Plenary Lecture

Magmatism and the Evolution of the Earth's Interior

Paul D. Asimow

V. M. Goldschmidt Conference

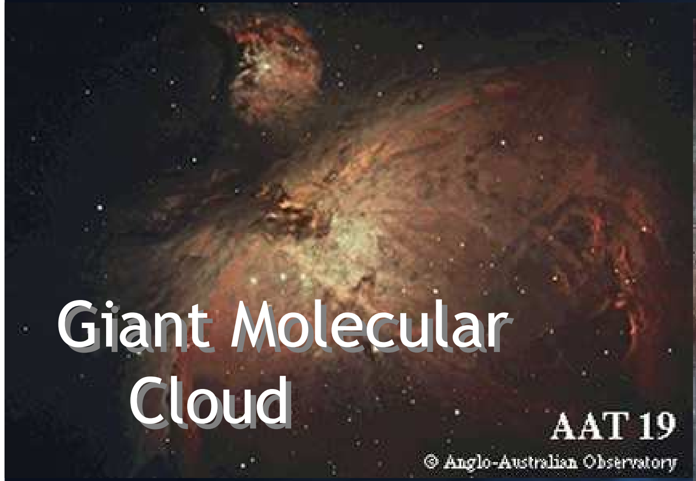
Cologne, Germany

August 21, 2007

CALIFORNIA INSTITUTE OF TECHNOLOGY
1891

CALIFORNIA INSTITUTE OF TECHNOLOGY • GEOLOGICAL AND PLANETARY SCIENCES •
Labor Bonus et Multus

Planetary Evolution

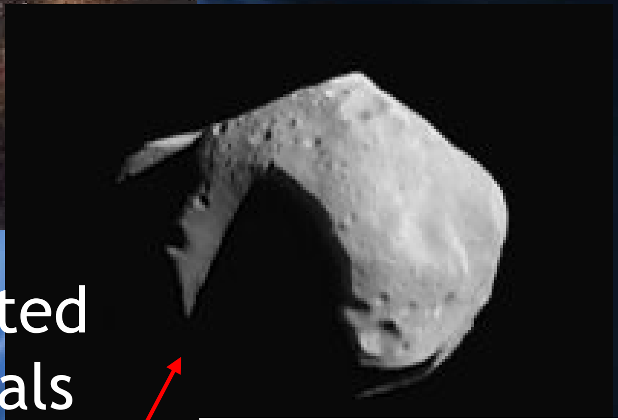


Giant Molecular Cloud

AAT 19

© Anglo-Australian Observatory

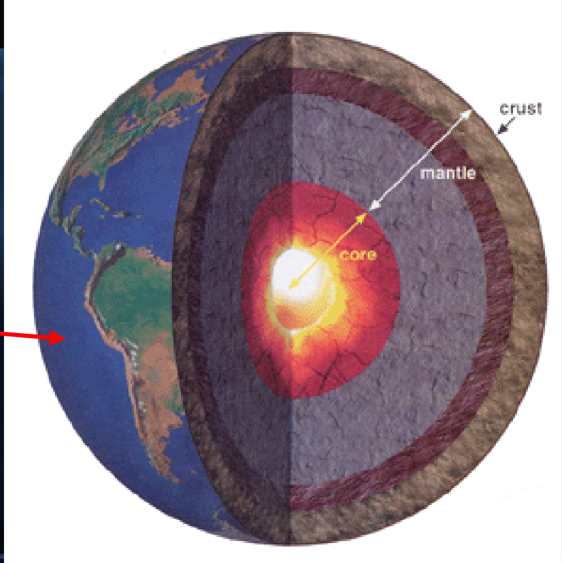
Solar Nebula



Undifferentiated Planetesimals

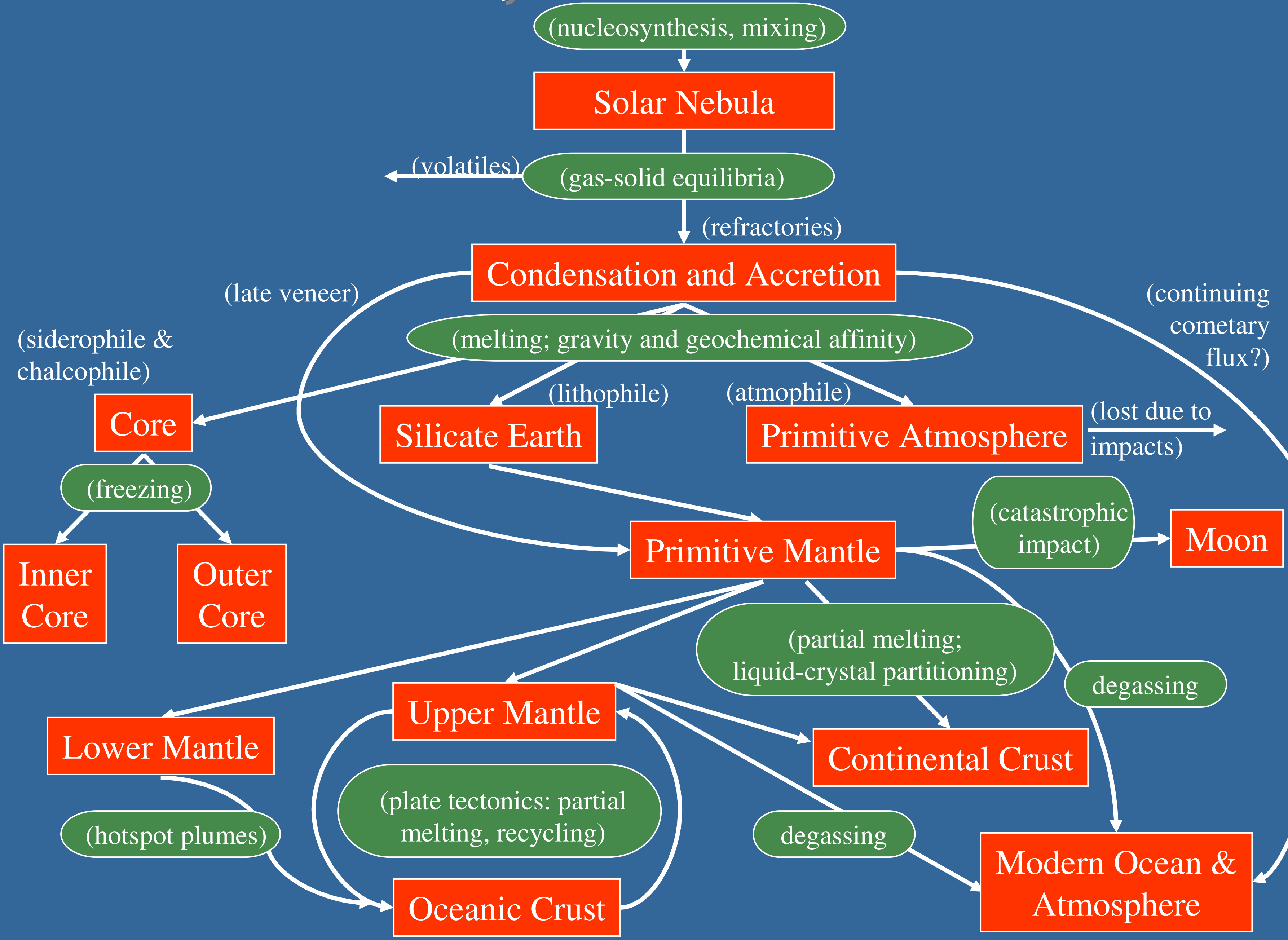
Today' topic:

How do you get from there to here?



Differentiated Planets

Summary of Earth Differentiation



(nucleosynthesis, mixing)

Solar Nebula

(volatiles)

(gas-solid equilibria)

(refractories)

Condensation and Accretion

(late veneer)

(continuing cometary flux?)

(melting; gravity and geochemical affinity)

(siderophile & chalcophile)

Core

(lithophile)

Silicate Earth

(atmophile)

Primitive Atmosphere

(lost due to impacts)

(freezing)

Inner Core

Outer Core

Primitive Mantle

(catastrophic impact)

Moon

(partial melting; liquid-crystal partitioning)

degassing

Upper Mantle

Lower Mantle

Continental Crust

(plate tectonics: partial melting, recycling)

(hotspot plumes)

degassing

Modern Ocean & Atmosphere

Oceanic Crust

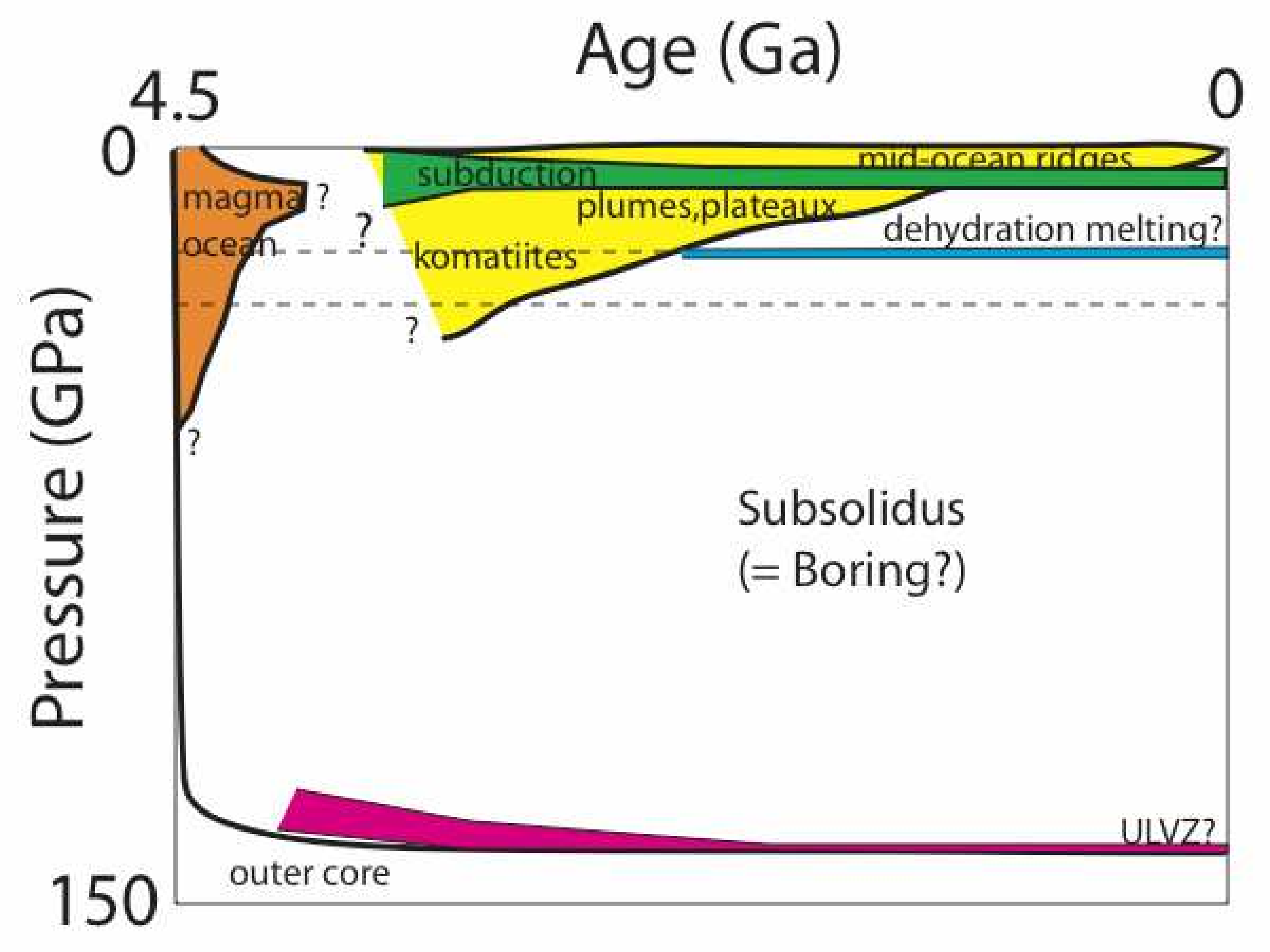
Bold Assertion

- Melting is the root of all geochemistry
  - Goldschmidt classified the elements according to their affinity for metallic, silicate, or sulfide *liquids*
- Igneous differentiation is ultimately responsible for the origin of all significant chemical heterogeneity in the Earth's interior
  - Solid-state processes only homogenize or process heterogeneities created by melting
  - Except for layered accretion, compositional differences among terrestrial reservoirs should be *petrologically reasonable differences*, traceable to their origin in particular igneous processes
  - It is therefore important to consider the range of petrological reason – what are all the magmatic environments and processes we can imagine, and what are their consequences?

The Magmatic Library

- In decreasing order of scientific understanding, the magmatic environments that have or may have affected the Earth's mantle include:
  - Upper mantle melting at mid-ocean ridges and hotspots
  - Subduction processing and continent formation
  - Komatiite genesis through the mid-Proterozoic
  - Dehydration melting at 410 km
  - Melting and reactions at core-mantle boundary
  - Magma ocean stage(s) during accretion and core formation
    - (and Primordial melting of parent bodies)
- Today we'll look at the last (and most uncertain)
  - and how recent progress in high-pressure melt physics is changing our view of magma ocean evolution

The Magmatic Library



Hot planet formation

- Assembling a planet means dumping lots of matter into a gravitational field, leading to large negative potential energy and positive kinetic energy, dissipated as heat by the time the matter comes to rest.

