Global seismology: The earthquake source

Earthquake location

Earthquake focus:
Latitude, longitude, depth

Earthquake epicenter:
Latitude, longitude

Earthquakes occur on fault planes, energy is released from a volume of rock as it slips. However, from far away we consider an earthquake to be a point source: latitude, longitude, depth
Locating earthquakes

For an earthquake at the surface there are three unknowns:
- latitude, longitude, origin time

need observations of seismic arrival times at three stations

Station at distance $r_1$:
- P-wave arrives at: $t_0 + r_1/\alpha$
- S-wave arrives at: $t_0 + r_1/\beta$

With increasing station distance the S-P time increases:

$$t_{S-P} = \frac{r_1}{\beta} - \frac{r_1}{\alpha}$$

Given the S-P time we can calculate the epicentral distance $r_1$.
Locating earthquakes

Given the S-P time at 3 stations we can locate the earthquake

\[ t_{1,S-P} = \frac{r_1}{\beta} - \frac{r_1}{\alpha} \]

\[ t_{2,S-P} = \frac{r_2}{\beta} - \frac{r_2}{\alpha} \]

\[ t_{3,S-P} = \frac{r_3}{\beta} - \frac{r_3}{\alpha} \]

Solve for latitude, longitude and origin time

Complications
- The Earth is not flat and we can only estimate \( \alpha \) and \( \beta \)
- There is an error associated with the arrival time measurement
- We also need to determine the focal depth

⇒ Use arrival times at many stations around the globe
Earthquake depth

To estimate depth we need:
- Seismic station above the earthquake
- Depth phases e.g. pP

\[ FR = \frac{\alpha}{2} \left( t_{pp} - t_p \right) \]

\[ h = EF = FR \sin \theta \]
Earthquake depth distribution

Indicate different patterns of deformation
- ridges
- subduction

Magnitude ...describes the size of an earthquake

Richter magnitude:

$$M_L = \log A - 2.48 + 2.76 \log \Delta$$

Empirical relation for:
- Local earthquakes in southern California
- Amplitude measured on a Wood-Anderson seismometer
\( m_b \) and \( M_s \)

**Body-wave magnitude**

\[
m_b = \log_{10} \left( \frac{A}{T} \right)_{\text{max}} + q(\Delta, h)
\]

**Surface-wave magnitude**

\[
M_s = \log_{10} \left( \frac{A}{T} \right)_{\text{max}} + 1.66 \log_{10} \Delta + 3.3
\]

Magnitude as a discriminator

\( M_s \) and \( m_b \) estimates are usually different for a given earthquake

- \( m_b \) measures the amplitude of the P-wave
- \( M_s \) measures the amplitude of the surface wave

**Nuclear explosions**

- Do not excite surface waves very well
- Use \( m_b \) vs. \( M_s \) to discriminate

Figure 4.10. A plot of surface wave magnitude \( M_s \) against body wave magnitude \( m_b \) for 26 nuclear explosions (solid circles) and 99 earthquakes (open circles), all in Eurasia. Solid line is the discriminant line \( m_b = 2.87 + 0.61 M_s \). Nuclear explosions are less efficient at generating surface waves than earthquakes with the same body-wave magnitude. (After Nowroozi 1986.)

How else can we discriminate?
Magnitude-frequency relation

Gutenberg-Richter relation:
\[ \log N = a - bM \]

Global average for \( b \) is \( \sim 1 \)
- There are ten times as many magnitude 4 as there are magnitude 5

<table>
<thead>
<tr>
<th>Earthquake magnitude</th>
<th>Number per year</th>
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<tbody>
<tr>
<td>( \geq 8.0 )</td>
<td>0–1</td>
</tr>
<tr>
<td>7-7.9</td>
<td>18</td>
</tr>
<tr>
<td>6-6.9</td>
<td>120</td>
</tr>
<tr>
<td>5-5.9</td>
<td>800</td>
</tr>
<tr>
<td>4-4.9</td>
<td>6,200</td>
</tr>
<tr>
<td>3-3.9</td>
<td>49,000</td>
</tr>
<tr>
<td>2-2.9</td>
<td>( \sim 350,000 )</td>
</tr>
<tr>
<td>1-1.9</td>
<td>( \sim 3,000,000 )</td>
</tr>
</tbody>
</table>

Earthquake energy

To measure all the energy released in an earthquake we must integrate over space and time ...difficult!

We can approximately relate magnitude to energy:
\[ \log_{10} E = 5.24 + 1.44 M_s \]

- A magnitude 5 earthquake releases about 30 times as much energy as a magnitude 4
- Even when you add together the energy release from all the small earthquakes, it is small compared to the one big event
Ground motion

Earthquake damage

How destructive is an earthquake?
- Earthquake size: magnitude and energy release
- Distance from populated regions
- Building standards

