Core-Mantle Boundary Physical Processes

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What Processes do we care about at the CMB?

- Thermal Coupling Mantle convection affects the heat flow from the core…influences the dynamo
- Mechanical and Electromagnetic Coupling Angular momentum transfer between core and mantle is not in doubt.Preferred model: A layer of conductance ~ 10^8 S. But pressure torques also probably important.
- Chemical Interaction Arising from disequilibrium at CMB. May affect core energetics and the dynamo process
- Material Transport between core and mantle.

Why do we care about Material Transport across the CMB?

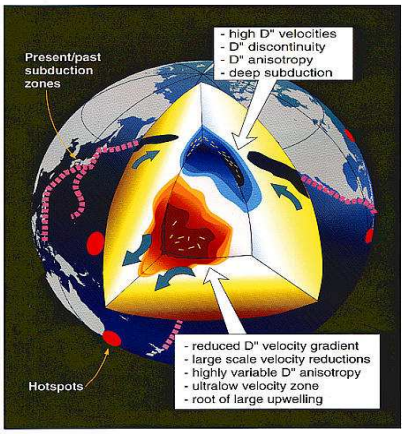
- May be relevant to the interpretation of geochemical reservoirs.
- May affect heat transport and mantle dynamics (e.g., if partial melting results from core constituents).
- May affect core energetics and the dynamo process
- May affect core-mantle coupling (geodesy)

Some "Facts" about the CMB

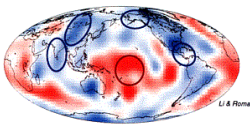
- Not necessarily sharp (despite being seismically well-defined)
- Material below is mostly liquid & material above is mostly solid (but the word "mostly" is very important!)
- Topography, perhaps several km.
- Topography + geodetics & geodynamo $\Rightarrow$ fundamental difference in rheology over a short distance.
- Coupling suggests material just above CMB is a nearly metallic conductor?

Relationship of the CMB to Overlying Mantle

- Region just above CMB is seismically anomalous (both as a layer and in lateral structure).
- This region may be the graveyard of slabs &/or repository of "primordial" material
- This region ***might*** be sampled in mantle circulation (plumes)



ULVZ



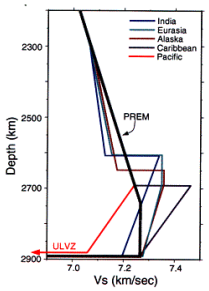
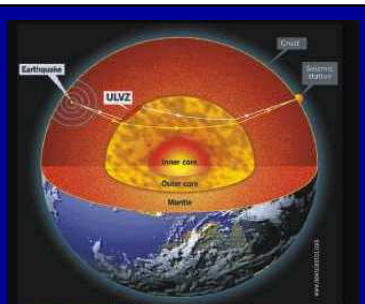
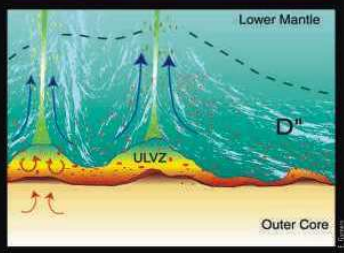


Fig. 4



Roundabout route: Some seismic waves from deep earthquakes pass straight into the outer core, but others first skid along the boundary between core and mantle, passing through the ultralow-velocity zones.



Sediments (brown) may be filling inverted "basins" at the core-mantle boundary, or the core may be infiltrating (red) or melting (yellow) the mantle. Courtesy of E. Garnero.

Two Extreme Viewpoints

•Mantle and Core do not exchange material.	•Mantle and Core exchange material.
•Thermal boundary layer to accommodate core heat.	•Thermal boundary layer is present but not dominant feature
•D'' results form primordial mantle differentiation and settling (slabs)	•D'' and ULVZ result from core-mantle exchange

Some Guiding Principles

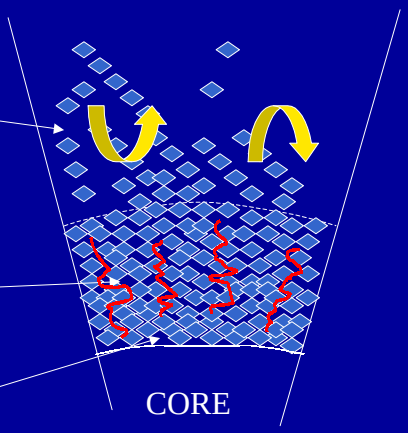
- Core and mantle cannot reach (global) chemical equilibrium! Even if they ever did (very unlikely) the system is continuously driven away form equilibrium by secular cooling.
- Core and mantle must reach *local* chemical equilibrium! Kinetics probably unimportant
- Consequences of equilibration may be small or large.. Depends on the thickness of the region affected
- Even a "large" effect does not have to affect surface observables! It may be confined to D''.