- Total gravitational binding energy of a uniform-density planet increases with the **square** of radius. For the Earth,

$$\Delta T = \frac{1}{MC_p}\int_0^R \frac{GMdM}{r} \xrightarrow{\text{uniform } \rho} \frac{3}{5C_p}\frac{GM}{R} \approx \frac{3\times 10^7\ \text{J/kg}}{10^3\ \text{J/kg/K}} = 30000\ \text{K!}$$

- Of course, slow accretion could allow this heat to escape, but models of accretion and timing constraints from short-lived isotopes show that accretion was much too fast and involved too many large collisions for Earth to stay cold.

- Differentiation is driven by further lowering the gravitational binding energy. The actual density structure of the Earth has 10% lower potential energy than the uniform sphere.

  - Hence, once core formation begins, it is **catastrophic** and **self-sustaining**. If Earth formed homogenous and then a core separated, enough energy would have been liberated to heat everything 3000 K and melt it completely.

Hot planet formation

- As an example, consider the probable moon-forming impact between an ~80% proto-Earth and a ~10% Earth-mass object…

Canup &
Asphaug

Magma Oceans

- This is a huge and speculative topic. There was a great burst of interest about 20 years ago, featuring major papers by:
  - Abe and Matsui: degassing of steam atmosphere creates blanketing layer that traps impact energy and keeps surface at or above melting point. Generates long-lived shallow magma ocean.
  - Agee and Walker: can create peridotite upper mantle from chondritic primitive mantle, maybe, with very particular consequences for lower mantle composition
  - Ringwood: trace element evidence suggests no perovskite fractionation
    - But Solomatov and Stevenson showed that turbulent crystal suspension leads to non-fractional crystallization
  - Righter and Drake: Model for core-mantle equilibration at base of upper mantle magma ocean
  - Ohtani and others: consequences of melt-crystal density relations for crystallization

Magma Oceans

- More recently, additional workers have shown that:
  - Elkins-Tanton et al., differentiation of Martian magma ocean could lead to unstable density stratification and rapid overturn
  - Boyet and Carlson: ^{142}Nd anomaly requires very early large-scale differentiation, perhaps by fractionation of magma ocean
    - But does presence of primordial noble gases (e.g., ^{3}He) in the mantle preclude a whole-mantle magma ocean?
- Probably there was (at least one) magma ocean stage, but depth is unknown and consequences for subsequent planetary state are highly controversial
- Obtaining real constraints on what *can* happen and what *did* happen in a terrestrial magma ocean is a **GRAND CHALLENGE** requiring serious collaboration among (at least) petrology, geochemistry, and geodynamics
  - Only a detailed fluid dynamic and phase equilibrium model can hope to make predictions specific enough to compare to any observation likely to persist to the present era

Aside: Today's Mantle is Solid*

- This is widely misunderstood due to confusion between "fluid" and "molten"
- Typical Example from WWW:

> "The core consists of a solid inner core and a fluid outer core. The fluid contains iron, which, as it moves, generates the Earth's magnetic field. The crust and upper mantle form the lithosphere, which is broken up into several plates that float on top of the hot molten mantle below."
>
> SOURCE: LiveScience reporting

- From the East Islip, NY, Middle School Science Teaching **Standards**:

> **Earthquakes** are formed when sections of earth's crust move past one another. Friction, the force opposing motion, prevents these plates from moving smoothly. The build up of friction causes stress, which releases as sudden jerking, or an earthquake. The crust is in the form of a plate, which is floating on molten mantle. Earthquakes release two types of waves: P waves and S waves. *P waves* are the primary waves that travel the fastest through the surface of earth. P waves are longitudinal while S waves are transverse. *S waves* are secondary waves which travel in a rolling fashion and are slower than P waves.

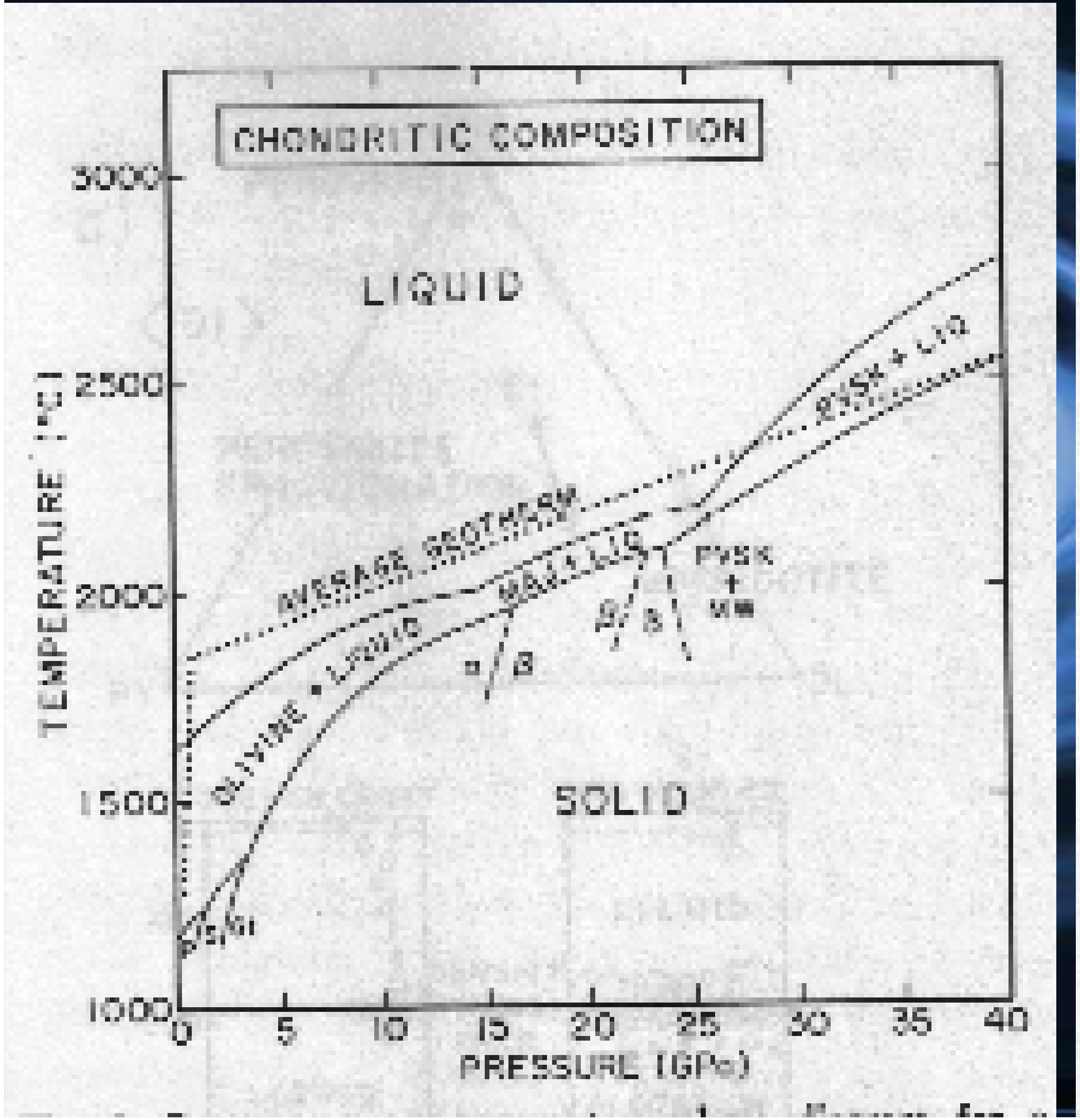
QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

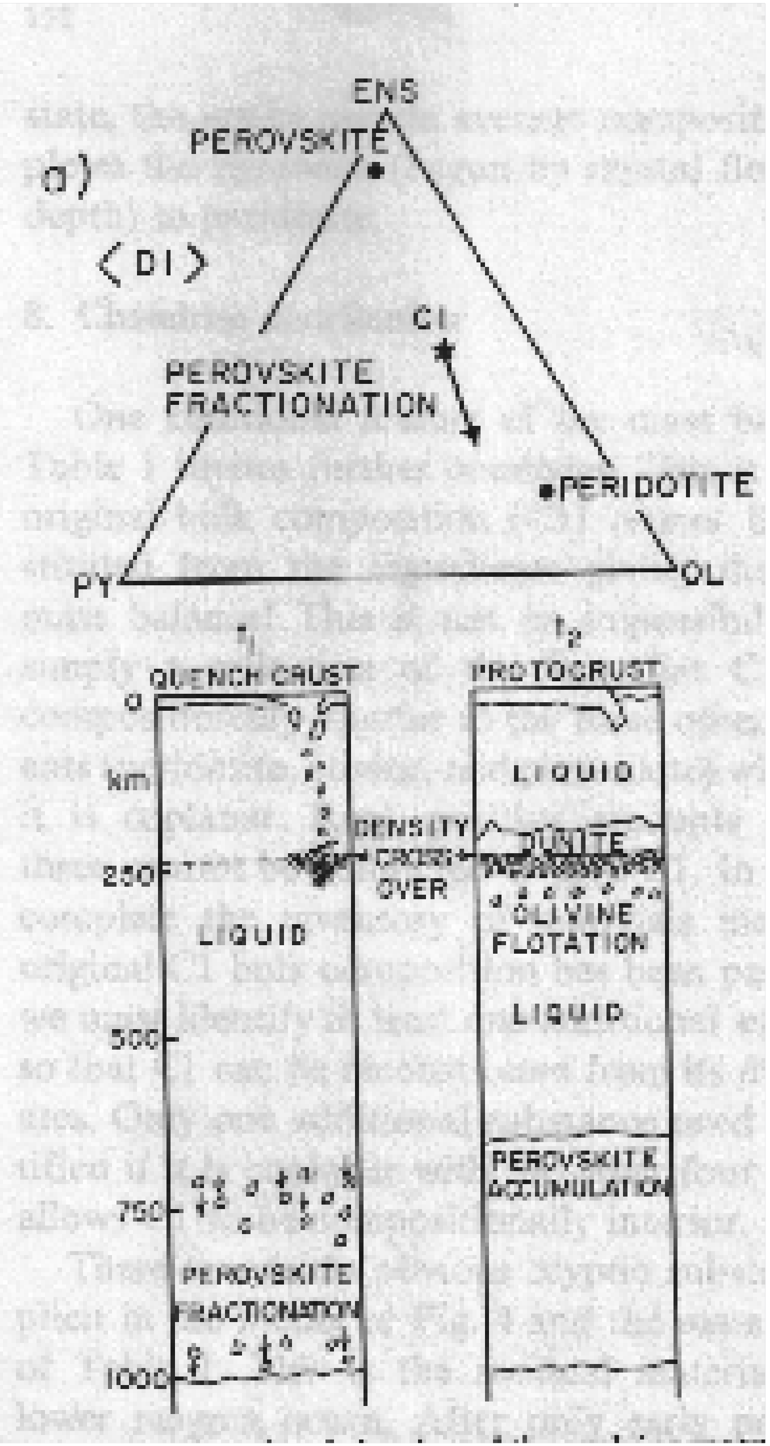
*Except in spatially restricted regions of active melt generation.

Magma Ocean Crystallization

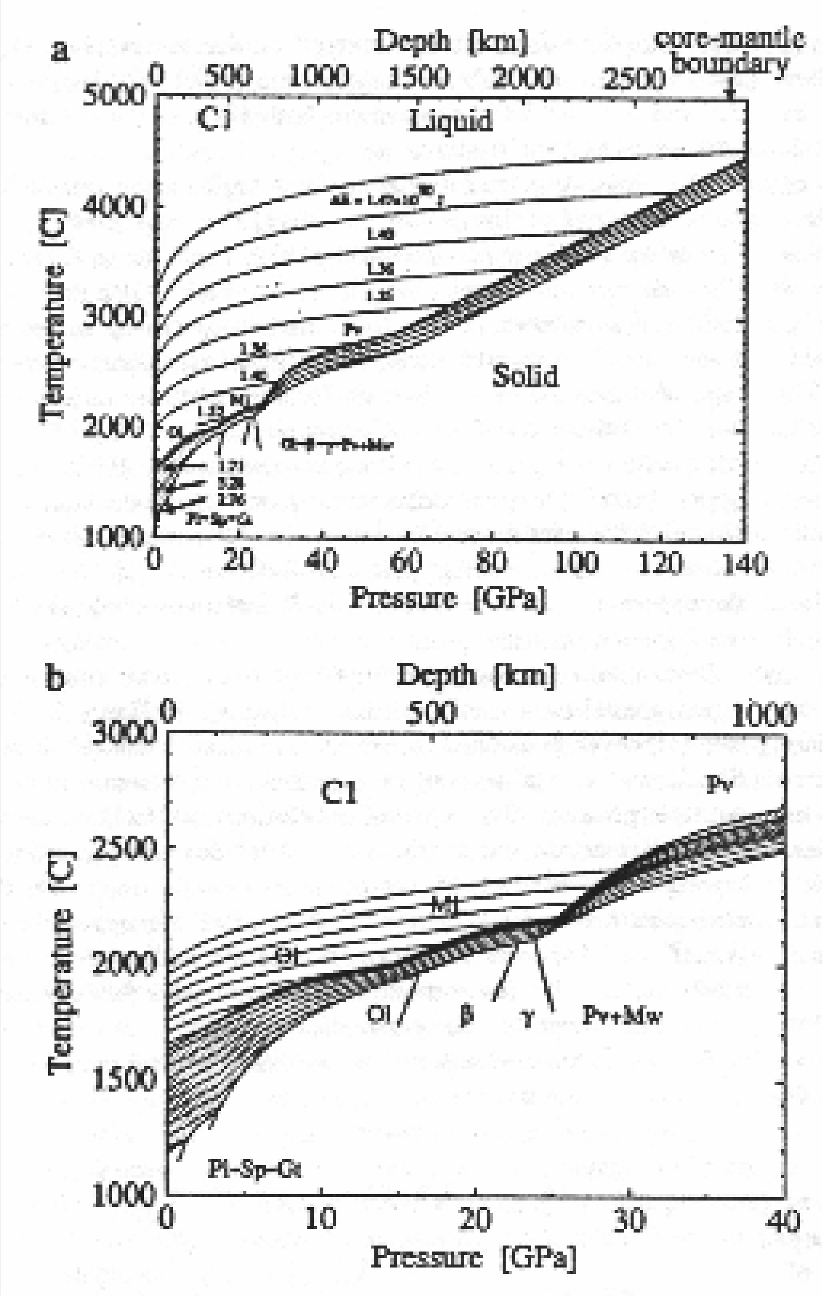
- Given that an early, deep (perhaps whole-mantle) magma ocean was likely and that core segregation must precede or accompany this state, subsequent Earth evolution can be thought of as beginning from a homogeneous silicate liquid of Fe-depleted chondritic (Bulk Silicate Earth) composition
- So, what happens as such a system cools? Several studies have looked at this…

