PTYS 542

# Mars Tectonics

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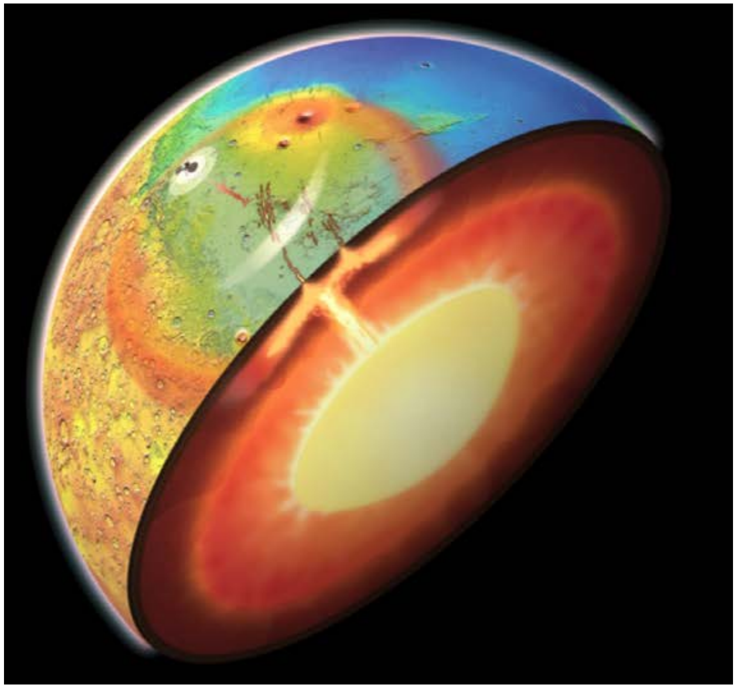
# Planetary structure and tectonics

- Crust: The chemically distinct silica-rich outer layer of a silicate planet
- Mantle: The mafic (Fe,Mg-rich) deep interior
- Lithosphere: The outer rigid portion of a planetary body that deforms primarily by brittle and elastic processes over geologic timescales
  - material beneath the lithosphere deforms viscously on geological timescales
  - the lithosphere can be thicker or thinner than the crust
  - below the lithosphere, the mantle deforms viscously over geologic timescales
- Tectonics: The deformation of the lithosphere through faulting and folding

# Planetary geodynamics

- Geodynamics – internally driven activity
  - heat is generated in planetary interiors
    - radioactive decay (U, Th, K)
      - terrestrial planets, non-resonant satellites
    - tidal heating
      - satellites in orbital resonances (Io, Europa…)
    - heat from accretion and differentiation (early)
  - heat is released at the surface
    - thermal conduction through the *lithosphere* (Mars)
    - volcanism (Io)
    - plate tectonics (Earth)

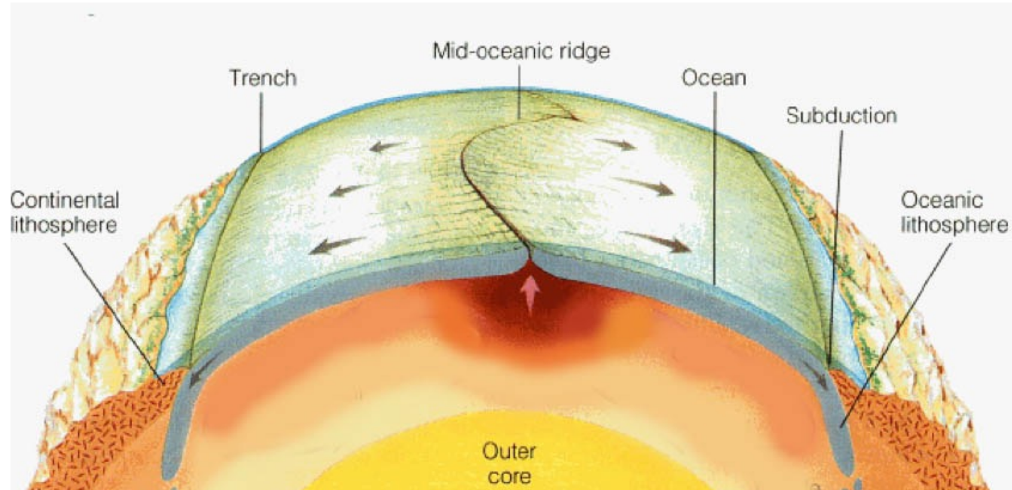


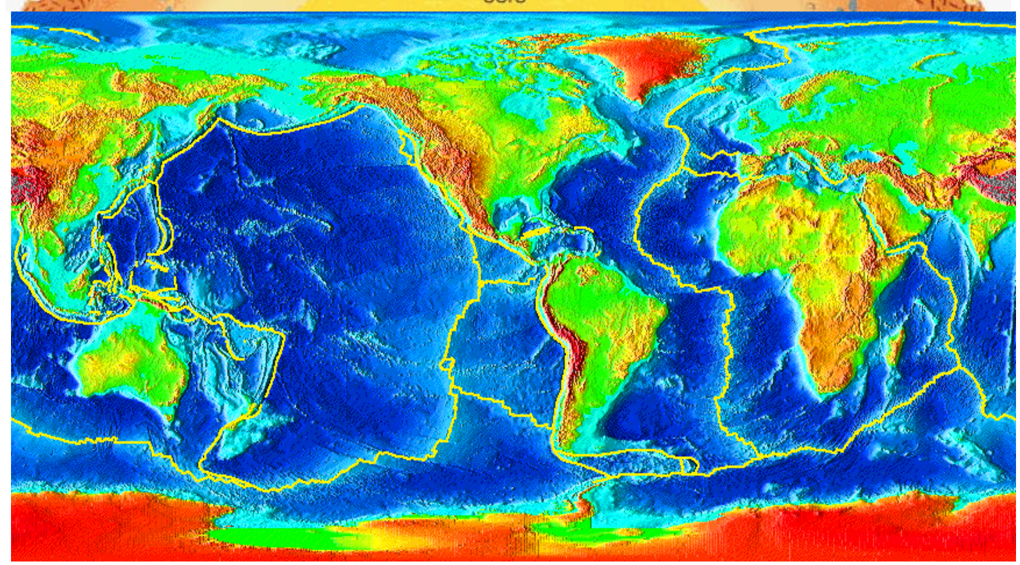
***Every planet does what it does simply because it is trying to get rid of heat***

**PTYS 512: Planetary global tectonics – how and why do planets do what they do?**

# Earth: Plate Tectonics

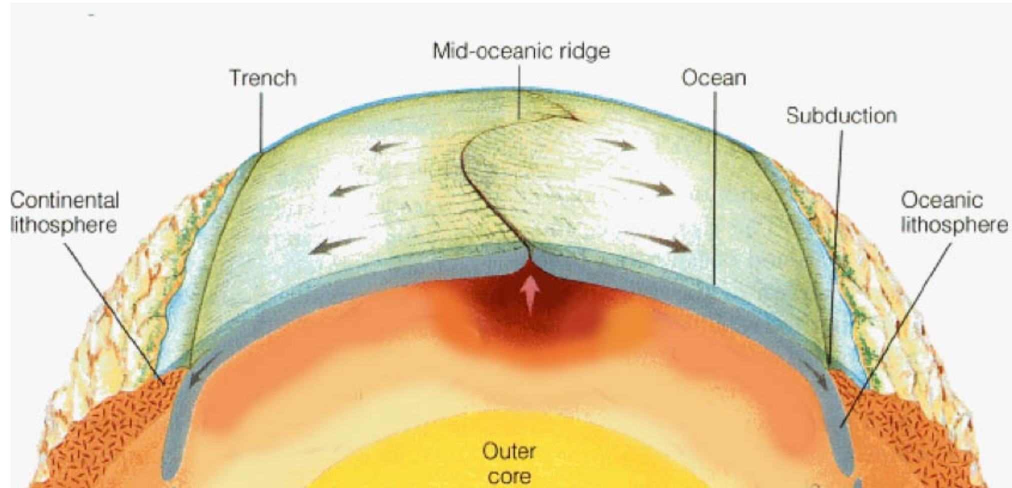
- Most tectonics on Earth is related to plate tectonics
  - 8 large plates
  - ~2 dozen small plates
  - moving at $v \sim$ 1-10 cm/year

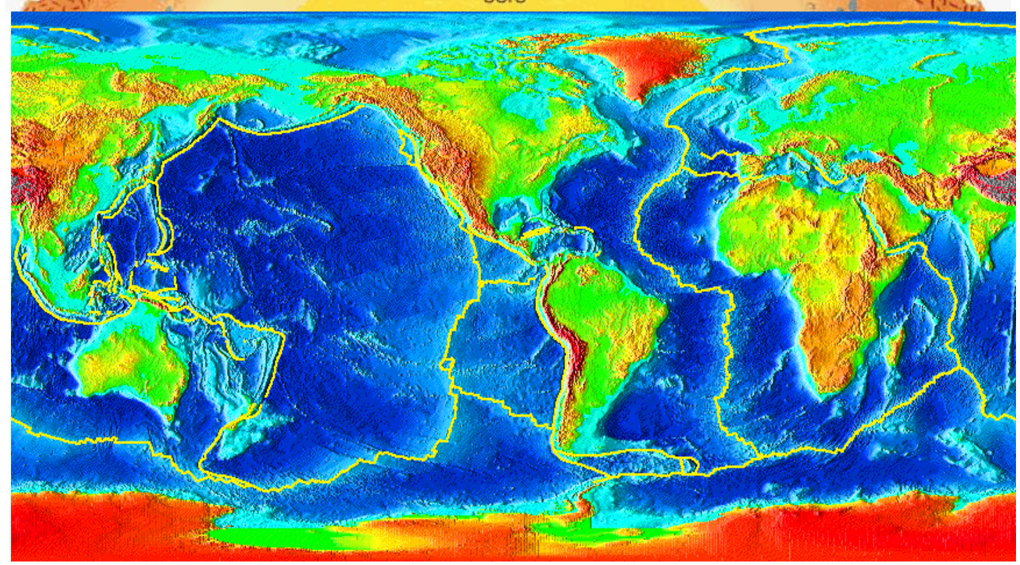


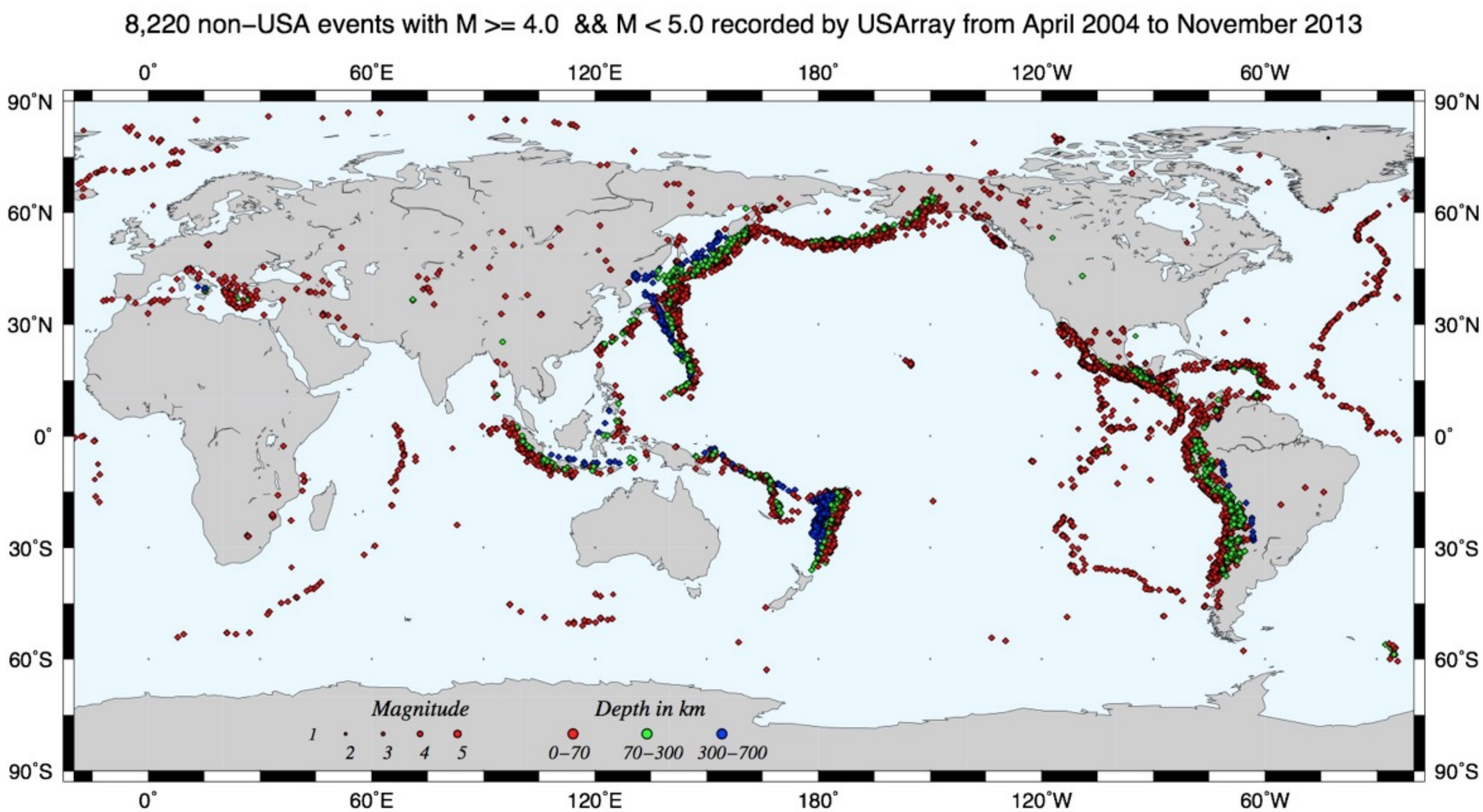
# Earth: Plate Tectonics

- How does Earth get rid of it's heat? Plate tectonics
- Heat is generated in the mantle
  - radioactive decay of U, Th, K
- Mantle convection brings that heat to base of the lithosphere
- Lithospheric plates in motion
  - oceanic plates recycled at subduction zones
  - new oceanic crust/lithosphere created at spreading centers
  - most heat is lost through cooling of newly created oceanic crust



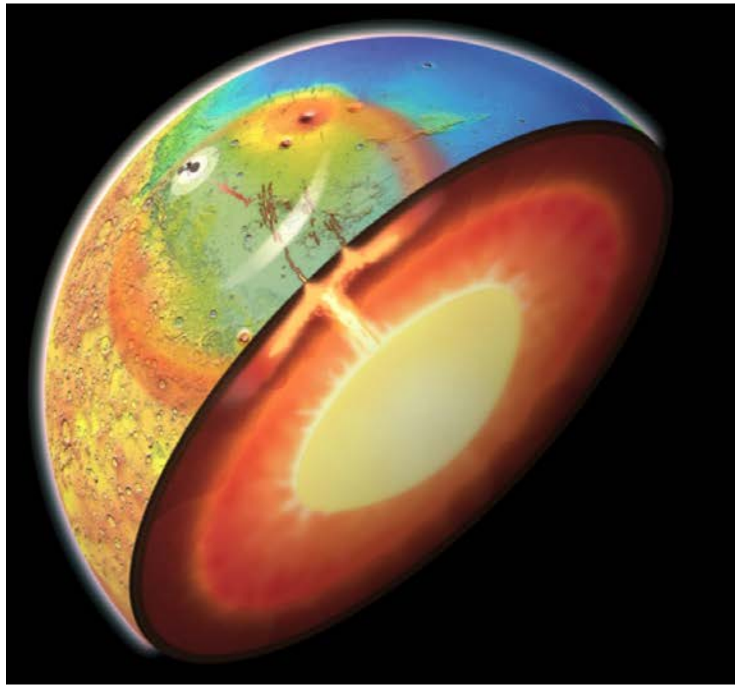
# Plate tectonics: Global seismicity




http://www.seismosoc.org/publications/SRL/SRL_85/srl_85-3_astiz_et_al-esupp/

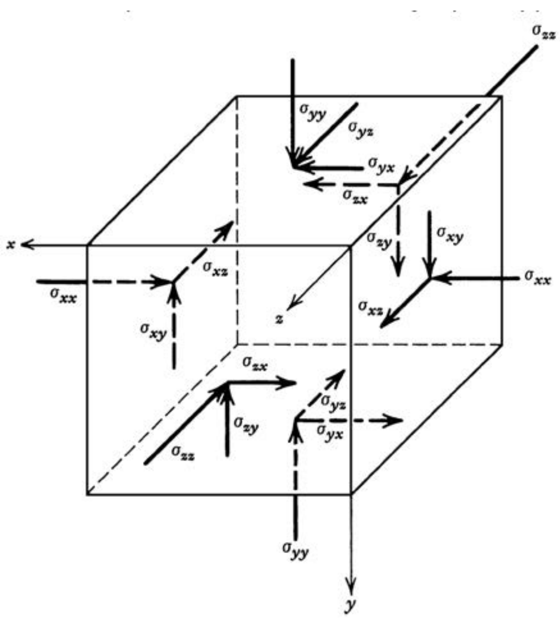
# How does Mars get rid of heat?

- Martian mantle is convecting
- Martian lithosphere is stationary
  - no plates or plate tectonics
  - “one-plate planet” or “stagnant lid”
- Heat passes through the lithosphere by conduction (like a pot on a stove)



# Tectonics 101

- Stress: force per unit area
  - represented with a 3x3 tensor of normal and shear stresses
- Strain: fractional change in length
  - represented with a 3x3 tensor of normal and shear strains



# Tectonics 101

- Stress: force per unit area ($\sigma$)
- Strain: fractional change in length ($\varepsilon$)
  - represented with a 3x3 tensor of normal and shear strains, or 3 principal strains
  - $\sigma_1\ \sigma_2\ \sigma_3$ , $\varepsilon_1\ \varepsilon_2\ \varepsilon_3$
- Linear elasticity: 1D
  - spring: Hooke's Law

    $$F = k\,x$$
  - Continuum: strain is proportional to stress

    $$\sigma = E\varepsilon$$
- Linear elasticity: 3D

$$\varepsilon_1 = \frac{1}{E}\sigma_1 - \frac{\nu}{E}\sigma_2 - \frac{\nu}{E}\sigma_3$$

$$\varepsilon_2 = -\frac{\nu}{E}\sigma_1 + \frac{1}{E}\sigma_2 - \frac{\nu}{E}\sigma_3$$

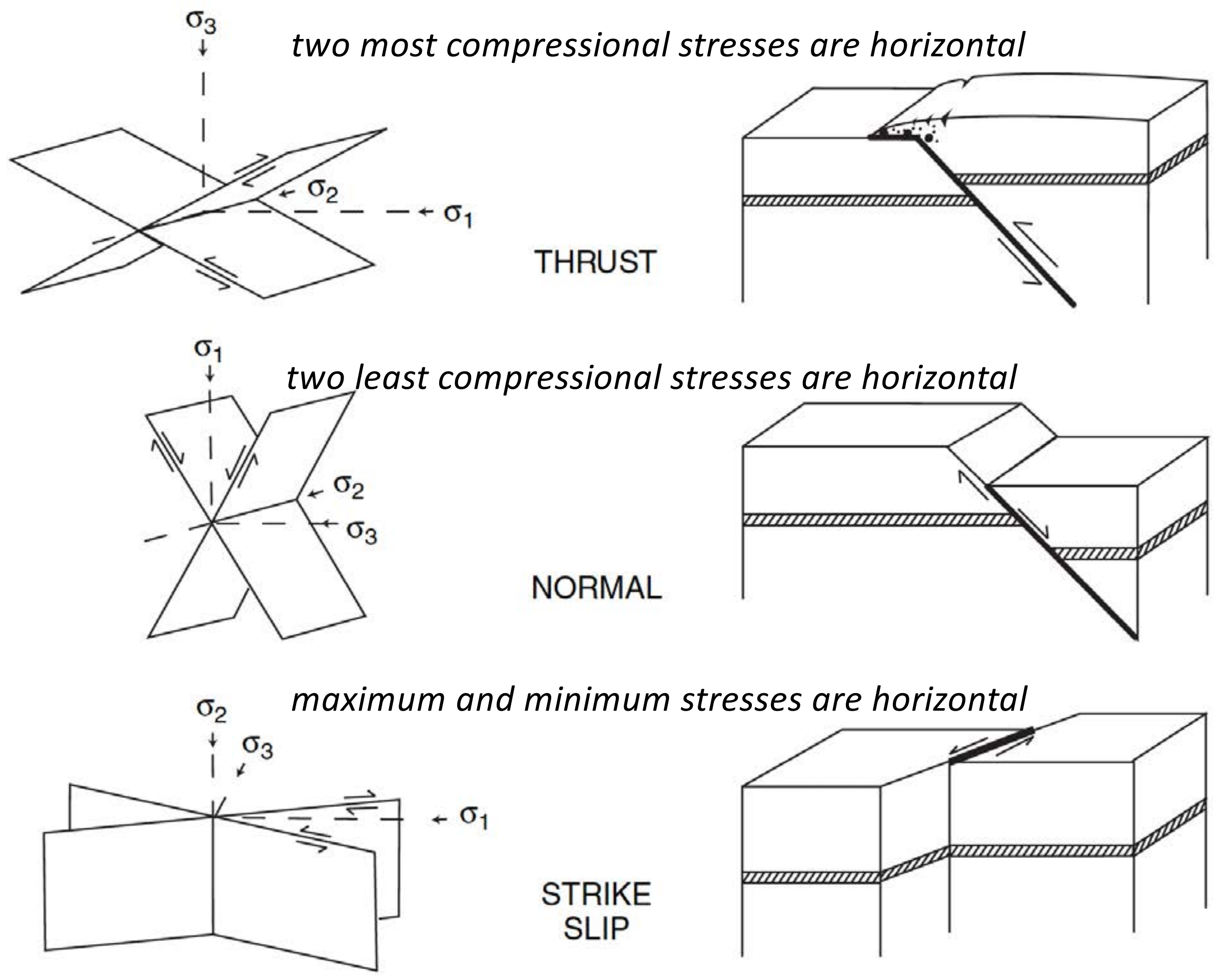
$$\varepsilon_3 = -\frac{\nu}{E}\sigma_1 - \frac{\nu}{E}\sigma_2 + \frac{1}{E}\sigma_3.$$

**Deformation → strain → stress**

# Tectonics 101

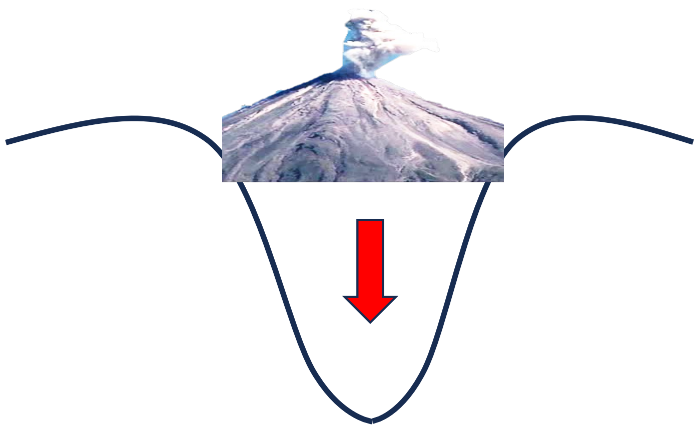
- When stress exceeds some critical value (yield strength) the lithosphere will fail → fault
- Directions and magnitudes of the three “principal stresses” determine what style of fault forms

  →<u>Anderson’s theory of faulting</u>



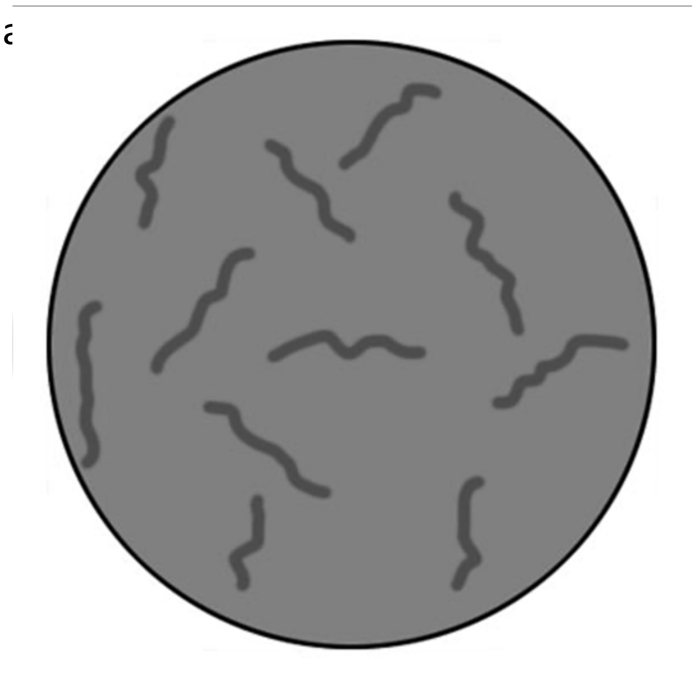
# What causes stress (and tectonics) on Mars?

- load (force) causes deformation of the lithosphere
- bending the lithosphere → strain → stress
- load (force) can be directed upwards or downwards
  - volcano ↓
  - ice cap ↓
  - warm mantle plume ↑
  - erosion ↑



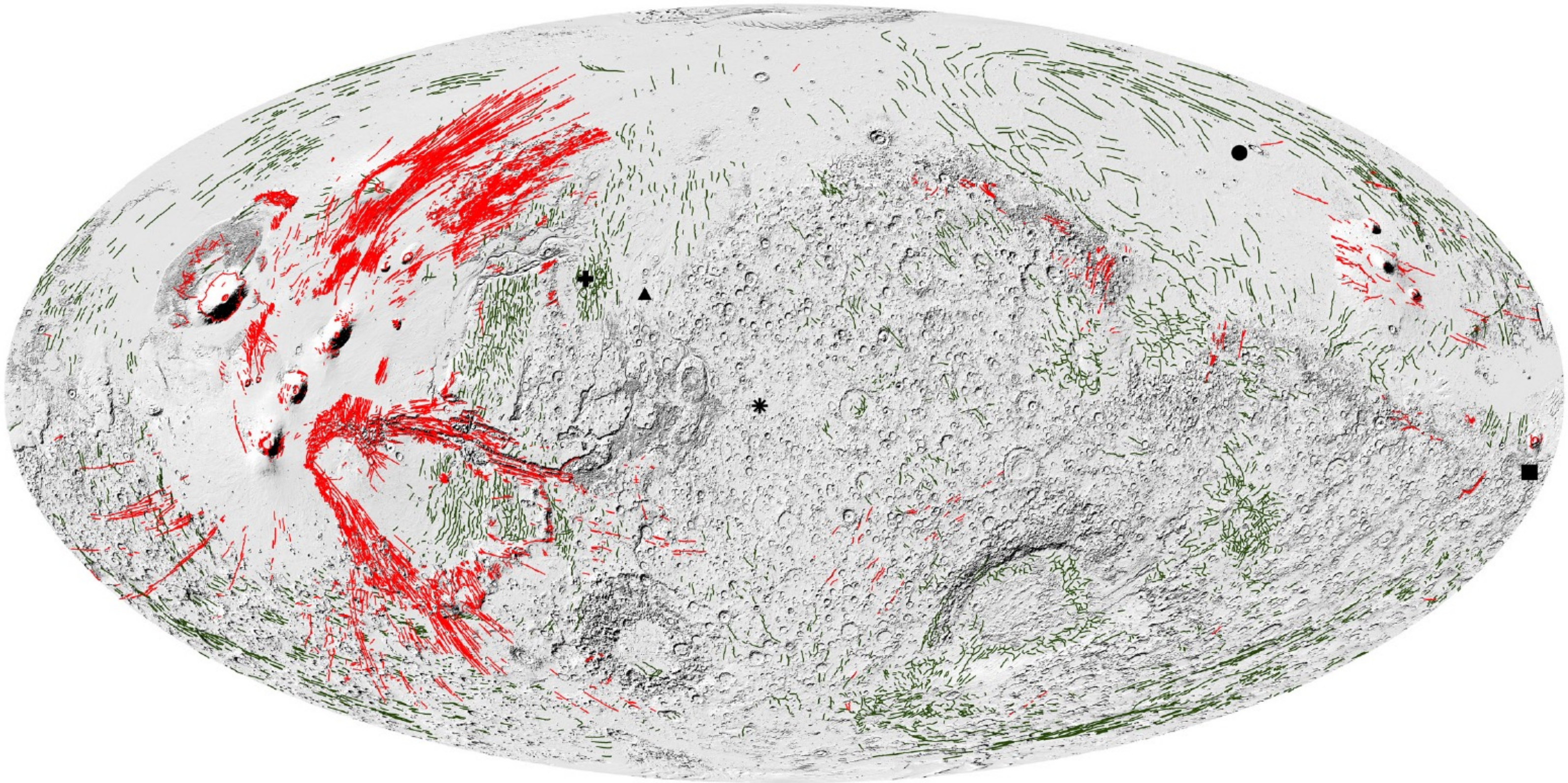
# What causes stress (and tectonics) on Mars?

