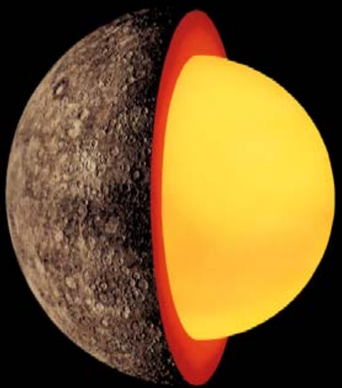
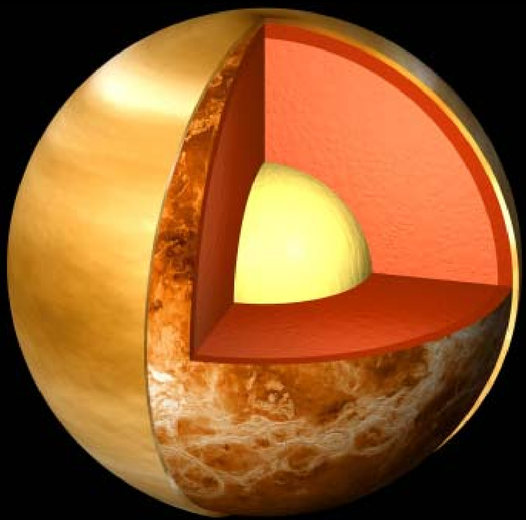
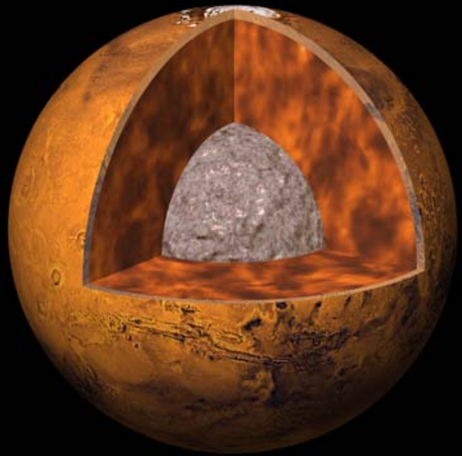
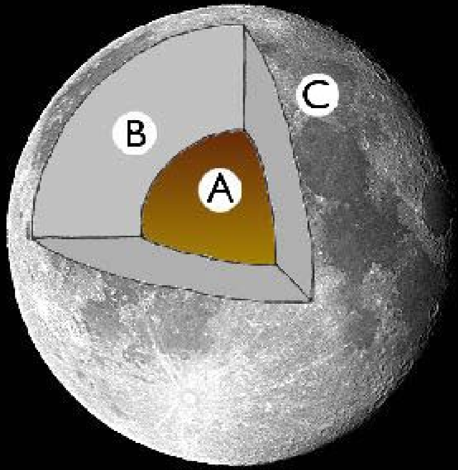
What do we know about the interior structure, dynamics and thermal evolution of terrestrial planets?



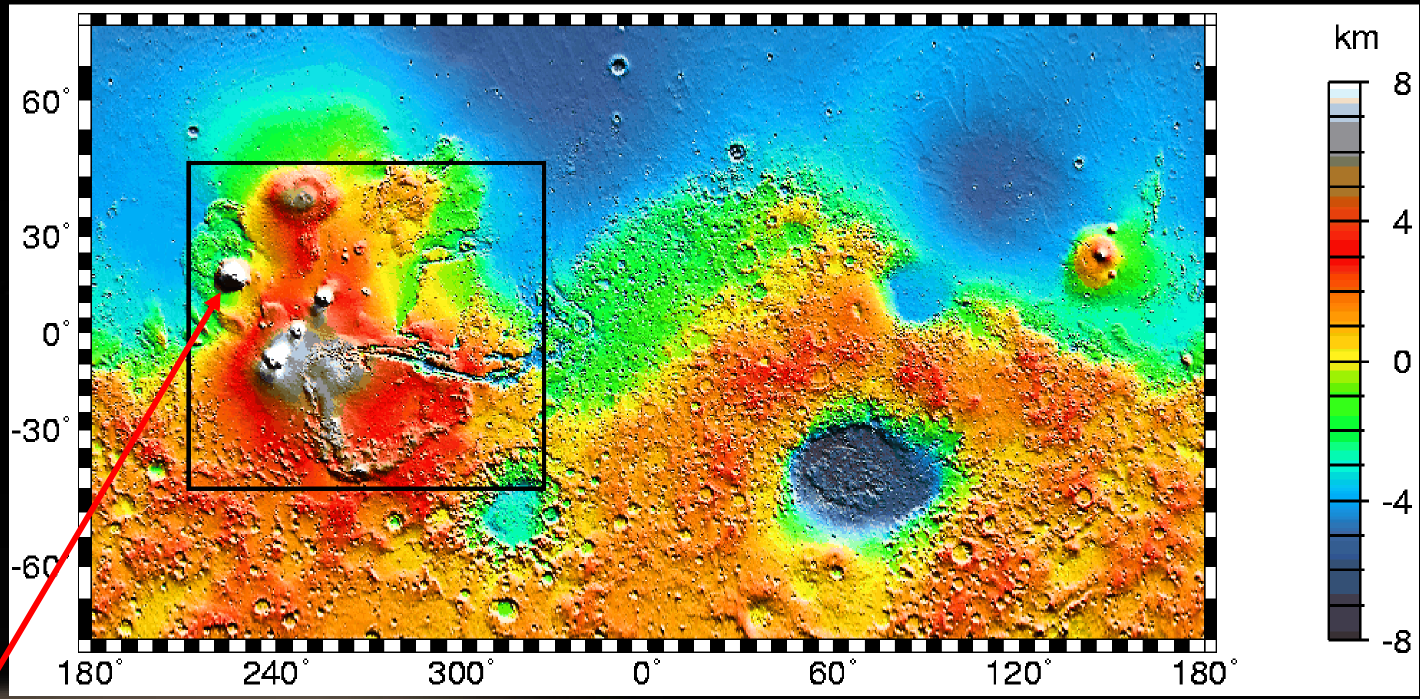


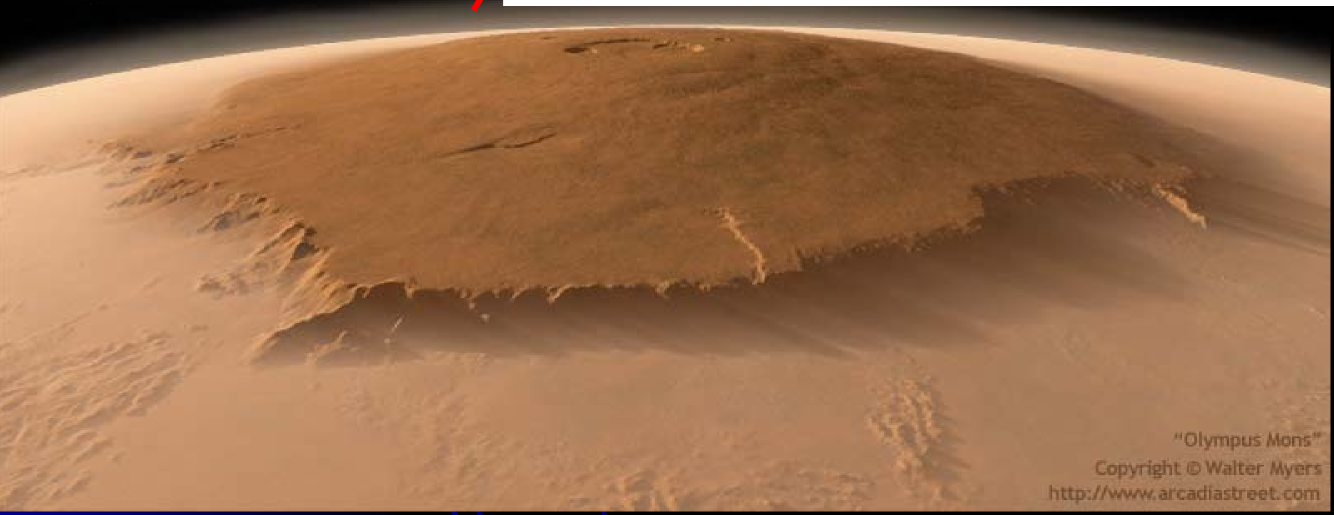




Doris Breuer, DLR Institute of Planetary Research, Berlin

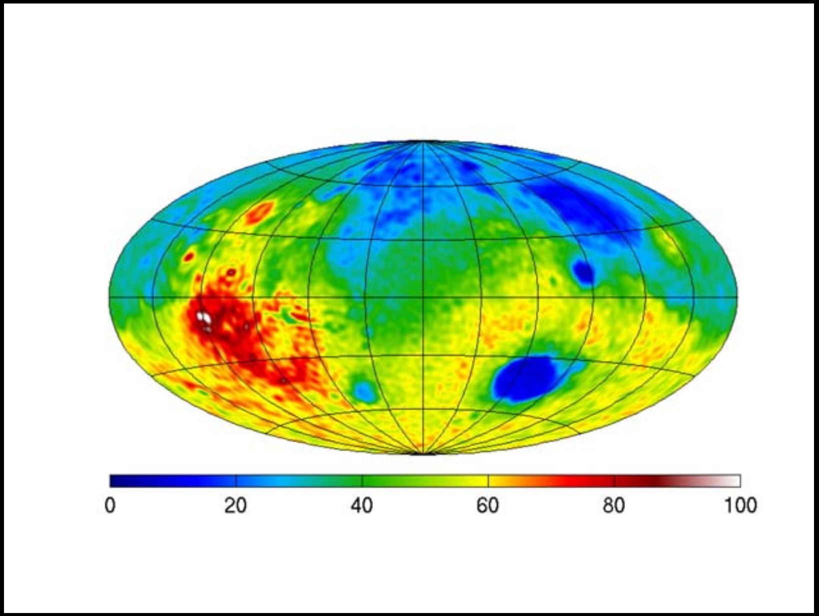
Mars


km
8
4
0
-4
-8
60°
30°
0°
-30°
-60°
180°
240°
300°
0°
60°
120°
180°


"Olympus Mons"
Copyright © Walter Myers
http://www.arcadiastreet.com

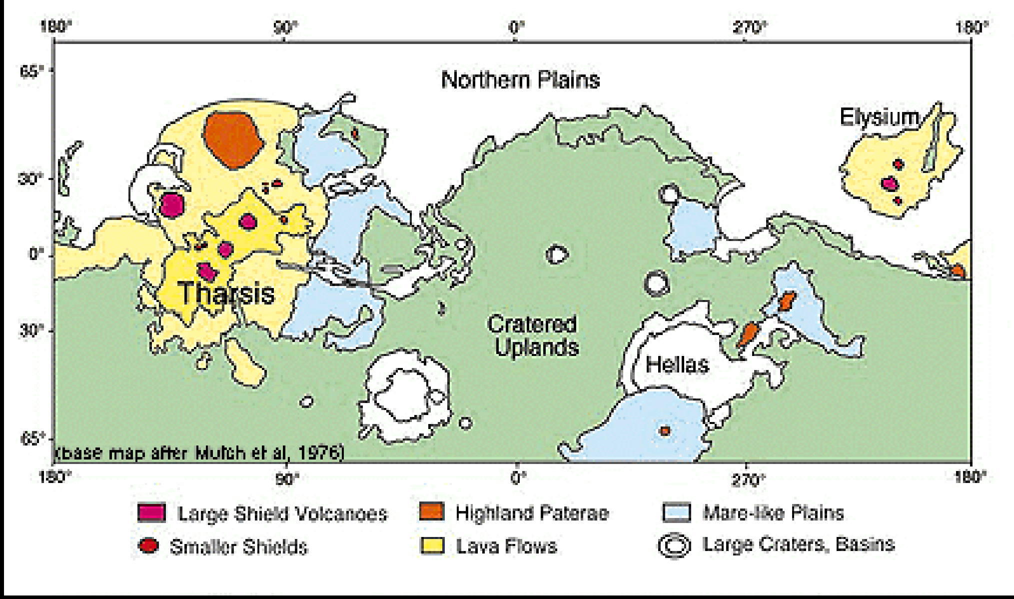
Crustal dichotomy

- Variation in age
- Crustal thickness variation (e.g., Zuber et al., 2000)
- Variaion in surface composition (e.g., Christensen et , 2000)

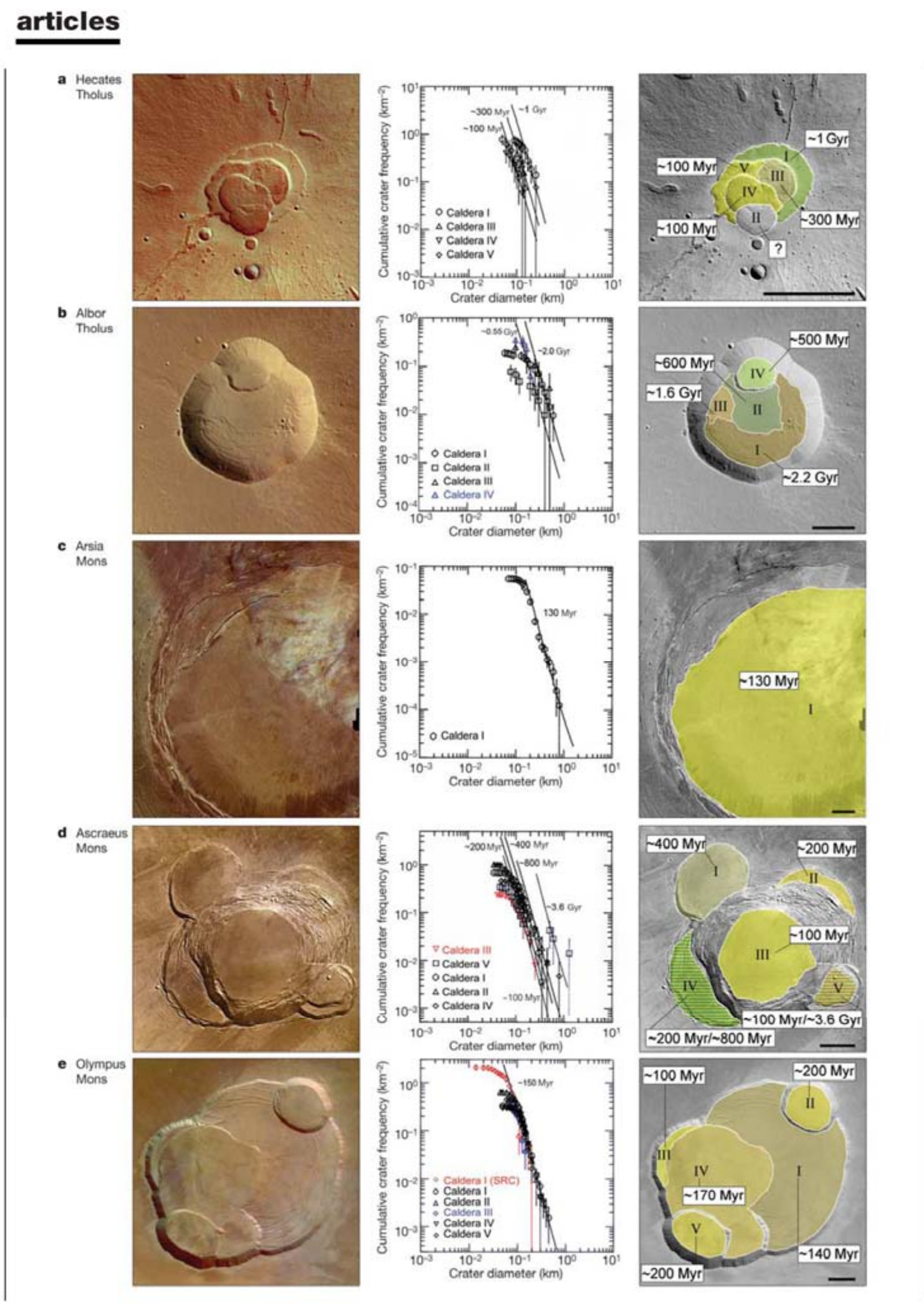


Volcanic activity

- Strong decrease of volcanic activity with time; first global distribution later concentration in two provinces
- Crustal dichotomy formed in the first few 100 Ma
- Bulk of the large volcanic provinces formed in first 1 Ga