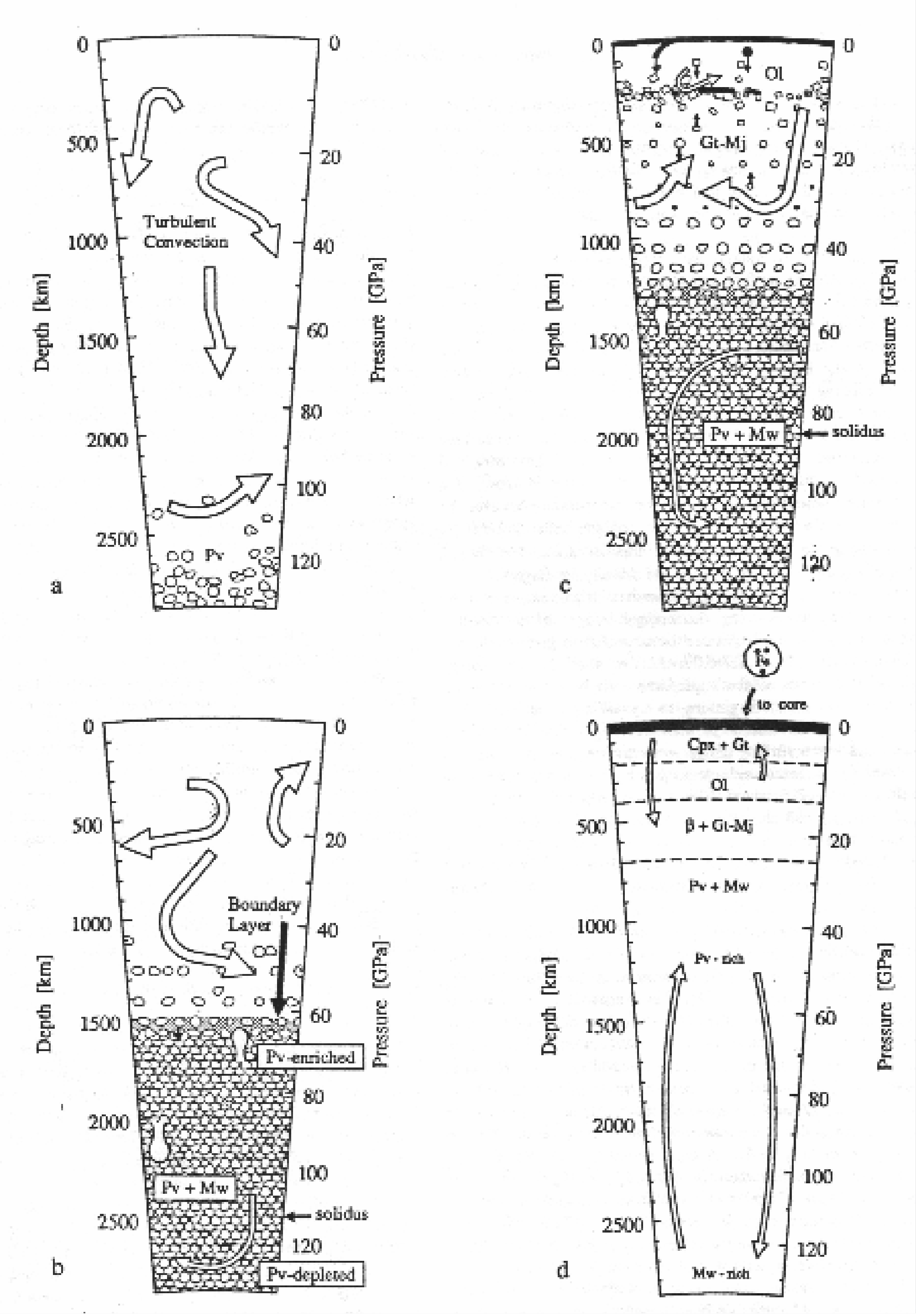
Magma ocean cooling models:
Agee and Walker 1988



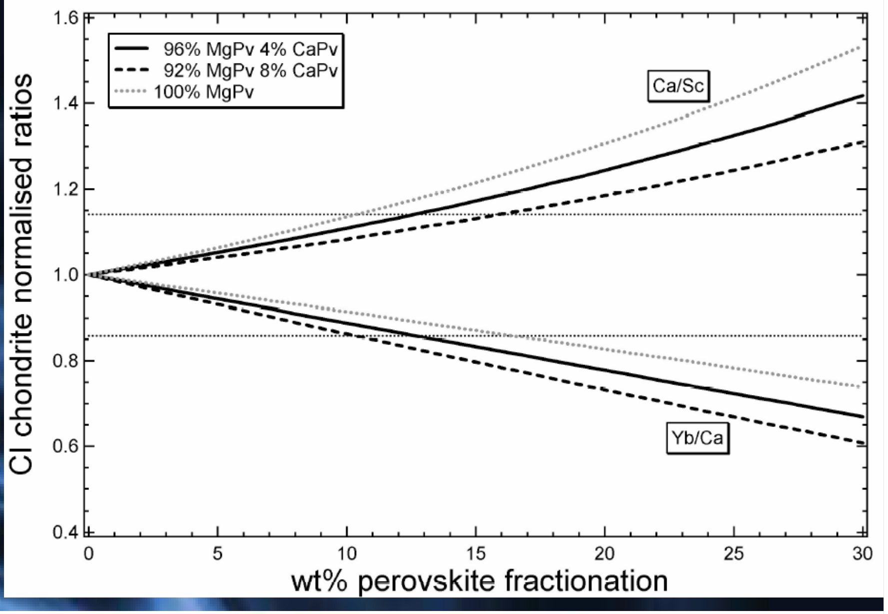


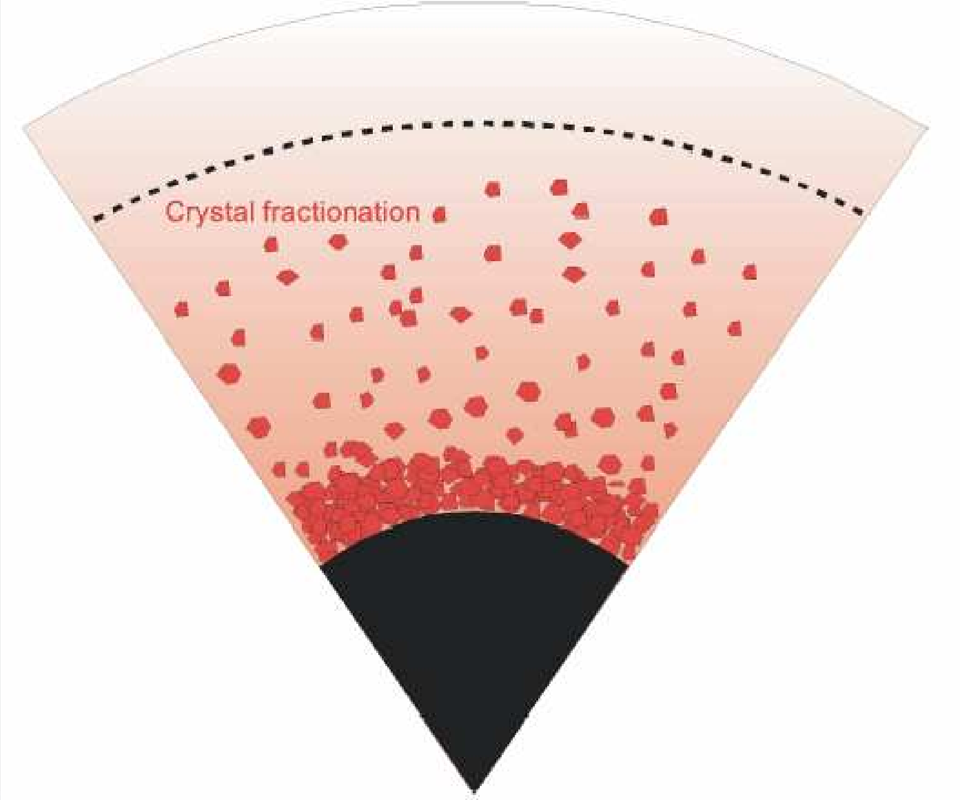
Magma ocean cooling models: Miller et al., 1991b

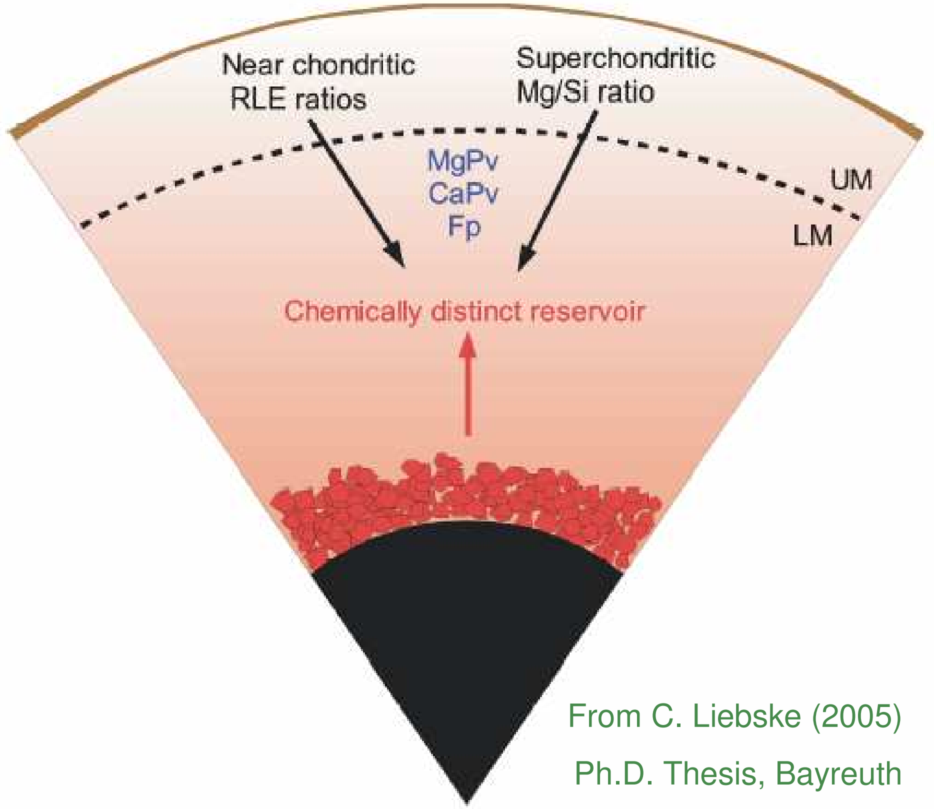




Magma ocean cooling models: Liebske (2005)







From C. Liebske (2005)

Ph.D. Thesis, Bayreuth

Magma Ocean Crystallization

- Many things differ among these models, but they all have in common:
  - Mg-perovskite is the liquidus phase throughout the lower mantle and is negatively buoyant
  - Crystallization begins at the bottom and proceeds upwards because the liquidus is steeper in P-T space than the liquid adiabat
- New data on melting curves of simple minerals and thermochemical properties of liquids in lower mantle suggest these common assumptions may not be right!

