

## **C2.3 Plate boundary earthquakes**

### **C2.3.1 Strike-slip faults**

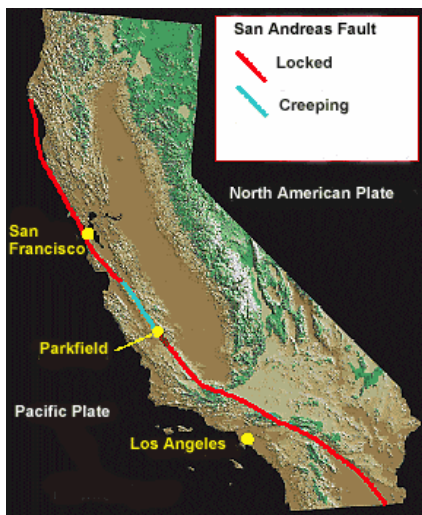
#### **C2.3.1.1. San Andreas Fault**

##### **Location and history**

- Formed by the collision of a mid-ocean ridge with a subduction zone.
- Triple junction located at each end of fault.
- Actually a system of faults, but up to 40% of motion accommodated on relatively straight central segment in Central California.

[http://geomaps.wr.usgs.gov/socal/geology/geologic\\_history/san\\_andreas\\_history.html](http://geomaps.wr.usgs.gov/socal/geology/geologic_history/san_andreas_history.html)

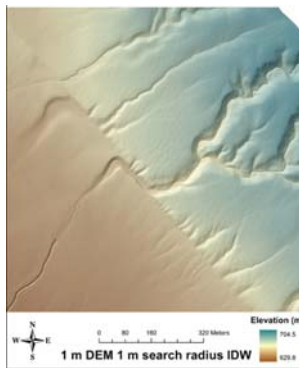
##### **Characteristics**



- Northern segment is locked and last ruptured in 1906 San Francisco earthquake.
- Southern segment last ruptured in 1857 Fort Tejon earthquake.
- Central creeping segment extends from Hollister to Parkfield and has numerous small earthquakes  $M < 5$ .
- At Parkfield the fault changes from creeping to locked and a series of characteristic, repeating  $M=6$  earthquakes has been observed.



(a)



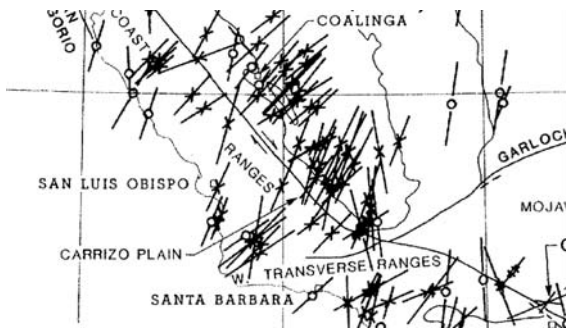
(b)



(c)

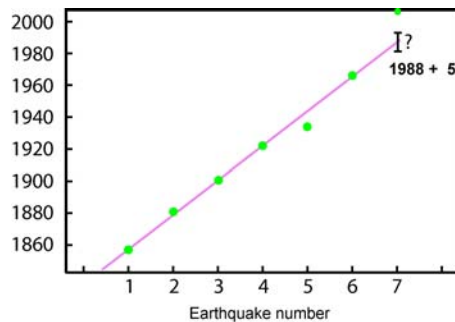
- (a) Fault creep in Hollister on the Calaveras Fault
- (b) Wallace Creek at Carrizo Plain showing offset of a number of major earthquakes, including the 1857 Fort Tejon earthquake (<http://lidar.asu.edu/KnowledgeBase/WCptcount/>)
- (c) Offset creeks at Carrizo Plain (USGS photo)

**Weak fault zone?**

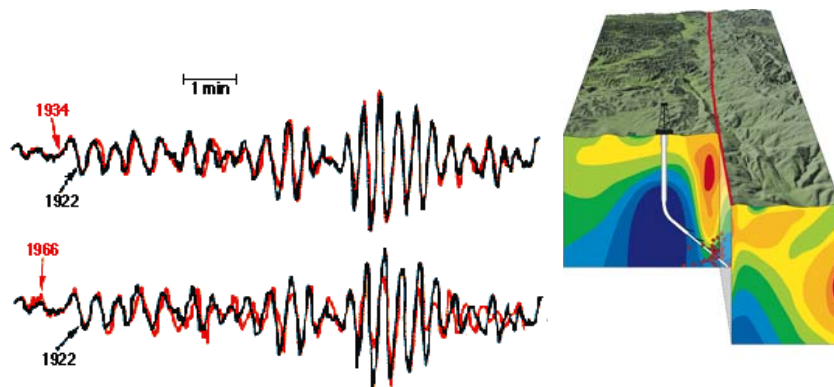


- Map showing direction of  $\sigma_1$  in Central and Southern California. The direction of maximum compressive stress is at a high angle to the San Andreas Fault.
- It is not at the  $45^\circ$  angle expected for a strong fault (Zoback et al., 1987).
- Suggest that the fault moves with a lower shear stress than expected. Requires a low co-efficient of friction on the fault plane.