- shortening or lengthening → strain → stress
  - interior volume change (expansion or contraction) forces a change in surface area
  - Why?
    - warming = expansion → extension in lithosphere
    - cooling = contraction → compression in lithosphere

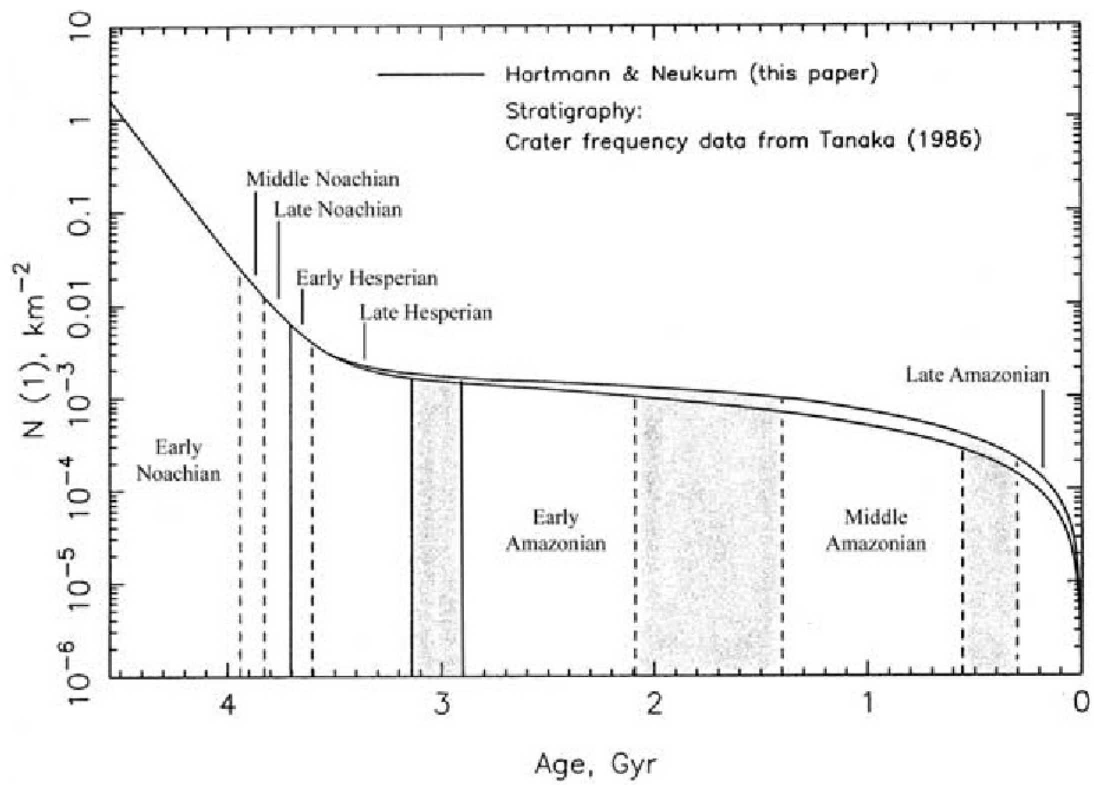


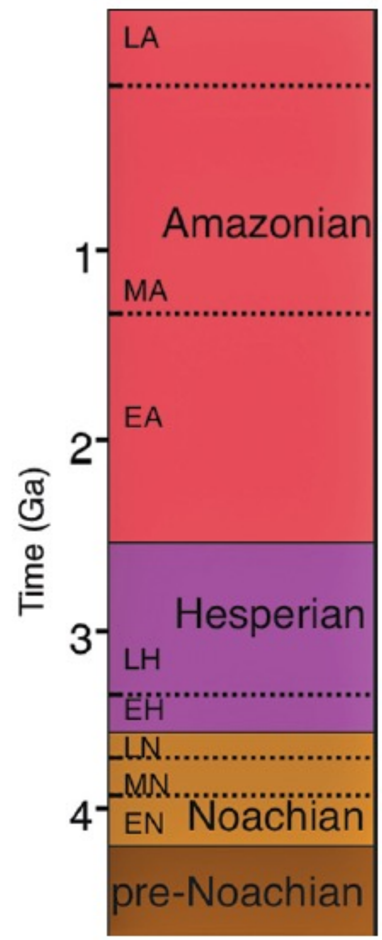
# Why study tectonics?

- Martian tectonics reveals the geodynamic evolution
- Deformation of the lithosphere and forces at play

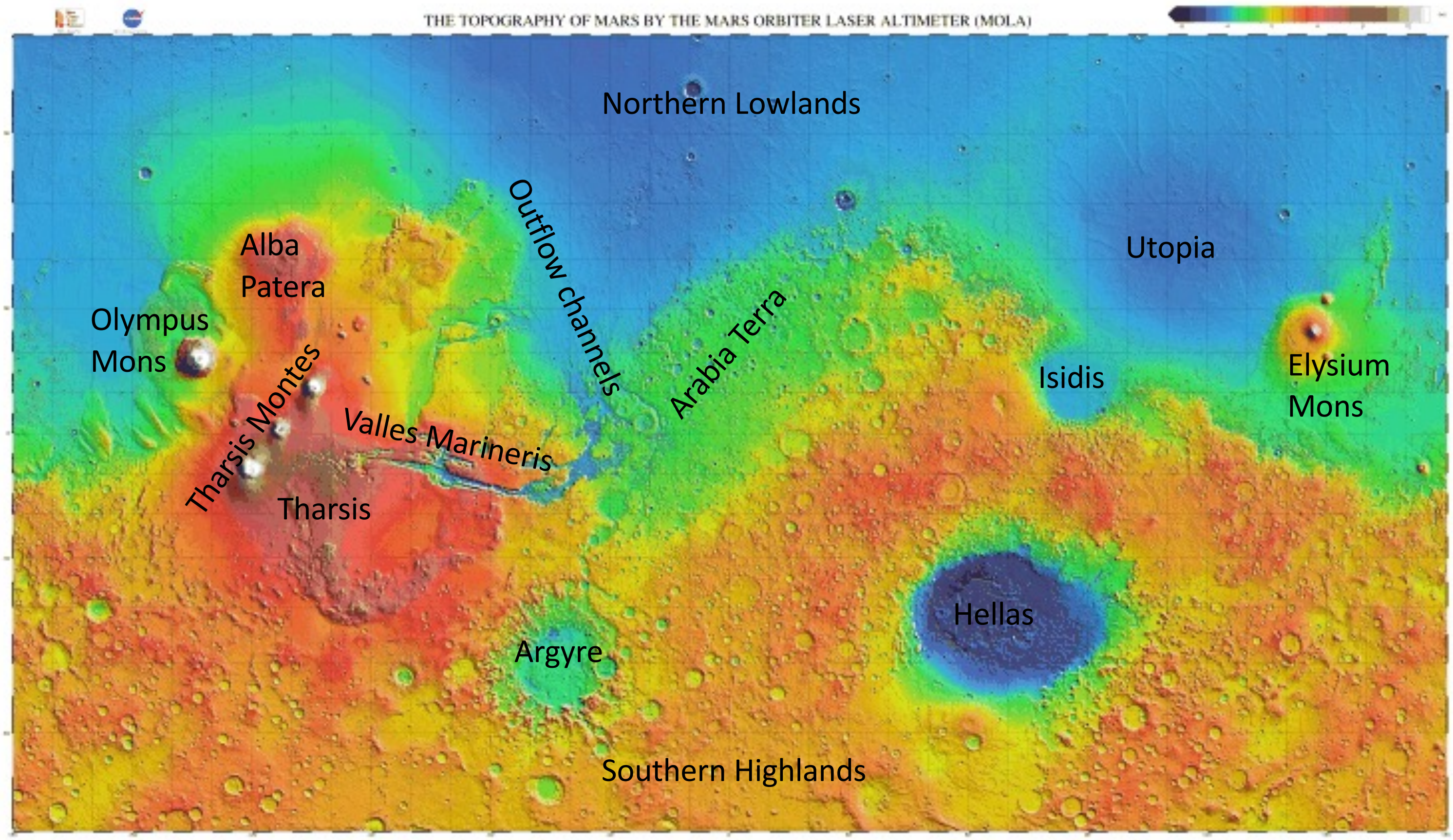


# Martian Chronology



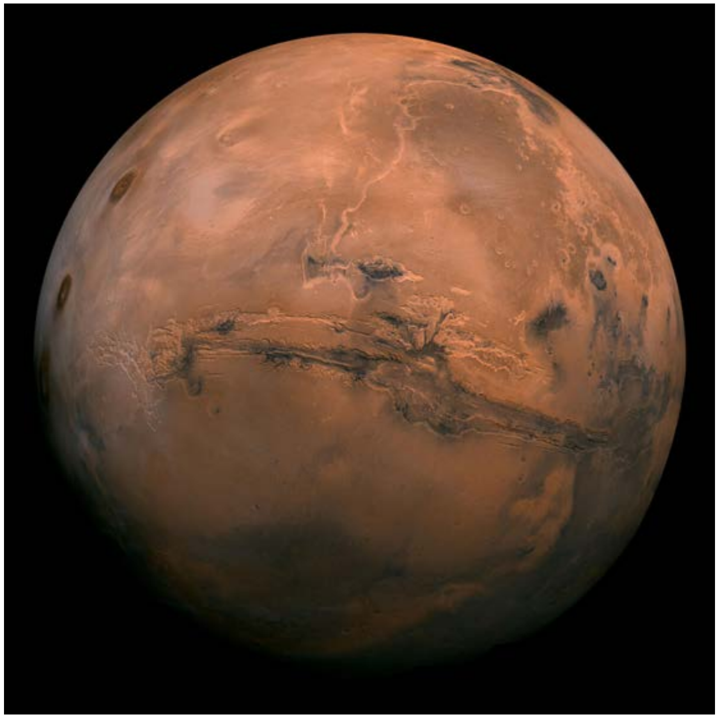
# Martian geography



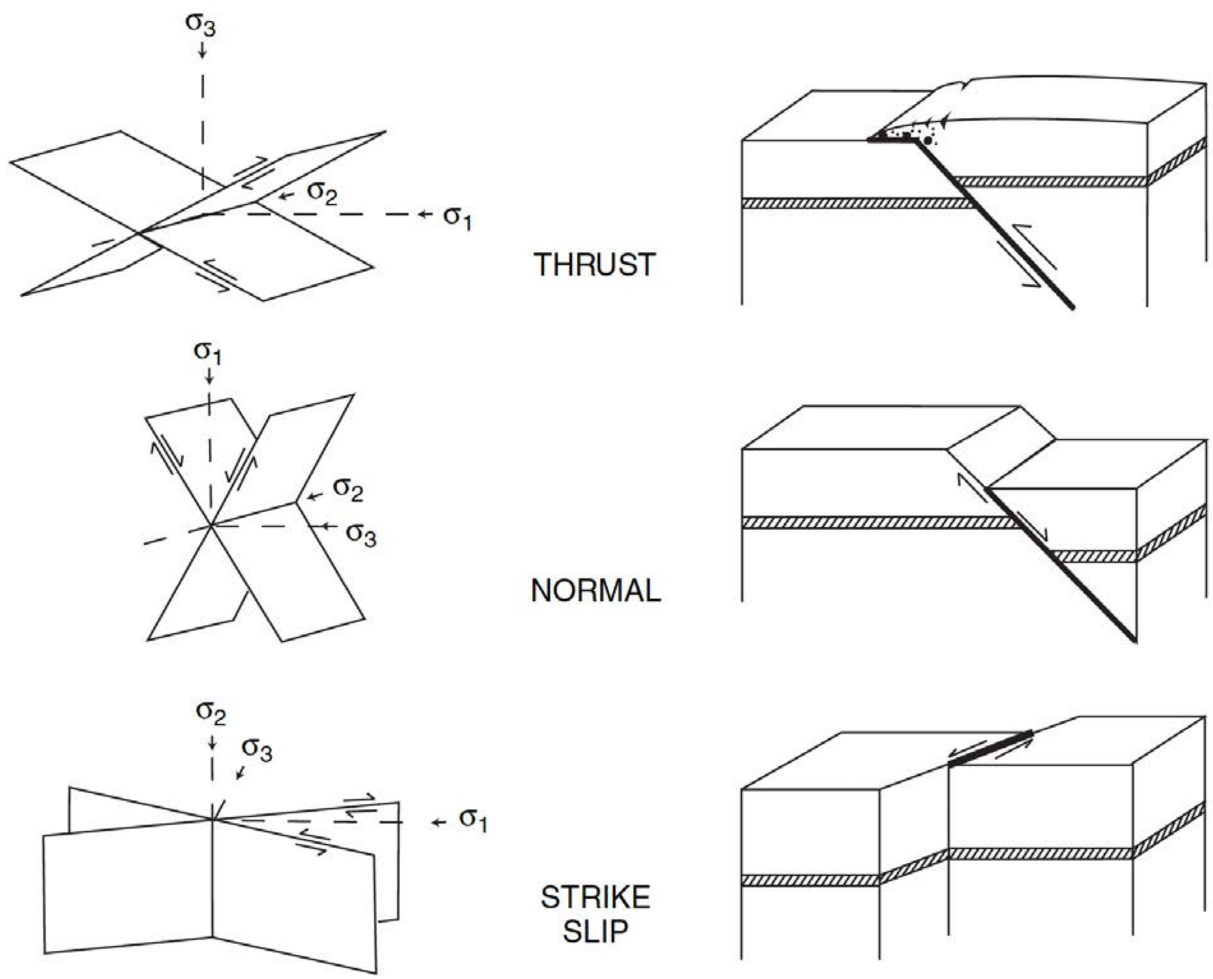

**(Topography: red=high, blue=low)**

# Mars tectonics

- In the absence of plate tectonics, most planetary tectonic structures accommodate small strains in strong lithospheres

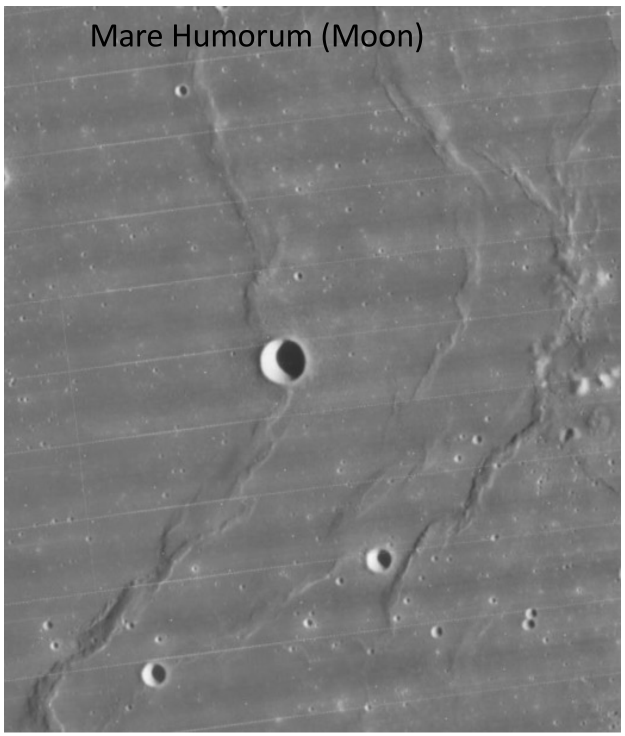


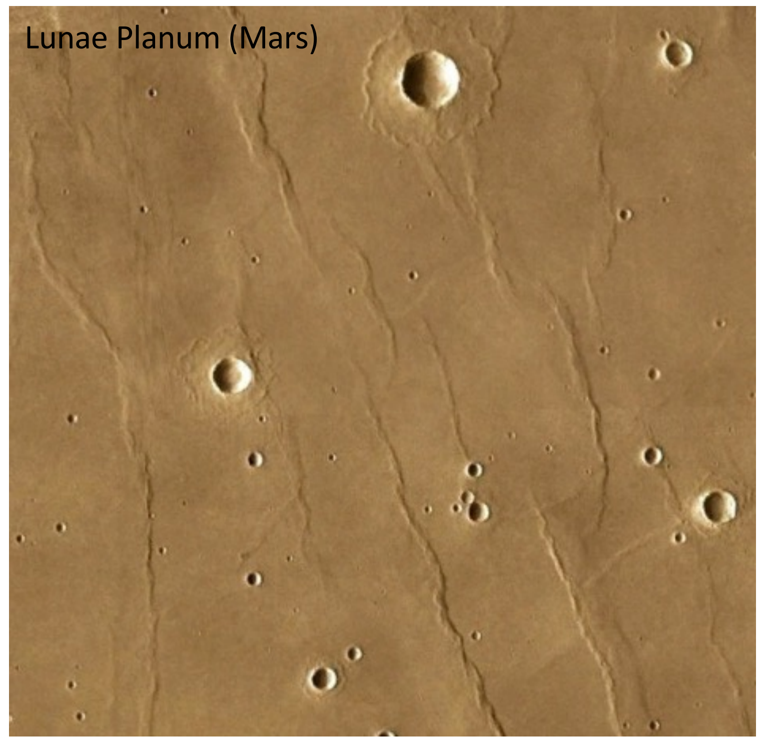
# Major types of tectonic features



# Compressional structures: Wrinkle ridges

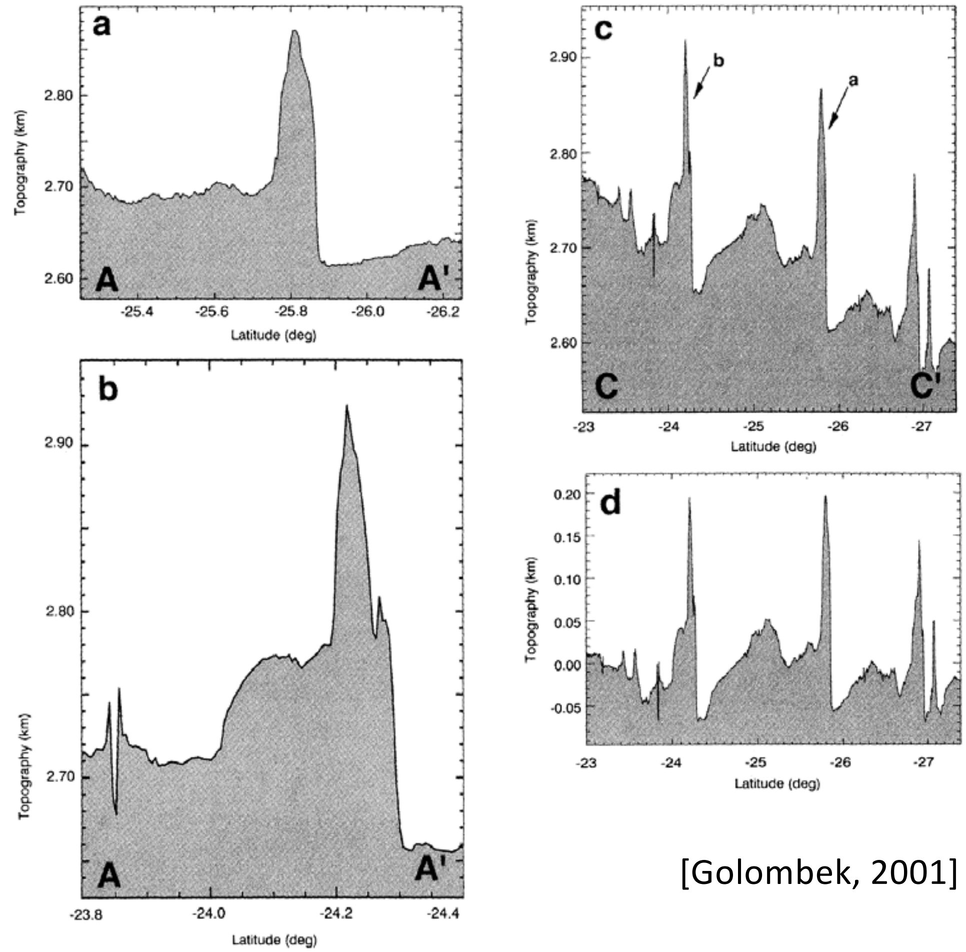
- <u>wrinkle ridges:</u> folding of a volcanic surface unit above a blind (not breaking the surface) thrust fault
  - mediated by layer-parallel slip between lava flows
  - ubiquitous on volcanic plains of the Moon, Mars, Mercury, Venus



# Wrinkle ridge morphology

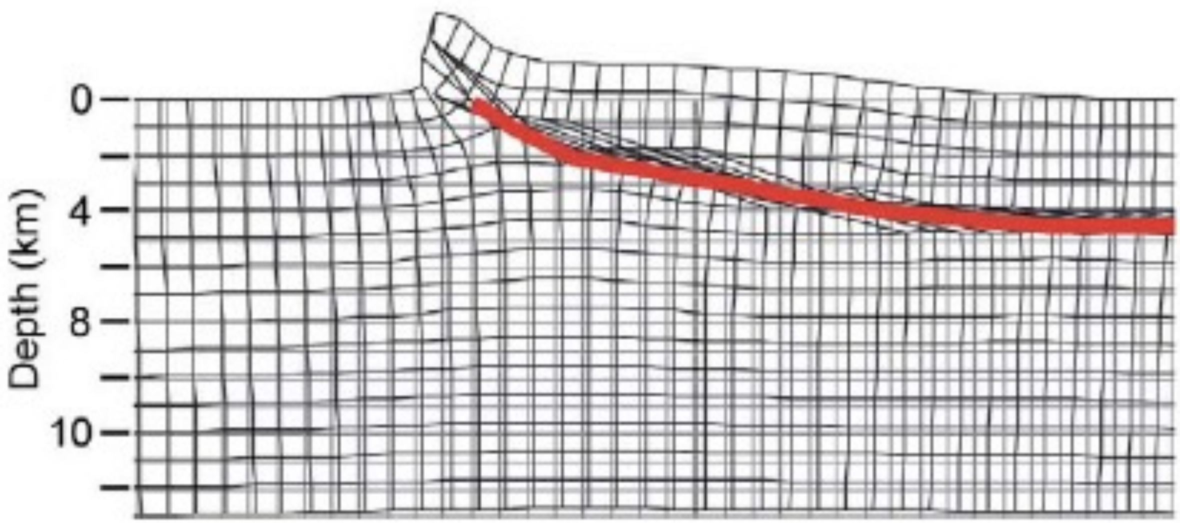
- common morphology involves 3 scales of ridges superposed
  - broad ridge, narrow ridge, wrinkle

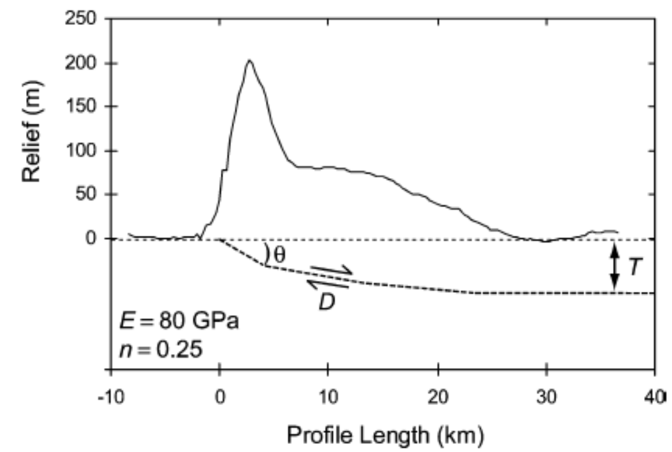


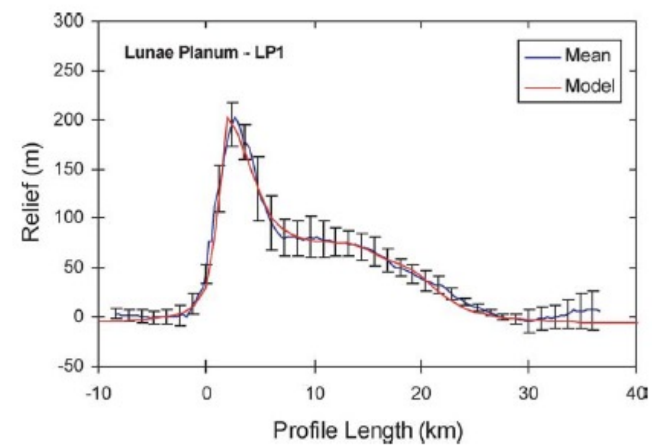

[Golombek, 2001]

# Wrinkle ridge structure: v1

- Shallow thrust faults connecting to a horizontal décollement at depth [Watters, 2004]

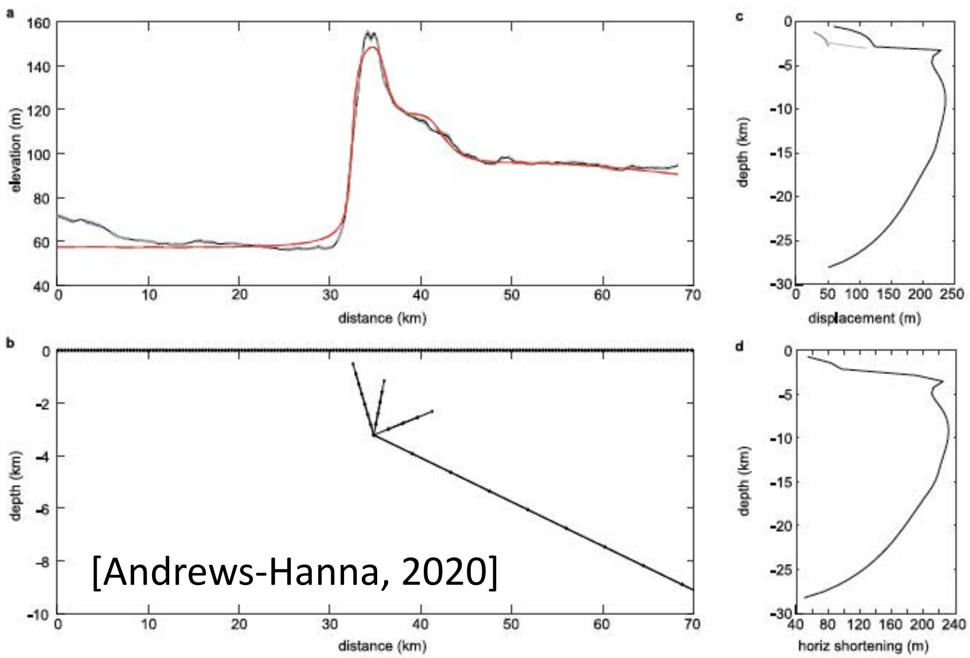


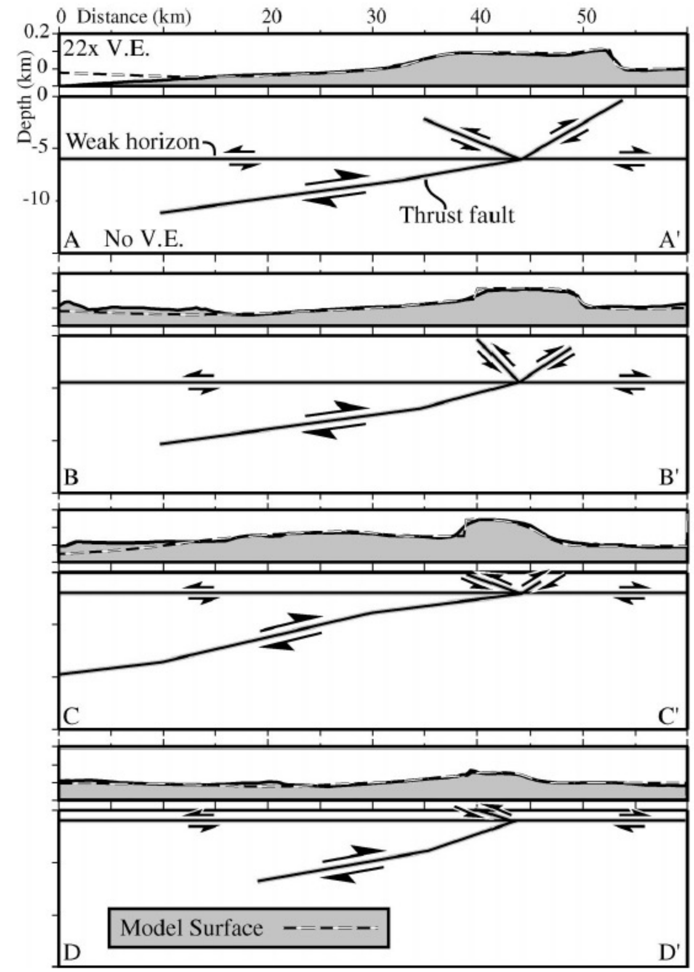



# Wrinkle ridge structure: v2

- Deeply penetrating thrust faults with backthrusts
  - layer-parallel slip between volcanic units
  - resulting stress field favors nucleation of backthrust



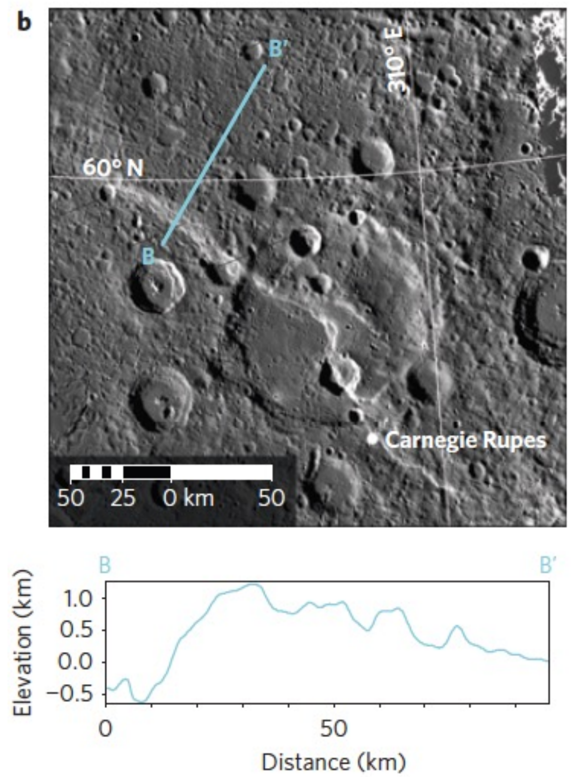

[Schultz, 2000; Okubo and Schultz, 2004]

