ExTerra

Magmatic connections:

The interplay of magmatic systems with their crustal containers

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Questions:

- What is the flux of mass and enthalpy into arc crust, and what does this imply for long term continental growth?

  Thermal aspect and melting efficiency

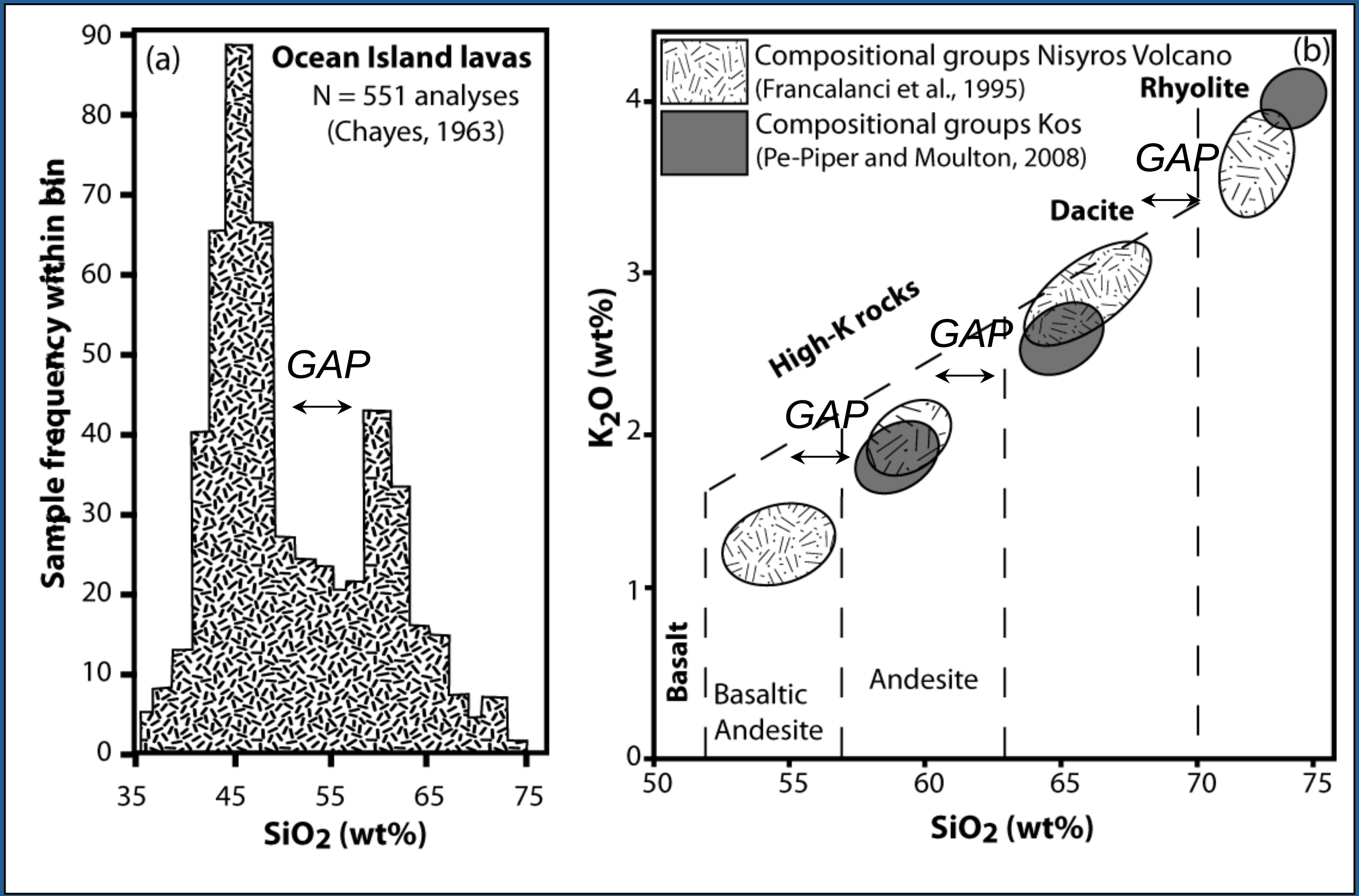
- By what means and rates is melt separated from its residue?

  Efficiency of melt-crystal dynamics

-How does foundering perturb the background melt flux?

  Generic dynamics and return flow;
  drip initiated melting

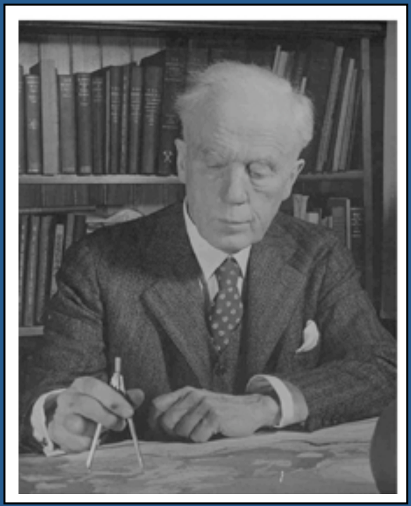
Compositional Gaps, or Daly Gaps - A paucity in the occurrence of intermediate erupted compositions.



A gap in this framework does not necessarily imply complete absence of certain compositions (such assertions can be hard to make rigorously) but the relative dearth of compositions.

A discussion of compositional gaps is a discussion of the relative abundances of rock compositions.

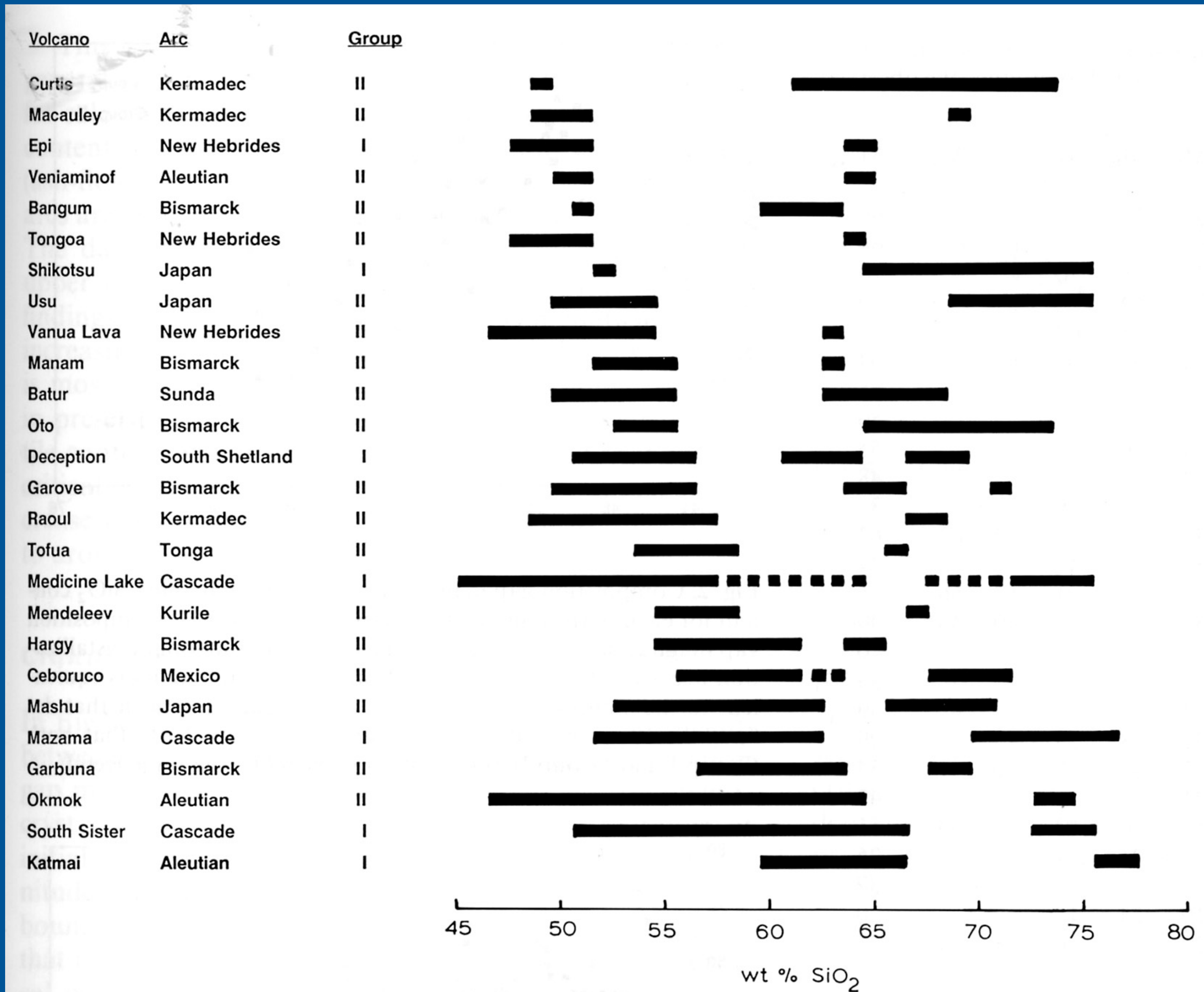
- helps determine the structure, extent, and properties of Earth's crust.



"…but still more to the circumstance that the rarer the rock species are the more "interesting" to most petrographers, the tendency has long reigned in petrographical literature to emphasize the diversity of igneous rocks. Like every other science, petrography has had to be analytic before it could be healthfully synthetic. But there is no little danger of a false perspective if, in the search for specific distinctions, a considerable effort is not made to estimate the actual value of those distinctions. Above all, petrography needs to be ever more closely linked with areal and structural geology, ***in order that the problem of rock origin may be phrased in the terms of the actual proportions of the different species."***

R. Daly, Igneous Rocks and Their Origin, 1914

Observations of Gaps are abundant - Here a compilation from Brophy in SiO_2.



Brophy, 1991

Explanations for Compositional Gaps

1. Melting:

   Partial melting of pre-existing crust and sampling of both melt and initially intruded magma (e.g. Chayes, 1963 and many more).

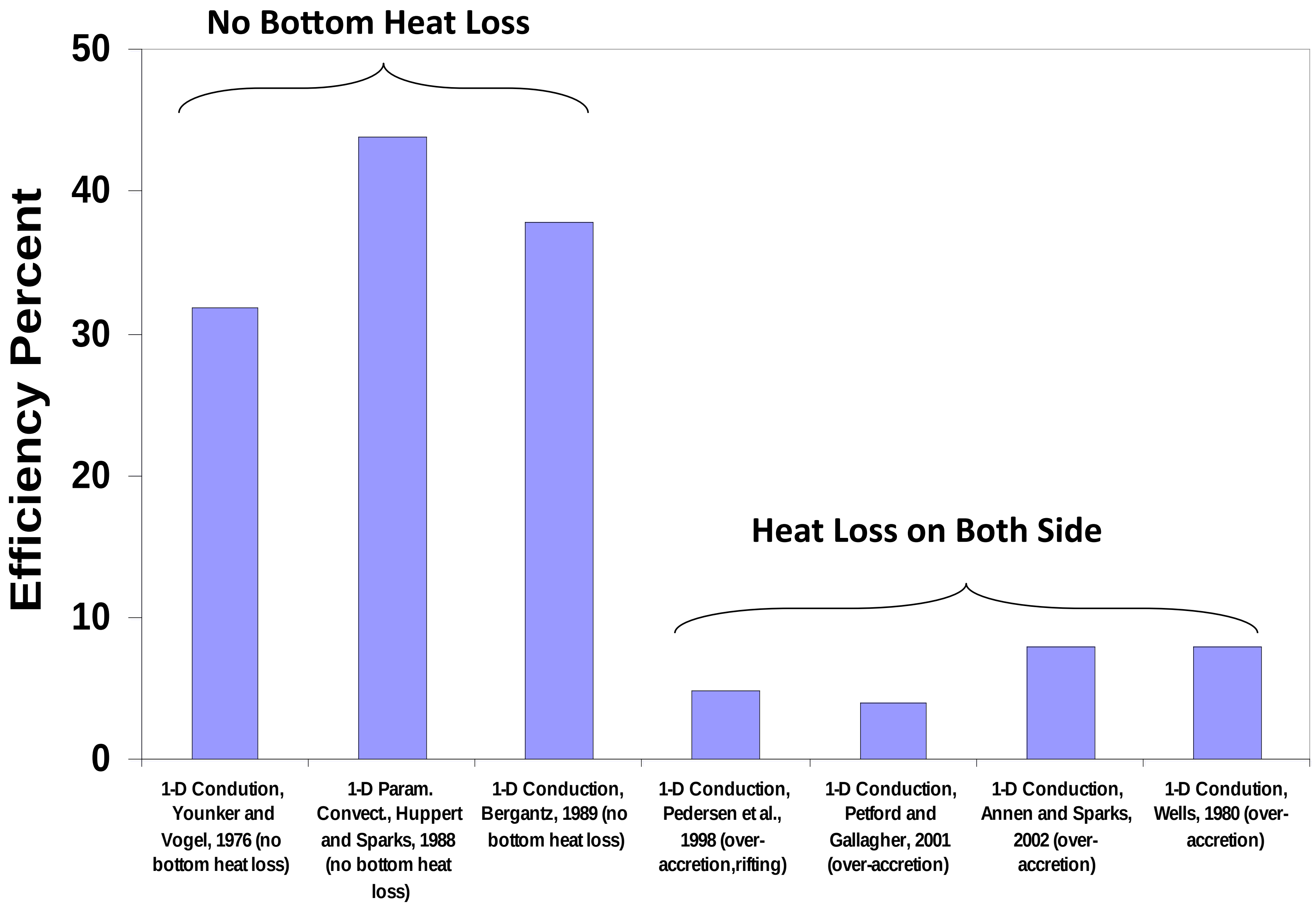
2. Crystallization:

   Fractional crystallization, modulated by gravitational or structural trapping, and/or modulated by phase equilibria constraints (e.g. Brophy, 1991, Grove et al., 1997, Thompson et al., 2002) .

These explanations are not mutually exclusive -- likely are many types of gaps. Here we focus on gaps of 5-15 wt. % SiO_2.

Melting has often been favored as it was viewed as a more efficient process, and crystal fractionation is usually thought to produce a continuum of compositions.

Summary of 1-D Conduction/Melting Simulations

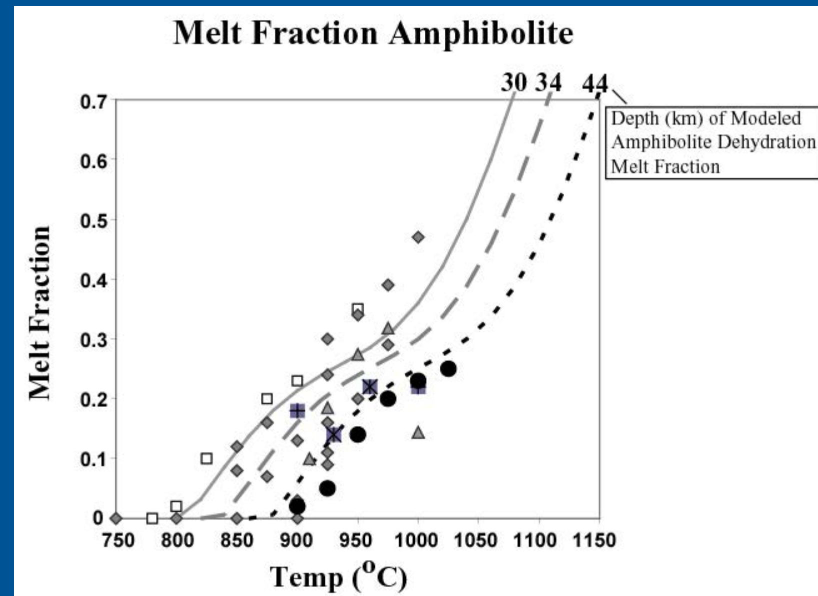


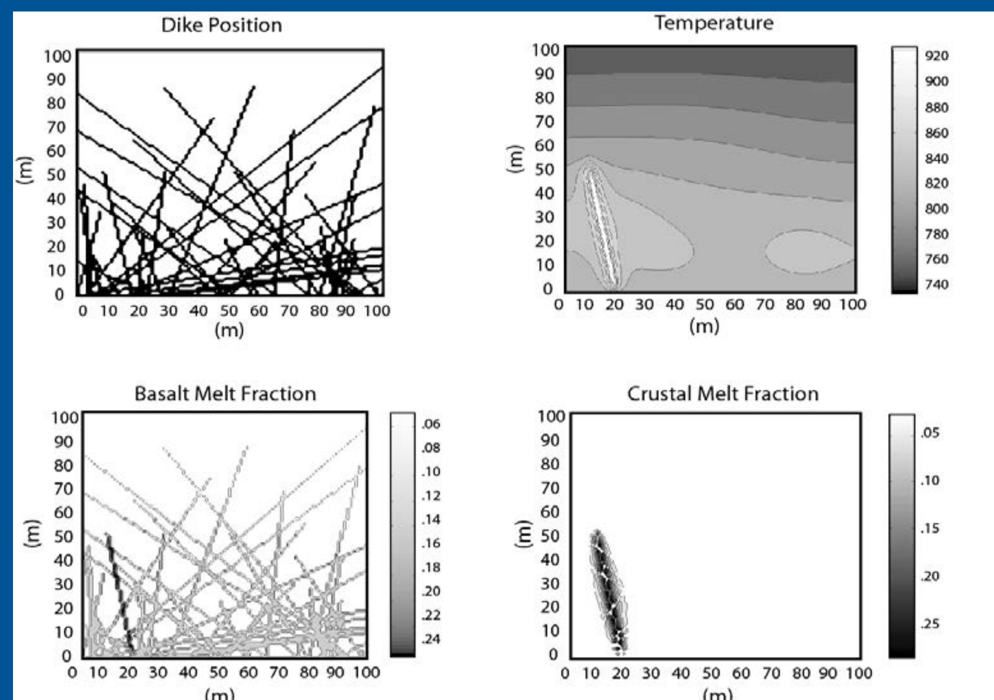
Stochastic simulations of magma intrusion into the lower crust:

- Survey of basalt flux and crustal thickness variations.

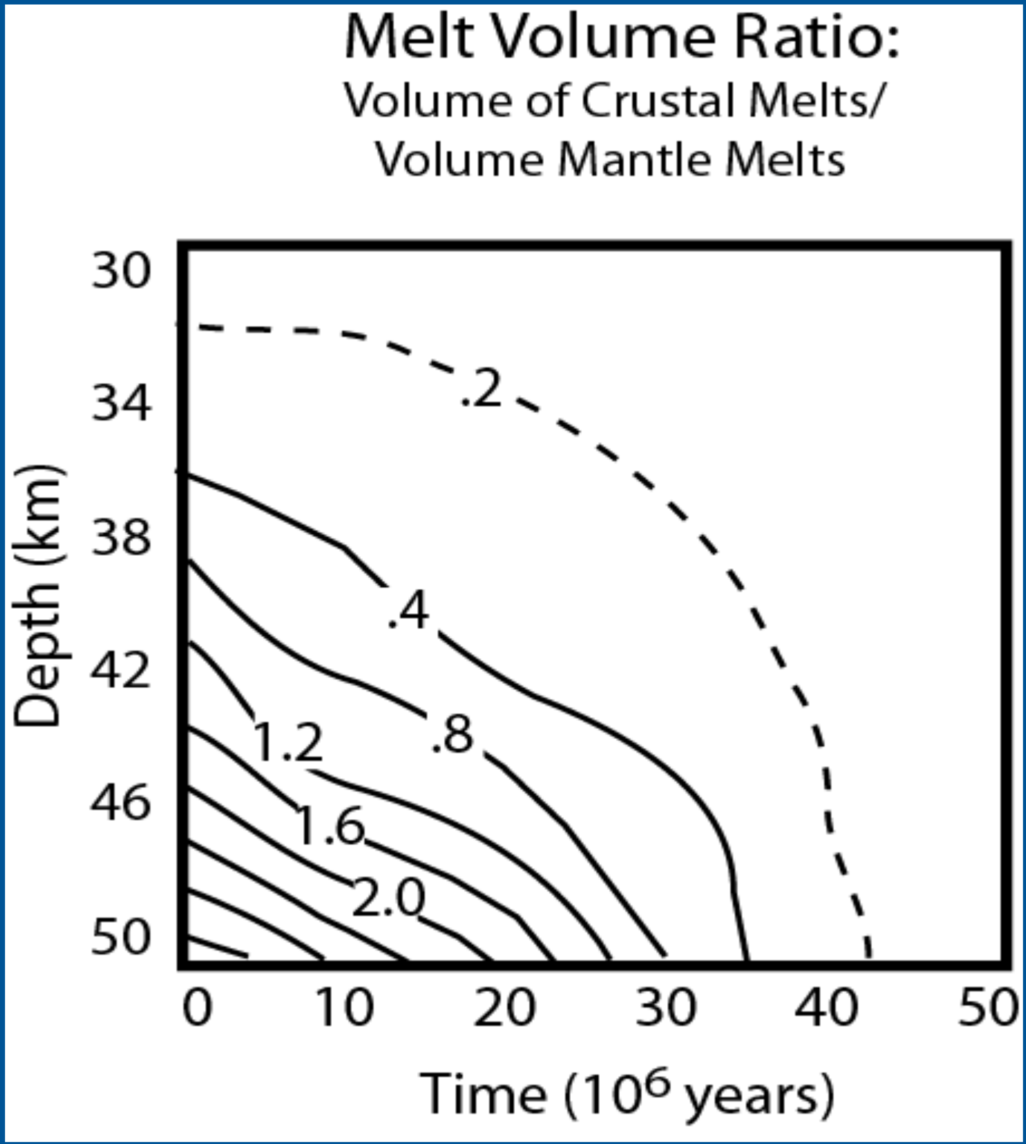
- Compilation of numerous realizations to examine probability of production.

- Long term melt productivity and dynamic response.





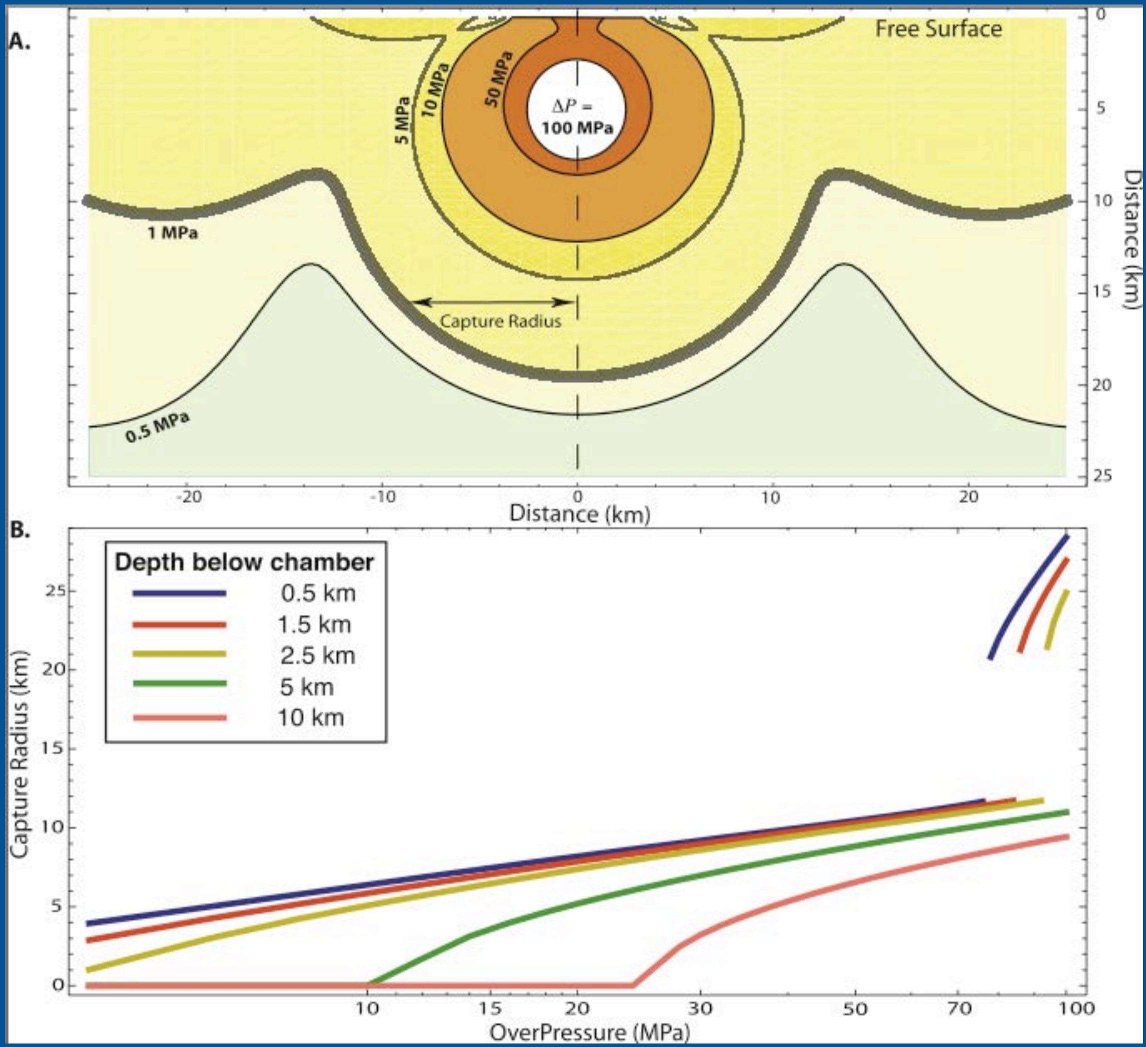
Dufek and Bergantz,J. Pet. 2005



Thin crust (on average) leads to less overall melt, although thin crust is more prone to variability.