**Parkfield**



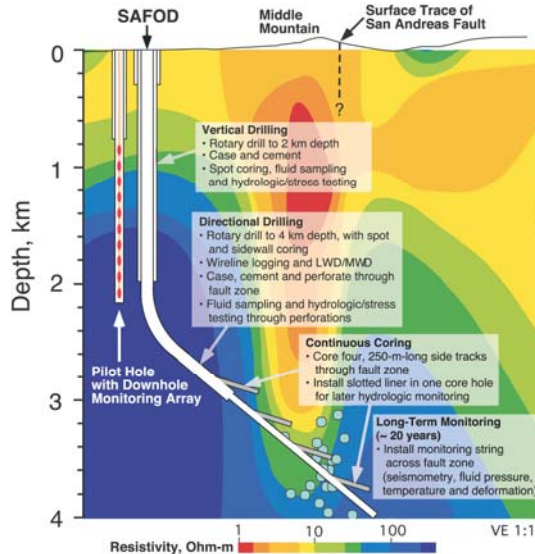
Parkfield has experienced a series of M=6 earthquakes since record began in 1857. The M = 6 earthquakes nucleate at depth of 10 km. This regular pattern led to a prediction of another earthquake in 1988. In anticipation of observing possible earthquake pre-cursors, many instruments were installed at Parkfield.



- A number of the repeating earthquakes have very similar waveforms. Seismograms above recorded at the deBilt seismic station in the Netherlands. The similarity of these characteristic earthquakes suggests that they have ruptured exactly the same part of the fault.
- Some have suggested that this can be explained by fluid cycling in the fault.

- Much smaller repeating earthquakes have also been observed at Parkfield with  $M=0$  to  $M=1$  and depths 2-7 km. These earthquake clusters are within the depth range of drilling and are a target of the SAFOD project.
- The predicted earthquake finally occurred in 2004, and not in the same place as previous earthquakes (Bakun et al., 2005)

**SAFOD (San Andreas Fault Observatory at Depth)**



[http://en.wikipedia.org/wiki/San\\_Andreas\\_Fault\\_Observatory\\_at\\_Depth](http://en.wikipedia.org/wiki/San_Andreas_Fault_Observatory_at_Depth)  
[http://www.earthscope.org/index.php/es\\_obs/safod\\_obs](http://www.earthscope.org/index.php/es_obs/safod_obs)

- Resistivity model is from Unsworth et al., (2000). Low resistivity in the fault zone is due to high porosity and saline fluids. Earthquakes begin where this feature terminates.
- Google “SAFOD” images to see how widely used this figure is! Also note how rarely the source is acknowledged.
- October 4 NSF Press release. “Geologists Recover Rocks From San Andreas Fault”. "Now we can hold the San Andreas Fault in our hands" Mark Zoback, 2007 [http://www.nsf.gov/news/news\\_summ.jsp?cntn\\_id=110106&org=NSF&from=news](http://www.nsf.gov/news/news_summ.jsp?cntn_id=110106&org=NSF&from=news)

**San Francisco Bay Area earthquakes.**

- Few earthquakes on the San Andreas Fault, which is locked at this location.
- Hayward Fault located on east side of Bay. Fowler Figure 4.14

**San Francisco Earthquake (1906)**

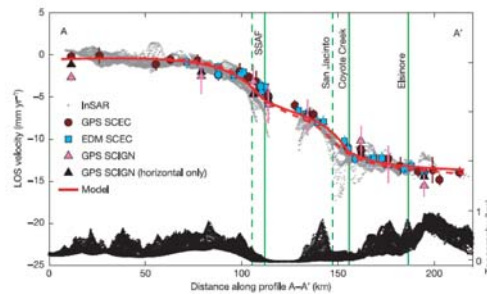
- Moment magnitude  $M_w = 7.8$
- Major right lateral earthquake. Offset fences gave idea that significant horizontal motion was occurring on the SAF.
- Maps labelled San Andreas rift zone for many years as sag ponds also noted on surface.

**Loma Prieta Earthquake(1989)**

- Moment magnitude = 6.9 (Surface wave magnitude = 7.1)
- Magnetic precursor to earthquake? Fraser-Smith et al., (1991)

**The Big One?**

- Is California overdue for a large earthquake on the San Andreas Fault?



- Fialko (2006) gives geodetic evidence that the Southern segment is overdue for a major earthquake with a slip deficit of 7-10 metres.

General information on San Andreas Fault <http://pubs.usgs.gov/gip/earthq3/contents.html>

