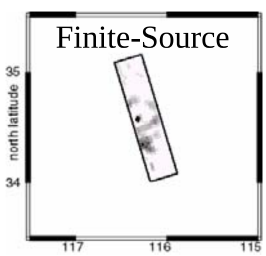
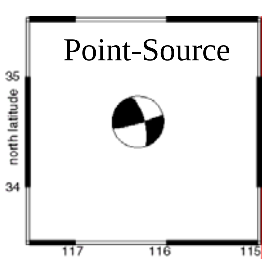
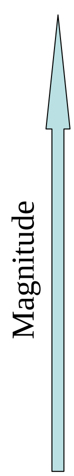
Earthquake Kinematics & Dynamics

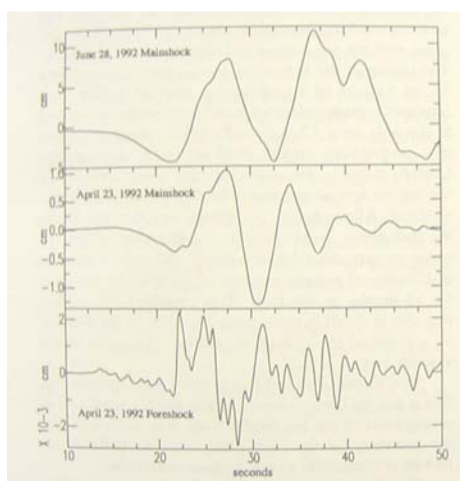
- Kinematics
  - Study of timing of seismic moment release
  - $M(t)=\mu A(t)u(t)$
    - Rupture velocity
    - Slip velocity / rise time
- Dynamics
  - Study of physical mechanisms governing earthquake rupture and seismic moment release
    - Initial stress state
    - Yield stress
    - Static & dynamic coefficient of friction
    - Frictional constitutive law
    - Pore pressure effects & melting

Sources









Kinematic Description of Finite Source Process

- Spatio-Temporal Descriptions of:
  - slip, rise time (slip velocity), and rupture speed
- Haskell Source Model
- Representation Theorem Models

First Point-Source Kinematics

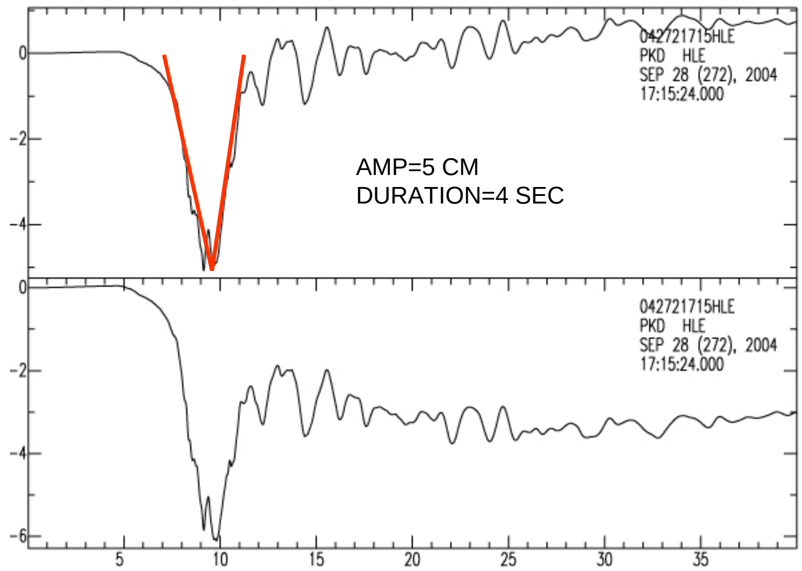
$$u_i(r,t) = \frac{2 \cdot R_i \cdot \dot{M}(t - r/\beta)}{4\pi\rho r \beta^3}$$

$$\int u_i(r,t)dt = \frac{1}{2}A\tau = \frac{2 \cdot R_i \cdot M_0}{4\pi\rho r \beta^3}$$

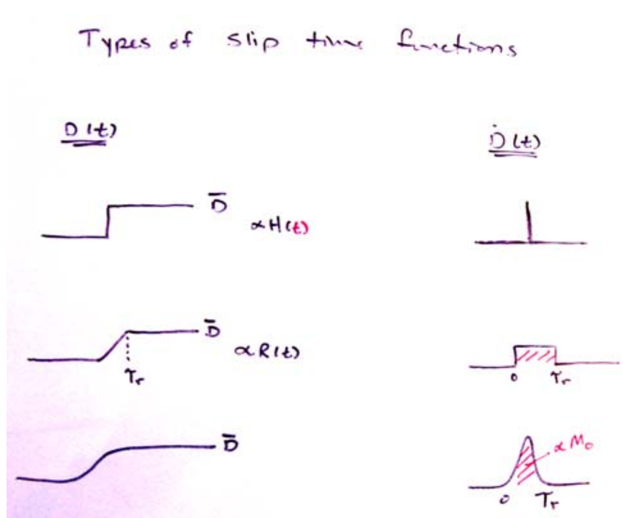
$$M_0 = \frac{(\pi\rho r \beta^3)A\tau}{R} = 3.14 * 2.67 * 8 \cdot 10^5 * (3.5 \cdot 10^5)^3 * 5 * 4$$

