UCSB Broadband Method for Computing Strong Ground Motion

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Motivation

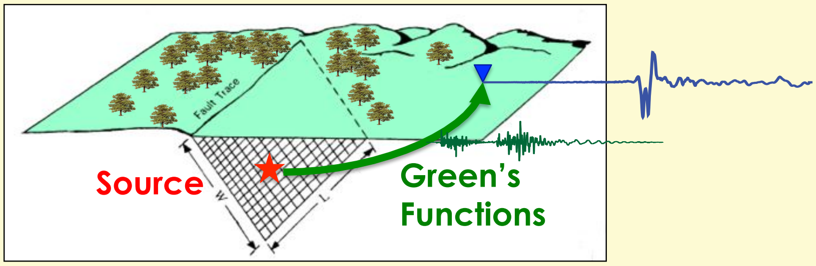
We use the representation theorem to compute broadband **ground motion** for a **unique source**

$$u_n(\boldsymbol{x},t)=\int_{-\infty}^{\infty}d\tau\iint_{\Sigma} s_i(\boldsymbol{\xi},\tau)\,c_{ijpq}\,\nu_j\,G_{np,q}(\boldsymbol{x},t-\tau;\boldsymbol{\xi},0)\,d\Sigma$$

Ground motion

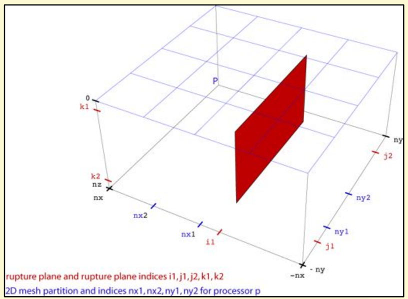
Source

Green's Functions



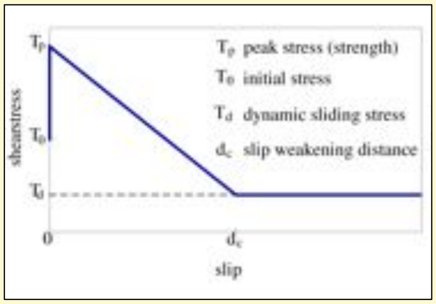
Source

Database



(using FEM code of Ma (2006))

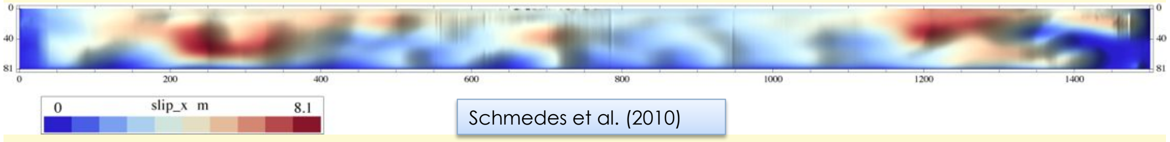
>300 strike slip ruptures of various sizes in simple 1D velocity structures with slip weakening friction law



Rupture dimensions:

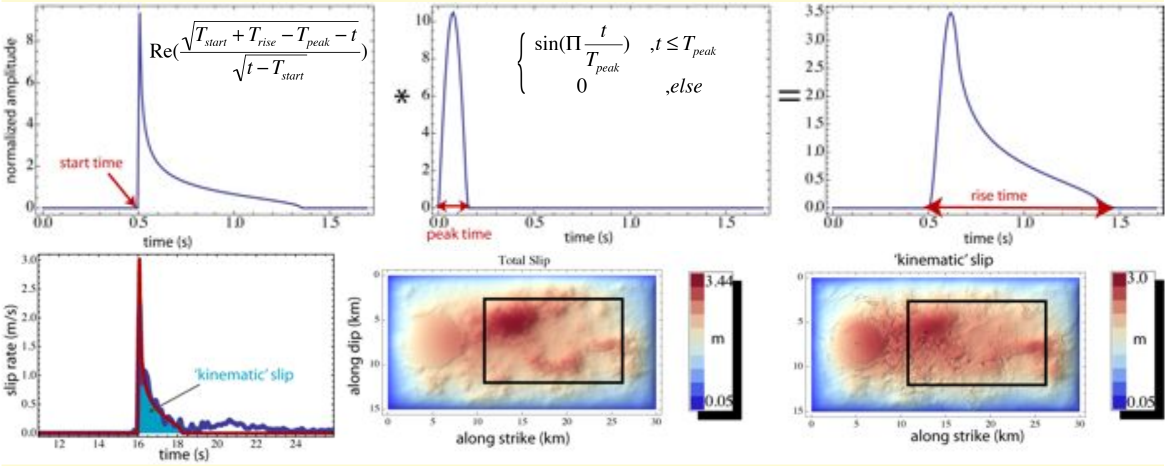
30km x 15km, 30km x 20km
60km x 12km, 60 km x 15 km , 60km x 20km
120 km x 15 km

6 300km long strike slip ruptures in 3D velocity model of southern CA (DynaShake)



Schmedes et al. (2010)

Sliprate Function



$$\mathrm{Re}\left(\frac{\sqrt{T_{start}+T_{rise}-T_{peak}-t}}{\sqrt{t-T_{start}}}\right) * \begin{cases} \sin\left(\Pi\frac{t}{T_{peak}}\right) & ,t \le T_{peak} \\ 0 & ,else \end{cases} =$$

- Fit new slip rate function to 5 Hz filtered computed slip rate functions (about 60 Million)
- Rectangle shows area that was used to compute the correlations. It excludes the boundaries and nucleation zone

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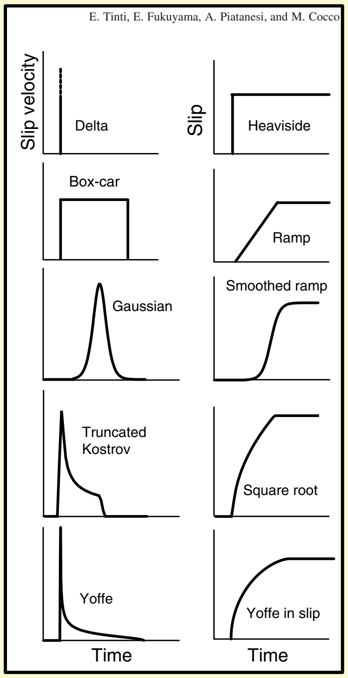
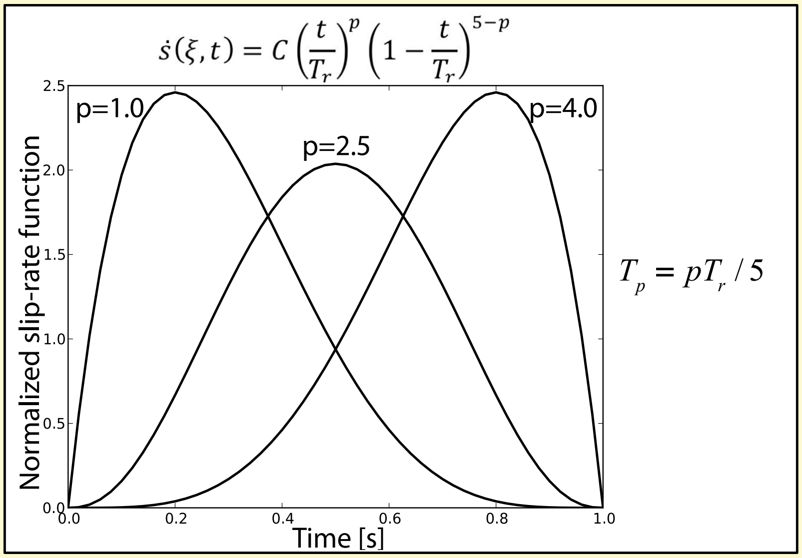
Sliprate Function



Tinti et al., BSSA, 2005

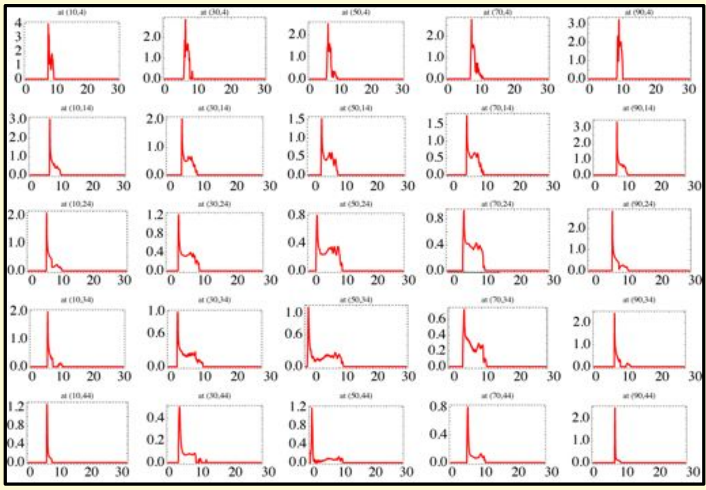


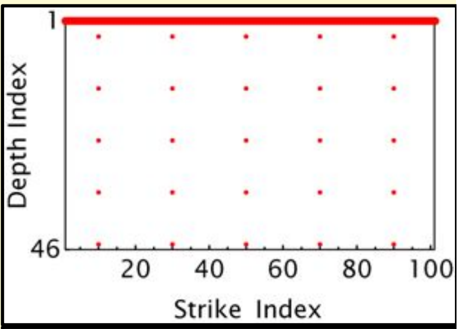
$$\dot{s}(\xi,t) = C\left(\frac{t}{T_r}\right)^p\left(1-\frac{t}{T_r}\right)^{5-p}$$

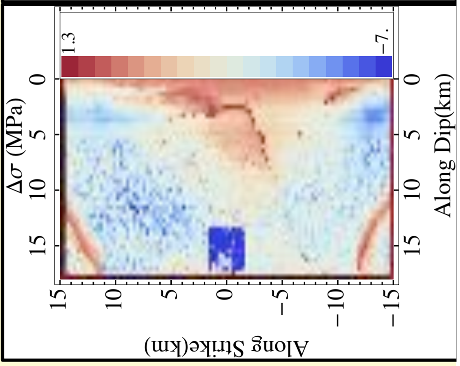
$$T_p = pT_r/5$$

Liu and Archuleta (2004)

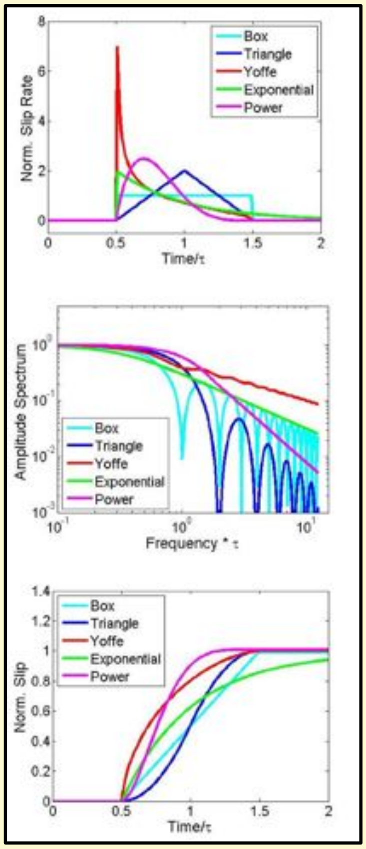
Sliprate Functions from Dynamic Rupture



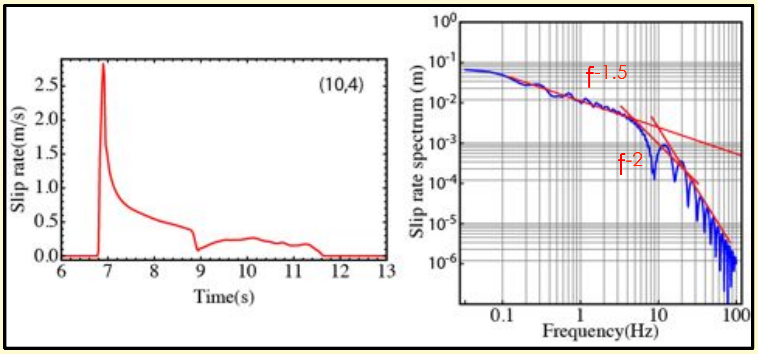




Liu, Q. and Archuleta, 2013



Sliprate Spectra



Results from dynamic rupture, normal fault, Q. Liu, 2013

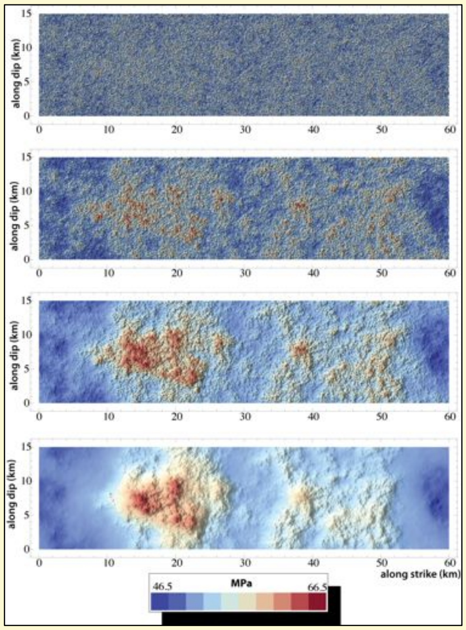
Influence of Autocorrelation of Initial Stress