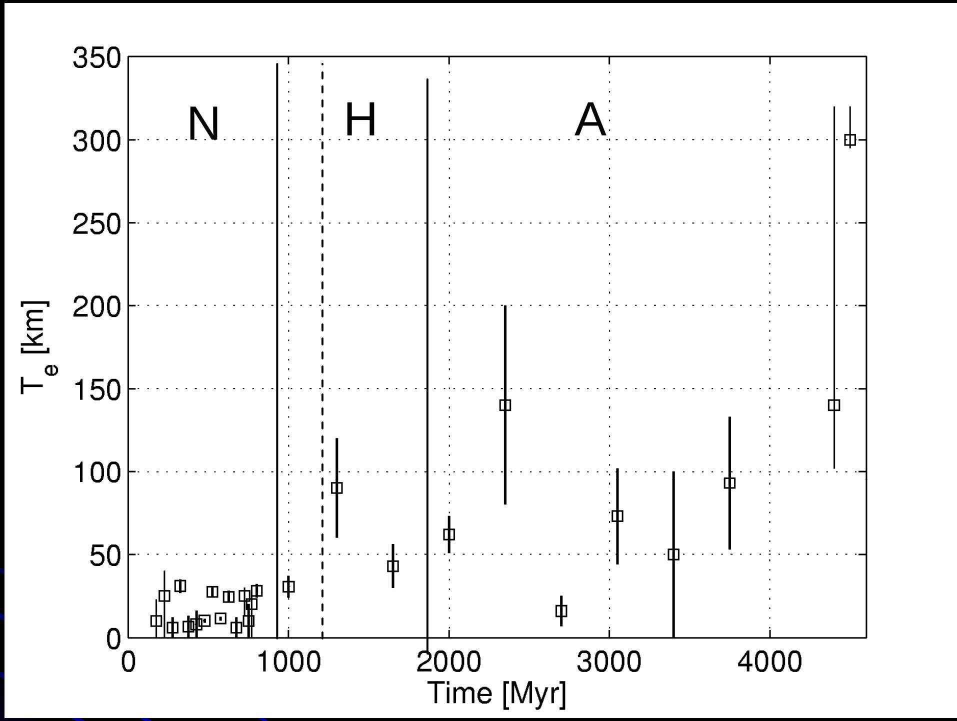


Episodic volcanism but also recent activity in Tharsis and Elysium



Neukum et al, 2004

Elastic Thickness Estimates - Mars

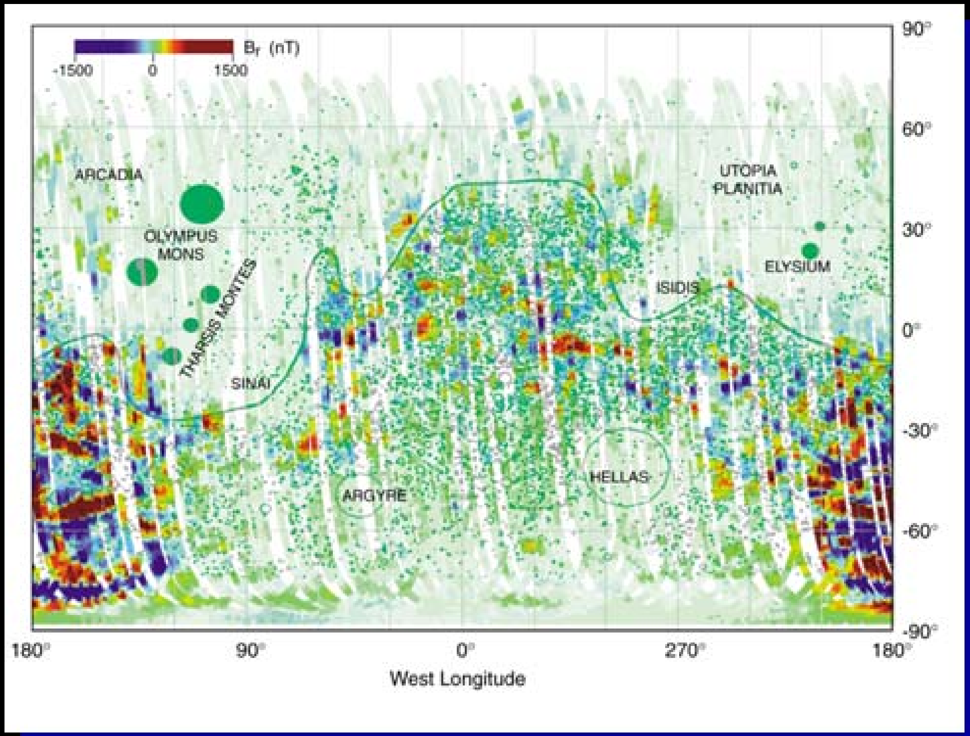


N = Noachian
H = Hesperian
A = Amazonian

- T_e during the Noachian / Early Hesperian ~ 15 km
- T_e during the Amazonian between 30 and 300 km
- General trend follows planetary cooling *but*
- Large T_e variations in the Amazonian

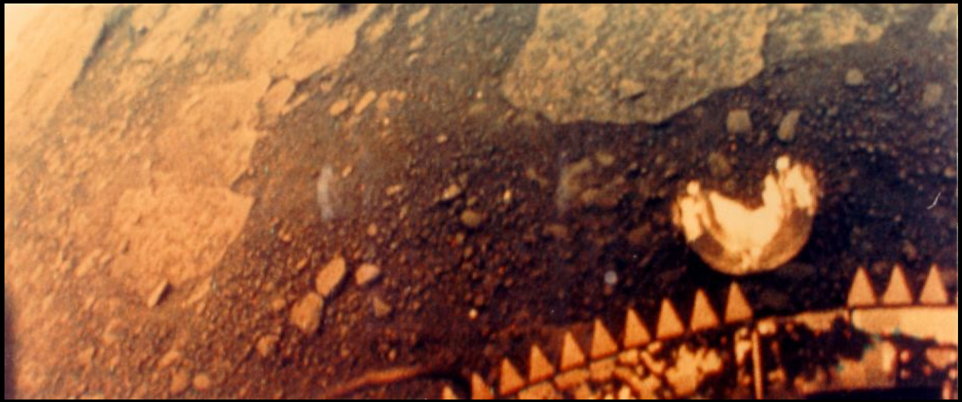
Early strong magnetic field

- Early crustal magnetization (first ~ 500 Ma)
- No present day internal magnetic field

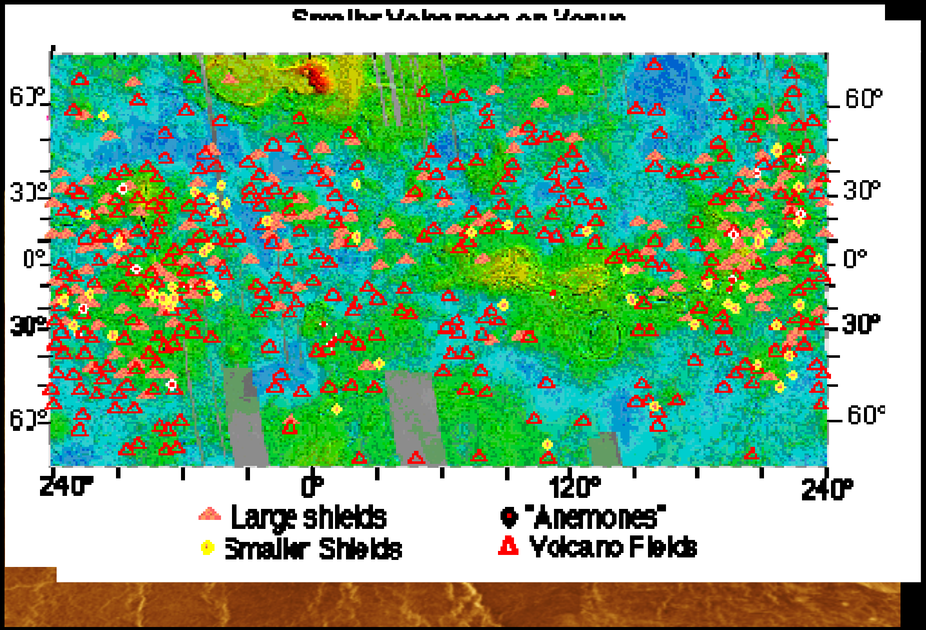


Venus

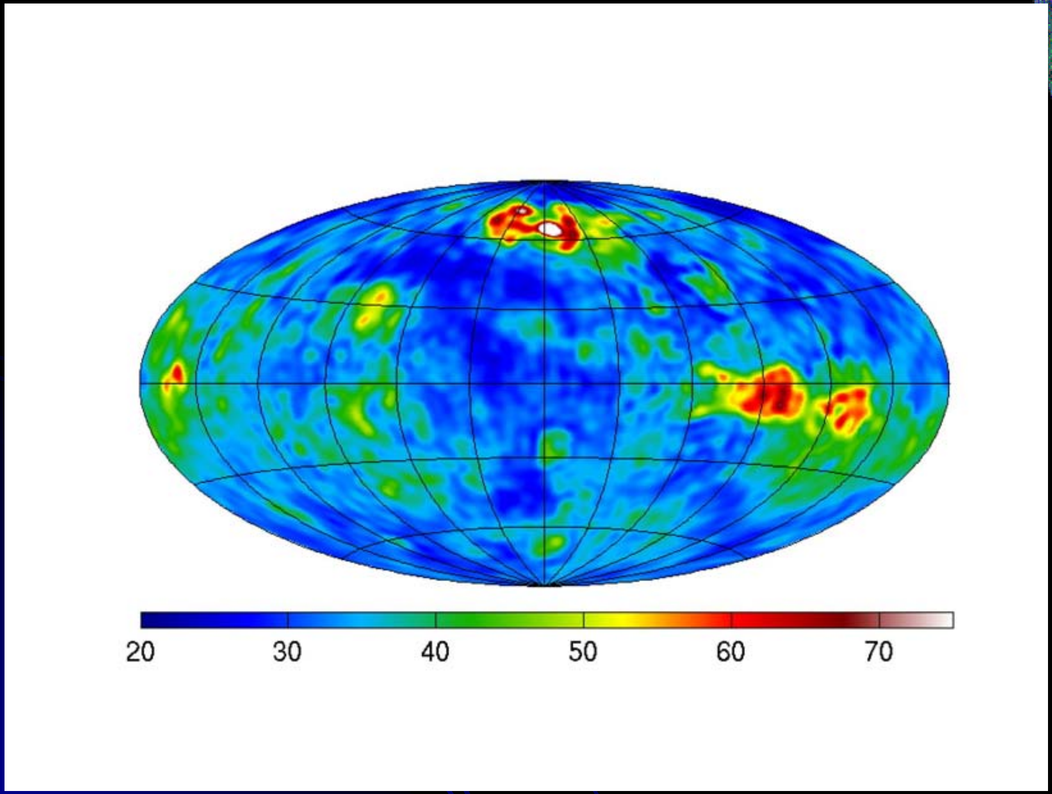
- Volcanoes and volcanic lava flows are homogenously distributed at the surface