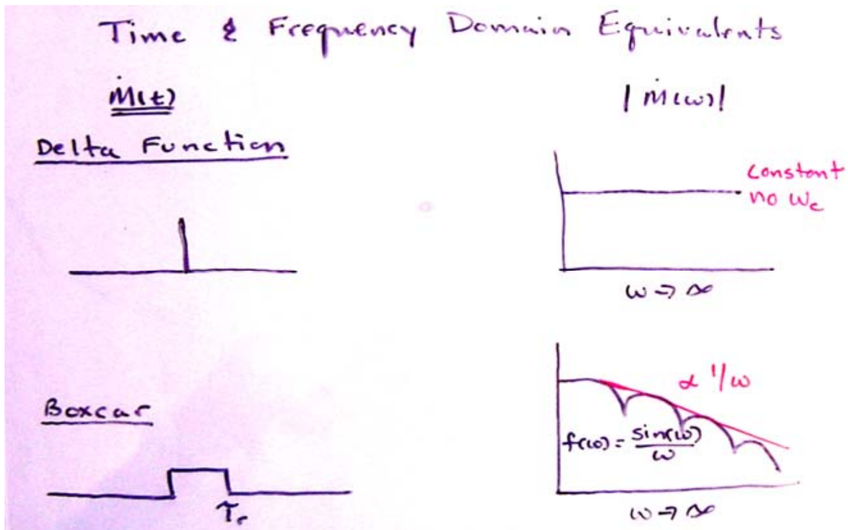
$$= 5.7 \cdot 10^{24} \ dyne\ cm$$

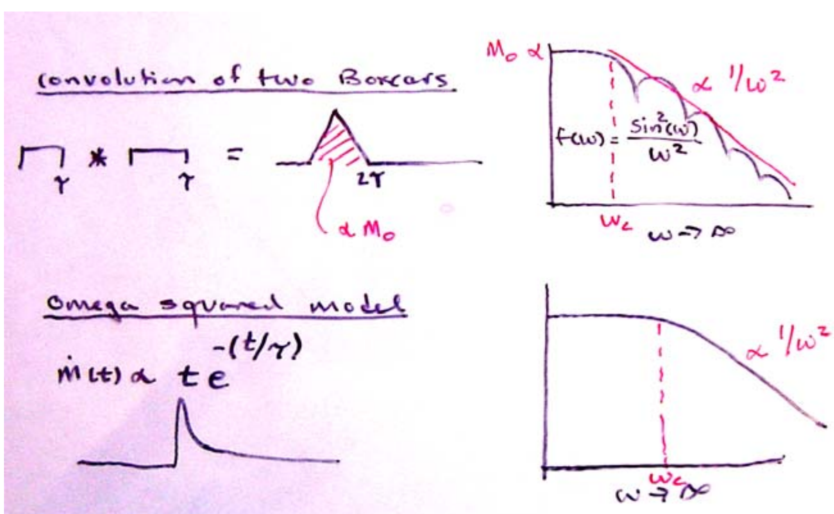
$$Mw = 5.8$$



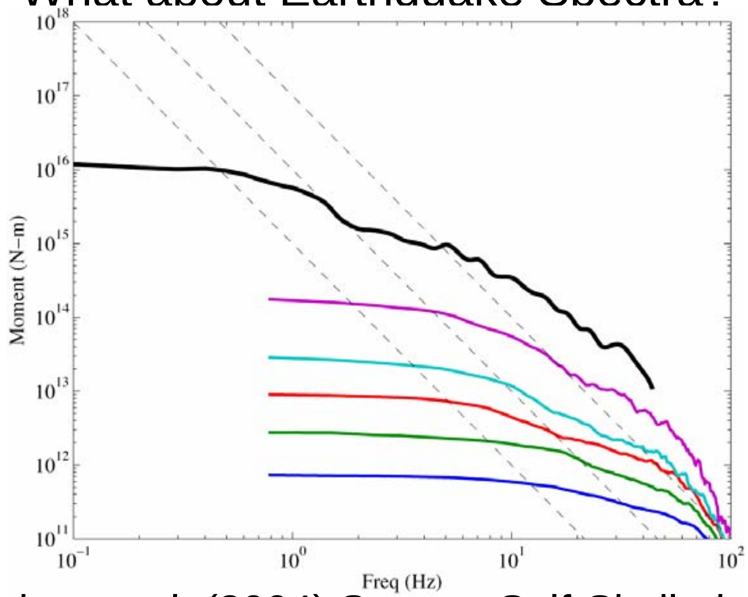
What is a Reasonable form for the Moment Rate Function?




Time & Frequency Domain Equivalents
$\dot{M}(t)$
$|\dot{M}(\omega)|$
Delta Function
constant
no ω_c
$\omega \to \infty$
Boxcar
T_r
$\propto 1/\omega$
$f(\omega) = \frac{\sin(\omega)}{\omega}$
$\omega \to \infty$

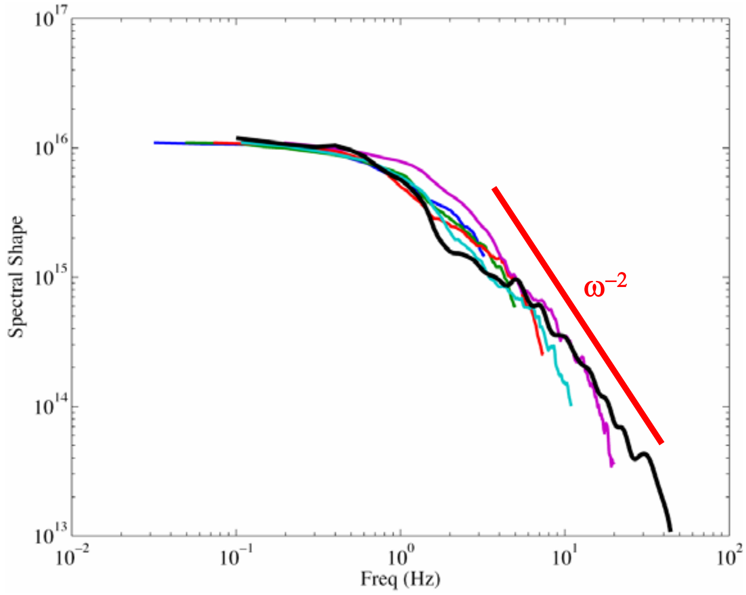

Convolution of two Boxcars
τ
τ
2τ
$\propto M_0$
$M_0 \propto$
$\propto 1/\omega^2$
$f(\omega) = \frac{\sin^2(\omega)}{\omega^2}$
ω_c
$\omega \to \infty$
Omega squared model
$\dot{M}(t) \propto t e^{-(t/\tau)}$
$\propto 1/\omega^2$
ω_c
$\omega \to \infty$

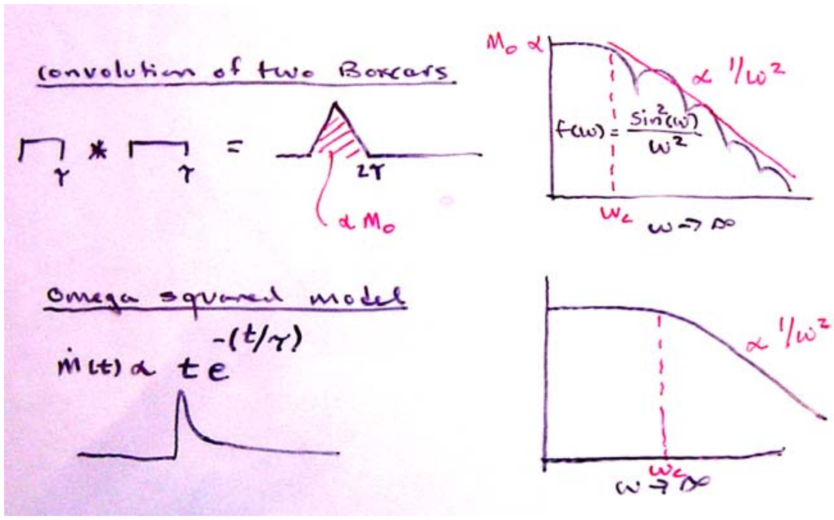
What about Earthquake Spectra?

