The Production and Fate of Fluids and Magmas at Active Margins

Terry Plank
Lamont Doherty Earth Observatory, Columbia University
The Production and Fate of Fluids and Magmas at Active Margins

I. The Global Water Cycle

II. Mantle Boundary Layers and Melting

III. The Volcano: from the Mantle to Eruption
I. Is the Ocean Shrinking?
H$_2$O in Ocean
$1.4 \times 10^{24}$ g

<table>
<thead>
<tr>
<th></th>
<th>$C_{H_2O}$ (wt%)</th>
<th>$F_{H_2O}$ ($10^{14}$ g/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>sediments</td>
<td>7.3</td>
<td>1.4</td>
</tr>
<tr>
<td>oceanic crust</td>
<td>0.8</td>
<td>5.3</td>
</tr>
</tbody>
</table>

Ocean would disappear after ~ 2 Ga of subduction!
Progressive dehydration reactions in subducting slab

Hacker (2008) G3
H$_2$O/Ce Fluid Thermometer (Slab Surface)

Plank, Cooper and Manning (2009) Nature Geoscience
Subduction Zone Thermal Models

Syracuse, van Keken, Abers (2010) PEPI
60% of structurally-bound \( H_2O \) released
Water Fluxes During Subduction

H\textsubscript{2}O Output?

H\textsubscript{2}O % in magma
Magma Mass Flux

60% of structurally-bound H\textsubscript{2}O released

Hacker (2008) G3
For $H_2O$, we need melt inclusions in olivine from well-quenched tephra
Arc Data: 2000

Centam

H$_2$O (least degassed) wt%
Arc Data: 2009

3.9 wt% H₂O  +/- 1.0 (1 stdev)
Izu Arc

Average Arc Growth Rates

\[(\text{km}^3/\text{km}/\text{Ma})\]

28  (Reymer & Schubert, 1984)
66  (Suyehiro et al., 1996)
56-60  (Dimalanta et al., 2002)

*Duration: 47 Ma*

Aleutian Arc

23-33  (Reymer & Schubert, 1984)
75-82  (Holbrook et al., 1999)
59-61  (Dimalanta et al., 2002)
89-182  (Jicha et al., 2006)

*Duration: 46 Ma*
Th output (g/yr) = \( C_{Th} \times \text{Magma Mass Flux} \)
Sedimentary section
(logs and ICPMS analyses)
5% agreement
Plank et al. (2007) G3

Igneous section
(n=26 ICPMS < 0.5 ppm Th)
Kelley et al. (2003) G3

Th Input well known
Th sediment flux g/yr/cm

Th ppm in arc primary magma

Fluxes from Plank and Langmuir (1993)

Primary magma = (Th_{6.0}/1.3 - DMM/15%)
(corrected for xl fractionation and mantle contribution)

Maximum Constraint on Arc Growth Rate

Aleutian Estimates
23-33  (Reymer & Schubert, 1984)
75-82  (Holbrook et al., 1999)
59-61  (Dimalanta et al., 2002)
89-182 (Jicha et al., 2006)
60% of structurally-bound H$_2$O released

Hacker (2008) G3
Outer-Rise Faulting hydrates the plate in the mantle section forming serpentine.

\[ \text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4 \]

13.8 wt\% H\text{2}O
Serpentinization of the Incoming Plate

Deep Faults

sub-Moho velocities decrease toward trench

Ivandic et al. (2008)

Ranero, 2003

Van Avendonk, MARGINS Volatiles TEI

sub-Moho velocities decrease toward Nicaragua
All serpentine-bound $\text{H}_2\text{O}$ bypasses arc?
Lose ocean In 1.7 Ga!

\[ C_{H_2O} (\text{wt}%) \]
\[ F_{H_2O} (10^{14} \text{ g/yr}) \]
\[ \text{past arc} \]

<table>
<thead>
<tr>
<th>Sediments</th>
<th>7.3</th>
<th>1.4</th>
<th>0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oceanic crust</td>
<td>0.8</td>
<td>5.3</td>
<td>2.5</td>
</tr>
<tr>
<td>Mantle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2% H_2O in 4 km mantle</td>
<td>5.7</td>
<td>5.4</td>
<td></td>
</tr>
</tbody>
</table>

A Problem!
I. Is the Ocean Shrinking?

