Magmatic connections:
The interplay of magmatic systems with their crustal containers

Joe Dufek
School of Earth and Atmospheric Sciences
Georgia Tech

Supplemental Reading: Dufek, Huber and Karlstrom, Chpt. 2.
Magma chamber dynamics and thermodynamics,
Modeling Volcanic Processes: The Physics and Mathematics of Volcanism
Questions:

- What is the flux of mass and enthalpy of melt into the crust, and what does this imply for long term continental growth?  
  *Thermal aspects and melting efficiency*

- By what means and rates is melt separated from its residue?  
  *Efficiency of melt-crystal dynamics*

- What is the nature of the volcanic-plutonic connection?  
  *A link between complimentary outcrops?*

- How much do chamber and eruptive processes mix material?  
  *Interpretation of outcrops and deposits*
Outline:

1. Magma chambers in context
2. Thermal system
3. Intro/thermodynamics
4. Surrounding stresses
5. Multiphase Dynamics/Melt Evolution
6. Link to eruptive dynamics
7. Some persistent open questions
The advection of mass and heat from mantle melts ultimately drives crustal magmatism.

*Singer et al. 2013*
Magma Chambers/intrusions influence:

1. Compositional diversity of the crust
2. Physical properties of the crust
3. Staging region for accumulation of magmas prior to eruption
4. Concentrating incompatible elements and relationships to ore deposits
Modern approaches have focused on examining two parallel sources of data:

- **Plutons**: Preserves an integrated record.
- **Volcanic deposits**: Closer to instantaneous snap-shot.

Connections?
Magmatic processes are recorded across a range of length and timescales.
What is a magma chamber?

Definitions/usage has varied over time.

Here I’ll used the more relaxed definition of a spatially connected body of magma in a suprasolidus state.

1. Magma chambers exist at least transiently --- as evidenced from large eruptions.
2. Thermally, chambers are transient features.
3. Likely locations of major element evolution in composition due to:
   1. Fractional crystallization
   2. Melting
   3. Mixing of melts
   4. Assimilation of crystals
Transient and crystal-rich mush dominated model

- Intrusion of magmas as source of mass and enthalpy
- Cooling and crystallizing of residual melt
- Buoyant rise of interstitial melt
- Heating of surrounding crust, hydrothermal systems
- Intrusion of magmas as source of mass and enthalpy
- Incremental emplacement

Hildreth, 2004
Hypothesis: A link between volcanic-plutonic realms?

Volcanic units?

Left-over = plutons?

Recharge

??

??
Volume of erupted tephra

Examples

Mono-Inyo Craters past 5,000 years

Mount St. Helens May 18, 1980 (~1 km³)

Pinatubo, 1991 (~10 km³)

Tambora, 1815 (>100 km³)

Long Valley Caldera 760,000 years ago (~600 km³)

Yellowstone Caldera 600,000 years ago (~1,000 km³)
Active deformation

Newman et al., 2012
Laguna del Maule System Model
Singer et al. 2013
Some Thermal Considerations

\[ \frac{\partial H_T}{\partial t} + \frac{\partial}{\partial x_i} \left( u_i H_T \right) = \frac{\partial}{\partial x_i} k \left( \frac{\partial}{\partial x_i} T \right) \]

Sensible Heat

\[ H_T = \rho \int_{T_{ref}}^{T} c_p dT + \rho \int_{T_{ref}}^{T} f L \]

Latent Heat

\[ \rho^* \left[ \frac{\partial T^*}{\partial t^*} + u_i^* \frac{\partial T^*}{\partial x_i^*} \right] = \left[ \frac{1}{\text{Pe}} \right] \frac{\partial^2 T^*}{\partial x_i^* \partial t^*} - \left[ \frac{1}{\text{Ste}} \right] R^* \]

Peclet: Adveective/diffusive heat transport

\[ \text{Pe} = \left[ \frac{c_p \rho \delta}{k} \right] u_0 \]

