EPS 20: Earthquakes in your backyard & tsunamis

Summer Session 2016

Horst Rademacher

Lect 4: Earthquakes in the US
Man-made Earthquakes

http://seismo.berkeley.edu/~horst/summer2016.html
Faults, Earthquakes and Plate Tectonics

Fault: Boundary Line between two plates
Accumulates mechanical stress from tectonic movement

How does the accumulated stress gets released?

Two possibilities:

Aseismic Creep
Coseismic Slip
Recap from last lecture II:

Steady creep
approx. 0.5 cm/year
No earthquakes
Difference between Creep and an Earthquake?

Aseismic Creep: Accumulated strain gets released continuously at low rate –

no or very little seismic hazard

Earthquake: Sudden release of large amount of accumulated strain –

large seismic hazard
Recap from last lecture IV:

Elastic rebound theory

Harry F. Reid
1859-1944
Johns Hopkins U.
### Recap from last lecture V:

<table>
<thead>
<tr>
<th>EQ</th>
<th>M</th>
<th>Slip [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>South Napa (2014)</strong></td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>Coalinga (1983)</td>
<td>6.5</td>
<td>0.9</td>
</tr>
<tr>
<td>Loma Prieta (1989)</td>
<td>7.1</td>
<td>1.6 ± 0.3</td>
</tr>
<tr>
<td>San Francisco (1906)</td>
<td>7.9</td>
<td>6.1 - 7.8</td>
</tr>
<tr>
<td>Maule (Chile) 2010</td>
<td>8.8</td>
<td>19</td>
</tr>
<tr>
<td><strong>Tohoku (2011)</strong></td>
<td>9</td>
<td>&gt;50</td>
</tr>
<tr>
<td>Alaska (1964)</td>
<td>9.2</td>
<td>&gt;30</td>
</tr>
<tr>
<td>Chile (1960)</td>
<td>9.5</td>
<td>90 ± 4.2</td>
</tr>
</tbody>
</table>

![Graph showing the relationship between moment magnitude (M) and average displacement (AD) for 56 EQs. The equation M = 6.93 + 0.82*\log(AD) is shown.](graph.png)
Recap from last lecture VI:

Coseismic Slip 1m at depth
a few cm on surface

South Napa EQ
24 Aug 14, M=6.0
Any Questions?

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Earthquakes in your backyard & tsunamis

