Tidal Heating in Solid Bodies

Some Questions and Puzzles

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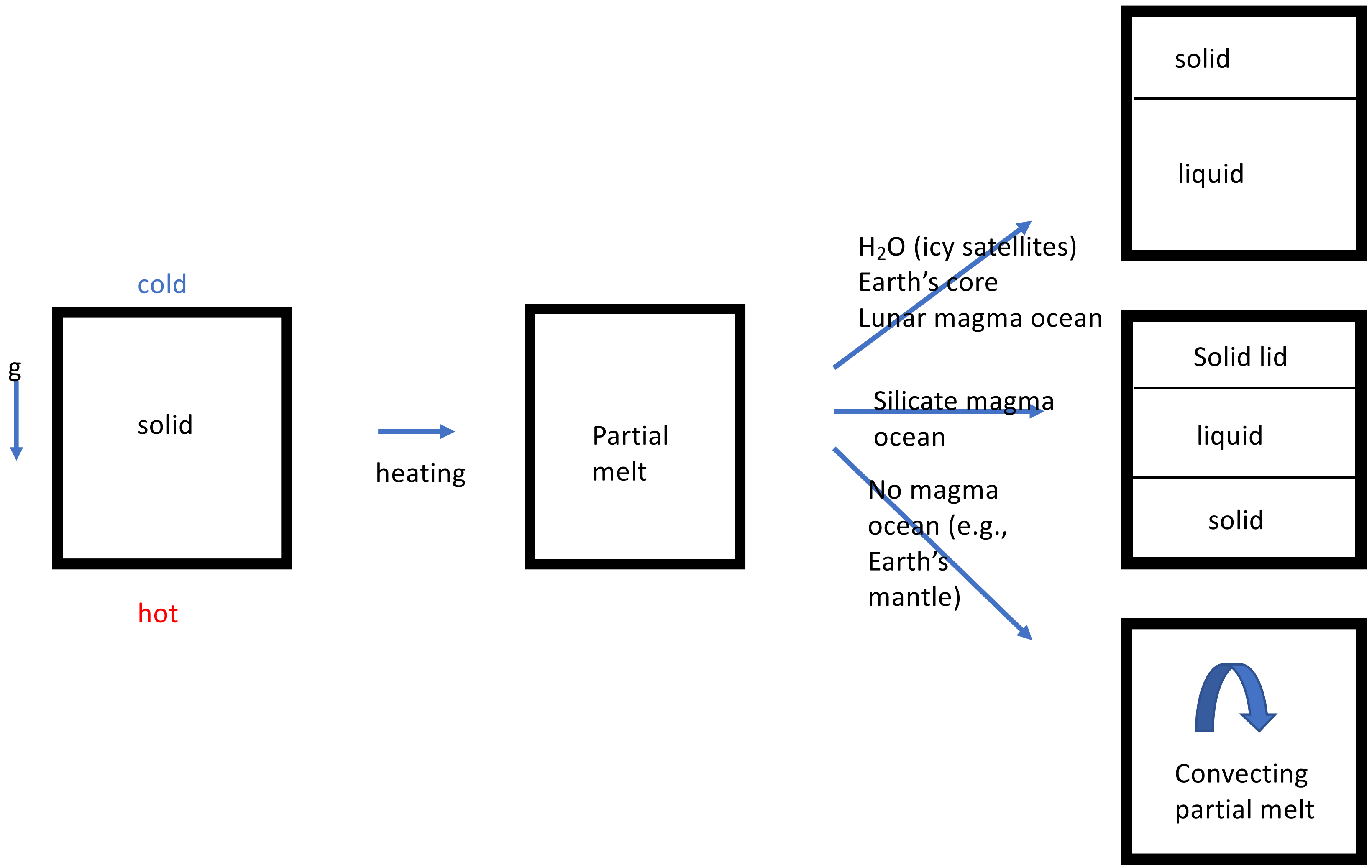
A Key Question

- Where does the dissipation take place?
  - In the shell?
  - In an asthenosphere (partial melt)?
  - Deeper region or core (could also be a partial melt)?

