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*

*These processes span many scales*
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$_2$.

<table>
<thead>
<tr>
<th>Volcano</th>
<th>Arc</th>
<th>Group</th>
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<tbody>
<tr>
<td>Curtis</td>
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<tr>
<td>Macauley</td>
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<td>II</td>
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<td>Vanua Lava</td>
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<td>Batur</td>
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<td>Oto</td>
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<td>Deception</td>
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<td>Katmai</td>
<td>Aleutian</td>
<td>I</td>
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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. % SiO₂.

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.
Efficiency Percent

No Bottom Heat Loss

Heat Loss on Both Side

Summary of 1-D Conduction/Melting Simulations

1-D Conduction, Younker and Vogel, 1976 (no bottom heat loss)
1-D Param. Convect., Huppert and Sparks, 1988 (no bottom heat loss)
1-D Conduction, Bergantz, 1989 (no bottom heat loss)
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1-D Conduction, Petford and Gallagher, 2001 (over-accretion)
1-D Conduction, Annen and Sparks, 2002 (over-accretion)
1-D Conduction, Wells, 1980 (over-accretion)
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.
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.
Tectonic Controls

Rowland et al., 2010

Mahony et al., 2011
Tectonic Controls

Rowland et al, 2010
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.
Volume fraction of all phases equals 1
\[ \sum_k \phi_k = 1 \]

Conservation of Mass
\[ \frac{\partial}{\partial t} \left( \phi_k \rho_k \right) + \frac{\partial}{\partial x_i} \left( \phi_k \rho_k u_{k,i} \right) = R_k \]

Conservation of Momentum
\[ \frac{\partial (\phi_k \rho_k u_{k,i})}{\partial t} + \frac{\partial (\phi_k \rho_k u_{k,i} u_{k,j})}{\partial x_i} = \]
\[ -\phi_k \frac{\partial P}{\partial x_i} \delta_{ij} + \frac{\partial}{\partial x_i} \left[ \tau_{ij} \right] + D_i + \rho_k \phi_k g_2 \delta_{i2} + R_k u_{k,i} \]

Conservation of Thermal Energy
\[ \phi_k \rho_k c_k \left[ \frac{\partial T_k}{\partial t} + u_i \frac{\partial T_k}{\partial x_i} \right] = \delta_{km} \frac{\partial q_k}{\partial x_i} + \pi k_m d \text{ Nu} \left( T_m - T_c \right) + \phi_k R_k L \]

Conservation of Chemical Species
\[ \frac{\partial}{\partial t} \left( \phi_k \rho_k C_{SiO_2} \right) + \frac{\partial}{\partial x_i} \left( \phi_k \rho_k u_{k,i} C_{SiO_2} \right) = \beta_{(f)} \]
**Multiphase Equations for Magma Chamber**

**Volume fraction of all phases equals 1**

\[ \sum_k \phi_k = 1 \]

**Conservation of Mass**

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

**Conservation of Momentum**

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\]

**Conservation of Thermal Energy**

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\phi_k \rho_k c_k \left[ \frac{\partial T_k}{\partial t} + u_i \frac{\partial T_k}{\partial x_i} \right] = \delta_{km} \frac{\partial q_k}{\partial x_i} + \pi k_m d \text{ Nu} \left( T_m - T_c \right) + \phi_k R_k L
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Conservation of Chemical Species
\[ \frac{\partial}{\partial t} (\phi_k \rho_k C_{SiO_2}) + \frac{\partial}{\partial x_i} (\phi_k \rho_k u_{k,i} C_{SiO_2}) = \beta_{(f)} \]
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.
- 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.
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

![Graph showing modeled compositional evolution of % SiO₂ against % Occurrence, with a peak around 65% SiO₂ and an initial magma point indicated.](image)
Examples of random sampling given this probability distribution.

$N=100$
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.

<table>
<thead>
<tr>
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<th>Lower Crust</th>
<th>Middle Crust</th>
<th>Upper Crust</th>
<th>Bulk Crust</th>
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<td>53.4</td>
<td>63.5</td>
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<tr>
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<td>15</td>
<td>15.4</td>
<td>15.9</td>
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<td>FeO</td>
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<td>6.02</td>
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<td>6.7</td>
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<td>3.59</td>
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<td>.61</td>
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<td>2.8</td>
<td>1.8</td>
</tr>
</tbody>
</table>
A Potential Resolution - Mass return back to the mantle (R-T instabilities, delamination, erosion...)

Xenoliths

Lee et al, 2006

Dynamic Models

Jull and Kelemen, 2001

Tomography

Boyd et al, 2004

How might foundering be related to an actively growing crust, being forced by mass and enthalpy input?
<table>
<thead>
<tr>
<th>Method</th>
<th>Location</th>
<th>Estimate of Basalt Flux ($m^3/m^2\text{yr}$)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity/Seismic</td>
<td>Marianas</td>
<td>$4.93 \times 10^{-4}$</td>
<td>Dimalanta et al., 2002</td>
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<td></td>
<td>Marianas</td>
<td>$1.92 \times 10^{-4}$</td>
<td>Crisp, 1984</td>
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<tr>
<td></td>
<td>Izu-Bonin</td>
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<td>Dimalanta et al., 2002</td>
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<td>Aleutians</td>
<td>$5.46 \times 10^{-4}$</td>
<td>Dimalanta et al., 2002</td>
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<td></td>
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<td>$3.40 \times 10^{-4}$</td>
<td>Crisp, 1984</td>
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<td>Tonga</td>
<td>$7.41 \times 10^{-4}$</td>
<td>Dimalanta et al., 2002</td>
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<td>New Hebrides</td>
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<td>Geochemical/Thermal</td>
<td>Eastern Nevada</td>
<td>$4.0 \times 10^{-4}$</td>
<td>Grunder, 1995</td>
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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).
• 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

- Dripping Instability Rate
- Basalt Flux from Mantle
- Melt Segregation (by compaction)
- Magma Mixing Rate (high melt fraction)

Units: $\text{m}^3/\text{m}^2\text{yr}$
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.
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.
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?
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

The graph illustrates the probability of extraction (%) as a function of crystal fraction. Different markers represent extraction at various depths:
- 10 km
- 20 km
- 30 km
- 40 km
- 50 km
- 70 km

The x-axis represents the crystal fraction, while the y-axis shows the probability of extraction.
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. Heterogeneities 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

- **No Bottom Heat Loss**
  - 1-D Conduction, Youkner and Vogel, 1976 (no bottom heat loss)
  - 1-D Param. Convect., Huppert and Sparks, 1988 (no bottom heat loss)
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  - 1-D Conduction, Wells, 1980 (over-accretion)
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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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.
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.
Overpressure can also influence phase equilibria. Below are examples of isochoric (constant volume) calculations performed by 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.

For this example, shell viscosity and thickness were varied to show three end-members:
1. No VE region initially
2. Intermediate thickness VE region initially present
3. Thick, low viscosity VE region

\[ t_{\text{maxwell}} \sim \text{shell viscosity, } 1/\text{rigidity, thickness of viscoelastic shell, i.e.} \]
\[ t_{\text{solid}} \sim \text{size & surface area/volume of magma body, thermal gradients (thermal maturity, depth magma type), sensible/latent heat ratio.} \]
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).

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