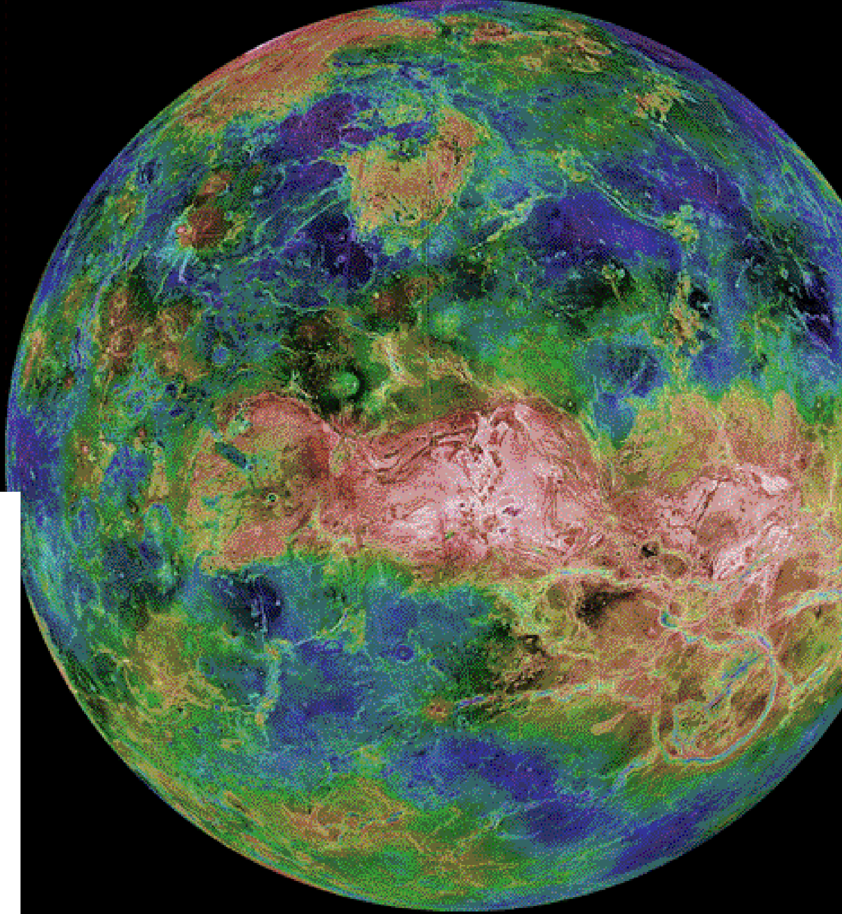


- Possibly a recent global resurfacing event (~ 500-700 Ma) renewed the surface

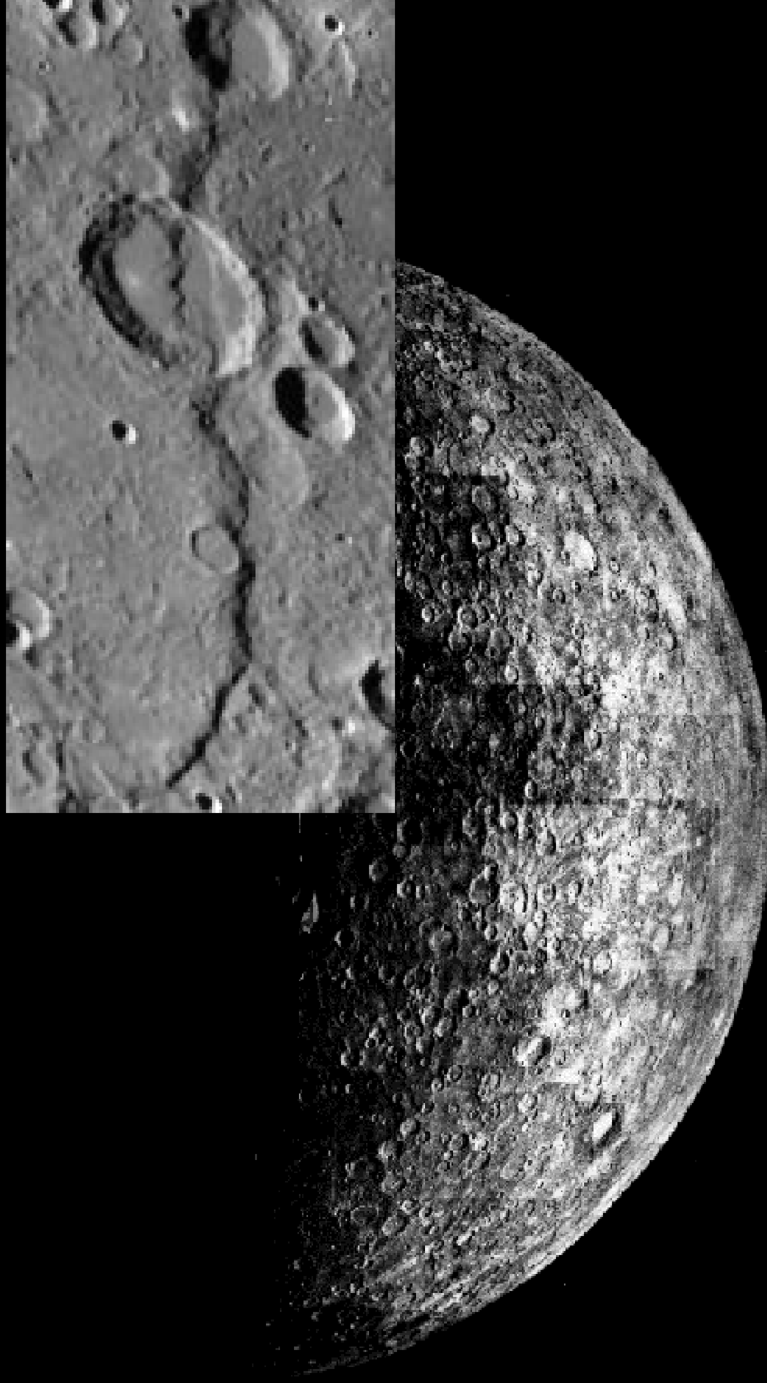


Venus:
crustal thickness





Mercury



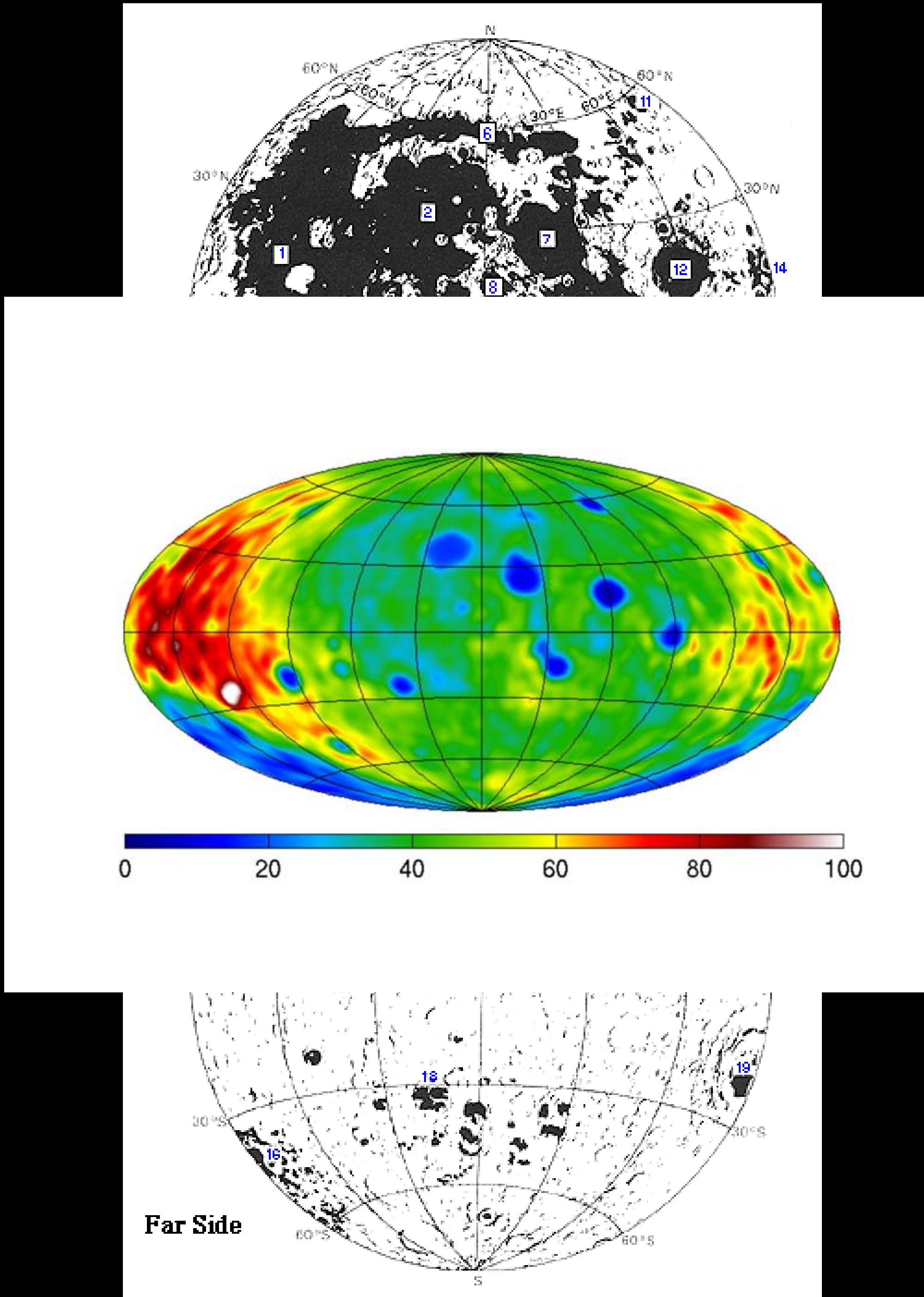
- Crater and scarps cover the surface
  - old surface
  - ~ 1-3 km decrease of radius caused by thermal contraction since ~4 Ga

Mercury

- Messenger flybys revealed volcanic resurfacing
- Volcanism more widespread than previously expected

Moon

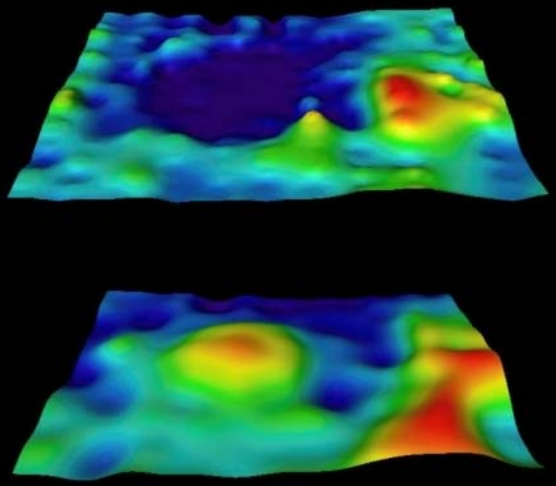
- Crustal dichotomy: lunar mare are primarily found on near side



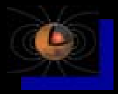
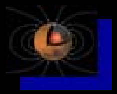
Moon

- Increase of TiO_2 with age suggests that source region moved to greater depth
- Volcanic activity extended, albeit at a small rate, until perhaps 1.5 Ga b.p.

MARE SMYTHII

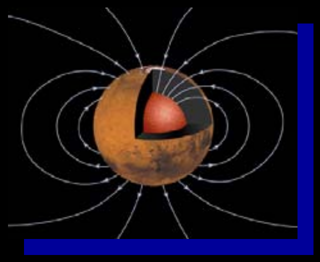


Planetary Data (Magnetic field)

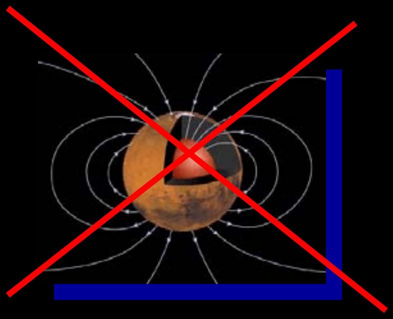
	Mercury	Venus	Earth	Mars	Moon	Ganymede	Io
Present dynamo		-		-	-		-
Early dynamo	?	?				?	?
Radius	0.38	0.95	1.0	0.54	0.27	0.41	0.28
Mass	0.055	0.815	1.0	0.107	0.012	0.018	0.015
Density [kg/m^3]	5430.	5250.	5515.	3940.	3340.	1940.	3554.
ρ_0 *[kg/m^3]*	5300.	4000.	4100.	3800.	3400.	1800.	3600.
MoI	0.34	?	0.3355	0.3662	0.3905	0.3105	0.378
R_c/R_p	0.8	0.55	0.546	0.5	0.25	0.3	0.5
Dipole Moment [10^{19} A m^2]	4.9	<0.4	7980.	<2.5	$<4\times10^{-9}$	14	?

Dynamo action ‘dicated‘ by mantle cooling

- If the mantle cools efficiently the interior the core can convect (or freeze out an inner core)



- If the mantle cools inefficently the interior the core can not convect (or not freeze out an inner core)



Some open questions

- What is the origin of the crustal dichotomy of Mars and also of the Moon?
- What is the origin of Tharsis on Mars?
  - Is the dynamo action linked with these processes?
- What is the origin of the resurfacing event on Venus, did Venus have had plate tectonics or even Mars?

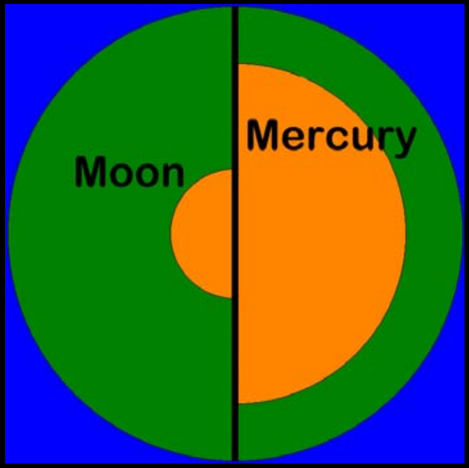
Some open questions

- Why lasted the volcanic activity on the small planets that long?
- What is the magnetic field evolution of the terrestrial planets?
- Why does the Earth have plate tectonics?
- ……?

What influences the thermo-chemical and the magnetic field evolution?

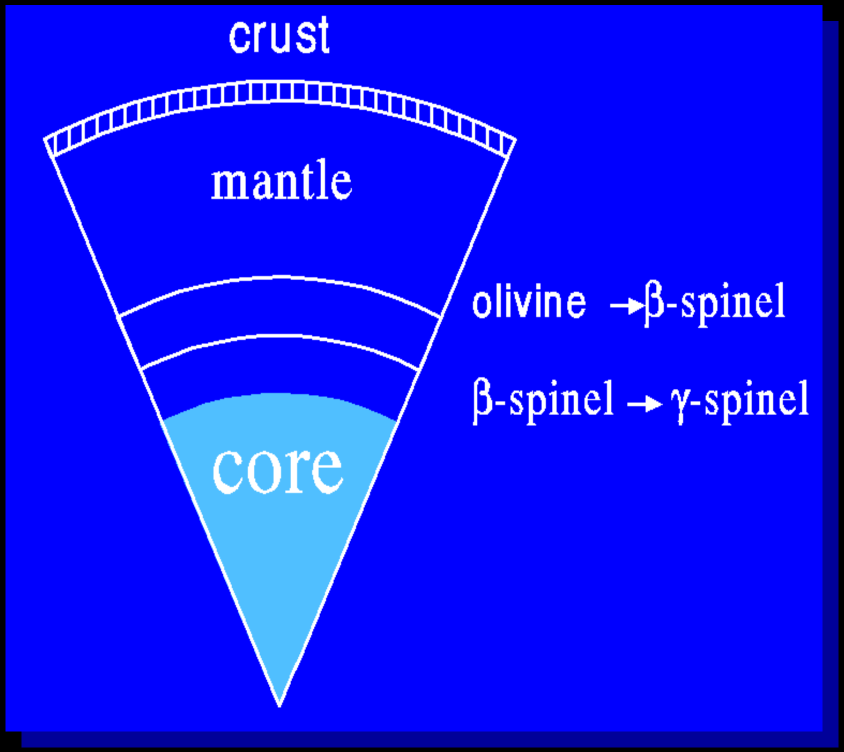
- Interior structure and composition

- Heat transport mechanisms



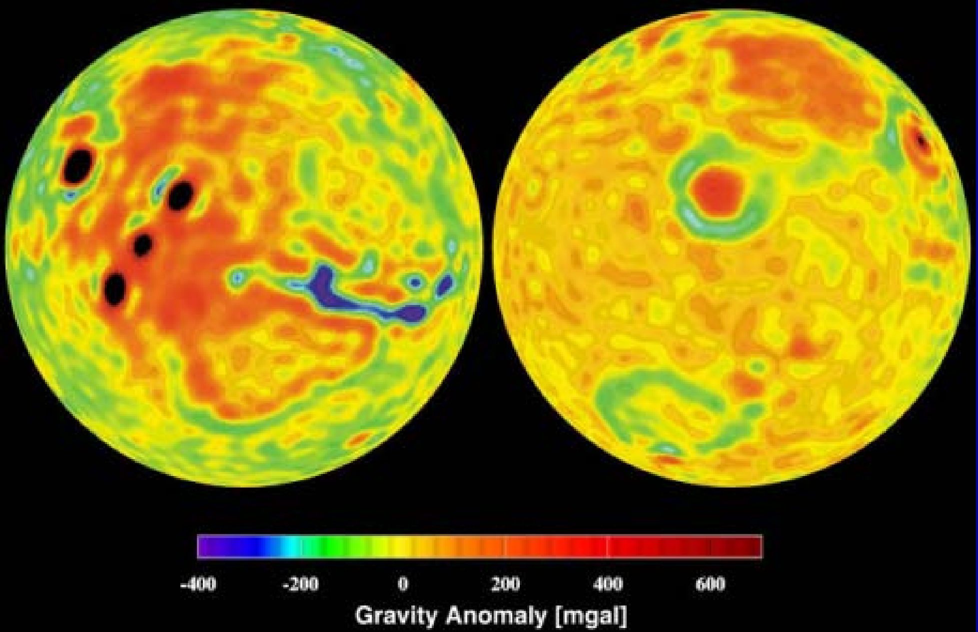
Interior Structure and Composition

- Mass of reservoirs (crust, mantle, core)
- Composition (rheology)
- Depth of phase transitions and chemical layers
- Variations of pressure, temperature, and density



Data

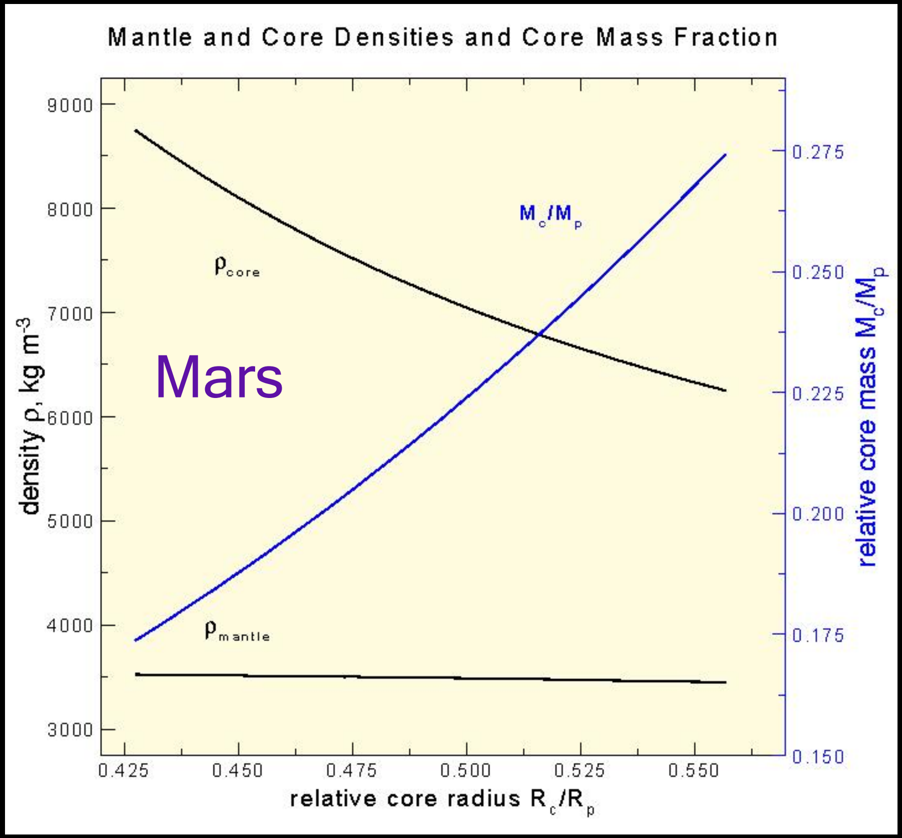
- Mass
- Gravity field, rotational state
- Chemistry / mineralogy of the surface
- Cosmochemical data (SNC)
- Data from the laboratory