Stefan: Sensible/latent heat contribution

\[ \text{Ste} = \frac{c_p T_0}{L} \]

Dimensionless rate of production of melt

\[ R^* = \rho^* \frac{\partial f}{\partial t^*} \]

Numerous modeling approaches applied to the magmatic problem from 1-D conduction to 3D multiphase dynamic simulations
Some Thermal Considerations

\[
\frac{\partial H_T}{\partial t} + \frac{\partial}{\partial x_i} \left( u_i H_T \right) = \frac{\partial}{\partial x_i} \left( k \frac{\partial T}{\partial x_i} \right)
\]

Thermal calculations can be quite sensitive to the variation in the physical parameters.

\[
H_T = \rho \int_{T_{\text{ref}}}^{T} c_p \, dT + \rho f L
\]

Related to temperature change

Related to phase change

\[
\rho^* \left[ \frac{\partial T^*}{\partial t^*} + u_i^* \frac{\partial T^*}{\partial x_i^*} \right] = \left[ \frac{1}{\text{Pe}} \frac{\partial^2 T^*}{\partial x_i^2} \right] + \left[ \frac{1}{\text{Ste}} \right] R^*
\]

Advective/diffusive heat transport

Sensible/latent heat contribution

Numerous modeling approaches applied to the magmatic problem from 1-D conduction to 3D multiphase dynamic simulations.

\[
\text{Pe} = \left[ \frac{c_p \rho_0 \delta}{k} \right] u_0
\]

\[
\text{Ste} = \frac{c_p T_0}{L}
\]
Steady Geotherms
## Summary of some thermal model results

<table>
<thead>
<tr>
<th>Study</th>
<th>Model type¹</th>
<th>Intr. style²</th>
<th>Total intr.³ (km)</th>
<th>$T_{init}$ (°C)</th>
<th>Rock type²</th>
<th>$T_{mol}-T_{solid}$ (°C)</th>
<th>$E$ (%)</th>
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<tbody>
<tr>
<td>Younker and Vogel, 1976</td>
<td>1-D, cond., no bottom heat loss</td>
<td>single intrusion</td>
<td>2.0</td>
<td>500</td>
<td>basalt, biotite-granite</td>
<td>L:1200, S:1100 L:1100, S:800</td>
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<td>Wells, 1980</td>
<td>1-D, cond., over-accretion</td>
<td>multiple intrusion</td>
<td>40.0</td>
<td>200</td>
<td>tonalite</td>
<td>L:1050, S:800</td>
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<td>Huppert and Sparks, 1988</td>
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<td>0.5</td>
<td>500</td>
<td>basalt, granodiorite</td>
<td>L:1200, S:1091 L:1000, S:850</td>
<td>44</td>
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<td>Bergantz, 1989</td>
<td>1-D, cond., no bottom heat loss</td>
<td>single intrusion</td>
<td>16.6</td>
<td>700</td>
<td>basalt, pelite</td>
<td>L:1250, S:980 L:1200, S:725</td>
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<td>Bittner and Schmelting, 1995</td>
<td>2-D, convection</td>
<td>single intrusion</td>
<td>5.0</td>
<td>756</td>
<td>basalt, granite</td>
<td>L:1100, S:950 L:1050, S:760</td>
<td>NA</td>
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<td>Barboza and Bergantz, 1996</td>
<td>2-D, convection</td>
<td>fixed $T$ bottom boundary</td>
<td>NA</td>
<td>600</td>
<td>pelite</td>
<td>L:1200, S:750</td>
<td>NA</td>
</tr>
<tr>
<td>Raia and Spera, 1997</td>
<td>2-D, convection</td>
<td>fixed $T$ bottom boundary</td>
<td>NA</td>
<td>1195</td>
<td>(CaAl₂Si₂O₆-CaMgSi₃O₈)</td>
<td>L:1547, S:1277</td>
<td>NA</td>
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<tr>
<td>Pedersen et al., 1988</td>
<td>1-D, cond., over-accretion</td>
<td>multiple intrusion</td>
<td>10.0</td>
<td>650</td>
<td>basalt, granodiorite</td>
<td>L:1250, S:1100 L:1000, S:710</td>
<td>5</td>
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<tr>
<td>Pedford and Gallagher, 2001</td>
<td>1-D, cond., over-accretion</td>
<td>multiple intrusion</td>
<td>1.0</td>
<td>650</td>
<td>basalt, amphibolite</td>
<td>L:1250, S:1050 L:1075, S:1010</td>
<td>4</td>
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<tr>
<td>Annen and Sparks, 2002</td>
<td>1-D, cond., over-accretion</td>
<td>multiple intrusion</td>
<td>8.0</td>
<td>variable, based on depth (600)</td>
<td>basalt, amphibolite</td>
<td>L:1300, S:620 L:1075, S:1010</td>
<td>8</td>
</tr>
<tr>
<td>Dufek and Bergantz, 2005a</td>
<td>2-D, cond. and convection, stochastic</td>
<td>multiple intrusion</td>
<td>variable (5.0)</td>
<td>variable, based on depth (640)</td>
<td>basalt, amphibolite</td>
<td>pressure dependent L:1240, S:640 L: 1100, S:850</td>
<td>0.5-10.4 (7.1)</td>
</tr>
</tbody>
</table>
Efficiency of Generating Crustal Melt

