



# Martian dichotomy formation by partial melting coupled to early Tharsis migration

April 13, 2011

at

Dept. of Geophysics, Charles Univ. in Prague

# Mars

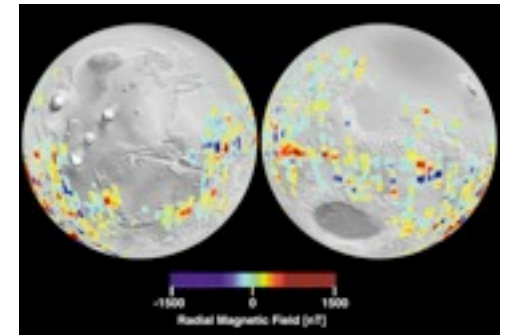
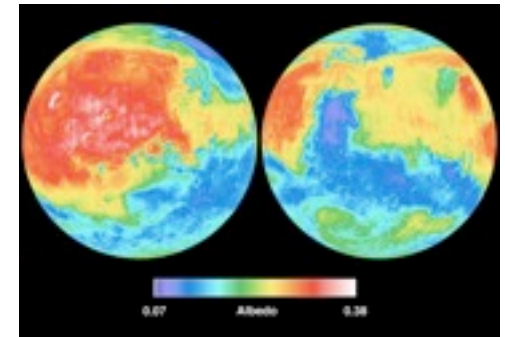
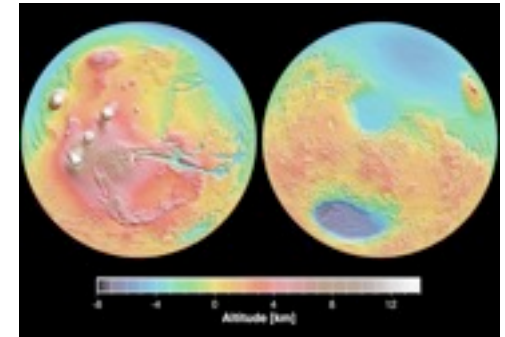
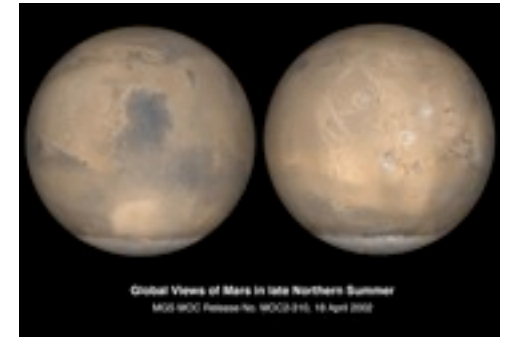
- radius 3400 km (Earth 6370 km)
- core radius 1300–1700 km, 0.38–0.50 R (3480, 0.55 R)
- surface gravity  $3.7 \text{ m/s}^2$  ( $9.8 \text{ m/s}^2$ )
- surface pressure 0.7–0.9 kPa (101.3 kPa)
- remanent crustal magnetization (10 x that of the Earth)



# Mars Global Surveyor (MGS) mission 1996–2006

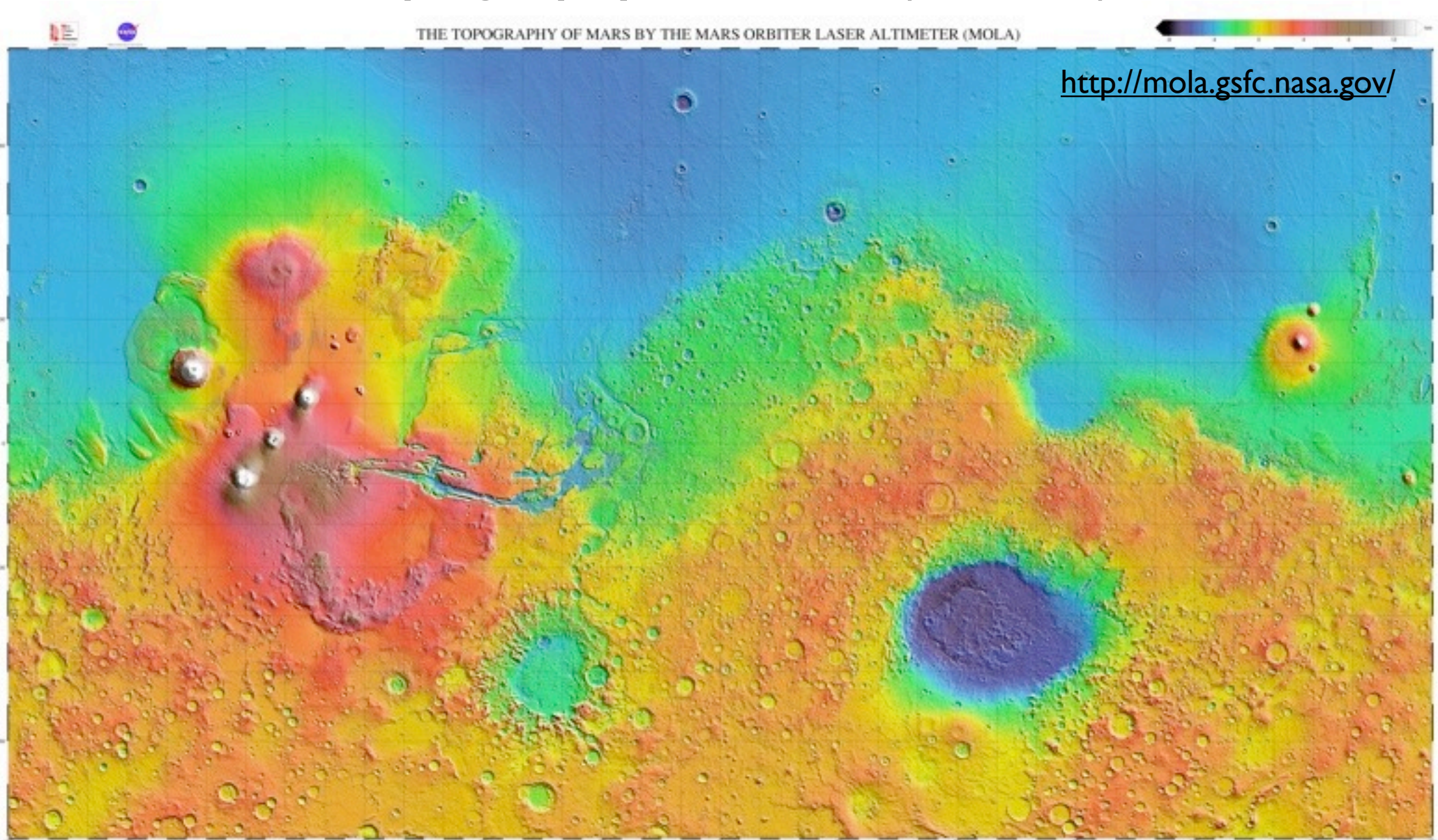


- Mars Orbiter Camera (MOC)
- Mars Orbiter Laser Altimeter (MOLA)
- Thermal Emission Spectrometer (TES)
- Magnetometer





# Topography of Mars (MOLA)

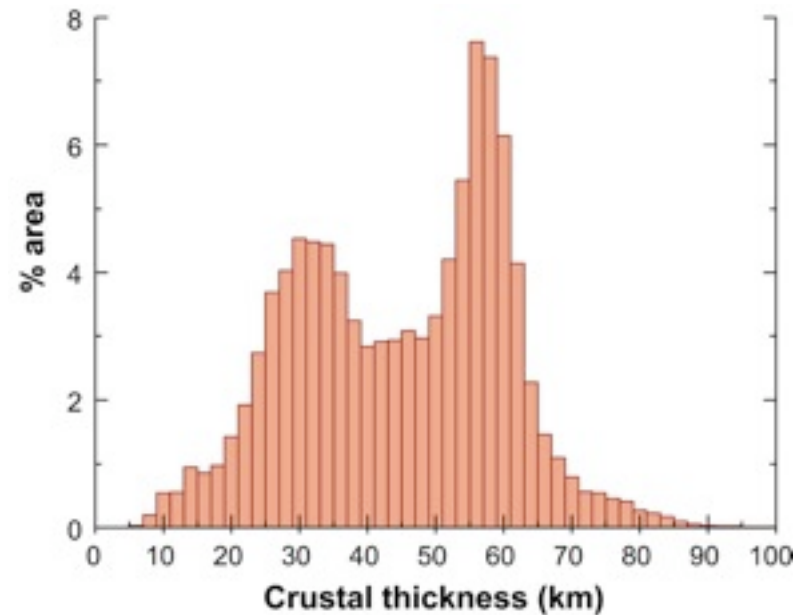
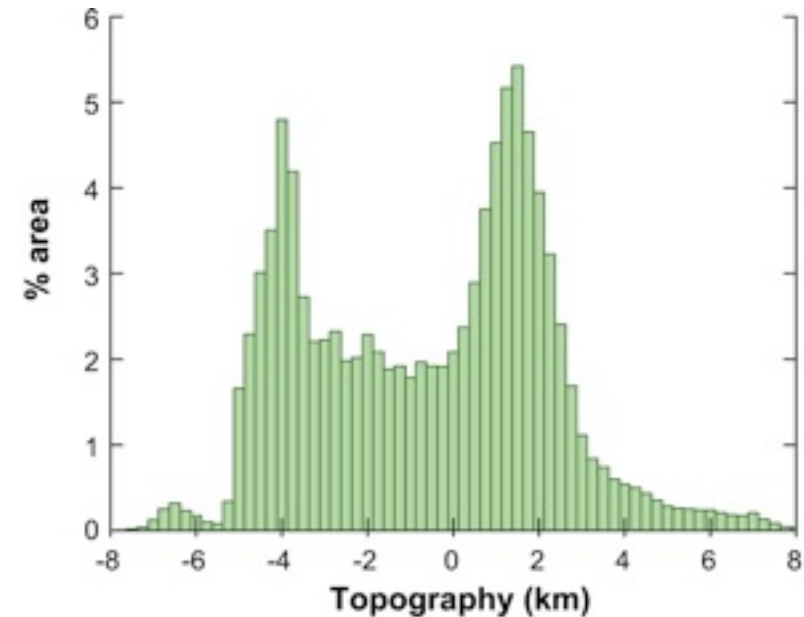


Two dominant features:

- hemispheric dichotomy
- Tharsis Rise

# Hemispheric dichotomy

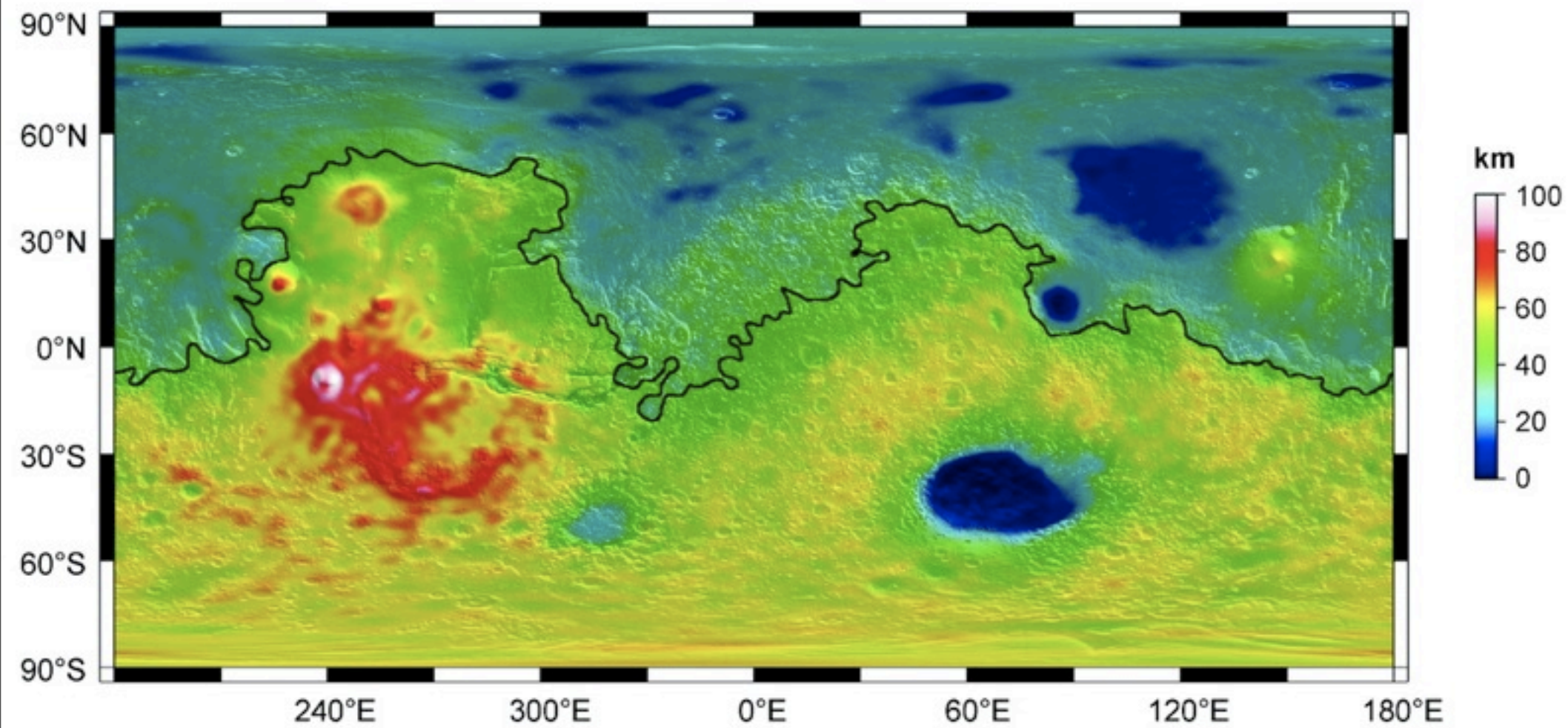
- COF–COM offset ~6km
- southern highlands, northern lowlands
- bimodal distribution of topography (5.5 km)
- first identified in early 1970's (Mariner 9)
  
- + gravity measurements, gravity–topography analysis
  
- the N-S difference in topography is a manifestation of a bimodal distribution of crustal thickness (26 km)
  
- of course, some assumption in the G-T analysis...



Watters et al. 2007 *Annu. Rev.*



# Model of crustal thickness



after Neumann et al. 2004 *JGR*

# Hemispheric dichotomy

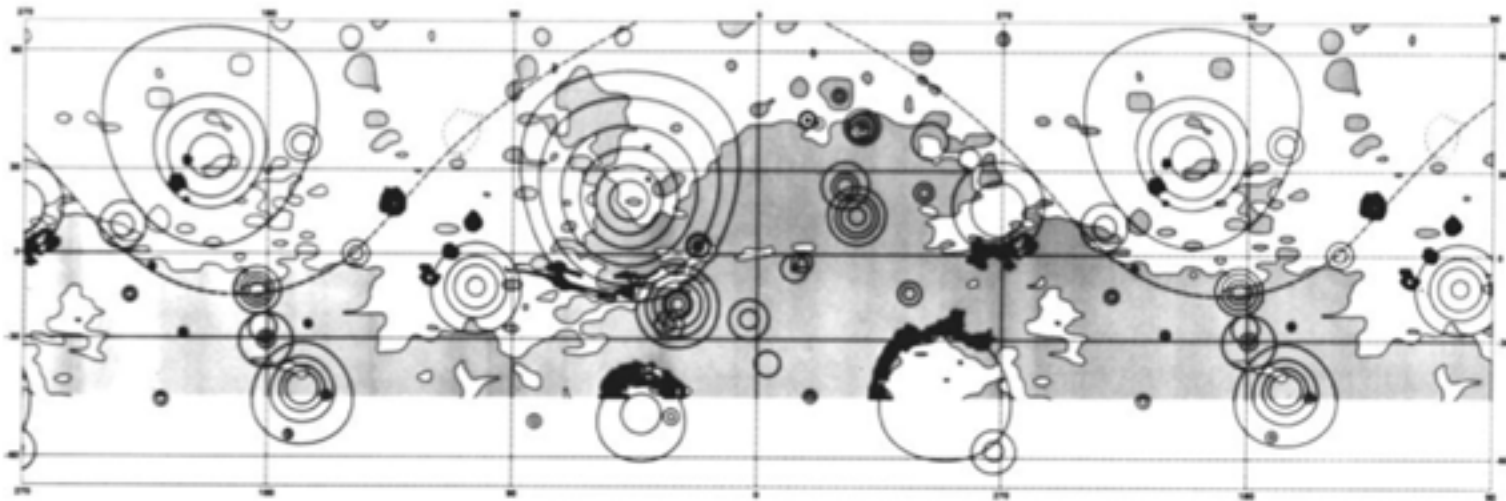
- ancient feature, probably in place by 4 Ga
- big debate about its origin
- endogenic origin?
  - by some external process (impact)
- exogenic?
  - generated by internal process (convection; on-time post-accretion process)