Magma Ocean Crystallization

- I want to introduce two simple tools for understanding processes in an *adiabatic* system such as a convecting magma ocean:
  - Pressure-entropy diagrams
  - The Grüneisen parameter
- With these we can begin to take mineral and melt physics data and build models of lower mantle phase equilibria (eventually to be coupled with dynamics)

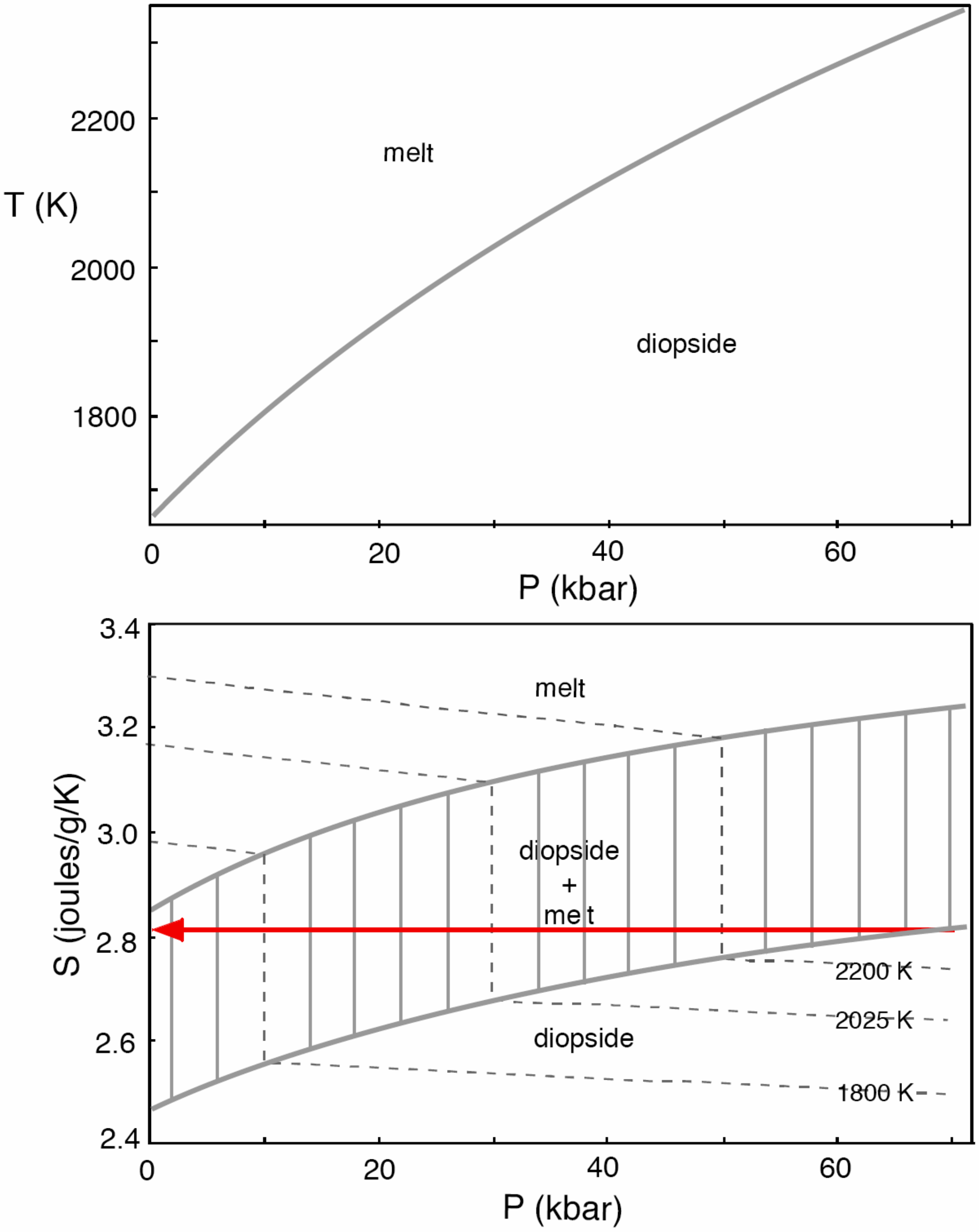
Pressure-Entropy diagrams

Many mantle processes are approximately adiabatic and reversible, hence isentropic:

- Decompression melting
- Convective geotherms

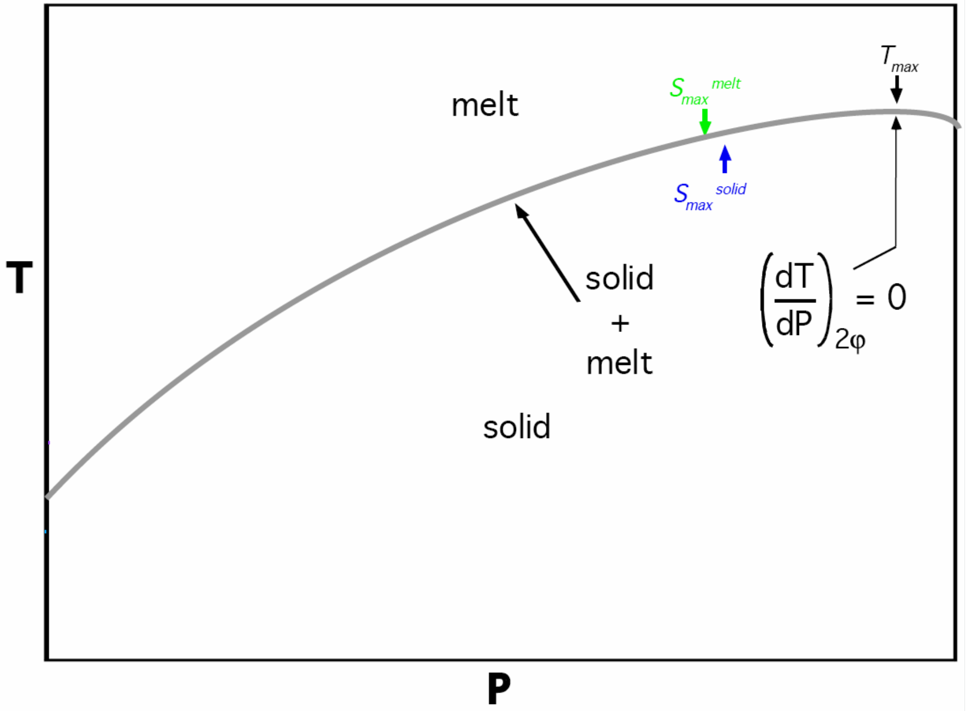
To show the details of an isentropic process, one should use entropy as an independent variable in calculations and plots!

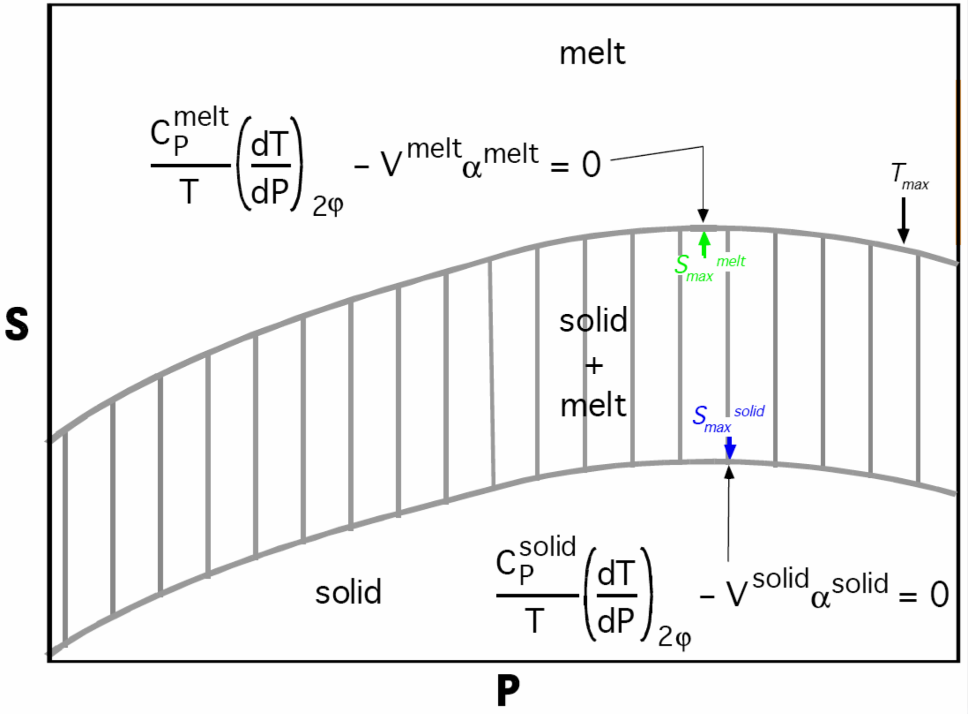
See Stolper and Asimow (in press), *Amer. J. Sci.*



Pressure-Entropy diagrams

Maxima in P-T space and in P-S space on solidus and liquidus





The Grüneisen Parameter

- γ is a thermodynamic derivative property that turns up frequently in mineral physics; it has several definitions…
  - 1. Thermal Pressure at constant volume

$$\gamma \equiv V\left(\frac{\partial P}{\partial E}\right)_V \longrightarrow \left(\frac{\partial P}{\partial T}\right)_V = \frac{\gamma C_V}{V}$$

  - 2. Isentropic Thermal Gradient

$$\gamma = -\left(\frac{\partial \ln T}{\partial \ln V}\right)_S \longrightarrow \left(\frac{\partial T}{\partial P}\right)_S = \frac{\gamma T}{K_S}$$

The Grüneisen Parameter

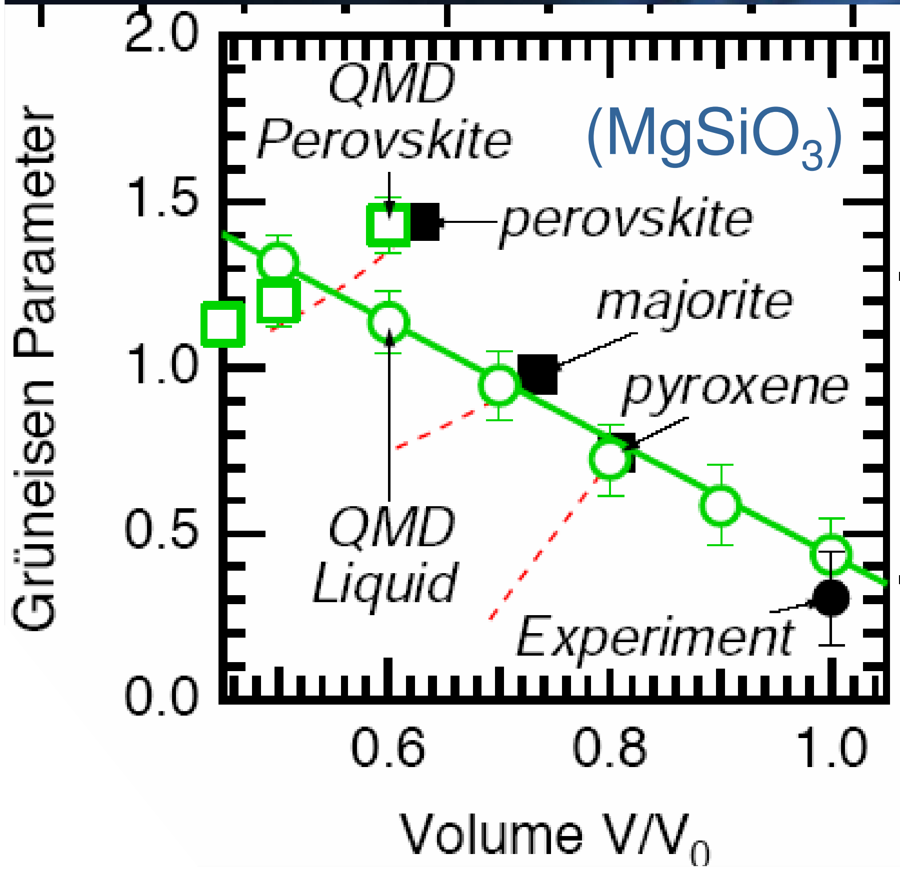
- γ is a particularly useful property because its behavior is relatively predictable; to a reasonable approximation, γ is a function only of volume for most materials.
- However, γ is hard to measure at high pressure
    - At ambient pressure, can combine thermal expansion, heat capacity, and bulk modulus measurements to define γ precisely ($\gamma = K_S V\alpha / C_P$)
    - At high pressure, these measurements are too imprecise (especially for non-crystalline materials!)
    - Can define γ in molecular dynamics models, where energy, volume, and pressure are all known
    - Can obtain γ from shock wave measurements, where energy, volume, and pressure are known:
        - Simultaneous shock and release velocity data
        - Multiple Hugoniot states of same composition and phase

