Implications of Planet Formation Models for the Initial State of Earth

Dave Stevenson, Caltech

KITP, March 16, 2004

Dynamical Questions

(with implications for chemistry and isotopes)

- What is the timescale of Earth formation? (Time to accumulate 90%? Time to accumulate 99%?)
- What is the size spectrum of bodies colliding with protoEarth? (Incomplete accumulation into runaway embryos? Role of tidal disruption?)
- What is the mixing? (The delivery of material from 0.5 AU or 2 AU or 5AU…)
- What is timing of gas loss (relative to all this)?

Relationship of these Issues to Data

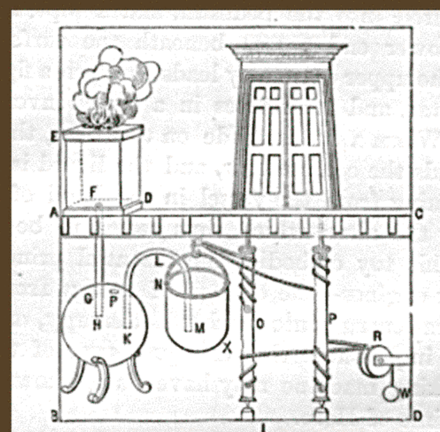
• Formation timescale ⇒	• Hf-W isotopes
• Small vs.Big bodies ⇒	• Hf-W isotopes & Core composition. Core superheat. Mantle layering?
• Mixing ⇒	• Oxygen isotopes

Summary

- Hf-W does not (necessarily) provide the timescale for earth formation. Late(~50 Ma) large impacts cannot be excluded.
- Mantle composition & core temperature indicate <u>both</u> large & small bodies in Earth formation
- Mixing of Earth & moon-forming giant impactor could cause the similar Earth & Moon oxygen isotope pattern *even if the projectile had Marslike oxygen*.

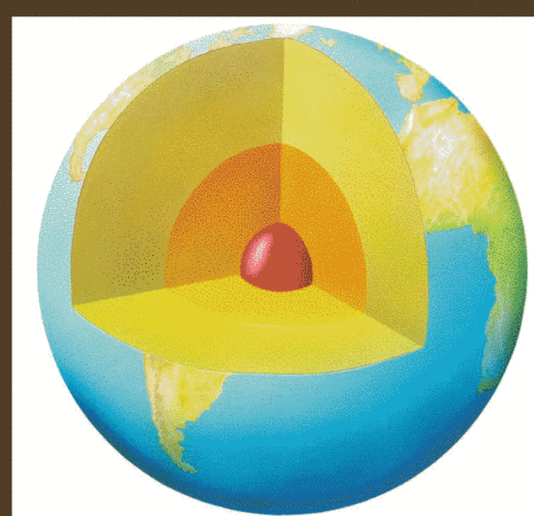
How to think about a Planet?

- Could discuss provenance- the properties of an apple depend on the environment in which the tree grows
- Or could discuss it as a machine (cf. Hero[n], 1st century AD)
- ***Need to do both***



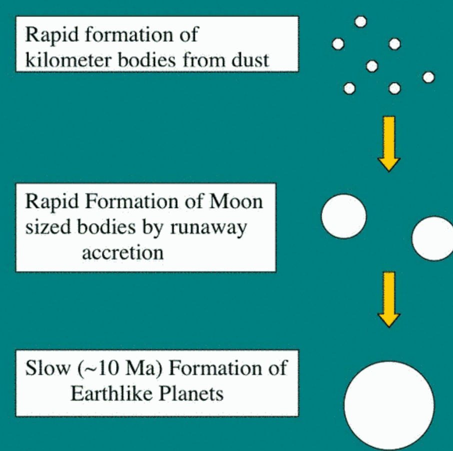
Earth

1. Most of the core is liquid and predominantly Fe.
2. Identity of other elements not known, but Si is suspected and requires high T.
3. Presence of the inner core explained if central T for Earth is 5000 to 6000K.
4. Increasing evidence of modest mantle layering- possibly primordial



Terrestrial Planet formation

- Early stages are fast but may nonetheless involve quite large bodies
- Orbit crossing limits growth of big bodies: Time ~ 10^7- 10^8 yr.
- Last stages in *absence* of solar nebula [astronomical obs.]
- Mixing across ~1AU likely (chemical disequilibrium?)



Some Important Numbers

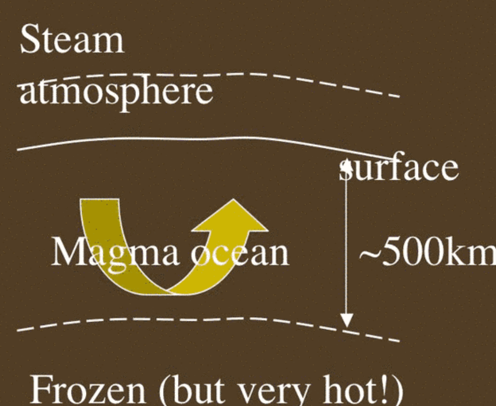
- $GM/RC_p \sim 4 \times 10^4$K *where M is Earth mass, R is Earth radius, C_p is specific heat*
- GM/RL ~1 *where L is the latent heat of vaporization of rock*
- Equilibrium temp. to eliminate accretional heat ~400K *(but misleading because of infrequent large impacts and steam atmosphere)*
- $E_{grav} \sim 10\ E_{radio}$ *where E_{grav} is the energy released by Earth formation and E_{radio} is the total radioactive heat release over geologic time*

The Importance of Giant Impacts

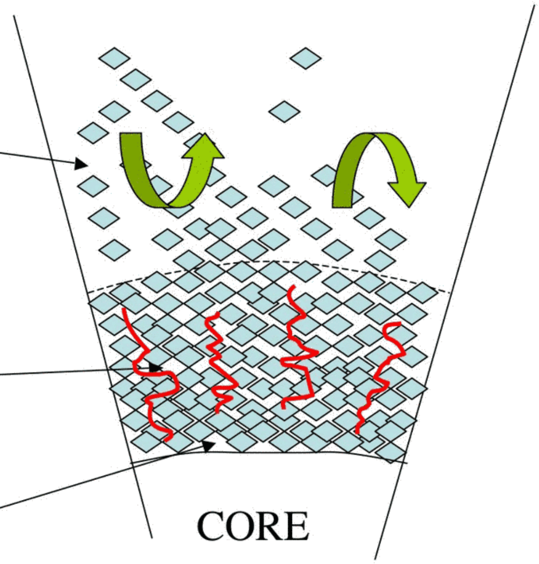
- Simulations indicate that Mars-sized bodies probably impacted Earth during it's accumulation.
- These events are extraordinary… for a thousand years after one, Earth will radiate like a low-mass star!

