Mantle Melting at Subduction Zones
(an experimental petrologist’s view)

Christy B. Till
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“Raw materials”
The Mantle

- Adam Kent (Wednesday Week 1)
The Mantle
The Mantle
The Mantle
Great diversity in arc magma compositions

What produces the diversity of arc magmas?

Data from GEOROC: 2014 Compilation of Arc Melt Inclusions
Great diversity in arc magma compositions

Data from GEOROC: 2014 Compilation of Arc Melt Inclusions
Great diversity in arc magma compositions

What produces the mantle-derived magmas that give rise to this diversity?

Data from GEOROC: 2014 Compilation of Arc Melt Inclusions
There’s H₂O involved in arc magma genesis

1. Petrology of lavas
2. Highly explosive nature of arc volcanoes
3. Melt Inclusions

amphibole (~2 wt% H₂O)

Physical and chemical analytical data for representative glass inclusions in olivine megacrysts, Mt. Shasta region, California

<table>
<thead>
<tr>
<th>Locality</th>
<th>S-1</th>
<th>S-1</th>
<th>S-1</th>
<th>S-7</th>
<th>S-11</th>
<th>S-13</th>
<th>S-17</th>
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<tr>
<td>Host</td>
<td>Fo82</td>
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<td>Fo85</td>
<td>Fo88</td>
<td>Fo90</td>
<td>Fo81</td>
<td>Fo89</td>
<td>Fo94</td>
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<tr>
<td>Diam.†</td>
<td>40</td>
<td>100</td>
<td>100</td>
<td>200</td>
<td>80</td>
<td>50</td>
<td>60</td>
<td>70</td>
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<tr>
<td>Vapor‡</td>
<td>n.o.</td>
<td>7</td>
<td>(3)</td>
<td>(10)</td>
<td>(3)</td>
<td>n.o.</td>
<td>n.o.</td>
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<td>K²O</td>
<td>0.21</td>
<td>0.25</td>
<td>0.18</td>
<td>0.16</td>
<td>0.22</td>
<td>0.25</td>
<td>0.17</td>
<td>0.18</td>
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Chemical composition:

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<th>SiO₂</th>
<th>54.1</th>
<th>51.8</th>
<th>56.4</th>
<th>55.8</th>
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<th>55.3</th>
<th>58.9</th>
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<td>18.6</td>
<td>15.1</td>
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<td>17.4</td>
<td>20.1</td>
<td>16.1</td>
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<tr>
<td>FeO</td>
<td>7.9</td>
<td>5.3</td>
<td>7.2</td>
<td>8.2</td>
<td>6.1</td>
<td>6.1</td>
<td>5.4</td>
<td>3.8</td>
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<tr>
<td>MgO</td>
<td>4.4</td>
<td>5.0</td>
<td>4.2</td>
<td>5.7</td>
<td>6.8</td>
<td>3.5</td>
<td>4.1</td>
<td>5.3</td>
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<td>CaO</td>
<td>8.2</td>
<td>9.9</td>
<td>7.1</td>
<td>9.2</td>
<td>12.2</td>
<td>7.7</td>
<td>7.9</td>
<td>12.6</td>
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<tr>
<td>Na₂O</td>
<td>3.7</td>
<td>3.5</td>
<td>4.0</td>
<td>2.7</td>
<td>2.3</td>
<td>3.8</td>
<td>2.7</td>
<td>2.6</td>
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<tr>
<td>K₂O</td>
<td>0.72</td>
<td>0.52</td>
<td>0.93</td>
<td>0.58</td>
<td>0.25</td>
<td>1.12</td>
<td>1.05</td>
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<td>TiO₂</td>
<td>0.98</td>
<td>0.89</td>
<td>1.20</td>
<td>1.17</td>
<td>0.56</td>
<td>1.13</td>
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<td>P₂O₅</td>
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<td>0.24</td>
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<td>n.d.</td>
<td>n.d.</td>
<td>0.15</td>
<td>0.15</td>
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<td>H₂O**</td>
<td>1.7</td>
<td>2.6</td>
<td>1.4</td>
<td>0.4</td>
<td>2.0</td>
<td>0.7</td>
<td>0.9</td>
<td>2.2</td>
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<tr>
<td>Cl</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>n.d.</td>
<td>0.07</td>
<td>0.09</td>
<td>0.11</td>
<td>0.19</td>
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<tr>
<td>S</td>
<td>0.02</td>
<td>0.09</td>
<td>0.01</td>
<td>n.d.</td>
<td>0.11</td>
<td>0.04</td>
<td>0.05</td>
<td>0.21</td>
</tr>
</tbody>
</table>