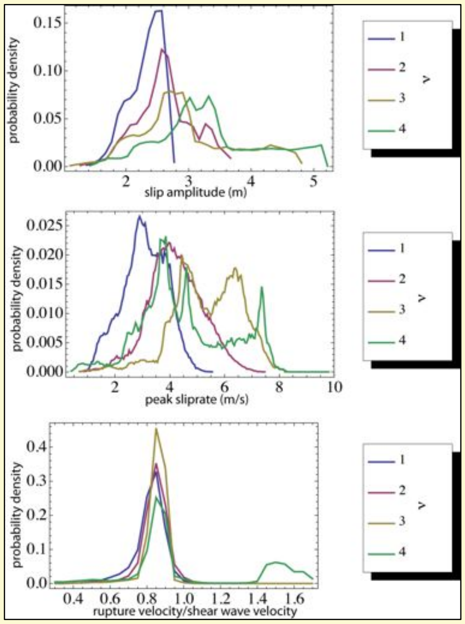
v=1

v=2

v=3

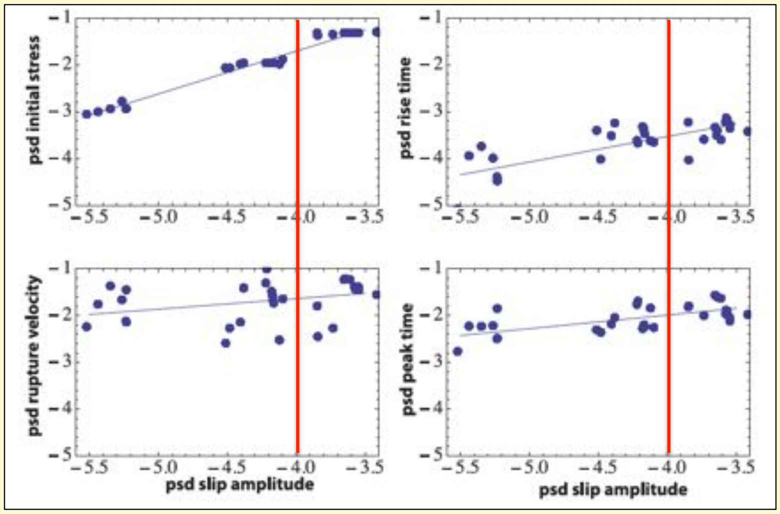
v=4





Strong dependency of rupture dynamics on autocorrelation of stress. Smooth ruptures have larger likelihood to transition to supershear speed (Schmedes et al., 2010)

Power Spectrum Relationships for Different Parameters



We use a von Karman PSD such that after k_c the behaves like a power law:

$$P(k)=k^{-v(s)}$$

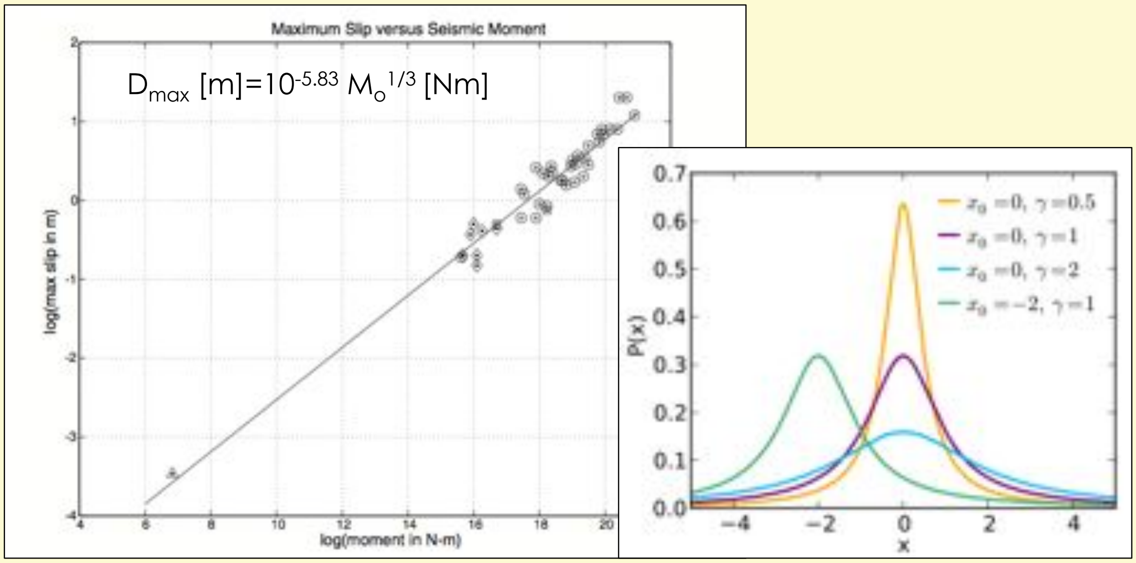
$$v(s)/2=v_{FS}(s)$$

$$v_{FS}(V_r)=0.23v_{FS}(s)+0.370$$

$$v_{FS}(T_r)=0.54v_{FS}(s)+0.675$$

$$v_{FS}(T_p)=0.29v_{FS}(s)+0.415$$

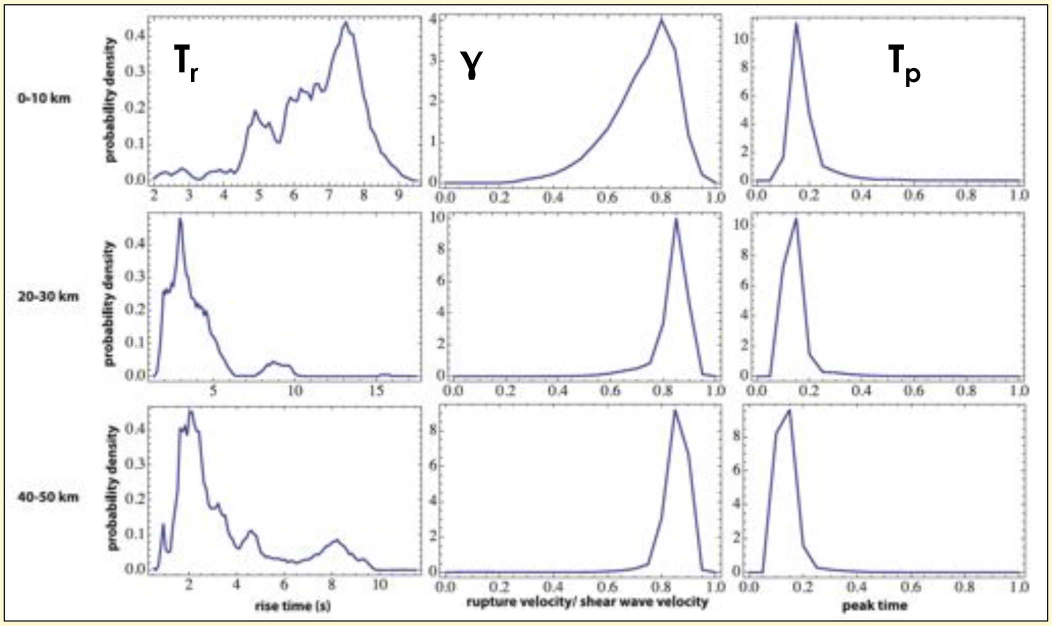
Marginal Distributions of Source Parameters



D_{max} [m]=$10^{-5.83}$ $M_o^{1/3}$ [Nm]

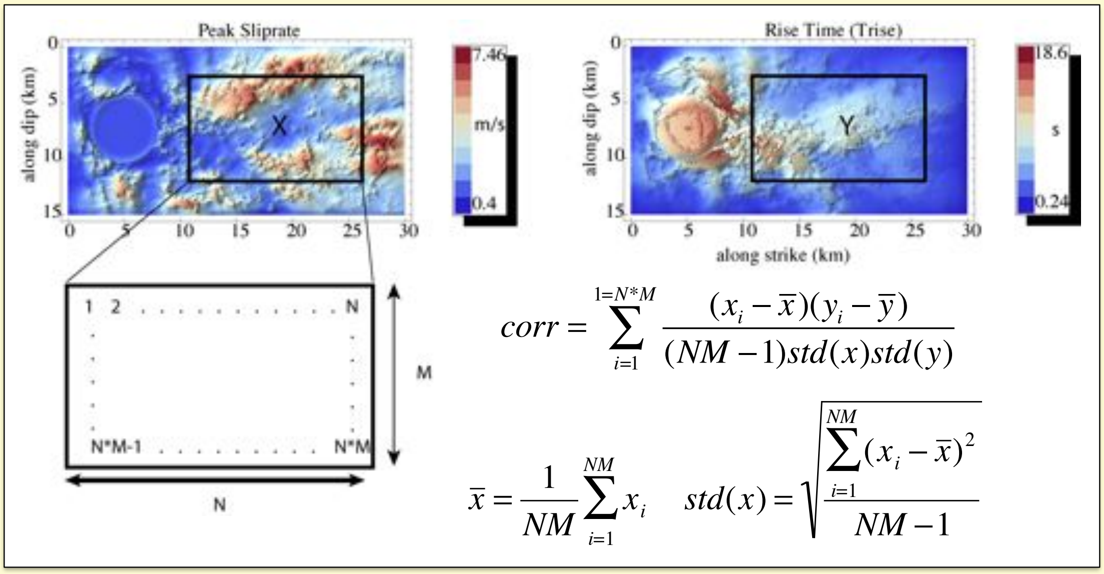
For slip, we use a truncated Cauchy, with limit values of 0 and maximum slip proposed by McGarr and Fletcher (2003)

Marginal Distributions of Source Parameters



For slip, we use a truncated Cauchy, with limit values of 0 and maximum slip proposed by McGarr and Fletcher (2003)

Correlations Between Source Parameters

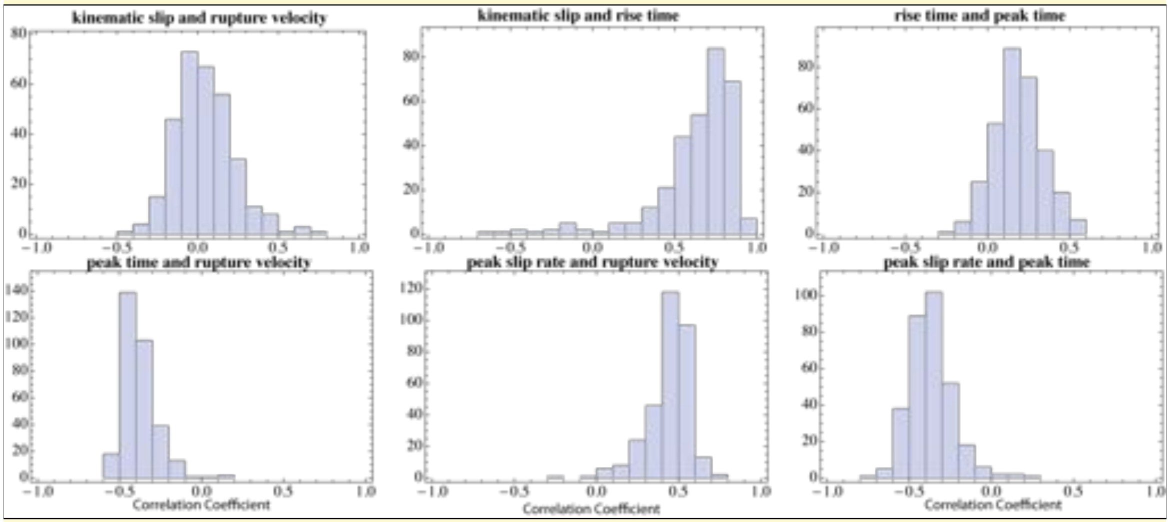


$$corr = \sum_{i=1}^{1=N*M} \frac{(x_i - \bar{x})(y_i - \bar{y})}{(NM-1)std(x)std(y)}$$

$$\bar{x} = \frac{1}{NM}\sum_{i=1}^{NM} x_i \qquad std(x) = \sqrt{\frac{\sum_{i=1}^{NM}(x_i - \bar{x})^2}{NM-1}}$$

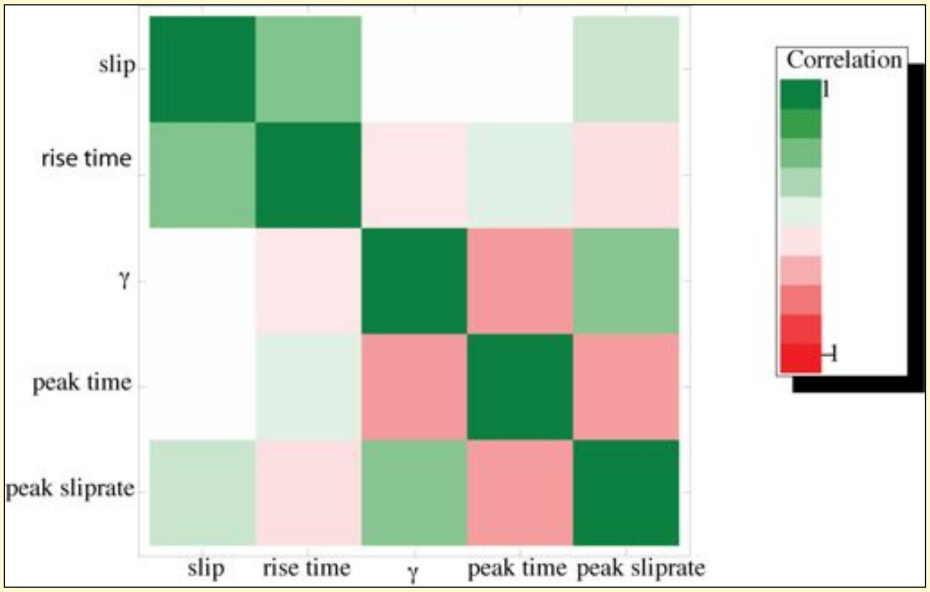
For each dynamic rupture and each possible pair of source parameter we calculated correlation.

