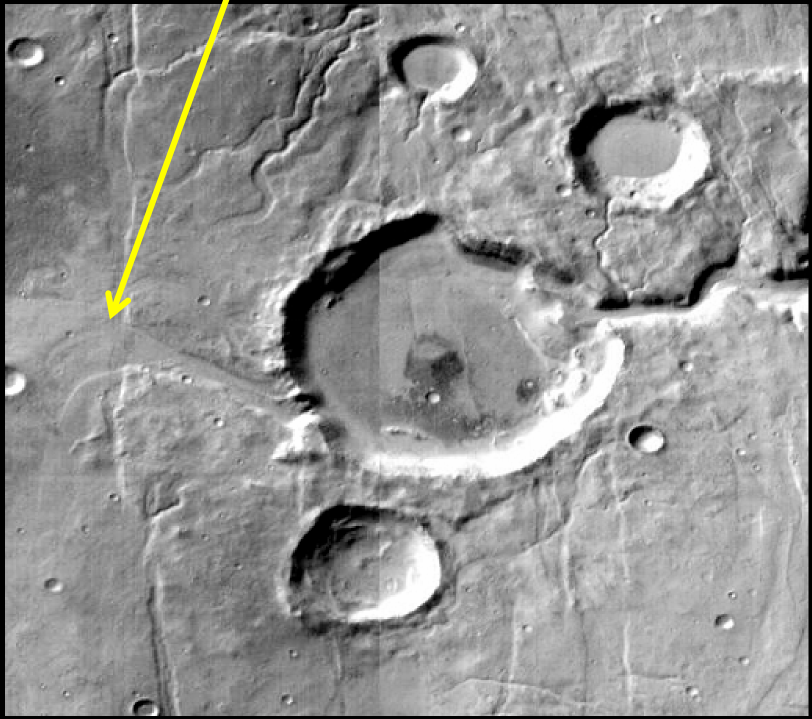


Fassett et al., 2008

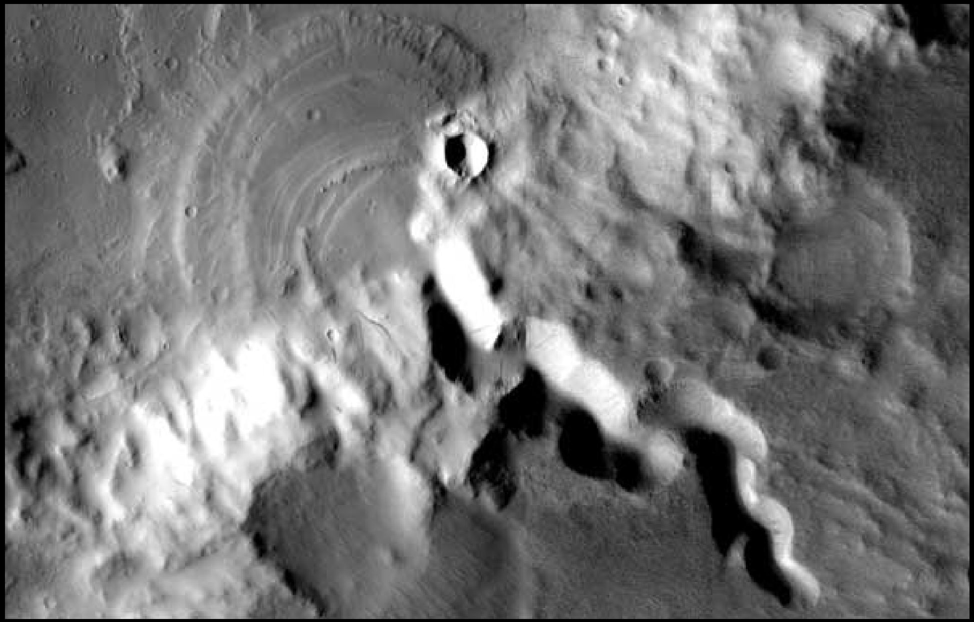
1.2. Sediments: Chronology

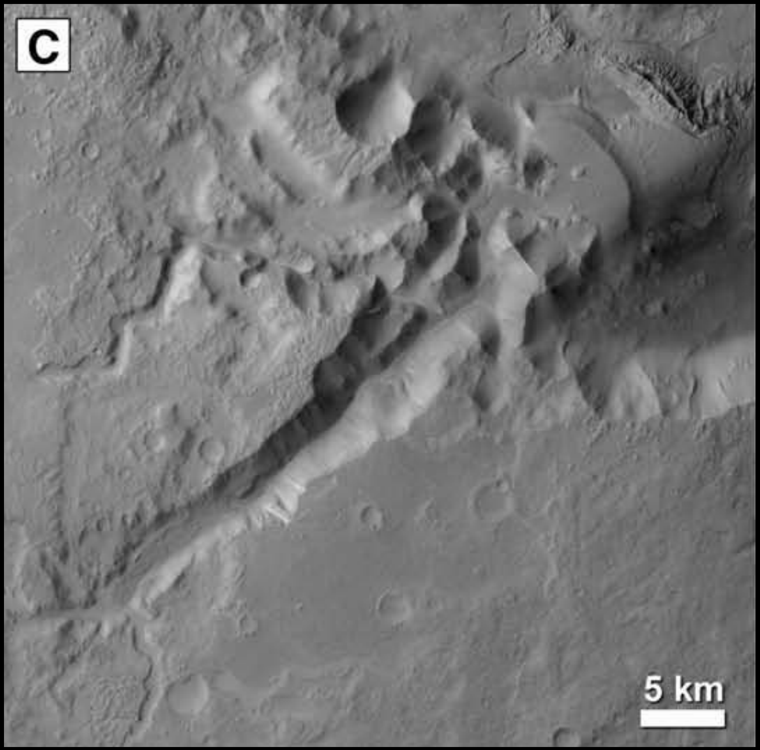
- Most paleolakes and fans in Noachian craters
- Several paleolakes in Hesperian plains
- No paleolakes after the Hesperian





2. Sediments: Delta fans duration





Modeling using observed flow properties
geometry of the accumulation zone
and postulated solid fraction.

Kleinhans, EPSL, 2010

Duration of delta accumulation: Few days to few years

No valley networks at source of delta fans.
Only 1-5 km^3 of sediments

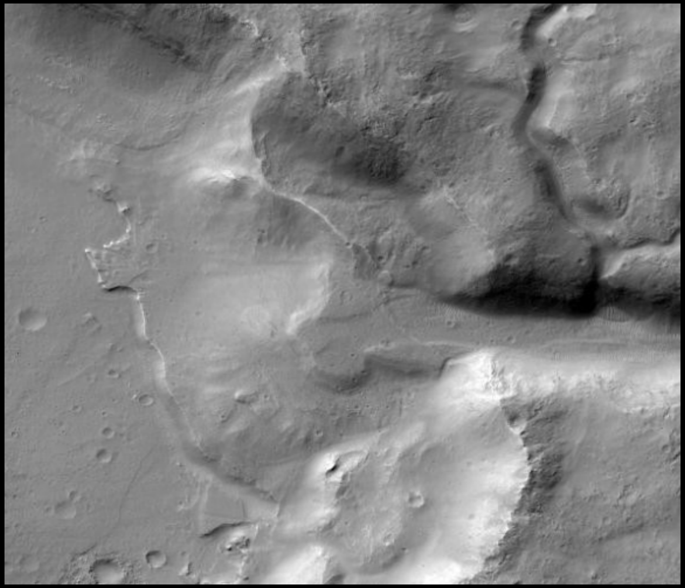
→

Fans formed by last burst of
sustained liquid water on Mars

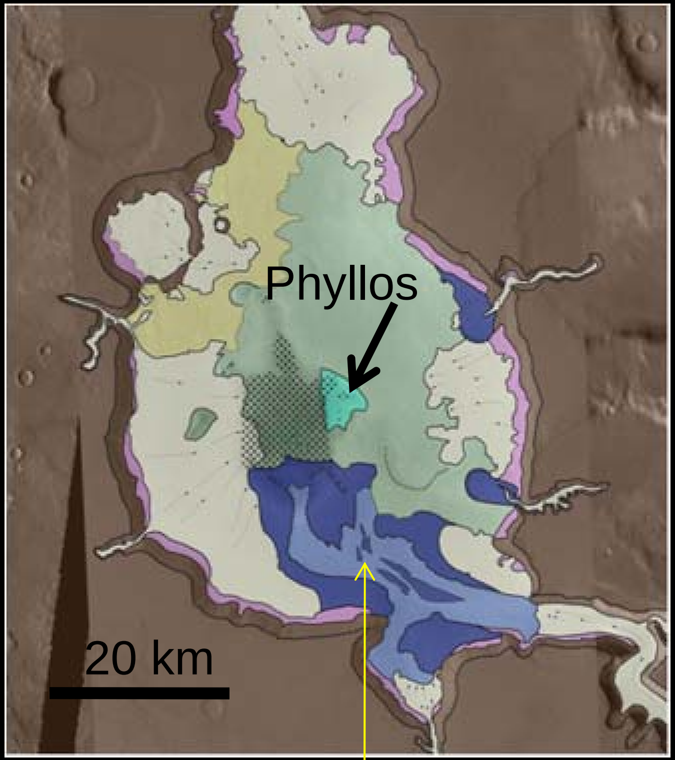
2. Sediments: Delta fans duration

Thicker fan deltas require longer period of deposition, but duration is unknown.

As for valley networks, periods > Myears are not required.



600 m deep fan

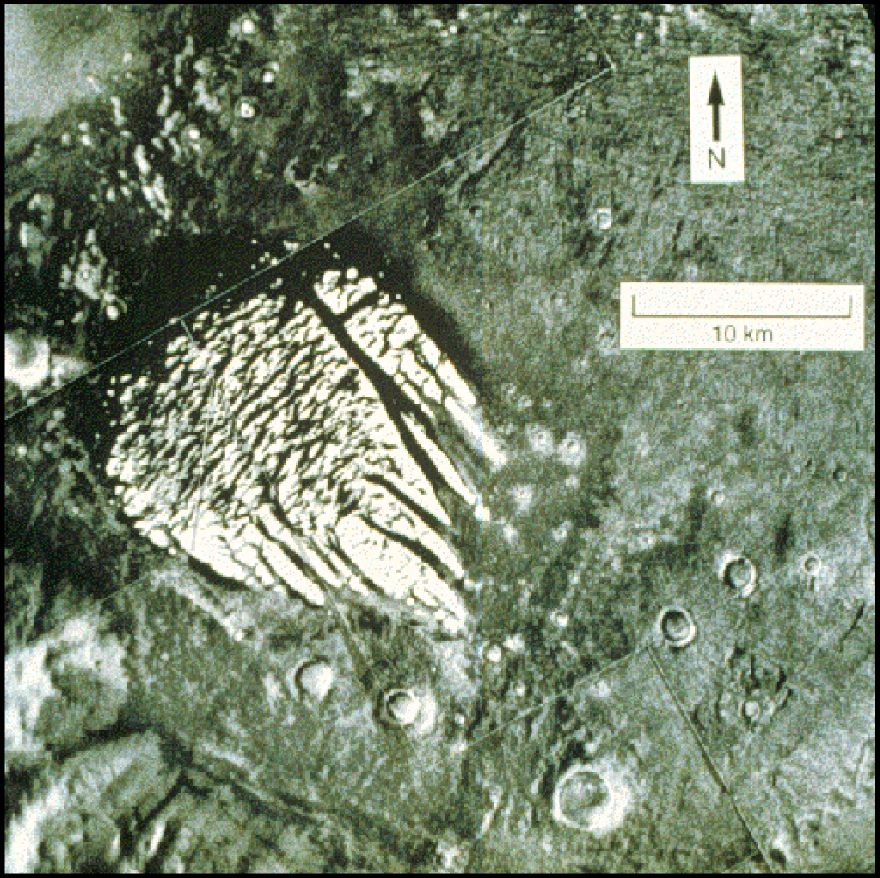


Ismenius Cavus fan=200 km^3 (100 times more volumes than the stepped fan)

2. Sediments with uncertain origin

Without landforms it is difficult to assess the origin of sediments:

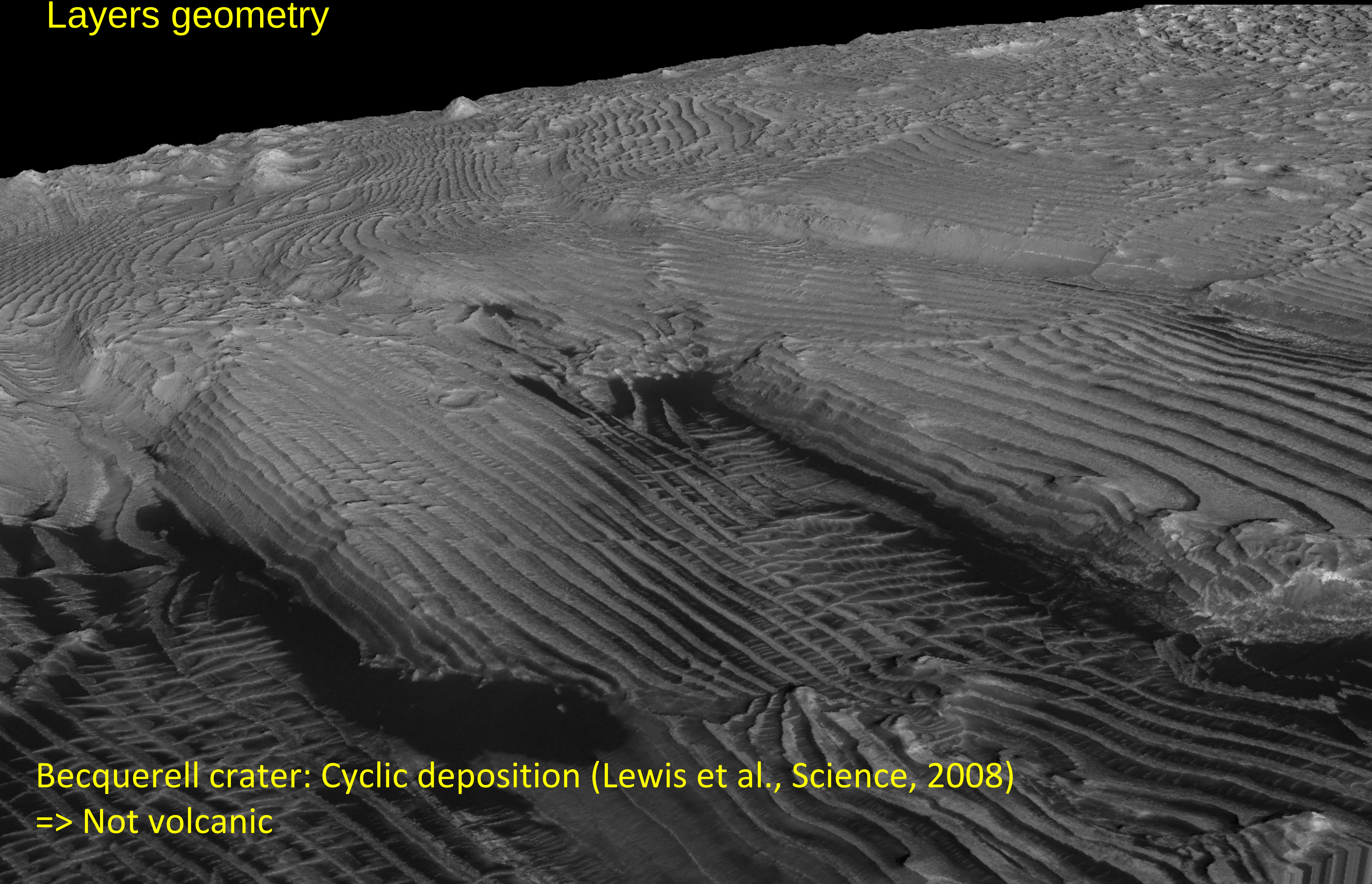
Glacial, fluvial, lacustrine, eolian, volcaniclastic (ash) are possible



White rock in Pollack Crater
Could be a pile of dust (Ruff, 2003)

2. Sediments with uncertain origin

Layers geometry

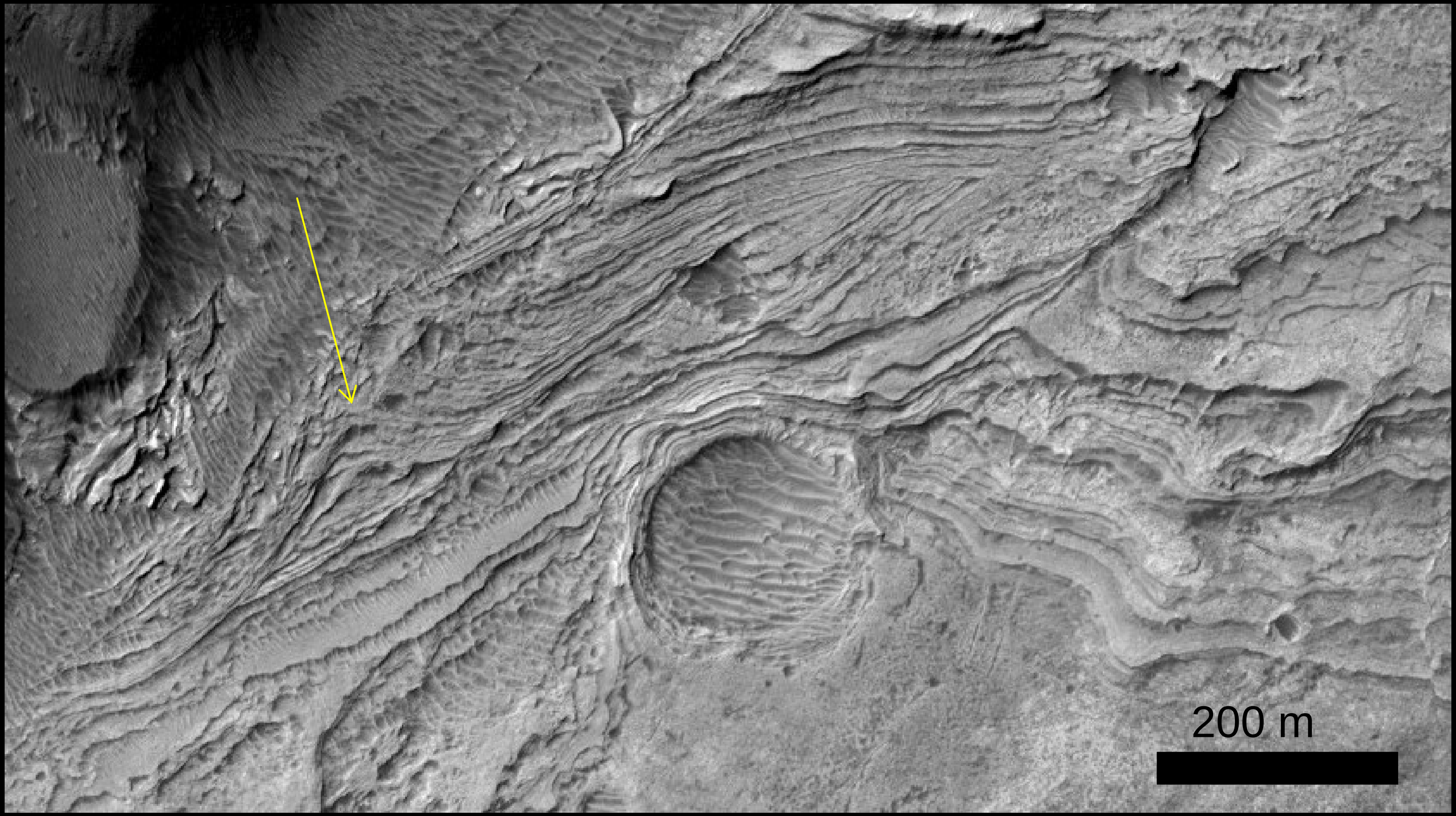


Becquerell crater: Cyclic deposition (Lewis et al., Science, 2008)
=> Not volcanic

2. Sediments with uncertain origin

Layers geometry and facies (e.g. Dromart et al., 2007, Metz et al., 2009)