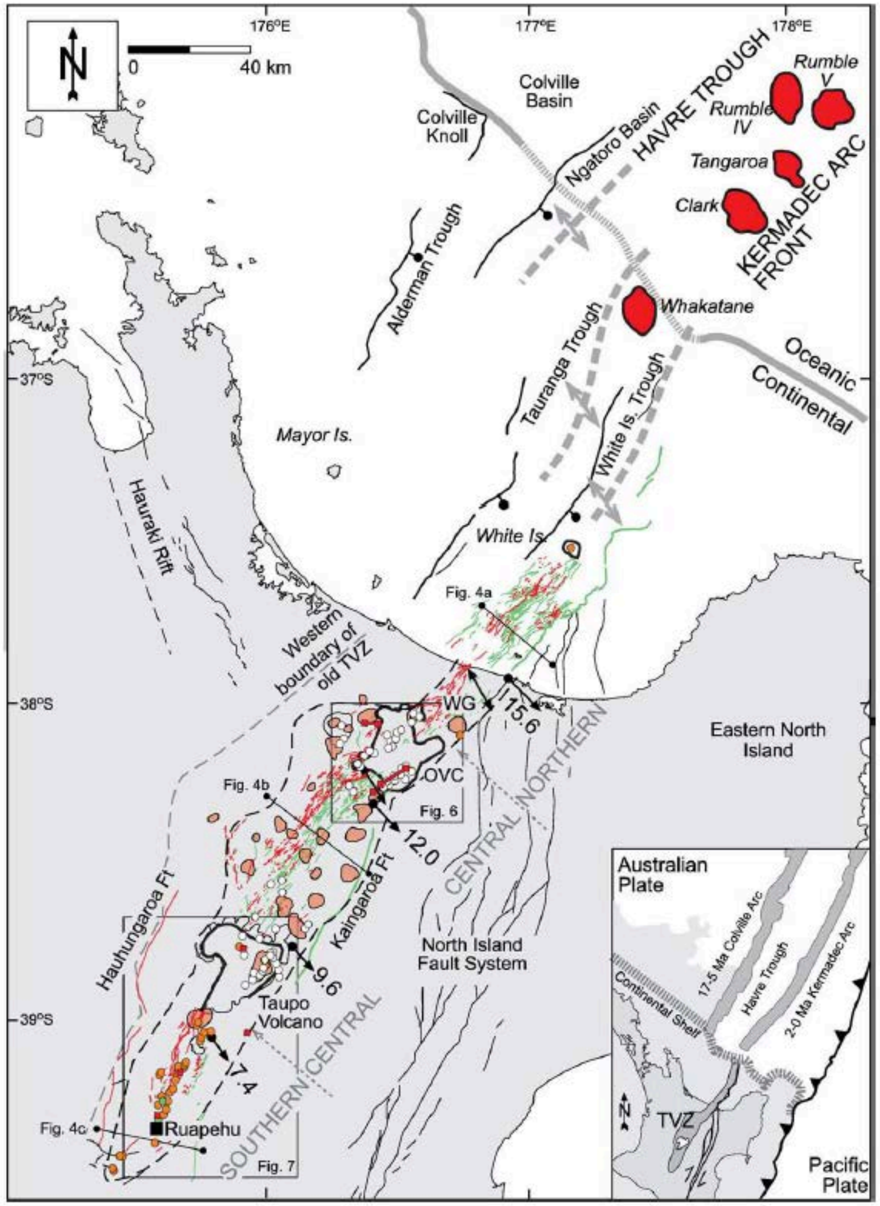
Note also that this is overall melt, and what we can sample at surface can be considerably limited.

Structural heterogeneity and stress feedback can also lead to concentration of magma.

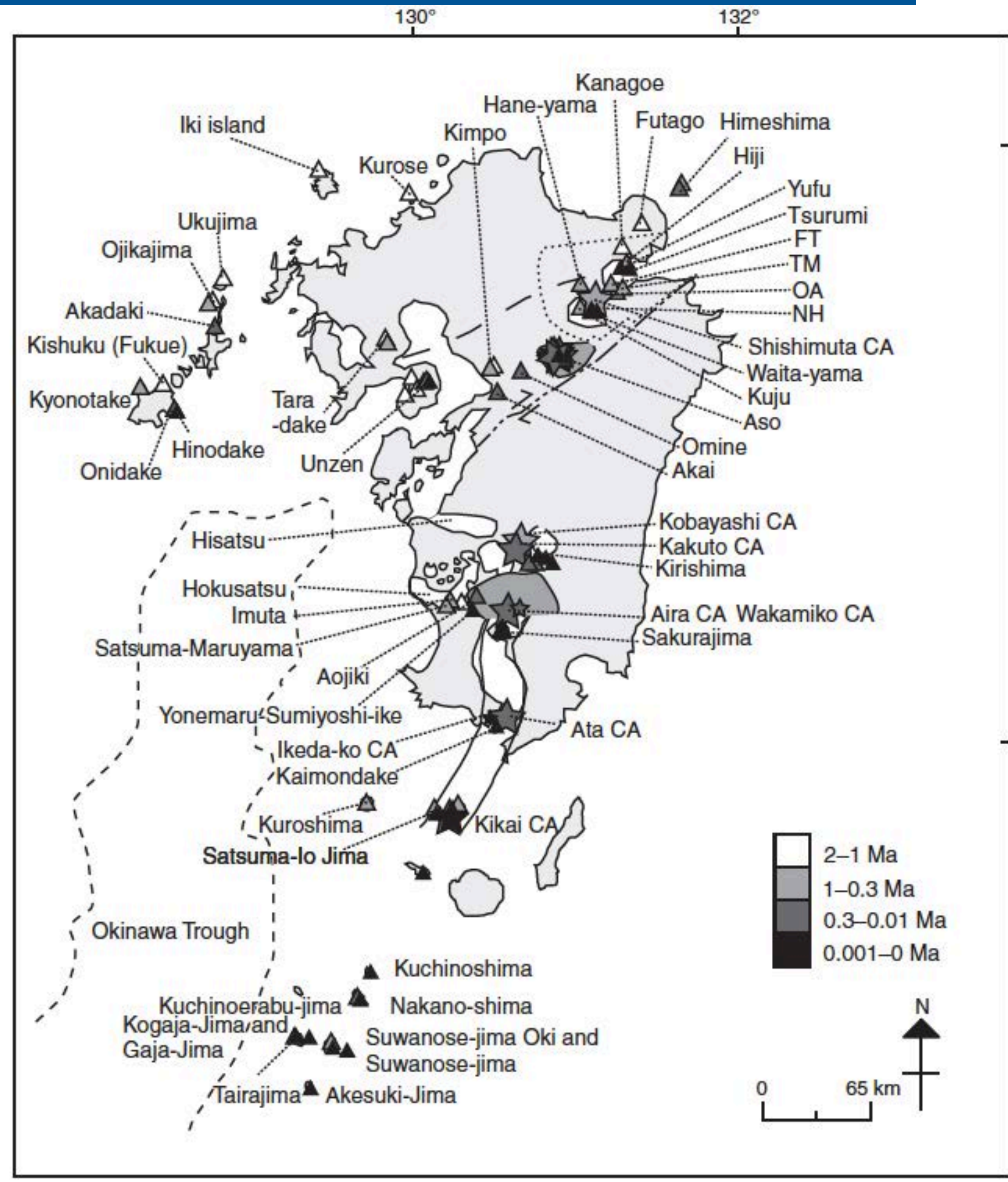


Karlstrom, Dufek and Manga 2009

Tectonic Controls

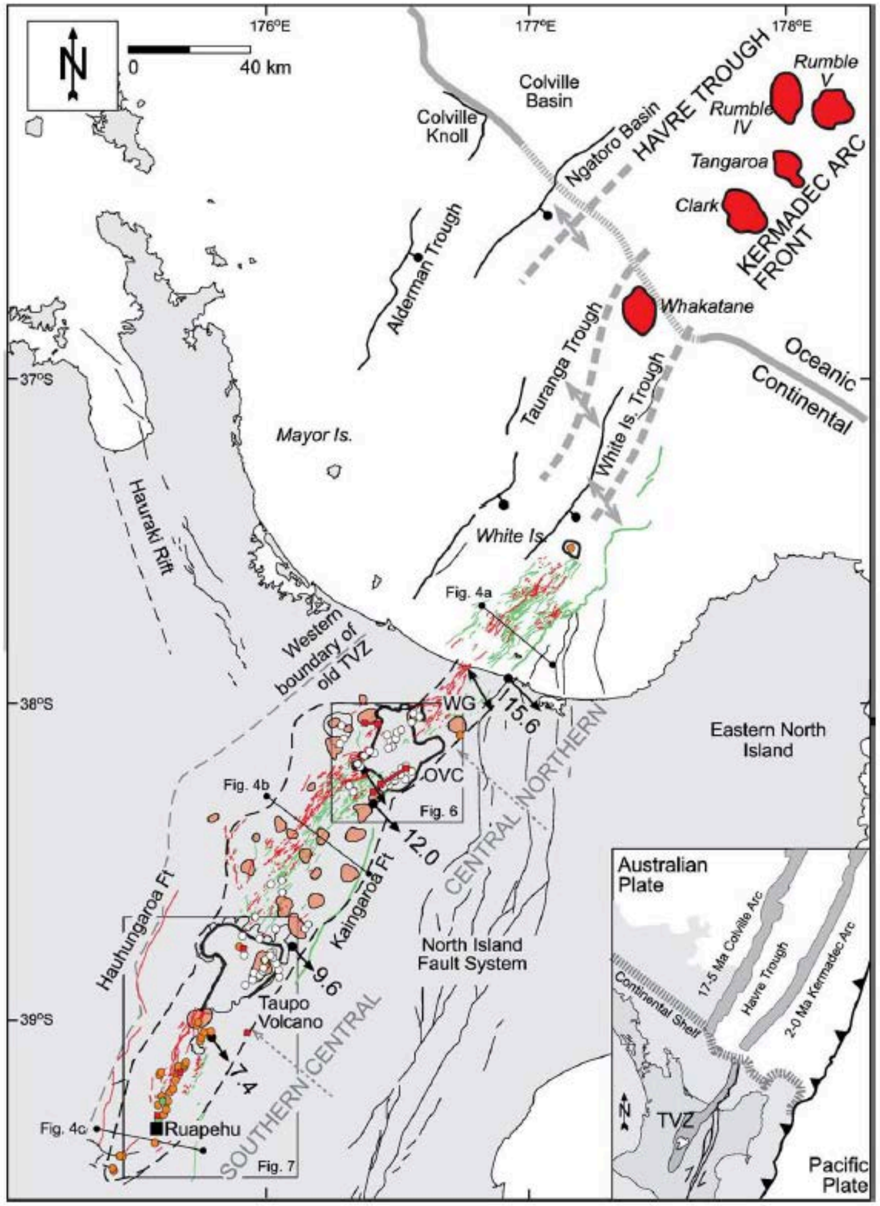


Rowland et al, 2010

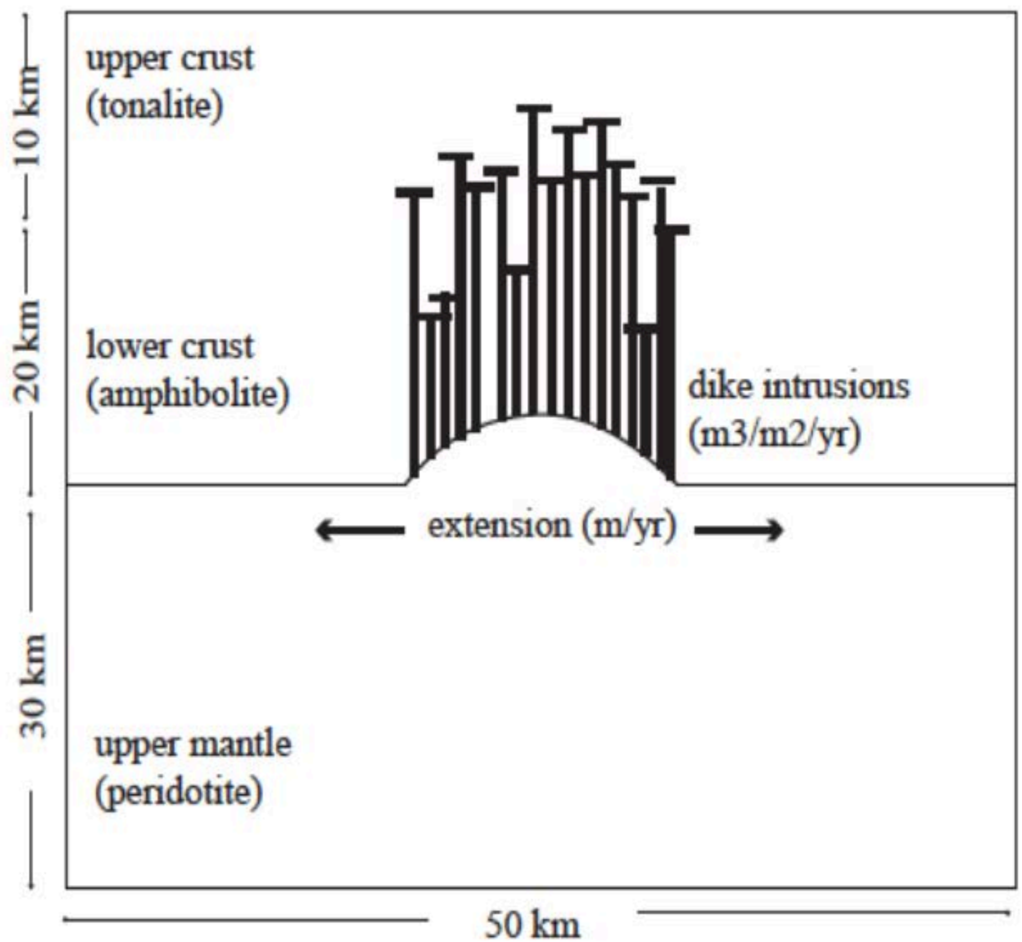


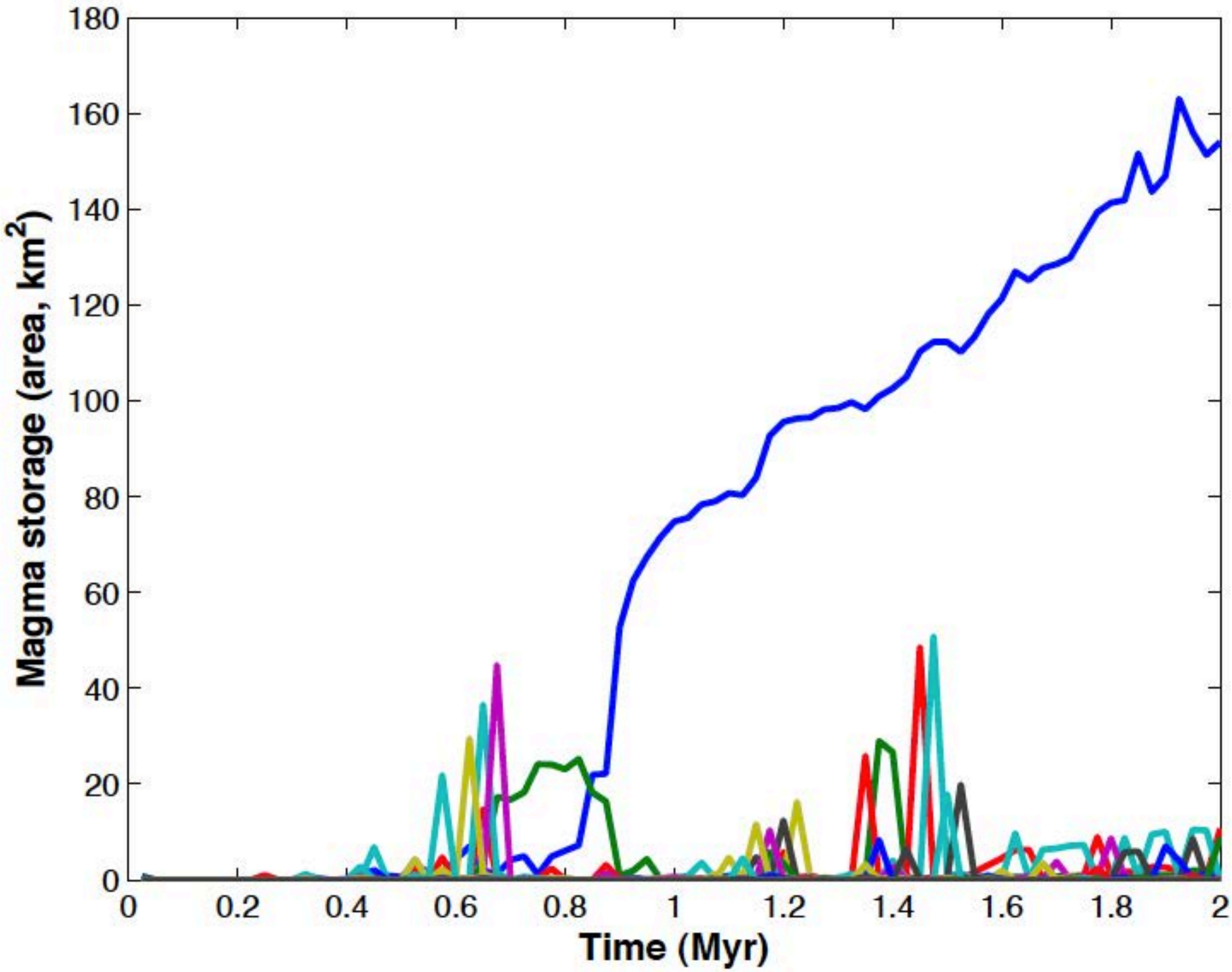
Mahony et al., 2011

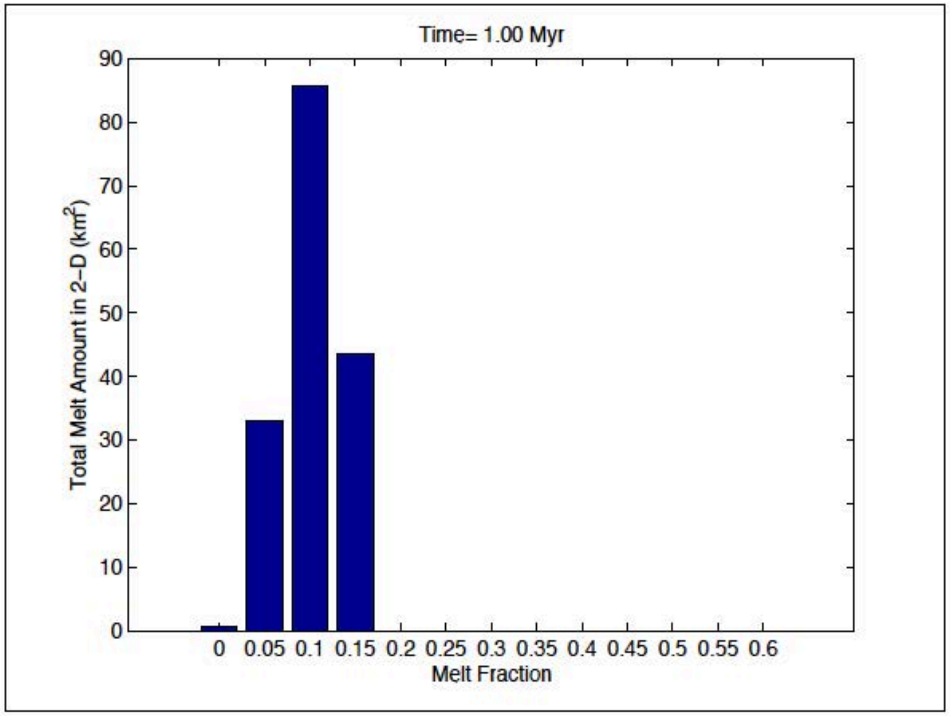
Tectonic Controls

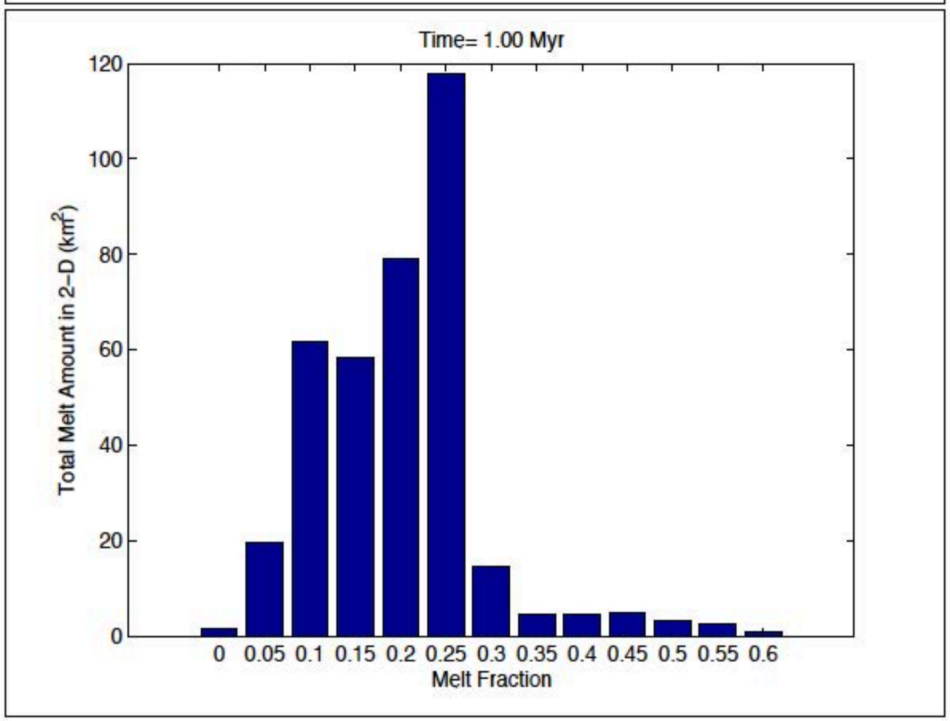


Rowland et al, 2010




Magma storage (area, km^2)
Time (Myr)
0
20
40
60
80
100
120
140
160
180
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2


Time= 1.00 Myr
Total Melt Amount in 2−D (km^2)
90
80
70
60
50
40
30
20
10
0
0 0.05 0.1 0.15 0.2 0.25 0.3 0.35 0.4 0.45 0.5 0.55 0.6
Melt Fraction


Time= 1.00 Myr
Total Melt Amount in 2−D (km^2)
120
100
80
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40
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0
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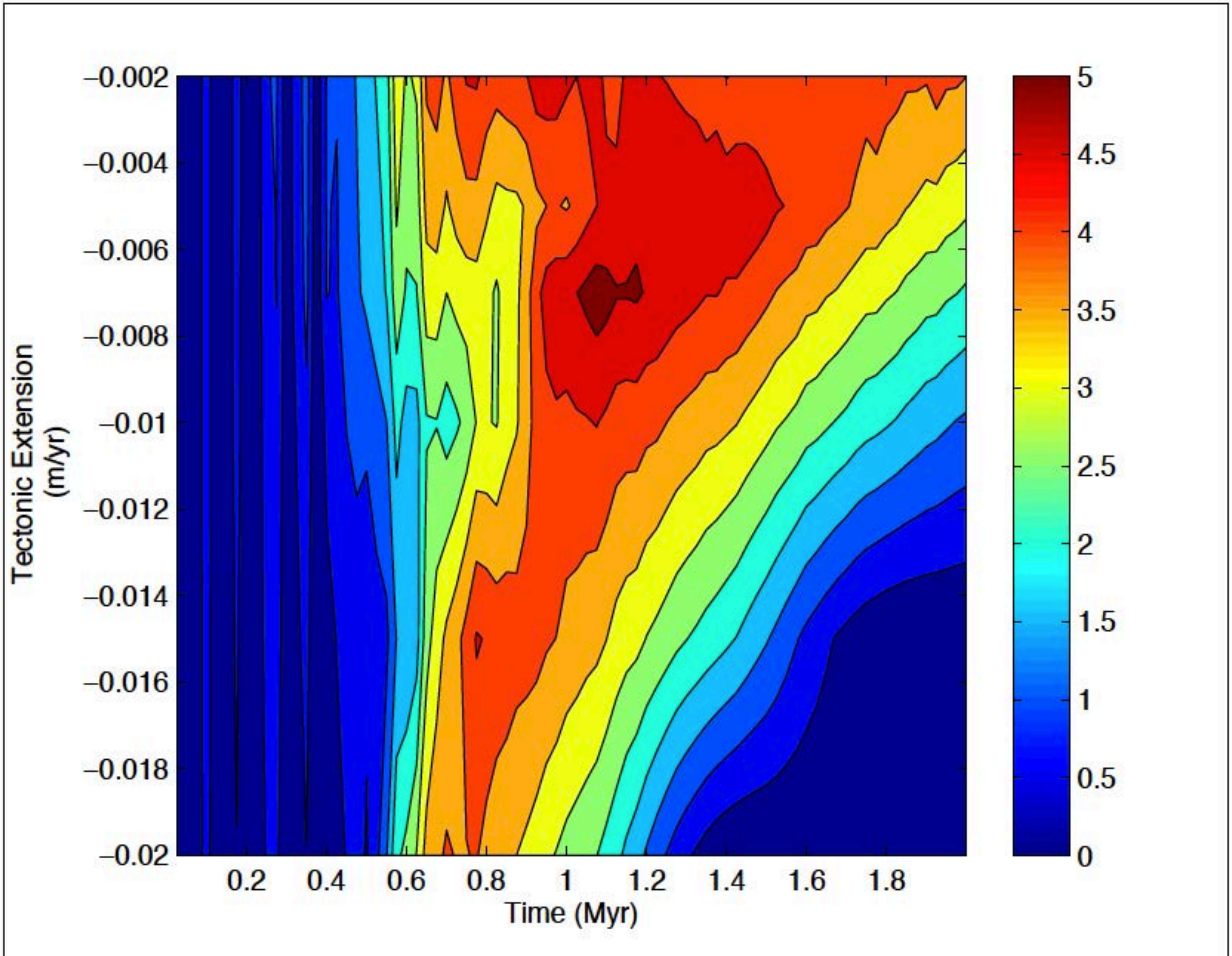
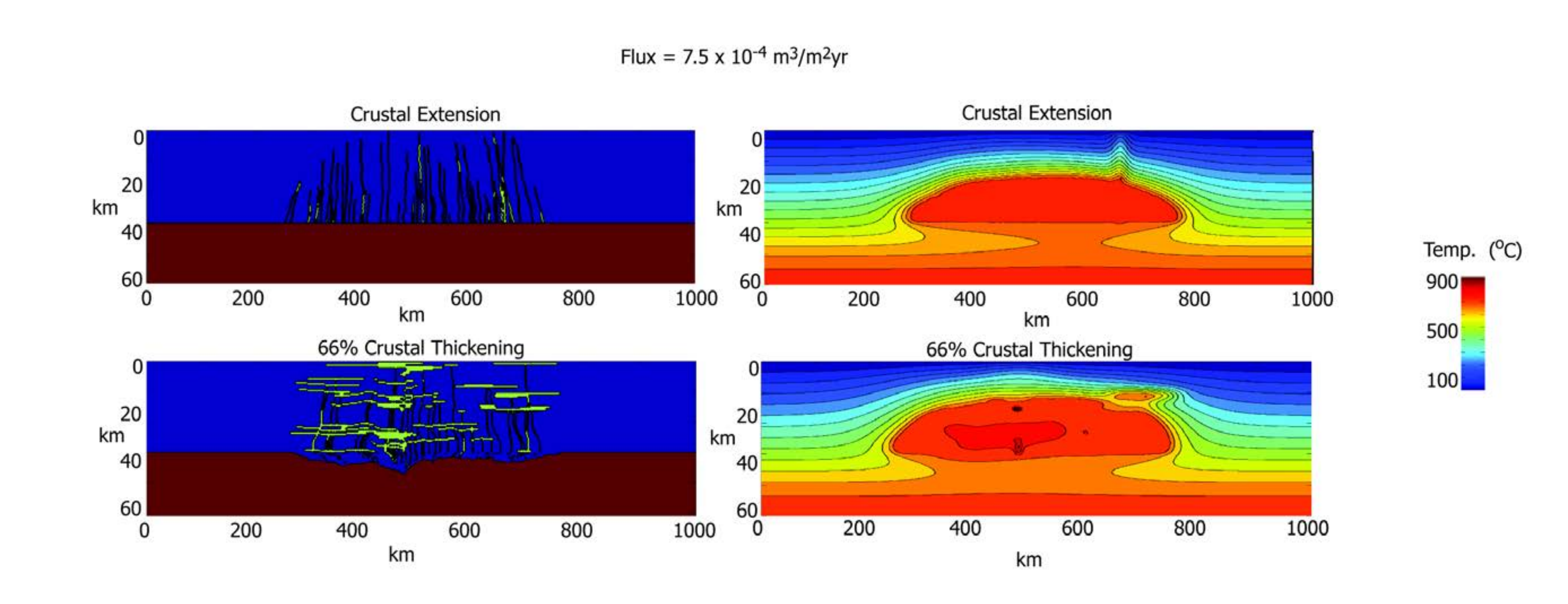
Melt Fraction



Tectonic Extension (m/yr)
−0.002
−0.004
−0.006
−0.008
−0.01
−0.012
−0.014
−0.016
−0.018
−0.02
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
Time (Myr)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0

Even with various considerations (i.e. variable flux, thickened crust, focused magmas, volatile rich, etc) melting is, averaged over the entire crustal column, a relatively inefficient process - a good rule of thumb is ~10% efficient *(Dufek and Bergantz, 2005; Karlstrom, Dufek and Manga, 2009; Karakas and Dufek, 2013)*



Yet compositional gaps are sometimes most evident in thermal environments most hostile to melting.