# Exogenic origin ??

- a single giant impact?
- ~~several mega impacts?~~



Wilhelms & Squyres 1973



Frey & Schultz 1988



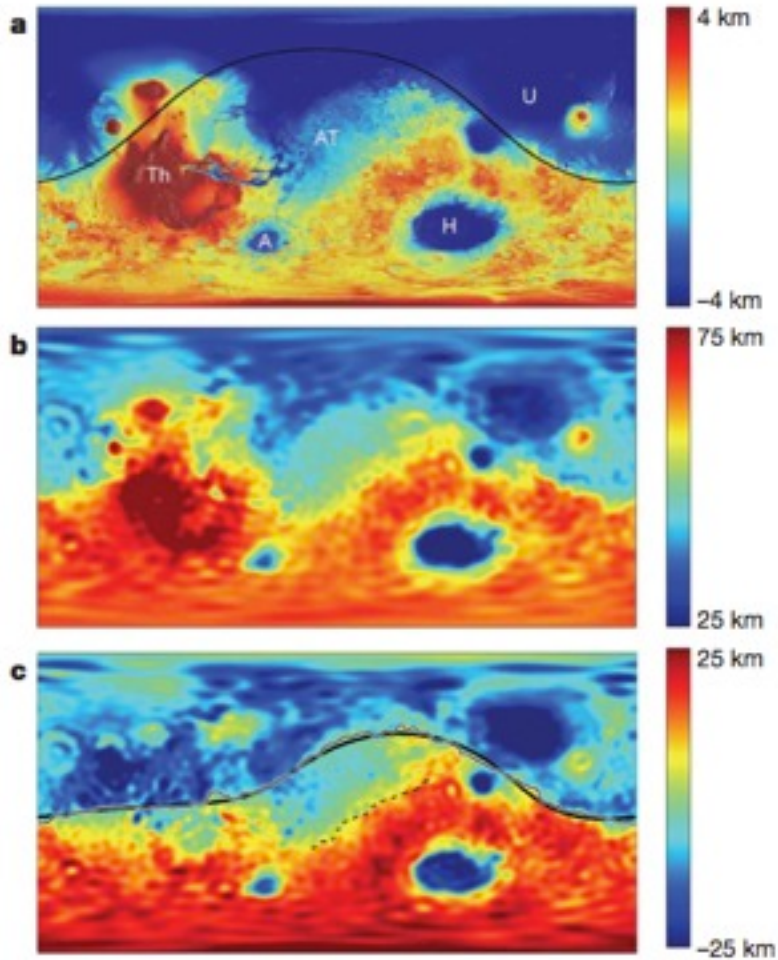
# Exogenic origin v.2008



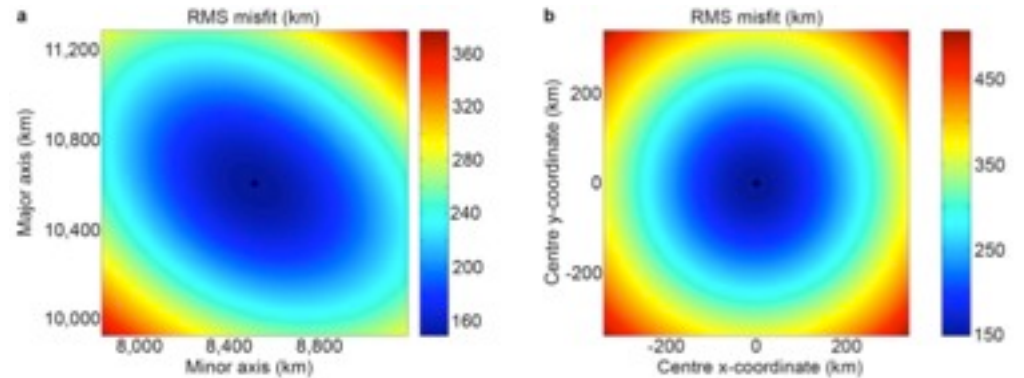
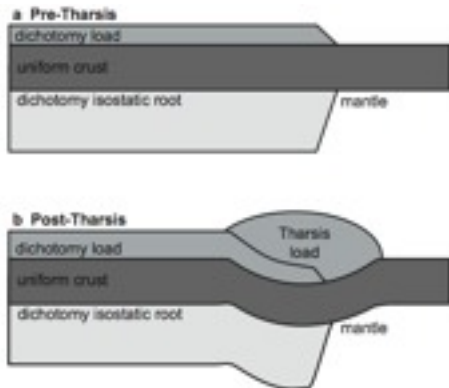
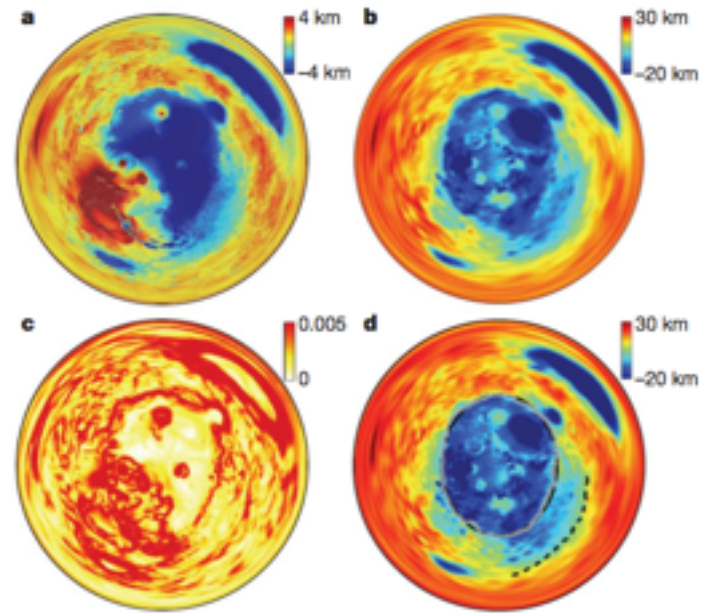
series of 3 papers in Nature

- crater geometry
- 3-D SPH impact modeling
- magnetic field argument

# Exogenic origin v.2008 1/3

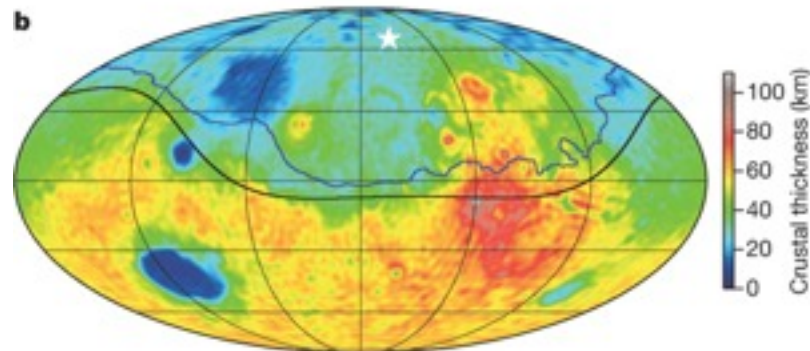
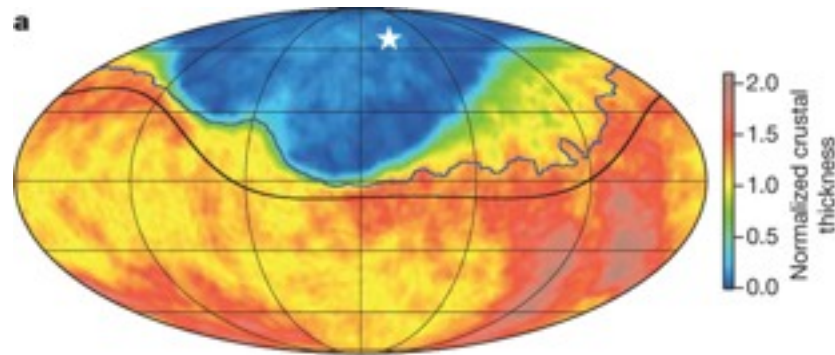
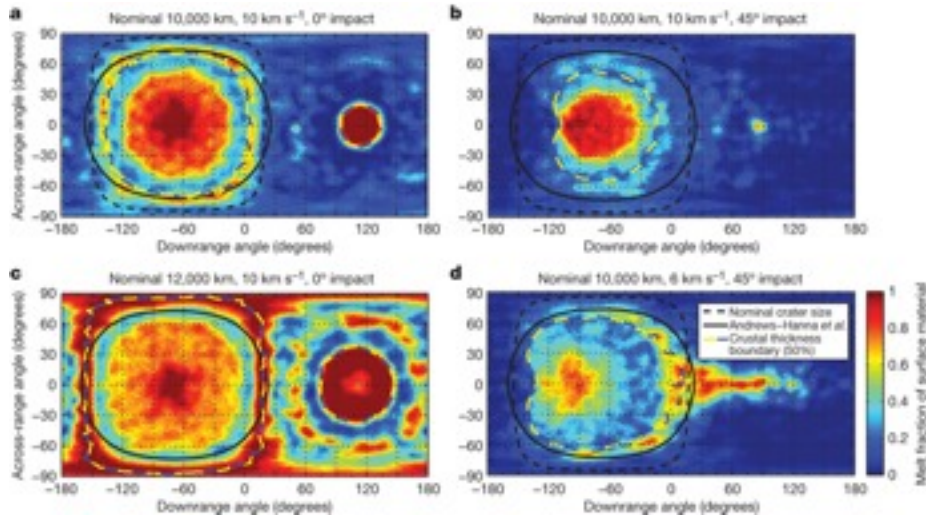


## crater geometry

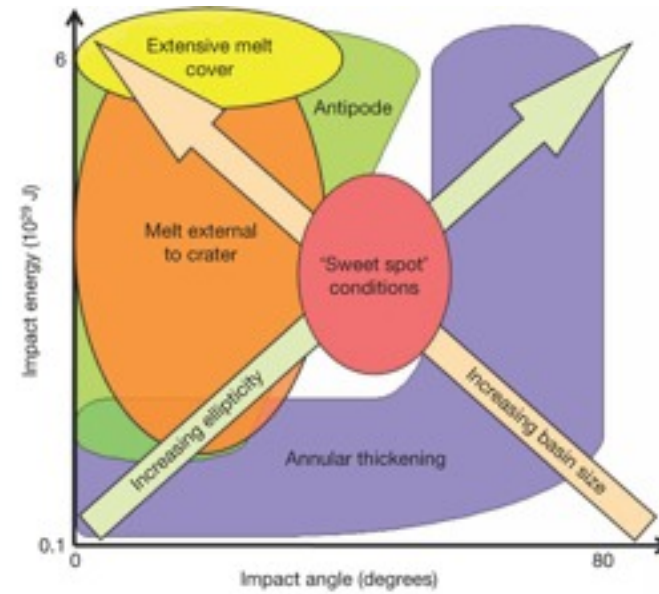


Andrews-Hanna et al. 2008

# Exogenic origin v.2008 2/3



## 3-D SPH impact modeling



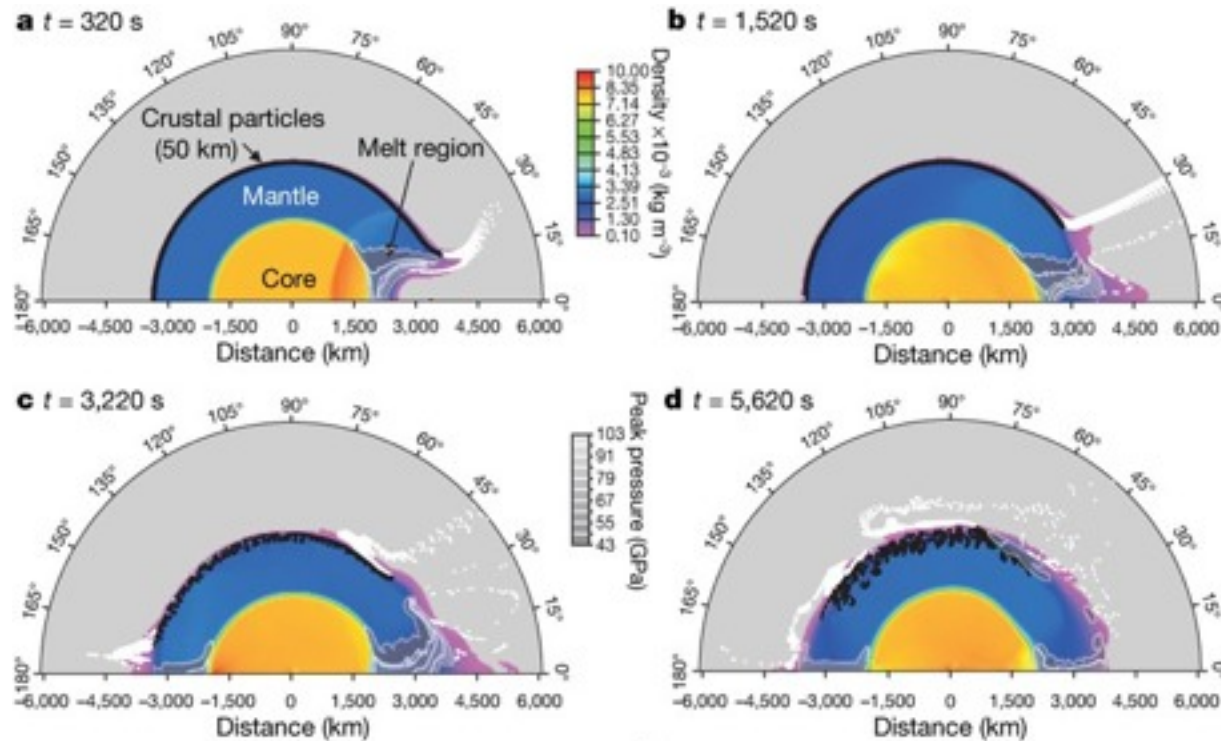
- impact energy  $3 \times 10^{29}$  J
- impact angle  $45^\circ$
- impact velocity 6 km/s
- impactor radius 1100 km
- crater radius 10000 km

Marinova et al. 2008



# Exogenic origin v.2008 3/3

antipodal shock demagnetization



axisymmetric hydrocode modeling

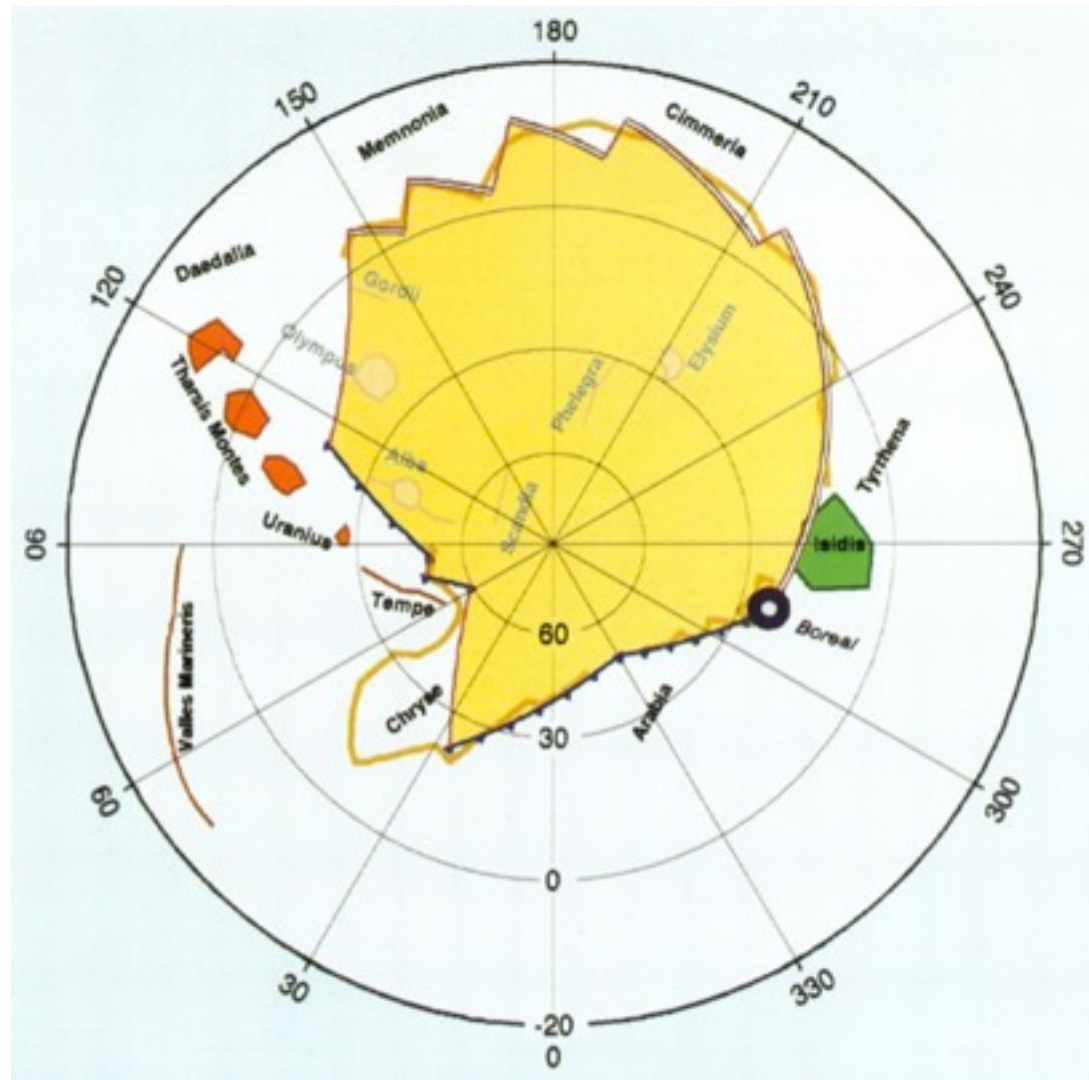
Nimmo et al. 2008

# Objections to giant impact model

- “removal” of Tharsis load may be spurious
- 3-D SPH impact models have low resolution
- crustal thickness in the southern highlands exhibits large (>100%) variation
- misfit between impact energies (Nimmo vs Marinova)
- misfit between impact location (Nimmo vs Andrews-Hanna)