Clinoforms seen in Melas Chasma paleolake
Difficult to do from orbit



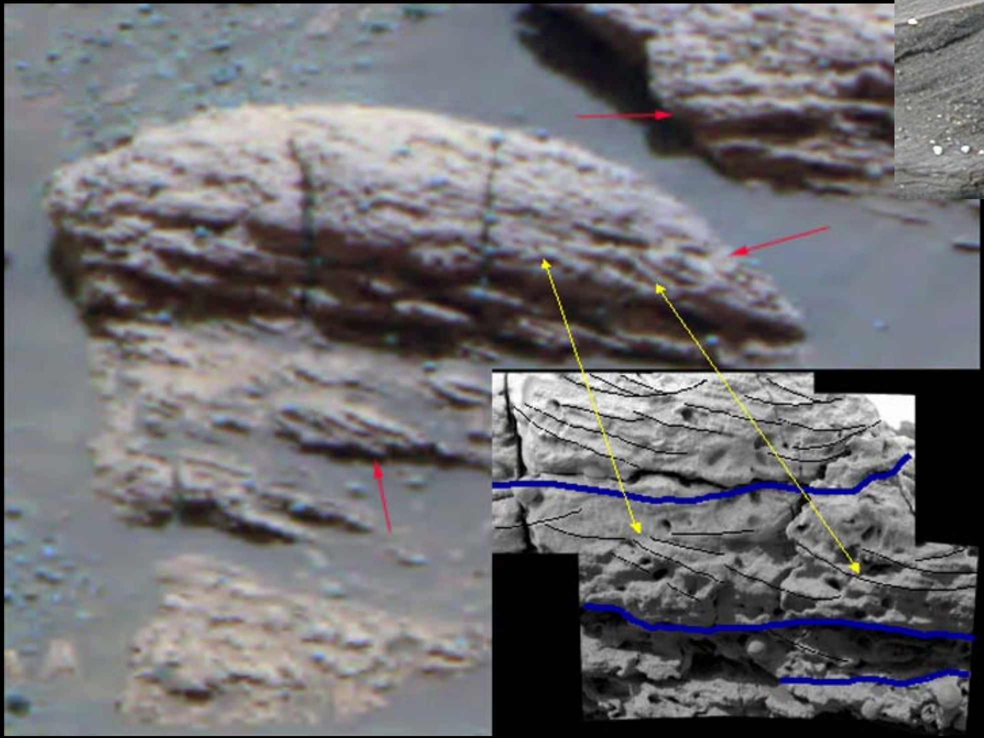
2. Sediments with uncertain origin

Layers geometry and facies

Facies analysis is easier
at the scale of *in situ* analysis

Fluvial sediments in Iceland

Cross-bedding at Meridiani Planum



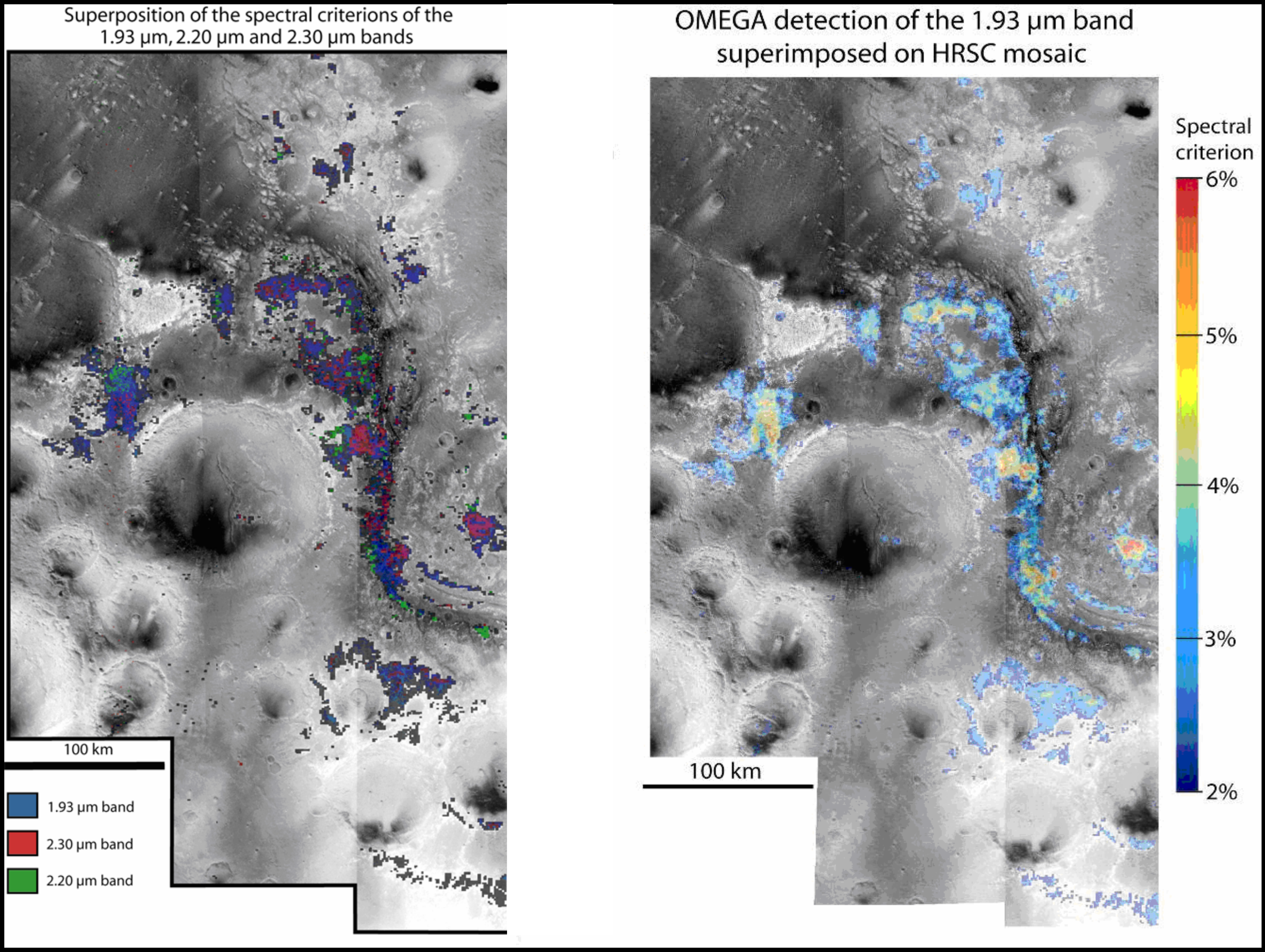
Not possible from orbital data

See Squyres et al., Grotzinger et al., 2006

2. Sediments with uncertain origin

Another method: Mineralogy

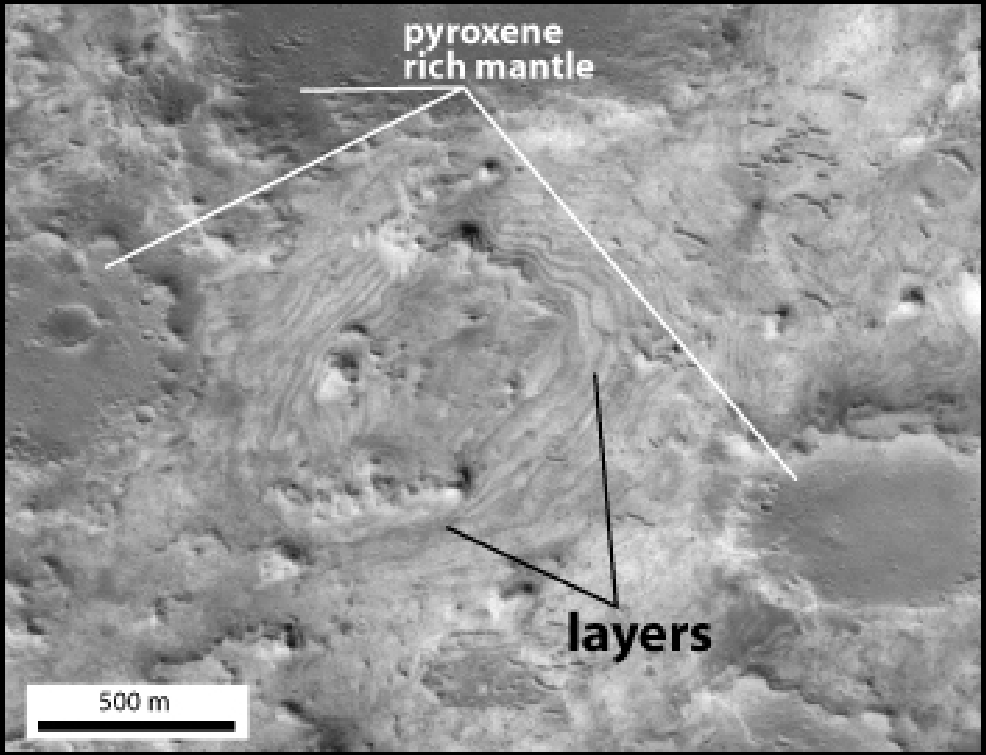
OMEGA map of Mawrth Vallis region (Loizeau et al., 2007)

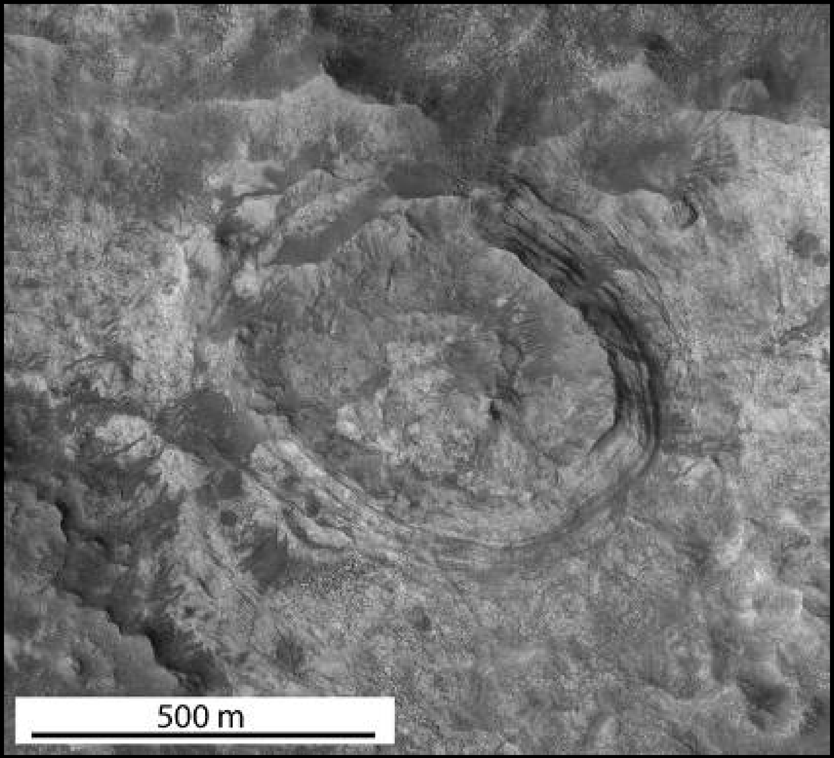


2. Sediments with uncertain origin

Phyllosilicates observed on thin layered deposits (<2-3 m thick)

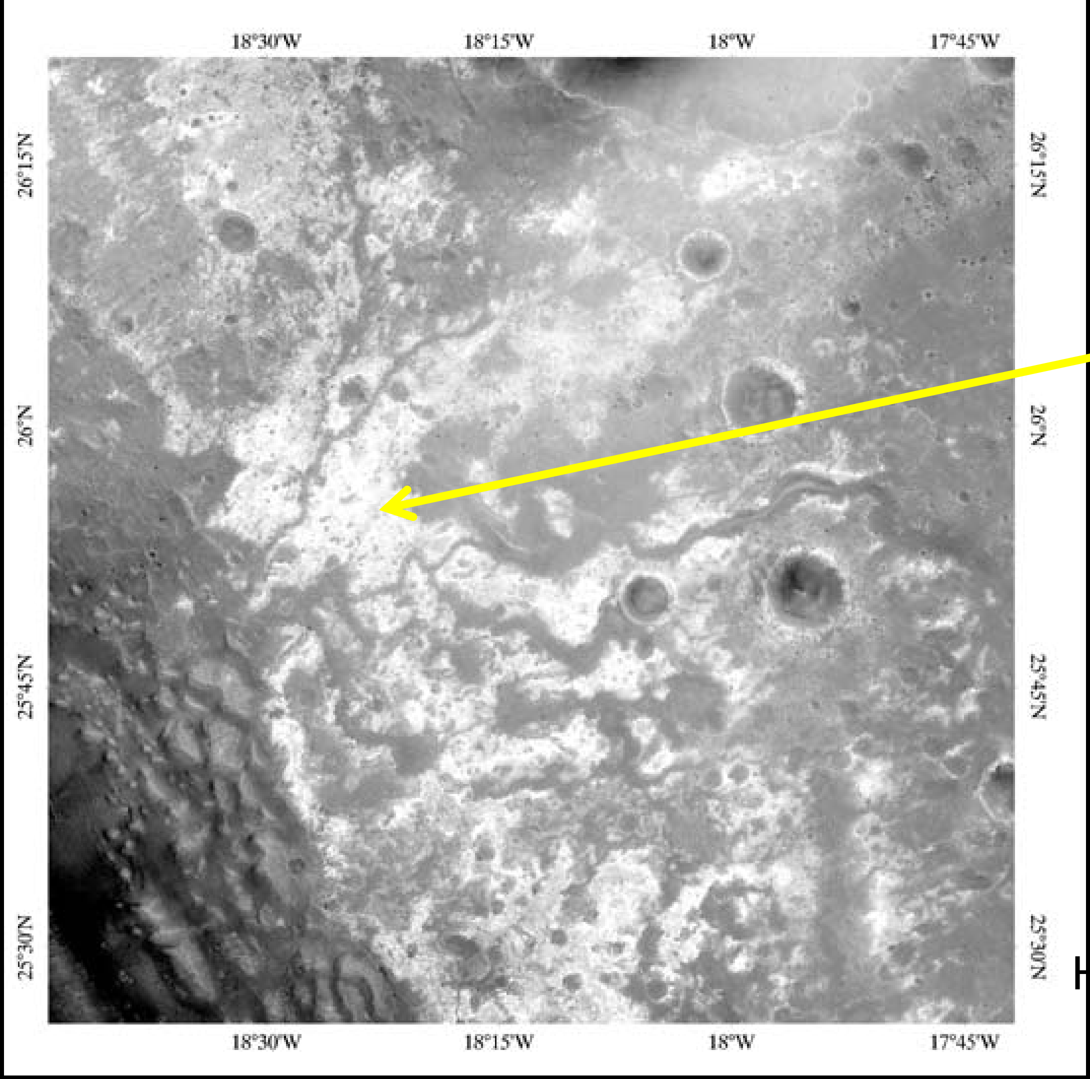
⇒ Sediments deposited by a variety of process and subsequently altered





2. Sediments with uncertain origin

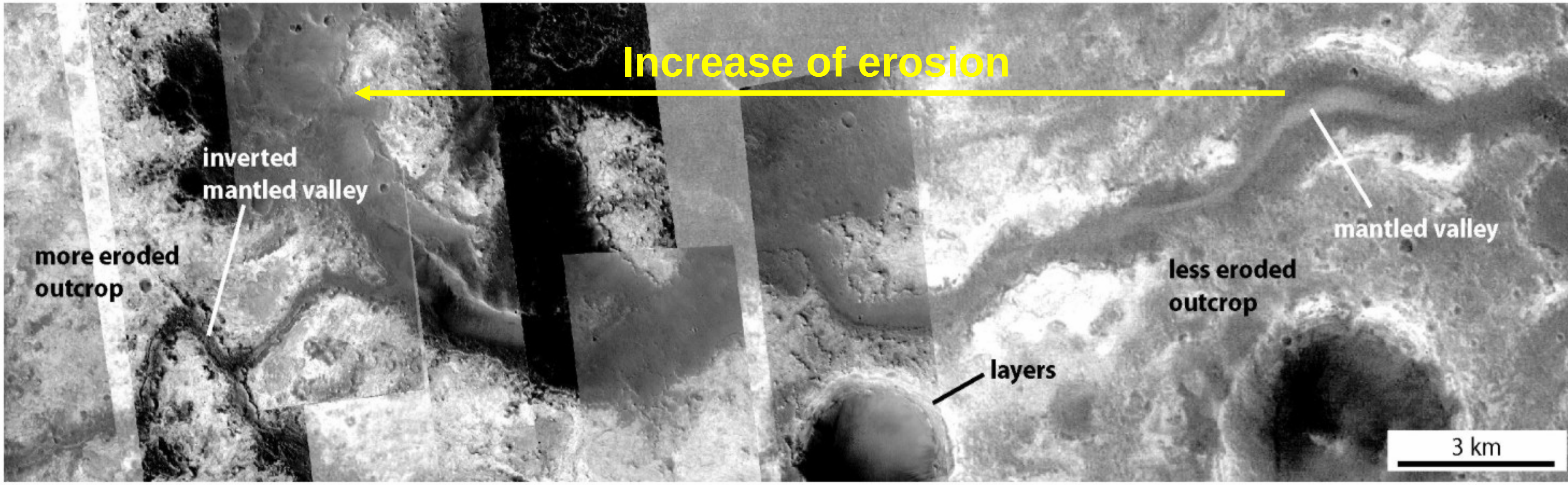
Valley networks erode into the phyllosilicate-bearing layers



Bright = Phyllosilicate-bearing deposits

Loizeau et al., JGR, 2007

2. Sediments with uncertain origin

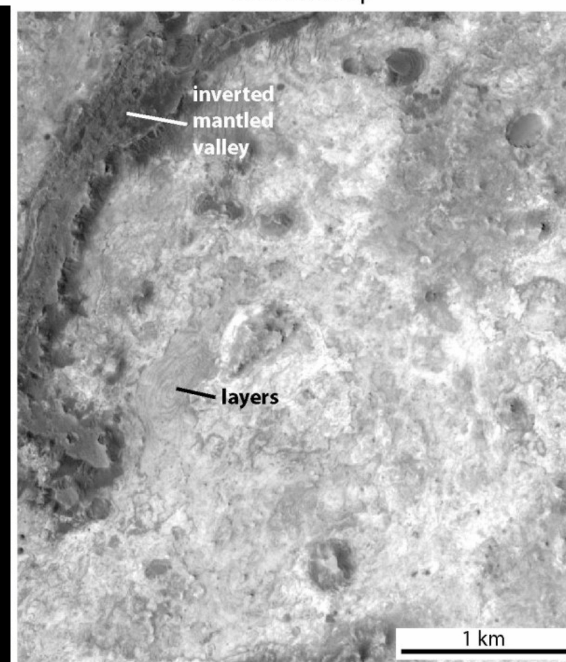


Valleys formed inside the altered sediments:

⇒ The alteration of sediments took place before the valley network erosion

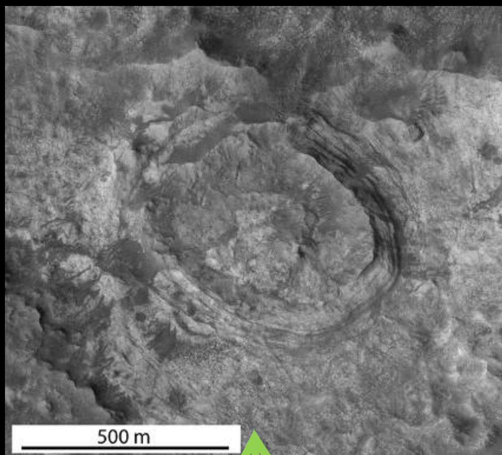
⇒ Sediments report events from an older period than landforms

MOC close-up

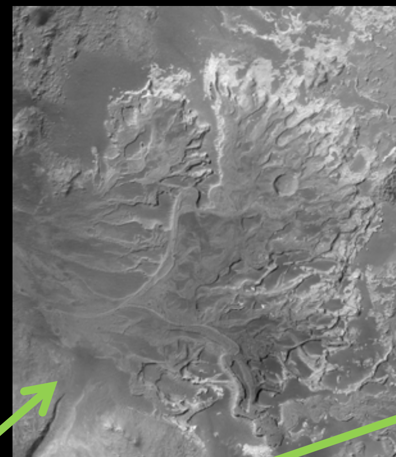


2. Sediments : Summary

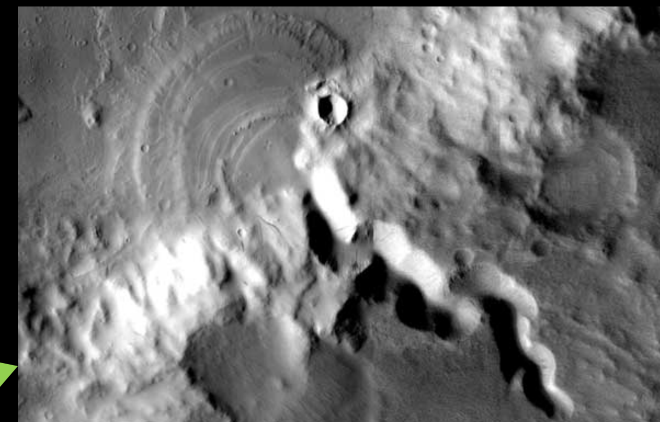
Mawrth Vallis, Nili, etc.



Eberwalde, Jezero, etc.



Short-lived



Ancient sed. Sediments (fluvial)

Sediments (eolian, polar, etc.)

Global valleys

2. Sediments: Summary

What we know:

1. Alluvial fans and delta fans are coeval with fluvial valleys,

and formed as a consequence of fluvial activity, mainly the latest activity

2. Delta fans involve deep lakes perennially

=> A warmer climate is required, but the duration of this period is poorly constrained

3. The oldest sediments display hydrated minerals

⇒ Landforms sign a terminal period of the early Mars climate,

earlier periods may have involved even a much extended role liquid water.