***Do wrinkle ridges reflect local shallow stress, or deep lithosphere-scale stress?***

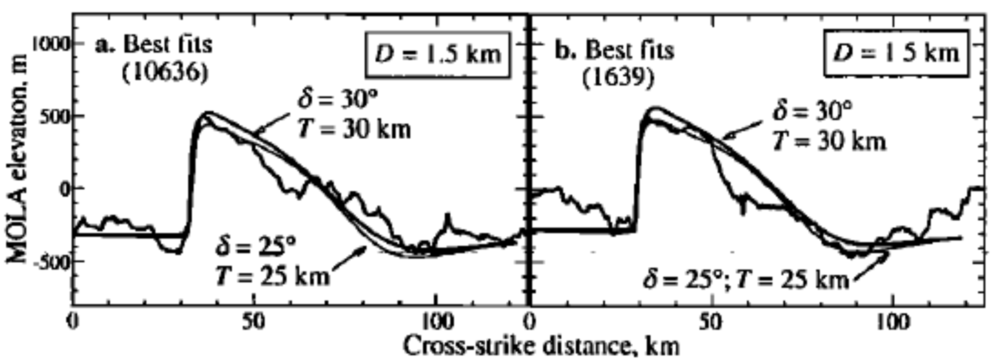
# Lobate scarps

- Surface-breaking thrust faults in ancient cratered surfaces
- Common on Mercury (and, less so, Mars)

Mercury



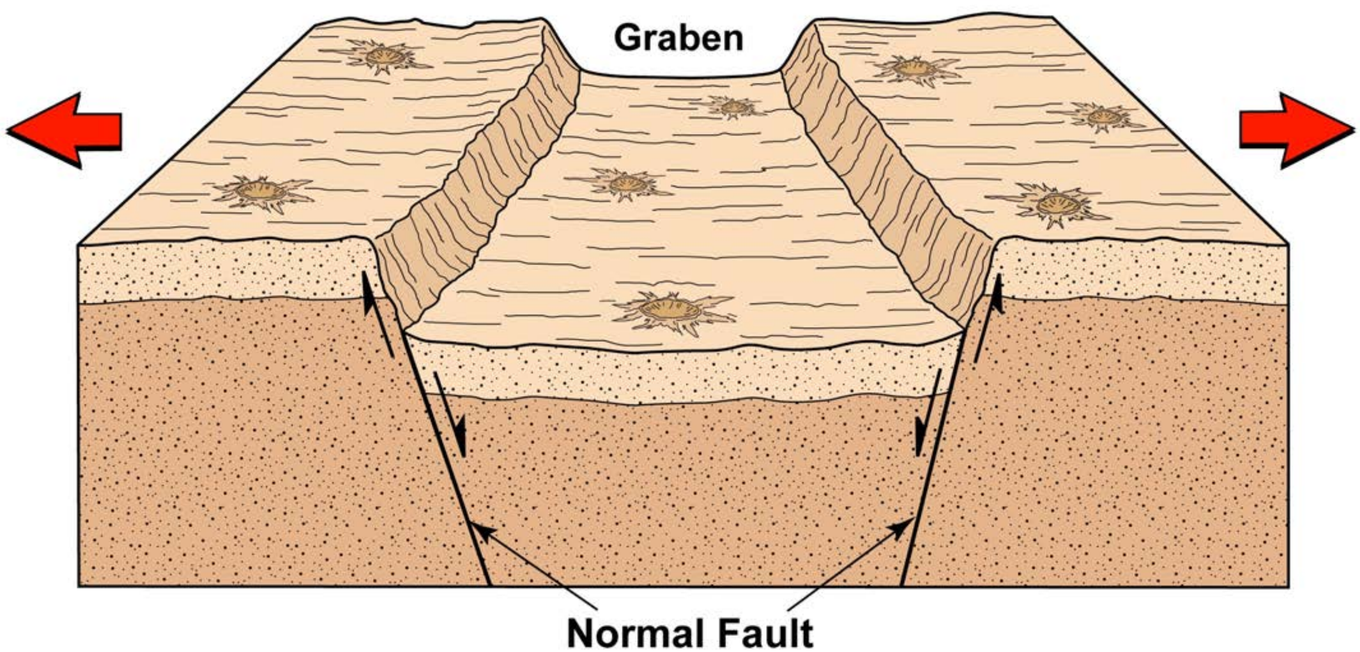

Amenthes Rupes, Mars




[Schultz and Watters, 2001]

# Graben

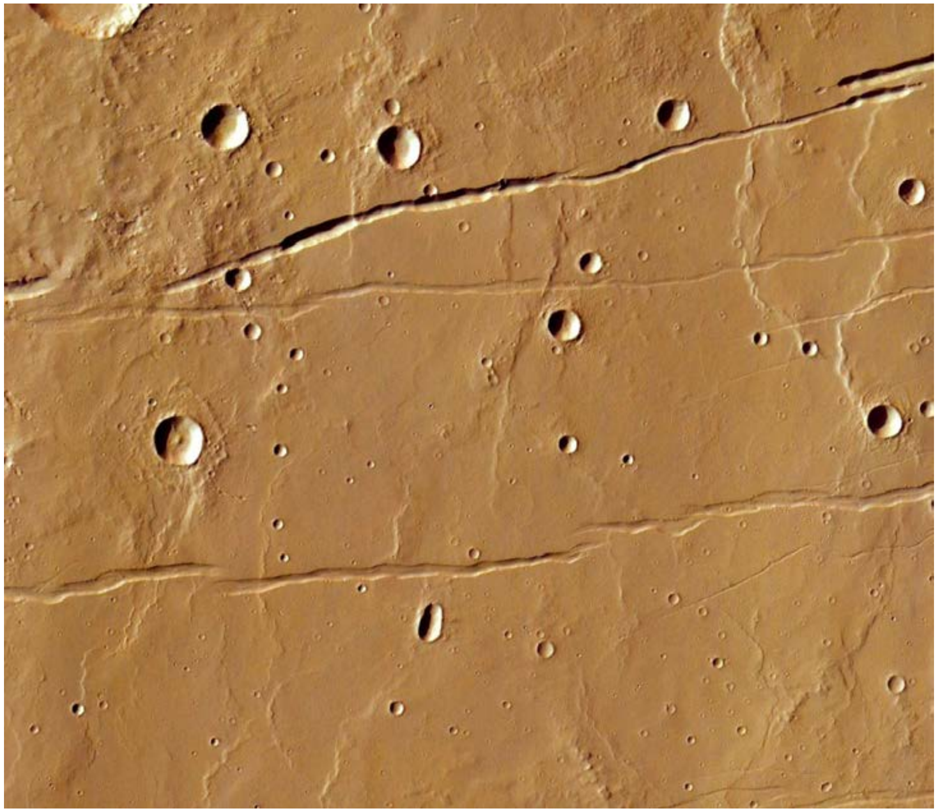
- Simplest extensional tectonic landform
- Two antithetic normal faults, block between drops downward

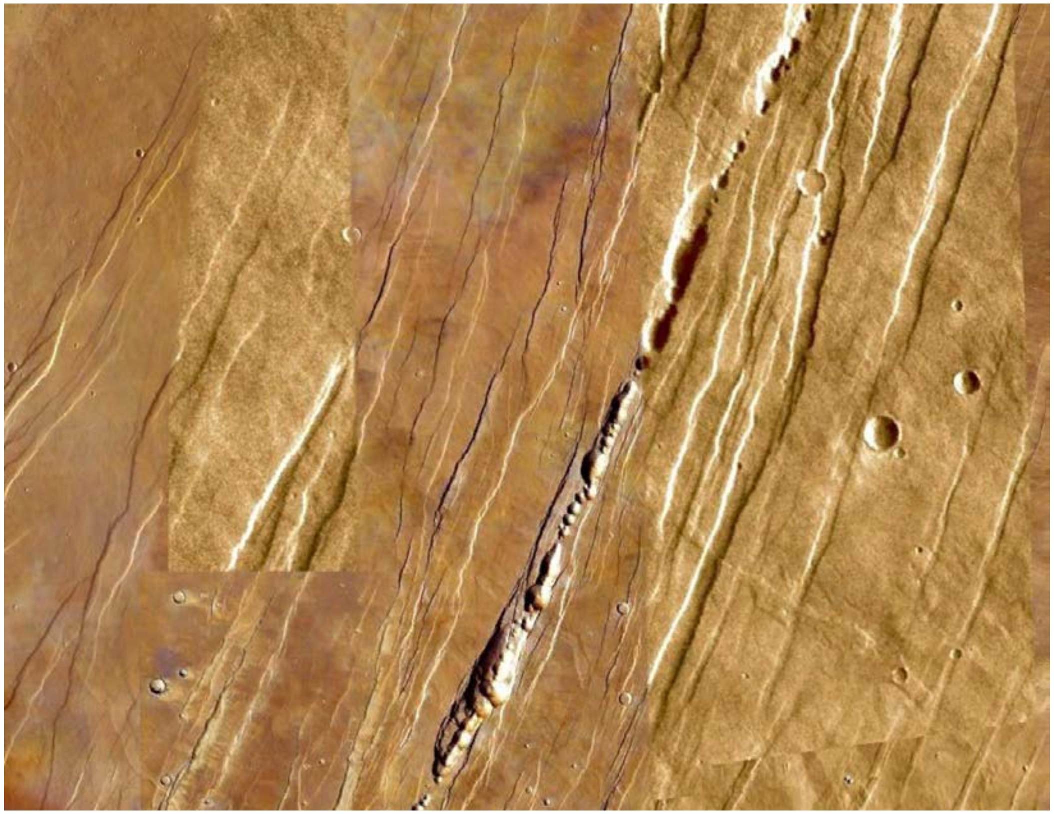



https://airandspace.si.edu/multimedia-gallery/3922hjpg

# Graben

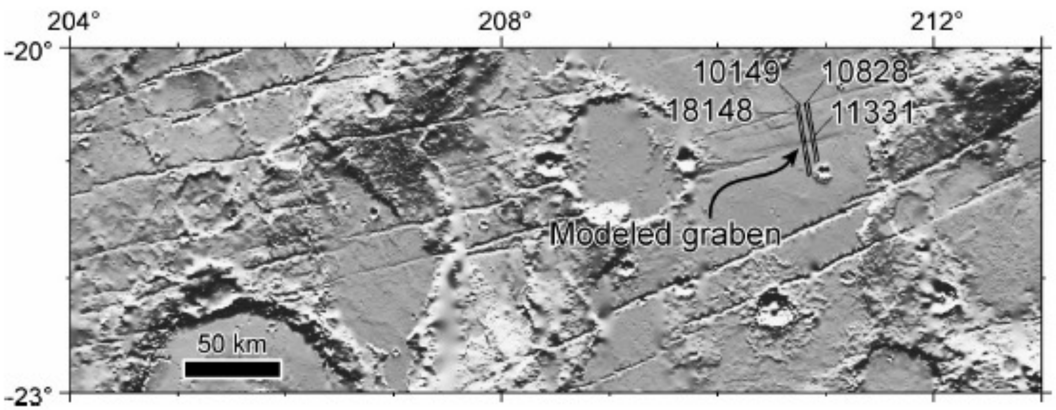
- Can occur in (relative) isolation, or in dense swarms



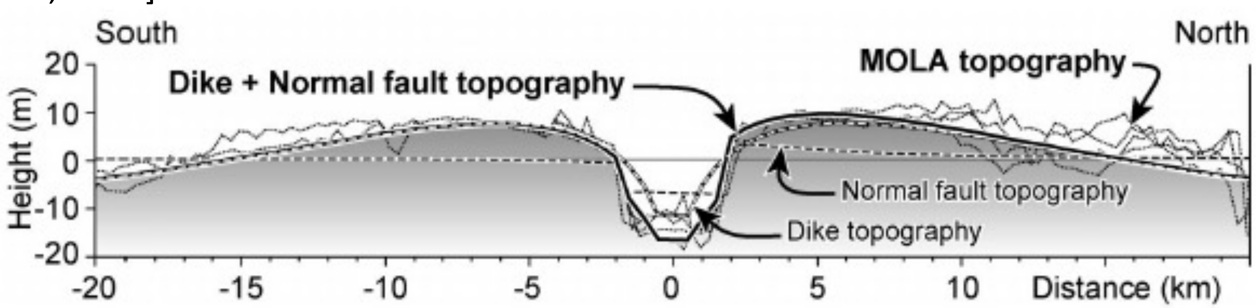


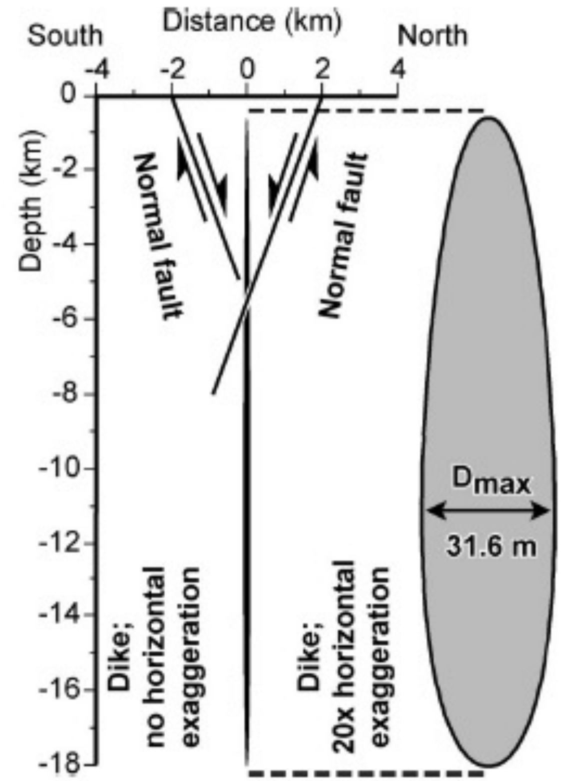
# Graben

- Collapse features suggest void space at depth → magma withdrawal in dike
- Topographic signature of dike induced uplift (rare)



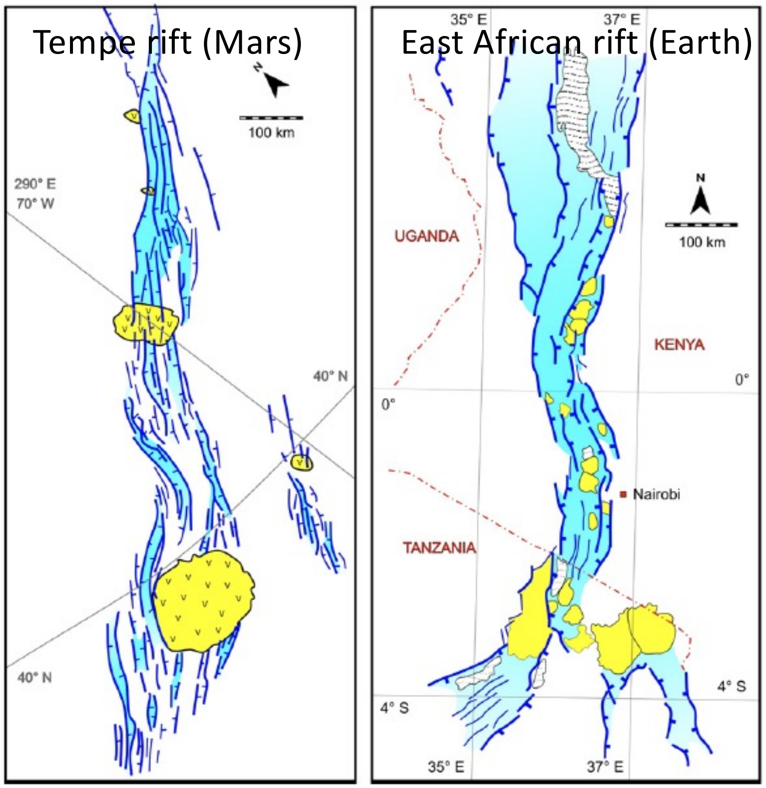

[Schultz, 2004]



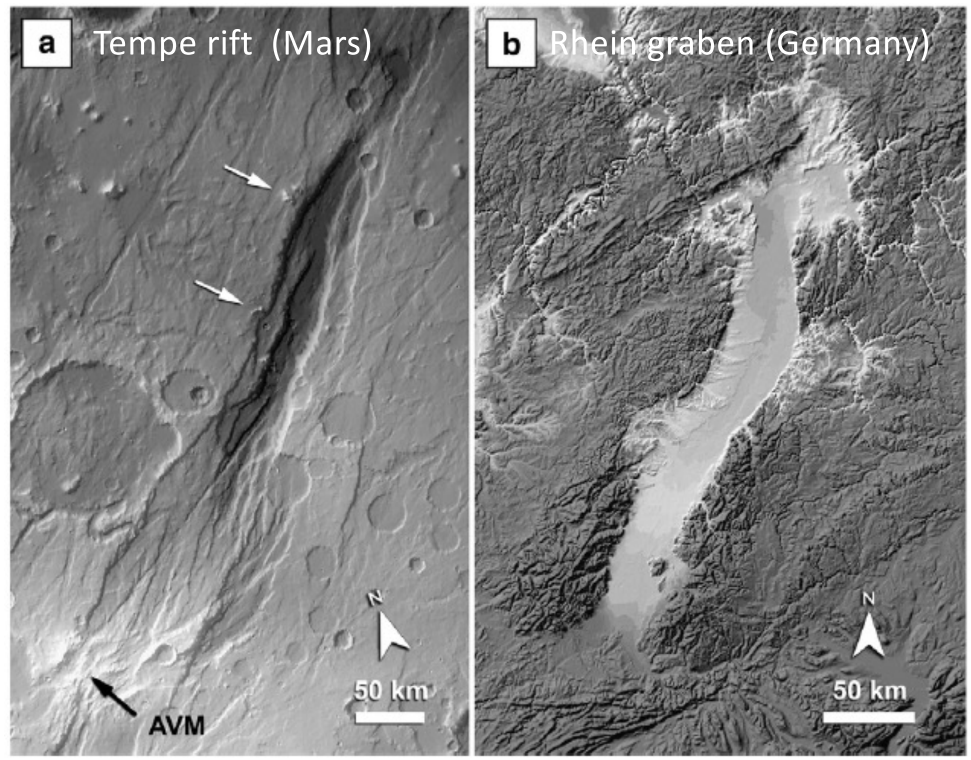



# Rifts

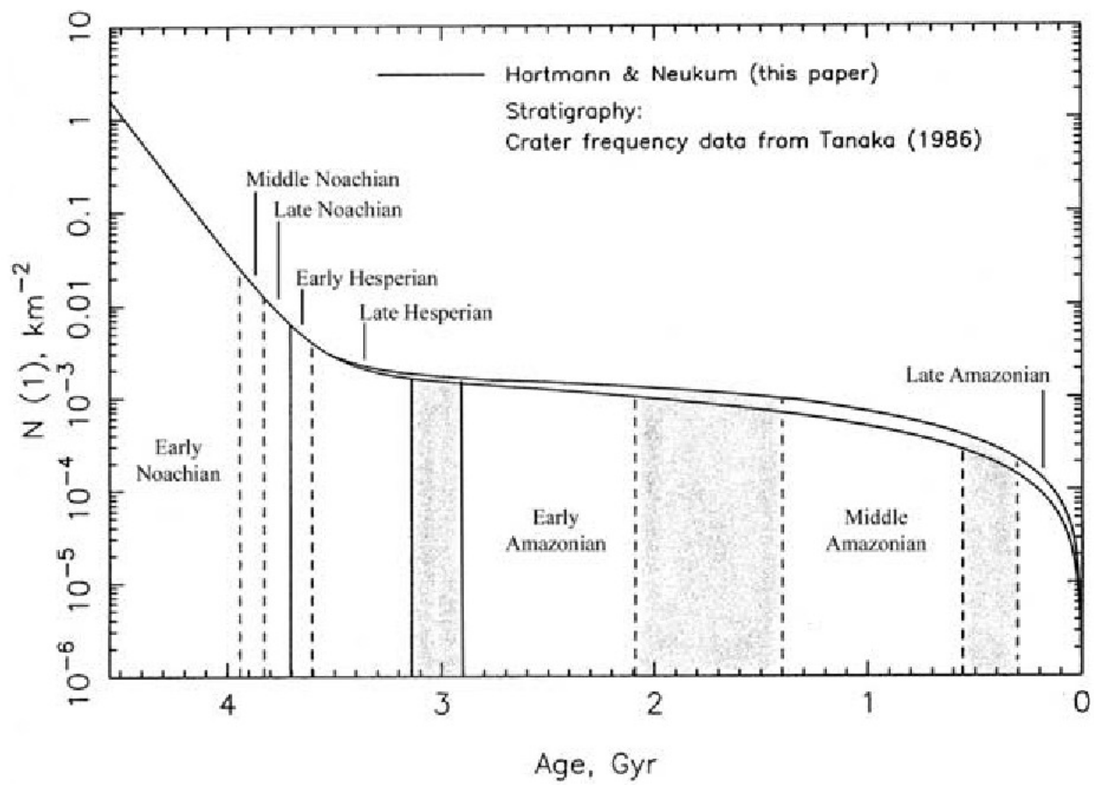
- Crustal extension across a population of asymmetric arcuate normal faults creating irregular graben and half-graben structures
- Accompanied by crustal thinning, volcanism, sedimentary filling, mantle uplift

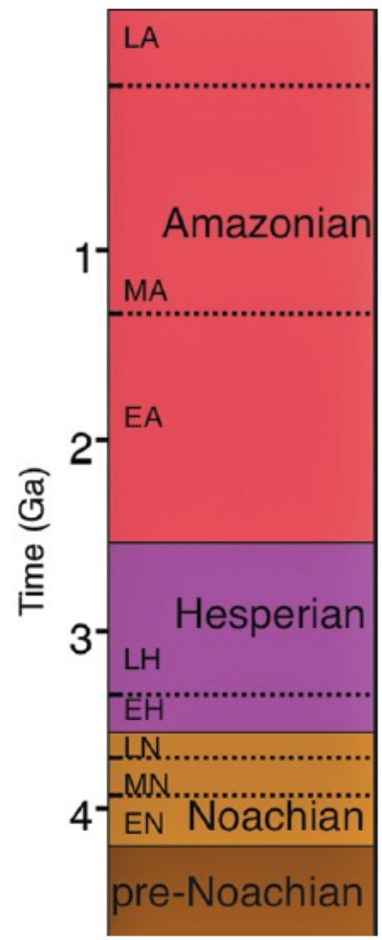



[Hauber, 2010]



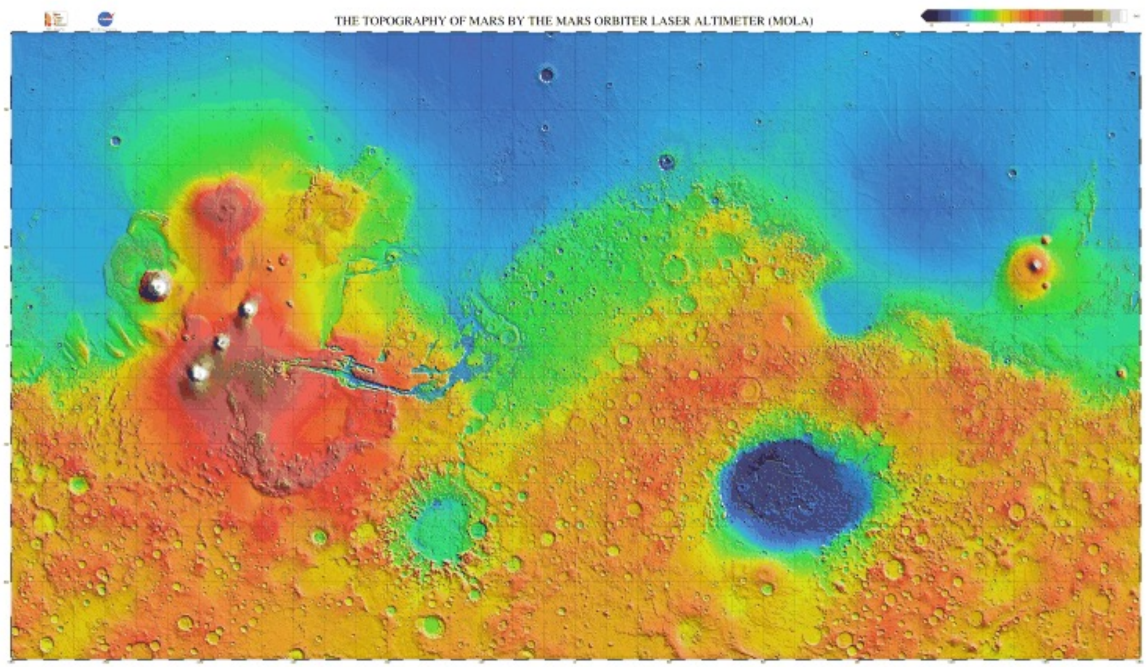
# Tectonic evolution of Mars

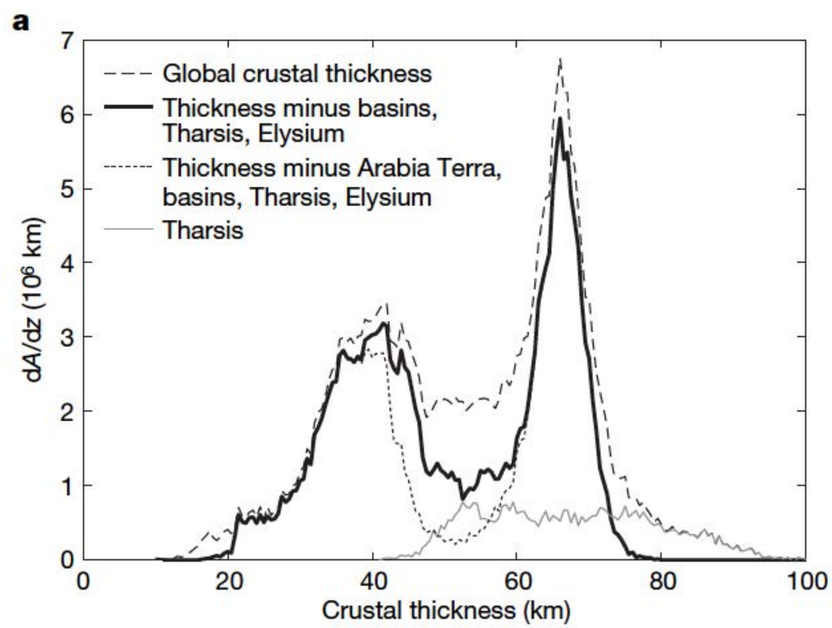


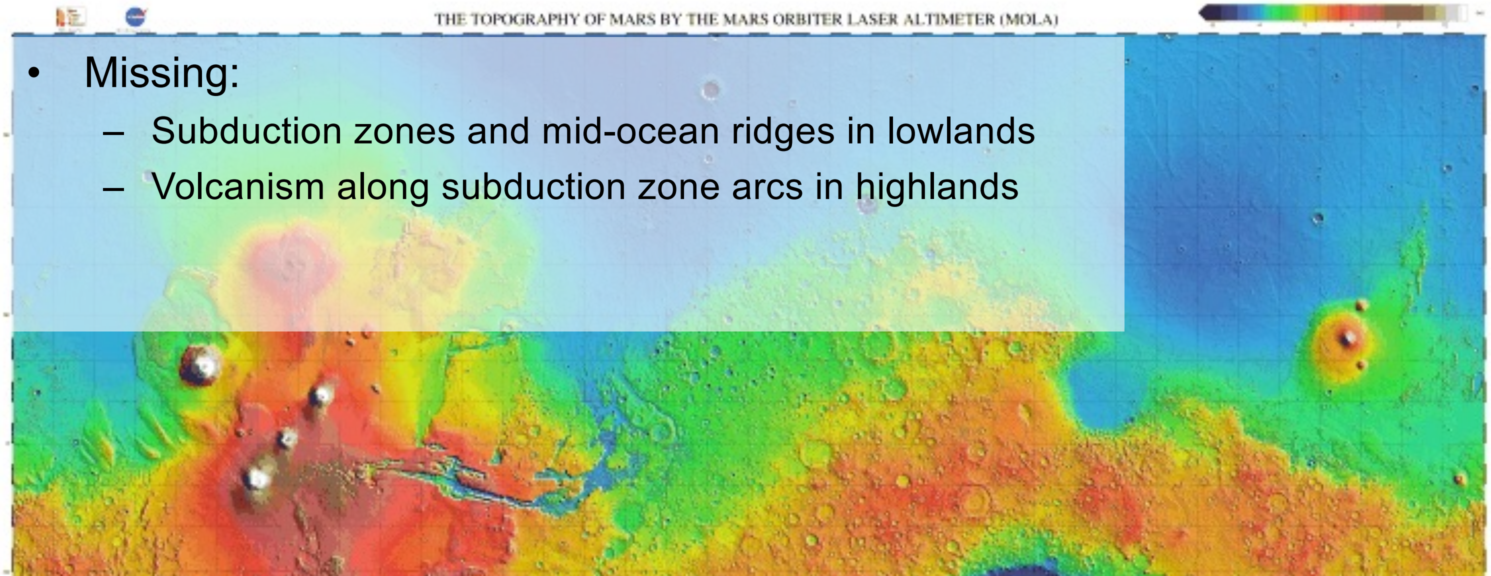
# Mars Dichotomy

- Distinct transition from southern highlands to northern lowlands
  - ~4 km elevation difference, ~20 km crustal thickness difference