# Endogenic origin??

early episode of plate tectonics on Mars

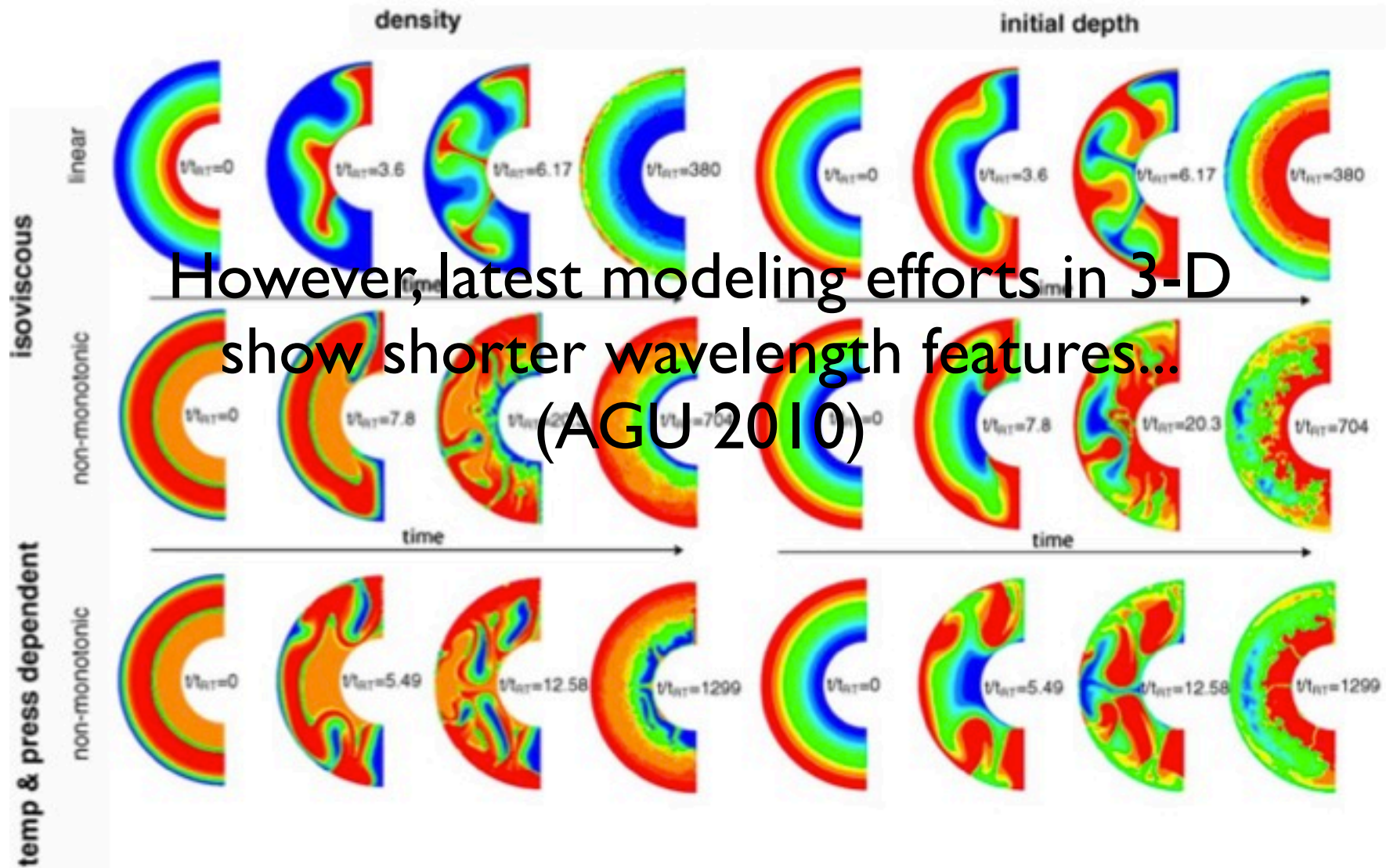


Sleep 1994



# Endogenic origin??

large-scale overturn of magma ocean cumulates



However, latest modeling efforts in 3-D show shorter wavelength features... (AGU 2010)

Elkins-Tanton et al. 2005 (2x)

# Endogenic origin??

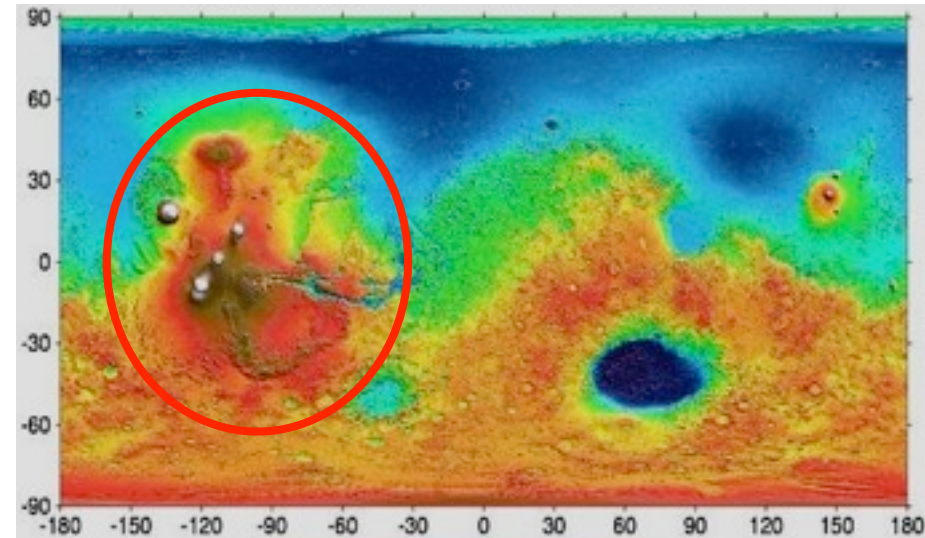
degree-I convection in Martian mantle



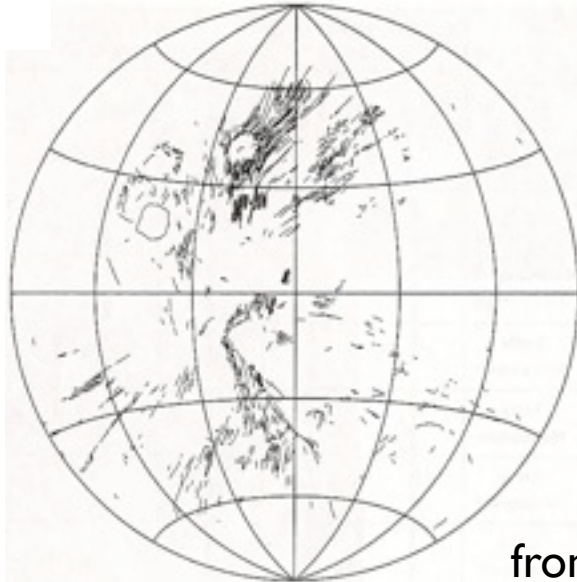
Zhong and collaborators

# Tharsis volcanic province

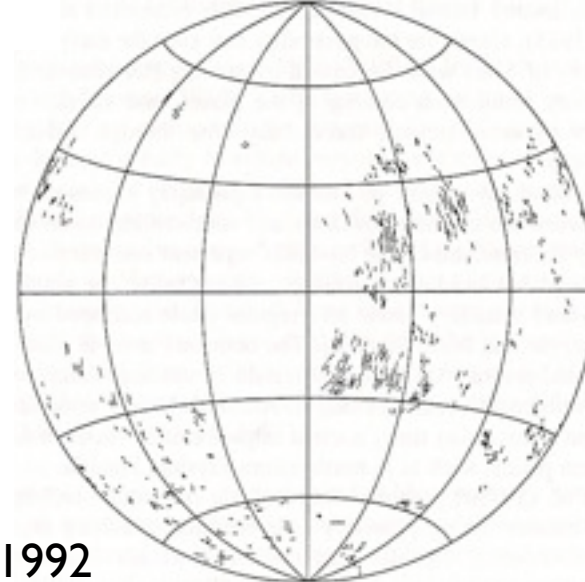
- topographic highs of several km, occupies ~25% of Martian surface
- location of successive and most volcanism in the last 4 Gyr [e.g., Tanaka et al. 1992]
- postdates dichotomy formation by one to few 100 Myr
- pattern of faults and ridges dominated by Tharsis [e.g., Banerdt et al. 1992]



extensional fault lines  
radial to Tharsis



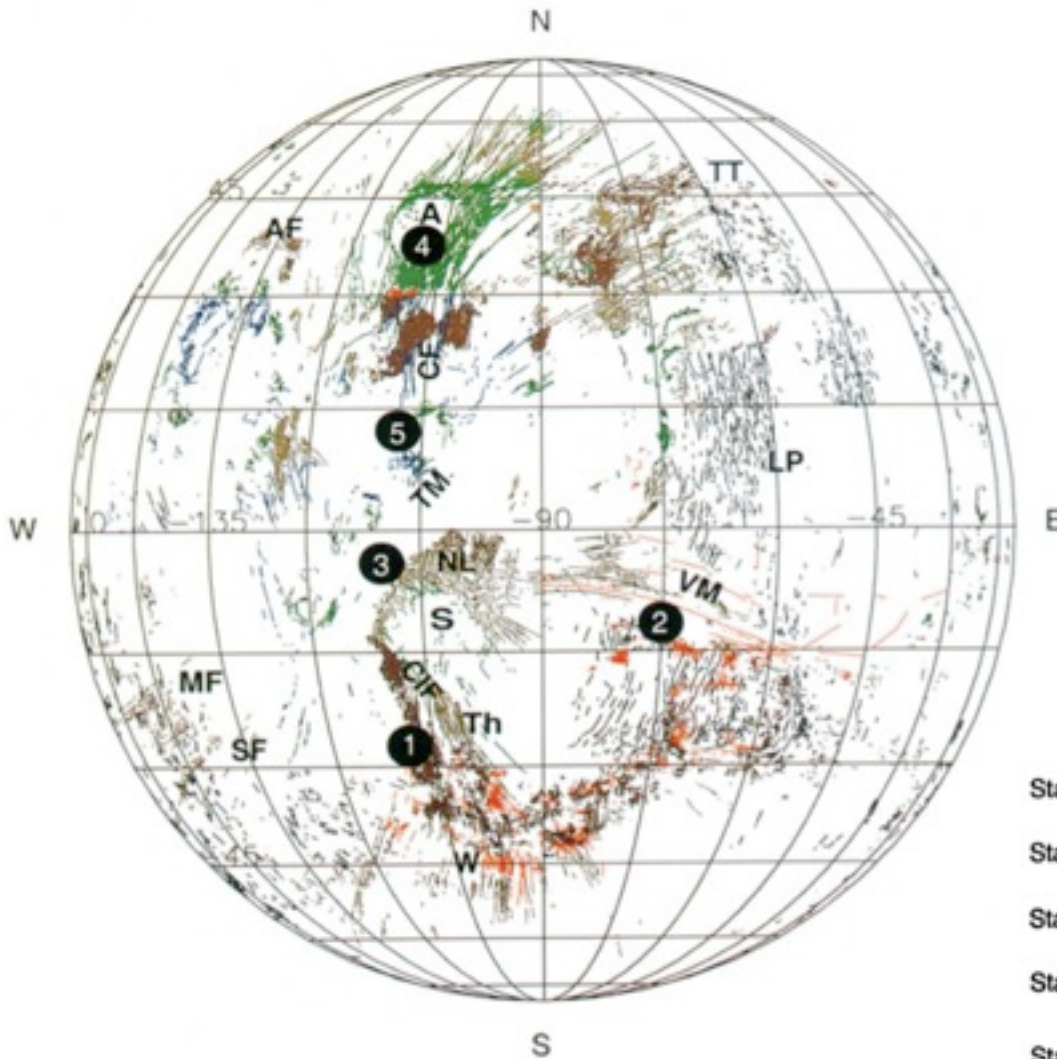
compressional features  
concentric around Tharsis



from Banerdt et al. 1992

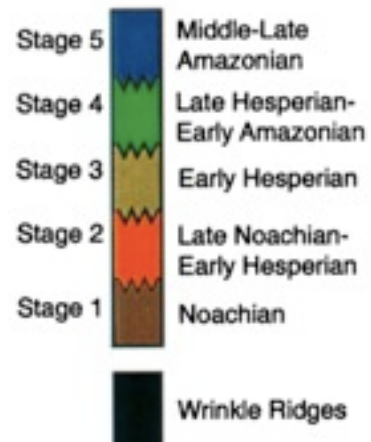


# Migration of tectonic center in Tharsis



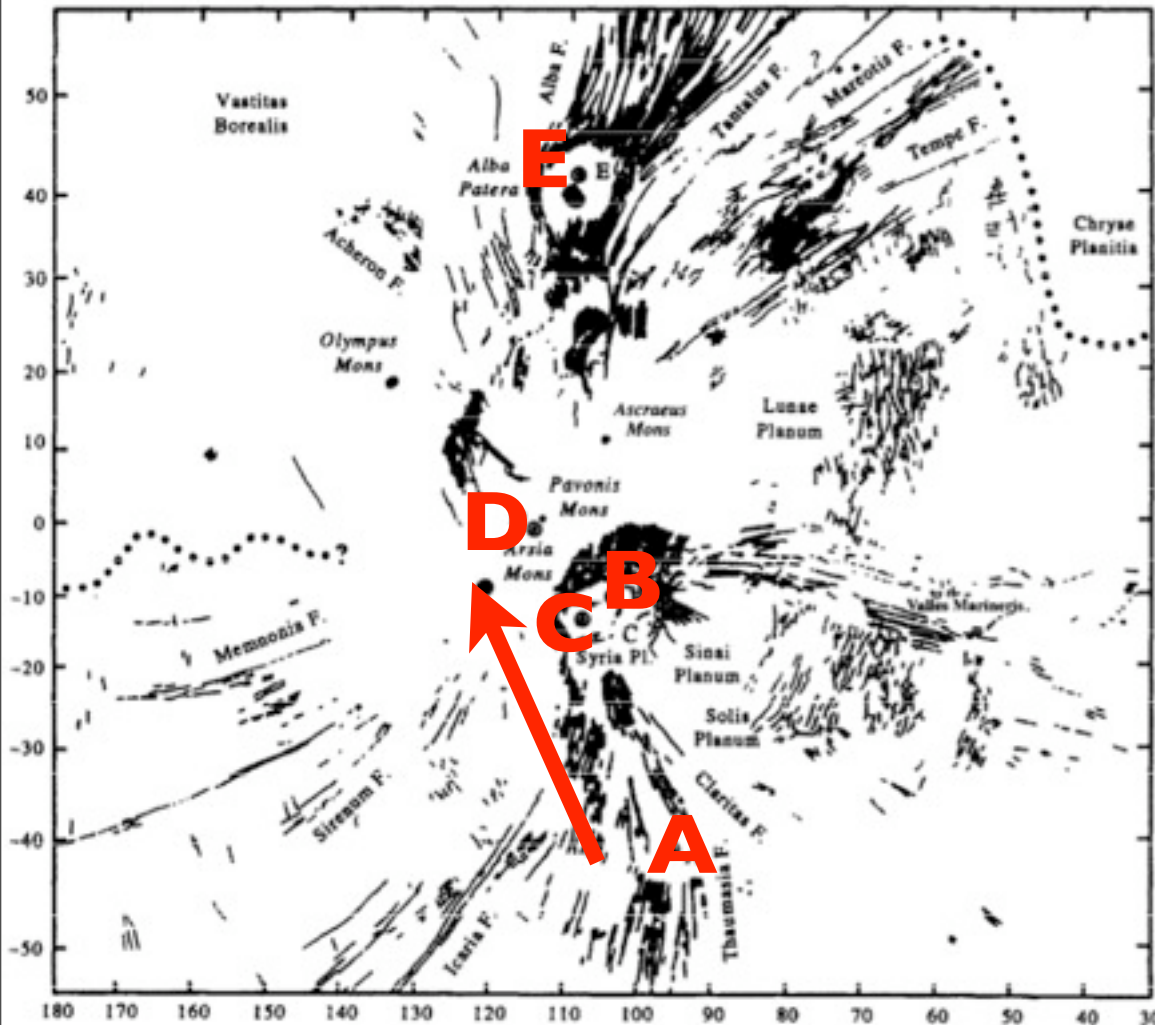
- 5 stages of tectonic activity [Anderson et al. 2001]
- 1. earliest center at Claritas Ridge (30°S)
- 2. center south of central margin of Valles Marineris, includes large Valles Marineris troughs
- 3. center near equator in Syria Planum