Differentiation in the Mantle?

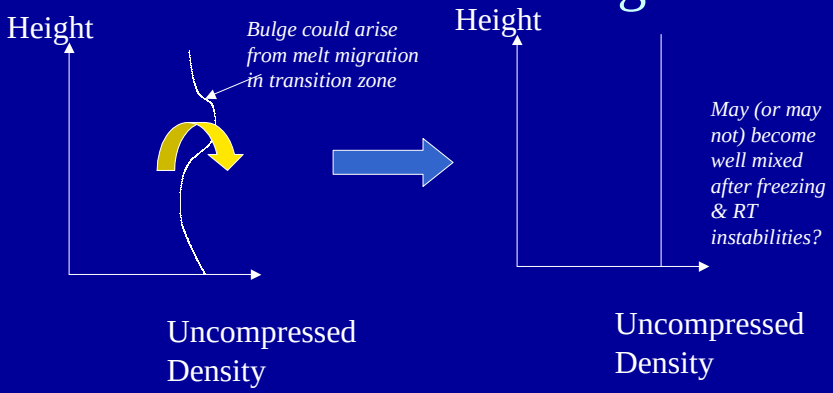
Dense suspension, vigorously convecting. May be well mixed

Much higher viscosity, melt percolative regime. Melt/solid differentiation?

High density material may accumulate at the base



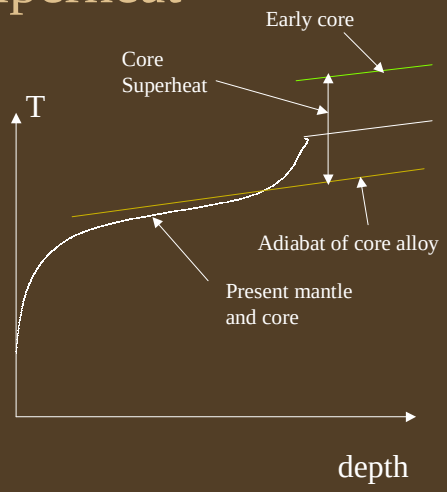
Rayleigh-Taylor Instabilities & Convective Stirring?



But this all depends on the (as yet unknown) phase diagram!

Core Superheat

- This is the excess entropy of the core relative to the entropy of the same liquid material at melting point & and 1 bar.
- Corresponds to about 1000K for present Earth, may have been as much as 2000K for early Earth.
- *It is diagnostic of core formation process*...it argues against percolation and small diapirs.



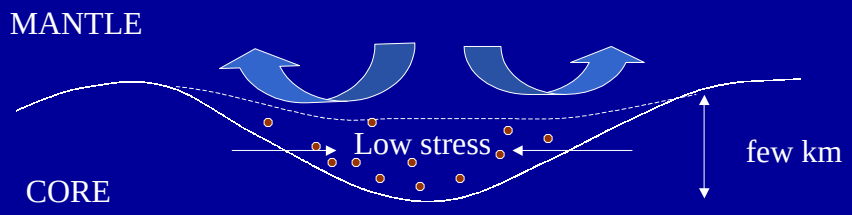
What are the Unimportant Processes?

- Solid state diffusion from core liquid into mantle solid -except on the grain scale and except for hydrogen and helium. (These are important exceptions!)
- Capillary action working against gravity (can only act over distances ~ tens of meters).
- Convective Entrainment of core into mantle (rheologically implausible, even for small amounts)

What are the potentially Important Processes?

