The role of water in mantle melting processes at subduction zones
What is MARGINS?
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- NSF Decadal program, unites Ocean Sciences and Earth Sciences
- 4 scientific initiatives aimed at multi-disciplinary study of Earth’s active continental margins
Four MARGINS Initiatives

1. Seismogenic zone (SEIZE)
2. Subduction Factory (SubFac)
3. Rupturing Continental Lithosphere (RCL)
4. Source to Sink (S2S)
Subduction Factory Initiative
Subduction Factory Initiative

Subduction Factory:

**Raw Materials**
(oceanic plates)

+ **“Process”**
(dehydration, melting)

= **Products**
(arcs, continents, mantle heterogeneity)
Subduction Factory Initiative

Focus Sites:
Central America
Izu-Bonin-Mariana
Subduction Factory Initiative

Focus Sites:

Central America

Izu-Bonin-Mariana
Ok, let’s get subducted by MARGINS science
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What is Subduction?
Isacks, Oliver & Sykes (1968) JGR
"Seismology and the New Global Tectonics"

What’s missing from this picture?
What is Subduction?

Isacks, Oliver & Sykes (1968) JGR
"Seismology and the New Global Tectonics"

What’s missing from this picture?
Volcanoes!
Exchange between Earth’s Surface and Interior

- Seawater circulates, hydrating oceanic crust as it ages
- When subducted, hydrated crust releases water, triggering mantle melting and transporting mass from the slab to the wedge
Water and Mantle Melting

Subducting plate is hydrated, then dehydrated
Water and Mantle Melting

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Water and Mantle Melting

To melt, something’s got to move

oceanexplorer.noaa.gov
To melt, something’s got to move
Ways we know about the wedge

Seismology/Geophysics

Bureau & Keppler, 1999

Experiments

Kelemen et al., 2003

Modeling

Pozgay et al., 2009

Volcanism
How important is water to the subduction “process”?  

- How much water is involved?  
- How does water relate to mantle melting?  
- Where do subduction zone magmas come from?
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Anatahan Volcano, Marianas
Eruption, Spring 2003

Evidence for Water in Arc Magmas

Explosive volcanism
Evidence for Water in Arc Magmas

Hornblende Andesite

Hydrous phenocrysts
Evidence for Water in Arc Magmas

Fluid-mobile element enrichments

Plank & Langmuir (1993)
Dissolved $\text{H}_2\text{O}$ in Natural Glasses

- Glasses and melt inclusions preserve magmatic liquids, with pre- or syn-eruptive volatiles
Dissolved H$_2$O in Natural Glasses

- Glasses and melt inclusions preserve magmatic liquids, with pre- or syn-eruptive volatiles
- Microbeam advances have pushed glass analyses to smaller scales
Dissolved $\text{H}_2\text{O}$ in Natural Glasses

- Glasses and melt inclusions preserve magmatic liquids, with pre- or syn-eruptive volatiles
- Microbeam advances have pushed glass analyses to smaller scales
- Volcanic products (esp. basalt) relate to mantle composition and conditions
Types of Subduction Zone Magmatism

- Arc volcanoes at volcanic front
- Spreading ridge at back-arc basin

From Taylor & Martinez (2002)
How wet are arc basalts?

Global

- Arc volcanoes
- Back-arc basins

$H_2O$, wt.%

Distance to Trench, km

MORB
How wet are arc basalts?

- Dissolved H$_2$O in glasses and melt inclusions
How wet are arc basalts?

- Dissolved H$_2$O in glasses and melt inclusions
- Low in MORB, medium at back arcs, high at arcs
How wet are arc basalts?

- Dissolved $\text{H}_2\text{O}$ in glasses and melt inclusions
- Low in MORB, medium at back arcs, high at arcs
- $\text{H}_2\text{O}$ increases with proximity to subduction
How wet are arc basalts?

Marianas:
3-6 wt.% H2O at arc
0.5-2.0 wt.% H2O at back-arc basin
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Schematic Phase Diagram

- Liquid
- Solid
- Liq + Xtal

Temperature

Olivine ("Mantle")

H₂O

Melt Fraction

Water in Mantle

L

S

Melt Fraction increases with temperature.

Tuesday, April 27, 2010
• Melt fraction increases with temperature
• Water increases melt fraction at a given temp.
Parameterization of wet melting shows how $F$ changes with $\text{H}_2\text{O}$ (builds on models of Katz et al., 2003, Langmuir et al, 2006)

- Pressure affects productivity
- Mantle composition is important

Kelley et al., in revision
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Tuesday, April 27, 2010
Back arc basins combine ridge and arc melting mechanisms.

We can use this hybrid character to constrain conditions at back arcs.
Proxies for Melting

Melt compositions filtered for most primitive, corrected for fractionation to primary melts (Fo90 eq.)