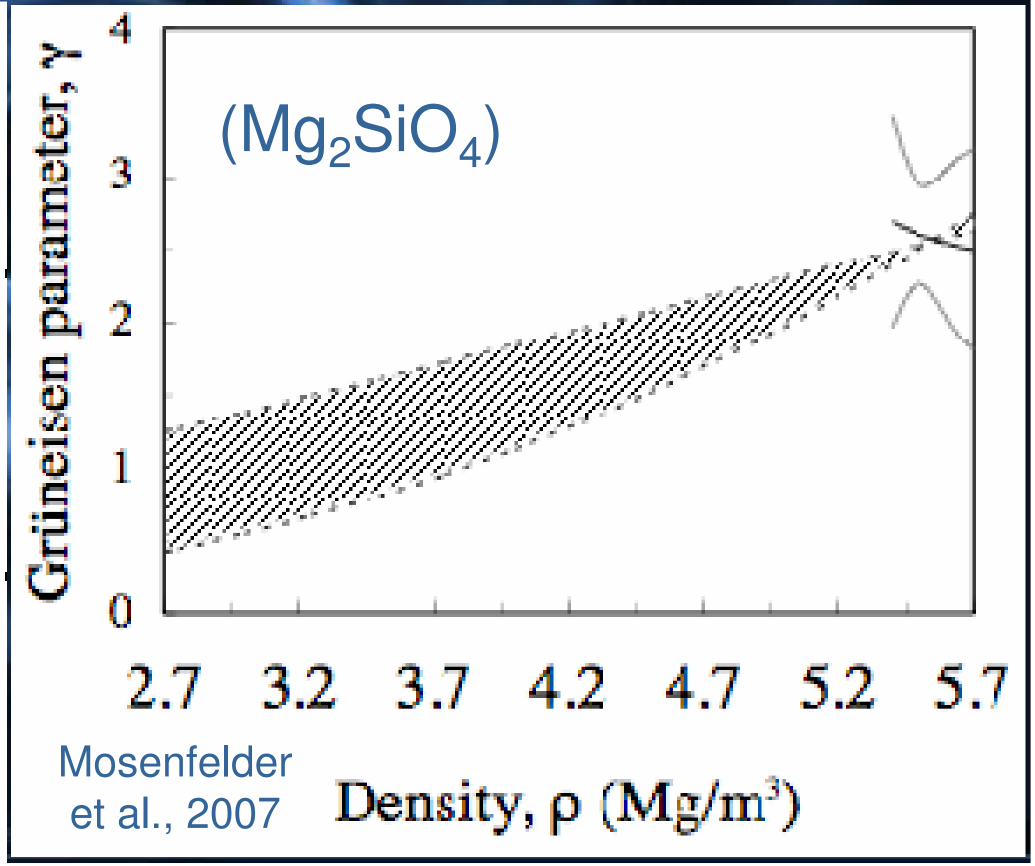
The Grüneisen Parameter

- For solids, γ decreases upon compression
  - A fair approximation is often $\gamma\rho$ ~ constant
  - In the absence of data, similar behavior was generally assumed for liquids, e.g. in all previous magma ocean models
- However, recently both computational and experimental studies have shown that γ for silicate liquids *increases* upon compression
  - This was long known to some (q.v. Brown et al. 1987) but not widely acknowledged

Grüneisen Parameter of melts

- Caltech shock wave data on forsterite and wadsleyite (Mosenfelder et al., 2007) suggest factor of ~3 **increase** from ambient pressure to 150 GPa in γ for Mg_2SiO_4 liquid.
- First Principles Molecular Dynamics simulations (Stixrude and Karki, 2006) show γ for $MgSiO_3$ liquid **increases** by factor of ~3 from ambient pressure to 150 GPa
- Unpublished work so far shows same result for diopside (theory) and diopside+anorthite (experiment) melts

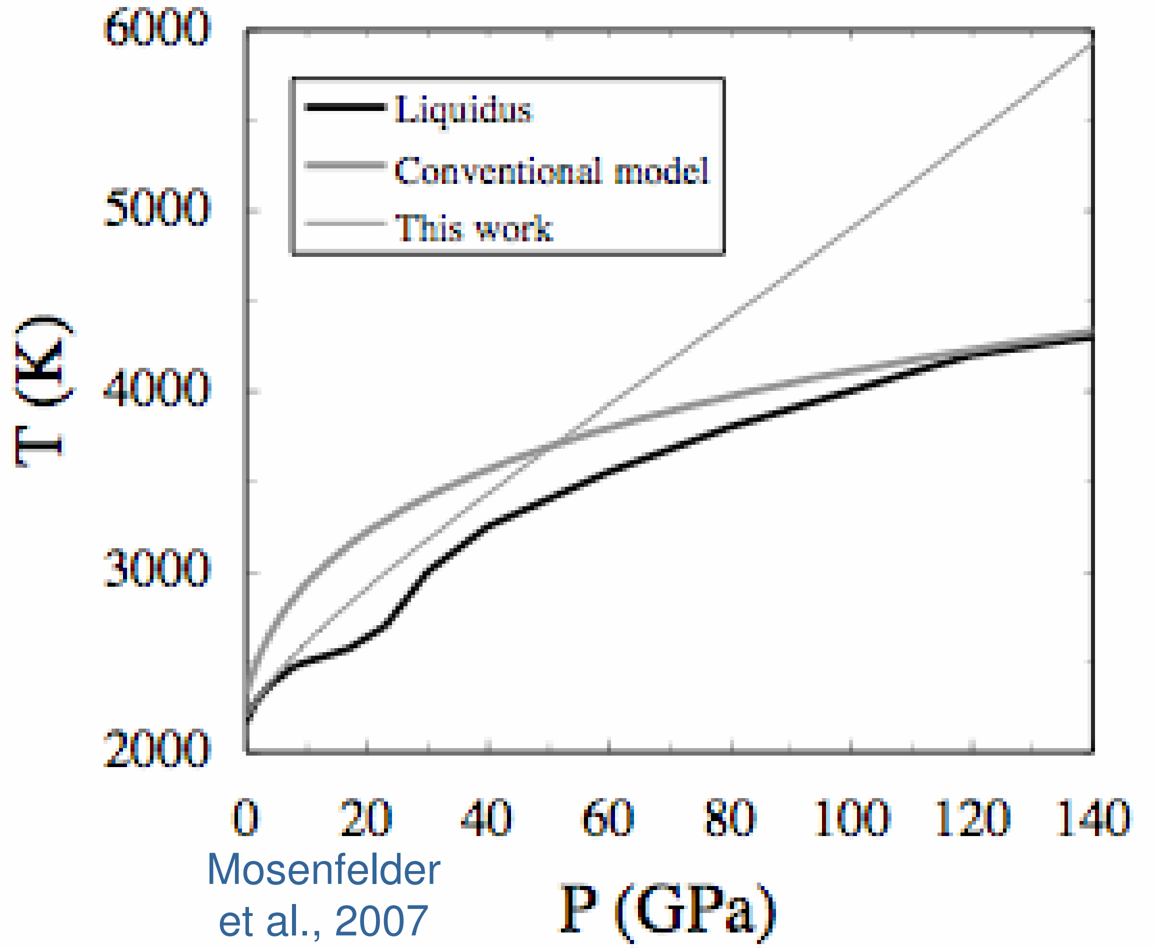




Mosenfelder et al., 2007

Grüneisen Parameter of melts

- Recalling that γ of ultramafic melt is the adiabatic gradient for a magma ocean, the new fact that γ strongly increases implies the possibility of *top-down* rather than bottom-up fractionation!
  - Mosenfelder et al. (2007) and recent talks by Stixrude have both made this observation, but nobody has yet developed it into a full model



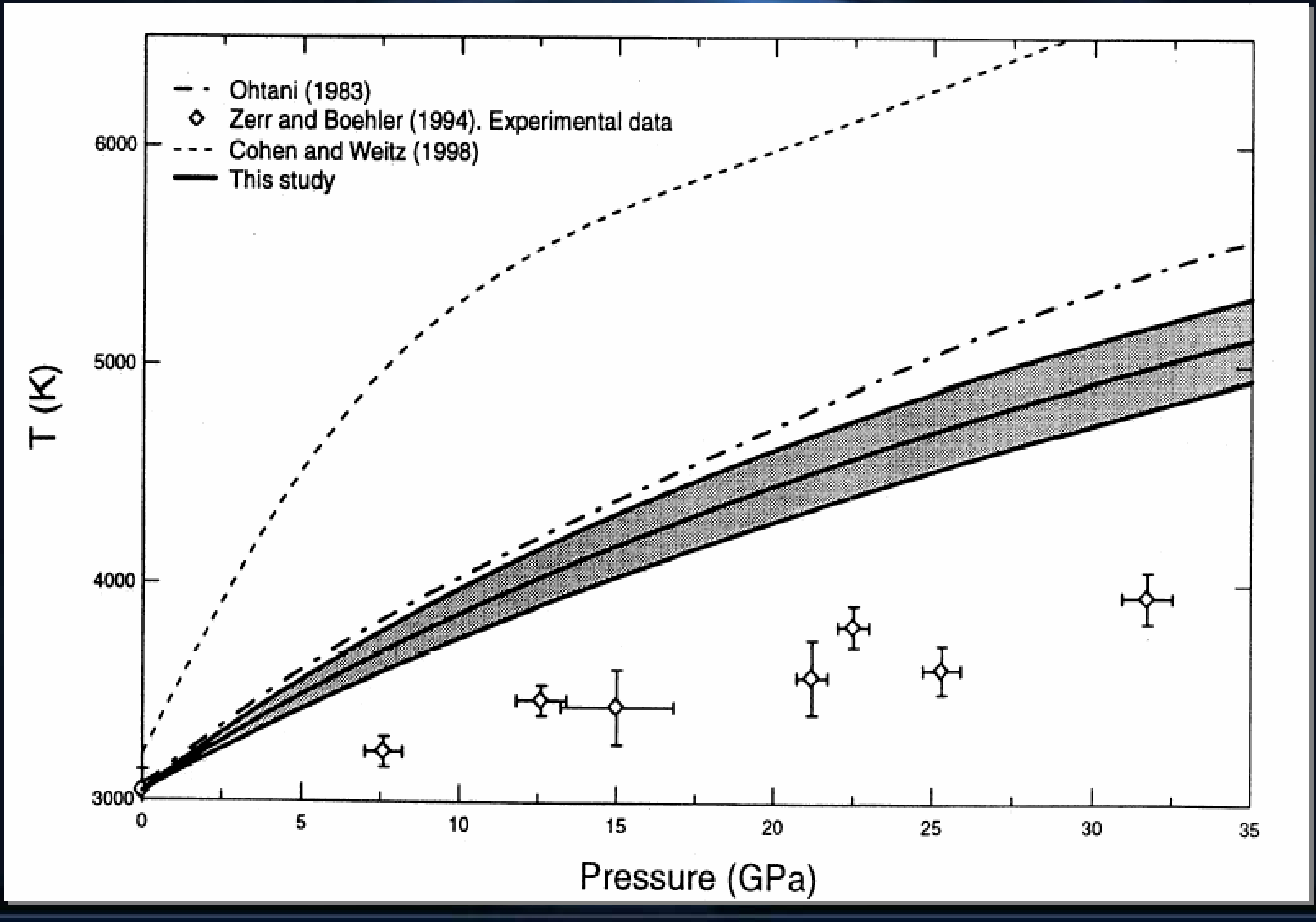
Mosenfelder et al., 2007

Attempted Self-Consistent Model

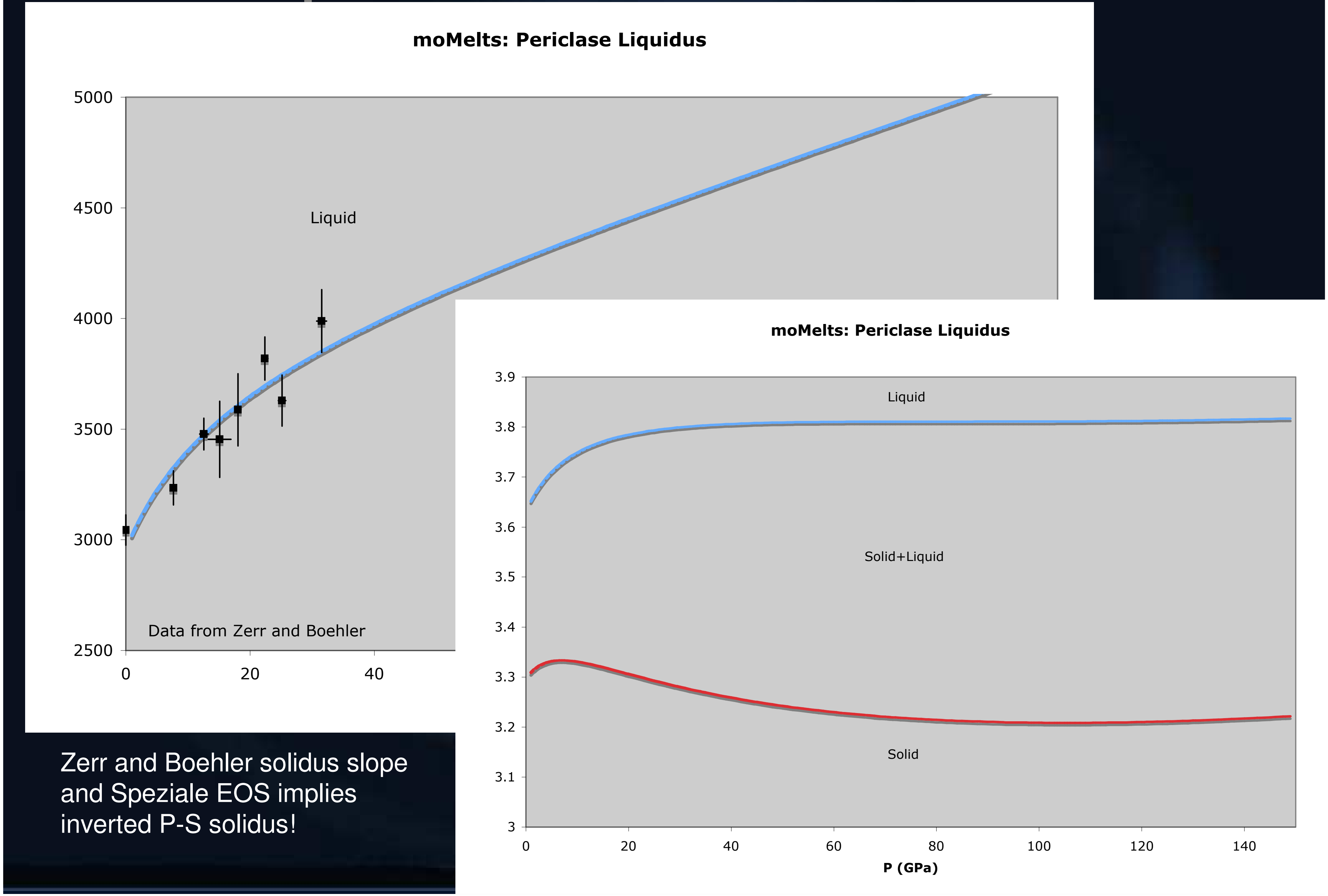
- Using Mie-Grüneisen-Debye theory to fit thermodynamic properties of all phases and a simple mixing model for liquid, we can build a preliminary model of the MgO-SiO_2 binary at all mantle pressures and temperatures
  - Each component requires seven parameters: V_o, K_{To}, K', γ_o, q, θ_0, C_{Vm}
  - For solids these are constrained; for melts they are derived by fitting the phase diagram; still uncertain
  - Can match most features of the P-T phase diagrams for MgO, Mg_2SiO_4, $MgSiO_3$, and SiO_2
- Furthermore, we can use P-S diagrams to assess the consequences for magma ocean adiabats
  - For computational ease, I built this model within the architecture of MELTS; I call it moMELTS