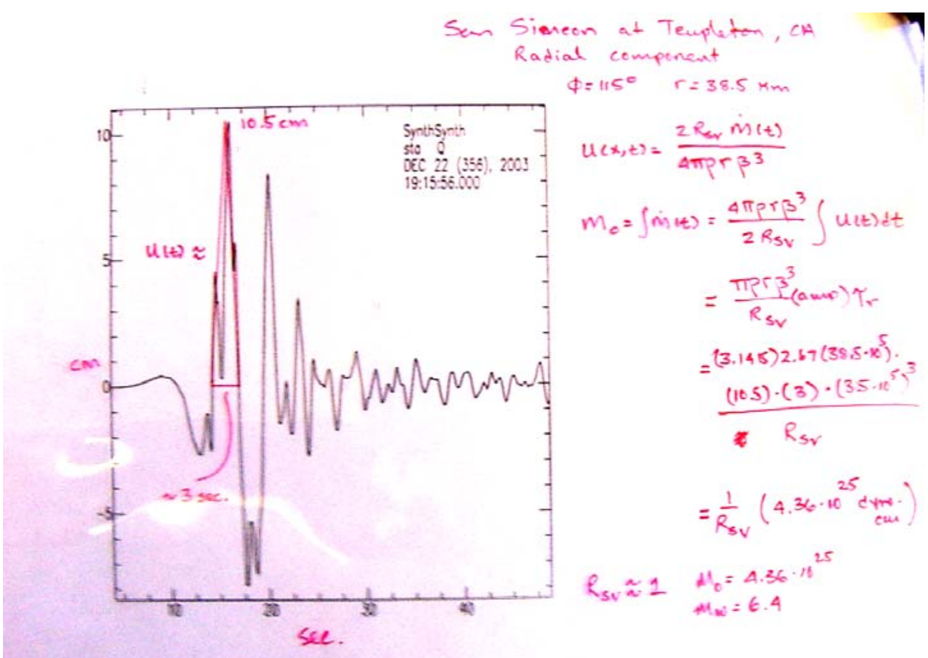


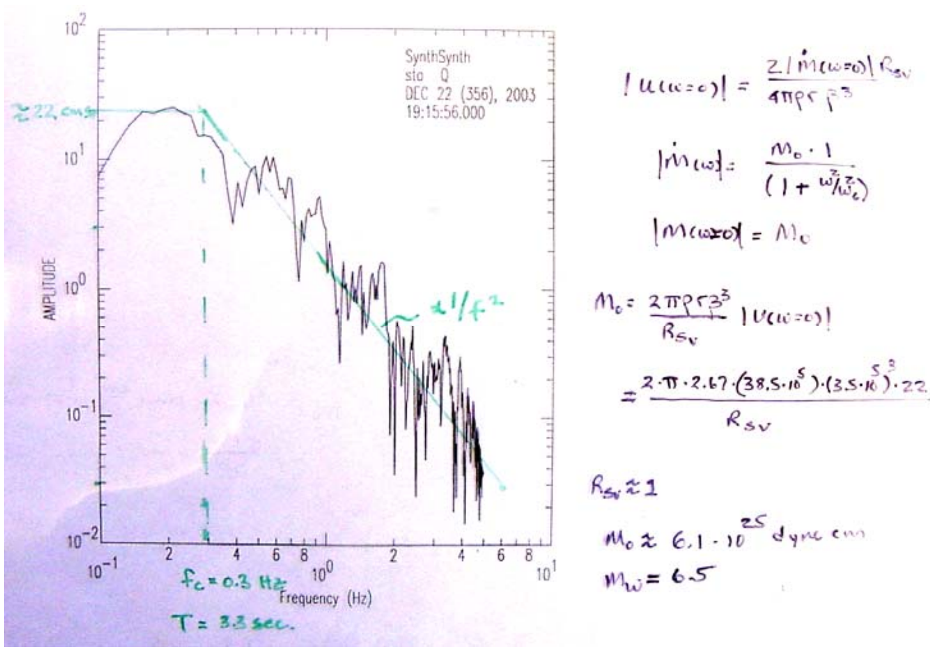
Prieto et al. (2004) Spectra Self-Similarity

Prieto et al. (2004) Spectra Self-Similarity

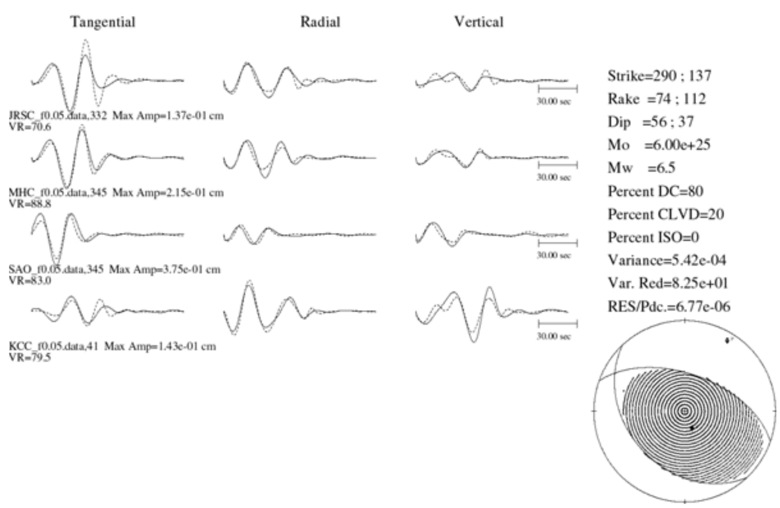



convolution of two Boxcars
2τ
∝ Mo
Mo ∝
∝ 1/ω²
f(ω) = sin²(ω)/ω²
ωc ω → ∞
Omega squared model
ṁ(t) ∝ t e^-(t/τ)
∝ 1/ω²
ωc
ω → ∞


San Simeon at Templeton, CA
Radial component
φ = 115° r = 38.5 km
10.5 cm
SynthSynth
sta: Q
DEC 22 (356), 2003
19:15:56.000
u(t) ≈
cm
~3 sec.
sec.
u(x,t) = 2 Rsv ṁ(t) / 4πρ r β³
Mo = ∫ṁ(t) = 4πρrβ³ / 2 Rsv ∫ u(t)dt
Rsv ≈ 1
Mw = 6.4



Moment Tensor Solution



Seismic moment tensor determined from 0.02-0.05 Hz, three-component, displacement seismograms. The source depth was found to be 8 km.

Haskell Source Model assumes

- constant dislocation rise time
- uniform fault growth

Start with the far-field solution

$$u(r,t) = \frac{2R_{SH}}{4\pi\rho\beta^3 r}\dot{M}(t - r/\beta)$$

$$M(t) = \begin{cases} 0 & t < r/\beta \\ \rightarrow M_0 & t \rightarrow \infty \end{cases}$$

$$M_0 = \int_0^\infty \dot{M}(t)\,dt$$

First break M(t) into 2 terms that depend on time.

1) slip rate $\dot{D}(t)$ where $\bar{D} = \int_0^\infty \dot{D}(t)\,dt$

2 Fault Length $L(t) = \int_0^L \delta(t - x/V_r)\,dx$

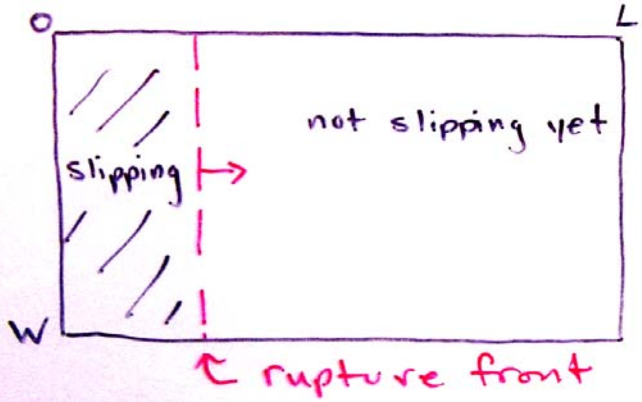
then $\dot{M}(t) = \mu W L(t) * \dot{D}(t)$

with a change of variable $z = t - x/V_r$

$$dz = \frac{-1}{V_r}dx$$

the L integral simplifies

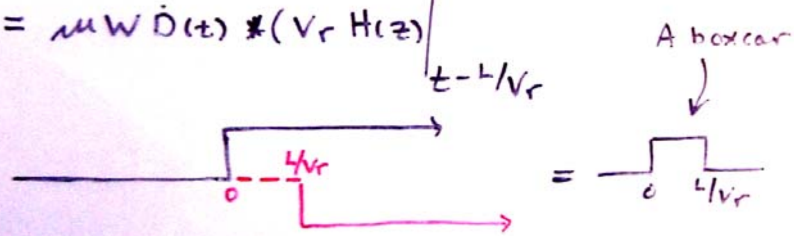
and a "ribbon" rupture model



the L integral simplifies

$$\dot{M}(t) = \mu W \dot{D}(t) * \int_{t}^{t-L/v_r} \delta(z)(-v_r)\,dz$$

$$= \mu W \dot{D}(t) * (v_r H(z))\Big|_{t-L/v_r}^{t}$$



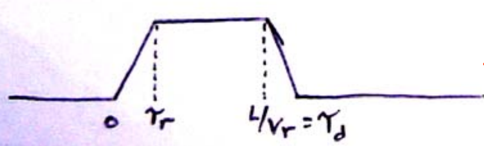
If it is assumed that $D(t)$ behaves like a ramp function where total offset is achieved at time τ_r then $\dot{D}(t)$ is a boxcar with duration τ_r.

