Tutorial II (Geological History)

Volcanism and Tectonics

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Workshop Mars III, Les Houches; 28 March- 2 April 2010

DLR Deutsches Zentrum für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

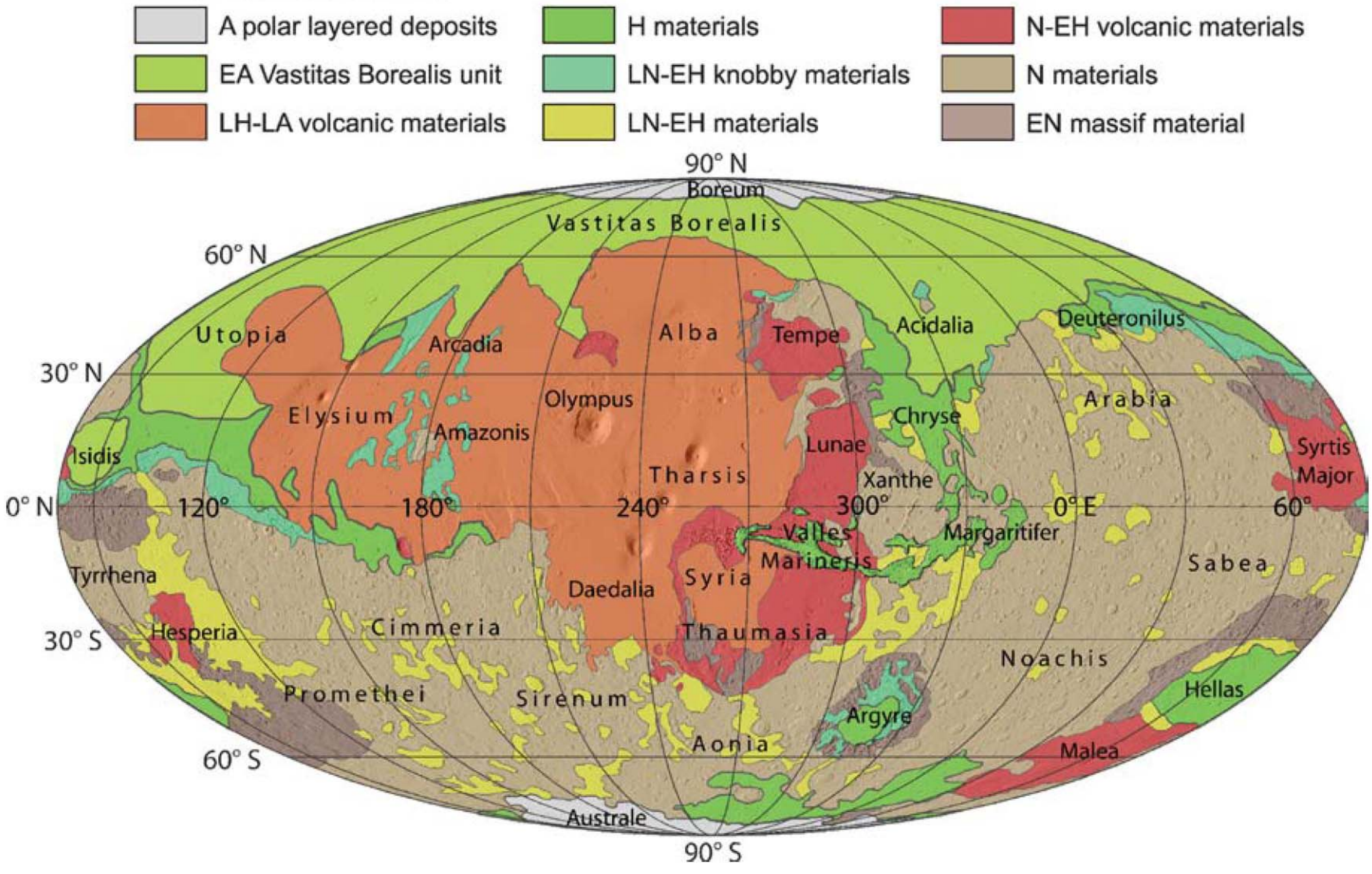
Volcanism on Mars: Tutorial Structure

- Distribution
- Morphology
- Eruption processes / style
  – influence of environmental conditions
- Composition
- Outgassing
  – volumes
- Ages
  – heat sources

Review papers:

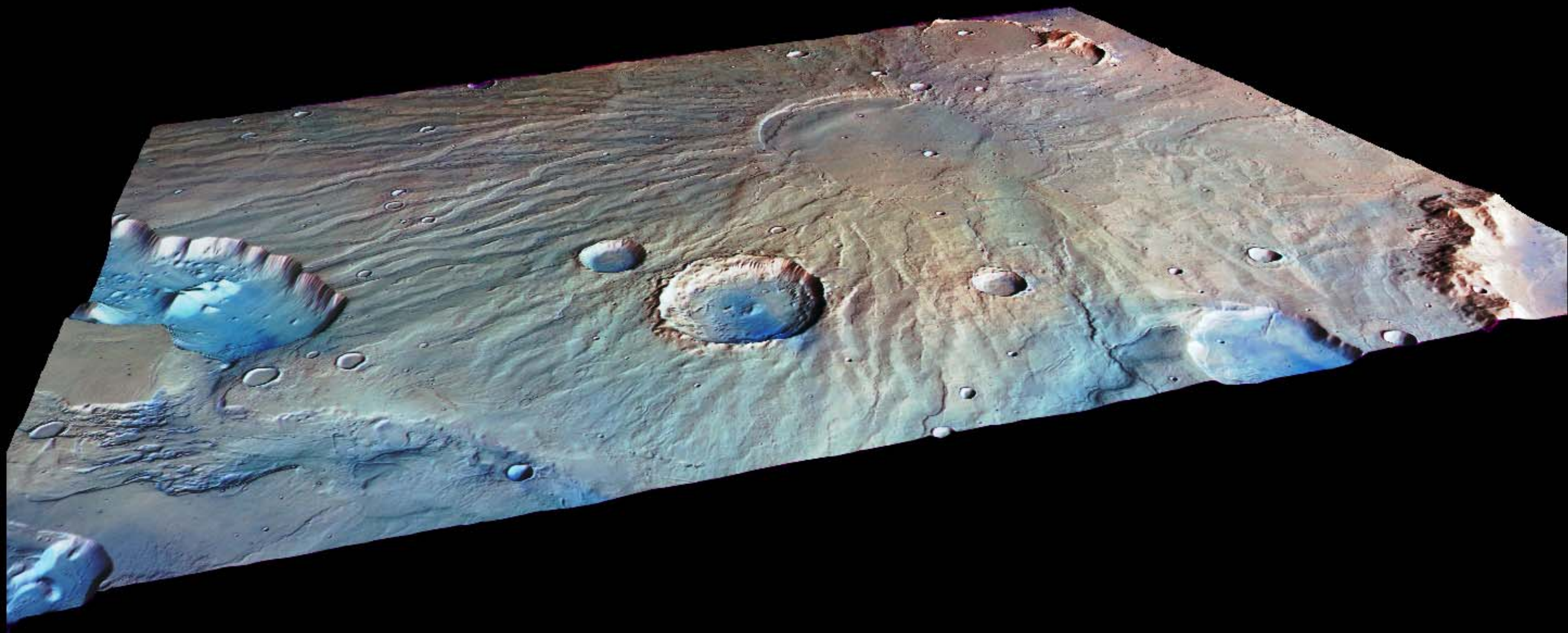
- Greeley & Spudis (1981)
- Wilson & Head (1994)
- Mouginis-Mark et al. (1992)
- Zimbelman (2000)

Mars: Simplified geologic map



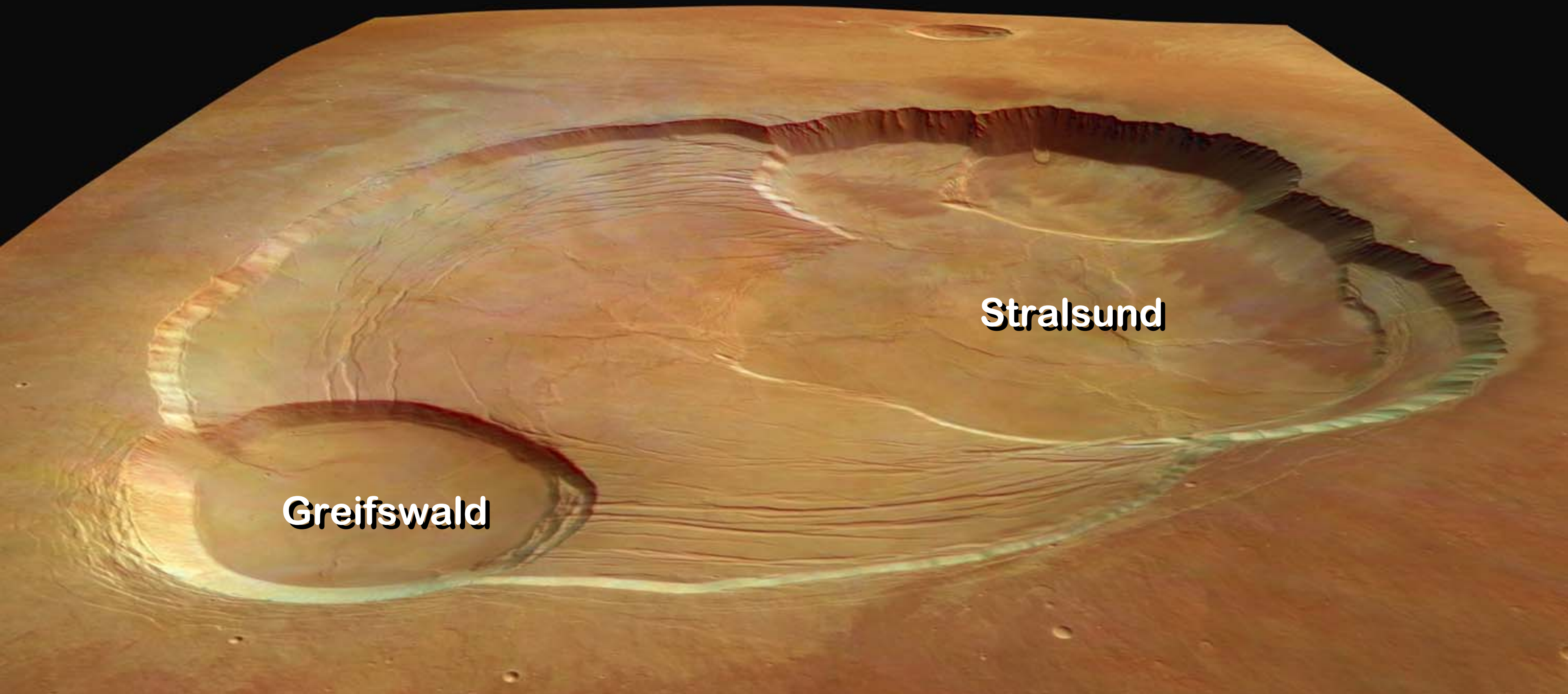
from Nimmo & Tanaka, *Ann. Rev. Earth Planet. Sci.* (2006)

Ancient highland paterae

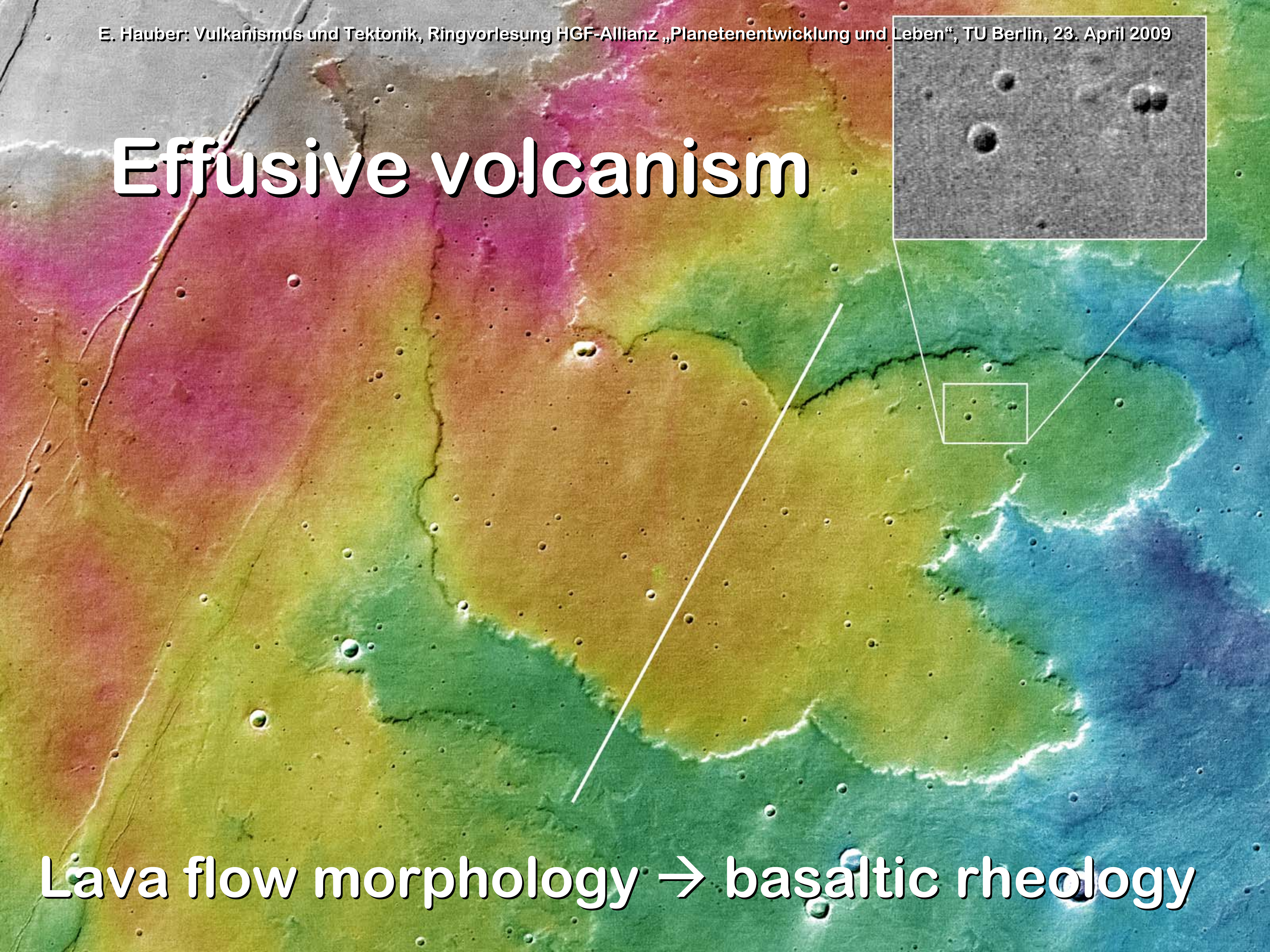


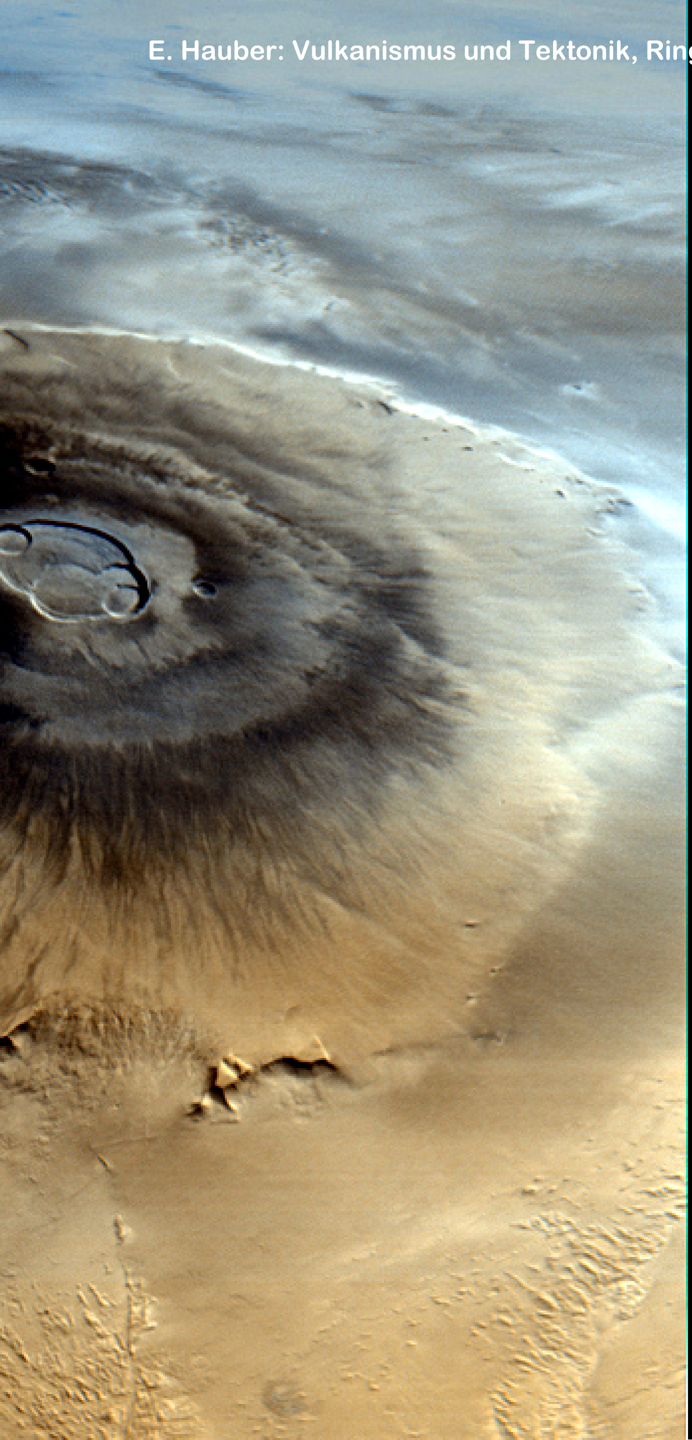
- Very old ages (3.8 – 3.5 Ga)
- Heavily dissected flanks → easily erodible material
- Ash or pyroclastic material (explosive eruptions)

Large shield volcanoes

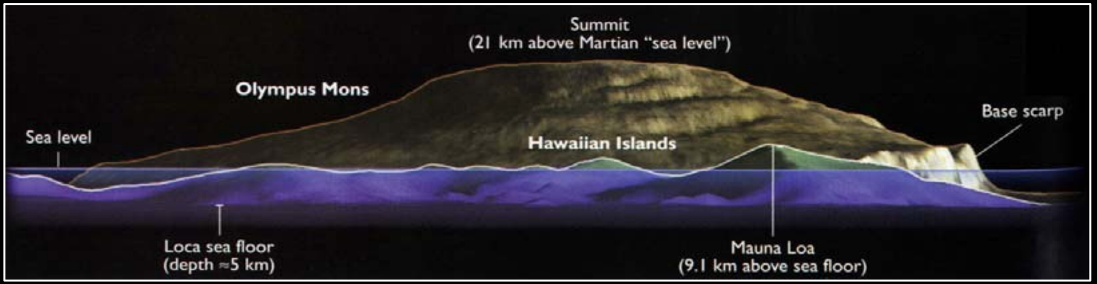


- Large diameters (up to 600 km)
- Gentle flank slopes (few degrees)
- Long-lasting activity (caldera collapse: ~100 to 400 Ma)


E. Hauber: Vulkanismus und Tektonik, Ringvorlesung HGF-Allianz „Planetenentwicklung und Leben“, TU Berlin, 23. April 2009
Effusive volcanism
Lava flow morphology → basaltic rheology



Giant Martian shield volcanoes



Why are they so large?

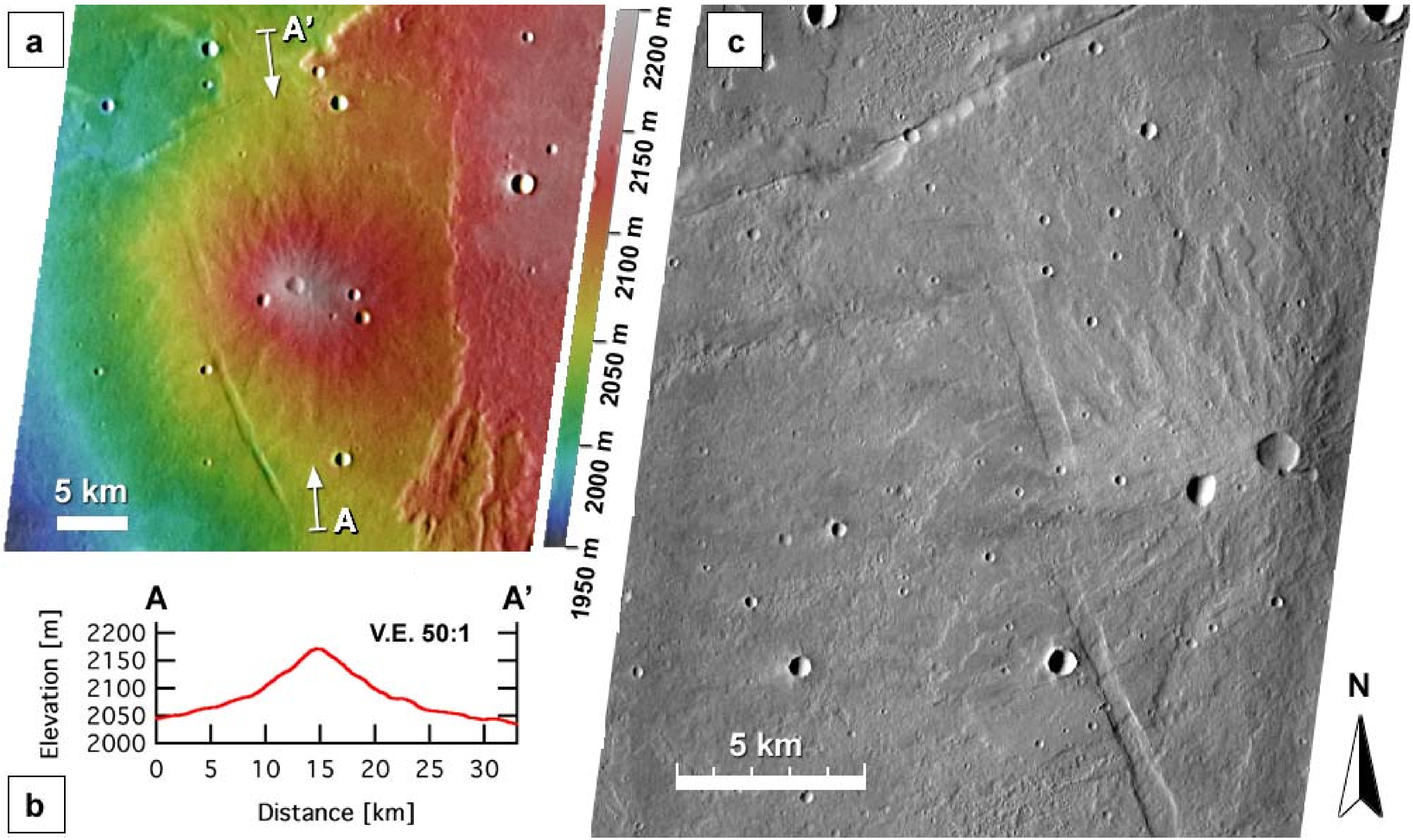
- no plate tectonics?
- strong lithosphere?
- long-lived hot-spots?

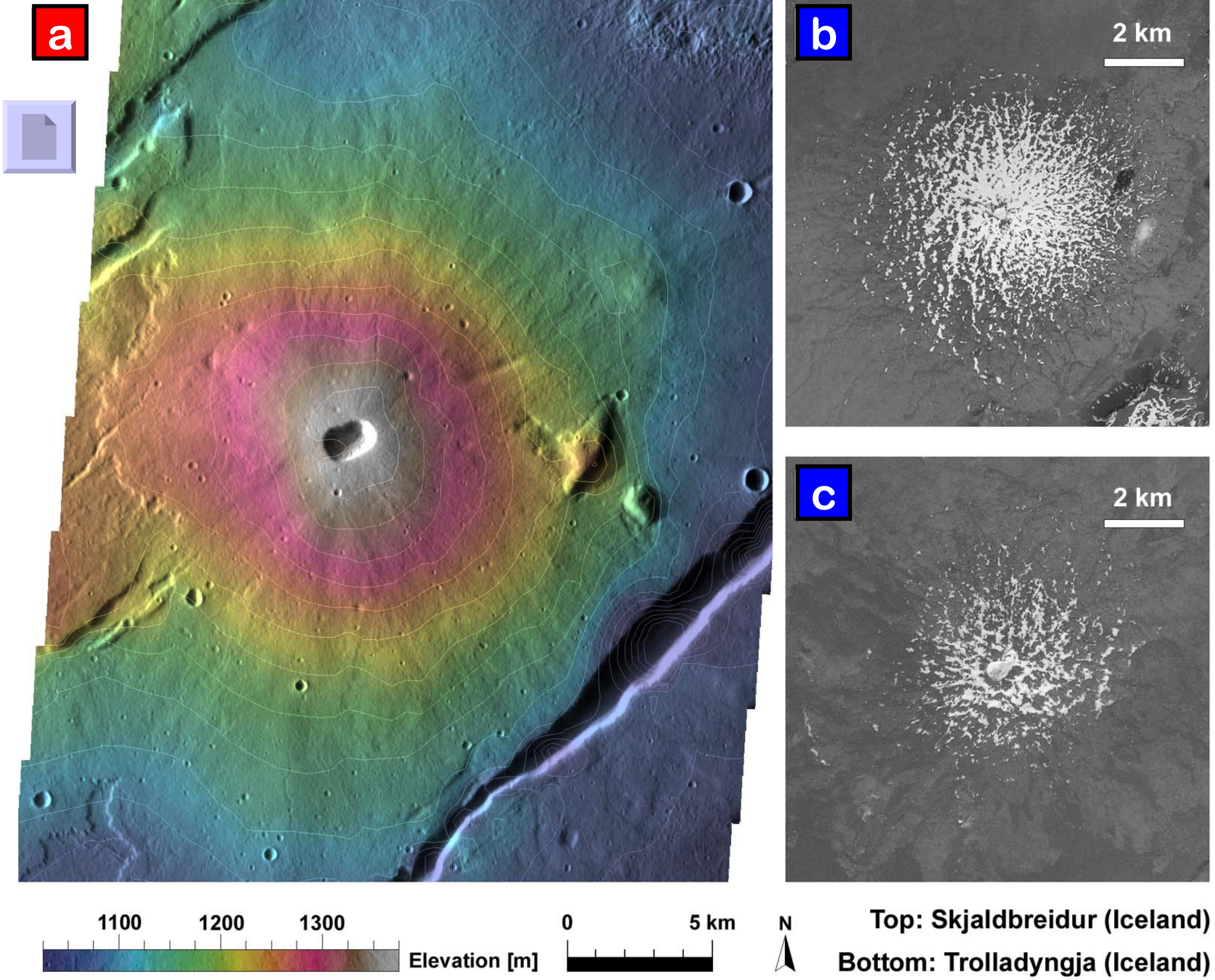
Olympus Mons vs. Hawaii

But…

…not everything is bigger on Mars!

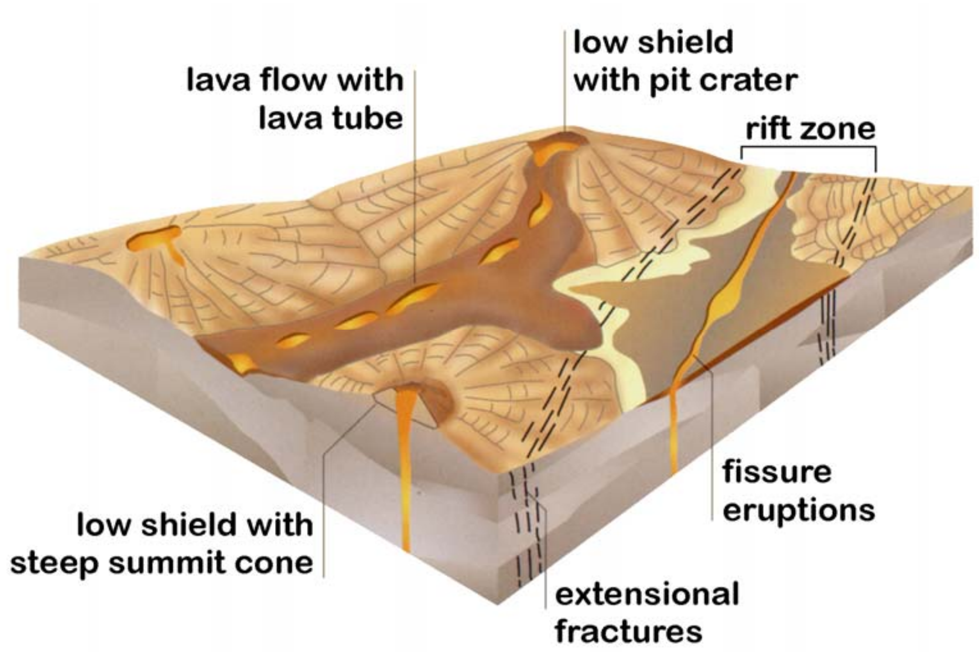
Example of a »small« low shield



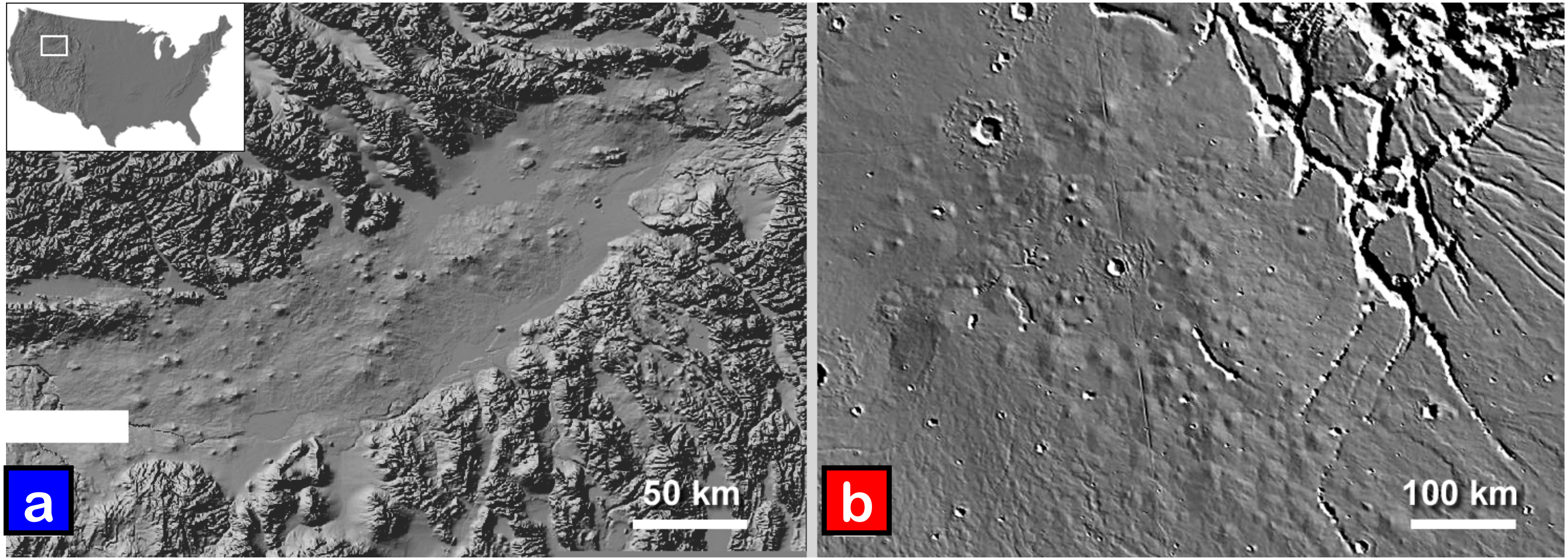


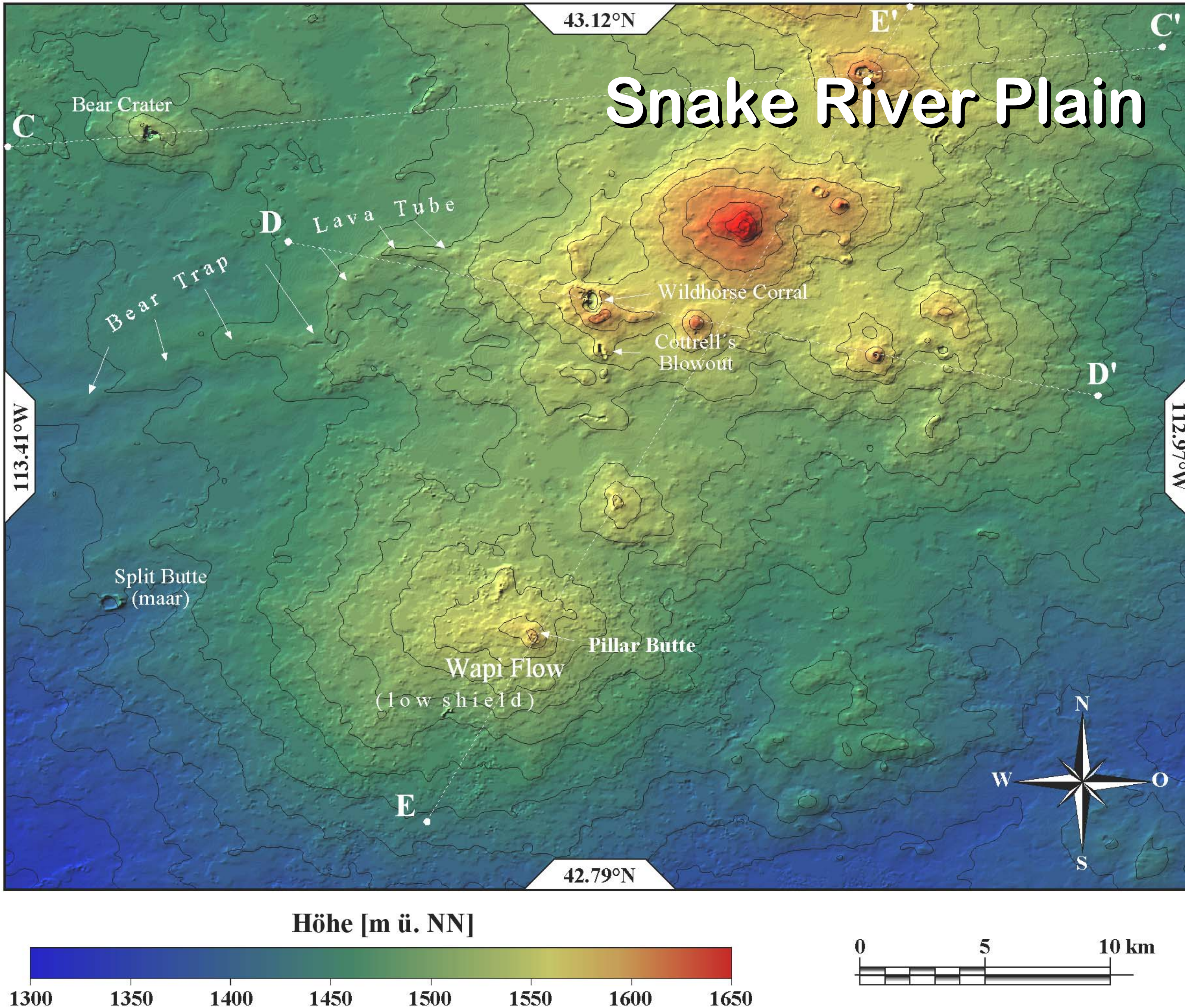
a
b
2 km
c
2 km
1100
1200
1300
Elevation [m]
0
5 km
N
Top: Skjaldbreidur (Iceland)
Bottom: Trolladyngja (Iceland)

Background

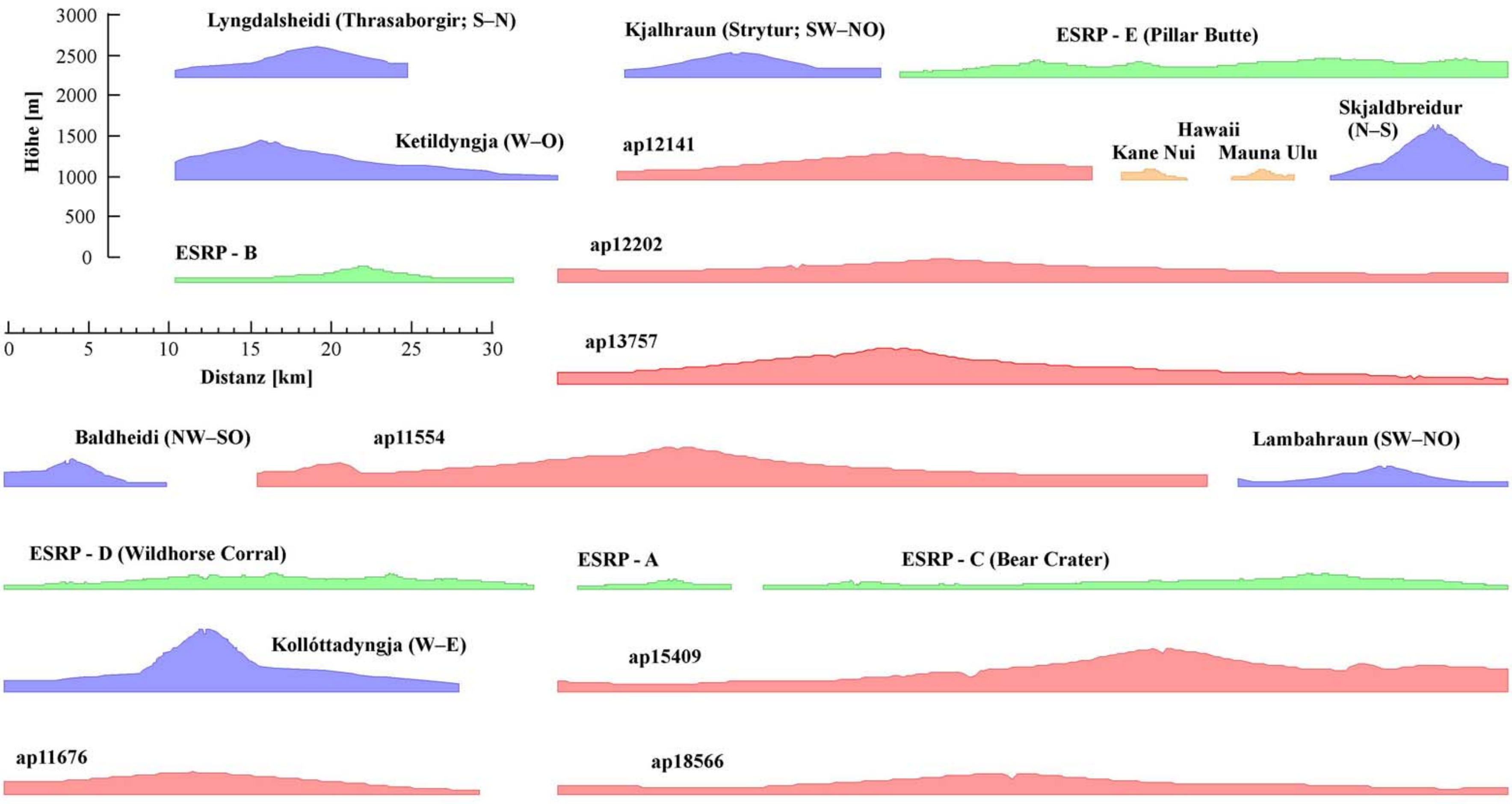


- Plains volcanism defined by Greeley (1977, 1982)
- Low shields on Mars compared to plains volcanism (e.g., Plescia, 1981)
- Mostly Viking-based studies




Snake River Plain
43.12°N
42.79°N
113.41°W
112.97°W
C
C'
D
D'
E
E'
Bear Crater
Lava Tube
Bear Trap
Wildhorse Corral
Cottrell´s Blowout
Split Butte (maar)
Pillar Butte
Wapi Flow
(low shield)
N
S
W
O
Höhe [m ü. NN]
1300
1350
1400
1450
1500
1550
1600
1650
0
5
10 km

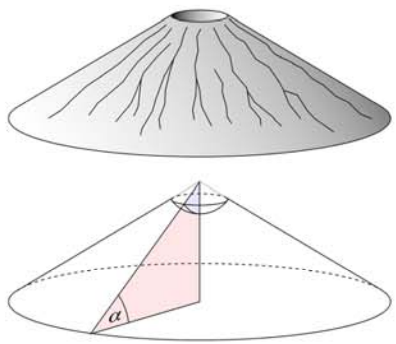
A comparison of low shields on Mars and Earth



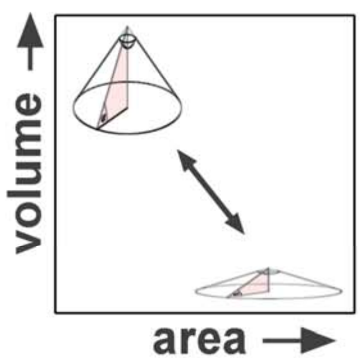
Mars | Snake River Plains | Iceland | Hawaii

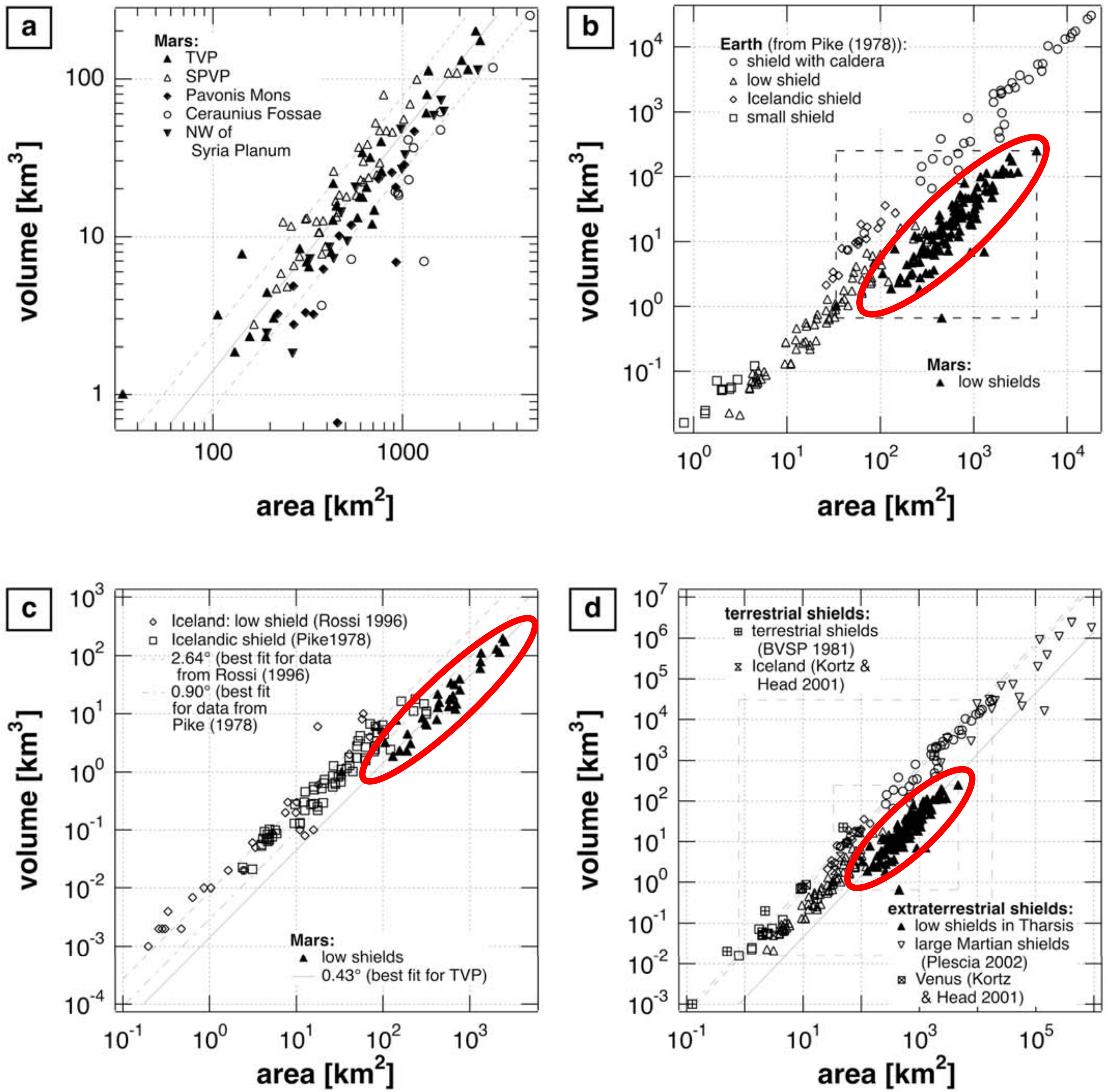

Skjaldbreiður (Iceland)
This is significantly steeper than the Martian low shields!