Total: 98.0 98.4 97.8 97.6 97.8 99.6 97.9 98.4

Anderson, 1974
Primitive Magmas

Store information about:

- Temperature of melting
- Pressure of melting
- Bulk composition of mantle
- Extent of melting
- Type of melting process

Modified from Richards (2011)
Many studies have worked on the P-T-X origin of primitive arc magmas in the mantle.
Debate as to origins in early 1990’s

Physical Model of Source Region of Subduction Zone Volcanics

J. Huw Davies
Seismological Laboratory, California Institute of Technology, Pasadena

D. J. Stevenson
Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena

- Slab eclogite melts
  - e.g., Ringwood, 1975, Marsh, 1979

- Flux melting of mantle wedge
  - e.g., Kushiro, 1968; Gill, 1981; Sisson and Grove, 1993a,b

- Sediment flux is a key player
  - e.g., Plank & Langmuir, 1988; Sisson and Bronto, 1998

- Dry decompression melting of the mantle
  - e.g., Plank & Langmuir, 1993
How we do an phase equilibria experiment
How we do an phase equilibria experiment
• At a pressure and temperature: what mineral assemblage ± melt is stable?
• What is the chemical composition of the phases in equilibrium with each other?
Melt-Mantle Equilibria from High P-T Experiments

Till et al., JGR, 2012
Melt-Mantle Equilibria from High P-T Experiments

An example:
- Undepleted Mantle Lherzolite Composition
- 4 kilobars

Till et al., JGR, 2012
Melt-Mantle Equilibria from High P-T Experiments

An example:
- Undepleted Mantle Lherzolite Composition

Pressure Increases
4-10 kbar

Till et al., JGR, 2012
Melt-Mantle Equilibria from High P-T Experiments

An example:
• Undepleted Mantle Lherzolite Composition

Till et al., JGR, 2012
Great diversity in arc magma compositions

Red Data Points Nominally Anhydrous Primitive Basalts from Cascades + IBM (Till, 2017)

Gray Data Points from GEOROC: 2014 Compilation of Arc Melt Inclusions
More recent experiments on melting of fertile mantle lherzolite (initially garnet-bearing) confirm that:

**alkaline basalts** are favored by **higher P** and **low F** (as a result **higher T**)

whereas **tholeiites** are favored by **higher F** and **lower P** (as a result **lower T**)

Figure after Kushiro (2001)
Good forward geochemical models of dry mantle melting

Grove et al., 2013; Till et al., 2012; Ghiorso et al., 2002; Kinzler & Grove, 1992
Forward geochemical models of dry mantle melting don’t all agree

Grove et al., 2013; Till et al., 2012; Ghiorso et al., 2002; Kinzler & Grove, 1992
Adiabatic Decompression or "Dry" Mantle Melting (Tholeiites)
Now what happens if H$_2$O added...
Flux or “Wet” Mantle Melting (Calc-Alkaline Magmas)

Kushiro, 1968…
$\text{H}_2\text{O}$ added $\rightarrow$ Depress solidus temps

Hirth & Kohlstedt, 1996
H$_2$O added $\rightarrow$ Depress solidus temps

...but by how much?