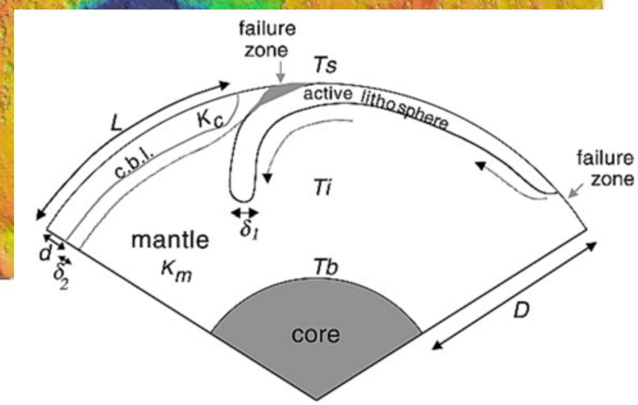


# Dichotomy formation: Plate tectonics?




- Missing:
  - Subduction zones and mid-ocean ridges in lowlands
  - Volcanism along subduction zone arcs in highlands

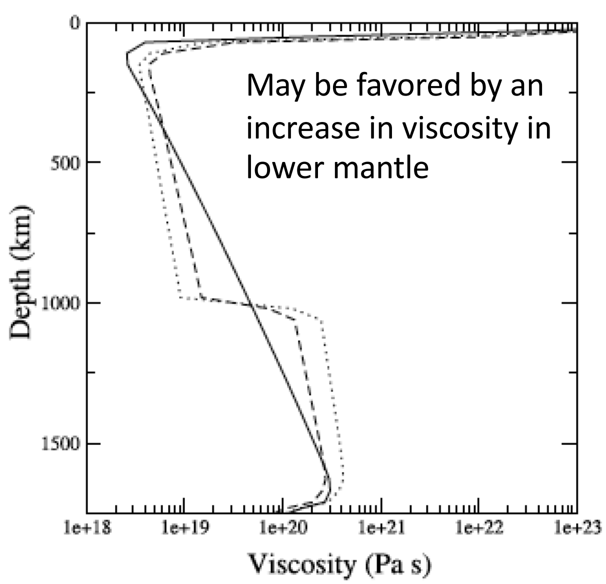


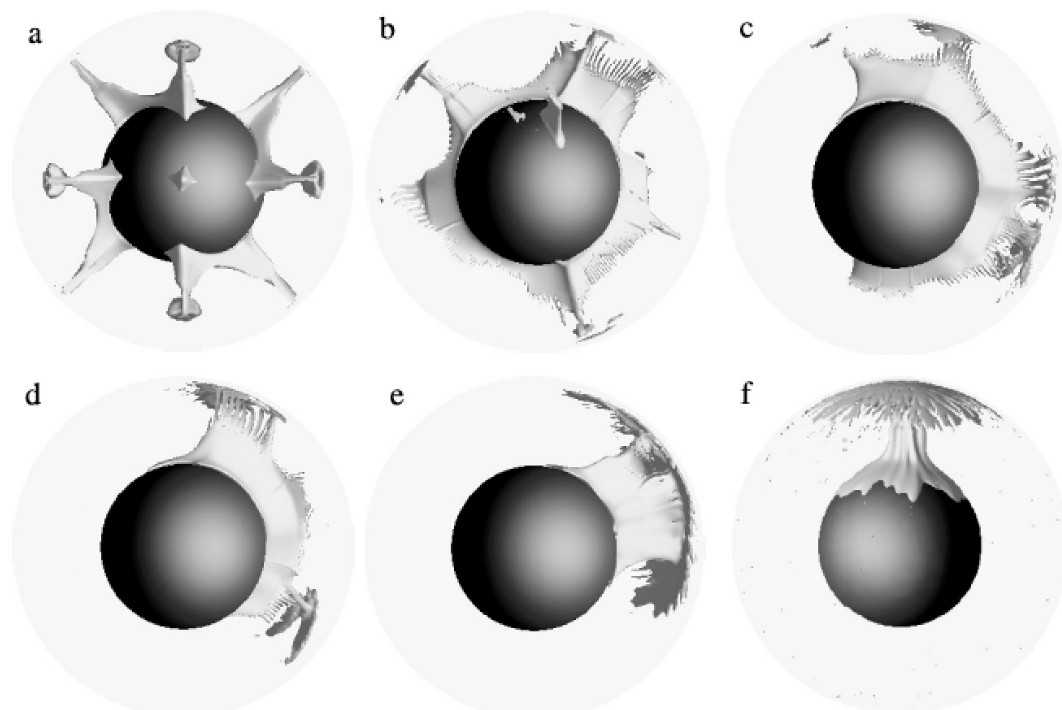

[Sleep, 1994; Lenardic et al., 2004]

# Dichotomy Formation: mantle convection?

- “Degree 1 convection” – Hemispheric asymmetry in mantle convection
  - mantle upwelling on one side of the planet, downwelling on other side
- Crustal thickening OR thermal erosion above upwelling

[*Roberts and Zhong*, 2001, 2006; *Elkins-Tanton et al.*, 2005; Keller and Tackley, 2009]

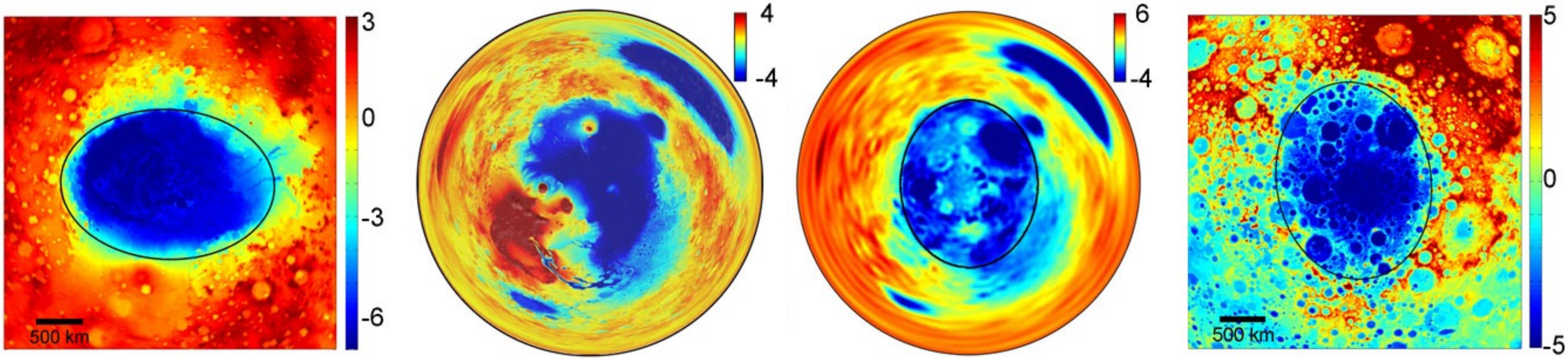


# Dichotomy formation: Giant impact

- Largest impact basins are elliptical [*Andrews-Hanna et al.*, 2008]
  - Hellas (Mars), Utopia (Mars), Sputnik (Pluto), South Pole-Aitken (Moon)
- Northern lowlands is a giant elliptical depression – “Borealis basin”
  - remove Tharsis to see true shape
  - Consistent with impact of a ~2000 km diameter projectile
    - 45° impact at 6-10 km/s [*Marinova et al.*, 2008]
- Hybrid model? – impact causes mantle upwelling? [Reese, 2010; Citron, 2018]

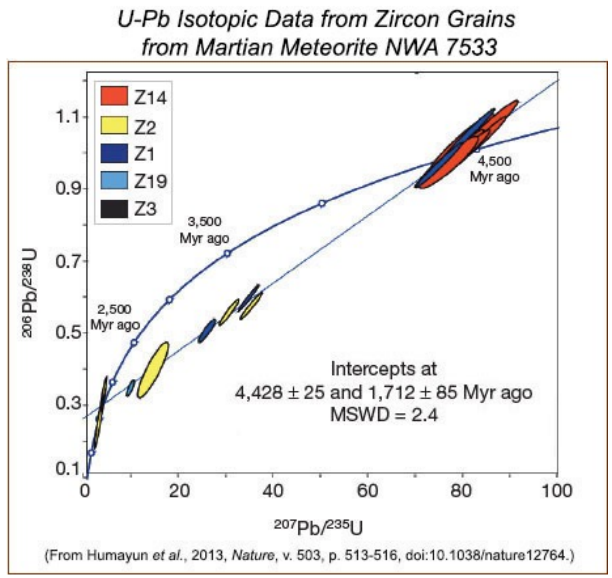
Hellas | Borealis Isostatic root | Borealis Topography | South Pole-Aitken



# The age of Borealis

- Borealis should have reset all surface ages on Mars
- Must be as old or older than:
  - Age of shergotite source region: 4.48-4.50 Ga
  - “Black Beauty” meteorite zircon ages ~4.43 Ga

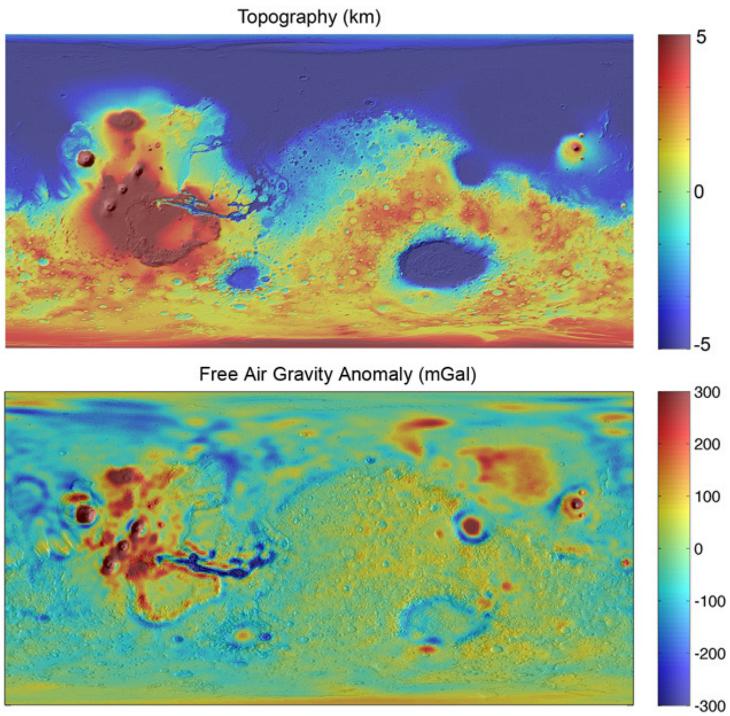
  [*Humayun et al.,* 2013; *Moser et al.,* 2013; 2015; *Wittman et al.,* 2015]

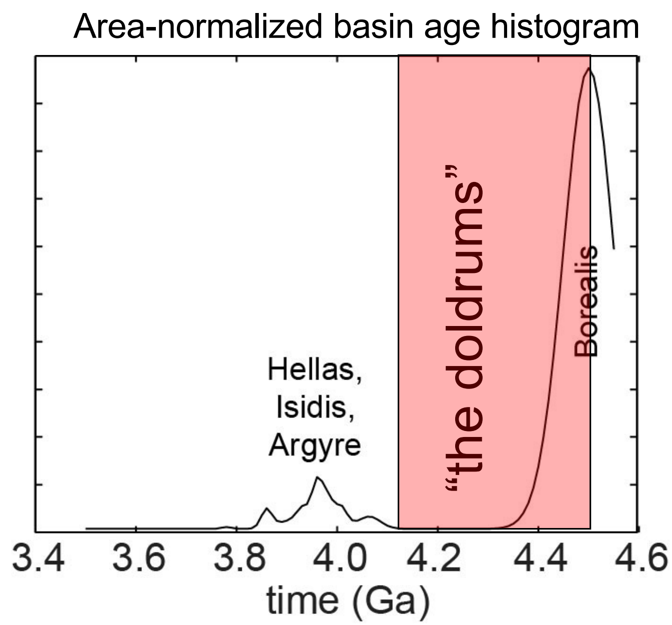




[Bottke and Andrews-Hanna, 2017; Bottke et al. 2010]

# Pre-Noachian tectonics

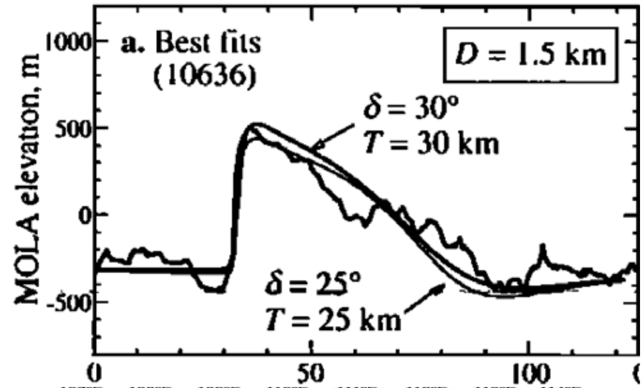
- Pre-Noachian: between Borealis and Hellas → no major rearrangements of crust
  - “The doldrums” 4.5-4.1 Ga
  - No plate tectonics, no giant volcanic rises, no giant impact basins
  - But tectonic processes are poorly constrained – no preservation of typical tectonic landforms



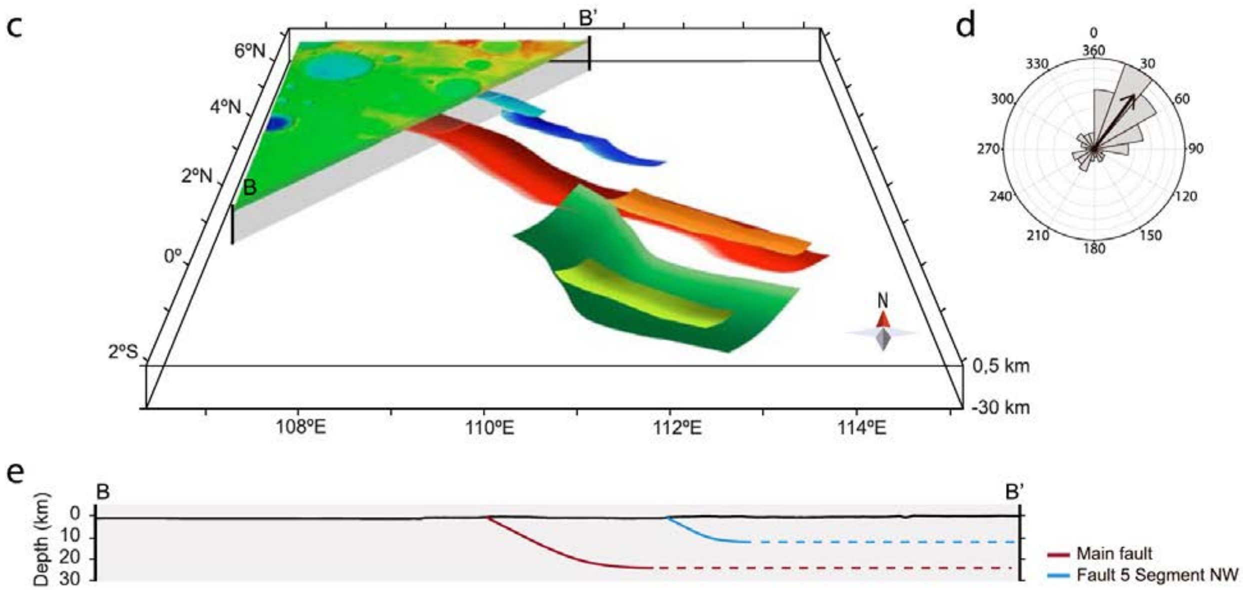
# Noachian compressional tectonics

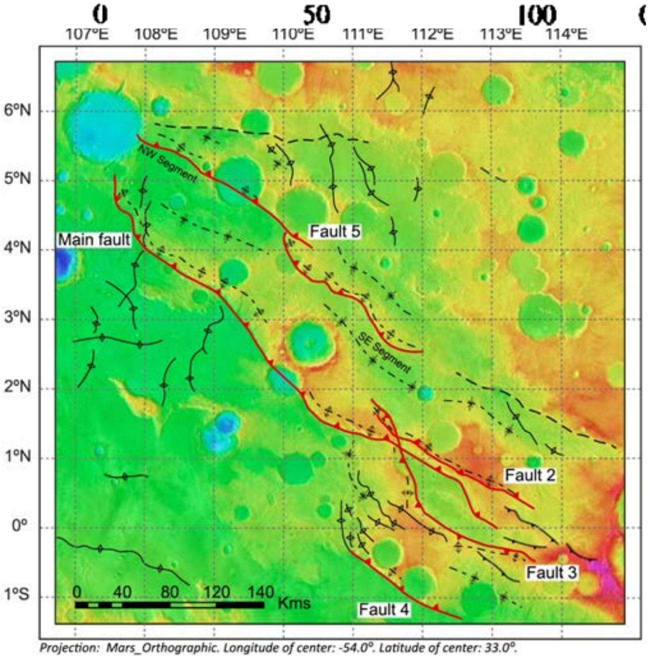
Watters, 2003




- Lobate scarps – late Noachian age
  - Thrust faulting parallel to dichotomy boundary [Watters, 2003]
  - Amenthes Rupes – lithosphere-scale thrust fault

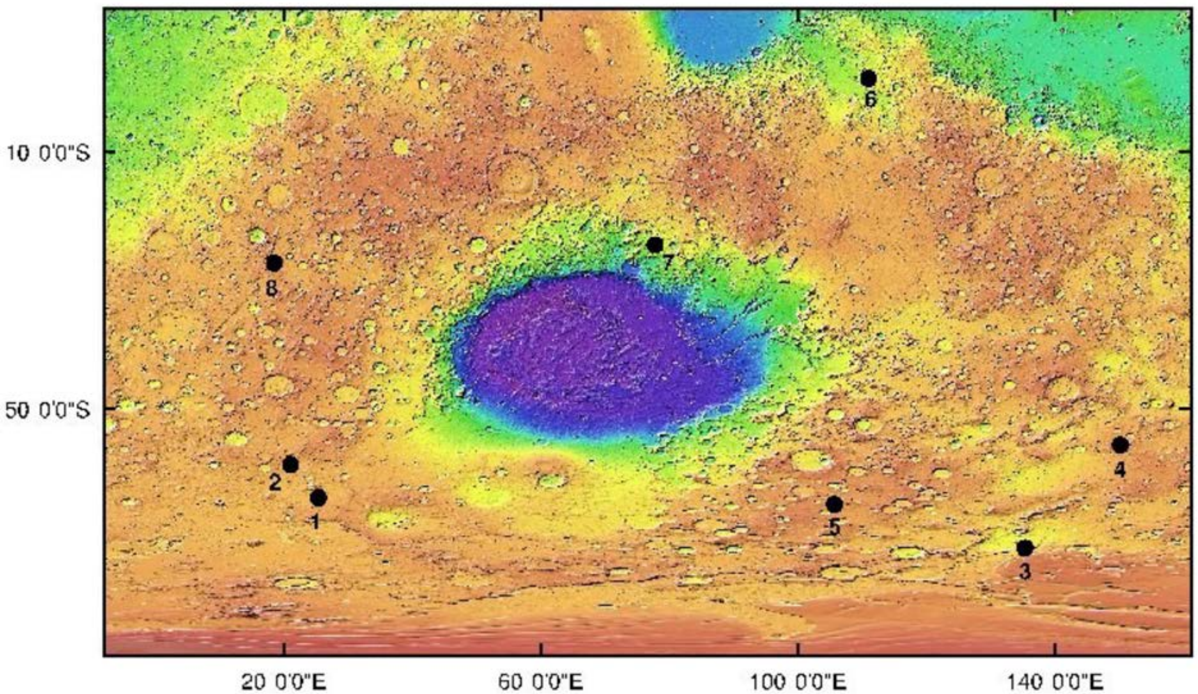
[Herero-Gil, 2019]

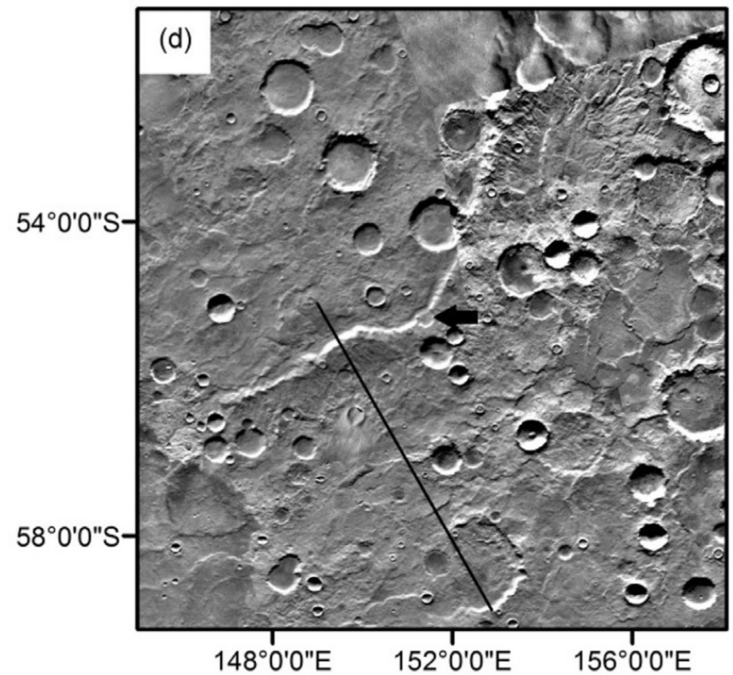


# Noachian compressional tectonics in the highlands

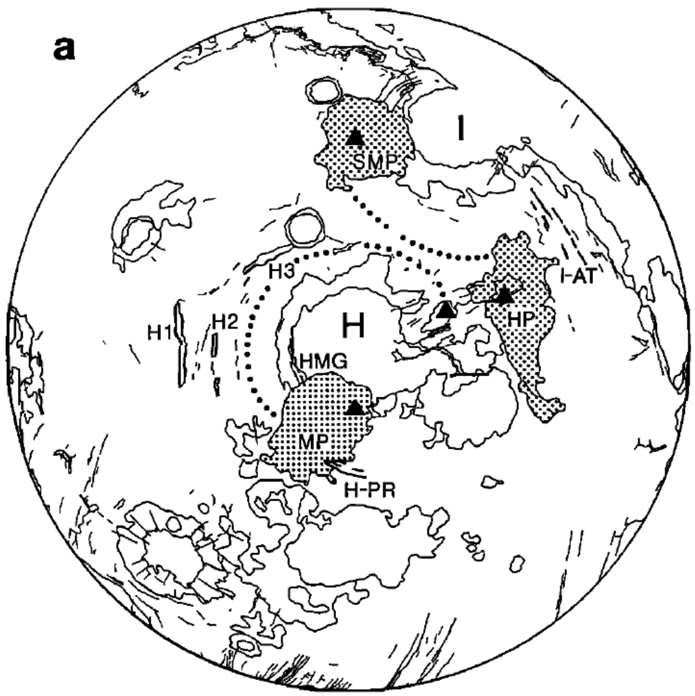
- Circum Hellas pattern? [Egea-Gonzales, 2017]



# Noachian extensional tectonics in the highlands

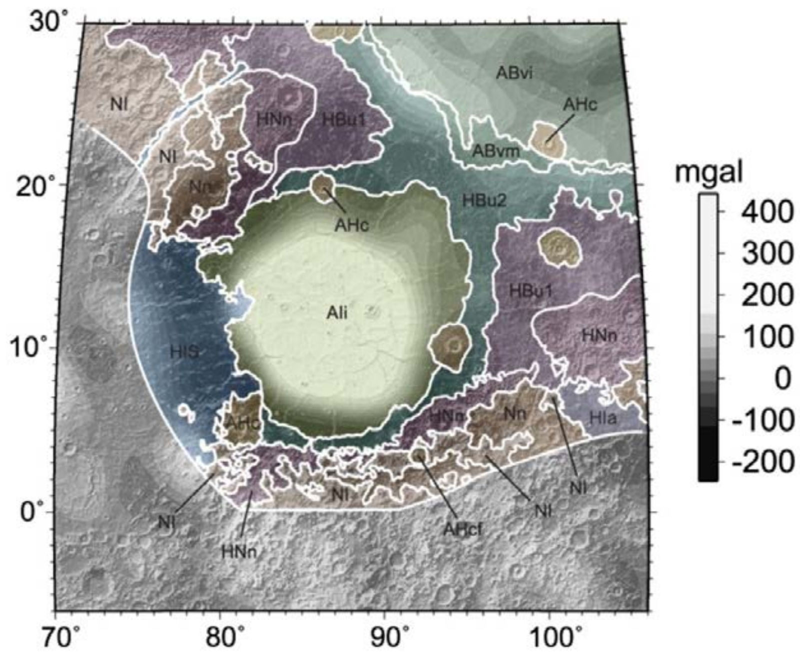
- Tectonic troughs and rifts
  - ancient rift valleys
  - circum-Hellas pattern? [Wichman and Schultz, 1984]



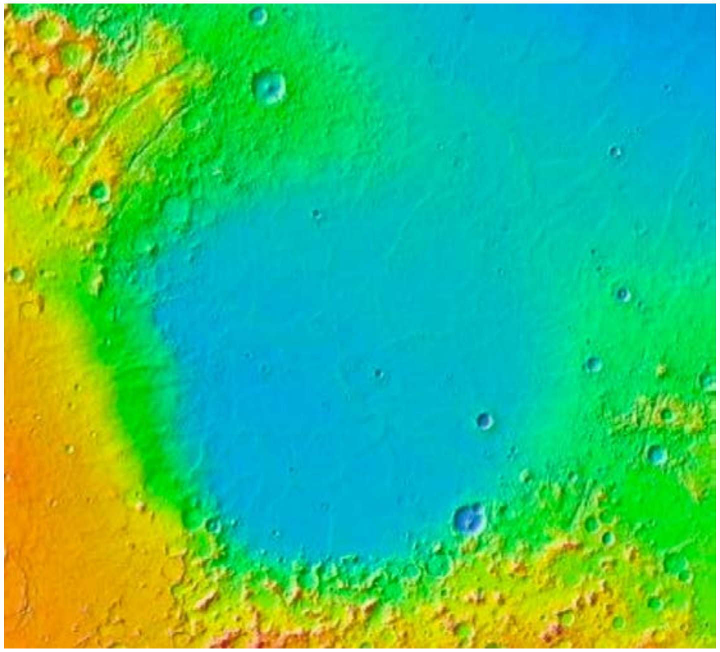

HELLAS-CENTERED

# Noachian extensional tectonics in the highlands

- Nilli Fossae – circumferential graben west of Isidis basin
  - response to lithosphere loading from volcanic filling of the basin
  - ~15 km of volcanic fill within basin [Ritzer, 2009; Searls, 2006]



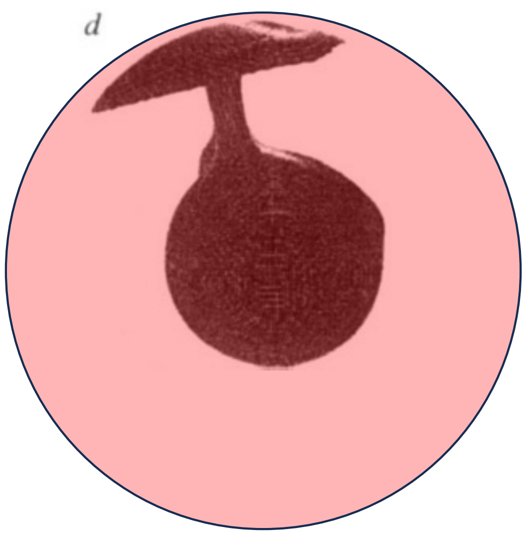

[Ritzer and Hauck, 2009]

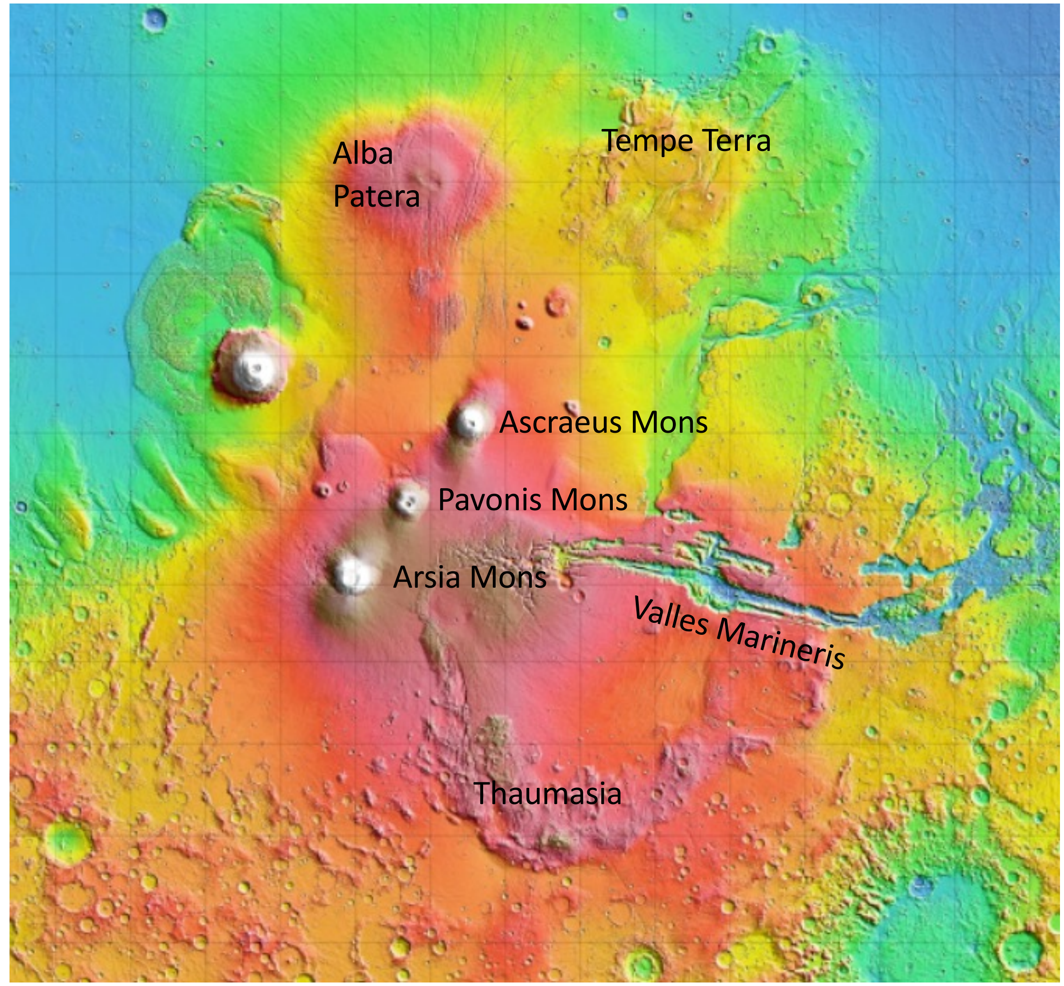


# Tharsis

- Tharsis construction began in the Noachian
  - likely began with uplift above a giant mantle plume
  - → extension