What role can fractionation and crystal-melt dynamics can play in these systems?

Due to the energetic constraints,we explored the idea of crystallization creating gaps:

- Considered both the thermal and dynamics aspect of this multiphase system.
- Included phase change and crystallization kinetics.
- Modeled evolving physical properties (density, viscosity, etc using major oxides from MELTS).
- Included a drag formulation to consider a wide range of crystal fraction from dilute suspensions to compaction flows.

Multiphase Equations for Magma Chamber

Volume fraction of all phases equals 1

$$\sum_k \phi_k = 1$$

Conservation of Mass

$$\frac{\partial}{\partial t}\left(\phi_k \rho_k\right) + \frac{\partial}{\partial \mathbf{x_i}}\left(\phi_k \rho_k \mathbf{u_{k,i}}\right) = R_k$$

Conservation of Momentum

$$\frac{\partial(\phi_k \rho_k \mathbf{u_{k,i}})}{\partial t} + \frac{\partial(\phi_k \rho_k \mathbf{u_{k,i}} \mathbf{u_{k,j}})}{\partial \mathbf{x_i}} =$$

$$-\phi_k \frac{\partial P}{\partial \mathbf{x_i}} \delta_{ij} + \frac{\partial}{\partial \mathbf{x_i}}\left[\tau_{\mathbf{ij}}\right] + \mathbf{D}_i + \rho_k \phi_k \boldsymbol{g}_2 \delta_{\mathbf{i2}} + R_k \mathbf{u_{k,i}}$$

Conservation of Thermal Energy

$$\phi_k \rho_k c_k \left[\frac{\partial \mathrm{T_k}}{\partial \mathrm{t}} + \mathbf{u_i} \frac{\partial \mathrm{T_k}}{\partial \mathbf{x_i}}\right] = \delta_{\mathrm{km}} \frac{\partial \mathrm{q_k}}{\partial \mathbf{x_i}} + \pi k_m \mathrm{d}\ \mathbf{Nu}\left(\mathrm{T}_m - \mathrm{T_c}\right) + \phi_k R_k L$$

Conservation of Chemical Species

$$\frac{\partial}{\partial t}\left(\phi_k \rho_k C_{SiO_2}\right) + \frac{\partial}{\partial \mathbf{x_i}}\left(\phi_k \rho_k \mathbf{u_{k,i}} C_{SiO_2}\right) = \beta_{(f)}$$

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Crystals and magma have distinct sets of conservation equations (denoted by *k* in these equations)

Conservation of Momentum

$$\frac{\partial(\phi_k \rho_k \mathbf{u_{k,i}})}{\partial t} + \frac{\partial(\phi_k \rho_k \mathbf{u_{k,i}} \mathbf{u_{k,j}})}{\partial \mathbf{x_i}} =$$

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Conservation of Momentum

$$\frac{\partial(\phi_k \rho_k \mathbf{u_{k,i}})}{\partial t} + \frac{\partial(\phi_k \rho_k \mathbf{u_{k,i}} \mathbf{u_{k,j}})}{\partial \mathbf{x_i}} =$$

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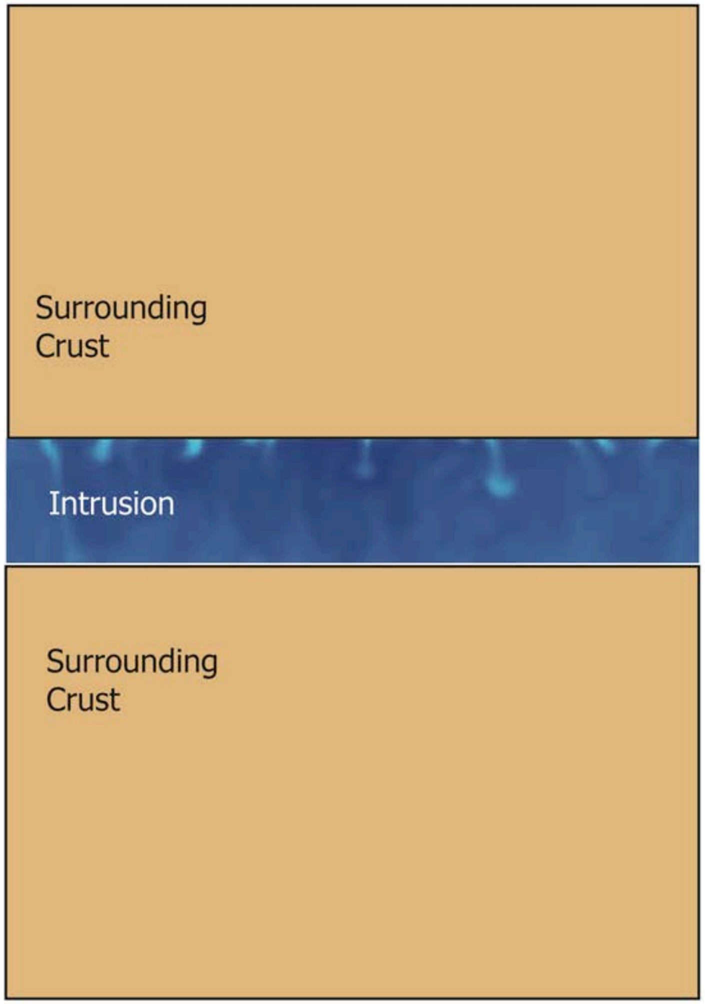
Crystallization

Coupled Thermal and Mechanical Multiphase Model



Surveyed intrusions with:

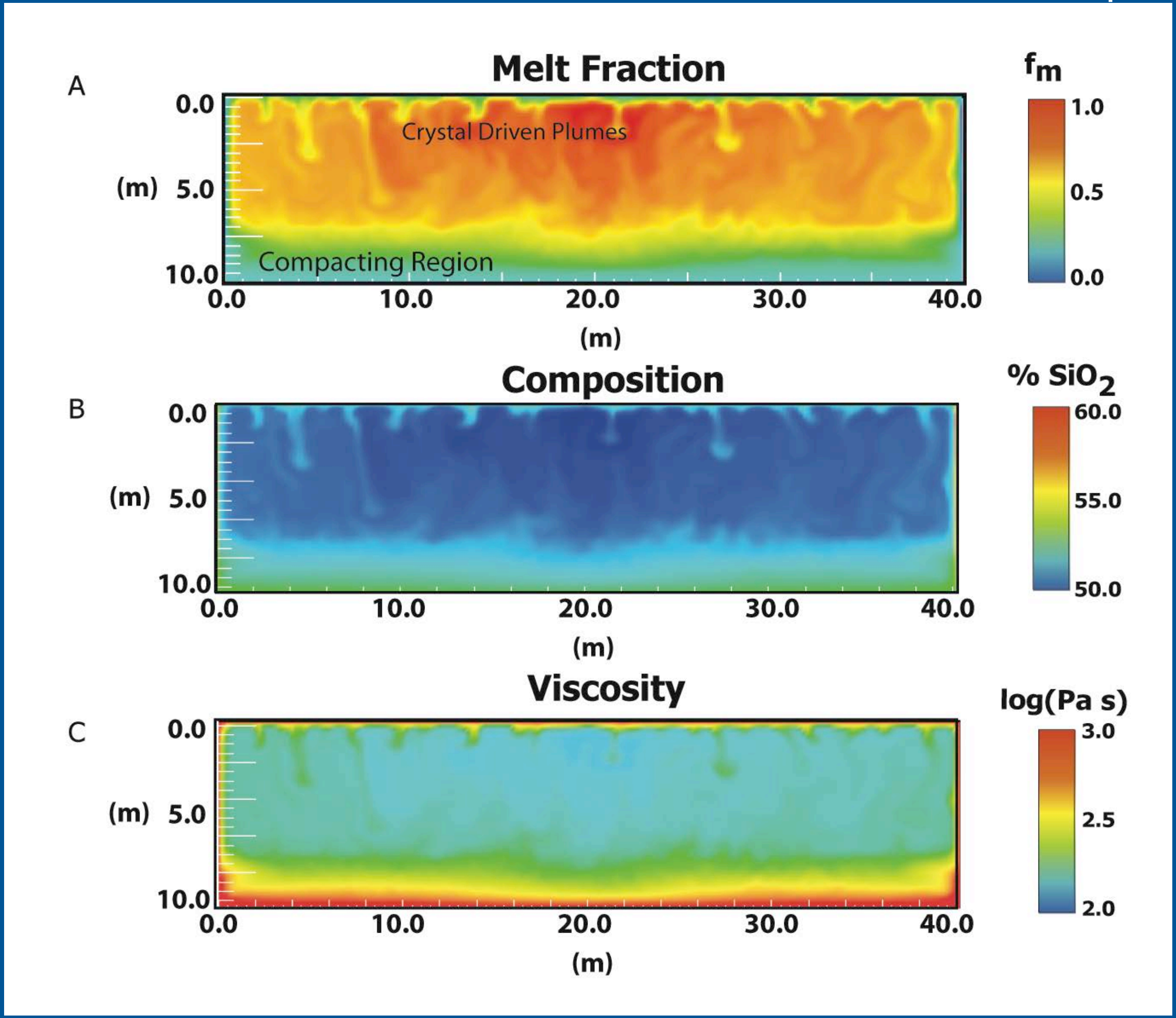
- Different thicknesses.
- Different initial compositions.
- Emplacement depths.

Probability of extraction:

- Examined the relative velocity between melt and crystals over all times and all spatial locations.
- Analogous to the measurement of the relative volume of erupted composition given exceptional exposure and if measured at fine resolution.
- Integrating the volume of separation in specific melt fraction bins (0.02 melt fraction) relative to the total volume of separation over the lifetime of the chamber.

An Example Simulation:

Basaltic intrusion, modeled intrusion depth: 24 km

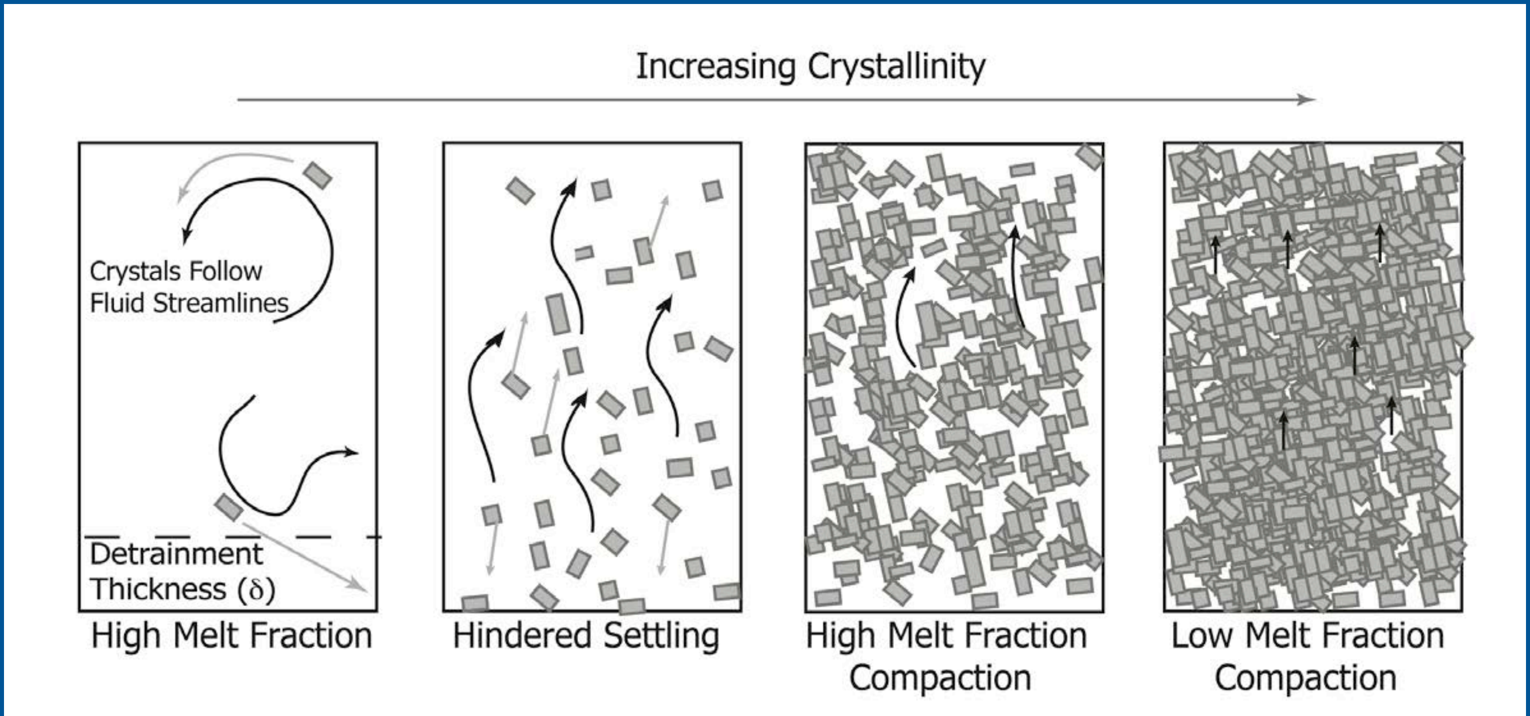


Dufek and Bachmann, 2010

Melt extraction probability is modulated by two factors:

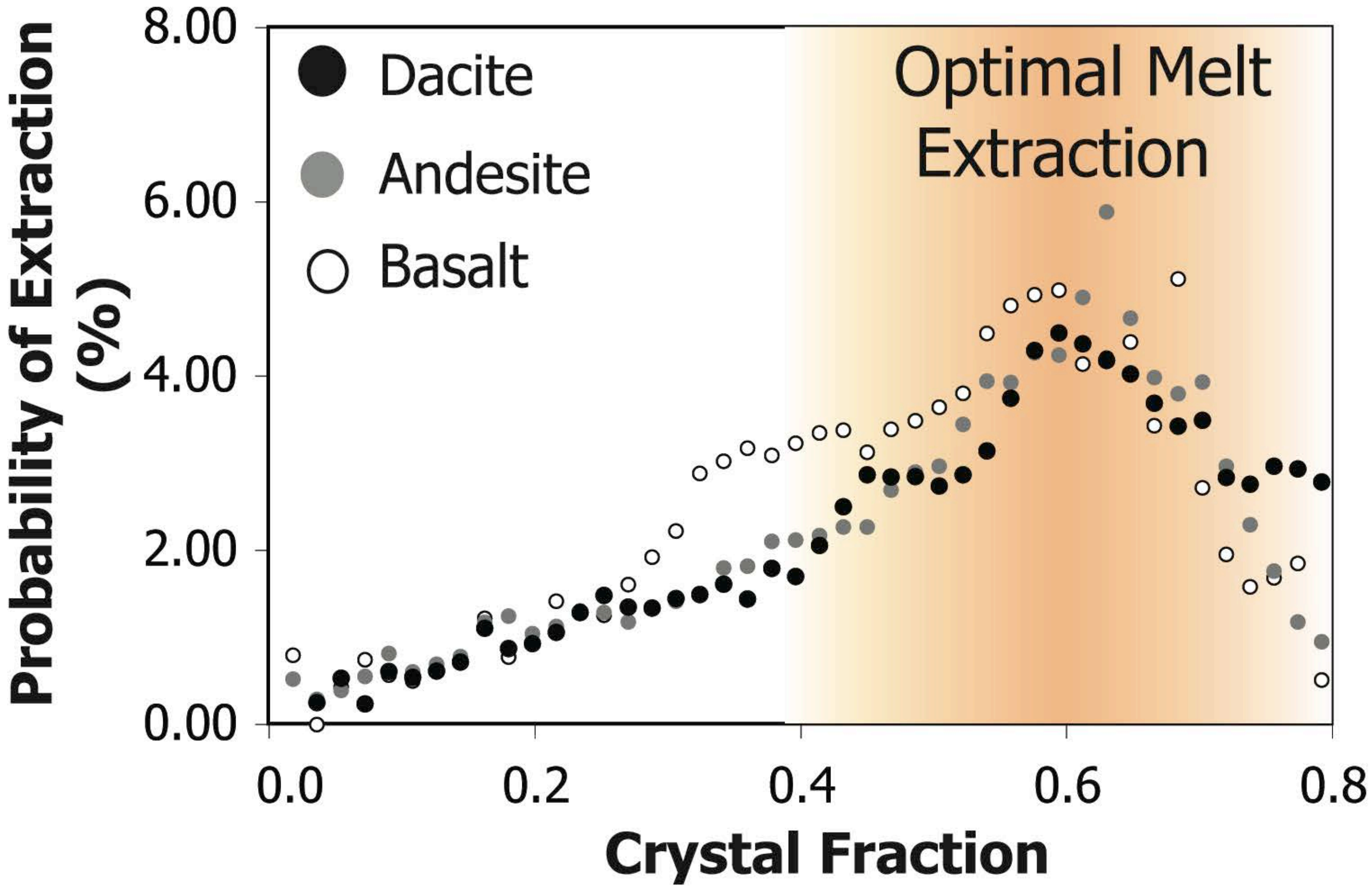
1. The length of time a given magmatic composition exists (thermal problem).

2. Separation velocity between crystal and melt phases.

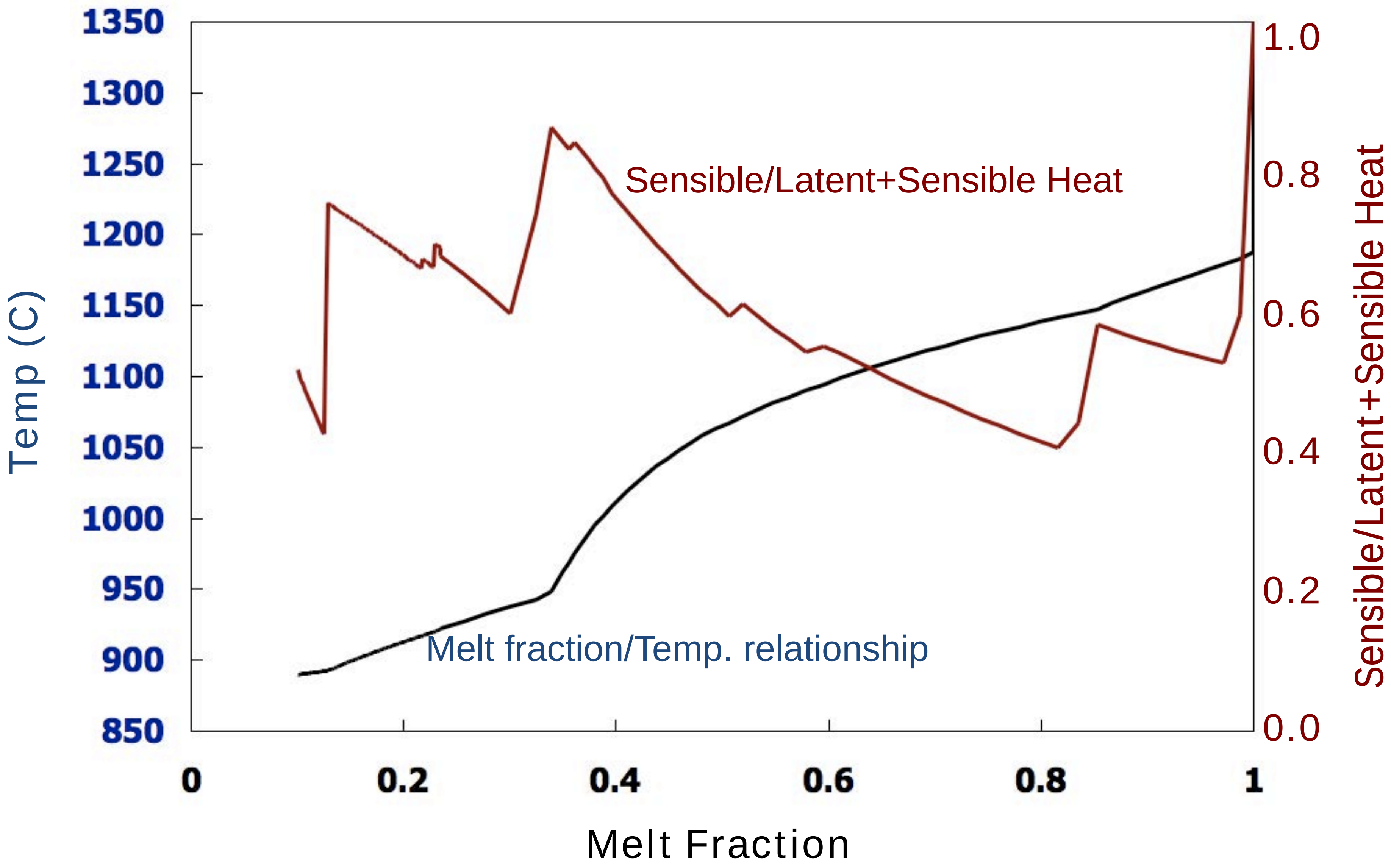


Melt Extraction probability

Reference Depth: 20 km

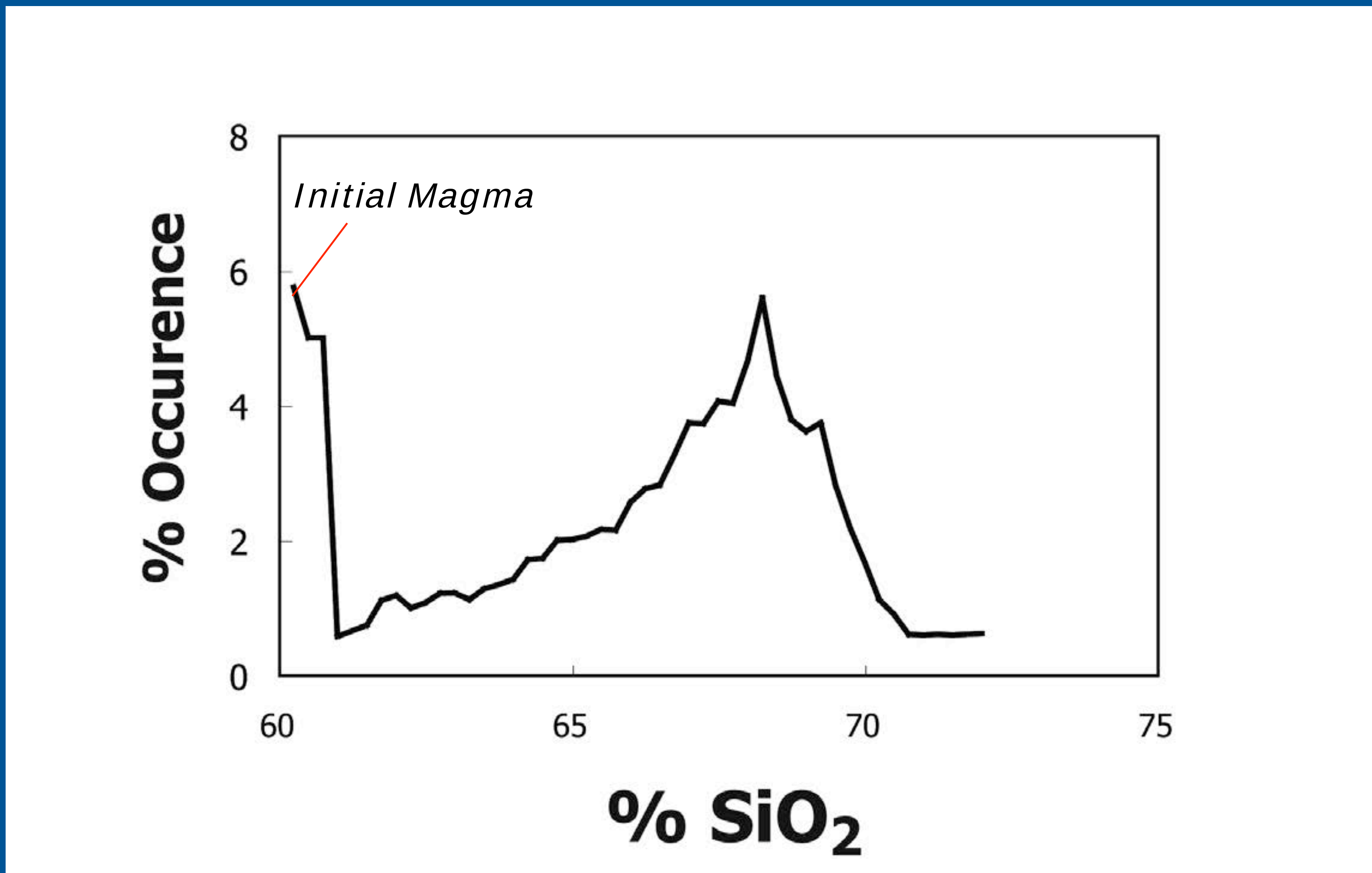


Partitioning of latent and sensible heating can have complex relationships with non-trivial results for the cooling history.