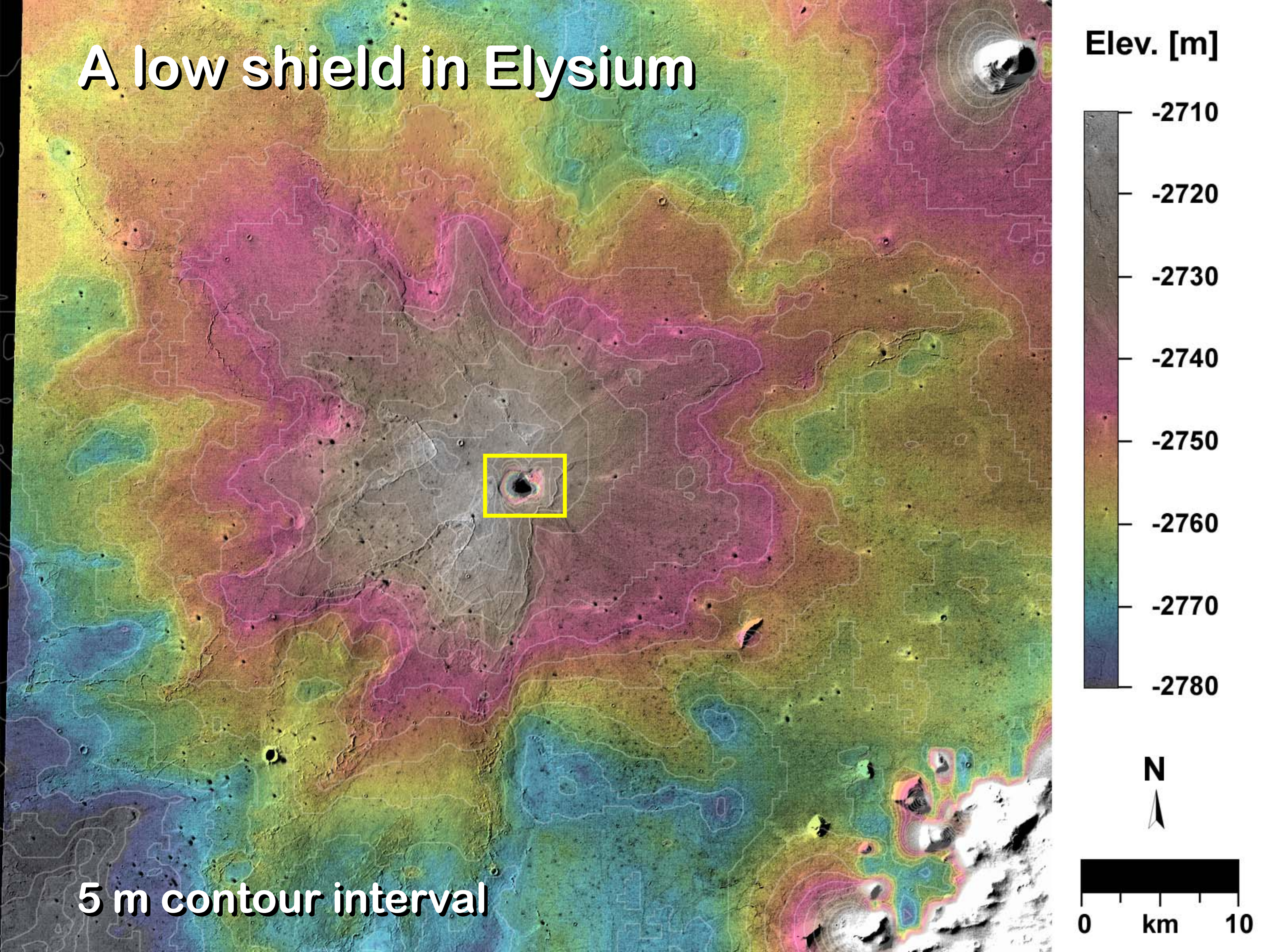
Flank Slopes



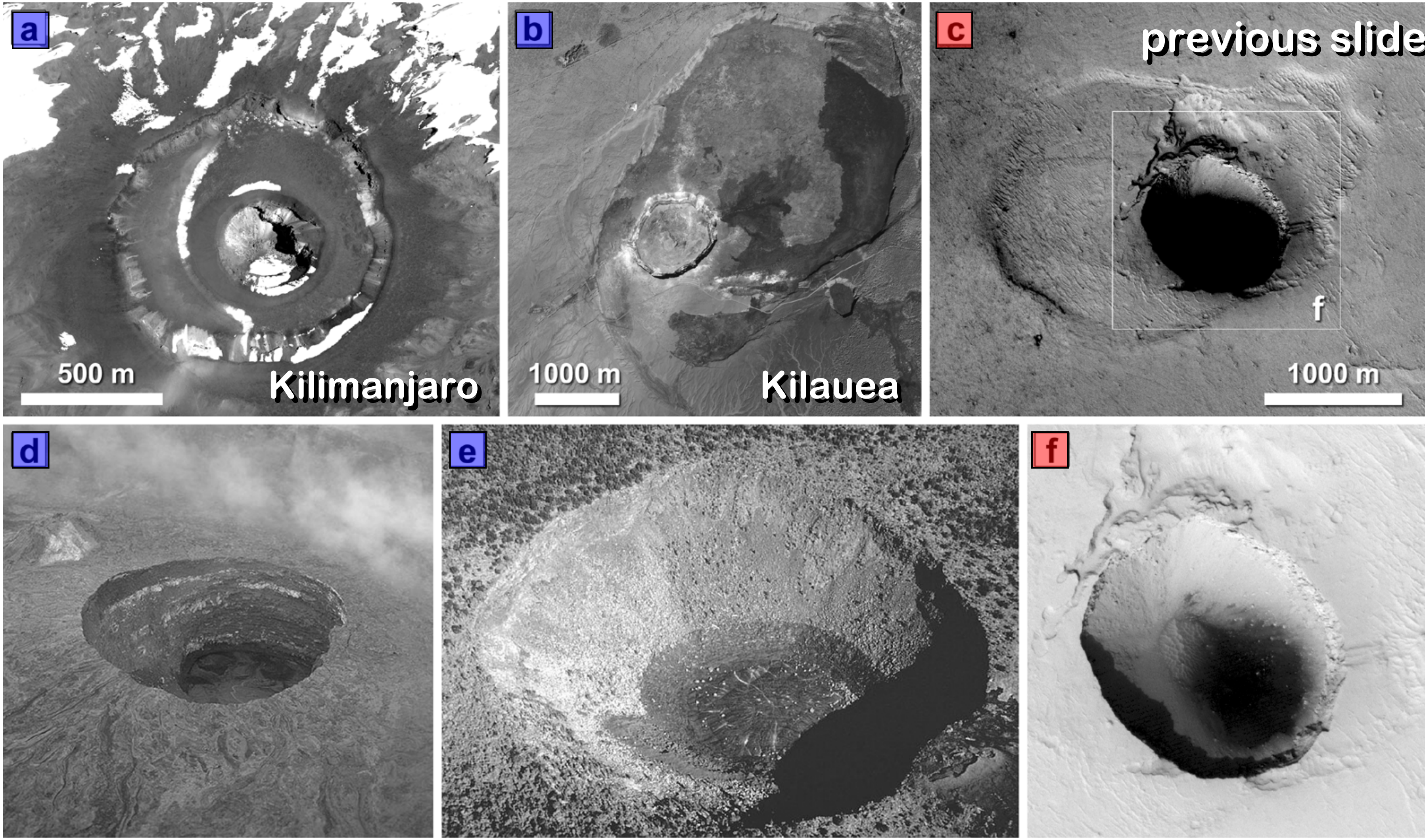
Our model: simple cones



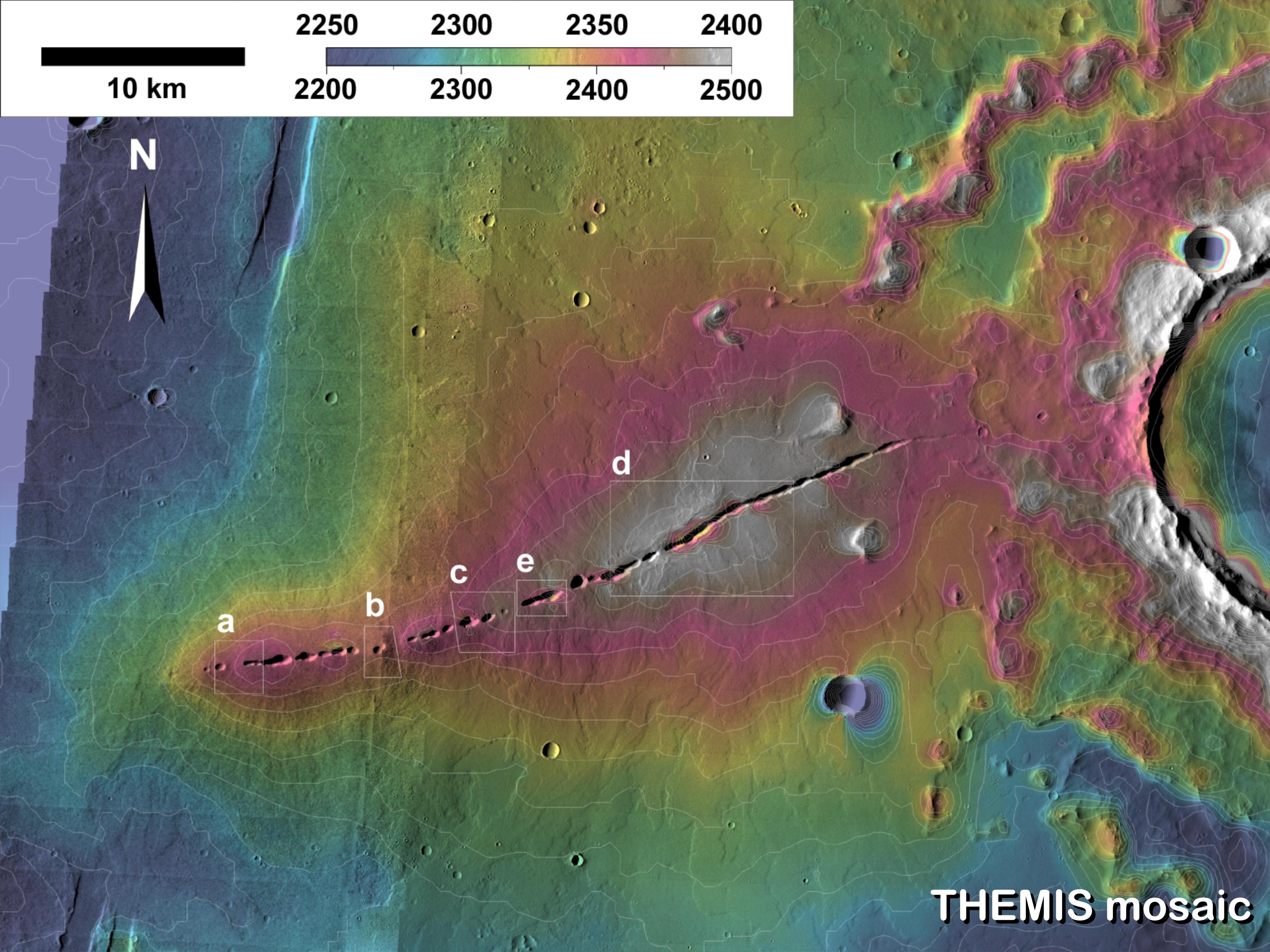



A low shield in Elysium
5 m contour interval
Elev. [m]
-2710
-2720
-2730
-2740
-2750
-2760
-2770
-2780
N
0
km
10

Calderas and pit craters

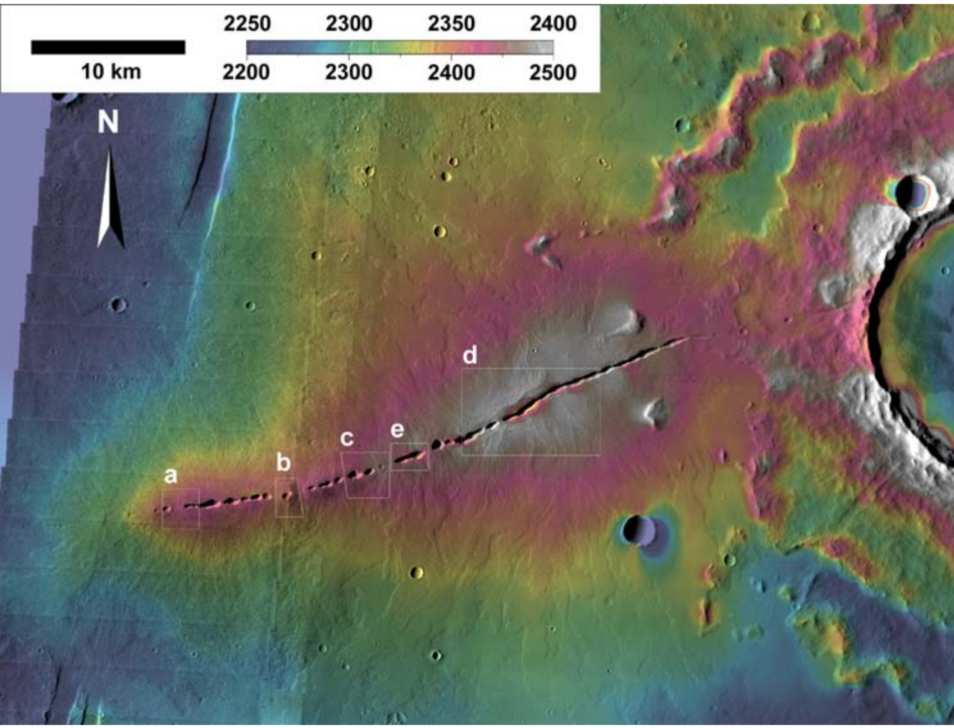


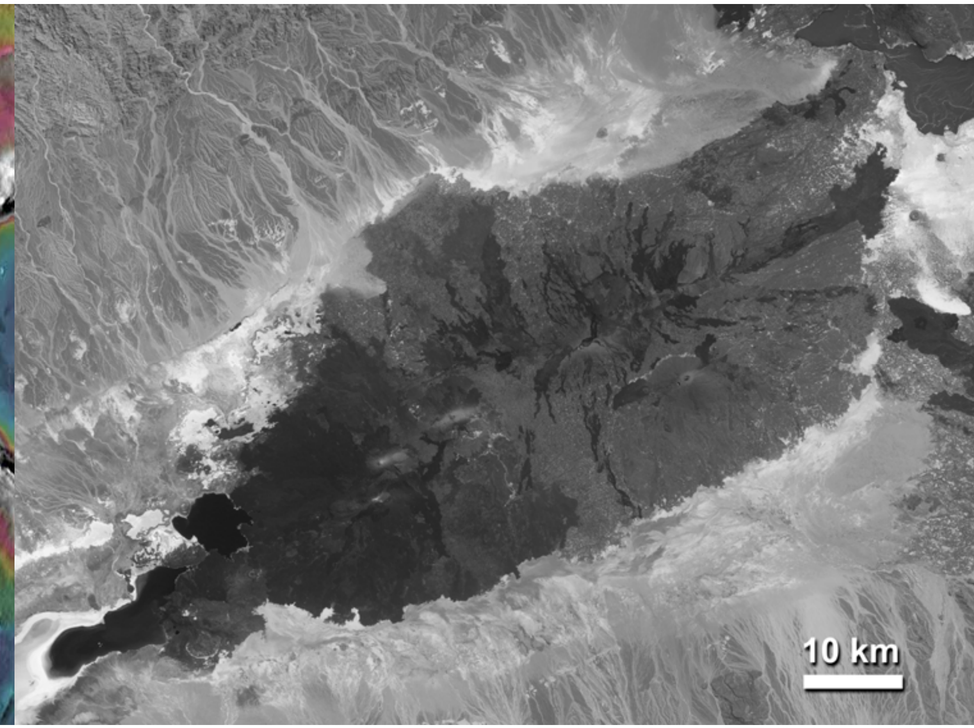
Size and morphology are very similar to terrestrial examples



10 km
2250
2300
2350
2400
2200
2300
2400
2500
N
a
b
c
d
e
THEMIS mosaic

More complex basaltic volcanoes

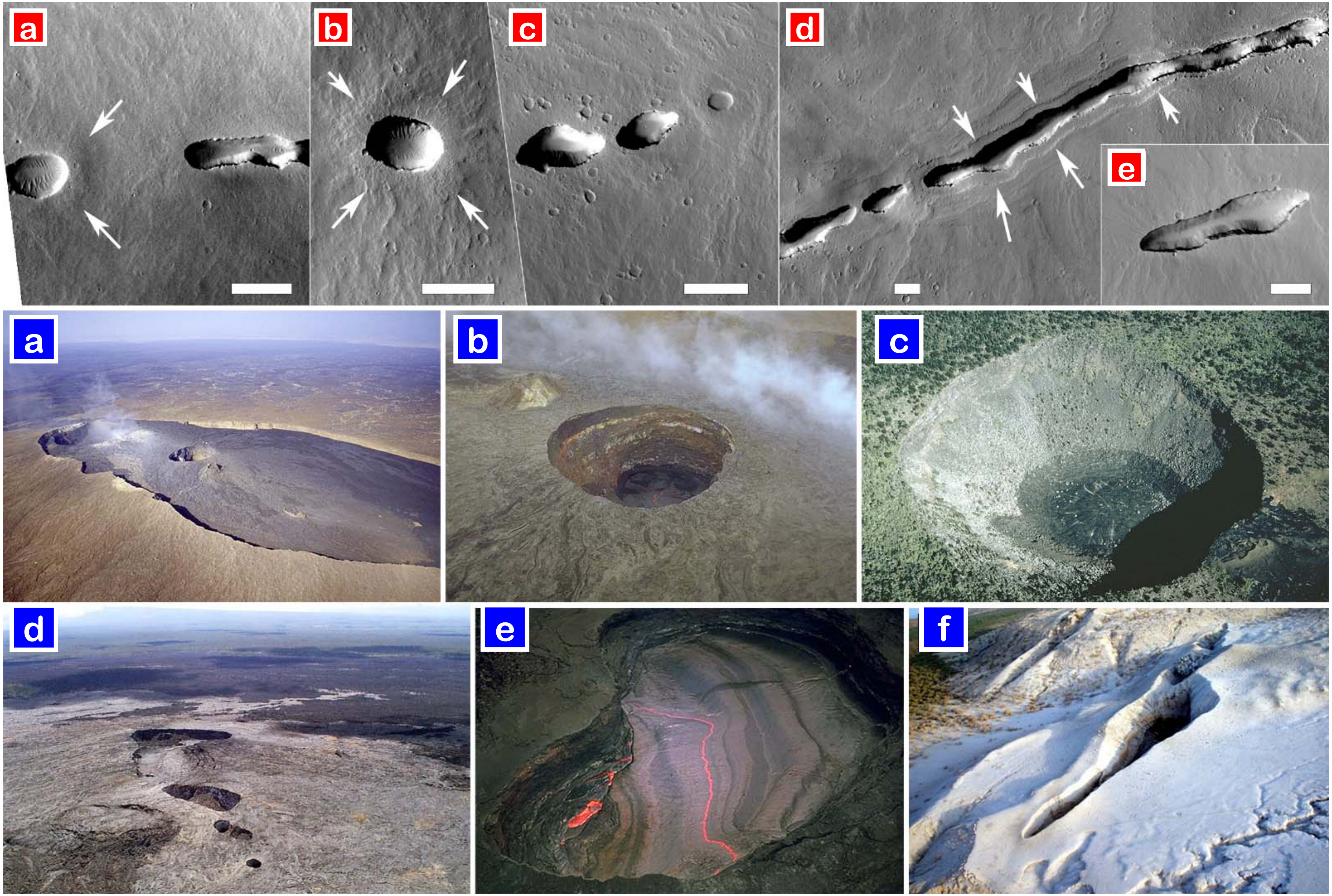


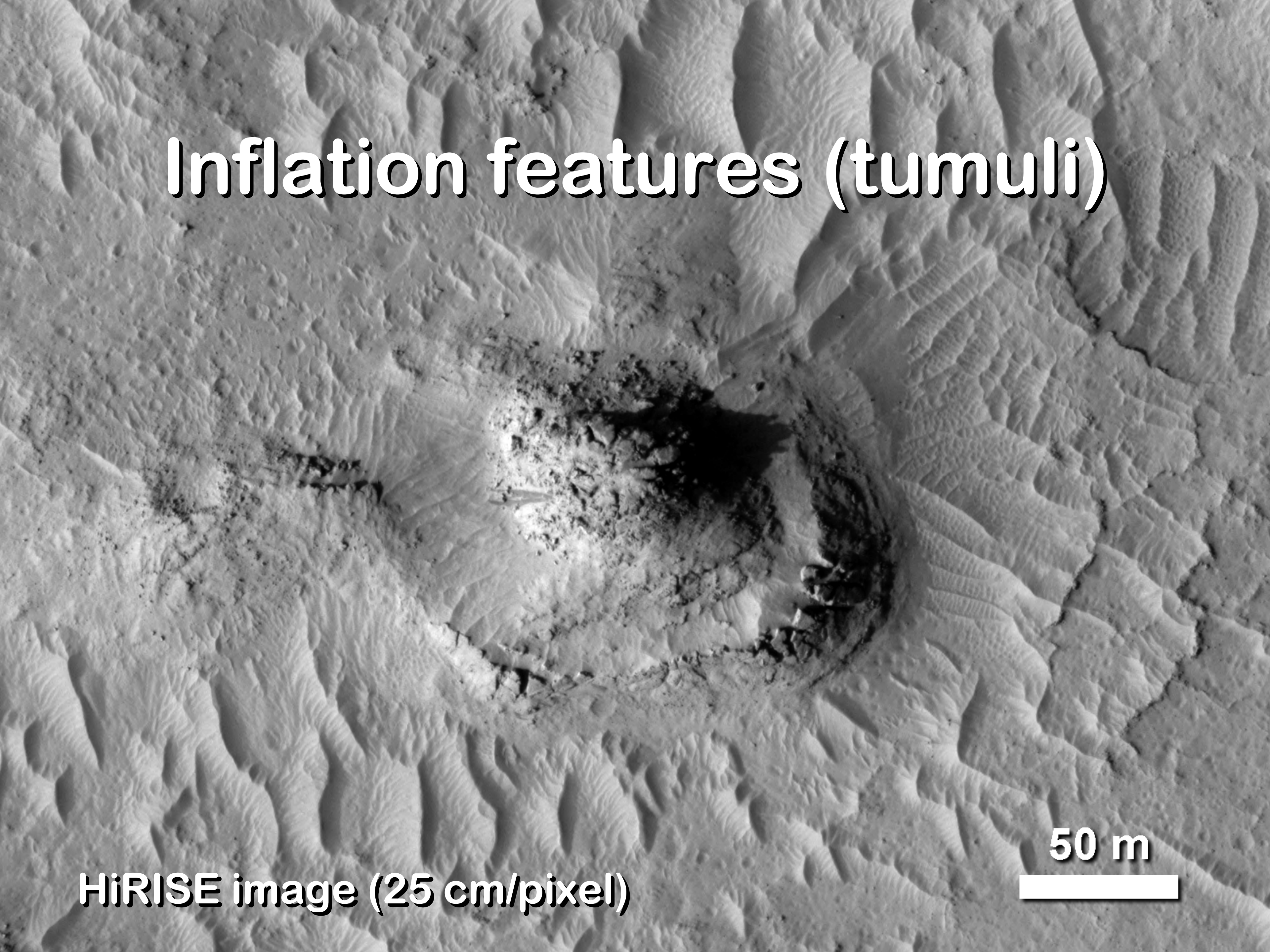


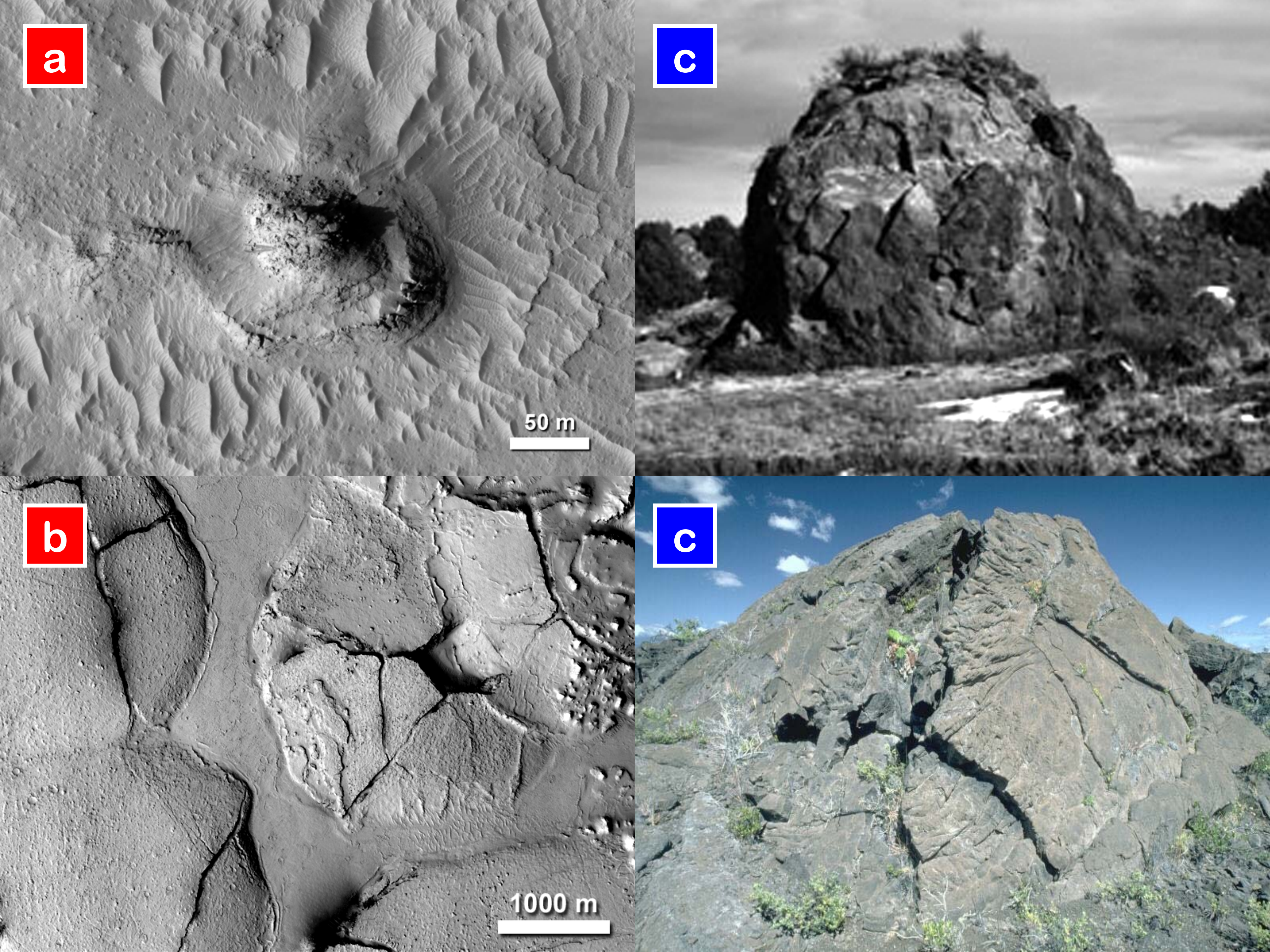
Mars (Tharsis, east of Jovis Tholus)

Earth (Erta Ale, Afar Region)

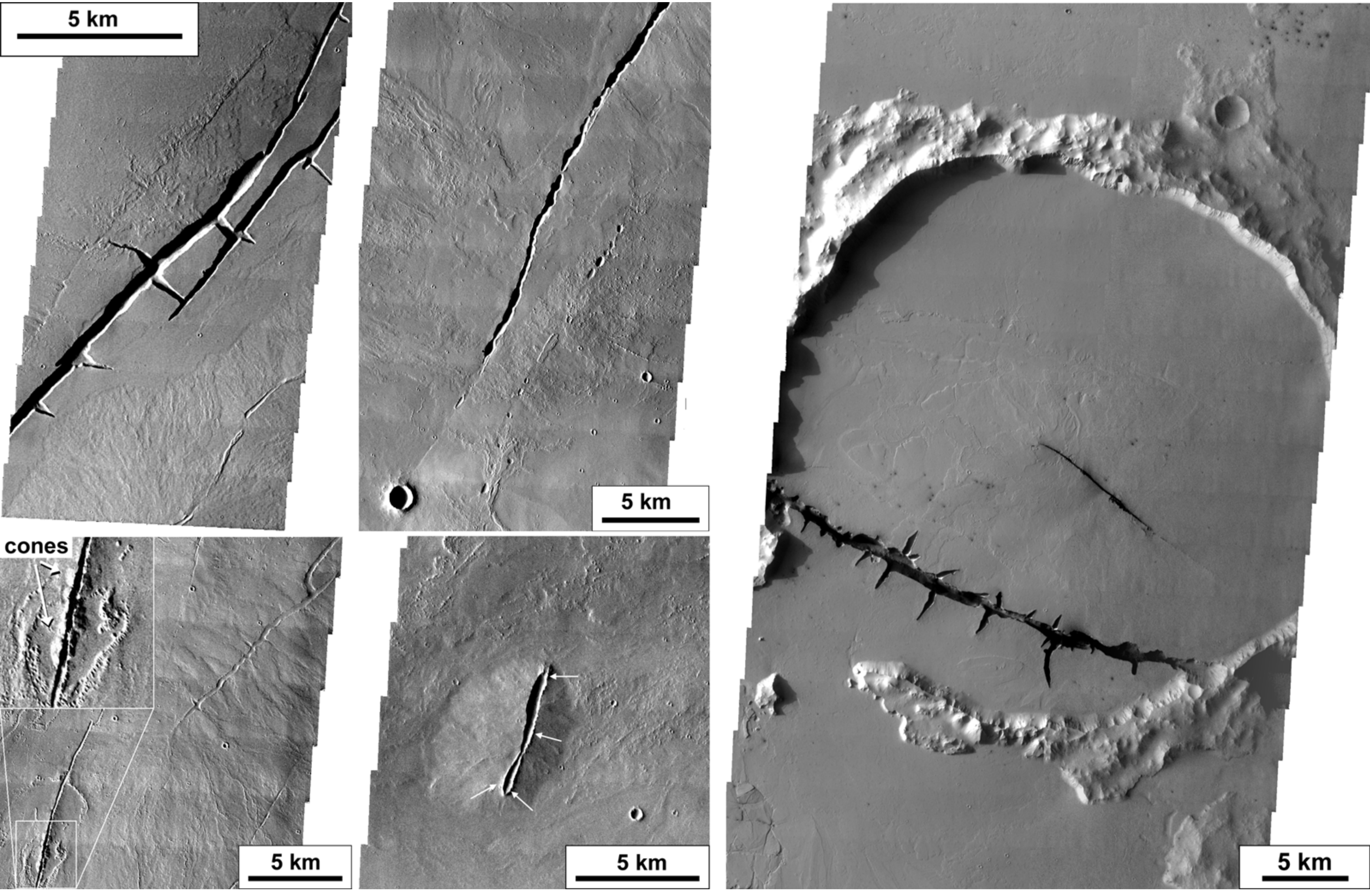
Vent structures

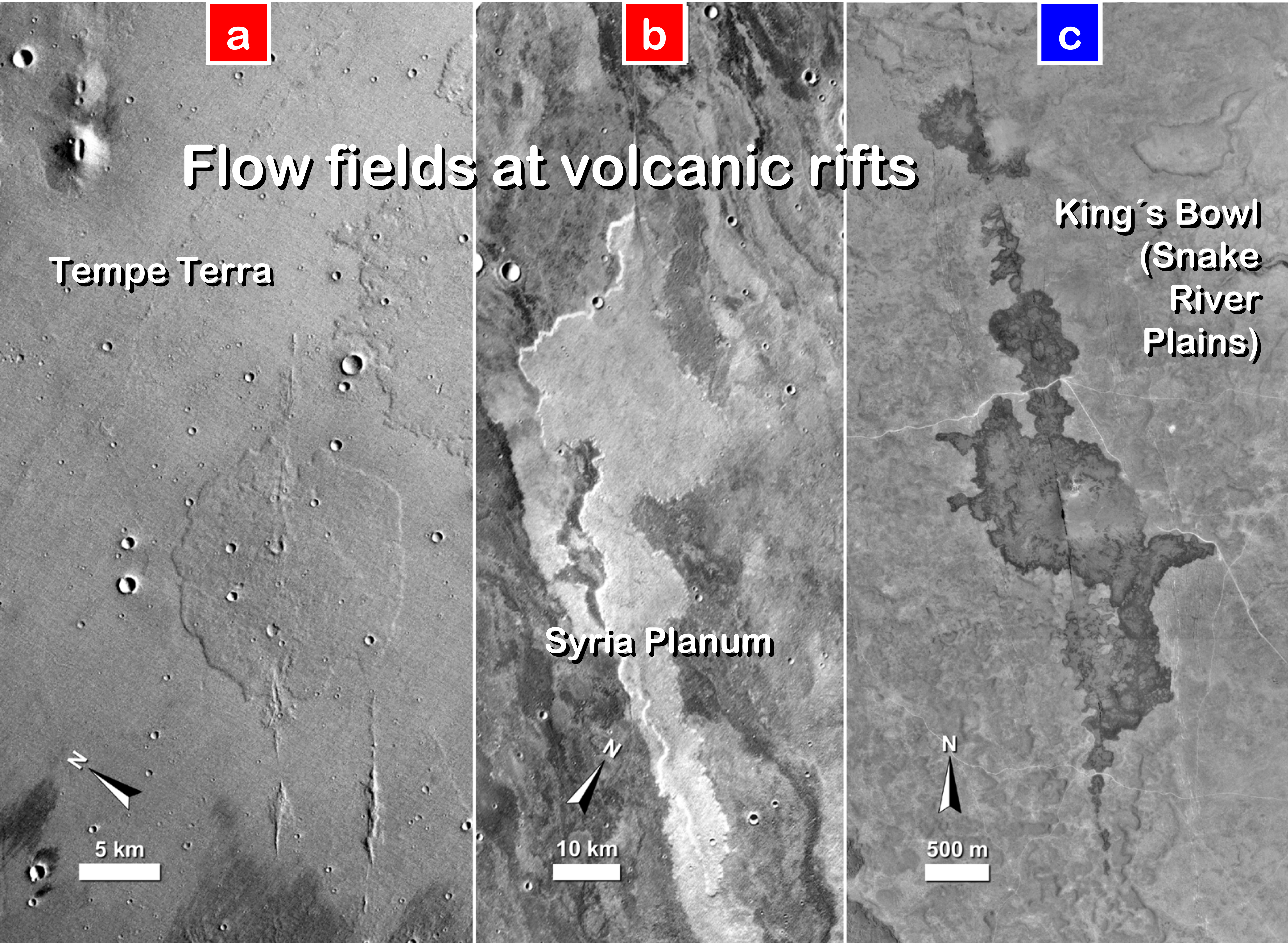



Inflation features (tumuli)
50 m
HiRISE image (25 cm/pixel)


a
50 m
c
b
1000 m
c

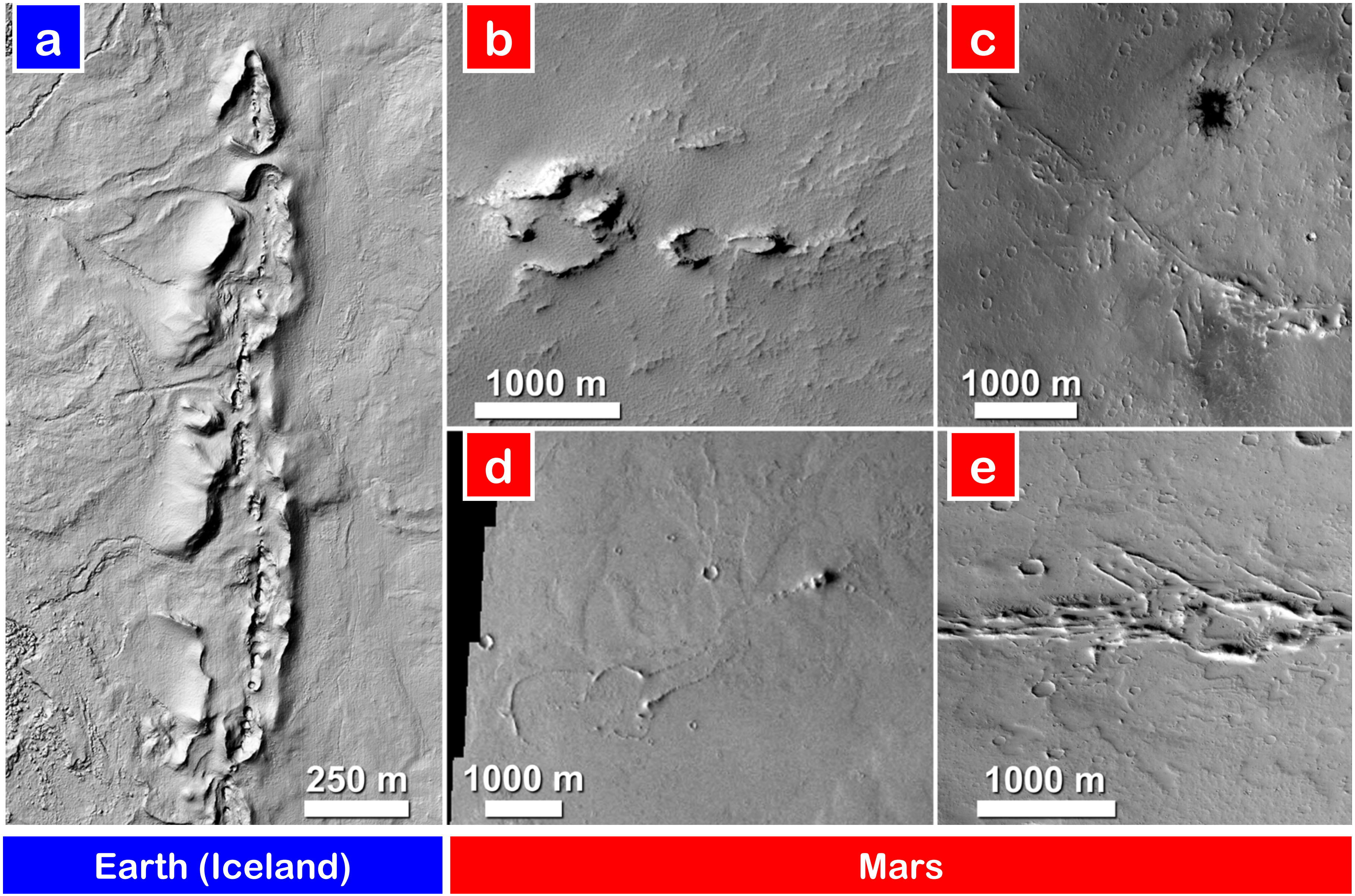
Fissure eruptions



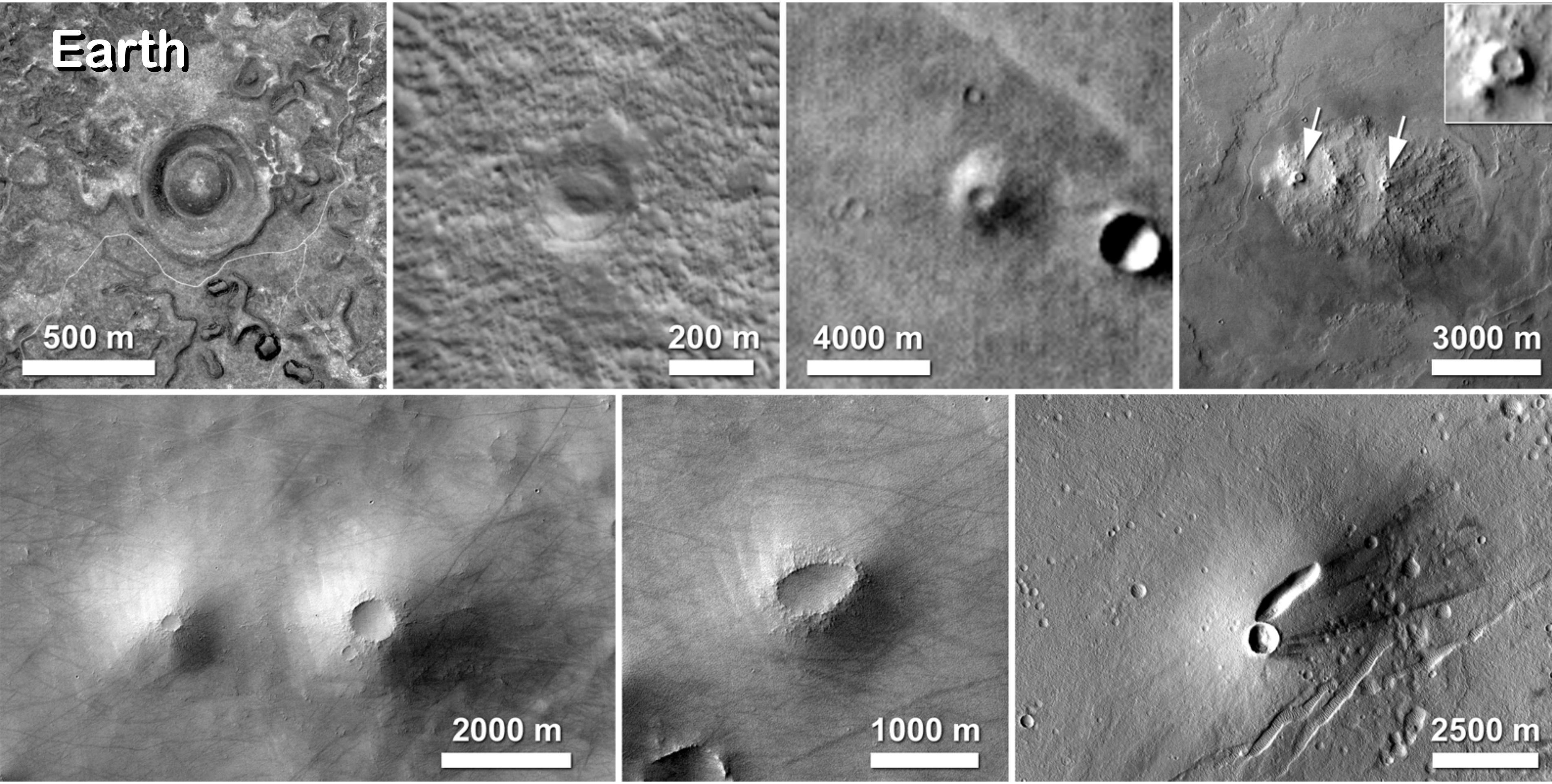


a
b
c
Flow fields at volcanic rifts
Tempe Terra
Syria Planum
King´s Bowl (Snake River Plains)
N
N
N
5 km
10 km
500 m

Spatter Cones (?)