Correlations



The correlations where calculated for 315 dynamic rupture scenarios.

Correlation Matrix



This shows the **mean** correlation for the 315 dynamic rupture scenarios

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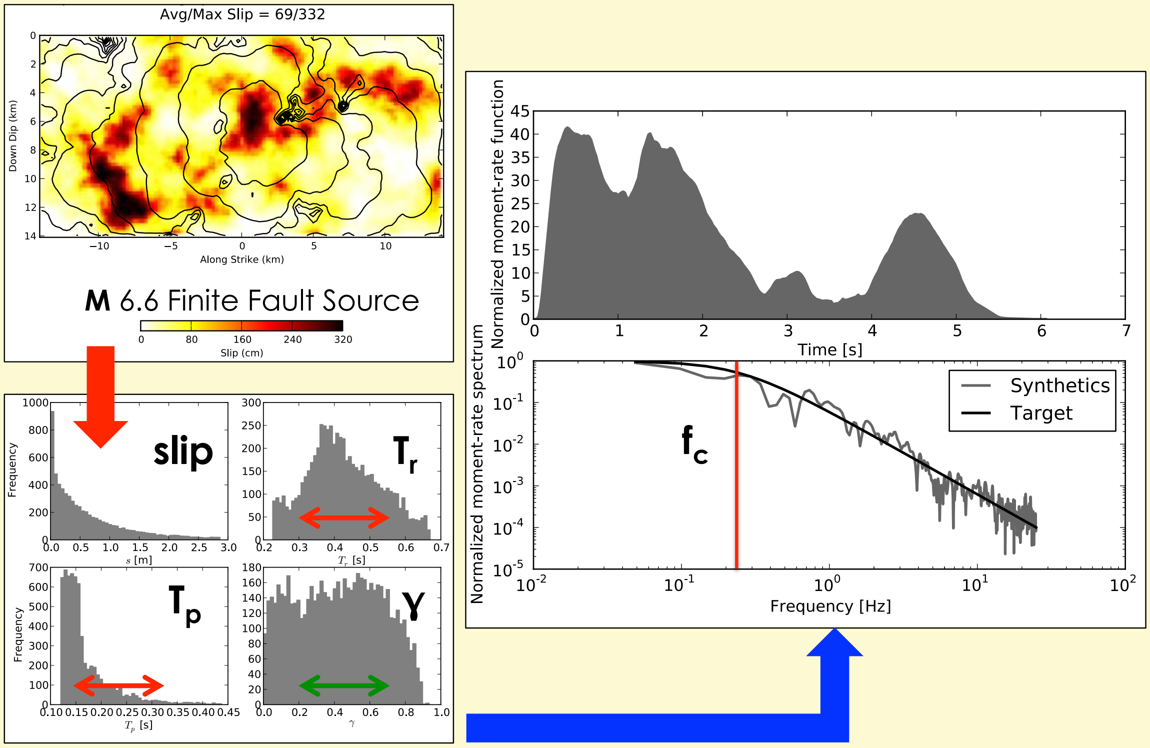
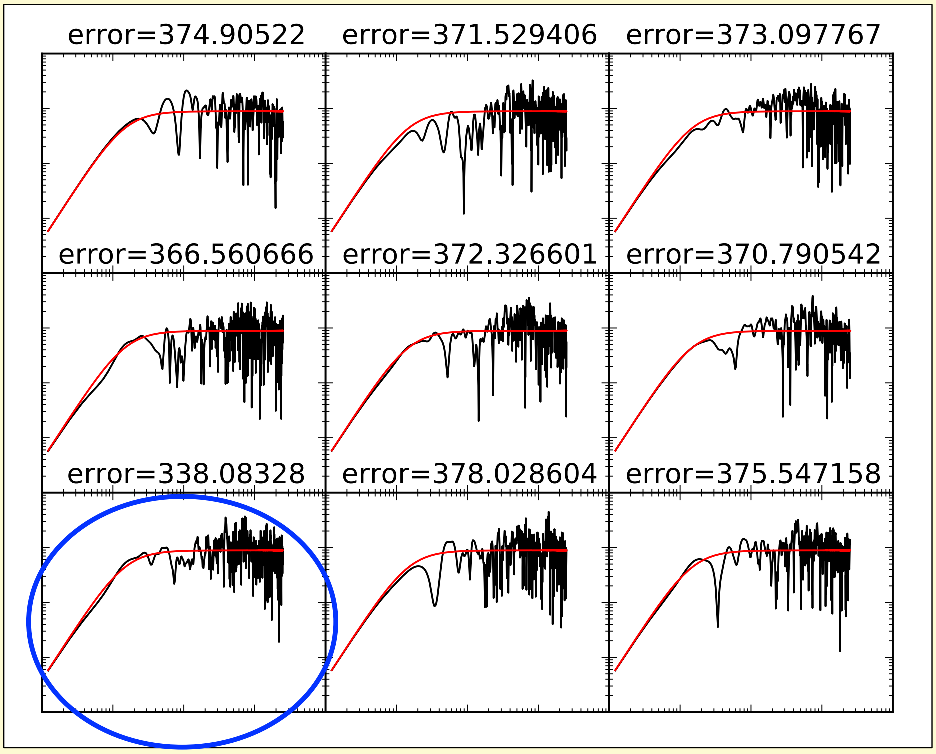
UCSB Kinematic Source Component

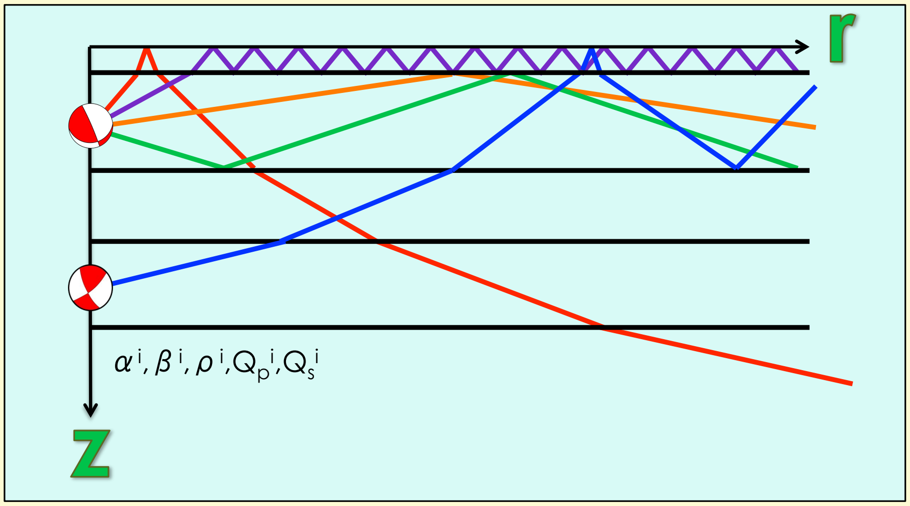


UCSB Kinematic Source Component

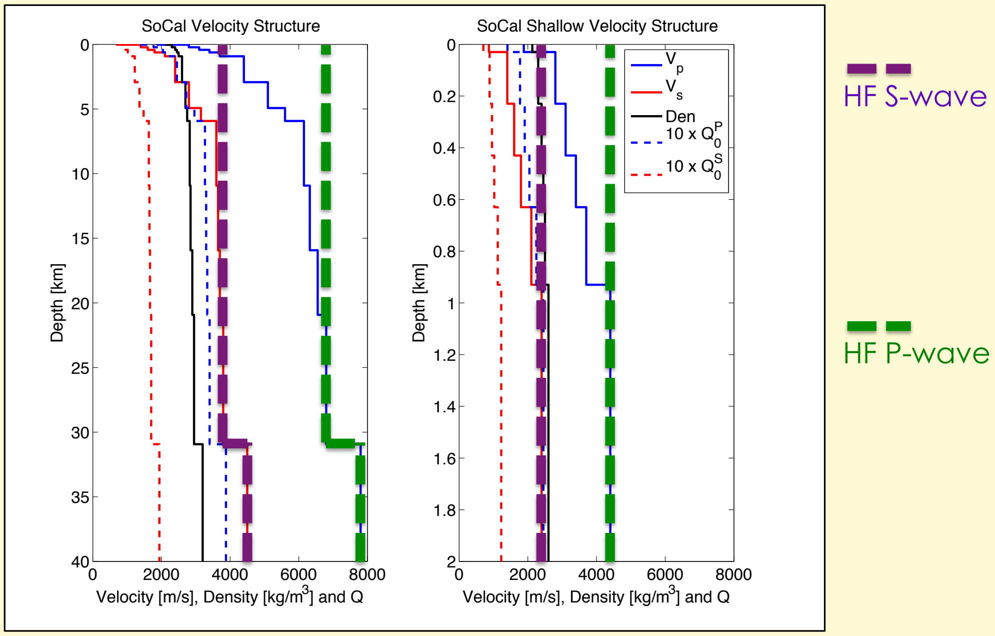


Green's Functions

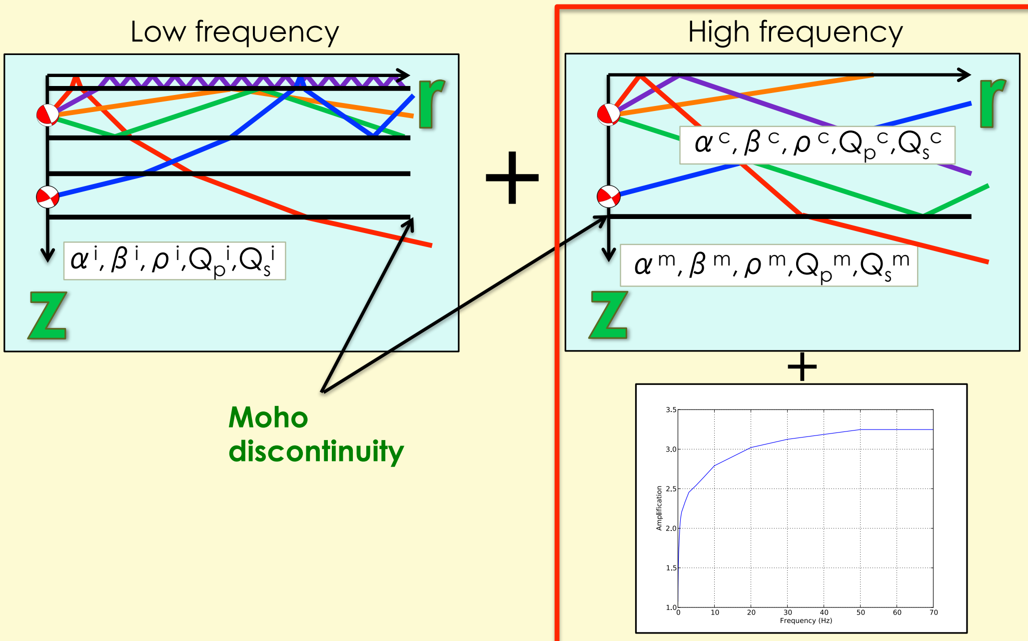
1D Velocity Structures



UCSB Hybrid Method



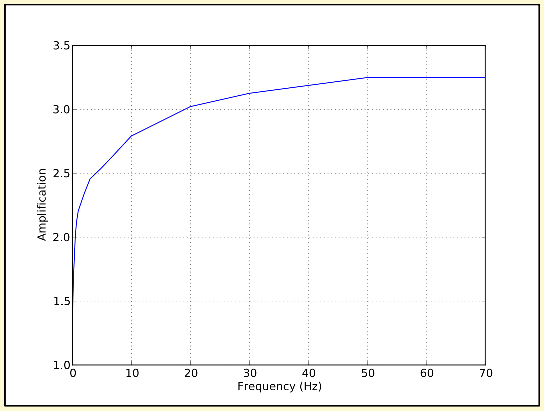
UCSB Hybrid Method



Amplify high-frequency portion of ground motion with quarter wavelength amplification method (Boore & Joyner, 1997)