MGS Gravity Field of Mars

Two-layered structural models

- Non-uniqueness of even simple interior structure models with $\rho_{crust} = 0$
  - two constraints: mean density, MoI factor
  - three unknowns: mantle and core density, core radius
- Reduce ambiguities by cosmochemistry
  - core densities ranging from pure Fe to eutectic Fe-FeS



Detailed Models of the Interior

Structural Equations

mass, *m*

$$\frac{dm}{dr} = 4\pi r^2 \rho$$

moment of inertia, θ

$$\frac{d\theta}{dr} = \frac{8}{3}\pi r^4 \rho$$

gravity, *g*

$$\frac{dg}{dr} = 4\pi G\rho - 2\frac{g}{r}$$

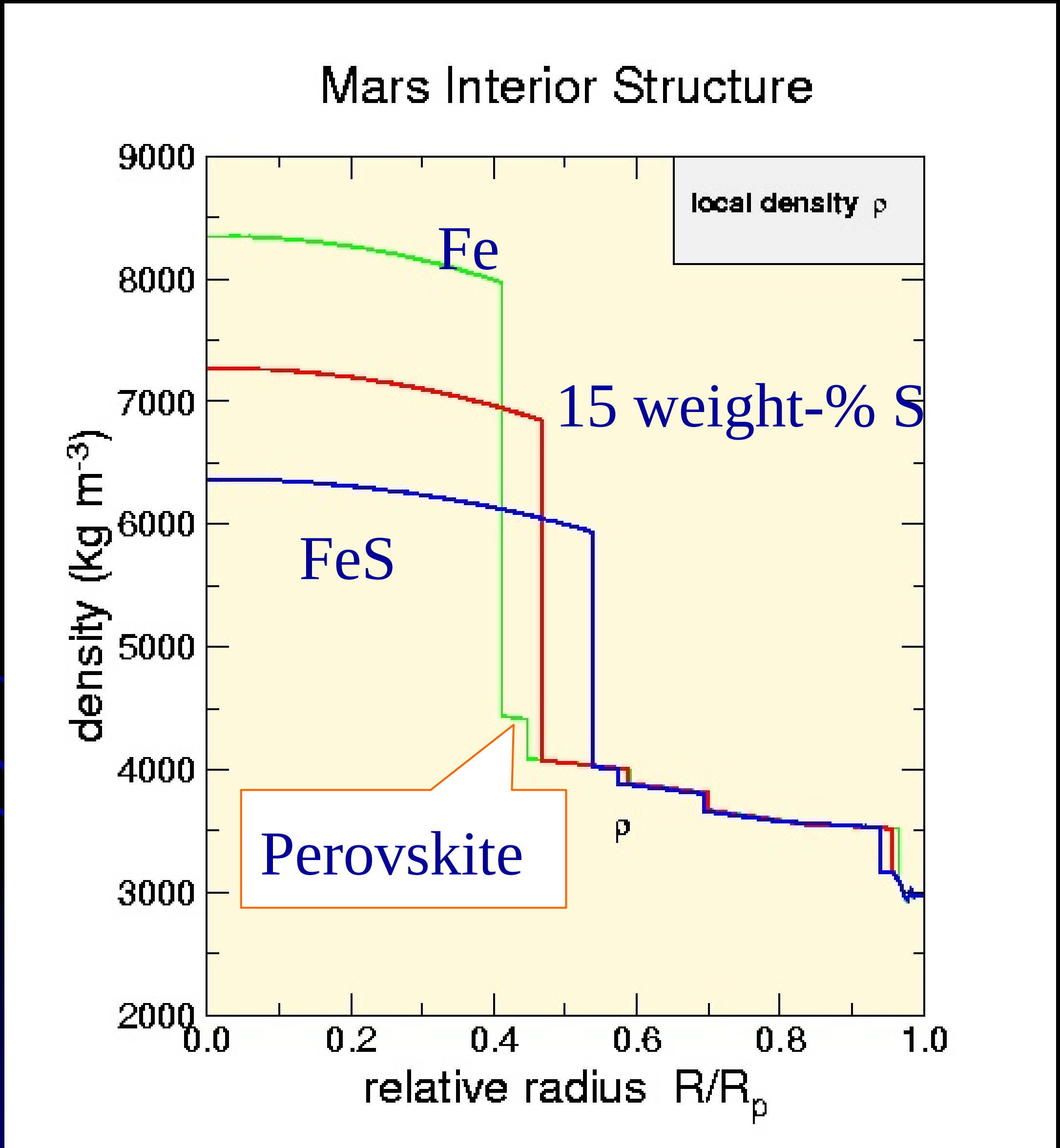
pressure, *p*

$$\frac{dp}{dr} = -g\rho$$

Model assumptions:

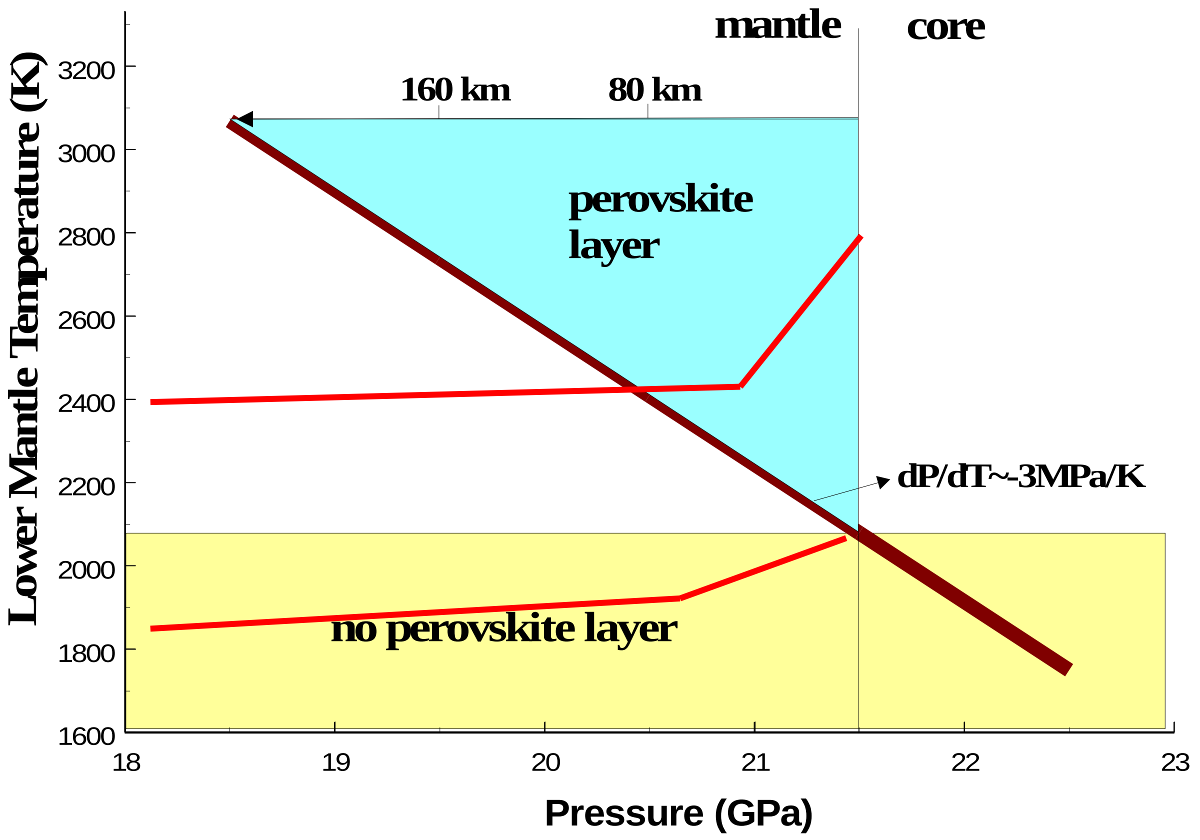
- Spherically symmetric and fully differentiated planets
- Hydrostatic and thermal equilibrium

Interior structure of Mars



Sohl and Spohn, 1997

Perovskite layer thickness near core/mantle boundary dependent on lower mantle temperature



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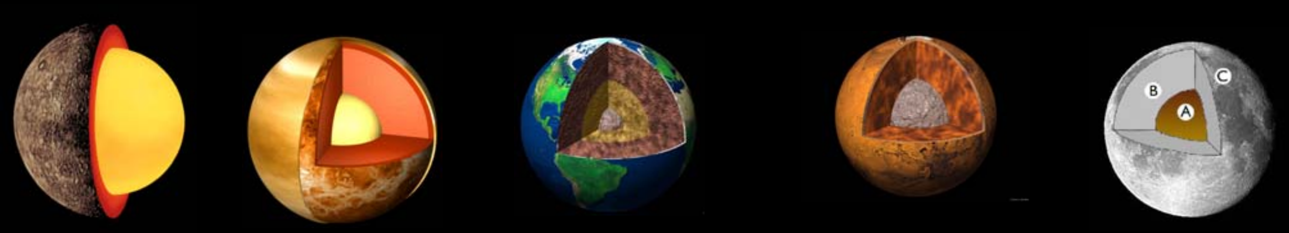
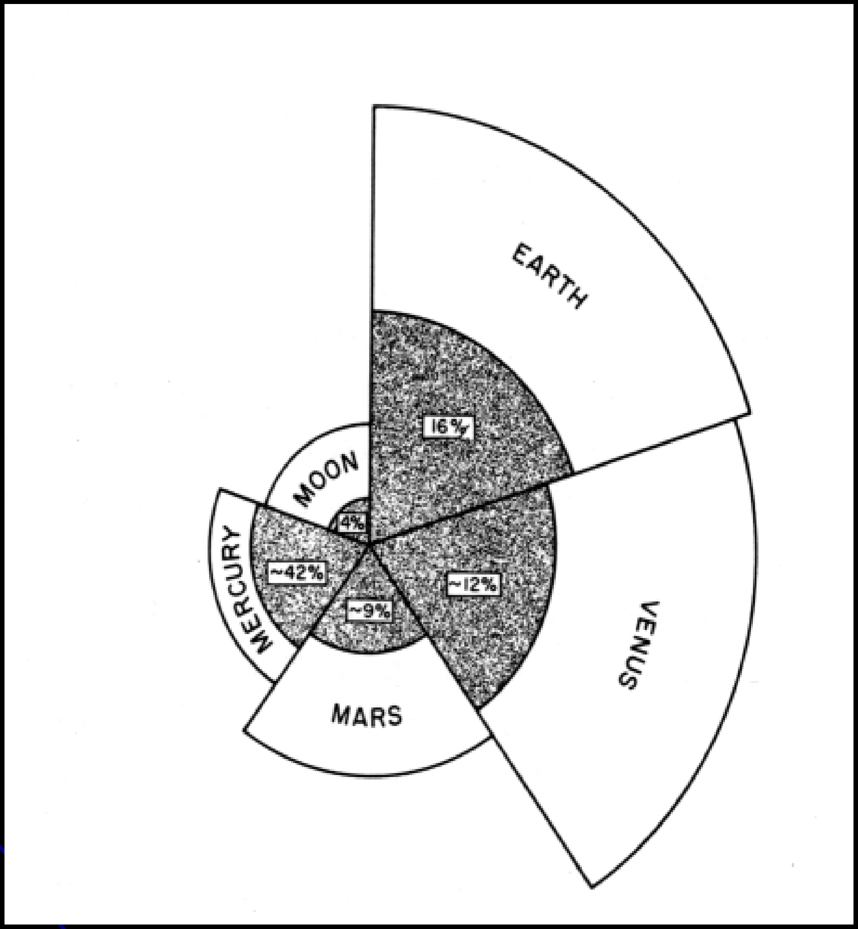