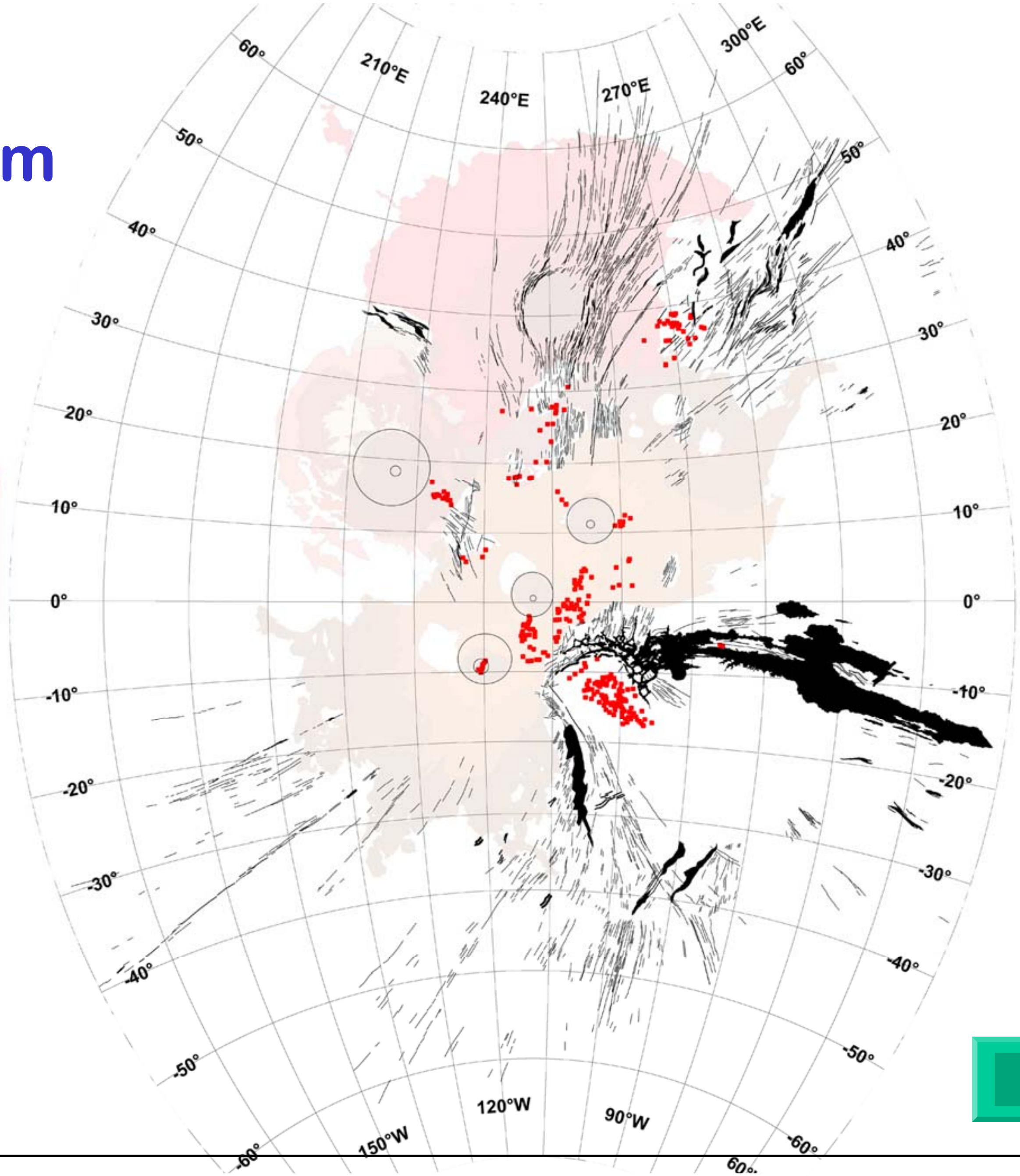
Candidate Cinder Cones



large W_{cr}/W_{co} ratios

Low shields & plains volcanism

- are found in clusters
- throughout Tharsis
- have different ages
- do not correlate with major physiographic features
- but are locally controlled by tectonic trends



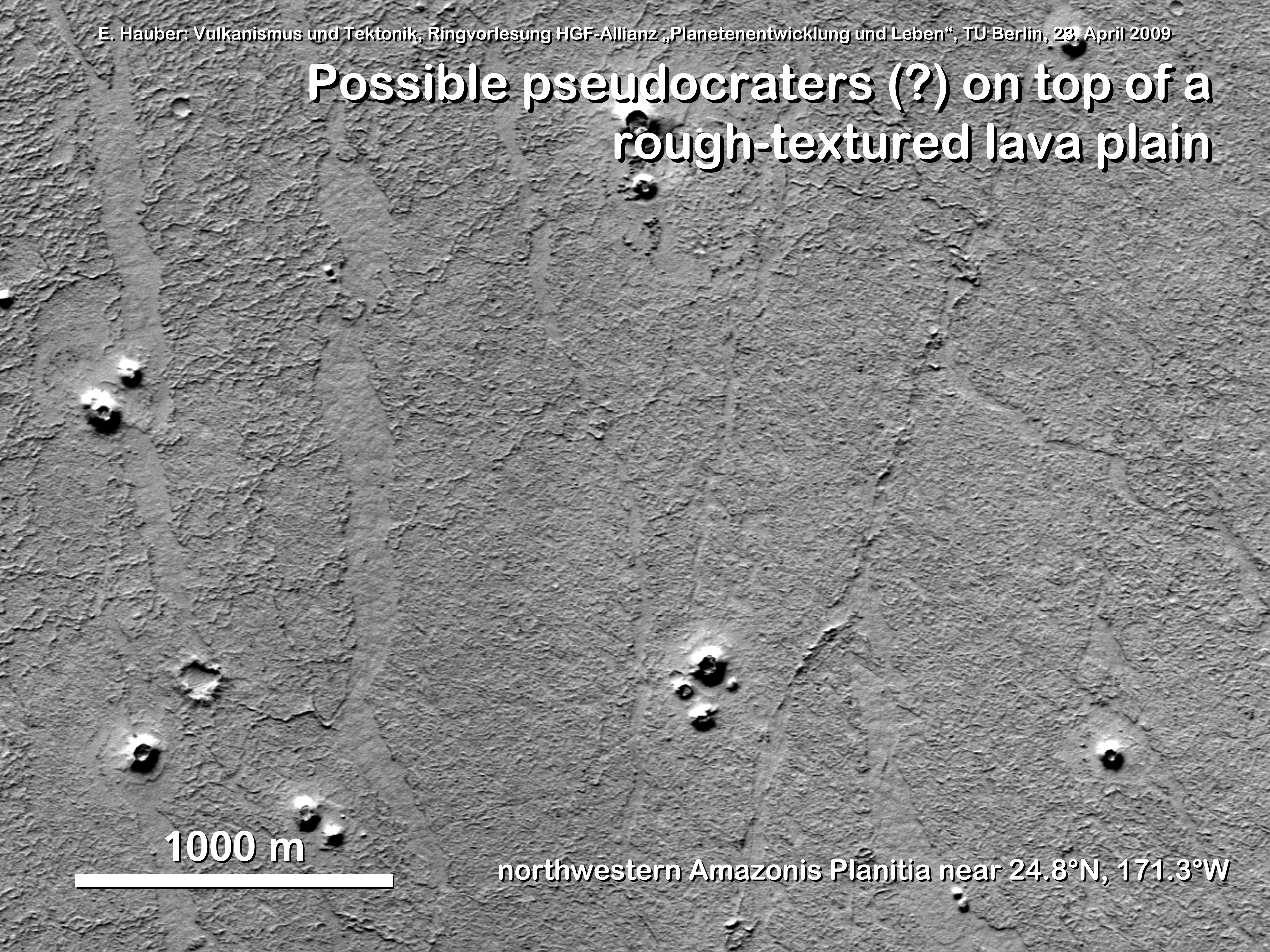
from Hauber et al., J. Volcanol. Geotherm. Res. (2009)

Säulenbasalte («columnar jointing»)

HiRISE (25 cm/pixel!)

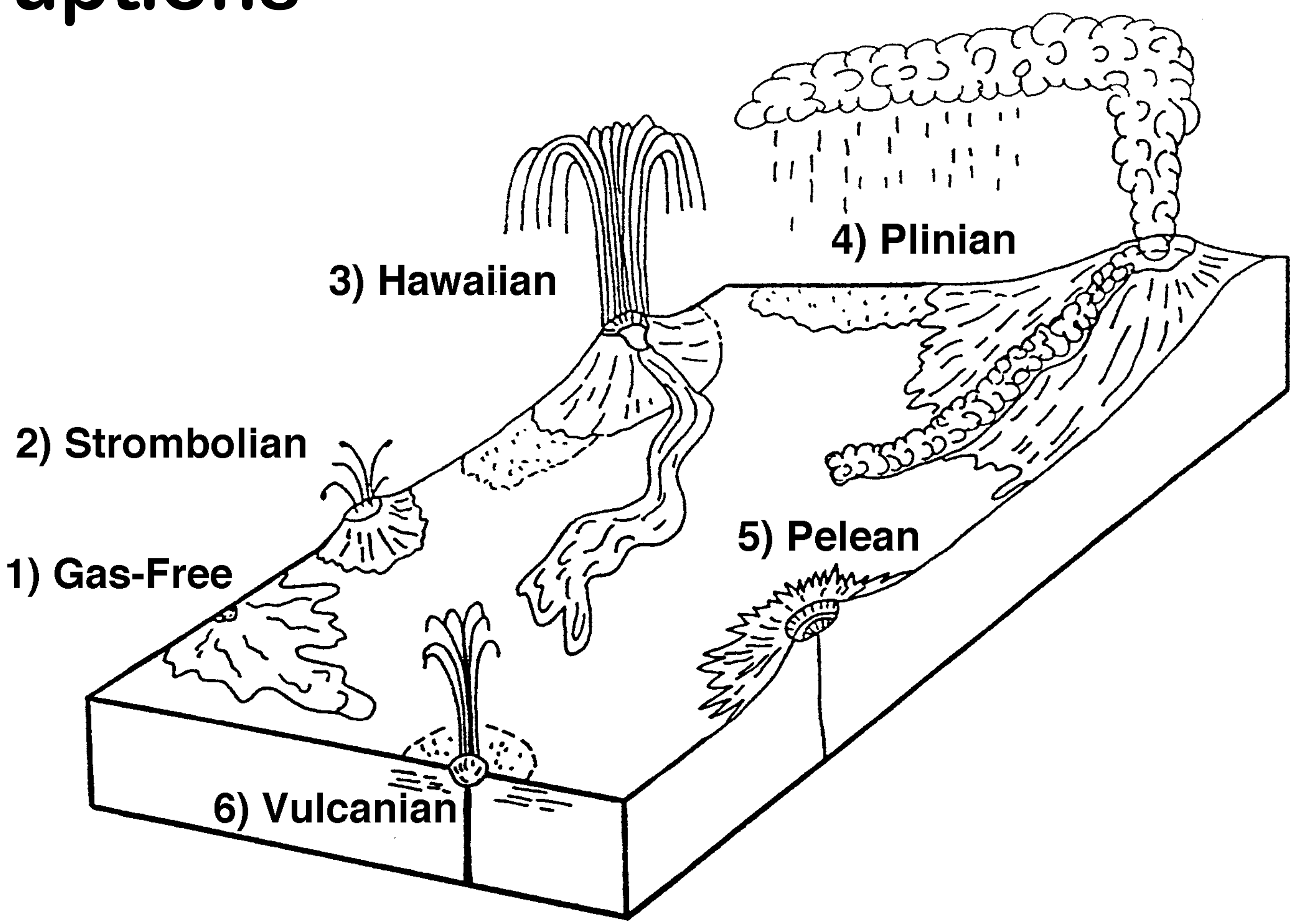
see Milazzo et al., Geology (2009)

Basaltsäulen („columnar jointing“)


E. Hauber: Vulkanismus und Tektonik, Ringvorlesung HGF-Allianz „Planetenentwicklung und Leben“, TU Berlin, 23. April 2009
Possible pseudocraters (?) on top of a rough-textured lava plain
1000 m
northwestern Amazonis Planitia near 24.8°N, 171.3°W

Pseudocraters near Lake Myvatn (Iceland)

Environmental control on volcanic eruptions



from Wilson & Head, Rev. Geophys. (1994)

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Lava fountain on Kilauea, Hawaii

Hawaiian Eruptions

Parameter	*compared to Earth*
Sinuous rilles	not expected
Cone diameter	2 x larger
Cone height	4 x lower
Central crater diameter	5 x larger
Grain sizes	10 x finer

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Lava flow on Etna, Sicily

Lava flows

Controlling factors which are different on Mars and Earth:
Gravity, Atmospheric pressure, crustal density profile, dike width

Parameter	*compared to Earth*
Heat loss by convection	100 x less efficient
Surface temperature	higher (~40°C)
Cooled skin thickness	almost identical
Effusion rates	5 x higher
Flow lengths	6 x longer

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Mauna Loa, Hawaii

Shield Volcanoes

- thousands of lava flows
- often complex caldera complexes
- often marked by rift zones
- extreme length of lava flows (several hundred km)
- extremely large diameters (up to 600 km)
- extremely high (up to 25 km above surroundings)
- extremely voluminous (stable source regions over hundreds of millions of years (or even billions of years)

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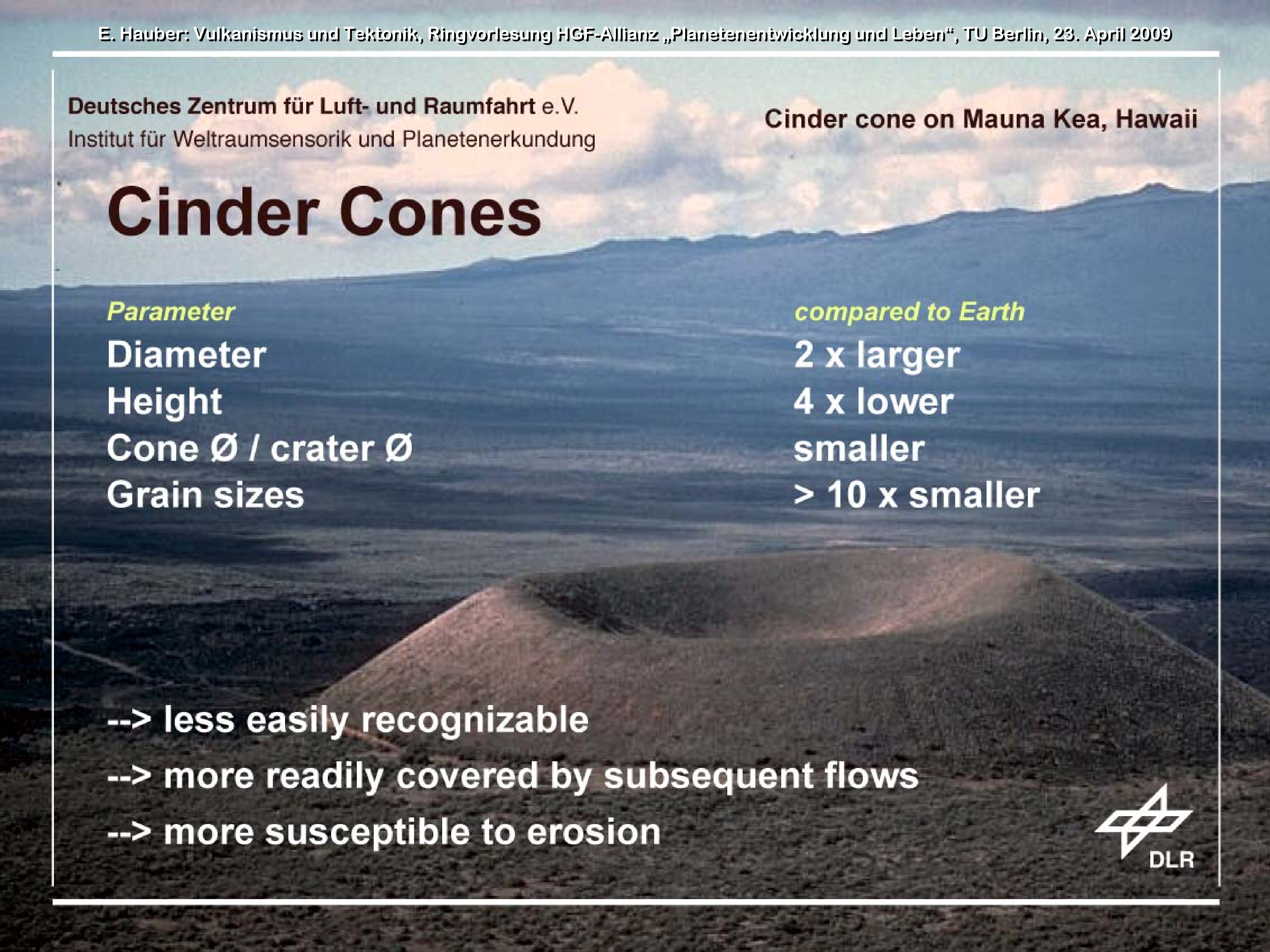

Cinder cone on Mauna Kea, Hawaii

Cinder Cones

Parameter	*compared to Earth*
Diameter	2 x larger
Height	4 x lower
Cone Ø / crater Ø	smaller
Grain sizes	> 10 x smaller

--> less easily recognizable

--> more readily covered by subsequent flows

--> more susceptible to erosion

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Explosion on Mt. Spurr, Alaska

Plinian Eruptions

Parameter	*compared to Earth*
Eruption velocities	1.5 x higher
Density of erupted gas	300 x lower
Size of largest clasts which are transported	150 x smaller
Eruption cloud height	5 x higher
Cloud shape	similar
Grain size of deposits	100 x smaller (<1cm)
Basaltic plinian eruptions	expected to be common (rare on Earth)

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Pyroclastic flow at Mt. St. Helens, USA

Pyroclastic Flows

Parameter	*compared to Earth*
Pyroclastic flow formation	more likely
Eruption speeds	1.5 x higher
Height of lava fountain feeding pyroclastic flows	>2 x higher
Travel distance	3 x greater (several hundred km)

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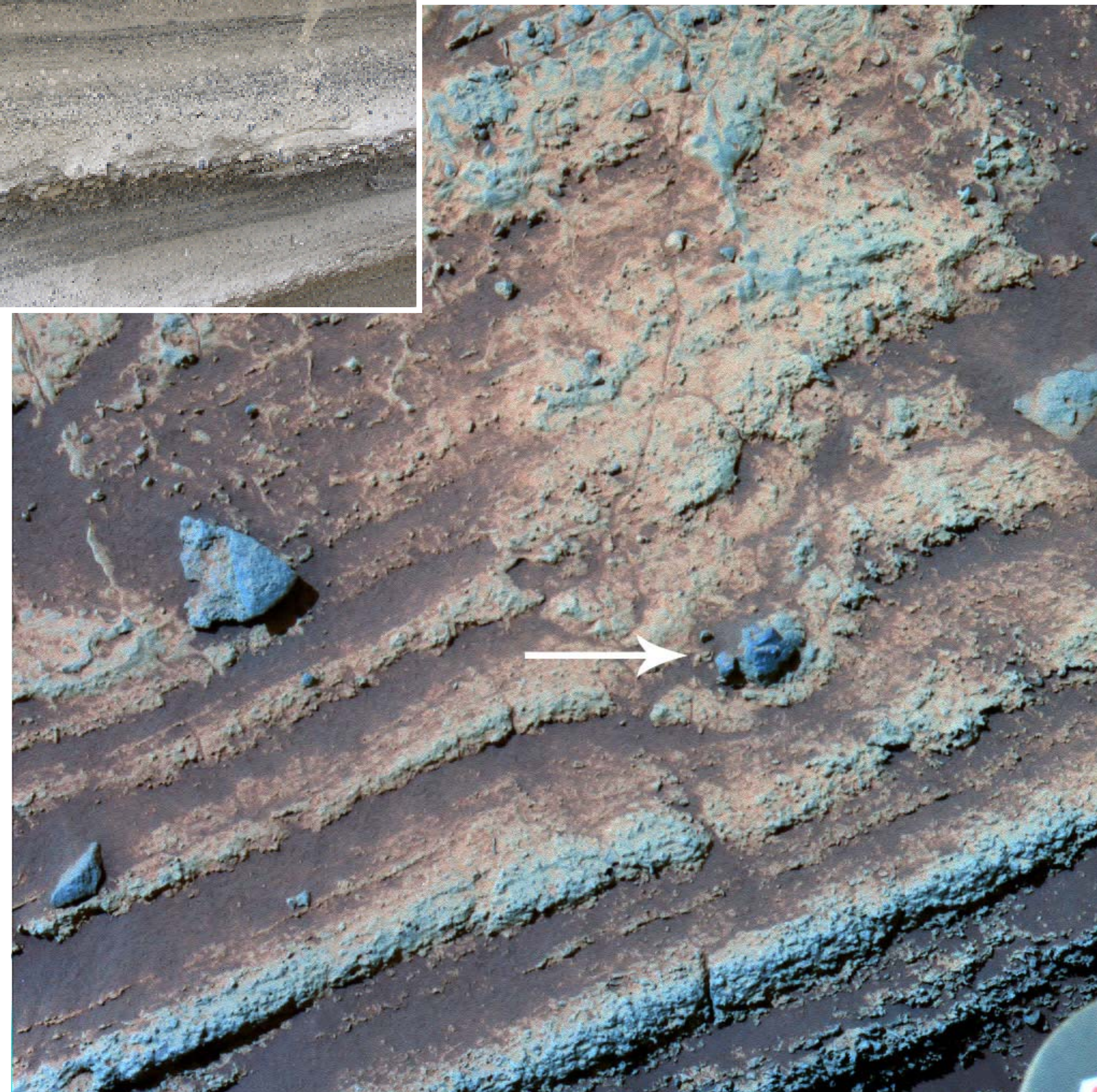
Eruption on Stromboli, Italy

Strombolian Eruptions

Parameter	*compared to Earth*
Nucleation depth	deeper
Bubble size, pressure	greater
Velocity range (large particles)	identical
Diameter of spatter cones	larger
Height of spatter cones	lower
Fine tephra	wider dispersed

DLR

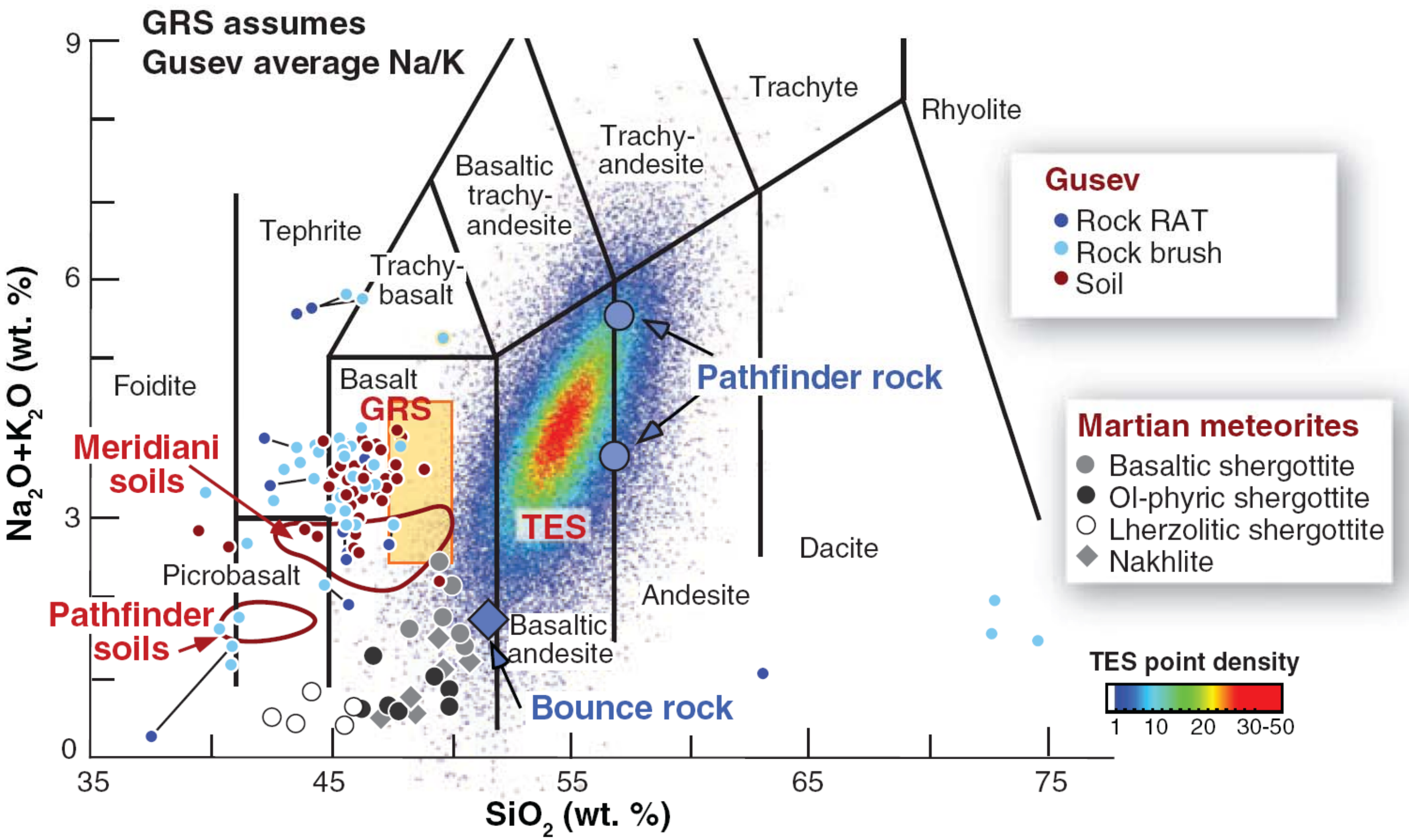
Home Plate (Gusev)



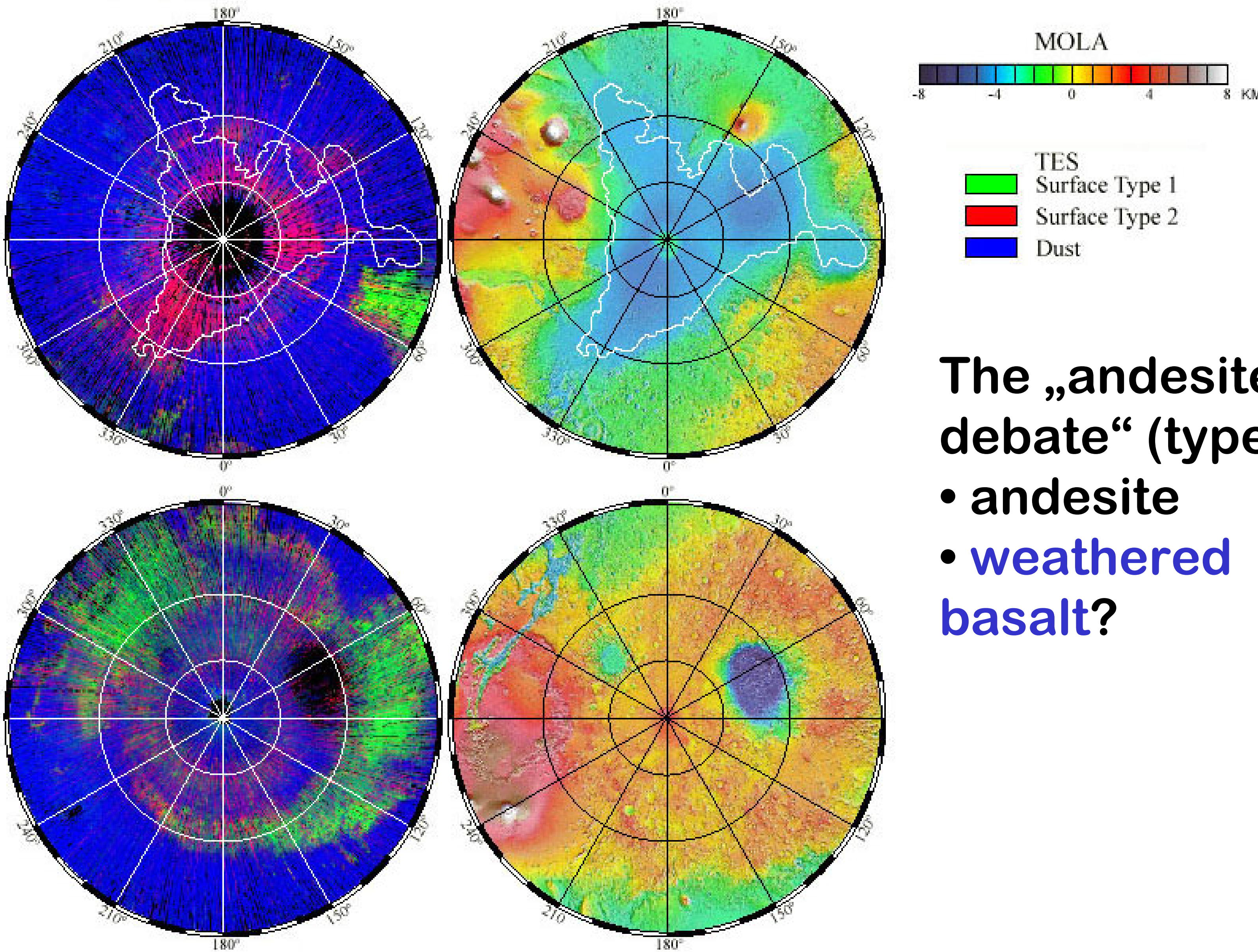
Evidence for explosive volcanism

Squyres et al., Science (2008)

Surface Composition



from McSween et al., Science (2009)

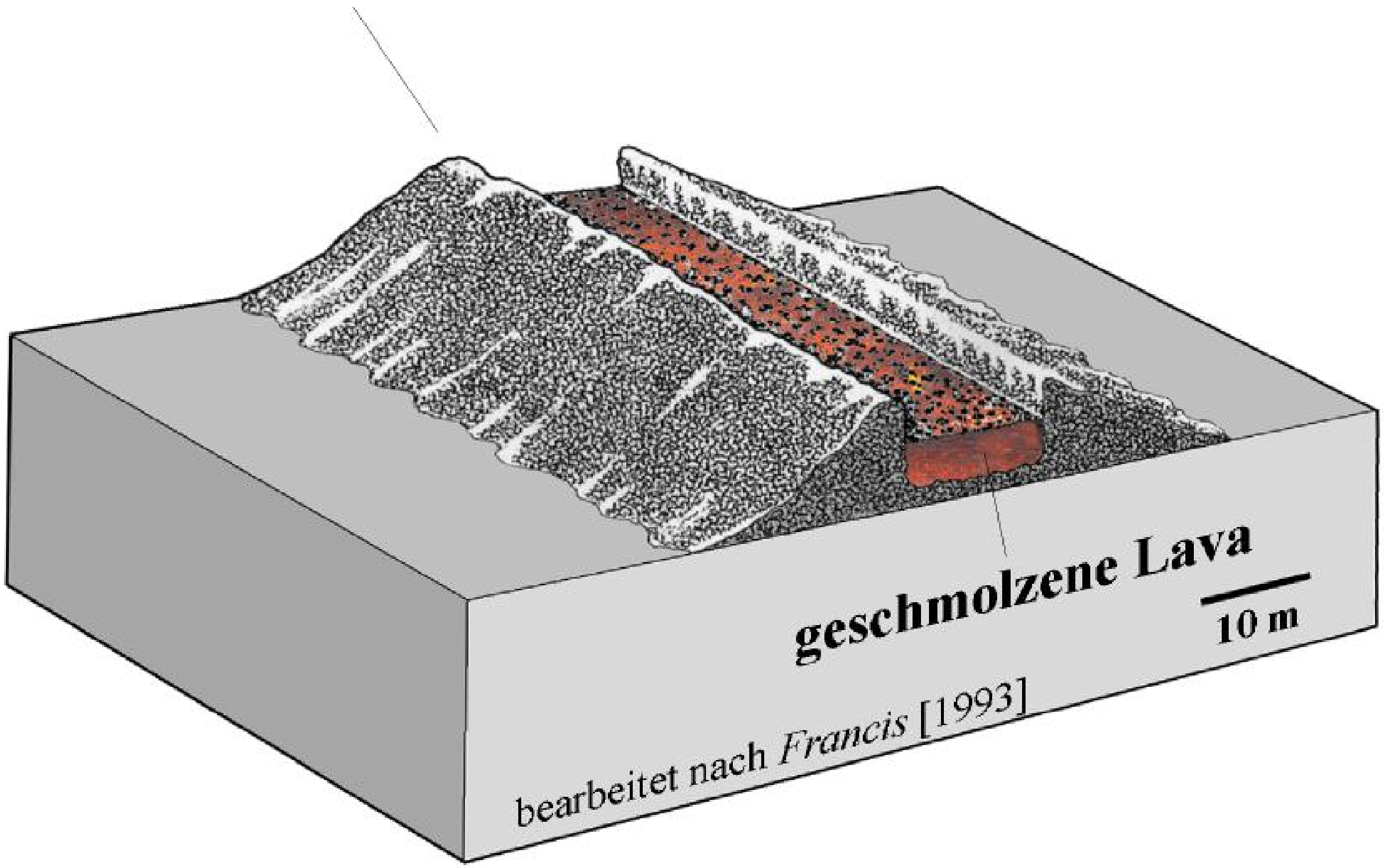


The „andesite debate“ (type 2):

- andesite
- weathered basalt?

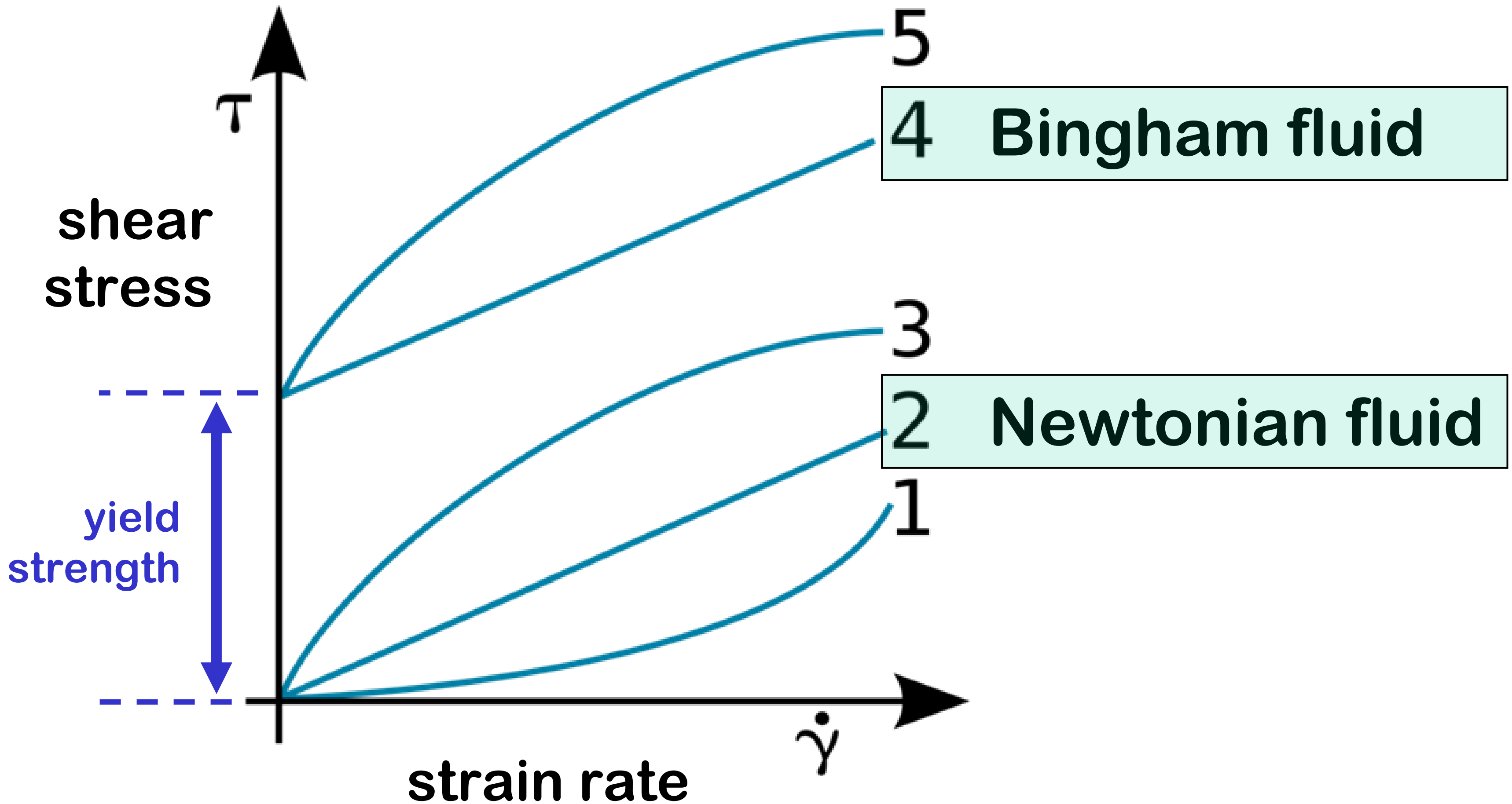
from Wyatt and McSween, Nature (2002)

Lava flow with lateral levées



levées as morphological constraints for rheology models (yield strength) (Hulme, 1974)

Rheology of lavas



Rheology: Methods

- "standard" techniques used for a long time in planetary science (poineered by, e.g., Hulme, 1974; Moore et al. 1987)
- based on the morphometry of lava flows
- assumptions as in other studies:
  - density (2500 kg m^{-3}; 2800 kg m^{-3})
  - thermal diffusivity (3×10^{-7} m^2 s^{-1})
  - Graetz number (300)

Yield strength (Pa)

$$\tau = h \cdot \rho \cdot g \cdot \sin\alpha$$

$$\tau = \rho \cdot g \cdot \frac{h^2}{w}$$

Plastic viscosity (Pa.s)

$$\eta = \frac{\rho \cdot h^4 \cdot g}{Q}$$

$$\eta = \frac{\rho \cdot g \cdot h^3 \cdot w \cdot \sin\alpha}{n \cdot Q}$$

Effusion rates (m^3/s)

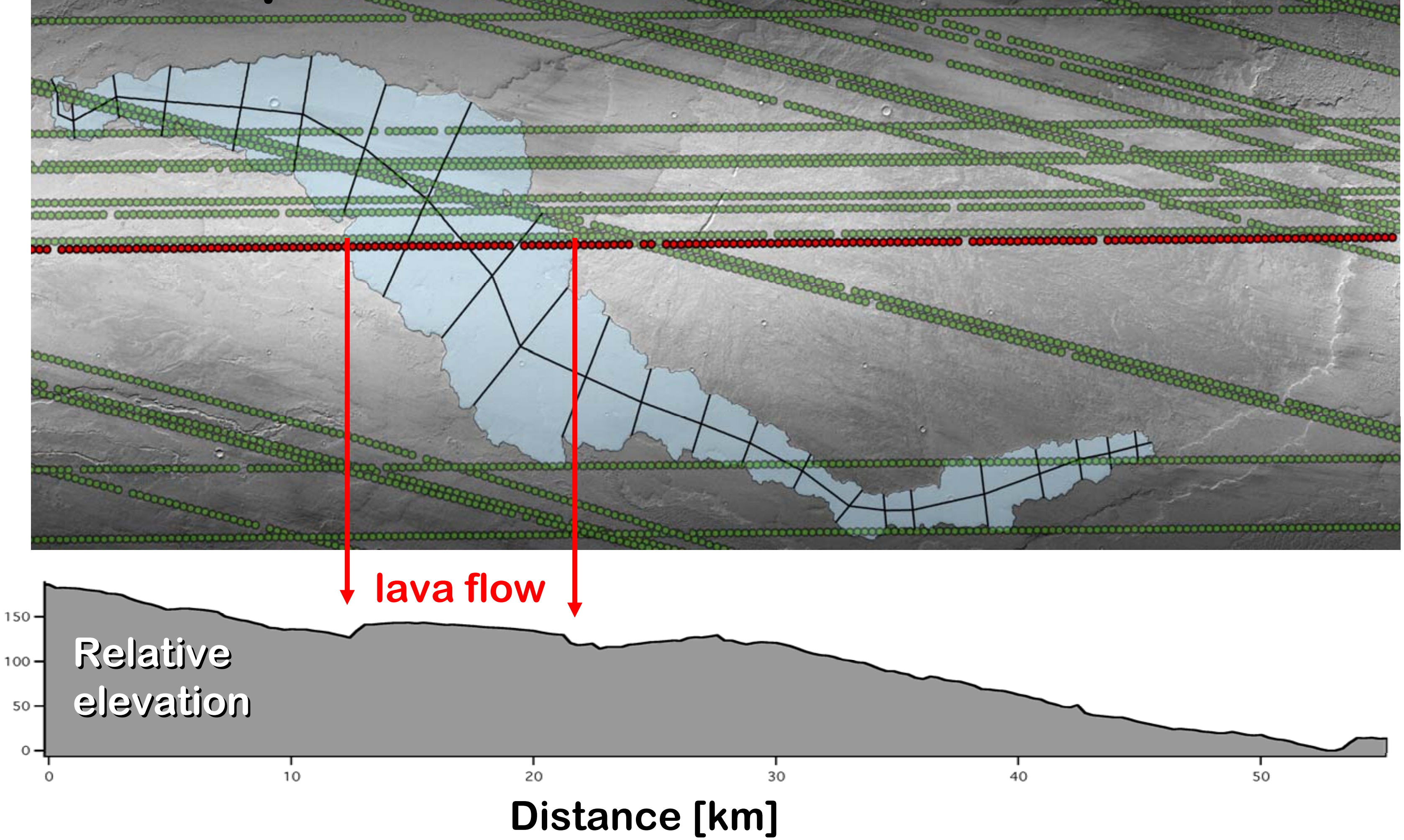
$$Q = Gz \cdot \kappa \cdot x \cdot \frac{h^2}{w}$$

Rheology: Lava Flow Morphometry

Step 1: Mapping of lava flow

Low shield with elongated vent embayed by younger lava flows

Step 2: Localization of MOLA shots



Results: Rheology (I)

- **Yield strength:** ~2 ×10^2 Pa
- **Effusion rate:** 500 – 2000 m^3 s^{-1}
- **Viscosity:** ~10^3 – 10^4 Pa s

Name	Flow Lenght (m)	Area (km^2)	Flow Width (m)	Flow Height (m)	Slope (°)	Yield strength a (Pa)	Yield strength b (Pa)	Ave. Yield Strength (Pa	Effusion Rate (m^3/s)	Viscosity 1 (Pa.s)	Viscosity 2 (Pa.s)	Ave. Viscosity (Pa.s)
a1	52194	196,03	3098	5,96	0,20	1,98E+02	1,07E+02	1,52E+02	2,44E+03	4,82E+03	2,23E+03	3,52E+03
a2	24645	107,54	4442	7,36	0,17	2,01E+02	1,14E+02	1,57E+02	1,34E+03	2,04E+04	9,03E+03	1,47E+04
b	24593	27,97	931	5,18	0,18	1,49E+02	2,69E+02	2,09E+02	3,98E+02	1,69E+04	3,11E+03	9,99E+03
c	18332	24,10	1211	6,09	0,20	1,93E+02	2,86E+02	2,39E+02	3,28E+02	3,91E+04	8,83E+03	2,40E+04
d1	22311	-	1125	4,77	0,16	1,27E+02	1,88E+02	1,58E+02	4,74E+02	1,02E+04	2,28E+03	6,24E+03
d2	18814	-	1142	5,60	0,20	1,81E+02	2,56E+02	2,19E+02	3,45E+02	2,65E+04	6,26E+03	1,64E+04
e	18598	20,36	1019	3,96	0,22	1,42E+02	1,43E+02	1,43E+02	4,31E+02	5,32E+03	1,75E+03	3,54E+03
f	16029	21,38	1139	3,54	0,23	1,34E+02	1,03E+02	1,18E+02	4,64E+02	3,15E+03	1,37E+03	2,26E+03

For density 2500 kg/m^3

Name	Flow Lenght (m)	Area (km^2)	Flow Width (m)	Flow Height (m)	Slope (°)	Yield strength a (Pa)	Yield strength b (Pa)	Ave. Yield Strength (Pa	Effusion Rate (m^3/s)	Viscosity 1 (Pa·s)	Viscosity 2 (Pa·s)	Ave. Viscosity (Pa·s)
a1	52194	196,03	3098	5,96	0,20	2,21E+02	1,20E+02	1,71E+02	2,44E+03	5,39E+03	2,50E+03	3,94E+03
a2	24645	107,54	4442	7,36	0,17	2,25E+02	1,27E+02	1,76E+02	1,34E+03	2,29E+04	1,01E+04	1,65E+04
b	24593	27,97	931	5,18	0,18	1,66E+02	3,01E+02	2,34E+02	3,98E+02	1,89E+04	3,48E+03	1,12E+04
c	18332	24,10	1211	6,09	0,20	2,17E+02	3,20E+02	2,68E+02	3,28E+02	4,38E+04	9,89E+03	2,68E+04
d1	22311	-	1125	4,77	0,16	1,42E+02	2,11E+02	1,77E+02	4,74E+02	1,14E+04	2,56E+03	6,98E+03
d2	18814	-	1142	5,60	0,20	2,03E+02	2,87E+02	2,45E+02	3,45E+02	2,97E+04	7,02E+03	1,84E+04
e	18598	20,36	1019	3,96	0,22	1,59E+02	1,61E+02	1,60E+02	4,31E+02	5,96E+03	1,96E+03	3,96E+03
f	16029	21,38	1139	3,54	0,23	1,50E+02	1,15E+02	1,32E+02	4,64E+02	3,53E+03	1,54E+03	2,53E+03

For density 2800 kg/m^3

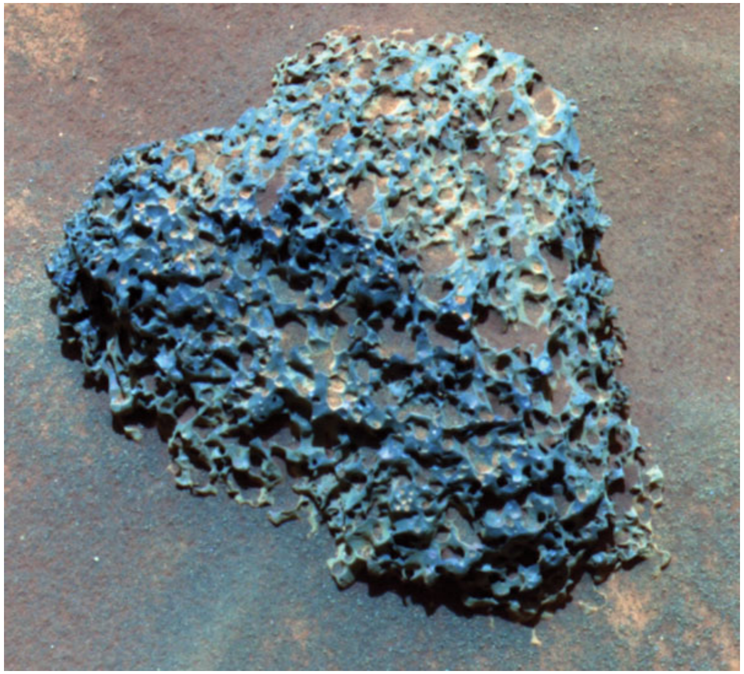
Results: Rheology (II)

Basalts!