Quarter wavelength amplification

We apply the quarter wavelength amplification method to the high-frequency portion of ground motion, using the S-wave low-frequency velocity structure



Average shear-wave above depth z is inversely proportional to two-way travel-time

$$\bar{\beta}(z) = \frac{z}{S_{tt}(z)}$$

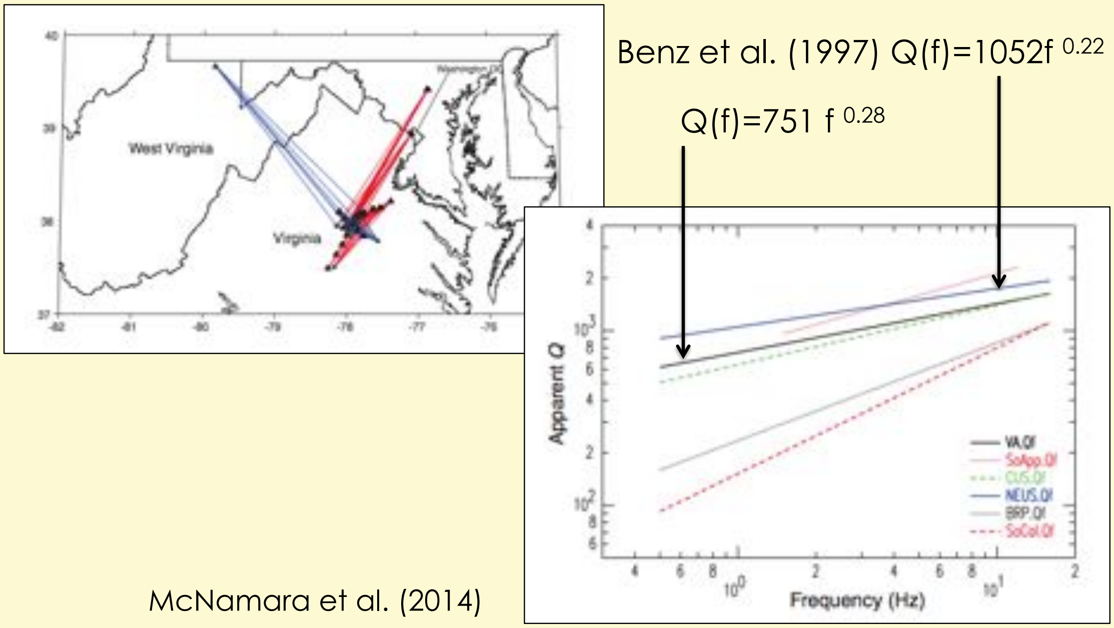
Frequency is inversely proportional to the two-way travel-time

$$f(z) = [4S_{tt}(z)]^{-1}$$

$$A\big(f(z)\big) = \sqrt{\frac{\rho_s \beta_s}{\bar{\rho}(z)\bar{\beta}(z)}}$$

Frequency dependent amplification

Q in Eastern North America (ENA)

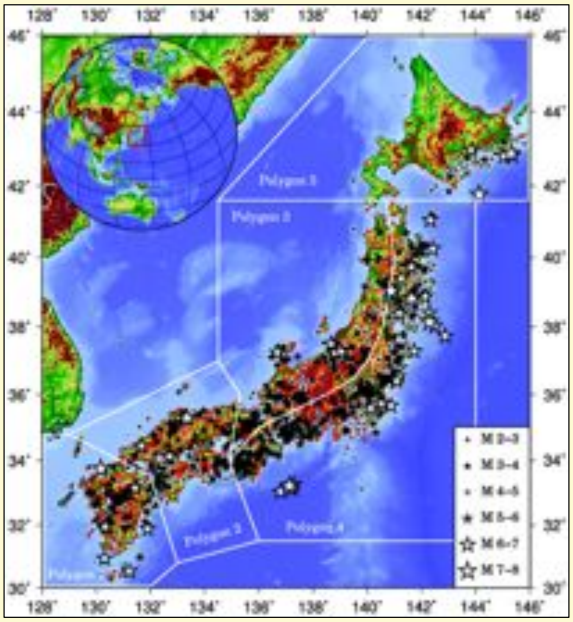


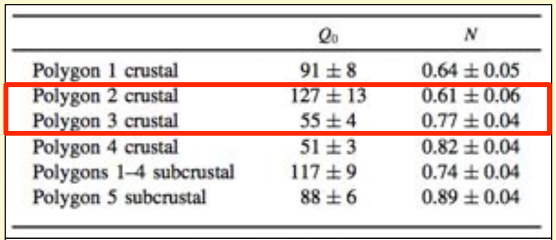
Benz et al. (1997) $Q(f)=1052f^{0.22}$

$Q(f)=751\ f^{0.28}$

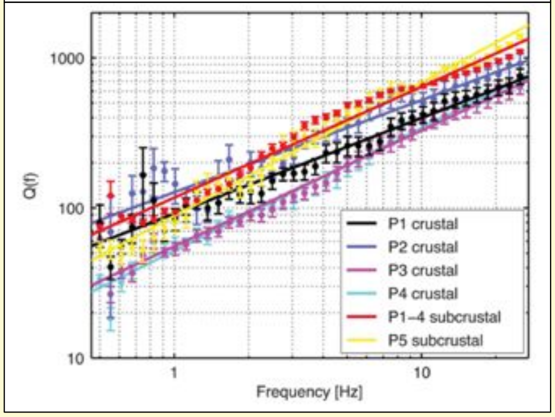
McNamara et al. (2014)

Q in Japan





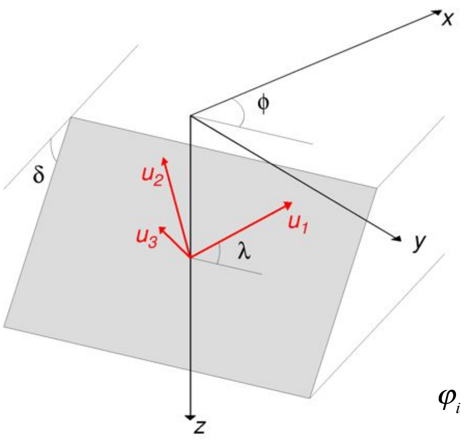
	Q_0	N
Polygon 1 crustal	91 ± 8	0.64 ± 0.05
Polygon 2 crustal	127 ± 13	0.61 ± 0.06
Polygon 3 crustal	55 ± 4	0.77 ± 0.04
Polygon 4 crustal	51 ± 3	0.82 ± 0.04
Polygons 1–4 subcrustal	117 ± 9	0.74 ± 0.04
Polygon 5 subcrustal	88 ± 6	0.89 ± 0.04

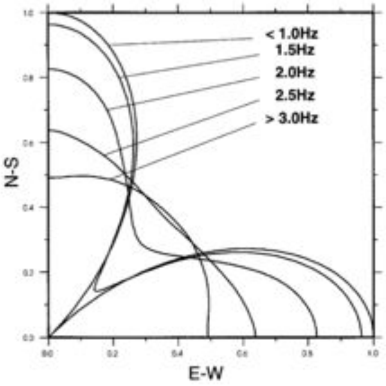


Oth et al. (2011)

Ground Motion

Random Perturbation to the Focal Mechanisms of Subsources

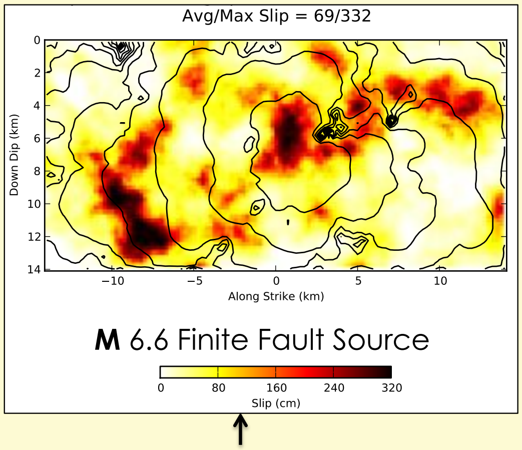




$$\varphi_i = \begin{cases} \varphi_0 & , \quad f \le f_1 \\ \varphi_0 + \dfrac{f - f_1}{f - f_2}(2r_i - 1)\varphi_P & , \quad f_1 < f < f_2 \\ \varphi_0 + (2r_i - 1)\varphi_P & , \quad f_2 \le f \end{cases}$$

Pitarka et al. (2000)

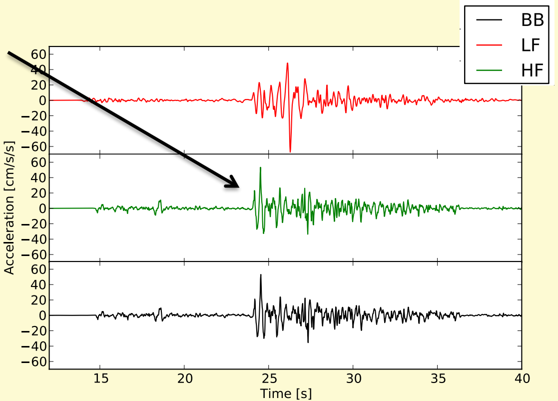
UCSB Hybrid Method

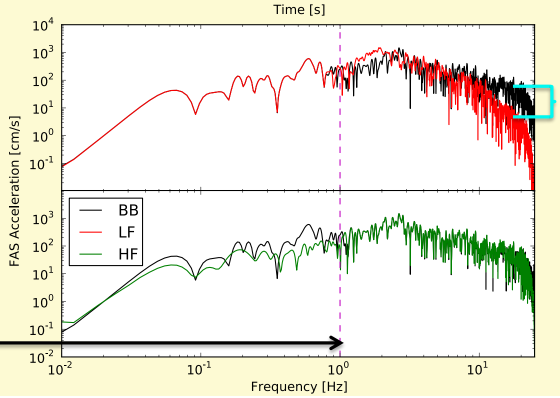


M 6.6 Finite Fault Source

For both HF and LF we use a **unique source**

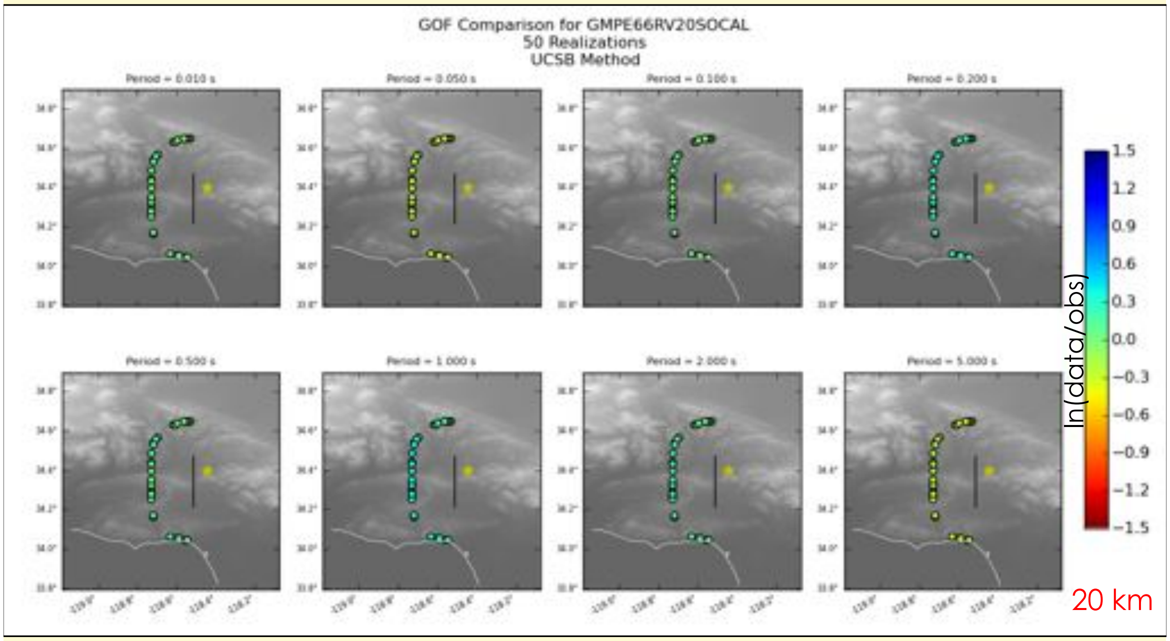
We align HF and LF at the S-wave arrival