EQ in North America
The strongest earthquakes in North America

<table>
<thead>
<tr>
<th>Location</th>
<th>Date UTC</th>
<th>magnitude</th>
<th>Lat.</th>
<th>Long.</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Chile</td>
<td>1960 05 22</td>
<td>9.5</td>
<td>-38.29</td>
<td>-73.05</td>
<td>Kanamori, 1977</td>
</tr>
<tr>
<td>3. Off the West Coast of Northern Sumatra</td>
<td>2004 12 26</td>
<td>9.1</td>
<td>3.30</td>
<td>95.78</td>
<td>Park et al., 2005</td>
</tr>
<tr>
<td>4. Near the East Coast of Honshu, Japan</td>
<td>2011 03 11</td>
<td>9.0</td>
<td>38.322</td>
<td>142.369</td>
<td>PDE</td>
</tr>
<tr>
<td>5. Kamchatka</td>
<td>1952 11 04</td>
<td>9.0</td>
<td>52.76</td>
<td>160.06</td>
<td>Kanamori, 1977</td>
</tr>
<tr>
<td>6. Offshore Maule, Chile</td>
<td>2010 02 27</td>
<td>8.8</td>
<td>-35.846</td>
<td>-72.719</td>
<td>PDE</td>
</tr>
<tr>
<td>7. Off the Coast of Ecuador</td>
<td>1906 01 31</td>
<td>8.8</td>
<td>1.0</td>
<td>-81.5</td>
<td>Kanamori, 1977</td>
</tr>
<tr>
<td>8. Rat Islands, Alaska</td>
<td>1965 02 04</td>
<td>8.7</td>
<td>51.21</td>
<td>178.50</td>
<td>Kanamori, 1977</td>
</tr>
<tr>
<td>9. Northern Sumatra, Indonesia</td>
<td>2005 03 28</td>
<td>8.6</td>
<td>2.08</td>
<td>97.01</td>
<td>PDE</td>
</tr>
<tr>
<td>10. Assam - Tibet</td>
<td>1950 08 15</td>
<td>8.6</td>
<td>28.5</td>
<td>96.5</td>
<td>Kanamori, 1977</td>
</tr>
<tr>
<td>11. Off the west coast of northern Sumatra</td>
<td>2012 04 11</td>
<td>8.6</td>
<td>2.311</td>
<td>93.063</td>
<td>PDE</td>
</tr>
<tr>
<td>12. Andreeof Islands, Alaska</td>
<td>1957 03 11</td>
<td>8.6</td>
<td>51.56</td>
<td>-175.39</td>
<td>Johnson et al., 1994</td>
</tr>
<tr>
<td>13. Southern Sumatra, Indonesia</td>
<td>2007 09 12</td>
<td>8.5</td>
<td>-4.438</td>
<td>101.367</td>
<td>PDE</td>
</tr>
<tr>
<td>14. Banda Sea, Indonesia</td>
<td>1938 02 01</td>
<td>8.5</td>
<td>-5.05</td>
<td>131.62</td>
<td>Okal and Reymond, 2003</td>
</tr>
<tr>
<td>15. Kamchatka</td>
<td>1923 02 03</td>
<td>8.5</td>
<td>54.0</td>
<td>161.0</td>
<td>Kanamori, 1988</td>
</tr>
<tr>
<td>17. Kuril Islands</td>
<td>1963 10 13</td>
<td>8.5</td>
<td>44.9</td>
<td>149.6</td>
<td>Kanamori, 1977</td>
</tr>
</tbody>
</table>
Earthquakes in your backyard

EQ in North America

Alaska

Kamchatka Peninsula

Kuril Islands

Aleutian Islands
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EQ in North America

Alaska
Historic Regional Seismicity

Alaska

Depth
- 0-33 km
- 33-75 km
- 75-125 km
- 125+ km

Alaska Peninsula and Aleutian Islands
Largest EQ ever recorded in US: M=9.2, 27 Mar 1964

Alaska

Anchorage, 4th Avenue
EQ in North America

Alaska

Subsidence and uplift:

>30m

Suggested reading:
http://seismo.berkeley.edu/blog/seismoblog.php/2015/03/27/today-in-earthquake-history-alaska
Denali EQ, Alaska
3 Nov 2002, M=7.9
rupture length on surface 209 mi

Strongest EQ in interior of Alaska

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EQ in North America

Denali fault

Nenana River

Parks Highway

11/3 M 7.9
10/23 M 6.7
EQ in North America
Denali Fault is right lateral strike slip
Any Questions?

http://seismo.berkeley.edu/~horst/summer2016.html
Three Main Shocks

1. **December 16, 1811** - Magnitude ~7.5
2. **January 23, 1812** - Magnitude ~ 7.3
3. **February 7, 1812** - Magnitude ~ 7.5

**Changed the course of the Mississippi River**

**Created Reelfoot Lake, TN**
New Madrid Seismic Zone is an old Rift zone 160 million years
Any Questions?

http://seismo.berkeley.edu/~horst/summer2016.html

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EQ along the East Coast?

From Wolin et al., GRL, doi:10.1029/2011GL050310
EQ along the East Coast?

Sella et al, 2006

Source: V. Klemann, GFZ
EQ along the East Coast?

Comparison of GPS vertical velocities and total moment release (1568-2003)

- 1933 Baffin Bay, $M_w=7.4$
- 1929 Grand Banks, $M_w=7.2$

Longer time span, but less uniform catalog (Schulte & Mooney only)

Moment release is higher in deglaciated region despite completeness issues

Wolin & Stein, 2010
Any Questions?

