Measuring earthquake source parameters in the Mendocino Triple Junction region using a dense OBS array: Implications for fault strength variations

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The study area – Mendocino triple junction
Strong fault in oceanic environment

Strong fault

- Laboratory strength profiles of olivine is well understood, and suggest oceanic lithosphere has a strength of ~500 Mpa at 20 km depth for a 30 Ma old lithosphere
- Highest apparent stresses occur on oceanic faults from a global compilation

Motivation – data analysis – results and interpretation – complexity problem

Choy and McGarr, 2002
Weak fault

- There exists wide variability of apparent stress for oceanic earthquakes – both lowest and highest occur in oceanic earthquakes.
- The subducting plate interface is maintained at low strength level as evidenced by the tremor activities.

Perez-Campos, McGuire, and Beroza, 2003
Goal: better understand earthquake processes in the complex geological setting.

Motivation – data analysis – results and interpretation – complexity problem
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Detection and location

• Build a regional catalog of 1153 earthquakes (compared to 134 existing cataloged events)
• Relocate using a 3D velocity model and waveform cross-correlation
ST-zone: Around the plate interface; M-Fault: Intraplate fault within oceanic mantle

T-Fault: Mendocino Transform Fault

[Map and graphs showing areas and fault zones]
Theoretical representation for displacement spectra

\[ D(f) = S(f) \ast P(f) \ast E(f) = I(f)e^{-\pi\kappa f} \ast \frac{1}{R^\gamma} e^{-\pi t^* f} \ast \frac{M_0 \phi}{4\pi \rho c^3} \frac{1}{1 + \left(\frac{f}{f_c}\right)^2} \]

**Motivation** – **data analysis** – results and interpretation – complexity problem

**Site response**

**Attenuation**

**Source spectrum**

**Instrument response**

**Geometric spreading**

**Moment and radiation pattern**

All the blue items contribute to the frequency-dependence of the spectral shape
Earthquake source parameters – corner frequency and stress drop

Brune source model (Brune 1969)

\[ u(f) = \frac{\Omega_0}{1 + (f / f_c)^2} \]

Boatwright source model (Boatwright, 1970)

\[ u(f) = \frac{\Omega_0}{[1 + (f / f_c)^4]^{0.5}} \]

Stress drop

\[ \Delta \sigma = \frac{7 f_c^3 M_0}{16 (k \beta)^3} \]

Note: lots of assumptions:
Rupture velocity ~ 0.9 * shear velocity \( \beta \)
k-value affects the magnitude of stress drop.
k = 0.26 for S-wave in this study (Kaneko and Shearer, 2014)
Method 1: Iterative stacking method

- In log domain, the observed displacement spectra at each station (j) for each event (i):

$$D_{i,j} = e_i + s_j + t_{k(i,j)} + r_{i,j}$$

Shearer et al., 2006
Motivation – data analysis – results and interpretation – complexity problem

Example from iterative stacking

Recorded displacement spectra in log10 domain:

\[ D(i,j) = \beta(j) + \gamma(i,j) + \epsilon(i) \]

Data vs summation

Station term7DFS04BHH

Propagation term 9s

Event spectrum 302
Examples of spectral fitting

Low stress drop

fc = 4.9
Δσ=0.04
M=1.4

High stress drop

fc = 10.4
Δσ=6.53
M=2.2

Motivation – data analysis – results and interpretation – complexity problem
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Map and cross-section views of stress drop distributions
Motivation – data analysis – **results and interpretation** – complexity problem

- **Red**: Transform fault (T-Fault)
- **Blue**: Intraplate Mantle fault (M-Fault)
- **Green**: Plate interface (ST-Zone)

- At shallower depth (< 25 km), both stress drop and apparent stresses are low
- At deeper depth (> 25km), both have higher variability, and maximum value increases
Brief summary 1

• (1) We observe the ST-zone have lower stress drop (and apparent stress) compared to the other two faults.

• (2) We observe along-depth variations within individual faults, with lower stress drop at shallower depths, while higher stress drop at deeper depths.

• However, both parameters are model dependent?

\[ \Delta \sigma = \frac{7f_c^3M_0}{16(k\beta)^3} \]
Remove model dependence?

• Both stress drop and apparent stress are model dependent (i.e., the Boatwright source model).