### C2.3.1.2 Anatolian faults system

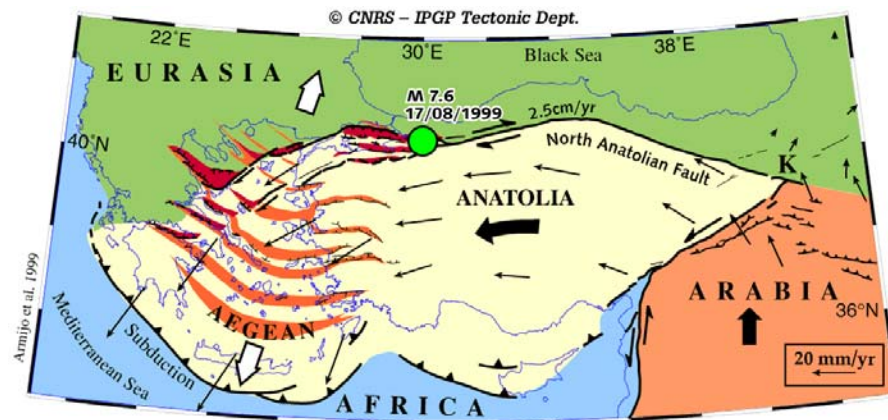


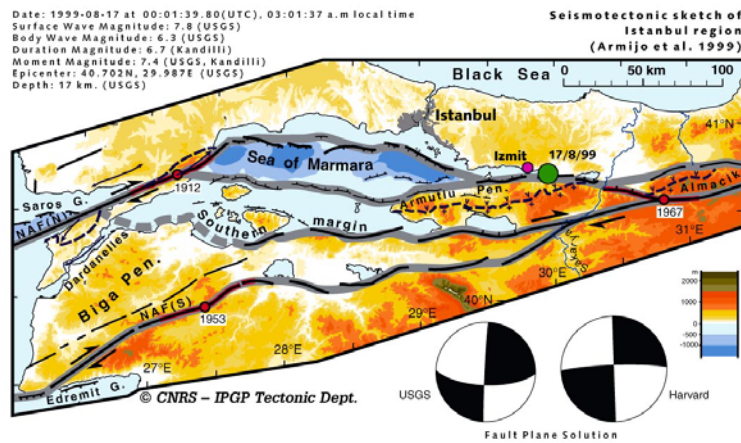
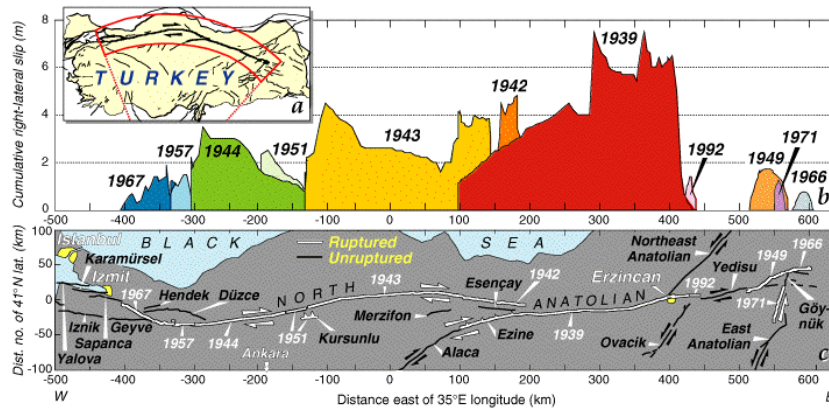
Figure courtesy of Roland Armijo, IGP, Paris

- East and North Anatolian Faults are a result of the collision of the Arabian and Eurasian plates, has forced the Anatolian Plate west.
- Subduction occurs in the Aegean Sea.
- Three plates meet at the Karloiva triple junction (K)

#### North Anatolian Fault (NAF)

- Westward propagating sequence of earthquakes began in Erzincan in 1939.
- No creeping segments observed.
- Stress modelling has shown that the sequence can be explained by each earthquake increasing the stress on the neighbouring segment (Stein et al., 1997)
- Latest earthquake August 17 1999 M = 7.6 and caused major loss of life in İzmit and other cities southeast of Istanbul.
- The 1999 İzmit earthquake was predicted (statistically) by Stein et al (1997).
- INSAR data was useful in constraining seismic moment as some of the rupture occurred under the Sea of Marmara.
- The 1999 earthquake has increased the risk of a major earthquake on the next segment to the west in the Sea of Marmara. Since this is closer to Istanbul this has serious consequences for Istanbul (Parsons, 2000).





- Fowler Figure 10.20
- Erzurum is the location of a major pull-apart basin and site of more recent earthquakes.



NAF at Duzce



NAF at Erzurum

**East Anatolian Fault (EAF)**

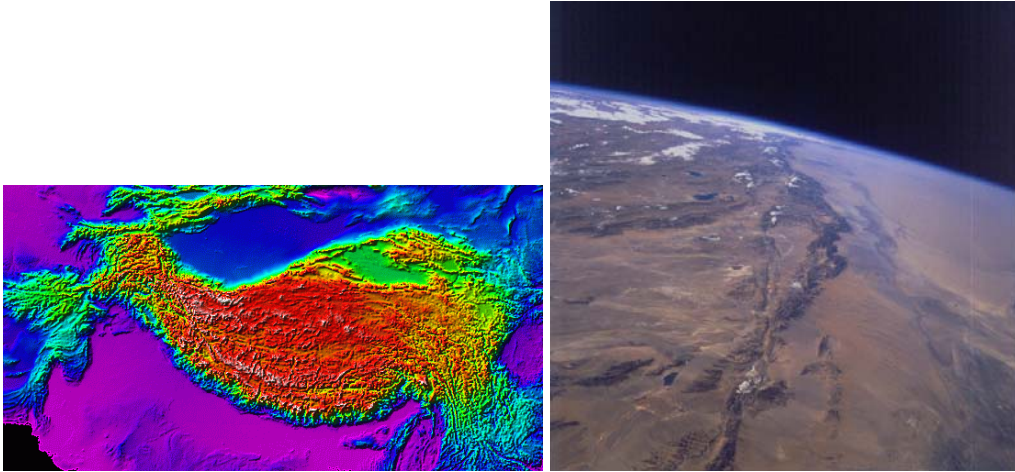
- Less studied than North Anatolian Fault
- Seismic hazard not well documented