*volatiles (H$_2$O, CO$_2$) lower melting temperature at a given depth*

- 150 ppm H$_2$O Solidi
  - Medard & Grove (2008)
  - Katz et al. (2003)
  - Hirschmann et al. (2009)

- 450 ppm H$_2$O Solidi
  - Medard and Grove (2008)
  - Katz et al. (2003)
  - Hirschmann et al. (2009)

Constant Degree of H$_2$O saturation in NAM
- Hirth and Kohlstedt (1996)
  - $a_{H2O}=0.1$ and $a_{H2O}=0.3$

- This paper
  - $a_{H2O}=0.1$ and $a_{H2O}=0.3$

H$_2$O-saturated peridotite: Till et al., CMP, 2012

H$_2$O + peridotite: Katz et al, 2003

carbonated peridotite: Dasgupta & Hirschmann, 2006
Melting in the presence of H$_2$O changes melt composition

“…produce elevated SiO2/(MgO + FeO) in hydrous peridotite partial melts, making them relatively SiO2-rich compared to anhydrous melts. The lower FeO + MgO concentrations result from the lower temperatures at which H2O-bearing melts coexist with mantle minerals.”

Gaetani and Grove, 1998
Melting in the presence of H₂O changes melt productivity.
Also relevant to back-arc basins

Kelley et al., 2006; Kelley et al., 2010
Now what happens if a lot of H$_2$O added? Depress solidus temps...

...but by how much?
Where does wet melting begin in the mantle wedge?

Green et al. Mantle H$_2$O-saturated solidus (predicts lower extents of melting)

Till Mantle H$_2$O-saturated solidus
What is the composition of early wet melts?
Quenched Melt & Fluid

1050°C, 3.2 GPa

1100°C, 3.2 GPa

(Till et al., Cont. Min. Pet., 2012)
What primitive compositions explained by wet melting....

Green Data Points Hydrous Primitive Basalts from Cascades + IBM (Till, 2017)
Gray Data Points from GEOROC: 2014 Compilation of Arc Melt Inclusions
Effect of mantle residue composition

Liquids in equilibrium with lherzolite based on the work of Till et al. (2012a, 2013).

Liquids in equilibrium with harzburgite based on the work of Mitchell and Grove (2015).

Liquids in equilibrium with dunite based on the work of Mitchell and Grove (2016).
Global Variation in Input + Thermal Structure

- Honshu (cold slab – 130 Ma)
- Nicaragua
- Cascadia (hot slab – 10 Ma)

van Keken et al., 2011
There’s regional variability in the composition of primitive melts (variations in residue + thermal state + flux from slab)
Limited forward geochemical models of wet mantle melting

Iherzolite melting at 0-6 wt% H2O

Harzburgite melting at 0–7 wt% H2O

Till et al., 2012

Mitchell & Grove, 2015
But flux of material from the subducting plate to the mantle may not be simply an aqueous fluid...

Other possibilities include:
- *Sediment diapirs*
- *Melts of sediments*
- *Melts of oceanic crust*
- *Combination of these (supercritical fluid)*

Kushiro, 1968…
Compelling Arguments for Slab Melt below Lassen

Walowski et al., 2016
Experimental H2O-saturated eclogite melts = dacite
Lassen Major Elements Consistent with Slab Melt

Walowski et al., 2016
Lassen Isotopic Composition Consistent with Slab Melt

Walowski et al., 2016
Experiments of eclogite melts reacted with mantle reproduce major + trace element composition of “adakites”

“Analysis of both the pristine and hybridized slab melts for a range of trace elements indicates that, although abundances of most trace elements in the melt increase during assimilation because melt is consumed, trace element ratios remain relatively constant”
Flux of material from the subducting plate = ?

Grove et al., 2012

Slab surface pressure-temperature conditions predicted (Syracuse et al. 2010)
Reaction with mantle as melt rises

Grove et al., 2012
Mantle melts seem to last equilibrate near the LAB

Plank & Forsyth, 2016

Till, 2017
P-T in the Context of Arc Flow Models

\[ \text{max}(\phi) = 0.07 \]
\[ \text{max}(F_{\text{melt}}) = 0.13 \]

\[ \text{max}(\phi) = 0.16 \]
\[ \text{max}(F_{\text{melt}}) = 0.16 \]

\[ \text{max}(\phi) = 0.06 \]
\[ \text{max}(F_{\text{melt}}) = 0.14 \]
Likely Melt Ascent Paths

Figure 8. Recalculated temperatures and pressures with subset of the literature dataset. The anhydrous peridotite solidus in a) is from Hirschman (2000) and the H2O-saturated peridotite solidi from Till et al. (2012) (lower temperature) and Green et al. (2014) (higher temperature). c) includes the calc-alkaline vs. tholeiitic fields of Miyashiro (1974).

