6: EARTHQUAKE FOCAL MECHANISMS AND PLATE MOTIONS

Hebgen Lake, Montana 1959 Ms 7.5

Owens Valley, California 1872 Mw ~7.5

Stein & Wysession, 2003
EARTHQUAKE LOCATIONS INDICATE PLATE BOUNDARIES
EARTHQUAKE MECHANISMS SHOW MOTION
Locations map plate boundary zones & regions of intraplate deformation even in underwater or remote areas

Focal mechanisms show motion type & direction

Slip & seismic history show deformation rate

Depths constrain thermo-mechanical structure of lithosphere

San Andreas Fault, Carrizo Plain

PACIFIC

NORTH AMERICA

36 mm/yr
1989 LOMA PRIETA, CALIFORNIA EARTHQUAKE
MAGNITUDE 7.1 ON THE SAN ANDREAS

Topic 6
1989 LOMA PRIETA, CALIFORNIA EARTHQUAKE

62 deaths, $6B damage

The two level Nimitz freeway collapsed along a 1.5 km section in Oakland, crushing cars

Freeway had been scheduled for retrofit to improve earthquake resistance
Houses collapsed in the Marina district of San Francisco

Shaking amplified by low velocity landfill
Arrival time of seismic waves at seismometers at different sites is first used to find the location and depth of the earthquake.

Amplitudes and shapes of radiated seismic waves used to study:
- size of the earthquake
- geometry of the fault on which it occurred
- direction and amount of slip

Seismic waves give an excellent picture of the kinematics of faulting, needed to understand regional tectonics.

They contain much less information about the actual physics, or dynamics, of faulting.
Seismic waves: Compressional (P) and Shear (S) waves

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Davidson et al
This will also show generalized seismic-wave behavior: **P** (compressive) & **S** (shearing) motion in the ground perpendicular to the direction of wave travel.
SEISMIC RAYS TRAVEL VARIOUS PATHS THROUGH THE EARTH

Click for animation
Snell’s law in a flat medium: \( \frac{\sin i_1}{v_1} = \frac{\sin i_2}{v_2} \)

Hence ray parameter \( p = \frac{\sin i}{v} \) is constant along a ray

Velocity increases with depth, so \( v_2 > v_1 \) and \( i_2 > i_1 \)
SNELL’S LAW DESCRIBES MANY FAMILIAR EFFECTS
Class Question 23: Snell’s law causes rays to change direction relative to the normal, the perpendicular to the interface between the two materials with different wave speeds.

Compare the direction of this change for the seismic wave and raindrop examples. Is there a difference and why?
Seismic waves: body and surface waves
EARTHQUAKE LOCATION

Least squares fit to travel times

Epicenters (surface positions) better determined than depths or hypocenters (3D positions) because seismometers only on surface
MAGNITUDE – SIZE OF EARTHQUAKE

Body wave magnitude:

\[ m_b = \log(A/T) + Q(h, \Delta) \]

\( A \) is the ground motion amplitude in microns after the effects of the seismometer are removed

\( T \) is the wave period in seconds

\( Q \) is an empirical term depending on the distance and focal depth.

Amplitude

Period 0.3-3s

Charles Richter 1900 - 1985
Surface wave magnitude (measured using the largest amplitude, zero to peak, of the surface waves):

\[ M_s = \log(A/T) + 1.66 \log \Delta + 3.3 \]  
(general form)

\[ M_s = \log A_{20} + 1.66 \log \Delta + 2.0 \]  
(for 20 second period Rayleigh waves)

(\(\Delta\) is in degrees)
COMPARE EARTHQUAKES USING SEISMIC MOMENT $M_0$

$M_0 = \mu \bar{D}S$

$\bar{D} =$ average slip (dislocation)