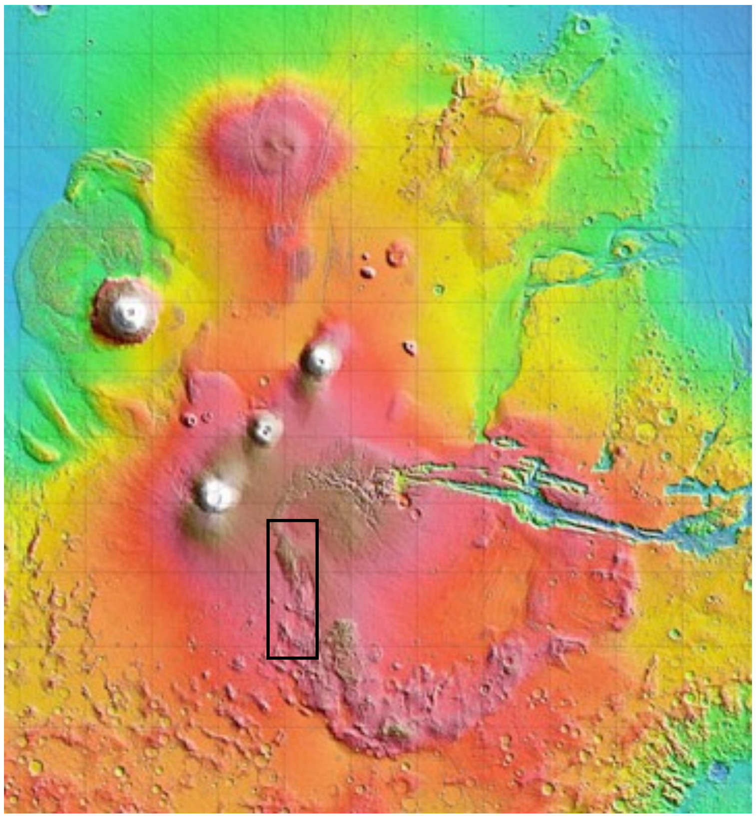
*Tharsis is the dominant cause of most martian tectonism*

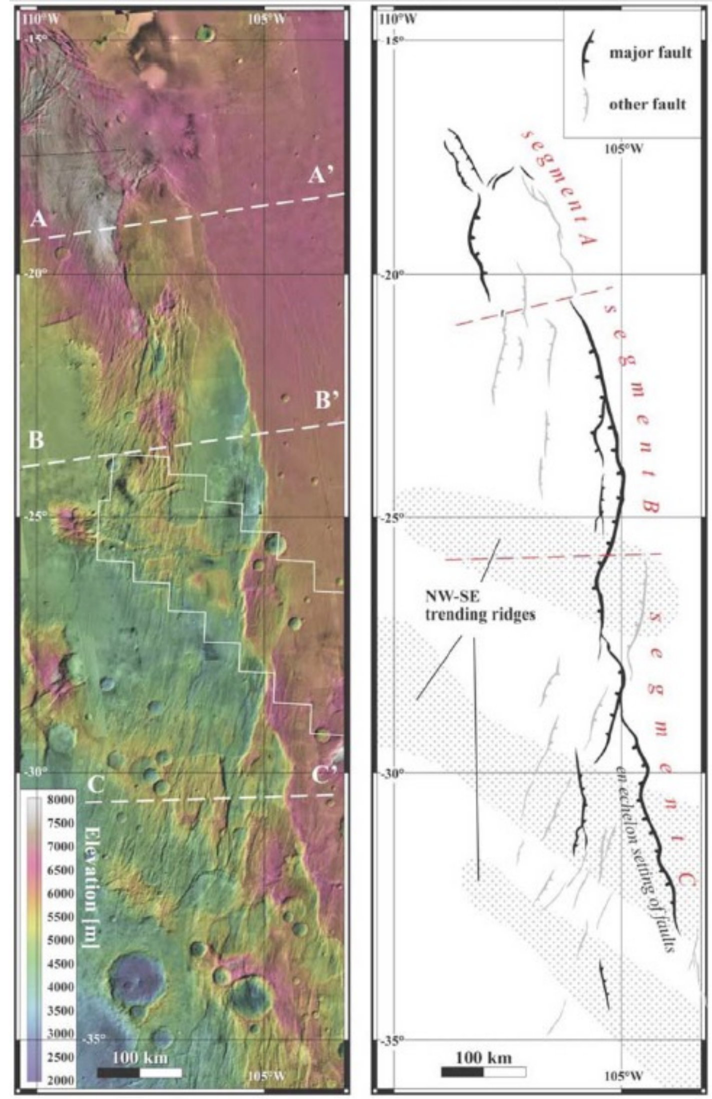


# Noachian rift zones in Tharsis

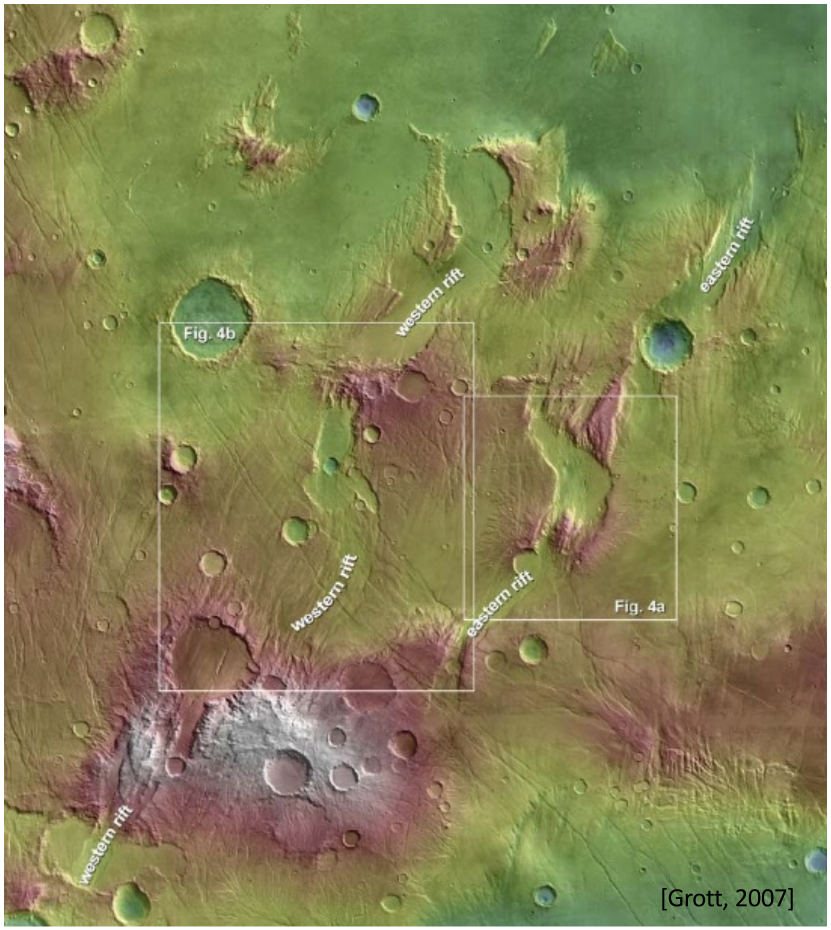
- Rifts in Claritas Fossae, Tempe Terra, Thaumasia
- Early phase of Tharsis uplift and extension

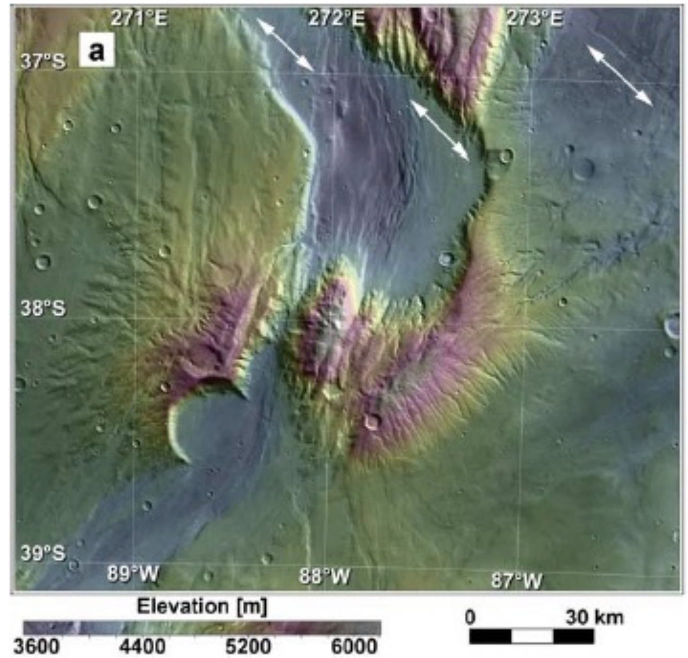


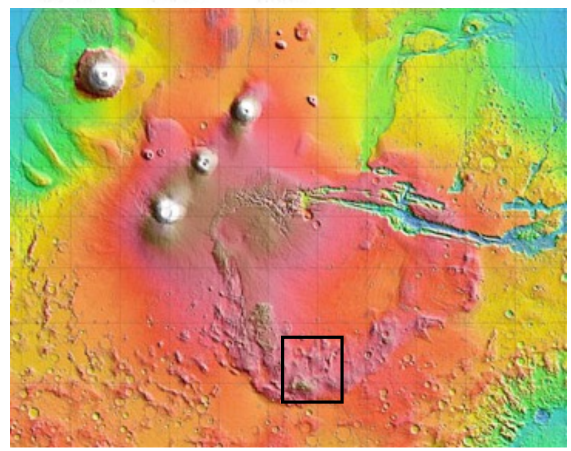



[Hauber, 2005]

# Noachian rift zones

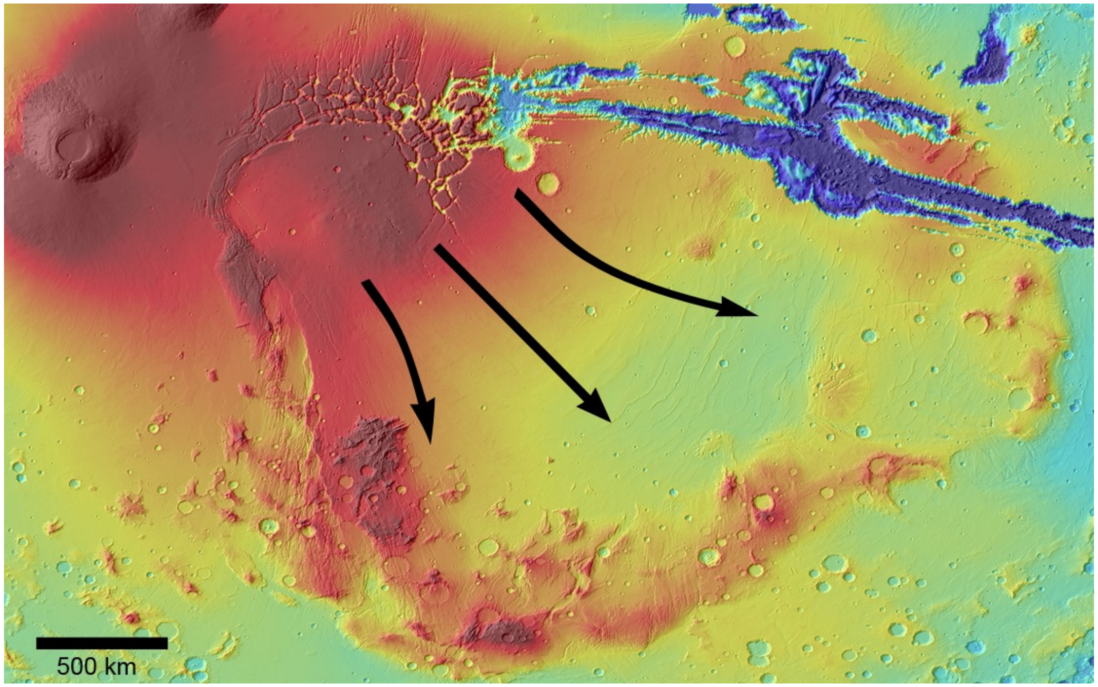


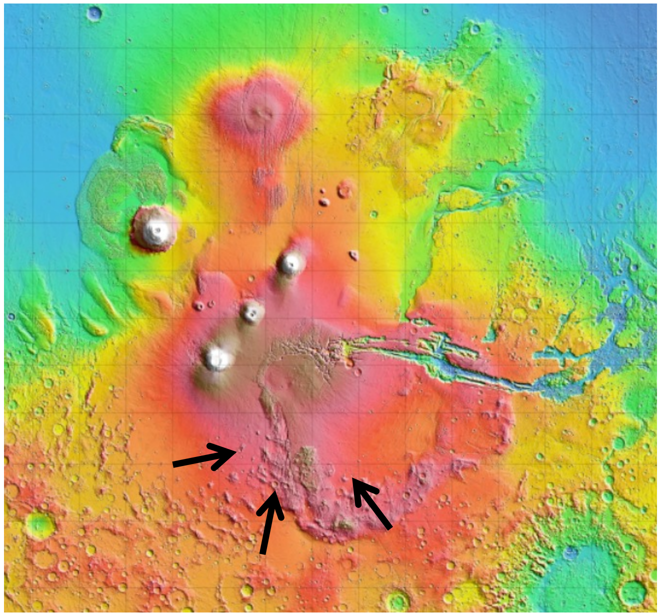



# Noachian compression in Tharsis

- Thaumasia highlands and Claritas Rise – Noachian rises
  - Resembles "orogenic" mountain belts on Earth – compressional tectonism

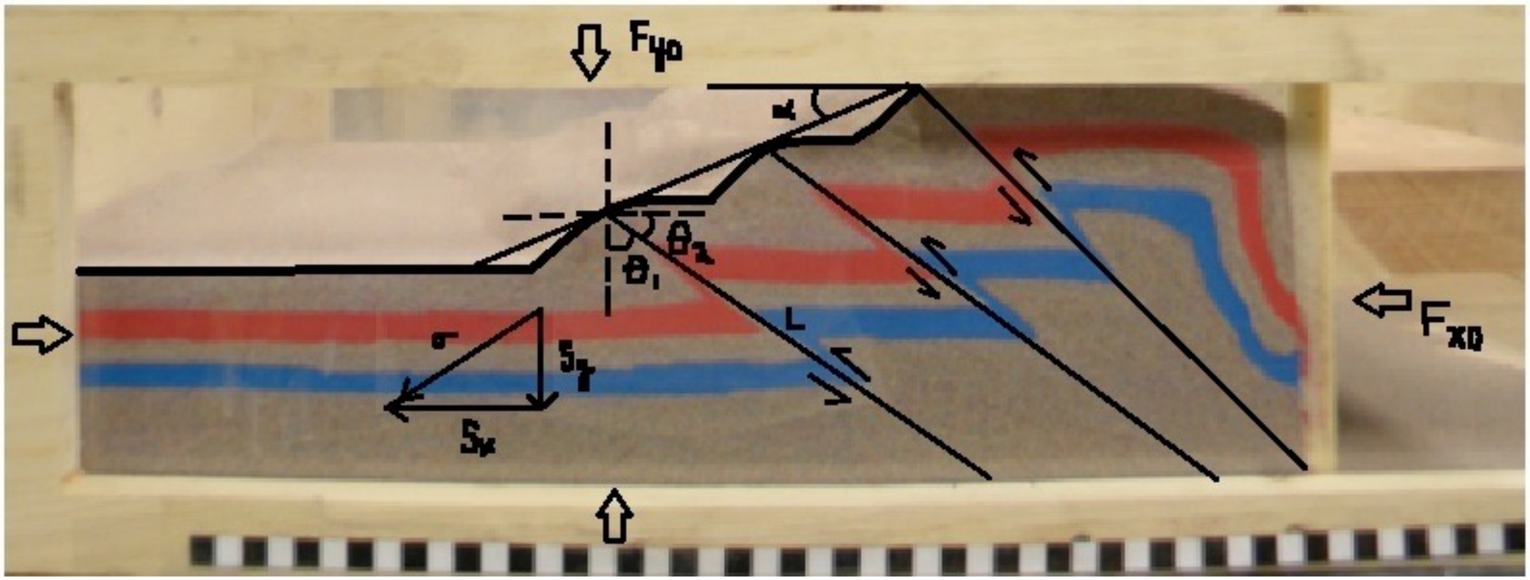


[Montgomery et al., 2009; Nahm, 2010]

# How are mountains built?

- Critical taper wedge mechanics
  - Slope controlled by friction

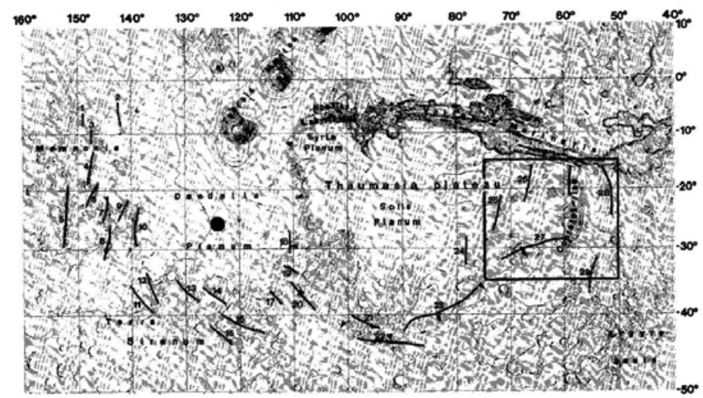


https://rocktraumacenter.wikispaces.com/2010+Compressional+Models

# How was Mt Lemmon built?

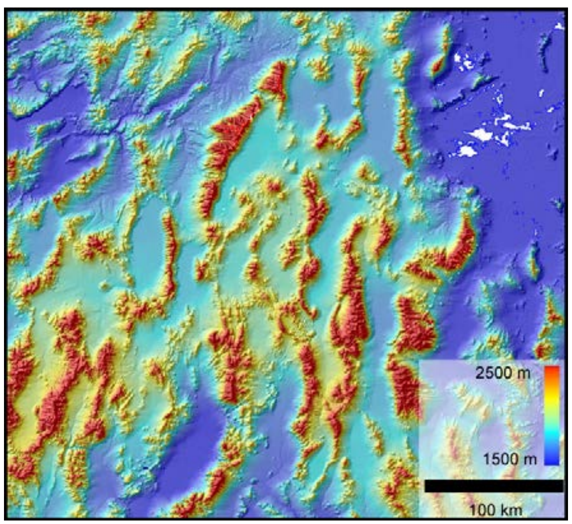
# South Tharsis Ridge Belt: Compression or extension?

- Belt of ridges SW of Tharsis
  - Compressional ridges related to Thaumasia highlands? [Schultz & Tanaka, 1994]
  - Basin and Range style extension? [*Karasozen, et al.,* 2010]



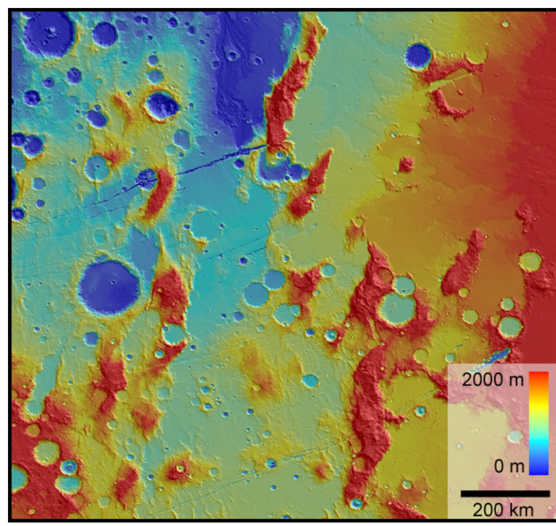
[Schultz & Tanaka, 1994]

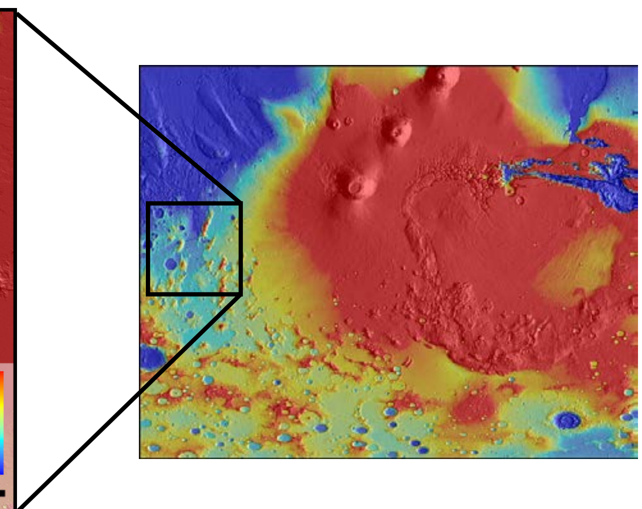
Basin and Range




[*Karasozen, et al.,* 2010]

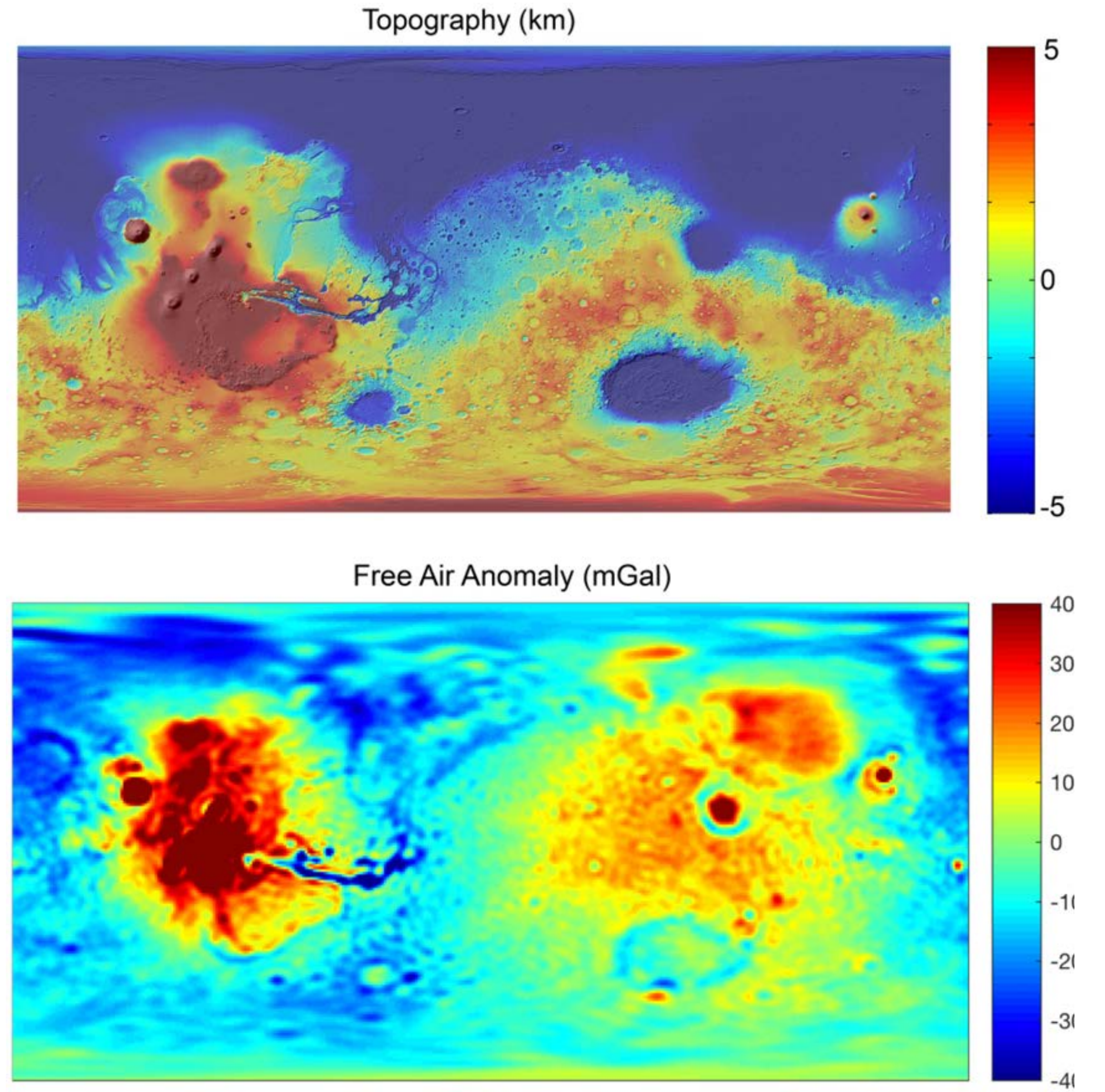
South Tharsis Ridge Belt



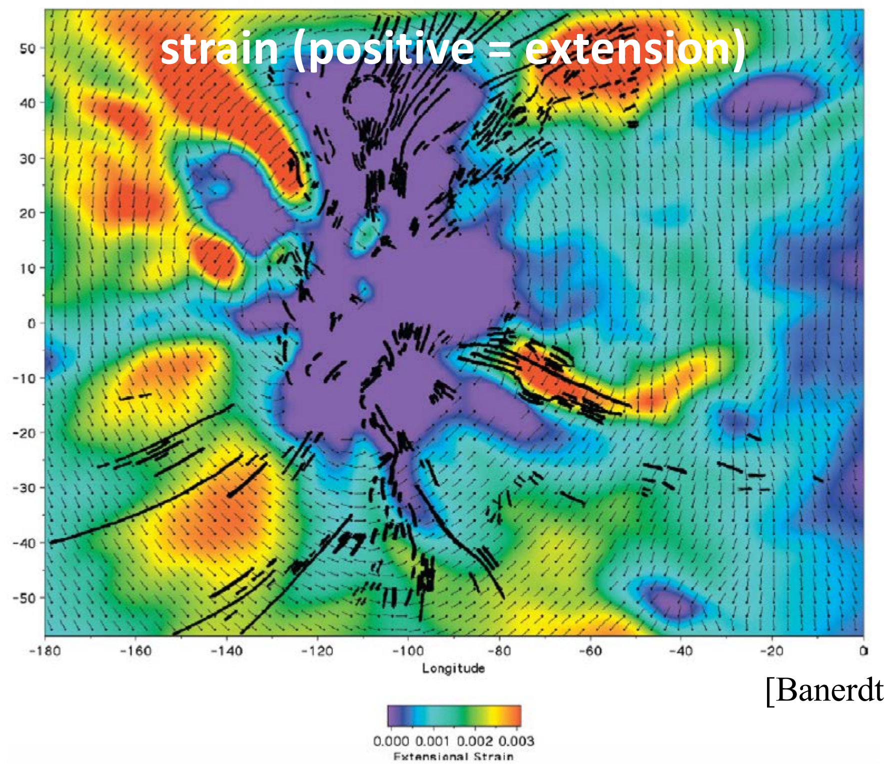
# Tharsis loading

- By late Noachian to early Hesperian, Tharsis has transitioned to being a downward load on lithosphere
  - less support by mantle plume
  - thick pile of basalt pushes down on the lithosphere
- Global deformation and tectonics