Name	Body	Yield strength (Pa)	Effusion Rate (m^3/s)	Viscosity (Pa.s)	Source	Note
Makaopuhi, Hawaii	Earth	1.0E+02	-	-	Shaw et al. (1968)	
Mauna Loa, Hawaii	Earth	3.5E+02 - 7.2E+03	4.17E+02 – 5.56E+02	1.4E+02 - 5.6E+06	Moore (1987)	
Mare Imbrium	Moon	2.0E+02	-	-	Booth and Self (1973)	
Mairan Domes	Moon	5.3E+04 – 13.1E+04	48.0 – 51.5	1.3 – 11.5E+08	Wilson and Head (2003)	
Artemis Festoon Lobe 1	Venus	4.12E+04	1.02E+04	7.12E+06	McColley and Head (2004)	
Atalanta Festoon	Venus	1.22E+05	9.52E+02	2.34E+09	McColley and Head (2004)	
Arsia Mons	Mars	0.39E+03 – 3.1E+03	5.6E+03 – 4.3E+04	9.7E+05	Warner and Gregg (2003)	
Olympus Mons	Mars	8.8E+03 – 4.5E+04	-	2.3E+05 – 6.9E+06	Hulme (1976)	
Flows near Ascraeus Mons	Mars	2.0E+02 – 1.3E+05	23 – 4.04E+02	1.8E+04 – 4.2E+07	Hiesinger (2007)	density 2500 kg/m^3
Large flows at Central Elysium Planitia	Mars	1.0E+02 – 5.0E+05	-	2.5E+05	Vaucher (2009)	density 2800 kg/m^3
Small flows at Central Elysium Planitia	Mars	<2.0E+02	-	>1.0E+03	Vaucher (2009)	density 2800 kg/m^3
Flows east from Jovis Tholus	Mars	1.00E+02	5.00E+03	1.00E+02	Wilson (2009)	density 2500 kg/m^3
a_1	Mars	1.52E+02	2.44E+03	3.52E+03	-	density 2500 kg/m^3
a_1	Mars	1.71E+02	2.44E+03	3.94E+03	-	density 2800 kg/m^3
e	Mars	1.43E+02	4.31E+02	3.54E+03	-	density 2500 kg/m^3
e	Mars	1.60E+02	4.31E+02	3.96E+03	-	density 2800 kg/m^3

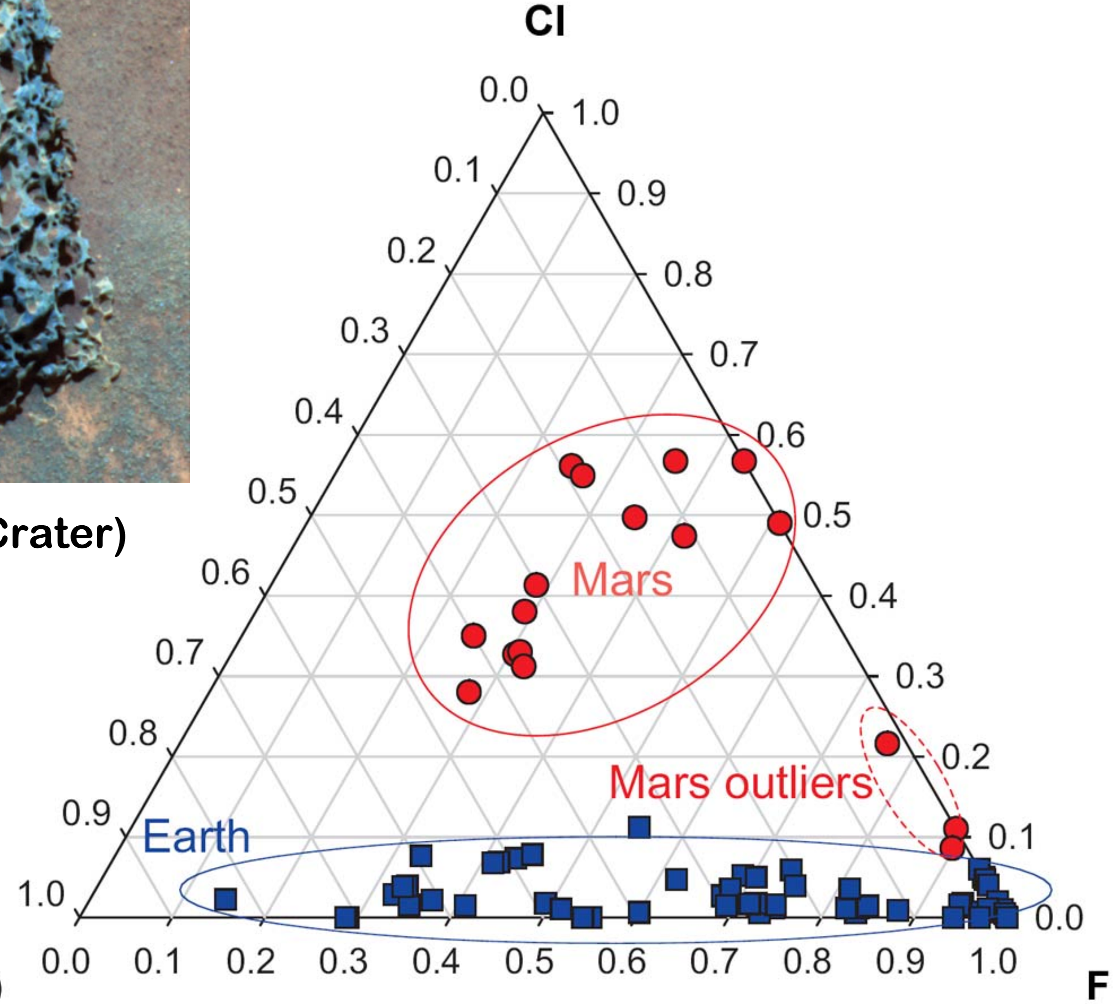
Hawaii, MORB	**$10^2 – 10^3$ Pa s**	**Griffiths (2000)**
Subduction zones: Andesite, Dacite	**$10^5 – 10^8$ Pa s**	**Griffiths (2000)**

Water content in Martian magmas



Vesicular Basalt (Gusev Crater)

Water content of SNCs is contentious (McSween, Nature, 2009)



from Filiberto and Treiman, Geology (2009)

Outgassing

- Mapping of exposed volcanic materials to determine their areal extent (conservative approach)
- Age assignment using impact crater distribution (Tanaka, 1986)
- Thickness estimation by examining partly buried impact craters or buried craters for which imprints of the rim are visible for lava plains (method of De Hon, 1974)
- Volumes estimates from areal extent and thicknesses
- assumed intrusive-to-extrusive ratio as on Earth (5:1 to 12:1; Crisp, 1984) → average ratio of 8.5:1

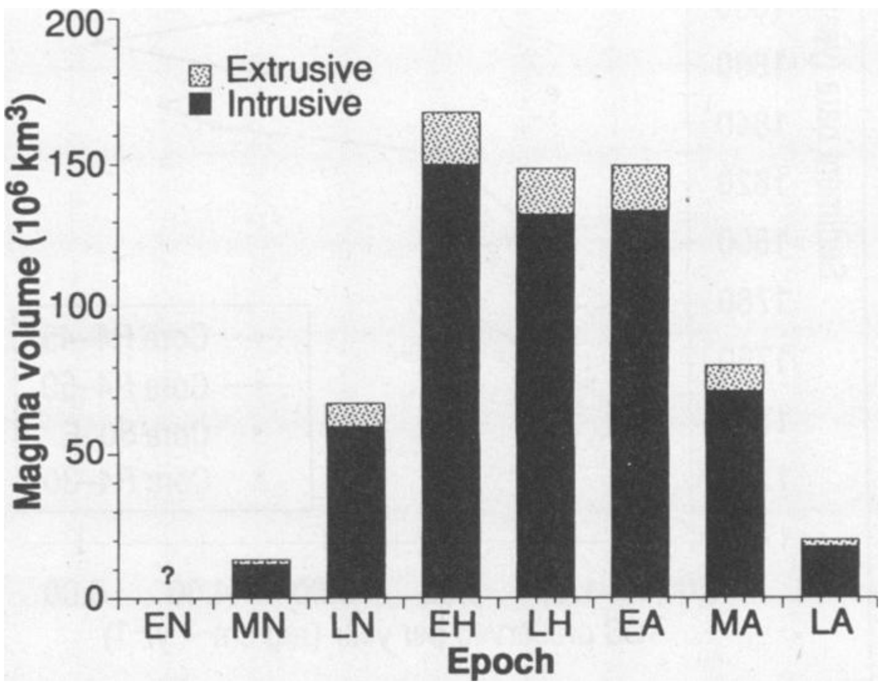
from Greeley and Schneid, Science (1991)

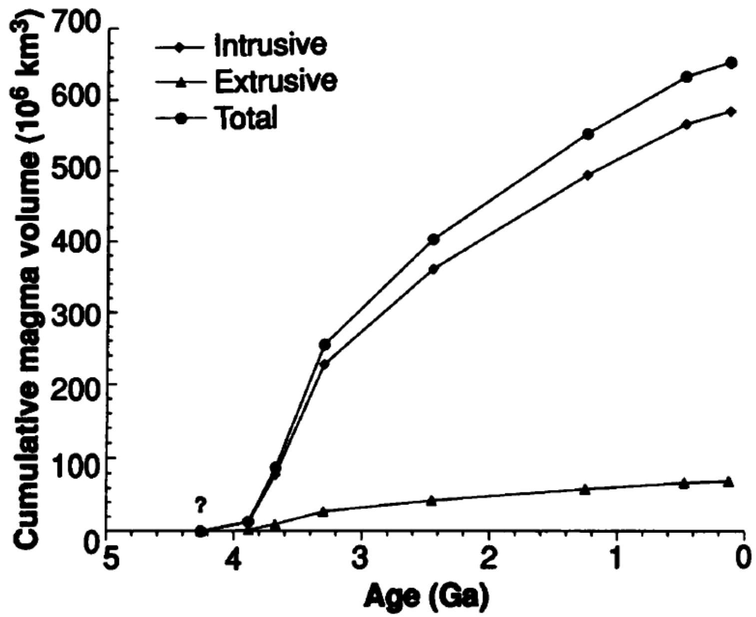
✓ Total area covered by volcanic units: 66.2 x 10^6 km^2 or 46 % of the surface

✓ Average thickness of volcanic plains: 170 m in LN to 320 m in MA

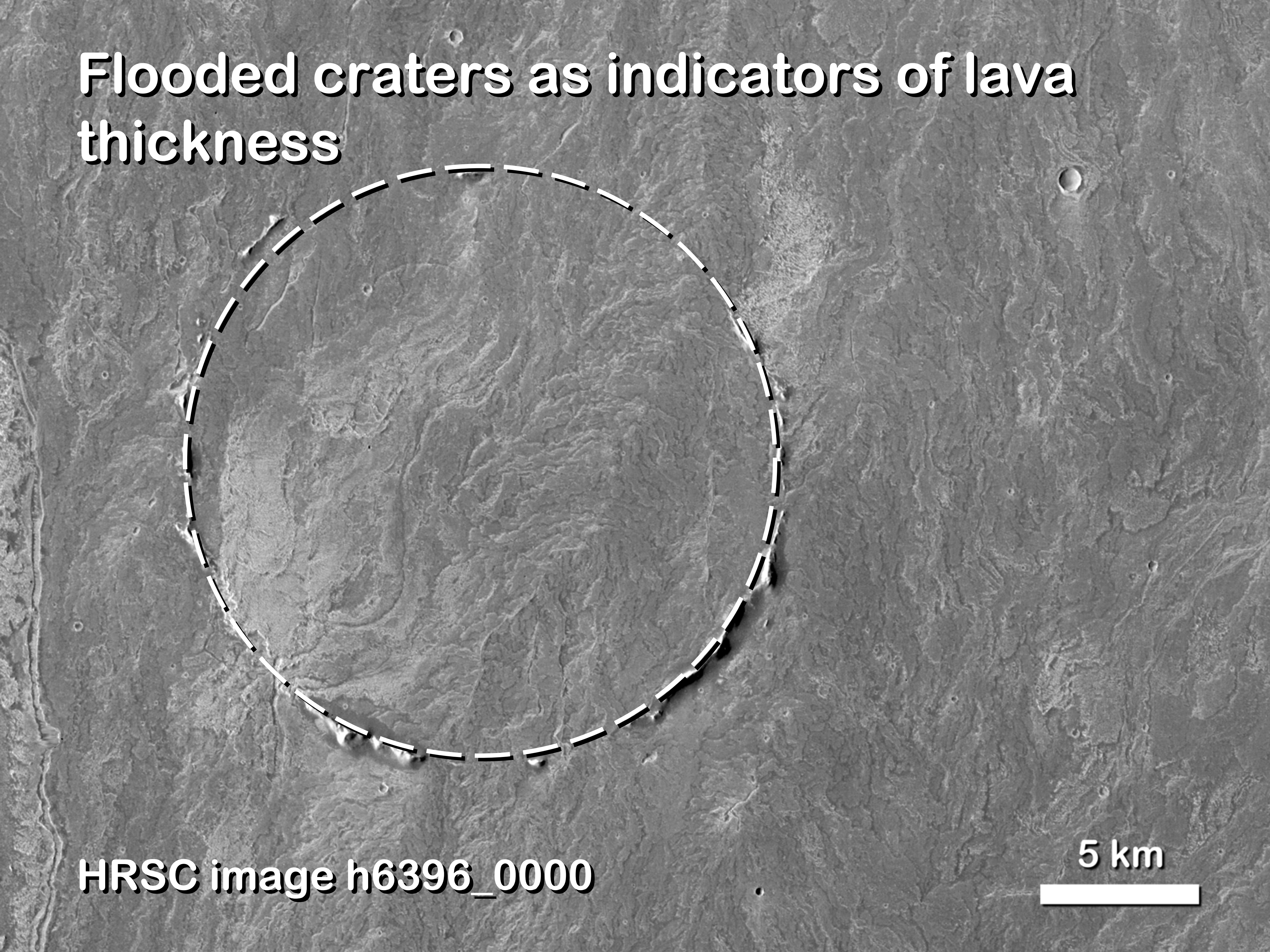
✓ Total magma volume: 654 x 10^6 km^3 or 0.17 km^3/yr

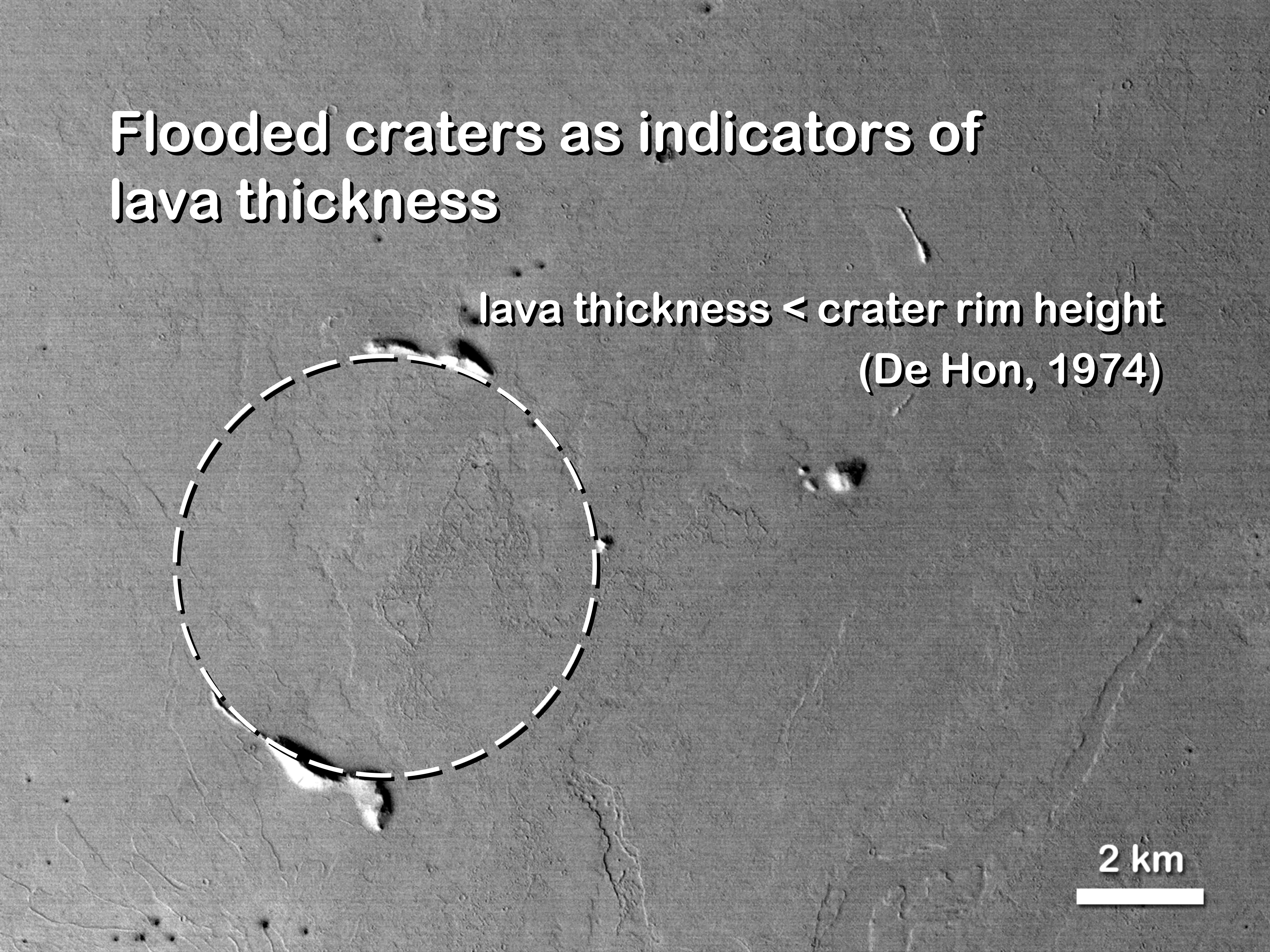
✓ On Earth: 26 to 34 km^3/yr

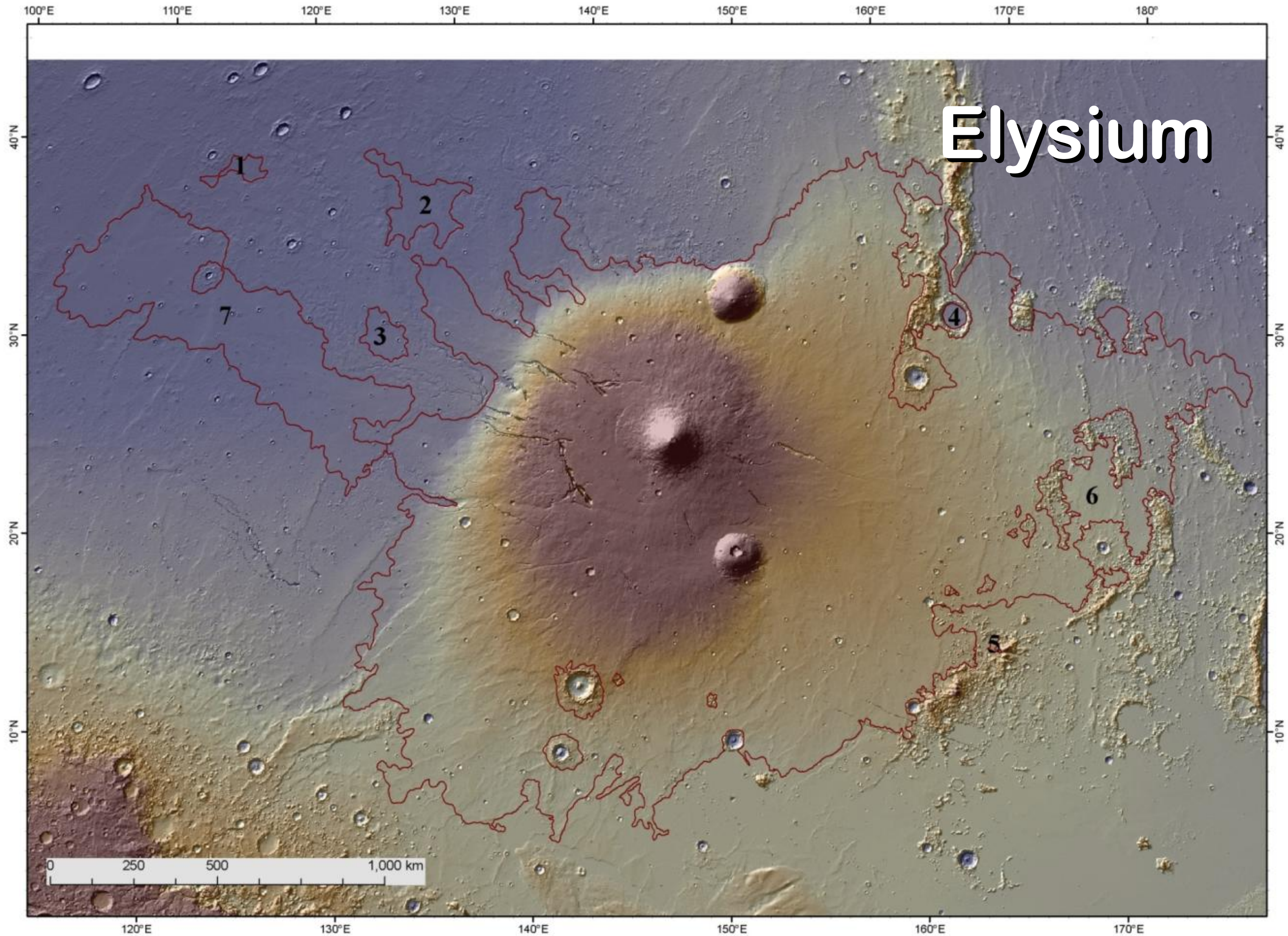




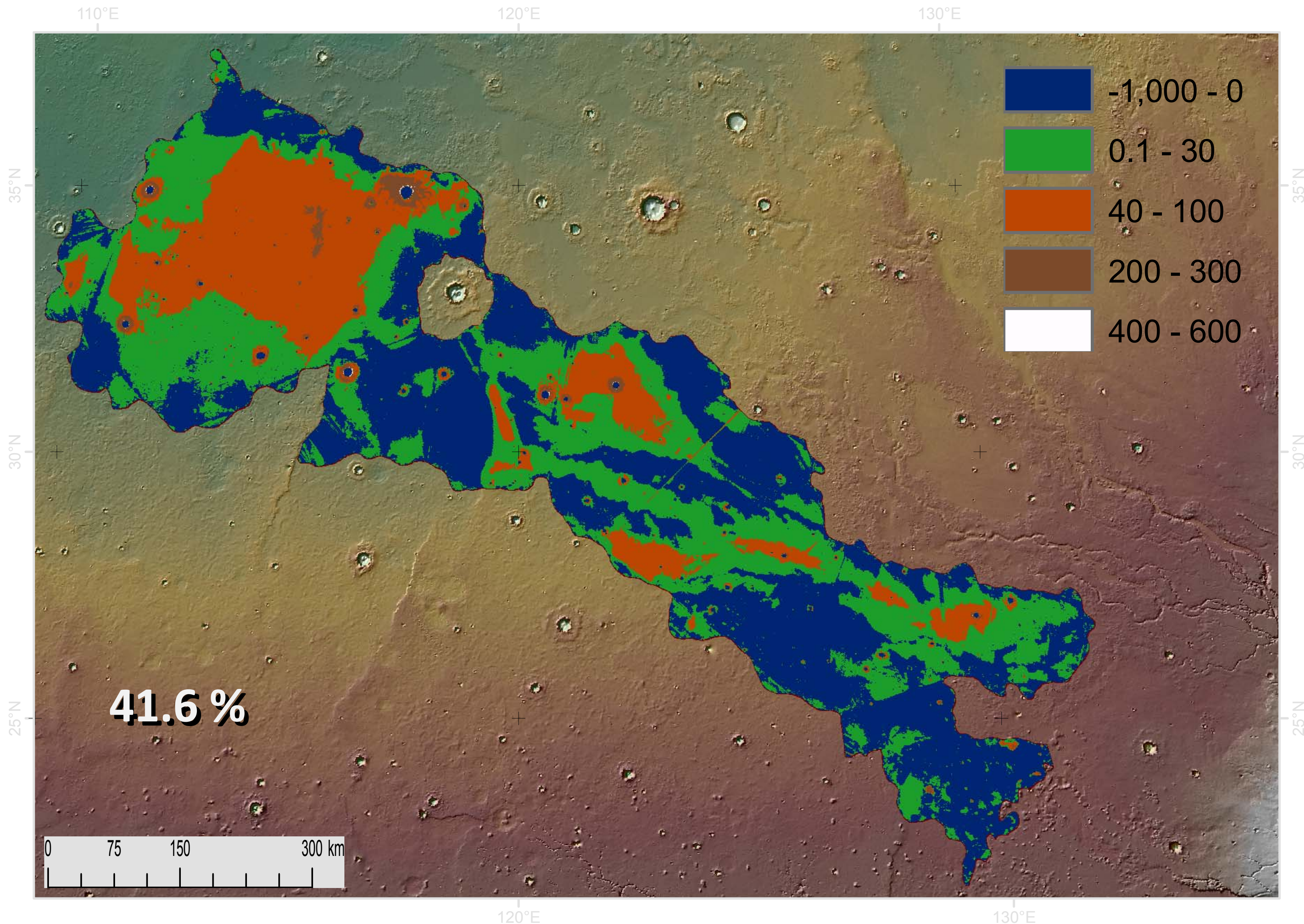
from Greeley and Schneid, Science (1991)


Flooded craters as indicators of lava thickness
HRSC image h6396_0000
5 km


Flooded craters as indicators of lava thickness
lava thickness < crater rim height
(De Hon, 1974)
2 km

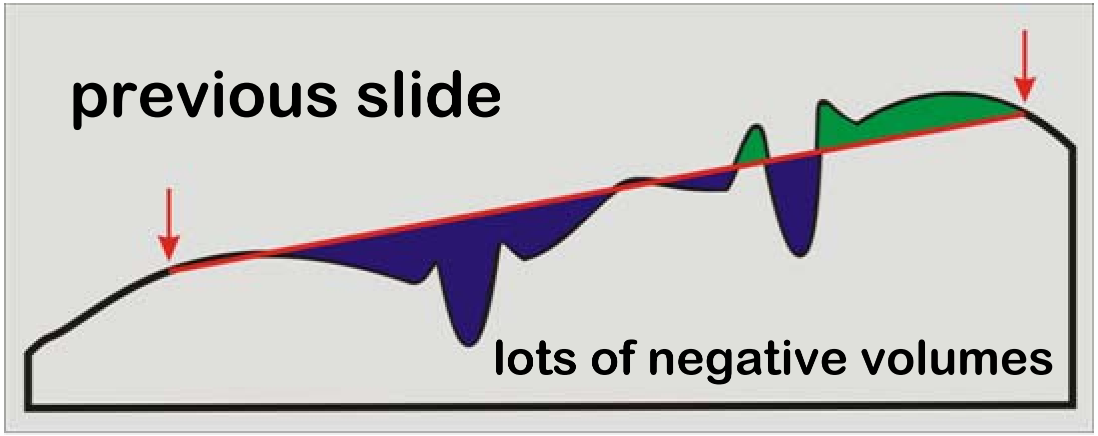


from Platz et al. (in preparation)

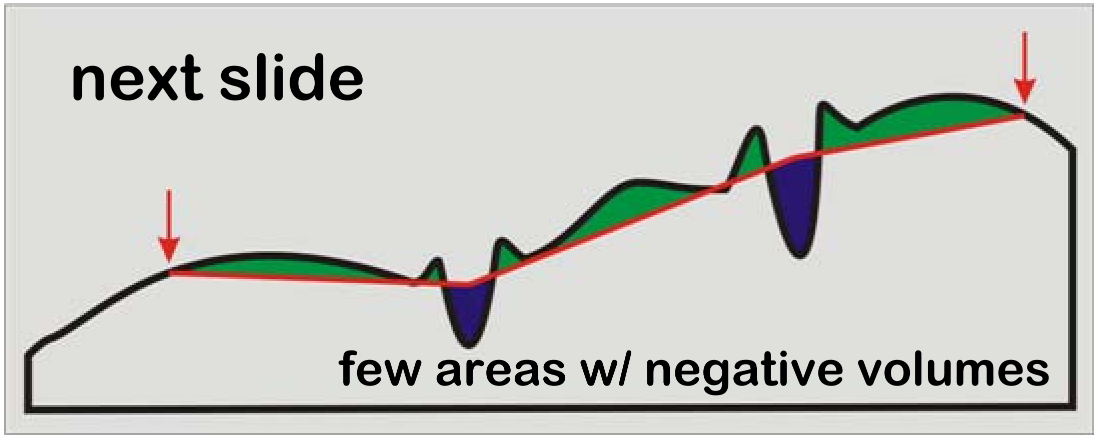


from Platz et al. (in preparation)

Reliable thickness estimates

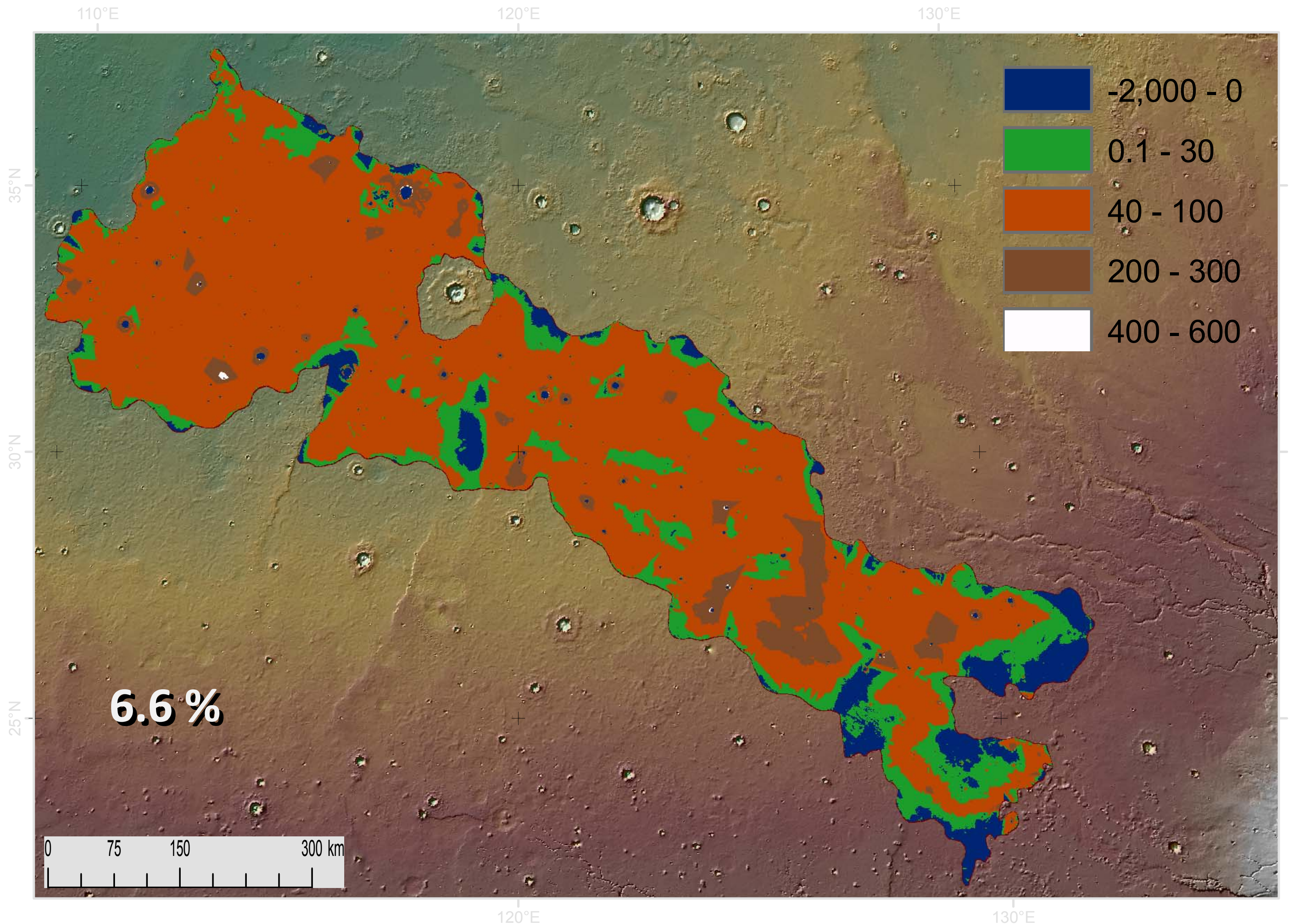


plane fit through perimeter of mapped unit: wrong estimate



plane adjusted using craters: improved estimate

from Platz et al., Earth Planet. Sci. Lett. (in press)



from Platz et al. (in preparation)

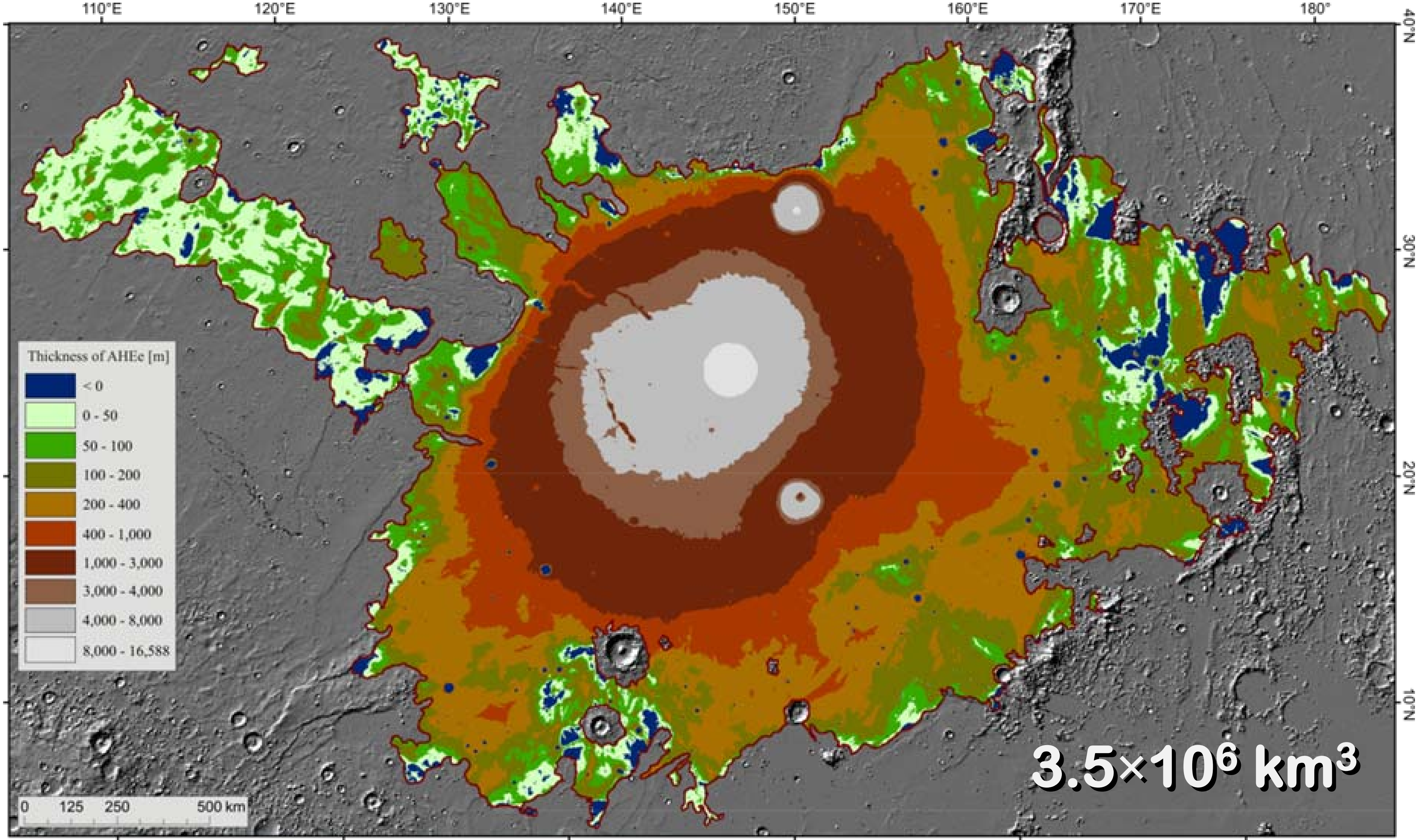


Figure 2: Distribution of thickness estimates in the Elysium volcanic region.