## Legend



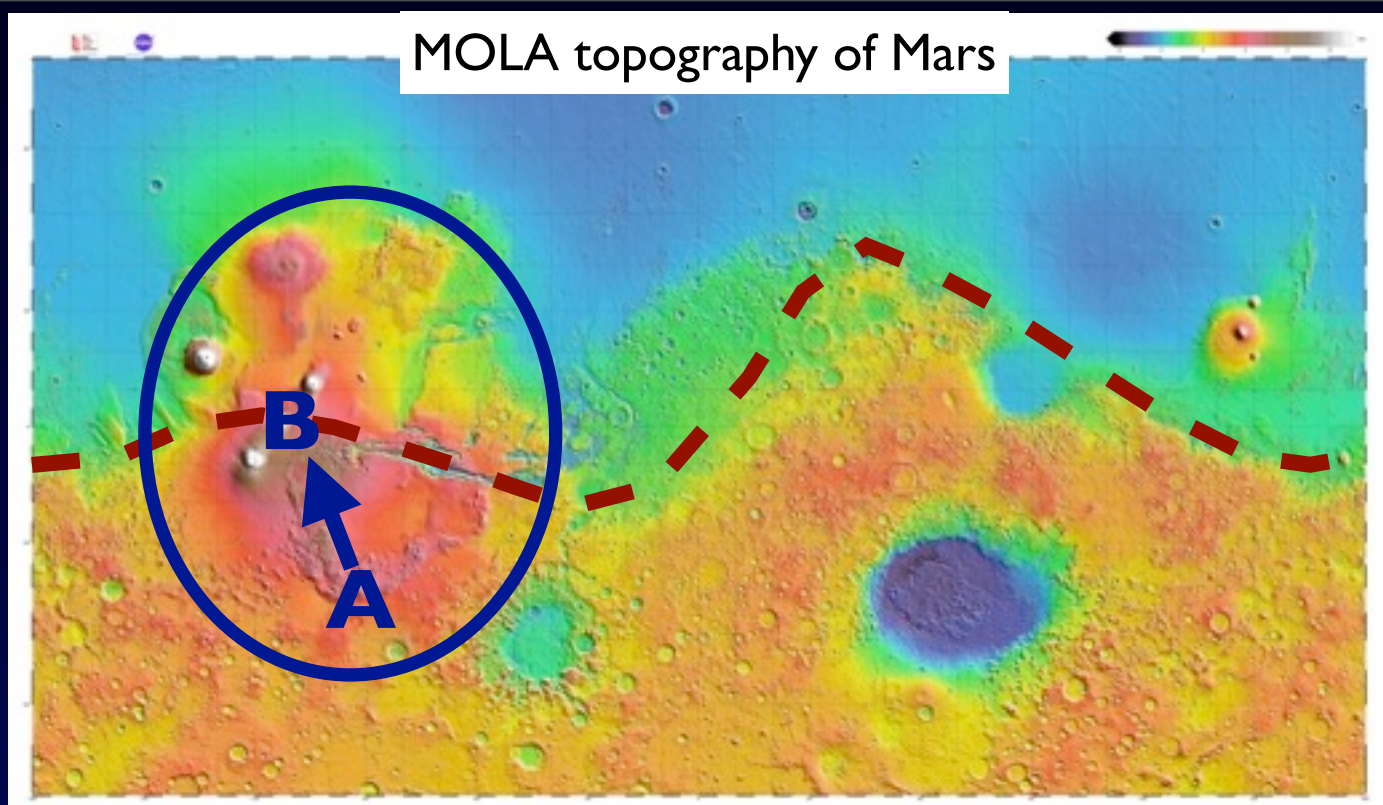
from Anderson et al. 2001

# Migration of tectonic/volcanic center in Tharsis



from Mège & Masson, 1996

- sequence of volcanic centers and adjacent tectonic deformation [Mège & Masson 1996]:  
A – Thaumasia (40°S)  
B,C – Syria Planum  
D – Tharsis  
E – Alba Patera
- volcanism started at Thaumasia and migrated to the boundary [Frey, 1979; Mège & Masson 1996; Johnson & Phillips 2005)



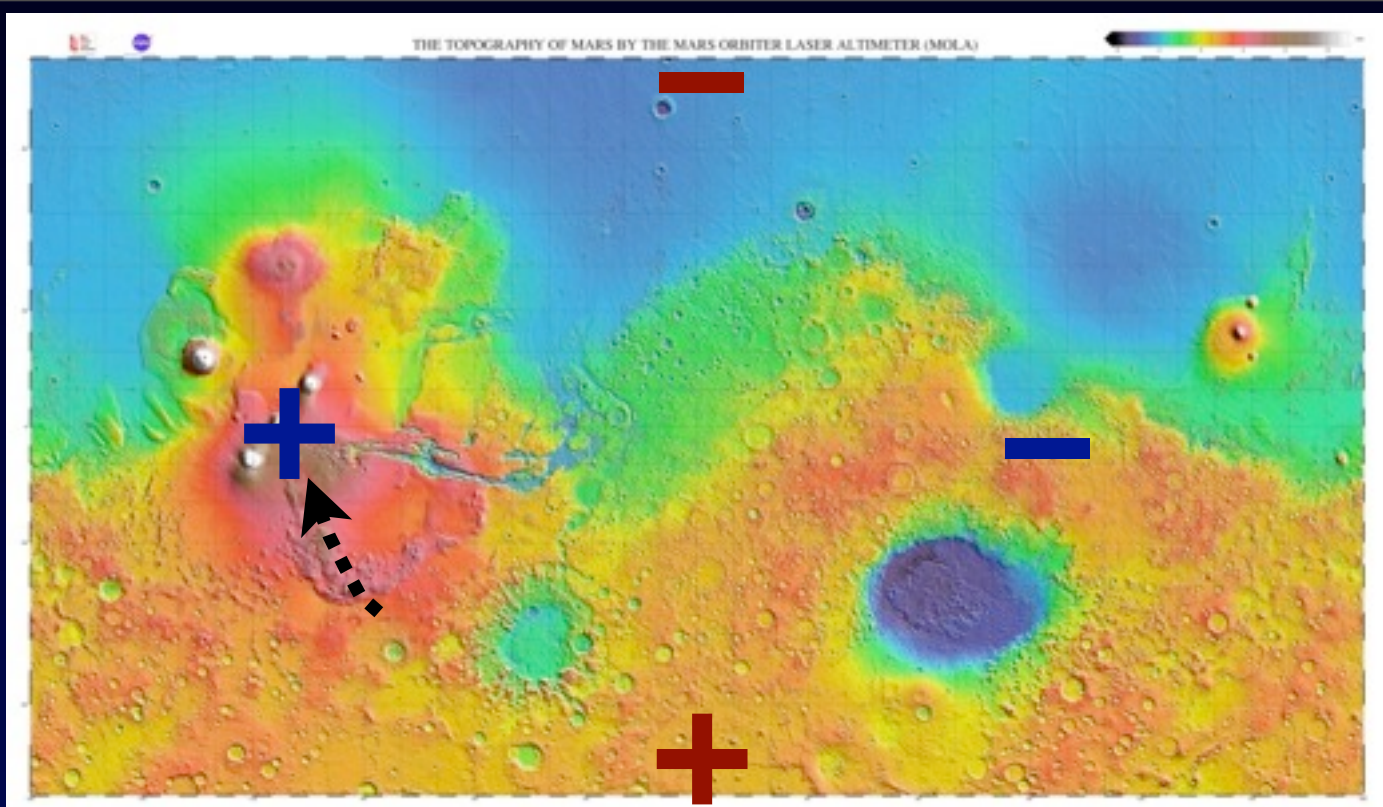
## Hemispheric dichotomy

- formed  $\geq 4.1$  Gyr [e.g. Watters et al. 2007]
- arguments for both exogenic (giant impact) and endogenic origin (large-scale mantle convection; overturn of magma ocean cumulates)

## Tharsis

- postdates dichotomy formation by one to few 100 Myr
- location of successive and most volcanism in the last 4 Gyr [Tanaka et al. 1992]
- Tharsis volcanism started in the south (**A**) and
- volcanic center migrated to its current location (**B**) over few 100 Myr [Frey, 1979; Mège & Masson 1996; Johnson & Phillips 2005]



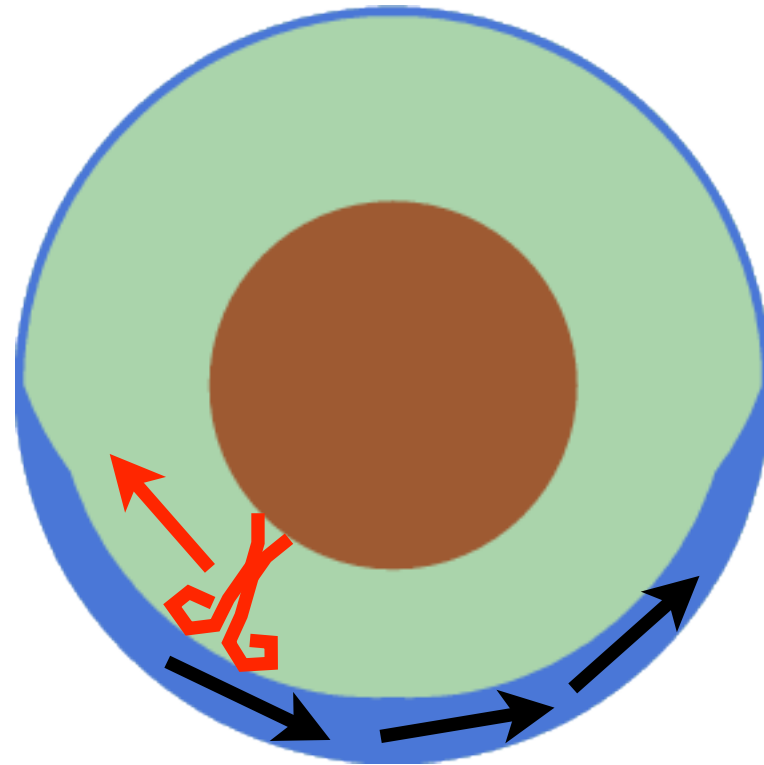


- Both the dichotomy and Tharsis are predominantly spherical harmonic degree 1 features, with their orientation offset by  $\sim 90^\circ$
- Can we explain their mutual orientation (also early Tharsis migration) as a result of long-wavelength interior processes?



# Model of “rotation of the lithosphere”

[Zhong 2009]

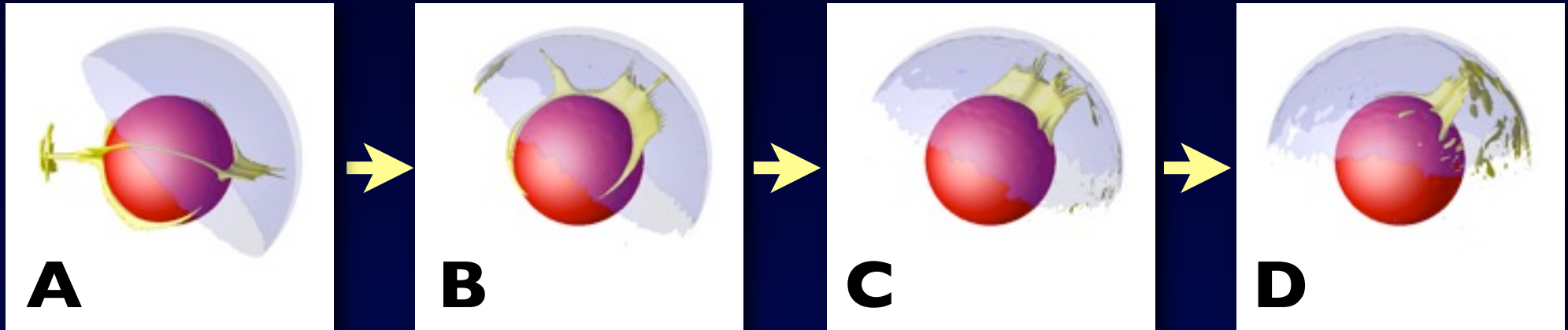


- one-plate planet (stagnant lid)
- longest-wavelength flow in the mantle
- poloidal–toroidal coupling ... buoyancy driven convection excites rotation of lithosphere

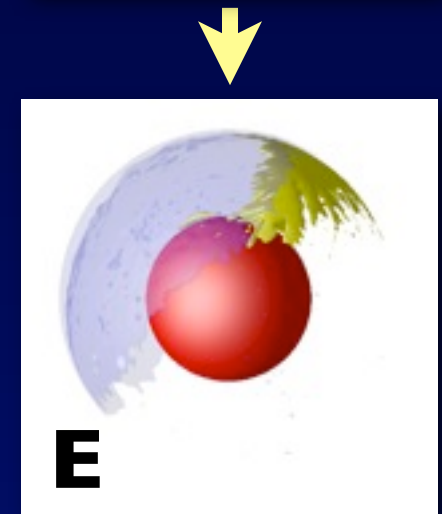
# “Rotation of the lithosphere” model

## Dichotomy and Tharsis are dynamically related

Zhong (2009)



- A. assumes a thicker lithosphere below the southern hemisphere – stiff melt residue after dichotomy-forming process involving partial melting
- B. involves degree-I flow
- C. initial orientation of the upwelling below the keel
- D. rotation of the I-plate lithosphere relative to plume
- E. stabilization near the keel edge

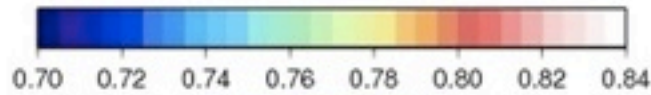
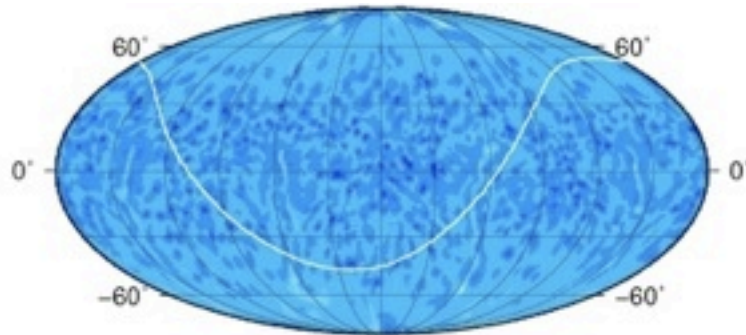


May explain the apparent migration of Tharsis and stabilization at the current location near dichotomy boundary.