Inadequate data on MgO liquid properties

Speziale et al. (2001) Lindemann fit to melting curve matches neither DAC data nor *ab initio* calculation. *Need new data on MgO melting and P-V-T data on liquid.*

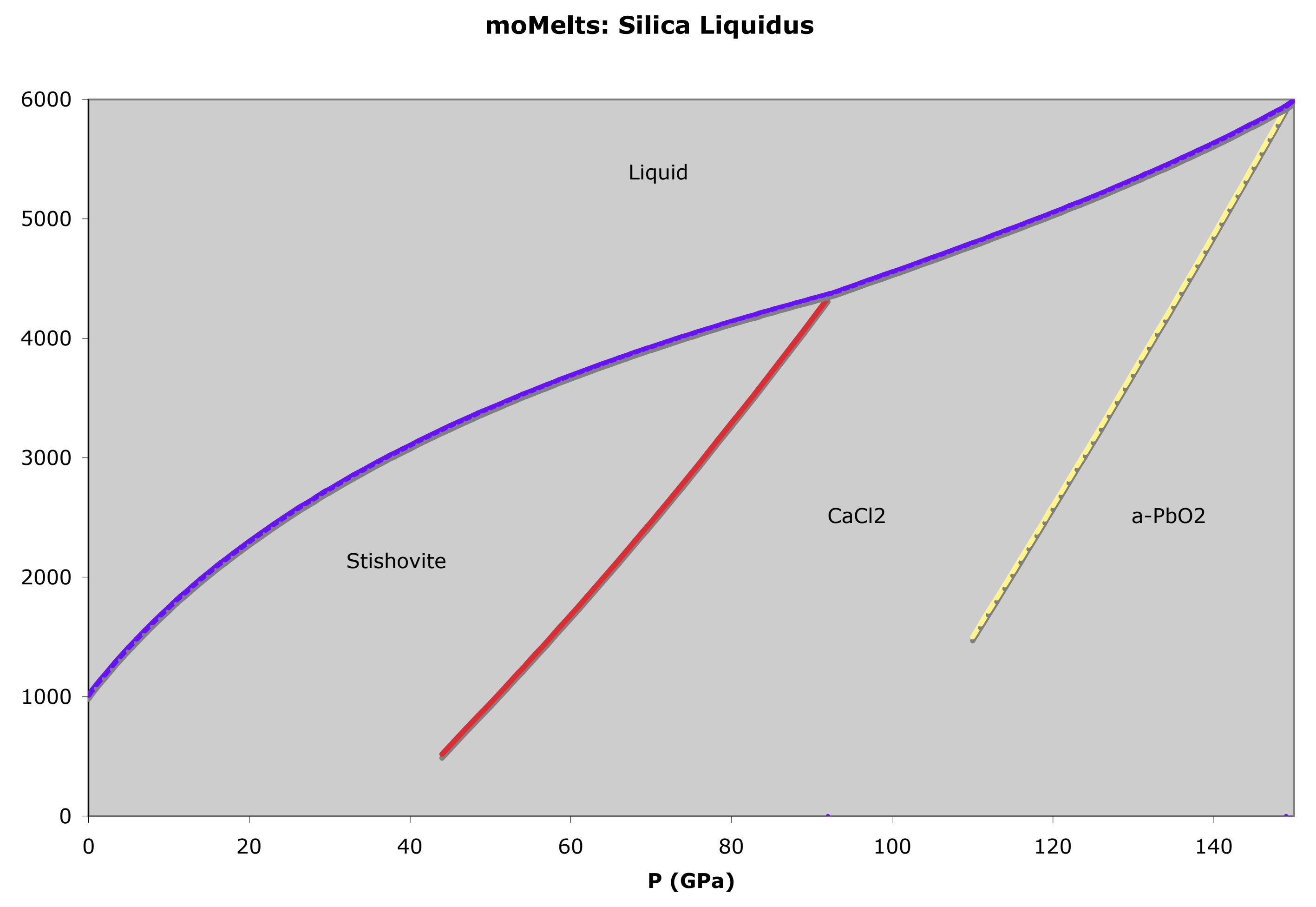


Attempted Self-Consistent Model



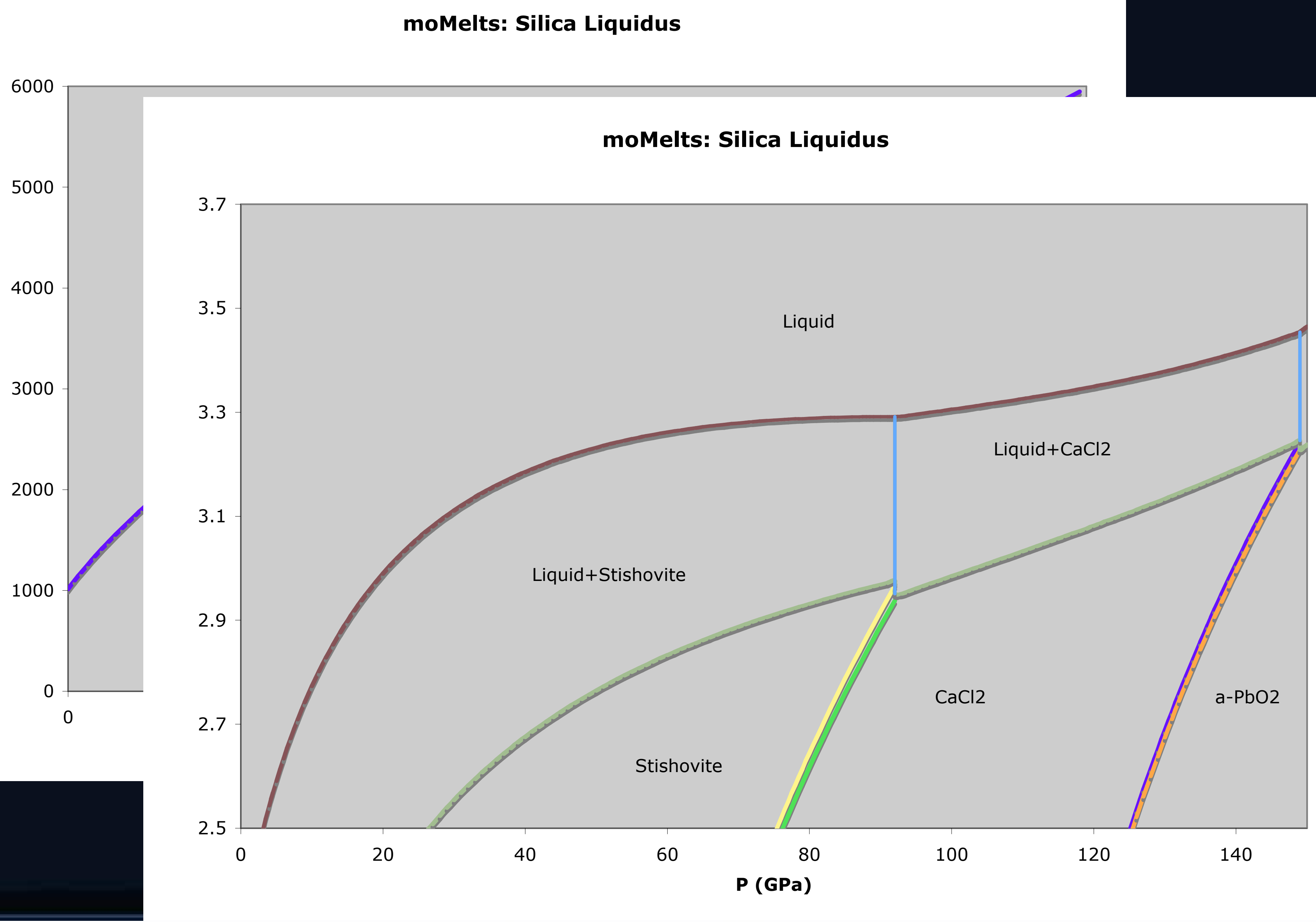
Zerr and Boehler solidus slope and Speziale EOS implies inverted P-S solidus!

Attempted Self-Consistent Model

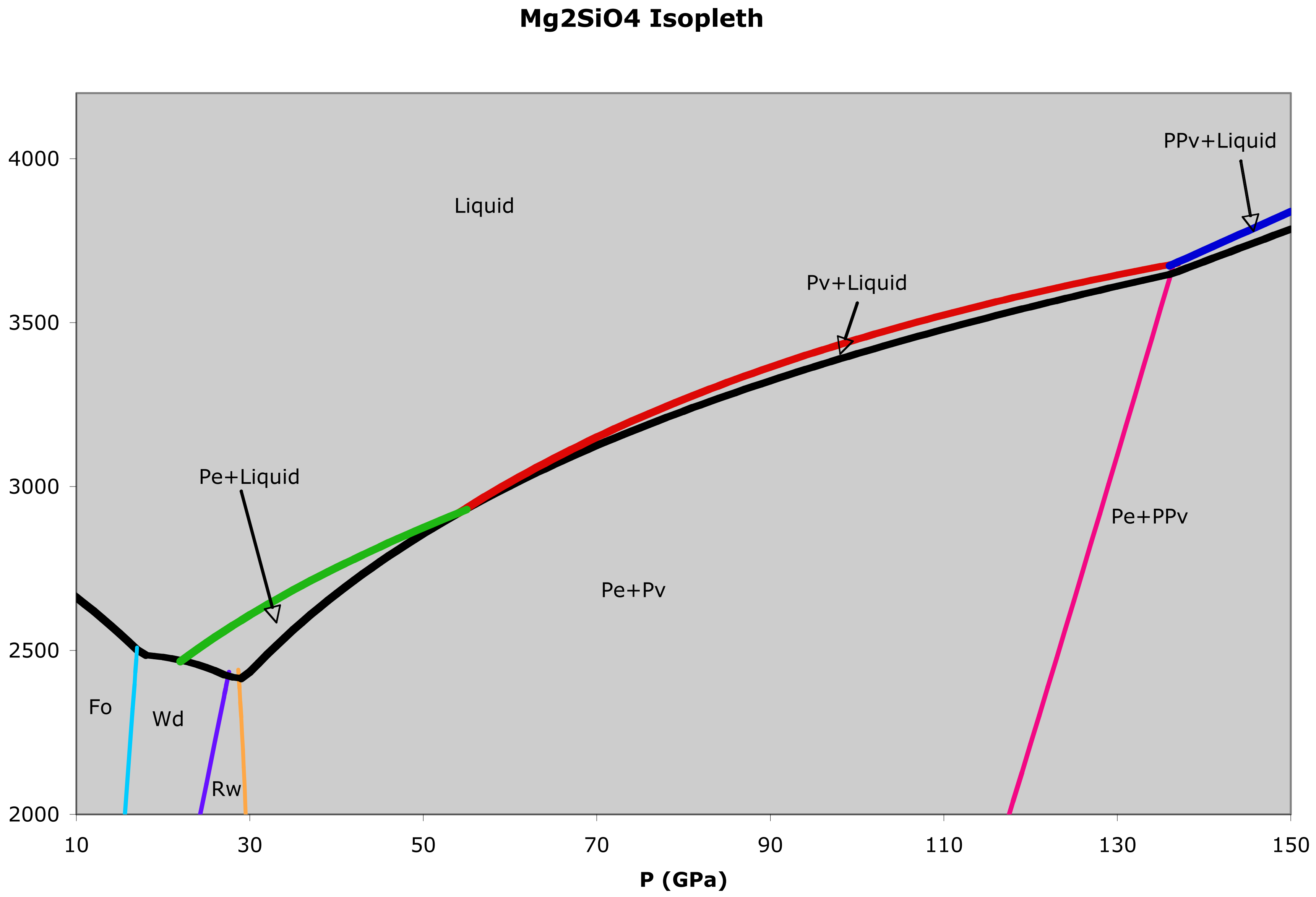


(Quartz, coesite, etc. not included)