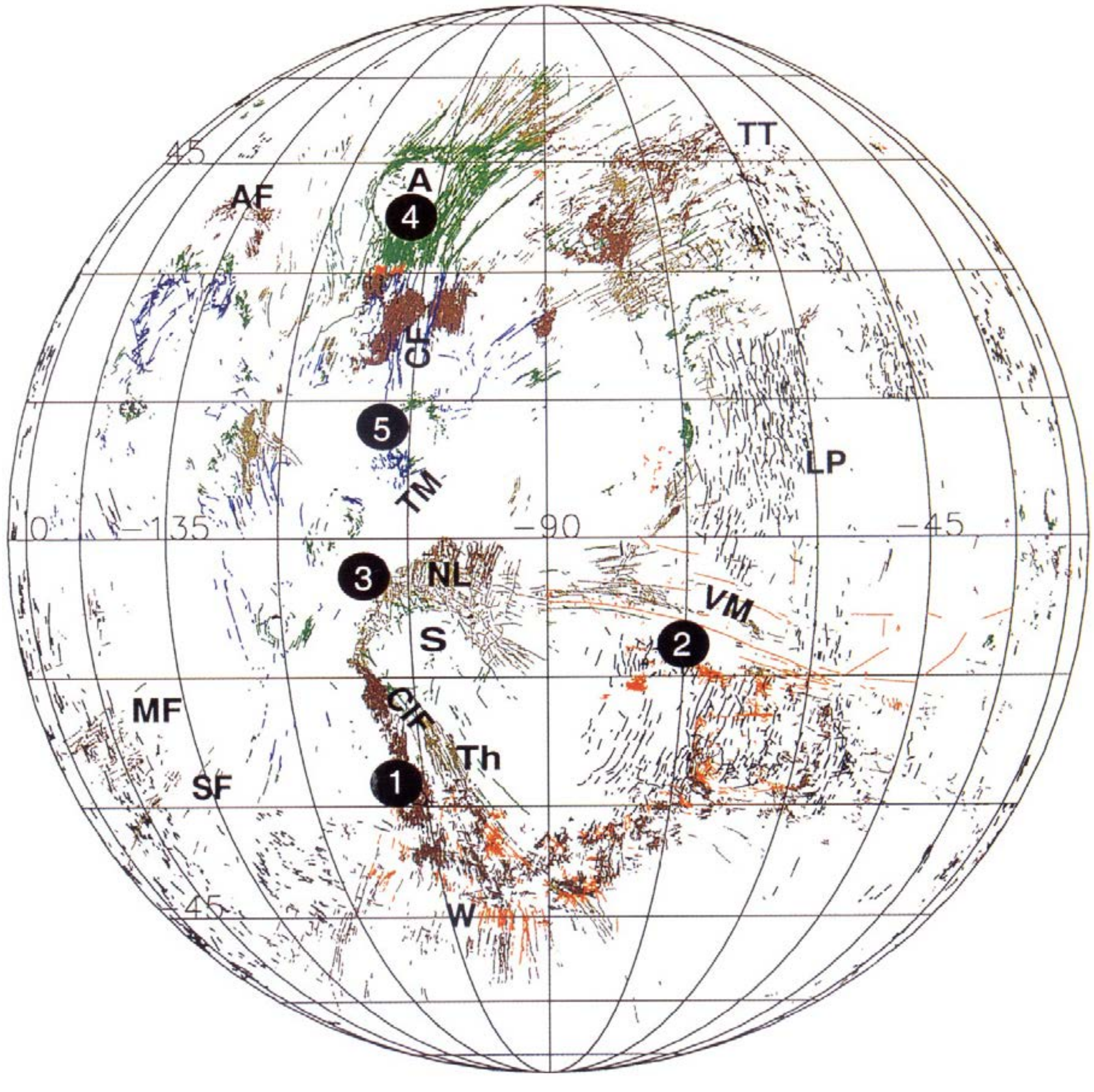


# Tharsis Loading

- Volcanic load deforms the lithosphere
  - Radial compression (circumferential thrust faults) within rise
  - Circumferential extension (radial graben) outside rise




[Banerdt and Golombek, 2001]



45
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MF
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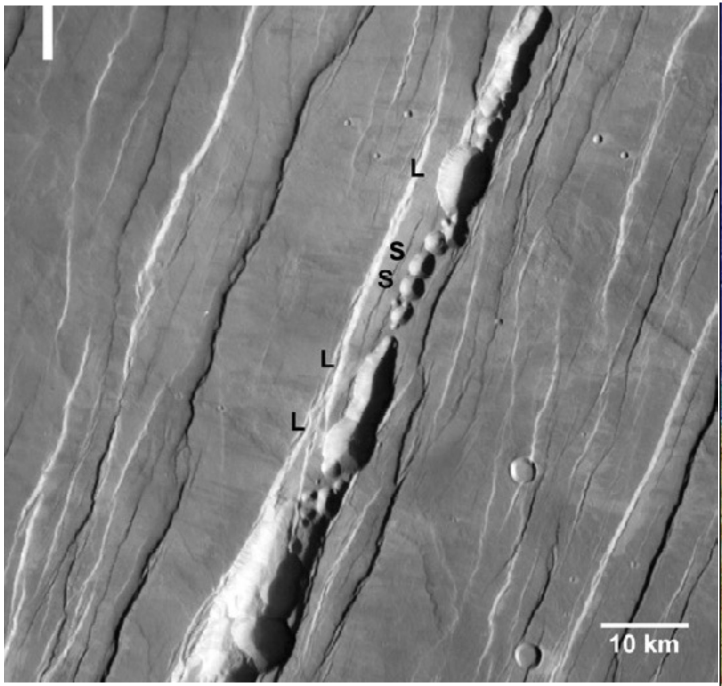
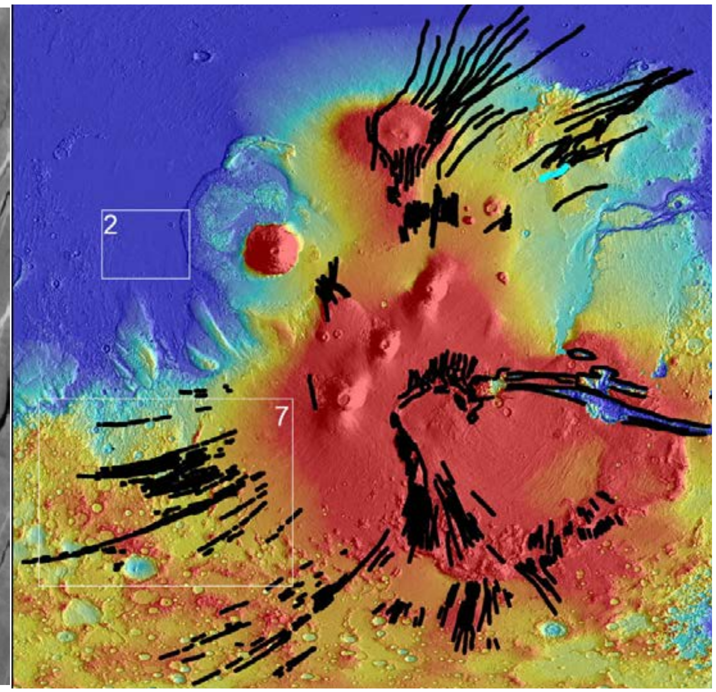
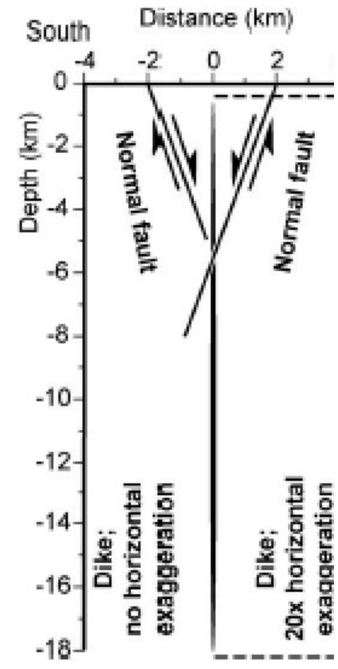
SF
1
−45
W

# Radial Graben



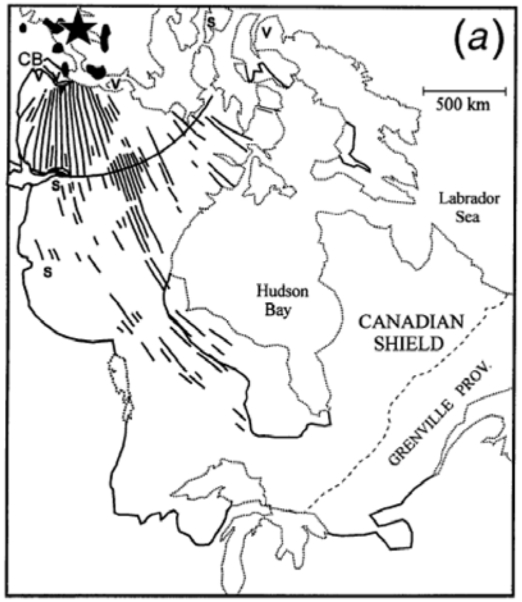




[*Schultz*, 2004]

- Long, narrow graben radiate 1000's of km outside of Tharsis
  - Late Noachian – Early Hesperian in age
  - Likely underlain by dikes – collapse pits, lava flows, topography
  - Giant dike swarms – form on Earth associated with large mantle plumes and continent breakups

# Giant dike swarms on Earth



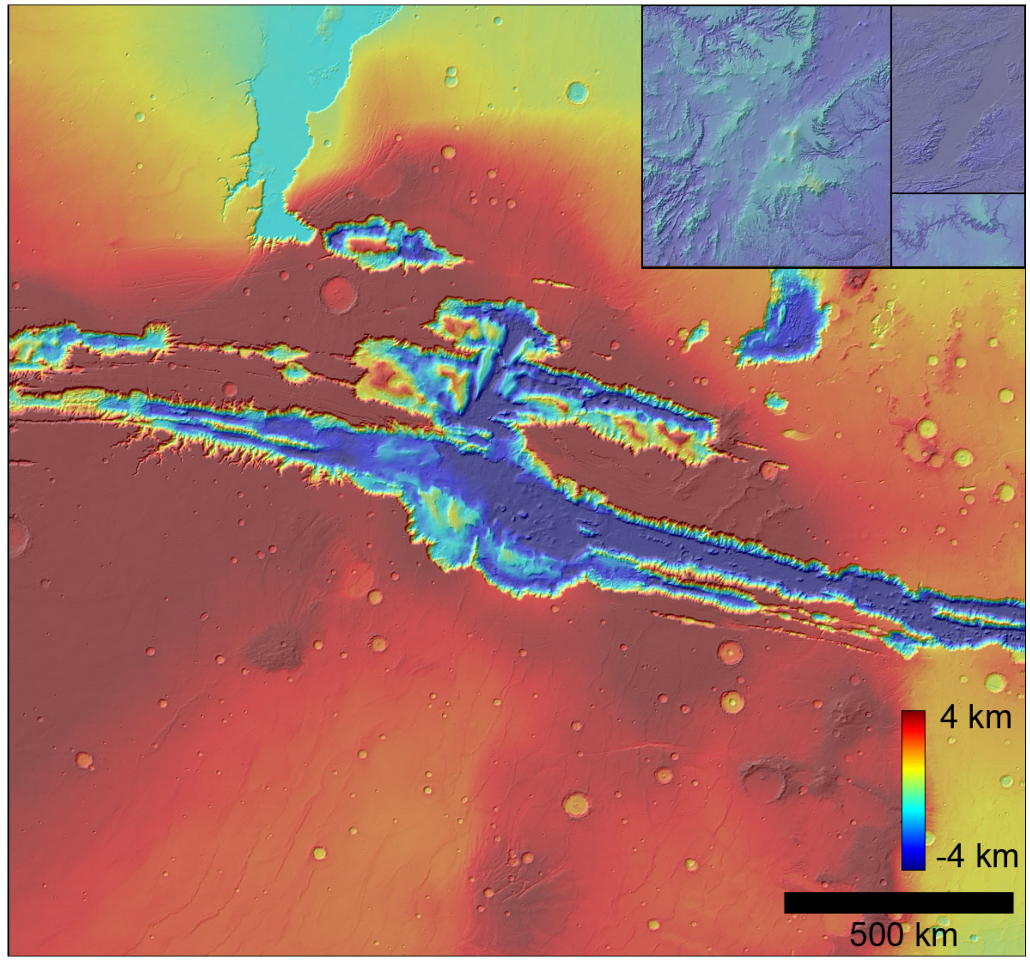

Mackenzie dike swarm
(1270 Ma)


Central Atlantic Magmatic Province
(200 Ma)

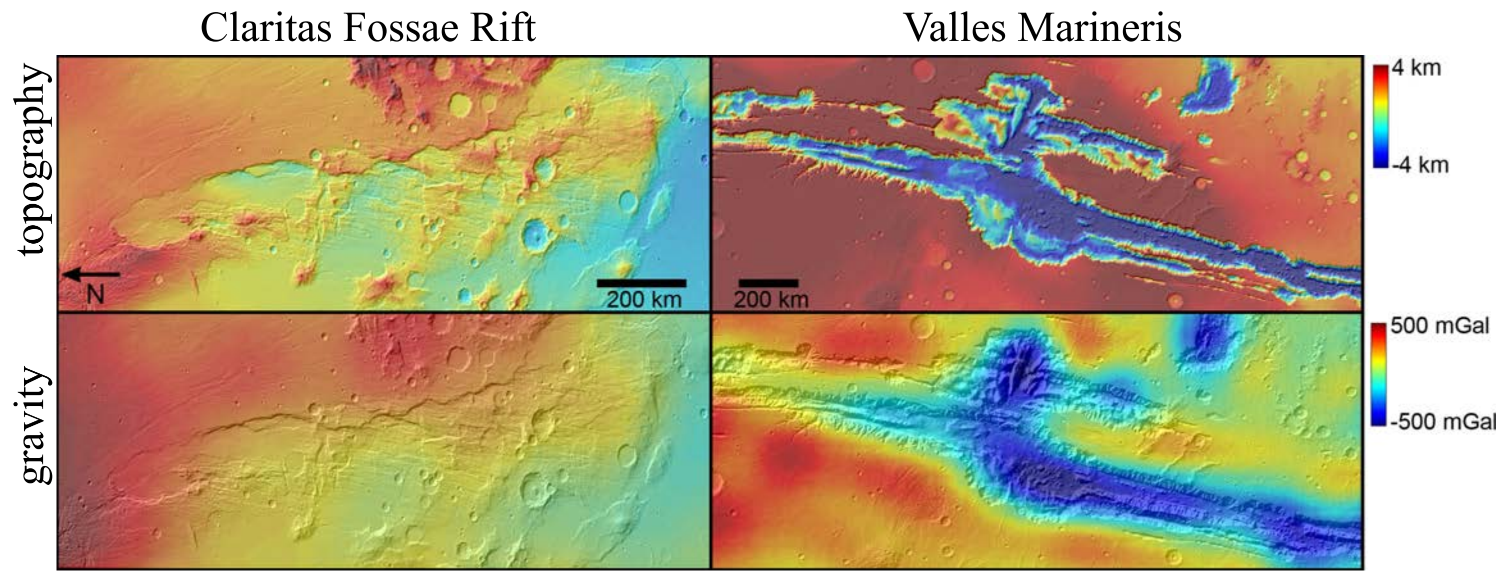
[Ernst et al., 2001]

# Valles Marineris

- Canyon system ~2000 km long, 8 km deep, 200 km wide
- Formation may have begun in Noachian, but continued through Hesperian
- Straight tectonic walls, plus erosion and landsliding
- Sedimentary layered deposits in interior



# VM Formation: Rift Zone?




- asymmetric half-graben
- dense population of faults
- arcuate normal faults
- weak gravity anomalies (isostatic compensation)

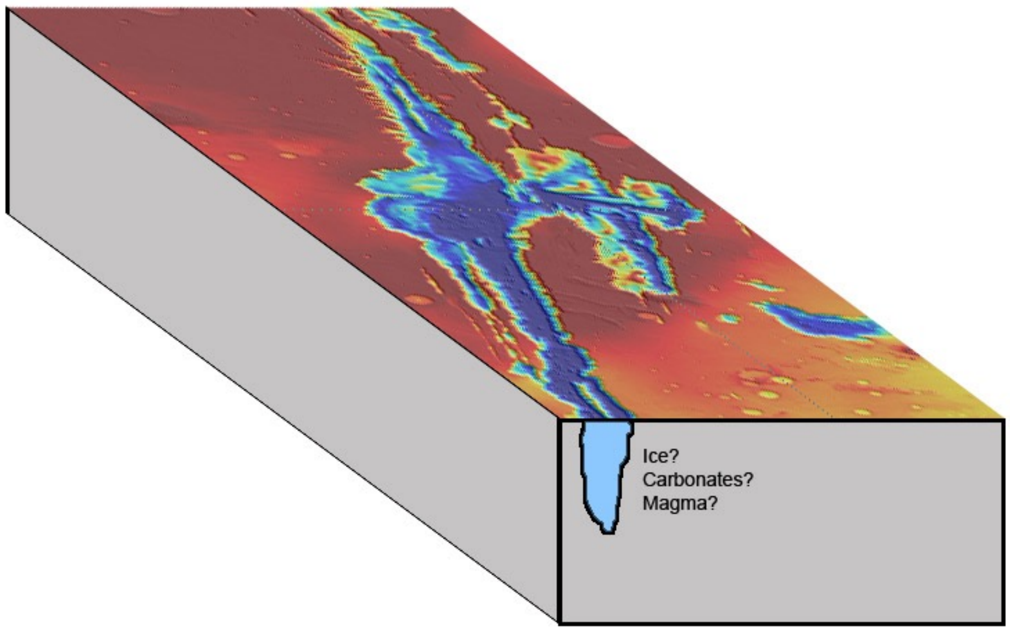
– rectangular troughs
– simple pairs of border faults
– linear trough walls
– large negative gravity anomalies (flexurally supported mass deficit)

*Valles Marineris is <u>NOT</u> analogous to typical rift zones*

# VM Formation: Vertical Collapse?

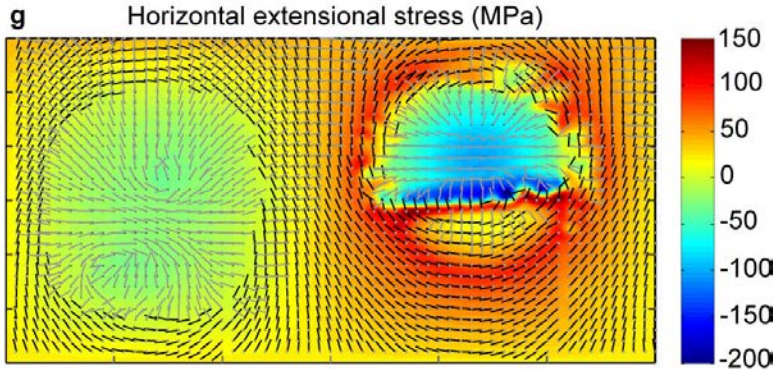
- Horizontal extension is problematic
  - inconsistent with rectangular troughs of uniform depth
- Long argued that vertical collapse must play a role
  - Melting of ground ice, dissolution of carbonates, removal of pore water, magma withdrawal, collapse into fissures

[*Sharp*, 1973; *Lucchita*, 1992; *Spencer and Fanale*, 1990; *Tanaka and Golombek*, 1989]

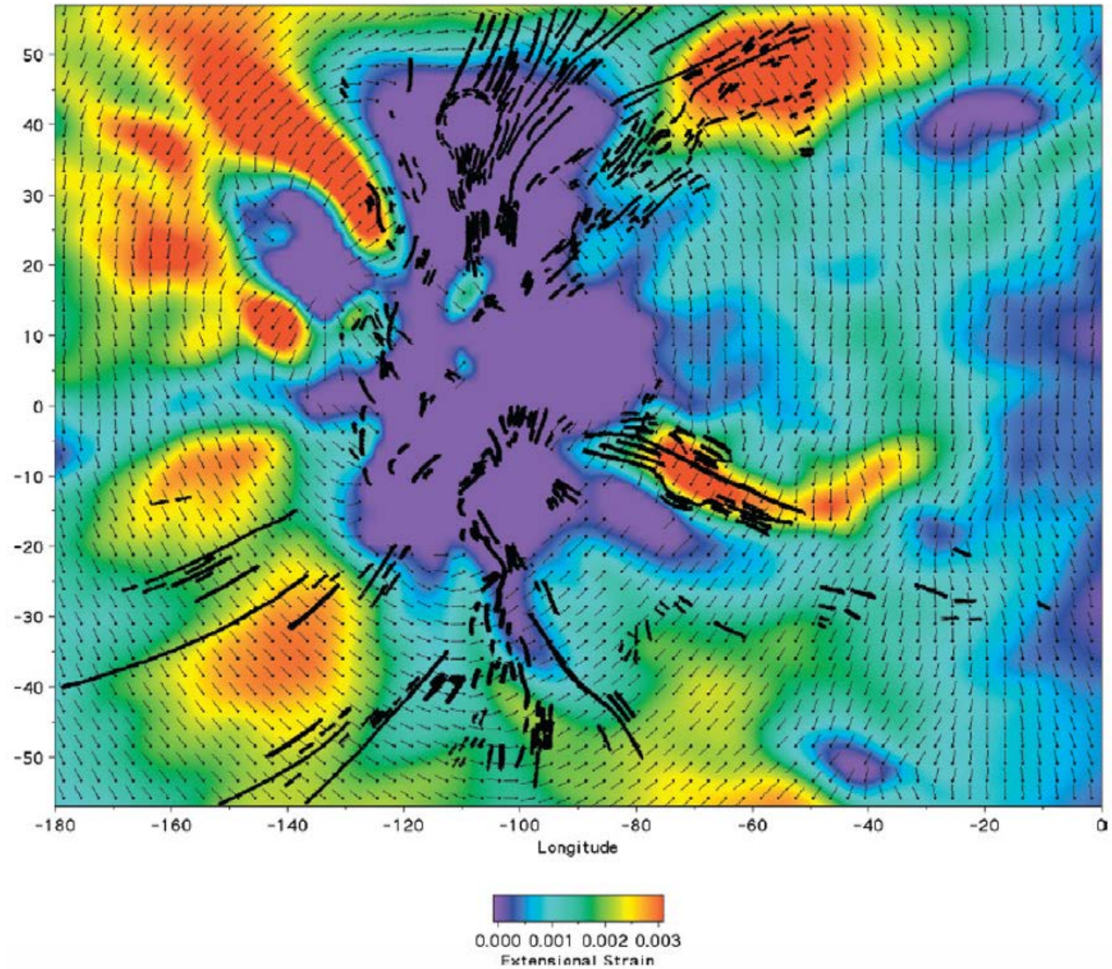


# VM Formation: Flexural extension?

- Flexural extension predicted at Valles Marineris
- BUT magnitude of extension alone is not enough



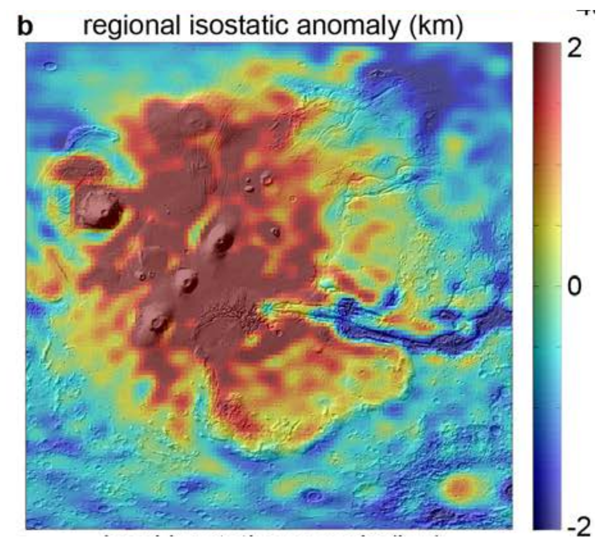

[*Andrews-Hanna*, JGR 2012b]

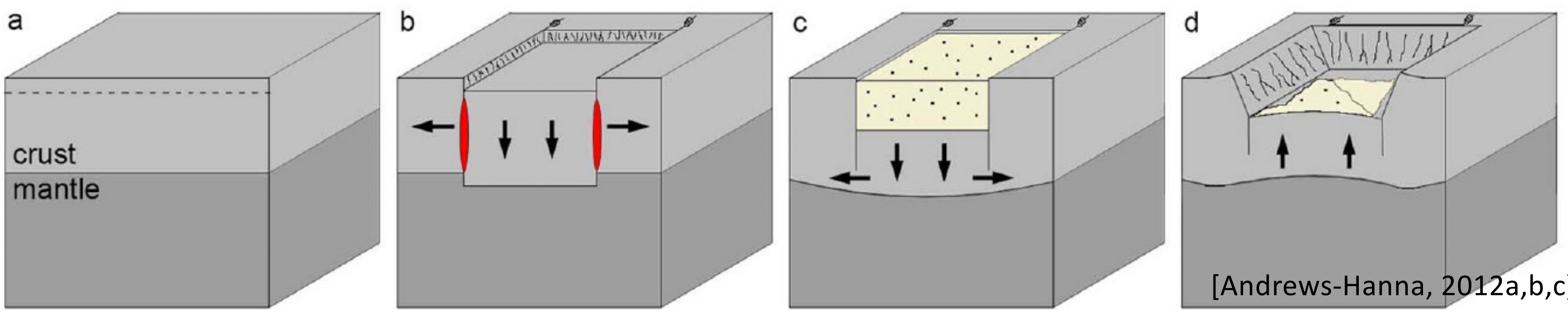


# A multi-stage origin for Valles Marineris

- Formation of Valles Marineris likely invoked some combination of extension, faulting, intrusion, collapse, subsidence, and sedimentation
  - Stage 1: Lithospheric support of Tharsis
  - Stage 2: Flexural extension, intrusion, and subsidence
  - Stage 3: Sedimentary infilling, continued subsidence
  - Stage 4: Erosion

**Valles Marineris is unique in the solar system, and its origin is still highly uncertain!**

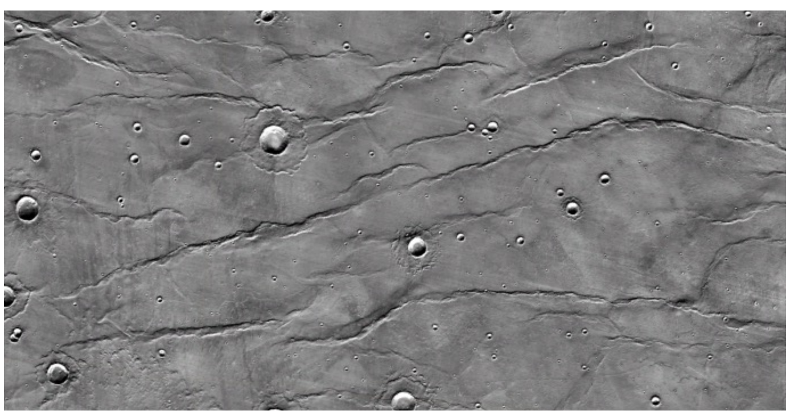


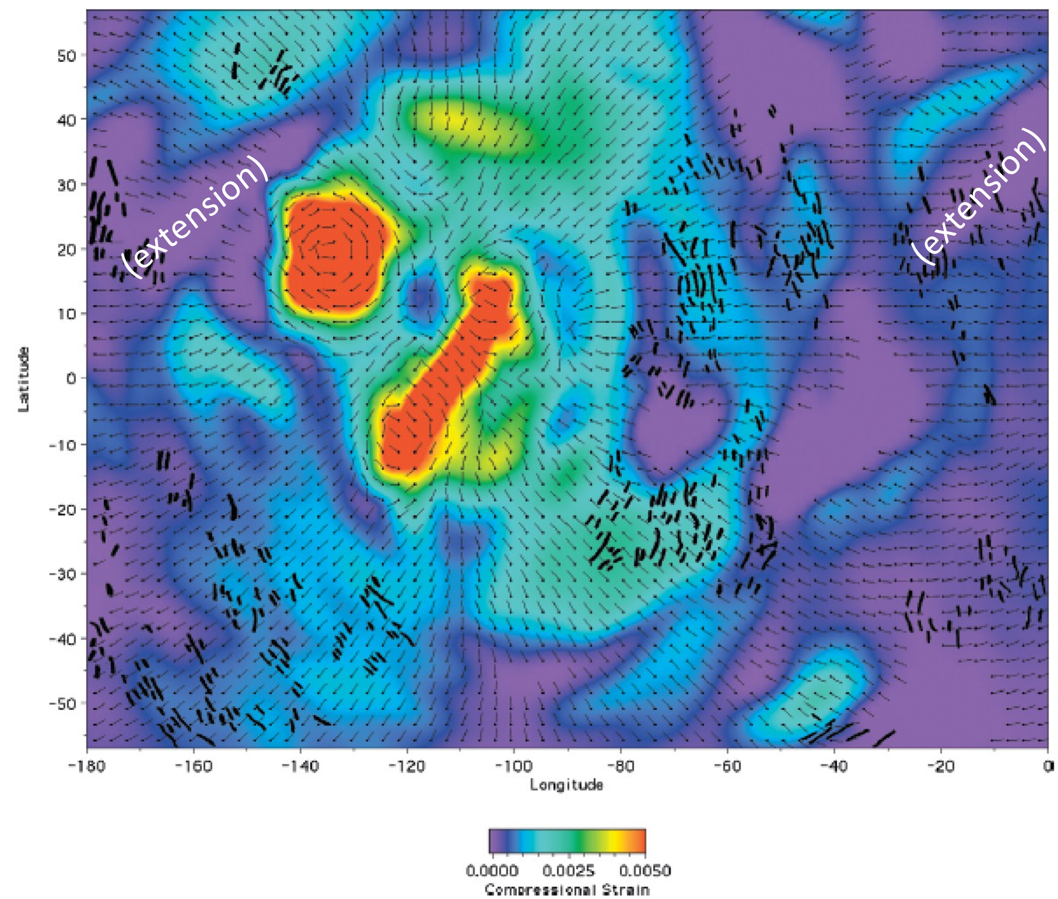

[Andrews-Hanna, 2012a,b,c]

# Wrinkle ridges: Tharsis-centric pattern

- Hesperian aged
- Concentric to Tharsis – Tharsis loading stresses control orientation [*Banerdt and Golombek*, 2000]
- BUT occur even where stresses should be weak or extensional
- Must be added source of <u>compression</u>