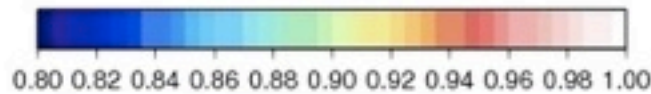
# Time evolution: convection + var. thickness lithosphere

yellow: temperature isosurface  
blue: lithospheric cap  
red: core-mantle boundary

temperature at  
400 km depth

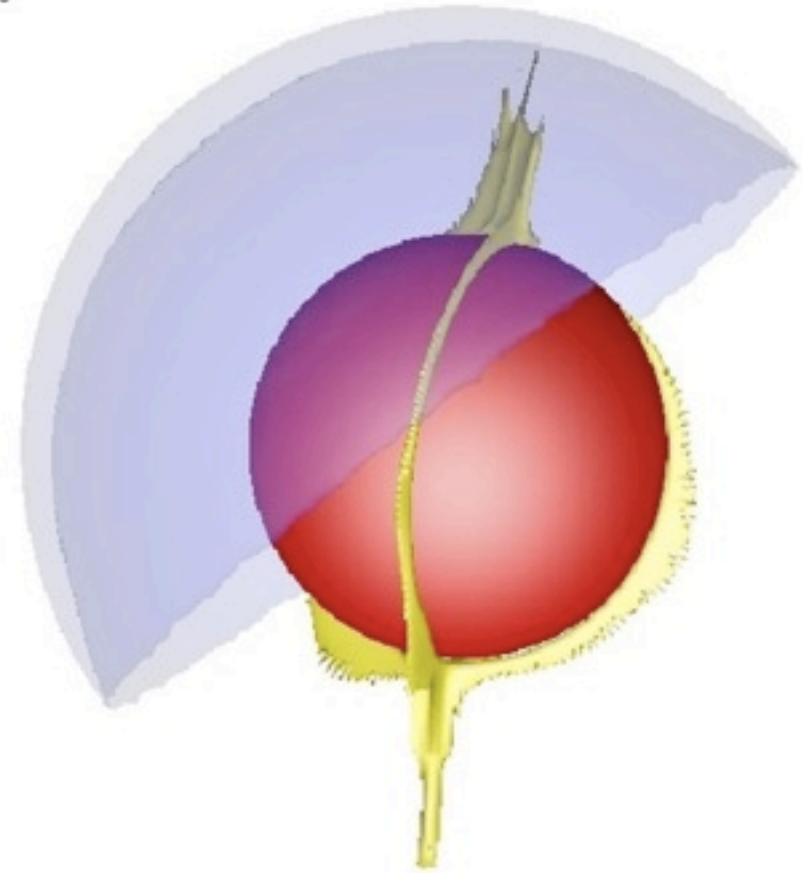


temperature  
200 km above  
CMB



temperature

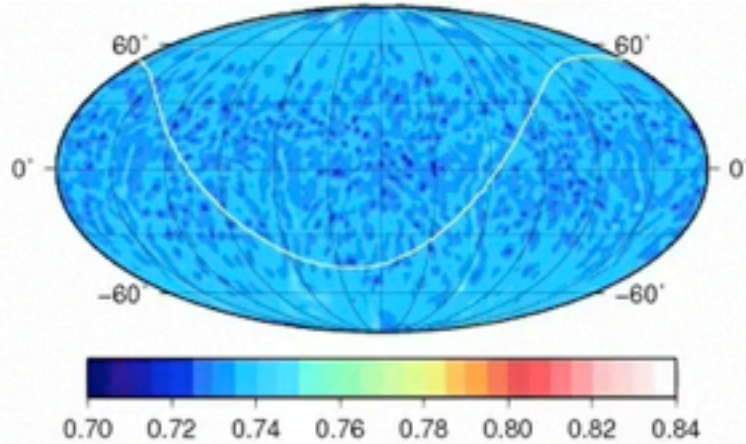
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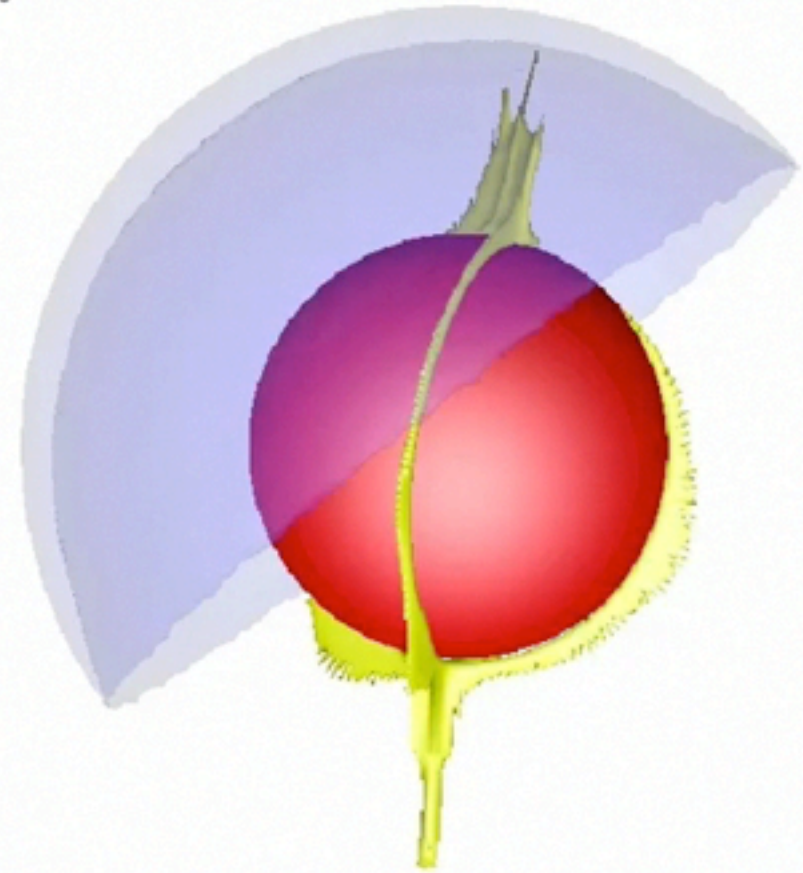
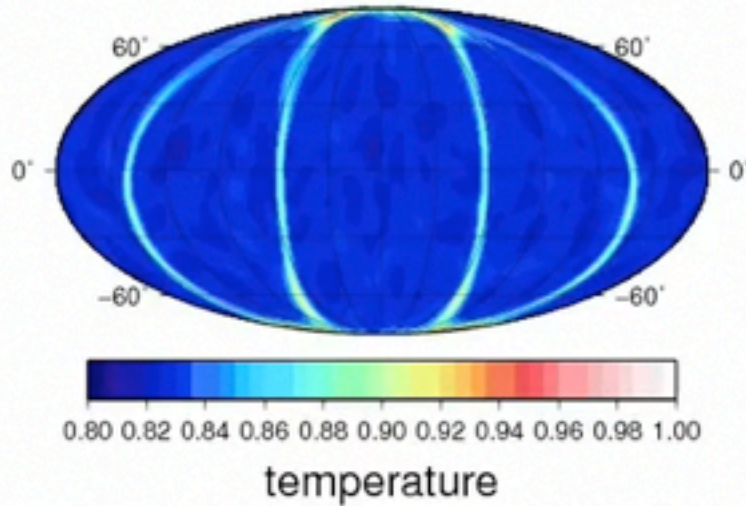
# Time evolution: convection + var. thickness lithosphere

yellow: temperature isosurface  
blue: lithospheric cap  
red: core-mantle boundary

temperature at  
400 km depth



temperature  
200 km above  
CMB



- 1. single plume forms, centered below the thick lithosphere
- 2. differential movement between plume and lithosphere
- 3. plume stabilizes at the cap boundary

Pattern of stress from interaction of mantle flow and lateral variation in viscosity?



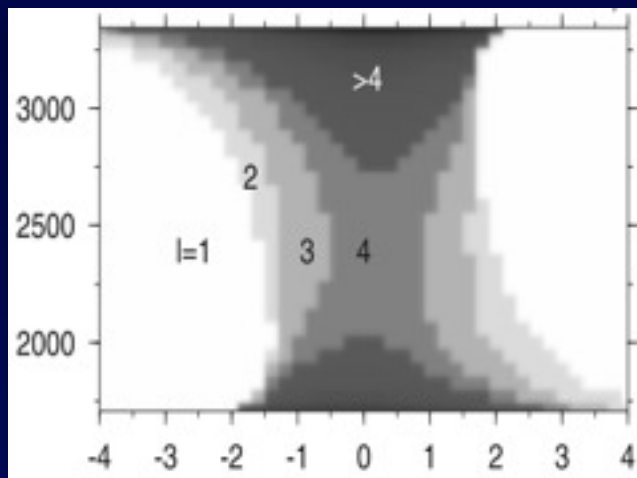
# Questions to ask

- degree-I flow in Martian mantle?
- relative rotation between the lithosphere and the mantle?
- how can the lithospheric thickness variation be produced?
- does it resemble at all to what we observe?
- is there any evidence for such scenario?

# Degree-1 convective planform naturally arises in models that include a moderate viscosity increase in mid-mantle

Rayleigh-Taylor instability analysis

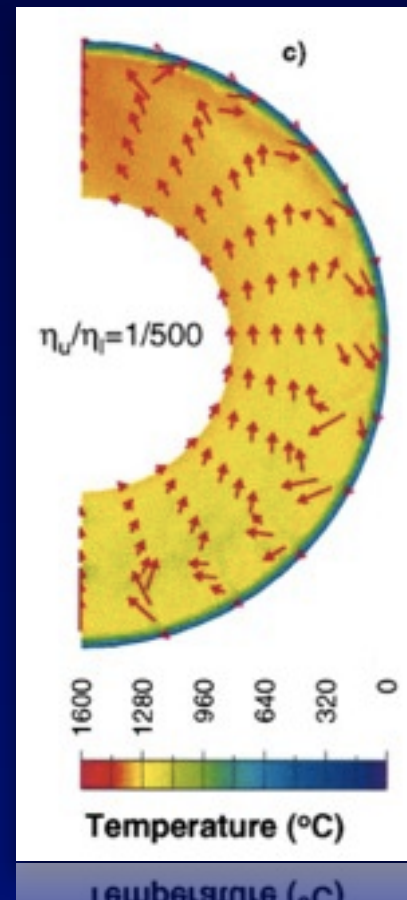
depth of viscosity layering vs. viscosity contrast



Zhong & Zuber 2001

modeling in 2-D axisymmetric geometry

temperature and flow field



3-D spherical shell modeling

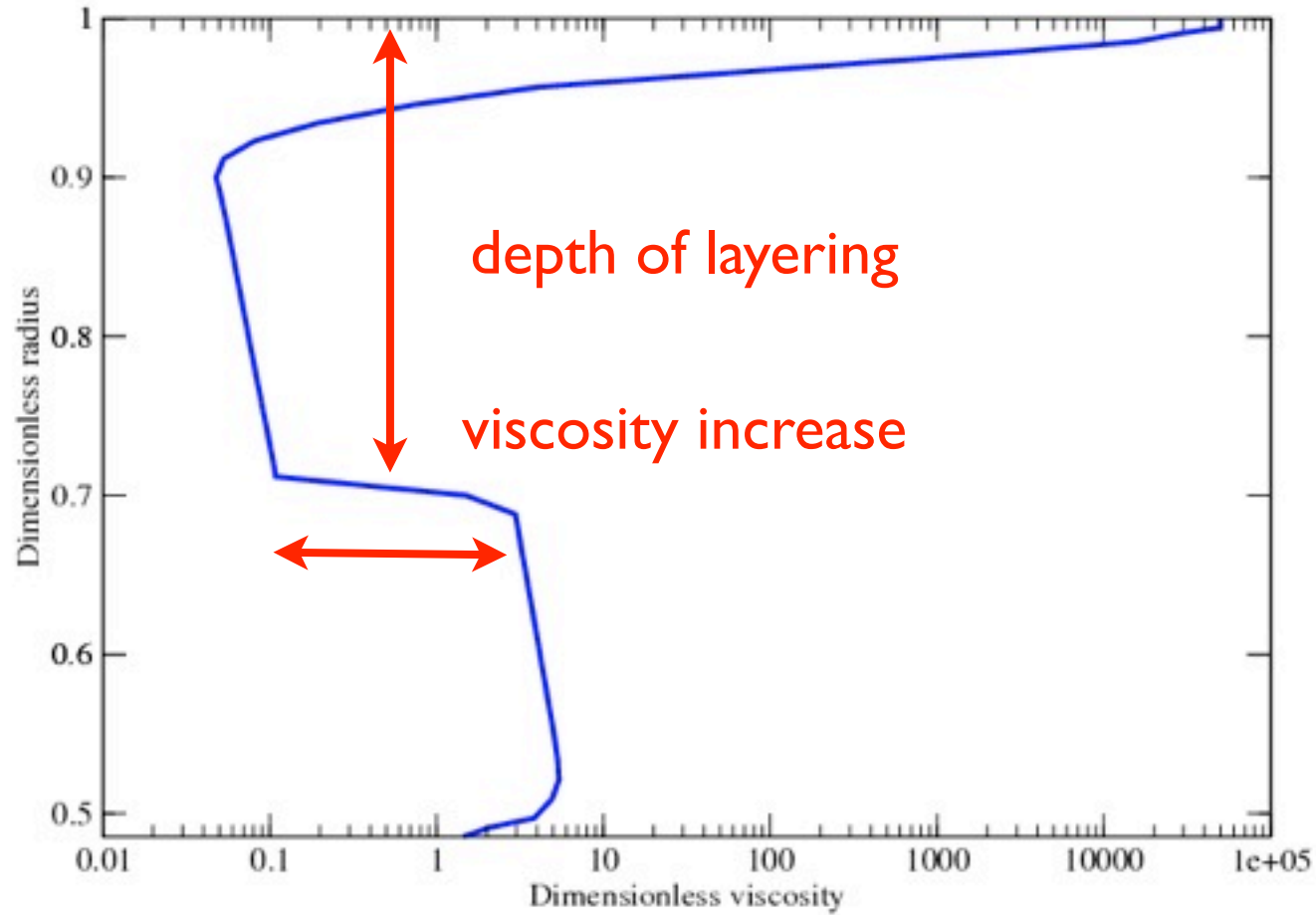
isosurface of positive temperature anomaly



Roberts & Zhong 2006

# average viscosity profile

Preferred convection wavelength given...



# Model

- convection in 3-D spherical shell
- extended Boussinesq
- both bottom and internal heating
- depth- and temperature-dependent viscosity

$$\nabla \cdot \mathbf{v} = 0, \quad (1)$$

$$-\nabla P + \nabla \cdot [\eta(\nabla \mathbf{v} + \nabla^T \mathbf{v})] + Ra\alpha(r)T\mathbf{e}_r = 0, \quad (2)$$

$$\frac{\partial T}{\partial t} + \mathbf{v} \cdot \nabla T = \nabla \cdot [\kappa(r)\nabla T] + H_{int} + H_A + H_V, \quad (3)$$

$$\eta = \eta' \exp \left[ \frac{E + V(1 - r)}{T + T_s} - \frac{E + V(1 - r_{cmb})}{1 + T_s} \right], \quad (5)$$



Parameter	Value	Unit
Planetary radius	3400	km
Core radius	1650	km
Grav. acceleration	3.73	$\text{m s}^{-2}$
Mantle density	3400	$\text{kg m}^{-3}$
Thermal diffusivity at CMB	$2 \times 10^{-6}$	$\text{m}^2 \text{s}^{-1}$
Thermal diffusivity at surface	$1 \times 10^{-6}$	$\text{m}^2 \text{s}^{-1}$
Thermal expansivity at CMB	$2 \times 10^{-5}$	$\text{K}^{-1}$
Thermal expansivity at surface	$4 \times 10^{-5}$	$\text{K}^{-1}$
Specific heat at constant pressure	1200	$\text{J K}^{-1} \text{kg}^{-1}$
Surface temperature	220	K
CMB temperature	2200	K
Activation energy	157	$\text{kJ mol}^{-1}$
Volumetric heat source	$7.4 \times 10^{-8}$	$\text{W m}^{-3}$