The "Inevitability" of a Magma Ocean

- Burial of accretional energy prevents immediate re-radiation - a chill crust can form.
- In presence of sufficient atmosphere (e.g., steam), the magma ocean is protected.
- Lower mantle can easily freeze because of pressure - this limits magma ocean depth



Differentiation in the Mantle?



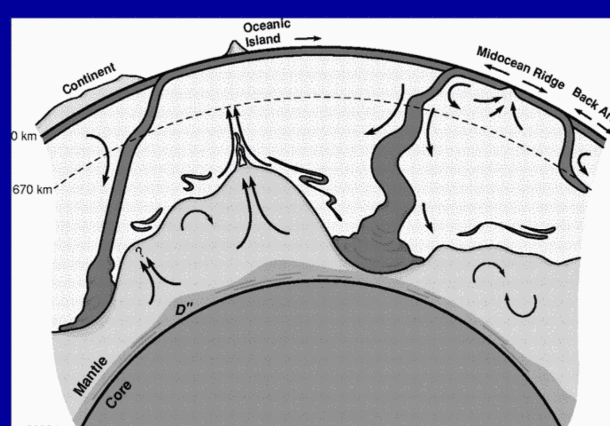
Dense suspension, vigorously convecting. May be well mixed

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

High density material may accumulate at the base

A Layered Mantle?

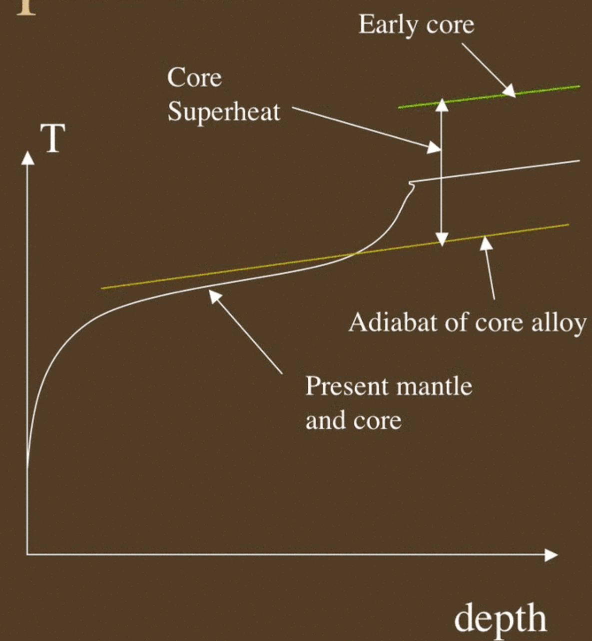
- Unlikely to arise in the magma ocean (suspended crystal stage)
- Could arise from percolative redistribution (melt migration near the solidus) *after magma ocean phase*
- Might (or might not) be eliminated by RT instabilities & thermal convection