We stitch HF and LF in the wavelet domain

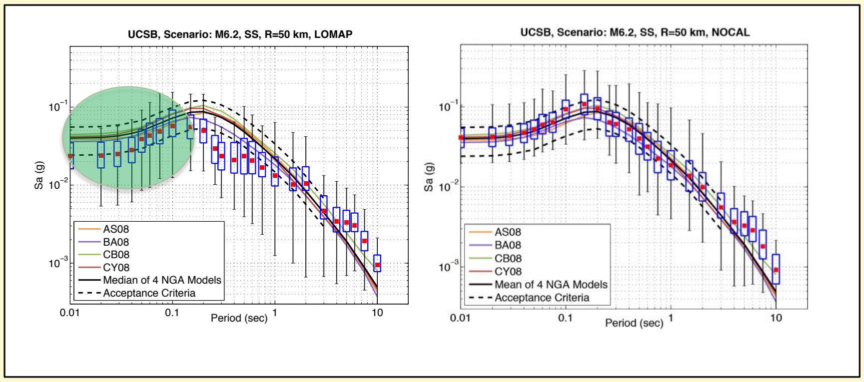
Results RV **M** 6.6

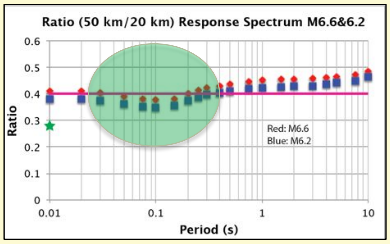


Under-prediction of high frequencies

1D Velocity Structure

Hybrid

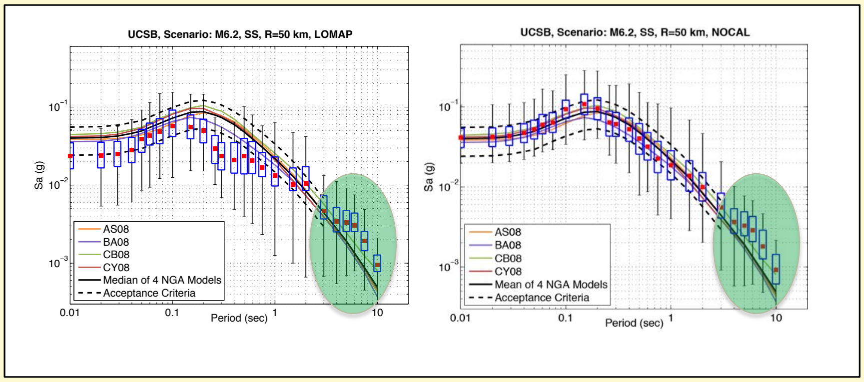


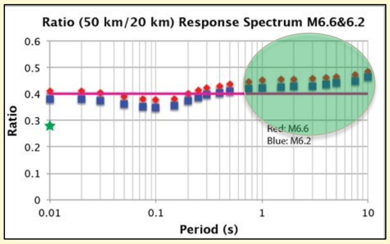


Over-prediction of low frequencies

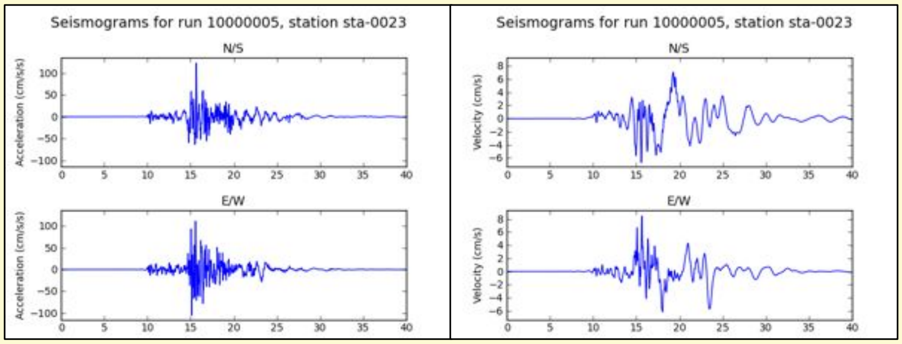
1D Velocity Structure

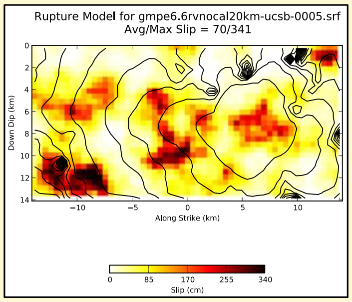
Hybrid

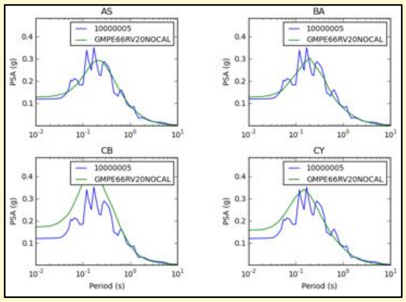




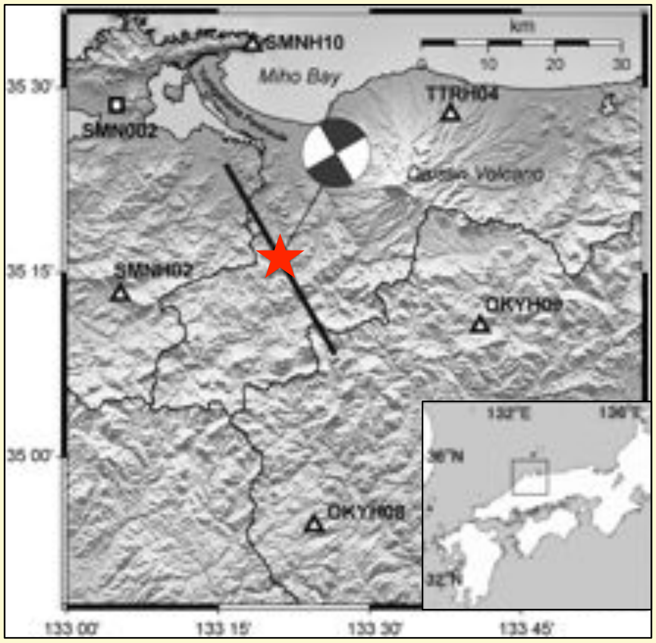
Results RV **M** 6.6 at 20 km



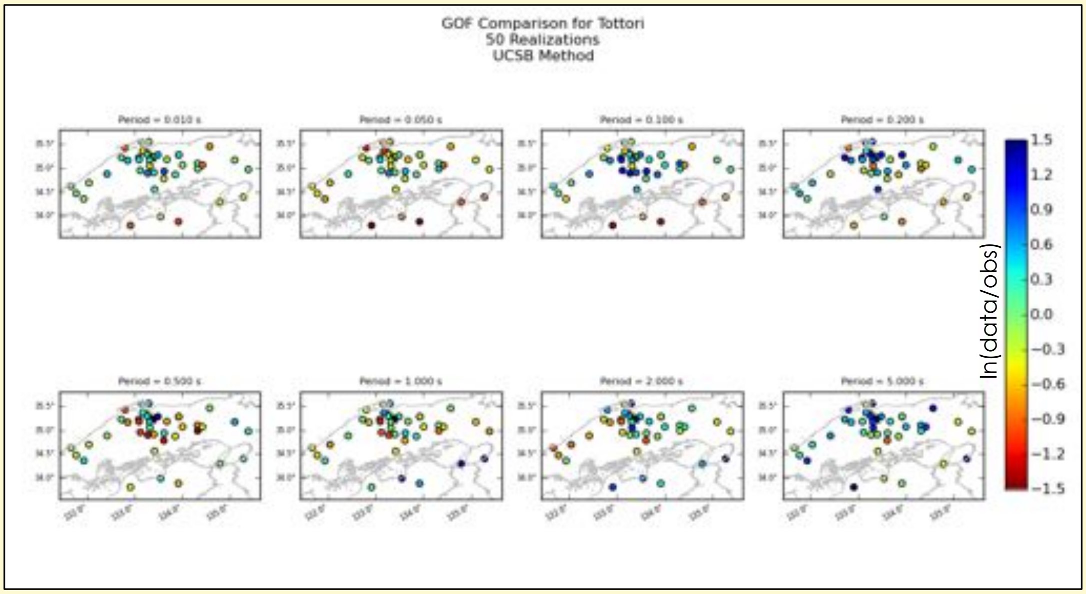




2000 Tottori **M** 6.59

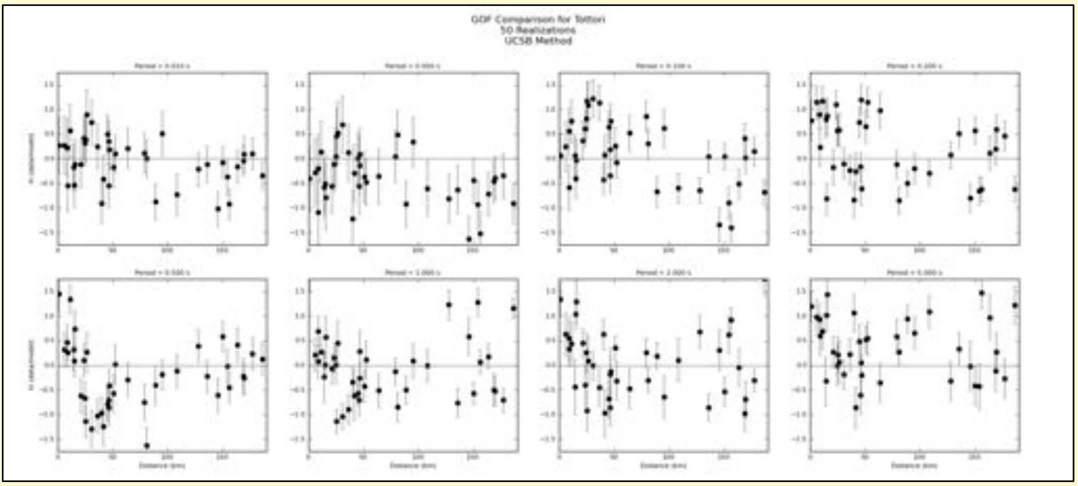


2000 Tottori **M** 6.59



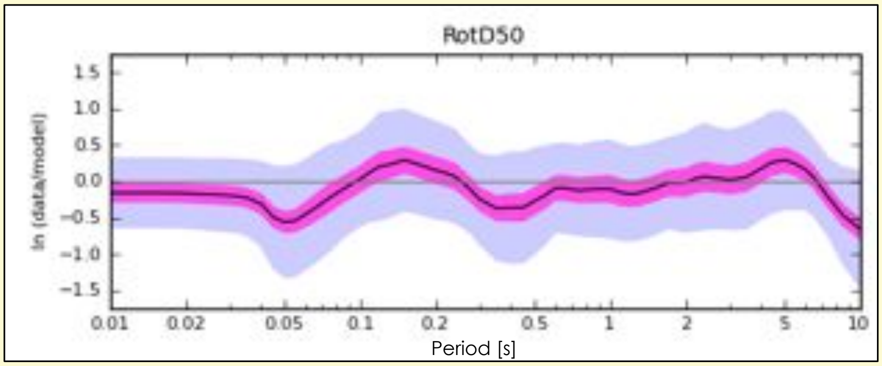
2000 Tottori **M** 6.59

ln(data/obs)



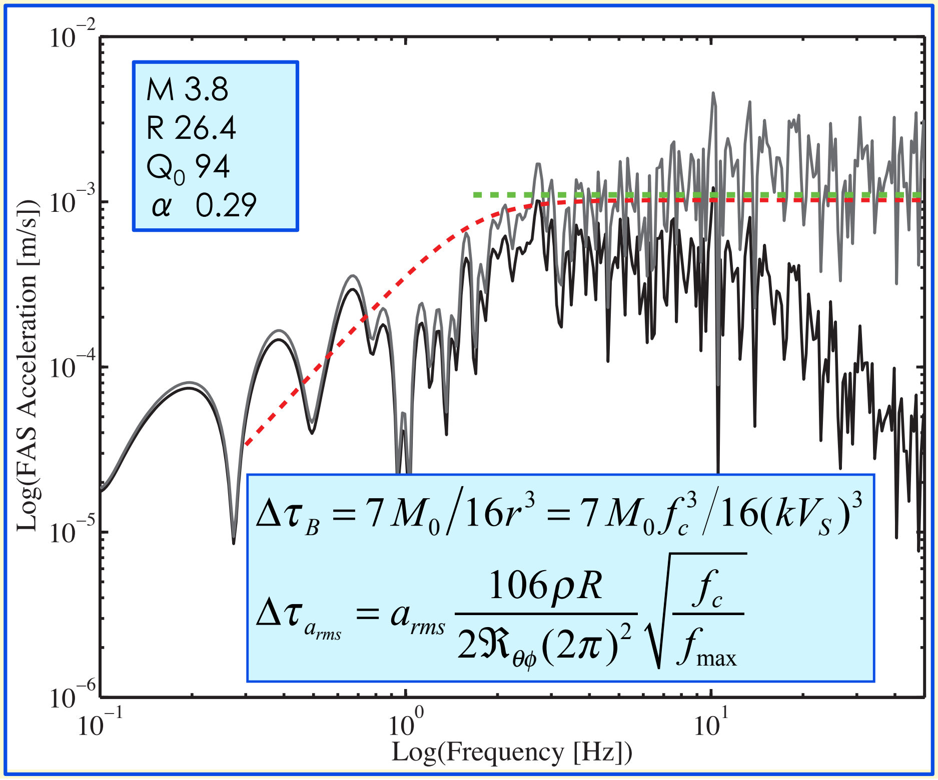
Distance [km]