- Flow of core fluid into the mantle aided by deviatoric stresses of mantle convection & presence of topography. (Requires percolation)
- Partial melting of lowermost mantle, perhaps because of water (hydrogen) from the core.
- Grain boundary wetting driven by chemical potential differences (like capillary action but stronger).
- Underplating of the CMB driven by supersaturation of the core.
- Redistribution along the CMB driven by P,T - dependent solubility

Suction of Core Fluid into Mantle



Mantle convection provides deviatoric sress that can suck core fluid into the mantle. Stress depends on rheology, but can be ~100 bars, implying affected region ~km

Percolation

- Requires melt interconnection (dihedral angle <60º)
- Metals have high surface energy; Fe alloys do not interconnect, at least at low pressure.
- *Not known for certain*

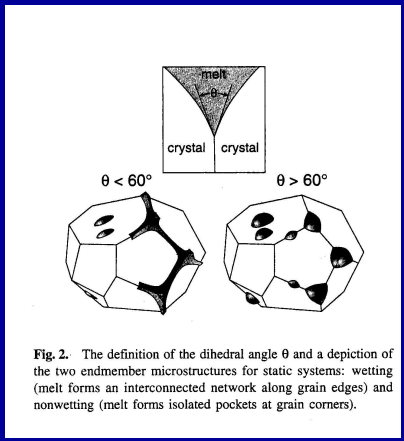
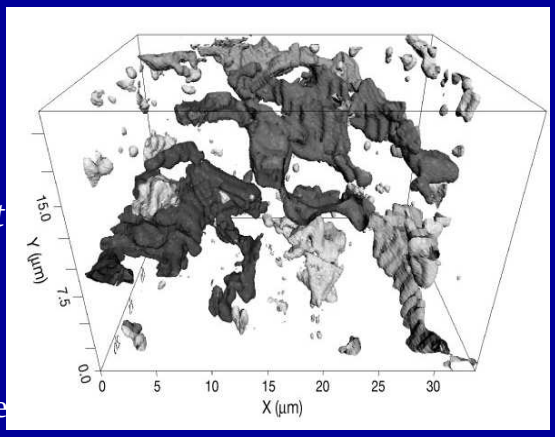


Fig. 2. The definition of the dihedral angle θ and a depiction of the two endmember microstructures for static systems: wetting (melt forms an interconnected network along grain edges) and nonwetting (melt forms isolated pockets at grain corners).

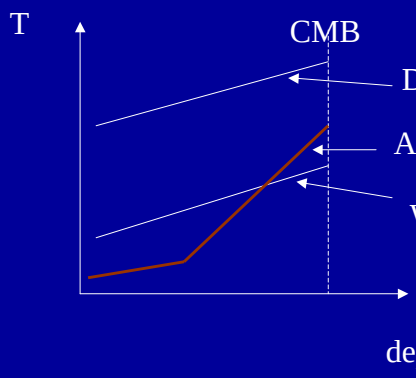
Effects of Shear on Percolation

- Experiments by Kohlstedt group indicate interconnection *but probably not down to very small melt fraction.*



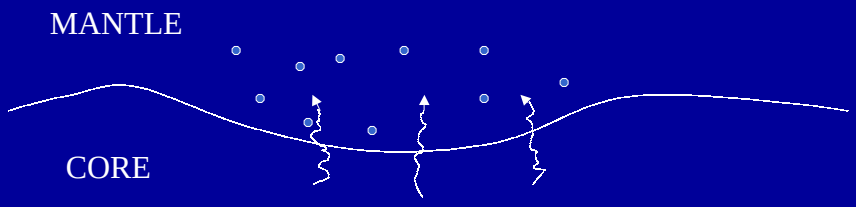
Olivine +Fe/Ni

Partial Melting of Lowermost Mantle caused by H from Core



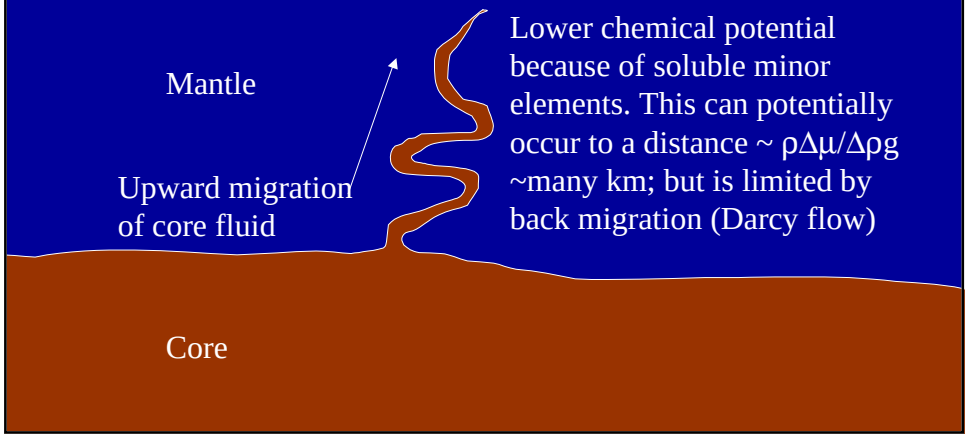
H fugacity of the core may be larger than that in the lower mantle because of the solubility of H in the core plus early outgassing of mantle