So the Haskell solution is the convolution of two boxcars, $B(\tau_r)$ and $B(L/V_r)$

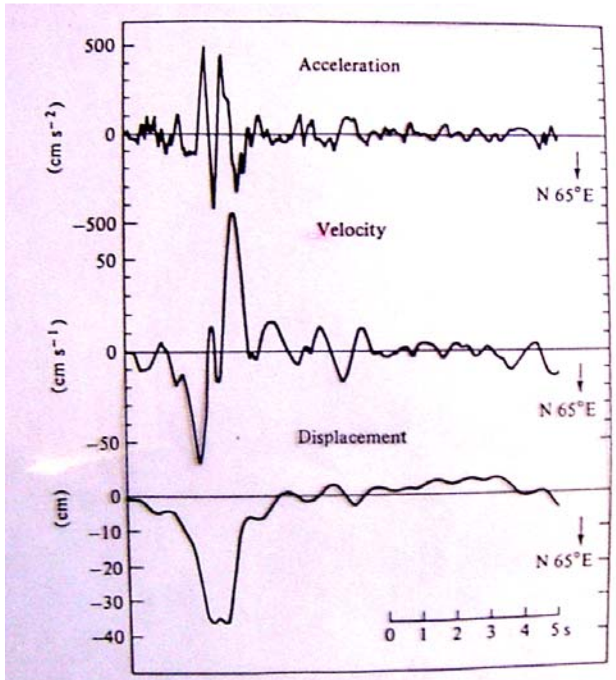
So the Haskell solution is the convolution of two boxcars, $B(\tau_r)$ and $B(L/V_r)$

If $\tau_r = \tau_d$ the convolution yields a triangle

If $\tau_r \neq \tau_d$ the convolution yields a trapezoid (see Box 9.2)



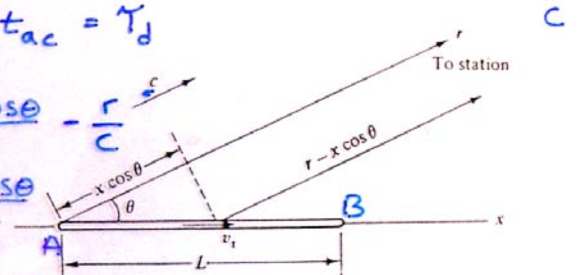
How reasonable can this be?



Directivity

Difference in arrival time from opposite ends of a fault

$t_{abc} - t_{ac} = \tau_d$



$$\tau_d = \frac{L}{V_r} + \frac{r - L\cos\theta}{c} - \frac{r}{c}$$

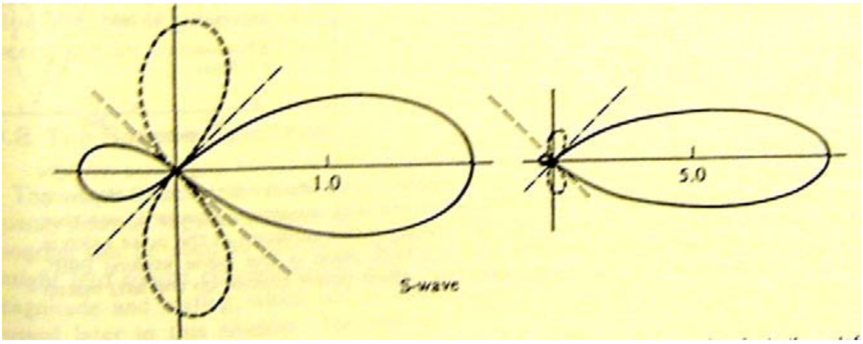
$$\tau_d = \frac{L}{V_r} - \frac{L\cos\theta}{c}$$

c is α or β for P & S waves

FIGURE 9.8 Geometry of a rupturing fault and the path to a remote recording station. (From Kasahara, 1981.)

