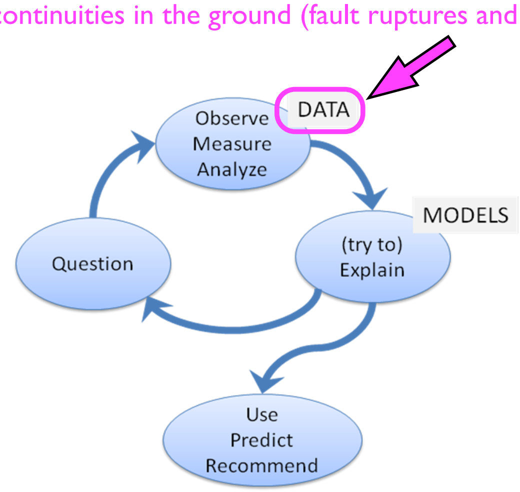
EOSC 256 - January 11, 2012

- Realization that faults cause earthquakes (late 1800's)
- 1906 SAF earthquake and elastic rebound theory
- Learning goals:
  - know why people finally connected earthquakes to faulting of the Earth's crust - what data? (1: surface rupture. 2: strain. 3: first motions from seismometers.)
  - explain (non-technically!) what elastic rebound theory is.
  - see how modern measurements are made of strain and surface rupture (GPS, InSAR, LIDAR)

Circa 1900: Evidence that faults, not collapses or explosions, cause earthquakes

- seismograms: displacement, velocity or acceleration versus time (shaking) (okay, 1920's)
- land surveys and geological reconnaissance:
  - (1) permanent differential displacement of points on the ground (strain)
    (strain is the *derivative* of displacement with respect to *position*, for example warping, distortion, compaction, or expansion)
  - (2) discontinuities in the ground (fault ruptures and scarps)



By the late 1800's it was becoming apparent that sudden breakage of rock along surfaces (faults) causes earthquakes

From the Steinbrugge Collection, Earthquake Engineering Research Center, University of California, Berkeley.
Image by Karl V. Steinbrugge.

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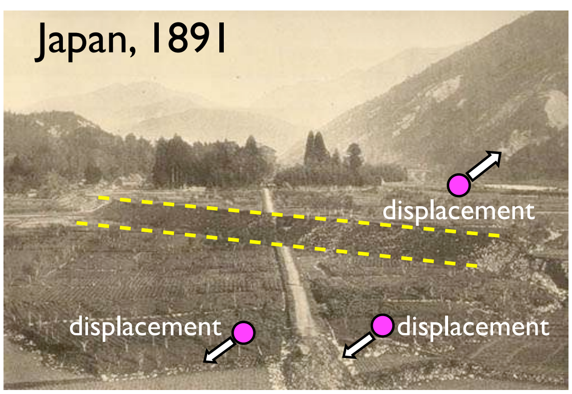


Photograph of the 1891 Nobi (Mino-Owari) earthquake **scarp** at Midori, taken by B. Koto, a professor of geology at the Imperial University of Tokyo. Based on his geological investigations, Koto concluded, "The sudden elevations, depressions, or lateral shiftings of large tracts of country that take place at the time of destructive earthquakes are usually considered as the effects rather than the cause of subterranean commotion; but in my opinion it can be confidently asserted that the sudden formation of the 'great fault of Neo' was the actual cause of the great earthquake."

surface ruptures and scarps: photos and surveys

permanent surface displacements

- points on surface moved relative to their pre-earthquake positions in a coherent way

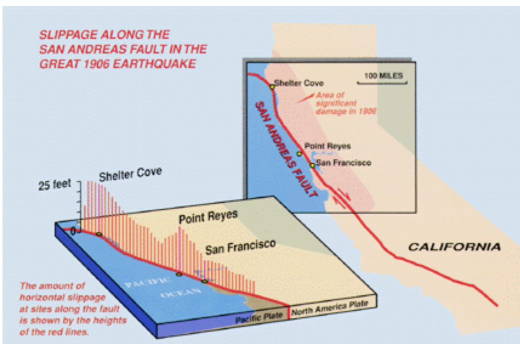
fault slip: displacement (offset) of ground on one side relative to the other