Migration of Hydrogen into Mantle (by Diffusion) causes melting

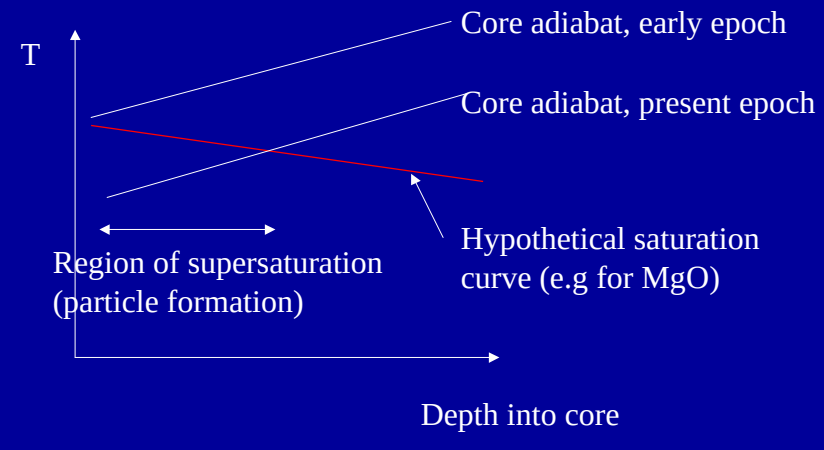


Partial melting provides pathways for atoms from the core (not just hydrogen). Diffusion in partial melt could proceed over ~10km or more, depending on density, melt fraction….

Grain Boundary Wetting (Etching) driven by Chemical Driving Forces?



Underplating of the CMB as the Cooling Core Supersaturates



Energetic Consequences of Supersaturation

Energy release ~ $-M_{core}\,(\Delta\rho/\rho)gR_{core}.(dx/dt)$

Mole fraction of saturated component

Solubility $x \sim \exp[-\Delta H/kT]$

$dx/dt = (dx/dT).(dT/dt)$

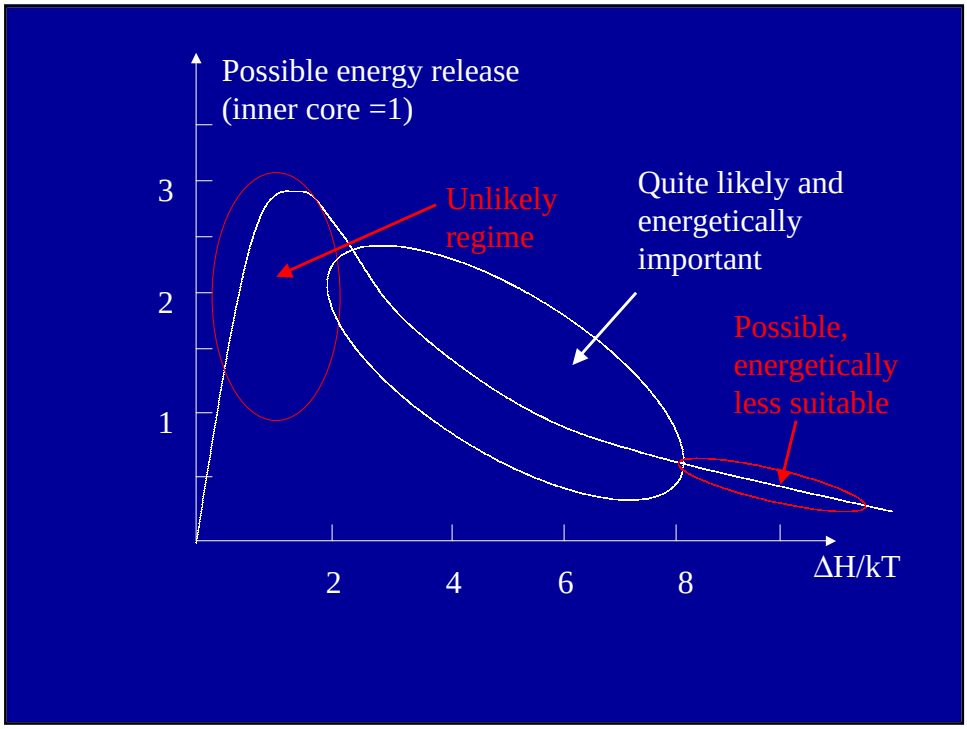
$\Delta x/x = (\Delta H/kT).(\Delta T/T)$