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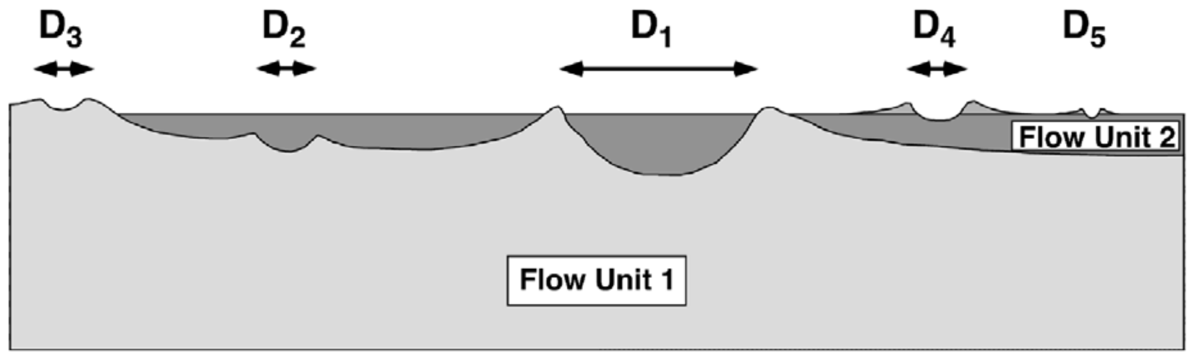
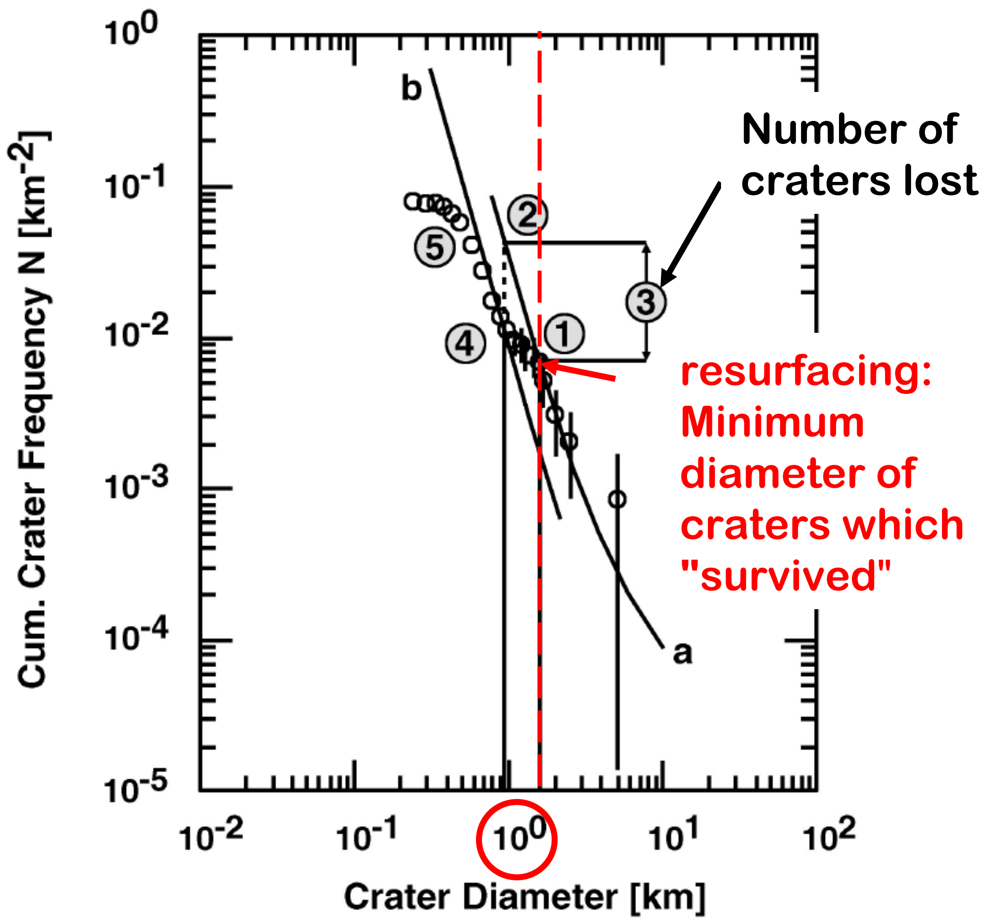
from Platz et al. (in preparation)

craters < D1 destroyed by resurfacing of flow unit 1 by flow unit 2



Thickness estimation by analysis of crater size frequency distribution



from Hiesinger et al., 2002

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EPSL-10303; No of Pages 8

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Confident thickness estimates for planetary surface deposits from concealed crater populations

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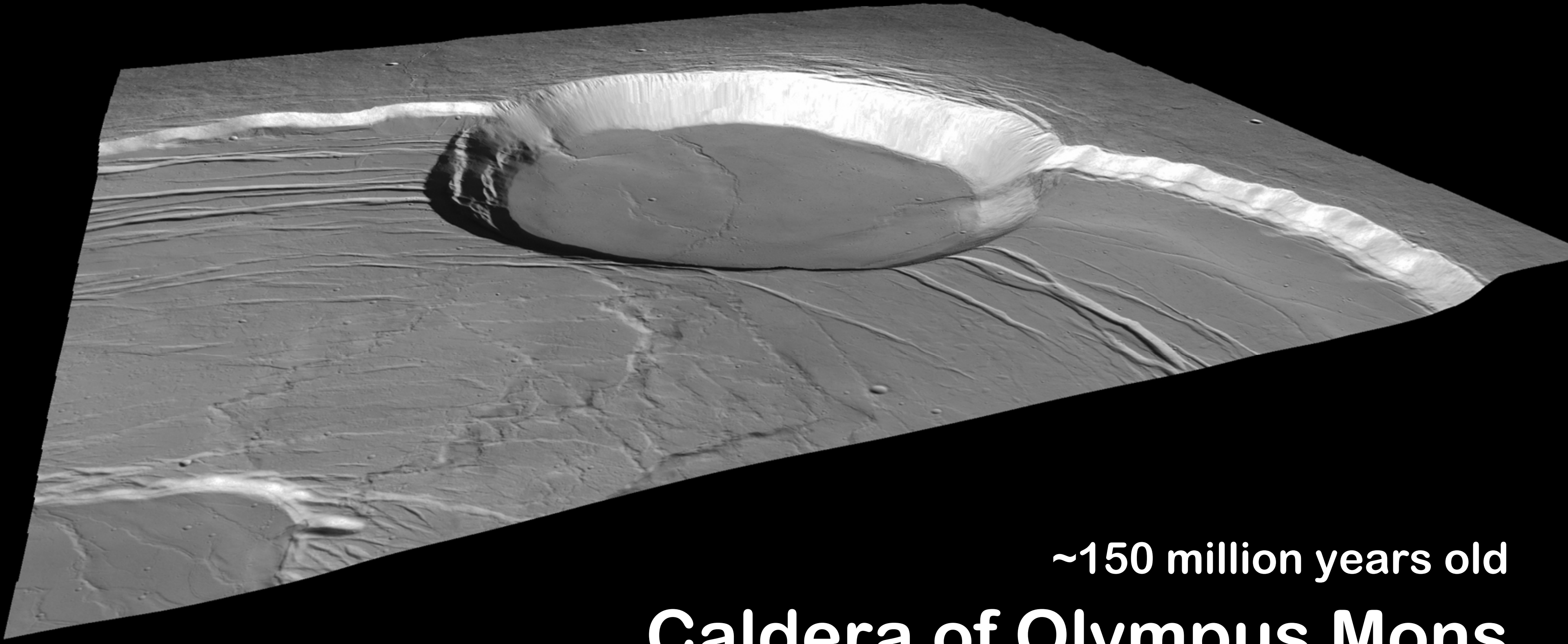
ABSTRACT

An improved technique is presented to determine more accurately deposit thicknesses of any surface units using crater size-frequency distributions (CSFDs). This new approach enables thickness estimates of deposits that completely cover their underlying unit, i.e., where no flooded craters are observed. Here, the crater populations of the unit of interest and its underlying unit (or a representative surface area) are measured and their cratering model ages determined. The CSFD of the younger unit is then treated as if it had the same age as the older unit and the expected cumulative numbers of craters for each bin size are calculated. The crater

Ages of Martian volcanism



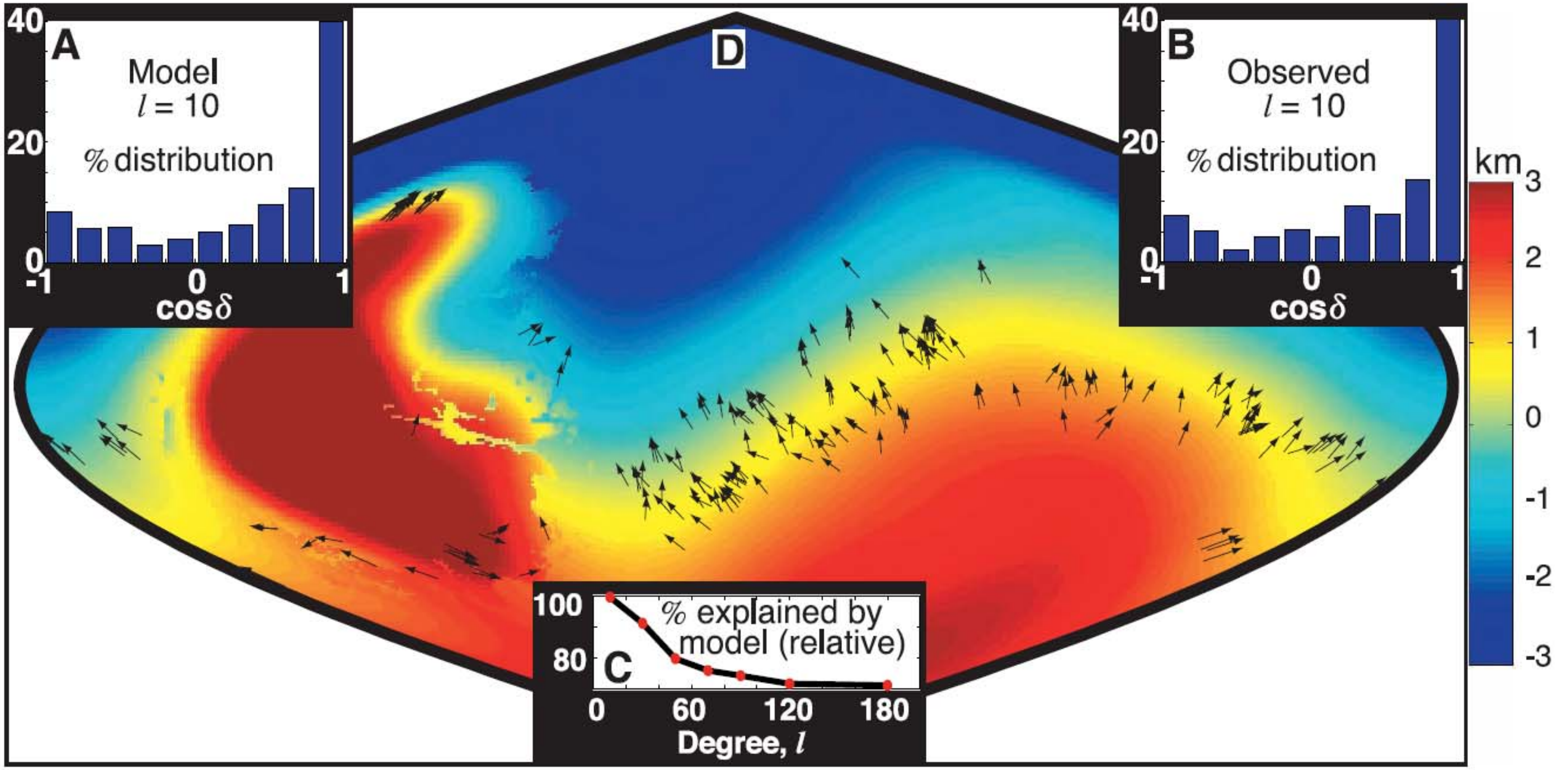
~150 million years old

Caldera of Olympus Mons

Tharsis: An old construct

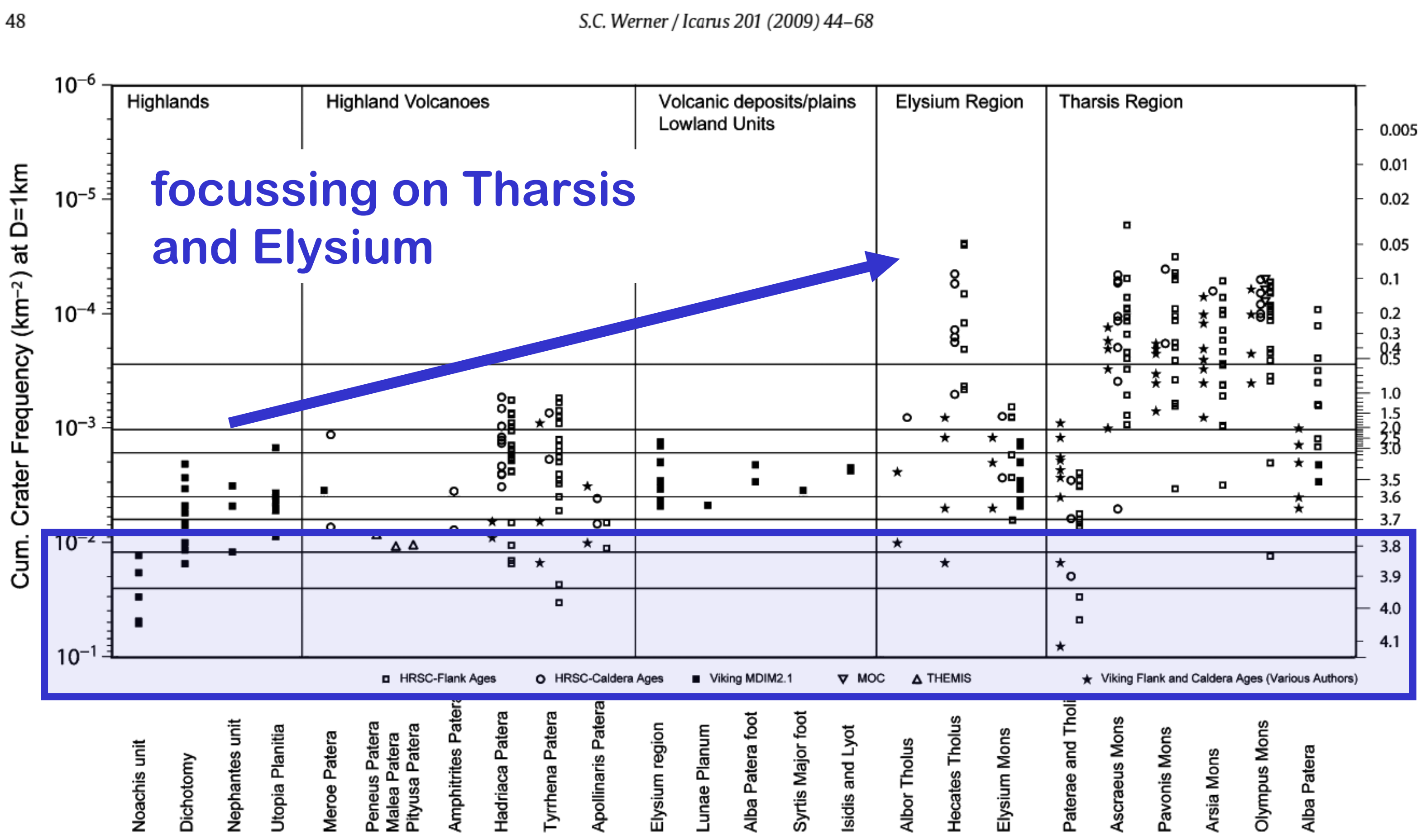
(but how old exactly…?)

Old valley networks formed after Tharsis



from Phillips et al., *Science* (2001)

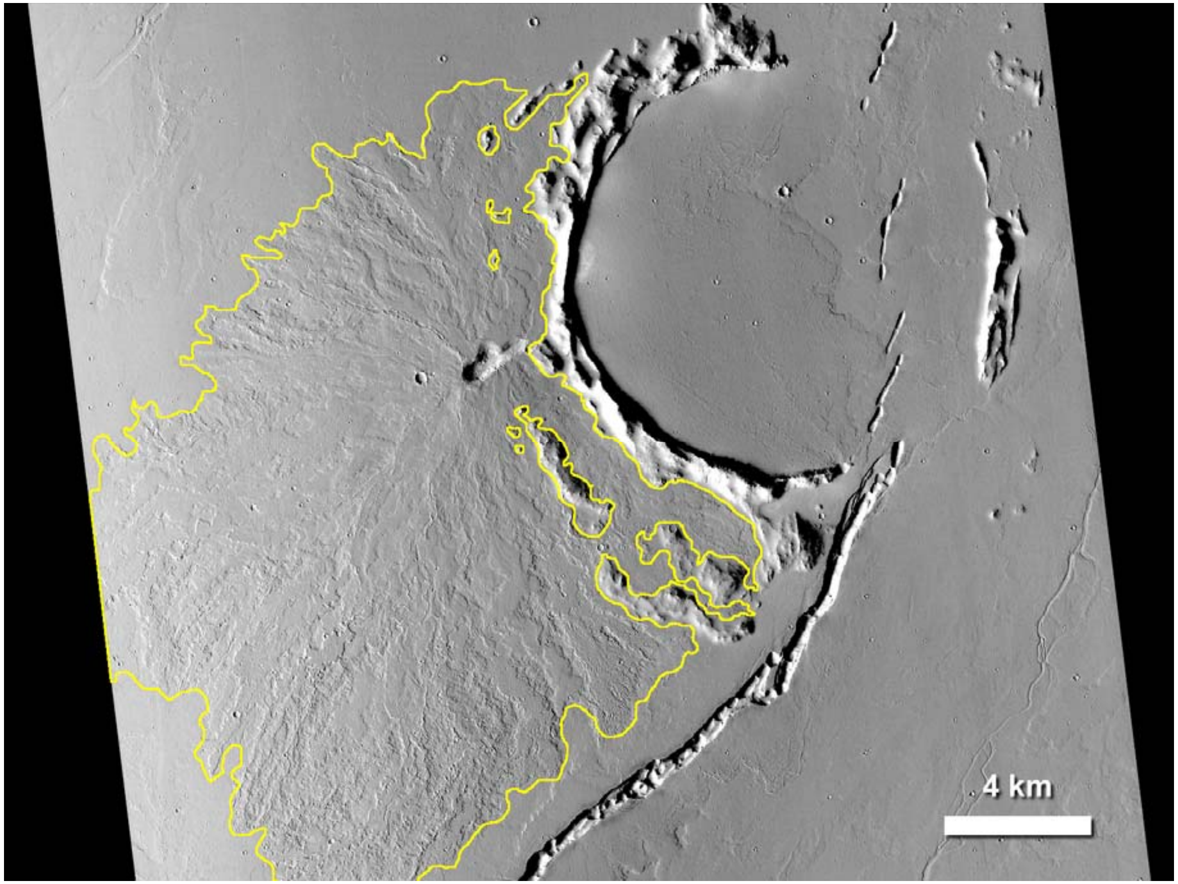
Chronology of Martian volcanism



from Werner, Icarus (2009)

Methods (I)

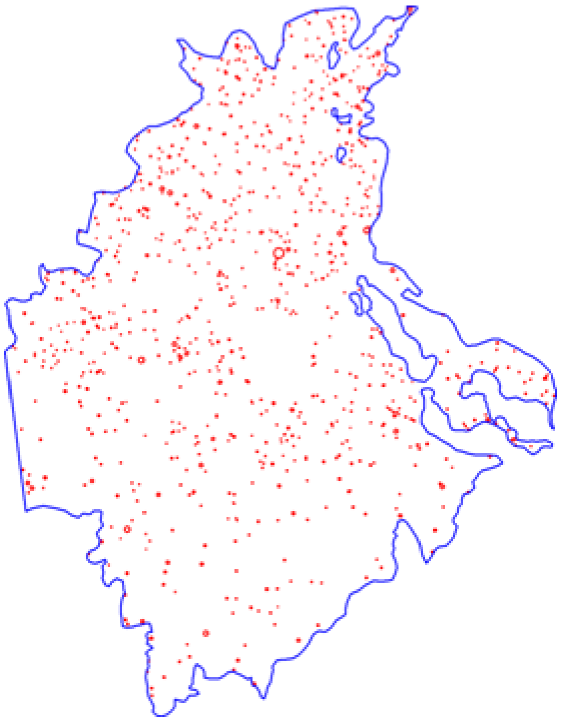
Mapping of volcanic units

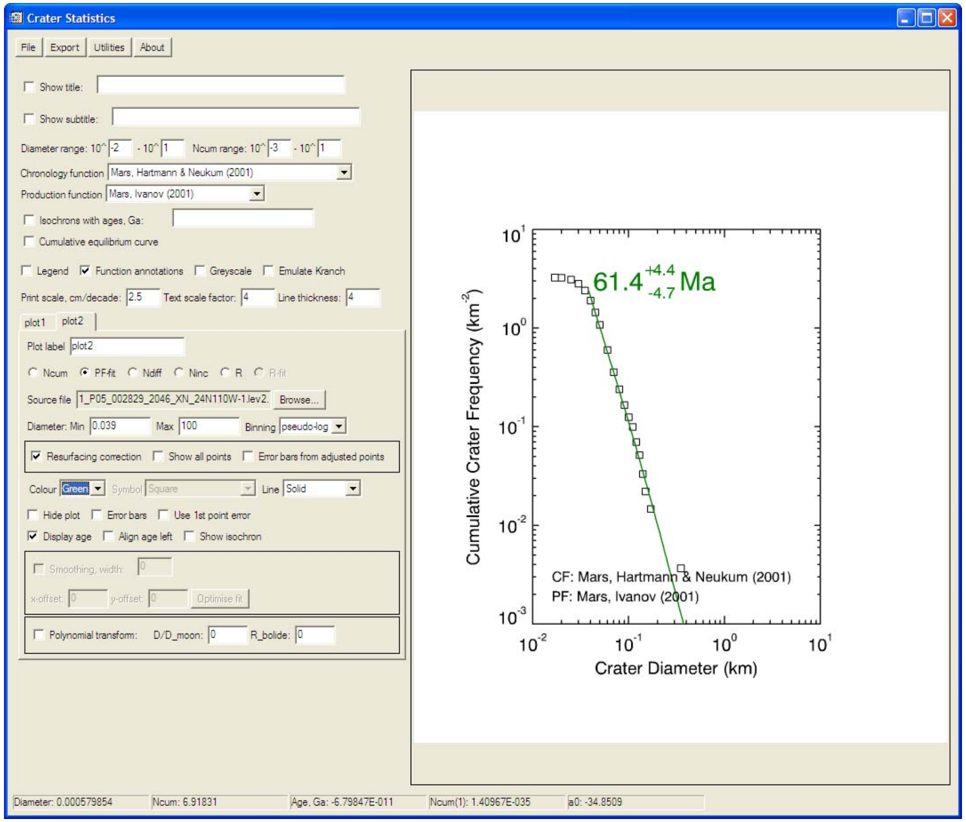


- craters with diameters of ≥ 50 m (Ø 10 pixels)
- sometimes only ≥ 100 m (Syria Planum: 250 m)

Methods (II)

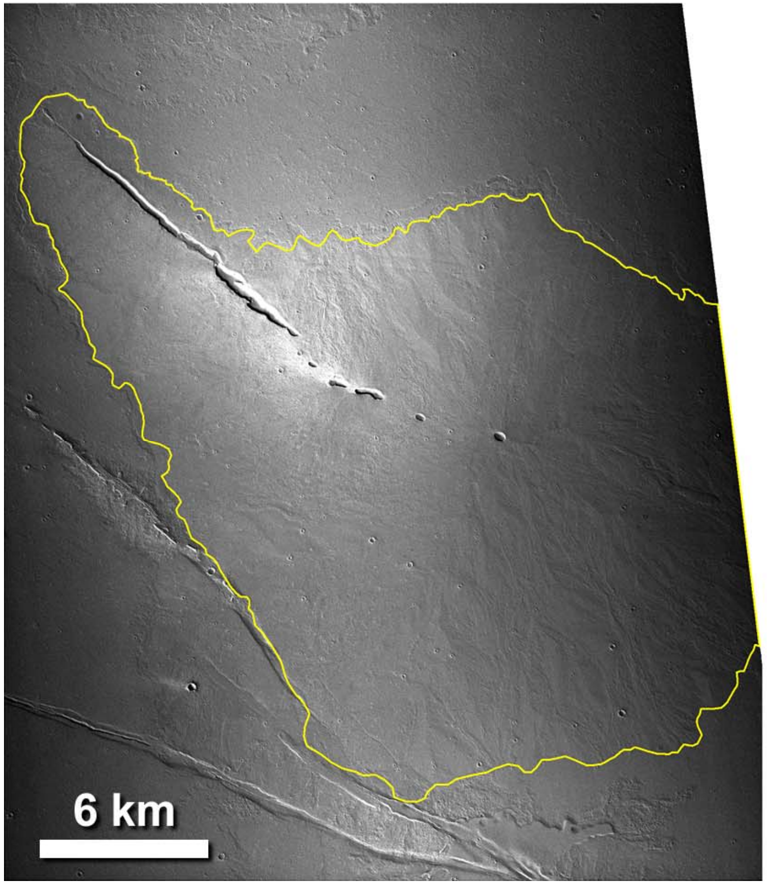
Crater size-frequency distribution

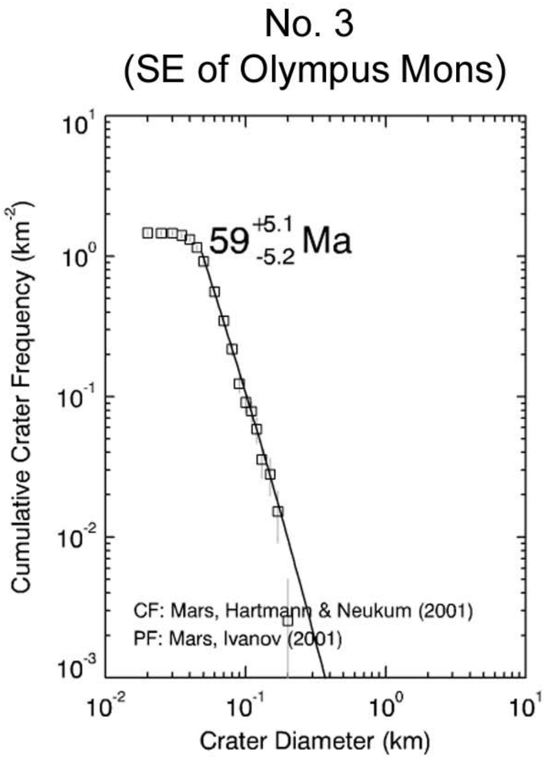




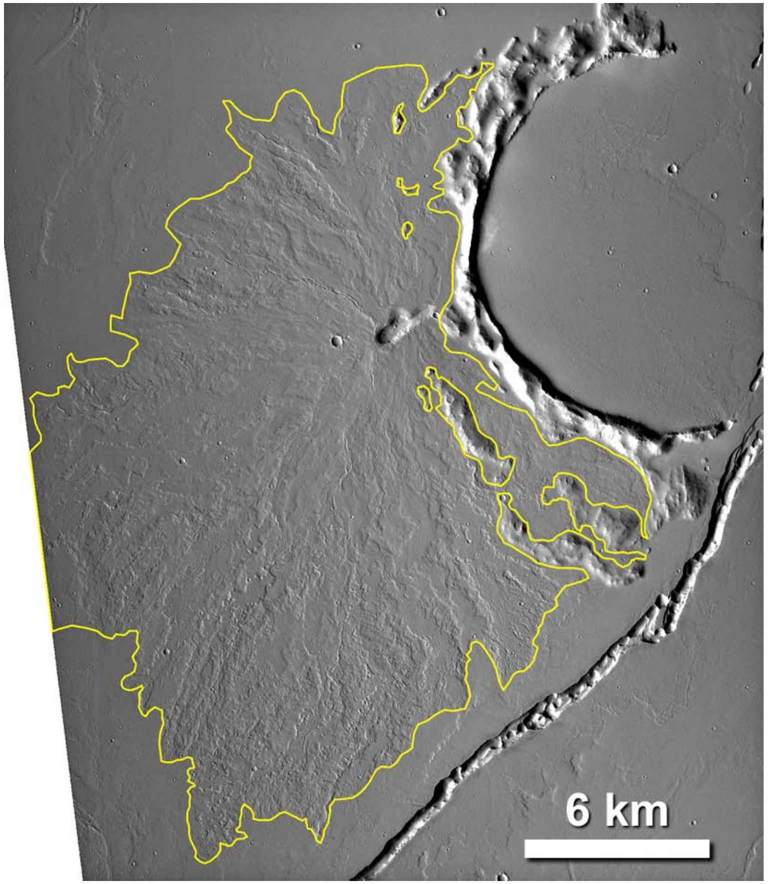
***CraterTools* and *CraterStats* developed @FU Berlin**

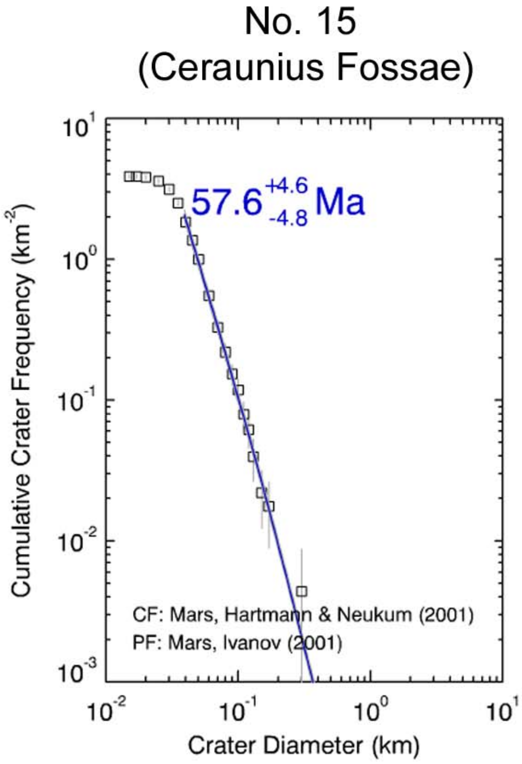
Example: SE of Olympus Mons



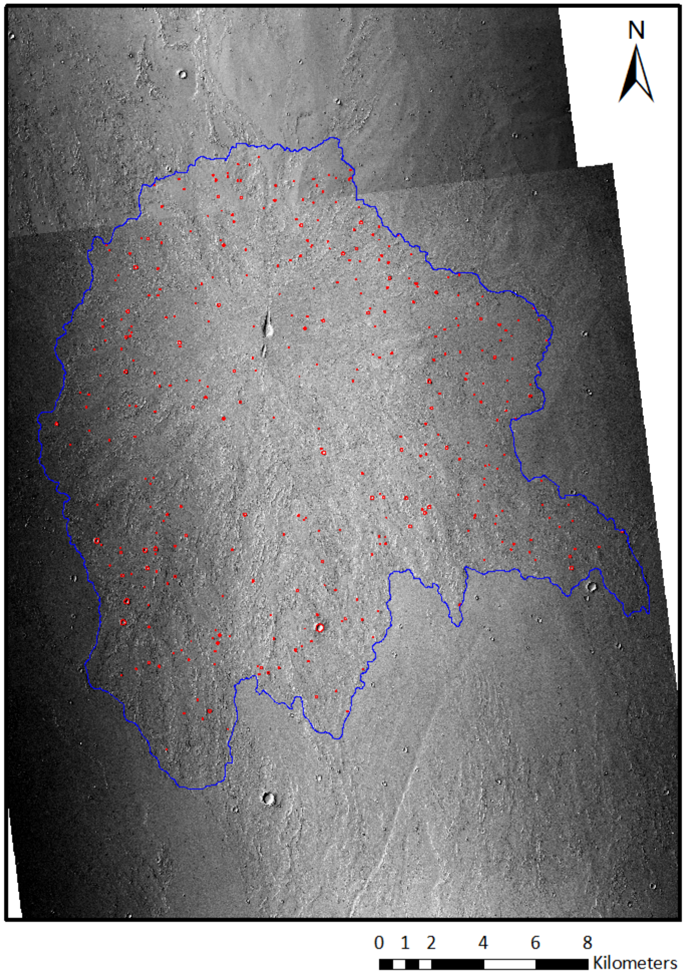


Example : Ceraunius Fossae

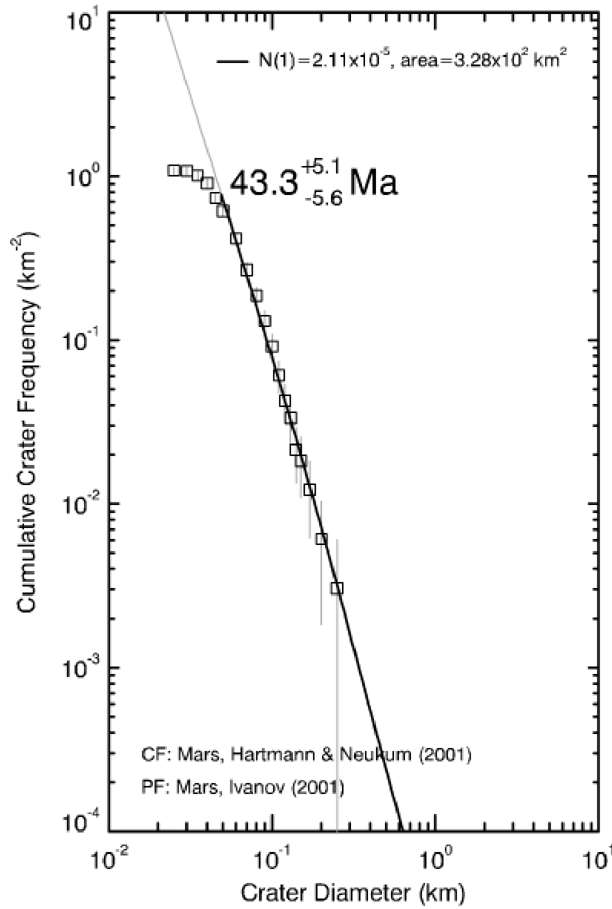


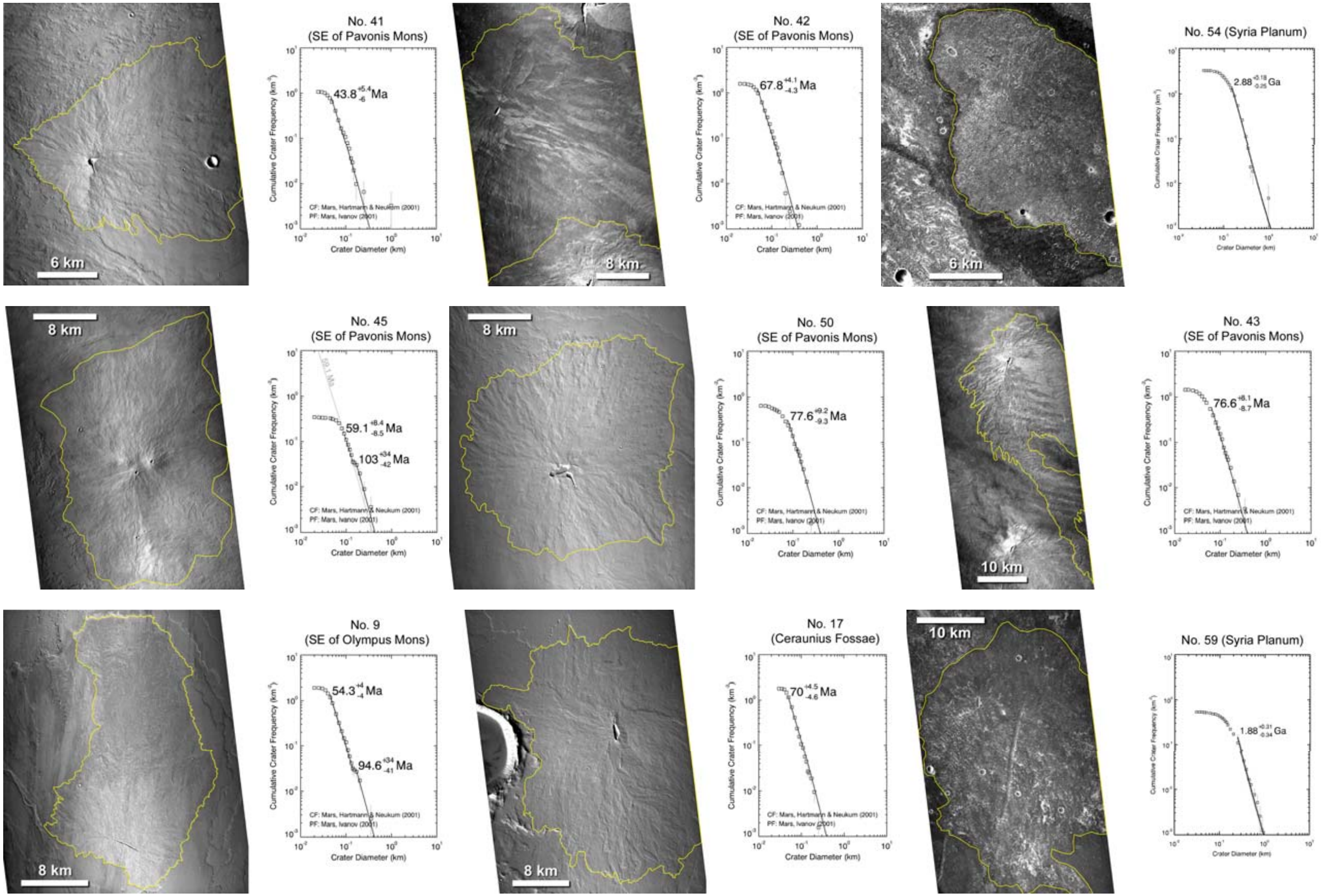


Mapping Area 2: South of Ascraeus Mons
P18_008235_Unit2



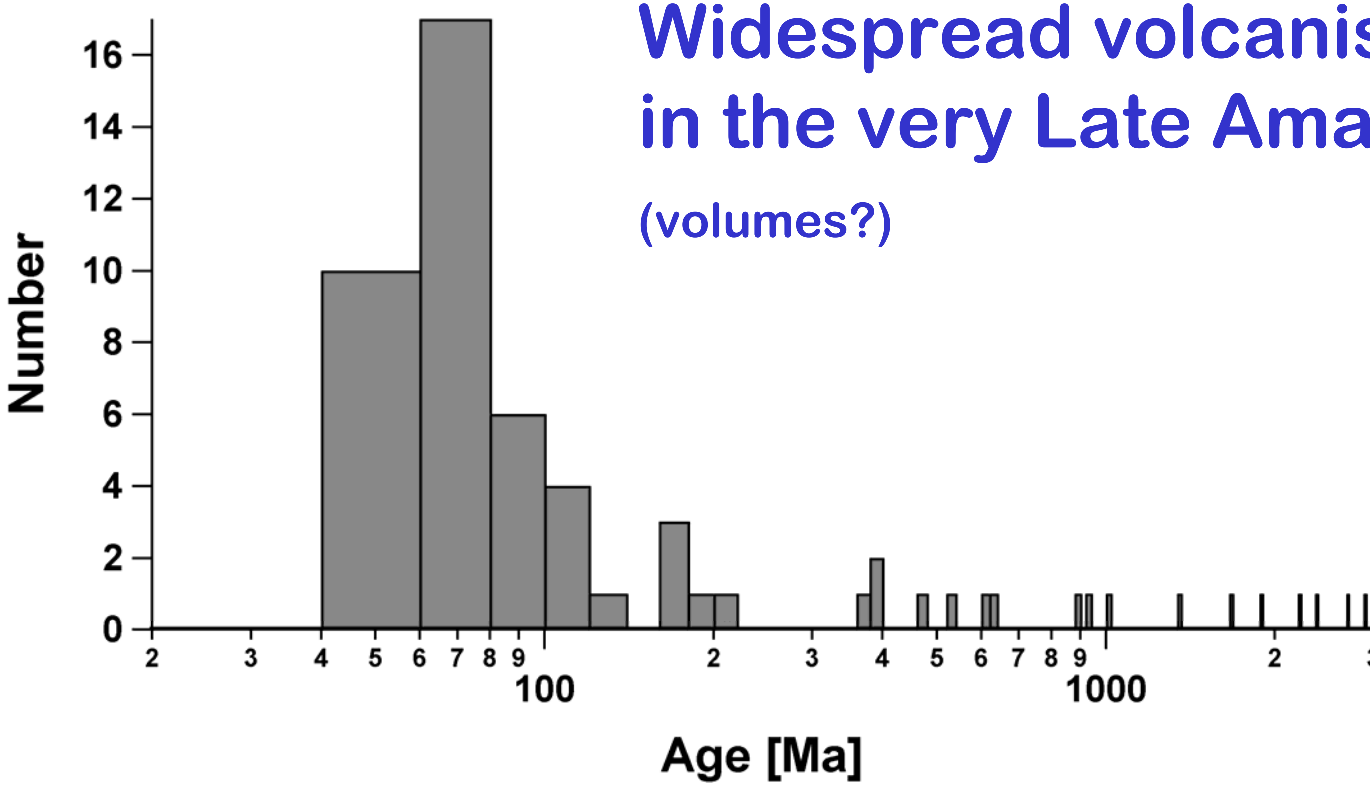
P18_008235_Unit2





more examples…

Low shield ages



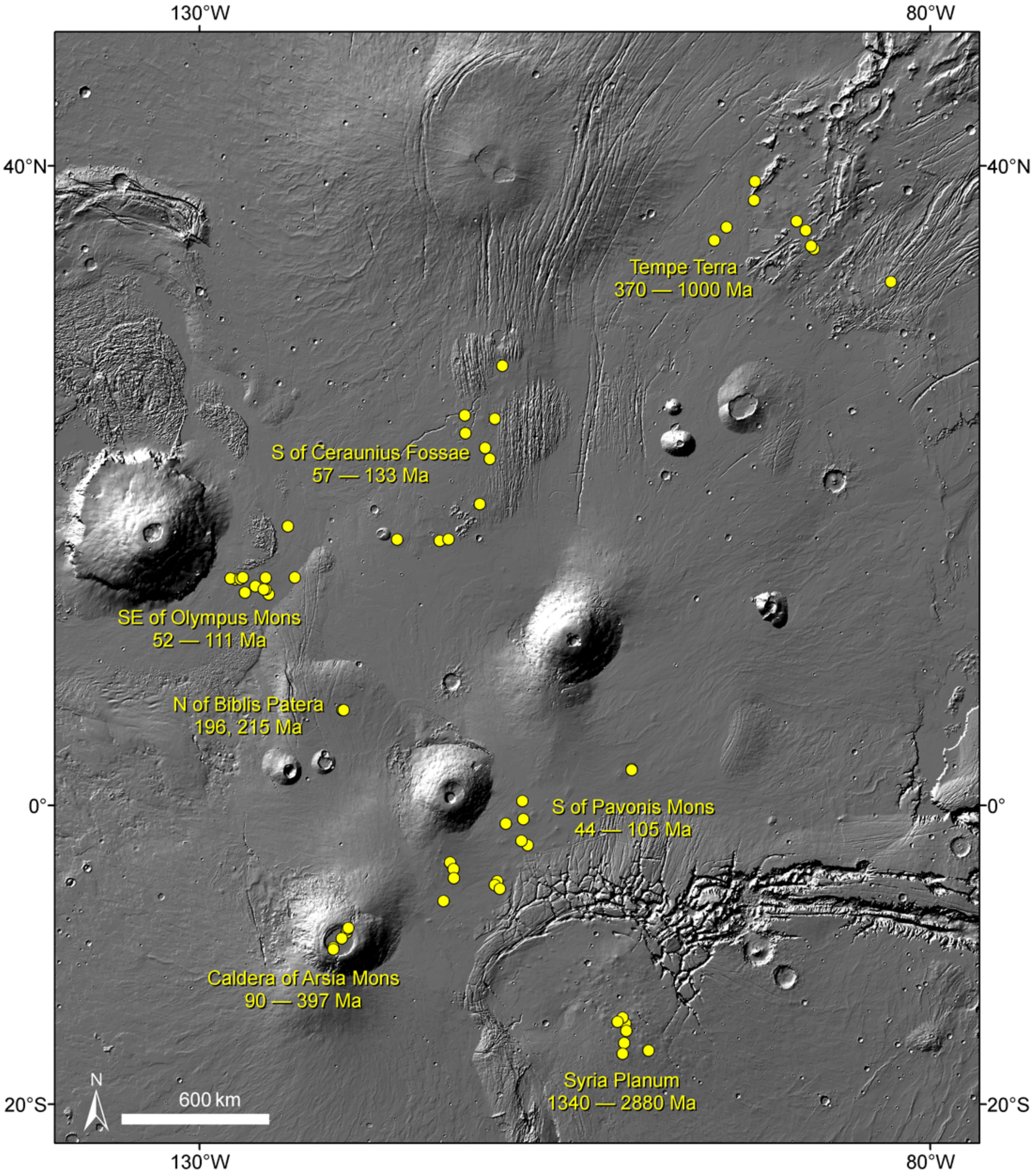
Widespread volcanism in the very Late Amazonian!

(volumes?)