Kellogg *et al*, 1999

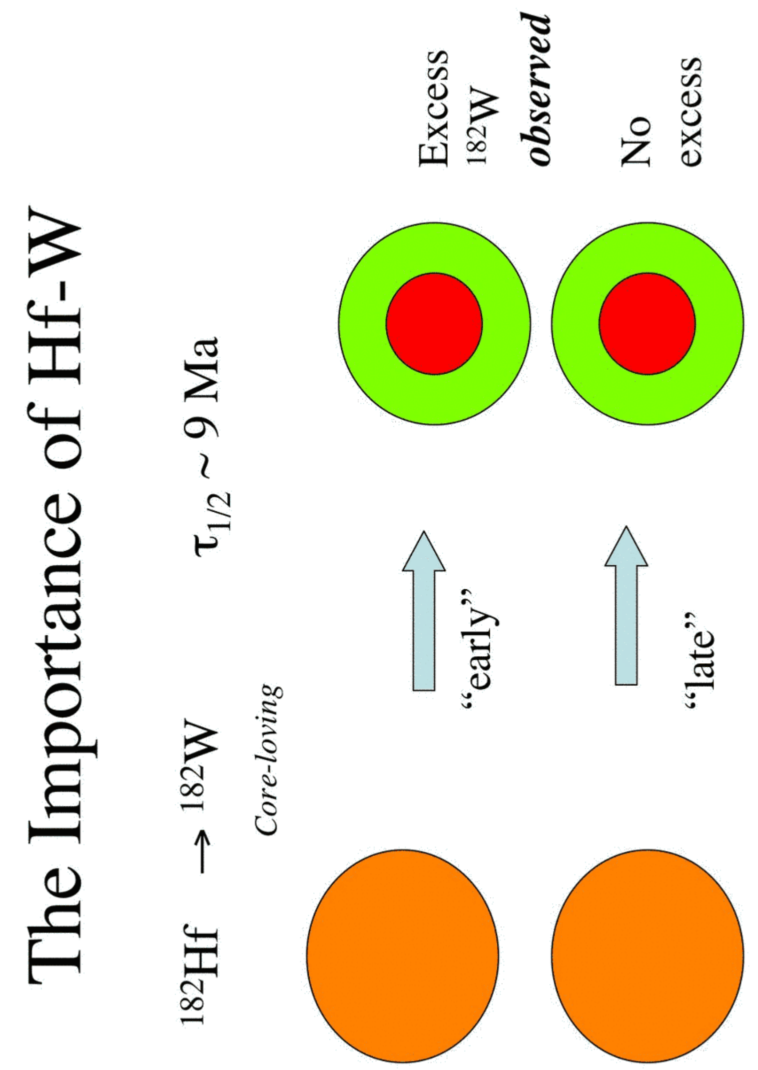
Core Superheat

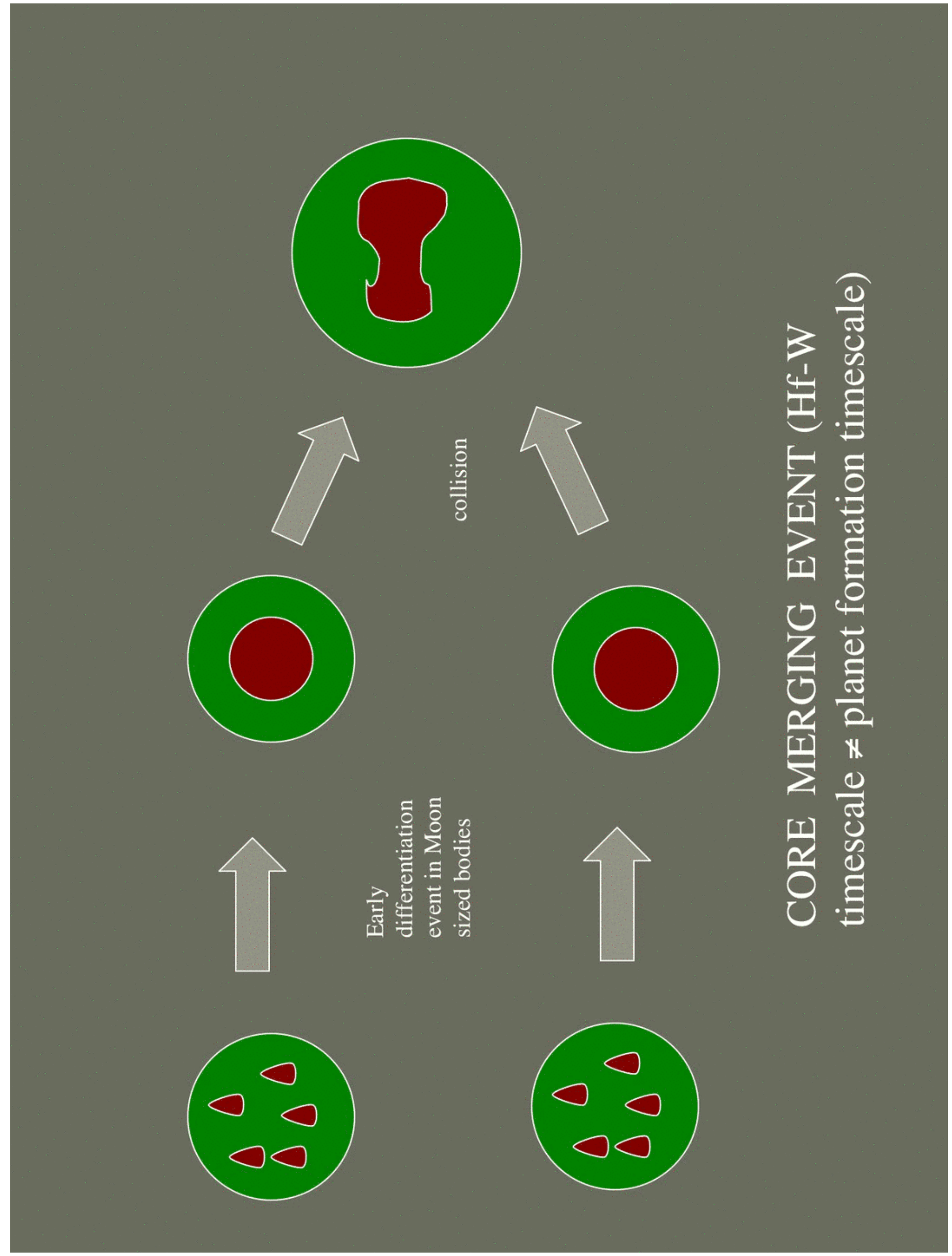
- This is the excess entropy of the core relative to the entropy of the same liquid material at melting point & and 1 bar.
- Corresponds to about 1000K for present Earth, may have been as much as 2000K for early Earth.
- *It is diagnostic of core formation process*

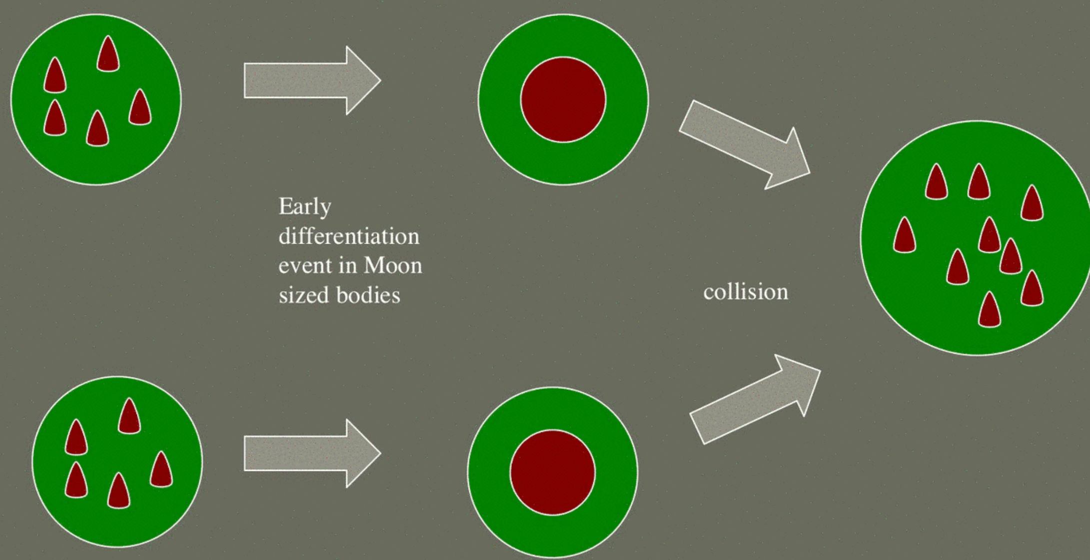


Formation of the Moon

- Impact "splashes" material into Earth orbit
- The Moon forms from a disk in perhaps ~100 years
- One Moon, nearly equatorial orbit, near Roche limit- tidally evolves outward

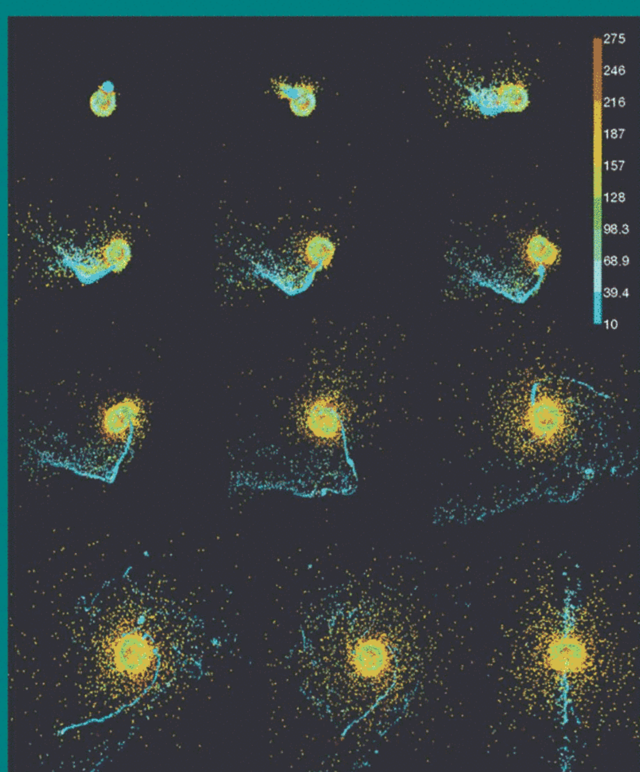

The Importance of Hf-W
^{182}Hf → ^{182}W
Core-loving
$\tau_{1/2}$ ~ 9 Ma
"early"
"late"
Excess ^{182}W *observed*
No excess