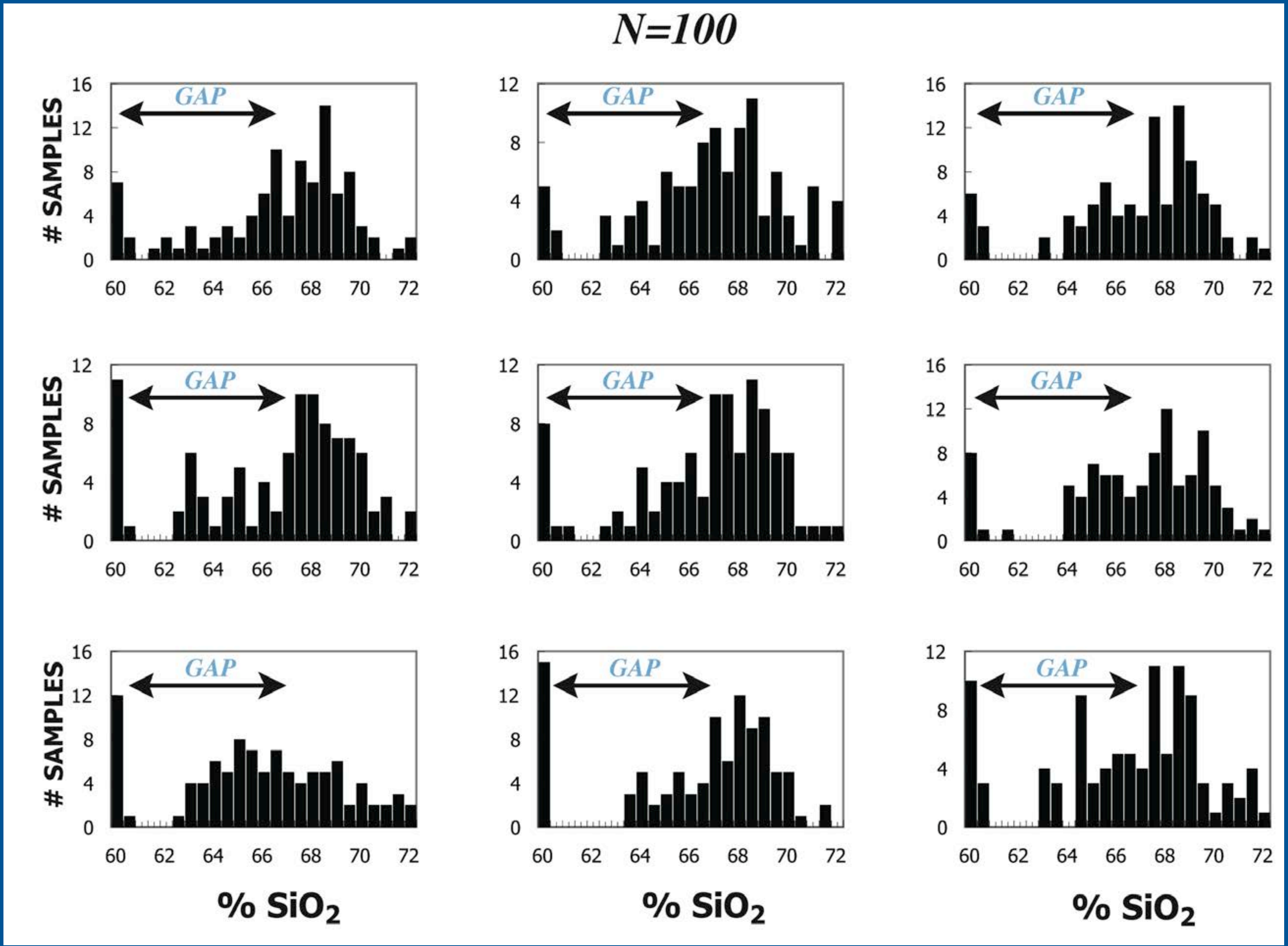


Of course we don't have the capability to sample at infinite resolution, so how do these probability distributions map back to a discrete number of samples in composition space?

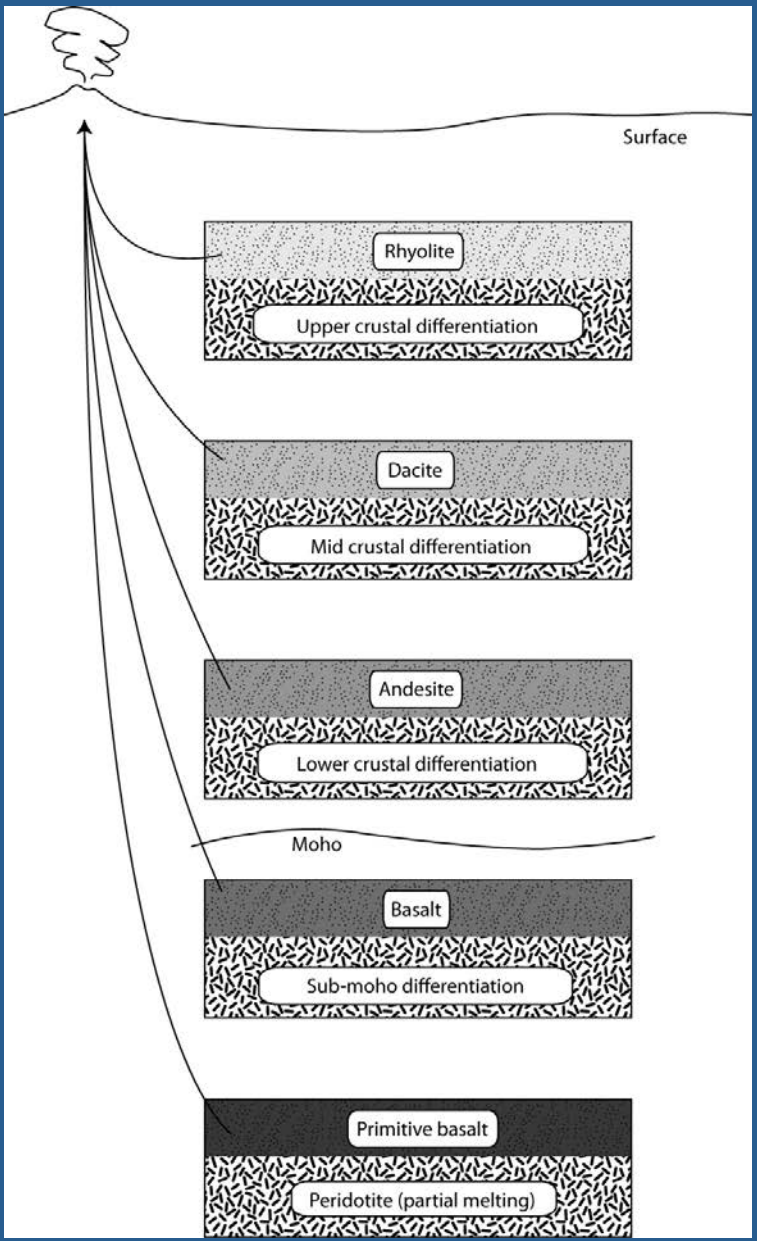
Modeled compositional evolution



Examples of random sampling given this probability distribution.

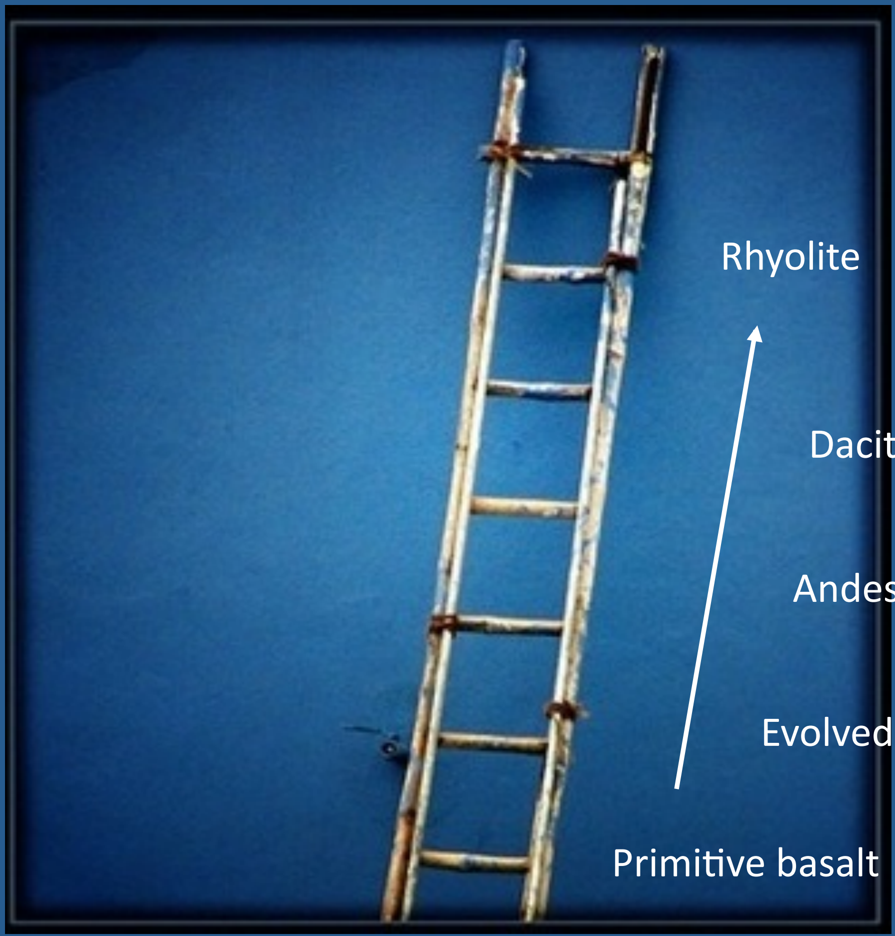


But also valid across a range of compositions and depths.

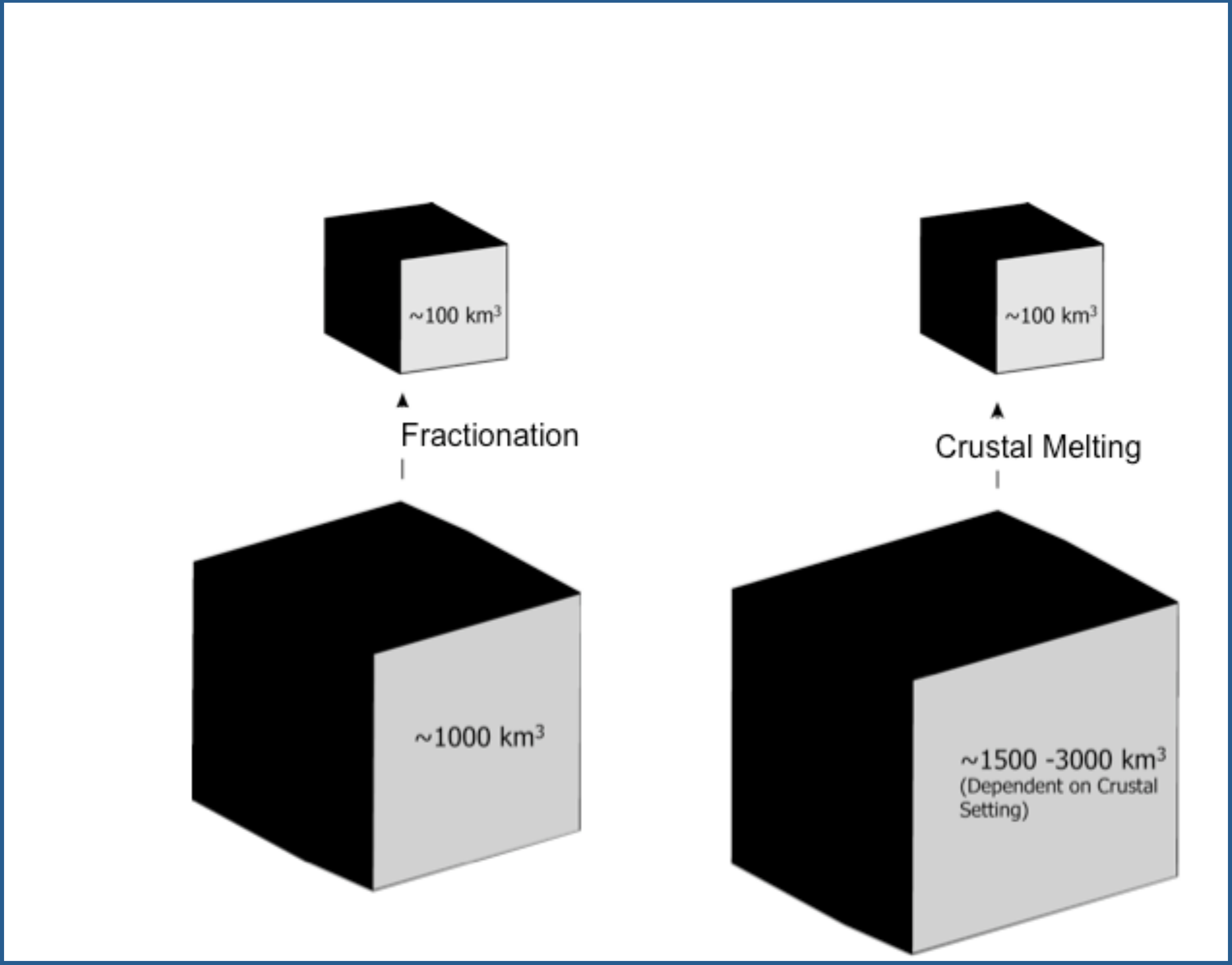


In particular, gap is particular stark where thermal gradients are large.

Compositional Ladder



Both Fractionation and Melting Create an Apparent Crustal Mass Balance Issue



Continental Crust Paradox

(Kay and Kay, 1988; Rudnick, 1995; C.T.A. Lee et al. 2006)

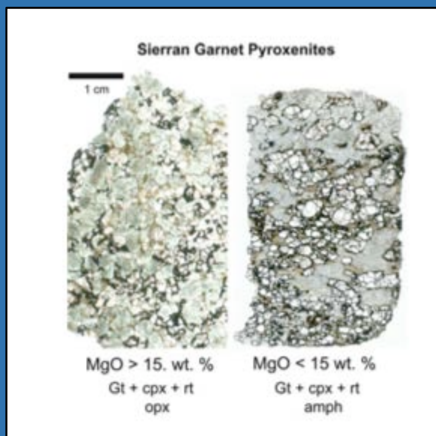
- Crust is more silicic than primitive mantle melt input.

Crustal Compositions
Compilation from *Rudnick and Gao, 2003*

	Lower Crust	**Middle Crust**	**Upper Crust**	**Bulk Crust**
SiO_2	53.4	63.5	66.6	60.6
Al_20_3	16.9	15	15.4	15.9
FeO	8.57	6.02	5.03	6.7
MgO	7.24	3.59	2.48	4.7
CaO	9.59	5.25	3.59	6.4
Na_2O	2.65	3.39	3.27	3.1
K_2O	.61	2.3	2.8	1.8

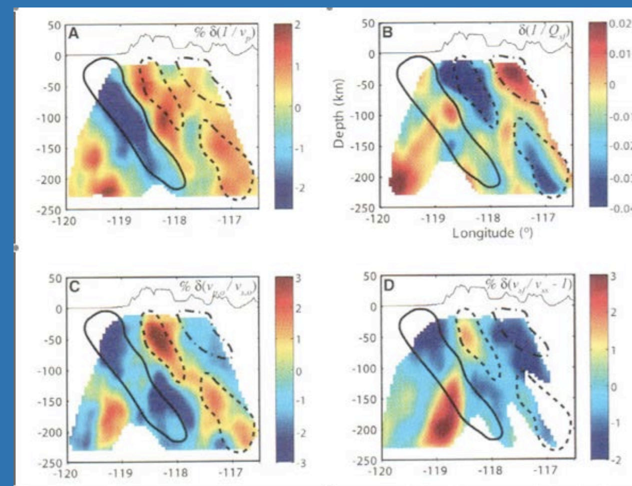
A Potential Resolution - Mass return back to the mantle (R-T instabilities, delamination, erosion...)

Xenoliths



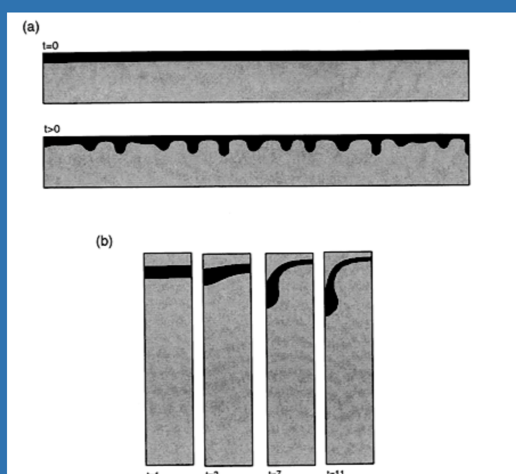
Lee et al, 2006

Tomography



Boyd et al, 2004

Dynamic Models



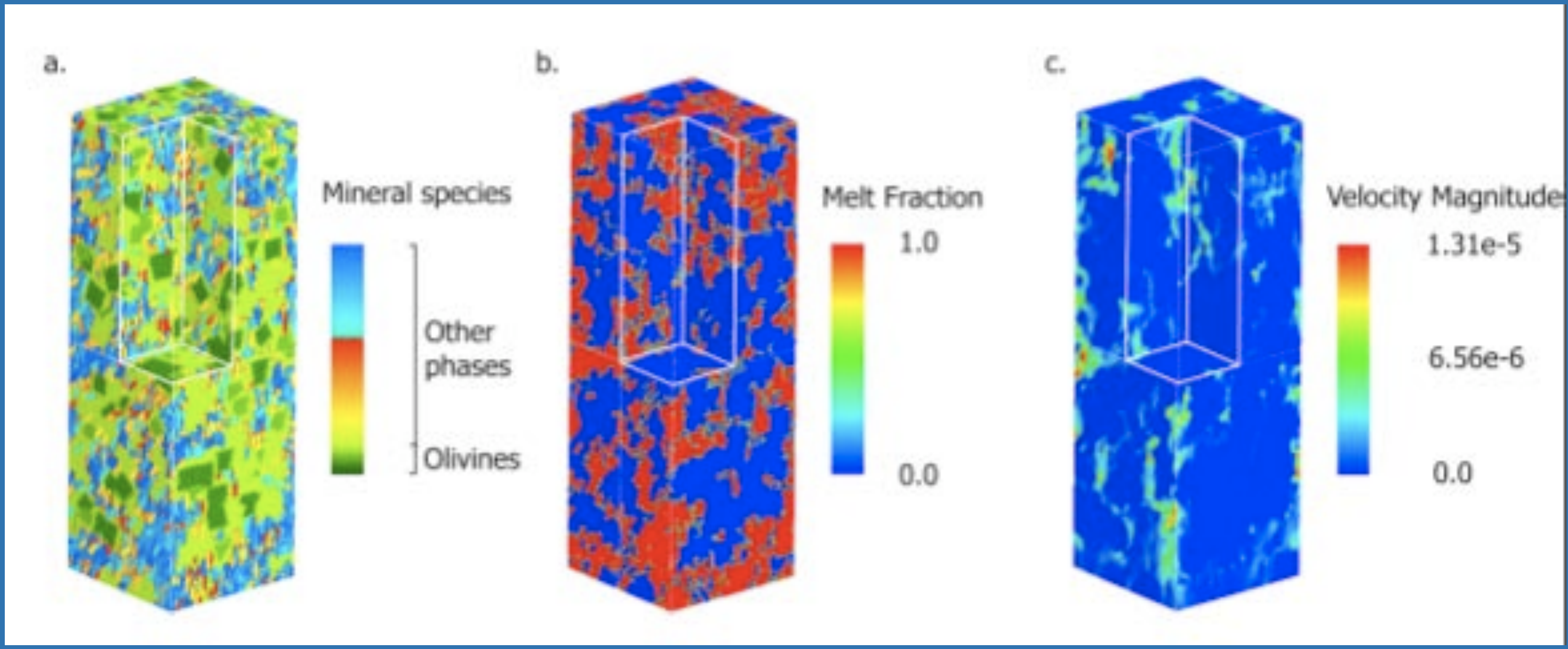
Jull and Kelemen, 2001

How might foundering be related to an actively growing crust, being forced by mass and enthalpy input?

Estimates of Basalt Flux (minimums?)

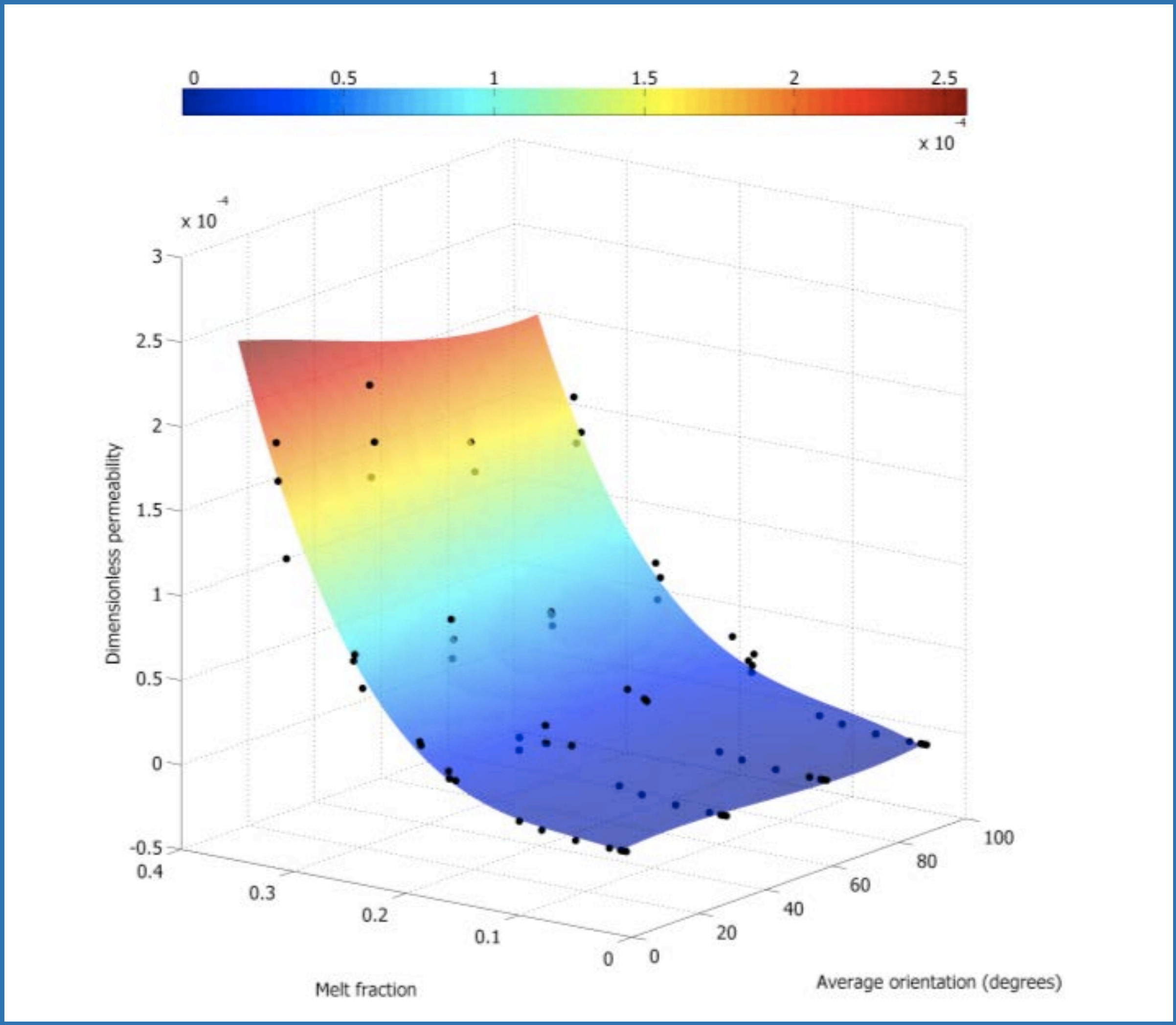
Method	Location	Estimate of Basalt Flux (m^3/m^2yr)	References
Gravity/Seismic	Marianas	4.93×10^{-4}	Dimalanta et al., 2002
	Marianas	1.92×10^{-4}	Crisp, 1984
	Izu-Bonin	4.89×10^{-4}	Dimalanta et al., 2002
	Aleutians	5.46×10^{-4}	Dimalanta et al., 2002
	Aleutians	3.40×10^{-4}	Crisp, 1984
	Tonga	7.41×10^{-4}	Dimalanta et al., 2002
	New Hebrides	1.04×10^{-3}	Dimalanta et al., 2002
	Kuril	4.72×10^{-4}	Crisp, 1984
Geochemical/Thermal	Eastern Nevada	4.0×10^{-4}	Grunder, 1995

Erosion, thermal in-efficiency, crustal flow - all reasons to suspect greater long term fluxes of magma into the crust

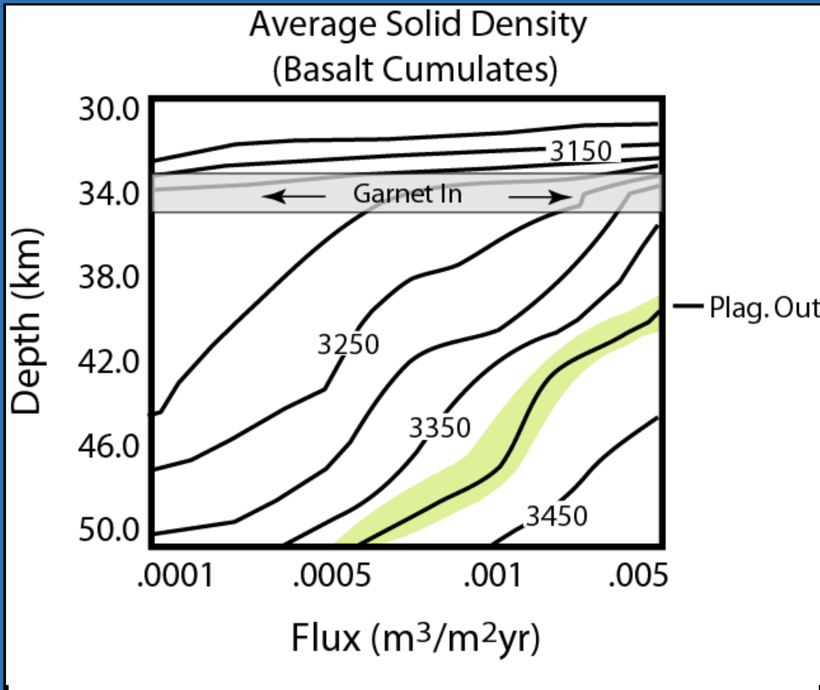


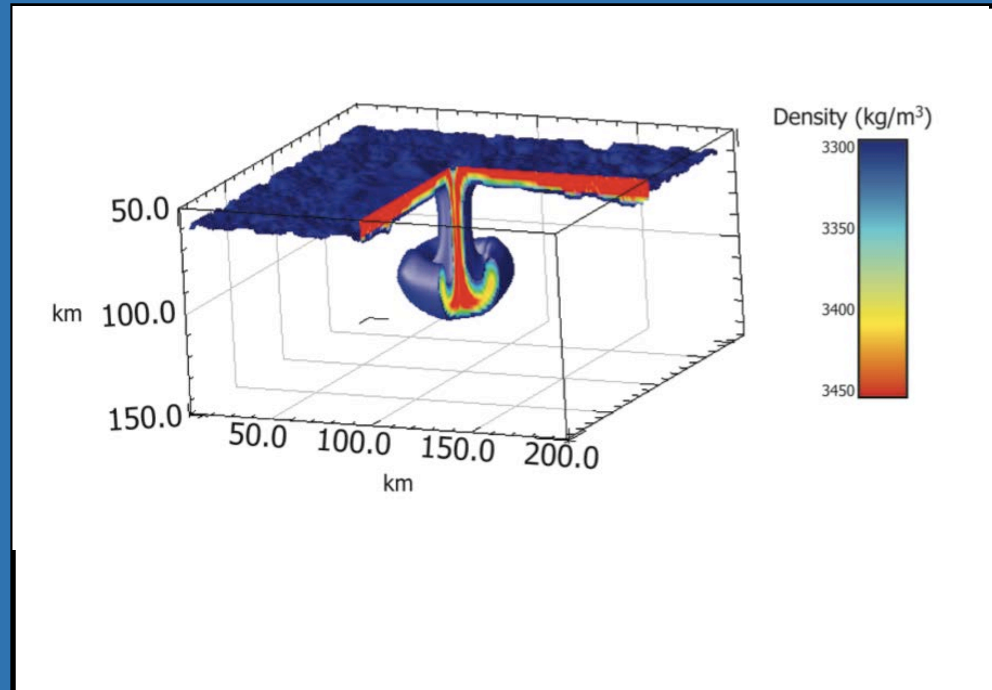
- Synthetic crystalline frameworks were created using phase proportions from pMELTS calculations and using the crystallization and nucleation theory of Avrami (1940) similar to the approach of Hersum and Marsh (2006).