Key Observations (Io)

- k_2
  - High if outer shell is decoupled (requires a magma ocean, not an asthenosphere!)
  - Lower for a partial melt
  - k_2/Q is measured(?) ~0.015 (Lainey)
  - Q is a lumped parameter (an average over the body) and so not simply related to a laboratory measurement
- Induction
  - Melt fraction of ~20% or more (but trade-off with layer thickness)
  - Assumes current lab experiments are relevant but probably OK.


cold
g
solid
hot
heating
Partial melt
H_2O (icy satellites)
Earth's core
Lunar magma ocean
Silicate magma ocean
No magma ocean (e.g., Earth's mantle)
solid
liquid
Solid lid
liquid
solid
Convecting partial melt

Why (Magma) Oceans?

- Liquid is in thermodynamic equilibrium at the surface
  - Earth's oceans
  - Exoplanets with dense (H_2) atmospheres
- Immiscible liquid phase that is more dense and has lower melting point
  - Earth's outer core
- Inability of solid state convection to remove the heat flow
  - Reason for oceans in Ganymede, etc
- Large difference between solidus and liquidus (so the the viscosity is high at the solidus)
  - This is relevant to water-ammonia oceans even at low heat flow
  - But the viscosity is not high enough at Earth mantle solidus that a lot of melting occurs (most of the melting is by pressure release)
- Severe (accretional, tidal) heating?

But this requires knowing the properties of partial melts

- COMPOSITION
  - Tells you what is in the melt and what is in the solid (partitioning)
- MELT FRACTION
  - This is a dynamical variable (do not confuse with degree of melting since we have open systems)
  - Under mid ocean ridges, degree of melting ~20-30%, and melt fraction is a few percent (?)
- SURFACE TENSION
  - Tells you whether the melt is interconnected
  - This is increasingly likely as melt fraction increases
  - Generally true in silicates (hence the electrical conductivity). Sponge topology.
- GRAIN SIZE
  - This is a dynamical variable
  - Usually interpreted as a balance between Ostwald ripening (surface tension driven) and recrystallization (driven by deviatoric stress) but can also be history dependent and impurity dependent.
- PERMEABILITY
  - Scales as grain size squared, but order of magnitude uncertainty even if you know the grain size
  - Changes as the material is deformed
- (BULK) VISCOSITY
  - Usually but not always similar to shear viscosity
  - Essential for melt extraction but usually not a rate limiting process

How do Systems Work on Earth?

- The initial step is percolation
- But melt gets channeled into a rapid transit system (think of it as wider conduits; melt velocity scales as channel width squared)
- Evidence: Isotopes and the behavior of Iceland at the end of the last ice age.
- This channelizing keeps the average melt fraction low (because the melt is moving faster and the melt production is not changing)
- Two leading ideas:
  - Kelemen et al (1995) flow focused by solution of the more easily melted minerals (dunite channels)
  - Holtzman, Kohlstedt…(2003) Strain localization of melt into bands (Melt may not go vertically). Arises because the viscosity goes down as melt fraction increases
- Both of these should work even better as heating rate increases!
- Feeds. melt into cracks and magma chambers

Extraction of mid-ocean-ridge basalt from the upwelling mantle by focused flow of melt in dunite channels