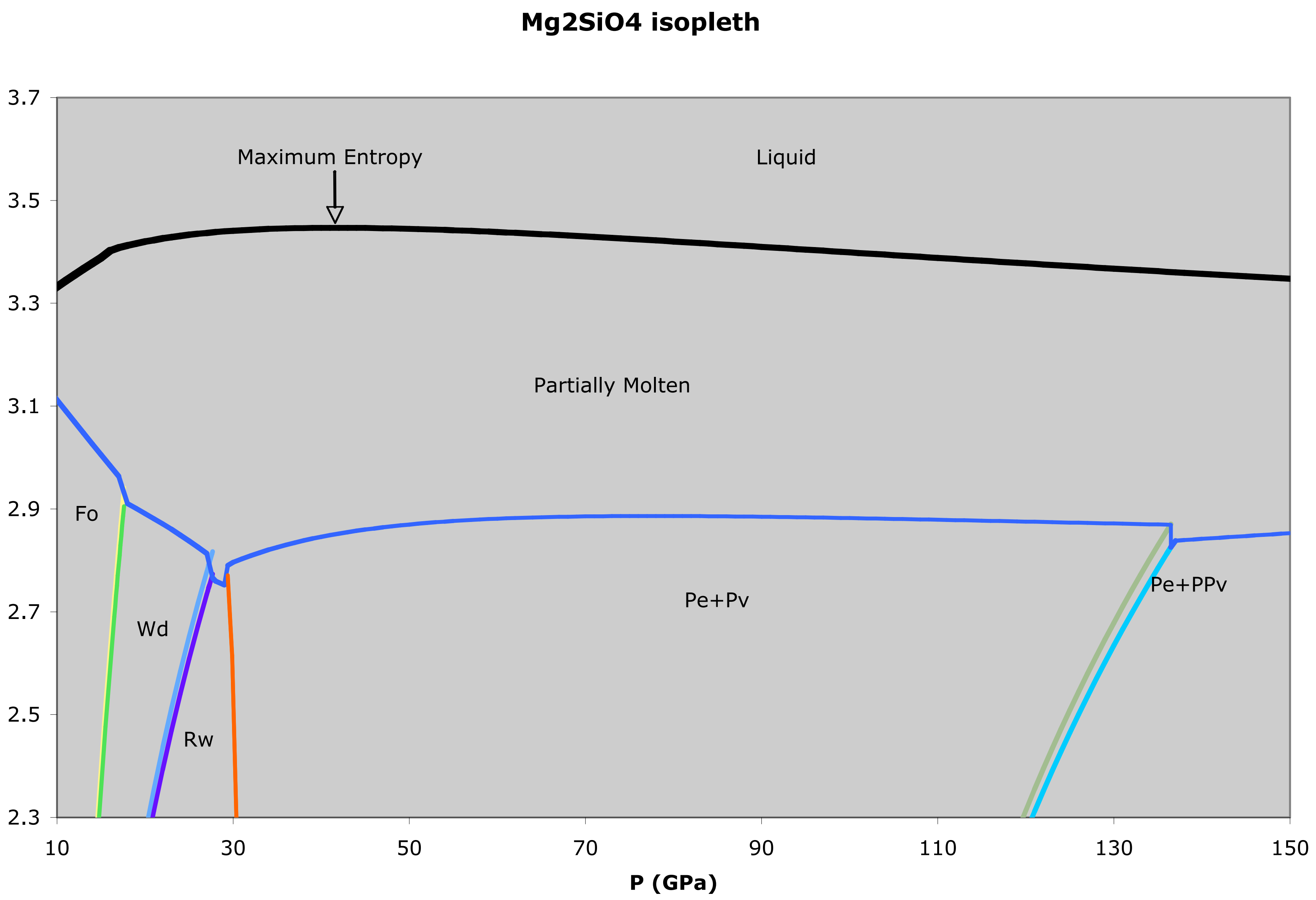
Attempted Self-Consistent Model



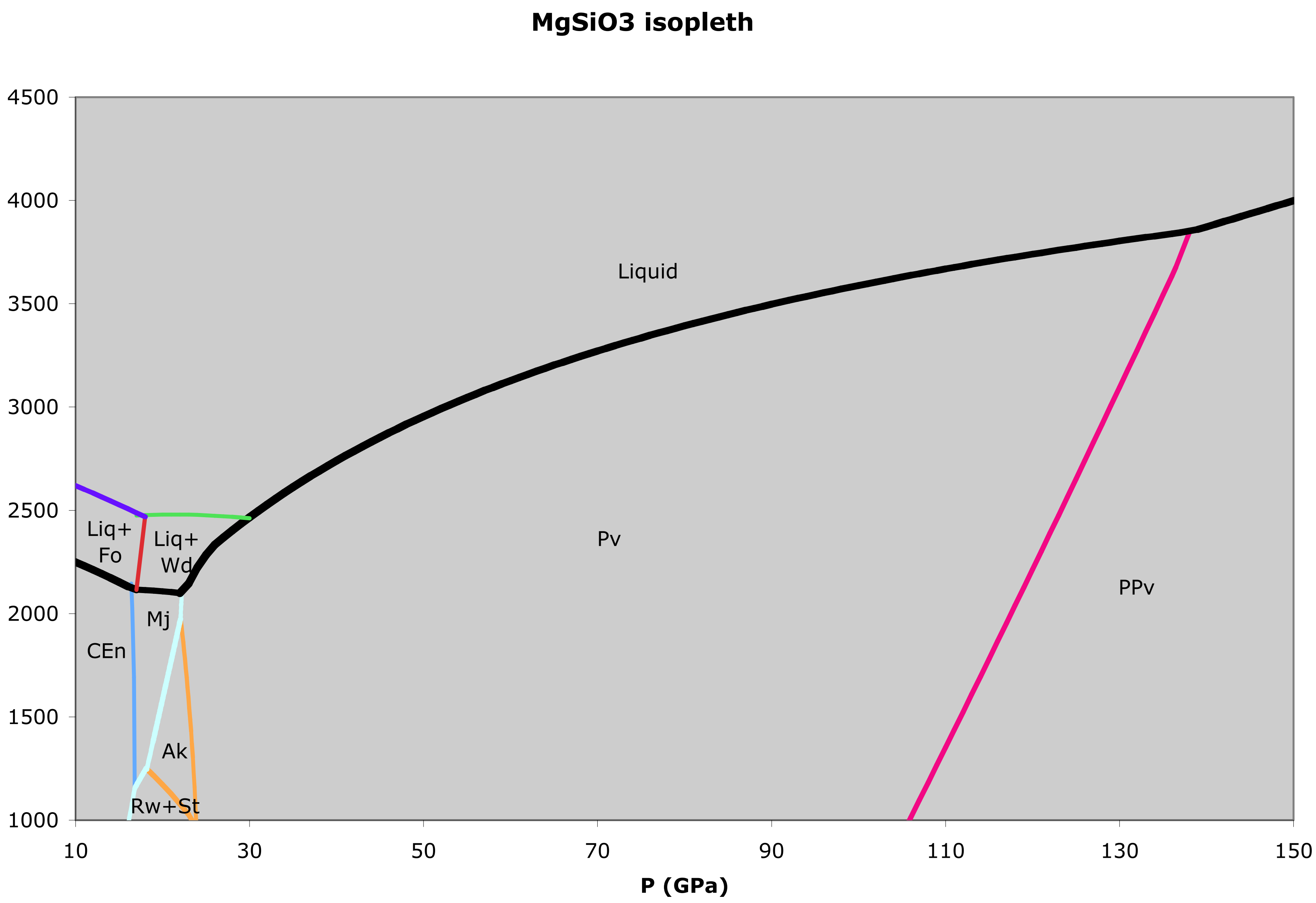
Attempted Self-Consistent Model



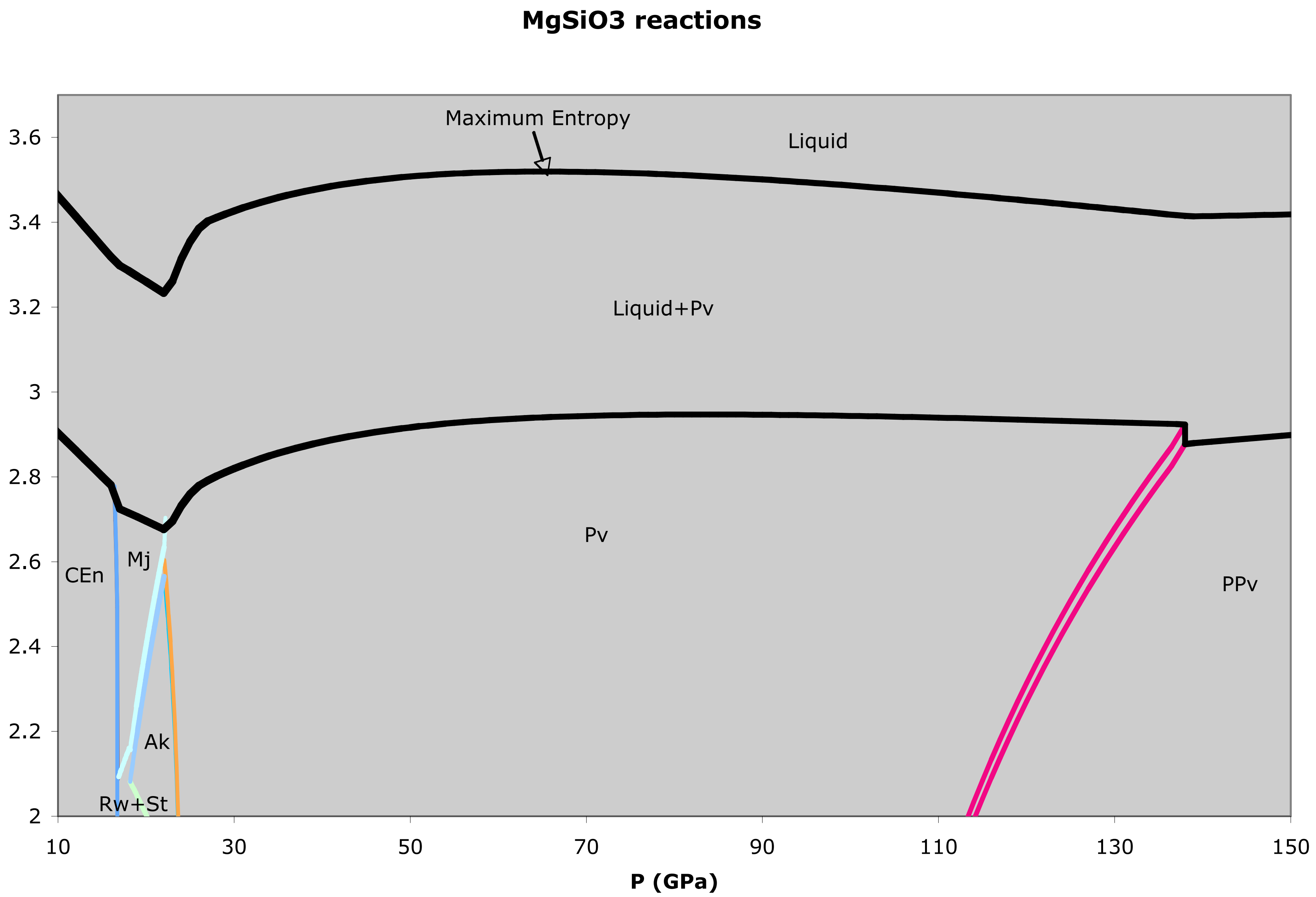
Attempted Self-Consistent Model



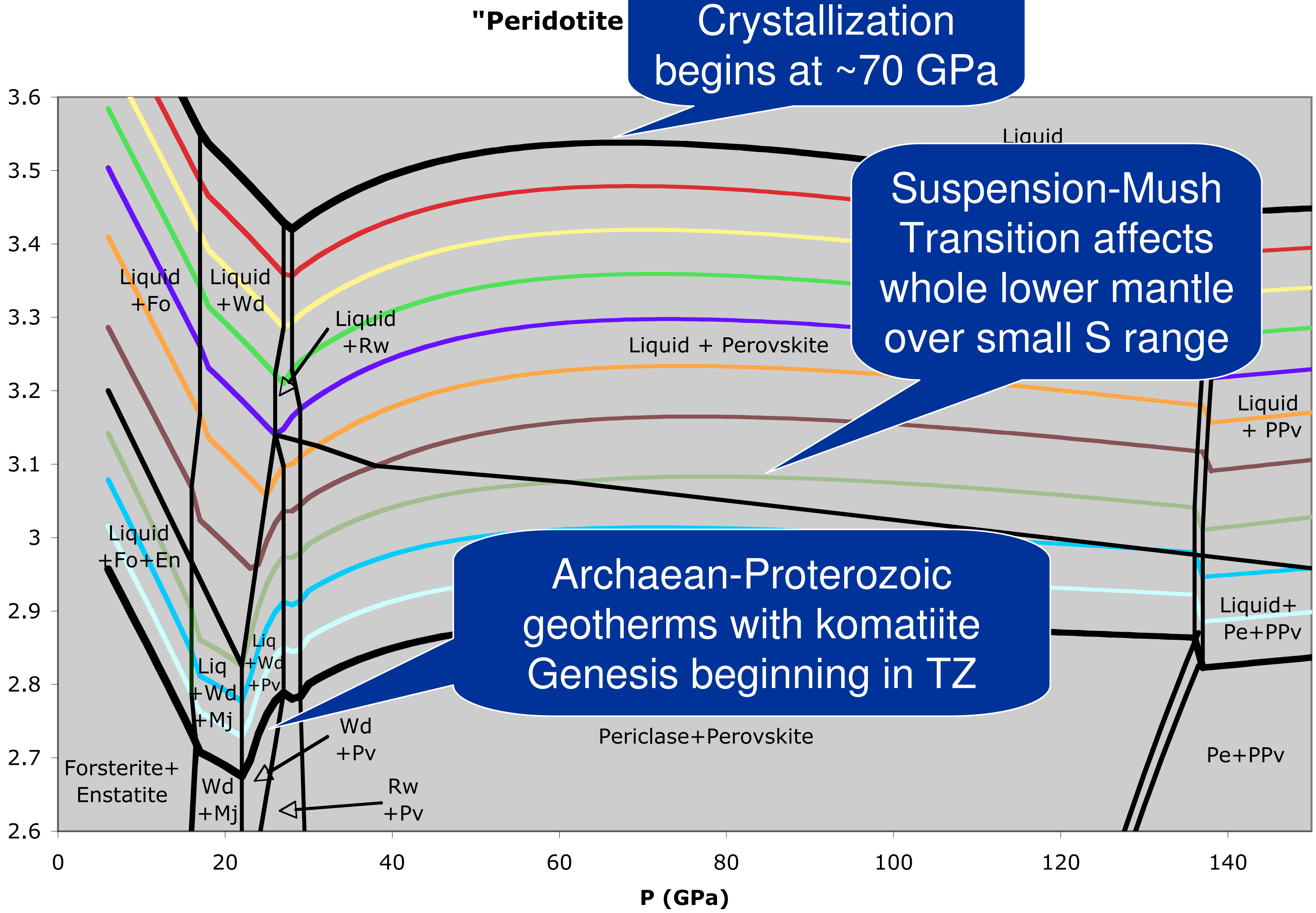
Attempted Self-Consistent Model



Attempted Self-Consistent Model



Attempted Self-Consistent Model



Perovskite Crystallization begins at ~70 GPa

Suspension-Mush Transition affects whole lower mantle over small S range

Archaean-Proterozoic geotherms with komatiite Genesis beginning in TZ

Preliminary results of model

- Increasing Grüneisen parameter of silicate liquids can indeed lead to an entropy maximum in mid-mantle on the liquidus
  - Surprisingly wide pressure range over which liquidus entropy decreases while solidus entropy and melting temperatures continue to increase
  - Probably implies further coordination increase in silicate liquids beyond 6, and more silicate phase transitions above 150 GPa
- Although magma ocean crystallization begins in mid-mantle, solid-state mantle displays normal decompression melting behavior
  - Caveats: consequence for magma ocean differentiation depend strongly on crystal suspension vs. fractionation
  - And effects of many other components will matter!

Conclusions

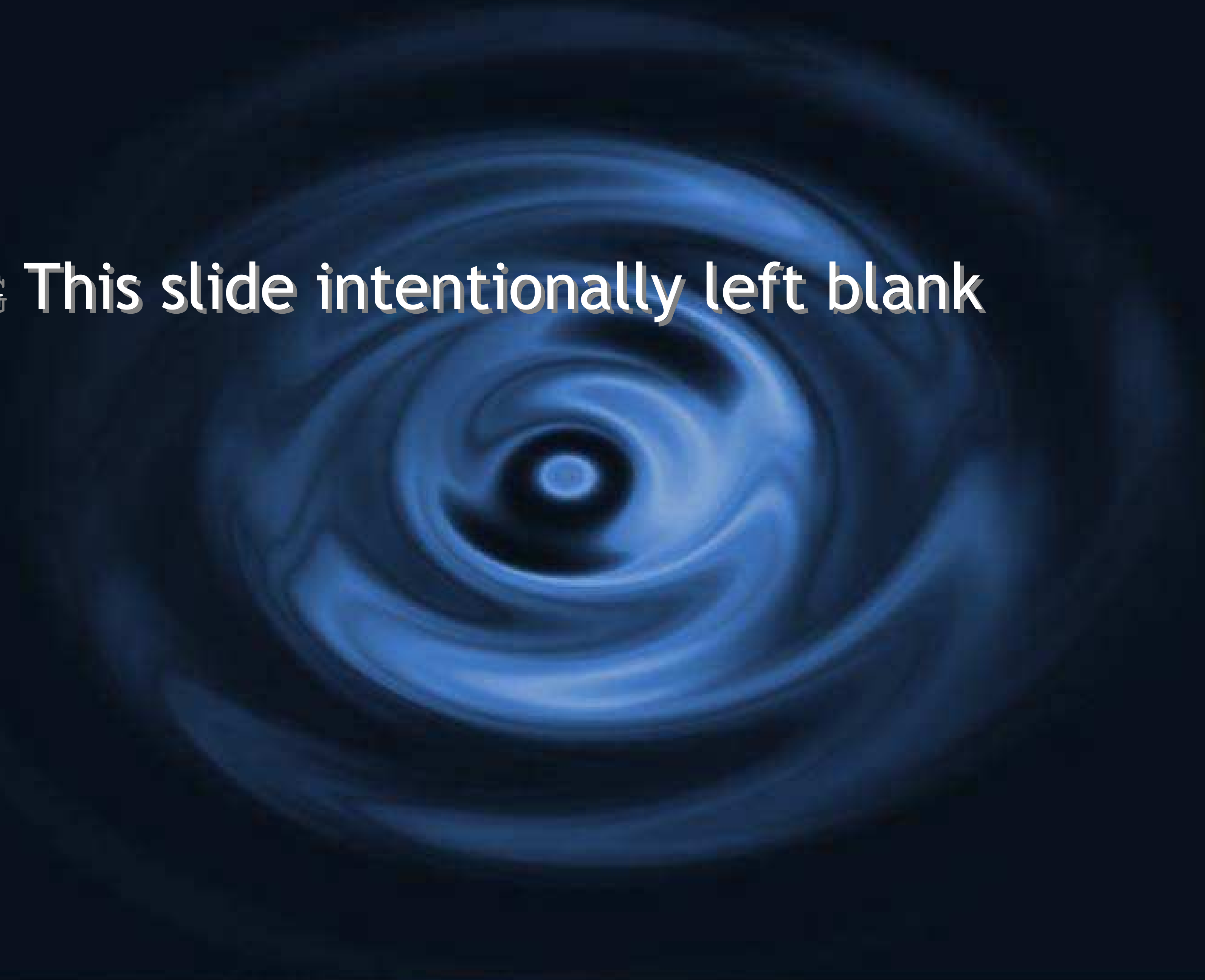
- Some melting processes and their effect on mantle evolution are pretty well understood, mostly those that give observable lavas
- Other ancient or ongoing melting processes have certainly affected the mantle, but constraining these effects, even qualitatively, in many cases remains beyond our ability
- Progress on thermodynamic properties of minerals at all mantle conditions is rapidly accumulating
- Progress on properties of melts is more challenging - will be sped along by computational as well as experimental approaches
  - Results so far indicate some big surprises!
- Sparse constraints on simple or natural systems can be interpreted with the help of phase equilibria to describe relevant chemical systems and model their behavior

Conclusions

- Ultimate dystopia for geochemists:

  “I’ve seen the future brother, it is murder.
  Things are gonna slide, slide in all directions.
  Won’t be nothing, won’t be nothing you can measure anymore.”
  -Leonard Cohen, “The Future”

- I disagree - the future promises substantial progress on many fronts, and lots of things to measure!