An enthalpy balance can give the maximum amount of melting:

\[
V_{\text{crust}}^{\text{eff}} = \frac{\rho^b V^b \left[ c_p^b (T_L^b - T) + L^b \right]}{\rho^c c_p^c (T_s^c - T_R^c) + \rho^c \left[ c_p^c (T - T_s^c) + L^c f \right]}
\]

This assumes all energy from an intrusion (b) is extracted and applied to only that area of the crust (c) that melts.

\[
E^\% = 100 \times \frac{V_{\text{crust}}^{\text{mod.}}}{V_{\text{crust}}^{\text{eff.}}}
\]

Models typically show less melting than this end-member.
Summary of 1-D Conduction/Melting Simulations

<table>
<thead>
<tr>
<th>Efficiency Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>20</td>
</tr>
<tr>
<td>30</td>
</tr>
<tr>
<td>40</td>
</tr>
<tr>
<td>50</td>
</tr>
</tbody>
</table>

No Bottom Heat Loss

- 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)
- 1-D Conduction, Pedersen et al., 1998 (over-accreration, rifting)
- 1-D Conduction, Petford and Gallagher, 2001 (over-accreration)
- 1-D Conduction, Annen and Sparks, 2002 (over-accreration)
- 1-D Conduction, Wells, 1980 (over-accreration)

Heat Loss on Both Side

- Efficiency Percent: 10, 20, 30, 40, 50

- 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)
- 1-D Conduction, Pedersen et al., 1998 (over-accreration, rifting)
- 1-D Conduction, Petford and Gallagher, 2001 (over-accreration)
- 1-D Conduction, Annen and Sparks, 2002 (over-accreration)
- 1-D Conduction, Wells, 1980 (over-accreration)
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.

Karlstrom, Dufek and Manga 2009
How does the method of accommodation influence crustal evolution?
Volatiles can increase melting by a factor of ~10% beyond the dry case.