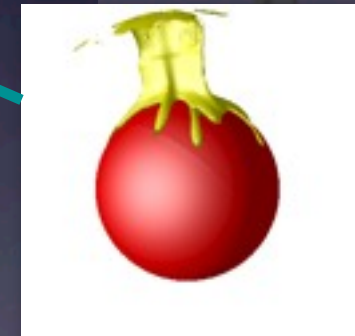
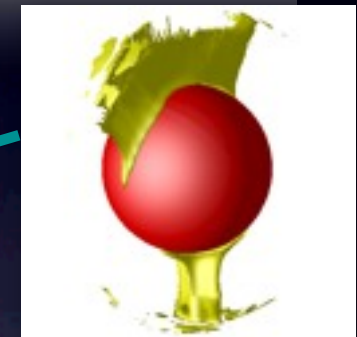
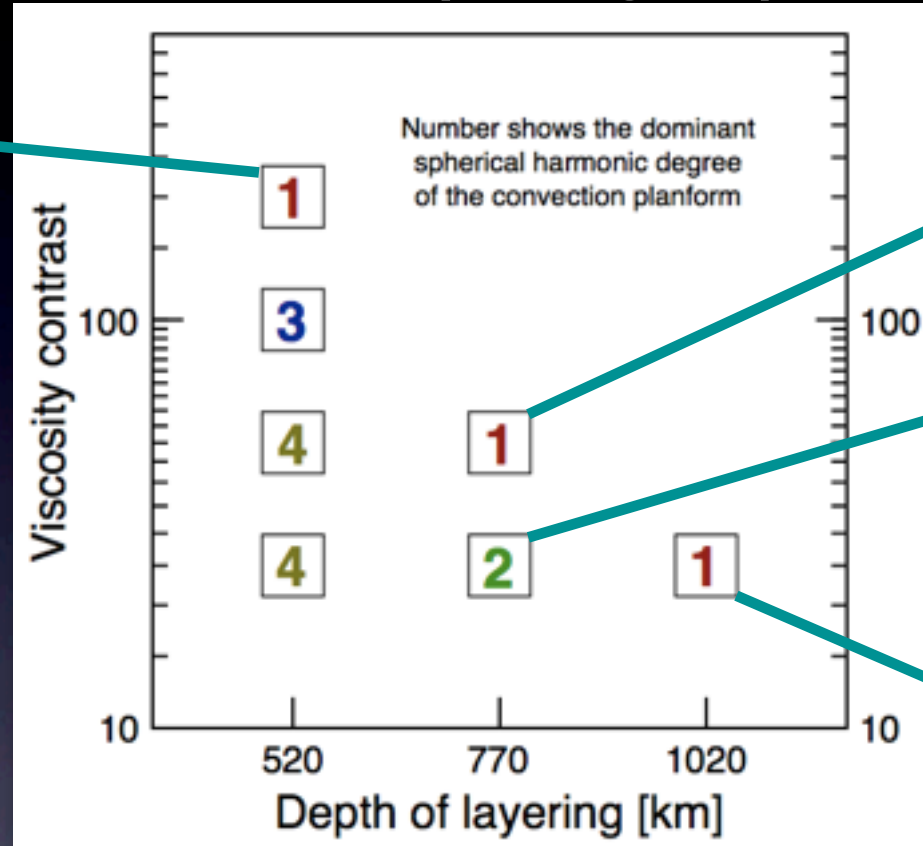
- CitcomS
- $48^3 \times 12 = 1.3\text{M}$  element

# CONDITIONS FOR DEGREE-1

## Effect of layering depth

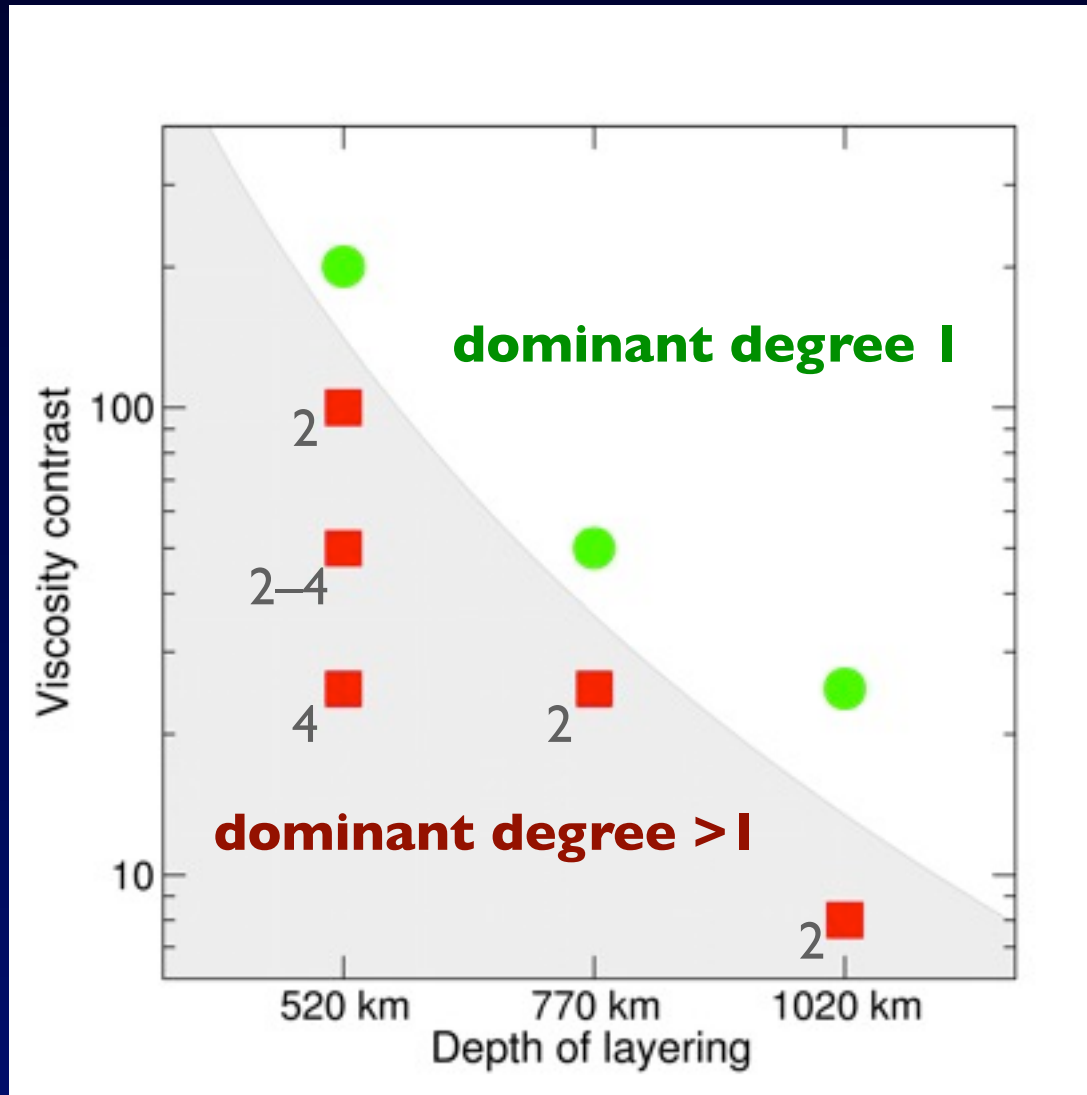


extends previous results  
by Roberts & Zhong  
2006



# Conditions for degree-1 convection

## Depth of viscosity layering vs. depth of layering



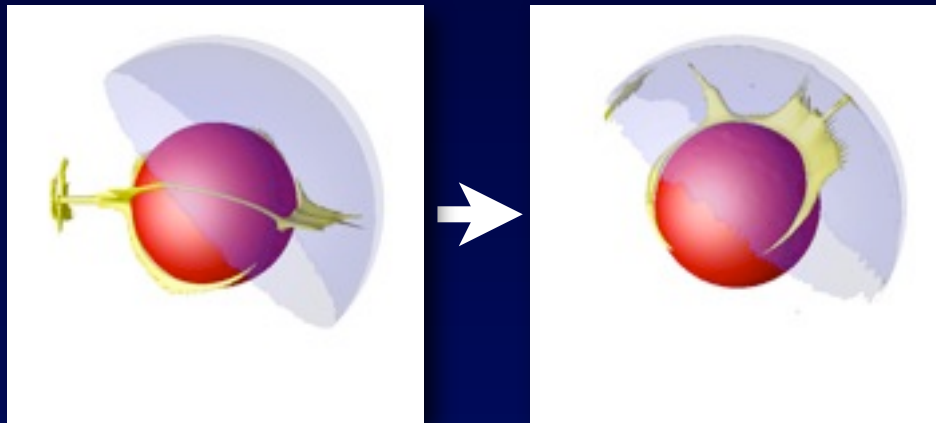
- viscosity increase from weaker upper mantle to stronger LM
- extends previous work by Roberts & Zhong (2006)
- thinner asthenosphere requires larger viscosity contrast for degree-1
- qualitative agreement with existing analyses (with simpler setup)
- the longest-wavelength flow is expected for a wide range of plausible parameters

Šrámek & Zhong 2010

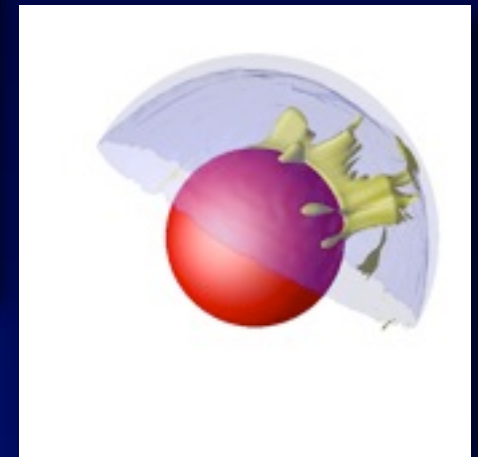
# Include thicker lithosphere in one hemisphere Initial orientation of upwelling relative to keel:

lithospheric keel increases the thickness of the stiff boundary layer that does not take part in convection

can increase convective wavelength



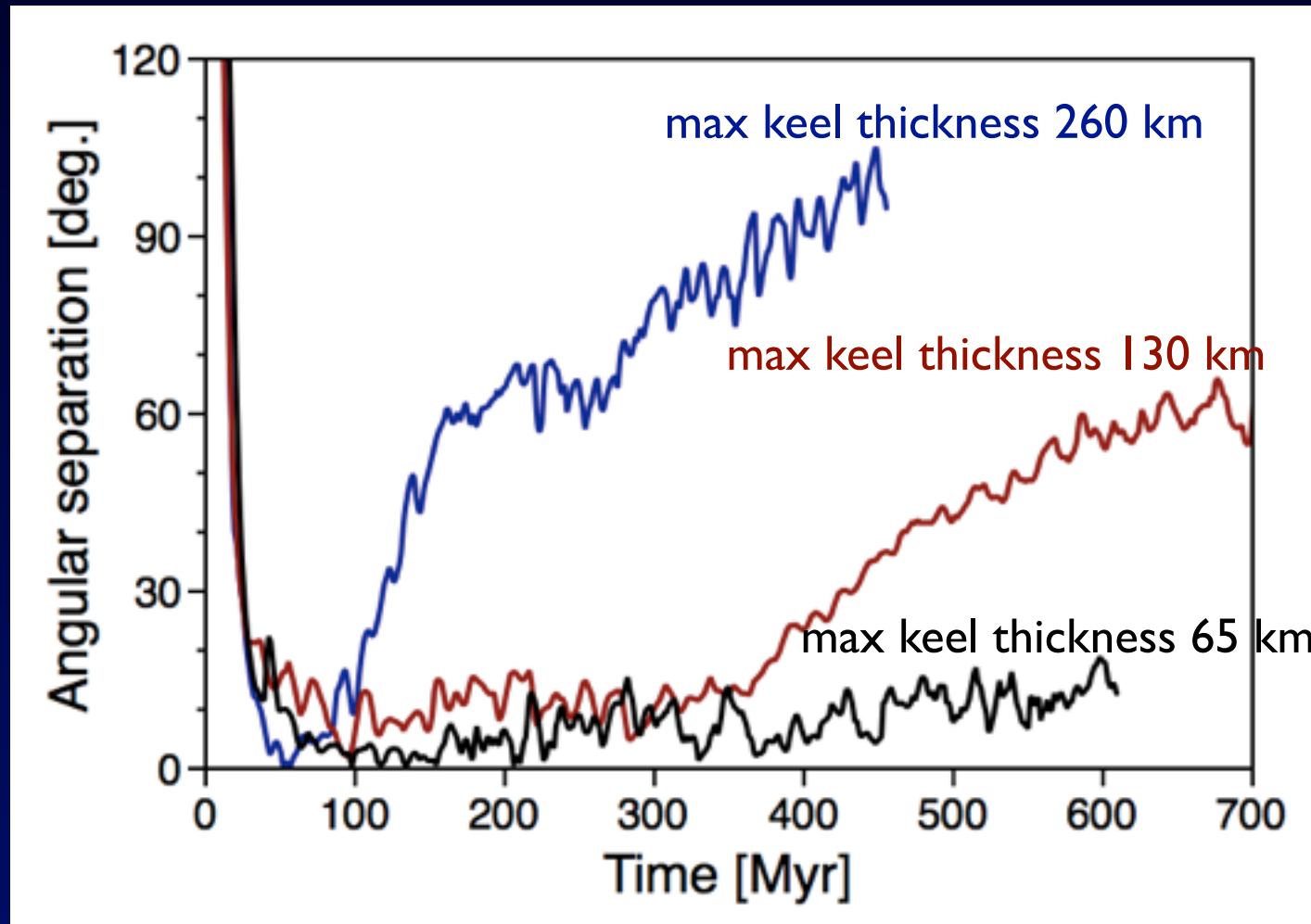
keel 260 km thick



difference in lithospheric thickness as low as ~30 km is sufficient to orient the upwelling below the keel



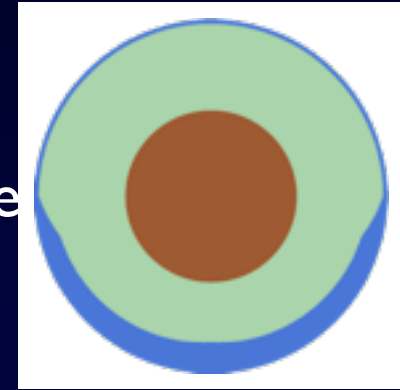
# Effect of keel thickness on separation rate



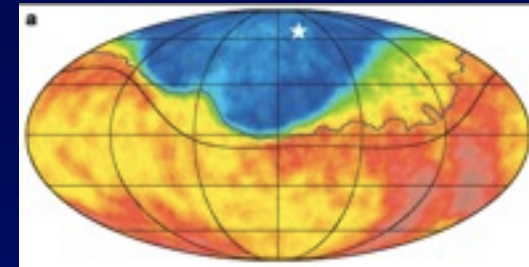
- rate of separation depends on keel thickness and viscosity in weak layer
- rate  $\sim$ independent of keel shape, weak layer thickness
- keel at least  $\sim$ 100 km thick necessary to get separation
- at least 150–200 km thick to explain Tharsis migration within few 100 Myr

# Exogenic/Endogenic dichotomy origin...

- Thick lithospheric keel in one hemisphere (the southern) is required for the rotation of the lithosphere.
- It is assumed to represent stiff (devolatilized) melt residue left after significant melting of the upper mantle, localized in one hemisphere; consistent with thicker crust.
- This is most easily explained if one adopts an endogenic model for the dichotomy formation; degree-1 convection; or overturn of solidified magma ocean cumulates [Elkins-Tanton 2005].
- If dichotomy was formed by a giant impact, a hemispheric redistribution of crustal material is expected (thicker crust in the south), but melting of the deeper mantle would occur below the impact site.
- Thicker crust with high concentration of heat-producing elements would effectively insulate the southern hemisphere relative to northern hemisphere, but significant lateral viscosity variations would be absent.