- This slide intentionally left blank

Melting at the Core-Mantle Boundary

- The post-perovskite phase transition appears to explain many of the features of the D” layer, but it does **not** explain the ULVZs
- The 15-30% deficits in V_S are most easily explained by partial melting
- Rost and Garnero suggest a 10% density excess in ULVZ. If real, hard to explain except by compositional anomaly or lots of core melt
- Most puzzling: ULVZ is patchy, yet CMB is isothermal
- Best guess: ULVZ is a compositionally distinct layer with higher intrinsic density *and* lower melting point

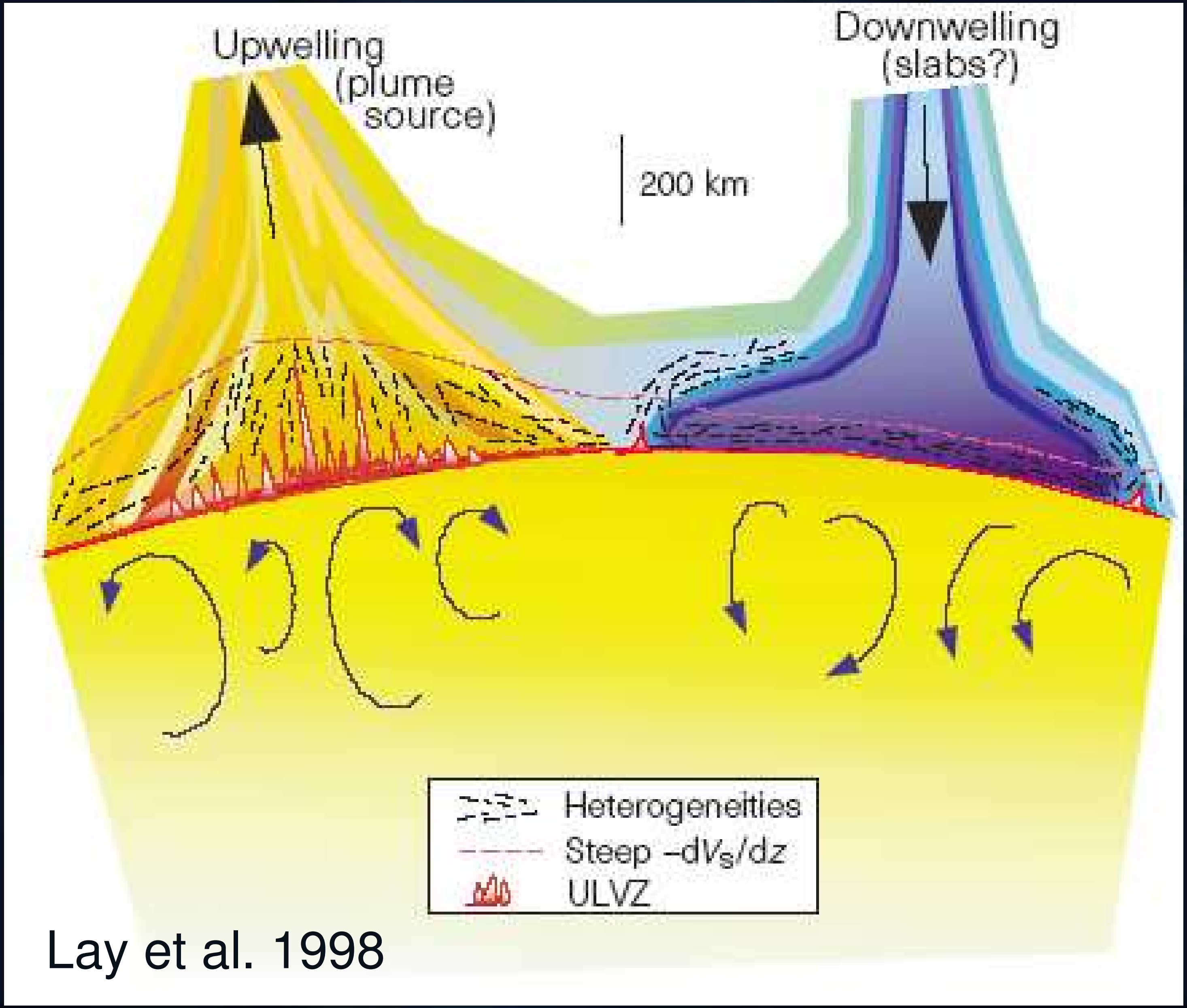
Melting at the Core-Mantle Boundary

- What compositions work?
    - UNKNOWN - we have essentially no data capable of resolving differences in melting points among different silicate and oxide components at CMB pressure
    - Hard to raise density by 10% without increasing FeO content considerably
        - The Banded Iron Formation hypothesis does this (!)
        - Some proposed reactions with the core can do this also (why patchy?)
        - Murakami et al. experiments suggest the opposite (!)
- Will the melt be stable?
    - UNKNOWN - we have almost no data on densities of silicate or oxide melts at CMB pressure
- What melt do you get when you heat multi-component candidate assemblages to partial melting at CMB?
    - UNKNOWN - No phase equilibria data at all, only preliminary speculations

Melting at the Core-Mantle Boundary

- What are the consequences for mantle evolution?
  - UNKNOWN - depends on...
    - Composition of the partial melt and its minor and trace element budget
    - Buoyancy of the partial melt
    - Permeability of the partially molten layer
    - Solubility of the partial melt in the core
    - Entrainability of the affected regions
- Where do we begin?
  - One approach is to construct self-consistent thermodynamic models that allow particular bulk compositions to be evaluated for seismic, phase equilibrium, and dynamical consequences
  - Get more data! Especially:
    - Equations of state of silicate and oxide liquids – useful directly for buoyancy and indirectly for thermodynamic calculations
    - Phase relations of simple and complex natural systems at CMB pressure
    - Both are potentially within near-future range of experimental and computational mineral and melt physics

Do ULVZ mark slabs or not-slabs?



Lay et al. 1998