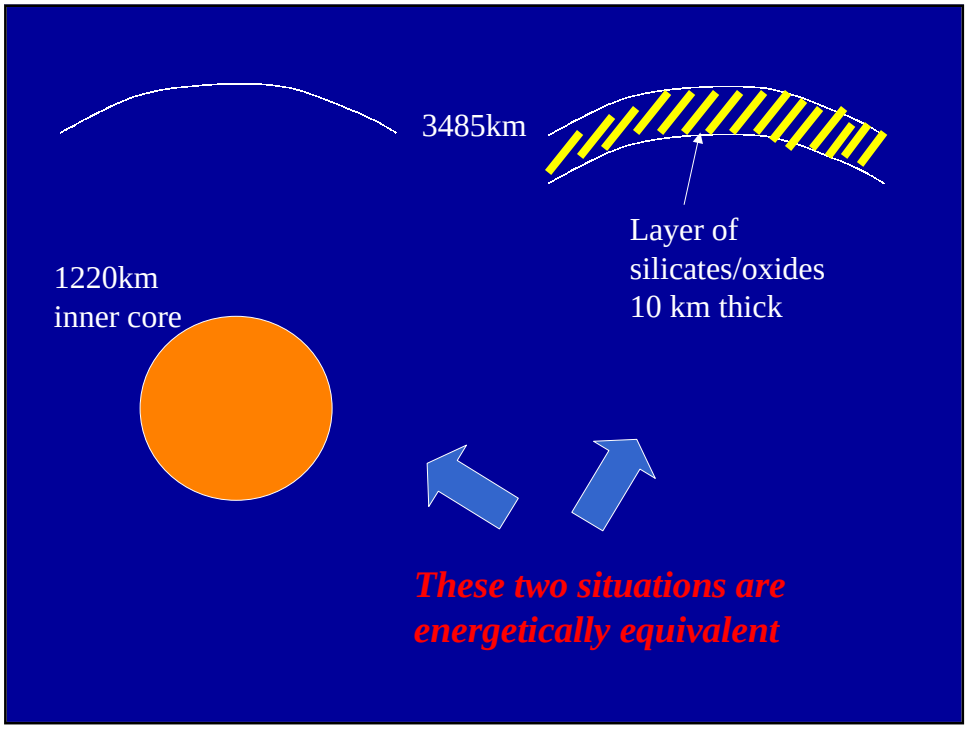
Total change over geologic time

$\Delta H/kT$ is the most important parameter

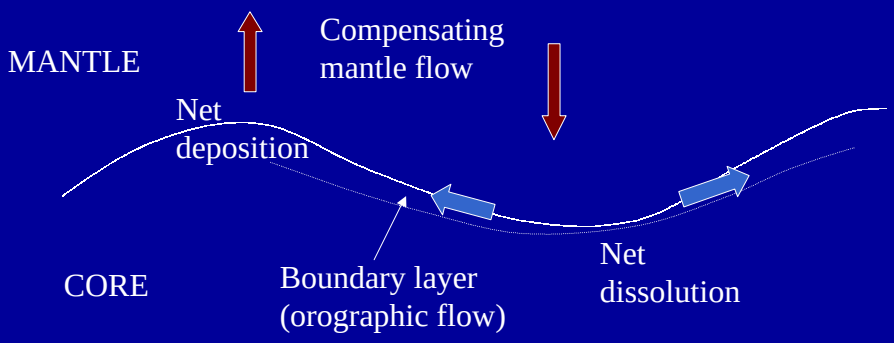
Regimes of Parameter Space

$\Delta H/kT < 1$	Very soluble, unlikely to supersaturate; temperature decrease too small to produce large change in solubility
$\Delta H/kT \sim$few	limited solubility, may supersaturate; large energy release
$\Delta H/kT >> 1$	very limited solubility but also not much material available to sediment up


Possible energy release
(inner core =1)
3
2
1
Unlikely
regime
Quite likely and
energetically
important
Possible,
energetically
less suitable
2
4
6
8
ΔH/kT


3485km
Layer of
silicates/oxides
10 km thick
1220km
inner core
These two situations are
energetically equivalent

Redistribution along the CMB driven by P,T -dependent solubility



This is shown for the case where solubility increases with pressure. In principle, you can transport ~km in 10 million years!