crustal thickness

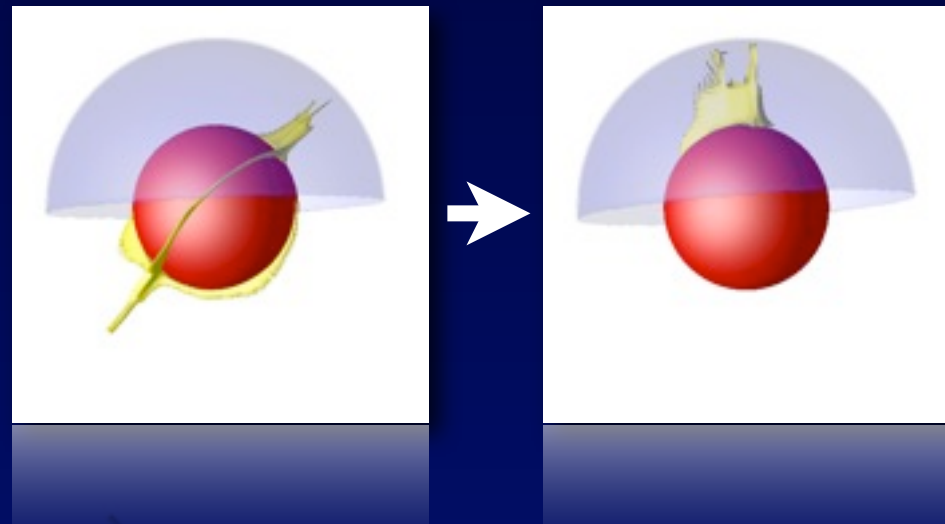


Marinova et al. 2008

# Lowered thermal conductivity in a near-surface layer in one hemisphere

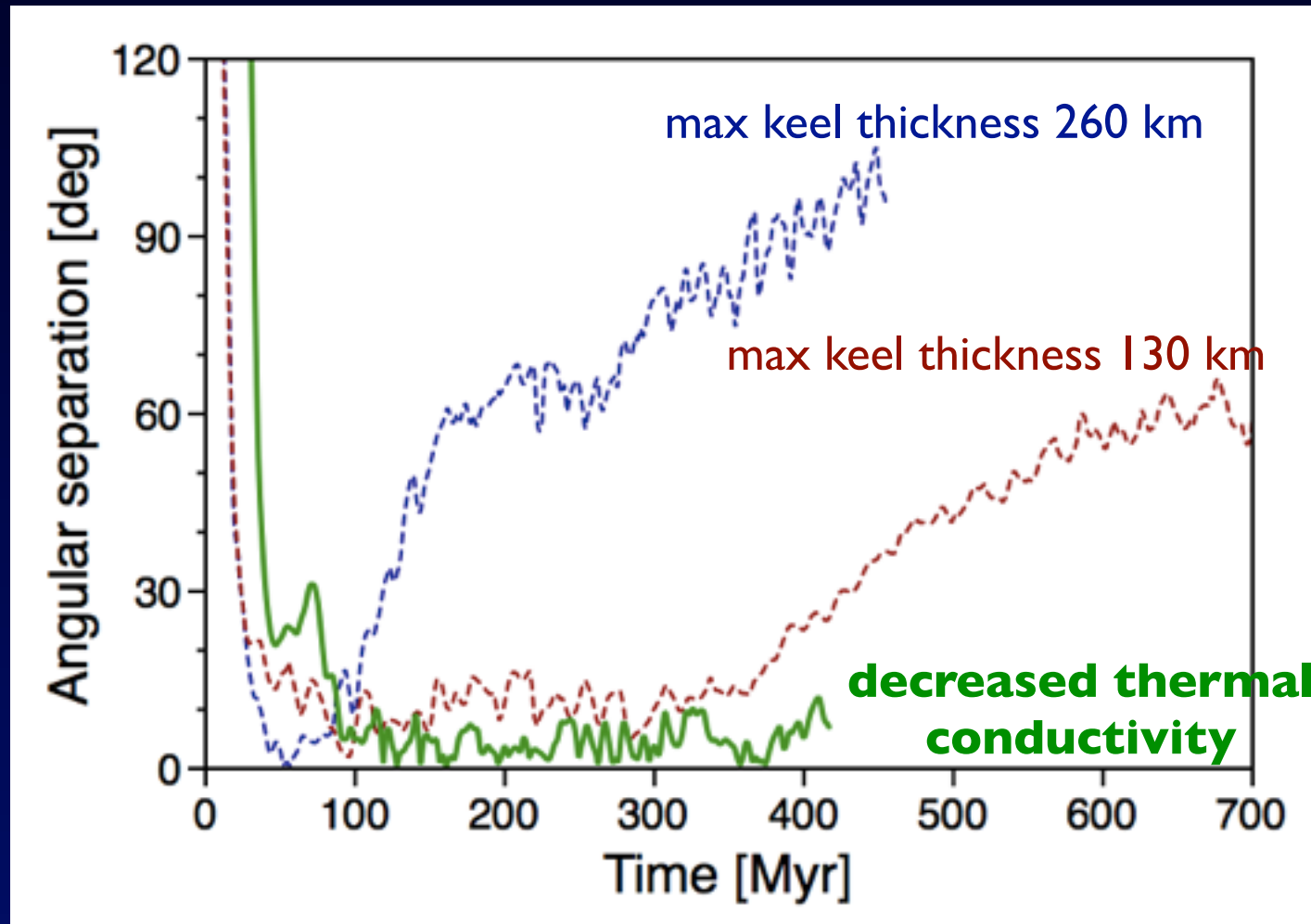
Approximates the post impact non-uniform  
crustal thickness distribution

the insulating cap controls the  
orientation of the upwelling



reduction of near-surface thermal  
conductivity by 30% sufficient to  
reorient the upwelling

# Lowered thermal conductivity in a near-surface layer in one hemisphere



- no strong lateral viscosity variations near base of lithosphere
- upwelling remains centered below the insulating cap
- only non-uniform crustal thickness does not explain Tharsis migration



So far, we have imposed the stiff lithospheric root.



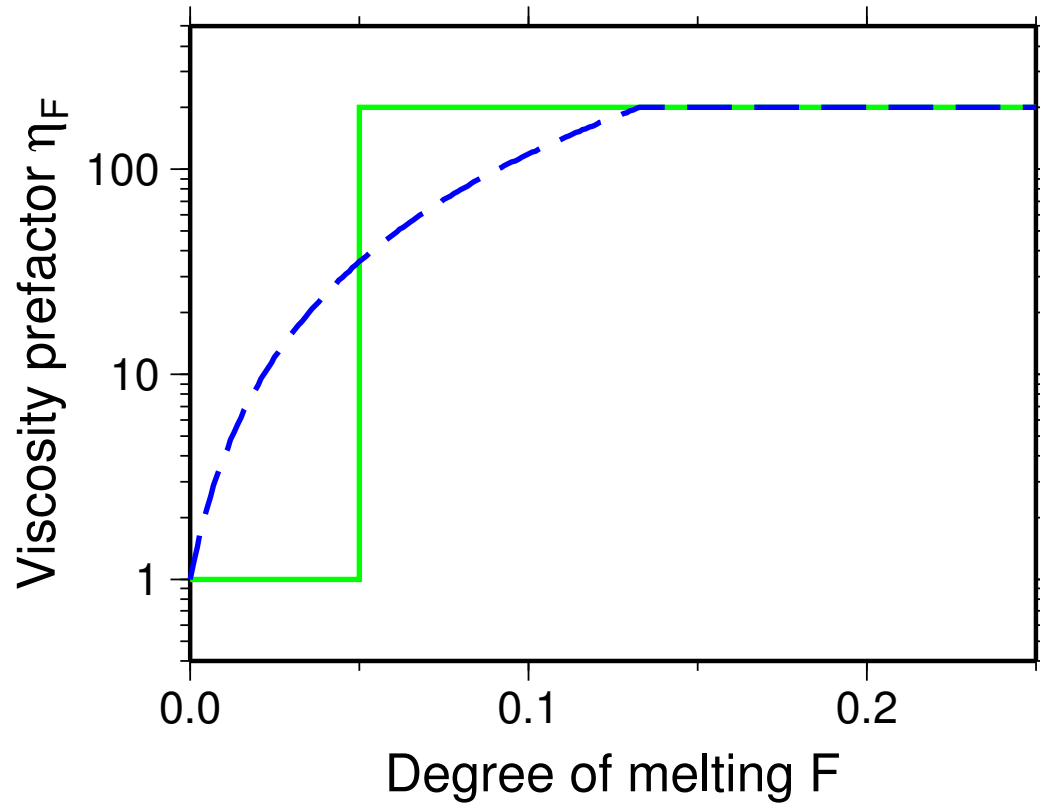
Is it possible to generate it self-consistently  
from partial melting?

# Implement partial melting in CitcomS

- use parametrization of Katz (2003):  $F=F(P,T)$
- in a given element, calculate equilibrium  $F$  from the local  $(P,T)$  condition at each tracer
- if this equilibrium  $F$  is larger than the actual  $F$  advected with the tracer, melt the appropriate amount (and update  $F$ )
- average the melt generation for over the element
- we assume that new melt is immediately extracted to the surface where it adds to local crustal thickness
- also need to advect the surface melt thickness field

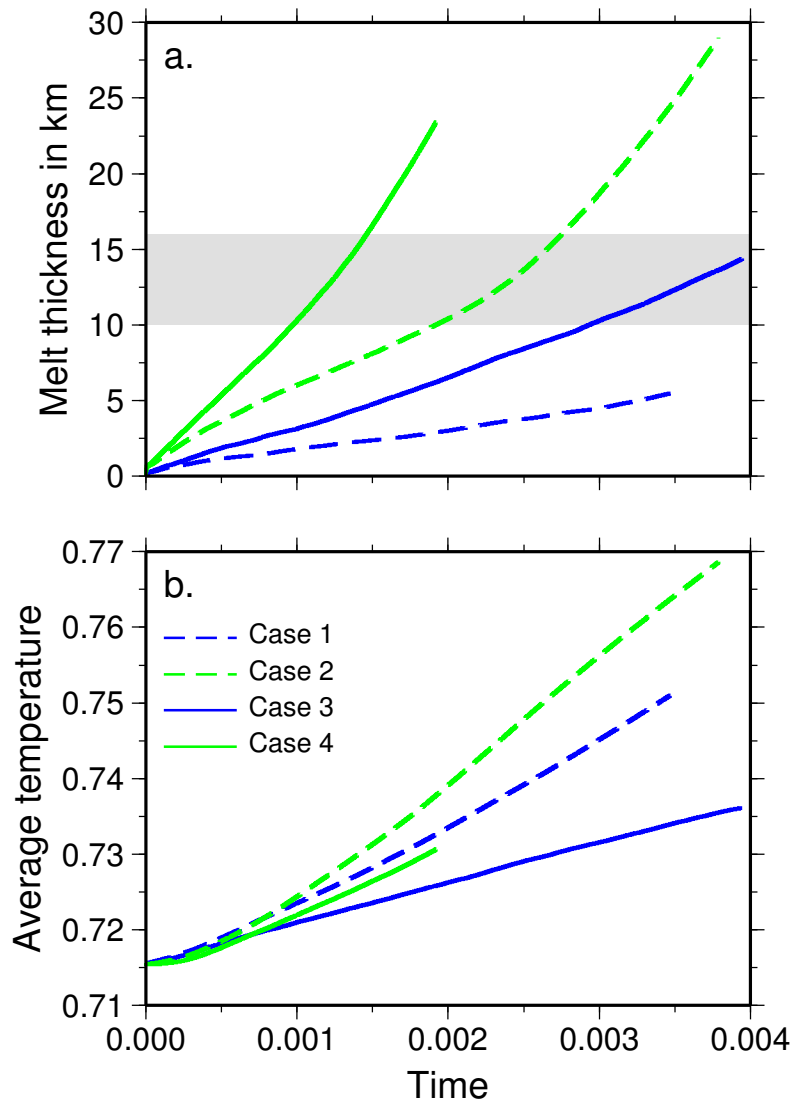
# Melt residue viscosity parametrization

devolatilized, therefore stiff



# 1st series of models

- we use both melt residue viscosity parametrizations
- internal heating rate corresponds to initial condition



- rate of melt production strongly depends on the mantle temperature
- the stiff melt residue adds a strong coupling between melting and flow
- addition to stiff melt residue leads to mantle overheating
- stronger effect with continuous  $\eta(F)$ , compared to step-function  $\eta(F)$
- it's ok, Mars should cool down with time anyway

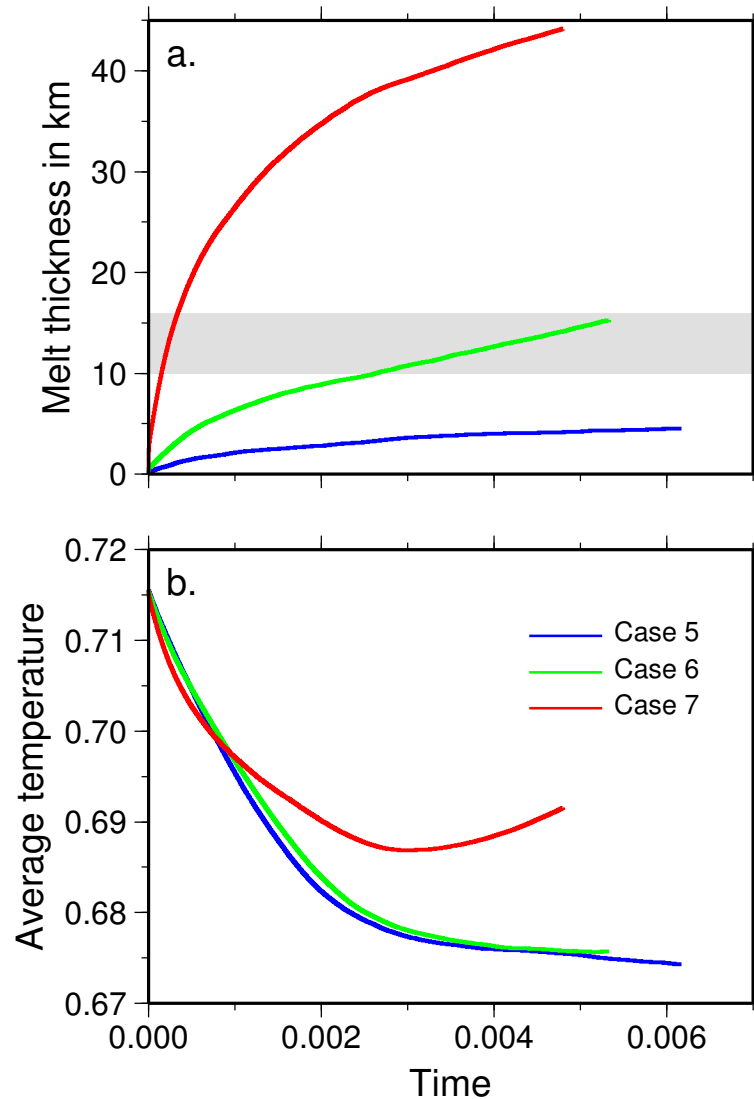
$T_{cmb} = 2000 \text{ K}$

$T_{cmb} = 2100 \text{ K}$



# 2nd series of models

- only use step-function melt residue viscosity
- internal heating rate is lowered



- lower heating rate more than compensates for overheating due to melt residue insulation
- for  $T_{cmb} = 2100$  K the amount of melt is comparable to what is necessary to generate the dichotomy