Early differentiation event in Moon sized bodies
collision
CORE MERGING EVENT (Hf-W timescale ≠ planet formation timescale)



EMULSIFICATION DURING IMPACT (Hf-W timescale ≈ planet formation timescale provided emulsification is sufficiently small scale)

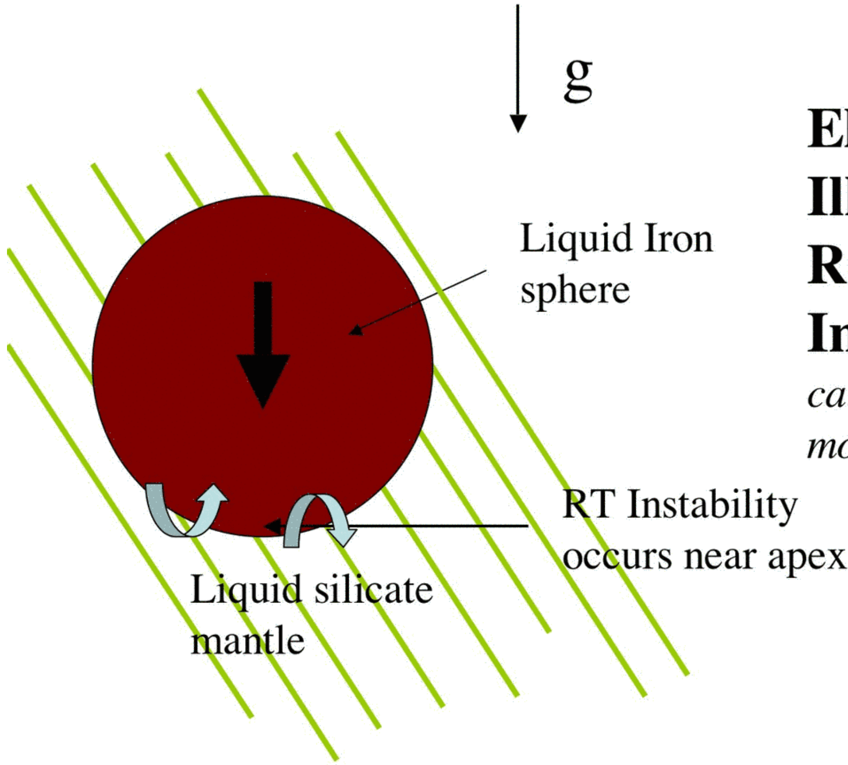
What Happens During a Giant Impact?



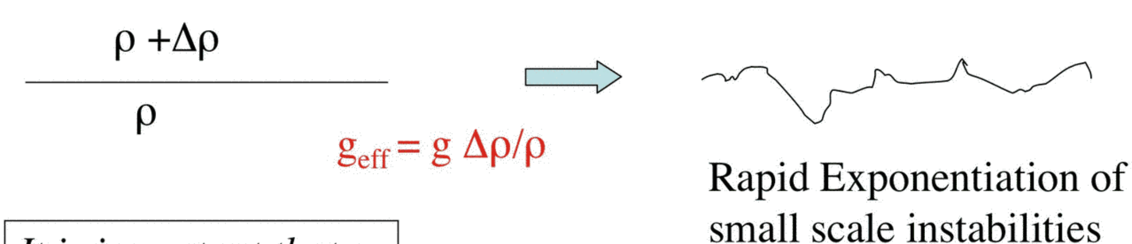
- Most of the material is melted; part is vaporized.
- Core of projectile is often intact and crashes into Earth, plunging to the core on a free fall time.
- Severe distortion (sheets, plumes; not spheres). But SPH does not indicate much direct mixing.

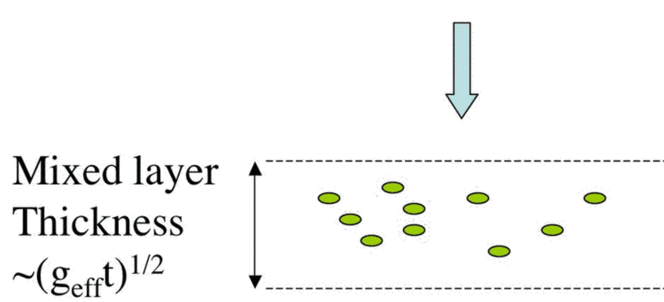
Canup & Cameron

Elementary Illustration of the Rayleigh-Taylor Instability *(The real calculations are much more complicated!)*



Development of a Low Viscosity Rayleigh-Taylor Instability





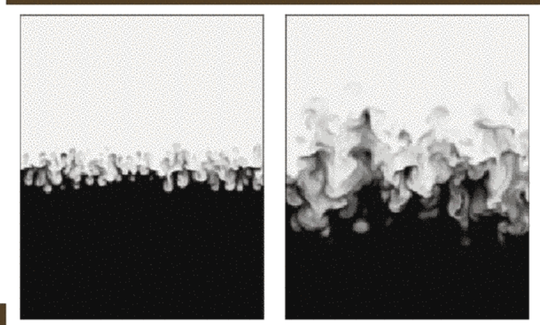
It is important that a Kolmogorov spectrum is quickly created…iron droplets down to cm in size in only ten minutes!

Guidance from Experimental Work and Numerical simulation

J. Fluid Mech. (1999), *vol.* 399, *pp.* 1–48. Printed in the United Kingdom

Self-similarity and internal structure of turbulence induced by Rayleigh–Taylor instability

By S. B. DALZIEL[1], P. F. LINDEN[1]† AND D. L. YOUNGS[2]
[1] Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Silver Street, Cambridge CB3 9EW, UK
[2] AWE, Aldermaston, Reading RG7 4PR, UK

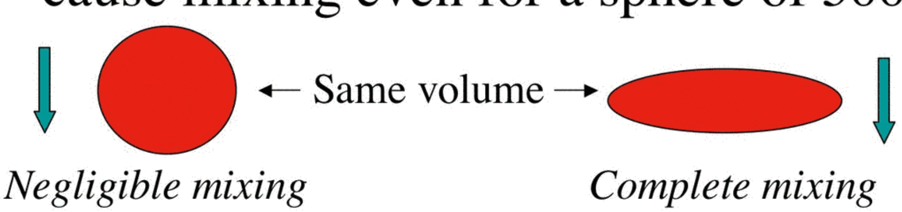


- Fastest growing mode is at scales ~ $(\nu^2/g)^{1/3}$ ~ 1 cm for kinematic viscosity $\nu \sim 10^2$ cm^2 /sec.
- Other important length scale is ~ $(\gamma/\rho\nu^2)^{-1}$ ~ 1 cm (where γ is surface tension). This is comparable... But diffusive equilibration time ~minutes or less.
- Calculations described here done with Tais Dahl (Un. Copenhagen)