Future Directions:

Ocean Crust Input  Serpentine Input  Arc/Continent Growth
II. Mantle Boundary Layers and Melting

*Boundary Layers Drive Melting...*

*Geodynamics: Turcotte & Schubert*

*Melting Creates Boundary Layers*

*b.holtzman 2009*
Rifting Continental Lithosphere

Gulf of California

Lizarralde et al (2007)

Controls of Mantle Temperature, Composition, Sediment,
Changes in Arc Crust Production Along Strike?

*Thicker crust beneath basaltic volcanoes*

Kodaira et al (2007 JGR, 2008 G3)

...or in Crustal Foundering?

Jull and Kelemen (2001)
Constraining Temperature Effect on Vs

(from Fe8.0 - Na8.0)

Wiens, Kelley & Plank (EPSL, 2006)
Melting of Mantle with Water (and CO$_2$)

Water saturated solidus = 800°C!

Melting with small amounts of water

From Grove et al (2006); (2009)
Melt Inclusion Studies

$H_2O$

$fO_2$
Melt Thermobarometers

\[ D = \frac{\text{MgO}^{\text{ol}}}{\text{MgO}^{\text{liq}}} = f(T) \]

- **olivine-melt thermometer**

**Melt Thermobarometers**

\[ \text{Mg}_2\text{SiO}_4^{\text{ol}} + \text{SiO}_2^{\text{liq}} = \text{Mg}_2\text{Si}_2\text{O}_6^{\text{opx}} \]

\[ a(\text{SiO}_2)^{\text{liq}} = f(P) \]

**silica-melt baromometer**

**Thermobarometer parameterizations from C-T Lee et al, EPSL, 2009**

**Solidus from Hirschmann (2000)**
Wedge Advective Boundary Layer and Melting

Should scale with convergence velocity?
Melting beneath Arcs

Nicaragua

Antilles (19°N)

Contours = temperature (100° intervals)
Velocity = Descent Rate

Models from Syrcuse, van Keken, Abers, 2010
Melting beneath Arcs

Marianas

deep melt equilibration

Kelley et al., submitted
Aleutians

From compilation in Syracuse & Abers (2006)

Nye et al white paper
What Drives Melting Beneath the (Western US) Continent?

After DePaolo & Daley (2000)

Elkins-Tanton (2006) JGR

From C. Conrad

Moucha et al. (2008)
Mantle Melting Regime from Magma Chemical Compositions

Transect at 37°N

S. Nevada

Colorado Plat.

US Array: Transportable Array

Courtesy of Yingjie Yang (Yang, Ritzwoller, Lin, Moschetti, Shapiro, JGR, 2008)
Combining Surface Wave Tomography and Petrologic Melting Depths
Petrologic Constraints on “Red” : P, T, H$_2$O
II. Mantle Boundary Layers and Melting

Future Directions:

Melting under Arcs

Melting under Continents
III. The Volcano: from the Mantle to Eruption
Root Zone of Volcano Extends into the Mantle…to the Slab?

Syracuse, Abers, Fischer, MacKenzie, Rychert, Protti, Gonzalez, Strauch (G3, 2008)
Thicker crust beneath basaltic volcanoes

Kodaira et al. (2007 JGR, 2008 G3)

Root Zone of Volcano Extends into the Mantle…?
Genetic code of mantle melt passed onto crustal magmas
Magma Stalling Related to H$_2$O Content?

Olivine-melt inclusion vapor-sat. depths

InSAR

Inflation Source

Coincidence in:
- geodetic inflation source
- depth of earthquakes
- melt inclusion trapping depths

Lu et al. (2002) JGR
Eruptive Vigor and Water Content, Viscosity, ….

Seguam Volcano, AK 1977 Eruption
VEI = 1

Irazu Volcano, C. Rica 1723 Eruption
VEI = 3

Fuego Volcano, Guat. 1974 Eruption
VEI = 4

3.3 wt% H₂O 1105 °C

3.2 wt% H₂O 1060 °C

4.5 wt% H₂O 1065 °C

Magma Ascent Rate?

Minutes to hours to days…….
III. The Volcano: from the Mantle to Eruption

Future Directions:

Connection to Mantle?

Stalling & Breathing?

Ascent and Eruption
Slab depth beneath volcanoes from compilation in Syracuse & Abers (2006)

From compilation in Syracuse & Abers (2006)