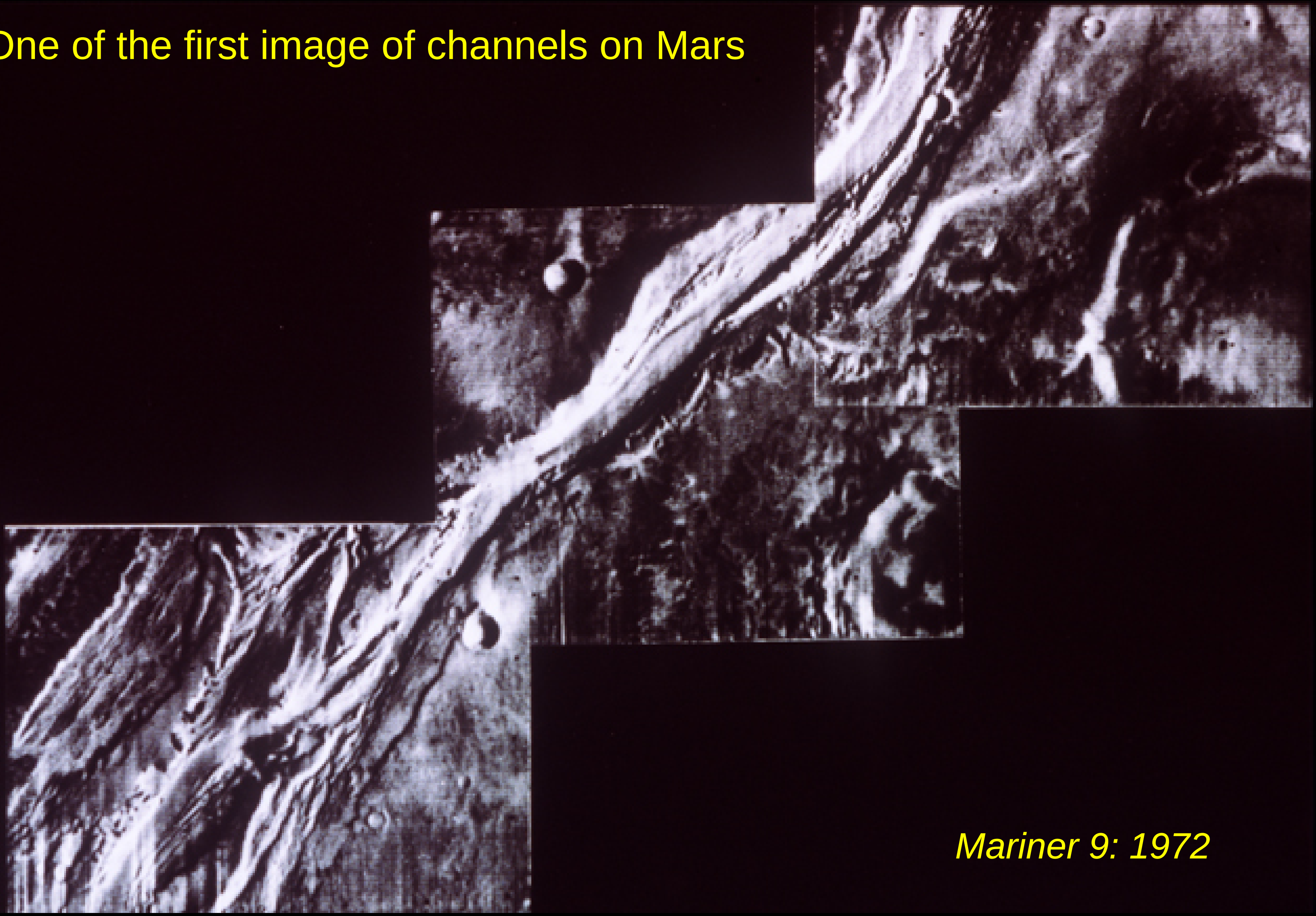
What we want to know:

- The duration of paleolake activity
- In situ analysis of ancient sediments such as in Mawrth Vallis

=> Sedimentary facies (geometry) and composition are fundamental

3. Outflow channels

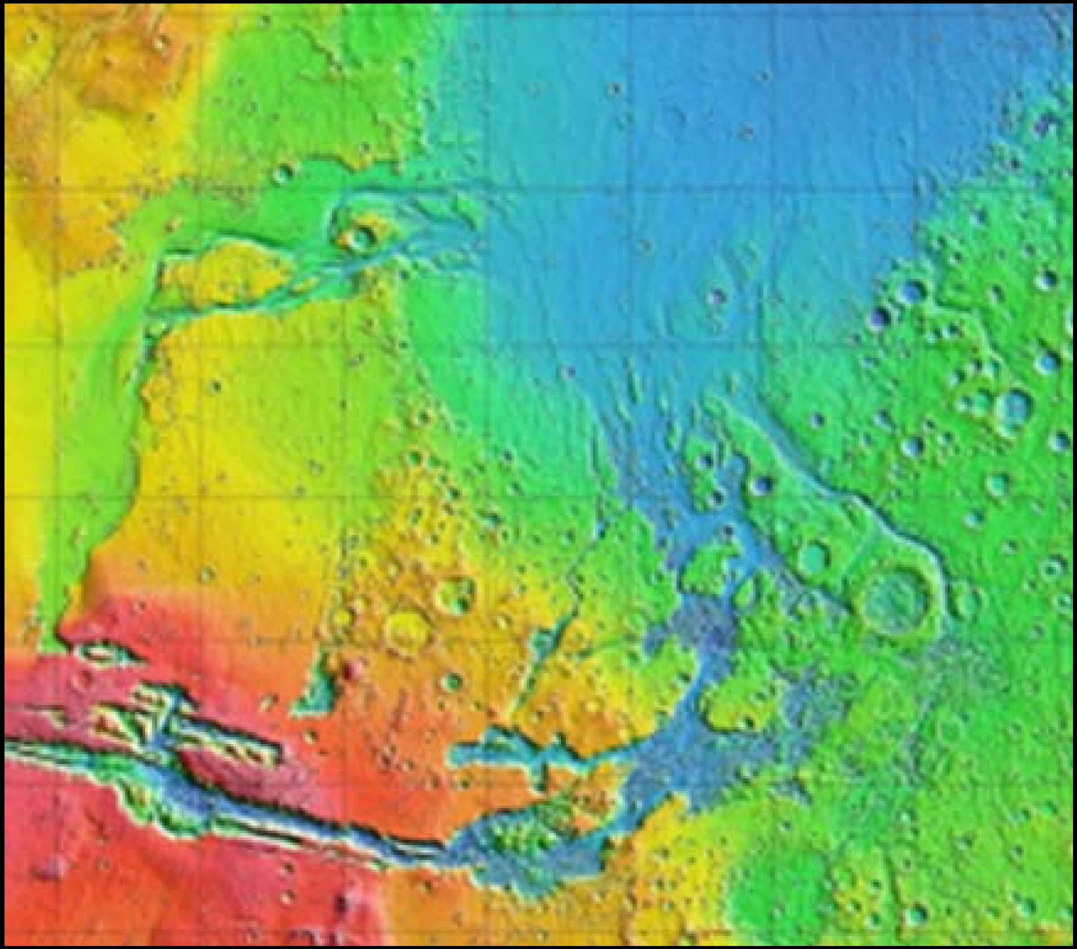
One of the first image of channels on Mars



Mariner 9: 1972

3. Outflow channels

Outflow channels are visible on the global map:
Huge structure: > 1000 km long, Locally >100 km wide, > 1 km deep

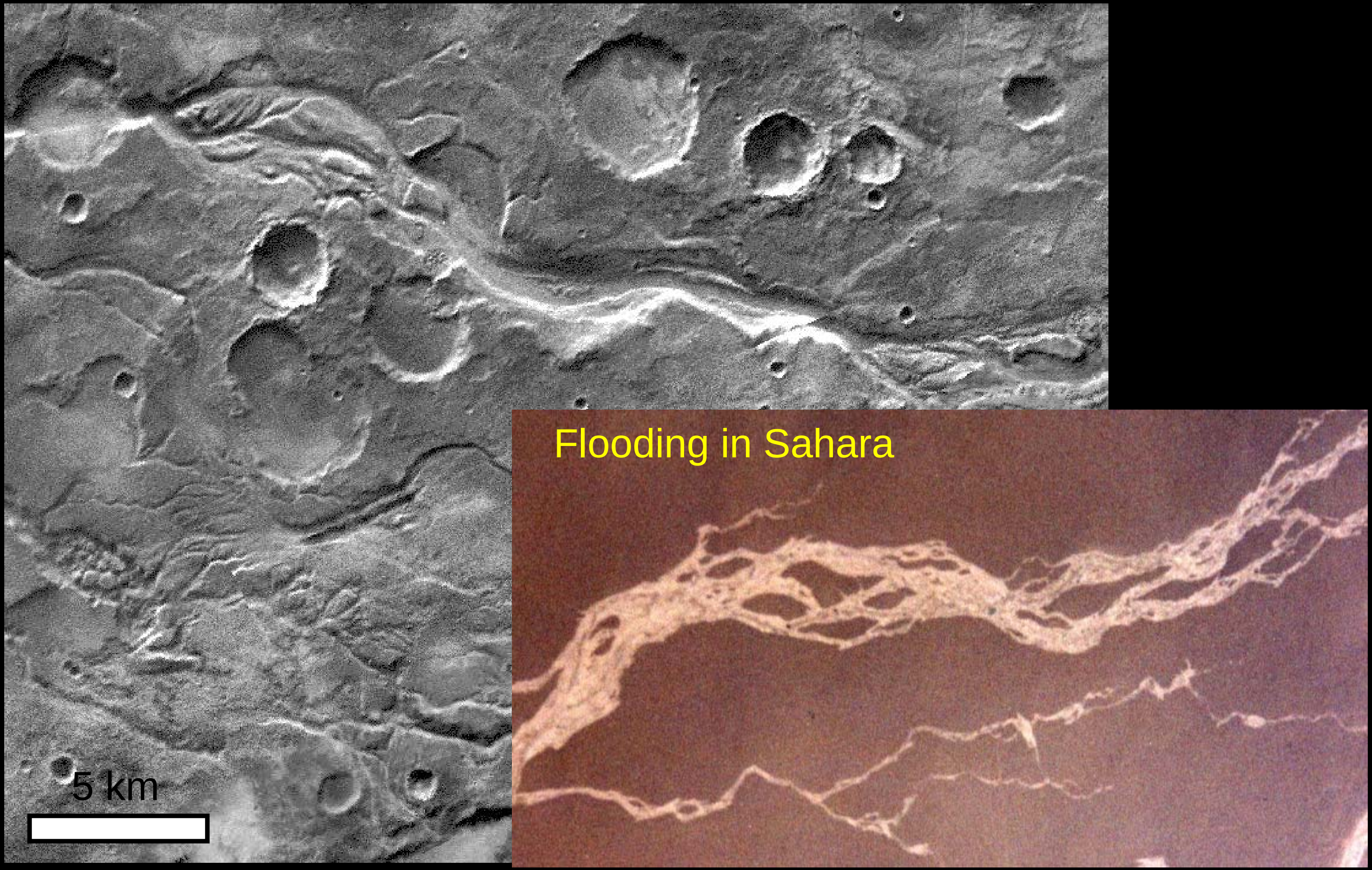


3. Outflow channels: Geometry

Strong erosion without branching valleys

Braided streams, with deeper erosion than on Earth

Mangala Vallis



3. Outflow channels: Geometry

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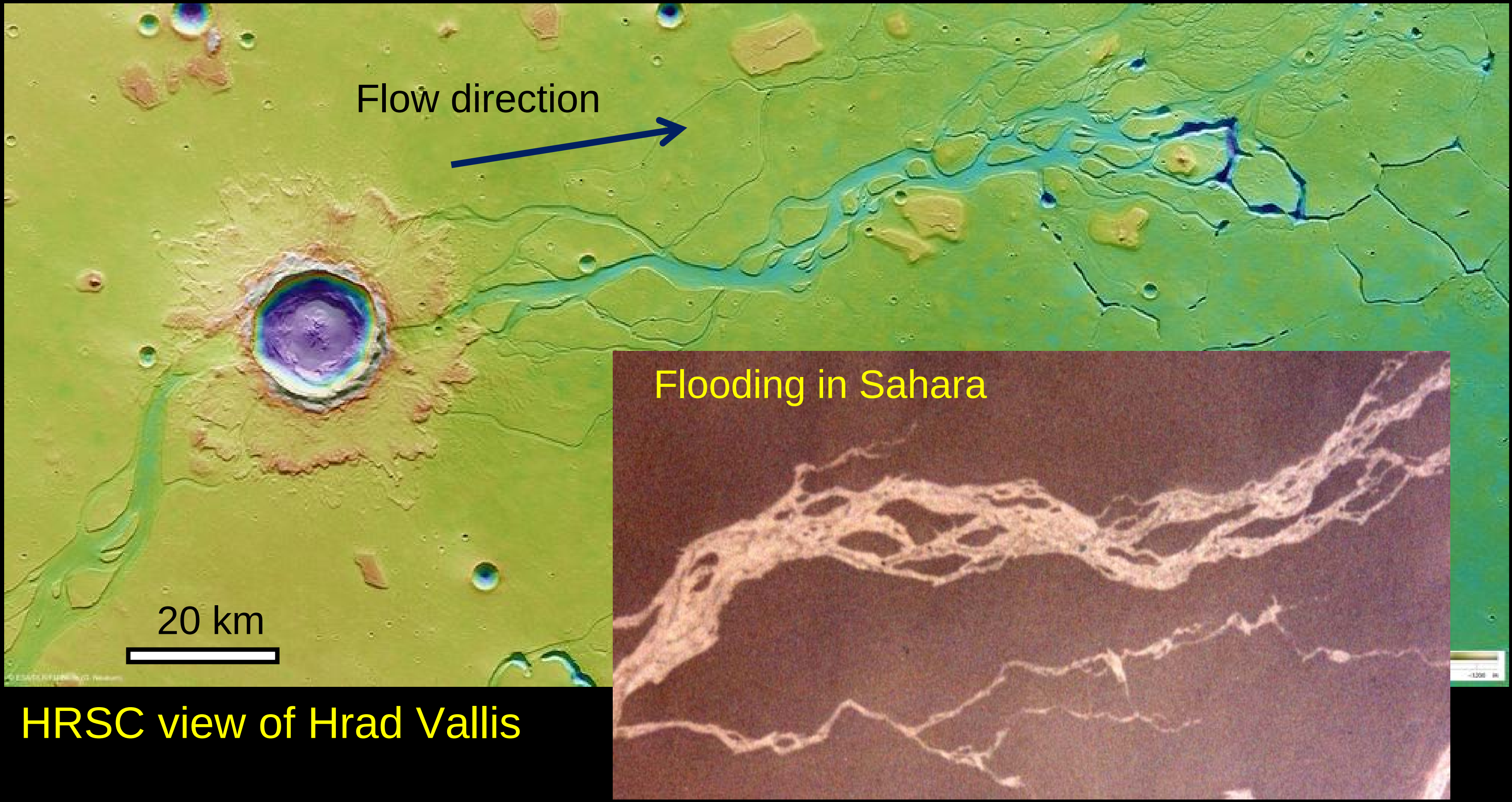
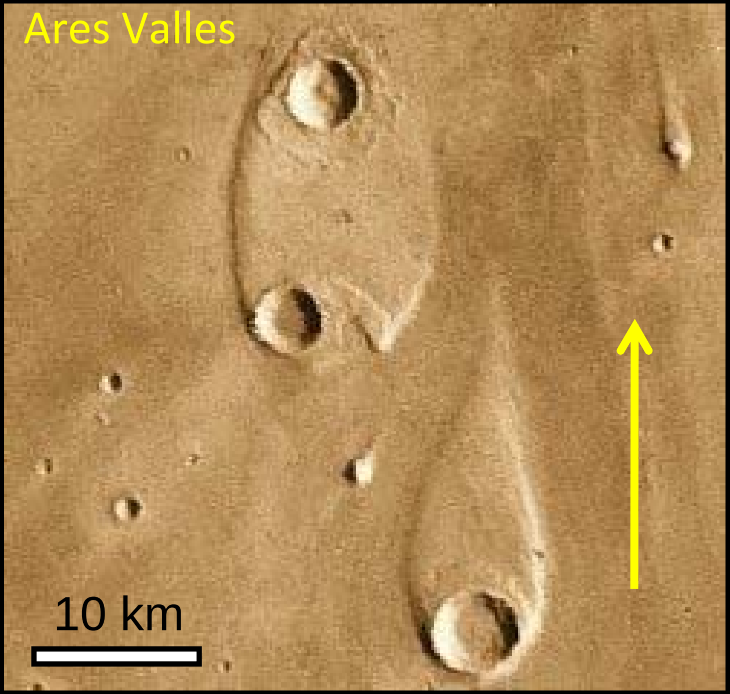


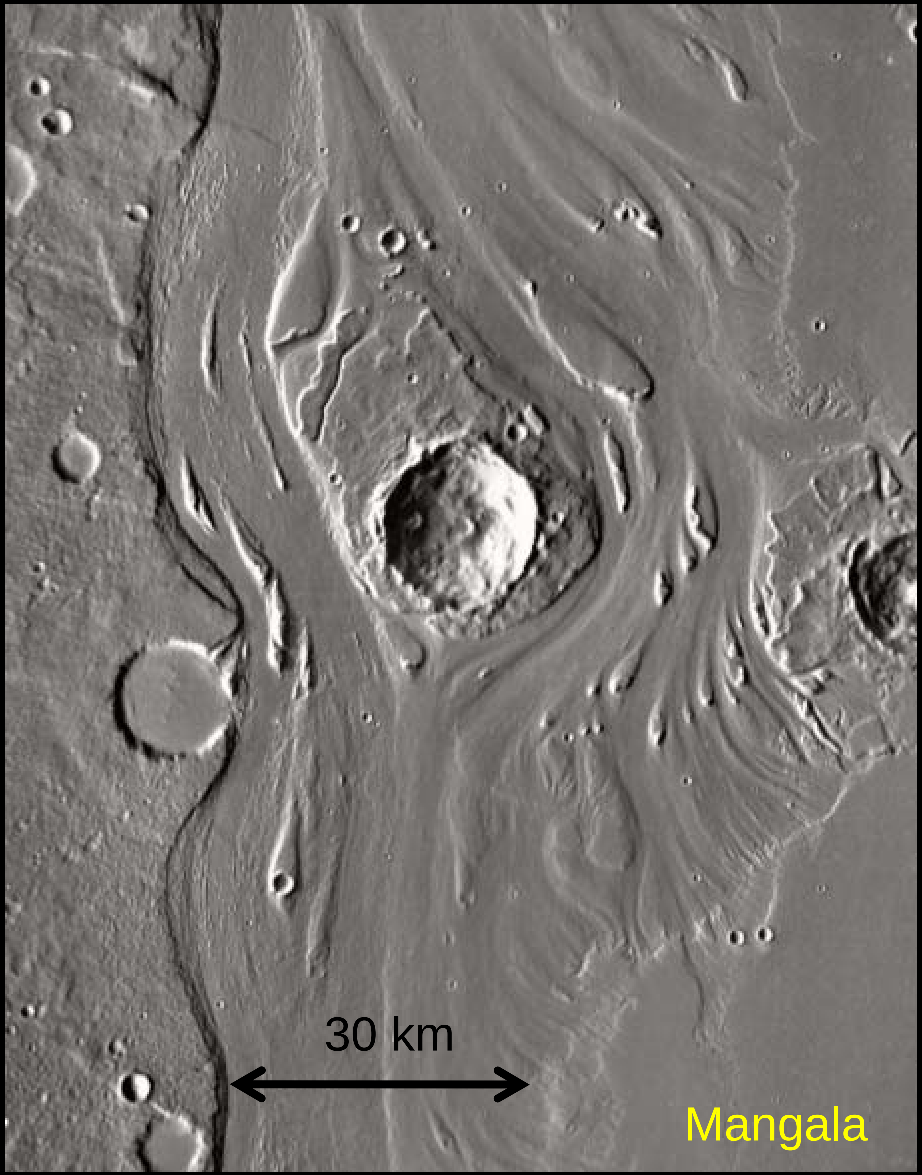
HRSC view of Hrad Vallis

3. Outflow channels: Geometry

Classical tear-drop shaped islands

Indicate flow direction

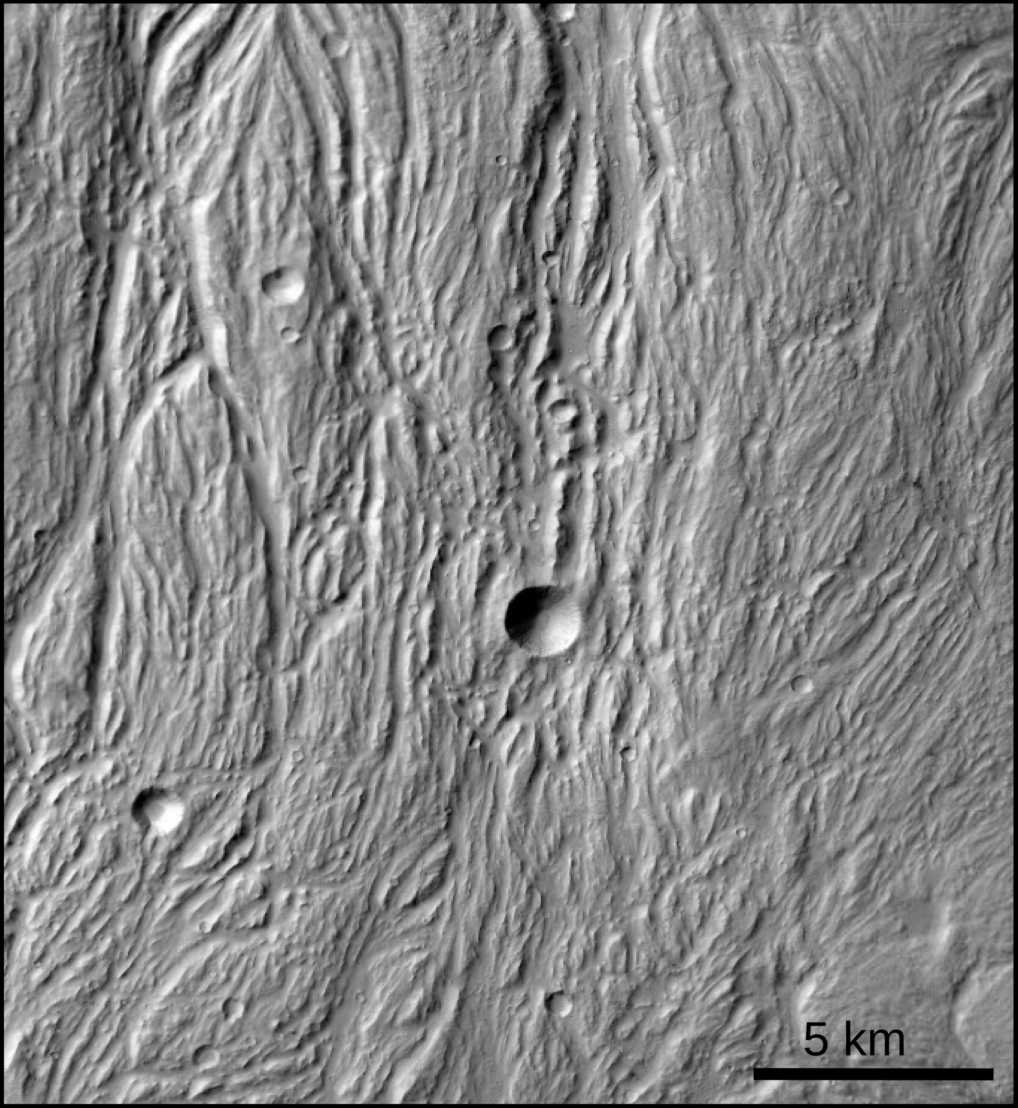




The valley « is » the channel

3. Outflow channels: Geometry

Scour marks : Indicate violent erosion (a small valley would flow in between scours)