Results

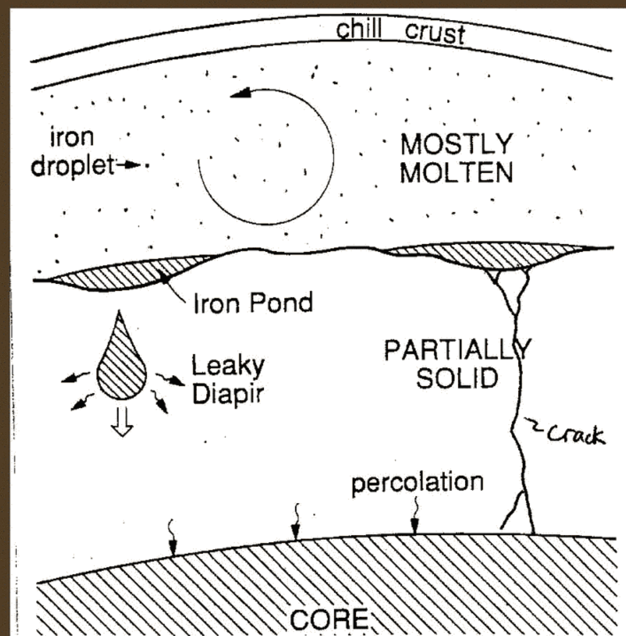
Fall velocity
Distance travelled

- Mixing $\propto g_{eff}H/U^2$. For ***iron spheres***, mixing is efficient for radii less than ~100 km. Mixing ~10% for radii of 500km. Negligible at 1000km.
- But in many cases, sheets and filaments are formed. Aspect ratio change of three can cause mixing even for a sphere of 500km.



Core Forming Processes between Giant Impacts

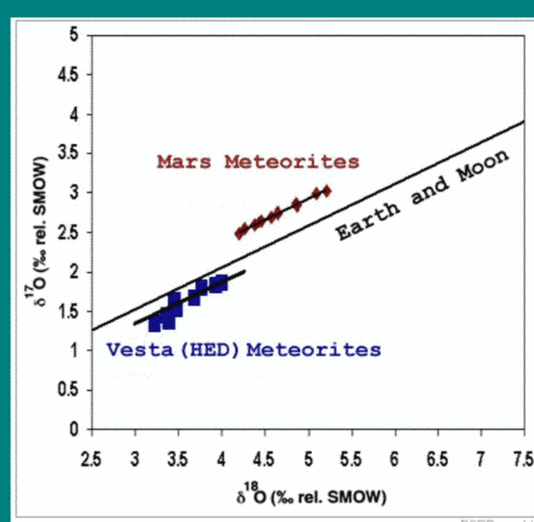
- Sustained deep magma ocean
- Siderophile equilibration at base of this ocean is expressed in mantle xenoliths- argument “against” giant impacts
- Pattern is unlikely to be the result of giant impacts.
- Does not explain core superheat

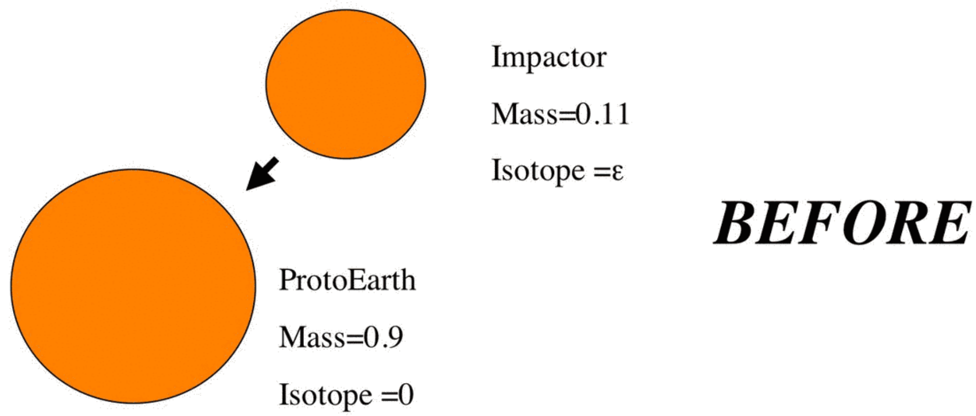


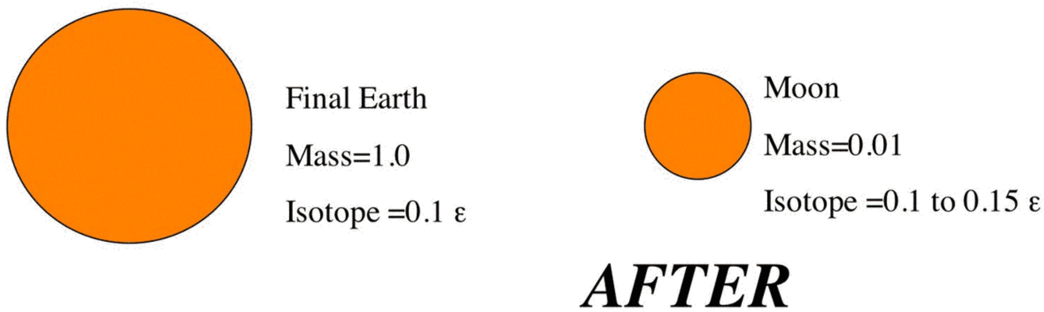
Stevenson, 1989

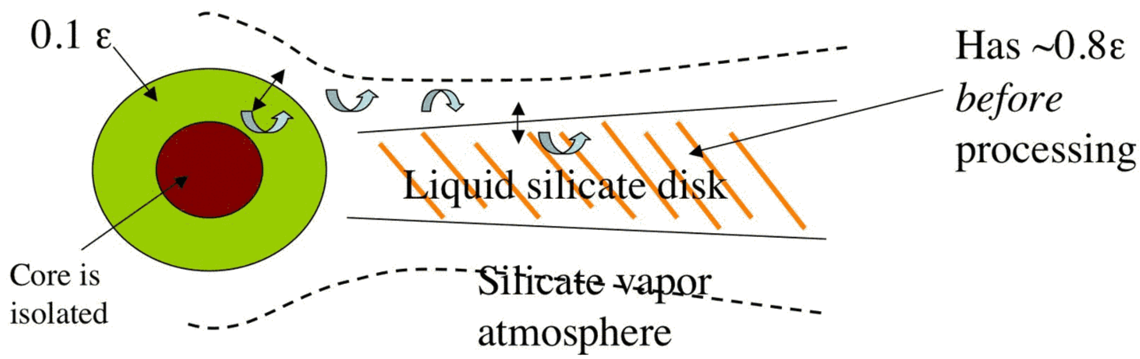
Oxygen Isotopes

- Fundamental origin of the differences between Earth, Mars and meteorites is ***not understood***
- Still, the “identity” of Earth & Moon is often taken to imply same “source”









IN BETWEEN

A disk exists for 10^2 10^3 years. Radiates at ~2500K. Vapor pressure ~10 to 100 bars.