2000 Tottori **M** 6.59



$\mathbf{M_o}$ α **A** scaling and $\Delta\,\sigma$ Something to Keep in Mind

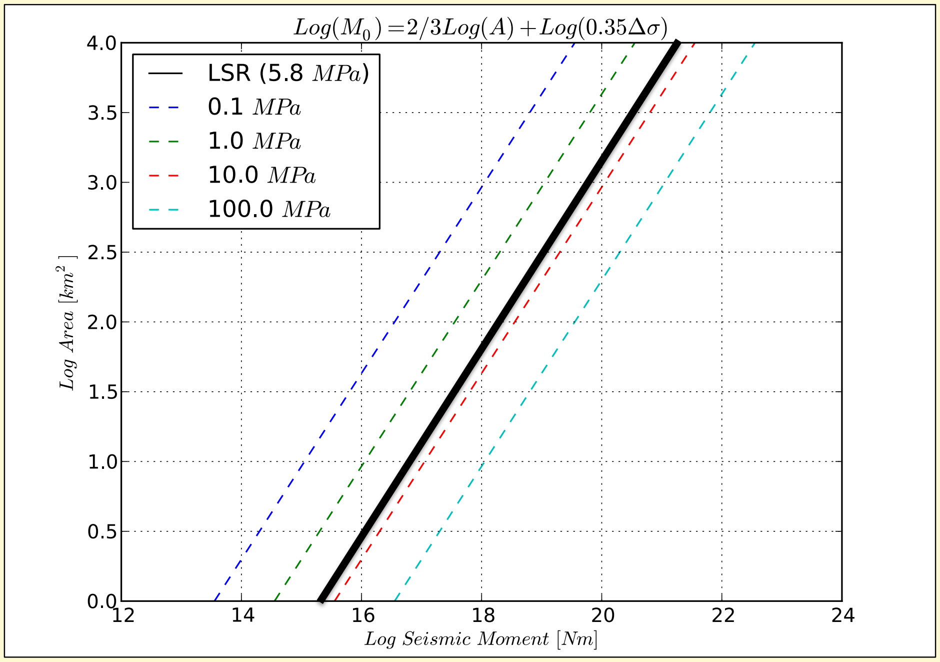
Estimating Stress Drop



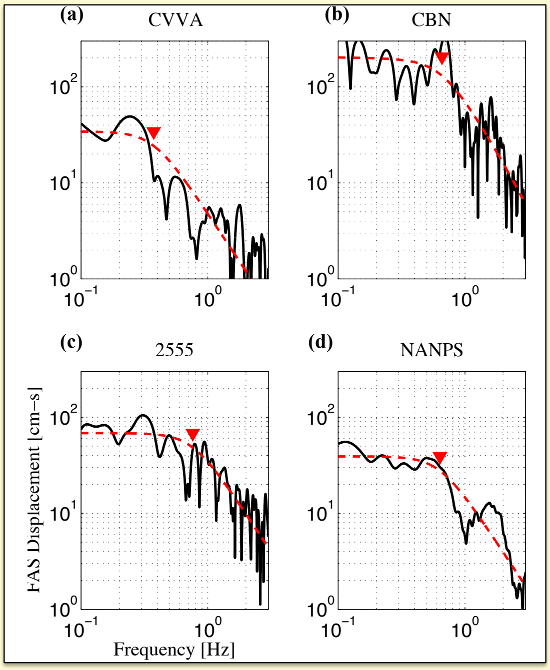
$$\Delta\tau_B = 7M_0/16r^3 = 7M_0 f_c^3/16(kV_S)^3$$

$$\Delta\tau_{a_{rms}} = a_{rms}\frac{106\rho R}{2\Re_{\theta\phi}(2\pi)^2}\sqrt{\frac{f_c}{f_{\max}}}$$

Leonard (2010)

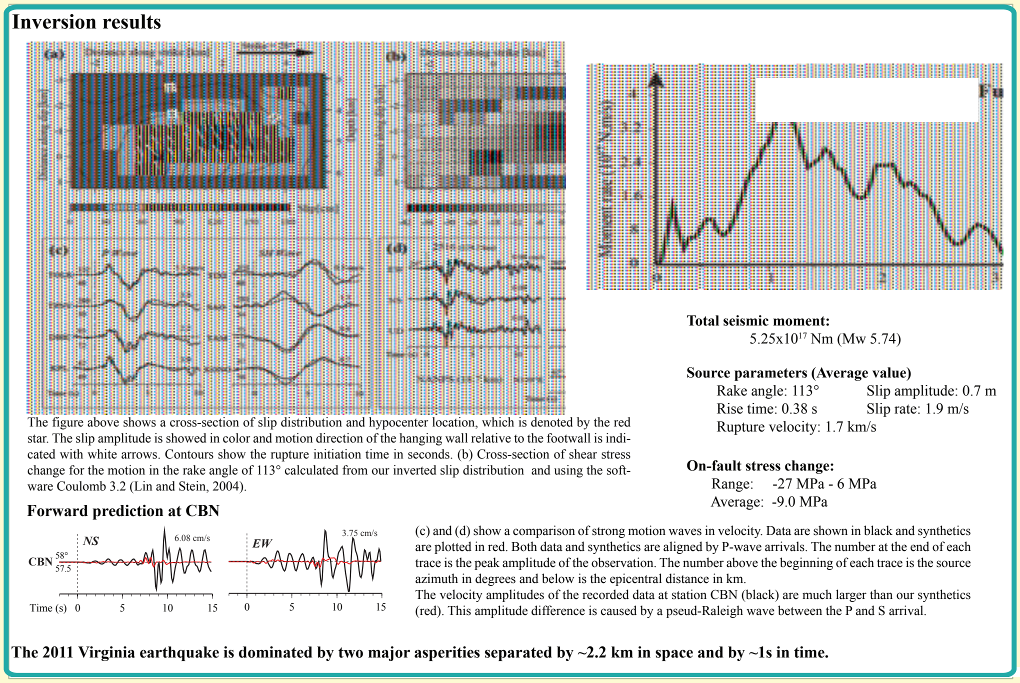


Dynamic Stress Drops of Mineral Virginia Earthquake (2011)



$\sigma_B \approx 23$ MPa

Static Stress Drop



Inversion results

The figure above shows a cross-section of slip distribution and hypocenter location, which is denoted by the red star. The slip amplitude is showed in color and motion direction of the hanging wall relative to the footwall is indicated with white arrows. Contours show the rupture initiation time in seconds. (b) Cross-section of shear stress change for the motion in the rake angle of 113° calculated from our inverted slip distribution and using the software Coulomb 3.2 (Lin and Stein, 2004).

Total seismic moment:
5.25×10^{17} Nm (Mw 5.74)

Source parameters (Average value)

Rake angle: 113°	Slip amplitude: 0.7 m
Rise time: 0.38 s	Slip rate: 1.9 m/s
Rupture velocity: 1.7 km/s	

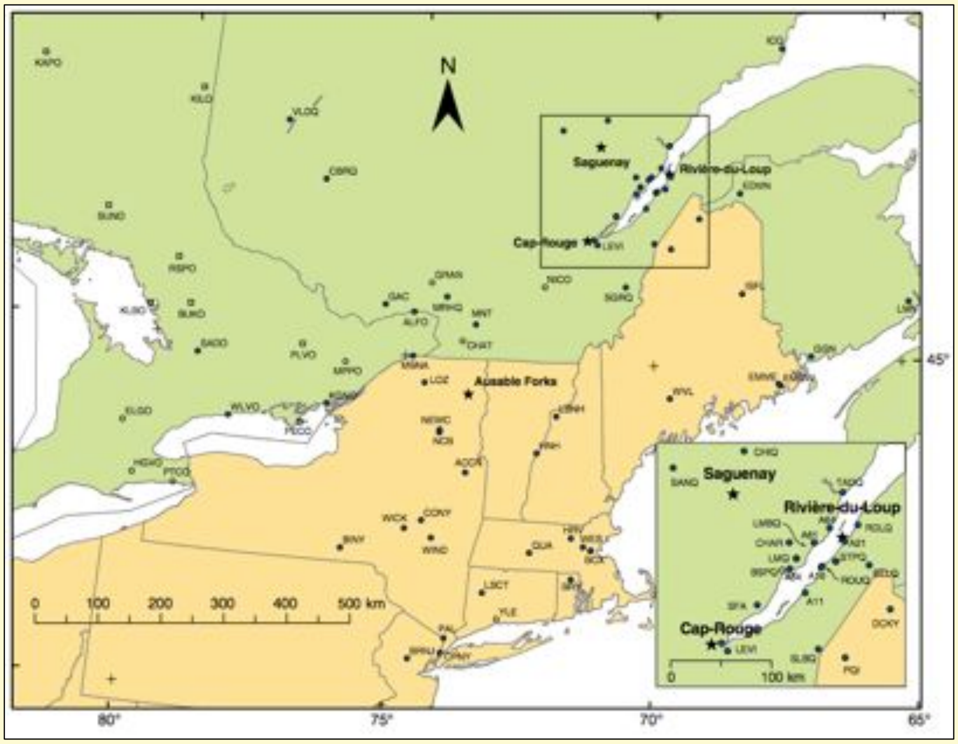
On-fault stress change:
Range: -27 MPa - 6 MPa
Average: -9.0 MPa

Forward prediction at CBN

(c) and (d) show a comparison of strong motion waves in velocity. Data are shown in black and synthetics are plotted in red. Both data and synthetics are aligned by P-wave arrivals. The number at the end of each trace is the peak amplitude of the observation. The number above the beginning of each trace is the source azimuth in degrees and below is the epicentral distance in km.
The velocity amplitudes of the recorded data at station CBN (black) are much larger than our synthetics (red). This amplitude difference is caused by a pseud-Raleigh wave between the P and S arrival.

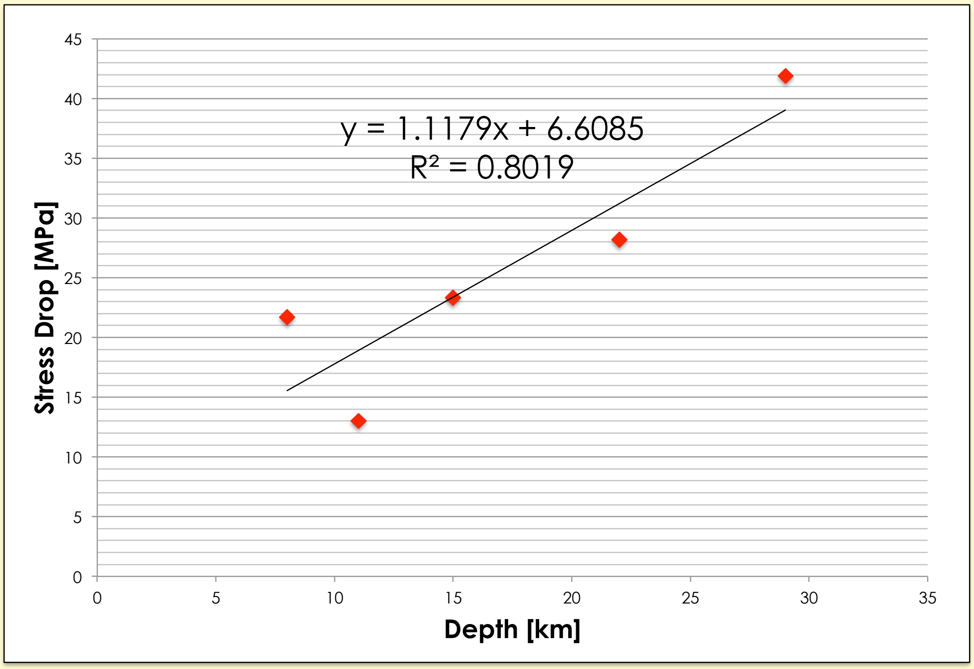
The 2011 Virginia earthquake is dominated by two major asperities separated by ~2.2 km in space and by ~1s in time.

