Imaging the central Cascadia forearc using airgun shots and amphibious arrays: From 2D to 3D
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Overarching question: To what degree does crustal structure control interplate locking and rupture?

Hypothesis: Rupture during large interplate earthquakes contains both a complex, possibly chaotic, component due to the complexities of dynamic friction that must be addressed stochastically and a deterministic part that is controlled by crustal structure.

Implication: Future earthquake probabilities are based on statistical analysis of past (historic and prehistoric) earthquake histories. With a better understanding of the impact of crustal structure on rupture, statistical models for future earthquake occurrence can be corrected for geologic controls, leading to more accurate forecasts.
Outline:

• Schematic view of the geological versus geophysical view of megathrust heterogeneity.

• Working towards a 3D crustal model for Cascadia – why we need controlled source amphibious experiments.

• Comparison to other regions where earthquakes have been well recorded and there is evidence for geologic control on rupture, with a focus on recent and planned work in Chile.
The geophysical view in 2D:

What controls the updip and downdip boundaries of the coseismic (locked) zone?

Aoki and Scholz (2003)
In 2.5D in the coseismic zone:

What controls along-strike continuity of locking along strike?
Are the same patches strongly coupled over multiple earthquake cycles?
Are the up-dip and down-dip low-coupling zones connected?
A geologic view of the megathrust

- Trench
- Outer accretionary wedge
- Seaward edge of cohesive wedge
- Impact of crystalline crust?
- Upper plate erosion
- Rupture zone of large earthquakes
- Broken-off crust
- Sediment
- Seamount
- Rough sea floor
- Subducting crust

(K. Wang, Nature, 2009)

A fully 3D problem.
Improving pre-earthquake locking, time/space distribution of slip, and afterslip models for large earthquakes provide an opportunity to test hypotheses about the link between geology and earthquake slip.

Examples:

See Hicks et al., EPSL, 2014 and Zhao, 2015 for correlations between slip and structure from earthquake tomography.
Example: Seamount subduction

What happens when topography is subducted beneath the outer wedge is well documented. It’s what happens at great depth that is a mystery.

(figure from Dominguez et al., 2000)

Figure 13. Schematic cross section illustrating material transfers inside the accretionary wedge induced by seamount subduction.
To apply new insights from earthquakes globally to Cascadia, we need a good crustal model:

1985, 1989 vintage seismic reflection data from the Canadian and Oregon margins (ODP site survey).


1994 onshore/offshore seismic reflection/refraction data offshore Cape Blanco OR (USGS) and northern California (NSF/USGS Mendocino Triple Junction seismic experiment).


1998/1999 SHIPS (USGS, UW, OSU, PGC, UVic, UTEP)
Case study in building on previous work:

1998/91 – 2D amphibious transect (piggy back on ODP site survey) with 8 OBS and 10 land stations (Trehu et al., 1994; Fleming and Trehu, 1999).
- Imaged Moho of subducting crust from abyssal plain to Coast Range.
- Defined steeply-dipping edge of Siletz
- Fortuitously crossed subducted seamount
- At most a thin “subduction channel beneath Siletzia.

1993/94 – complementary receiver function transect from coast across the arc.
- Extended Moho mapping to the East
- Defined hydrated upper mantle wedge beneath Coast Range.

1996 – 2.5 D - 2D amphibious transect – 18 OBS and 35 onshore stations (29 in line from coast to Cascades; 6 off line) (Gerdom et al., 2000; Trehu et al., 2012)

2012 – 3D – piggyback on Ridge-to-Trench with 33 onshore stations and add-on lines of shots parallel to coast.
Why here?

Low angle thrust earthquakes on the plate boundary and potential field indicators of correlation between seismicity and structure.

Also corresponds to a segment boundary in ETS, locking from GPS modeling, paleoseismic history, and slip patchiness in the 1700 earthquake.

Figures from Wells et al. (JGR, 2003); Tréhu et al. (SRL 2015)
Central OR seismicity and subducted seamounts:

- Earthquakes are on the plate boundary.
- Most of the earthquakes are associated with a seamount that is in contact with Siletz basement.
- A 2nd cluster underlies a thinned “patch” of the Siletz terrane.

Argument for shallow depth:

- Raytracing $P$, $pP$, $P_{m}P$, $S$, $S_{m}S$ in a 2D crustal model
- OBS data
- Relative locations (hypoDD)

(Tréhu et al., SRL, 2015)
OBS52 - hydrophone

OBS52 - vertical

Water depth = 120 m; reduction velocity = 6.5 km/s
Quick look at the 3D model (using Doug Toomey/William Wilcock etomo package)

(Kenyon et al., in prep)
Next: more resolution tests, generation of isovelocity surfaces, inversion of PmP picks, relocation of earthquakes in 3D.

(Kenyon et al., in prep)
What next for Cascadia?

Still more work needed on the 2012 data to be definitive, but the existing data point

Endmember GPS models:

(d) Schmalzle et al. (2014)
Gamma model

(e) Schmalzle et al. (2014)
Gaussian model
Many new tools developed in the quiet time from 1964 to 2004!

Go to places where there have been recent, well-recorded earthquakes to link slip and structure:

A. A geologic view of the megathrust

B. A seismological/geodetic view of the megathrust

(K. Wang, Nature, 2009)

Scholtz and Campos (2012)
1989/91 data: current focus

Merged with receiver functions. Note difference in resolution.

(Bostock et al., 2002)

(1993/94 data)

(Trehu et al., 1994)
Look to Chile for insights into Cascadia

(Contreras-Reyes and Osses, 2010)
Partially filled a seismic gap.

No controlled source seismic data (yet).

Several seismogenic slip models published, as well as pre-, syn- and post-locking and creep.

(Schurr et al., Nature, 2014)
Significant foreshocks, well recorded by IPOC.

(Ruiz et al., 2014; Hayes et al., 2014)
Correct gravity for the effects of bathymetry and slab dip:

(Trehu et al., in prep)
Interesting correlations between Pisagua earthquake sequence, geodetically-derived locking, and corrected gravity anomalies. Suggests control by crustal structure but relating gravity anomalies to geology is non-unique. Motivation for a proposal to acquire 3D tomography of this region.

(Trehu et al., in prep)
Joint OSU, GEOMAR, Un Chile Santiago project proposed to US NSF and Germany. Both proposals recommended for funding, with Langseth scheduled for 2016 and Sonne scheduled for 2018/19.

Phase 1 – focus on 2014 rupture area with minor onshore component. 50 OBSIP OBSs plus 16 from GEOMAR.

Phase 2 – focus on remaining locked segment with more ambitious onshore component designed based on phase 1 data.
Conclusions:

• Exciting time to explore the link between geology and slip in earthquakes.
• Doing so requires the depth resolution provided by controlled source seismology (in addition to monitoring & modeling pre-syn- and post-earthquake deformation).
• Understanding these links for recent large earthquakes globally will lead to better estimates of what to anticipate when combined with deformation monitoring.
• Upper plate and lower plate structure are both important.
• Old data should be preserved and made readily available internationally.
• Potential field data are critical for planning for and extrapolating from seismic data.