$V_r \approx 90\% \, \beta$

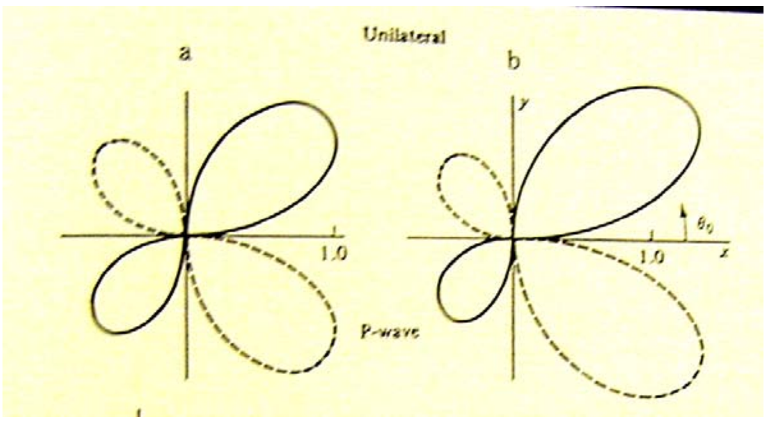
Directivity & Radiation Patterns



Vr/β=0.5

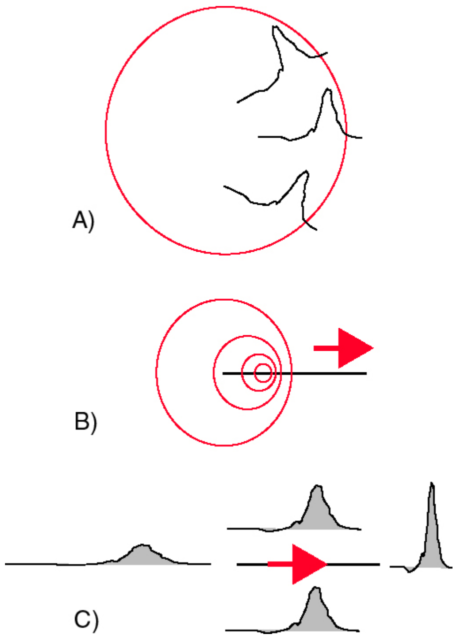
Vr/β=0.9

Directivity & Radiation Patterns

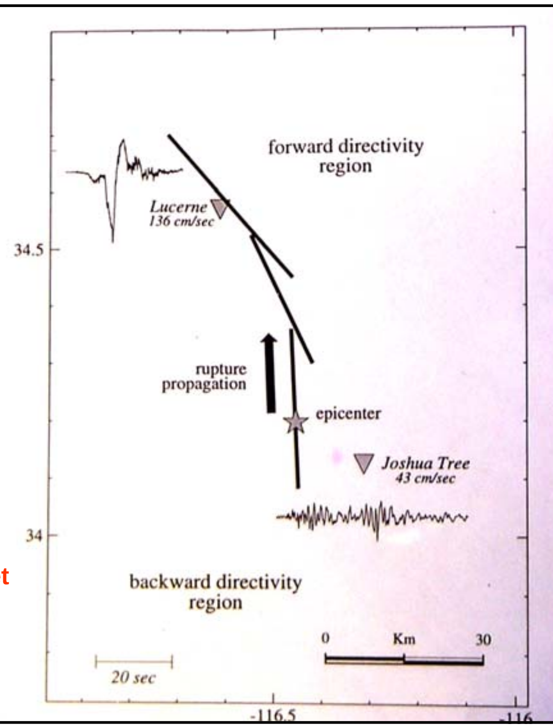


Vr/β=0.5

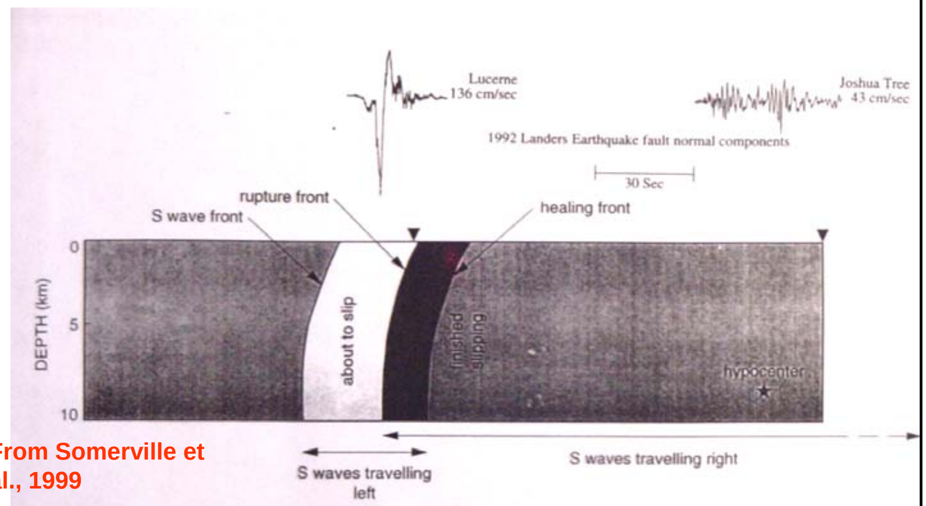
Vr/β=0.9



Shaded area is constant under the moment rate functions. i.e. it is the same for all of the moment rate functions.