3. Outflow channels: Discharge rates

Calculation of discharge rates (Manning)

$$Q = A(g_{\mathrm{m}} s R^{4/3} / g_{\mathrm{e}} n^2)^{1/2}$$

Channel depth is high

Slope is often low (<0.01°)

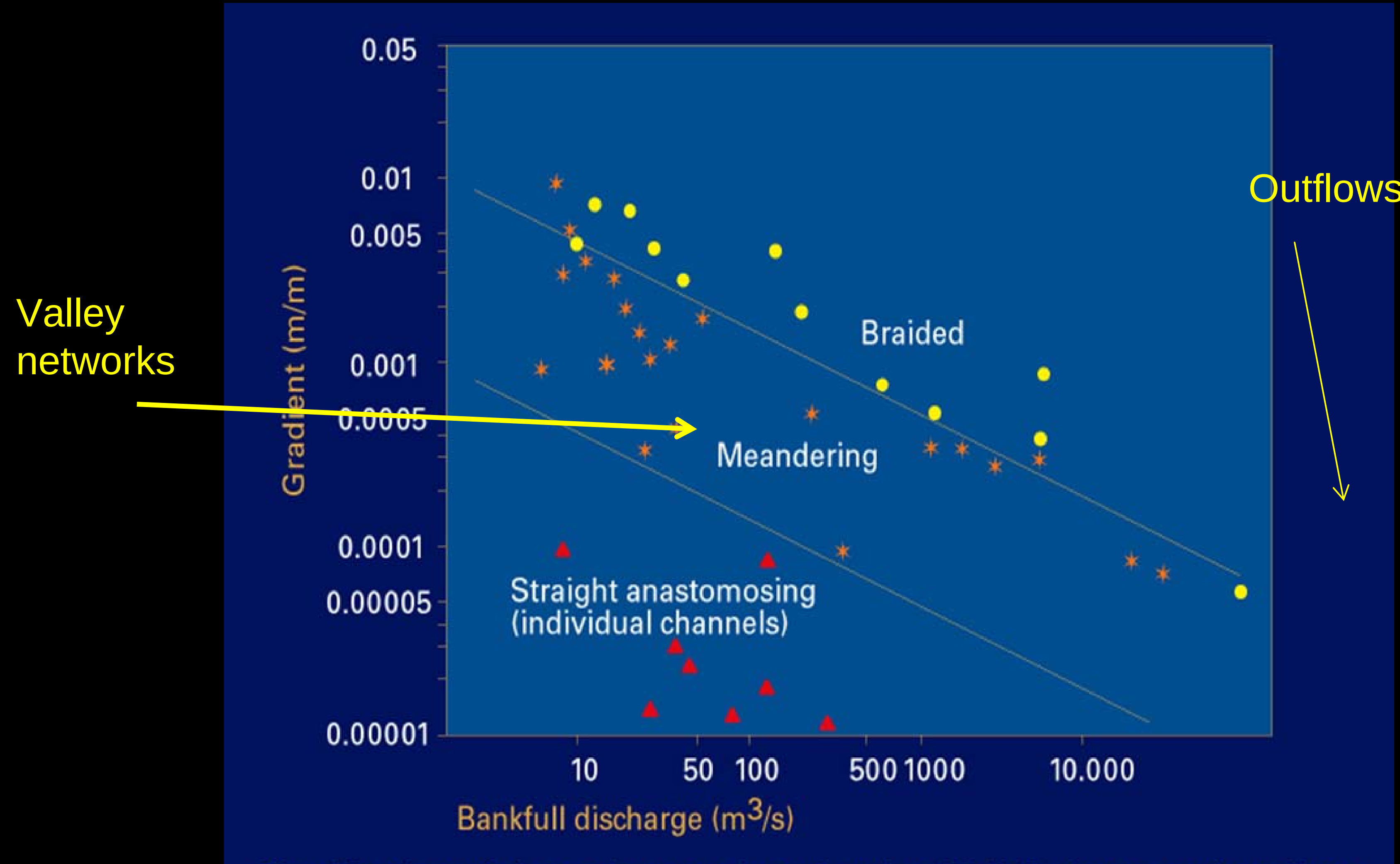
Up to Q=10^7 m^3/s
Multiple episodes

Up to Q=10^9 m^3/s
One major episode

To be compared to the Amazon river (100,000 m3/s)

3. Outflow channels: Discharge rates

Terrestrial classification of rivers : Outflow channels require a huge discharge rate



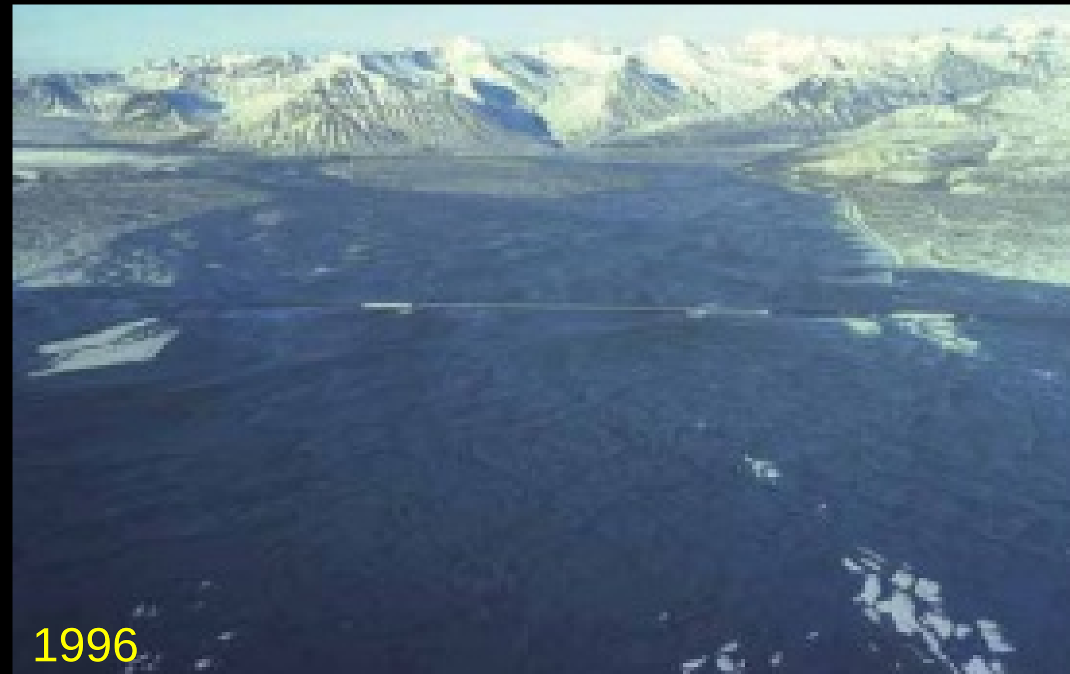
Classification of channel pattern based on bankfull discharge and gradient

After Smith 1993

3. Outflow channels: Terrestrial analogues

Floods can form by

subglacial volcanic activity



Icelandic jökullhaups

(Glacial surges)

Typical discharge rates:

1 10^6 m^3/s

3. Outflow channels: Terrestrial analogues

Washington State Scablands: Floods created by glacial lake discharge

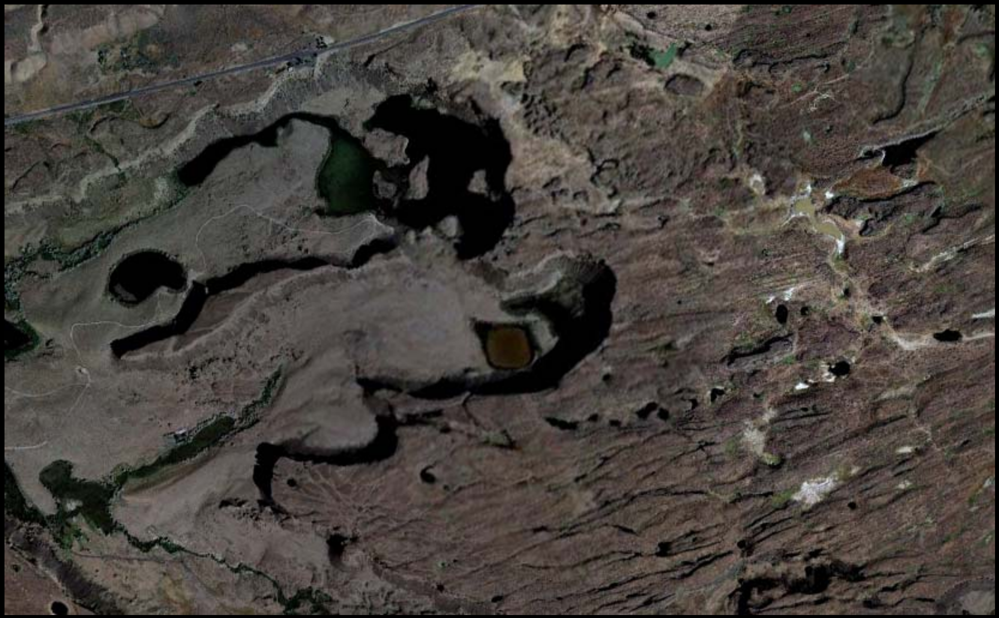
Typical discharge rates: 1 10^7 m^3/s

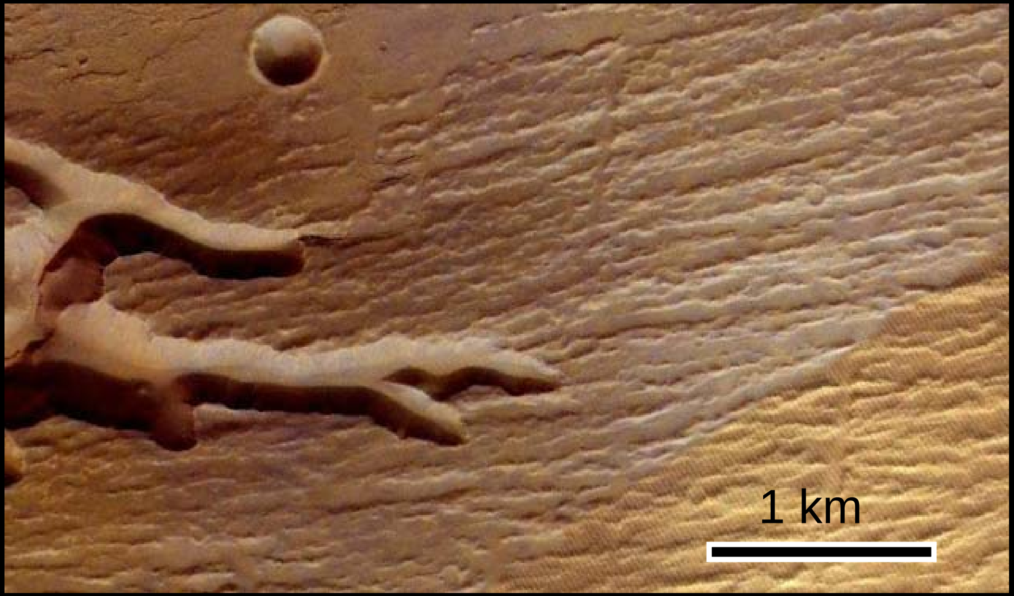
Baker , 1977, 1990

3. Outflow channels: Terrestrial analogues

Presence of cataracts

Scour marks on the plateau

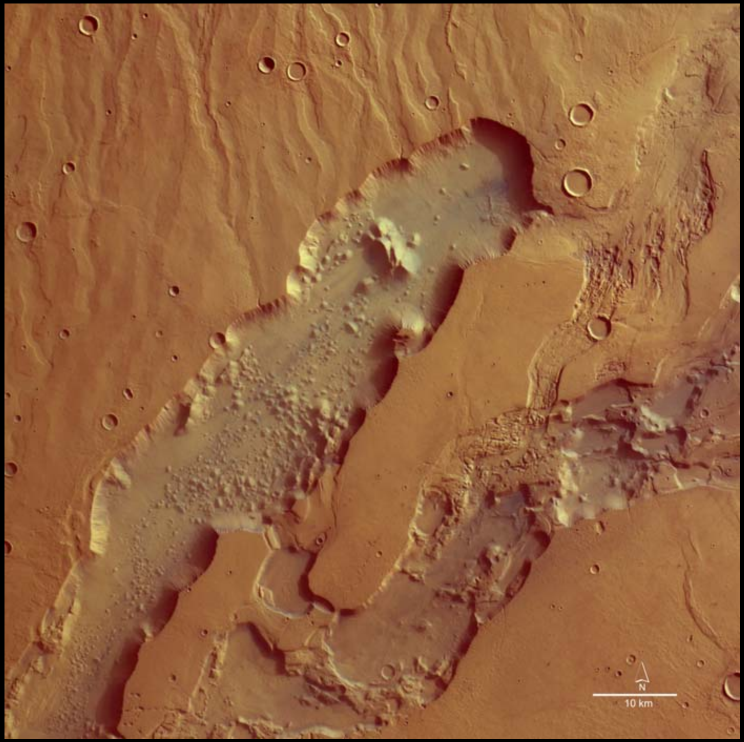


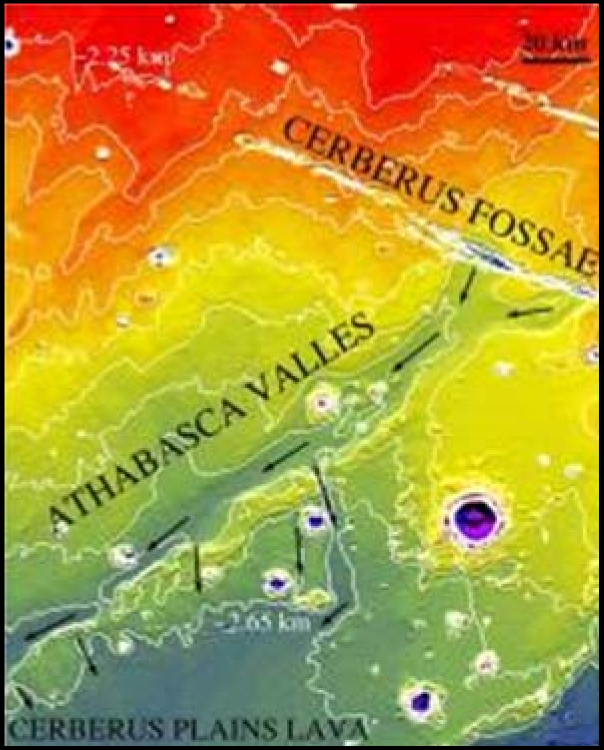


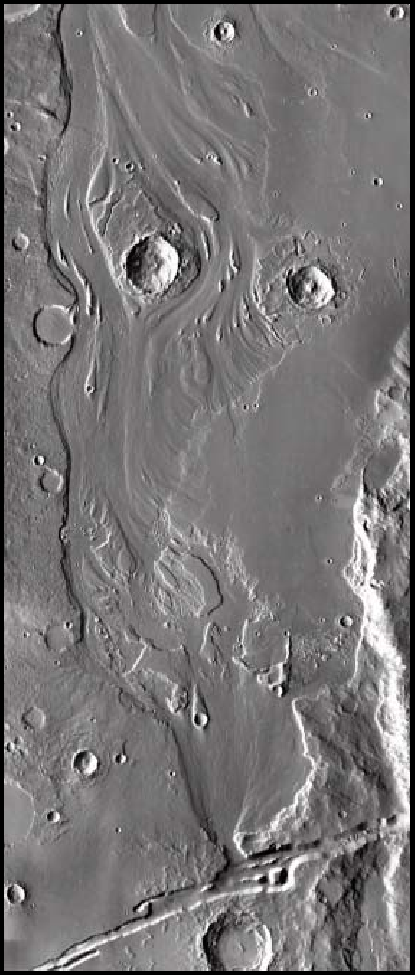
3. Outflow channels: Channel source area

A common characteristic: No tributary - Point source discharge

⇒ Very different from valley networks
⇒ No basin catchment
⇒ First indication of strong discharge







3. Outflow channels: Channel source area

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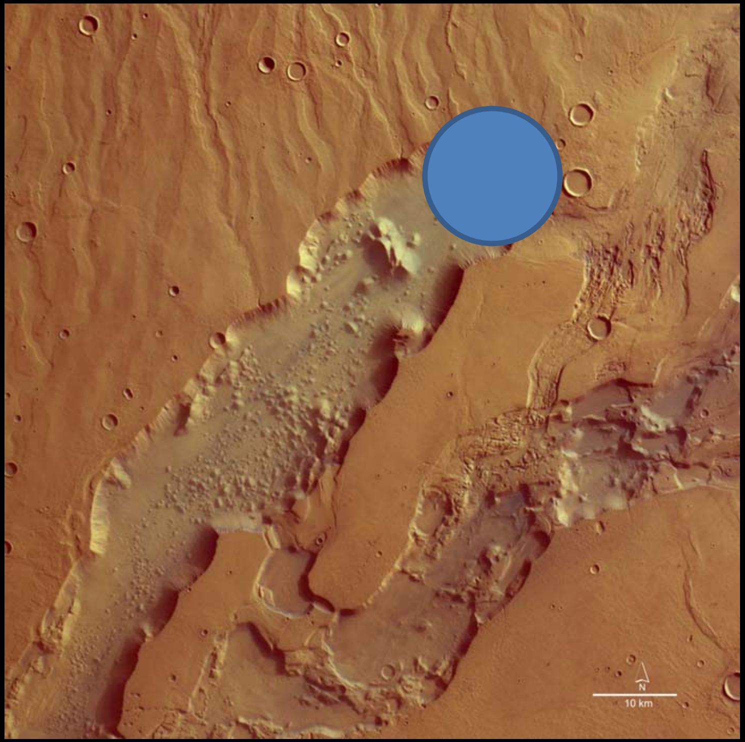
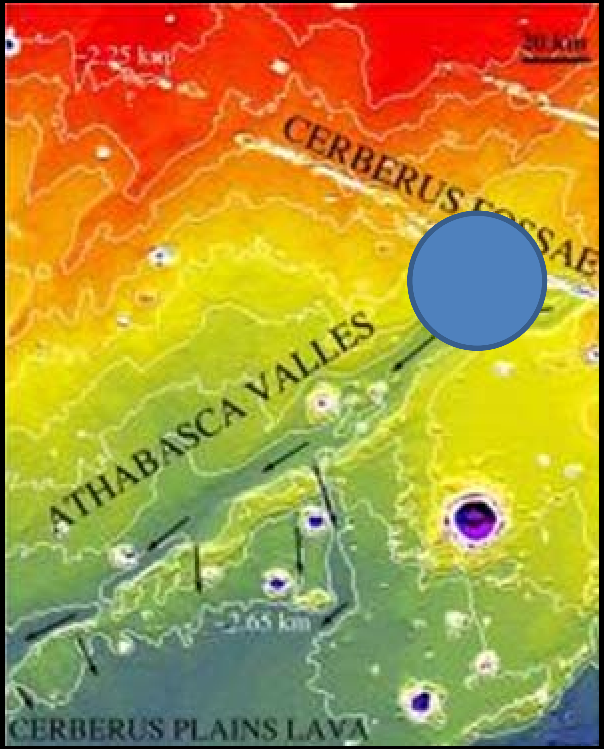
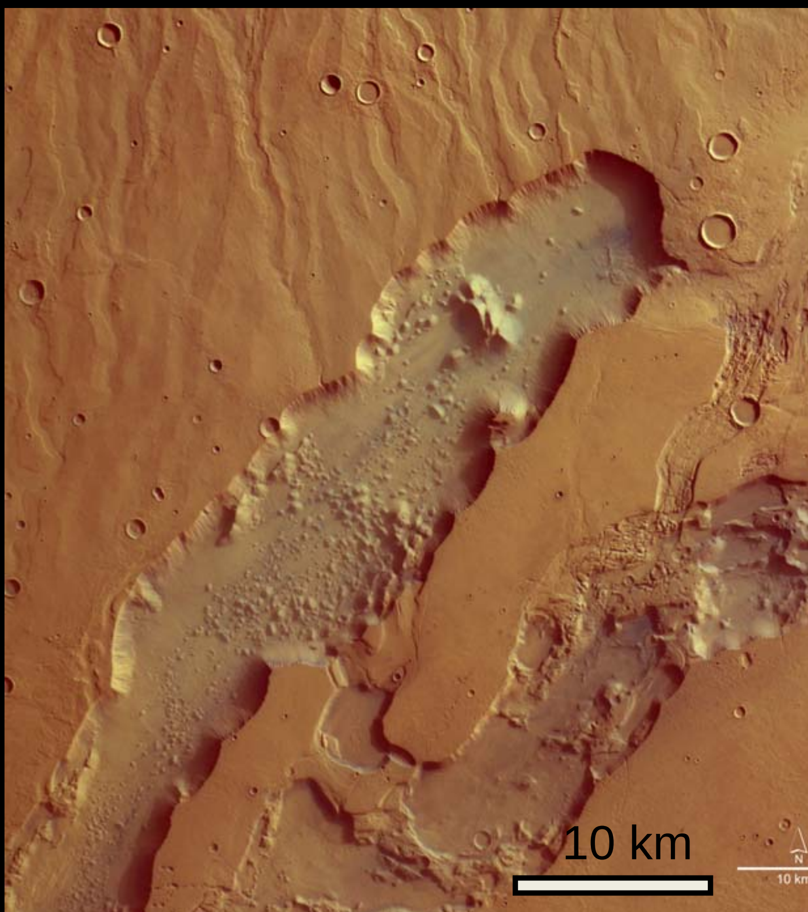


