Subduction Cycles – the Incoming Plate

[Diagram showing subduction cycle with input flux, serpentine and fluid forearc output, volcanic arc output, back-arc output, fluids, mantle flow, magmas, and returned to mantle.
Subduction Input Water Budget

Bound water budget in $10^8$ Tg/Myr (van Keken et al., 2011)

Input:
- Sediment 0.7
- Oceanic Crust 6.3
- Upper mantle 3.0 ?

Output:
- 0-100 km depth 3.2
- 100-230 km 1.6 – 3.4
- > 230 km 2.2 – 3.4

Water subducted beyond 100 km depth is highly dependent on unknown mantle hydration
How to hydrate the mantle: Mid ocean ridge processes?

“History of the Ocean Basins”
Hess (1962)

Serpentinization limited to tectonic features like “Megamullions” and transform faults
Oceanic upper mantle is dry due to melt extraction at the MOR
Seismic studies show high velocities (~ 8.1 km/s), so little serpenization
How to hydrate the mantle: bend faulting?

- Normal faults penetrate the mantle when the plate bends at trenches.
- Modeling suggests that pressure gradients from the bending stresses will drive fluids downward.
- Ocean water will react with fresh mantle peridotite to produce serpentine minerals.
- Water will be transported away from faults into the surrounding rock by existing porosity and cracks.

Composition Map

Strain Rate Map

Pressure Map

2-D thermomechanical map by Faccenda et al. [2009]
Potential Importance of Incoming Plate Faulting

- Incoming plate normal faulting earthquakes are numerous in all subduction zones.
- They are concentrated in the upper 10 km of the subducting mantle.
- 2 wt % water in the upper 5 km and none below multiplies global input by factor of 2.
- 3 % water in the upper 5 km & 1% water 5-15 km multiplies global input by factor of 4.

Emry & Wiens [2015]
Seismic Detection of Mantle Serpentinite

- Serpentinization drastically reduces seismic velocity and raises $V_p/V_s$
- All three serpentine minerals contain 13 wt % water
- Lizardite/Chrysotile reduces velocity much more than Antigorite
- Water can be calculated from $w(\%) = -0.31 (\Delta V_p \%)$

*Christensen [2004]*
Upper Mantle Serpentinitization: Central America

Sub-Moho seismic velocity in subducting Cocos plate

Maximum depth of extensional earthquakes
Lefeldt et al. [2009]

H2O distributed in mantle

• Low velocities show strong serpeninization of the Nicaragua mantle
• Serpentinitization is bounded by the maximum depth of extensional earthquakes
• Estimate 3-4 wt % water in the upper 5 km of the subducting mantle
• Serpeninization is stronger in Nicaragua, where there is extensive faulting

van Avendonk et al. [2011]
Low velocities can result from anisotropy or mis-identification of the moho.

This study shows that mantle velocities are reduced by up to 600 m/s between outer rise and trench.

The remaining question is whether all the velocity reduction results from serpentinization or is some due to water-filled cracks?

Depth extent not well constrained.

Ivandic et al. [2010]
Electromagnetic imaging of high porosity channels

Key et al. [2012]

- Controlled Source EM images low resistivity regions in crust and upper 5 km of mantle associated with plate bending
- Low resistivity indicates high water porosity along faults extending into the mantle
Another example: Tonga

- Active source seismic transect of Tonga trench
- Shows low uppermost mantle Vp of 7.3 km/s
- Consistent with 30% mantle serpentinization, or 3-4% water
- Low mantle velocities near the trench also found in Alaska, Chile, Kuriles

Contreras-Reyes et al. [2011]
Plate-bending faults and serpentinization of the Mariana incoming plate

- Tensional earthquakes occur down to the upper 15 km of the mantle
- Do tensional earthquake depths control the depth of mantle serpentinization?
- Does depth of faulting cause along-strike changes in subducted water?

Emry et al., [2014]
Depths and mechanisms from waveform inversion
2012-2013 Mariana Trench Experiment
Investigate slab and forearc serpentinization

20 broadband, 60 short period, and 5 tethered hydrophones
Preliminary Results from the Mariana Trench

Earthquake Locations

- Incoming plate earthquakes in upper 25 km
- Concentrated within 30 km of the trench
- Ambient noise correlation should allow deeper resolution and provide $V_s$ for $V_p/V_s$ ratio
- $V_S$ structure shows slow velocities (4.0-4.1 km/s) up to 15 km below subducting moho

From work by Melody Eimer and Hope Jasperson

Cai et al., AGU poster, 2015
Temporal variation in faulting depth?

Incoming plate faulting triggered by 2011 Tohoku M$_w$ 9.0 event

 Depths of Extentional events from OBSs

- Maximum depth of extensional earthquakes prior to the 2011 event was ~ 20 km
- Extensional events are now found to ~ 40 km depth
- The 2011 event increased tensional stresses and deepened the neutral plane
- Which depth limits possible serpentinization?
- Is there more hydration at “coupled” trenches?
- Lefeldt $et$ $al$ [2012] suggested serpentinization is limited by depth of extensional microearthquakes and not larger events

Obana $et$ $al$ [2012]
Along-strike variation in water input?

- Contrasting segments of the Alaska trench
- Semidi segment is locked, Shumagin segment is slipping
- Semidi segment has megathrust earthquakes; Shumagin may have no large events
- Seafloor fabric is nearly parallel to the trench in Shumagin, but highly oblique in Semidi
- Much more incoming plate, thrust zone, and intermediate depth seismicity in Shumagin

*Shillington et al, in press*
Contrast between adjacent segments

- Much larger velocity reduction (and thus Serpentinization) observed in Shumagin, consistent with more faulting
- Water content of the slab is highly variable along strike
- No apparent connection with megathrust activity; faulting and fabric are key?
- May have great effects on deeper arc and slab processes
Conclusions

- The amount of water subducted into the mantle is poorly known due to the lack of constraints on water in the incoming plate mantle.

- The oceanic mantle is likely serpentinized at the plate bending region and trench (not “outer rise”). Different estimates can vary the amount of subducted water by factors of 3.

- Seismic studies show low mantle seismic velocities at several trenches, with corresponding estimates of 20-30% serpentinization and 3-4 wt % bound water.

- Key questions include how much velocity reduction comes from water filled cracks, as well as the depth extent of the serpentinization

- Serpentinization seems highly variable along strike and may be partially controlled by the incoming plate fabric