Imaging Circum-Pacific Subduction Zones with Earthquakes: Fluid Pathways and the Origins of Volcanic Arcs

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• Water and volcanism
• Imaging
• Lessons from Central America
Wet + hot mantle make volcanoes; water controls explosivity

- Where does H₂O originate?
- What pathways?

(Schmidt and Poli, 1998)
Water in Subduction Zones

- 200 Tg/yr (±90%)
- 350 Tg/yr (+/- 2x)
- 500-1500 Tg/yr + serpentinite

Input: km thick wt% H₂O

- Sediment: 0.7, 7-8 (bound)
- Basalts: 2-3, 1.5-2.5
- Gabbro: 4-5, 0-2?
- Serpentinite: 0-50, 0-13

How Hydrated?
Water release is by metamorphic dehydration of crust

Lines: descent path followed by slab surface

1 GPa ~ 30 km

(Hacker et al., 2003)
Wedge melting facilitated by $\text{H}_2\text{O}$

**Melting Temperature (solidus)**

*Hydrous pseudo-phase diagram*

- Blue: 0 bulk wt\%
- Green: 0.05 bulk wt\%
- Red: 0.1 bulk wt\%
- Cyan: 0.3 bulk wt\%
- Purple: water saturated

- Grove 2001 (melt present)
- Kawamoto & Holloway 1997

**Eruption Style:**
*Magma velocity vs. $\%\text{H}_2\text{O}$*

*Model for 1 m wide basaltic dike*

- Effusive
- Explosive

**Wt\% H$_2$O in solid**

(Katz et al., 2003)

**Wt\% H$_2$O in magma**

(Zimmer, in prep.)
Melting: control by \textit{geometry, H}_2\textit{O inputs, thermal structure}

(Stern, 2002; Schmidt & Poli, 1998)
What is subduction geometry?
Traditional: Seismicity

(Syracuse and Abers, 2006)
Subduction geometry and crustal dehydration

Seismic velocities track hydration: $V_p$ versus dry mantle

(after Hacker, 2008; Hacker and Abers, 2004)
Subduction geometry and crustal dehydration: 

*P*-coda scattered wave imaging

(Rondenay, Abers & van Keken, Geology, 2008)

Alaska

Oregon Cascades

Seismic velocities track hydration

receiver functions migrated to dVs/V
Observe: dehydration feeds arcs, but does not produce the volcanic front

Alaska: cool
- dehydrates ~ 130 km depth

Cascadia: hot, young
- dehydrates ~ 50 km depth

receiver functions migrated to dVs/Vs
TUCAN
Tomography (and other things)
Under Costa Rica and Nicaragua

- **Cooperative** US, Nicaragua, Costa Rica Seismic Array (BU/LDEO, Brown, INETER, OVSICORI)
- 48 broadband seismographs, 2004-2006
- main lines sample change in volcano geochemistry
Hypocenters and slab shape: Joint inversion with 3D structure

- Seismic zone is ≤ 10 km wide
- $H$ varies 2x along strike

Joint inversion for hypocenters + $V_p$ + $V_s$

1025 earthquakes: 37,000 arrivals
Nicaragua vs. Costa Rica
Scattered wave images

• Crust: 25-30 km vs. 36-42 km
• Slab depth: 180 km vs 90 km (imaged as base of slow, hot wedge)
• *Melting region is 150 vs 50 km taller*

(MacKenzie et al., 2010 EPSL)
Melting below Central America volcanoes: 
Geochemistry variations along strike

(Carr et al., 2006; 2007; etc.)

• Nicaragua has:
  – deeper/more melting
  – more ‘slab-derived fluid’

than Costa Rica
Shear wave Attenuation ($1/Q_s$): Temperature + hydration?

- $1/Q_s$ High beneath arc and back-arc

Nicaragua has higher $T$ and/or $H_2O$

Rychert et al. (2008)
High $V_p/V_s$ column under arc: melt pathway?

Nicaragua

Costa Rica

Syracuse et al. (Gcubed, 2008)
Quantitative comparison: wedge velocities

\[ V_p = \sqrt{\frac{\kappa + (4/3)\mu}{\rho}} \]
\[ V_s = \sqrt{\frac{\mu}{\rho}} \]

\( \kappa, \mu \) covary

\( \mu \) varies only

Shear modulus (\( \mu \)) reduction: melt signature?

\( T \) effect

\( \delta T_{f=\infty} \) anharmonic
Hot Wedge & Melting Column

Numerical Simulation

Temperature

Melt-porosity

Cagnioncle et al., JGR, 2007
Ongoing work: Nicaragua image vs. petrologic prediction

**Sharp:** Compositional boundary
(Cocos Plate Moho)

**Eclogitization/dehydration**

**Gradient:**
Thermal boundary above slab

Syracuse et al., 2010; van Keken et al., 2010
Fluids sourced from different layers in the slab

Syracuse et al., G3, 2009

Δ Vp/Vs

Spiegelman, van Keken, Hacker, Wilson (in prep)
Fluid flow through the Nicaraguan arc
Summary: the fluid cycle

... and dehydration of subducting crust fluxes hot wedge...

... producing high melt-fraction conduits when dehydrates.
Translating this mapping to the surface

• How can understanding deep volcanic plumbing translate into hazard understanding?
  – Can we assess eruption size absent historic record?
  – Are there eruption precursors in the mantle?

• What is the link between slab devolatilization and explosivity:
  – Quantitative volatile estimates?
  – Link between mantle temperatures and viscosity?
  – Can differentiation (SiO$_2$ content) be predicted?
Seismic proxies for $T$, melt

Shear Attenuation ($1/Q_s$)

- Faul & Jackson (2005), adjusted to 2.5 GPa
- $d=1$ mm, 10 mm

Poisson’s Ratio $\sim \frac{V_p}{V_s}$

- Takei (2002) poroelastic theory
- Free H$_2$O (other theories scale differently)

Faul & Jackson (2005), adjusted to 2.5 GPa
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