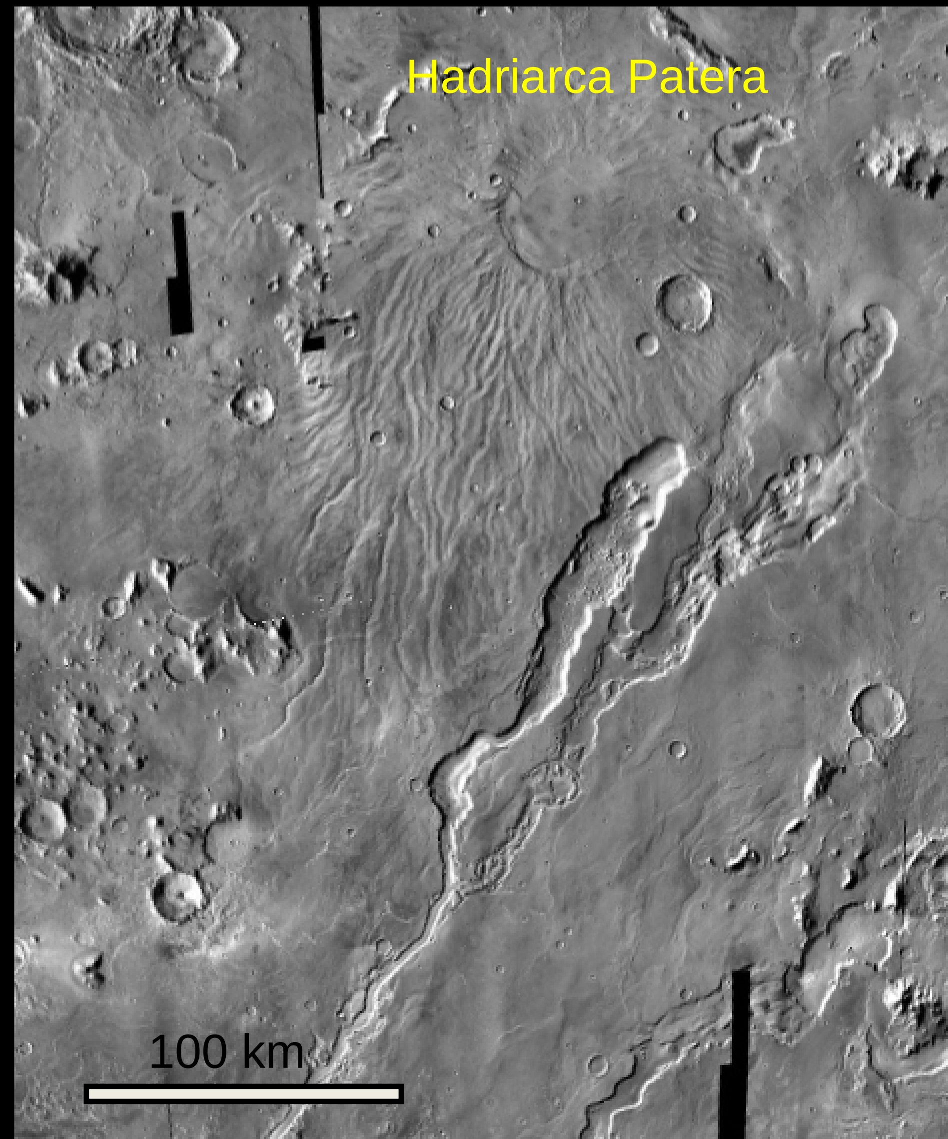


3. Outflow channels: Connection with volcanic activity

Dao Vallis heads on Hadriarca Patera

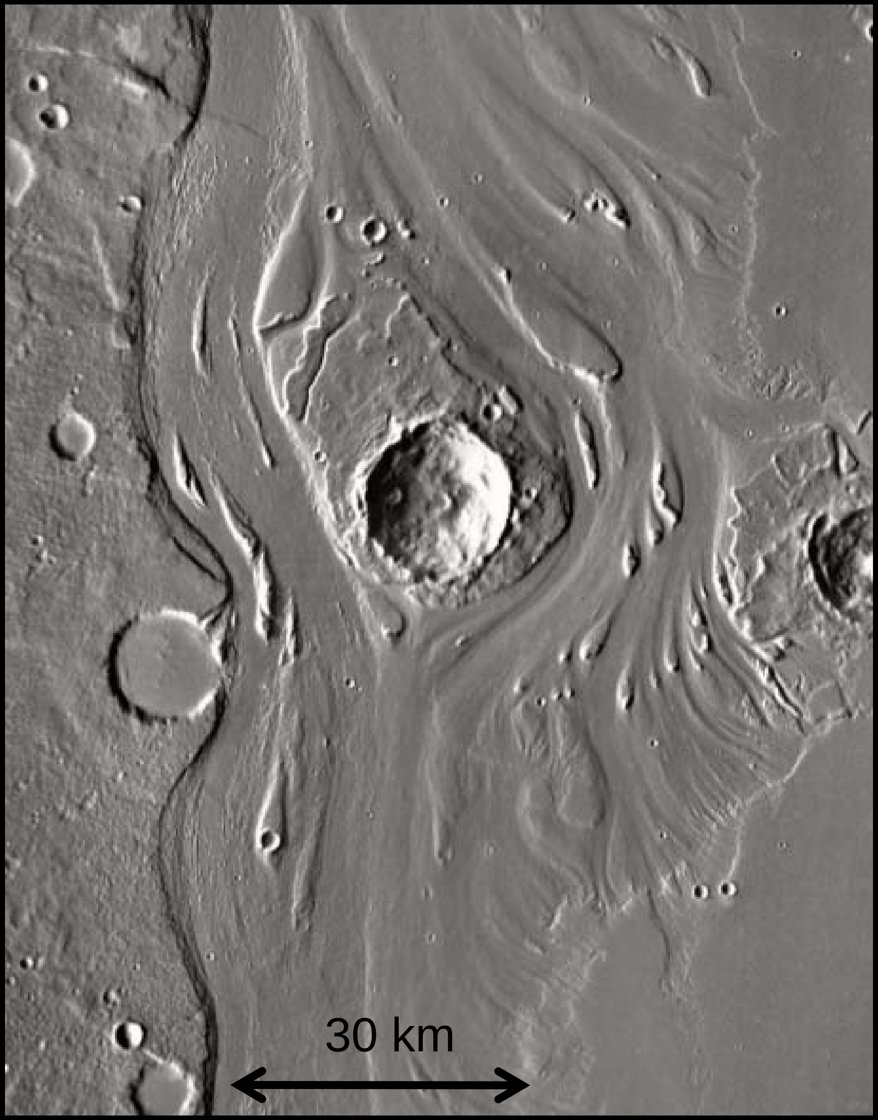
=> Clear volcanic context





3. Outflow channels: Channel source area

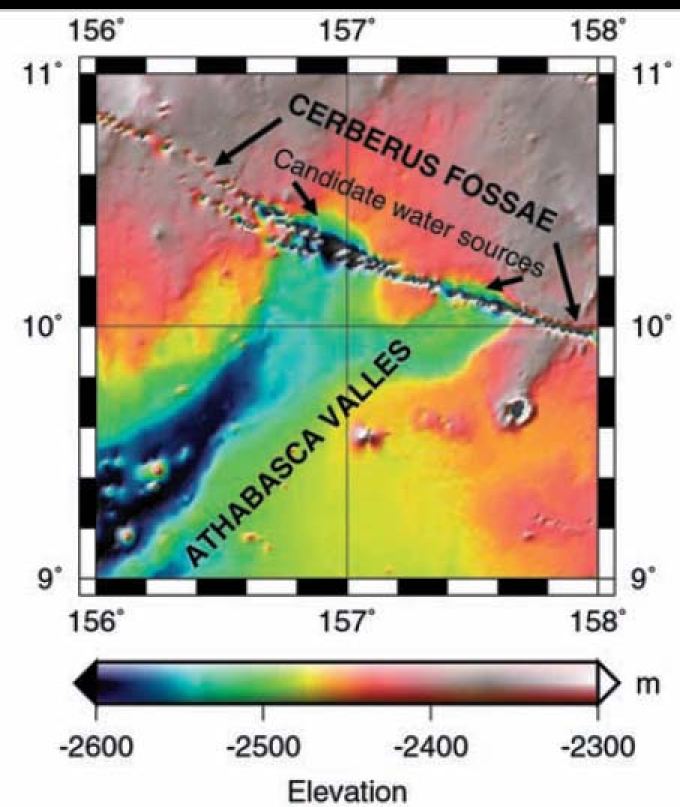
>1000 km long outflow from a small fissure

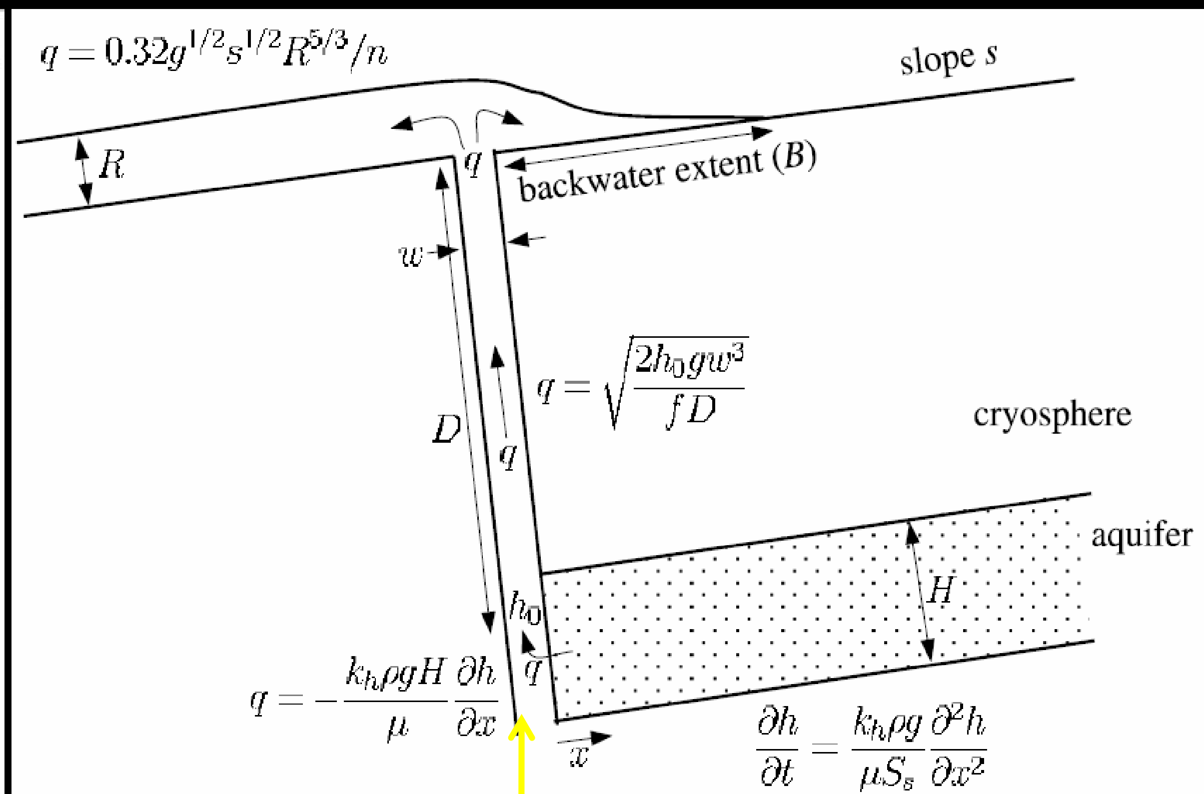


3. Outflow channels: Process Modeling

Manga (2004) groundwater accumulation in fissure with sudden release

Obtain Q=10^6 m^3/s, few hours to few days of activity





Fissure

3. Outflow channels: Connection with volcanic activity

Circum-Chryse outflow
with origin in chaotic terrains

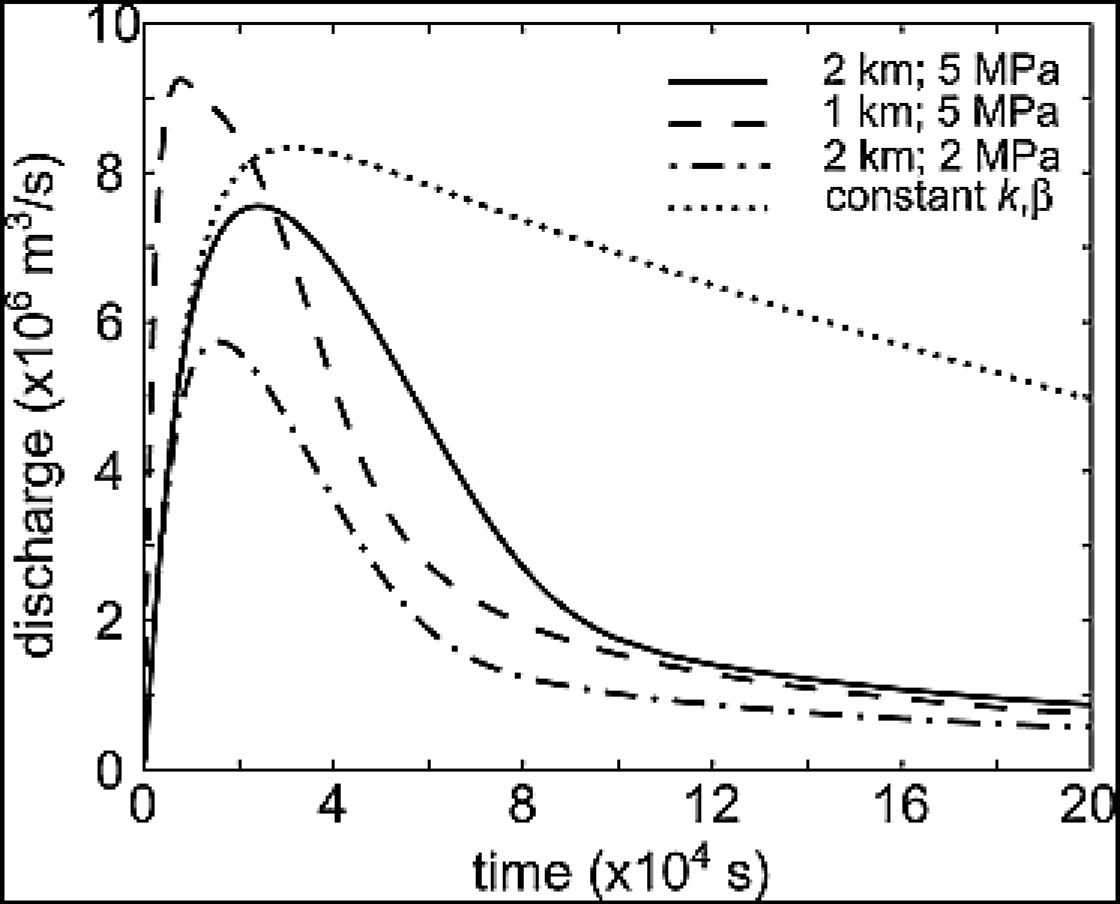
Ex: Ares Vallis, Kasei Vallis

Different models involves overpressure
 of subsurface aquifers
Ground ice melting and sudden release
of aquifers

3. Outflow channels: Process Modeling

Attempts to model outflows from pressurized subsurface aquifers

For Ares Vallis chaotic terrains



Model assumes episodic release of groundwater

Initial discharges: up to 1.10^7 m^3/s

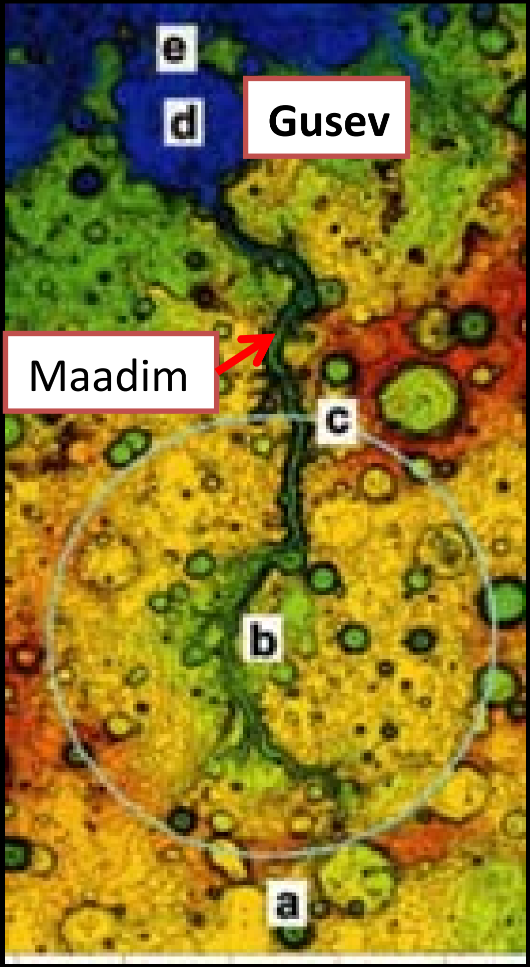
Total volume: up to 5000 km^3

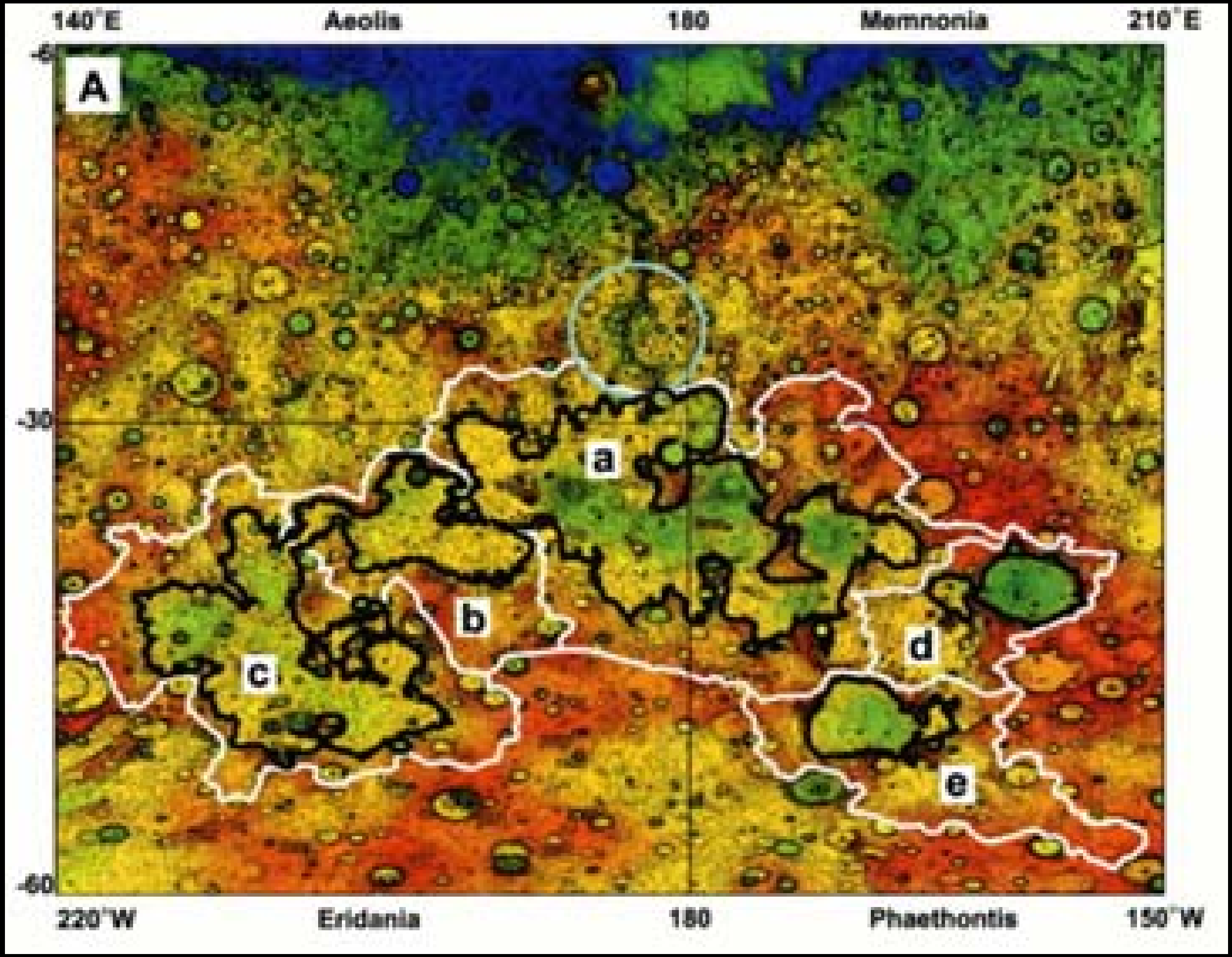
Duration of one burst:
Few days
(do not require liquid water stability at the surface)