Dufek and Huber, 2013



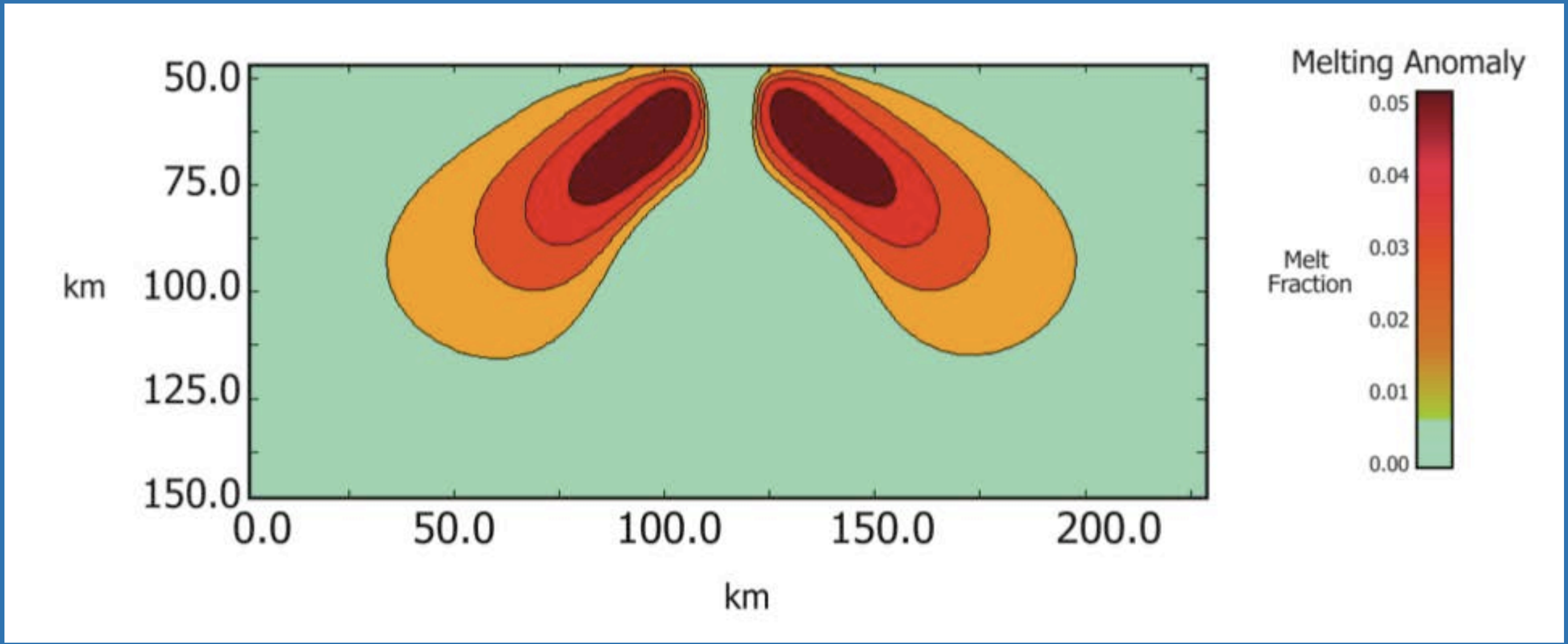
The microscale model produces a parameterization of permeability that is incorporated into the drag relationship for the macroscale, multiphase model



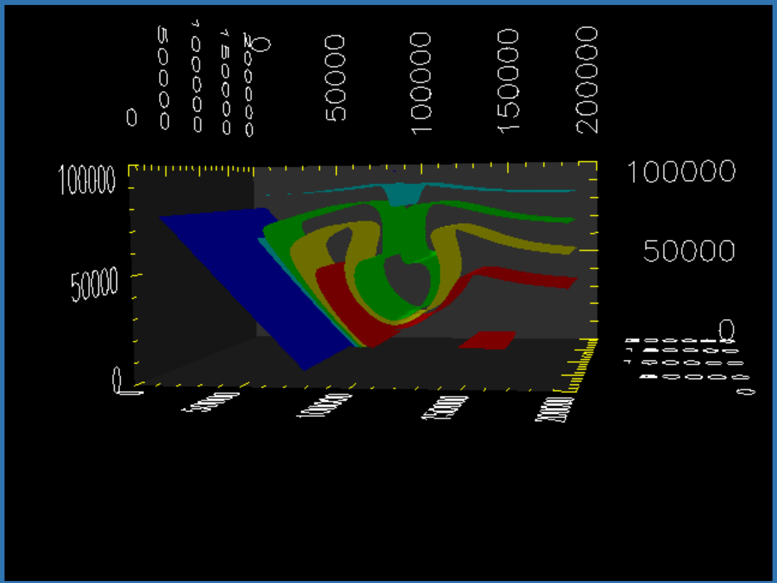


We explored a range of 3D delamination geometries, including isolated ‘drips’, 3D arc sections, and sections progressively being modified by intrusion.

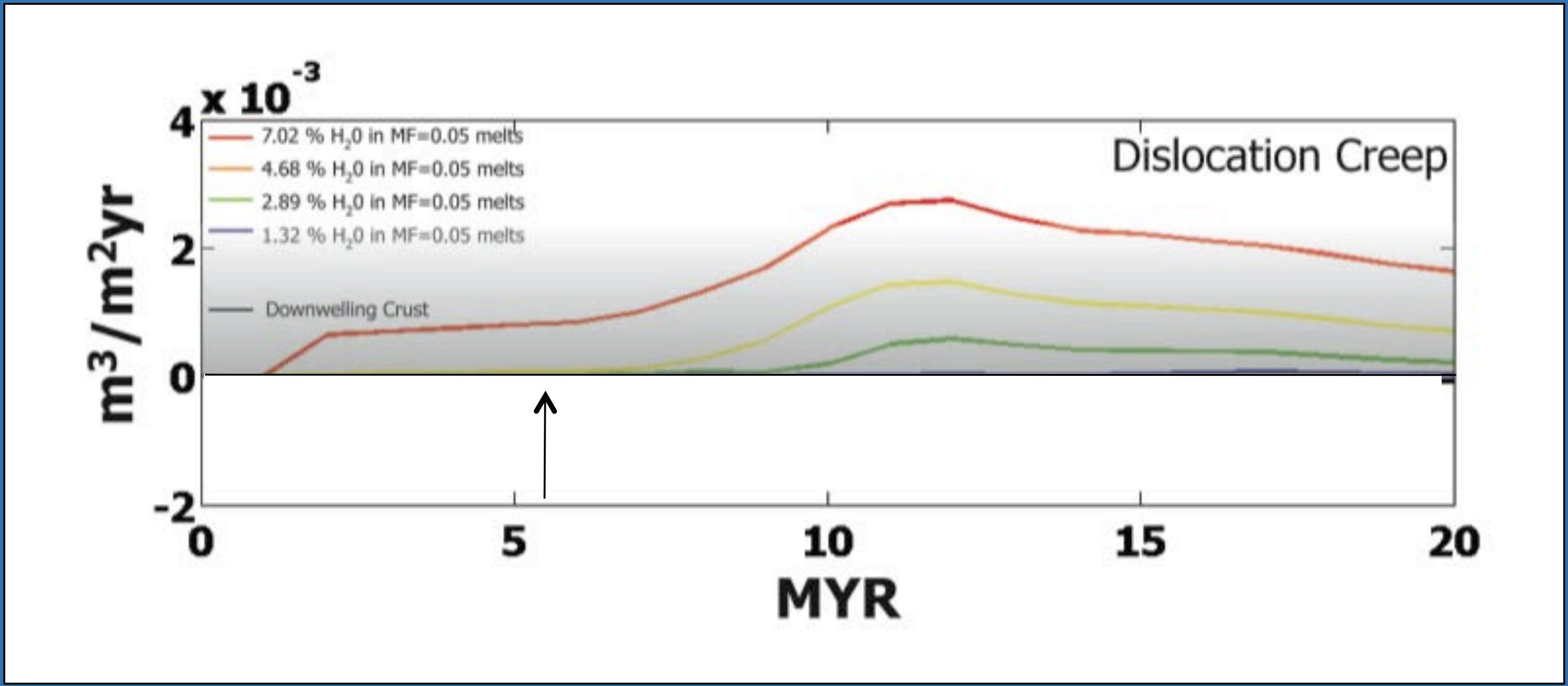
Here a central root that has compacted, has gone unstable (5 MYR from initiation). We also explored geometries associated with thickened subduction settings.



Melt anomalies associated with upwelling mantle surround the delaminating drip in simple geometries (radial pattern for a central root, back arc emphasized for subduction geometries).

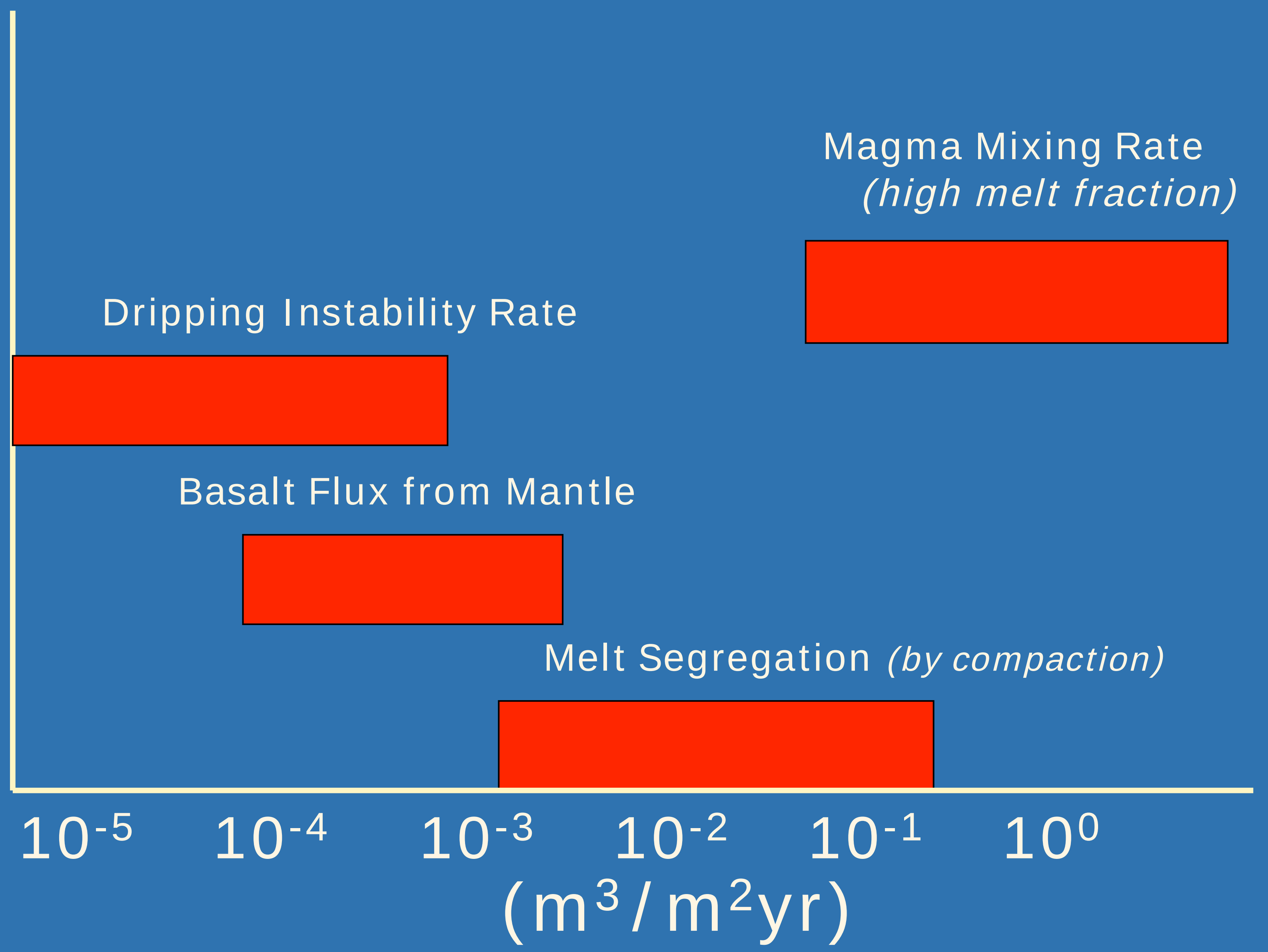


Flux as measured 75 km depth



- Peak melt upwelling flux appears after (up to several MYR) delamination peak flux
- Melt Fluxes generated by the upwelling return flow are sensitive to mantle water content.
- However, even hydrated cases do not exceed typical arc background fluxes substantially.

Magmatic Rates in the Lower Crust



Summary

- By what means and rates is melt separated from its residue?

** In many crustal settings, compositional gaps are generated due to the dynamics of melt crystal separation with preferential segregation in window 50-70 % crystals.*

** The stress field, dynamics, and thermodynamics are all important for chamber evolution and coupled models provide a means to integrate geophysical and geochemical data sets.*

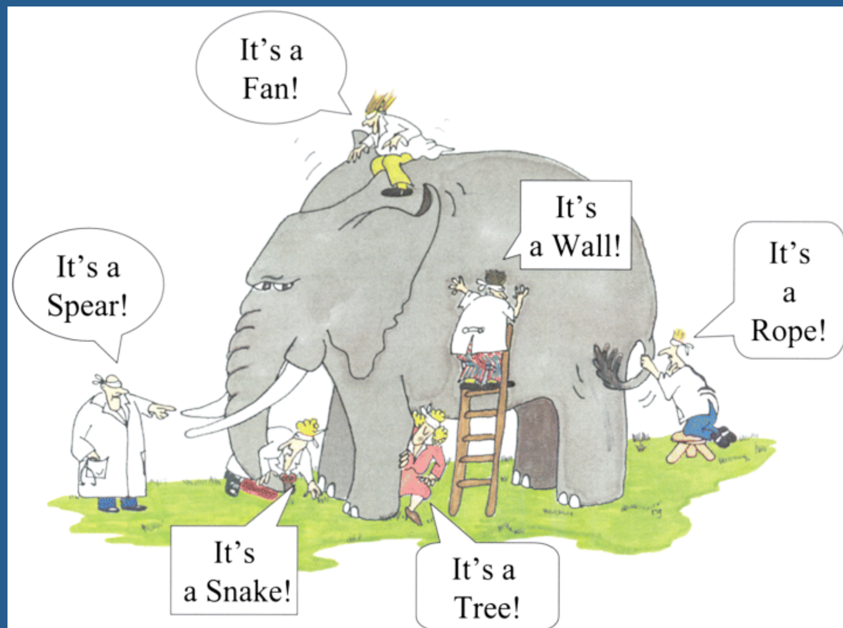
-How does delamination perturb the background melt flux?

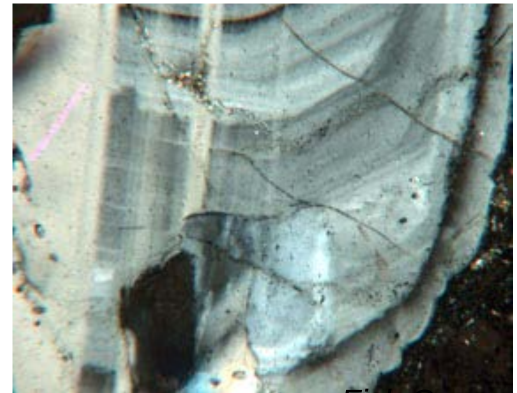
** Both fractionation and crustal melting are inefficient.*

** Small decompression melting perturbations can be generated by return flow (but flare-up appears unlikely).*

** However conditions conducive to foundering and rates inferred from nature appear viable.*

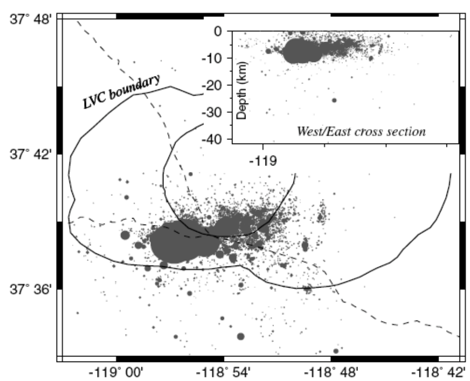
Magmatic processes are recorded across a range of length and timescales



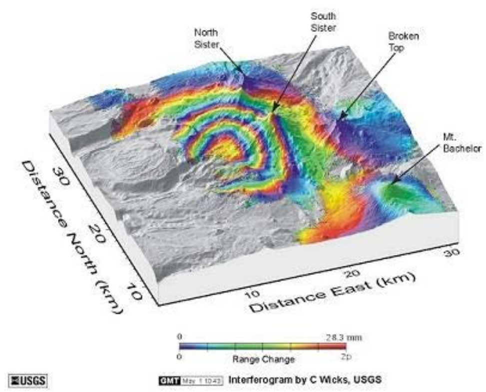


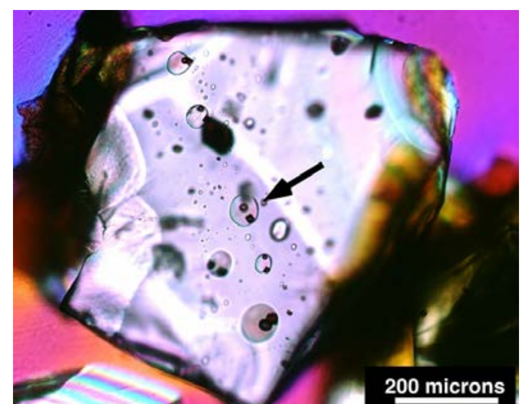
Fish Canyon

Jones



Newman et al., 2001

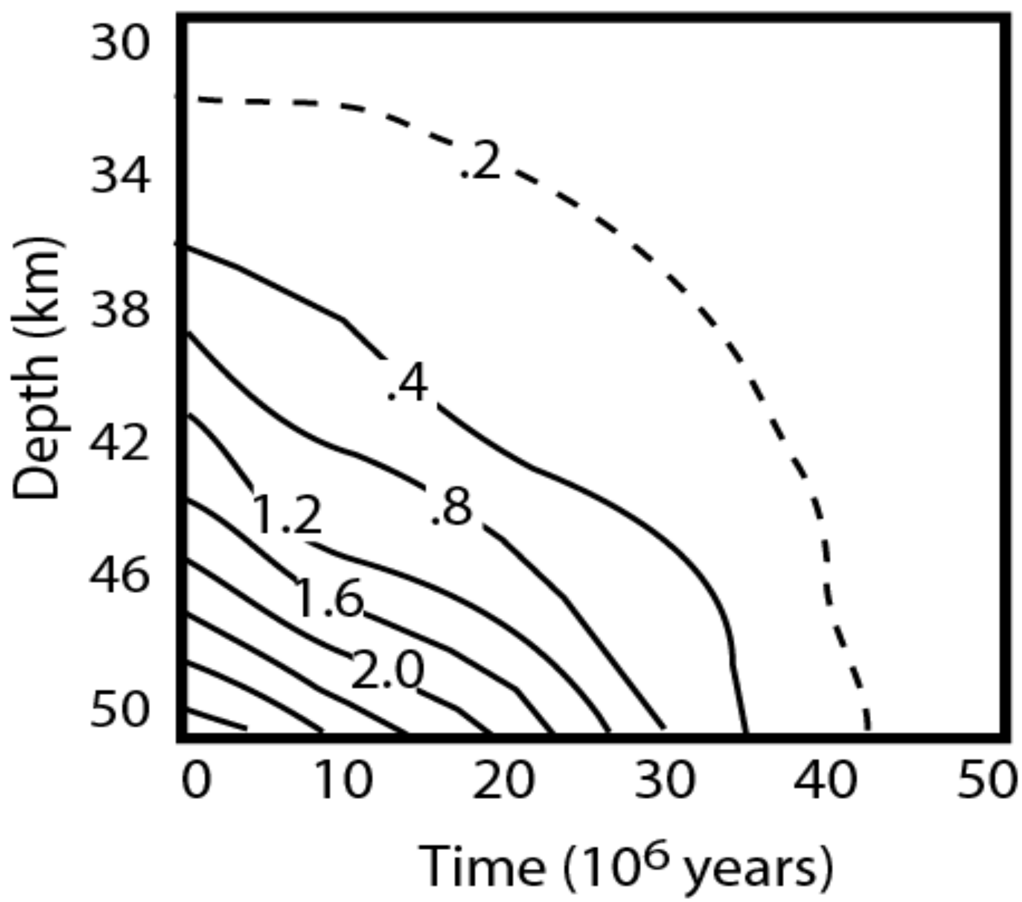




A. Kent

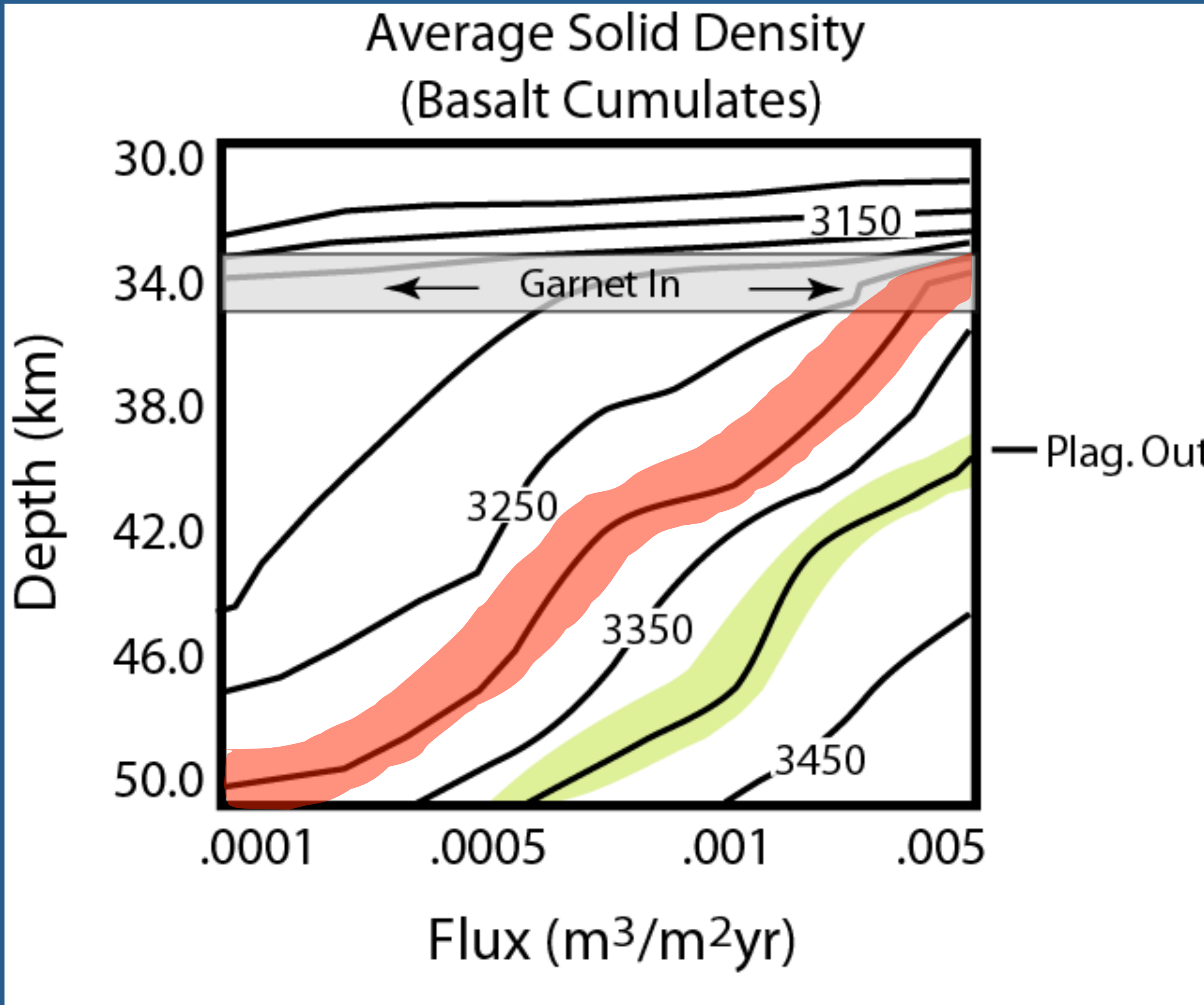
Melt Volume Ratio:

Volume of Crustal Melts/
Volume Mantle Melts

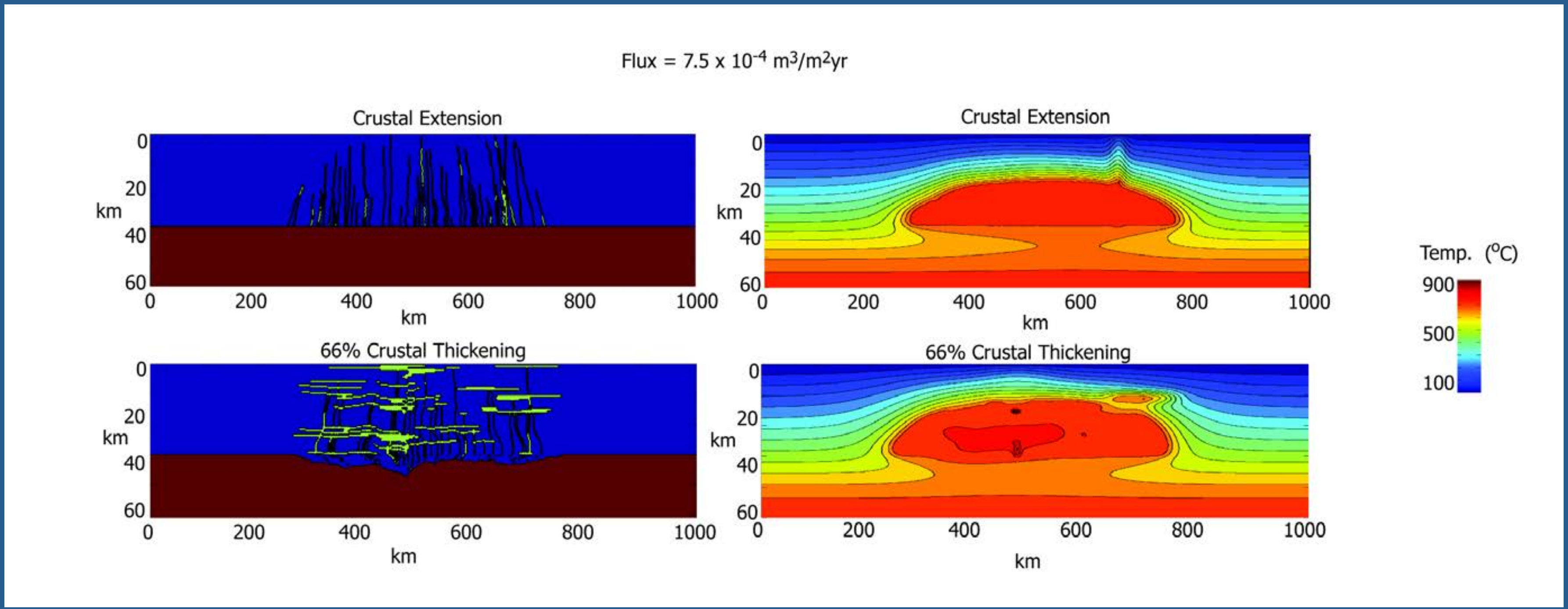


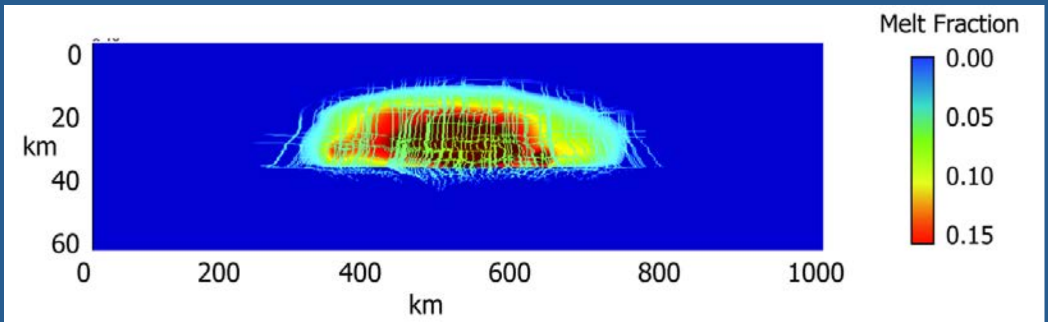
Thin crust (on average) leads to less overall melt, although thin crust is more prone to variability.

Note also that this is overall melt, and what we can sample at surface can be considerably limited.

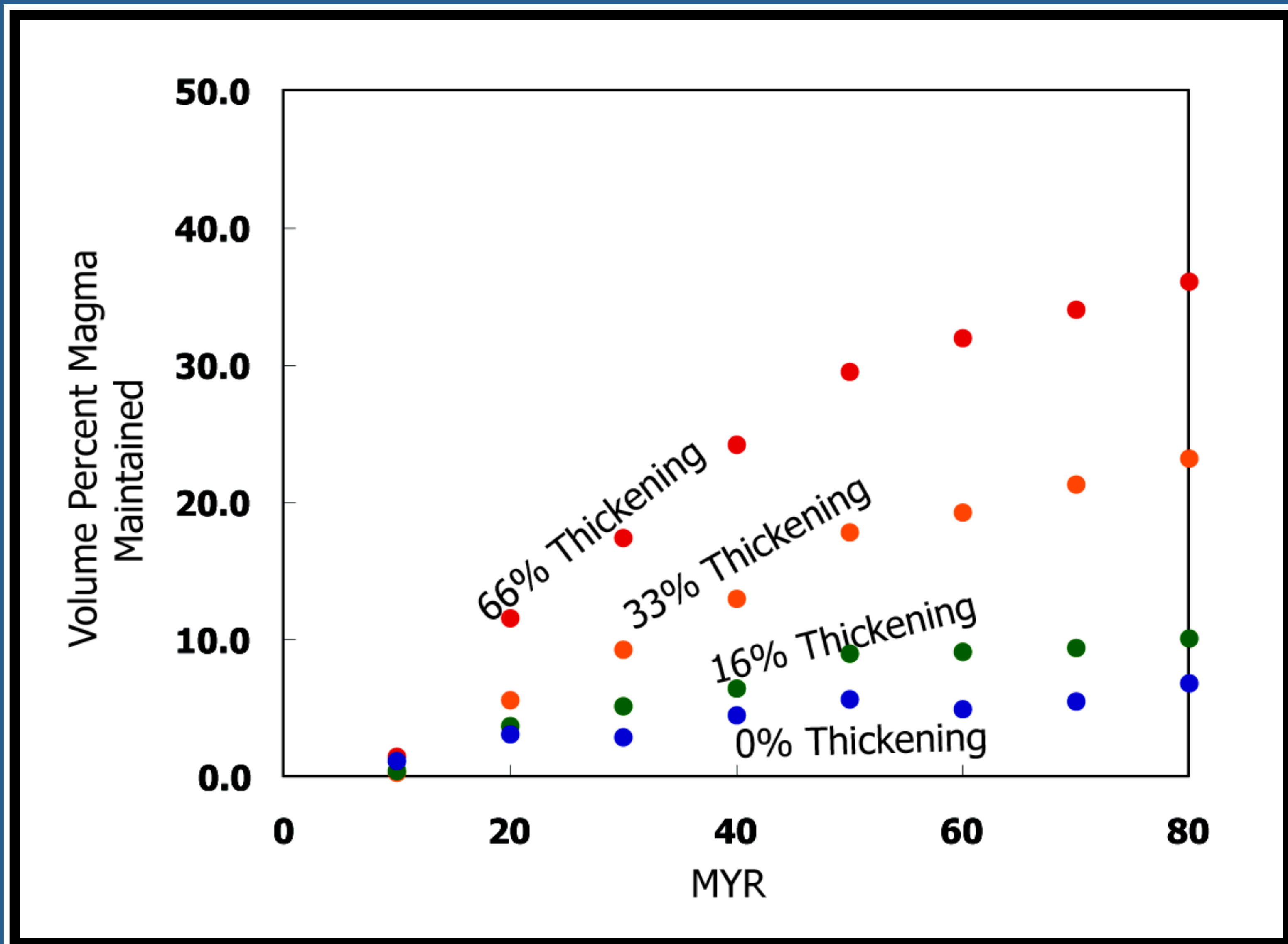

Average Solid Density
(Basalt Cumulates)
30.0
34.0
38.0
42.0
46.0
50.0
Depth (km)
3150
Garnet In
3250
3350
3450
Plag. Out
.0001
.0005
.001
.005
Flux (m3/m2yr)

How does the method of accommodation influence crustal evolution?

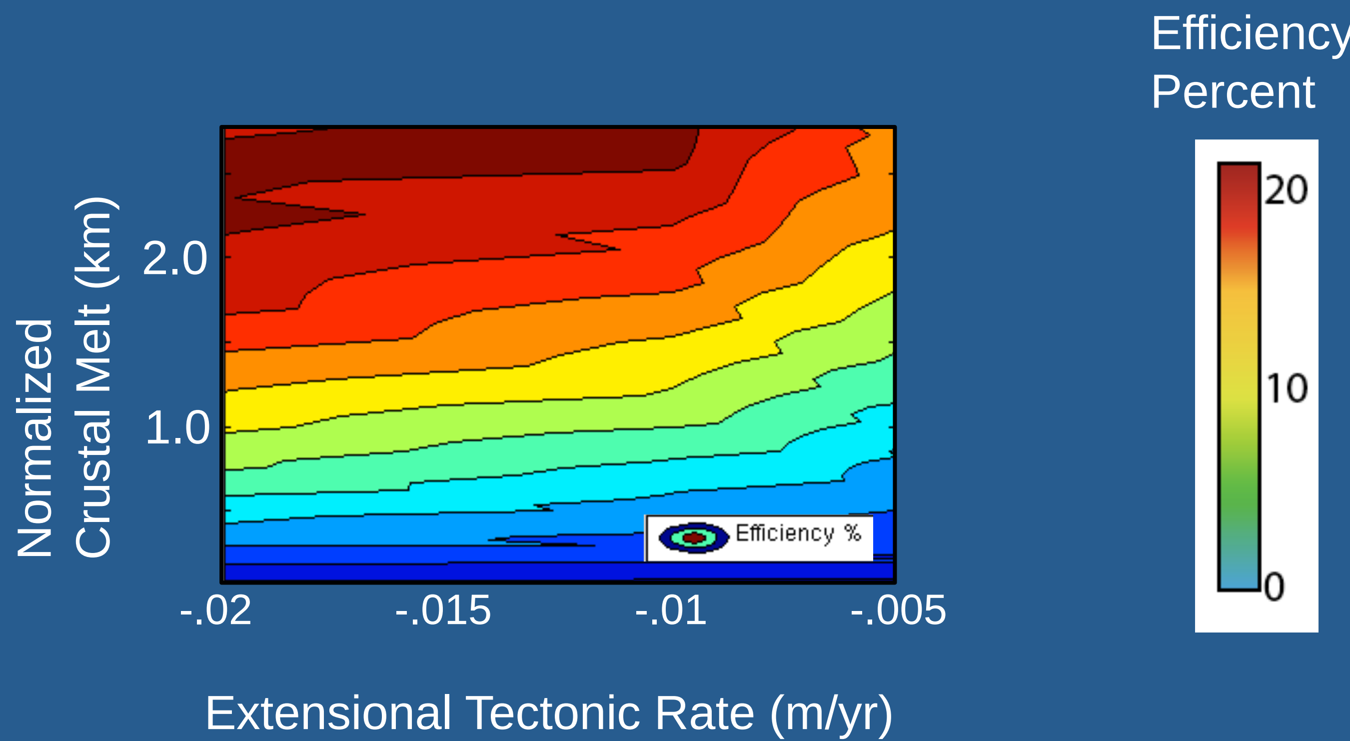




Crustal Thickening Promotes Greater Melting Efficiency - and further progress in melting reactions



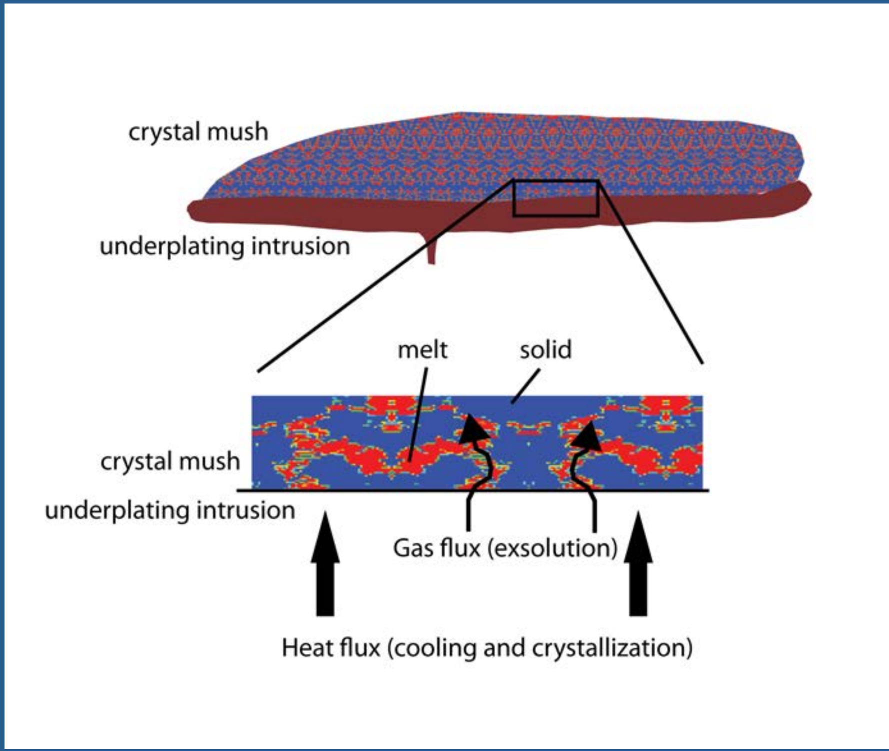
Magmatic Environments are often in strongly forced tectonic regions

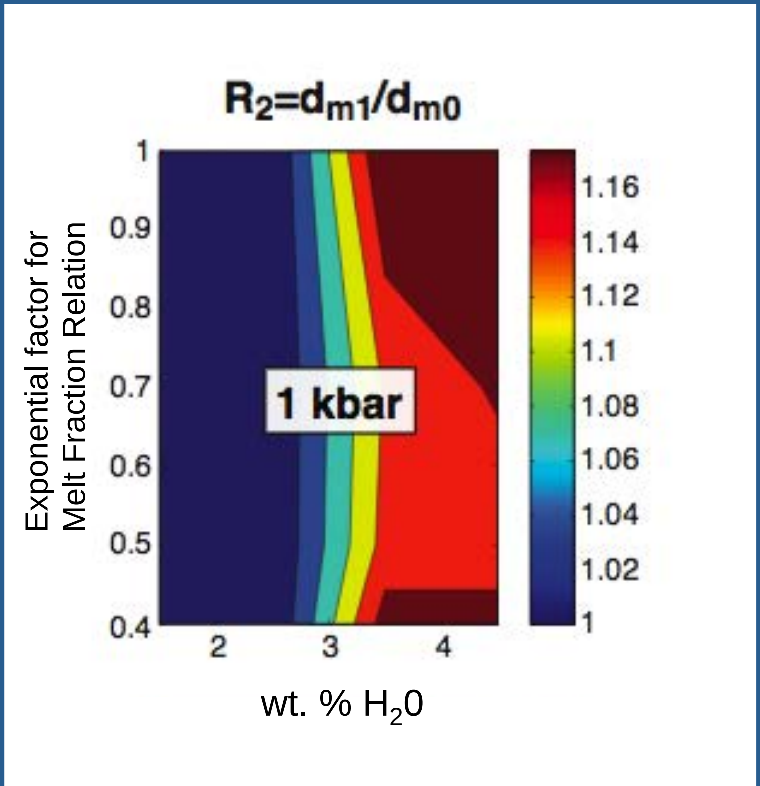


On a large scale how does tectonic forcing influence the melting productivity?

Karakas Poster

What about volatiles?

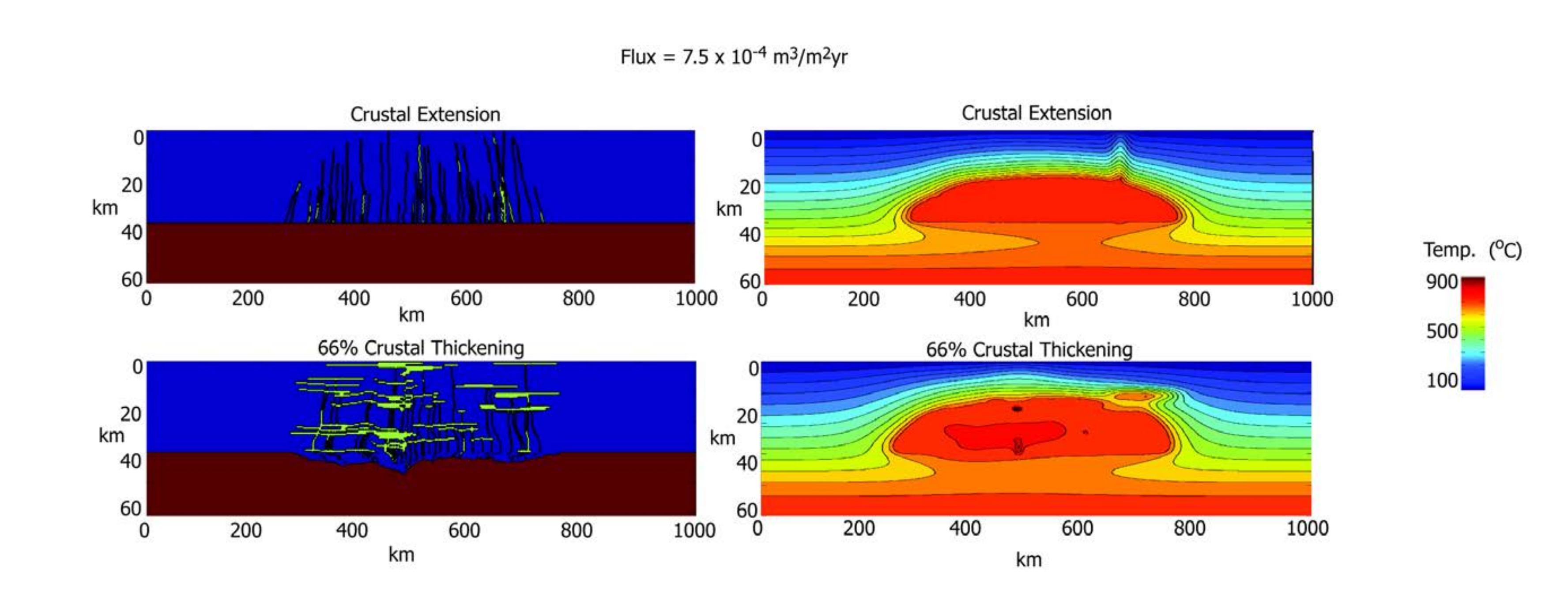




Huber et al., 2009

Volatiles can increase melting by
a factor of ~10% beyond the dry case.

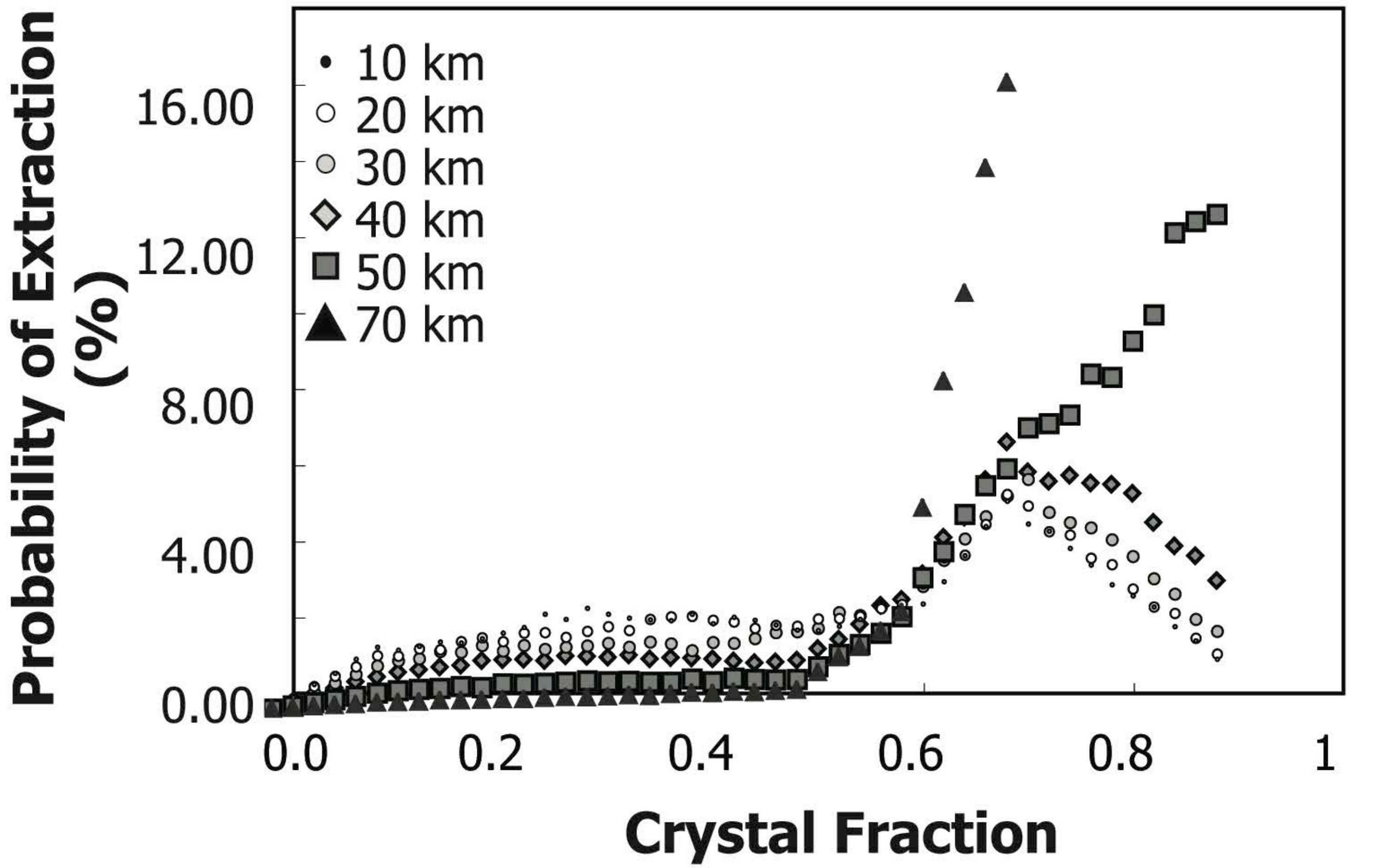
Even with these considerations (I.e. variable flux, thickened crust, focused magmas, volatile rich, etc) melting is, averaged over the entire crustal column,a relatively inefficient process -
- a good rule of thumb is ~10% efficient.



Yet compositional gaps are sometimes most evident in thermal environments most hostile to melting.

What about the role fractionation and crystal-melt dynamics can play in these systems?