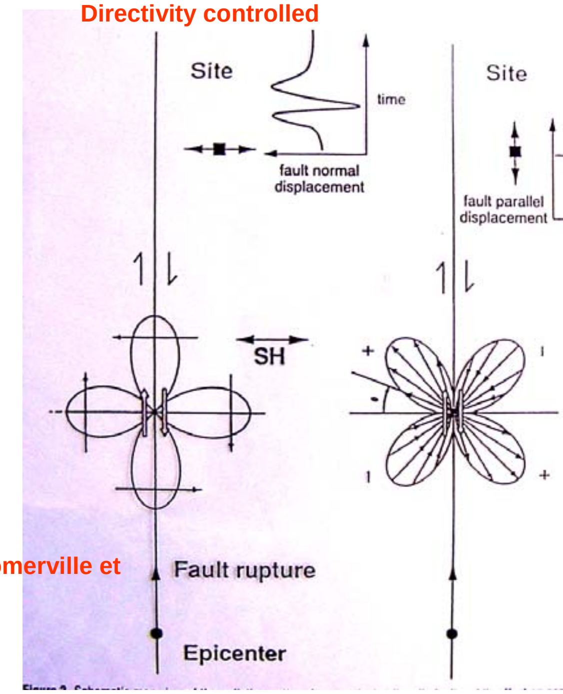
From Somerville et al., 1999



From Somerville et al., 1999

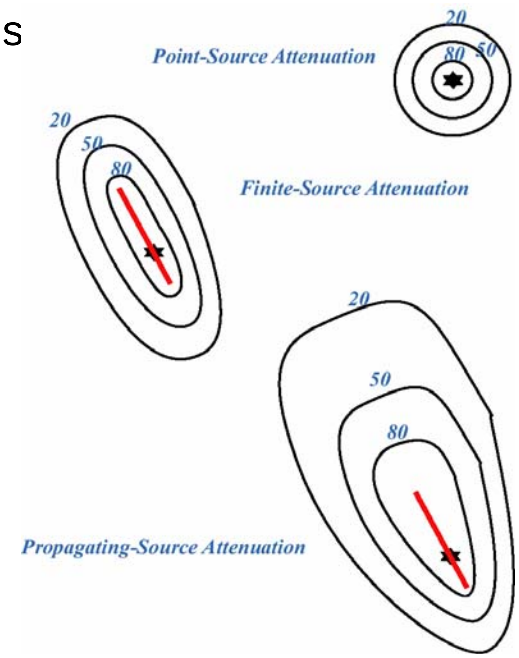
Directivity controlled

Fling controlled



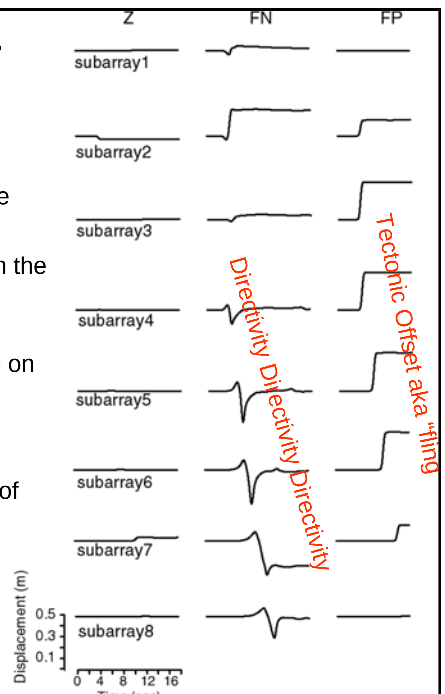
From Somerville et al., 1999

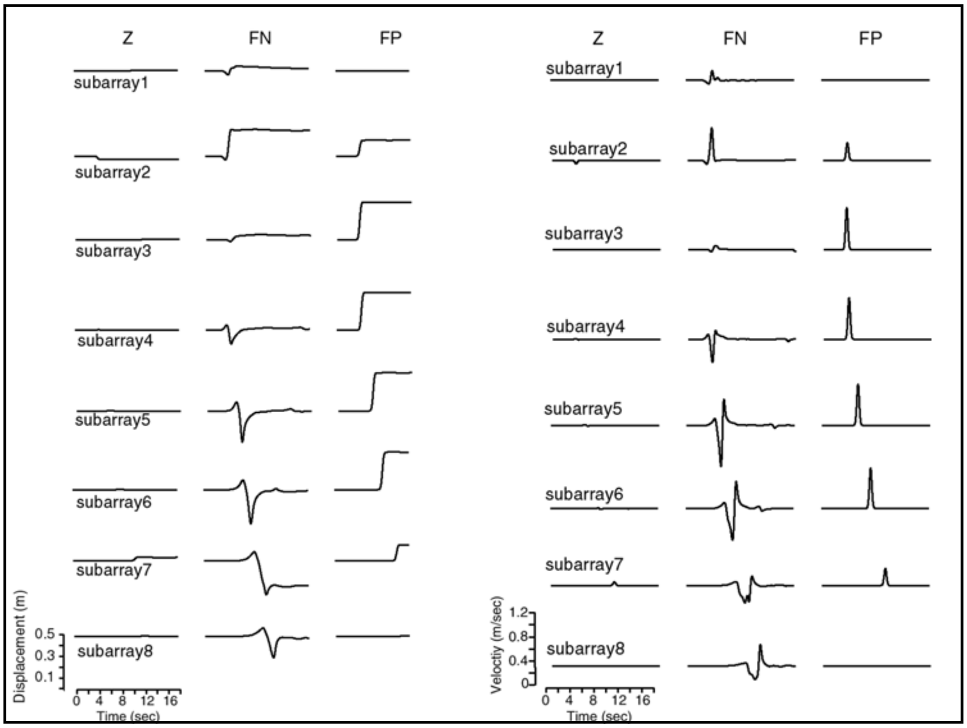
Attenuation Models

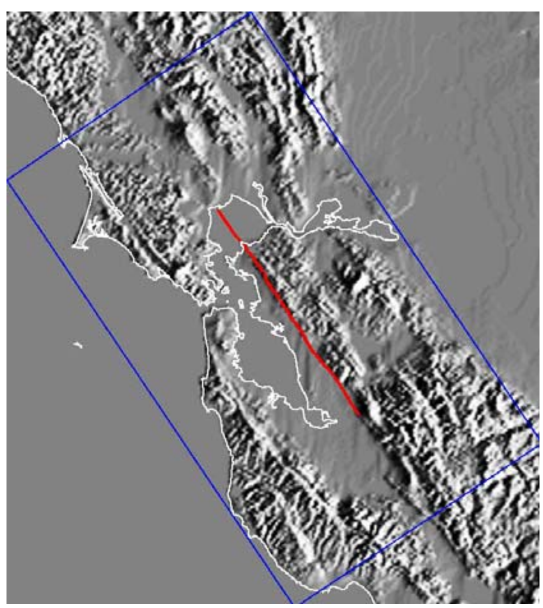


Near-Fault Ground Motions – Caltrans Project

- Unilateral, uniform slip, strike-slip rupture
- Computed using finite-differences
- Recording stations are located 15m from the fault
- Directivity builds displacement response on the FN component.
- The displacement (fling) on the FP component is constant along the length of the fault

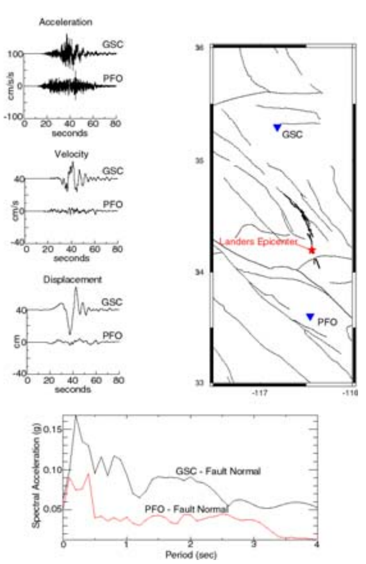


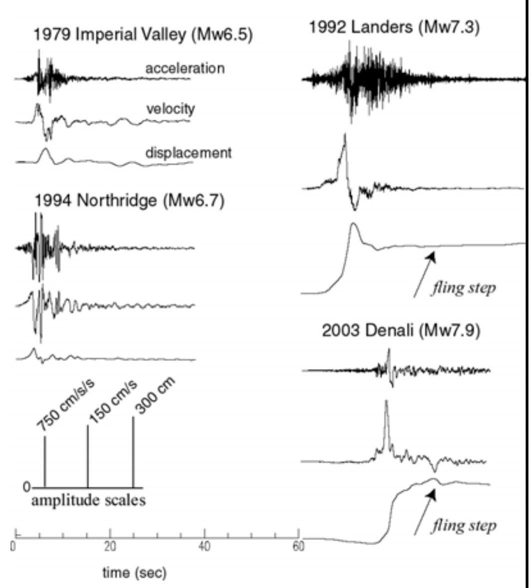

Z
FN
FP
subarray1
subarray2
subarray3
subarray4
subarray5
subarray6
subarray7
subarray8
Displacement (m)
0.5
0.3
0.1
0 4 8 12 16
Time (sec)
Z
FN
FP
subarray1
subarray2
subarray3
subarray4
subarray5
subarray6
subarray7
subarray8
Velocity (m/sec)
1.2
0.8
0.4
0
0 4 8 12 16
Time (sec)



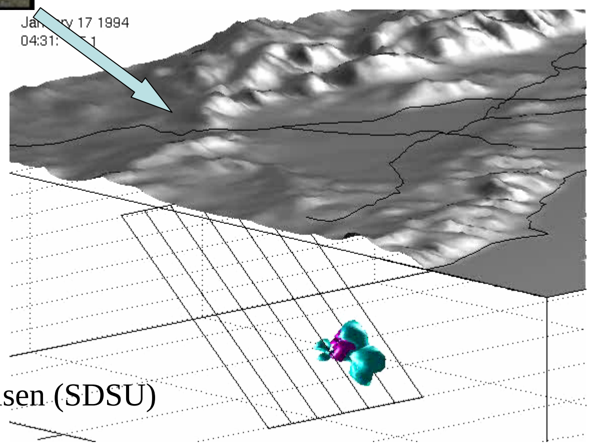
[1906 Rupture at Tomalas Bay]

Is Directivity & Fling Observed?





Not Just a Strike-Slip Phenomenon



Courtesy of Kim Olsen (SDSU)

Some Examples of Finite-Source Inversions

$$u_n(t,\vec{x}) = \int d\tau \iint \left[u_i(\vec{\zeta},\tau)\hat{\nu}_j C_{ijkl}\right] \cdot G_{nk,l}(\vec{x},t-\tau;\vec{\zeta},0)d\Sigma$$

$$u_n(t,\vec{x}) = \int \left[u_i(\tau)\hat{\nu}_j C_{ijkl}\Sigma\right] \cdot G_{nk,l}(\vec{x},t-\tau)d\tau$$

Spatial point-source

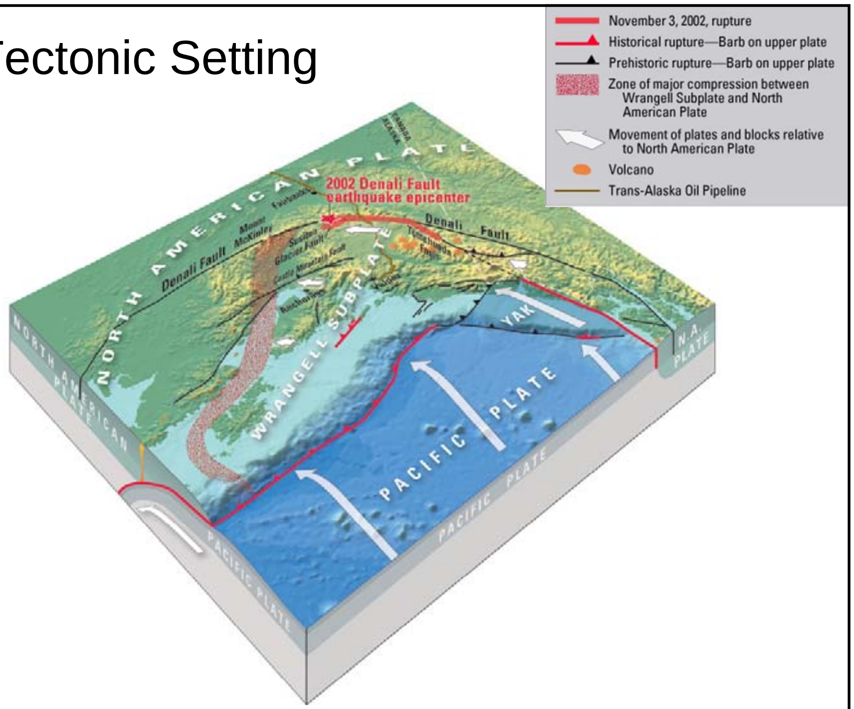
$$u_n(t,\vec{x}) = \left[u_i\hat{\nu}_j C_{ijkl}\Sigma\right] \cdot G_{nk,l}(\vec{x},t)$$