<table>
<thead>
<tr>
<th>Year</th>
<th>Epicenter</th>
<th>$M_L$</th>
<th>$M_c$</th>
<th>Fatalities</th>
<th>Comments</th>
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</thead>
<tbody>
<tr>
<td>1906</td>
<td>San Francisco, Calif.</td>
<td>8.3</td>
<td>7.9</td>
<td>700</td>
<td>San Francisco fire</td>
</tr>
<tr>
<td>1908</td>
<td>Messina, Italy</td>
<td>7.5</td>
<td>—</td>
<td>120,000</td>
<td></td>
</tr>
<tr>
<td>1923</td>
<td>Kamto, Japan</td>
<td>8.2</td>
<td>7.9</td>
<td>143,000</td>
<td></td>
</tr>
<tr>
<td>1960</td>
<td>Chile</td>
<td>8.5</td>
<td>9.5</td>
<td>3,700</td>
<td></td>
</tr>
<tr>
<td>1960</td>
<td>Agadir, Morocco</td>
<td>5.9</td>
<td>—</td>
<td>14,000</td>
<td></td>
</tr>
<tr>
<td>1964</td>
<td>Alaska</td>
<td>8.6</td>
<td>9.2</td>
<td>131</td>
<td></td>
</tr>
<tr>
<td>1970</td>
<td>Peru</td>
<td>7.8</td>
<td>—</td>
<td>46,000</td>
<td></td>
</tr>
<tr>
<td>1971</td>
<td>San Fernando, Calif.</td>
<td>6.5</td>
<td>—</td>
<td>65</td>
<td>Great rock slide</td>
</tr>
<tr>
<td>1973</td>
<td>Hoeheng, China</td>
<td>7.4</td>
<td>—</td>
<td>~100</td>
<td>Predicted</td>
</tr>
<tr>
<td>1976</td>
<td>Tangshan, China</td>
<td>7.8</td>
<td>—</td>
<td>&gt;200,000</td>
<td>Not predicted</td>
</tr>
<tr>
<td>1980</td>
<td>El Asnam, Algeria</td>
<td>7.7</td>
<td>—</td>
<td>3,500</td>
<td></td>
</tr>
<tr>
<td>1985</td>
<td>Mexico</td>
<td>7.9</td>
<td>8.0</td>
<td>9,500</td>
<td></td>
</tr>
<tr>
<td>1989</td>
<td>Loma Prieta, Calif.</td>
<td>7.1</td>
<td>—</td>
<td>62</td>
<td></td>
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</tbody>
</table>
Fault planes

Stress builds deforming the rock

Rock ruptures and slides releasing stress

Physics and chemistry of the Earth’s interior – The earthquake source

Fault planes solutions

First motion

The first motion direction observed at many stations around an earthquake can tell us the type of fault and orientation of the fault planes.

Consider a strike-slip earthquake on the San Andreas Fault:

Figure 4.18. (a) Plane view of an earthquake strike-slip fault. A, B, C, D, E, and F are six seismograph stations which recorded the earthquake. The first P-wave recorded at stations A, C, and E would be compressional (positive, up); the first P-wave at stations B and F would be dilatational (negative, down); station D would record no first P-wave arrival. (b) The distribution of polarity of the first P-wave motion falls into four quadrants. The lobes indicate the relative magnitude of the first motion at any location. Arrow shows the magnitude at location C.
**Fault plane solutions**

**First motion within a sphere**

In spherical Earth we plot the lower hemisphere

![Schematic diagram of first motion within a sphere showing fault plane solutions.](image)

**Indicate fault type**

...and stress regime

![Diagram showing different types of faults and their stress regimes.](image)

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Figure 4.19 (a) Schematic cross section through the earth, centre $O$. The focal sphere is an imaginary small sphere centred on the earthquake focus $C$. The lower focal hemisphere is stippled. The ray path for the first arrival at seismograph $S$ intersects the lower focal hemisphere at an angle from the vertical. (b) Projection of the lower focal hemisphere onto a horizontal plane. $N$ is north. Seismograph $S$ plots at $i$, $d$, where $i$ is the angle of incidence shown in (a) and $d$ is the geographic azimuth of $S$ from the earthquake focus. The polarity of the first motion recorded at $S$ is then plotted at $i$, $d$. (c) Fault-plane solution for the strike-slip earthquake shown in Figure 4.1a. Compression, positive first motion, shaded dilatation, negative first motion, white.

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Figure 4.20 A fault-plane solution for a strike-slip earthquake. The strike and dip of the nodal planes are given by $a$ and $d$. The strike-slipping nodal plane was chosen as the fault plane because the earthquake epicentre lies on an east-striking transform fault. The fault plane is not vertical in this instance; it is dipping at $W$. [after Sykes (1967).]

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Fig. 3.36 The three main types of fault and their focal mechanisms. Left: the orientations of such faults plane and the principal deviatomic stresses, $\sigma_1$, $\sigma_2$, and $\sigma_3$. Right: focal mechanisms and orientations of $P$- and $T$-axes.
Fault plane solutions
Mid-ocean ridges

Fig. 3.38 Fault-plane solutions for earthquakes along the Mid-Atlantic oceanic Ridge, showing the prevalence of extensional tectonics with normal faulting in the axial zone of the spreading center (based on data from Huang et al., 1986).

Fault plane solutions
Subduction zones

Fig. 3.39 Fault plane solutions for selected large shallow earthquakes in the subduction zone along the west coast of Mexico (after Stegk et al., 1984). The focal mechanisms indicate low-angle overthrusting, as the Cocos plate is subducted to the northeast under Mexico.
Summary

Earthquake locations tell us where the Earth is deforming
- Along tectonic plate boundaries
- Ridges are shallow, subduction is deep (earthquakes to ~700 km)

Earthquake focal mechanisms indicate the stress regime
- At mid-ocean ridges: normal faults $\rightarrow$ extension $\rightarrow$ new plate formation
- At subduction zones: reverse faults $\rightarrow$ compression $\rightarrow$ plate destruction
- At transform faults: strike-slip faults $\rightarrow$ conservation

Magnitude tells us about the amount of energy released

Plus Earthquake energy propagates through the Earth.
By recording it around the Earth we can “image” the Earth’s internal structure …next lecture