Comparison of Processes

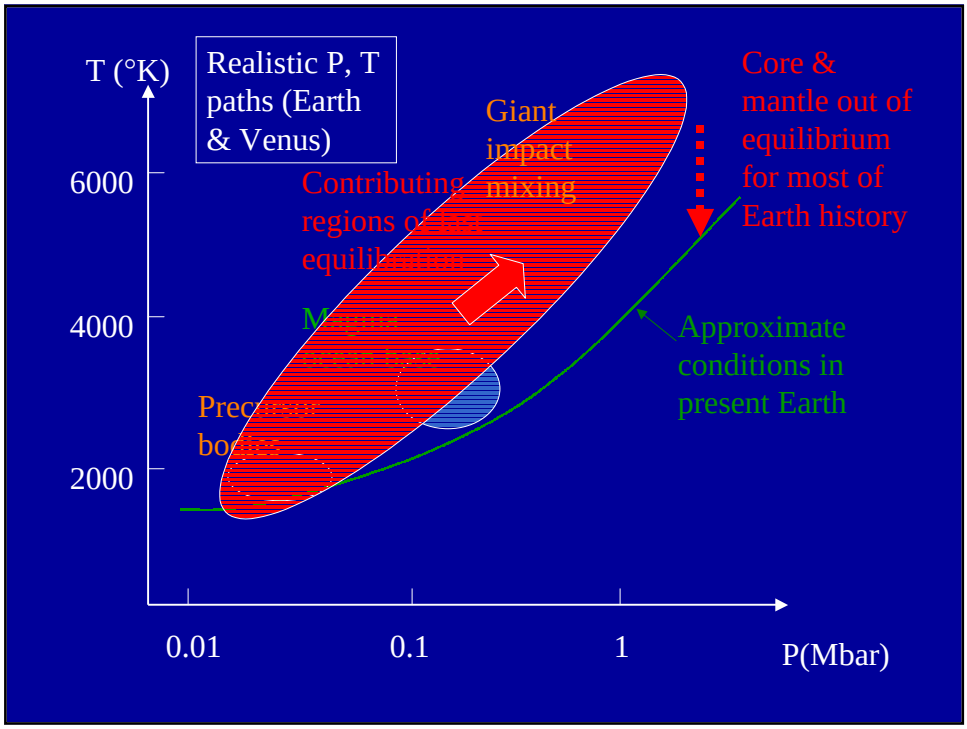
Process	Enabling Steps	Transport Rate (km/Ga)
Suction	Percolation; dynamic topo	10
Wet melting	Excess H in core	100
Etching	Percolation; chem reaction	10
Underplating	Supersaturation	100
Topographic redistribution	T,P dependent solubility	100

Conclusions

- Several different processes exist for transport across the CMB. Any one of them can have important consequences over geologic time.
- ***None*** of them is guaranteed to be important. But it is unlikely that they are ***all*** unimportant.
- Tens to hundreds of km of mantle thickness have been affected.
- Influence on geochemical reservoirs depends on the extent to which this layer has been sampled by large scale mantle circulation or plumes.

What do we need to know?

- Mineral physics data: Phase diagrams, melting, partitioning.
- Characterization of seismic structure at multiple scales (topography, long wavelength structure, scattering…)
- Geochemical Evidence for or against role of the core.
- Dynamical modeling of infiltration (to test against these data)



Repeating the Important Points

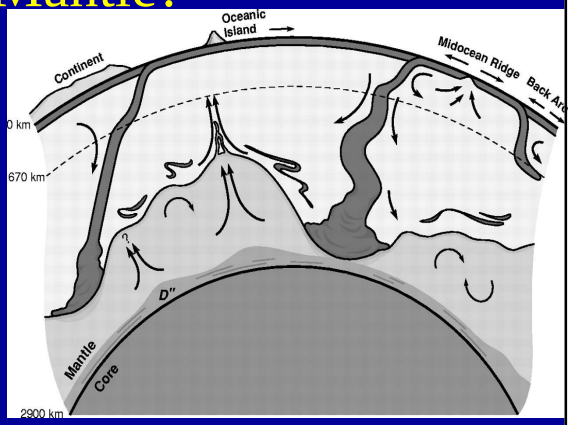
- Core-mantle interaction could influence the core significantly even if it does not greatly affect the accessible mantle
- If the core ever equilibrated at high T, then it will probably supersaturate as it cools. This can significantly add to dynamo energy sources. ***It can easily be as important as inner core growth.*** Of course, some planets may not cool much… this will limit all sources ∝ dT/dt
- Mantle "drying" may cause hydrogen flow across the CMB.
- Core infiltration can "metasomatize" the lowermost mantle (as well as affecting the electromagnetic coupling).
- Differences among planets determined mainly by cooling rate and degassing. Plate tectonics is the main control!