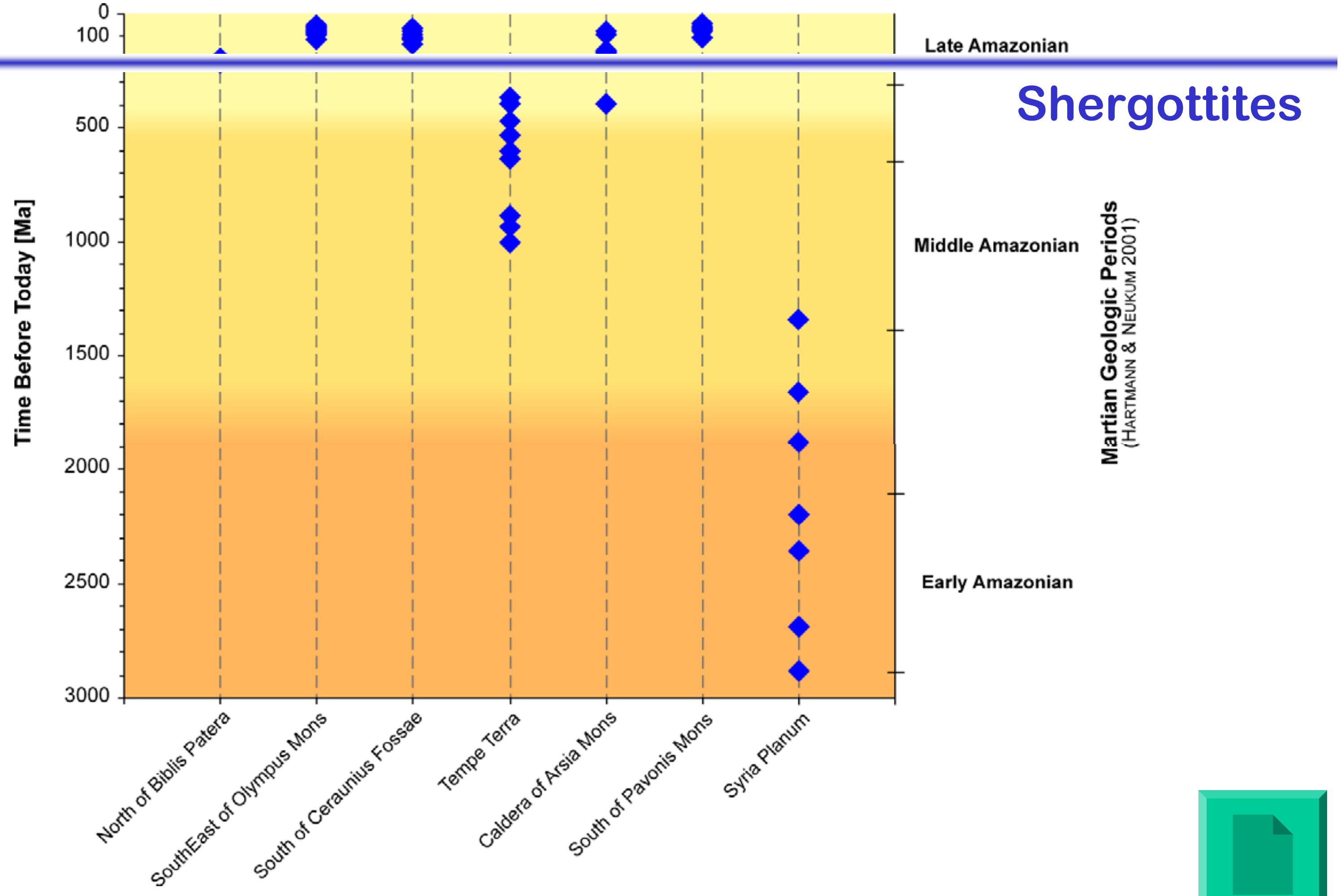
from Hauber et al. (2010)

Results

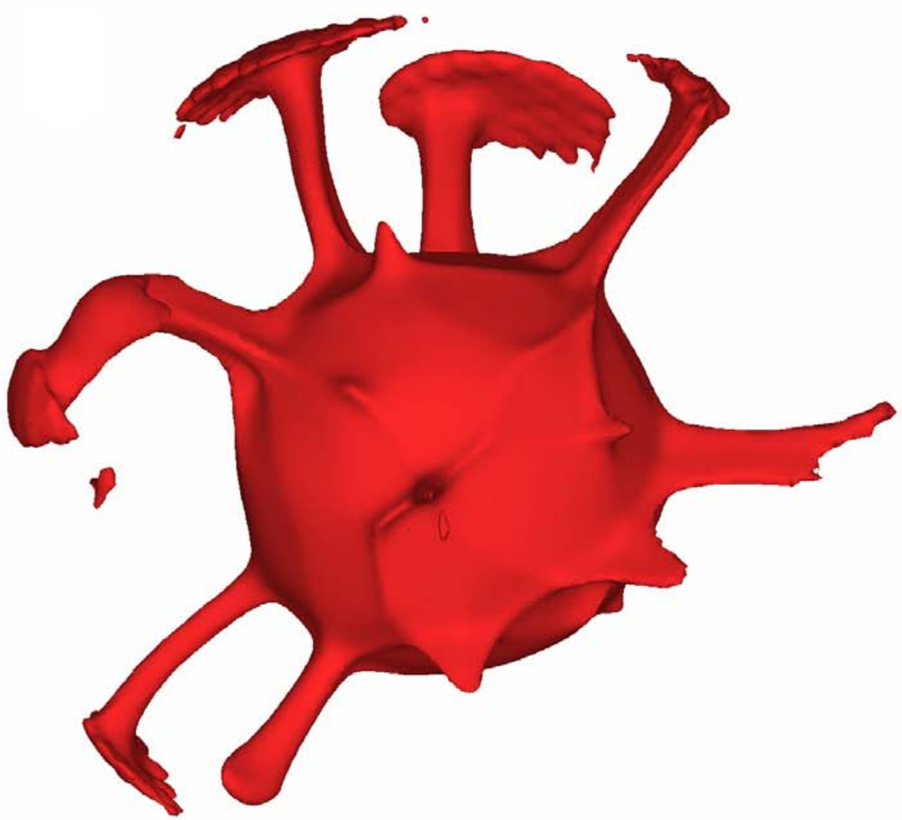
- 60 volcanoes and lava flows dated
- Most shields have ages of 50 – 120 Ma
- Tempe Terra shields are significantly older (~400 – 1000 Ma)
- Syria Planum shields are the oldest (>1.5 Ga)

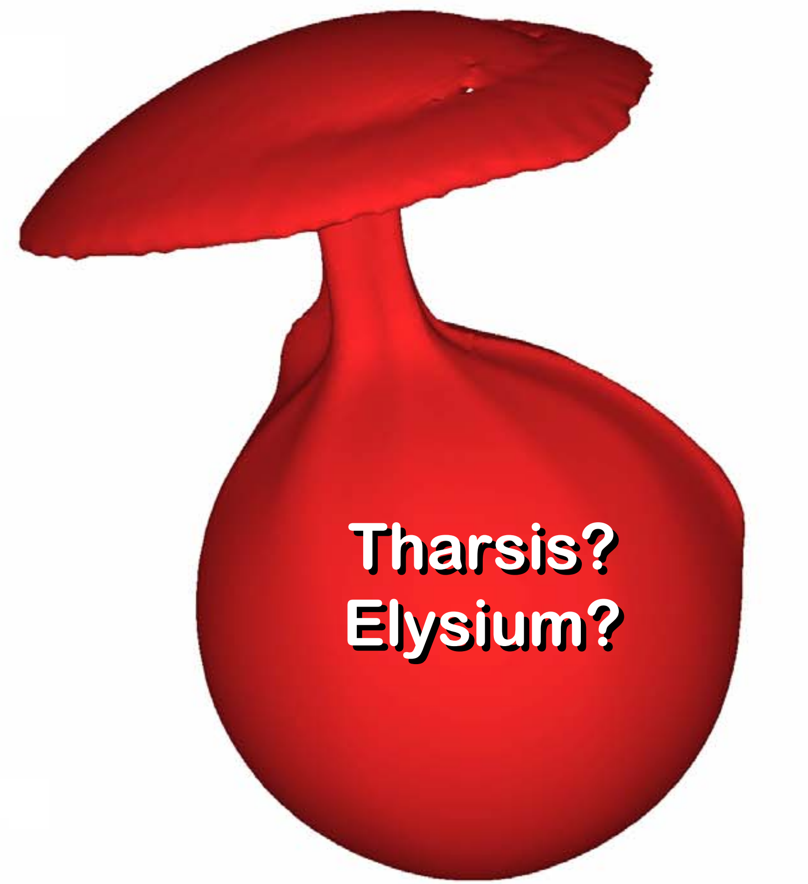


Low shield ages by region



Long-lived plumes on Mars?

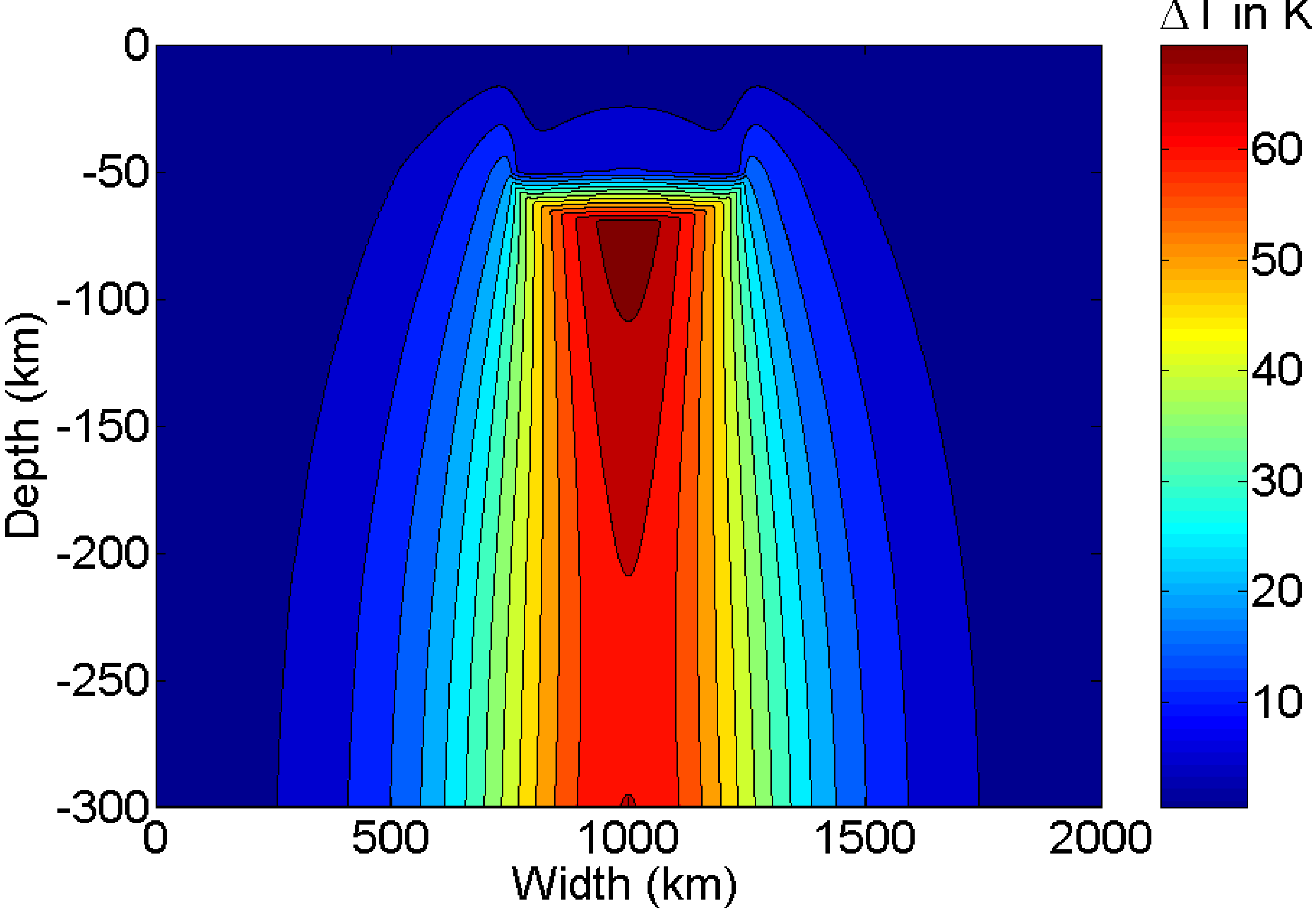




e.g., Harder & Christensen, Nature (1996)

Melt generation under a thickened crust?

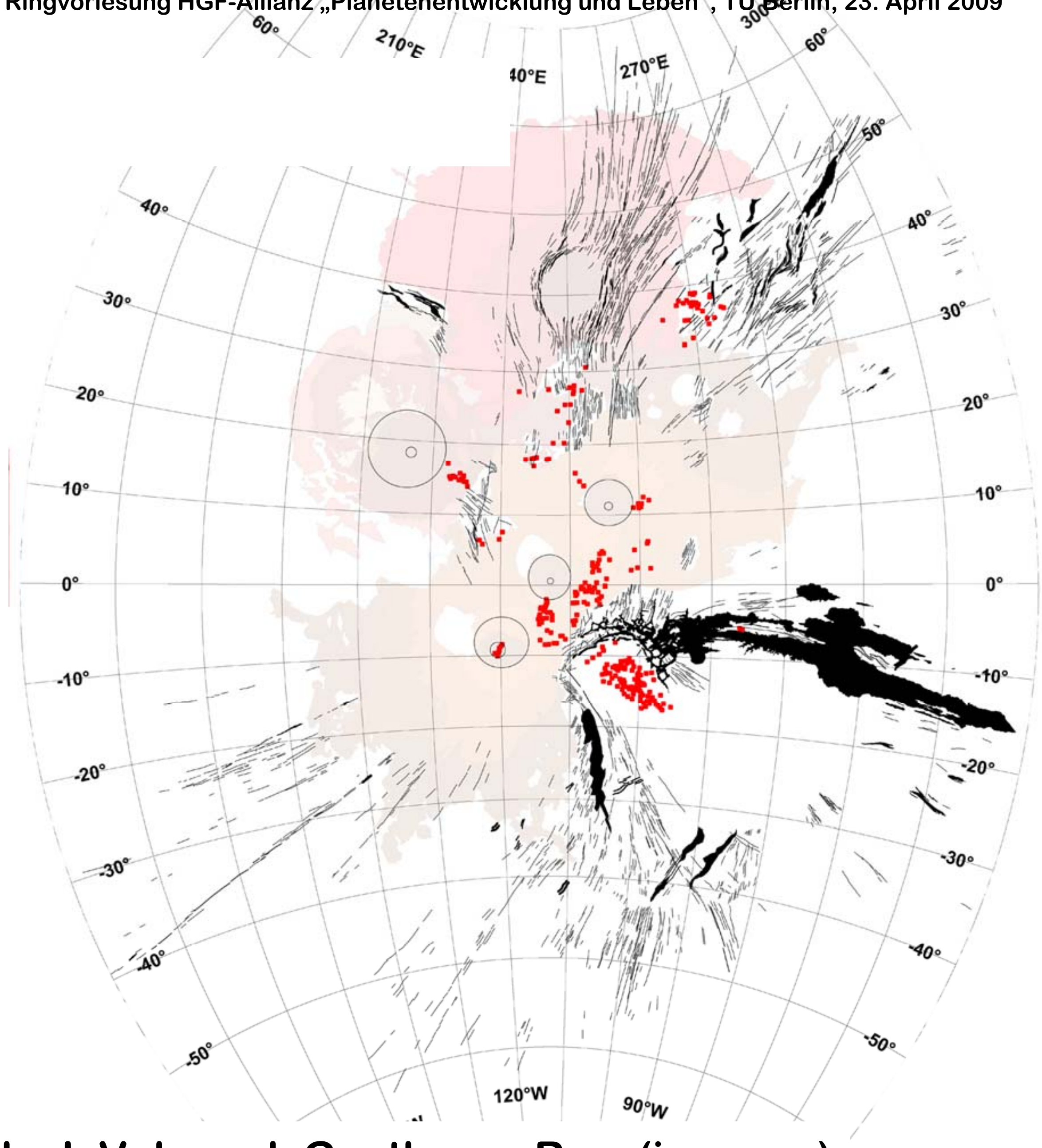
model results for a 500 km-wide zone of thickened crust



see the model by Schumacher and Breuer, Geophys. Res. Lett. (2007)

Tharsis

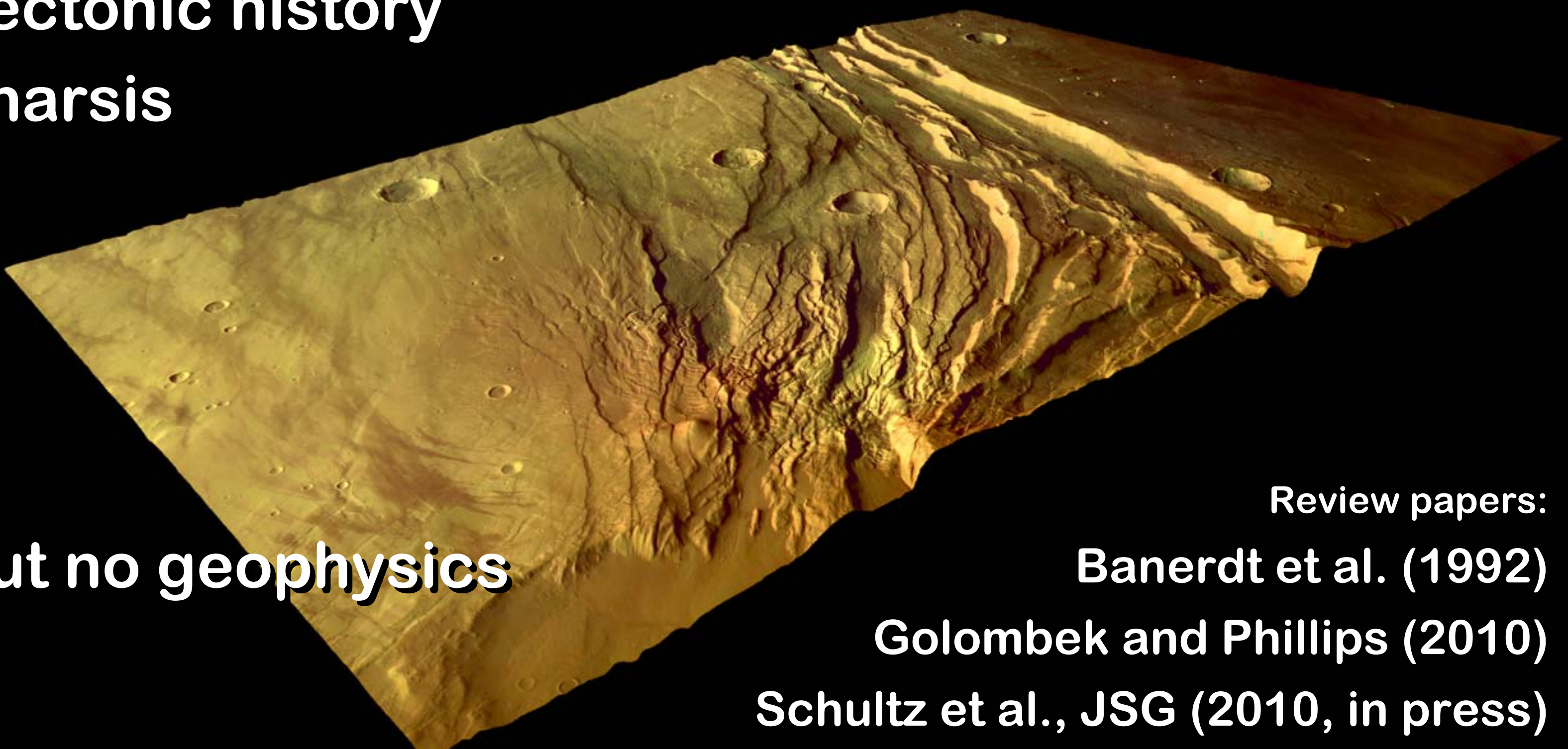
Focus of Martian volcanism and tectonism



from Hauber et al., J. Volcanol. Geotherm. Res. (in press)

Tectonics on Mars: Tutorial structure

- Dichotomy
- Tectonic regime
- Morphological elements
- Tectonic history
- Tharsis



- but no geophysics

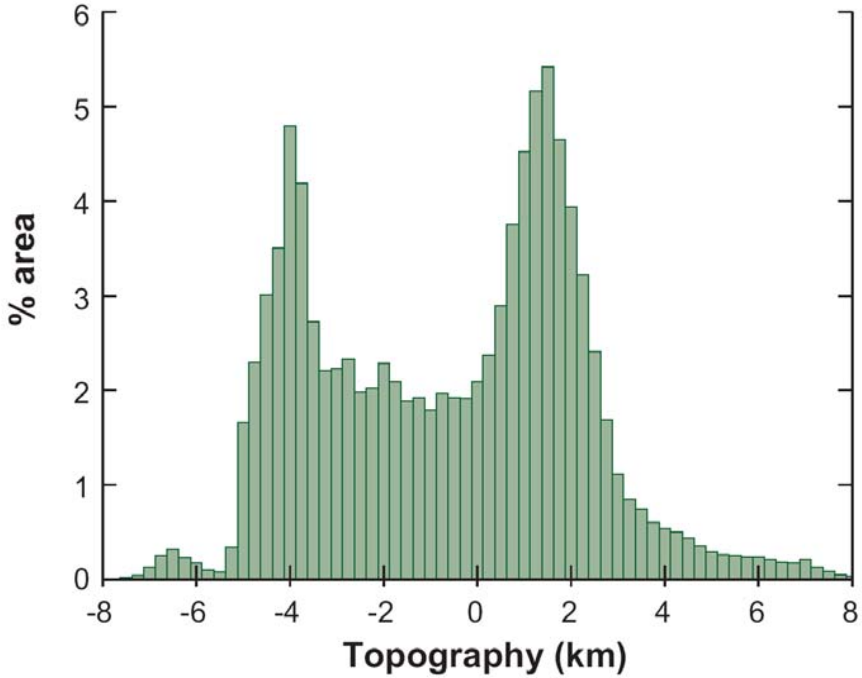
Review papers:

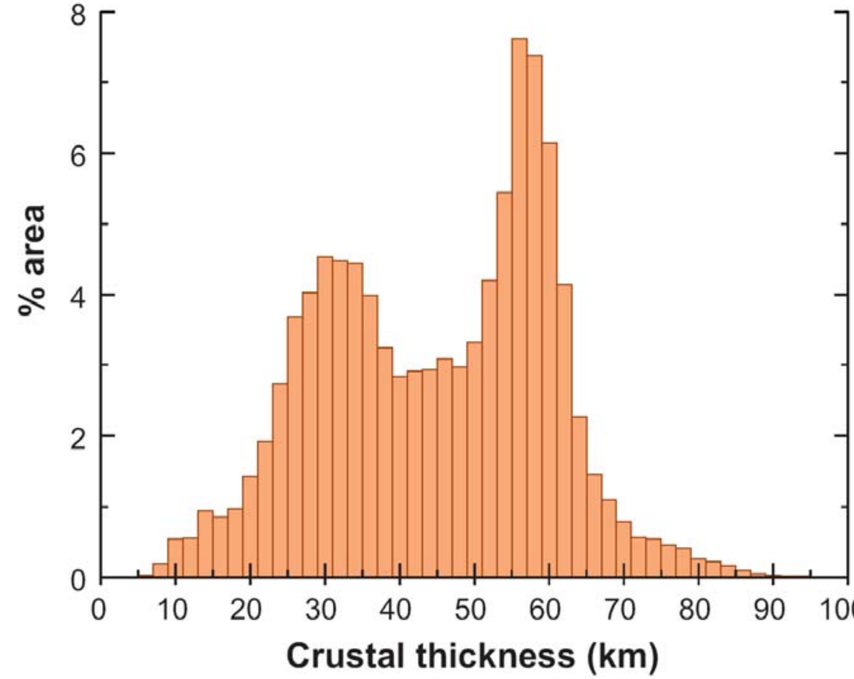
Banerdt et al. (1992)

Golombek and Phillips (2010)

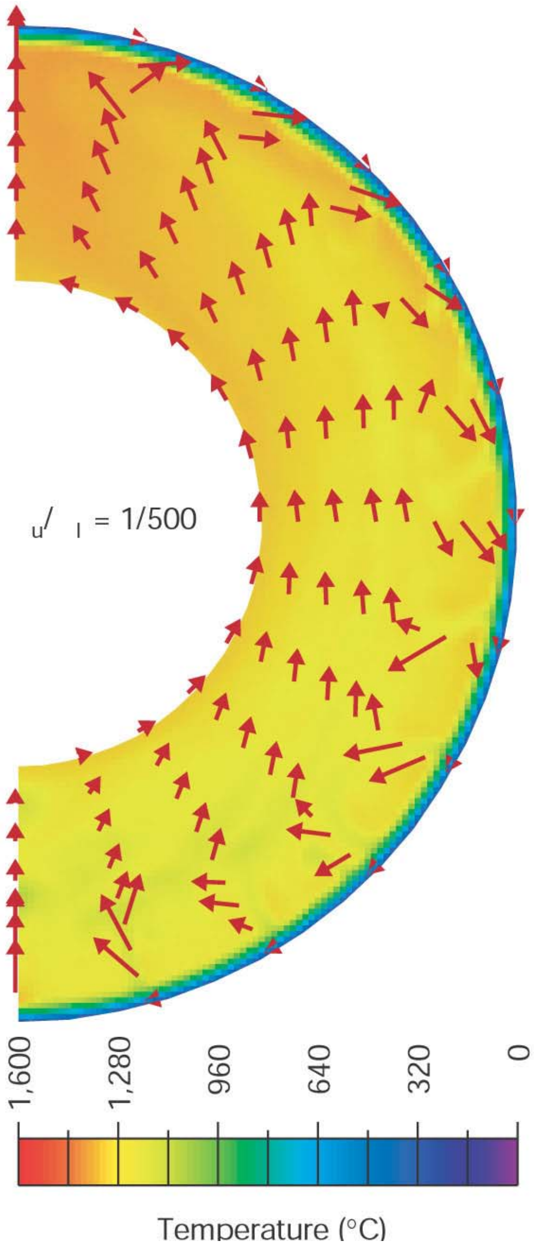
Schultz et al., JSG (2010, in press)

Global (crustal) dichotomy





from Watters et al., Ann. Rev. Earth Planet. Sci. (2007)



Crustal dichotomy

- Planet-wide magma ocean
  - fractional crystallization
  - buoyant anorthositic crust
  - complementary mafic cumulate mantle
    - compositionally stratified
    - gravitationally unstable
  - overturn: dense, iron-rich and relatively cool cumulates into the Martian interior
  - analogy to the Moon (Hess and Parmentier, *Earth Planet. Sci. Lett.,* 1995).
- Degree-1 mantle convection
  - Zhong and Zuber, *Earth Planet. Sci. Lett.* (2001)

Impact formation of crustal dichotomy?

Problem:
"[...] but the heat imparted to young crust by large impacts would tend to erase topographic relief by magmatism and crustal flow."
(Solomon et al., *Science*, 2005)

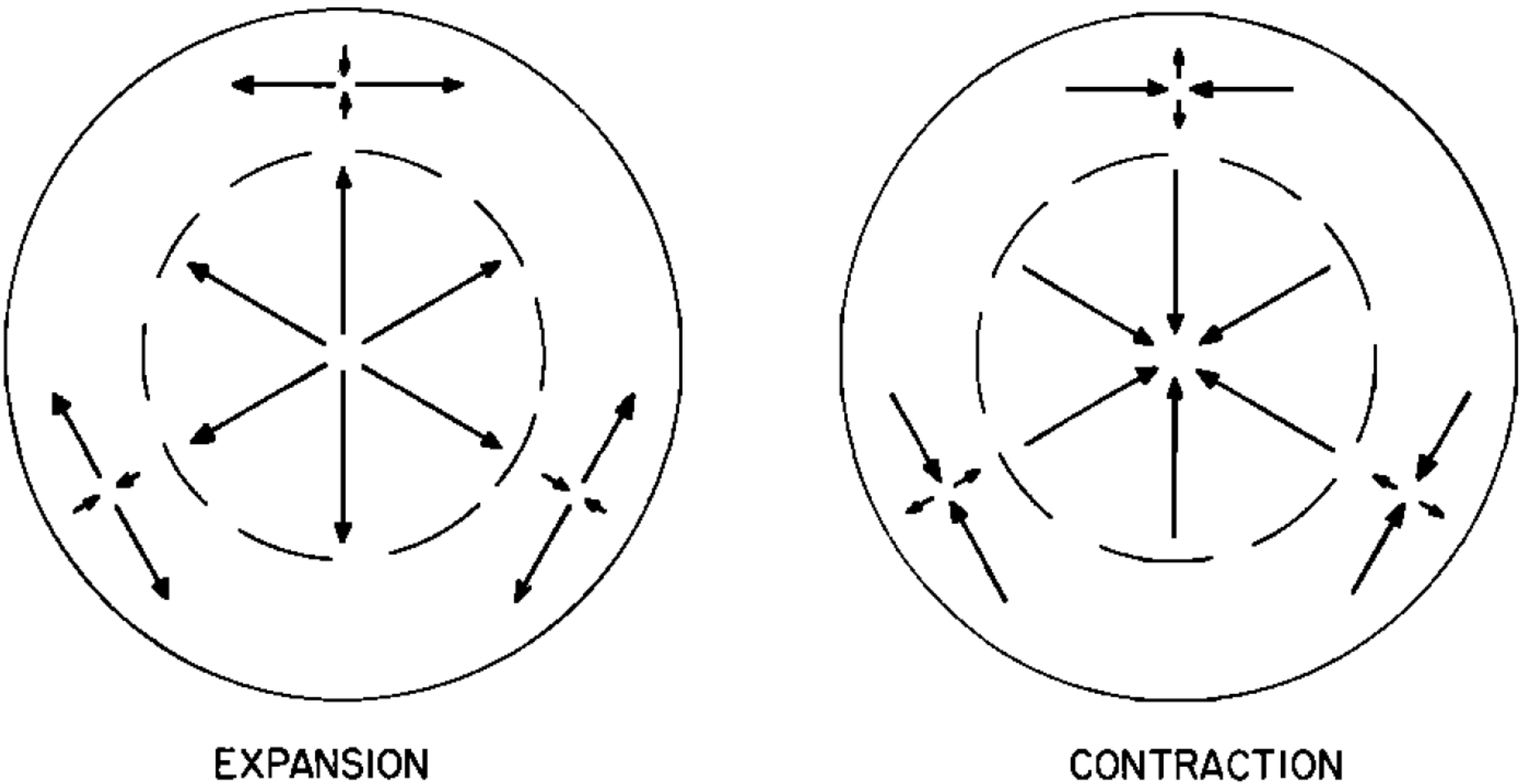
However, this problem can be modeled away:

- **low impact velocities**
- **oblique impacts**

(Marinova et al., *Nature*, 2008)

from Andrews-Hanna et al., *Nature* (2008)

Thermal evolution of planets



Early stage (heating)

Later stage (cooling)

- from Solomon (1975)

Tectonic regime: One plate planets

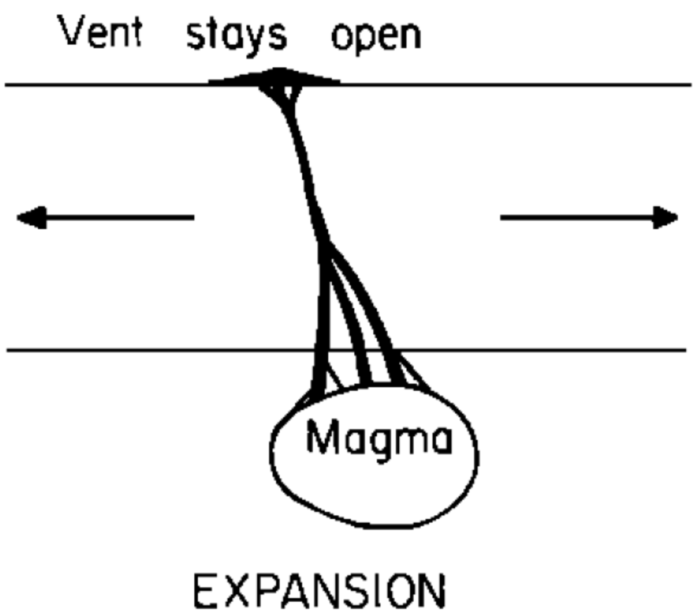


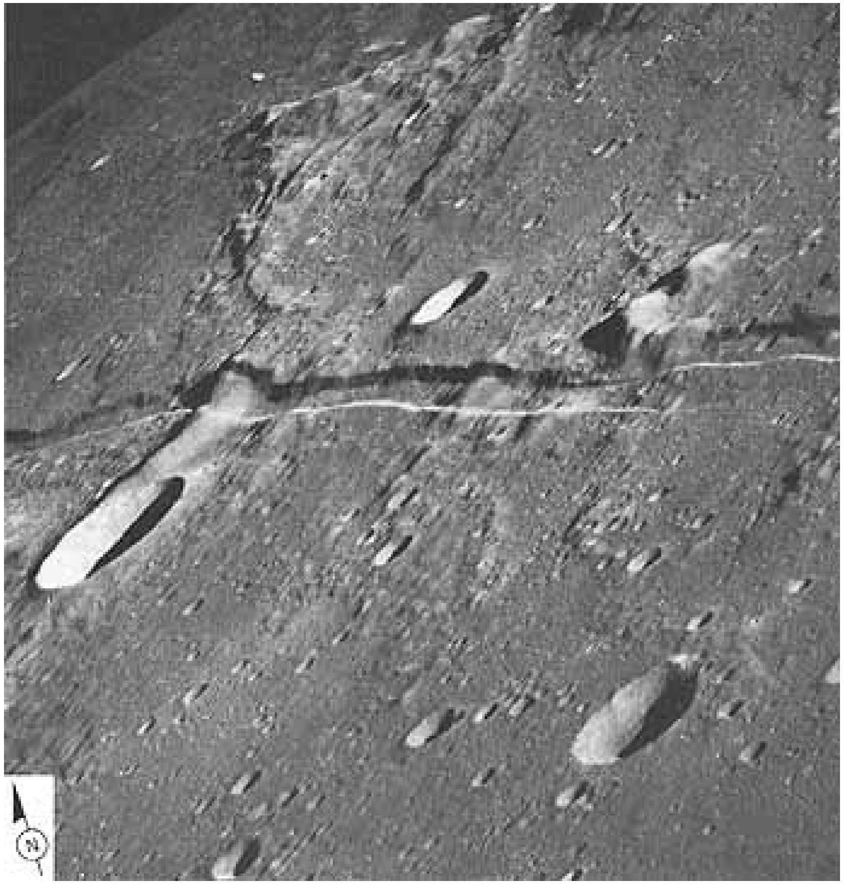
Plate tectonics on Mars?

No unambiguous morphological evidence

Very early phase of plate tectonics possible from geophysical modeling (→ would explain core dynamo)

- from Solomon (1975)

Morphological elements (I)
Simple Grabens



Apollo AS10-31-4645

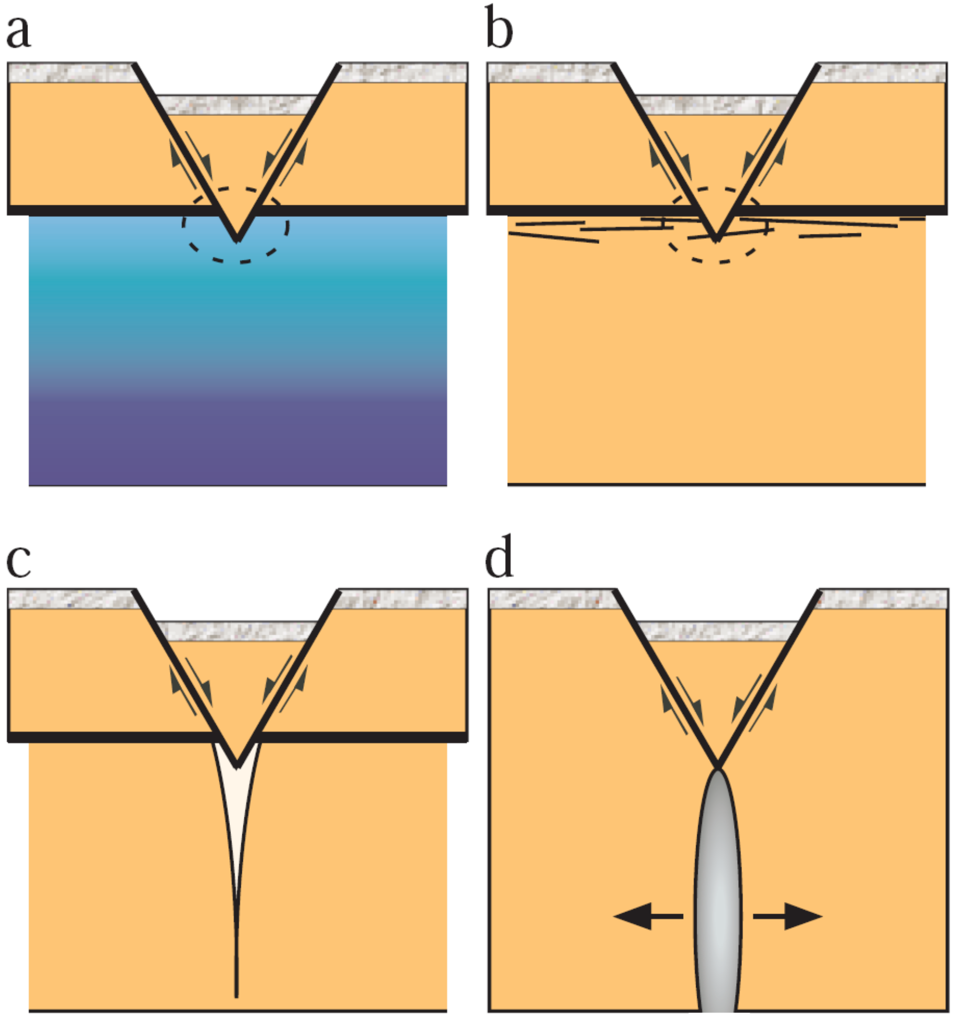
Apollo AS8-13-2225


GoogleEarth
1000 m
HRSC
20 km
Grabens on Earth and Mars
Image © 2007 DigitalGlobe
E. Hauber: Vulkanismus und Tektonik, Ringvorlesung HGF-Allianz „Planetenentwicklung und Leben“, TU Berlin, 23. April 2009

Simple Grabens: Previous Models

faulting at bimaterial interface (e.g., brittle over quasiplastic rheology)

faulted upper layer separated by sills or detachment zones from undeformed substrate



graben wedge falling into space-accomodation tensile crack in substrate

graben faults nucleated by dike dilation at depth

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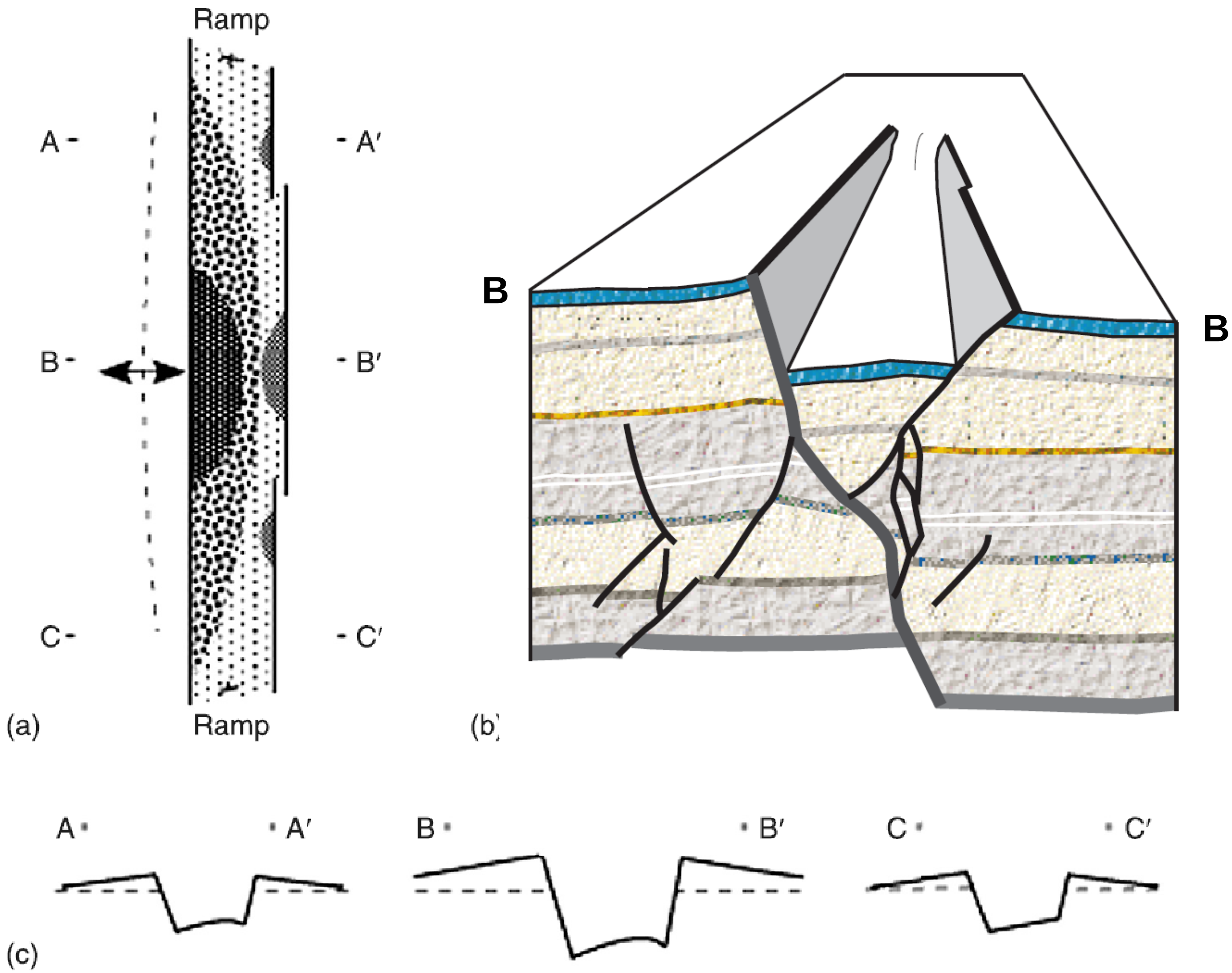
from: Schultz et al., in: The Geology of Mars, Cambridge Univ. Press (2007)

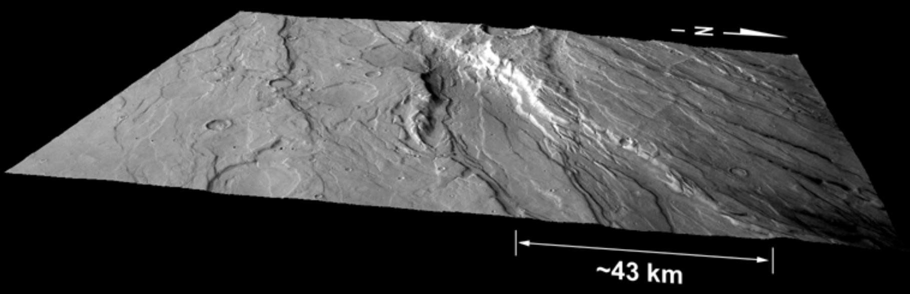
The new "hourglass" model of planetary simple grabens

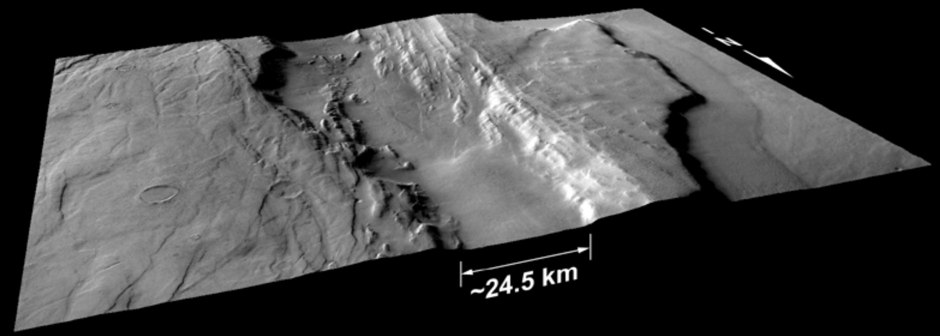


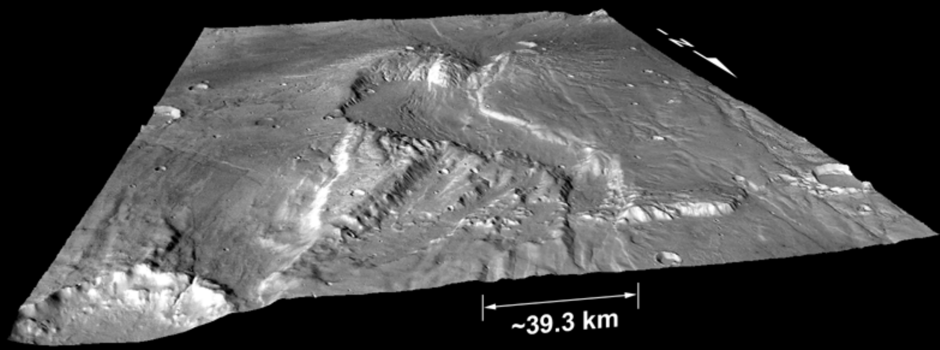
from: Schultz et al., in: The Geology of Mars, Cambridge Univ. Press (2007)

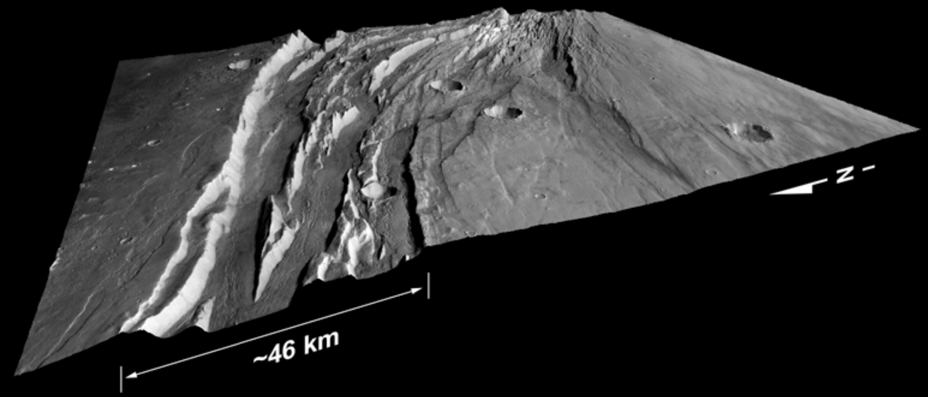
Morphological elements (II)