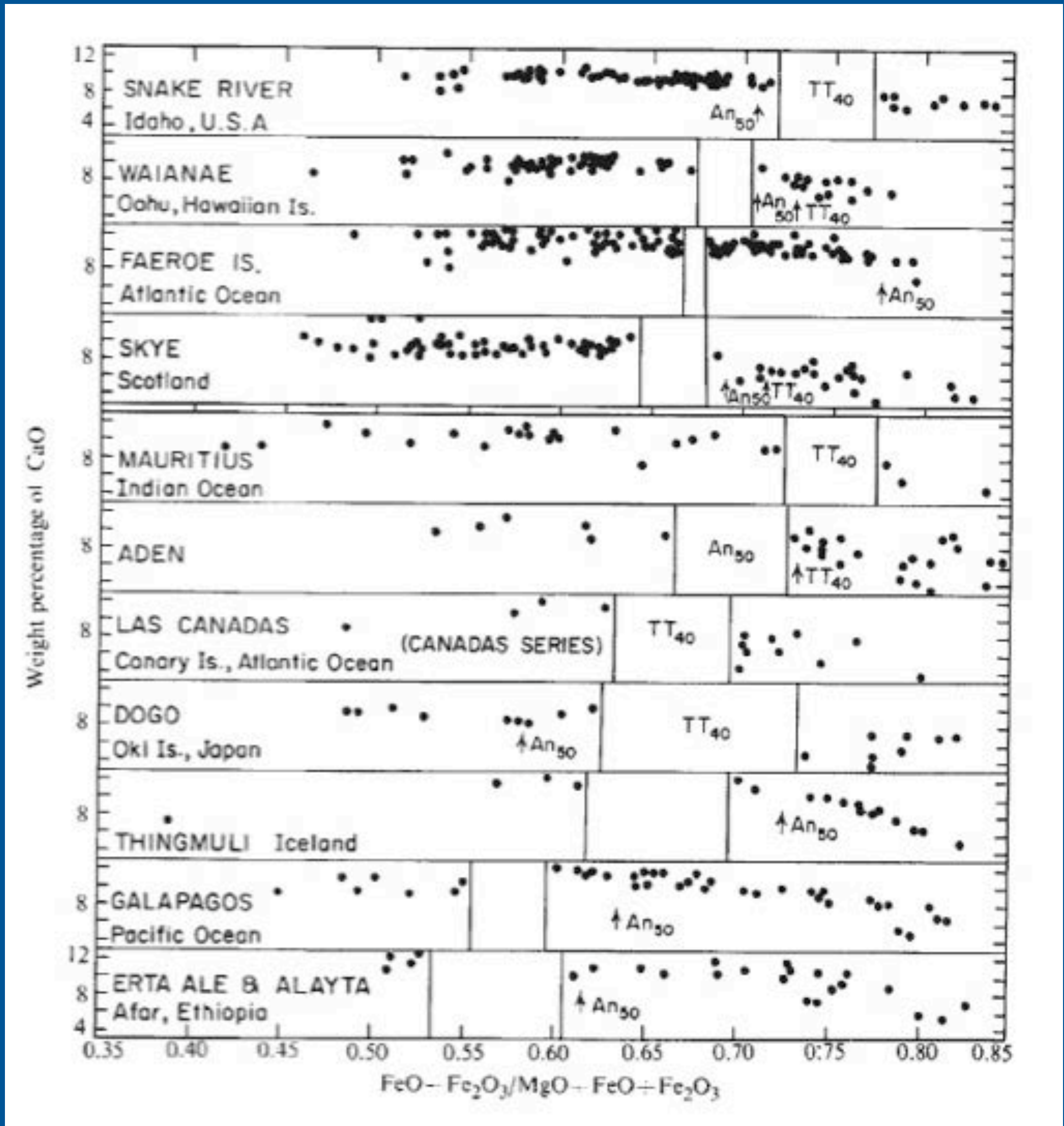
Andesitic Initial Composition



Over-Pressure Evolution can deviate from the rigid container end-member due to:

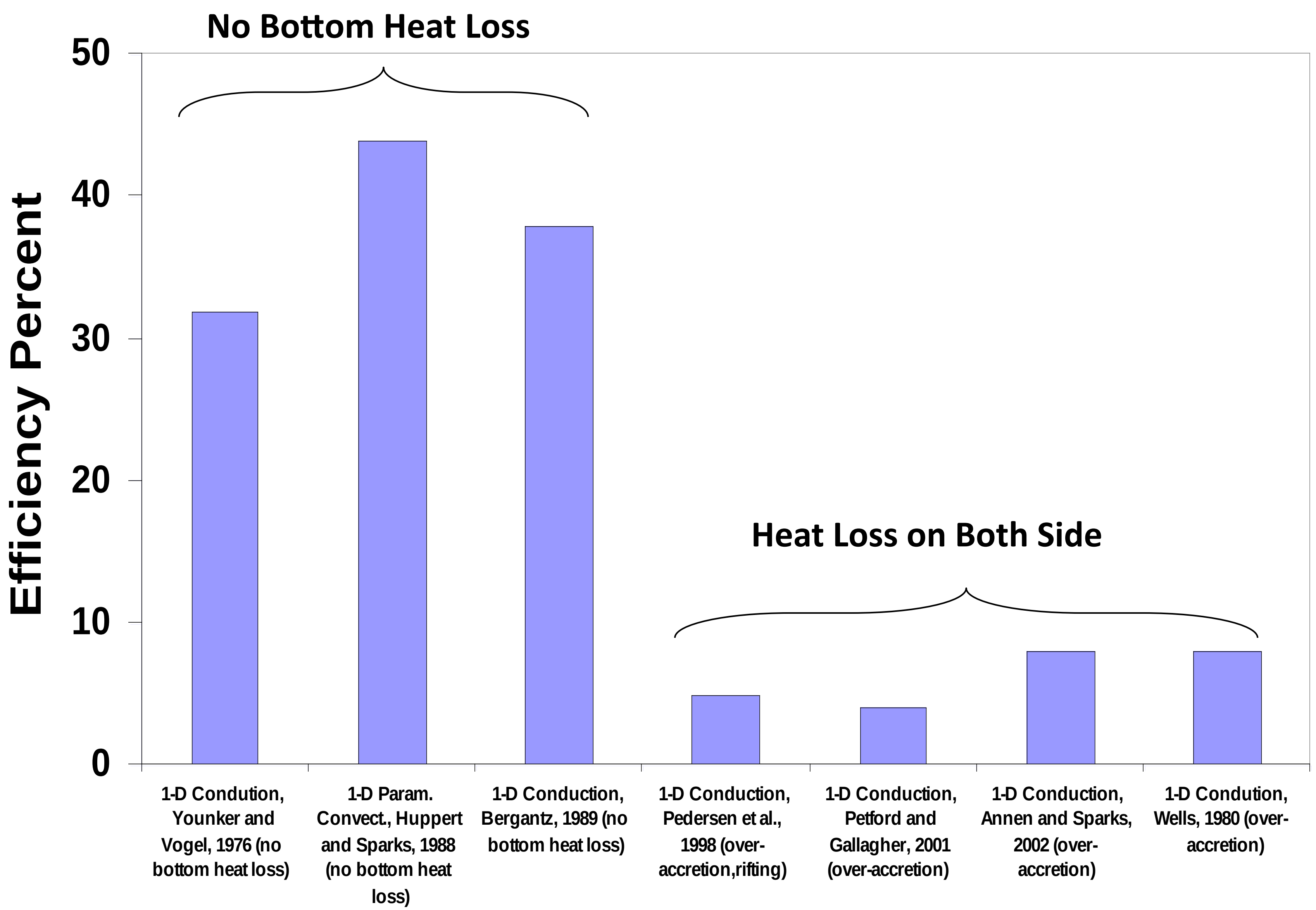
1. Instantaneous elastic response of the crust due to over-pressure in a chamber.
2. Time-dependent viscoelastic response of the crust to over-pressure.
3. Heterogeneties of phase production in a chamber.
4. Variability of compressibility in a chamber (i.e. phase proportions of bubbles in a chamber.
5. Two-way feedback between the stress-state of the system and the phase equilibria.

But also present in other oxides....



Thompson, 1972

Summary of 1-D Conduction/Melting Simulations



Directly coupling MELTS with multiphase dynamics calculations

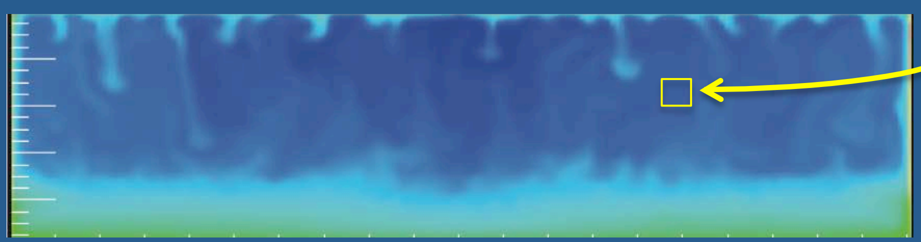
- Conservation of mass, enthalpy and momentum is solved for discrete phases, and the phase equilibria, melt composition, thermodynamic variables are solved at each position and time.

- More accurate computation of the sensible to latent heat partitioning than is available with other approaches.

- Provides detailed assessment of geochemistry.

- Allows calculation of wide parameter space of enthalpy, pressure, and water contents

- Implemented in a parallel computational architecture.



From enthalpy, pressure and composition MELTS provides phase equilibria, temperature, and thermodynamic variables

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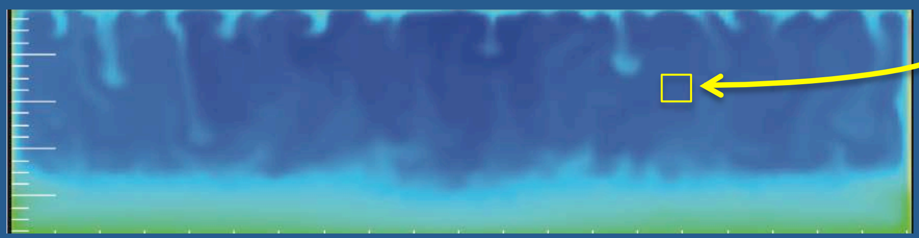

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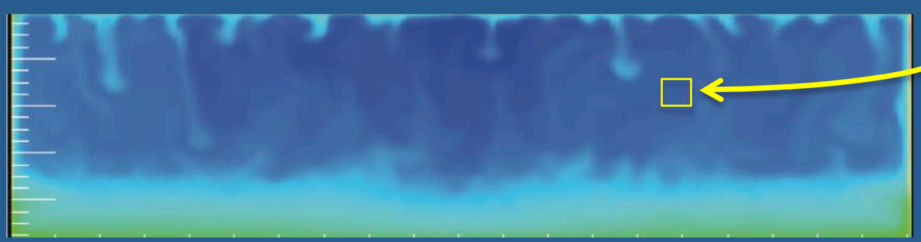

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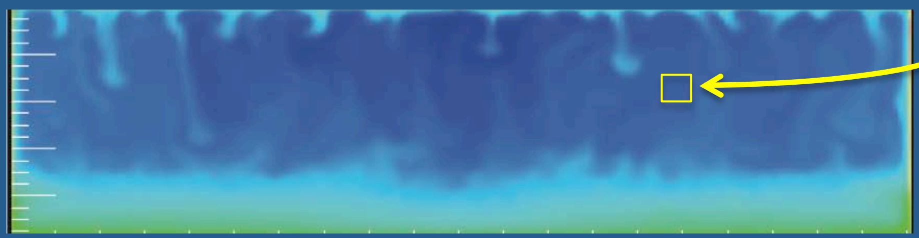
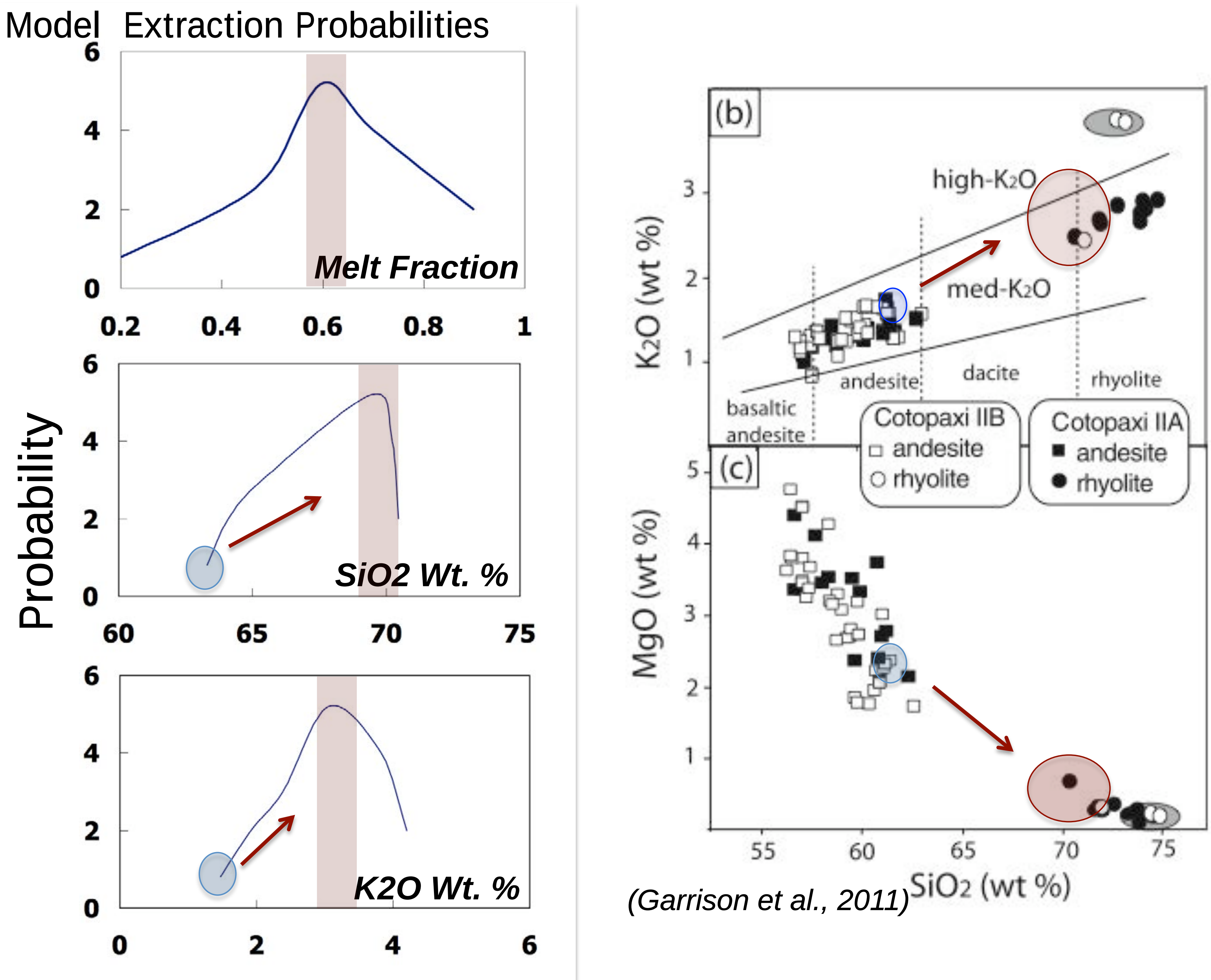


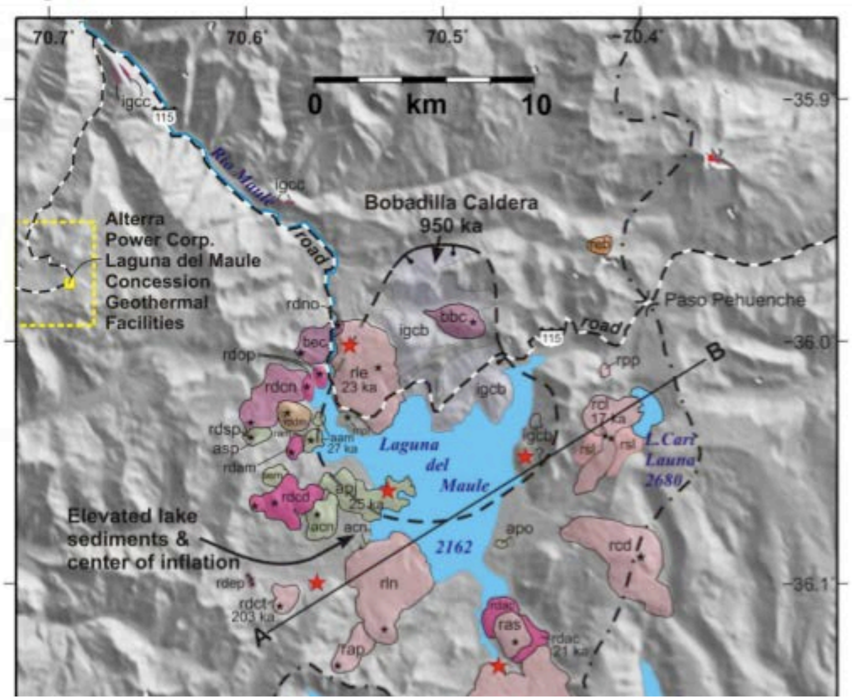
From enthalpy, pressure and composition MELTS provides phase equilibria, temperature, and thermodynamic variables

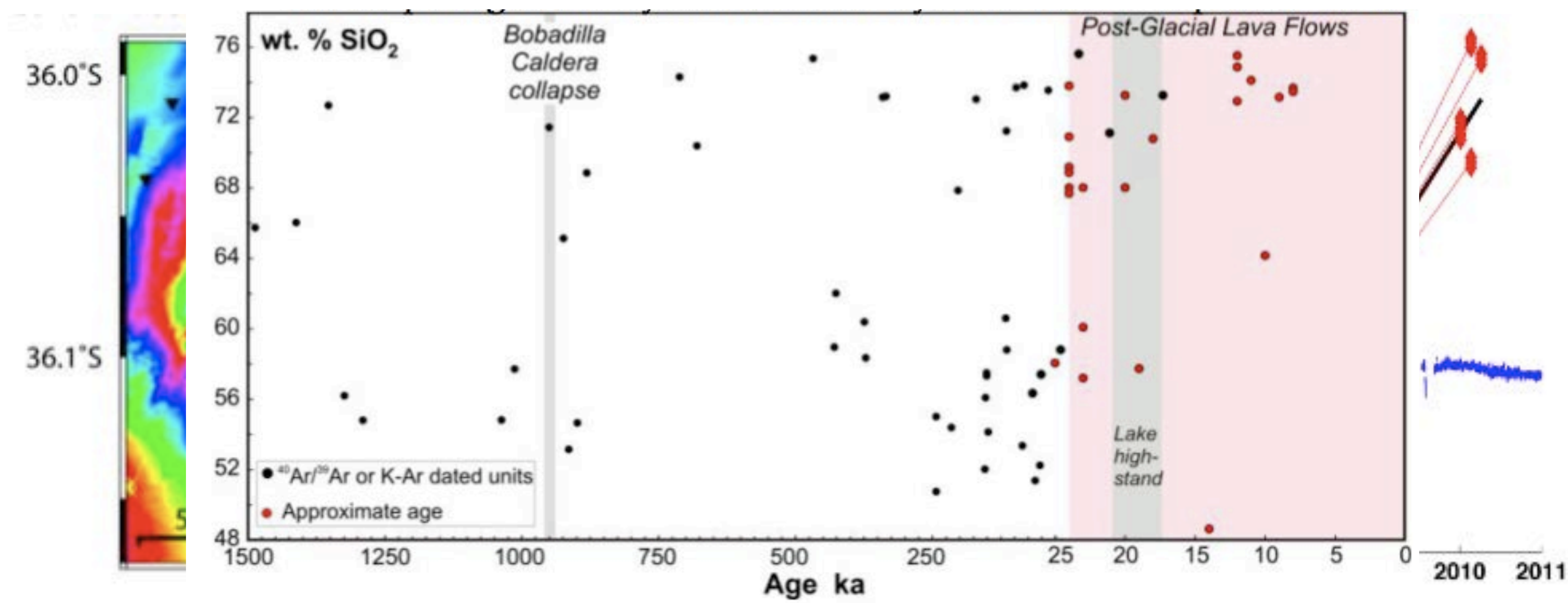


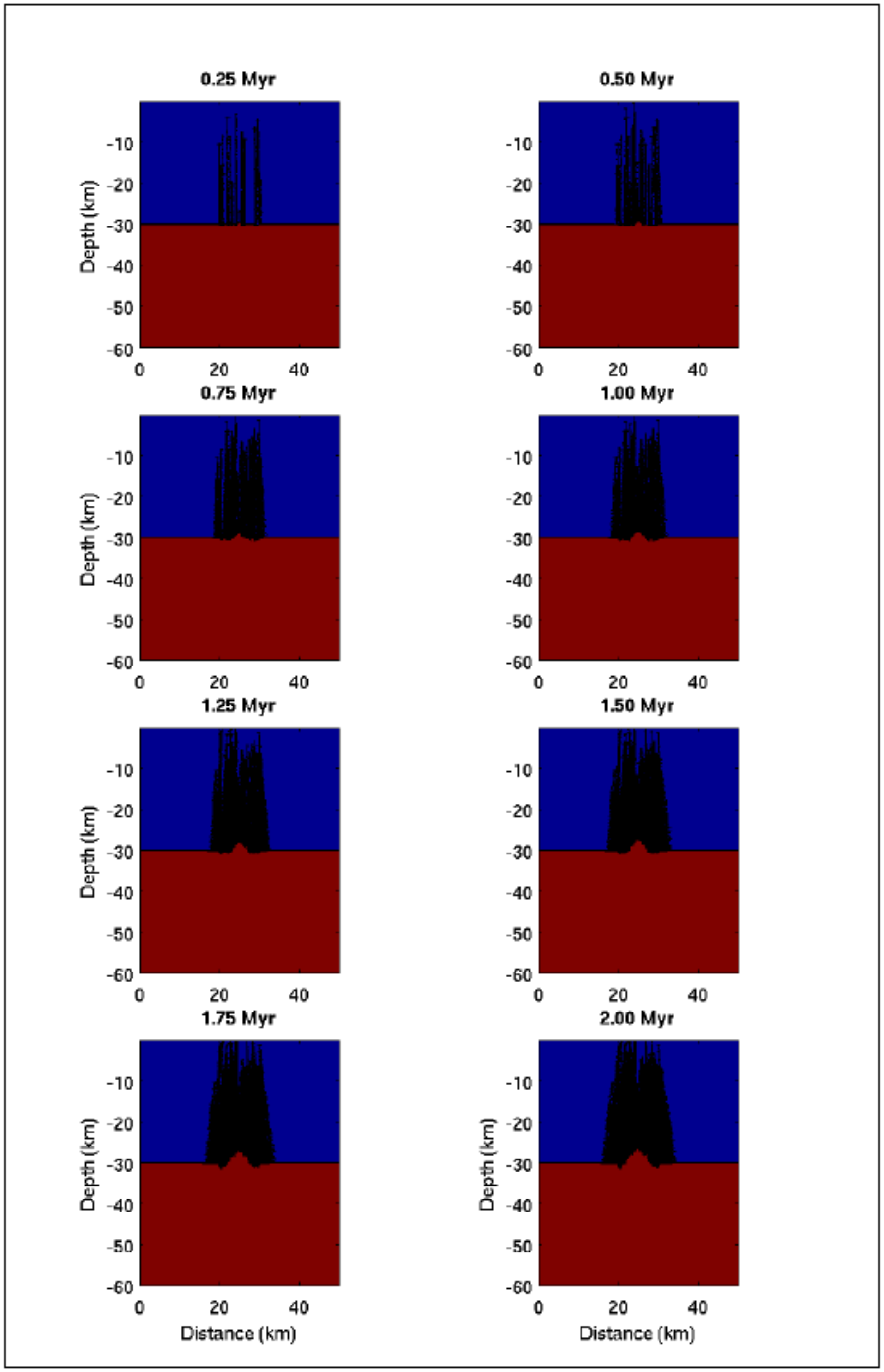
(Garrison et al., 2011)

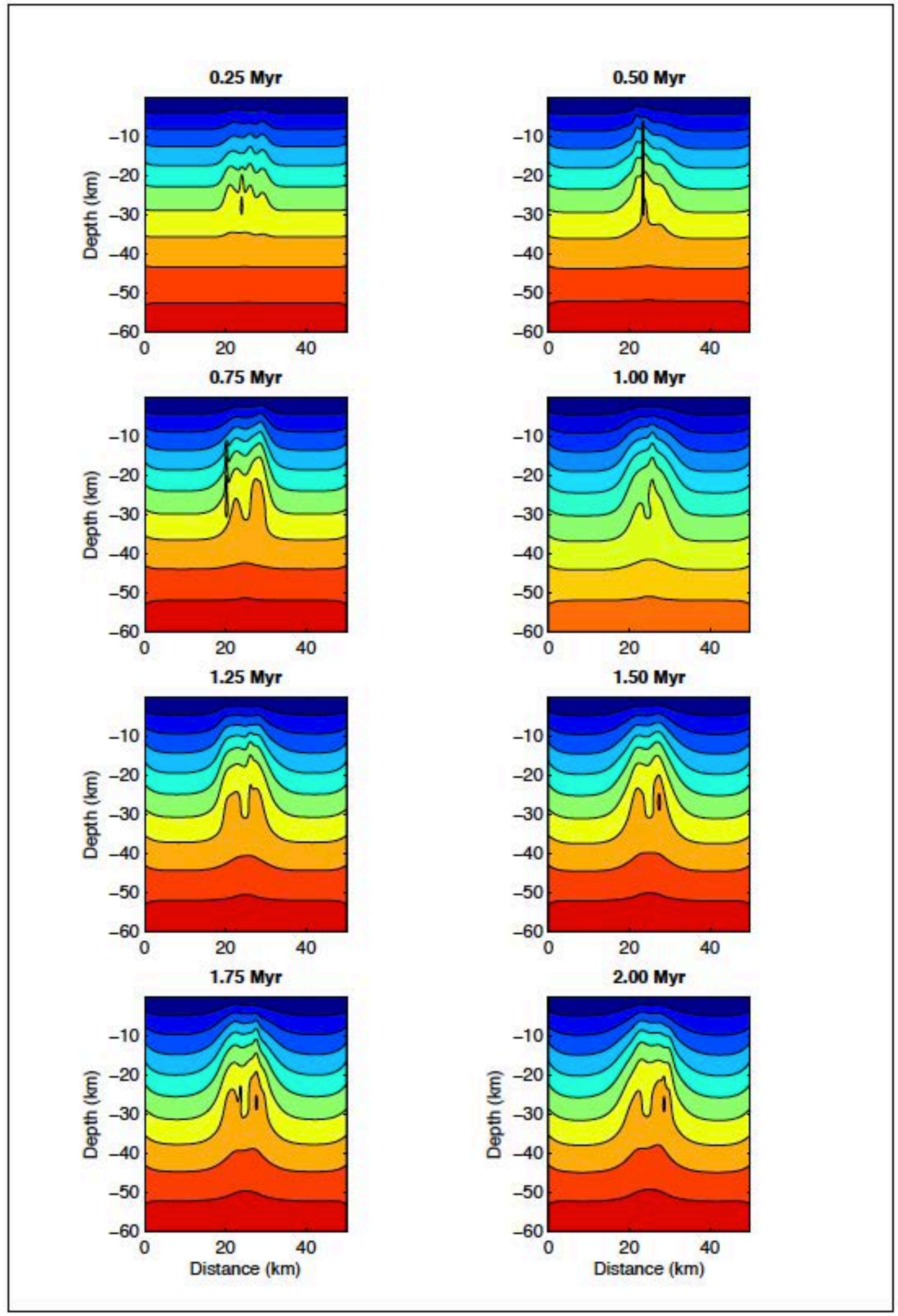
This sort of modeling can tie together data sets that are often treated in isolation.