The End

(back up slides follow)

Consequences of a Layered Mantle?

- Some evidence from seismology (especially for D")
- Might be a consequence of transport across the CMB
- Reduces the ***observable*** (geochemical) effect of transport across the CMB by limiting transport into upper mantle



Kellogg *et al*, 1999

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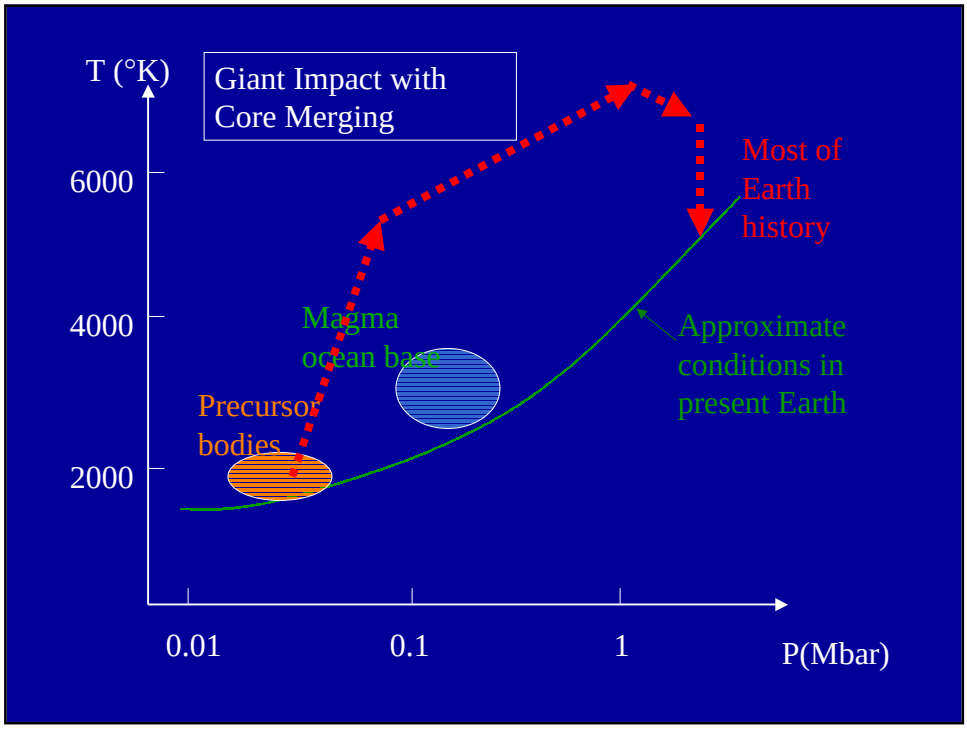
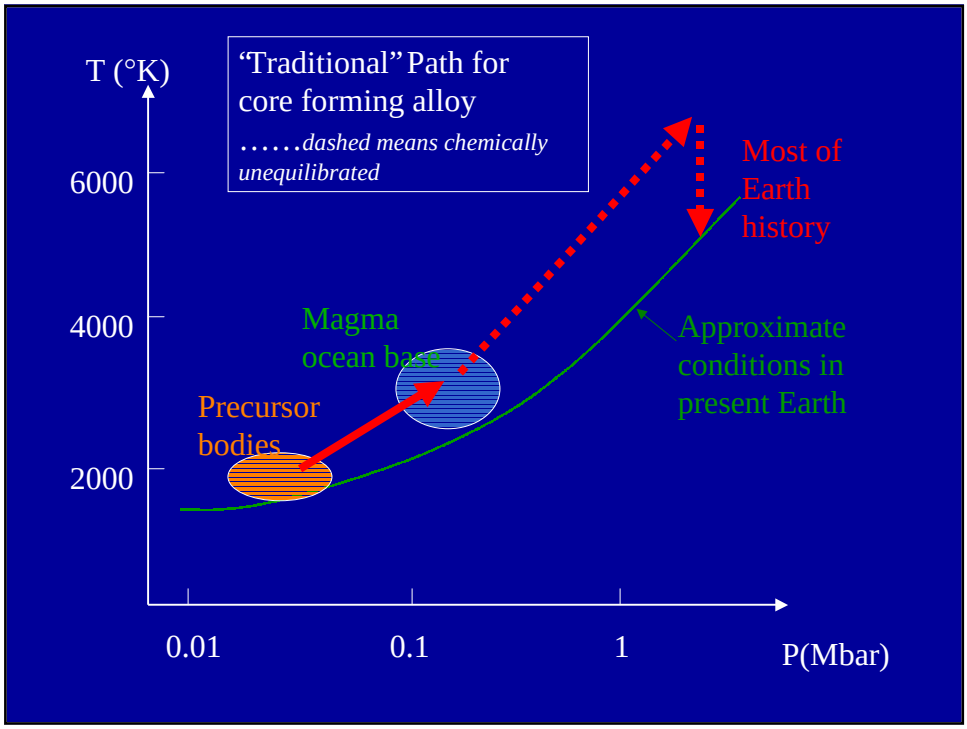
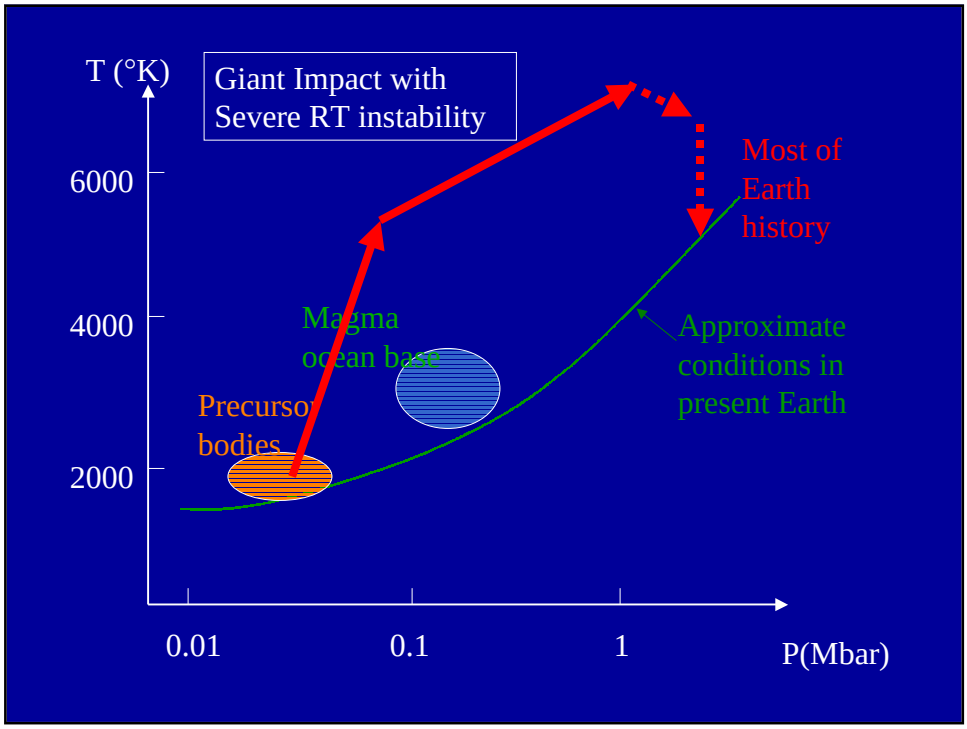



T (°K)
"Traditional" Path for core forming alloy
……dashed means chemically unequilibrated
6000
4000
2000
Most of Earth history
Magma ocean base
Approximate conditions in present Earth
Precursor bodies
0.01
0.1
1
P(Mbar)


T (°K)
Giant Impact with Severe RT instability
6000
4000
2000
Most of Earth history
Magma ocean base
Approximate conditions in present Earth
Precursor bodies
0.01
0.1
1
P(Mbar)

Earth

1. Most of the core is liquid and predominantly Fe.
2. Identity of other elements not known
3. Presence of the inner core explained if central T for Earth is 5000 to 6000K.
4. Age of inner core is not known; probably important for dynamo generation.