Spatial and temporal point-source

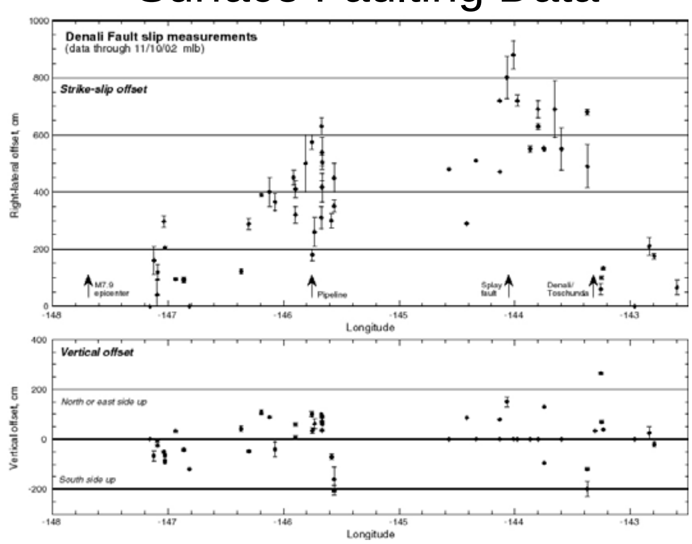
$$u_n(t,\vec{x}) = M_{ij} \cdot G_{ni,j}(\vec{x},t)$$

M has units of moment. i and j refer to directions of forces and derivatives. i.e. they define couples

Tectonic Setting

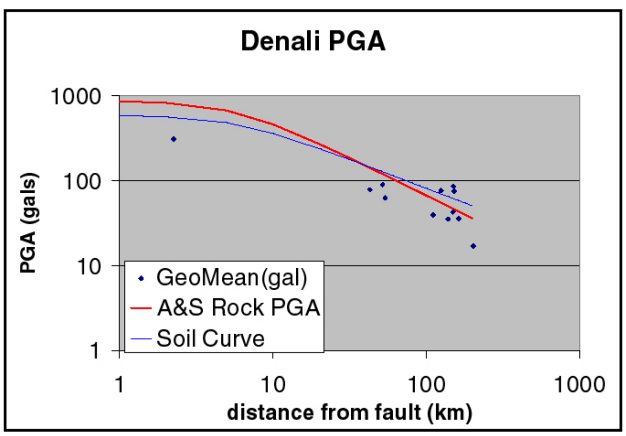


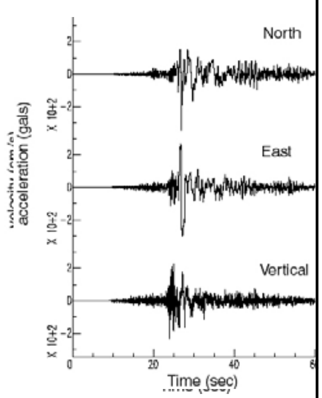
Surface Faulting Data



Surface faulting data was provided courtesy of the Denali Earthquake Geologic Field Team. The surface offsets indicate that the rupture process was principally right-lateral strike-slip, although some vertical offsets were observed.

Strong Ground Motions

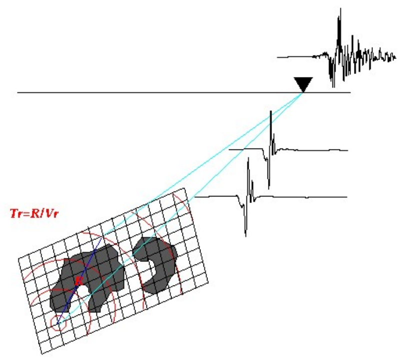




Kinematic Method

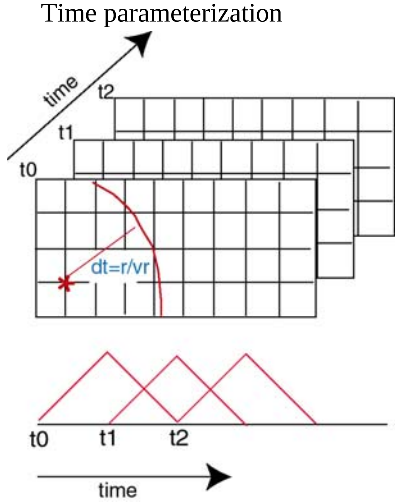
$$U_n(x,t) = \int d\tau \iint \left[u_i(\xi,t)\hat{\eta}_j c_{ijpq} \right] \cdot G_{np,q}(x,0;\xi,t-\tau)d\Sigma$$

- Extension of Hartzell and Heaton (1983)
  - Use broadband displacement waveform data (0.01 to 5.0 Hz)
  - Use horizontal GPS deformation data
  - Apply surface slip constraining equation
  - Apply slip positivity, seismic moment minimization, and smoothing constraining equations
- Solve for spatial and temporal distribution of fault slip

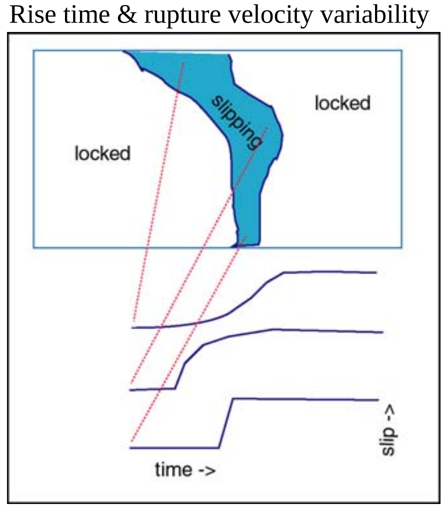


Kinematic Model Cont.

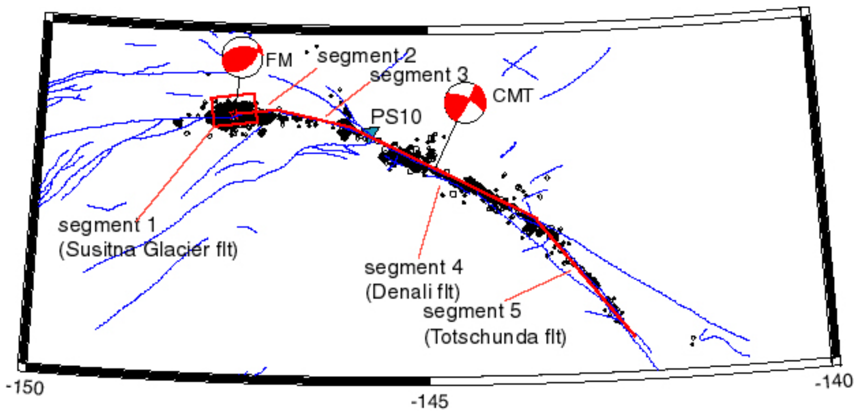
Time parameterization



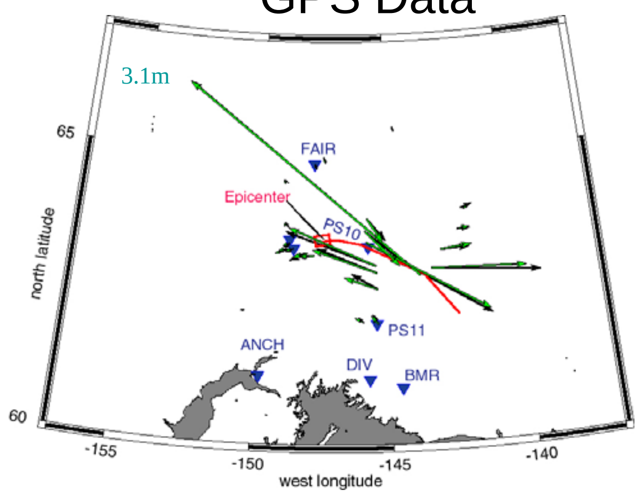
Rise time & rupture velocity variability