Huber et al., 2009

Exponential factor for Melt Fraction Relation

wt. % $H_2O$
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 \( \sim 10\% \) efficient \((\text{Dufek and Bergantz, 2005; Karlstrom, Dufek and Manga, 2009})\)
Magma reservoirs spend most of the active time at high crystallinities

- Reduced thermal gradients at higher crystallinity
- Latent heat effect
  - Dacitic upper crust: high latent/sensible heat ratio near eutectic

Simplified crystallinity relationship
Latent heat effect in silicic magmas

\[ M# = \text{Thermal energy released for a non-linear phase diagram} / \text{Thermal energy released for a linear phase diagram} \]

Mt Pelée; Annen et al., 2008
Partitioning of latent and sensible heating can have complex relationships with non-trivial results for the cooling history.
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

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

**Plinian Column:**
- Buoyant plume
- Particle+Gas Flow

**Pyroclastic Flow:**
- Particulate gravity current
- Particle+Gas Flow

**Magma Chambers:**
- Bubbles and crystal discrete phases
Dynamics

Density Drivers:

1. Composition
2. Thermal Buoyancy
3. Crystal Phases
4. Bubble Phase
BBO and Stokes Number

Lagrangian equation of motion

\[ \rho_d \frac{dN}{dt} = (\rho_d - \rho_m) g \delta_y + \rho_m \frac{Du_i}{Dt} \]  
\[ \text{buoyancy} \quad \text{Shear and Pressure terms} \]

\[ - \frac{1}{2} \rho m \frac{d}{dt} \left[ V_i(t) - u_i[Y(t), t] - \frac{1}{6} r^2 \left( \frac{\partial^2}{\partial x_j^2} u_i \right) \right] \]  
\[ \text{Virtual Mass Term} \]

\[ - 6\pi \eta \mu \left[ V_i(t) - u_i[Y(t), t] - \frac{1}{6} r^2 \left( \frac{\partial^2}{\partial x_j^2} u_i \right) \right] \]  
\[ \text{Stokes Drag Term} \]

\[ \frac{d}{d\tau} \left[ V_i(\tau) - u_i[Y(\tau), \tau] - \frac{1}{6} r^2 \left( \frac{\partial^2}{\partial x_j^2} u_i \right) \right] \]  
\[ \left[ \pi \nu(t - \tau) \right]^{\frac{1}{2}} \]  
\[ \text{Basset history term} \]
BBO and Stokes Number

Lagrangian equation of motion

For most magmatic conditions the added mass, Bassett history, and pressure gradient terms can be neglected leaving (in dimensionless form):

\[ \frac{d\mathbf{V}_i}{dt} = -\frac{1}{\text{St}} \left[ \mathbf{V}_i - \mathbf{u}_i \right] + \frac{1}{\text{Fr}_d^2} \delta_{ij} \]

\( \text{St} = \frac{\tau_m}{\tau_d} \)

Stokes #: Magmatic timescale/disperse phase timescale

Densimetric Froude #

\[ \text{Fr}_d = \frac{\mathbf{u}_0}{\sqrt{\frac{\rho_d - \rho_m}{\rho_d} g \mu_0 \tau_m}} \]

Disperse Phase Timescale

\[ \tau_d = \frac{\rho_d r^2}{6\pi\mu} \]
Direct Numerical Simulation (DNS) of Multiphase Wake Flow, Re~100.

Diagram from Tang et al. 1992
Stokes Numbers and Stability Factor

From Raju and Meiburg, 1994
- Crystal and bubble phases have largest density difference.

- Low St --- crystals travel with melt.

- However mixing can still be efficient.

In this overturn simulation a significant proportion (>20%) of the crystal cargo may have originated from a distance of 100 m or more from each other. Therefore, a single mixing event is capable of juxtaposing crystals that originated from spatially distinct regions of the chamber, and with completely different histories (compositional zoning, textures, etc.).
How much do hand samples represent crystals that have travelled together?

Ruprecht et al. 2008

Relative distance between crystals

Travelled Together

Gathered

cumulative frequency

$\frac{a_0}{a_{\text{final}}}$
If crystals are gathered do they react quickly enough to preserve the signal?
• Considers both the thermal and dynamics aspect of this multiphase system.

• Included phase change.

