Earthquake Focal Mechanisms and Waveform Modeling

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The Dynamic Earth, USGS
The size of the event

Scalar seismic moment $M_o = \mu A u$

$\mu$ is the shear modulus of the rocks involved in the earthquake

$A$ is the area of the rupture along the fault (LxW)

$u$ is the average displacement on $A$. 
Type of faulting and slip direction

Strike, Dip, and Rake

- Strike, the azimuth of fault plane
- Dip, angle with the horizontal
- Rake, angle between slip vector and strike

(Shearer, 1999)
Extracting source parameters from waveforms?

- First motion polarity
- Waveform modeling of long period body and surface waves
First motion polarities

(a) Epicenter

(b) (c) Surface projection

(d) Fault-plane solution

(e) Normal fault earthquake

(f) (g) Surface projection

(h) Fault-plane solution

(i) Reverse fault earthquake

(j) (k) Surface projection

(l) Fault-plane solution
SOMETIMES FIRST MOTIONS DON’T CONSTRAIN FOCAL MECHANISM

Few nearby stations, so arrivals are near center of focal sphere

Mechanism has significant dip-slip components, so planes don’t cross near center of focal sphere

Additional information is obtained by comparing the observed body and surface waves to theoretical
Seismic signals

Epicentral Distance ($\Delta$)

Source + Path + Receiver response
Ground motion recorded on seismogram as a combination of factors

SYNTHETIC SEISMOGRAM AS CONVOLUTION

\[
\begin{align*}
\text{Source} & \quad x(t) & \ast & \quad \text{Structure} & \quad q(t) & \ast & \quad \text{Instrument} & \quad i(t) & = & \quad \text{Seismogram} & \quad u(t) \\
\end{align*}
\]

Frequency domain

\[
\begin{align*}
u(t) &= \frac{1}{2\pi} \int_{-\infty}^{\infty} U(\omega) e^{i\omega t} \, d\omega \\
U(\omega) &= \int_{-\infty}^{\infty} u(t) e^{-i\omega t} \, dt \\

s(t) &= w(t) \ast r(t) = \int_{-\infty}^{\infty} w(t - \tau) r(\tau) \, d\tau \\

u(t) &= x(t) \ast e(t) \ast q(t) \ast i(t) \\

U(\omega) &= X(\omega) \ E(\omega) \ Q(\omega) \ I(\omega)
\end{align*}
\]
Source signature around the epicenter

Area = $M_0$

$\theta = 90^\circ$

Fault

Rupture direction

Area = $M_0$

$\theta = 0^\circ$

Area = $M_0$

$\theta = 180^\circ$

Area = $M_0$

$\theta = 270^\circ$

Stein & Wysession, 2003
**Single force**

- $F_x$

**Single couple**

- $M_{xy}$

**Double couple**

- $M_{xy}$
- $M_{yx}$

- $-M_{yy'}$
- $M_{xx'}$

Stein & Wysession, 2003
Relation between fault planes and stress axes

- P-axis bisects dilatational quadrant
- T-axis bisects compressive quadrant
- B-axis intersection of both nodal planes

Stein & Wysession 2001
- (P) Pressure – Smallest moment
- (T) Tension – Largest moment
- (N) Null

- The eigenvalues are magnitude and the eigenvectors are the axes
- The axes and their eigenvalues are composed of strike, dip and rake
Moment Tensor Basics

- A moment tensor is a complete description of equivalent forces of a general seismic point source (Jost and Herrmann, 1989) in an elastic medium (Shearer, 1999).

\[
M = \begin{bmatrix}
M_{11} & M_{12} & M_{13} \\
M_{21} & M_{22} & M_{23} \\
M_{31} & M_{32} & M_{33}
\end{bmatrix}
\]

(Shearer, 1999)
Moment Tensors (9 components)
Figure 4.4-6: Selected moment tensors and their associated focal mechanisms.

<table>
<thead>
<tr>
<th>Moment tensor</th>
<th>Beachball</th>
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</thead>
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| \[
\frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}
\] | \[ \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \] |
| \[-\frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}\] | \[ \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix} \] |
| \[\frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & -1 \\ 0 & 0 & 0 \\ -1 & 0 & 0 \end{pmatrix} \] | \[\frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & -1 & 0 \end{pmatrix} \] |
| \[\frac{1}{\sqrt{2}} \begin{pmatrix} -1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \] | \[\frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \] |
| \[\frac{1}{\sqrt{6}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & -2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \] | \[\frac{1}{\sqrt{6}} \begin{pmatrix} -2 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \] |
| \[\frac{1}{\sqrt{6}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix} \] | \[\frac{1}{\sqrt{6}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix} \] |

Dahlen and Tromp, 1998
Earthquakes are mostly double-couple (DC)

Bodywave radiation patterns

P amplitude
S amplitude

ISO DC CLVD
Surface wave radiation patterns (showing DC only)

Julian et al., 1998
TELESEISMIC BODY WAVES

Initial portion of seismogram includes direct P wave and surface reflections pP and sP

Hence result depends crucially on earthquake depth and thus delay times

Powerful for depth determination

Gives information about rupture processes.

Figure 4.3-6: Cartoon of the paths of surface-reflected waves.

Stein & Wysession, 2003
Regional Waveform Modeling in Eastern Mediterranean Region

- The broadband network coverage is increasing
- The velocity models are getting improved
- Rupture direction and depth effects
Very complex regional wave propagation pattern
The WENA1.0 model is constructed by joining a regionalized crustal model of Western Eurasia and North Africa to a high-resolution sediment model and an a priori upper mantle model (Pasyanos, 2004).
Combining fundamental mechanisms with earth response (Green’s functions)

Three fundamental mode synthetics

Sum to produce any arbitrary mechanism

Dreger, 1999
Synthetic Seismogram

Vertical

Radial

Transverse
Regional Waveform Modeling
(Body + Surface Waves)

**Observed data**
- Offset correction (Removal of mean)
- Rotation for angle of radial direction
- Instrument response removal
- Low-pass filtering

**Synthetic data**
- Green’s functions for unit source
- Combined with three fundamental faults

**Modeling**
- Inversion (e.g. Dreger, 1996)
- Forward modeling (search the best fit for the range of strike, dip and rake) (Walter WR, 1992)
.. small event, good fit

Al-Thoubi et al., GSF 2007
EVID: 0  DATE: 2007 115 04:19:

Depth = 10 km
Mw = 5.07035
Moment = 5.01791509E+16
Strike = 262
Dip = 59
Rake = 75
Resources

- NEIC fast moment tensors - from teleseismic P waveforms
  [NEIC fast moment tensors](http://gldss7.cr.usgs.gov/neis/FM/fast_moment.html)

- Harvard CMT solutions - Centroid moment-tensor
  (from teleseismic long period body waves)
  [Harvard CMT solutions](http://www.seismology.harvard.edu/projects/CMT/)

- EMSC rapid source parameter determination - European-Mediterranean Seismological Centre - uses P & S waves – results in 24 hours
  [EMSC rapid source parameter determination](http://www.emsc-csem.org/)

- NEIC broadband depths and fault-plane solutions
  [NEIC broadband depths and fault-plane solutions](http://neic.usgs.gov/neis/nrg/bb_processing.html)

- Swiss (ETHZ) moment tensor solutions – Regional moment tensor inversion