Andrews-Hanna and Phillips (2007)

3. Outflow channels: Non-Volcanic triggerred outflow channels

Maadim Vallis is an outflow channel
Likely triggerred by lakes overflow





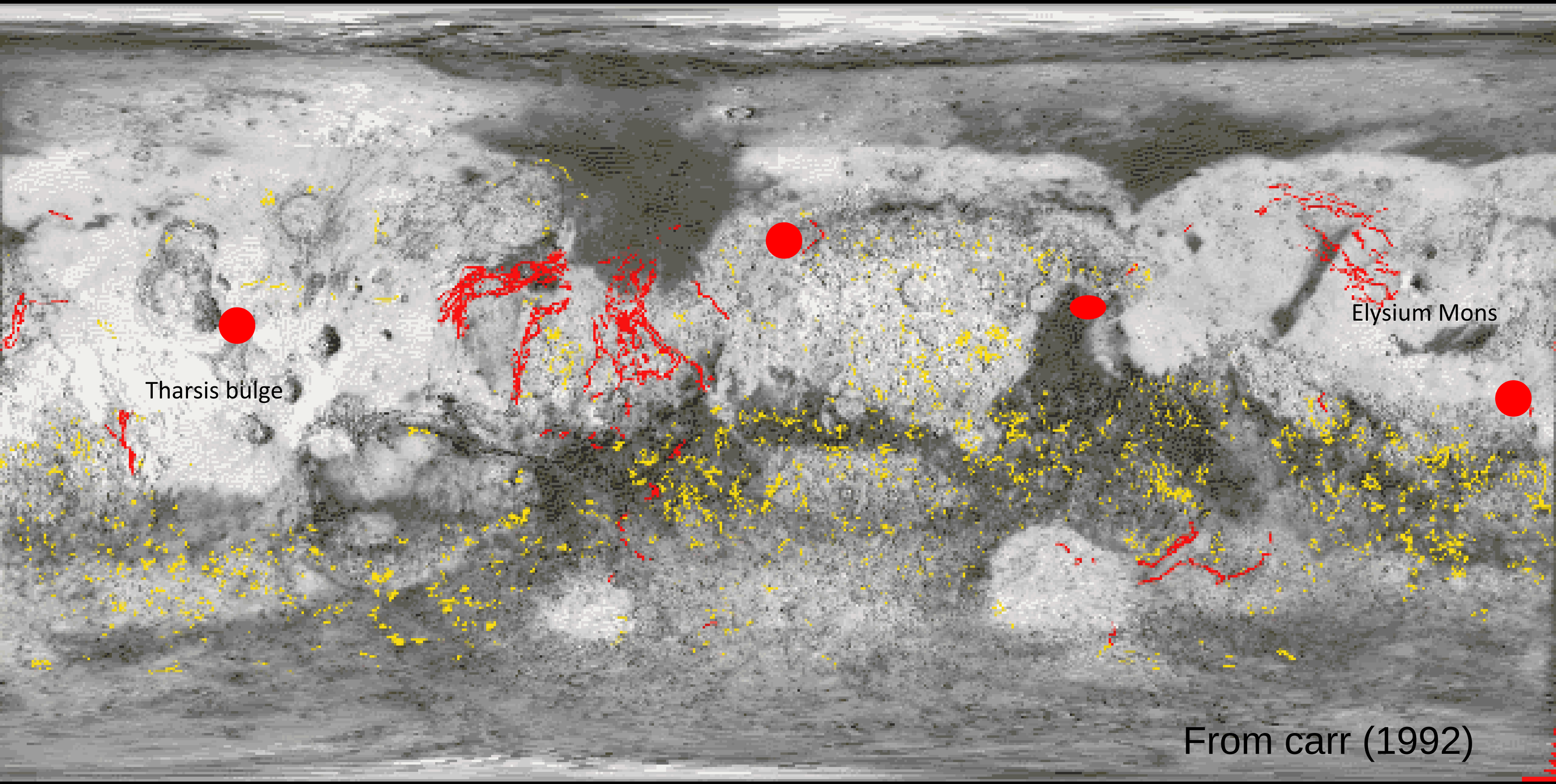
Irwin et al., Science, 2002

3. Outflow channels: Global distribution

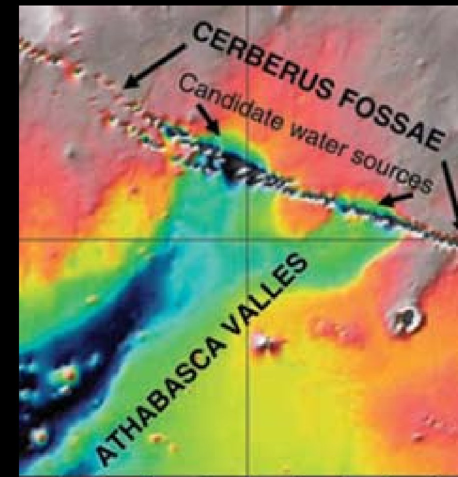
Outflow channels are linked with volcanic regions

No homogeneous distribution

Outflow channels (red) and valley networks (yellow)



3. Outflow channels: Chronology



Maadim
Kasei 1, Ares
Hrad
Mangala
Athabasca

Global valleys

Outflow channels occurred at all epochs

3. Outflow channels: Summary

What we know:

1. Outflow channels form from rapid episodic burst of groundwater (few days)

2. Outflow channels formation require no stability of water

$\Rightarrow$ No implication for climate

3. Groundwater likely formed by deep ground ice melting in volcanic regions

$\Rightarrow$ They are the best evidence of local deep ground ice reservoirs

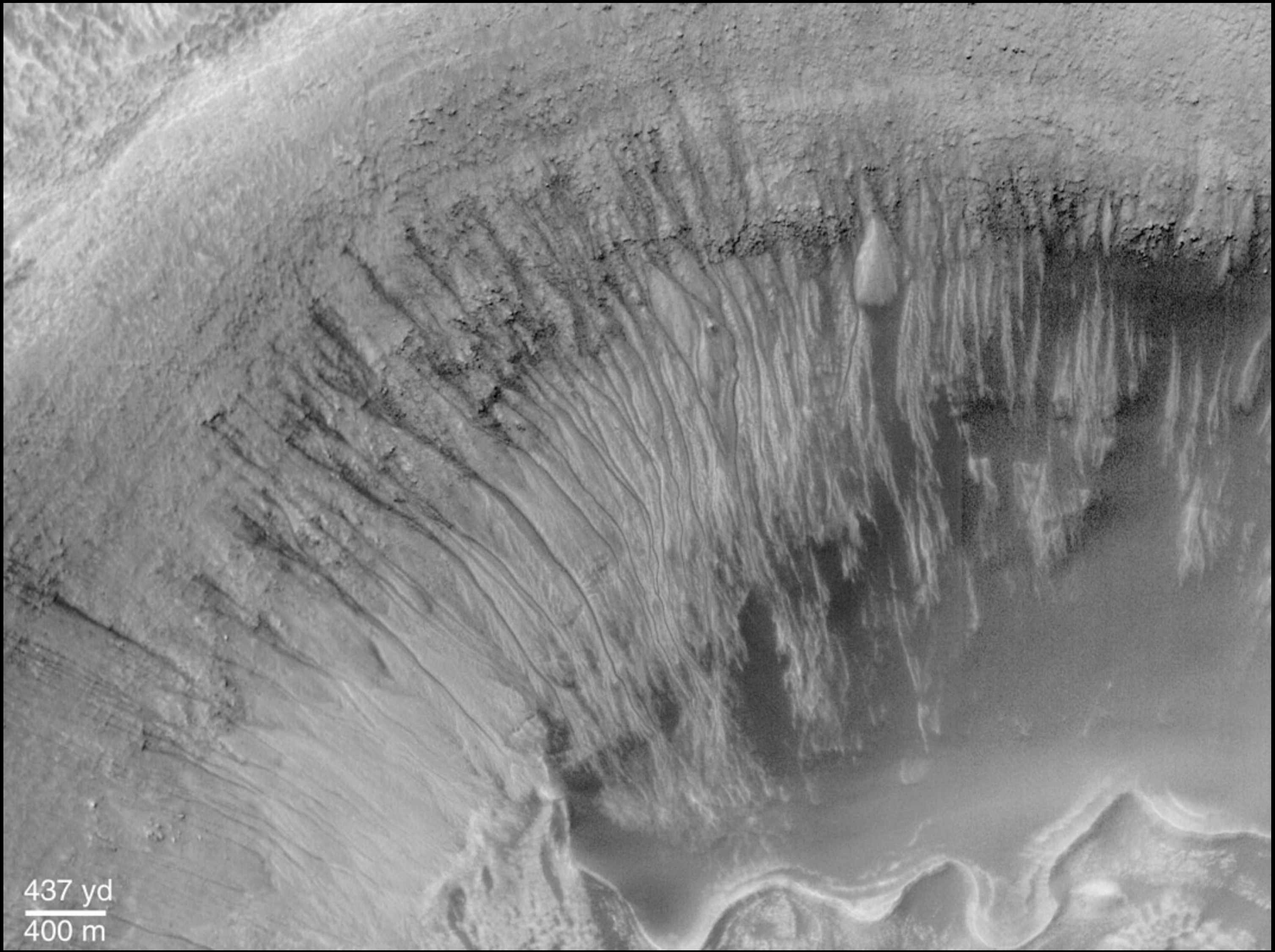
(in volcanic regions such as Cerberus, Tharsis, Elysium)

What we want to know:

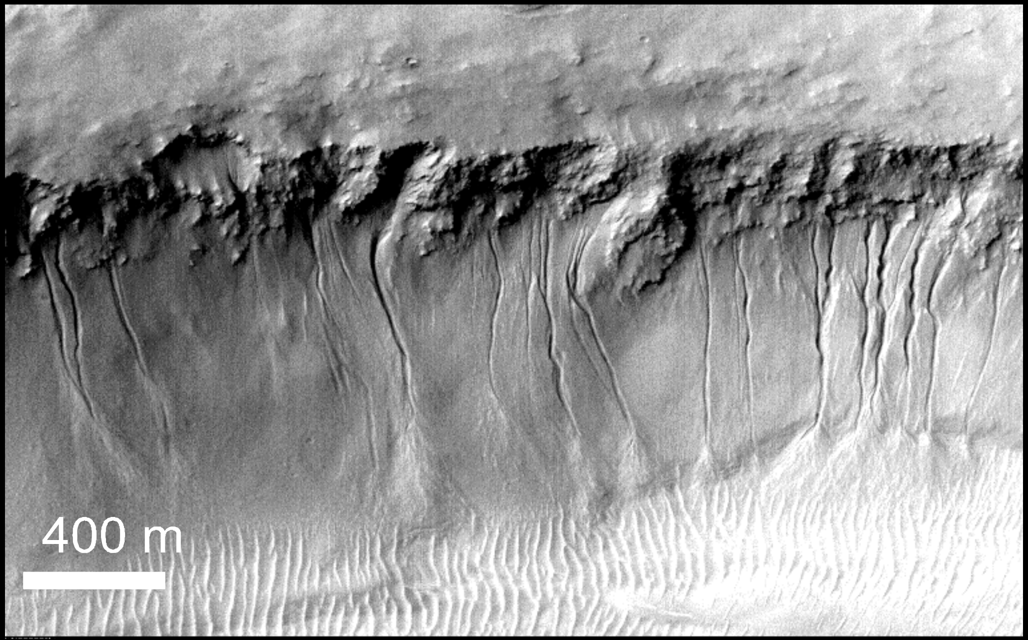
- What was the role of surface glaciers in their formation?
- What is the exact formation of chaotic terrains?

4. Recent gullies

Recent gullies discovered by the MOC camera of MGS

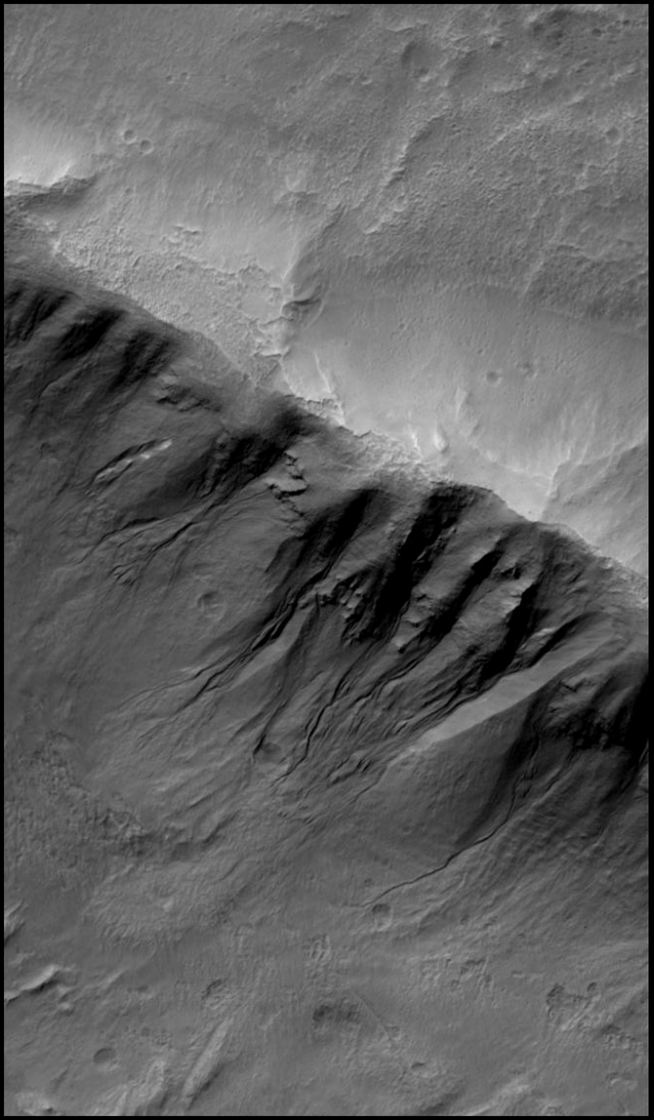


4. Recent gullies



Malin and Edgett (Science, 2000):
Seepage of water from aquifers

More recent consensus:
Gullies formed by surface processes
(near surface ice/snowmelt due to insolation)
(Costard et al, 2002, Christensen, 2003, etc.)



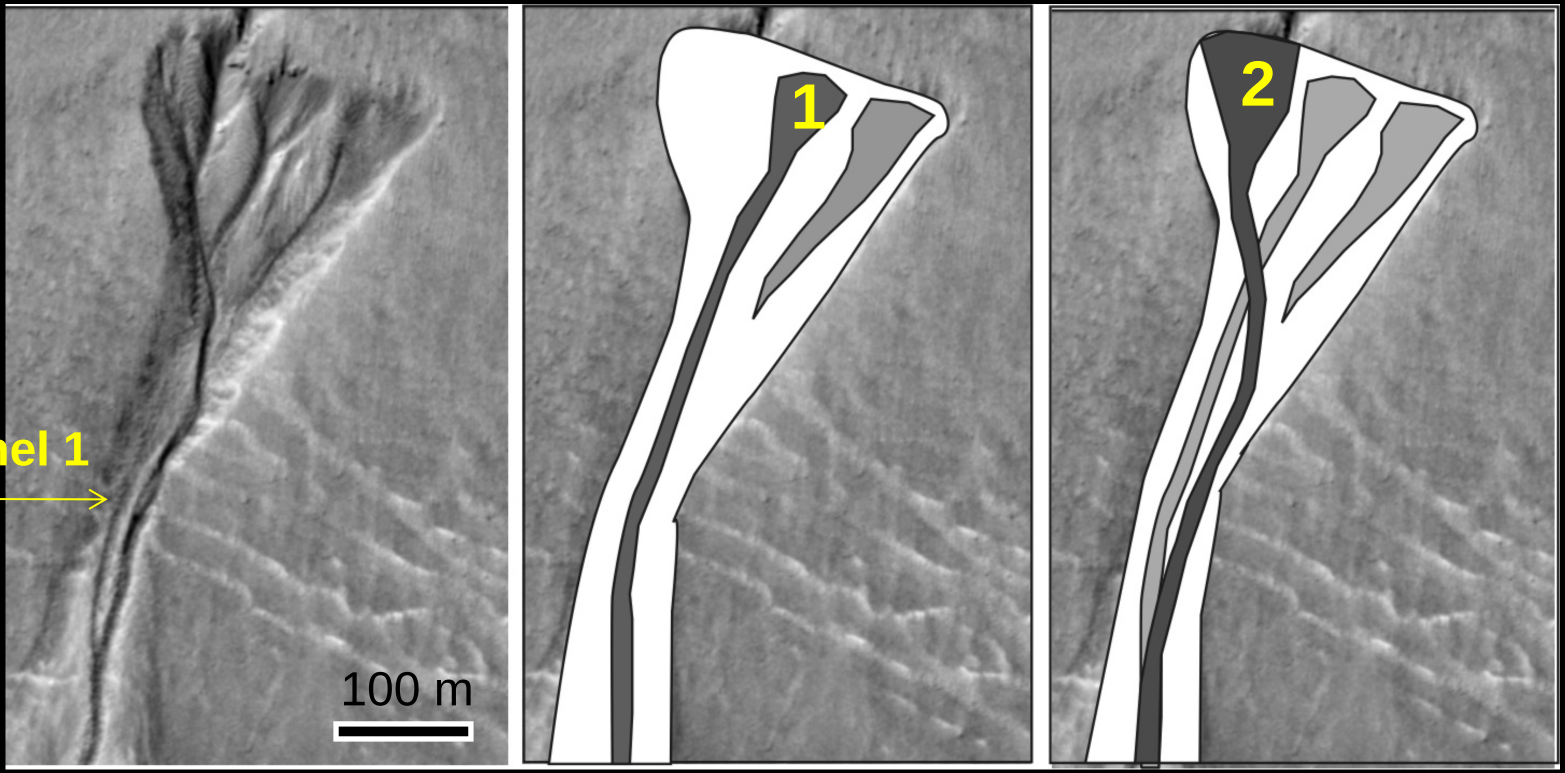
Gullies on isolated hills

4. Recent gullies: Observations

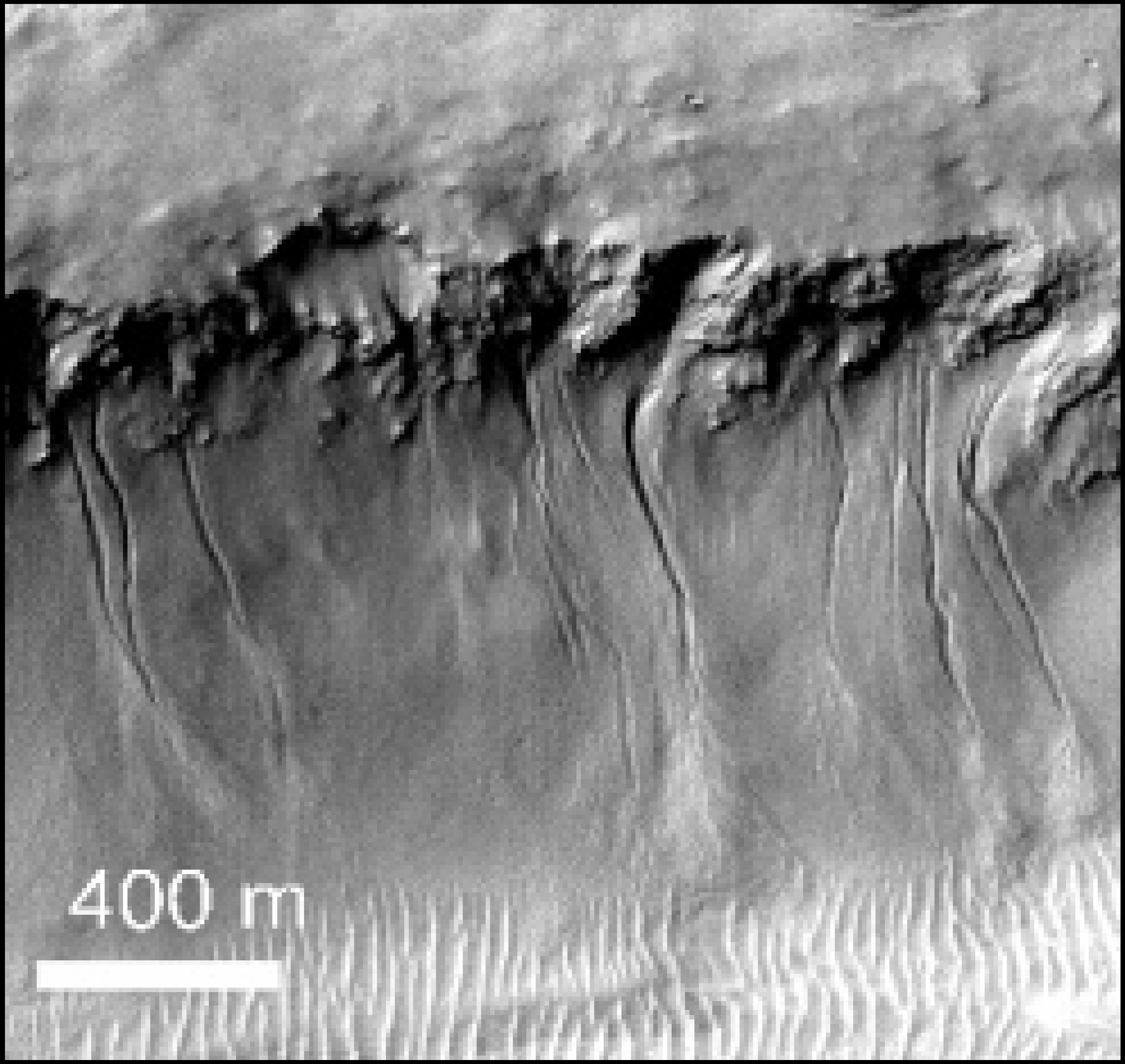
Gullies are episodic : They do not form in simultaneously