Timescale for exchange between vapor & atmosphere ~10c/(Gσ) ~ week. Aided by "foam".

Convective timescale in disk or Earth mantle ~week

Convective timescale in atmosphere ~days

Summary

- Hf-W does not (necessarily) provide the timescale for earth formation. Late(~50 Ma) large impacts cannot be excluded.
- Mantle composition & core temperature indicate <u>both</u> large & small bodies in Earth formation
- Mixing of Earth & moon-forming giant impactor could cause the similar Earth & Moon oxygen isotope pattern *even if the projectile had Marslike oxygen*.

Dynamical Questions

(with implications for chemistry and isotopes)

- What is the timescale of Earth formation? (Time to accumulate 90%? Time to accumulate 99%?)
- What is the size spectrum of bodies colliding with protoEarth? (Incomplete accumulation into runaway embryos? Role of tidal disruption?)
- What is the mixing? (The delivery of material from 0.5 AU or 2 AU or 5AU…)
- What is timing of gas loss (relative to all this)?

What are the Relevant Data?

- Hf -W systematics

  $^{182}Hf \rightarrow {}^{182}W$ (9 million year half life)

  Hf goes to mantle & crust

  W goes to the core

  ∴Early core formation ⇒Excess ^{182}W in mantle.
  This is observed (to a small extent)
- Abundances of core-loving elements suggest that at least part of core formation was high T and P.

Interstellar medium contains gas & dust that undergoes gravitational collapse

A "solar nebula" forms: A disk of gas and dust from which solid material can aggregate

A Best Guess for Core Formation

- Earth's core is an aggregate of different sources:

  (a) Cores from smaller bodies (which do <u>not</u> equilibrate inside Earth but carry memory of small precursor bodies and are severely heated when accreted onto Earth.)

  (b) Rain-out and diapiric descent from Earth's magma ocean, carried memory of the "last pressure" of equilibration (25GPa, 2500K?)

  (c) *Maybe* higher temperature equilibrates if there are giant impacts that emulsify iron with the molten silicates

  (d) *Maybe* CMB interaction products (135GPa, >4000K)
- Evidence comes from mantle composition and from Hf-W isotope systematics

Dynamics of a Sinking Iron Sphere

- We solve for the *centrifugal effect* arising from the flow of silicate around the iron sphere.
- We include *self gravity*
- We construct a *boundary layer analysis* for the mixed zone
- We find that mixing is limited to within typically 30 to 45 degrees of the apex.

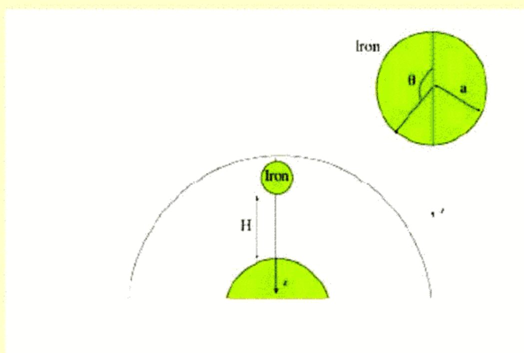


Figure 2: Sketch of the iron sphere and important parameters

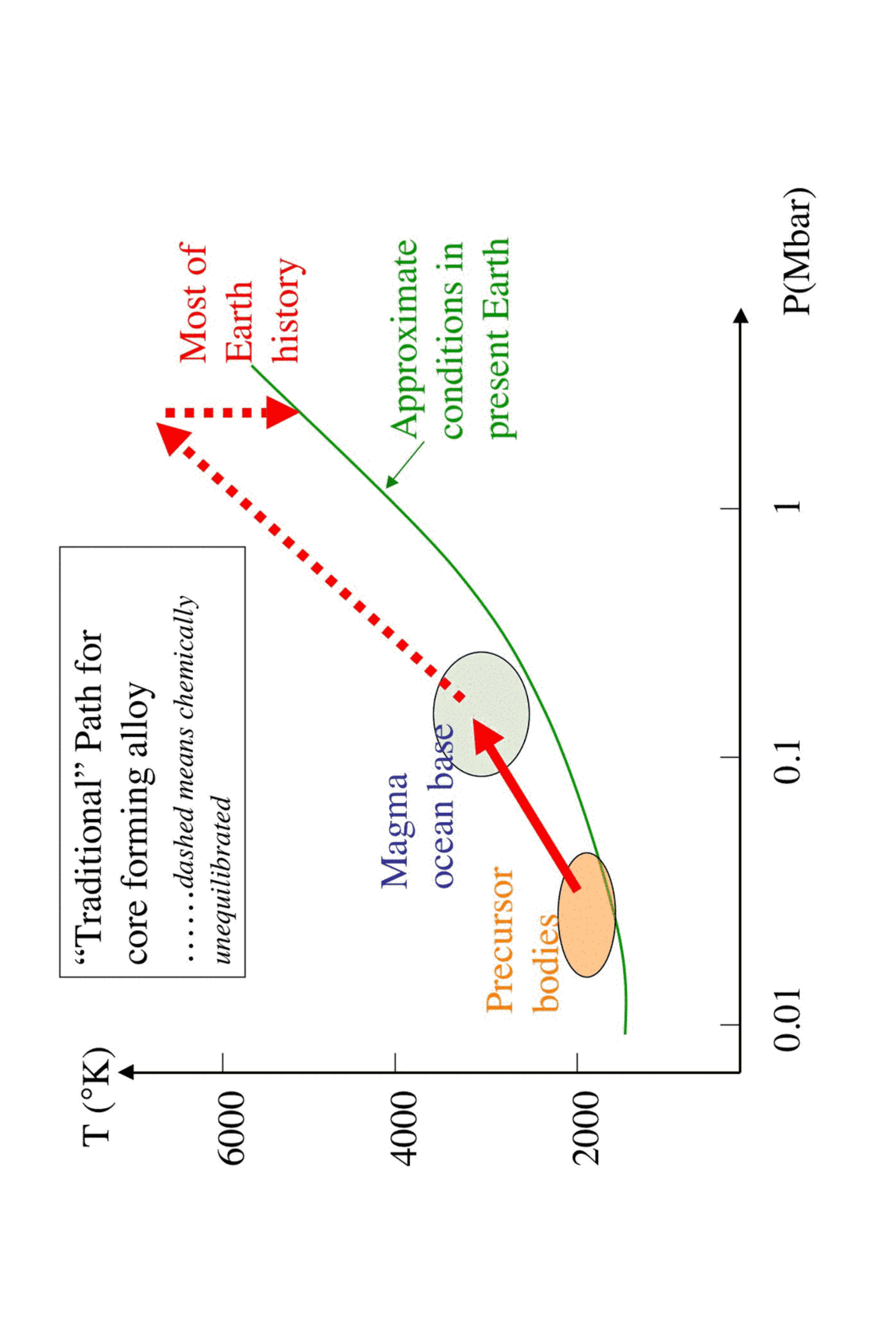
$$g_{eff} = A\left[g\cos(\pi-\theta) - g_s - \frac{dU}{dt} - 2g(1+\cos\theta)\right]$$