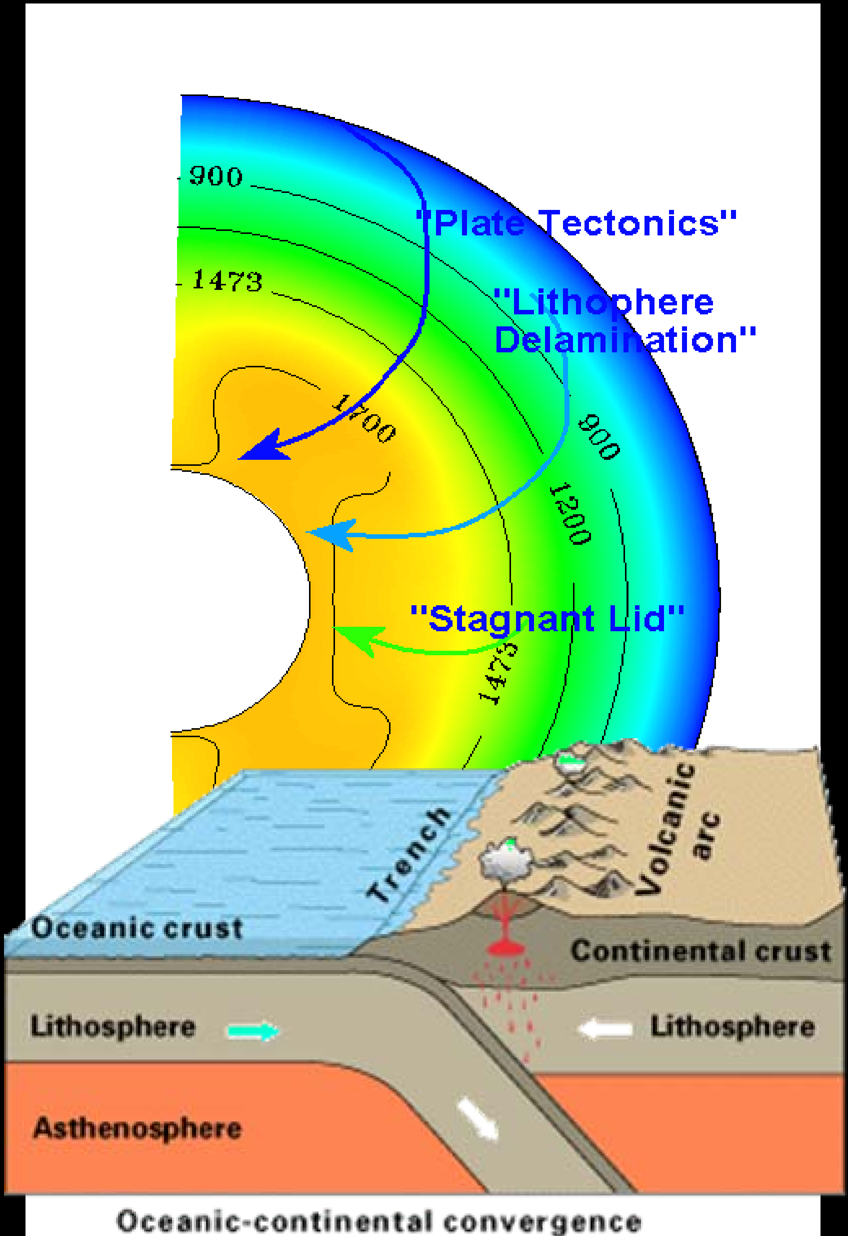
Interior structure



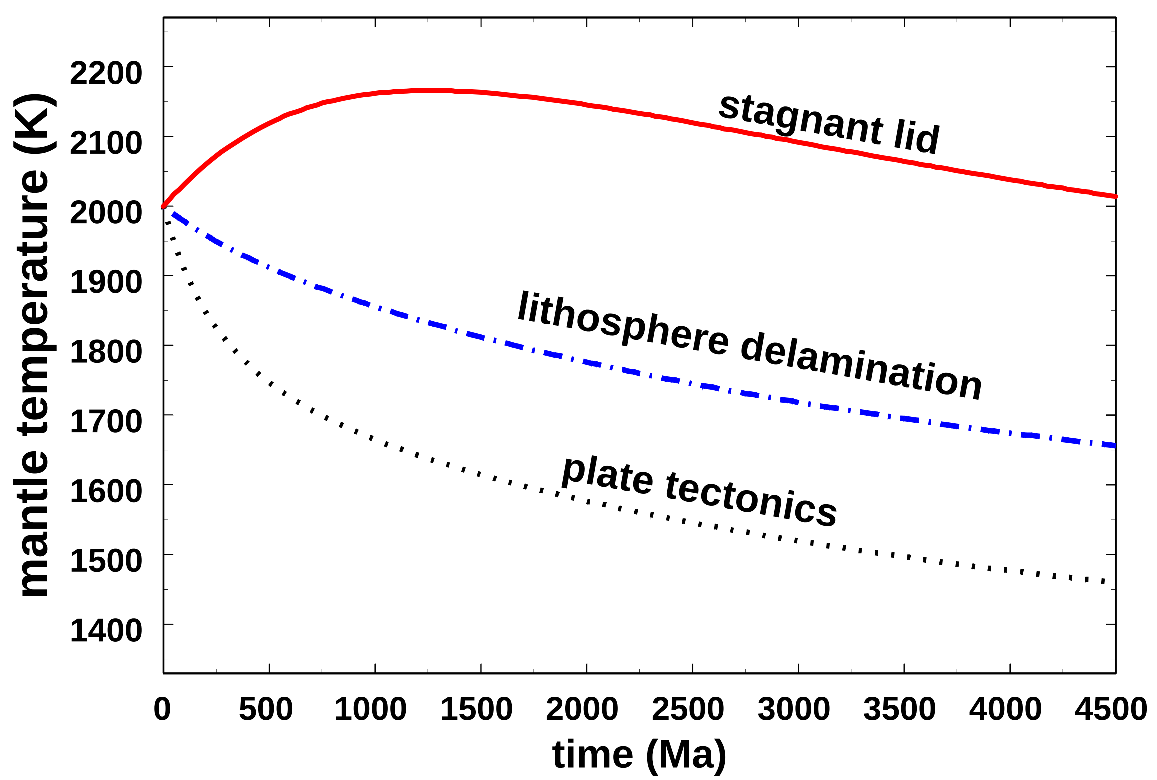
Heat Transport Mechanisms

- Plate tectonics:
  Earth, early Mars?, Venus?
  (not today but episodic)
- Stagnant lid convection:
  Mercury, Venus, Mars, Moon
- Lithosphere delamination:
  Venus?

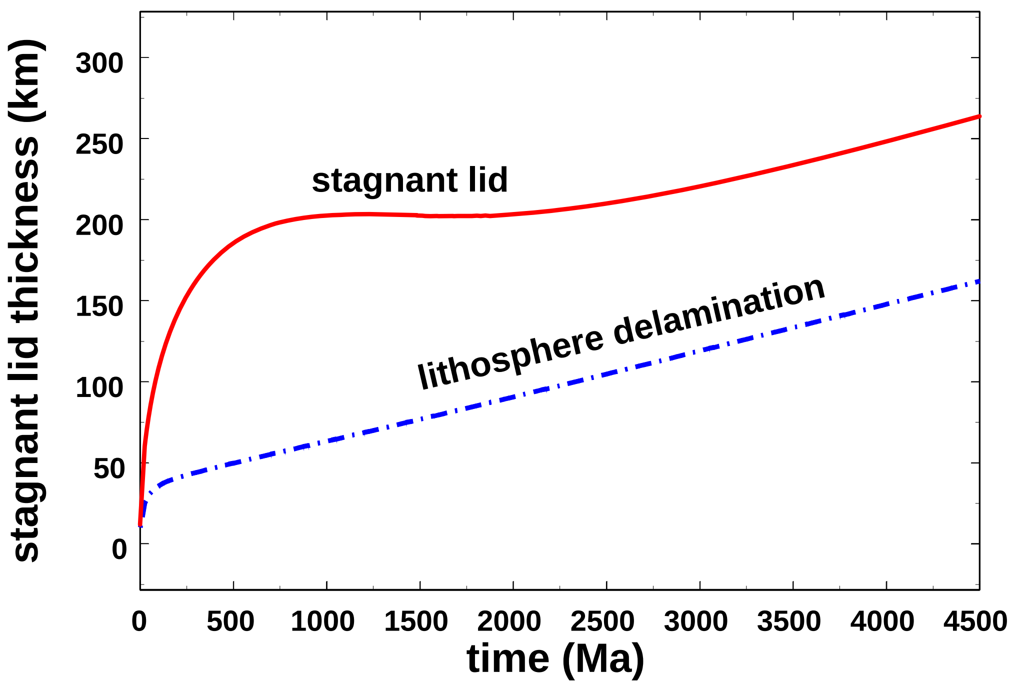
Magma transport (volcanism)

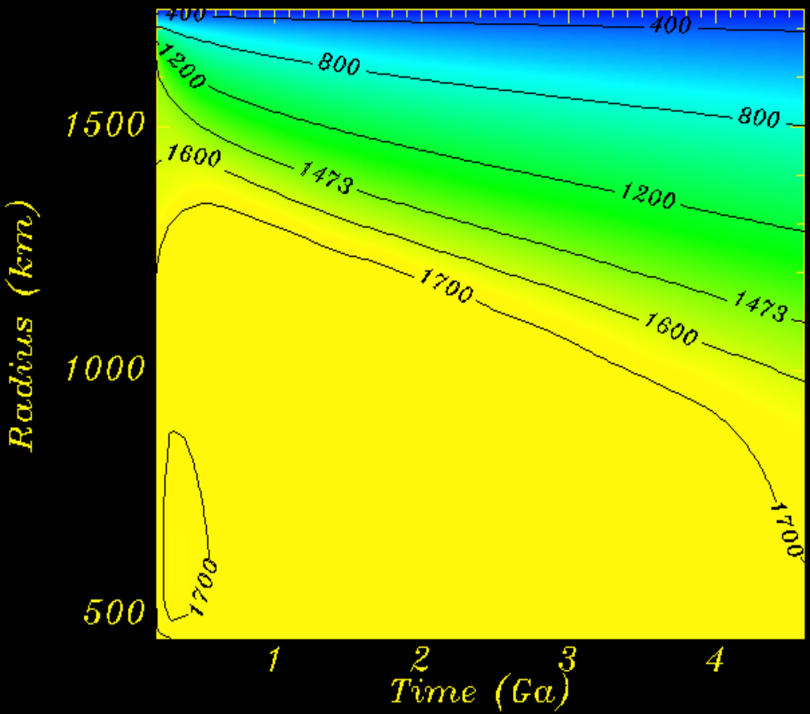


Mantle temperature



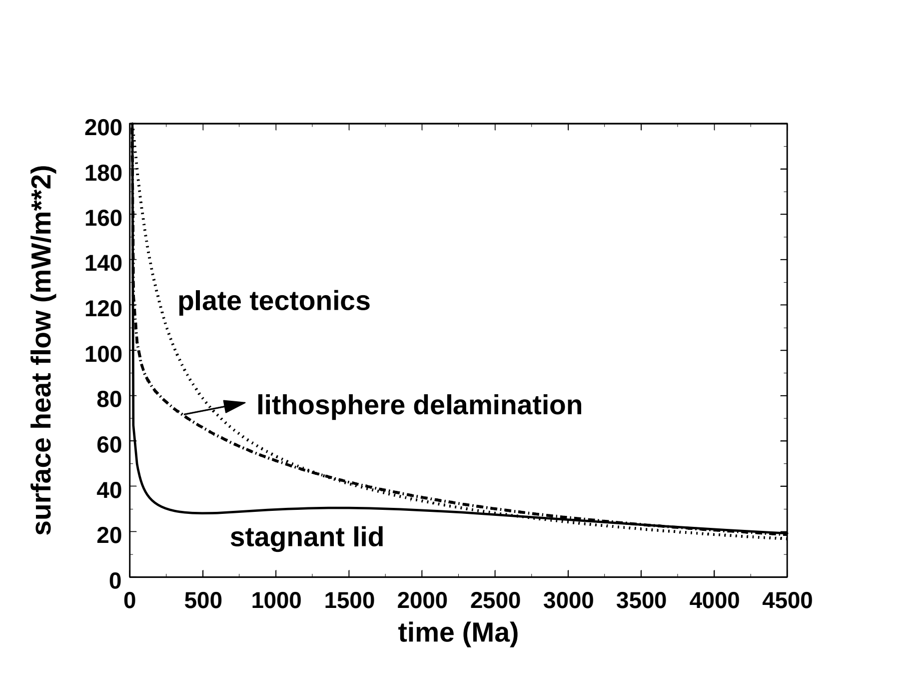
Lithosphere thickness





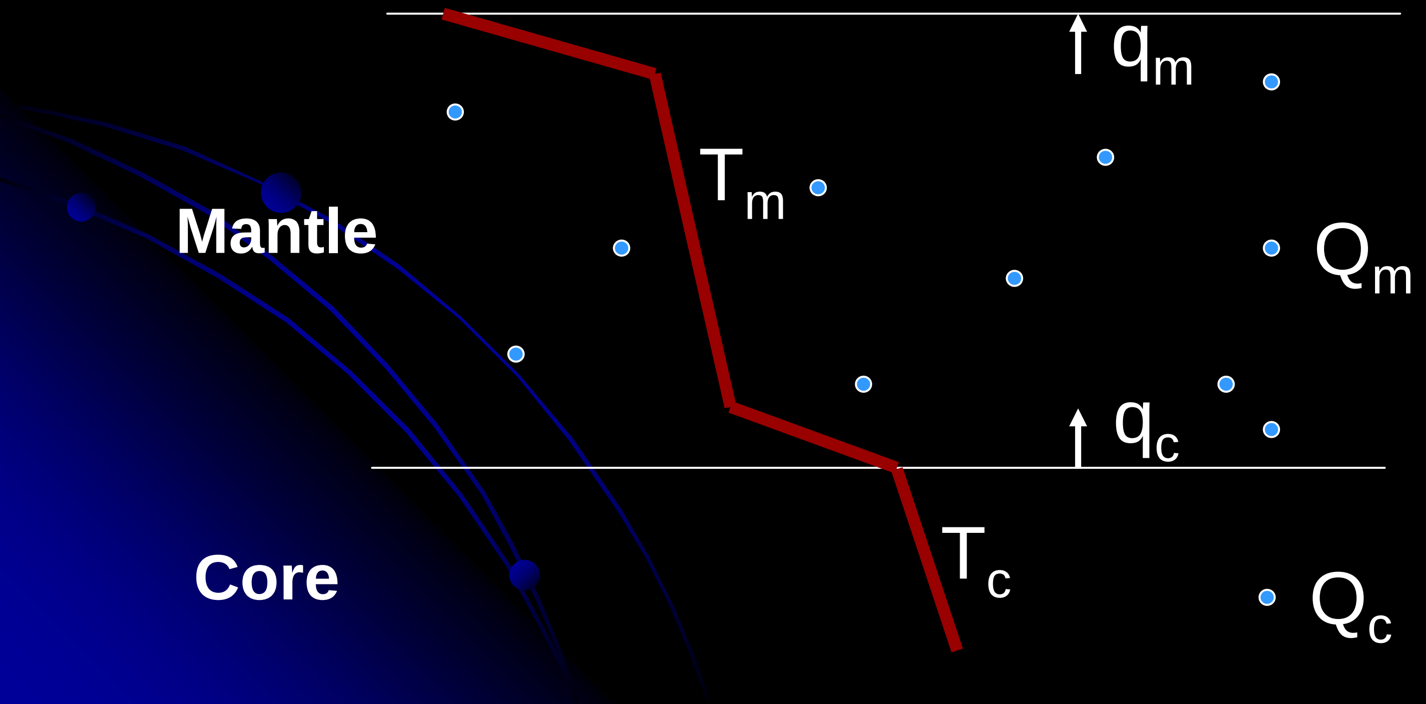
Parameterized Models

- Simple scaling laws (e.g. Nu ~ Ra^b)
- Global parameters as function of time (e.g. mean temperature, heat flow)

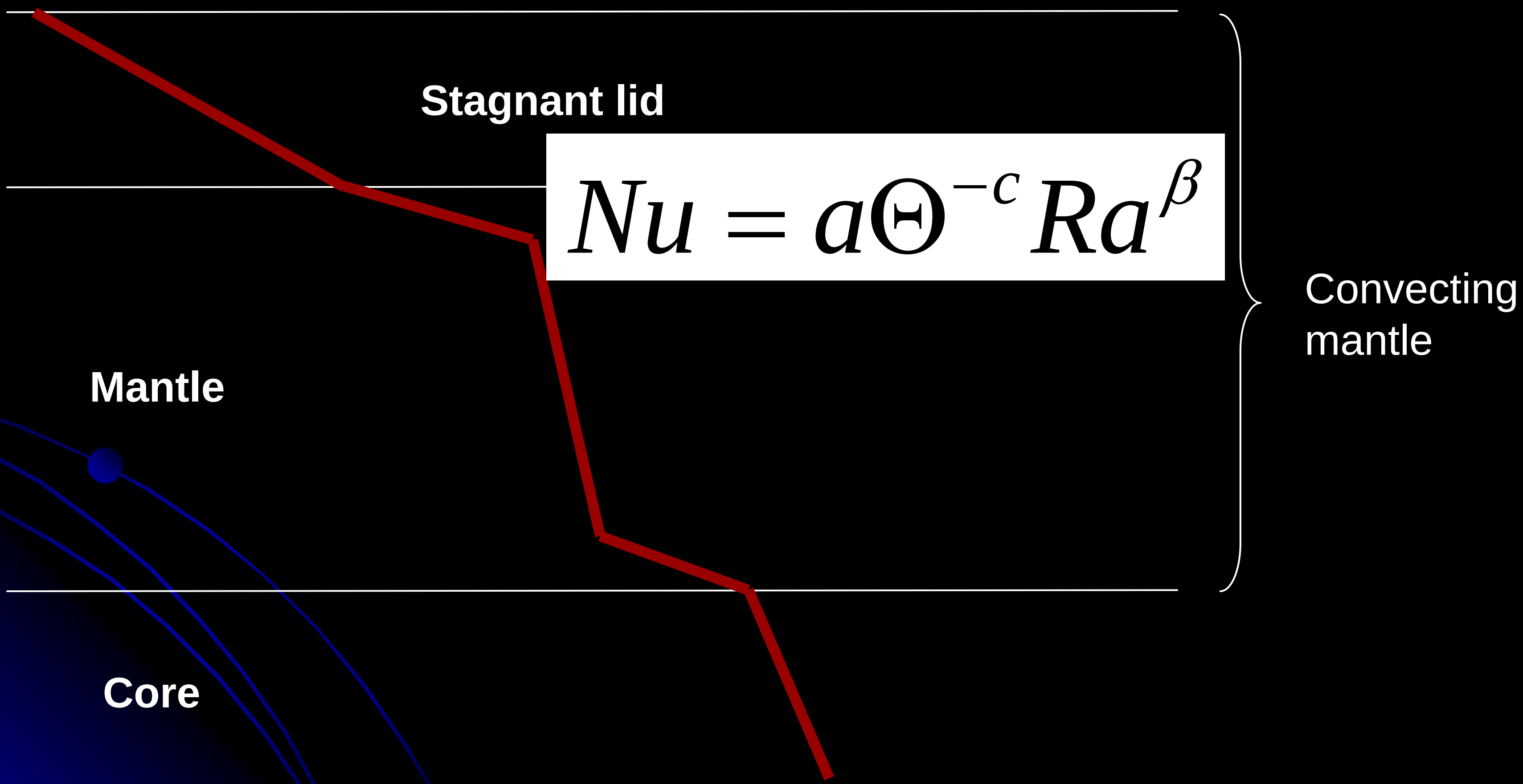


$$\rho_m C_m V_m (St+1)\frac{dT_m}{dt} = -q_m A_m + q_c A_c + Q_m V_m,$$

$$\rho_c C_c V_c \frac{dT_c}{dt} = -q_c A_c + Q_c V_c + (E_g + E_L)\frac{dm_{ic}}{dt}$$