$T_{cmb} = 2000$  K

$T_{cmb} = 2100$  K

$T_{cmb} = 2200$  K

$T_{\text{cmb}} = 2000 \text{ K}$



$t = 127 \text{ My}$



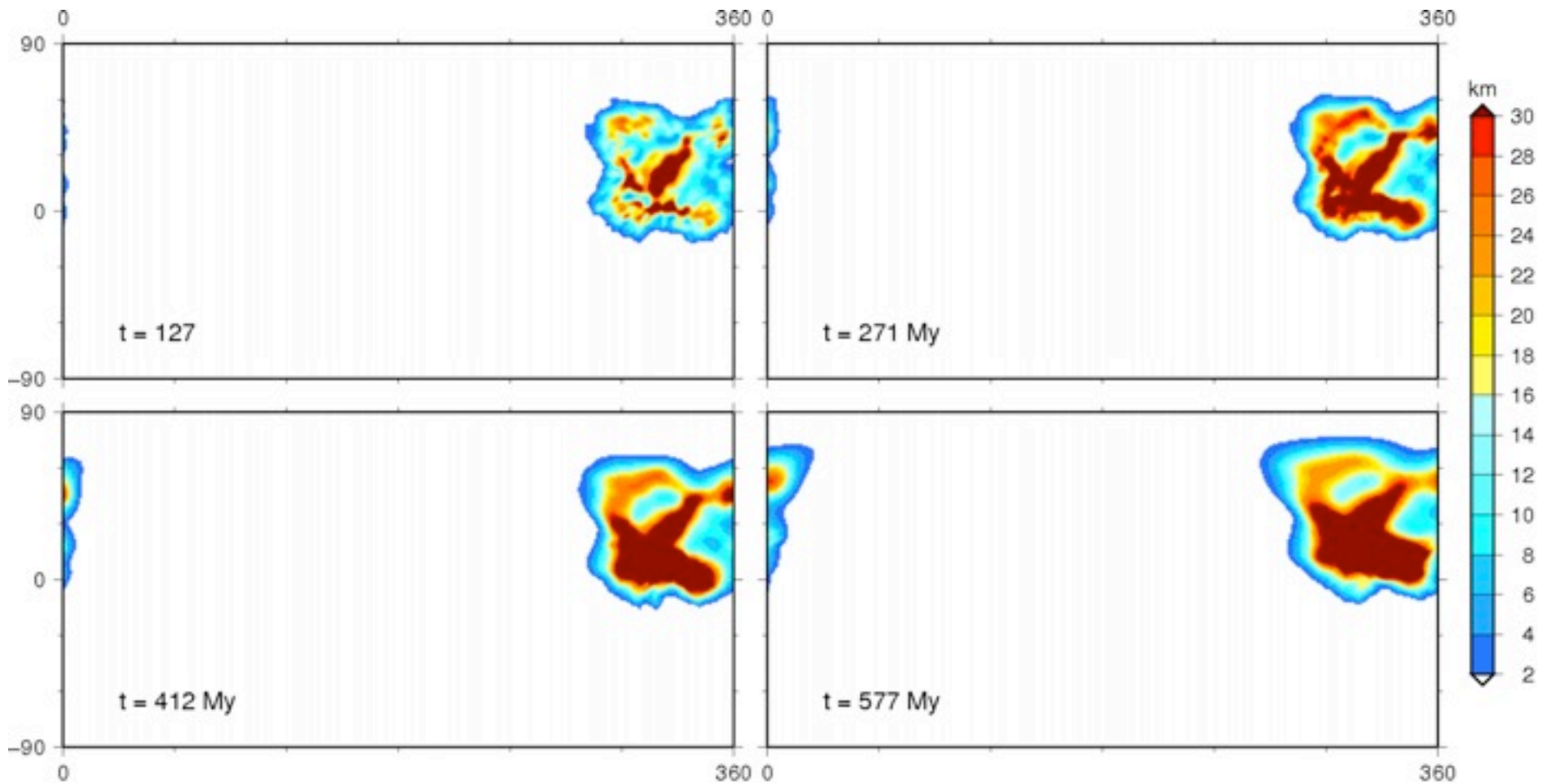
$t = 271 \text{ My}$



$t = 412 \text{ My}$



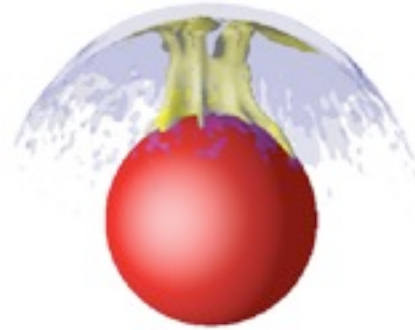
$t = 557 \text{ My}$



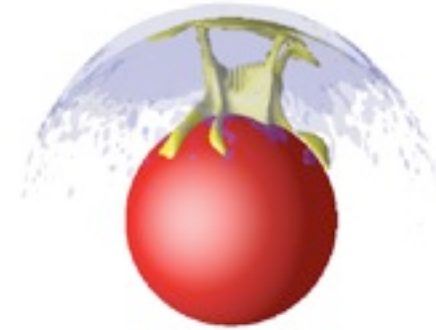
$T_{\text{cmb}} = 2200 \text{ K}$



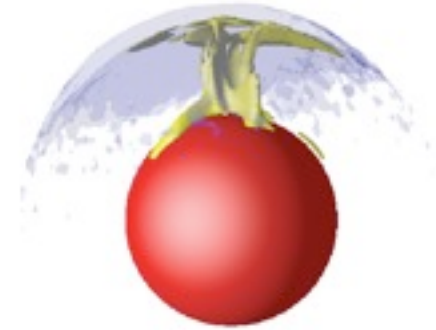
$t = 0$



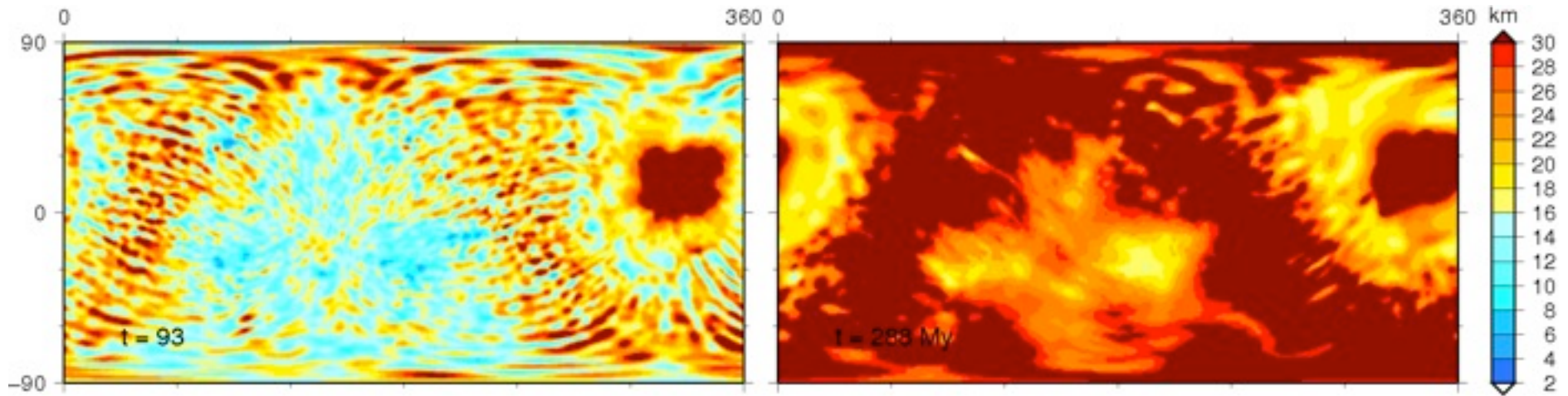
$t = 93 \text{ My}$



$t = 195 \text{ My}$



$t = 288 \text{ My}$

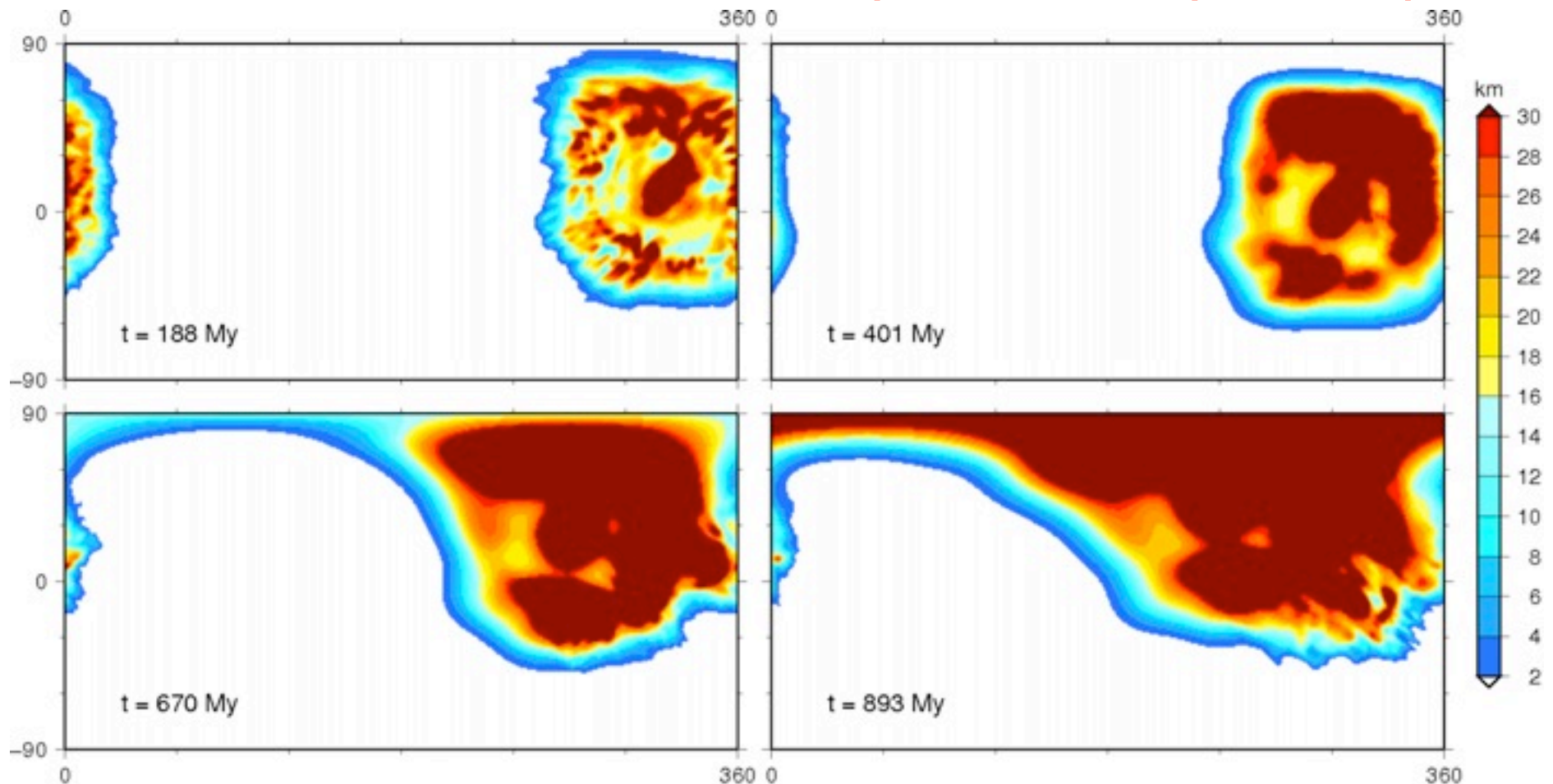


$T_{cmb} = 2100 \text{ K}$



$t = 188 \text{ My}$

we do observe a plume–lithosphere separation

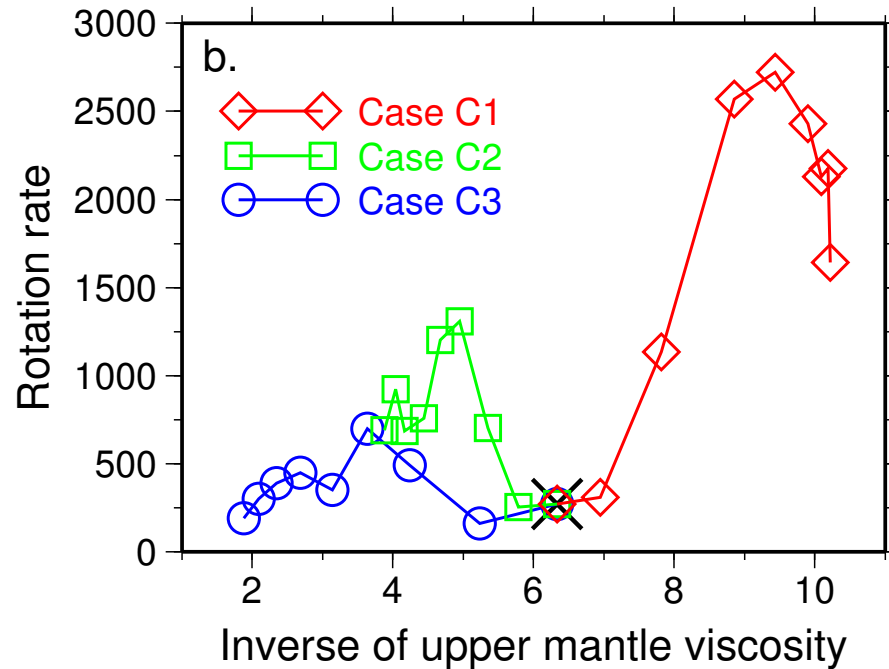
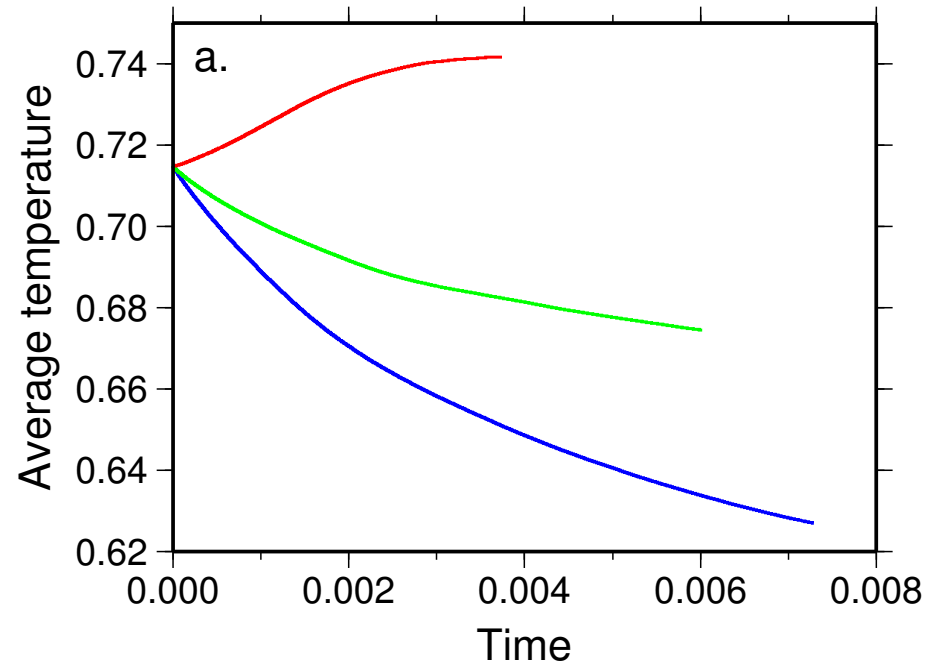




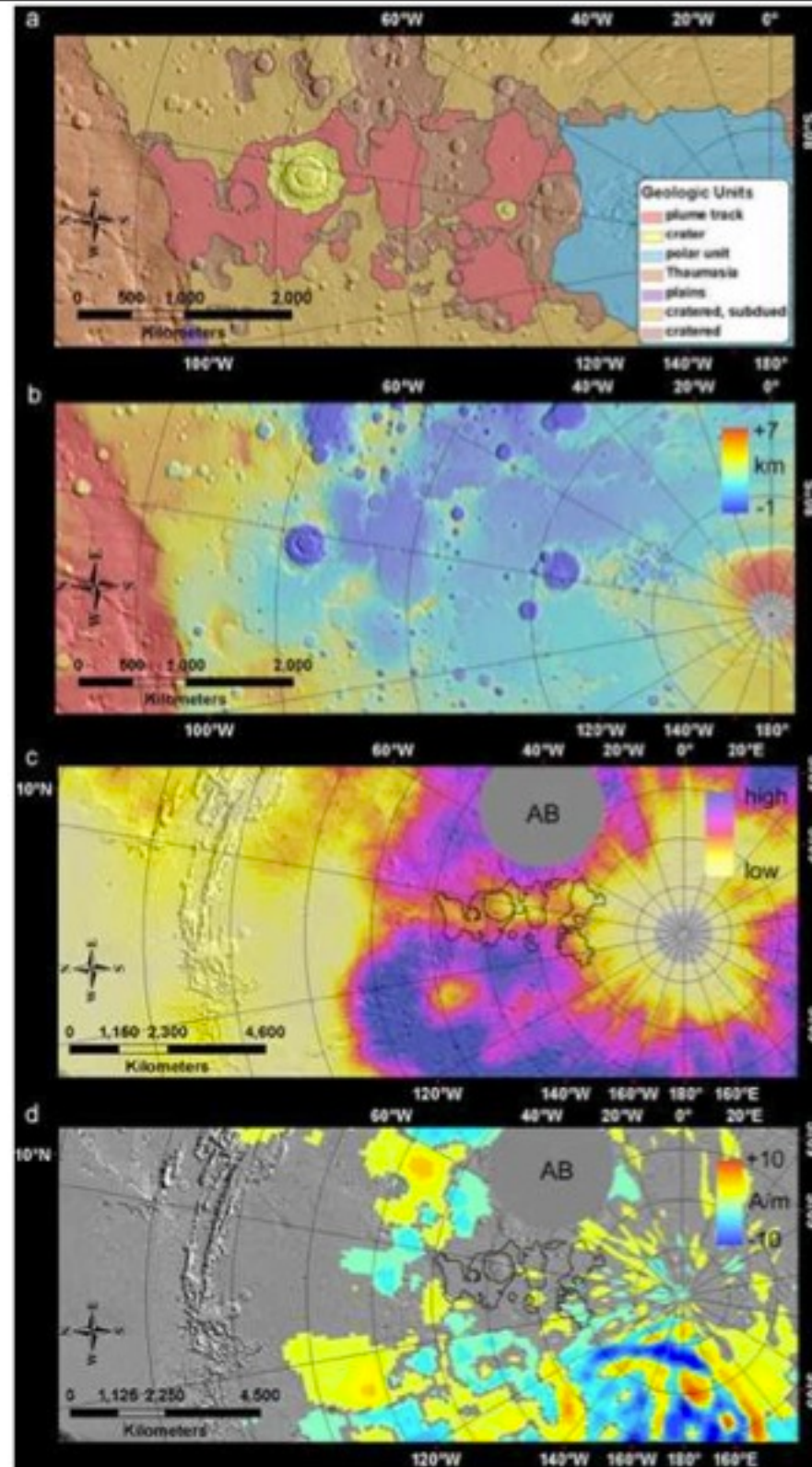
# How does the rotation cease?

- Tharsis remained in its current location for the last ~3.5 My
- This may be explained by the effect of secular cooling through a combination of
  - decreasing melt production rate
  - increasing viscosity
  - melting of previously devolatilized mantle at later times

# Effect of viscosity on separation rate



# Observational evidence?



Hynek et al. (submitted)

# Summary

- Model of “rotation of the lithosphere” relates the formation and evolution of Tharsis to the preexisting crustal dichotomy
- May explain the inferred early migration of Tharsis and its current position
- Requires variations in lithospheric thickness
- This can be produced by partial melting including the effect of devolatilization on viscosity of melt residue
- We can find a model that broadly satisfies the observation constraints...
- ...but might want to consider a more realistic model



# More realistic

- include crustal flow and redistribution
- possibly account for melt migration and extraction
- include effect of core cooling and use exponentially decaying internal heat sources
- when partial melting and melt residue dynamic effect are included, initial condition seems to be important