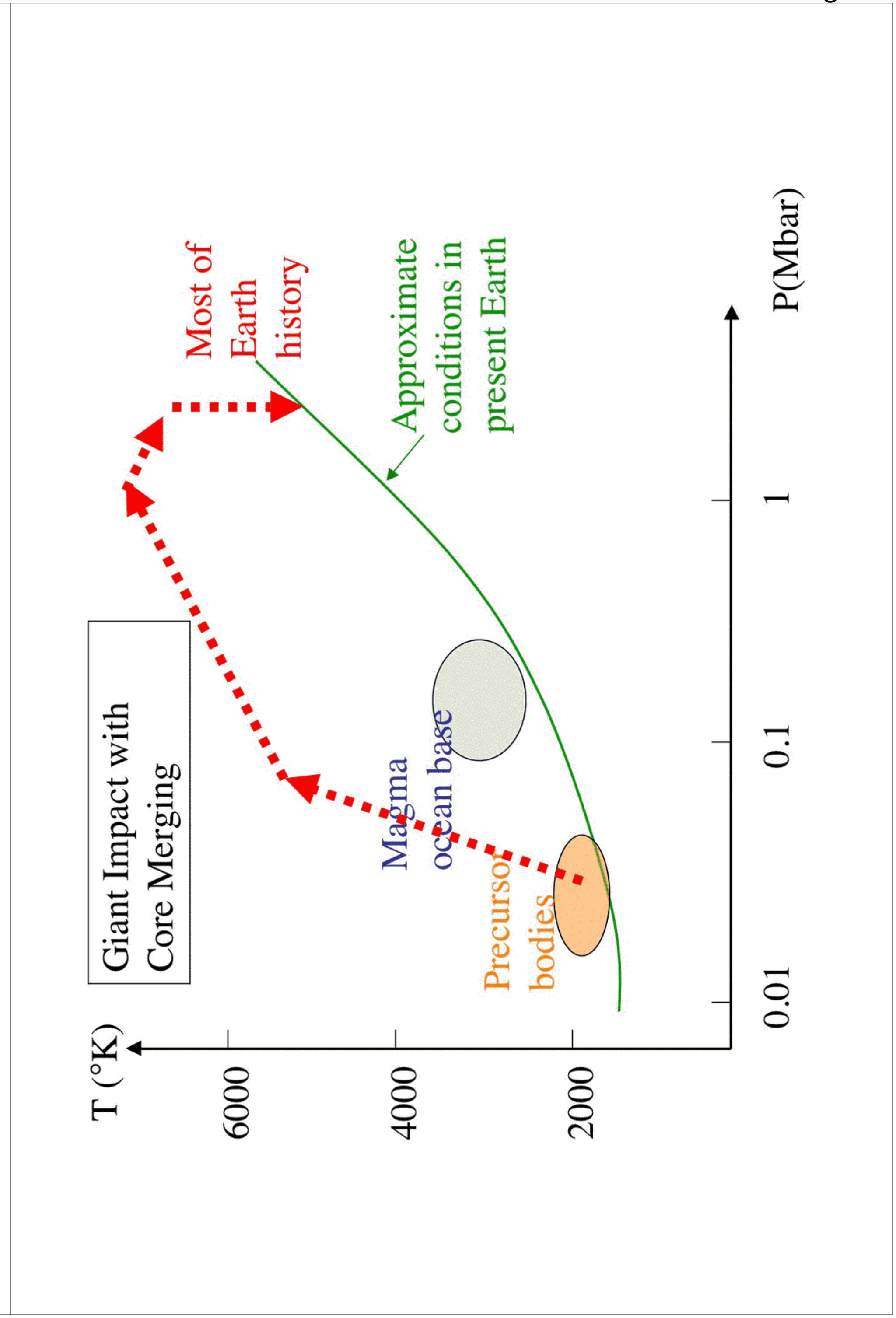
Direct gravity effect; Self gravity of sphere; Free fall correction; Centrifugal effect

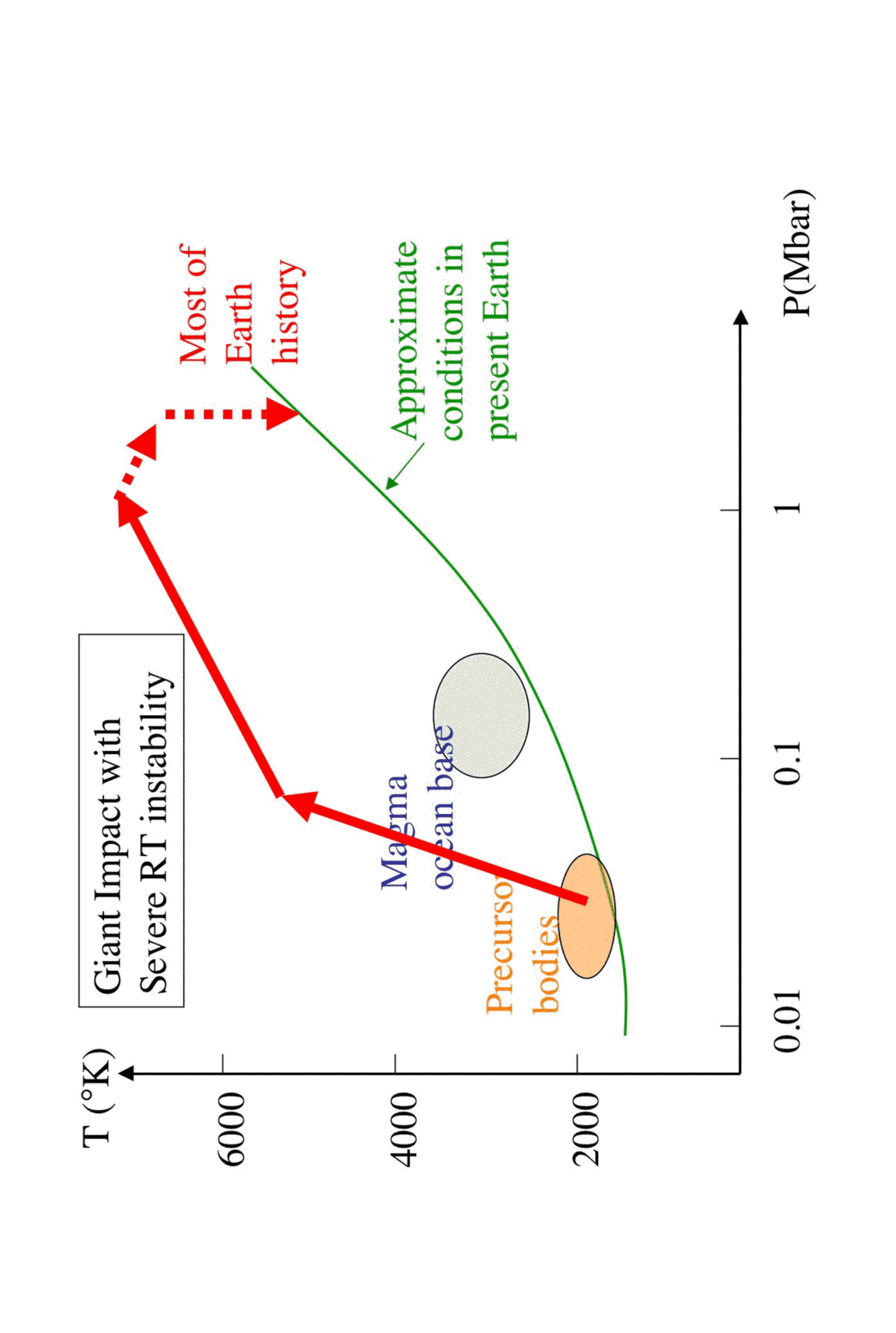
Summary of Initial Condition Constraints & Parameters