$S =$ "average" fault area

<table>
<thead>
<tr>
<th>Location</th>
<th>$M_0$</th>
<th>$M_s$</th>
<th>Slip</th>
</tr>
</thead>
<tbody>
<tr>
<td>San Fernando, 1971</td>
<td>$1.2 \times 10^{26}$</td>
<td>6.6</td>
<td>1.4 m</td>
</tr>
<tr>
<td>San Francisco, 1906</td>
<td>$5.4 \times 10^{27}$</td>
<td>7.8</td>
<td>4 m</td>
</tr>
<tr>
<td>Alaska, 1964</td>
<td>$5.2 \times 10^{29}$</td>
<td>8.4</td>
<td>7 m</td>
</tr>
</tbody>
</table>

Magnitudes, moments (dyn-cm), fault areas, and fault slips for several earthquakes

Alaska & San Francisco differ much more than $M_s$ implies

$M_0$ more useful measure

Units: dyne-cm or Nt-M

Directly tied to fault physics

Use moment magnitude $M_w$

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Bigger earthquakes involve more slip on larger faults.

Longer shaking from longer fault.
LARGER EARTHQUAKES GENERALLY HAVE LONGER FAULTS AND LARGER SLIP

M7, ~ 100 km long, 1 m slip; M6, ~ 10 km long, ~ 20 cm slip

Important for tectonics, earthquake source physics, hazard estimation

Wells and Coppersmith, 1994

Figure 4.6-7: Empirical relations between slip, fault length, and moment.
Approximate fault as planar with geometry represented by:

Three angles: strike \( \phi_f \), dip \( \delta \), slip \( \lambda \), or

Two orthogonal unit vectors: fault normal \( \mathbf{n} \) and slip vector \( \mathbf{d} \)

Coordinate axes chosen with \( x_3 \) vertical and \( x_1 \) oriented along the fault in the plane of the earth's surface, such that the fault dip angle, \( \delta \) measured from the \(-x_2\) axis, is \(< 90\). Slip angle \( \lambda \) is measured between the \( x_1 \) axis and \( \mathbf{d} \) in the fault plane.

\( \phi_f \) is the strike of the fault measured clockwise from north.
Most earthquakes consist of some combination of these motions, and have slip angles between these values.
Class Question 24: For each of these plate boundaries, which fault type would we expect and which plate is which?

a) The San Andreas fault

b) The Cascadia (Pacific Northwest) subduction zone

a) The Mid-Atlantic ridge
Fault may curve, and require 3D description.

Rupture can consist of sub-events on different parts of the fault with different orientations.

Can be treated as superposition of simple events.

ACTUAL EARTHQUAKE FAULT GEOMETRIES CAN BE MUCH MORE COMPLICATED THAN A RECTANGLE

1992 Landers, California Mw 7.3
Seismograms recorded at various distances and azimuths used to study geometry of faulting during an earthquake, known as the focal mechanism.

Use fact that the pattern of radiated seismic waves depends on fault geometry.

Simplest method relies on the first motion, or polarity, of body waves.

More sophisticated techniques use waveforms of body and surface waves.
Polarity of first P-wave arrival varies between seismic stations in different directions.

First motion is compression for stations located such that material near the fault moves “toward” the station, or dilatation, where motion is “away from” the station.

When a P wave arrives at a seismometer from below, a vertical component seismogram records up or down first motion, corresponding to either compression or dilatation.
First motions define four quadrants; two compressional and two dilatational.

Quadrants separated by nodal planes: the fault plane and auxiliary plane perpendicular to it.

From the nodal planes fault geometry is known.

Because motions from slip on the actual fault plane and from slip on the auxiliary plane would be the same, first motions alone cannot resolve which is the actual fault plane.
FIRST MOTIONS ALONE CANNOT RESOLVE WHICH PLANE IS THE ACTUAL FAULT PLANE

Sometimes geologic or geodetic information, such as trend of a known fault or observations of ground motion, indicates the fault plane.

Often, aftershocks following the earthquake occur on and thus delineate the fault plane.

If the earthquake is large enough, the finite time required for slip to progress along the fault causes variations in the waveforms observed at different directions from the fault, so these directivity effects can be used to infer the fault plane.