The second event crosses the first channel without connecting to it

Channel 1



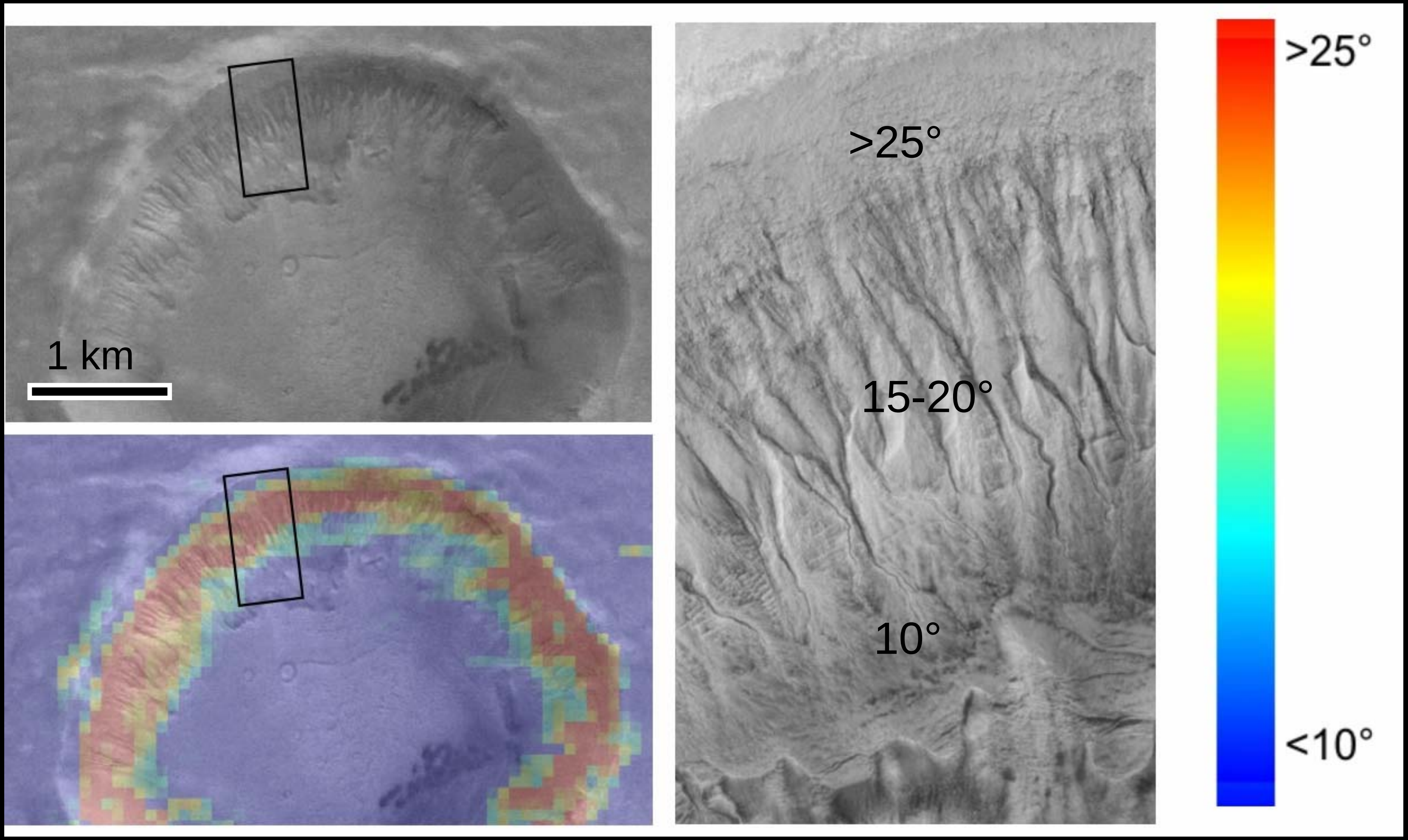
4. Recent gullies: Observations



Gullies stop on slopes.
Not on the flat area

=> Not typical of river streams

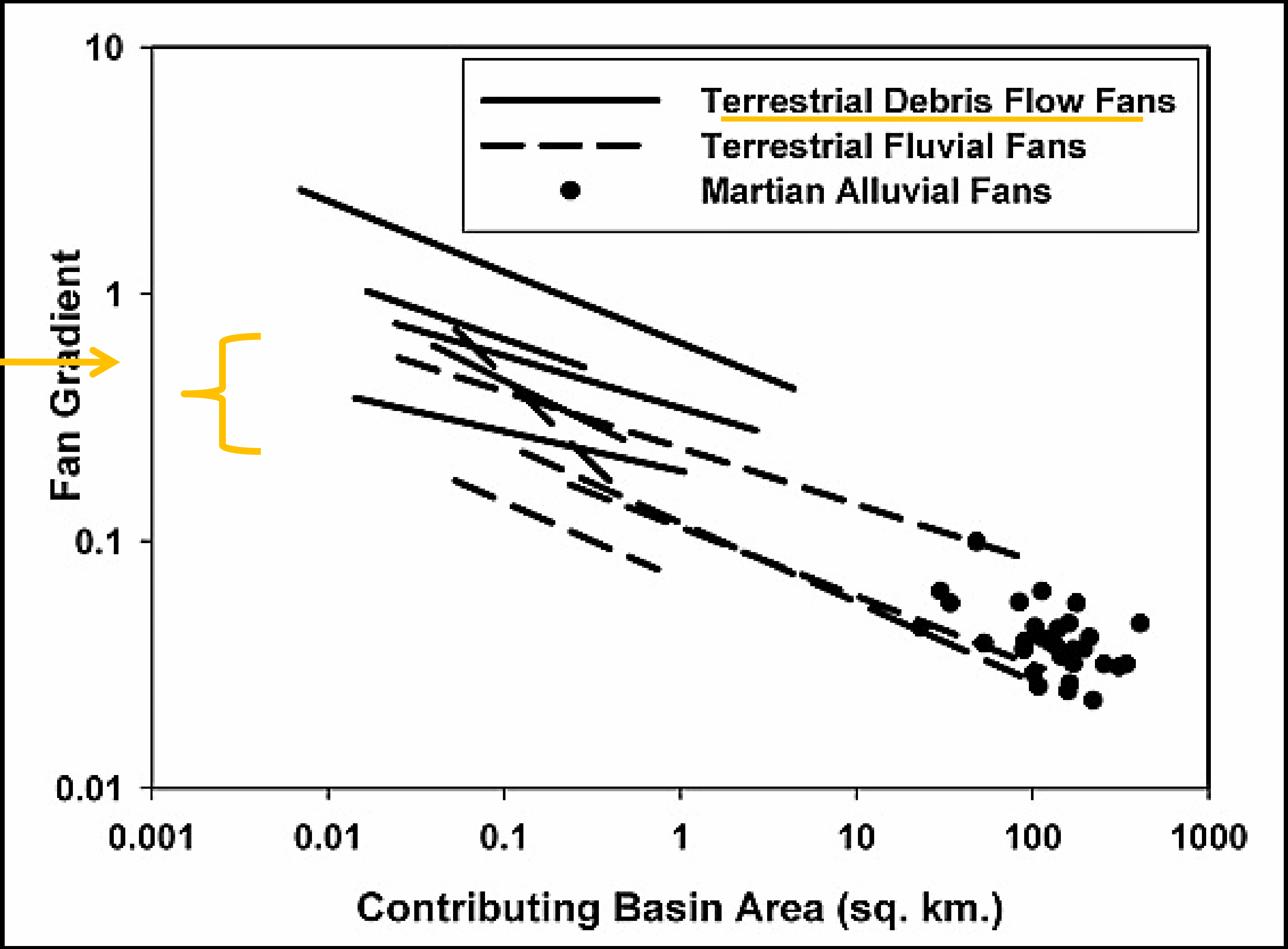
4. Recent gullies: Slopes



Most of sinuous gullies occur on slope 10 to 25° steep
(Kreslavsky, 2008, Reiss et al., 2009, Mangold et al., 2010)

4. Recent gullies: Slopes

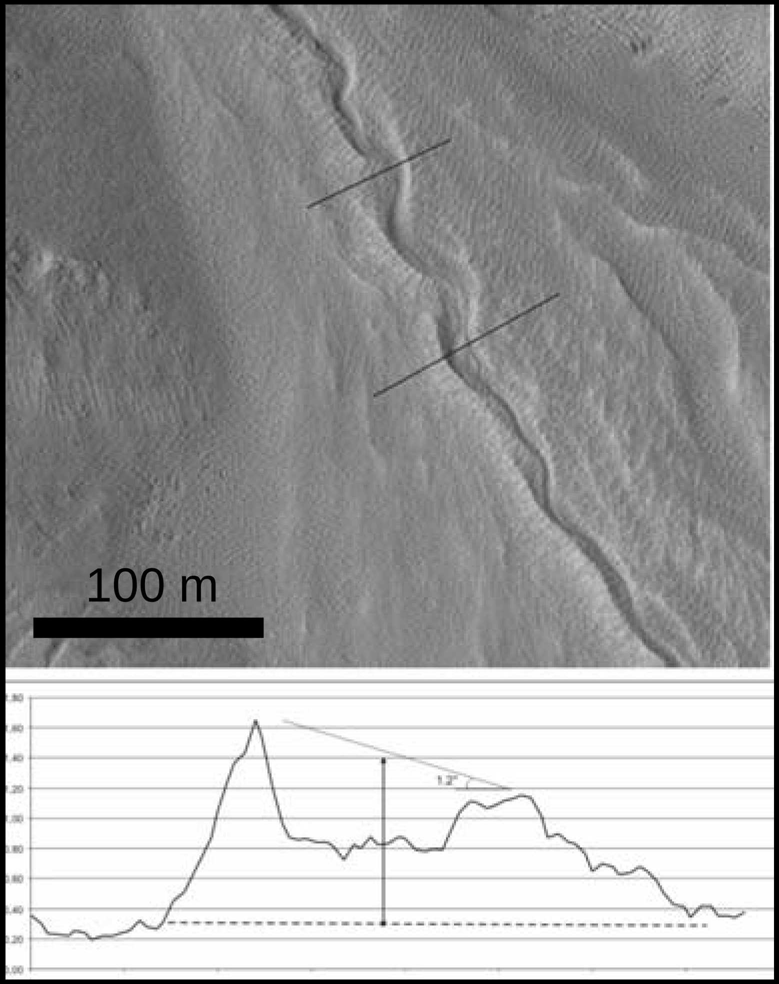
Gullies fan
at 10-15°

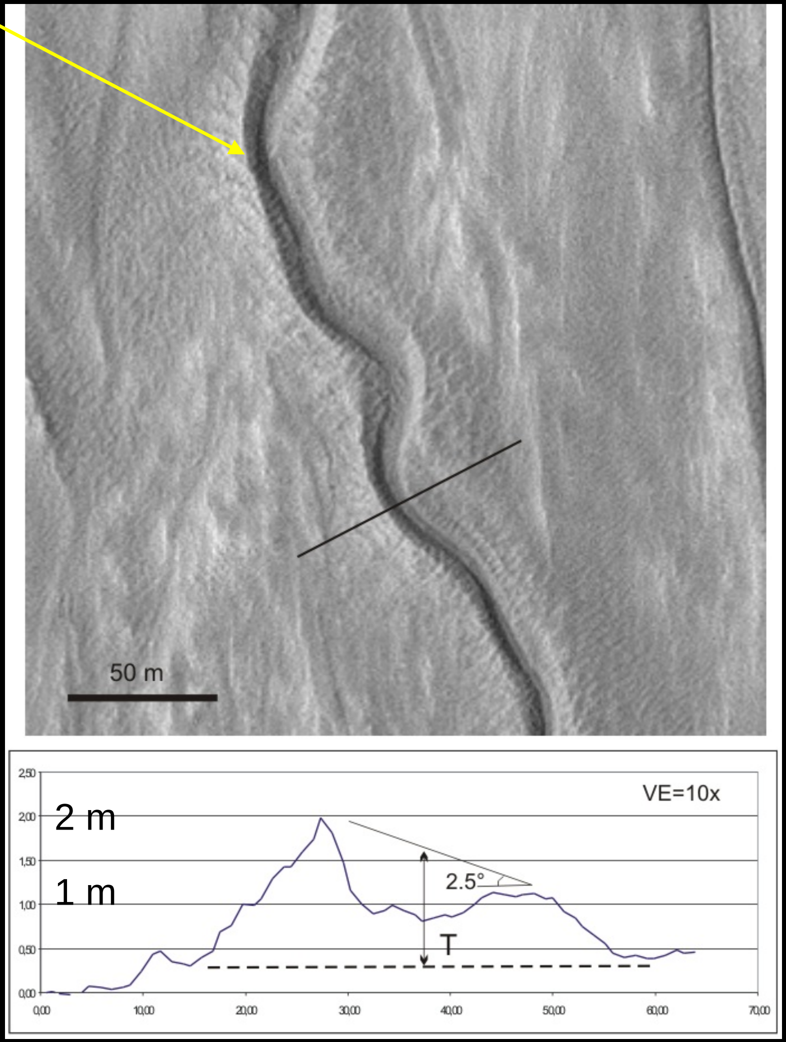


4. Recent gullies: Flow process

Channels are often bordered by levees

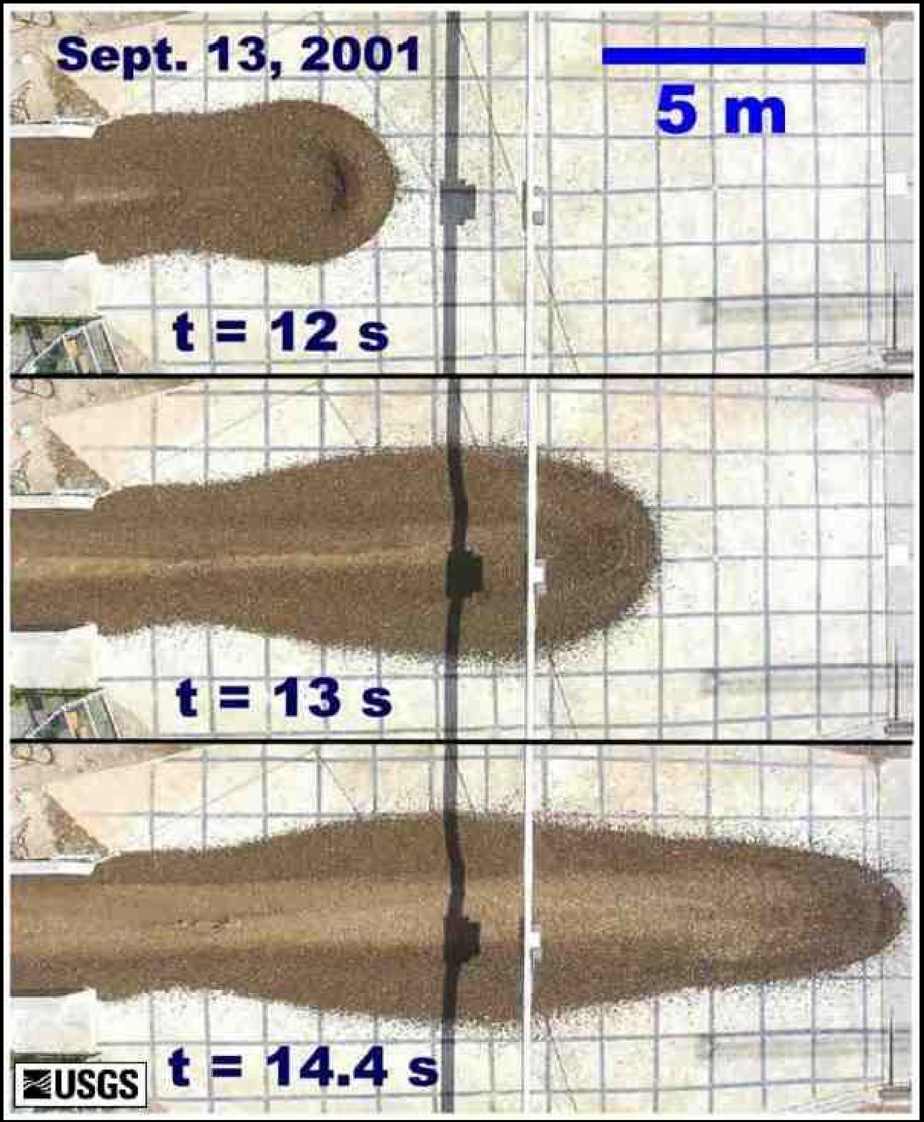
=> mass flow, not progressive erosion





Photoclinometry profile

4. Recent gullies: Flow process



Experiment by Iverson (web page)
Debris flows formation=viscous material

Debris flows can stop on steep slopes

Mechanical behavior => Bingham fluid

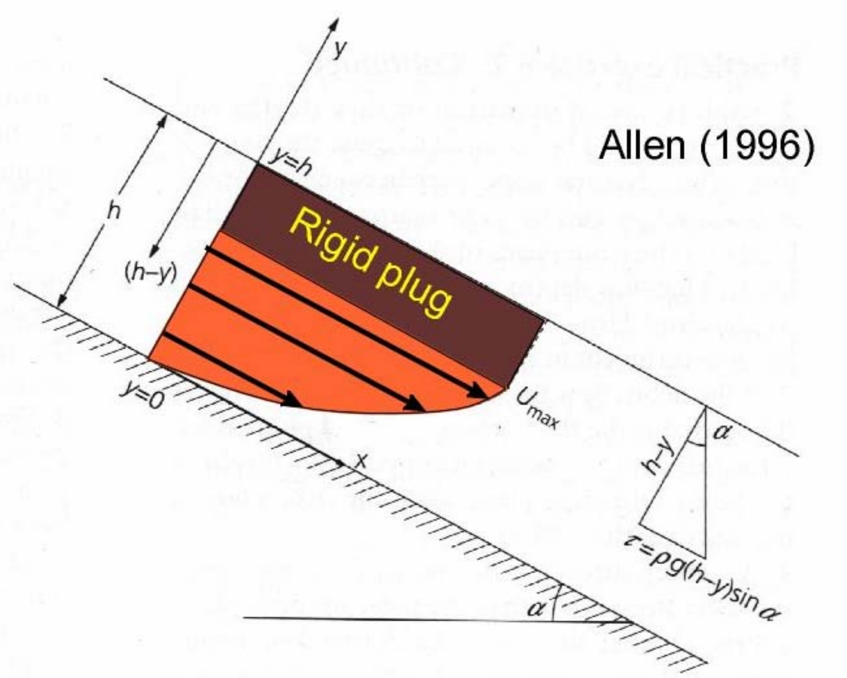
= viscous slurry ≠ pure liquid water run off

$\tau = K + \mu \, d\gamma/dt$ but if $\tau < K$: no flow

Viscosity

Yield strength (Threshold)