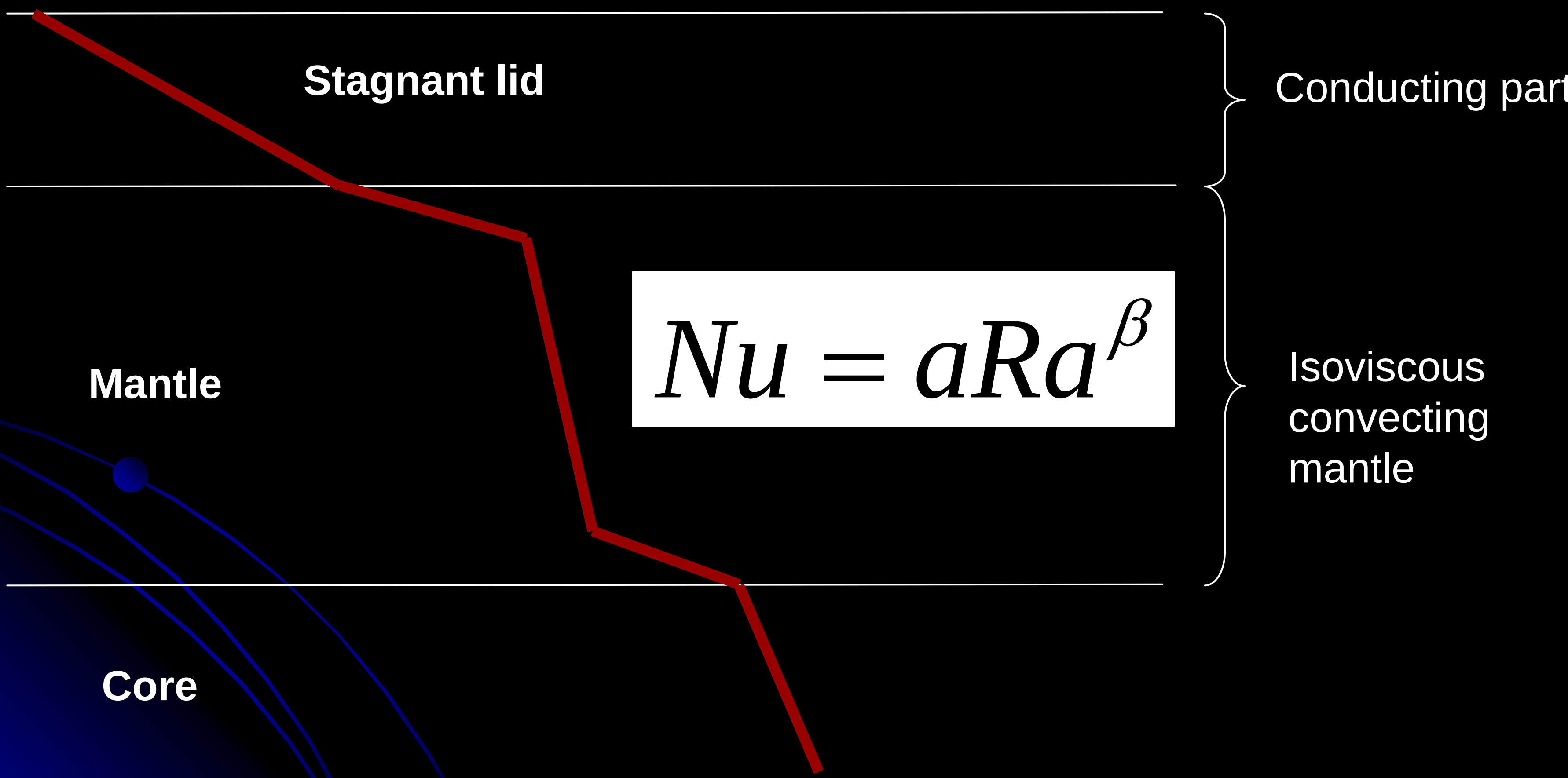


Two different approaches I



$$Nu = a\Theta^{-c} Ra^{\beta}$$

Two different approaches II



$$Nu = aRa^{\beta}$$

$$\rho_m C_m (T_m - T_l) \frac{dl}{dt} = -q_m + k \frac{\partial T}{\partial z}\bigg|_{z=z_l}$$

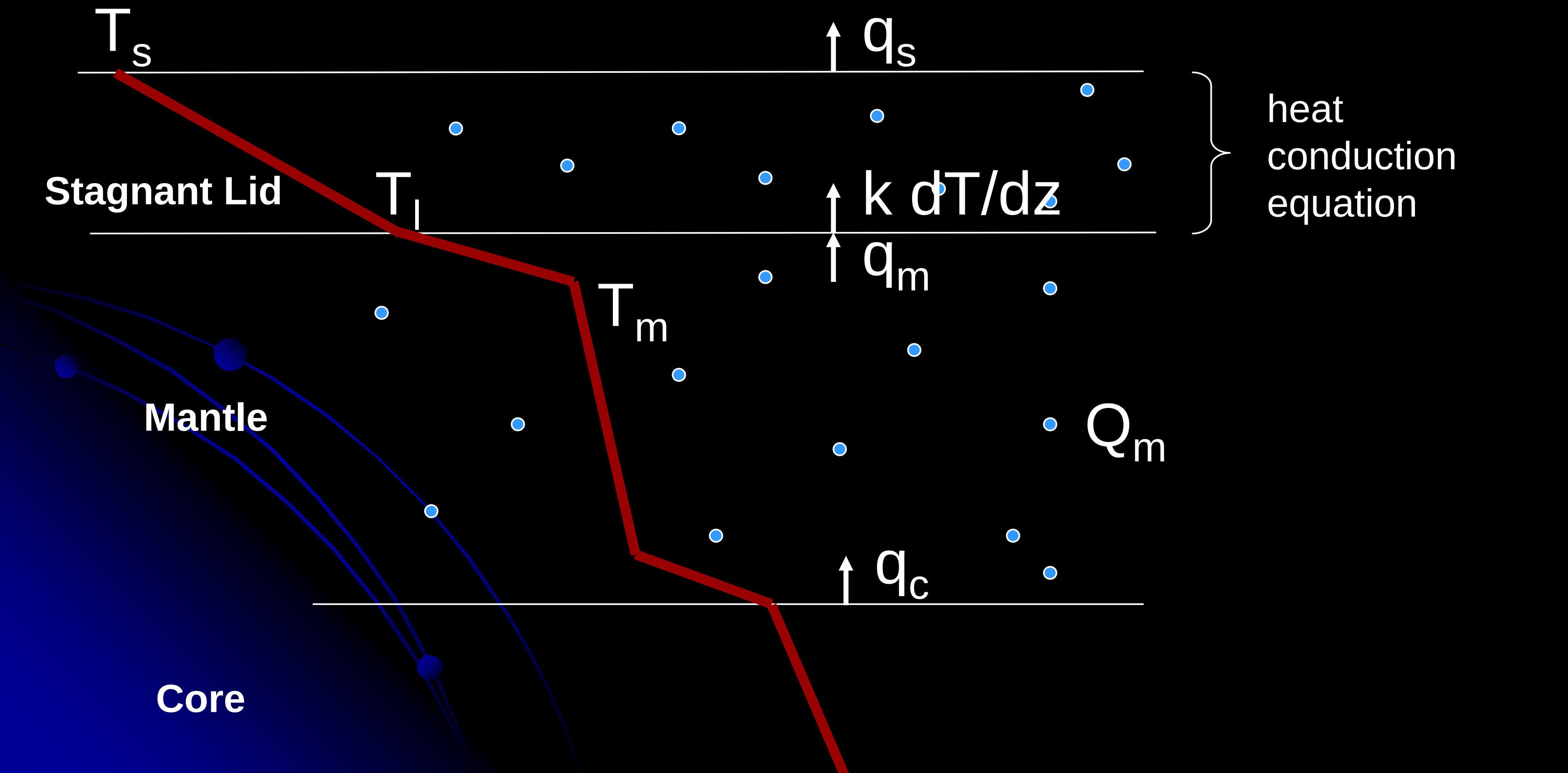
$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 k_l \frac{\partial T}{\partial r}\right) + Q_l = 0$$

Plate tectonics

$$T_l = T_s = 220K$$

Stagnant lid convection

$$T_l = T_m - \Delta T_e$$



Why do one-plate planets show long lasting volcanic activity?

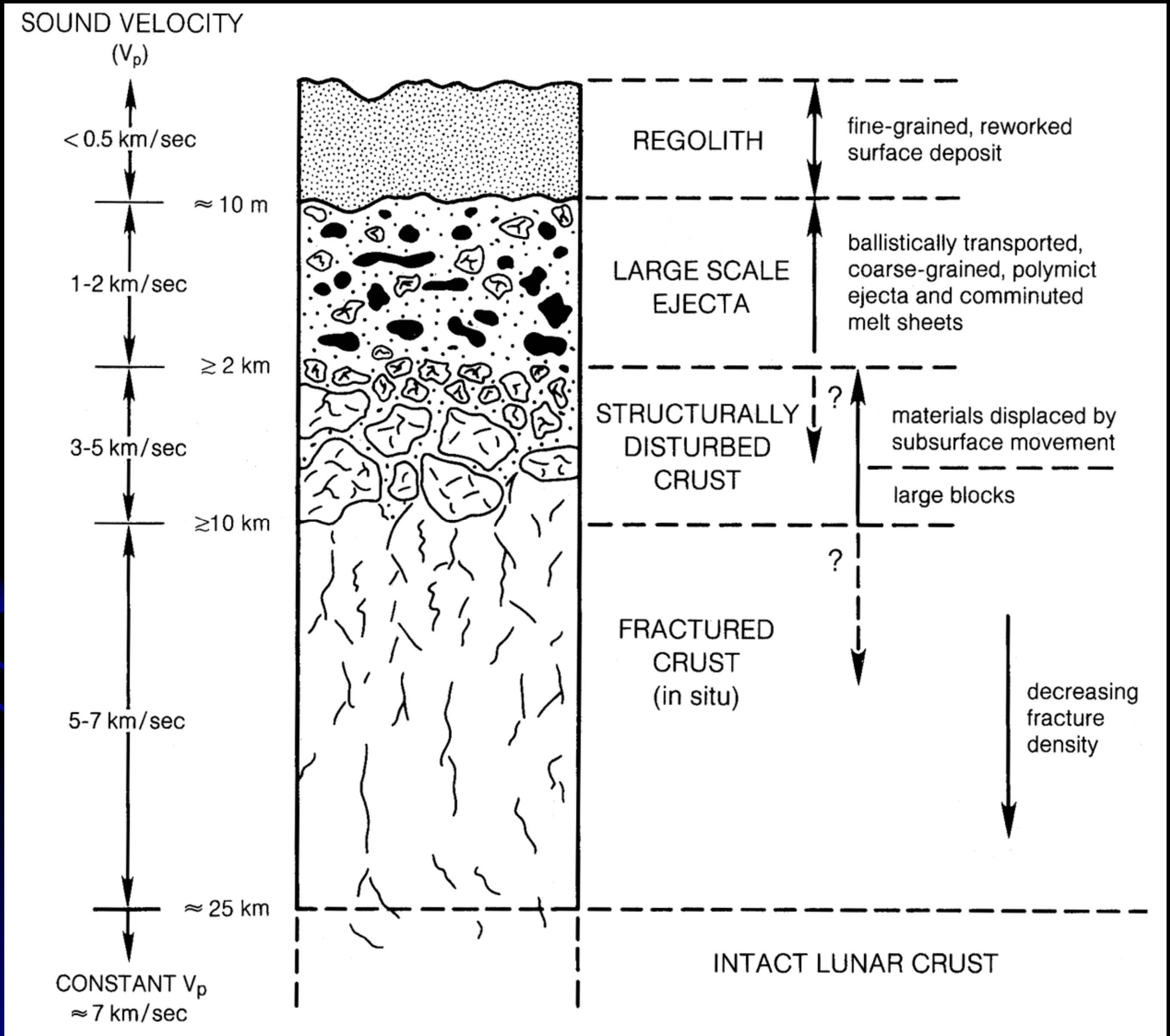
- Early thermal evolution models predict volcanic inactivity early in the evolution for the small planets

  - Larger amount of heat production elements?
  - Lower mantle melting temperatures?
  - Some mechanism of a slower cooling due to inefficient heat transport?

Thermal Conductivity

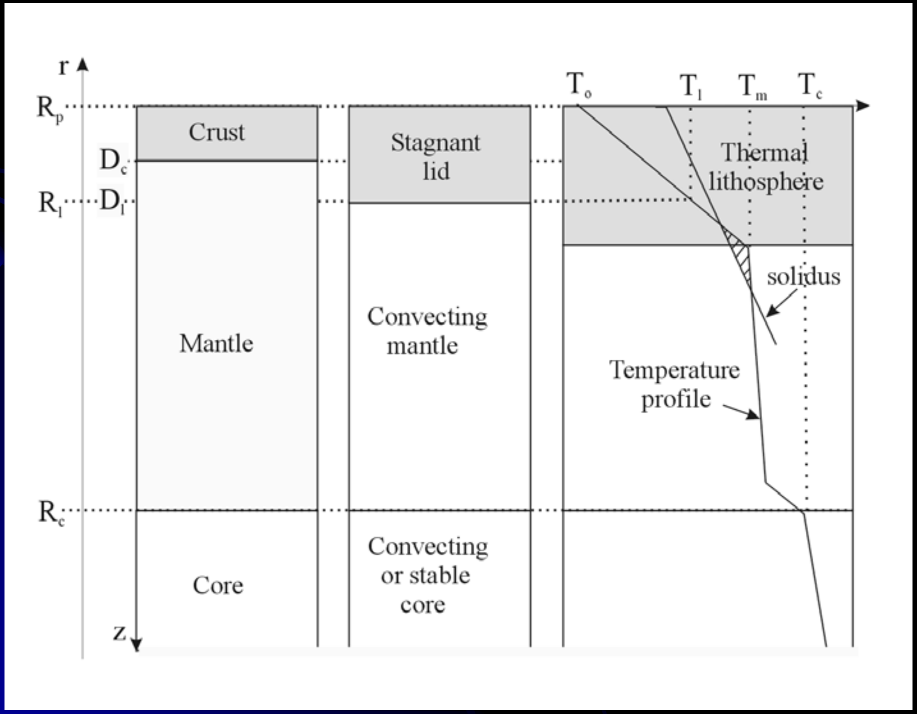
- Mantle material
  - Dependent on temperature and pressure
    ~ 3 – 4 W/(mK)
- Crustal material
  - ‘Compact‘ crust (e.g. basalt and andesite) ~ 2 W/(mK)
  - Fractured surface layer 0.01 – 0.5 W/mK