3D-views of Martian rifts

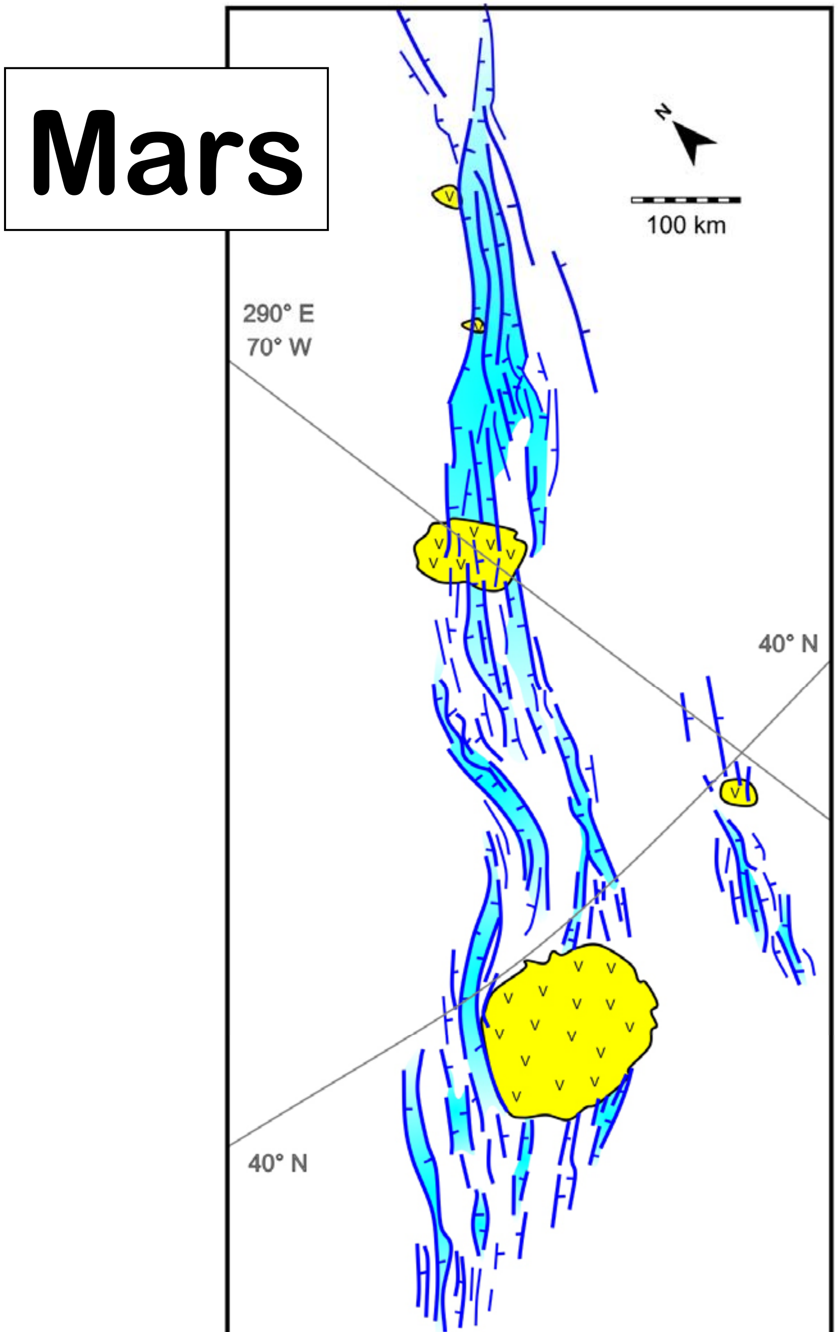




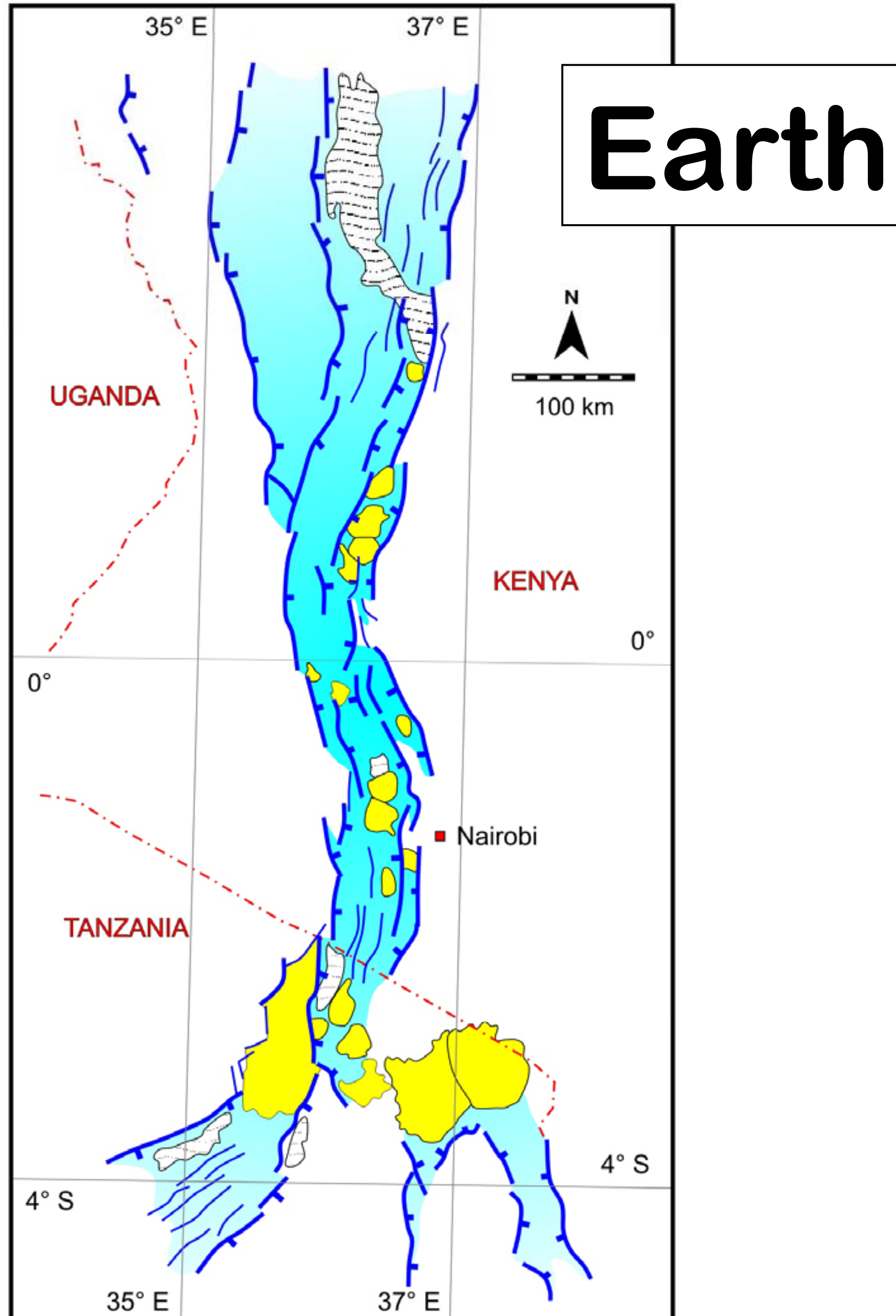




Hauber et al., Earth Planet. Sci. Lett. (in press)



Mars
100 km
290° E
70° W
40° N
40° N



Earth
35° E
37° E
100 km
UGANDA
KENYA
0°
0°
Nairobi
TANZANIA
4° S
4° S
35° E
37° E

Comparison of physical parameters

	Mars	Venus	Earth
Extension [km]	<10	~20	~5-40
Elastic Thickness [km]	10-20	10-30	3-38
Heat Flow [mW m^{-2}]	28-66	18-25	~50-100

Similarities

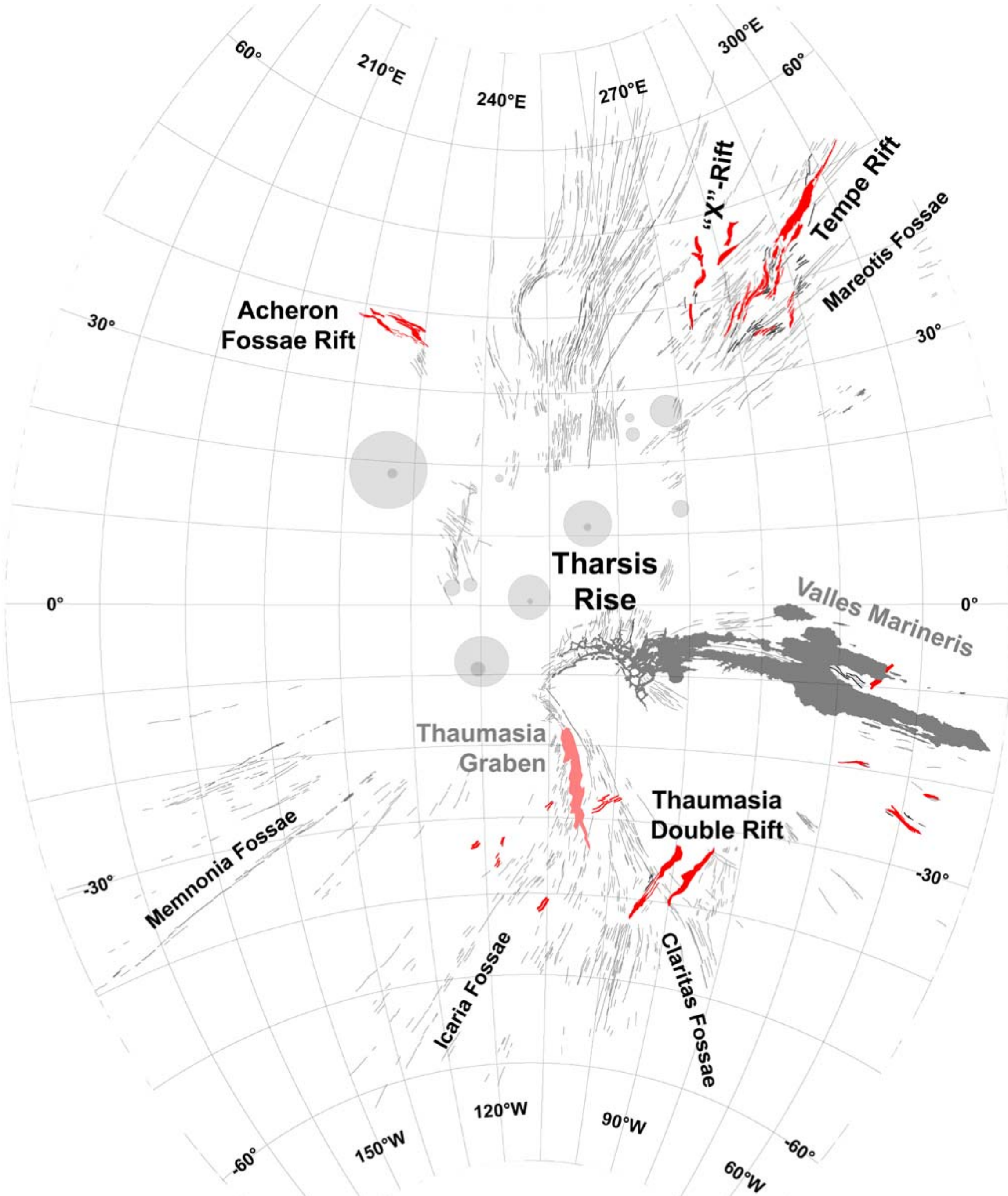
- dimensions
- structural geology
- rift-related volcanism
- lithospheric properties

Differences

- global distribution
- geodynamic setting
- relation to hot spots
- absolute ages

from Hauber et al., Earth Planet. Sci. Lett. (in press)

Martian Rifts



- Dimensions and structural architecture similar to terrestrial continental rifts
- Moderate extension (few km)
- Ages: ~4 to 3.5 Ga
- Thin elastic lithosphere, high heat flux
- Located at periphery of Tharsis
- No obvious radial orientation to Tharsis

Hauber et al., Earth Planet. Sci. Lett. (in press)

Morphological elements (III)

Contractional faults

- Wrinkle ridges
- Lobate scarps
- Fold-and-thrust belt

Wrinkle ridges

Wrinkle ridges are a wide-spread surface feature on terrestrial planets: Mercury, Moon, Mars, Venus (and Earth!)

Mercury | **Moon** | **Mars**

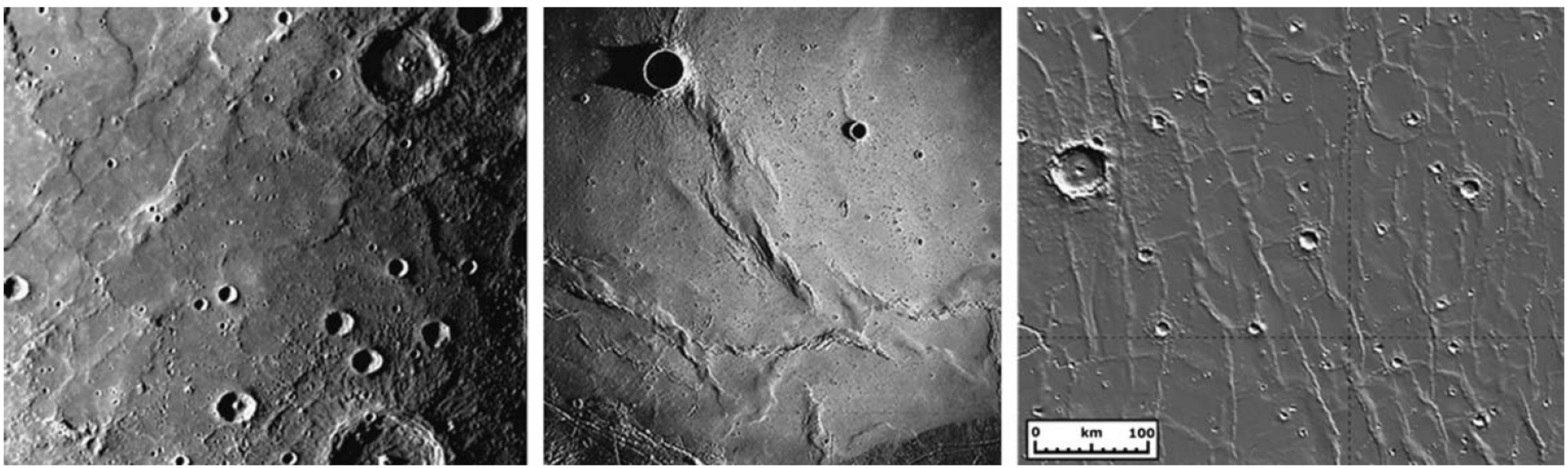


Fig. 15 Wrinkle ridges on the plains of Mercury and similar features on the Moon and Mars. *Left*, wrinkle ridges in the plains of Mercury. View is ~385 km in width (Mariner 10 image 0000167). *Middle*, the southern part of lunar Mare Serenitatis showing the development of wrinkle ridges in the mare basalts. View is ~70 km in width (Apollo image). *Right*, wrinkle ridges in Lunae Planum on the eastern part of the Tharsis rise (MOLA digital topographic image). Note the similarities in the ridges in terms of general trends, separation, convergence, cross-cutting, and circularity around apparently buried craters

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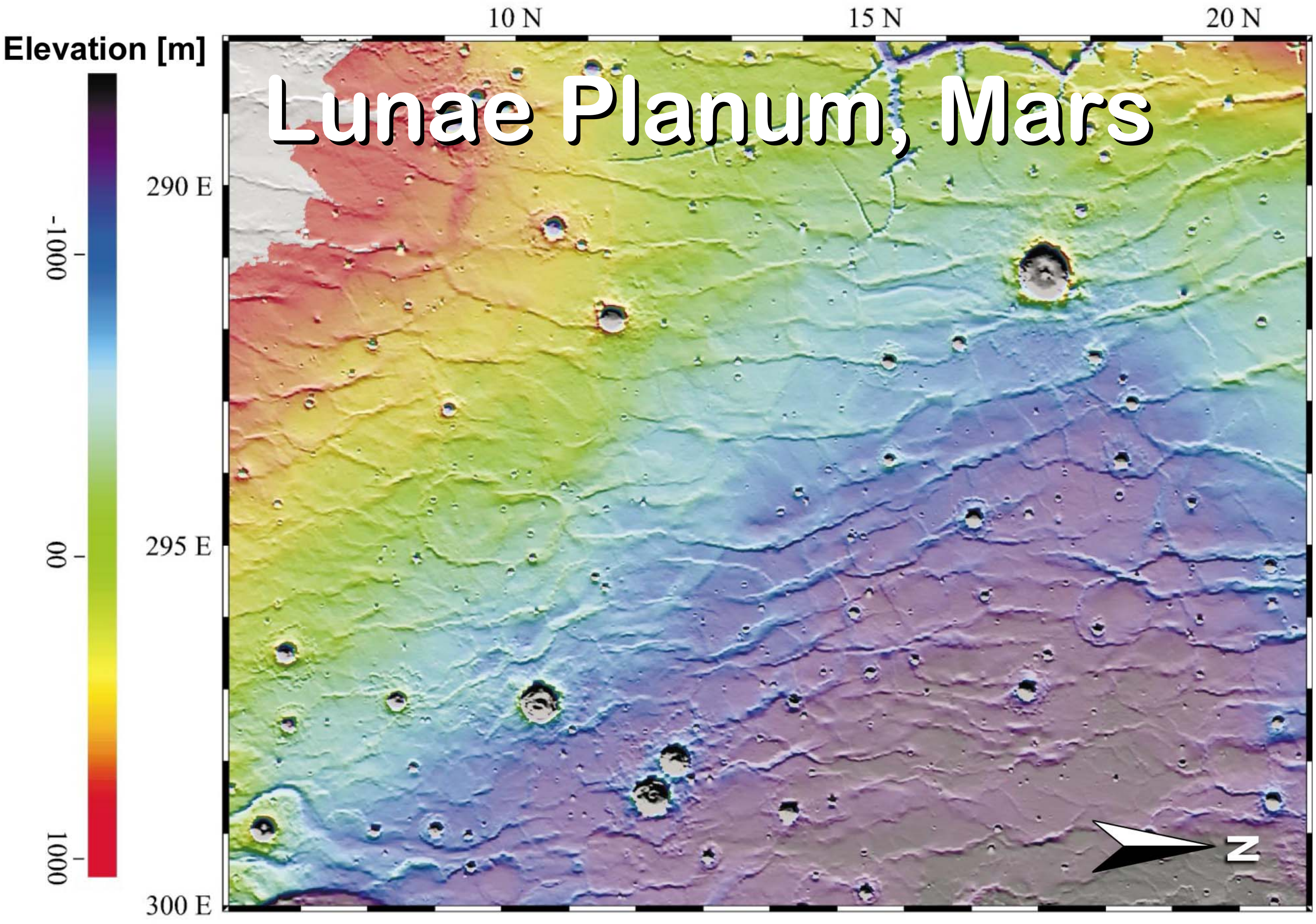
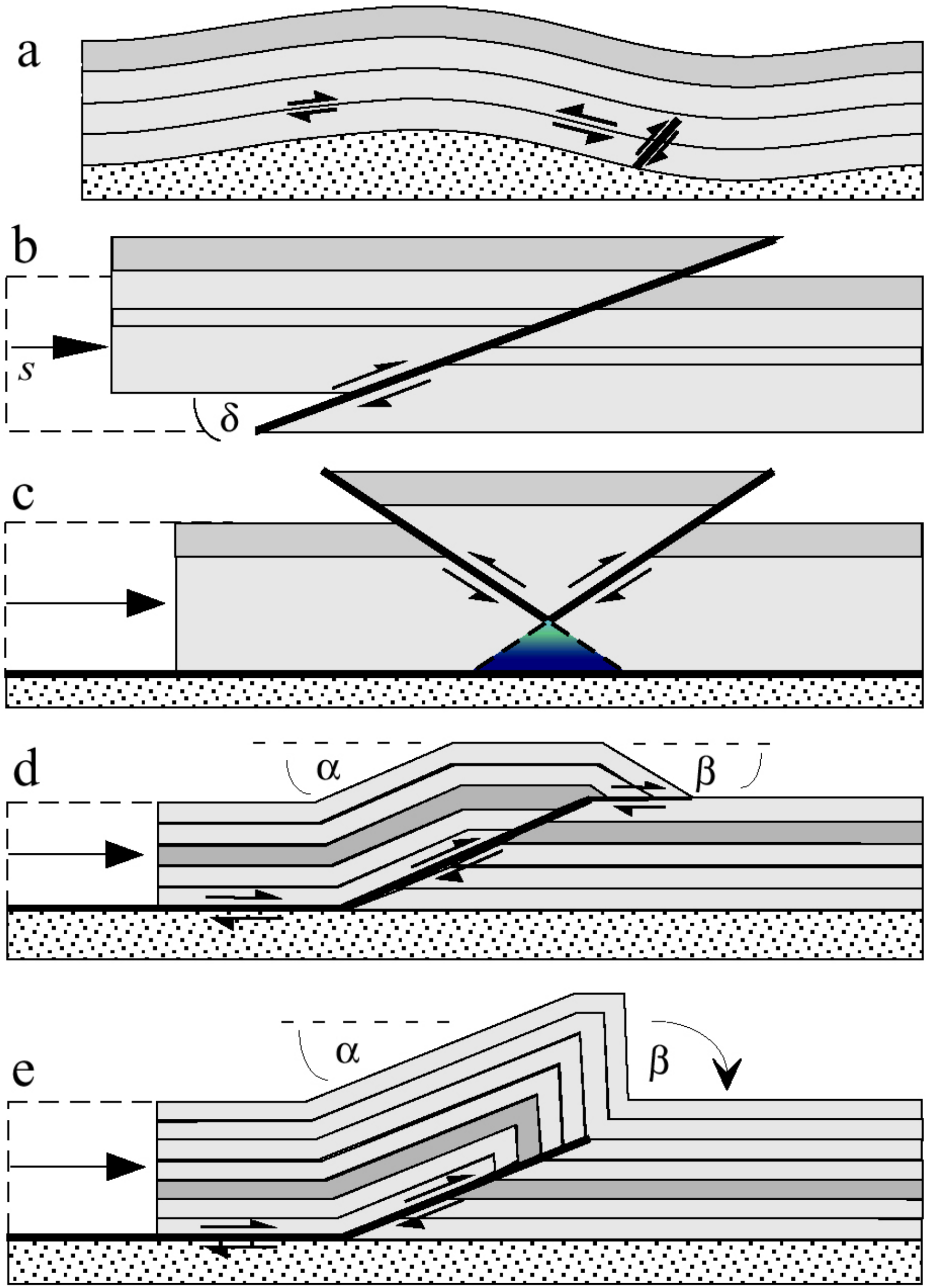
- **from Head et al., Space Sci. Rev. (2007)**



- from Mueller & Golombek, Ann. Rev. Earth Planet. Sci. (2004)



E. Hauber: Vulkanismus und Tektonik, Ringvorlesung HGF-Allianz „Planetenentwicklung und Leben“, TU Berlin, 23. April 2009

Structural models proposed for planetary wrinkle ridges

- a) Buckle folds with nucleations of thrust faults
- (Watters, 1988)
- b) Simple thrust fault
- c) Conjugate thrust fault
- (Allemand & Thomas, 1992; Mangold et al., 1998)
- d) Fault-bend fold
- (Suppe, 1983; Suppe & Connors, 1992)
- e) Fault-propagation fold
- (Mercier et al., 1997)

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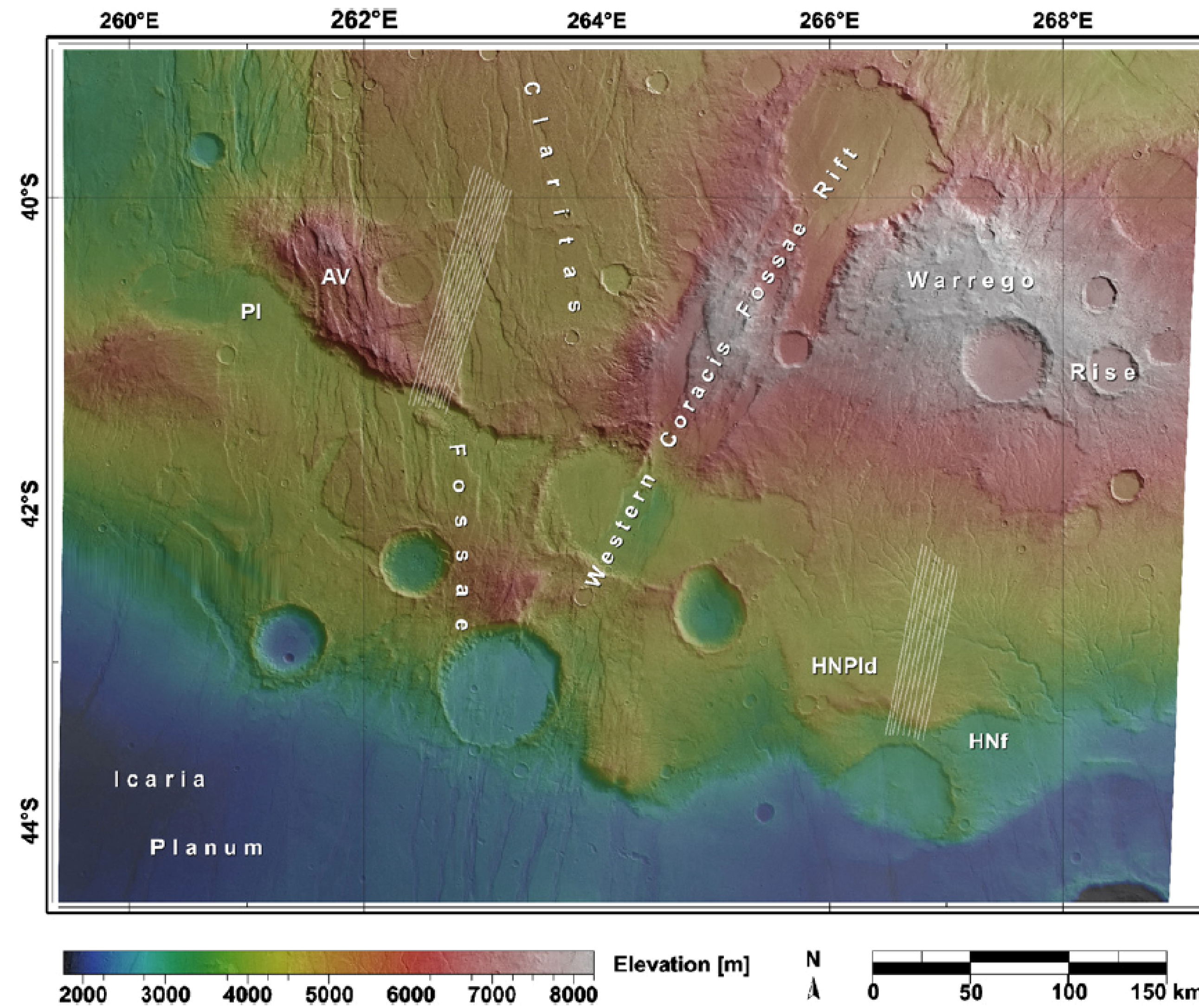
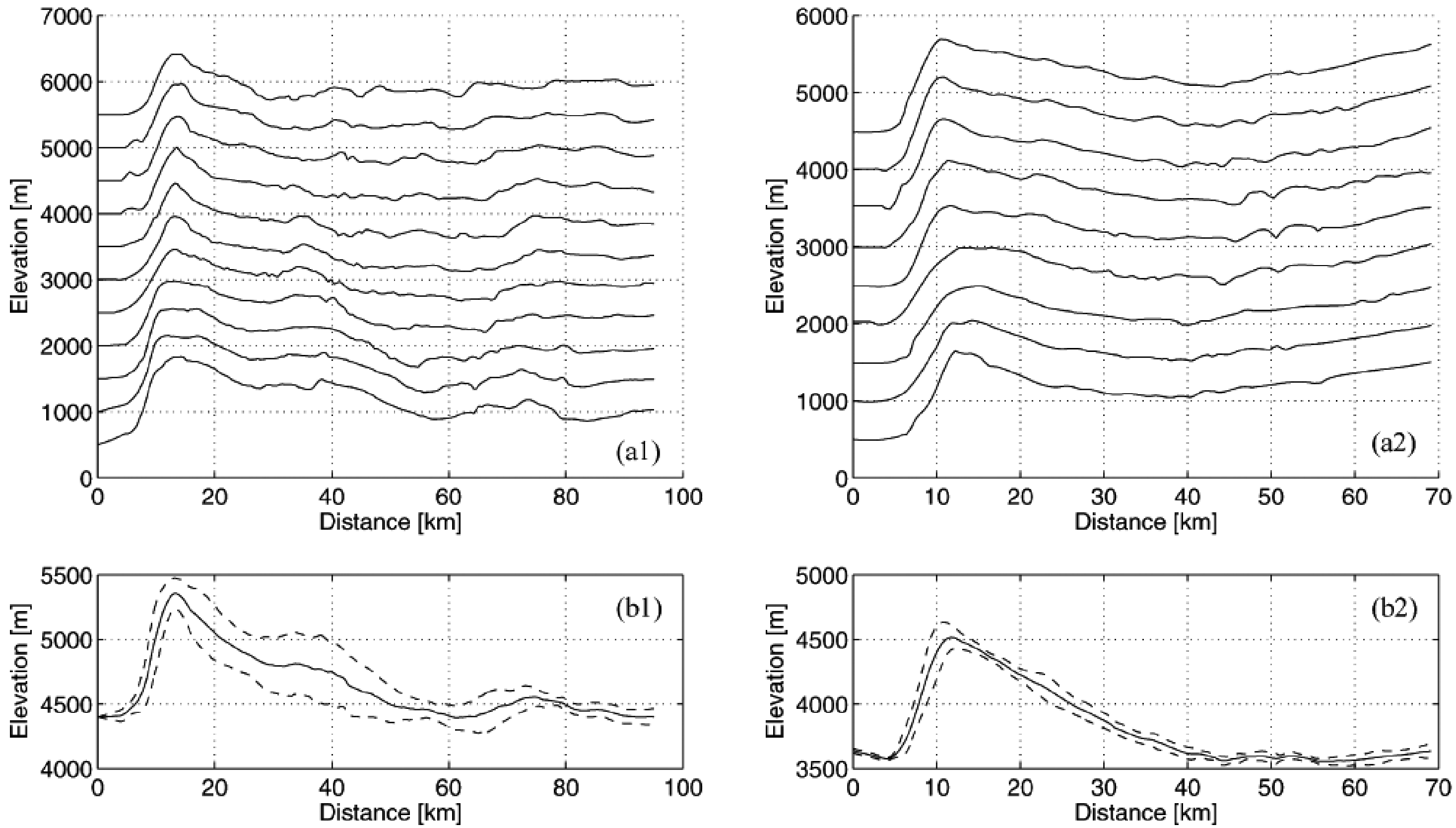
from
Schultz, *J. Geophys. Res.* (2000)

Lobate Scarps: A case study



from Grott et al., Icarus (2007)

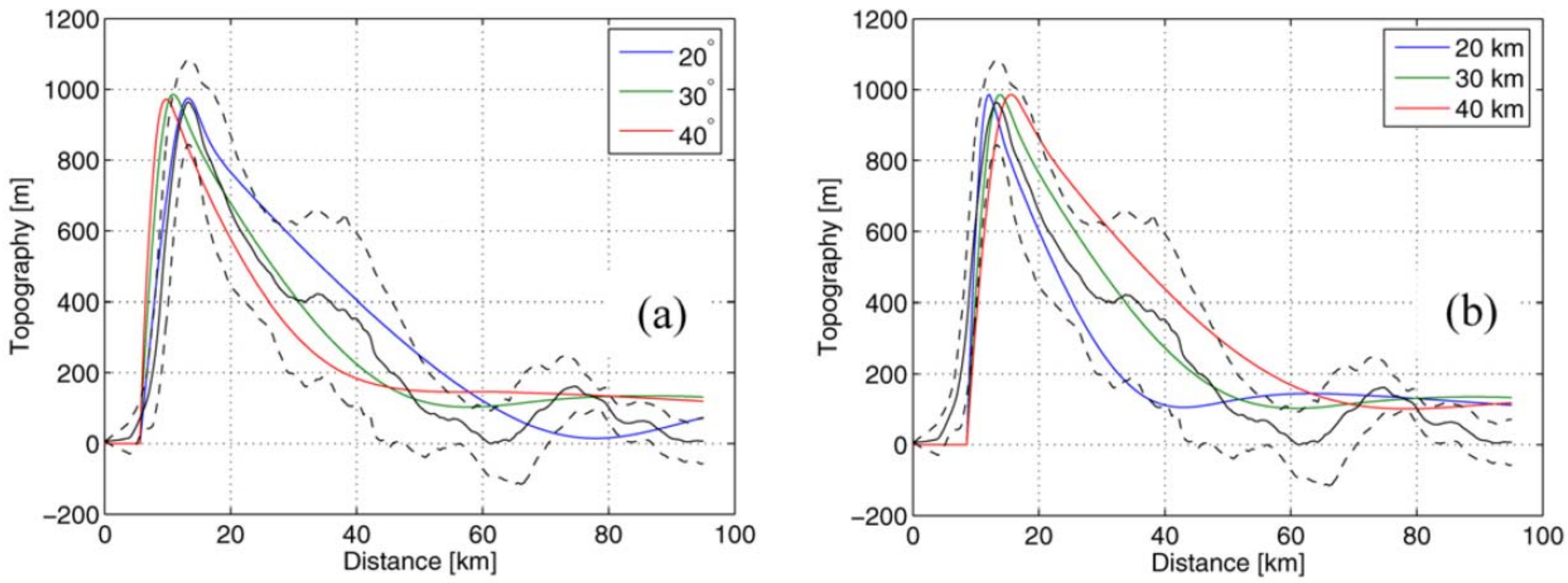
Lobate Scarps: Topography



from Grott et al., Icarus (2007)

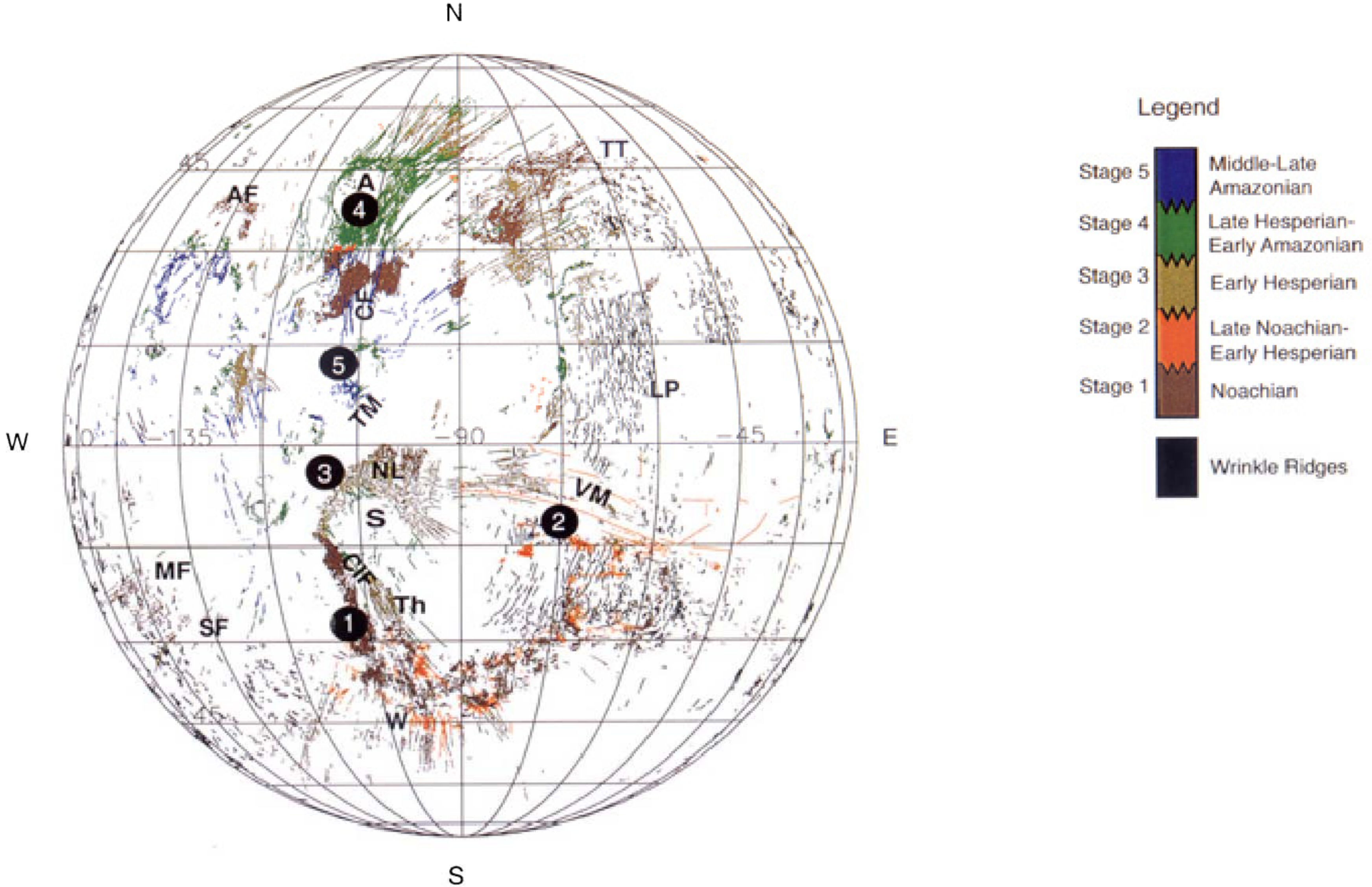
Lobate Scarps: Modeling

- scarp emplacement between 4.0 and 3.7 Gyr
- seismogenic layer thickness at the time of faulting: 27–35 km and 21–28 km
- paleo-geothermal gradients of 12–18 and 15–23 K km^{-1}
- heat flows of 24–36 and 30–46 mW m^{-2}



from Grott et al., Icarus (2007)

Paleotectonic map (western hemisphere)



from Anderson et al., J. Geophys. Res. (2001)

Table 3. Primary and Secondary Centers Identified From the Vector and Beta Analytical Techniques[a]

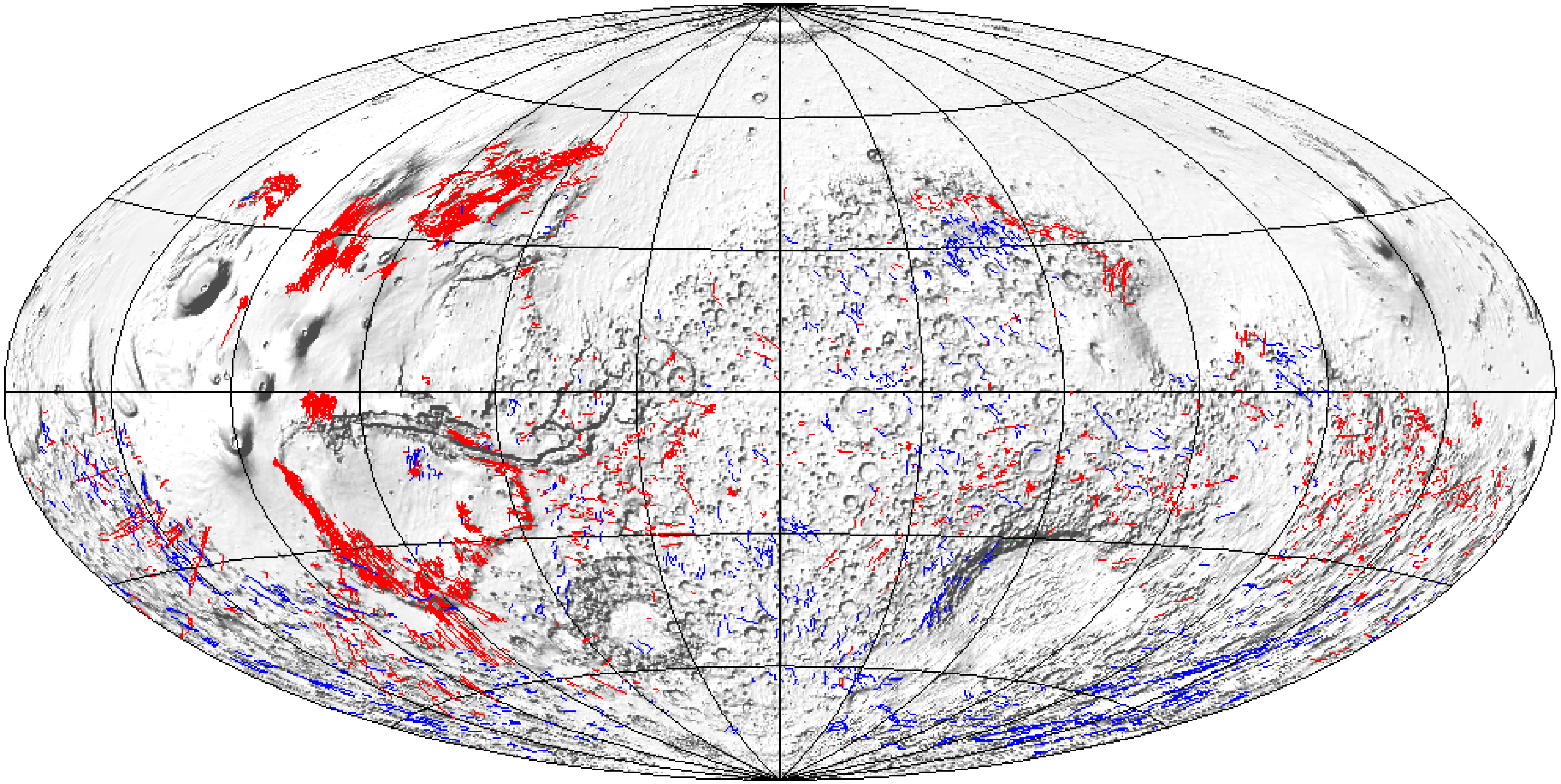
Stage	N	Center Name	V_c[b]	N_r^v,%	P_{95}	B_c	(N^B)[c]	N_i^B,%	$E_k(N^B)$[d]		(N_r^B)[e]	$E_k(N)$[d]	
									3σ	7.4σ		3σ	7.4σ
Stage 1	8972				125		40,230,226		1893	4669		266	656
Primary		Claritas	27°S, 106°W	815 (9.1%)		14°S, 106°W		3,620,720 (9.0%)			2691		
Secondary		Tempe SW	33°N, 81°W	488 (5.4%)									
		Uranius	24°N, 90°W	419 (4.7%)									
Stage 2	1577				27		1,242,160		333	821		47	116
Primary		Valles	16°S, 77°W	207 (13.1%)		12°S, 78°W		158,997 (12.8%)			564		
Secondary		Warrego	35°S, 96°W	168 (10.7%)		42°S, 89°W,		> 74,530 (> 6%)			> 386		
Stage 3	4496				66		10,102,108		949	2341		134	331
Primary		Syria NW	4°S, 107°W	379 (8.4%)		3°S, 108°W		1,202,151 (11.9%)			1551		
Secondary		Tempe SW	30°N, 80°W	298 (6.6%)		30°N, 80°W		303,063 (3%)			779		
		Ulysses	10°N, 124°W	271 (6.0%)									
		Pavonis	6°N, 114°W	299 (6.7%)									
		Syria S	19°S, 104°W	328 (7.3%)									
Wrinkle ridges	4554				67		10,349,700		961	2370		135	332
		Lunae E	18°N, 48°W	394 (8.7%)		~13°S, 48°W		620,982 (6%)			1114		
		Syria NW	4°S, 108°W	373 (8.2%)		7°S, 107°W		1,511,056 (14.6%)			1738		
Stage 3 + wr[f]	9050				133		40,946,725		1909	4710		268	662
Primary		Syria NW	4°S, 107°W	567 (6.3%)		8°S, 109°W		3,111,951 (7.6%)			2714		
Stage 4	3666				55		6,716,066		774	1909		109	269
Primary		Alba	37°N, 107°W	358 (9.8%)		42°N, 104°W		691,755 (10.3%)			1176		
Stage 5	1187				22		703,613		250	617		35	86
Primary		Ascraeus S	8°N, 106°W	207 (17.5%)		7°N, 106°W		96,395 (13.7%)			428		
Secondary		Olympus				25°N, 135°W		49,253 (7%)			231		
All Features	24452				359		298,894,115		5159	12726		725	1788
Primary		Syria NW	4°S, 107°W	1464 (6.0%)		3°S, 109°W		17,936,276 (6.7%)			5989		
Secondary		Claritas	20°S, 104°W	1446 (6.0%)									
		Alba	28°N, 108°W	1142 (4.8%)									
		Tempe	30°N, 82°W	1071 (4.4%)									
All Extensional Features	19896				278		197,916,660		4198	10355		590	1455
Primary		Claritas	20°S, 104°W	1339 (6.7%)									
Secondary		Syria NW	3°S, 107°W	1292 (6.5%)		4°S, 109°W		16,229,166 (8.2%)			5557		
		Tempe	30°N, 82°W	935 (4.7%)									
		Alba	34°N, 107°W	1026 (5.2%)									
		Ascraeus N	14°N, 109°W	1164 (5.9%)									
		Ceraunus	22°N, 109°W	1163 (5.9%)									