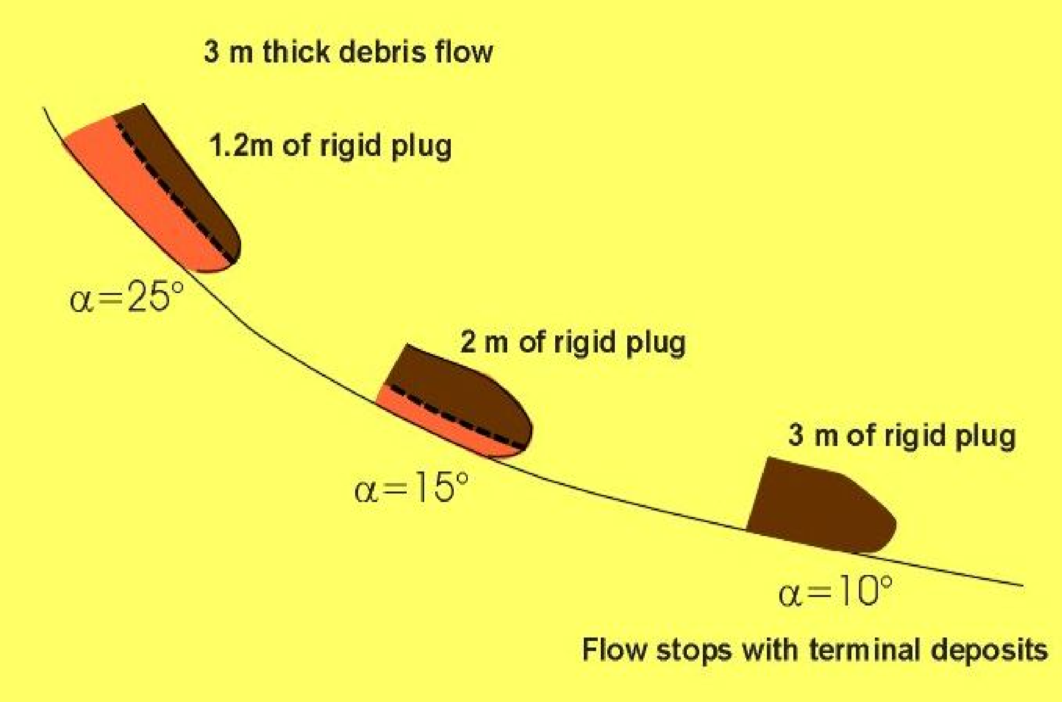
=> Minimum thickness to flow



Bingham plastic model of debris flows

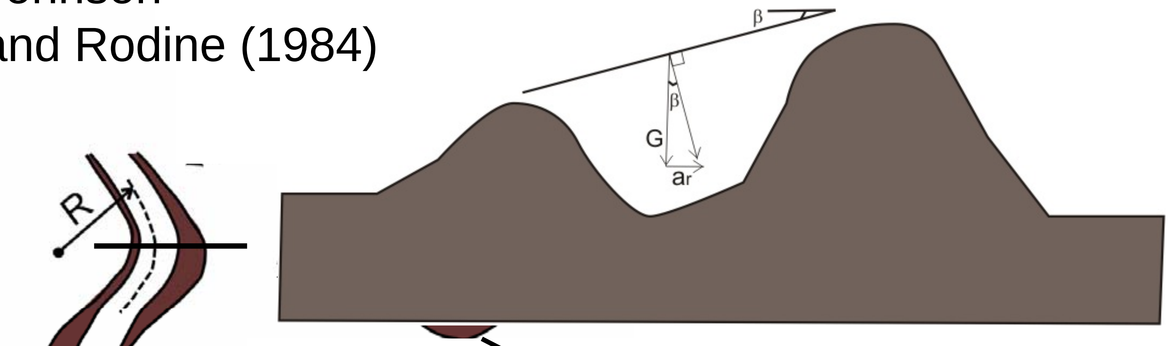
Shear stress $\tau = \rho g h \sin \alpha$

→ A material flowing on a 20° slope may stop at 10° slope



4. Recent gullies: Flow property

Johnson and Rodine (1984)



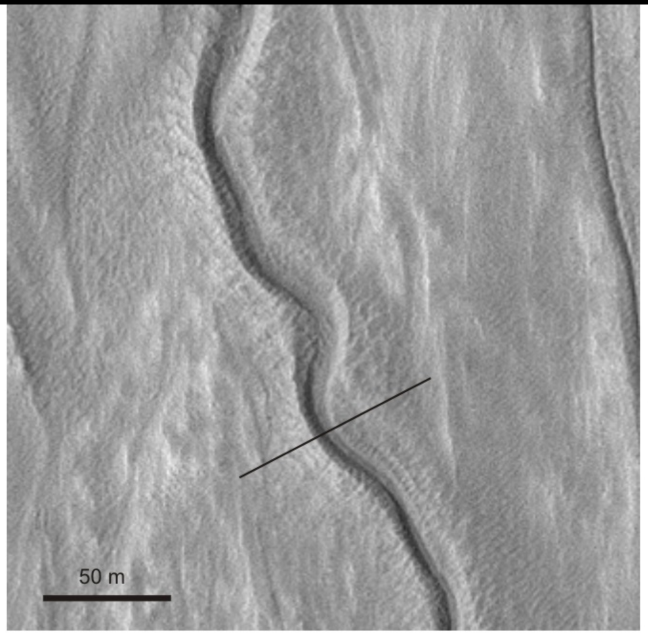
$ar = U^2/R$

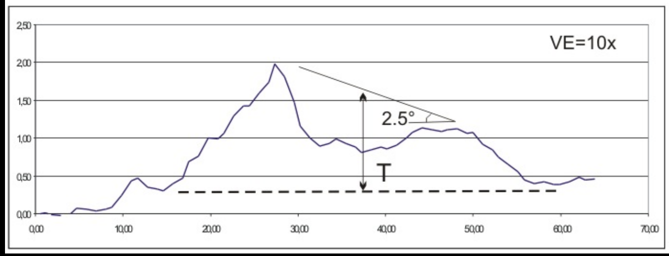
$G = g.\cos\alpha$

$\tan\beta = ar/G = U^2/(R.g.\cos\alpha)$

$U = (g.R.\cos\alpha.\ \tan\beta)^{1/2}$

Mean velocity — Radius of curvature — Slope — Tilt





Tilt β=2.5°
R=25 m
Tflow=1.2 m
Slope α=10°

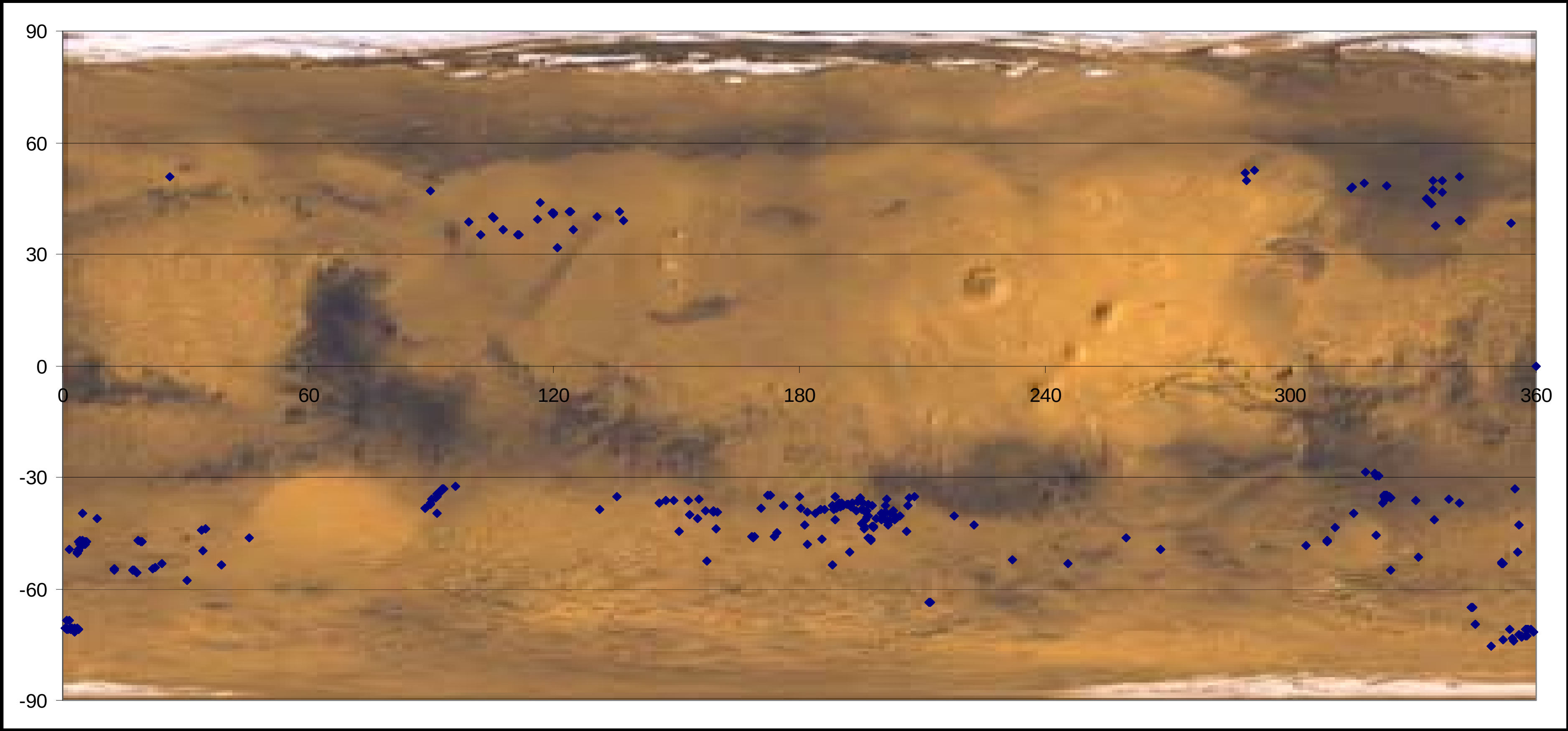
=> **V= 2.0 m.s^{-1} μ= 460 Pa.s**

Photoclinometry profile

Low velocity, high viscosity
(about Hawaiian volcanic flows)

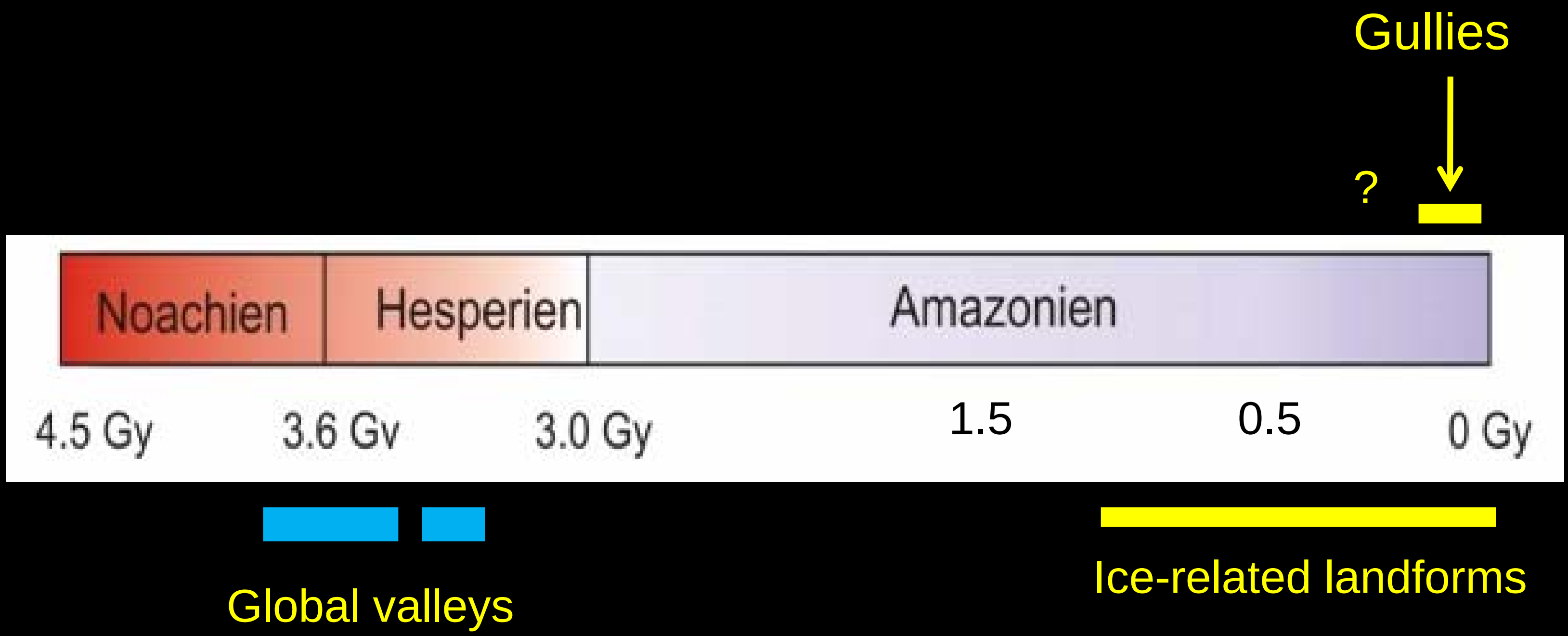
4. Recent gullies: Geographic distribution

Distribution latitude > 30 N and 30 S
No equatorial flows



Presence in latitude range where many ice related features exist

4. Recent gullies: Chronology



4. Recent gullies: Summary

What we know:

1.Gullies are formed by episodic mass flows on slopes >15°

=> Gullies do not require sustained liquid water (conditions close to current)

2. Gullies are not due to classical river streams

⇒Debris flows / Mud flows fit observed properties with < 50% liquid water

3. Gullies are very recent and form at mid-latitudes

What we want to know:

1.Did gullies require exotic fluids: brines, CO_2, etc.

2.Are gullies active currently (under debates)

5. Summary : Classification of sediment-water flows

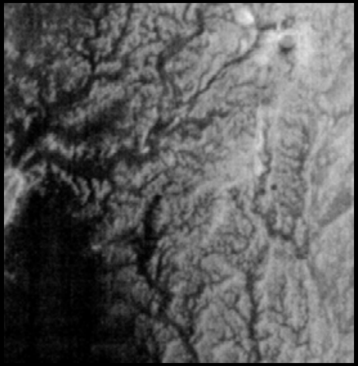
Pure water
0% solid

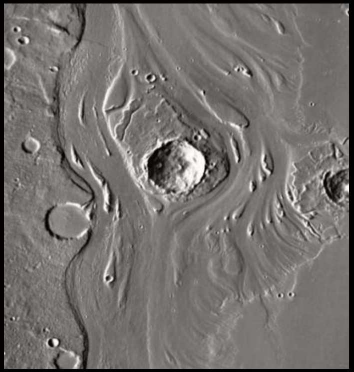
~50%

~90%

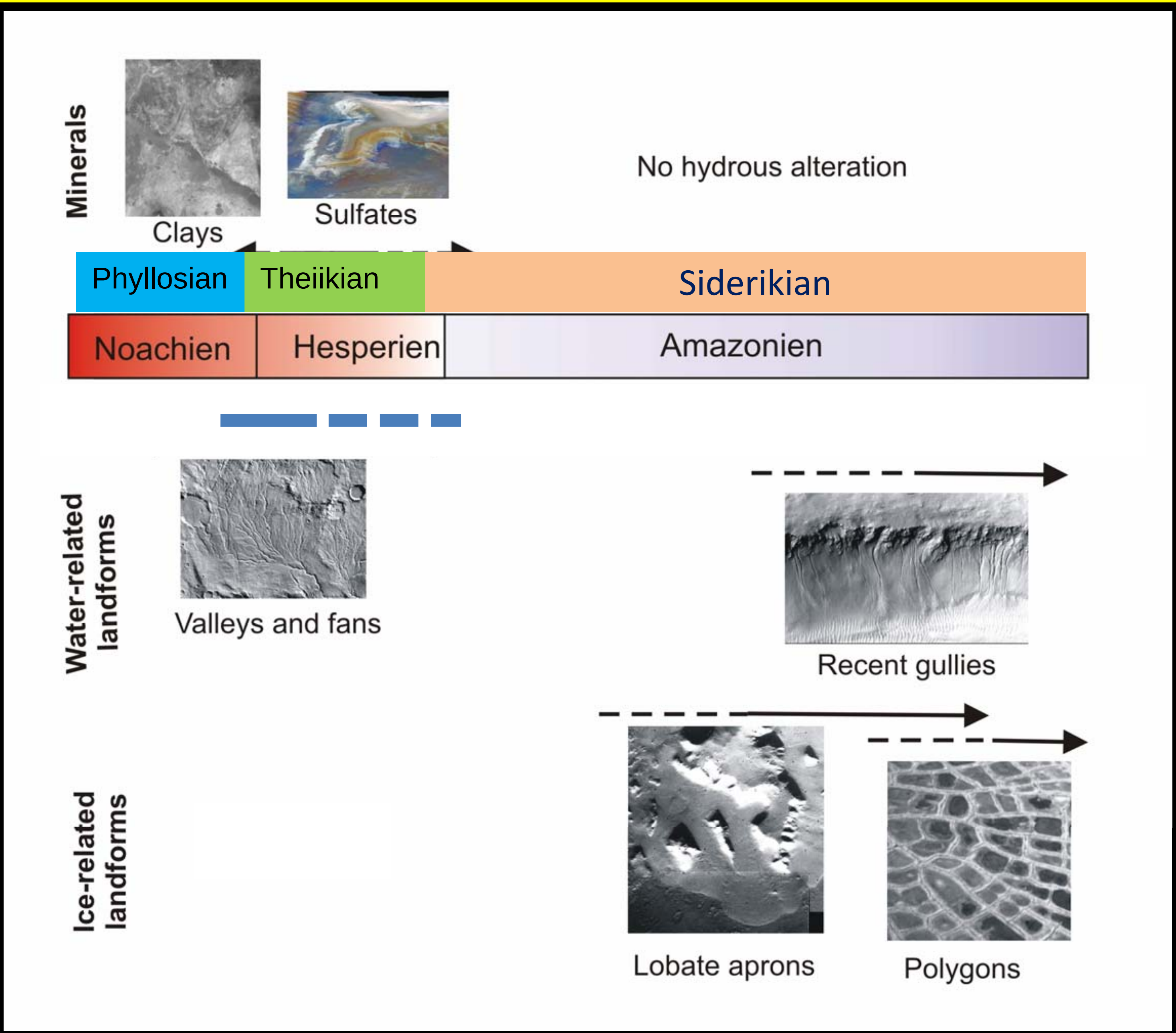
100 % solid

Normal stream flow		
Concentrated stream flow	Manning Two-phase fluid (sediment inside water)	→ Valley networks → Outflow channels
Debris flows	One-phase fluid (viscous slurry~lavas) Bingham	→ Recent Gullies
Granular flow	Grain flow Coulomb	→ Landslides

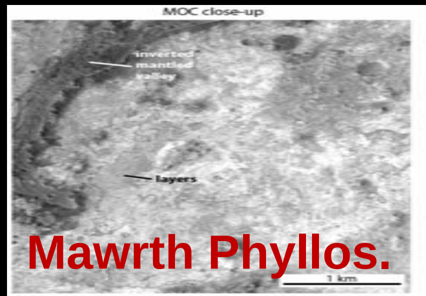


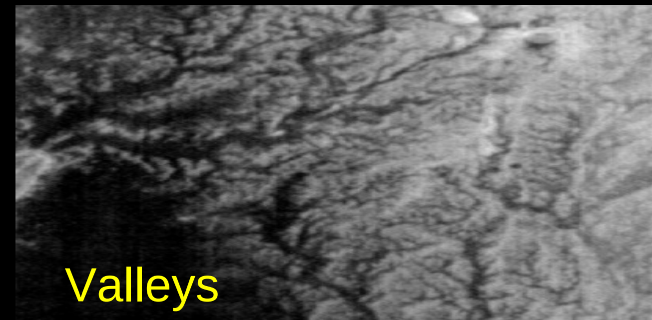


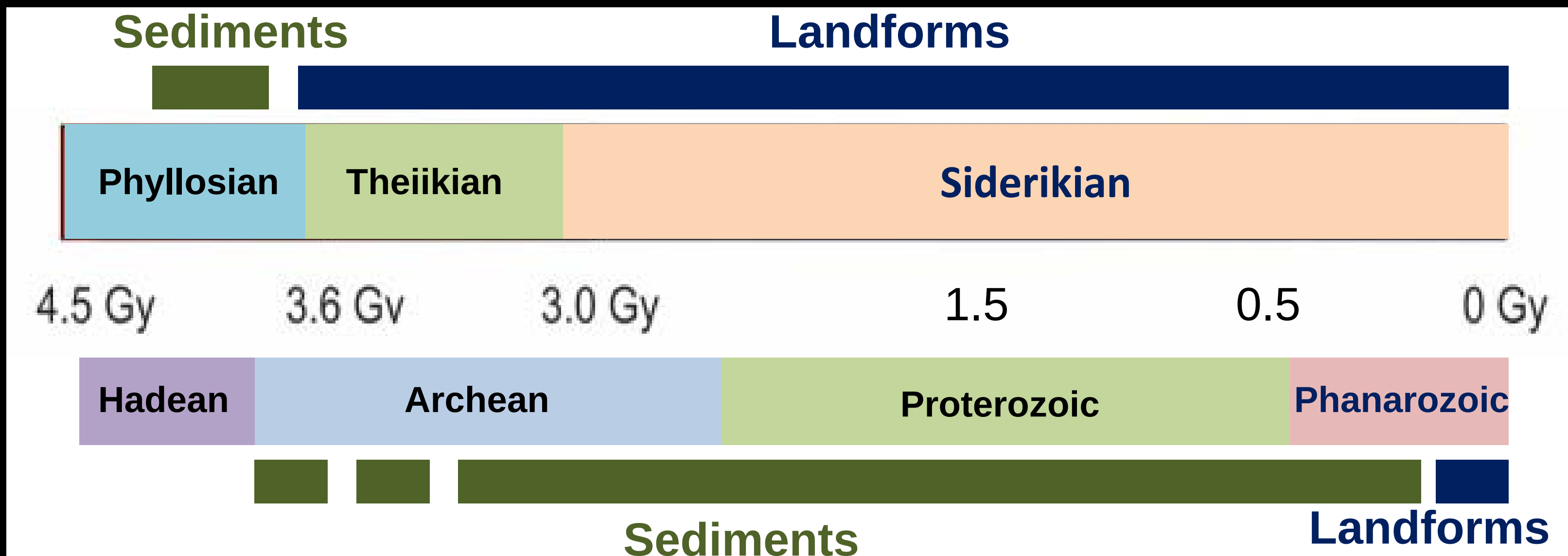
5. Summary : Chronology of water-related landforms and sediments



MARS


MOC close-up
inverted mantled valley
layers
1 km
Mawrth Phyllos.


Valleys


Sediments
Landforms
Phyllosian
Theiikian
Siderikian
4.5 Gy
3.6 Gy
3.0 Gy
1.5
0.5
0 Gy
Hadean
Archean
Proterozoic
Phanarozoic
Sediments
Landforms

EARTH


Archeans BIFs


Valleys