- Ti is incompatible, not part of slab flux
- Ti makes a fair proxy for melt fraction (F)
- Water correlates with Ti, F

Mariana trough
Batch Melting Model

Glass Measurement (Fo90)

\[ F = \left( \frac{C_{Ti}^o}{C_{Ti}^1} \right) - D_{Ti} \]

\[ C_{H_2O}^o = C_{H_2O}^1 \left[ F \left( 1 - D_{H_2O} \right) + D_{H_2O} \right] \]

\( \text{Melt Fraction} \)

\( \text{Concentration of water in the mantle} \)

\( \text{batch} \)

\( \text{pooled batch} \)

\( \text{pooled fractional} \)

\( \text{TiO}_2 \) (wt%)
Proxies for Melting

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Water and Melting at Back Arcs

• $\text{H}_2\text{O}$ correlates with $F$ at global back-arc basins

$\text{K}e\text{l}e\text{y et al., 2006}$
Water and Melting at Back Arcs

- $\text{H}_2\text{O}$ content of back arc mantle: up to 0.5 wt.%
- NAM capacity 0.2-0.3 wt.% (Hirschmann et al., 2005)
Water and Melting at Back Arcs

- Dry magmas are analogous to MORBs, reveal mantle conditions

\[ \text{Melt Fraction (\%)} \]

\[ \text{H}_2\text{O in the mantle (wt. \%)} \]

Tuesday, April 27, 2010
Mantle Temperature at Back Arcs

Kelley et al., 2006

- Dry magmas show a range of mantle potential temps
Seismic Velocities at Back Arcs

• Seismic velocities vary at 40-100 km depth beneath back-arc basins

Wiens et al., 2006
Storage capacity may be greater than 0.2 wt.% at 100 km depth. Thus the inferred average water contents of the back-arc regions can largely be accommodated in the crystal structures of upper mantle minerals without the formation of a free hydrous phase at 100 km, although the full range of water contents in back-arc basalts requires that localized regions may exceed the minimum storage capacity.

At shallower depths the water storage capacity is further reduced and water is involved in the formation of hydrous melts; the possible effect of melt on seismic velocity is discussed in the next section.

Discussion of the seismic effects of water in the upper mantle involves some assumptions, since published relations assume water is stored in pure olivine. However, assuming that the seismic effects of upper mantle peridotite are similar to olivine, increasing the upper mantle water content from normal MORB (0.005 wt.%) to the average water content of the Mariana back-arc (0.166 wt.%) will reduce the shear velocity by about 1.5%. This is clearly much less than the observed maximum variation of 7% at depths of 60–80 km or even the 4.5% variation in the average velocity at 40–100 km depth. Although some of the observed trends in the data may be influenced by water content, such as the high mantle velocities of the dry North Fiji Basin relative to the trend of the other back-arcs (Fig. 6a), our observation that the velocity variations are dominated by temperature and not water content is consistent with available data.

5.2. The relative variation of mantle temperature and seismic velocity

The amplitude of the inferred temperature differences is generally consistent with the observed variations in seismic velocity and ridge elevation. Fig. 6a plots the average seismic velocity between 40 and 100 km depth as a function of $T_p$ as determined from the major element systematics. A linear regression through this data gives a slope of 1.2 ms$^{-1}$°C$^{-1}$, and a larger slope ($\sim 1.8$ ms$^{-1}$°C$^{-1}$) is suggested using only the Lau and Mariana end points. Both of these values are larger than previous experimental ultrasonic determinations of the derivative of velocity with respect to temperature [18,58] and are nearly an order of magnitude larger than the values of 0.20 ms$^{-1}$°C$^{-1}$ suggested by previous seismic velocity and MORB geochemistry correlations [4]. Recent experiments at seismic frequencies including both elastic and inelastic effects, however, suggest that the velocity derivative is in the range of 1.0 to 2.0 ms$^{-1}$°C$^{-1}$ at temperatures of 1350 °C and typical upper mantle grain sizes of 1–10 mm [11,59]. The observed seismic velocity variations are therefore consistent with the petrologically constrained temperature range of 100 °C between these back-arc basins.

While the observed seismic velocity variation between different back arcs may be due entirely to temperature, upper mantle melt content could also affect seismic velocities. Estimates of mantle melt porosity beneath spreading centers range from nearly
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What about Arc Melting?

- Melt inclusions provide pre-eruptive $H_2O, TiO_2$
- Marianas provides an arc/back-arc pair
What about Arc Melting?

• Arc melt inclusions show higher H$_2$O, lower TiO$_2$

• Arc is not a simple extension of the back-arc trend

Kelley et al., in revision
What about Arc Melting?

- Arc melt inclusions indicate higher F, wetter mantle
- Arc is not a simple extension of the back-arc trend

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**Seismic Tomography Images**

*Pozgay et al., 2009*

- Red zones are slow/attenuating
- Arc and back arc “red zones” appear separated
Melt Thermobarometry

- Using model of Lee et al., 2009 to determine P-T of melt equilibration

- Mariana trough shows P-T above dry mantle solidus, shallow
Melt Thermobarometry

• Using model of Lee et al., 2009 to determine P-T of melt equilibration

• Mariana trough shows P-T above dry mantle solidus, shallow
Melt Thermobarometry

- Using model of Lee et al., 2009 to determine P-T of melt equilibration
- Arc shows P-T near dry mantle solidus, deep
Melt Thermobarometry

- Using model of Lee et al., 2009 to determine P-T of melt equilibration

- Arc P-T is below a depleted dry mantle solidus, deep
$1000/Q_p > 12$
• Mariana trough well-explained by model curve for P-T, fertile mantle
• Mariana arc appears to be explained by same model, but...
• Need to incorporate important variations in T, P, X

Kelley et al., in revision
• Arc melts are deeper, hotter than mean back arc
• Instead, use arc P-T with **depleted** mantle model, predictions explain arc data well
Summary

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  Models show melt fraction increases with H$_2$O, but also sensitive to P-T conditions, composition

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• Where do subduction zone magmas come from?
  Back arc magmas show shallow equilibration,
  arc melts are deeper