East Anatolian Fault at Hazar Golu, Eastern Turkey

**C2.3.1.3 Northern Tibet**

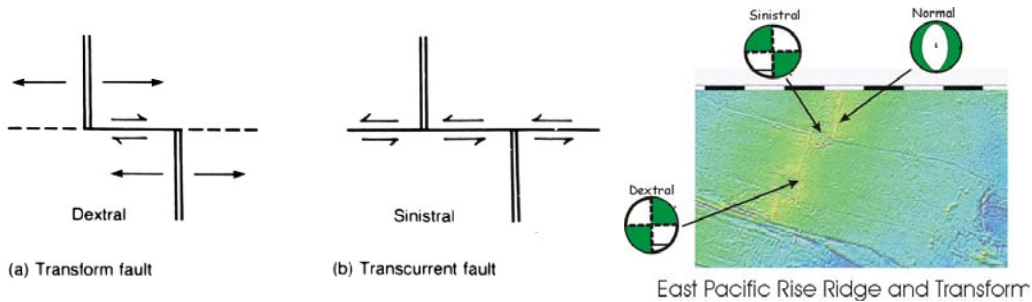
- Altyn Tagh and Kunlun faults are a consequence of India-Asia collision.
- Altyn Tagh Fault marks the boundary between the actively deforming Tibetan Plateau and relative stable Tarim Basin.



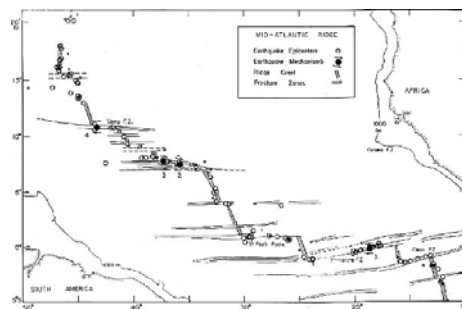
- Debate over rate of motion, which has consequences tectonic models of the India-Asia collision (Bedrosian et al., 2001). Geodetic measurements give slow rate (Bendick et al., 2000) while paleoseismology gives higher rates (Meriaux et al., 2003).

**C2.3.1.4 Transform faults on mid-ocean ridges.**

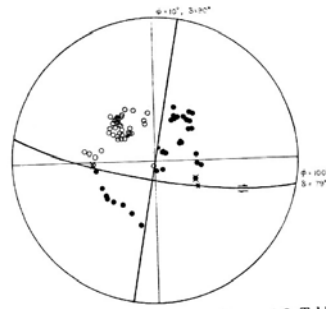
- Direct of **first motion** gave important evidence for nature of mid-ocean ridges.
- Prediction by Tuzo Wilson in 1965 showed that motion could distinguish between transform fault and transcurrent faults.
- Seismic evidence from Sykes (1967) obtained through study of focal mechanisms.



Wilson (1965)



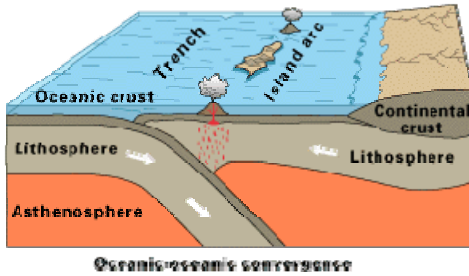
Sykes (1967)



## C2.3.2 Earthquakes at convergent margins and subduction zones

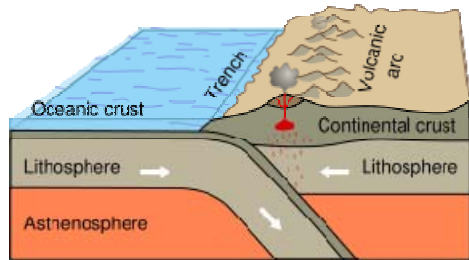
### C2.3.2.1 General characteristics

- Majority of yearly seismic energy release occurs in subduction zone earthquakes.
- Dipping zones of earthquakes are called Wadati-Benioff zones.
- Three possible configurations ([http://en.wikipedia.org/wiki/Convergent\\_boundary](http://en.wikipedia.org/wiki/Convergent_boundary))



#### (1) Both plates oceanic crust

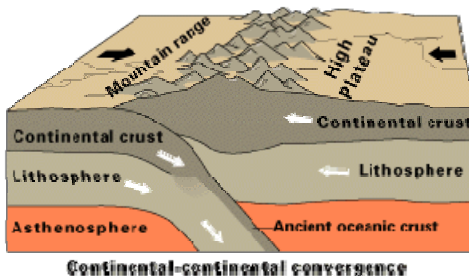
e.g. Aleutians, Kurils, Marianas



#### (2) Oceanic crust - continental crust

More dense oceanic crust subducts below less dense continental crust

e.g. Cascadia, west coast South America, Sumatra



#### (3) Both plates continental crust.

Continental crust is too buoyant (low density) for subduction and a mountain belt forms

e.g. India-Asia collision in Himalaya and Tibet, Arabia-Eurasia collision in Eastern Anatolia