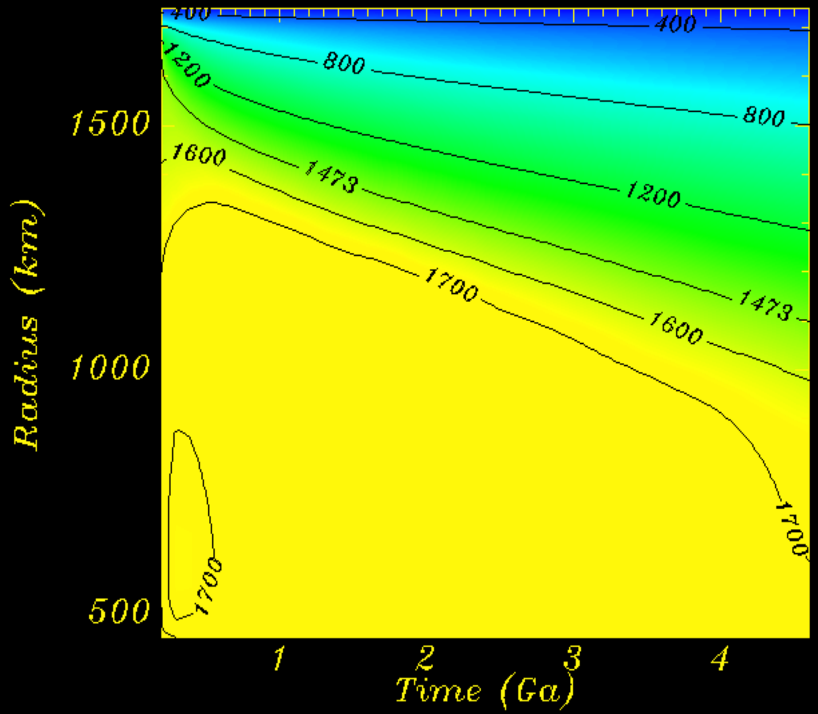
Regolith layer



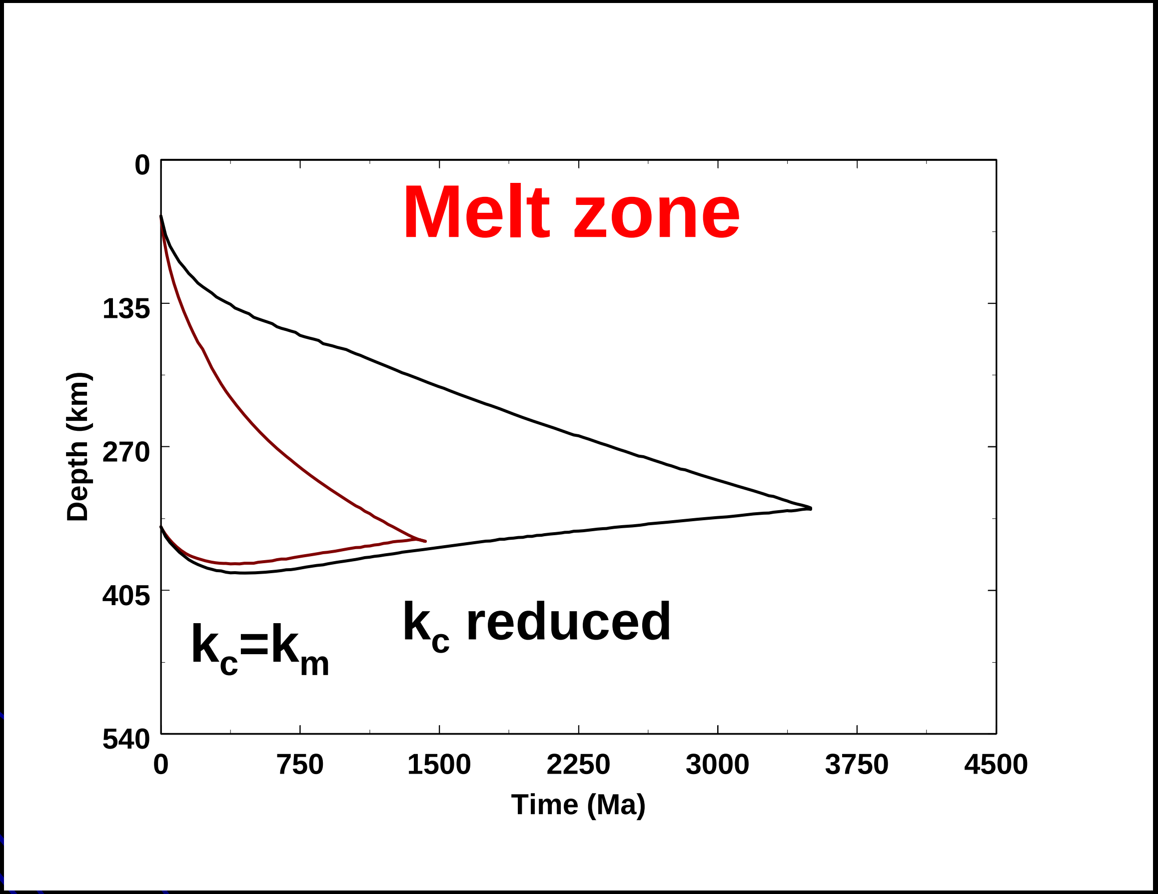
Crust Formation in a One-Plate Planet

- Melt production underneath the stagnant lid



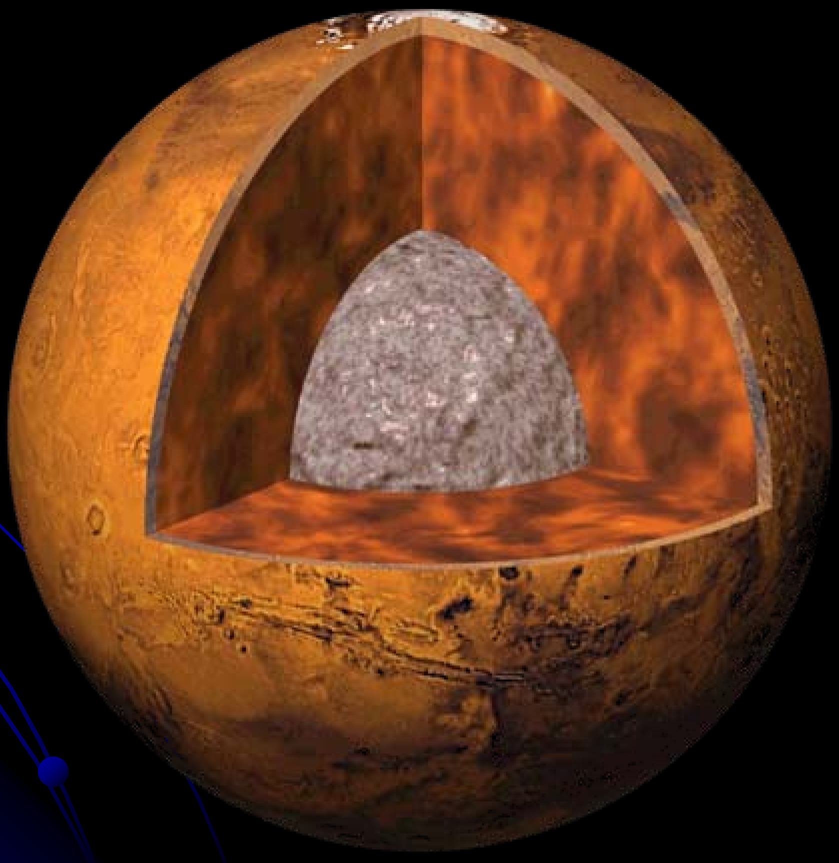


Mercury

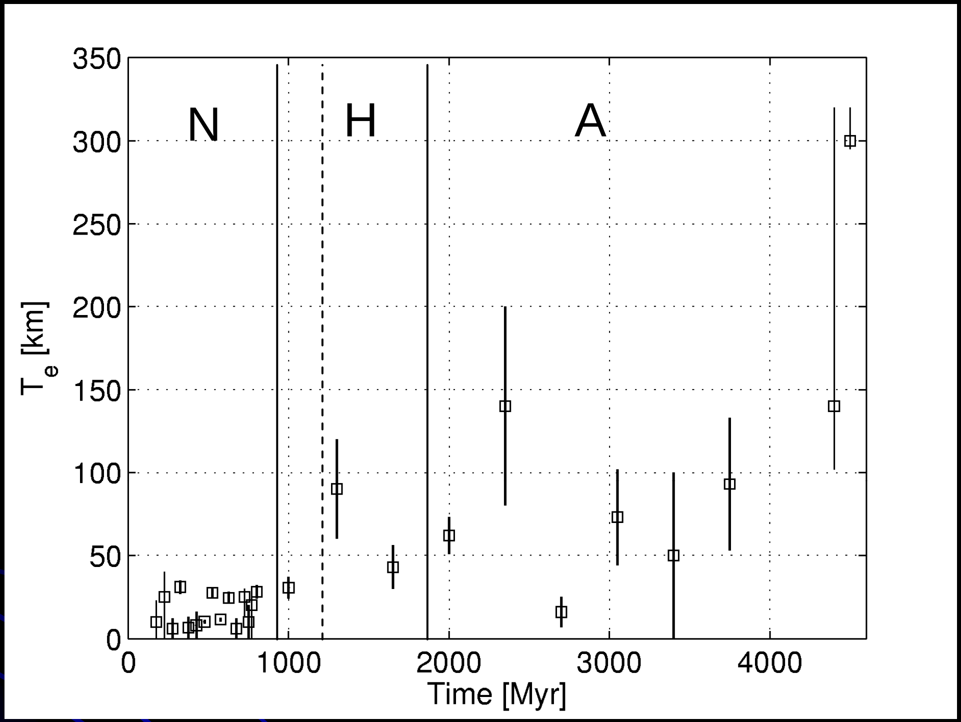


Mercury: Breuer et al., 2008; Moon: Ziethe et al., 2009 and
Mars: Schumacher and Breuer, 2006, 2007

What can we learn form the observed evolution of the elastic thickness on Mars?



Elastic Thickness Estimates - Mars



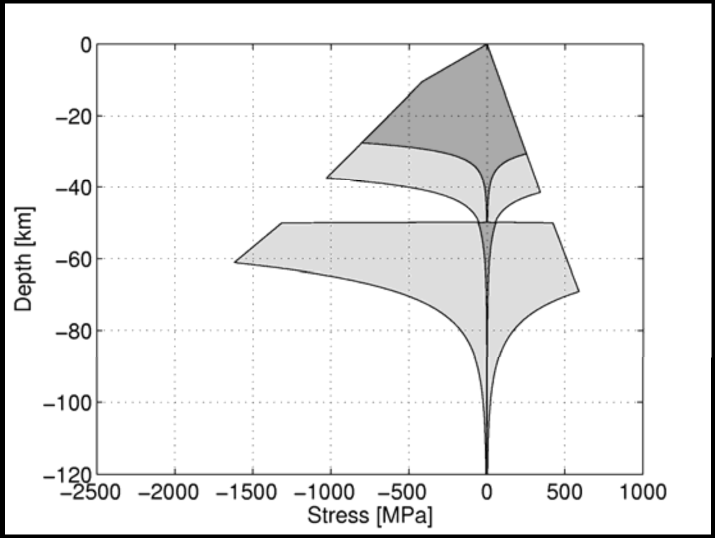
N = Noachian
H = Hesperian
A = Amazonian

- T_e during the Noachian / Early Hesperian ~ 15 km
- T_e during the Amazonian between 30 and 300 km
- General trend follows planetary cooling *but*
- Large T_e variations in the Amazonian

Modeling - Elastic Thickness

- Strength Envelope
- Bounding stress / temperature for decoupling

$$T(\sigma_y) = \frac{Q}{R}\left[\log\left(\frac{\sigma_y^n B}{\dot{\epsilon}}\right)\right]^{-1}$$



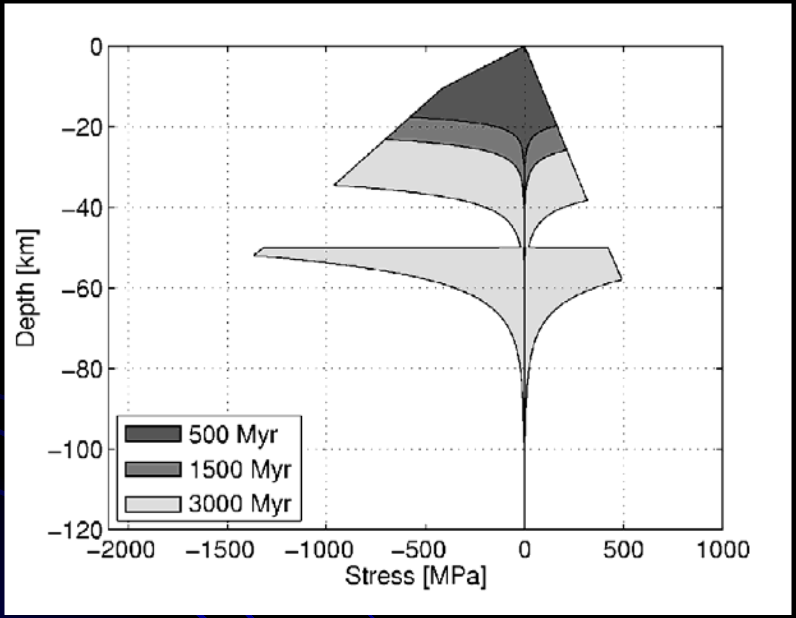
decoupled

coupled

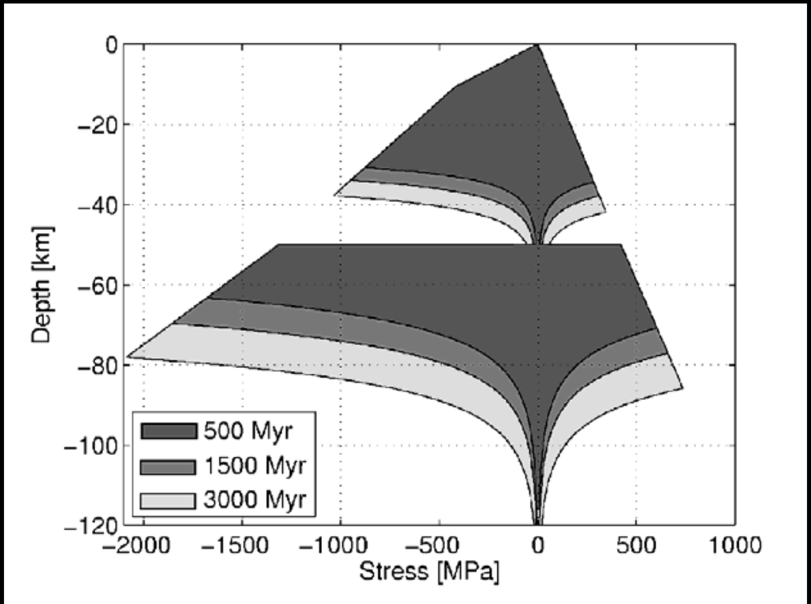
- Elastic thickness T_e
  - Decoupled: $T_e = (T_{e,m}^3 + T_{e,c}^3)^{\frac{1}{3}}$
  - Coupled: $T_e = T_{e,m} + T_{e,c}$