Other Values of Dynamic Stress Drops for ENA



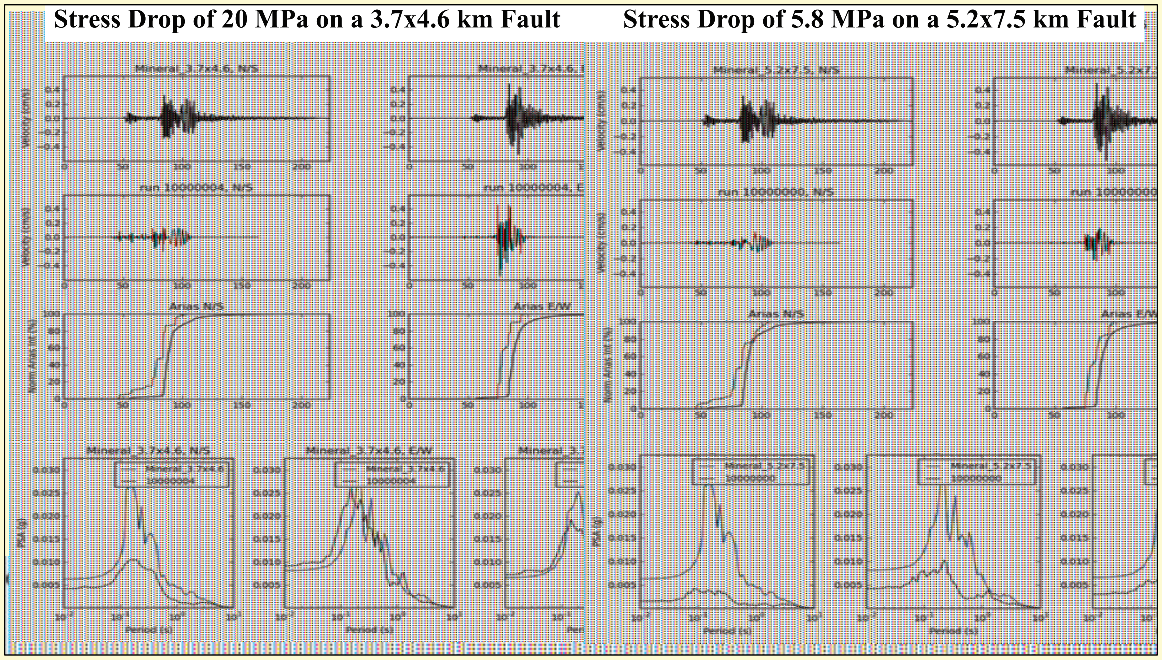
Boatwright and Seekins (BSSA, 2011)

Other Values of Dynamic Stress Drops for ENA



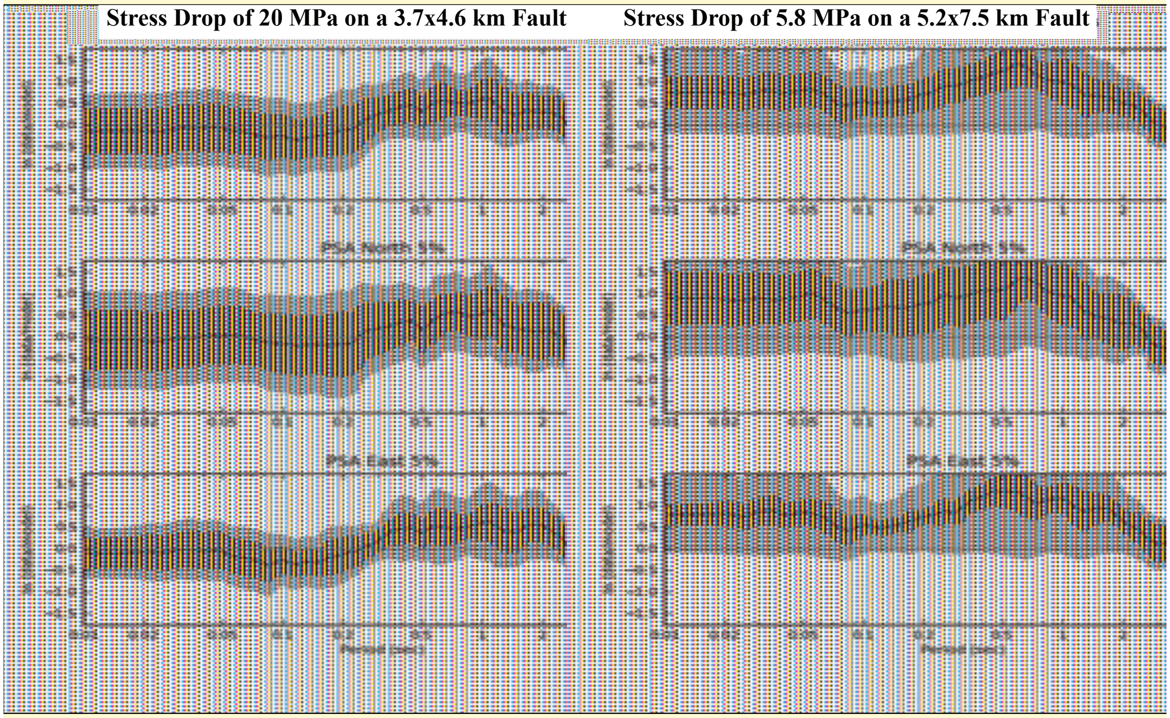
Boatwright and Seekins (BSSA, 2011)

Results


Stress Drop of 20 MPa on a 3.7x4.6 km Fault

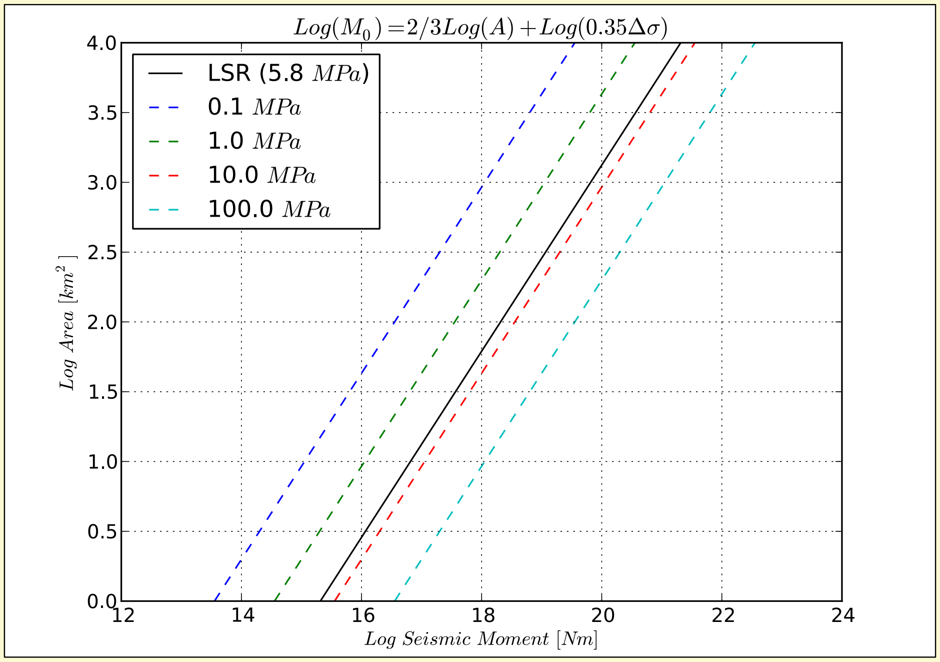
Stress Drop of 5.8 MPa on a 5.2x7.5 km Fault

Results


Stress Drop of 20 MPa on a 3.7x4.6 km Fault

Stress Drop of 5.8 MPa on a 5.2x7.5 km Fault

Proposed Scaling



Conclusions

Modeling of wave-propagation with 1D velocity structures has the following problems:

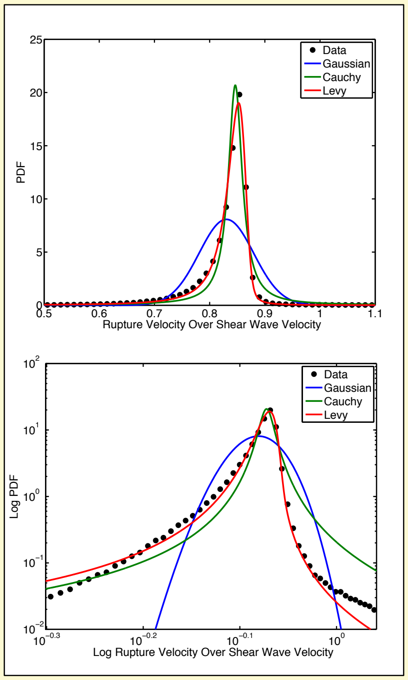
- Under-prediction of high-frequency strong ground motion due to glancing of high incident angle rays off of shallow layers.
- Over-prediction of surface waves due to trapping of energy in upper shallow layers.

✓ To overcome this we have constructed a new method that separates high- and low- frequencies wave-propagation.

✓ We use a **unique source** for both high- and low-frequency wave propagation. The source parameters are stochastic but correlated.

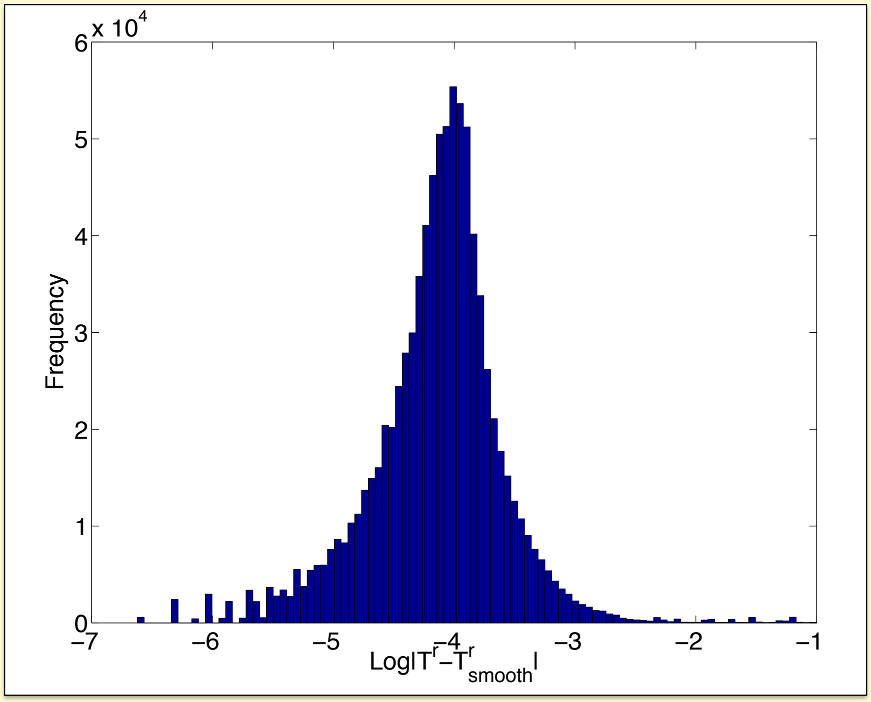
Future Research

- Inclusion of Scattering functions in the Green's functions using Zeng (1991) method.
- Incorporation of statistics of dynamic rupture simulations on rough faults.



Fang and Dunham, 2013; Trugman and Dunham, 2014

Future Research



Acknowledgments

We thank Chen Ji for fruitful discussions on this topic and Scott Callaghan, Fabio Silva and Tom Jordan for technical help.

Thank You!
Questions?

Input Files

Velocity model

- <u>numberLayers, placeholder</u> [the number of layers (including halfspace) in the 1D model, an input that is of no importance for the 1D broadband modeling]
- <u>Vp</u>, <u>Vs</u>, <u>density</u>, <u>thickness</u>, <u>Qp</u>, <u>Qs</u> [P-wave velocity, S-wave velocity, density, thickness of layer, quality factor for P-wave, quality factor for S-wave]
- numberLayers line: : <u>Vp</u>, <u>Vs</u>, <u>density</u>, <u>0.0</u>, <u>Qp</u>, <u>Qs</u> [P-wave velocity of halfspace, S-wave velocity of halfspace, density of halfspeace, for halfspace use thickness 0.0, quality factor for P-wave in halfspace, quality factor for S-wave in halfspace]

Input Files

Example input:

```
8  1.0
1.2 0.3 1.7   0.1     27.0    18.0
1.6 0.5 1.8   0.2     45.0    30.0
1.9 1.0 2.1   0.2     90.0    60.0
4.0 2.0 2.4   1.0    420.0   280.0
4.7 2.7 2.6   2.5    567.0   378.0
6.3 3.6 2.8  23.0    864.0   576.0
6.8 3.9 2.9  13.0    936.0   624.0
7.8 4.5 3.3   0.0   1080.0   720.0
```

Input Files

GreenFar.in

line: nameVelmod [name of file containing velocity model]

line: minDepth, dz1, Nz1, dz2, Nz2 [minimal depth for Greens functions, depth sampling increment for first Nz1 sources, Number of sources with dz1 sampling, depth sampling increment for Nz1+1…Nz1+Nz2 sources, Nz2 number of sources with dz2]

line: minEpi, dx1, Nx1, dx2, Nx2 [minimal eicentral distance for Greens functions, epicentral distance sampling increment for first Nx1 sources, Number of sources with dx1 sampling, epicentral distance sampling increment for Nx1+1…Nx1+Nx2 sources, Nx2 number of sources with dx2]

line: Nt, dt, tBefore [number of time steps, time increment, seconds to be saved before first arrival. This should never be set to 0 (because of wrap-around artifacts!!!]

line: nameGreenDB [name of the file containing the Greens function database]

line: minDepthFar, NFar [for sources with epicentral distance index NFar… Nx1+Nx2 every source that is more shallow than minDepthFar, the Greens Function will be replaced with a source that is at the closest but larger depth than minDepthFar. This is done, because for larger distances there can be a problem with too shallow sources.]