Click for animation 1989 Loma Prieta, California Ms 7.1
SEISMIC RAYS BEND DUE TO VELOCITY INCREASING WITH DEPTH

Snell’s law for ray path in sphere places arrivals recorded at distant stations where they would be on hemisphere just below earthquake.

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Ray parameter

\[ p = \frac{r \sin i}{v} = \frac{dT}{d\Delta} \]

Constant along the ray
Class Question 25: Take a ball - we’re using tennis balls in the picture – and mark quadrants such that two are colored black (compressional). Hold it over your head and look up at it. For the assignment, upload a picture of yourself with the ball.
Although the focal mechanisms look different, they reflect the same four-lobed P-wave radiation pattern.

However, because the fault plane and slip direction are oriented differently relative to the earth's surface, the projections of the radiation pattern lobes on the lower focal hemisphere differ.

To see this, mark the P wave quadrants on a ball, look up at it from below, and rotate it.
FOCAL MECHANISMS FOR DIFFERENT FAULTS

All have same N-S striking plane, but with slip angles varying from pure thrust, to pure strike-slip, to pure normal.

- $\lambda = 90^\circ$: Pure dip-slip (thrust)
- $\lambda = 120^\circ$: Mostly dip-slip with some strike-slip
- $\lambda = 150^\circ$: Mostly strike-slip with some dip-slip
- $\lambda = 180^\circ$: Pure strike-slip (right lateral)
- $\lambda = 210^\circ$: Mostly strike-slip with some dip-slip
- $\lambda = 240^\circ$: Mostly dip-slip with some strike-slip
- $\lambda = 270^\circ$: Pure dip-slip (normal)

Stein & Wysession, 2003
Slow Mid-Atlantic Ridge has earthquakes on both active transform and ridge segments. Strike-slip faulting occurs on a plane parallel to the transform. On ridge segments, normal faulting occurs with nodal planes parallel to the ridge trend, showing extension in the spreading direction.

Fast East Pacific Rise has only strike-slip earthquakes on the transforms. No normal faulting since there is no axial alley.
MECHANISMS SHOW BOTH NOMINAL PLATE BOUNDARY

Aleutian Trench: thrust
San Andreas: strike slip
Gulf of California: normal & strike slip

AND OTHER BOUNDARY ZONE DEFORMATION

Los Angeles Basin: thrust
Basin & Range: normal

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TRENCH-NORMAL CONVERGENCE - ALEUTIAN TRENCH 54 mm/yr

PACIFIC wrt NORTH AMERICA pole

BASIN & RANGE EXTENSION

STRIKE SLIP - SAN ANDREAS

LA BASIN SHORTENING

EXTENSION - GULF OF CALIFORNIA

Topic 6
Caused some of the highest ground accelerations ever recorded. It illustrates that even a moderate magnitude earthquake can do considerable damage in a populated area. Although the loss of life (58 deaths) was small due to earthquake-resistant construction the $20B damage makes it the most costly earthquake to date in the U.S.
EXTENSION
TERCEIRA RIFT

STRIKE-SLIP
GLORIA TRANSFORM

OBLIQUE CONVERGENCE
NORTH AFRICA

NUBIA

NORTH AMERICA

EURASIA

Argus et al., 1989
MECHANISMS & FAULTS SHOW CONVERGENCE DIRECTION

Meghraoui et al. (2004)
NUBIA-SOMALIA SPREADING

Normal fault mechanisms show E-W extension across East African Rift

Rift Valley, Lake Bogoria, Kenya. Area is 30kmx30km and contains numerous faults on the downthrown side of a large bounding fault with maximum displacement ~1km.
Class Question 26: A destructive magnitude 6.3 earthquake struck near L'Aquila, Italy, in April 2009. The area, part of an active seismic zone along the Appennine mountain range, has had large earthquakes in the past.

1) Describe the focal mechanisms in areas a), b), and c)

2) Suggest a model of plate geometry and motions for what's going on to cause the earthquakes.