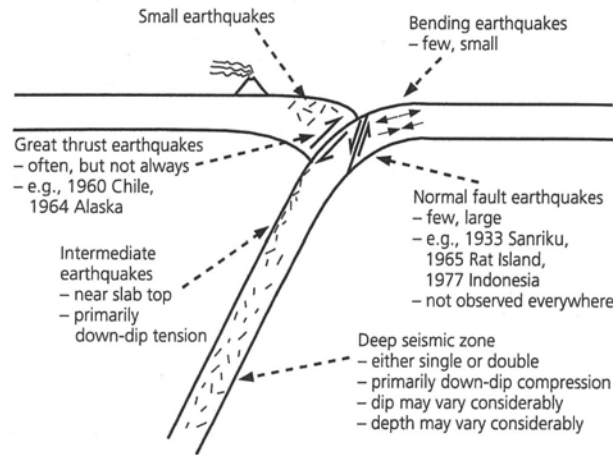
- Subduction zone geometry, from ocean to land includes : trench, accretionary prism, forearc basin, volcanic arc, back arc basin.
- The descending slab takes time to heat up to the temperature of the surrounding mantle. As a consequence, it has a slightly **higher seismic velocity** than the surrounding mantle. This allows the slab to be located with seismic tomography. Details of this method in C3.

Fowler 9.60a Western North America

Fowler 9.60b Japan

Fowler 9.60c Tonga trench in South Pacific

- Earthquakes occur in a range of tectonic settings.



Stein and Wysession (2003)

- (a) Small earthquakes in both the over-riding and subducting plate. Proximity to surface can cause strong shaking and serious damage.
- (b) Megathrust earthquakes, up to  $M = 9$ . Cascadia (1700), Chile (1960), Alaska (1964), Sumatra (2004).
- (c) Intermediate focus earthquakes (70-300 km) occur within the relatively cold slab interior. Occur as slab straightens. Sometimes a second plane occurs in centre of slab forming a double Benioff zone (Brudzinski et al., 2007; Fowler Figure 9.48)
- (d) Deep-focus earthquakes (300-700 km). No agreement on cause. Could be due to slab being resistant to crossing from upper to lower mantle. Alternatively could be due to olivine to spinel-phase transition. Examples include Tonga-Kermadec subduction zone, Hindu Kush, Bolivia 1994 -  $M = 8.3$  at 600 km depth ([http://www.agu.org/sci\\_soc/bolivian.html](http://www.agu.org/sci_soc/bolivian.html))

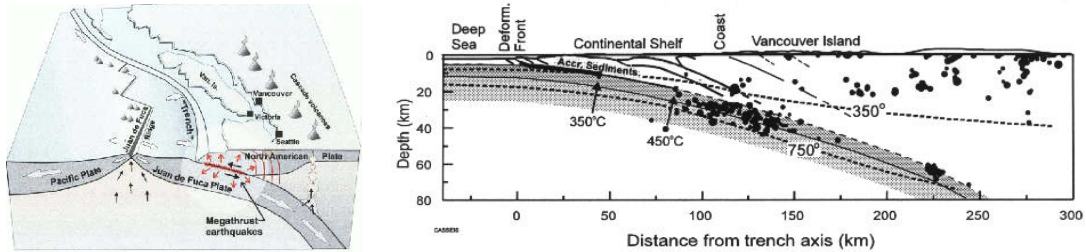
- Range of subduction angles (Fowler 9.46). Note that line of volcanoes (volcanic arc) occurs where the subducting plate reaches depth of  $\sim 100$ km.
- Water released from the slab melts the overlying mantle.
- Slab melting is relatively rare and forms adakites.
- Subduction angle can vary along strike within a subduction zone. For example, the Andean margin in South America has generally steep subduction. In Northern Chile (NC) and Peru (P), the slab has a low angle ( $10-20^\circ$ ) and travels a long way east before descending into the mantle. Fowler Figure 9.46.
- Range of seismicity distributions (Fowler Table 9.6). Slabs can sometime break off. This happens in ocean-ocean subduction zones (Brudzinski and Chen, 2003) and beneath continent-continent collisions where the buoyant crust cannot subduct.