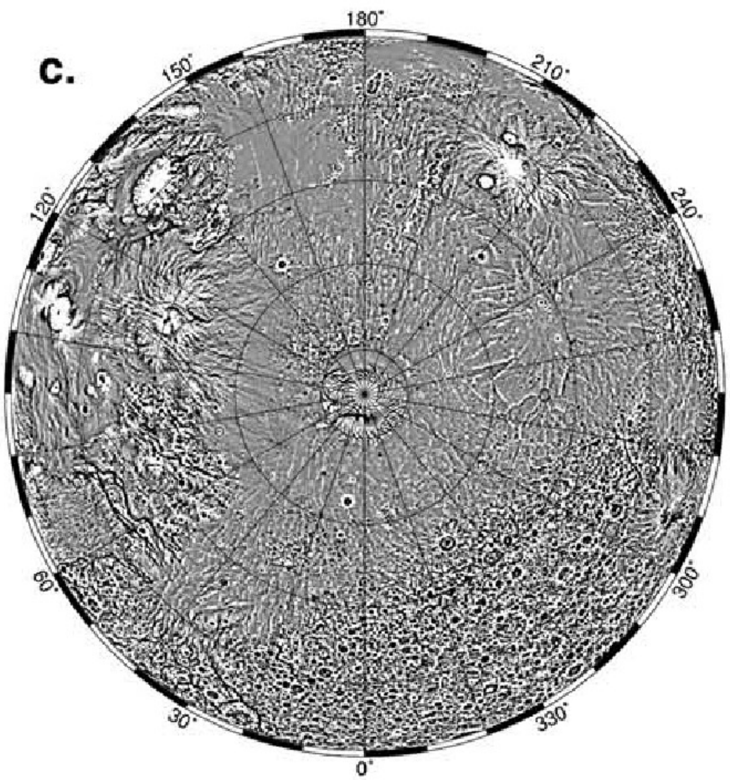


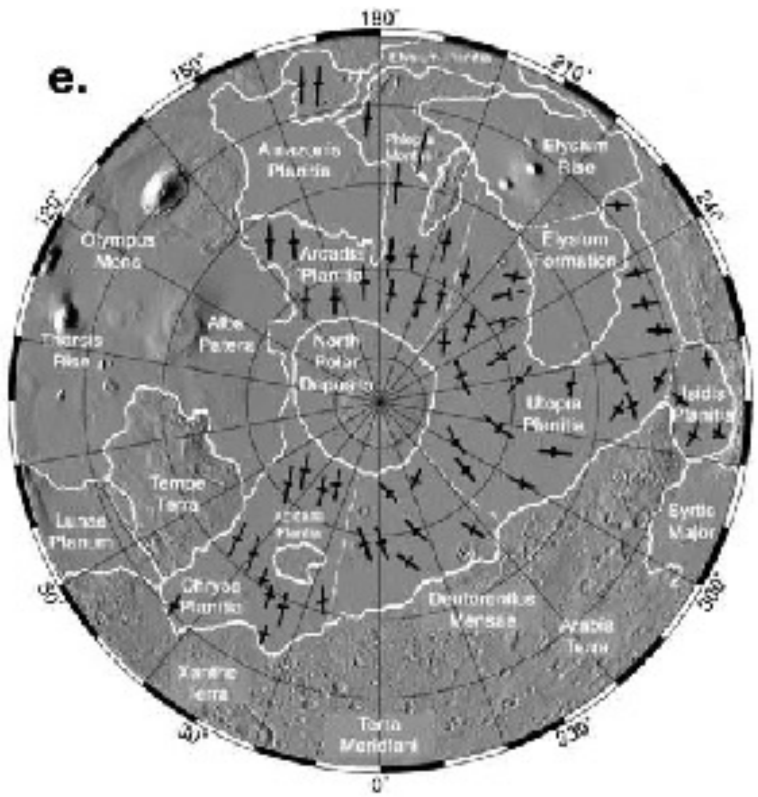
Compressional strain

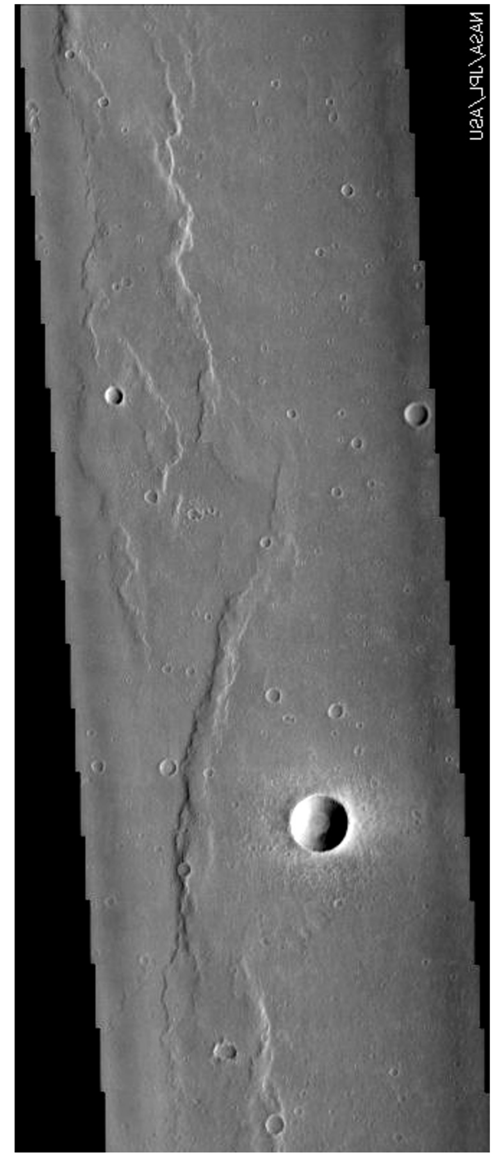


# Northern Lowlands Wrinkle Ridges

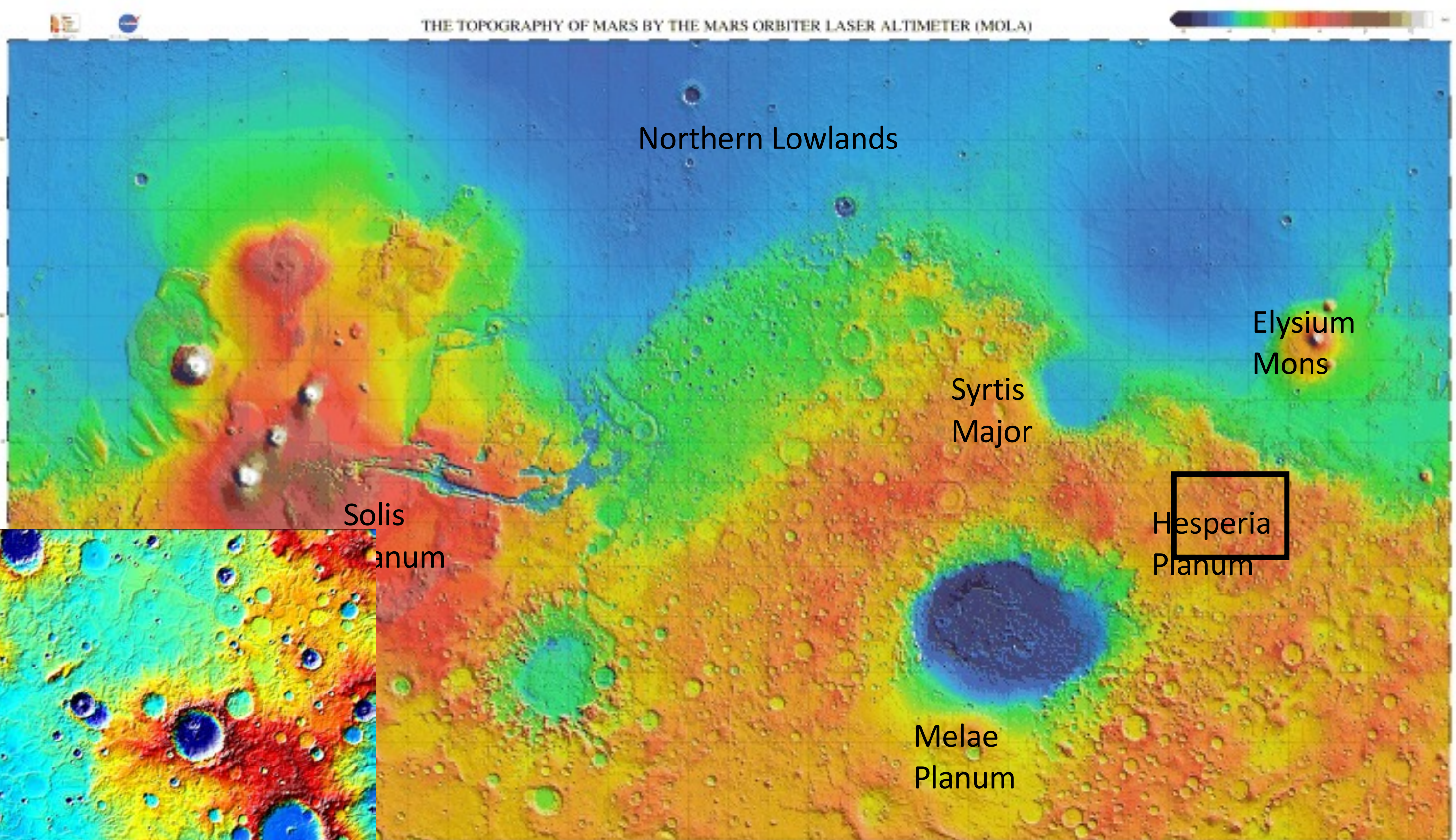
- global population of wrinkle ridges
- dominantly circumferential to Tharsis

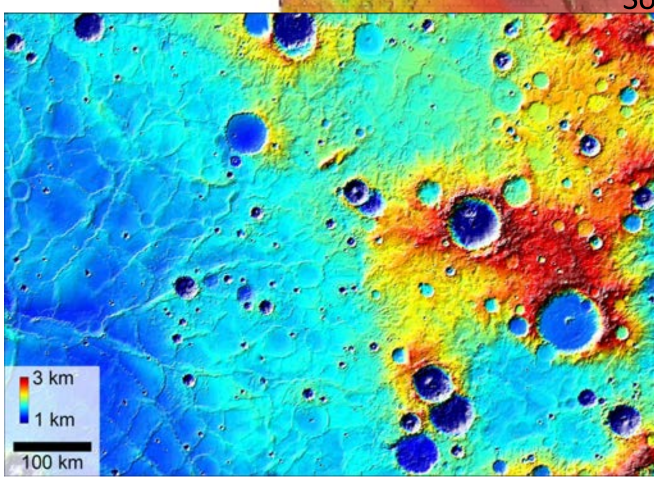


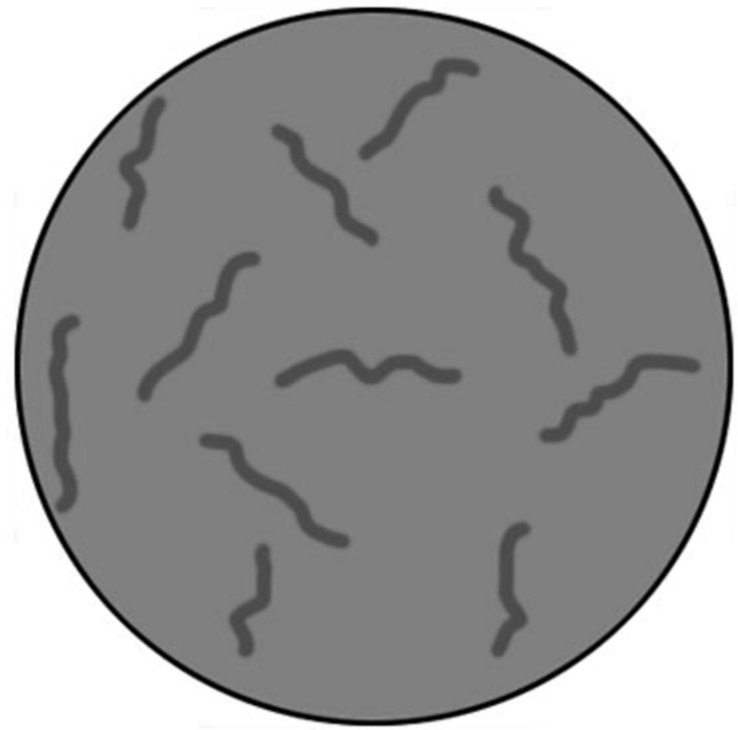
# Hesperian plains



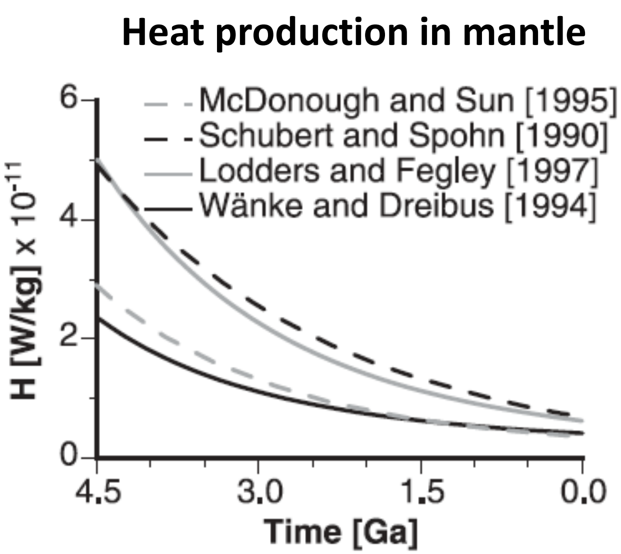
# Global contraction

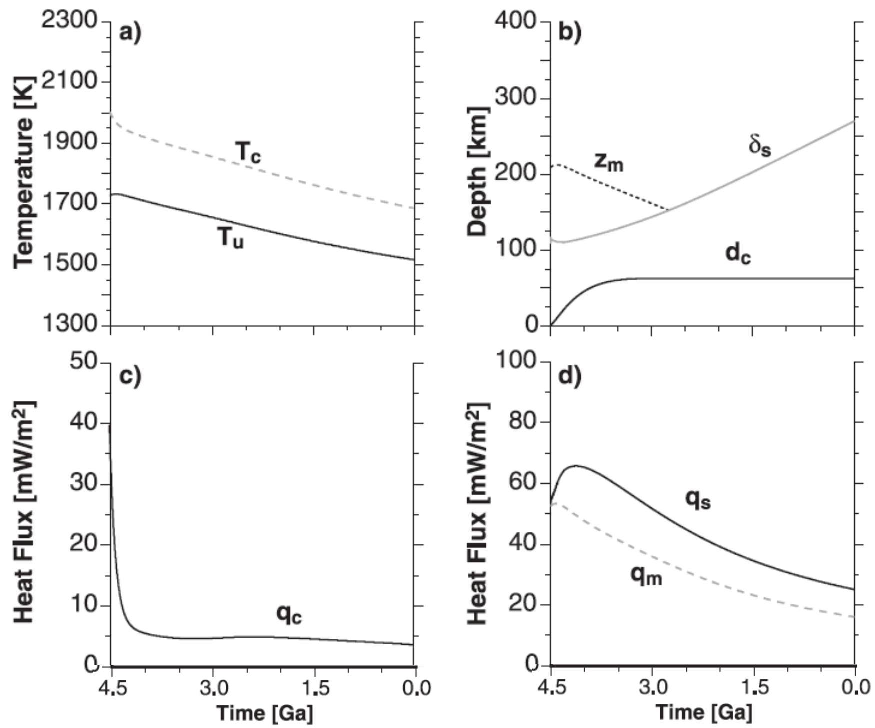
- Key observations:
  - Pervasive wrinkle ridges in Hesperian volcanic terrains
  - Tharsis-centered wrinkle ridge pattern found even where Tharsis stresses predict extension
- By the Hesperian, pervasive compressional tectonism require addition of a global compressional stress field
  - Contraction of interior due to cooling
    → compression in lithosphere
- Cooling and contraction:
  - Decay of radioactive isotopes
  - Decrease in heat flow
  - Cooling of interior
  - Isotropic compression of lithosphere



# Mars Thermal Evolution

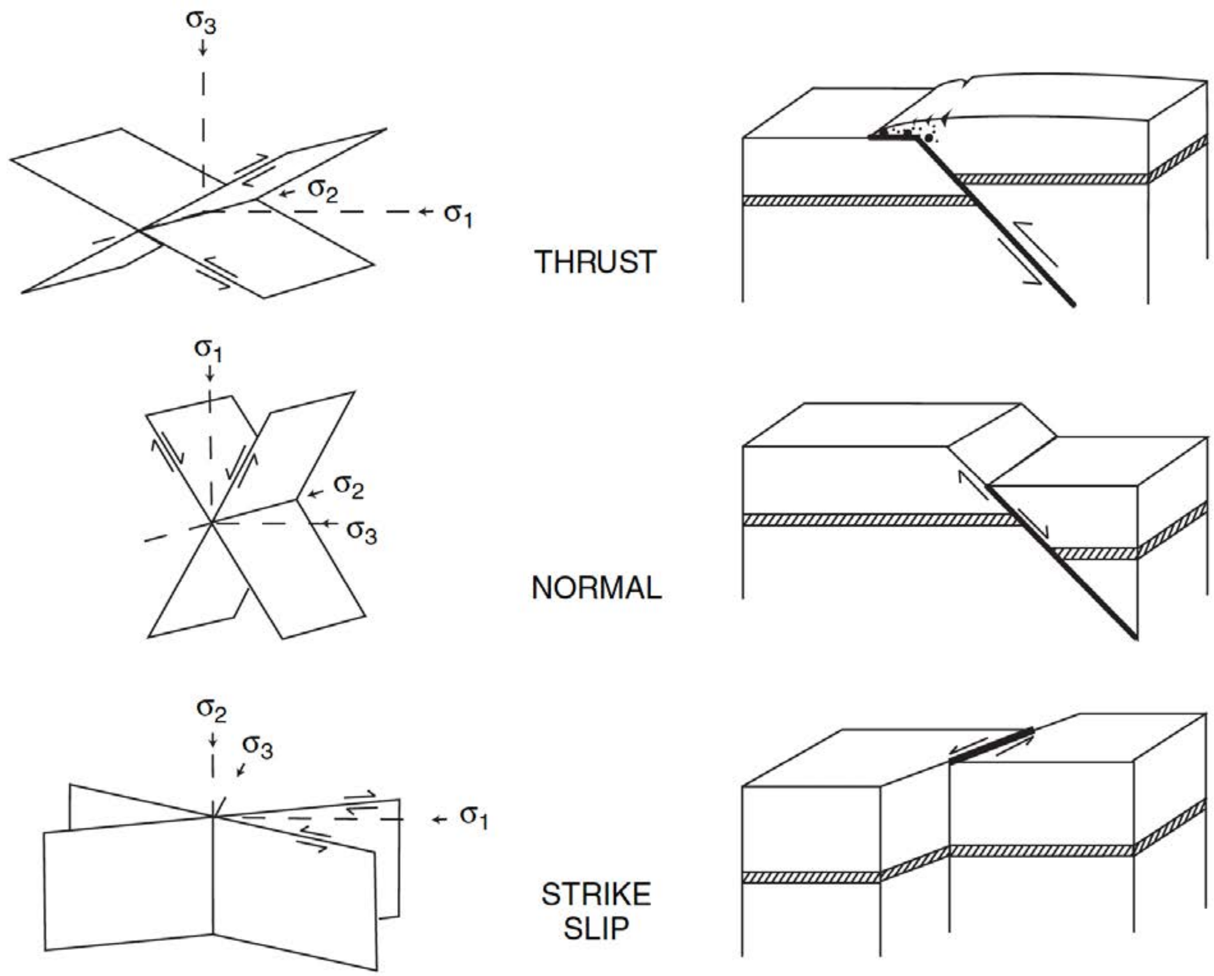
- Cooling rate ~ 53 K/Gyr [Hauck and Phillips, 2001]



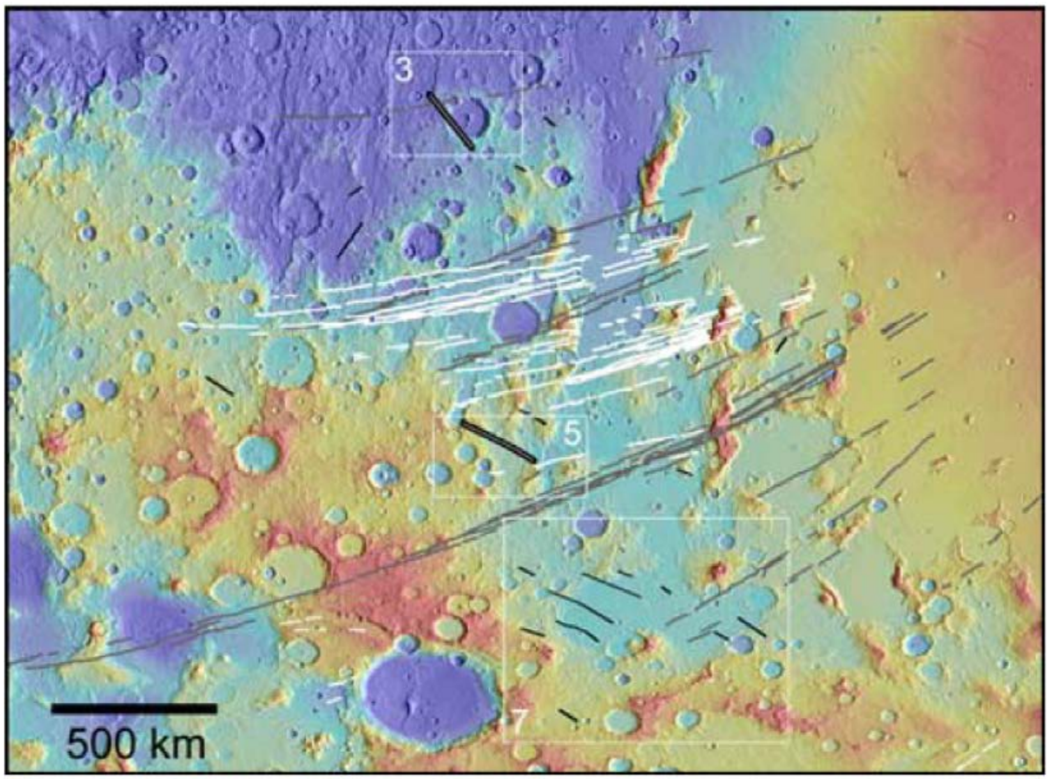
# Stress evolution

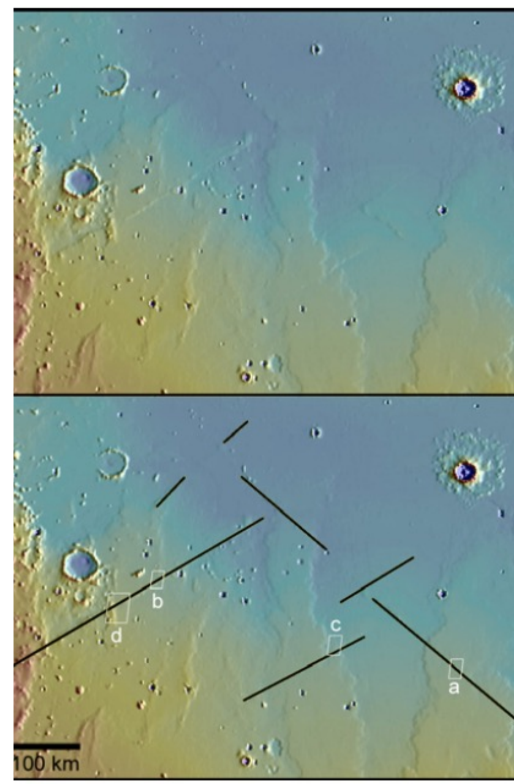
- Global contraction would have caused many areas that began in an extensional stress state ($\sigma_2$ and $\sigma_3$ horizonal) to transition to a compressional stress state ($\sigma_1$ and $\sigma_2$ horizontal)
- Must pass through a strike-slip stress-state ($\sigma_1$ and $\sigma_3$ horizontal)



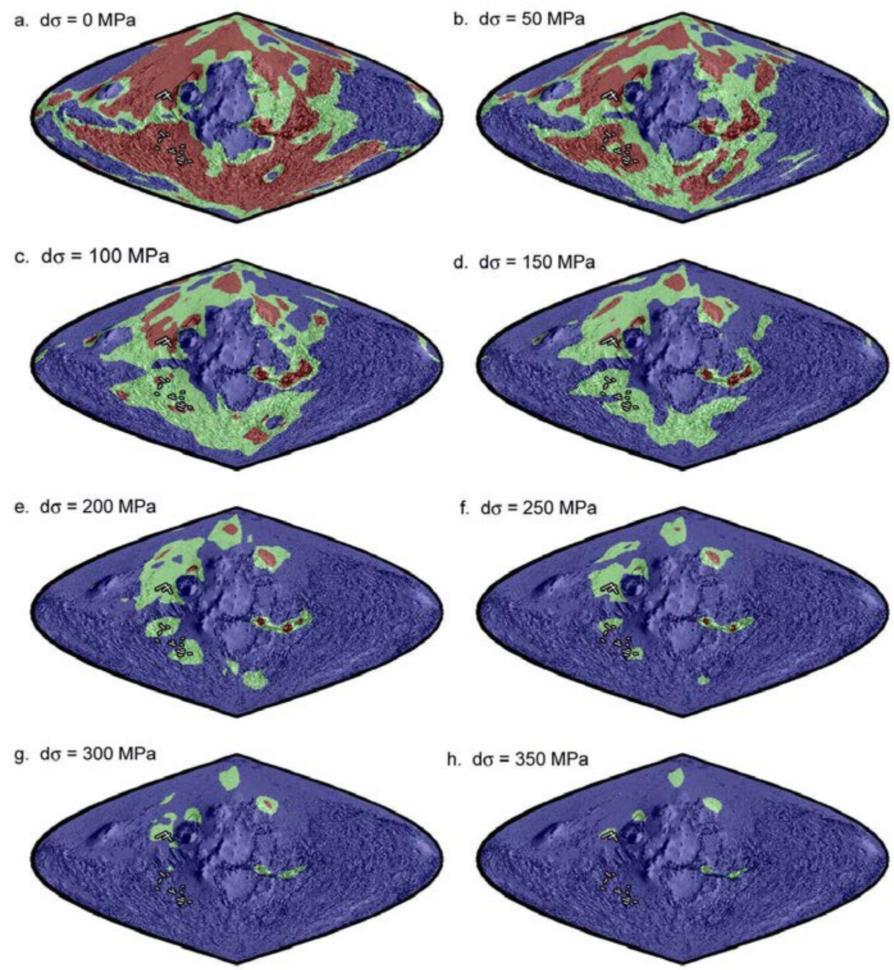
# Faulting west of Tharsis

- Observe transition from extension (graben), to strike-slip faulting, to compression (wrinkle ridges) [Okubo and Schultz, 2006; Andrews-Hanna, 2008]



# Evolving Tectonics around Tharsis



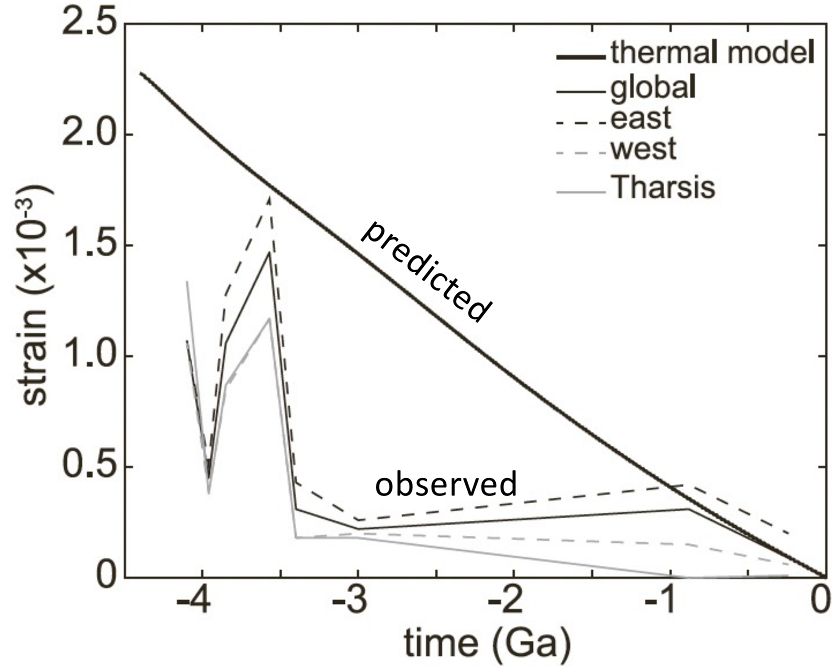

Increasing compression

**Extension**
**Strike-slip**
**Compression**

[Andrews-Hanna, 2008]

# Strain history

- Gradual cooling and contraction is dominant paradigm to understand the evolution of Mars (and Mercury, and the Moon), BUT…
  - *Predicted:* even more compression in ancient surfaces
  - *Observed:* little ancient compression
  - *Predicted:* steady rate of compression
  - *Observed:* rapid pulse of compression in early Hesperian, with little since
  - *Predicted:* compressional faulting today at rates similar to past 3 Ga
  - *Observed:* little or no active compressional tectonic seismicity