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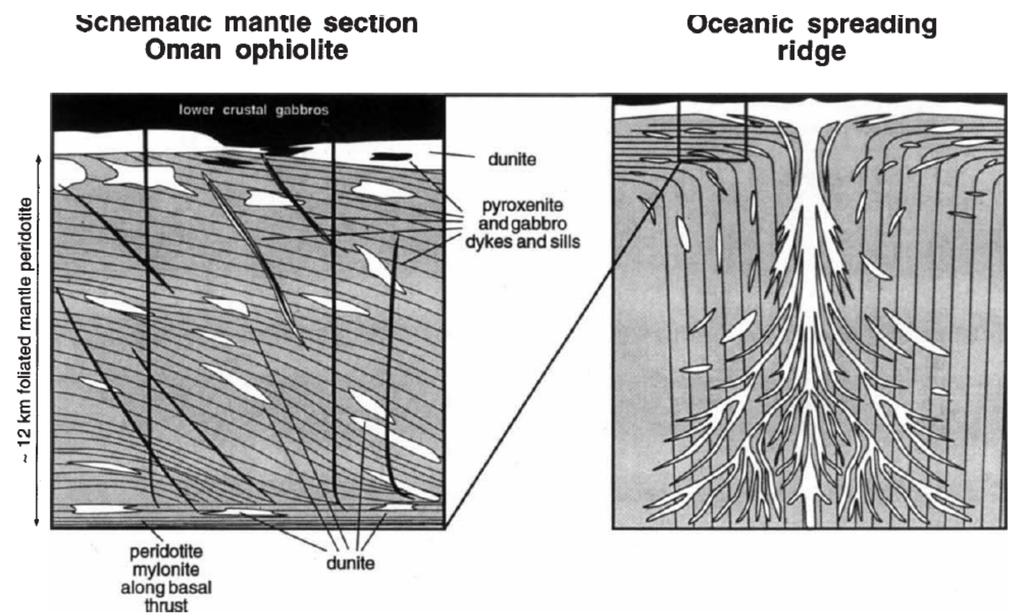
Like residual peridotites from mid-ocean ridges, peridotites from the mantle section of the Oman ophiolite are far from equilibrium with mid-ocean-ridge basalt (MORB). By contrast, dunites from Oman are close to equilibrium with MORB, indicating that they were conduits for focused melt flow. Formation of dunite conduits by porous flow is sufficient to explain extraction of MORB from the mantle, and fracture mechanisms may not be necessary in this process.



Melt Segregation and Strain Partitioning: Implications for Seismic Anisotropy and Mantle Flow

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F. Heidelbach,[2] T. Hiraga,[1] J. Hustoft,[1]

One of the principal means of understanding upper mantle dynamics involves inferring mantle flow directions from seismic anisotropy under the assumption that the seismic fast direction (olivine *a* axis) parallels the regional flow direction. We demonstrate that (i) the presence of melt weakens the alignment of *a* axes and (ii) when melt segregates and forms networks of weak shear zones, strain partitions between weak and strong zones, resulting in an alignment of *a* axes 90° from the shear direction in three-dimensional deformation. This orientation of *a* axes provides a new means of interpreting mantle flow from seismic anisotropy in partially molten deforming regions of Earth.

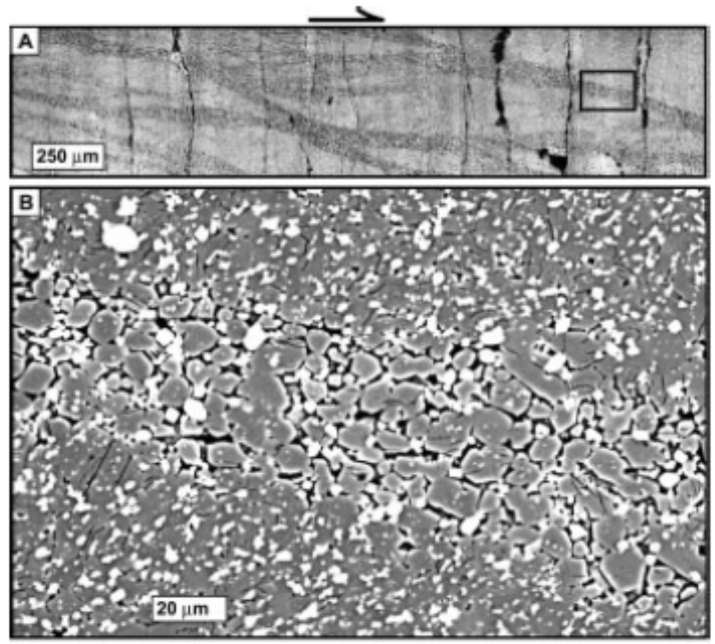

Fig. 1. Microstructures. (**A**) Reflected-light image of a sample of olivine and chromite and 4% MORB sheared between tungsten pistons. The melt-rich bands are visible as the darker regions oriented 10° to 20° to the sample walls, forming an anastomosing network. (**B**) SEM backscattered electron image of one band. The chromite grains (white) are smaller than the olivine grains (gray). Chromite tends to sit in melt (black) tubules, reducing the permeability.