### Seismic gaps

Fowler Figures 9.51 and 9.52



### C2.3.2.1 Cascadia subduction zone



- No trench present, just an accretionary prism
- Cluster of intra plate earthquakes
- Slab is young and warm so subduction occurs at a shallow angle
- Subduction zone locked from surface to depth of 30 km

#### Megathrust earthquakes

- Current deformation shows that fault is currently locked with Vancouver Island being uplifted (Fowler Figure 9.53 and 9.54)
- This trend is reversed during a great earthquake with rapid subsidence causing coastal flooding.
- Deformation during earthquake cycle illustrated in Fowler Figure 9.53
- Compared with observed uplifts in Fowler Figure 9.54  
[http://earthquakescanada.nrcan.gc.ca/zones/cascadia/megafig2\\_e.php](http://earthquakescanada.nrcan.gc.ca/zones/cascadia/megafig2_e.php)

#### Evidence from Cascadia for past megathrust earthquakes:

- Evidence for land level changes
- Tsunami deposits in coastal Washington
- Turbidite record offshore
- Native American records
- Tree rings show when forest flooded and killed by salt water. Evidence for a major earthquake in 1700.
- Japanese historical records describe a major tsunami on January 28, 1700 (Atwater et al., 2005).
- Now believed that 1700 tsunami was caused by a Cascadia megathrust earthquake.

More information in:

- [http://www.ess.washington.edu/SEIS/PNSN/HAZARDS/CASCADIA/cascadia\\_event.html](http://www.ess.washington.edu/SEIS/PNSN/HAZARDS/CASCADIA/cascadia_event.html)
- [http://en.wikipedia.org/wiki/Cascadia\\_Earthquake](http://en.wikipedia.org/wiki/Cascadia_Earthquake)
- [http://earthquakescanada.nrcan.gc.ca/historic\\_eq/15-19th/1700/1700\\_e.php](http://earthquakescanada.nrcan.gc.ca/historic_eq/15-19th/1700/1700_e.php)
- [http://earthquakescanada.nrcan.gc.ca/zones/cascadia/megafig2\\_e.php](http://earthquakescanada.nrcan.gc.ca/zones/cascadia/megafig2_e.php)

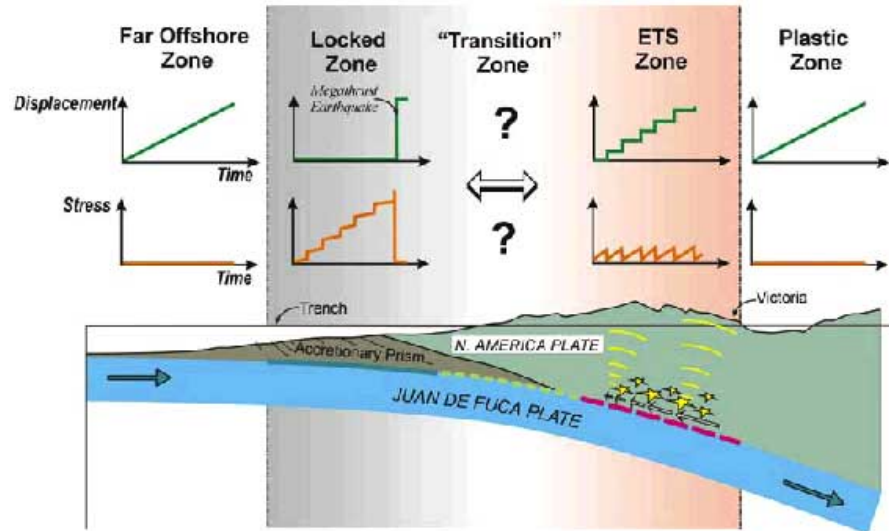
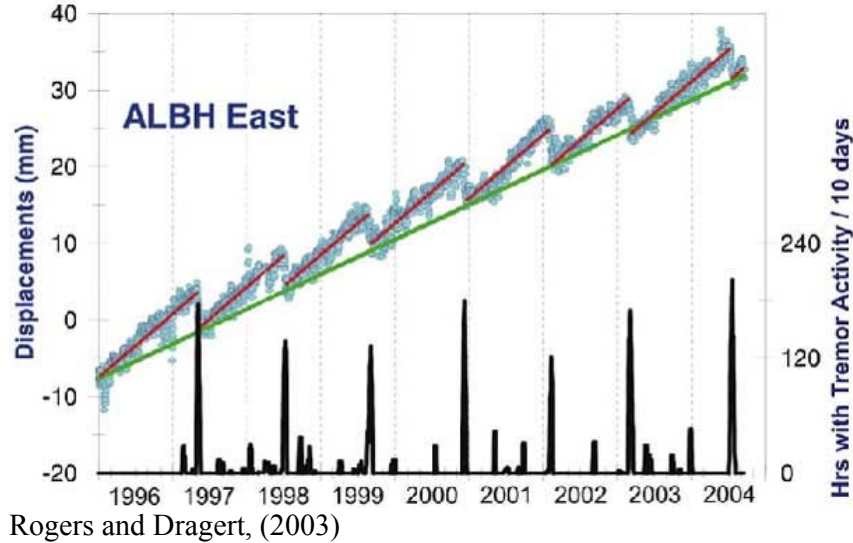
Tsunami

- [http://www.pac.dfo-mpo.gc.ca/sci/osap/projects/tsunami/tsunamieventsbc\\_e.htm](http://www.pac.dfo-mpo.gc.ca/sci/osap/projects/tsunami/tsunamieventsbc_e.htm)
- [http://www.es.ucsc.edu/~ward/movies\\_eqtsu\\_index.htm](http://www.es.ucsc.edu/~ward/movies_eqtsu_index.htm)