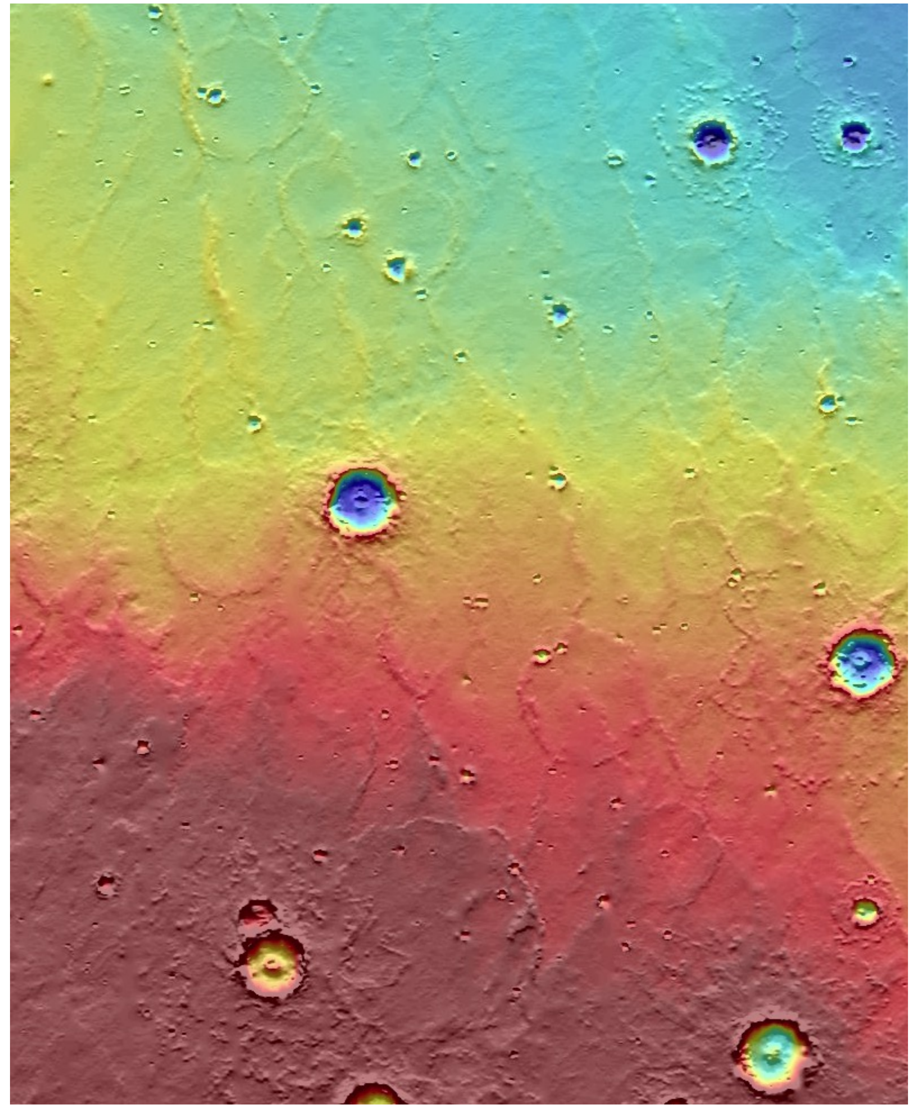

[Andrews-Hanna, 2023]

*Why did Mars experience a Hesperian pulse in contractional tectonics?*

- *Is this a true record of the actual strain rate?*
- *Is the tectonic record biased?*

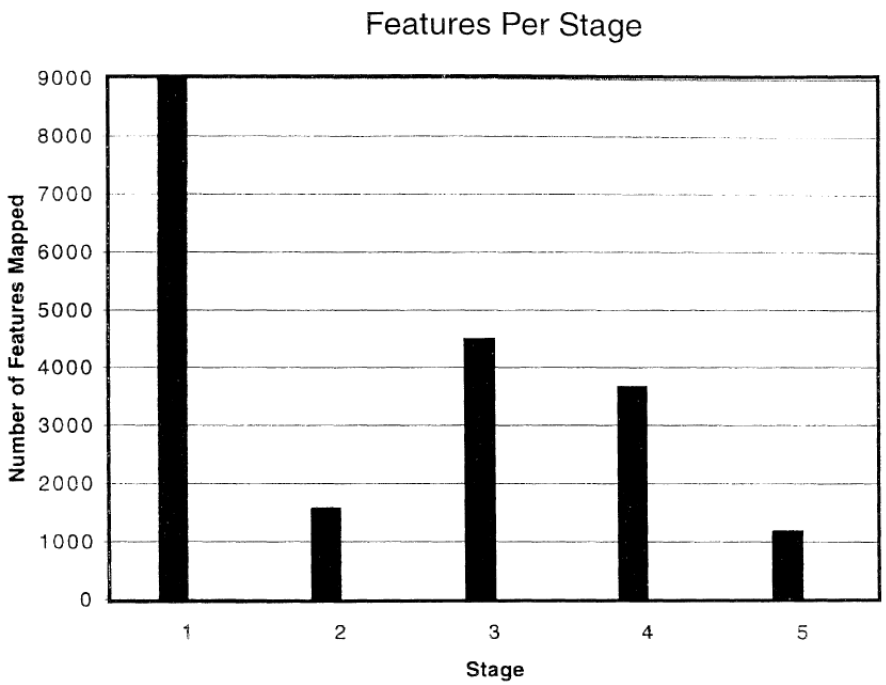
# Age of Tharsis

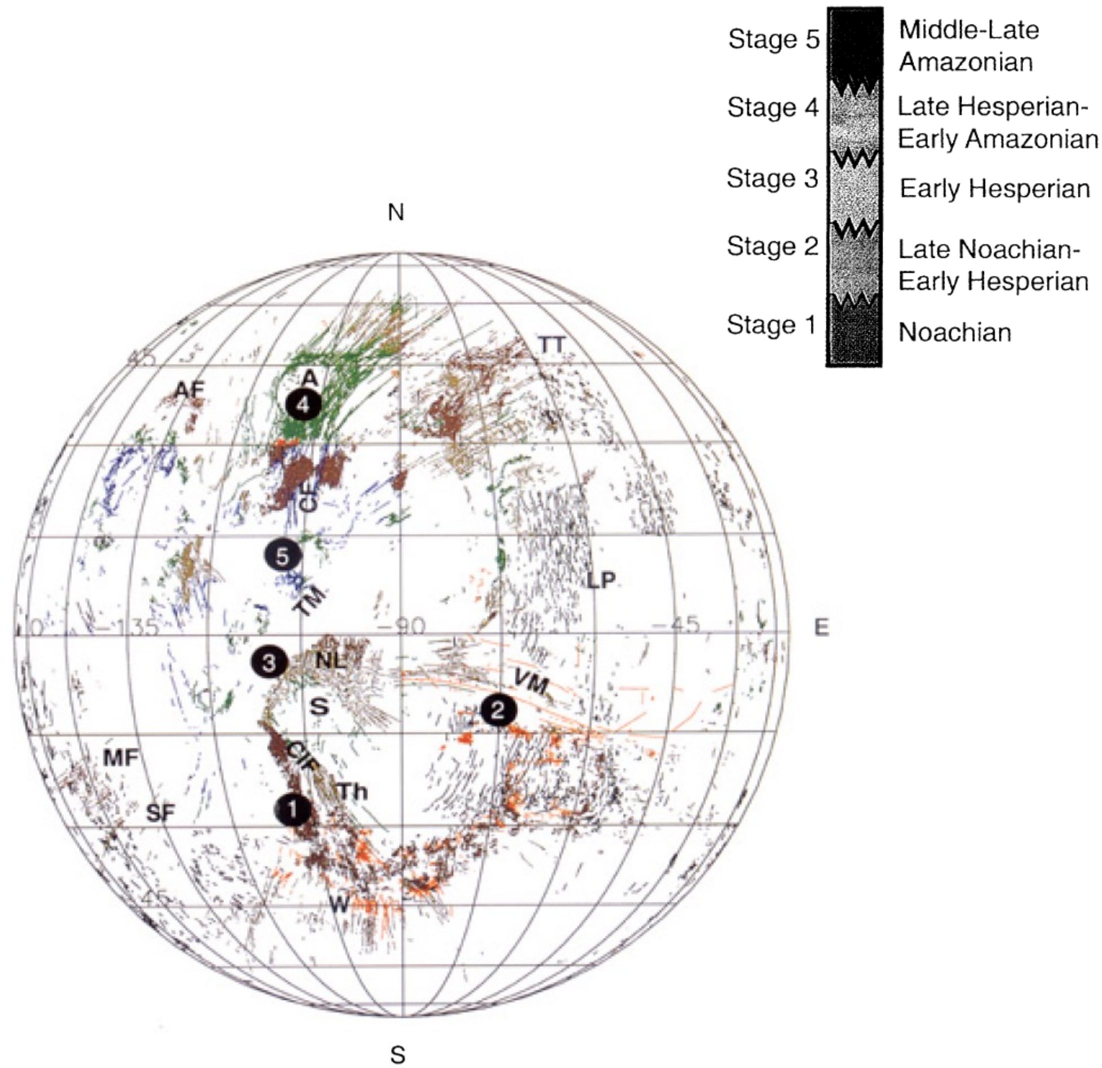
- Buried craters reveal ancient surface at shallow depths within rise
- Ancient parts of surface also Noachian in age
  - characterized by extensional tectonics and magnetic anomalies [Johnson and Phillips]
- First stages may have consisted of uplift, fracturing, intrusion in the Noachian



# Age of Tharsis

- Multiple centers and stages of Tharsis-focused activity [Anderson, 2001]
- Peak activity is in Noachian

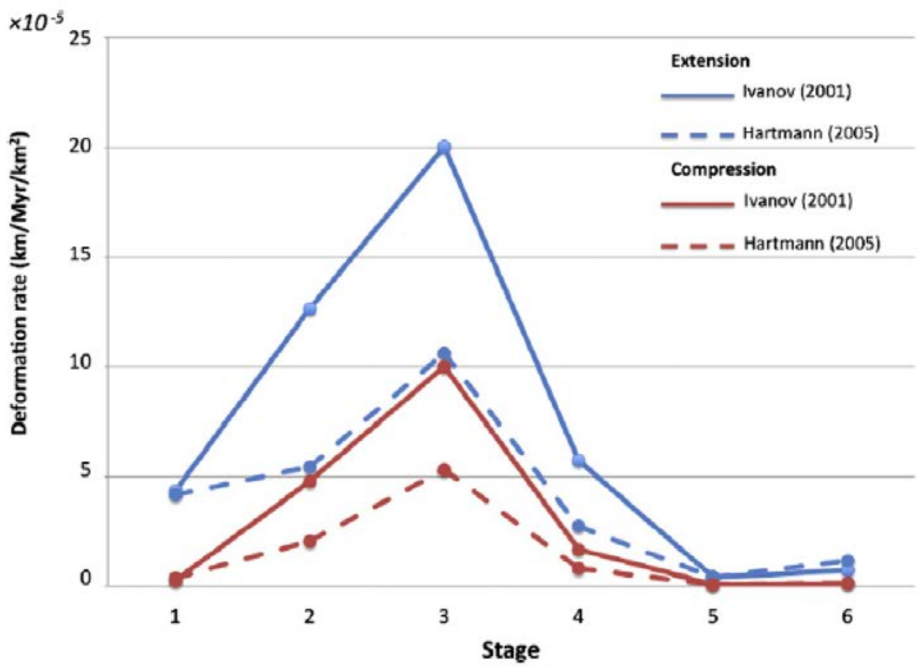


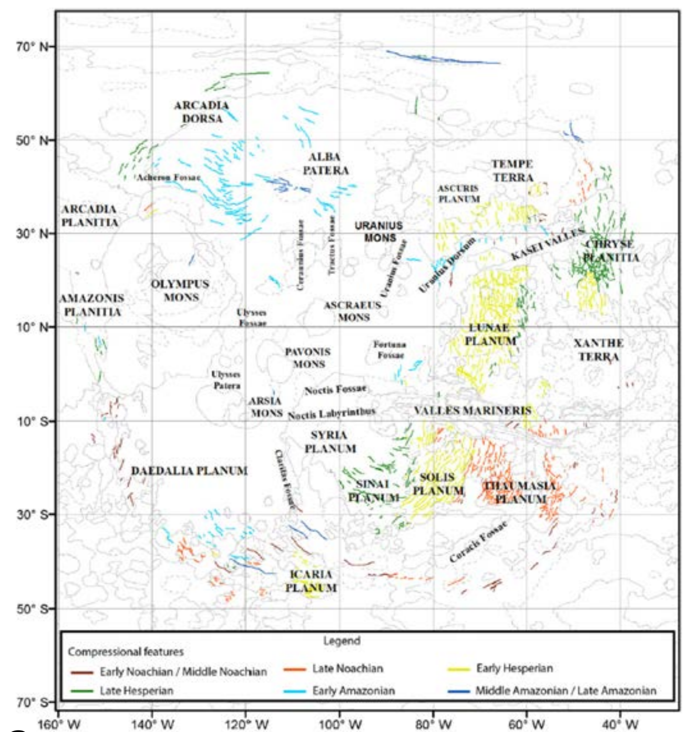




[Anderson, 2001]

# Age of Tharsis

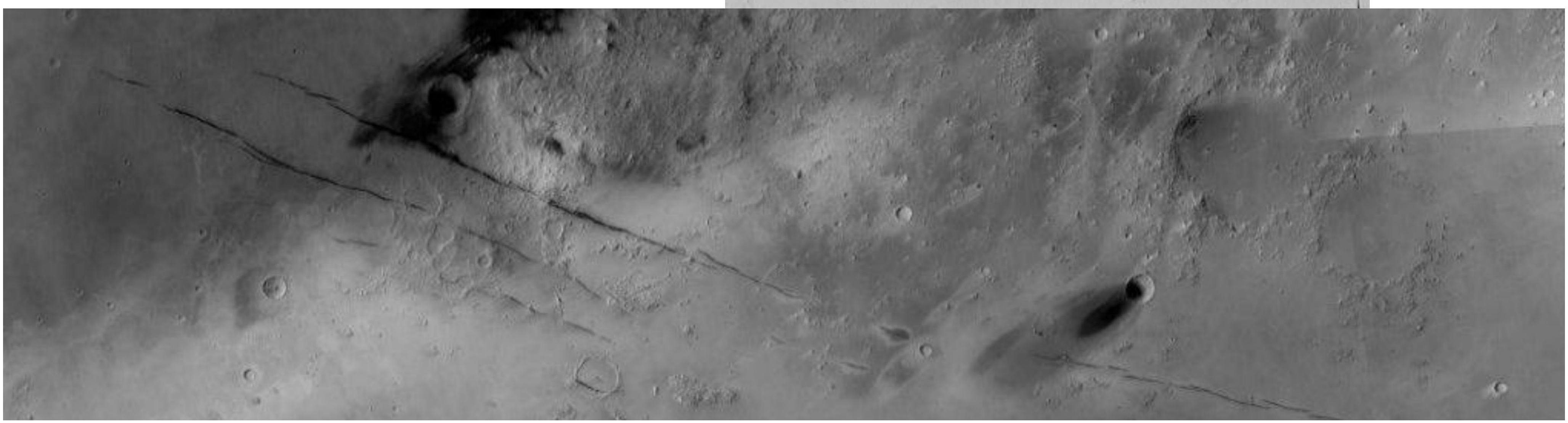
- Revised ages of surface units and tectonic mapping
  - Tharsis activity picking up in Late Noachian, peaking in Early Hesperian [Bouley et al., 2018]



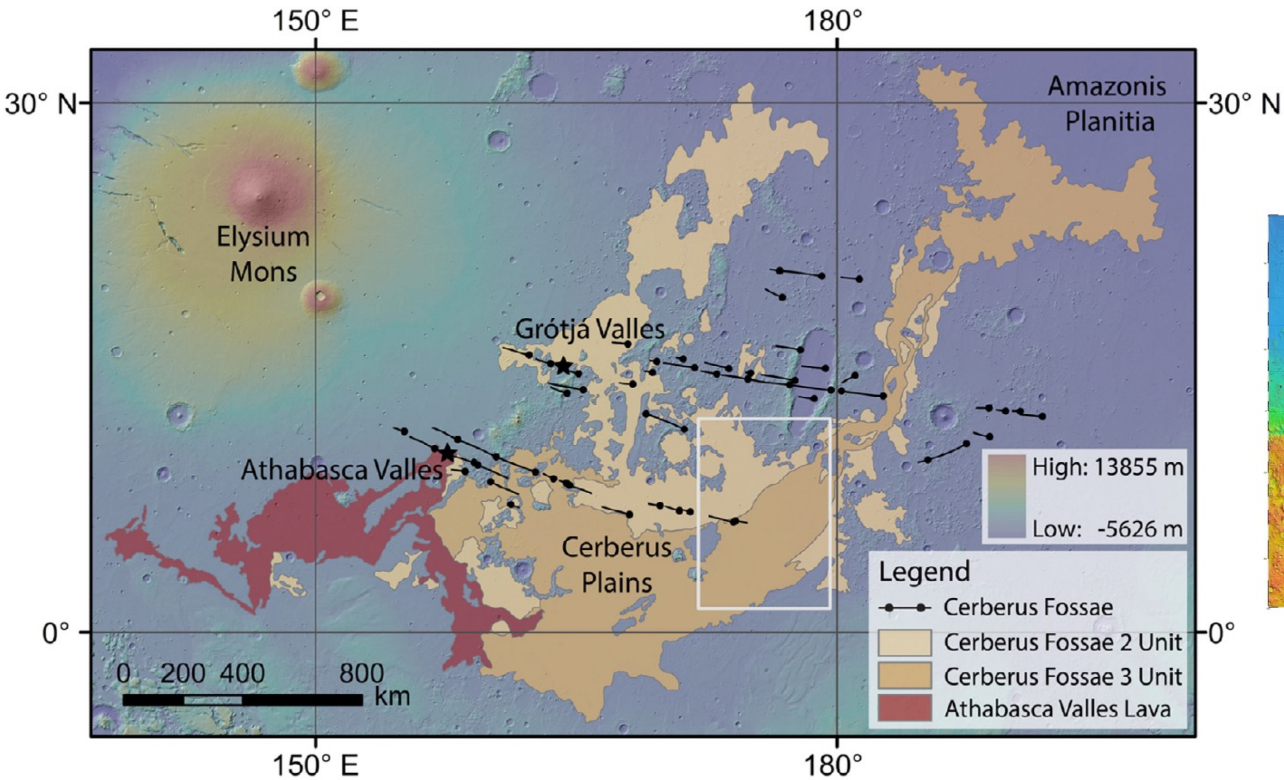



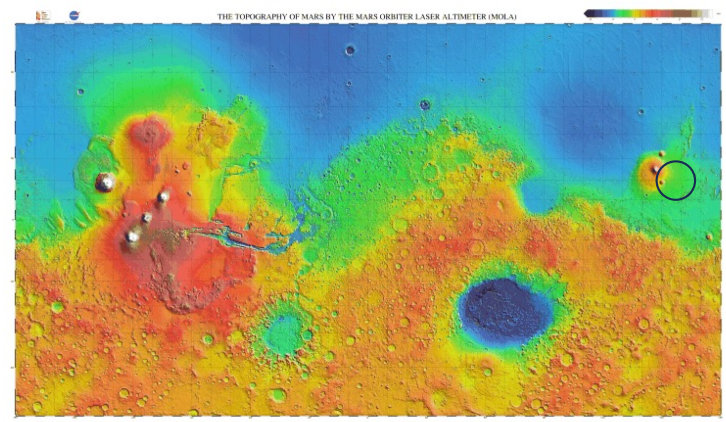

**Or does this reflect the bias in strain history observed globally?**

# Amazonian Volcanism and Tectonics: Cerberus Fossa, Elysium



# Late Amazonian volcanism in Elysium Planitia

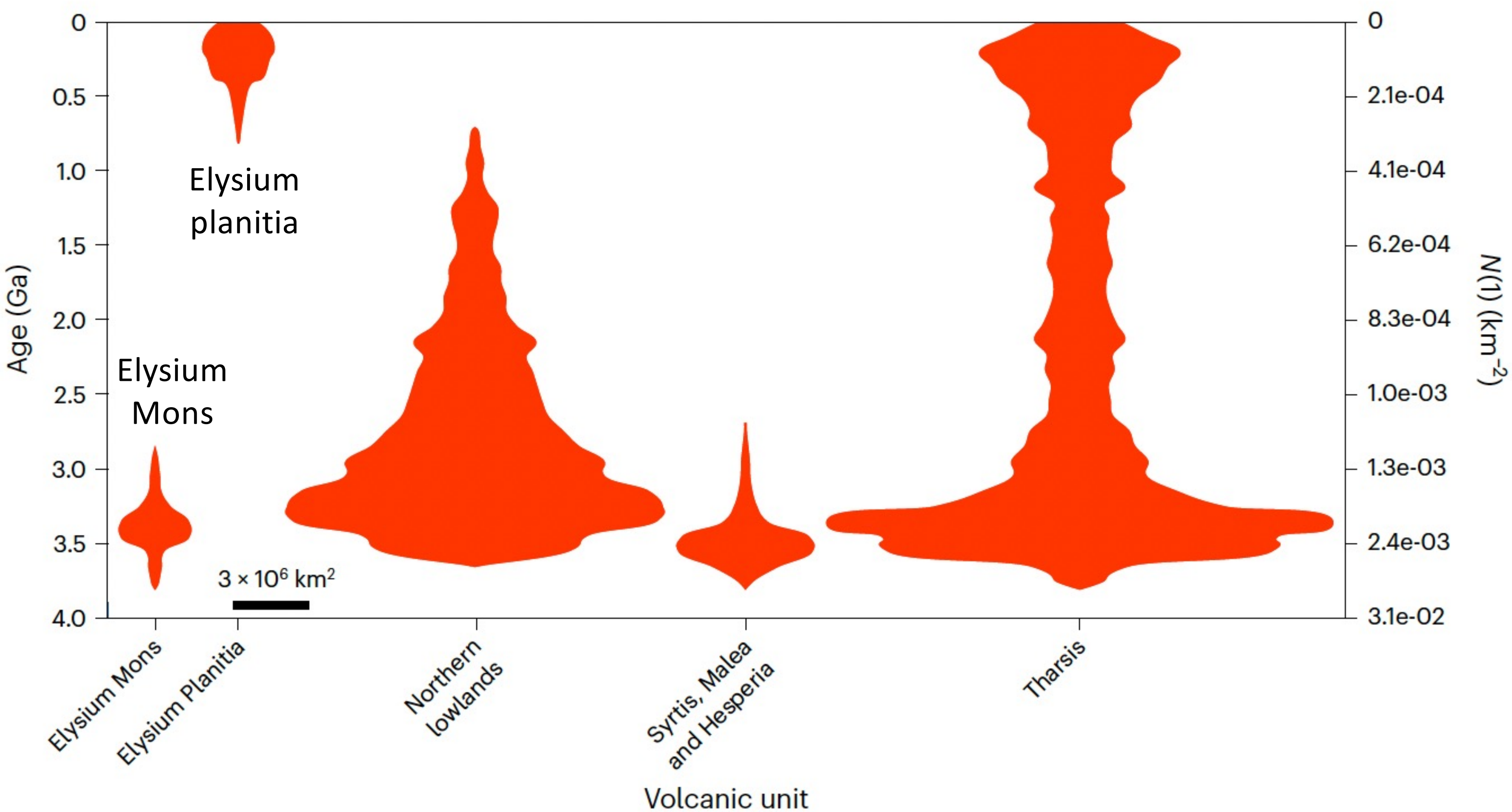


# Geologically recent explosive volcanism

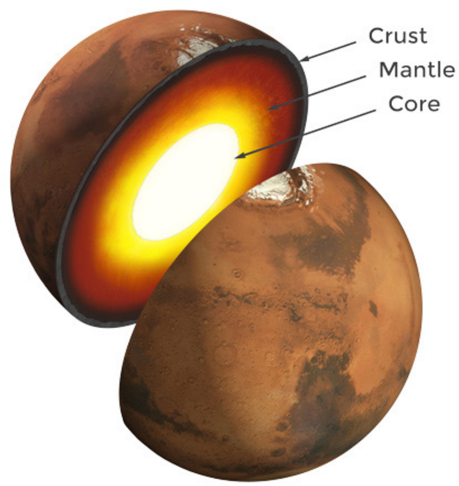
- Dark, thin, mantling unit around one of the Cerberus fossae fissures
  - pyroclastic deposit from explosive volcanic eruption
  - ~53 kyr old!!

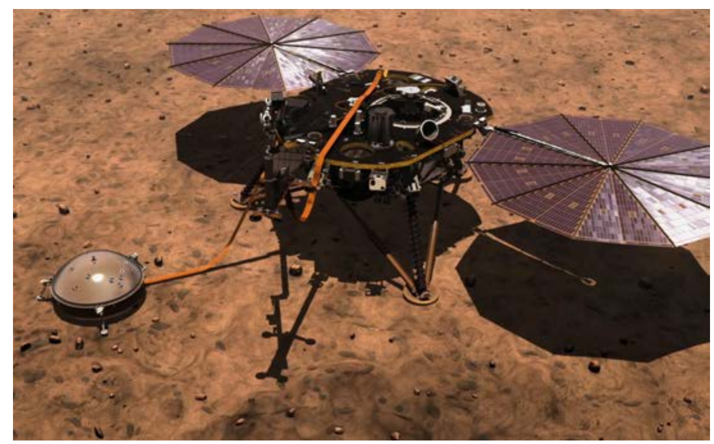
# Global volcanic history



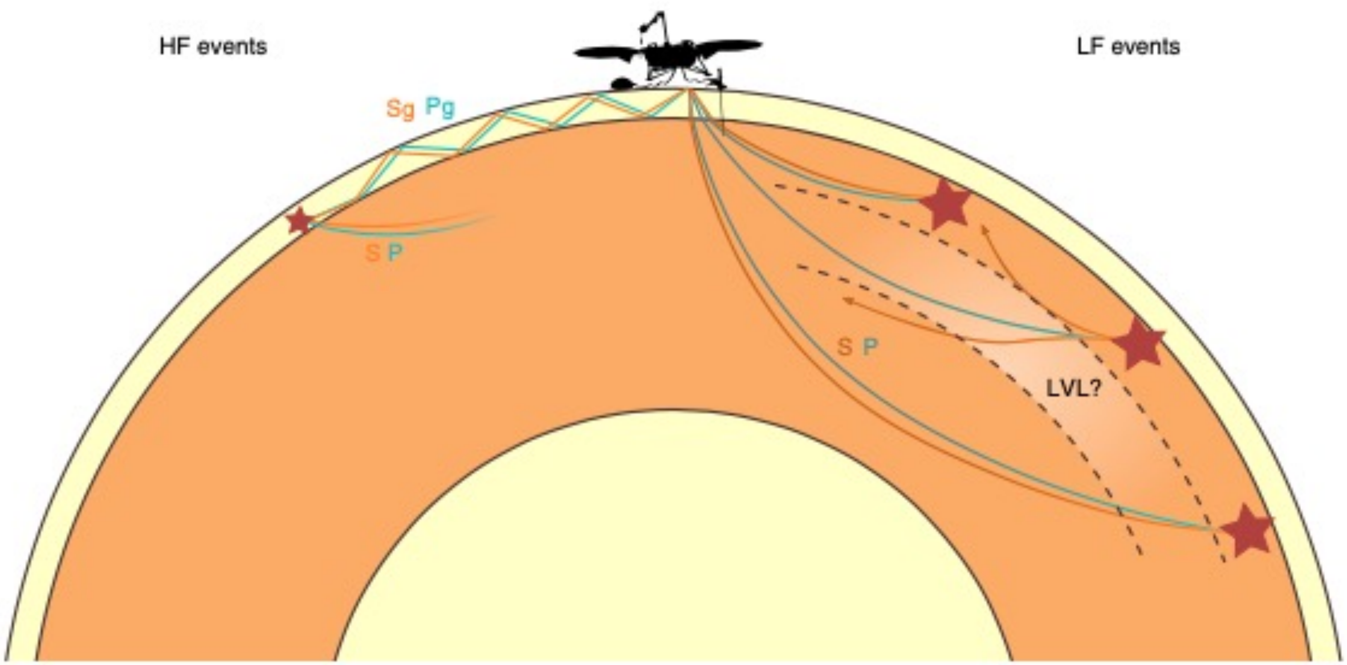
# InSight

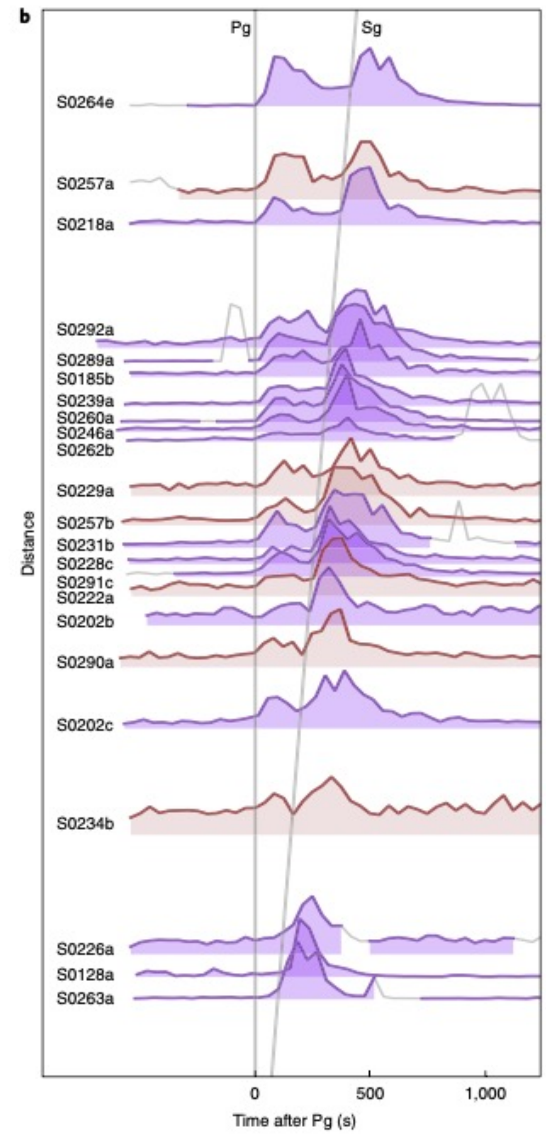
- NASA's latest Mars lander
  - SEIS – seismometer to look for Mars quakes, probe the interior structure
  - Heatflow probe $HP^3$ – measure the heat flow from the interior



# InSight




- Seismometer identifies seismic waves from Marsquakes