Input Files

Example Input:

```
velocity.soil2
5.0 0.3 15 0.5 25
0.05 0.5 30  1. 100
4000 0.01 3.0
Green_1d.soil
0.4 35
```

Input Files

KinModel.inp

1. line: rupL, ddW [rupture length, down-dip width, i.e., dimensions of fault plane in m]
2. line: hypoStrike, hypoDip [position of hypocenter on fault along dip, position of hypocenter on fault along dip, in m]
3. line: hypoX, hypoY, hypo [hypocenter coordinates in m]
4. line: M0, fc [seismic moment in Nm and corner frequency in Hz]
5. line: strike, dip, rake (strike, dip, rake of event)
6. line: dx, dt [grid spacing (m), time increment for slip rate function (has to be same as for Green's function!]
7. line: NSources [number of sources]
8. line: seed1, seed2, seed3 [random seeds]
9. line: nameVelMod [name of file containing velocity model]

Input Files

Example Input:

```
20000 25000
16000 19400
-15782. -2786.9 17500.
1.23e+19 0.2
122. 40. 105.
200 0.01
20
12124224 12421 534234
velocity.soil2
```

Input Files

syn1D_LAH.inp

1. line: subStrike, subDip [# point sources for each subfault (subfaults are interpolated)]
2. line: perturbAz, perturabRake, perturbDip [perturbation of azimuth, rake and dip for the high frequencies]
3. line: fDeterministic, fStochastic, kappa [until frequency fDeterministic radiation pattern is deterministic, above fStochastic it is stochastic. In between there is a linear transition, kappa value in s]
4. line: nameSources [name of file containing names of source model files]
5. line: nameStation [name of file containing station locations]
6. line: switchTimeSeries [1: displacement, 2: velocity, 3: acceleration. Note that the post processing programs work on velocity]
7. line switchFormat [1:SAC, 2: TXT. Post processing works on TXT]

Input Files

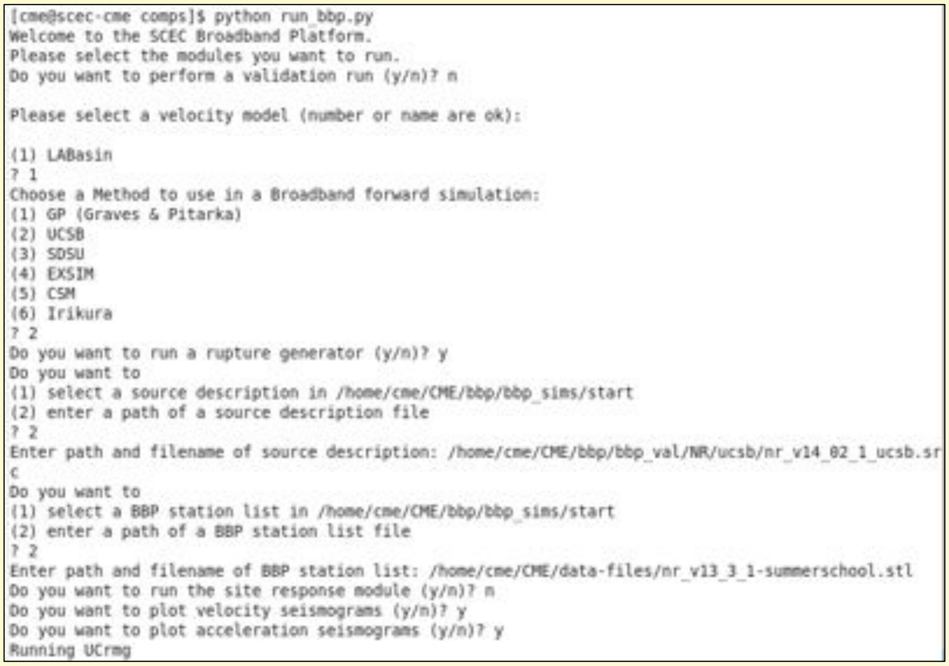
Example input:

```
2 2                    ! # of point source for each subfault
60.0,   30.0,   15.0   ! Perturbation on strike, rake, and dip
1.0,  3.0, 0.03
source_SCEC.list
stations25
2       ! 1 for Displacement, 2 for Vel., 3 for Acc
2       ! 1 for SAC;  2 for TXT;  3 for Binary
```

Exersise

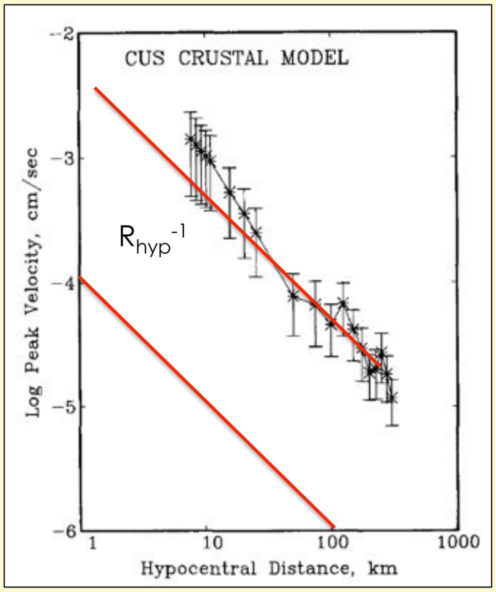
```
FAULT_WIDTH = 27.00
HYPO_ALONG_STK = 6.00
DLEN = 0.5
HYPO_DOWN_DIP = 19.40
DWID = 0.5
RAKE = 105.00
FAULT_LENGTH = 20.00
DEPTH_TO_TOP = 5.00
CORNER_FREQ = 0.2
MAGNITUDE = 6.73
LAT_TOP_CENTER = 34.344
STRIKE = 122
LON_TOP_CENTER = -118.515
DIP = 40
SEED = 1343642
```

Exersise



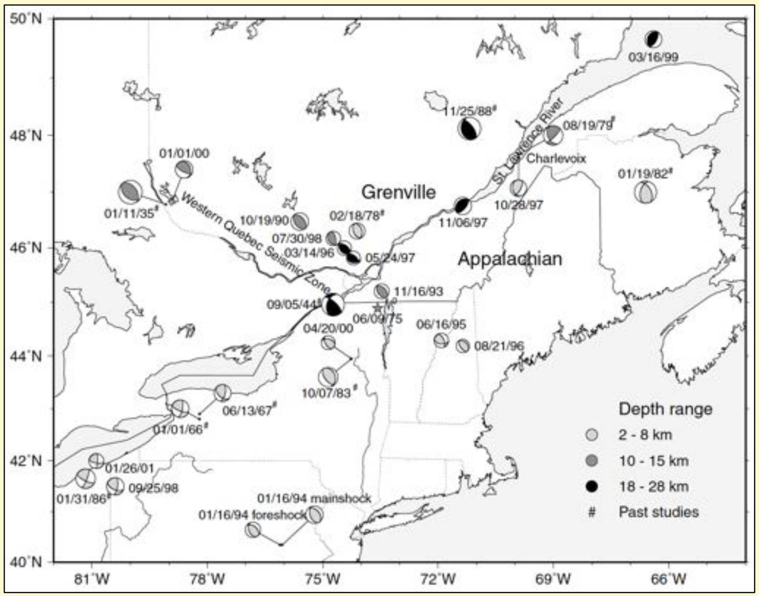
```
[cme@scec-cme comps]$ python run_bbp.py
Welcome to the SCEC Broadband Platform.
Please select the modules you want to run.
Do you want to perform a validation run (y/n)? n

Please select a velocity model (number or name are ok):

(1) LABasin
? 1
Choose a Method to use in a Broadband forward simulation:
(1) GP (Graves & Pitarka)
(2) UCSB
(3) SDSU
(4) EXSIM
(5) CSM
(6) Irikura
? 2
Do you want to run a rupture generator (y/n)? y
Do you want to
(1) select a source description in /home/cme/CME/bbp/bbp_sims/start
(2) enter a path of a source description file
? 2
Enter path and filename of source description: /home/cme/CME/bbp/bbp_val/NR/ucsb/nr_v14_02_1_ucsb.sr
c
Do you want to
(1) select a BBP station list in /home/cme/CME/bbp/bbp_sims/start
(2) enter a path of a BBP station list file
? 2
Enter path and filename of BBP station list: /home/cme/CME/data-files/nr_v13_3_1-summerschool.stl
Do you want to run the site response module (y/n)? n
Do you want to plot velocity seismograms (y/n)? y
Do you want to plot acceleration seismograms (y/n)? y
Running UCrmg
```

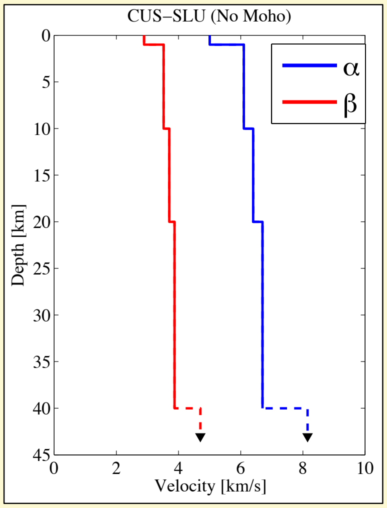
1D Green's Functions



Burger *et al.* (1987)

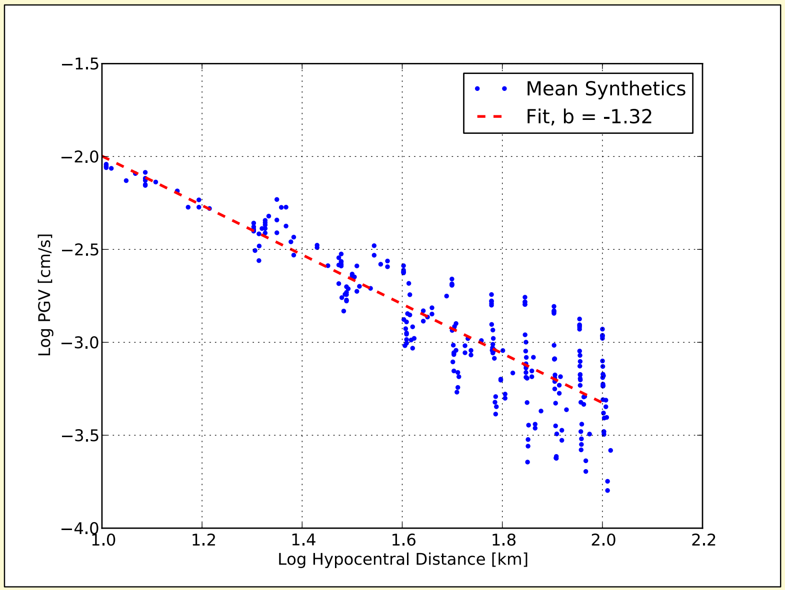
Geometric attenuation for typical focal mechanisms in ENA





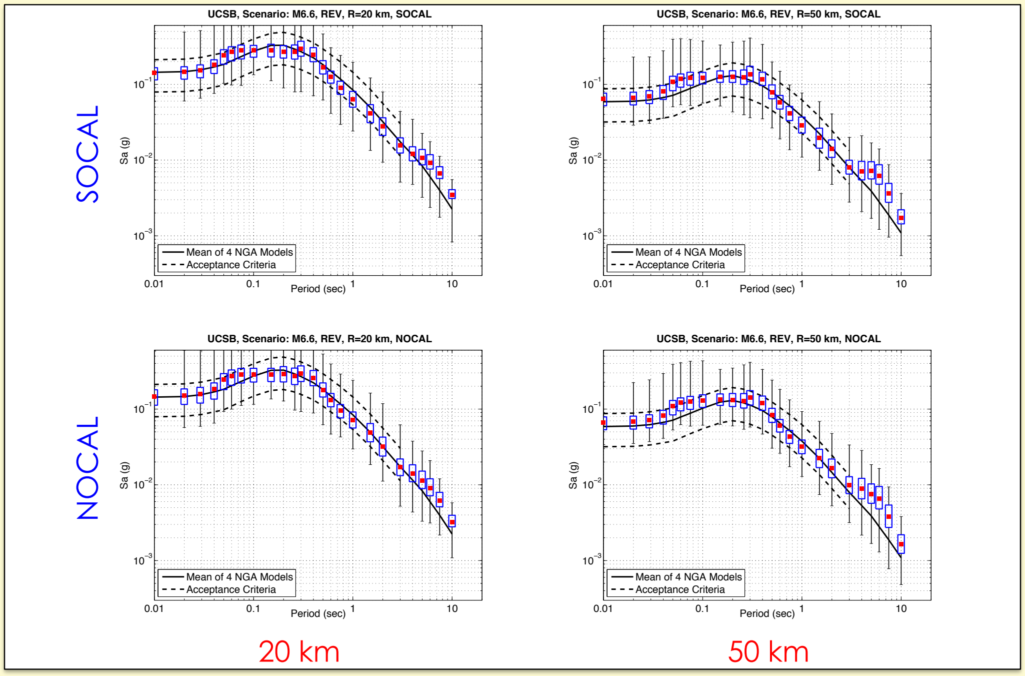
Du *et al.* (2003)

Geometric attenuation for typical focal mechanisms in ENA: SLU structure



- Average over azimuths every 20˚.
- Same moment for all events.

Results RV **M** 6.6



Effect of Standard Deviation on Ground Motion