[a] N is the total number of radial features; V_c is the geographic location of the center identified from the vector analysis (lat/long); N_r^v (%) is the number of radial features defining the center (also given as % of N) ; P_{95} is the *Jowett and Robin* [1988] Gaussian peak statistic for 95% confidence level, to which the N_r^v values should be compared; B_c is the geographic location of the center identified from the beta analysis (lat/long); N^B is the total number of intersections derived by the beta analysis program from N; N_i^B is the number of intersections (also given as % of N^B) that determine the center; $E_k(N^B)$ is the expected value for the *Kamb* [1959] method significance level relative to the population of

from Anderson et al., J. Geophys. Res. (2001)

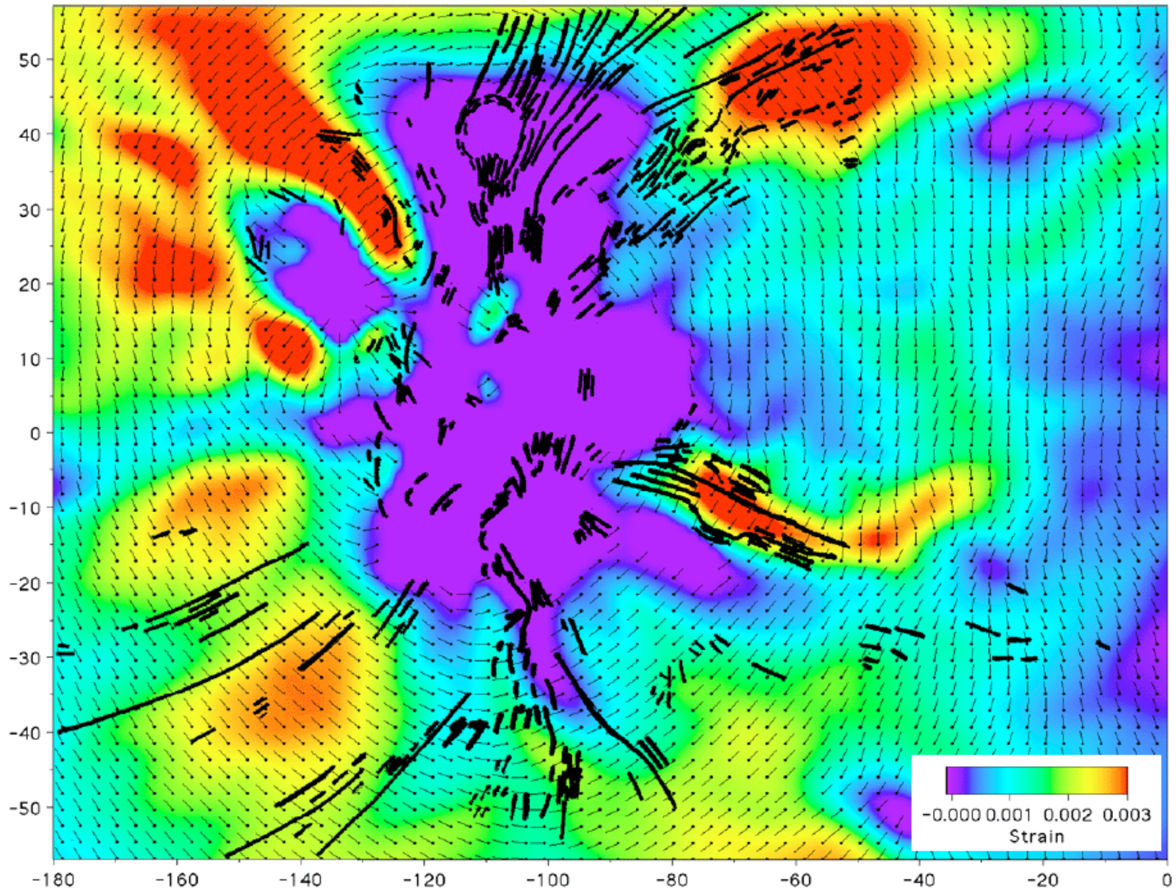
Global fault data set

available online at http://europlanet.dlr.de



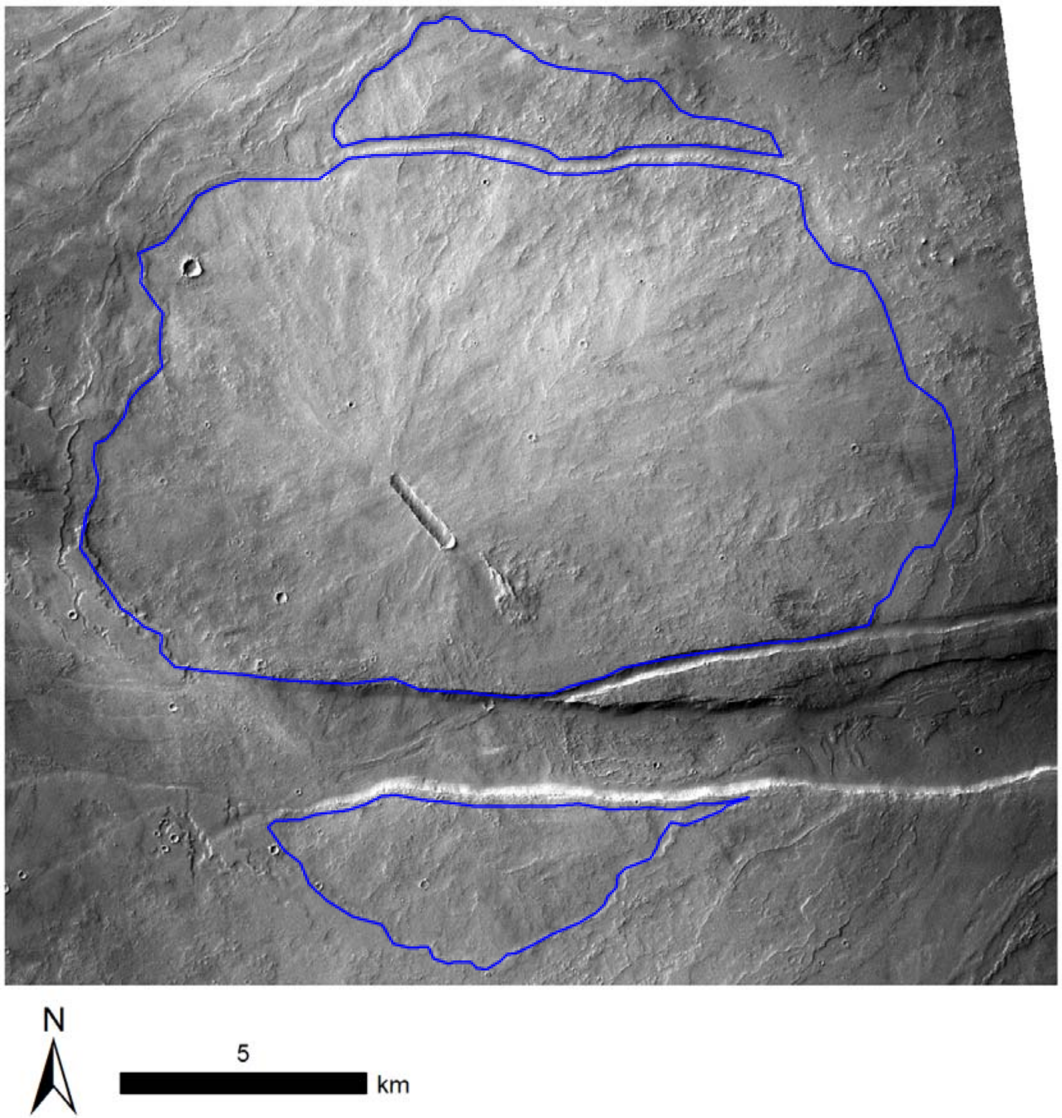
from Knapmeyer et al., *J. Geophys. Res.* (2006)

Tharsis modeling: Strain distribution



from Banerdt & Golombek, LPSC (2000)

Late-stage tectonic deformation



- Young faulting (very Late Amazonian)
- Faults as pathways for fluids
- Faults as pathways for gas escape (methane)?

Fluid circulation along fractures

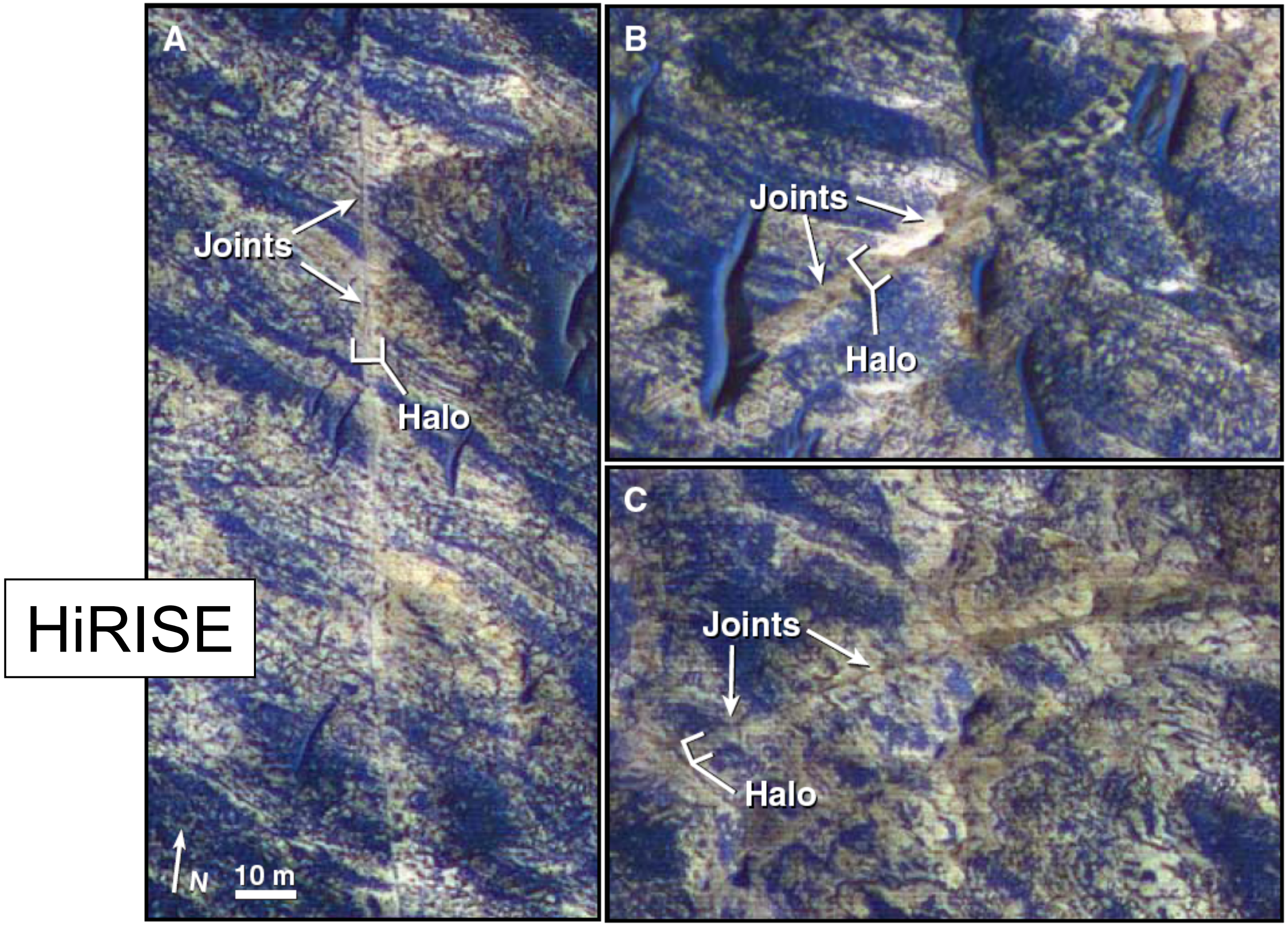
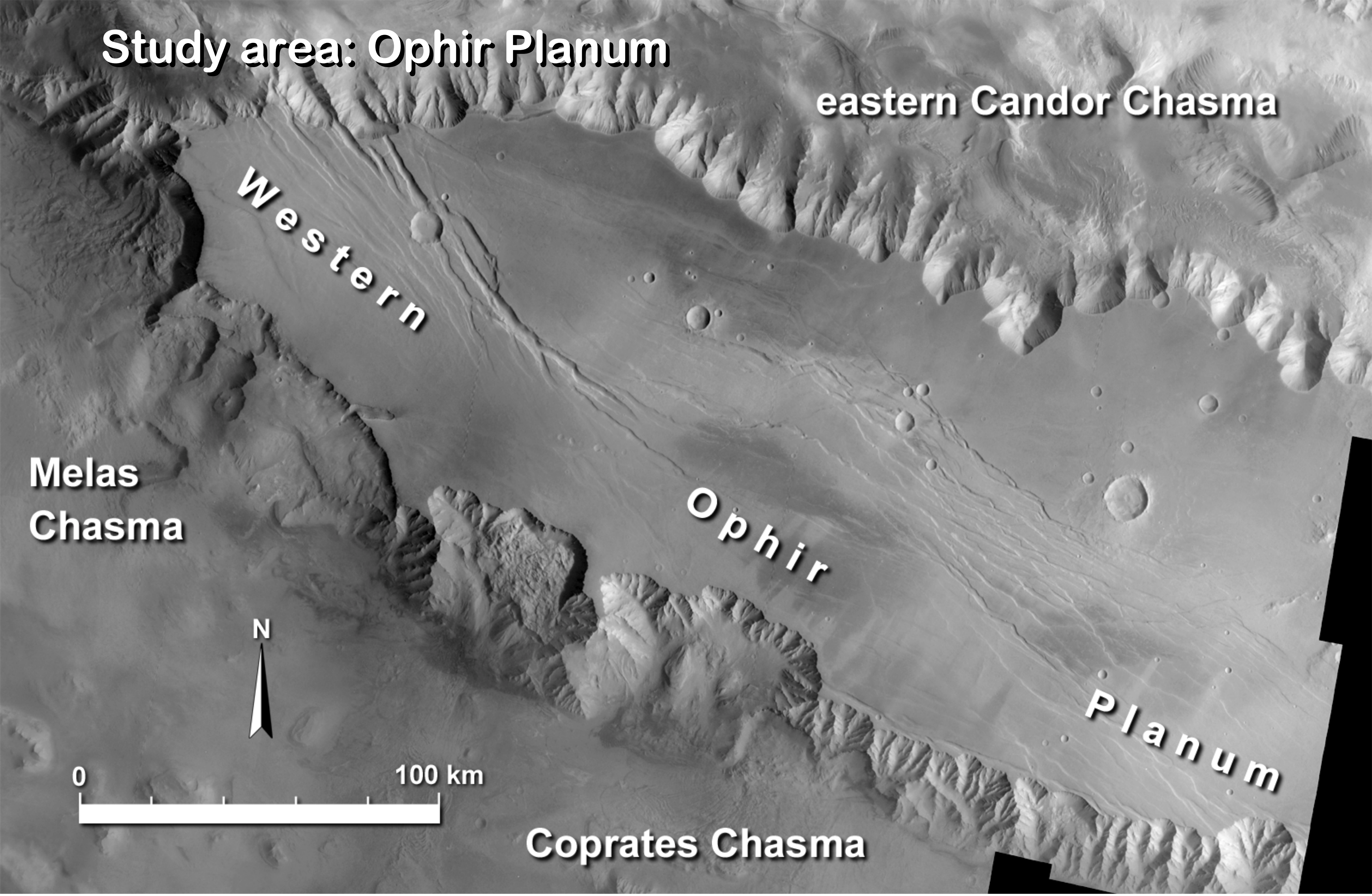
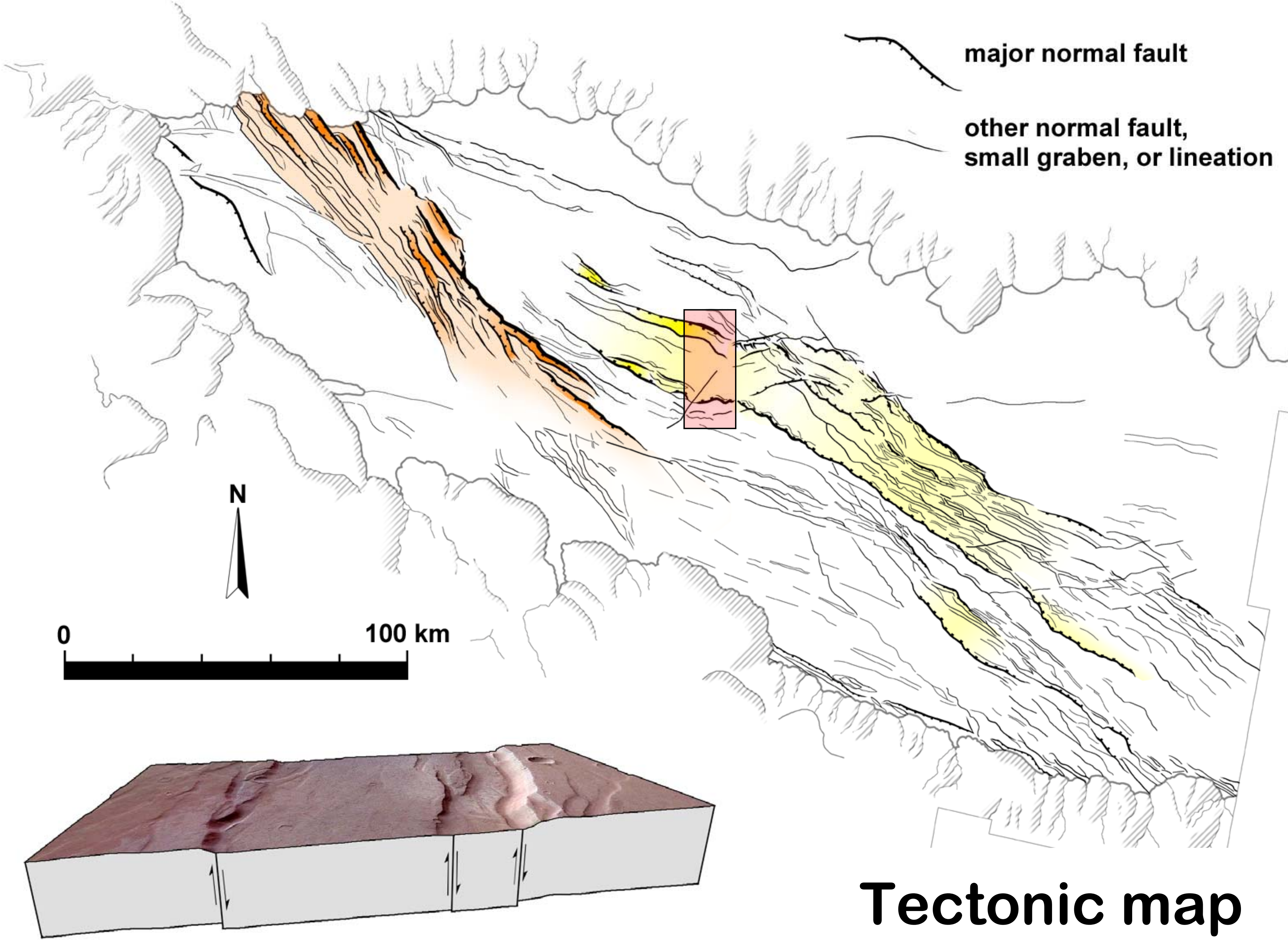


Fig. 2. (**A** to **C**) Examples of joints and surrounding halos of light-toned bedrock. The joints are the thin dark lineations. The scale bar and north arrow apply to each panel.

from Okubo and Schultz (2007)

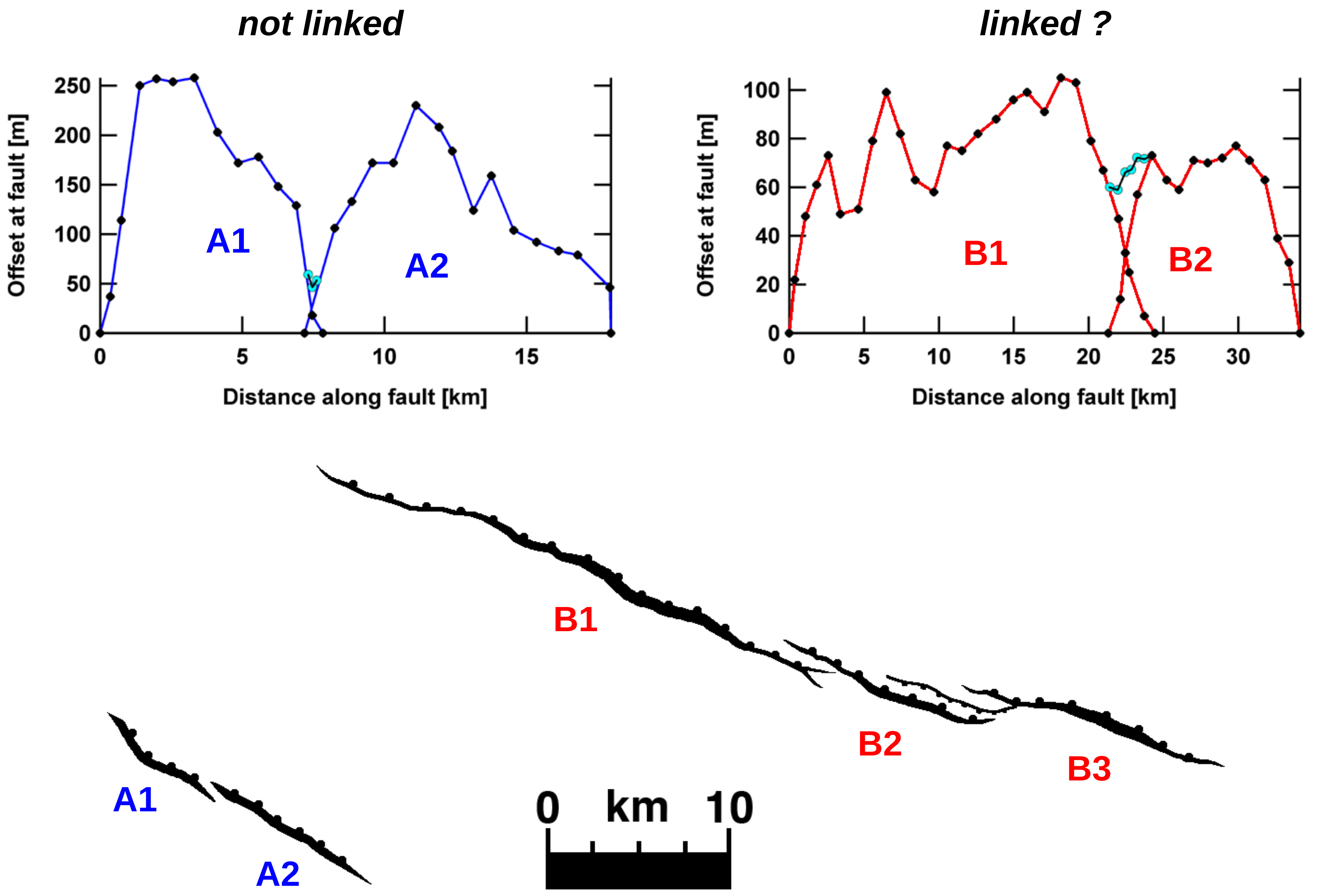


Fault scaling

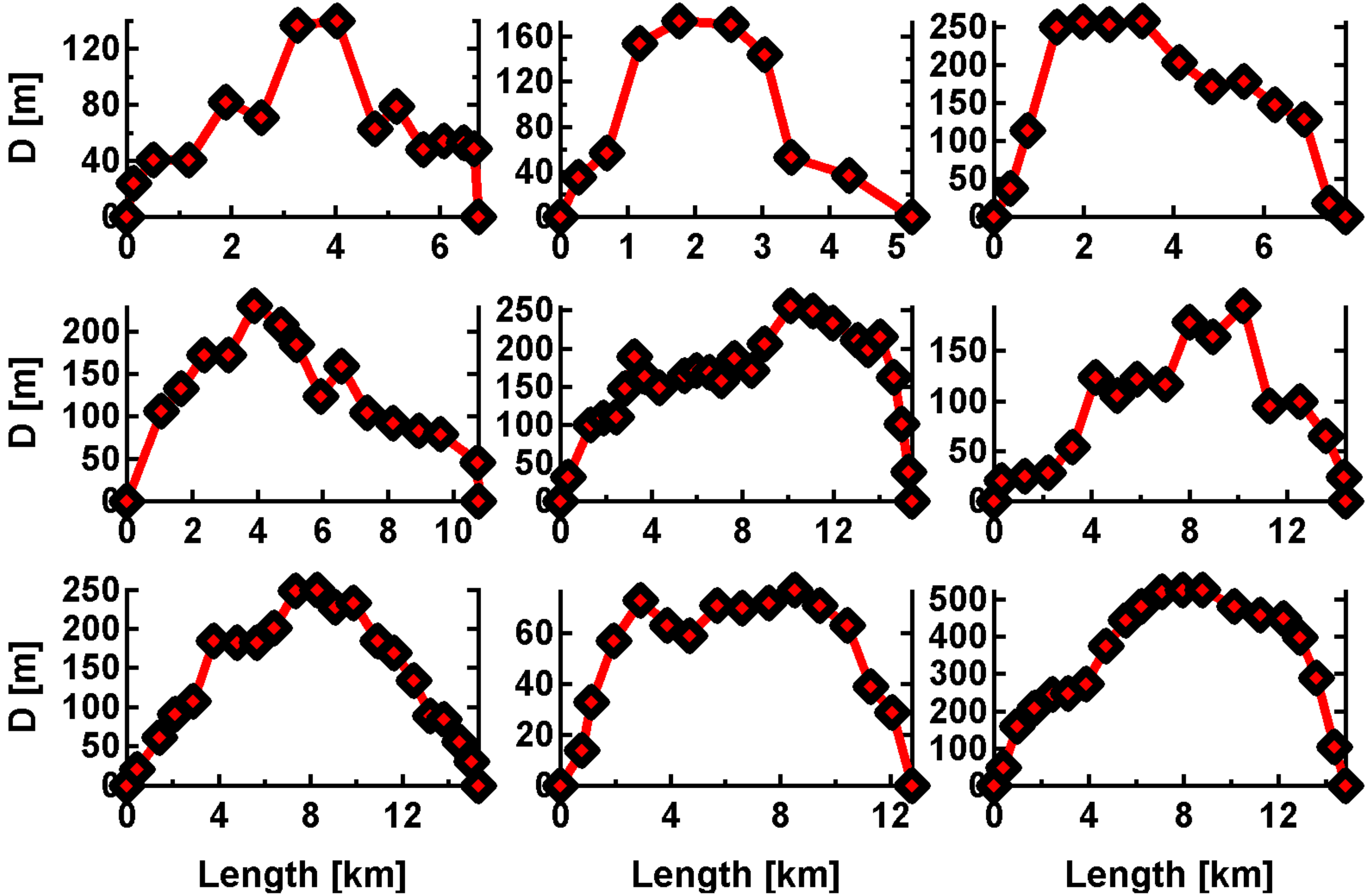


Tectonic map

Relay ramps and fault linkage

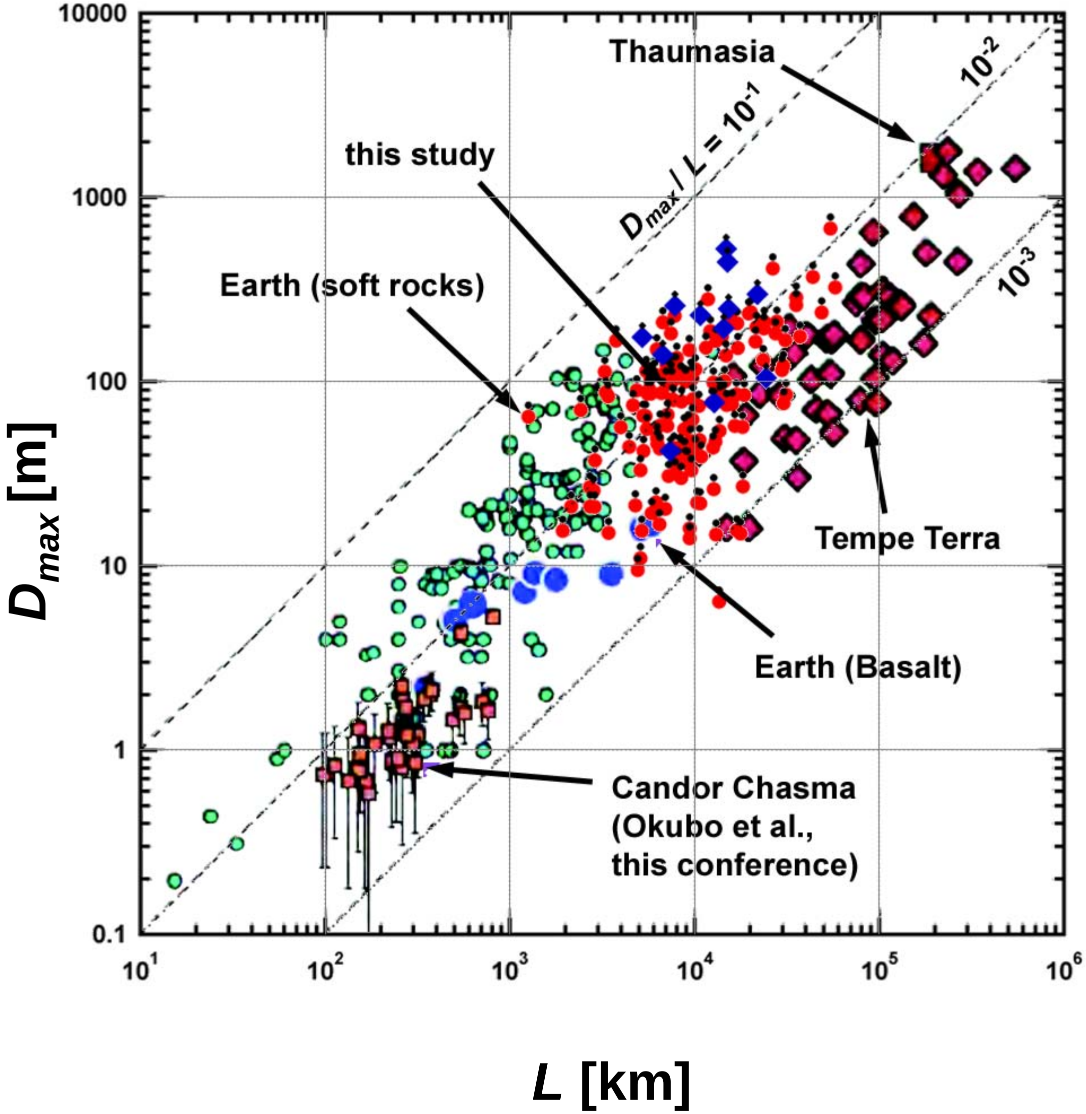


Displacement profiles (from HRSC DEM)



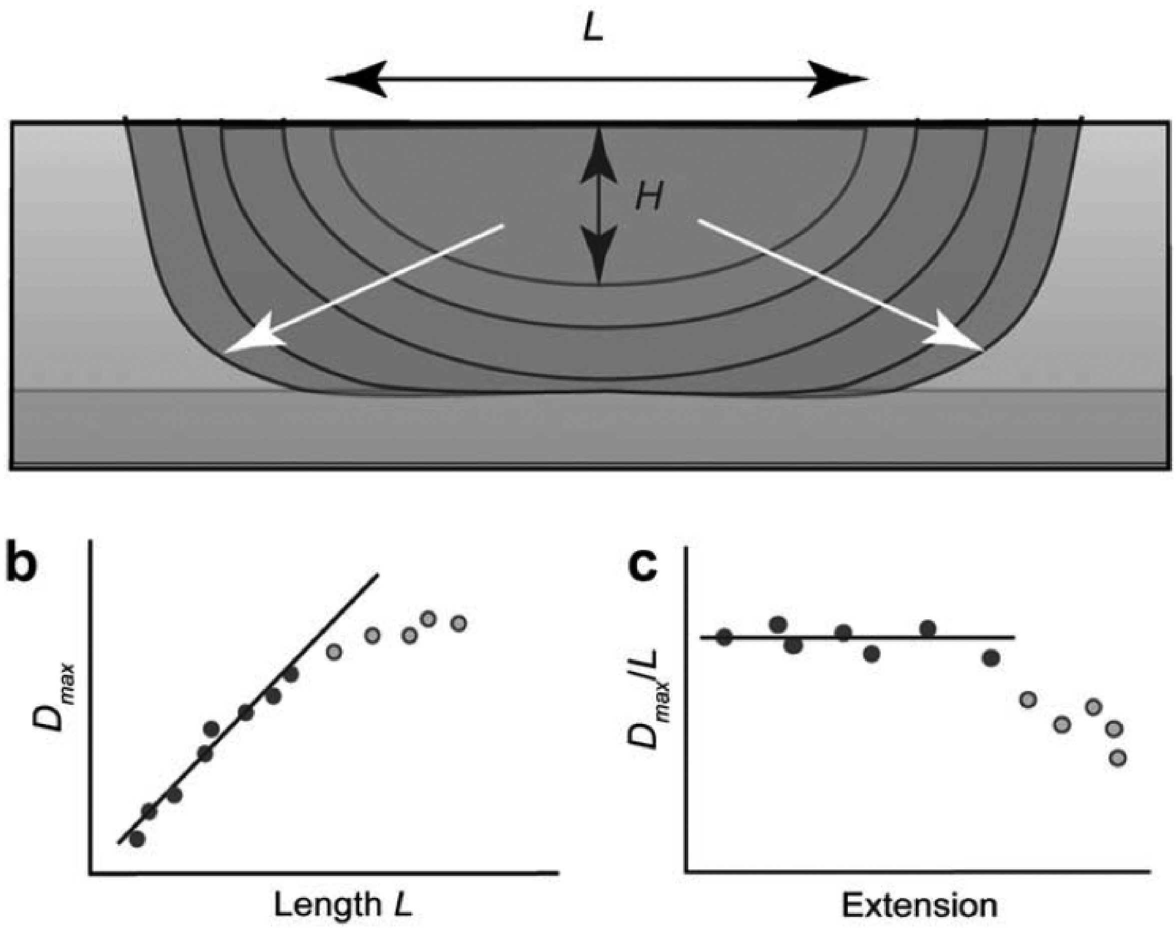
from Hauber et al. (2007)

Same scaling laws on Earth and Mars



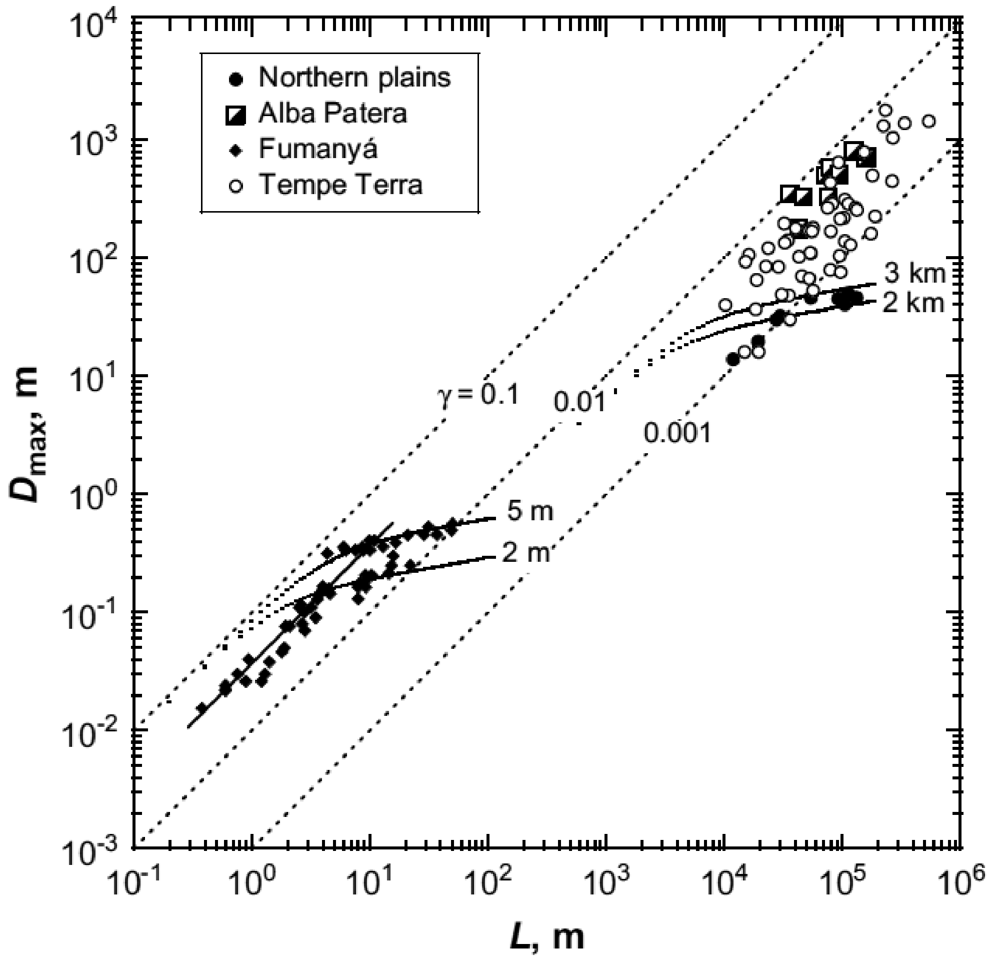
from Schultz et al., *J. Struct. Geol.* (2006)

Fault growth



from Polit et al., J. Struct. Geol. (2009)

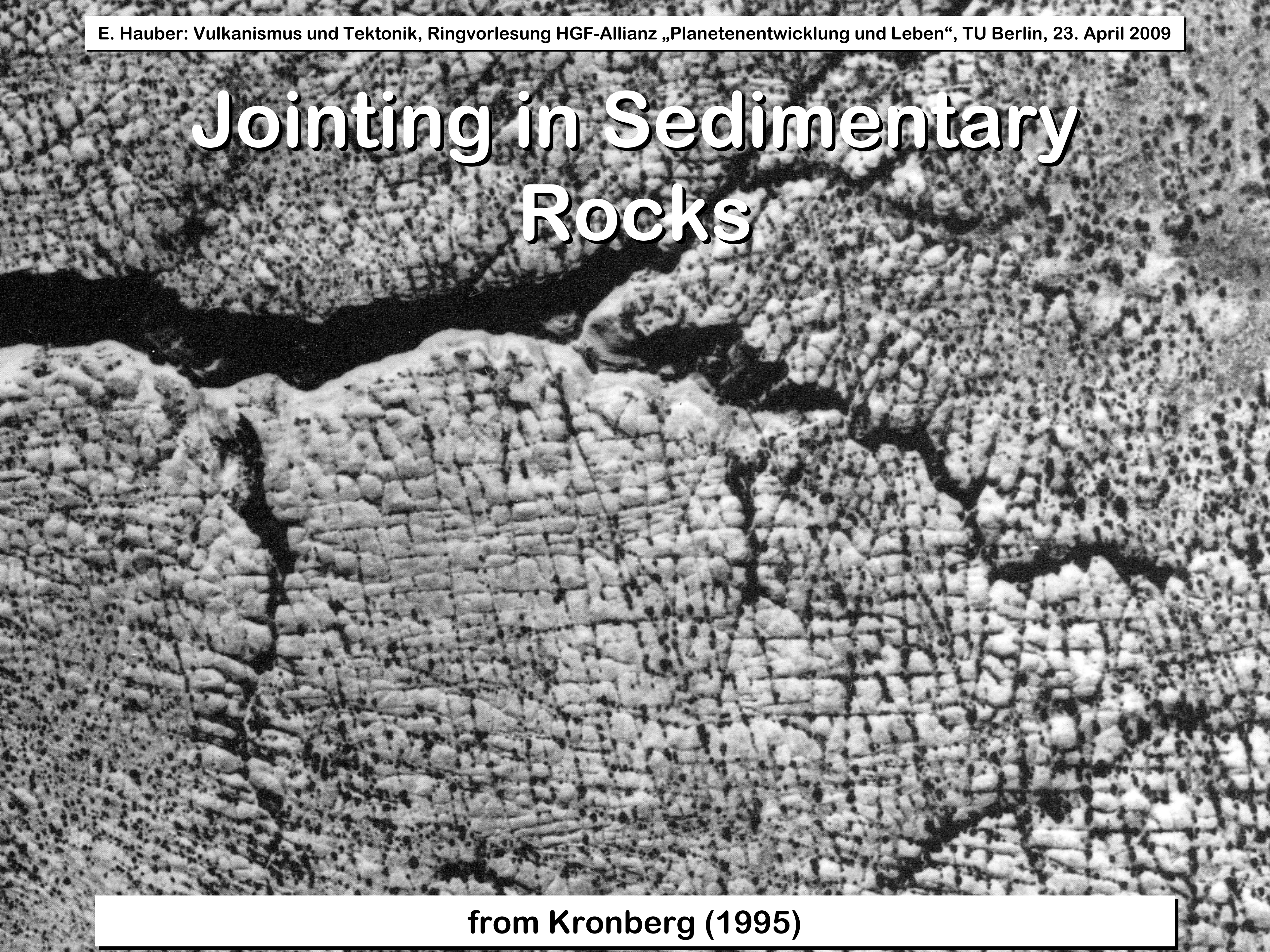
Fault scaling: Applications



- **Faults in northern plains: restricted in 2-3 km depth**
- **Thickness of sedimentary cover?**

from Polit et al., J. Struct. Geol. (2009)

Jointing in Sedimentary Rocks

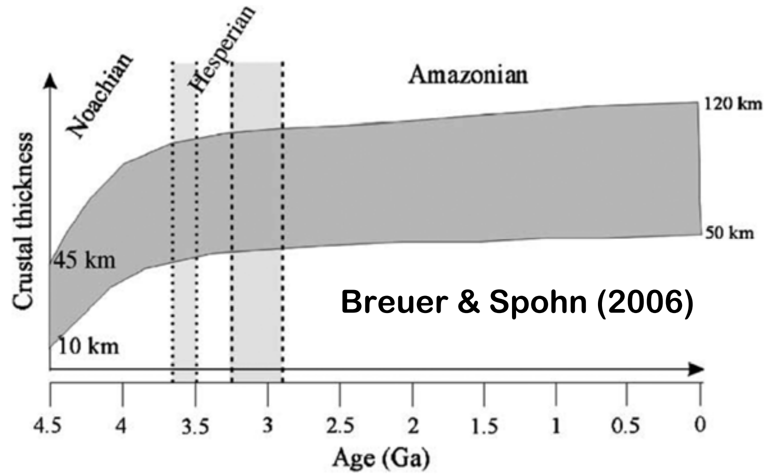


from Kronberg (1995)


E. Hauber: Vulkanismus und Tektonik, Ringvorlesung HGF-Allianz „Planetenentwicklung und Leben“, TU Berlin, 23. April 2009
Joints seen from Orbit!
Image: HiRISE on Mars Reconnaissance Orbiter
50 m

Summary

- Mars was endogenically active over all of ist history
- Activity decreased with time, shows episodic pattern, more and more focused in Tharsis and Elysium
- Volcanism mostly effusive
- Tectonic deformation mostly vertical (plume tectonics, one plate-planet)



Breuer & Spohn (2006)

Major questions

- Chronology of volcanism and tectonics (absolute ages)
- Volumes of volcanism (crustal production, outgassing)