Figure 10. A.) Comparison of tholeiitic basalts used for the pressure and temperature recalculations to incremental batch melts of a depleted Hart and Zindler mantle composition with 90% melt extraction and dF/dP = 1% per kilobar and an adiabatic gradient of 1.5°C per kilobar using the forward mantle model of Till et al. (2012) as modified by Behn and Grove (2015). Gray batch melting curves shown for comparison as described in B. B) Comparison of the calc-alkaline basalts used for pressure and temperature recalculations to isobaric batch melting curves for a depleted Hart and Zindler (1986) mantle composition at 10, 15 and 20 kbars as predicted by the forward lherzolite melting model of Till et al. (2012) as modified by Behn and Grove (2015). C) Comparison of all rock types to the batch melting and near-fractional melts of spinel lherzolite. The calc-alkaline basalts are consistent with 1-10% batch melts of a depleted mantle at 10-20 kbar. The tholeiites can be modeled by either batch melting at average higher pressures and extents of melting or by near-fractional melting between 20-9 kbars.

Decompression Melting + Channelized Flow

Flux Melting + Reactive Porous Flow

High MgO magmas
Tholeiitic basalt
Calc-alkaline basalt
Primitive high-Mg andesite

Till, 2017
Thermal req-equilibration of diapir happens in $<10^5$ years.

Ascent velocity $>5\times$ sub rate (such that ascend rather than subduct).

Grove et al., 2002
Comparison to thermal models

- **Petrologic P-T Constraints**
  - High MgO Primitive Magmas
  - Tholeiitic Basalts
  - Calc-Alkaline Basalts
  - Primitive High-Mg Andesite
  - Global mean of petrologic slab P-T constraints ± 2 sigma

- **Geodynamic Models**
  - Vertical Sections through Models
    - Kelemen et al., 2003: 100 km to slab
    - Kelemen et al., 2003: 150 to slab
    - Kincaid and Sacks, 1997
    - van Keken et al., 2002: Japan, non-linear
    - van Keken et al., 2002: Cascadia, non-linear

- **Slab Surface Paths**
  - Abers et al. 2006
  - Kelemen 2003
  - Gerya et al., 2002
  - Syracuse et al., 2010

The diagram shows a comparison of P-T paths from modern thermal models of subduction zones to thermobarometry dataset. The models tend to only reproduce the cooler petrologic observations.
## Major element Occam’s razor model for an “average” subduction zone

<table>
<thead>
<tr>
<th>Primitive magma Type</th>
<th>Melting Mechanism</th>
<th>Mantle Residue</th>
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<tbody>
<tr>
<td>Calc-alkaline basalts-andesites</td>
<td>Flux Melting</td>
<td>Lherzolite</td>
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<tr>
<td>Tholeiites</td>
<td>Decompression Melting</td>
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<tr>
<td>Primitive High-Mg andesites</td>
<td>Flux Melting</td>
<td>Harzburgite</td>
</tr>
<tr>
<td>High MgO liquids</td>
<td>? Damp ? Melting</td>
<td>Harzburgite</td>
</tr>
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- **Calc-alkaline basalts-andesites**
- **Tholeiites**
- **Primitive High-Mg andesites**
- **High MgO liquids**

![Diagram of subduction zone](image_url)
Debate as to origins in early 1990’s

Slab eclogite melts

e.g., Ringwood, 1975, Marsh, 1979

Flux melting of mantle wedge

e.g., Kushiro, 1968; Gill, 1981; Sisson and Grove, 1993a,b

Dry decompression melting of the mantle

e.g., Plank & Langmuir, 1988; Sisson and Bronto, 1998

Sediment flux is a key player

Plank & Langmuir, 1993
Future Opportunities

- integrated quantitative slab to surface evolution of melts
- major + trace element + isotopic constrained models
- quantitative forward models of melt composition as a function of $\text{H}_2\text{O}$ content for range of intensive variables ($X, P, T, f_{\text{O}_2}$)

experiments & thermobarometry of natural samples

experiments & modeling