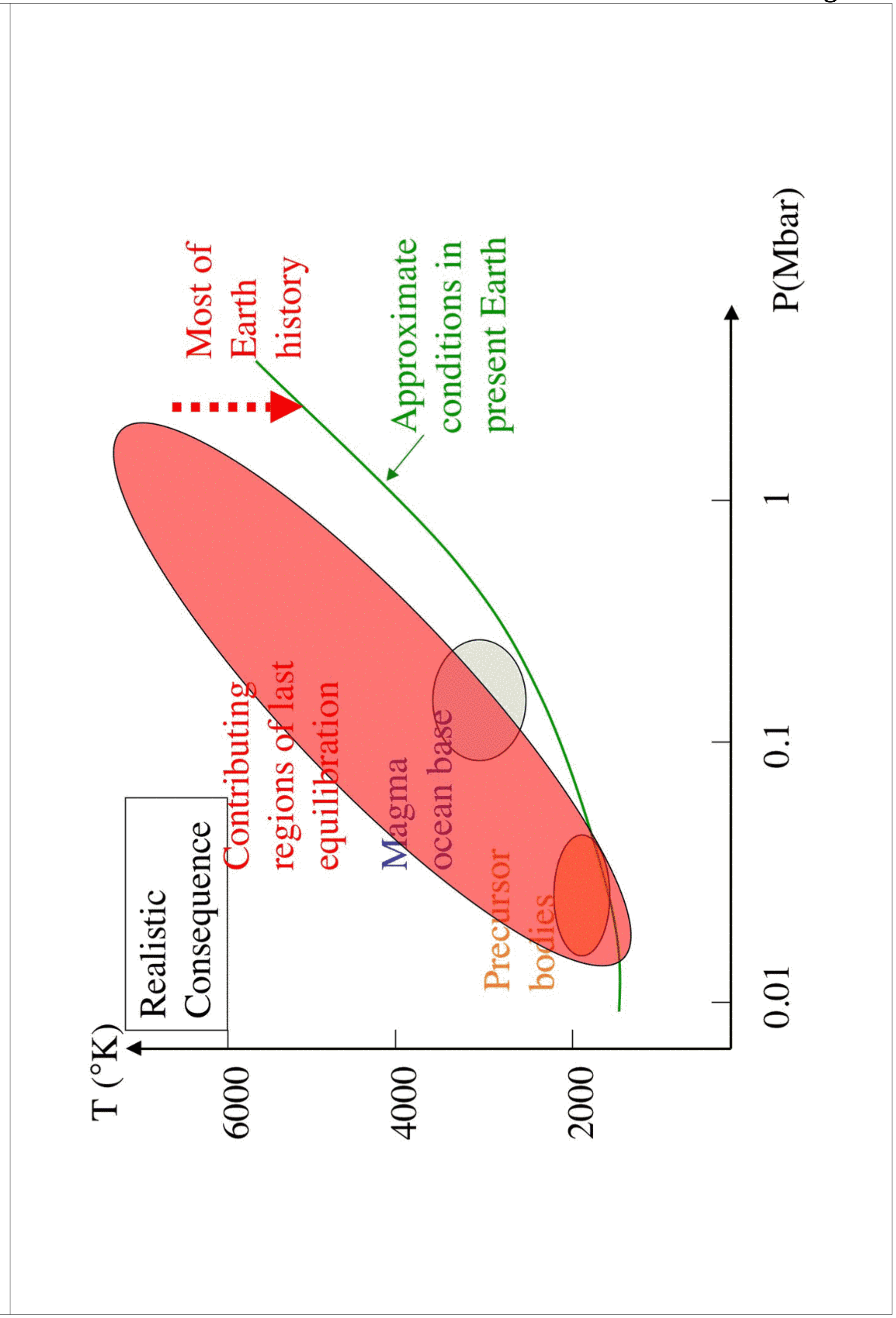
- Severe heating and deeply buried heat are a natural outcome of current ideas of Earth formation. This implies a magma ocean & hot initial core (probably no inner core).
- Core may have excess T relative to mantle because a lot of the core formation heating goes into core material
- Mantle might be initially layered and capable of extensive "metasomatism"

Issues	Action Items
• T,P paths & degree of equilibration	• Fe Alloy compositions Light elements and K in the core
• Sustained Segregation from the mantle - layered mantle? D//?	• Liquidus phase. Nature of liquid at solidus. Role of water. Better understanding of melt migration


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


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


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


Realistic
Consequence
Contributing
regions of last
equilibration
Most of
Earth
history
Approximate
conditions in
present Earth
Magma
ocean base
Precursor
bodies
T (°K)
6000
4000
2000
P(Mbar)
0.01
0.1
1

Summary for Terrestrial Planets

- It is currently popular to argue that the Hf-W isotopic record tells us the timing of Earth formation, but this is probably incorrect in detail: Earth formation can stretch out over tens of millions of years. It is bounded below by ~ 5 Myr.
- Composition of the core is linked ot Hf-W through the (dis)equilibration. High Si in the core likely if high T equilibration.
- High initial core T in all cases. Expressed in core superheat.