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

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

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

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

Volume fraction of all phases equals 1
\[ \sum \phi_k = 1 \]

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

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

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

Conservation of Chemical Species
\[ \frac{\partial}{\partial t} (\phi_k \rho_k C_{SiO_2}) + \frac{\partial}{\partial x_i} (\phi_k \rho_k u_{k,i} C_{SiO_2}) = \beta_{(f)} \]

Crystals and magma have distinct sets of conservation equations (denoted by \( k \) in these equations)
**Multiphase Equations for Magma Chamber**

**Volume fraction of all phases equals 1**

\[ \sum_k \phi_k = 1 \]

**Conservation of Mass**

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

**Conservation of Momentum**

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

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\[ \phi_k \rho_k c_k \left[ \frac{\partial T_k}{\partial t} + u_i \frac{\partial T_k}{\partial x_i} \right] = \delta_{km} \frac{\partial q_k}{\partial x_i} + \pi_k m d \text{ Nu} \left( T_m - T_c \right) + \phi_k R_k L \]

**Conservation of Chemical Species**

\[ \frac{\partial}{\partial t} (\phi_k \rho_k C_{SiO_2}) + \frac{\partial}{\partial x_i} (\phi_k \rho_k u_{k,i} C_{SiO_2}) = \beta_{(f)} \]
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

![Graph showing the probability of extraction versus crystal fraction for different rock types (Dacite, Andesite, Basalt). The optimal melt extraction zone is indicated.]
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.
Observations of Gaps are abundant - Here a compilation from Brophy in SiO₂.

<table>
<thead>
<tr>
<th>Volcano</th>
<th>Arc</th>
<th>Group</th>
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<tbody>
<tr>
<td>Curtis</td>
<td>Kermadec</td>
<td>II</td>
</tr>
<tr>
<td>Macauley</td>
<td>Kermadec</td>
<td>II</td>
</tr>
<tr>
<td>Epi</td>
<td>New Hebrides</td>
<td>I</td>
</tr>
<tr>
<td>Veniaminof</td>
<td>Aleutian</td>
<td>II</td>
</tr>
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<td>Bangum</td>
<td>Bismarck</td>
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<td>Tonga</td>
<td>New Hebrides</td>
<td>II</td>
</tr>
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<td>Shikotsu</td>
<td>Japan</td>
<td>I</td>
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<tr>
<td>Usu</td>
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<tr>
<td>Katmai</td>
<td>Aleutian</td>
<td>I</td>
</tr>
</tbody>
</table>
Link to eruptions and syn-eruptive mixing

Lowenstern and Hurwitz, 2008
Caldera

~1 m

Kalymnos

Kos

Caldera

Tilos
Kos Plateau Tuff - Using EEL to constrain eruptive conditions
A survey of 3D dynamics

Flux = 0.004 km$^3$/s

Flux = 0.002 km$^3$/s

Flux = 0.0015 km$^3$/s
Eruptive Flux: $10^5 \text{ m}^3/\text{s}$

Scale in meters

- ~1.0 m
- ~10 cm
- ~1.0 cm
- ~0.1 cm
- ~0.01 cm
- ~0.001 cm
Well-mixed ash (St<1) particles in pyroclastic density currents - welded ignimbrites likely eruptively well mixed.
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, magma chamber pressure evolution, modification of crustal stress fields, and accurate calculations of sensible to latent heat ratios.
- Crustal Stress Model: Input: Viscoelastic Location, Output: V.
- Dynamics Model: Input: R, Output: c, Q, Viscoelastic Location.
Both Fractionation and Melting Create an Apparent Crustal Mass Balance Issue

Persistent questions….
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*

<table>
<thead>
<tr>
<th></th>
<th>Lower Crust</th>
<th>Middle Crust</th>
<th>Upper Crust</th>
<th>Bulk Crust</th>
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<tr>
<td>SiO₂</td>
<td>53.4</td>
<td>63.5</td>
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<td>Al₂O₃</td>
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<td>15</td>
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</table>
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?
Magmatic Rates in the Crust

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

Rates shown in units of $m^3/m^2$ yr.