Large Scale Instability?

- Partial melts are Rayleigh-Taylor unstable if an upward displacement causes more melt to form (the decompression effect)
- May be relevant to extensional environments. on Earth or coronae on Venus (Hernlund et al, 2008)

Tackley & Stevenson 1993

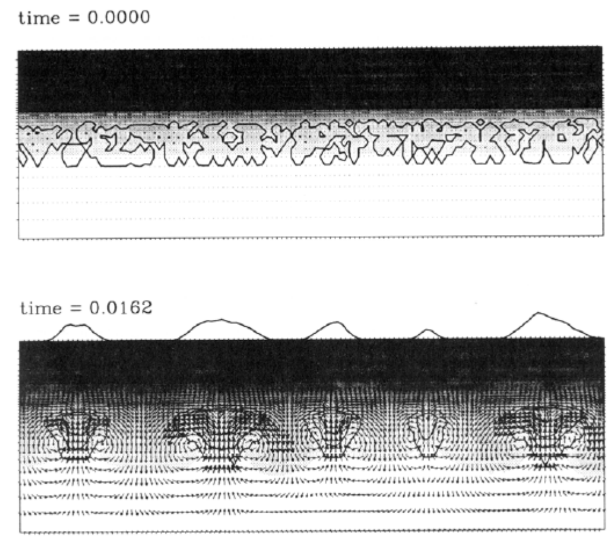

Figure 4. Simulation in a 4x1 cartesian box for Rm=50k, M=150, Ra=0. Upper plot shows random initial condition, lower plot shows subsequent development of upwellings. Temperature (shaded), velocity (arrows), melt fraction (contours) and eruption rate (graph), as figure 2.

- Note that the usual ideas of Rayleigh –Benard convection have to be changed when you have a partial melt because the consequence of heating is not thermal expansion but creation of more melt (a large effective thermal expansivity if the melt is buoyant), but the melt must leave the solid even if the convection ins vigorous (because the upper boundary condition for the average medium is zero vertical velocity. And percolation is not diffusive.

Two limiting Cases?

- Rapid melt transport to the base of a fractured lid, where melt is fed into cracks(conduits) or transient magma chambers as quickly as it arrives
  - Low average melt fraction
  - No magma ocean
  - Induction data not satisfied!
- Rapid melt transport out of the tidally heated region into a magma ocean
  - Not much tidal heating in that ocean?
  - Melting of the deeper region is matched by freezing on its surface as the ocean is cooled from above. Rapid melt escape mediates local Q.
  - OR melting with in the outer shell; the outer shell is recycled and the magma ocean is passive
- Petrological Framework for any of this is mysterious

The Way Froward involves a better understanding of the properties of partial melts

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- SURFACE TENSION
  - Tells you whether the melt is interconnected
  - This is increasingly likely as melt fraction increases
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- GRAIN SIZE What determines this in a tidally deformed medium?
  - This is a dynamical variable
  - Usually interpreted as a balance between Ostwald ripening (surface tension driven) and recrystallization (driven by deviatoric stress) but can also be history dependent and impurity dependent.
- PERMEABILITY
  - Scales as grain size squared, but order of magnitude uncertainty even if you know the grain size But dynamically determined by the tidal stress field
- (BULK) VISCOSITY
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The Way Forward

1 .Tidal stresses in Io (assuming high enough rigidity/viscosity) ~ $\rho g h \sim 1 bar$
Convective stresses ~? In a partial melt they could be ~ $f\Delta\rho gR$ ~ 10 bar?
But this could be an overestimate

If tidal stresses are important for rheology then we need experiments on texture/ grain size under tidal conditions (oscillatory stress)

2.Boundary between melt and lowermost part of the lid needs more modeling. Relevant physics includes melt filled cracks (work of Alan Rubin, for example).

3. Better understanding of the possible range of petrologies and irreversible evolution (loss of volatiles)