An example is a recently proposed project to work on Laguna del Maule, Chile with U. Wisc, Madison (PI Singer, Thurber, Feigl), USGS (Fierstein, Hildreth), U Alberta (Unsworth), Alterra Power, and our group.

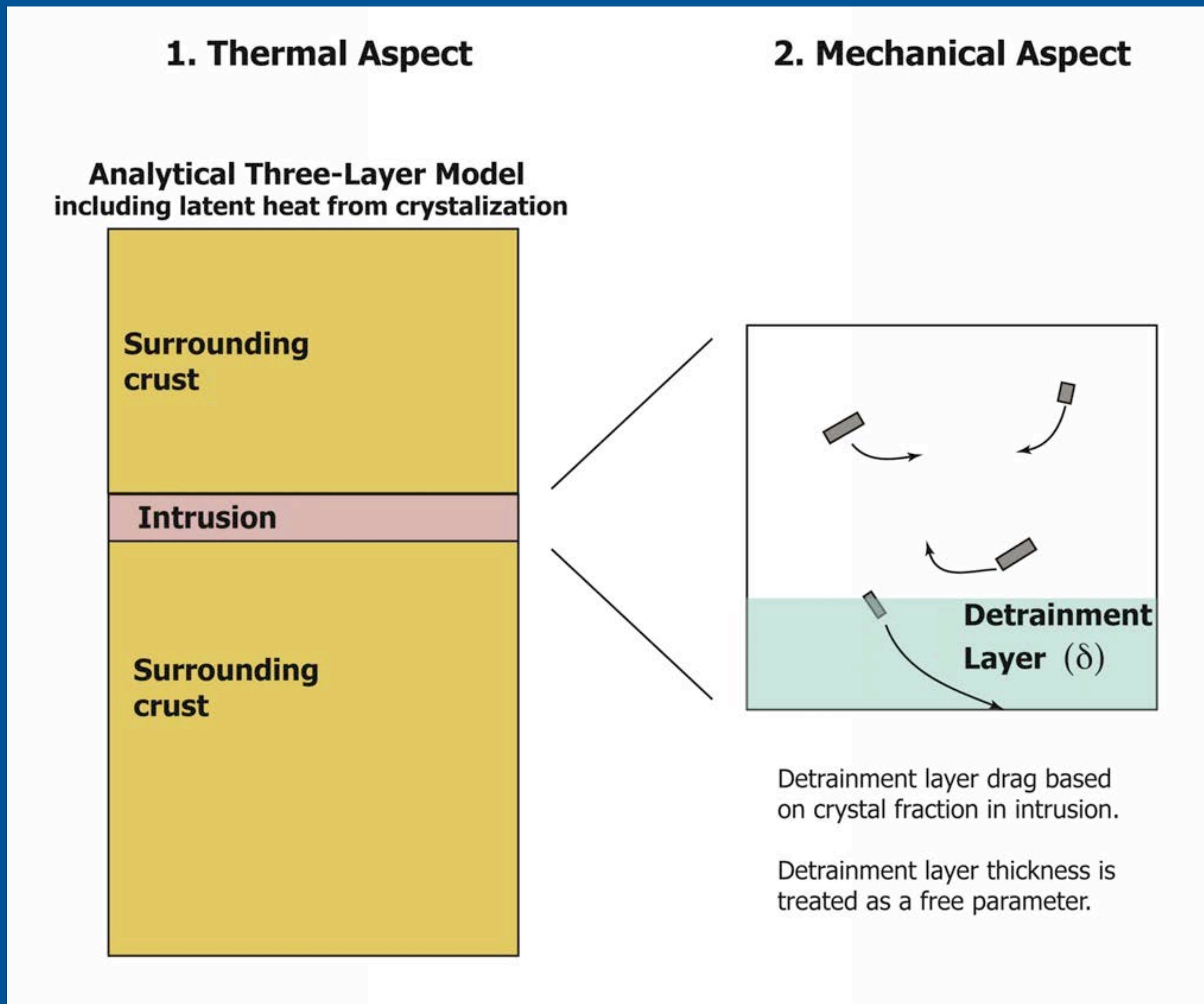




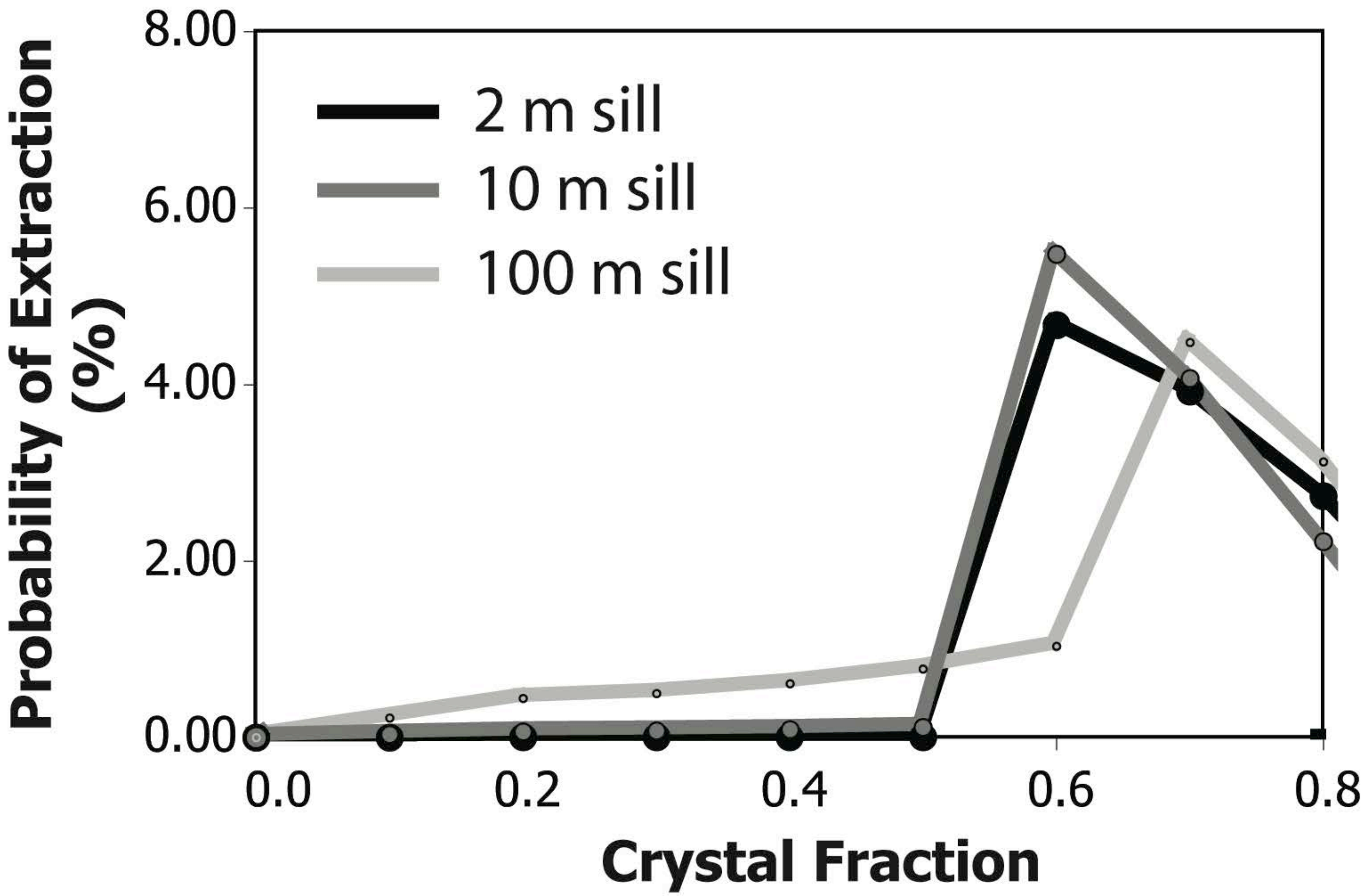

0.25 Myr
0.50 Myr
0.75 Myr
1.00 Myr
1.25 Myr
1.50 Myr
1.75 Myr
2.00 Myr
Depth (km)
Distance (km)


0.25 Myr
0.50 Myr
0.75 Myr
1.00 Myr
1.25 Myr
1.50 Myr
1.75 Myr
2.00 Myr
Depth (km)
Distance (km)

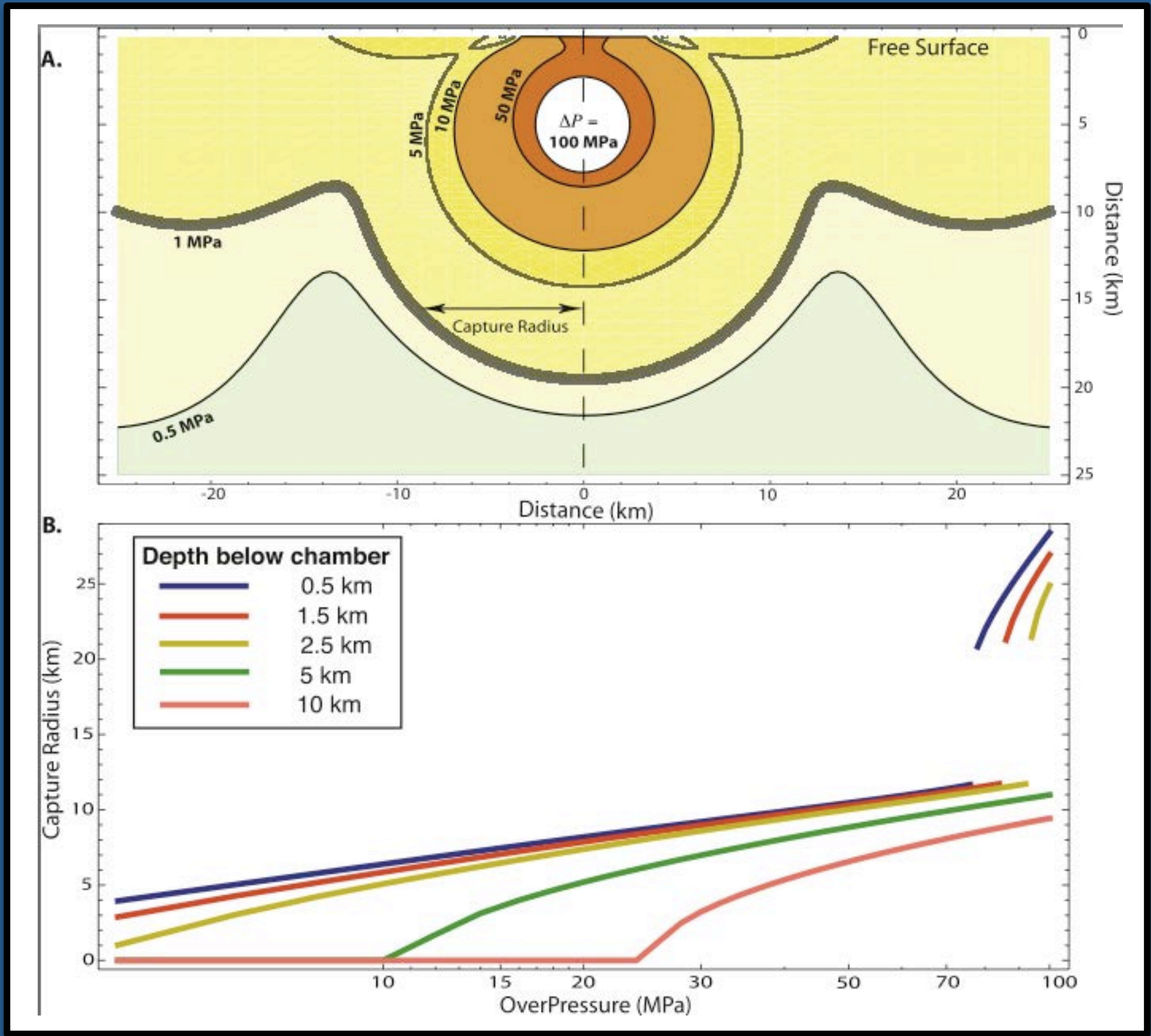
To examine the hypothesis that the combined effect of thermal longevity and degree of mechanical coupling produce gaps, we developed a paired down analytical model.



Analytical Result, Basaltic Magma, 5 km depth

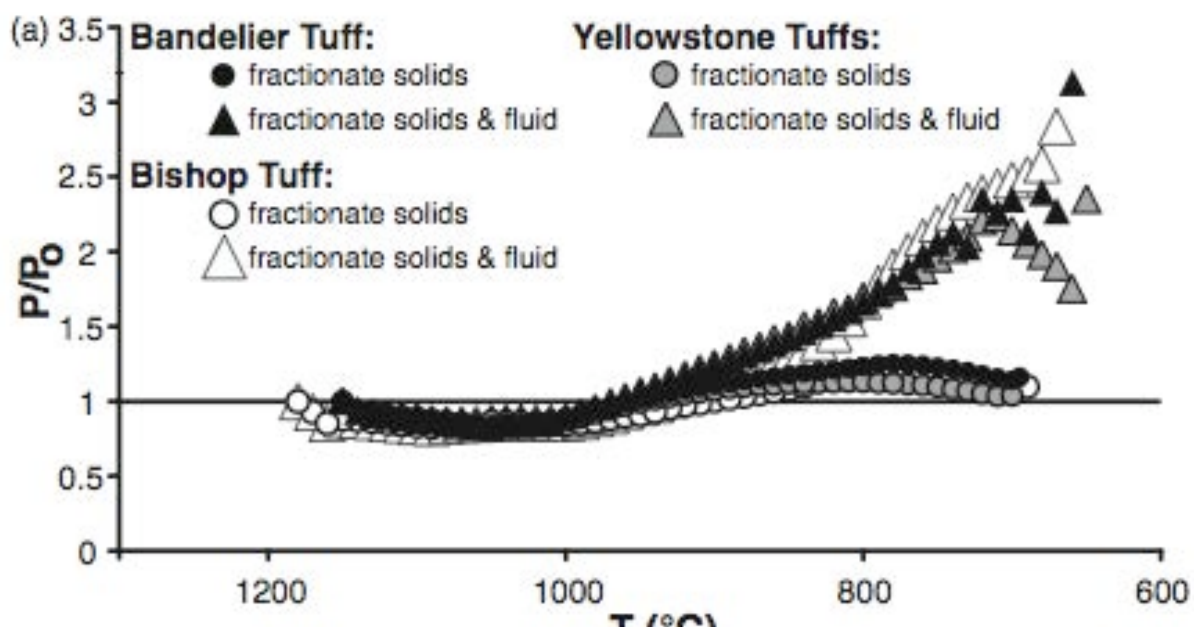


Magma overpressure can be generated by melting and intrusion, which can influence crustal stress fields.



Karlstrom, Dufek and Manga 2009

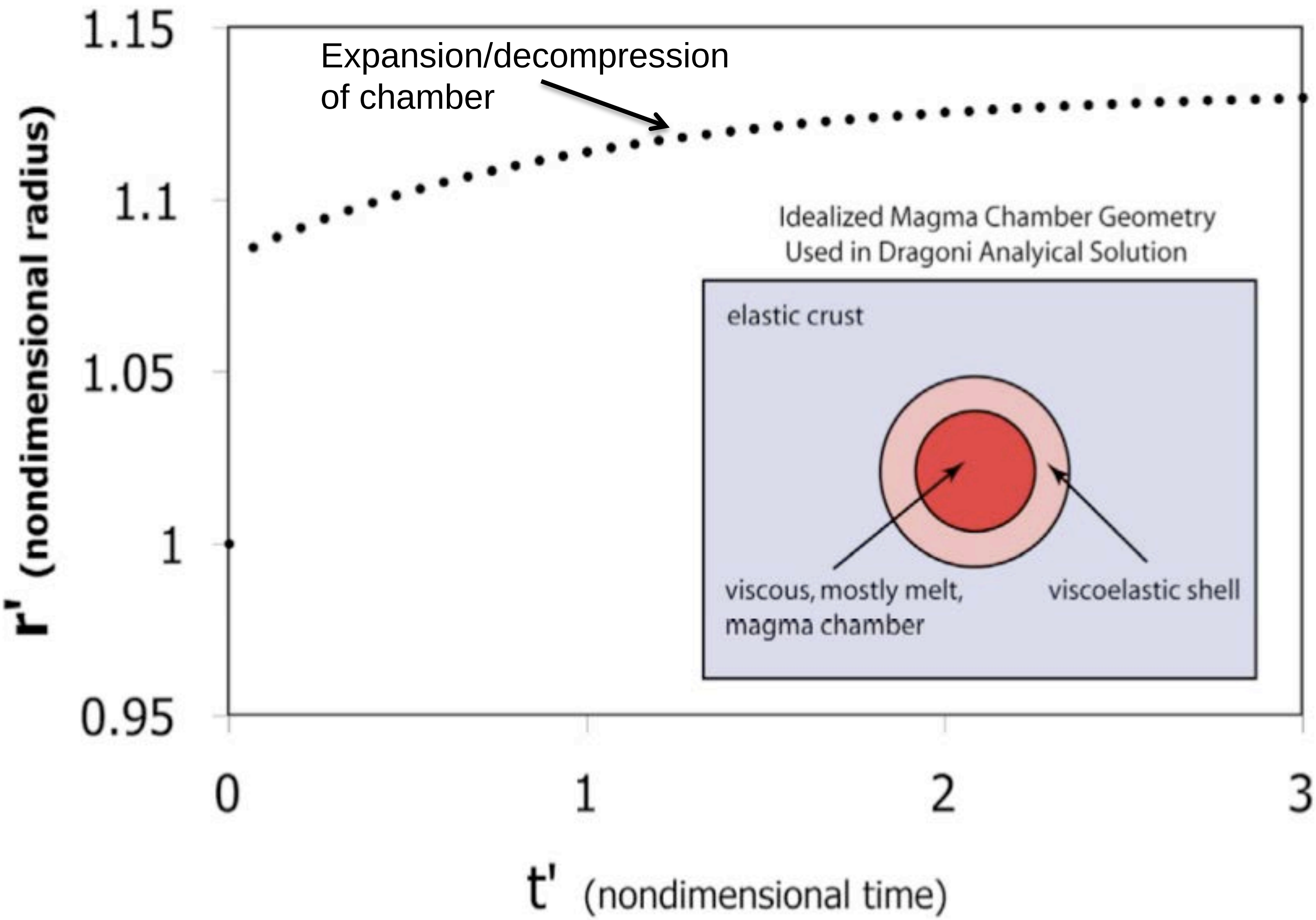
Overpressure can also influence phase equilibria. Below are examples of isochoric (constant volume) calculations performed by Fowler and Spera (2010).



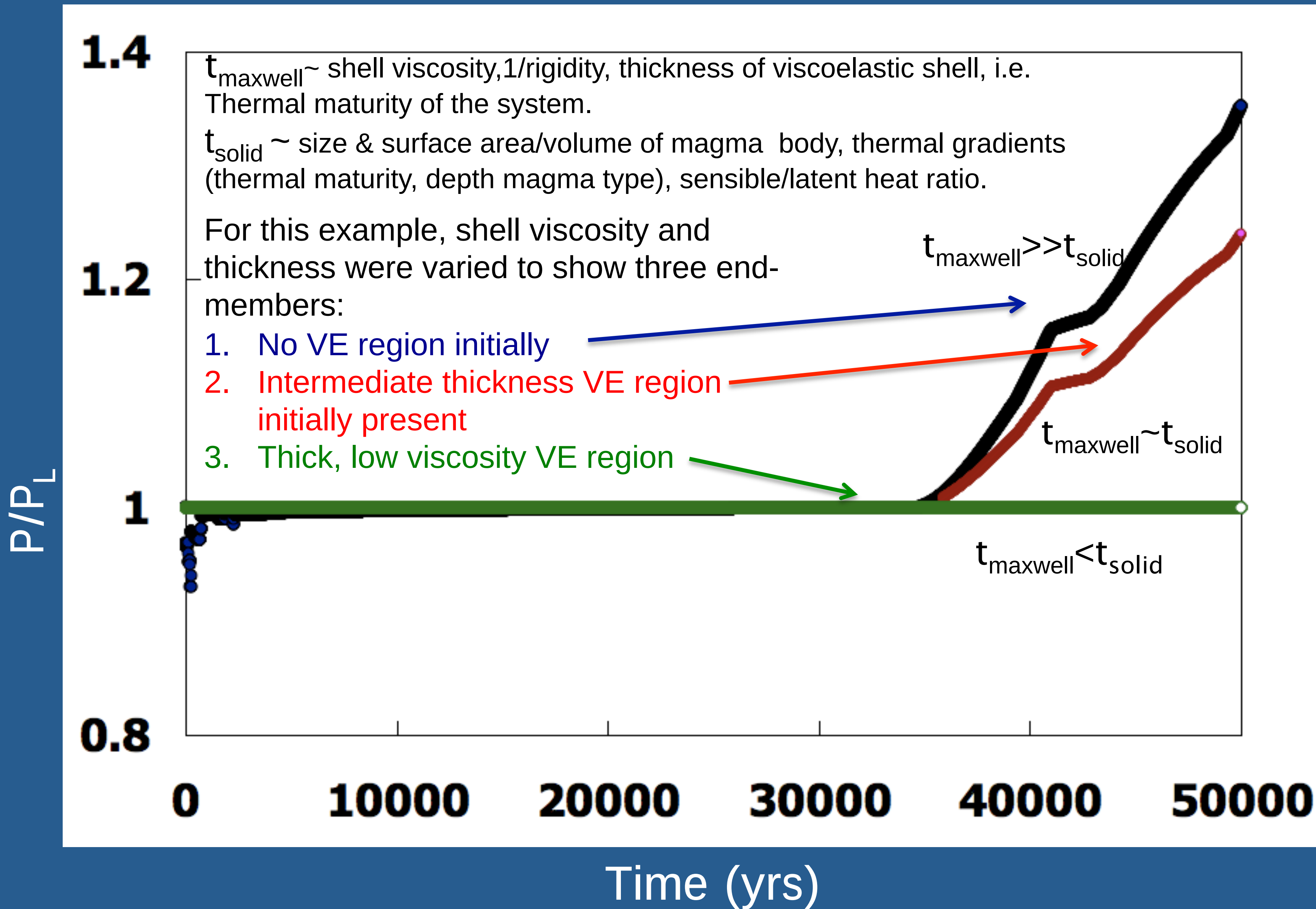
Fowler and Spera, 2010

We can think of these calculations as end-members assuming a perfectly rigid crustal container, and identical P-T conditions throughout the chamber.

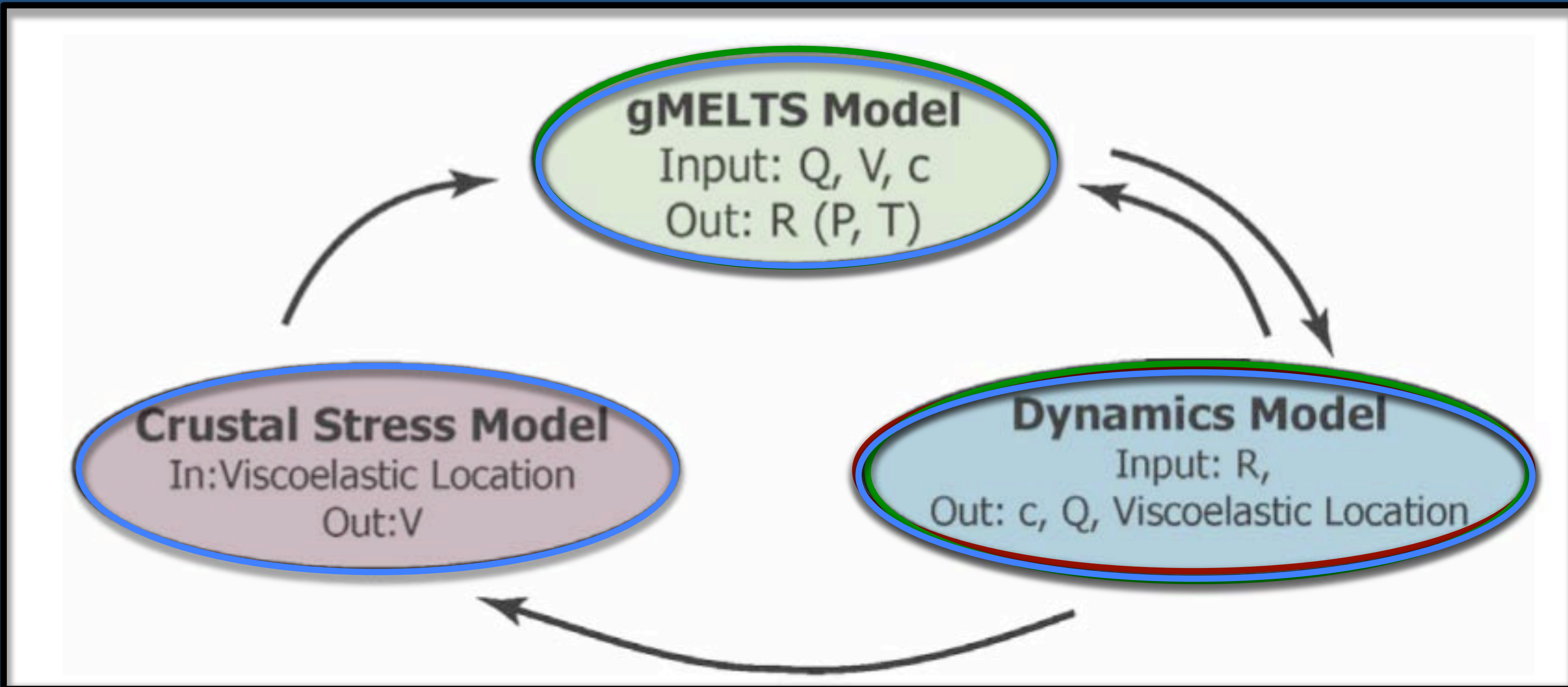
Crustal container is not, in general, completely rigid and can have elastic and viscoelastic response.



As an example, consider the pressure evolution of a 1 km diameter dacitic magma chamber with 5 wt% water.



Coupled multiphase dynamics, stress field and thermodynamics models provide the context to integrate disparate observations.



Multiphase dynamics in magma chambers and its role in melt extraction and composition (Daly gaps).

Determination of detailed phase equilibria, melt residence times and accurate calculations of sensible to latent heat ratios.

Magma chamber pressure evolution, modification of crustal stress fields, and influence on phase equilibria.