• What if we directly compare the shape of the spectra, instead of source parameters?
• Do we see regional variations among different faults?
• Do we see along-depth variations within individual fault system?
• Typically, smaller earthquakes have higher corner frequency.
• Shift spectra along the dash line to a reference M3.5 earthquake.
• Generate the shifted-stacked spectra for different faults.
The ST-Zone has much low “high-frequency” amplitude compared with T-Fault and M-Fault.
Average spectral shape for each depth range within individual faults

- Shallower regions have lower “high-frequency” amplitude compared to deeper depth
Motivation – data analysis – **results and interpretation** – complexity problem

- Corner frequency from the “shifted-stacked” spectra exhibit consistent regional and along depth variations compared with stress drop variations.
Comparison with three M>6.5 earthquakes in 1992

Motivation – data analysis – results and interpretation – complexity problem
• The 1992 M7 mainshock has lower stress drop, consistent with the surrounding earthquakes.
• The 1992 M6.5, M6.7 aftershocks have higher stress drop, consistent with surrounding earthquakes.
Both model-dependent stress drop and model-independent spectral shape confirms the between-fault lateral variations, and within-fault along-depth variations.

Suggesting the spatial variations are robust features and different fault systems operate at different strength level.

Comparison with 1992 earthquake sequence suggests that the spatial variation is stable with time, and should be incorporated into earthquake hazard models.
However....

- For individual earthquakes, there exists strong variability.
- Is the observed variability real? Or simply due to uncertainties in data processing?

Can we independently verify the between-event variability?
The waveform for a nearly co-located smaller event can be regarded as the empirical Green’s function for the mainshock (i.e., including path and site effects).

Key: obtain event source spectra and source time function.

Kane et al., 2013
Method 2: individual pair analysis – time domain deconvolution

- **Goal**: obtain source-time function, source duration, and rupture length and velocity.
- **Theoretically**, larger events have longer duration and lower corner frequency. But, “reality” is sometimes different.
M4.4 Earthquake has shorter duration ~ 0.12 s

M4.0 Earthquake has longer duration ~ 0.2 s
Time domain versus frequency-domain

(A) Event 5, Mw 4.4

(B) Event 21, Mw 4.0

(C) duration = 0.12s

(D) duration = 0.2s
Brief summary 3

• For the two largest earthquake, relatively variability in time-domain is consistent with frequency domain.
• The larger M4.4 earthquake has shorter duration, higher corner frequency, and higher stress drop.
• The smaller M4.0 earthquake has longer duration, lower corner frequency, and lower stress drop.

<table>
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<tr>
<th>$M_w$</th>
<th>$M_0$ (Nm)</th>
<th>SH06</th>
<th>$L_c$ (m)</th>
<th>$\tau_c$ (s)</th>
</tr>
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<tbody>
<tr>
<td>4.0</td>
<td>4.12e+14</td>
<td>6.8</td>
<td>730</td>
<td>0.2</td>
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<tr>
<td>4.4</td>
<td>2.24e+15</td>
<td>8.9</td>
<td>550</td>
<td>0.12</td>
</tr>
</tbody>
</table>
Motivation – data analysis – results and interpretation – **complexity problem**

**However…**

- Both events have considerable complexity in source time function.
- The Omega-square model is for simple circular model, will this fit complex earthquakes?
Some Events deviate from Omega-square model
Selected M>=4 events in Yr2 and Yr4 datasets

- The Year-2 deployment in 2012 only covered six-month (due to battery failure). And didn’t record M>5 earthquakes.
- The Year-4 deployment in 2014 recorded for one-year, and captured a M5 aftershock-sequence, and will provide higher spatial temporal resolution.
M4.4 event from Yr2 dataset

This part is in progress with contributions from IRIS intern Alex Allen and graduate student Colin Pennington.
Motivation – data analysis – results and interpretation – complexity problem

M>4 events from Yr4 dataset

Yr4 array in 2014 and 2015

7D - offshore CI

Strong motion

5E - onshore CI

PBO

NC/BK

M5.7 EQ in 2015

Yr2 array in 2012

and 2015

-125 -124.8 -124.6 -124.4 -124.2 -124

40.2

40.22

40.24

40.26

40.28

40.3

40.32

40.34

40.36

40.38

40.4

M5.7 mainshock,
M4.25 foreshock
M4.3 aftershock

Four selected EGF events

07/2014 10/2014 01/2015 04/2015 07/2015 10/2015
Foreshock-mainshock-aftershock in Jan, 2015: are there similarities in spectral complexity? What is causing these complexities?
Conclusions:

• Cascadia Initiative provides excellent opportunity to understand the previously understudied region due to the difficulty to access.
• The focused array recorded high-quality small-to-moderate earthquakes.
• There exists systematic lateral and along-depth variations of source parameters and frequency-contents of spectra, which could be indicators of strength variations within complex fault system.
• Independent time-domain deconvolution is consistent with relative variability from spectral analysis.