Construction of Kinematic Model for Denali Earthquake



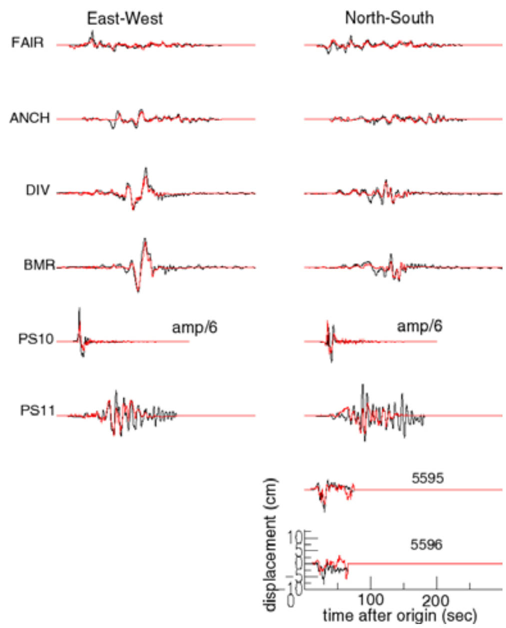
GPS Data



GPS data are from both the continuous Alaska Deformation Array, and campaign-mode observations of Hreinsdóttir et al. (2003). Black arrows show observed values and Green shows the values predicted by the model. Inverted triangles show the locations of the regional seismic stations. The red lines show the 5-segment fault model.

Regional Seismic Waveform Data

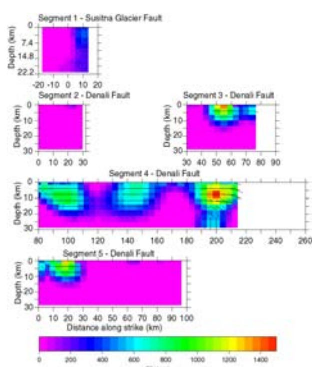
Observed (black) and synthetic displacement waveforms (red) are compared. Station PS10 was not used to invert for the slip model and the fit is a forward prediction.



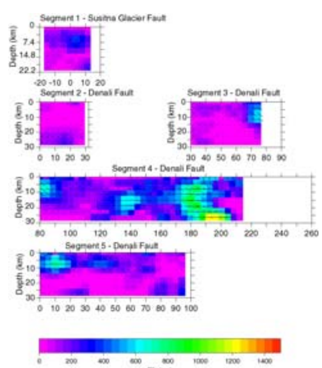
- Data Sources
  - US Geological Survey
  - Geophysical Institute, UA, Fairbanks
  - Alyeska
- Data from 8 stations were integrated to displacement, bandpass filtered between 0.01-0.5 Hz and resampled to 2 sps.

Kinematic Inversion Results

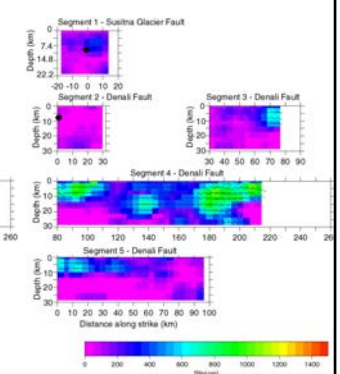
GPS Model



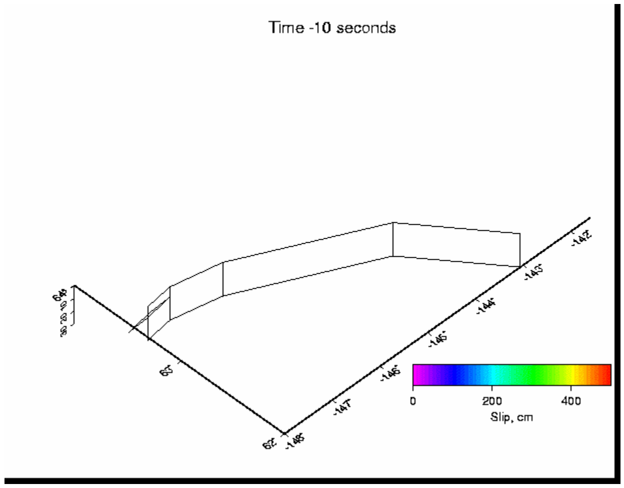
Seismic Model



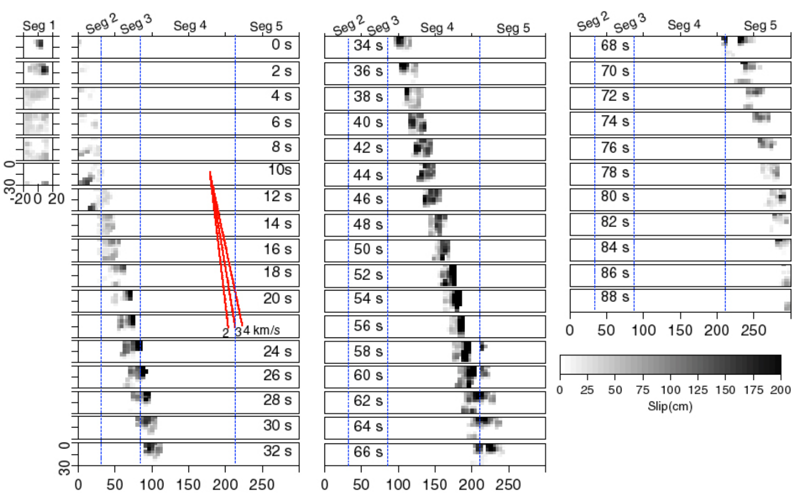
Combined Inversion Model



Rupture Kinematics

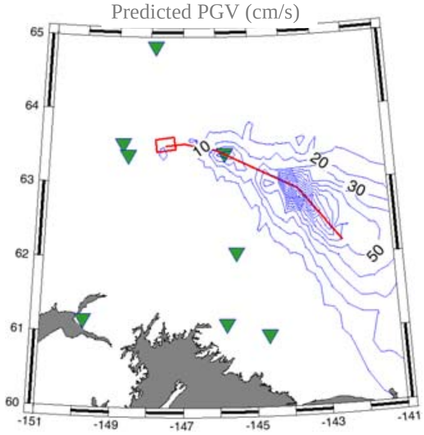


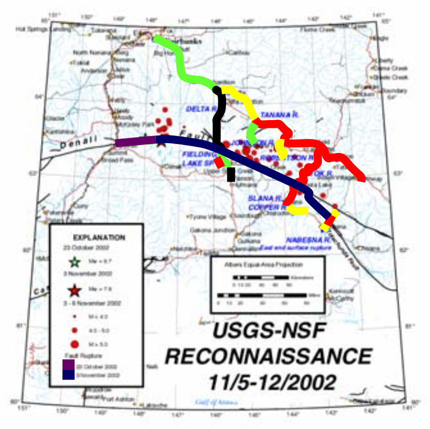
Rupture Kinematics



Estimated PGV vs. Observed Liquefaction

Predicted PGV (cm/s)





Realtime Finite-Source Applications