Seismo-tectonics of the Juan de Fuca ridge

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Endeavour Segment

- Tectonic features
  - Large OSCs
  - History of ridge jumps and failed rift propagation

- Volcanic features
  - Several seamount chains
  - Seamounts at OSCs

- Hydrothermal features
  - 5 high-T vent fields in elevated central portion.
Outline

1. Crustal and Upper Mantle Structure
   - High-density, multi-scale seismic tomography experiment of an entire ridge segment
   - Thorough analysis methods

2. Mid-ocean ridge dynamics
   - Sub-seafloor deployed OBSs
   - 3 year study focused at hydrothermal vents
I. ETOMO experiment

• Multi-scale seismic tomography
  – 68, four-component OBS from SIO and WHOI OBSIP pool
  – ~5000 sources from 30-element array of R/V Marcus Langseth

• Structure
  – Topmost mantle structure ($Pn$)
  – Lower crustal structure and thickness ($Pg$ & $PmP$)
  – Shallow to mid-crust structure ($Pg$)
  – Off-axis crustal magma bodies ($Pg$)
Topmost Mantle Structure from *Pn*
Brandon van der Beek (UO)

- Mantle low-velocity anomaly is not centered under the ridge axis.
- Low velocities attributed to melt at near-Moho depths.
- Melt transfer between the mantle and crust is not well focused.
- The Endeavour hydrothermal system does not overlie the mantle anomaly.
Pn Seismic Anisotropy

- Preliminary estimates of Pn anisotropy indicate a small CCW rotation.
- The $\cos(2\theta)$ signal is more complicated than the EPR results and may vary between Pacific and JdF.
- Significant crustal signals need to be better modeled.
Crustal thickness and lower crustal structure
Dax Soule (UW)

• What about the axial magmatic system in the deeper crust?

• Where does melt focusing occur?
  – Not in the mantle
  – Do hydrothermal processes control melt focusing?
Preliminary crustal thickness map
Lower crustal axial magma storage

• Mid-to-lower crustal magma system is aligned with the ridge axis

• Low velocity zone beneath Endeavour seamount which underlies the West-Valley / Endeavour OSC
Upper Crustal Structure
Robert Weekly (UW)
Eunyoung Kim (Seoul National University)

- Off-axis crustal magmatism is common.
- Are there off-axis volcanic eruptions?
- Crustal anisotropy is variable and reflects tectonic fabric.
• Segment ends are anomalously slow, a result of tectonic segmentation.

• Near segment center, anomalies parallel the seafloor topography, providing constraints on the volcanic construction of the upper crust.
Off-axis lava flows heading down the outer flanks of the abyssal hill ridges

3-4 km off-axis at the Cleft segment, Stakes et al, 2006
Crustal seismic anisotropy

Anisotropy checkerboard resolution test

![Graphs and map showing mean travel time residual vs. azimuth for different depth ranges: 0 - 1 km, 1 - 2 km, 2 - 3 km. Equations for the residual functions are also shown: 12.6 cos (2θ + 1) for 0 - 1 km, 12 cos (2θ + 2) for 1 - 2 km, and 4.5 cos (2θ + 4) for 2 - 3 km.](image)

Anisotropy checkerboard resolution test
Crustal seismic anisotropy

Y, km

X, km

% Anisotropy

Orientation
Off-axis velocity/attenuation anomalies
Anne Wells (UO)

• Surprising discovery of numerous off-axis magma bodies.

• Why?
  – Mantle melt delivery is not rise centered.
  – And the segment has a tectonic fabric/history that may be providing ready routes for crustal intrusions.
Off-axis Crustal Magmatism

- Many off-axis anomalies with low seismic velocity and high attenuation.
- Coincident with mid-crustal reflectors observed in MCS data.
- Wide-angle seismic data also indicate that off-axis melt sills are present.

🌟 mid-crustal reflector
_S. Carbotte, pers. comm._
Off-axis crustal magma bodies

Attenuation of Pg phases:

OBS 63

Seismic Data

Starting waveform model

Waveforms including Attenuation

OBS 58

Range (km)

Shot Number

20050 20060 20070 20080 20090 20100 20110

20050 20060 20070 20080 20090 20100 20110

Time - Range/7.2 (s)

Range, OBS$63$, OBS$58$
Rough estimates of anomalous volumes

- The anomalous seismic properties ($\Delta V_p \approx -4\%; Q_p \approx 8-40$) are consistent with zones of elevated temperature and possibly partial melt.

- The bodies are located from 2 to 4 km depth and extend 10-15 km beneath axis-parallel ridges.
Off-axis crustal magma bodies

- One attenuation anomaly overlies a zone of off-axis mantle low velocities.
- Others are distributed on both ridge flanks.
- Require lithospheric weaknesses that allow melt penetration from below.
Seismic Structure Conclusions

- Melt accumulations in the shallow mantle are not rise centered.
- Melt delivery to the base of the crust likely gives rise to off-axis magmatic activity.
- The northern and southern OSCs are associated with low velocities from the mantle to the upper crust — magmatism and cracking.
- Shallow crustal anisotropy is 3D and variable in intensity
- Shallow crustal structure provides constraints on seafloor volcanism
2. Earthquakes

- Seismic imaging provides a snapshot of structure, specifically where heat and cracks are.
- Earthquakes represent the dynamics of the ridge segment: where and when lithosphere breaks.
Keck OBS


- Monitor temporal changes to seismicity within the hydrothermal system.

- Prototype for cabled observatory
1. Two large swarms in early-2005: late January & late February

2. Marked decrease in the number of earthquakes following the 2005 swarms
January Swarm

February Swarm
Borehole Pressure Changes

January = Intrusion on West Valley

February = Intrusion on N Endeavour

Pressure records from Earl Davis
Previous Swarms

- Navy SOSUS array records acoustic waves from large earthquakes.
- Entire segment ruptured between 1999 and 2005 producing swarms.
- 2005 swarms marked termination of 6-year spreading “event” that consisted of several diking episodes.
- Seismicity rate, both at the segment center and in the region, drops to <20% of the earlier values.

*Bohnenstiehl et al., 2001; Hooft et al., 2010; Weekly et al., 2013*
Hydrothermal system

• Earthquakes overlying the magma sill have both normal and reverse focal mechanisms.

• This reflects areas that alternate between extension and compression.
Inflation of a magma sill

Does the magma sill continue inflating after the end of the 6-year spreading episode?
Hydrothermal Reaction Zone

- Vents with highest heat fluxes
  - Greater EQ activity
  - Lower seismic velocities (cracks and/or hot rock)
  - Increased seismic anisotropy

- Implications
  - Inflation of magma chamber plays an important role in heat transfer
  - Reaction zone is ~1 km in vertical extent

Heat Flow (MJ/s per vent field)


Number of earthquakes

Depth, km

Depth, km

Depth, km

Number of earthquakes
Conclusions

- **Mantle melt delivery**: does not underlie the ridge axis
- **Crustal magma storage**: Lower crustal magma system is beneath the ridge axis, but numerous off-axis magma bodies.
- **Upper crustal construction**: Off-axis eruptions at abyssal ridges with lavas flowing down the outer flanks.
- **Overlapping Spreading Centers**: are associated with magmatism and cracking.
- **Magmatic-hydrothermal system**: Magma inflation stresses the overlying crust and causes earthquakes and cracking. This allows water to access hot rock and results in high heat fluxes at the vent fields.