#### Episodic tremor and slip (ETS)

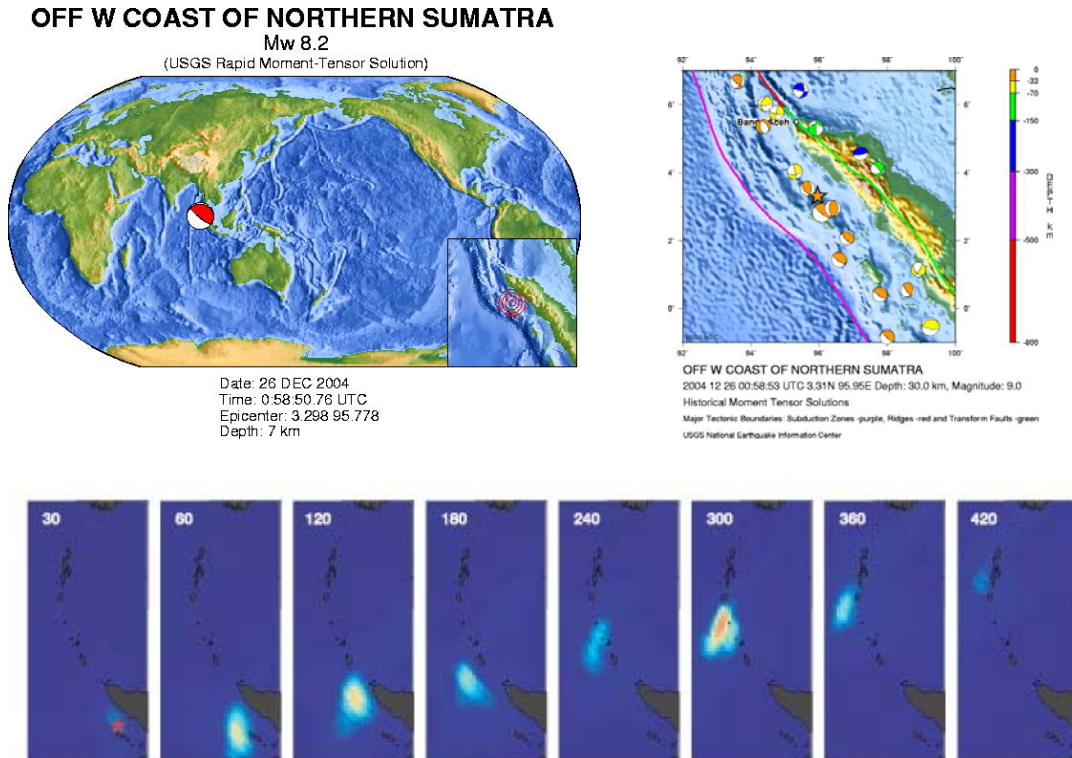
- First reported by Dragert et al., (2001).
- Sequence of events described by Rogers and Dragert (2003)
- Shown to be coincident with periods of tremor.

- Tremor is a seismic event that lacks the sharp onset characteristic of an earthquake.
- Previously harmonic tremor was only observed beneath volcanoes as magma moved to the surface.
- Locations of tremors in Cascadia migrate during the slip event.
- Also observed in subduction zone beneath Japan (Ito et al., 2007)



- GPS stations on Vancouver Island move eastward as North American plate buckles due to plate convergence with a locked fault
- Every 14 months a **silent slip** event occurs and Vancouver Island moves west for 10 days
- Reason for periodicity unknown. Linked to Earth tides or wobble?
- Risk of megathrust earthquake is significantly higher during a silent slip event. Proposed to have emergency service conduct practice drills prior to these events.
- More reading : [http://gsc.nrcan.gc.ca/geodyn/ets\\_e.php](http://gsc.nrcan.gc.ca/geodyn/ets_e.php)

### C2.3.2.2 Sumatra earthquake 2004

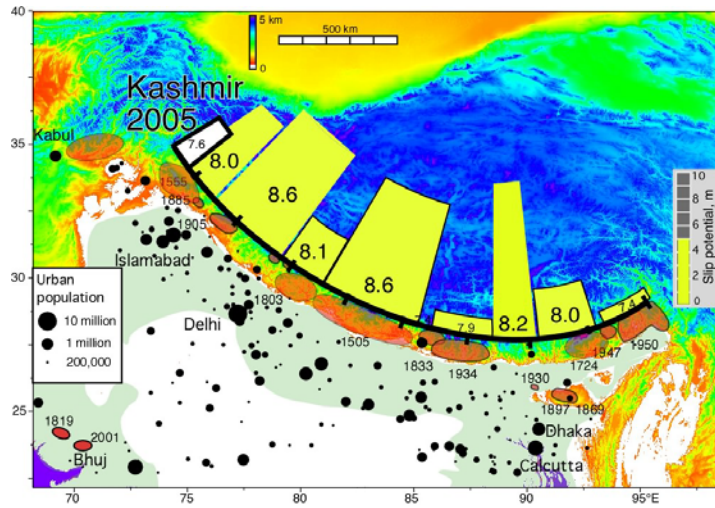


Ishii et al., Nature, (2005). Time is shown in seconds. Rupture lasted 500 seconds.