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http://seismo.berkeley.edu/~horst/summer2016.html
Hawaii

EQ in North America
Hawaii  
Hot Spot =  
Magmatic Blowtorch

Source: ICDP
Shield Volcanoes on Big Island

Mauna Kea

Mauna Loa

Photos: Horst Rademacher
Kilauea Volcano Halemaumau Crater

Photo: Horst Rademacher

Source: Cannon, Burgmann, BSL
EQ in North America

Hawaii

Loihi Seamount
Any Questions?

http://seismo.berkeley.edu/~horst/summer2016.html
Not only faults produce earthquakes......

Earthquake magnitude, 1980 - 2014
- 5.0+
- 4.0-5.0
- 3.0-4.0
- 0.1-3.0
Man made Earthquakes

Why?


Man made Earthquakes

Common answer: Fracking!
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Man made Earthquakes

Shale gas extraction

Hydraulic fracturing uses high-pressure injections to crack open rock and release oil and gas. Opponents say it may pollute ground water and trigger earthquakes. It is banned in several countries.

Non-conventional drilling technique
- The gas is trapped in layers accessible only by horizontal drilling
- Waste water is treated and re-used

Conventional gas drilling technique
- Reserves of gas are easily accessible using vertical drilling

1. Water, sand and chemicals are injected at high pressure to crack open the rock and release the gas inside.
2. Hydraulic fracturing
3. Water is pumped out
4. Gas is collected and transported to a pipeline

30-40% of the injected liquid remains in the rock, with the mixture of sand and natural gas.

Source: IFP New Energy
Man made Earthquakes

What is hydraulic fracturing?

Generating fissures = making Earthquakes
Man made Earthquakes

Fracking generates only microearthquakes magnitudes $< 2$

Seismic Hazard is in Wastewater Injection
Man made Earthquakes

Wastewater injection reactivates dormant faults

Largest EQ generated So far
M 5.7 in Oklahoma
Substantial EQ Hazard

http://seismo.berkeley.edu/blog/seismoblog.php/2015/04/22/fracking-injecting-and-quakes
Man made Earthquakes

So far in California: No connection between Wastewater Injection and Earthquakes found
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Any Questions?

http://seismo.berkeley.edu/~horst/summer2016.html
EQ along the West Coast
EQ along the West Coast

Part of Pacific Rim of Fire
Complex section of Pacific Rim of Fire

EQ along the West Coast

Subduction = convergent margins

Transform = sliding plate margins

Spreading = divergent margins

We have all three different kinds of Plate-Plate Interaction
Pacific Plate

EPR:
8500 km long

Antarctic Plate

Gulf of California
Sea of Cortez

Cocos Plate

Nazca Plate

Easter Island

West Coast spreading
West Coast: Spreading

Divergent Plate Margin

Golf of California opens like a tectonic zipper

Baja California moves away from mainland Mexico

Further reading:
http://seismo.berkeley.edu/blog/seismoblog.php/2010/04/05/opening-a-tectonic-zipper
Last big EQ: Cucapah-El Mayor
4 April 2010, M=7.2
West Coast: Spreading

Last big EQ: Cucapah-El Mayor
4 April 2010, M=7.2
Last big EQ: Cucapah-El Mayor
4 April 2010, M=7.2

Seismic field work in a desert is easy
West Coast: Spreading

Last big EQ: Cucapah-El Mayor
4 April 2010, M=7.2

coseismic slip 1.50 m

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Any Questions?

http://seismo.berkeley.edu/~horst/summer2016.html
West Coast:

Cascadia
Earthquakes in your backyard
West Coast: Cascadia

Spreading Centers
Subduction Zone

- earthquakes
- volcanoes
- tsunamis

<table>
<thead>
<tr>
<th>Source</th>
<th>Affected area</th>
<th>Max. Size</th>
<th>Recurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subduction Zone</td>
<td>W.WA, OR, CA</td>
<td>M 9</td>
<td>500-600 yr</td>
</tr>
<tr>
<td>Deep Juan de Fuca plate</td>
<td>W.WA, OR,</td>
<td>M 7+</td>
<td>30-50 yr</td>
</tr>
<tr>
<td>Crustal faults</td>
<td>WA, OR, CA</td>
<td>M 7+</td>
<td>Hundreds of yr?</td>
</tr>
</tbody>
</table>
West Coast: Cascadia

Seismicity

Explorer Plate

Great Cascadia earthquake 1700 AD

Juan de Fuca Plate

Gorda Plate

Pacific Plate

Gorda ‘Plate’

Earthquake magnitude

3 – 4  4 – 5  5 – 6  6 – 7  7 – 8

Young (0-2 m.y.) volcanism and major volcanoes

Neogene faults (< 15 m.y.)

worrisome gap
How do we know about giant EQ in 1700 CE?

- tales by Native Americans
- tsunami deposits
- ghost forests

...a great seismic detective story
How do we know about giant EQ in 1700 CE?

Detective I: Brian Atwater
U of Wash/USGS
How do we know about giant EQ in 1700 CE?

Detective II: Kenji Satake
EQ Research Inst.
U of Tokyo

Orphan Tsunami at Japanese East Coast on 26 Jan 1700
West Coast: Cascadia

How do we know about giant EQ in 1700 CE?

Time and size of a giant earthquake in Cascadia inferred from Japanese tsunami records of January 1700

Kenji Satake*, Kunihiko Shimazaki†, Yoshinobu Tsuji‡ & Kazue Ueda†

* Seismotectonics Section, Geological Survey of Japan, Tsukuba 305, Japan
† Earthquake Research Institute, University of Tokyo, Tokyo 113, Japan

GEOLOGICAL evidence shows that great earthquakes have occurred in the recent prehistoric past in the Cascadia subduction zone, off the Pacific coast of North America. The most recent event (or series of events) is dated at about 300 years ago1*, but the precise...
West Coast: Cascadia

Cascadia has largest EQ Hazard in the US: potentially $M > 9$

Why is this important?
Further reading:

http://www.newyorker.com/magazine/2015/07/20/the-really-big-one?intcid=mod-most-popular
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Any Questions?

http://seismo.berkeley.edu/~horst/summer2016.html
Unique feature
three tectonic
plates meet:

Triple Junction
Plate tectonics: Triple Junctions

Afar Triangle

East Pacific Rise
Mendocino Triple Junction is seismically the most active region in California

Suggested reading:
http://seismo.berkeley.edu/blog/seismoblog.php/2010/01/10/mendocino_seismic_energy
West Coast: Triple Junction

Earthquake Damage

M = 6.9, 2010
Eureka

M = 7.2, 1992
Mendocino
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Any Questions?

http://seismo.berkeley.edu/~horst/summer2016.html
West Coast: Transform faults

San Andreas Fault:
The Mother of all Earthquake Faults

810 miles long from Salton Sea to Cape Mendocino
San Andreas Fault (SAF)
West-Coast: Transform faults

San Andreas Fault (SAF)

Many side branches, determines the landscape of California

What is the strike of SAF?
Remember dip, strike and rake?
**Transform faults**

Named after San Andreas Lake south of San Francisco

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**San Andreas Fault**

Discovered in 1895:

Andrew Lawson (1861-1952) UC Berkeley

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Robert Wallace (1917-2007) USGS

Studied every aspect of it

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1990

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**San Andreas Fault System, California**
San Andreas Fault:

Tectonic Evolution
last 40 million years
Transform faults

San Andreas Fault

On average, large earthquakes recur on the San Andreas fault about every 150 years.

1906
M 7.8

1857
M 7.9

1680
M 7.7

Northern San Andreas Fault

Creeping Segment (no large earthquakes)

Southern San Andreas Fault
Transform faults

San Andreas Fault

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Any Questions?

http://seismo.berkeley.edu/~horst/summer2016.html