Strength Envelopes – Wet Crust

Wet mantle



Dry mantle

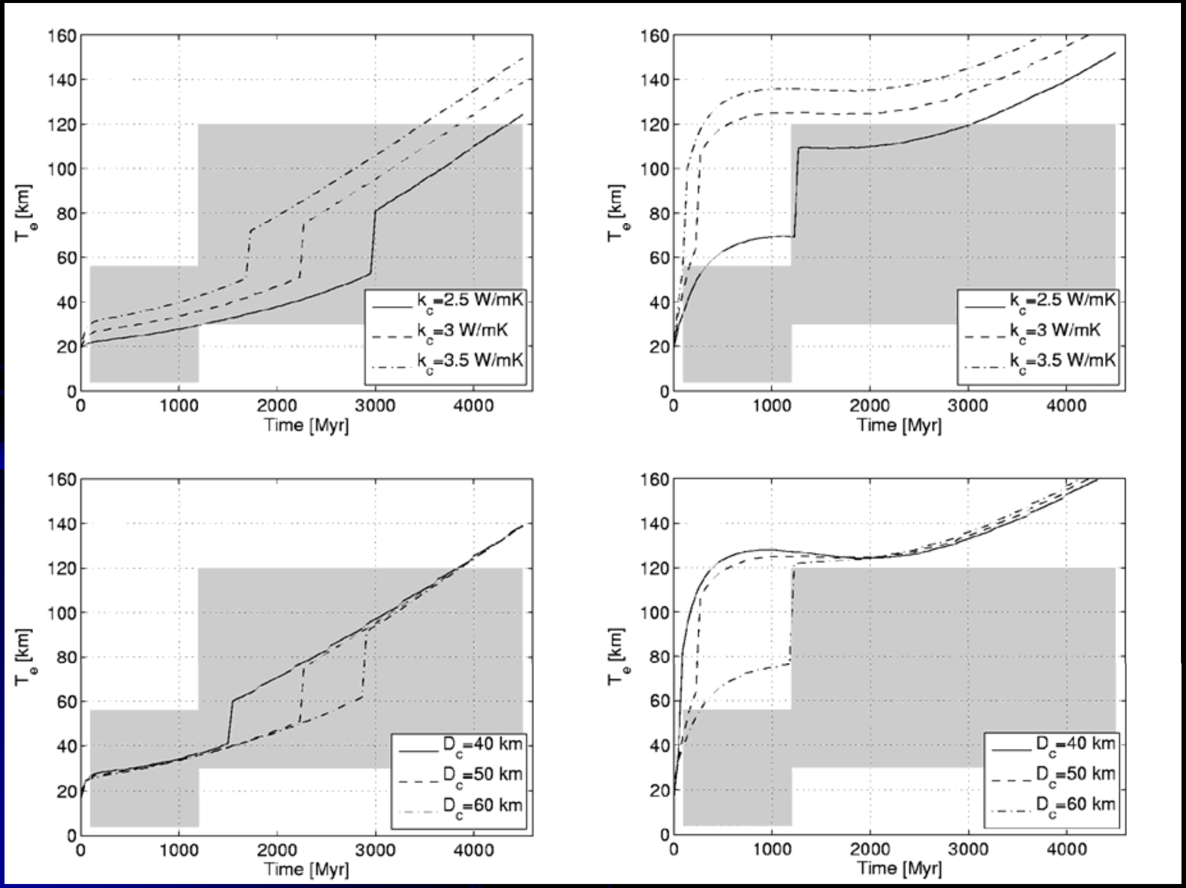


- Generally low T_e
- Long decoupling phase

- Generally large T_e
- Short decoupling phase

Elastic Thickness Evolution – Wet Crust

Wet mantle Dry mantle



Wet mantle:

- ➢ Low T_e
- ➢ T_e grows from 30 to 100 km

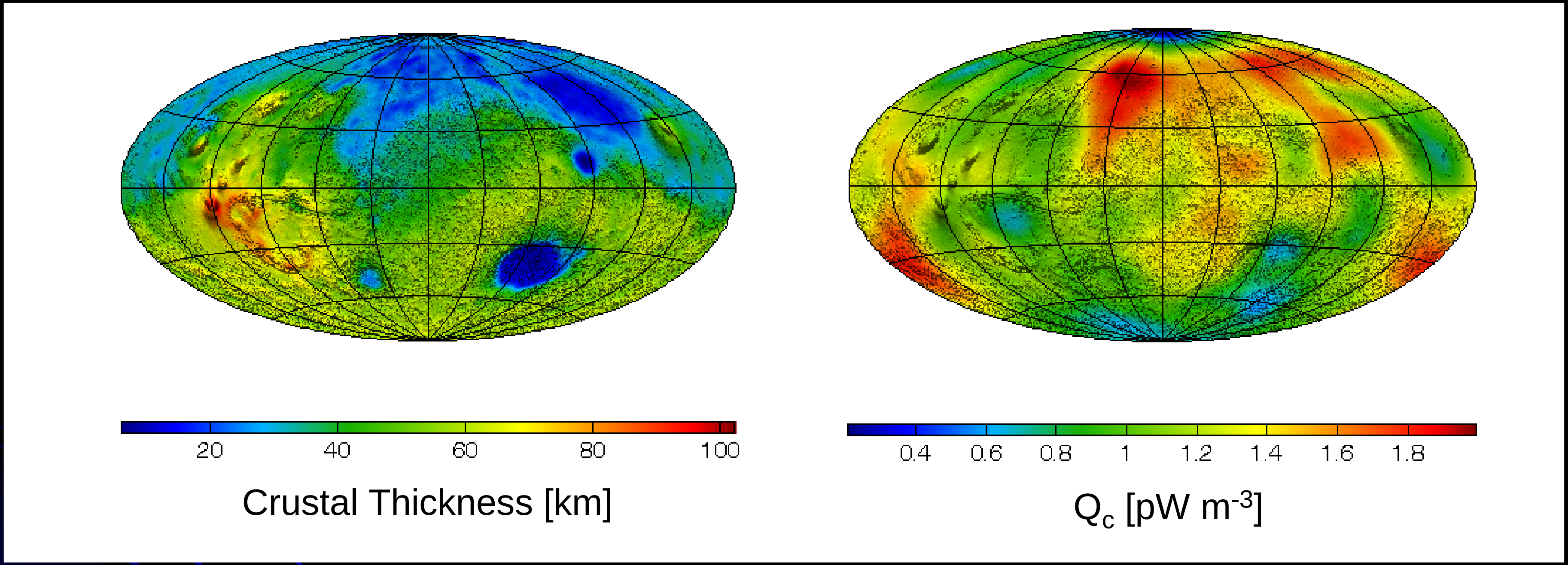
Dry mantle:

- ➢ Large T_e
- ➢ T_e grows from 50 to 140 km

Conclusion I

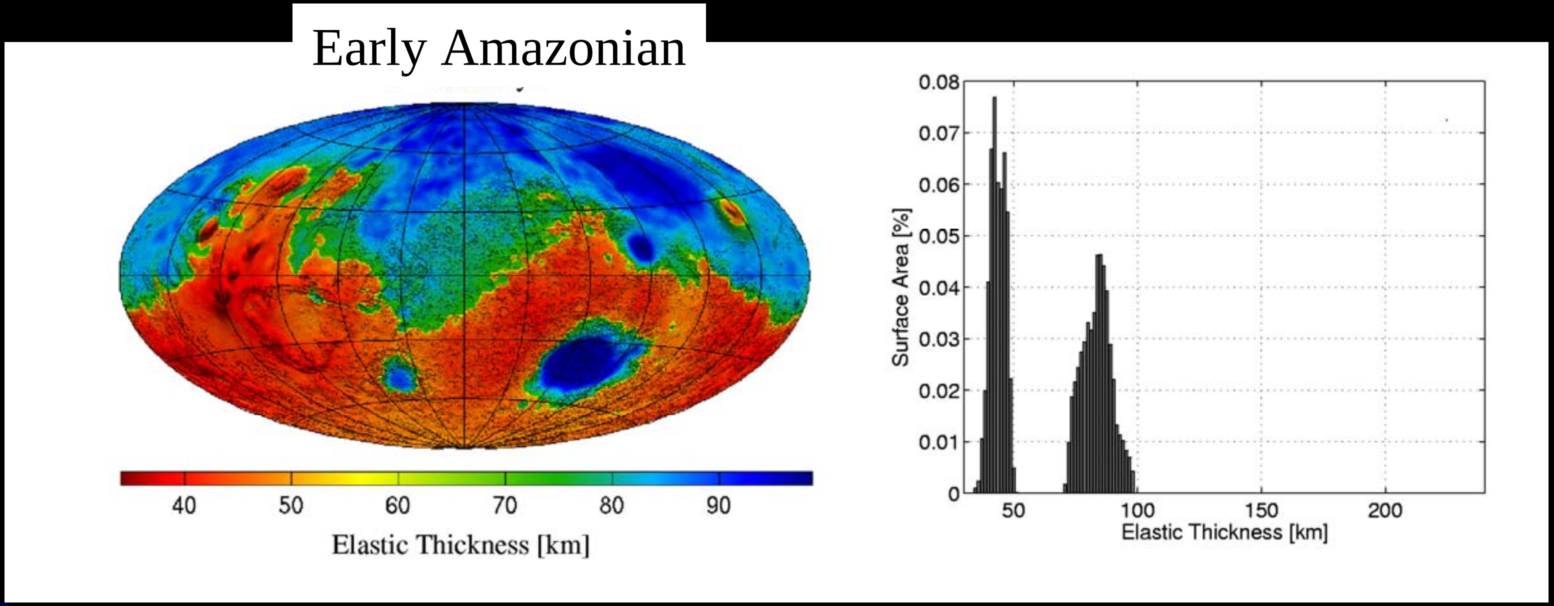
- A phase of rapid lithospheric growth occurred during the Hesperian and T_e increased from 30 to 60 km.
- The increase may be explained by the vanishing of the incompetent crustal layer and mechanical coupling of crust and mantle.
- The effect is only observable for a weak crustal rheology, e.g. wet diabase.
- The low T_e values in the Noachian are best compatible with a wet mantle rheology.

Lithospheric Modeling – Spatial Heterogeneity



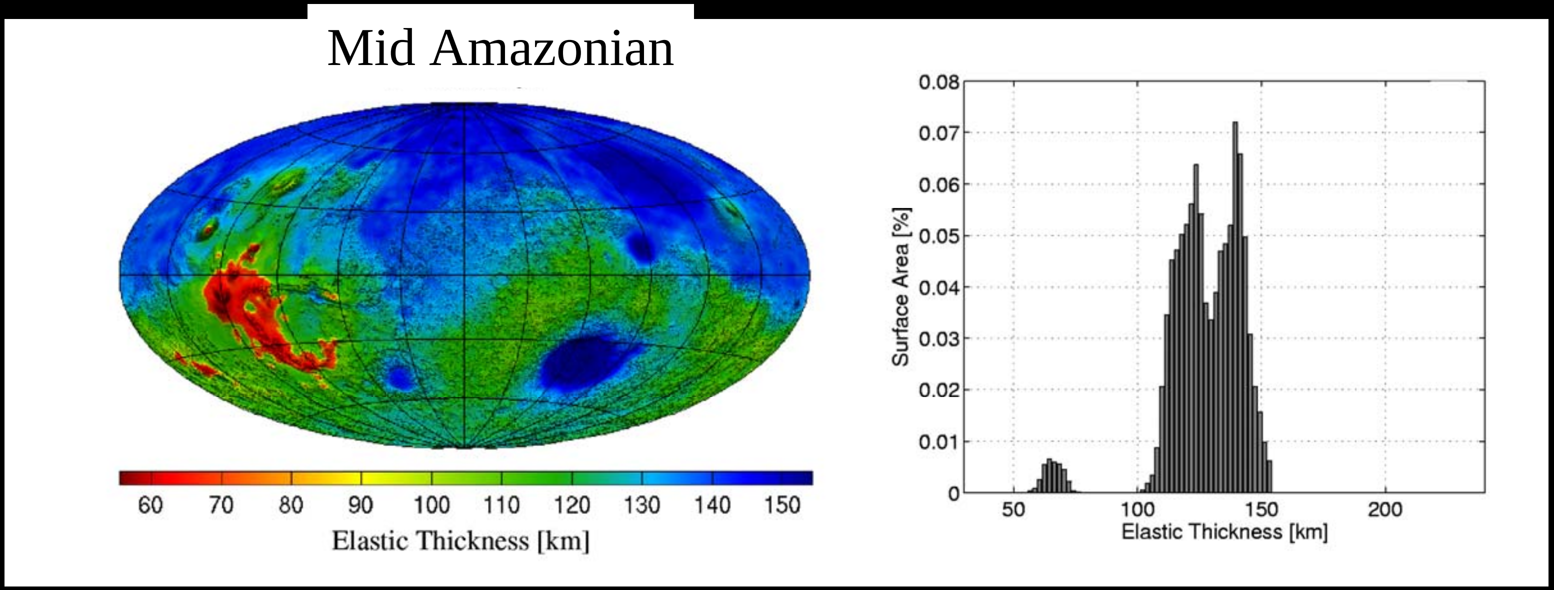
- Use constant background heat flow F_l and lid thickness D_l (we do not consider hot spots)
- Include varying crustal thickness [Neumann et al. 2004]
- Include varying abundance of HPE [Taylor et al. 2006]

Results – Elastic Thickness Distribution



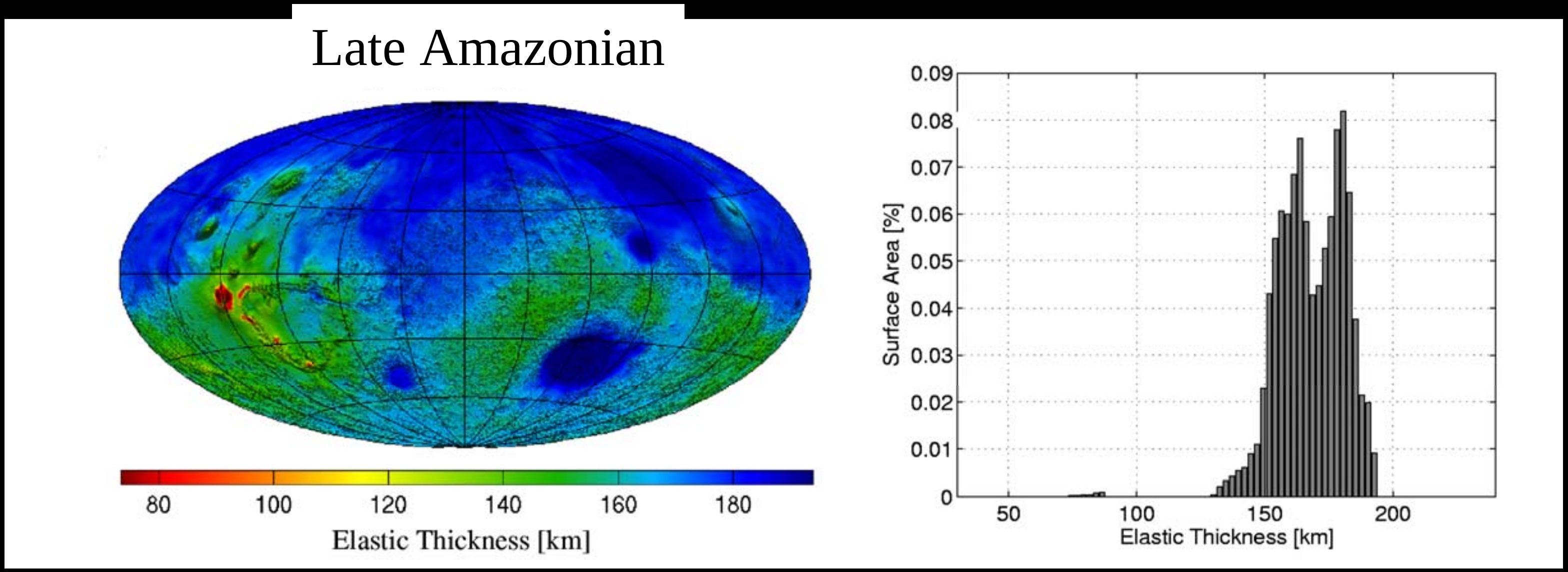
- T_e is small for large crustal thicknesses
- Q_c distribution has little influence on the results
- T_e distribution is bimodal, caused by rheological decoupling
- 30 km < T_e < 100 km

Results – Elastic Thickness Distribution



- T_e distribution is essentially trimodal, caused by the crustal dichotomy and rheological decoupling
- Rheological decoupling is limited to central Tharsis
- 55 km < T_e < 160 km

Results – Elastic Thickness Distribution



- T_e distribution is essentially bimodal, caused by the crustal dichotomy
- 75 km < T_e < 190 km

Conclusion II

- Rheological decoupling important up to the Amazonian (maybe today)
- Lithospheric structure similar to a two layer continental lithosphere on Earth

- D_c and Q_c variations result in spatial variations of 74 km < T_e < 190 km.

What needs to be done in the future?

- a lot ……
- we need more modeling but also more planetary data (e.g., seismic network)