- 2004 earthquake and tsunami occurred with rupture on a very low angle thrust fault. In this region the subduction is **oblique**. However motion is **partitioned** between **strike-slip motion** on the Sumatra Fault (onshore) and **thrusting** to southwest (offshore).
- Rupture at 2.8 km/s for 8 minutes. Slip 10 m. Rupture length 1300 km. Rupture area 210,000 km<sup>2</sup> (Ishii et al., Nature, 2005)
- Animation of rupture using a detailed seismic network in Japan (HIINET) is available at <http://www.seismology.harvard.edu/~ishii/>
- USGS info <http://earthquake.usgs.gov/eqcenter/eqinthenews/2004/usslav/>
- [http://en.wikipedia.org/wiki/2004\\_Indian\\_Ocean\\_earthquake](http://en.wikipedia.org/wiki/2004_Indian_Ocean_earthquake)
- <http://www.tsunamis.com/tsunami-pictures.html>

### C2.3.2.3 Himalaya and Tibetan Plateau

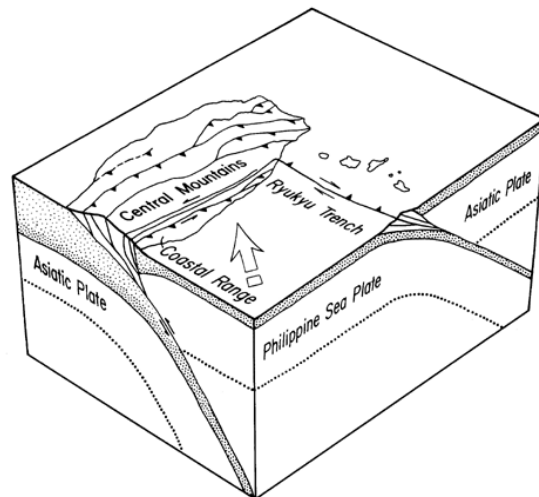
- Fowler Figure 10.16. **Thrust faults** at low elevation where India is underthrusting Asia. **Normal faults** at higher elevation as Tibetan Plateau extends and collapses.
- Paleoseismology determines earthquake dates prior to historical record (Lave et al., 2005).
- Many segments of the Himalaya are overdue for a large earthquake (Bilham et al., 2001). Given poor construction this represents a major hazard, as evidenced by the 2005 Kashmir earthquake in Pakistan.



<http://cires.colorado.edu/~bilham/>  
<http://cires.colorado.edu/~bilham/HimHazardScience.html>

### C2.3.2.4 Earthquakes on thrust faults - Taiwan

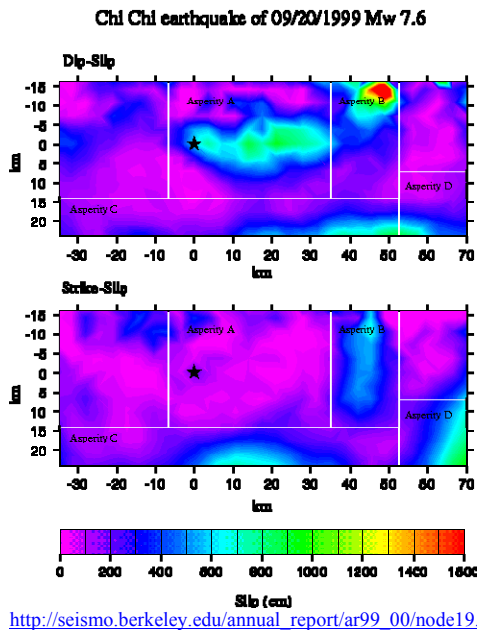
- Taiwan is a mountainous island that has formed as continental crust entered a subduction zone. The collision zone becomes more mature (older) from south to north. Series of major thrust faults run the length of the island
- Chi-Chi earthquake occurred on September 21 1999 and was a  $M_W = 7.6$  thrust earthquake.
- Referred to as the 921 earthquake in Taiwan.
- Very large and very fast ground rupture, exceeding 12 m at northern end at the Shihkang dam (below).
- Virtual field trip at National Central University of 921 earthquake ruptures  
<http://basin.earth.ncu.edu.tw/Virtual%20Field%20Trip/WF/>



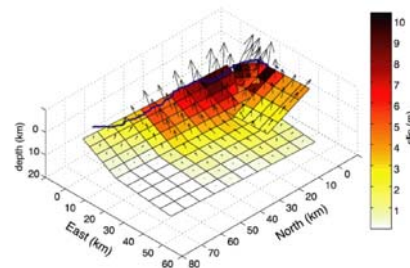




- Damage at a school near Wufong. Offset running track is now preserved as part of the 921 earthquake museum.
- The recent Chelungpu drilling project (TCDP) directly sampled the fault at depth (Ma et al., 2006).



- Slip distribution mapped from **strong motion** seismic data (left).
- Hypocentre marked by star. Area of high slip (red) is in north close to Shihkang Dam.
- Slip distribution also computed from **co-seismic** GPS data (Johnson and Segall, 2004).



Johnson and Segall, Tectonophysics, (2004)

### C2.3.3 Earthquakes at extensional plate boundaries

African Rift Valley. Fowler Figure 10.54

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