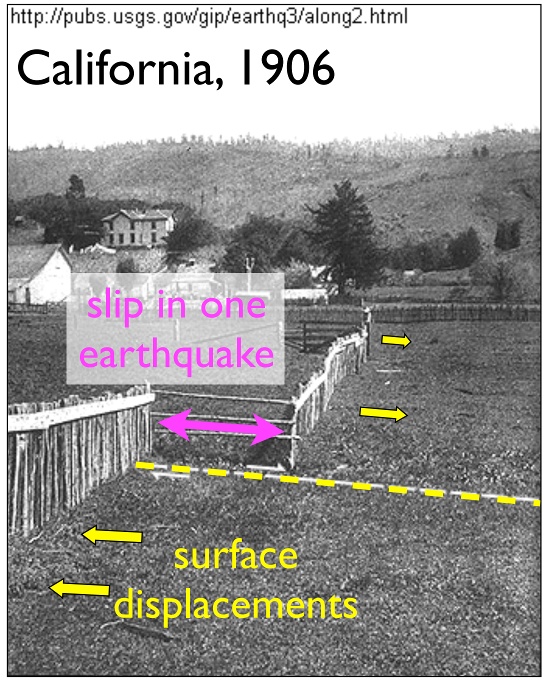
1908: Incredibly detailed Lawson Report describing the effects of the 1906 San Francisco earthquake

surface displacements
(units of length)
points on surface moved relative to their pre-earthquake positions

fault slip is the relative displacement across the fault

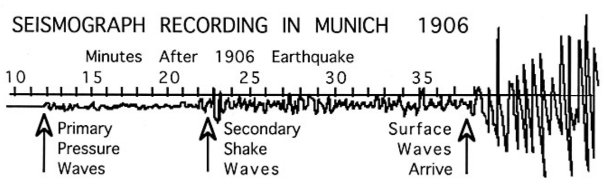
this can vary along the fault

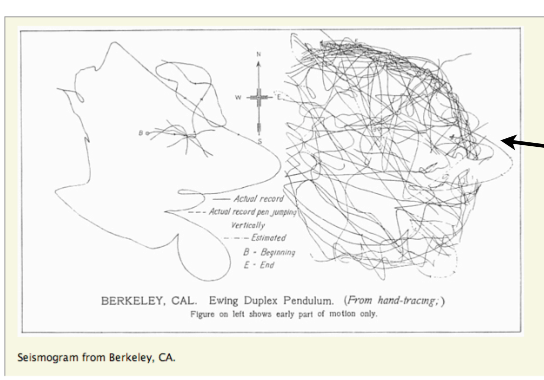




What were people doing with seismographs (seismograms) around 1900?

- Not many seismographs existed worldwide
- Mainly used to get timing and location of earthquakes

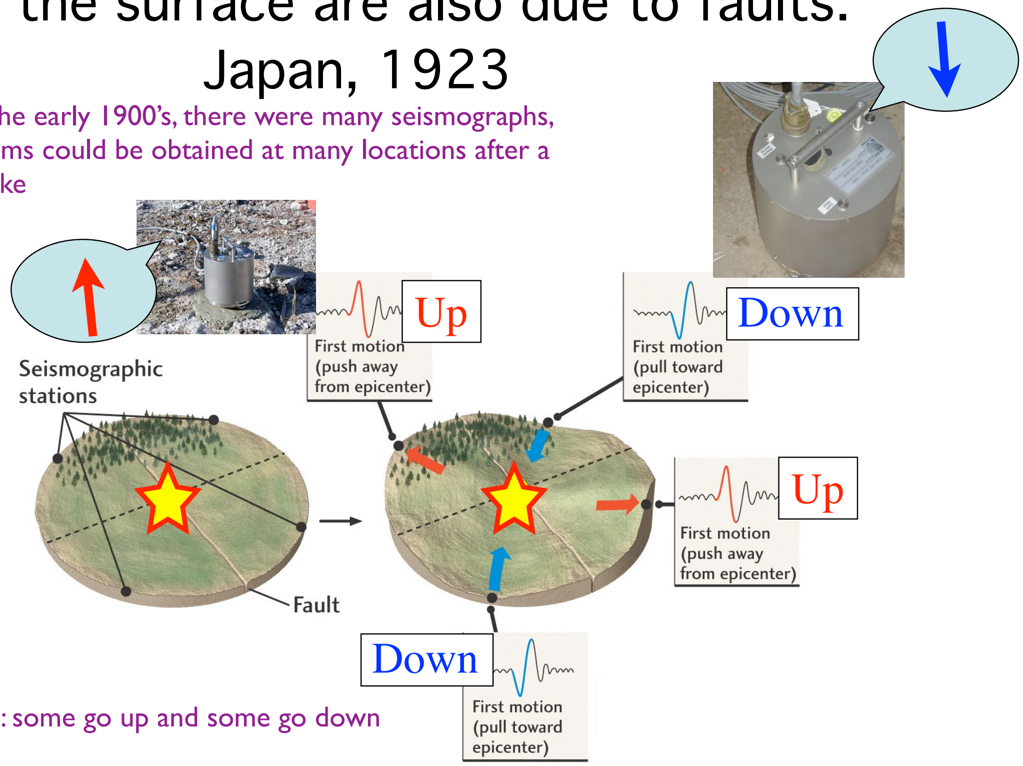




?!!!
Pendulum seismograph record
(vertical motion actually lifted the pen from the page!)

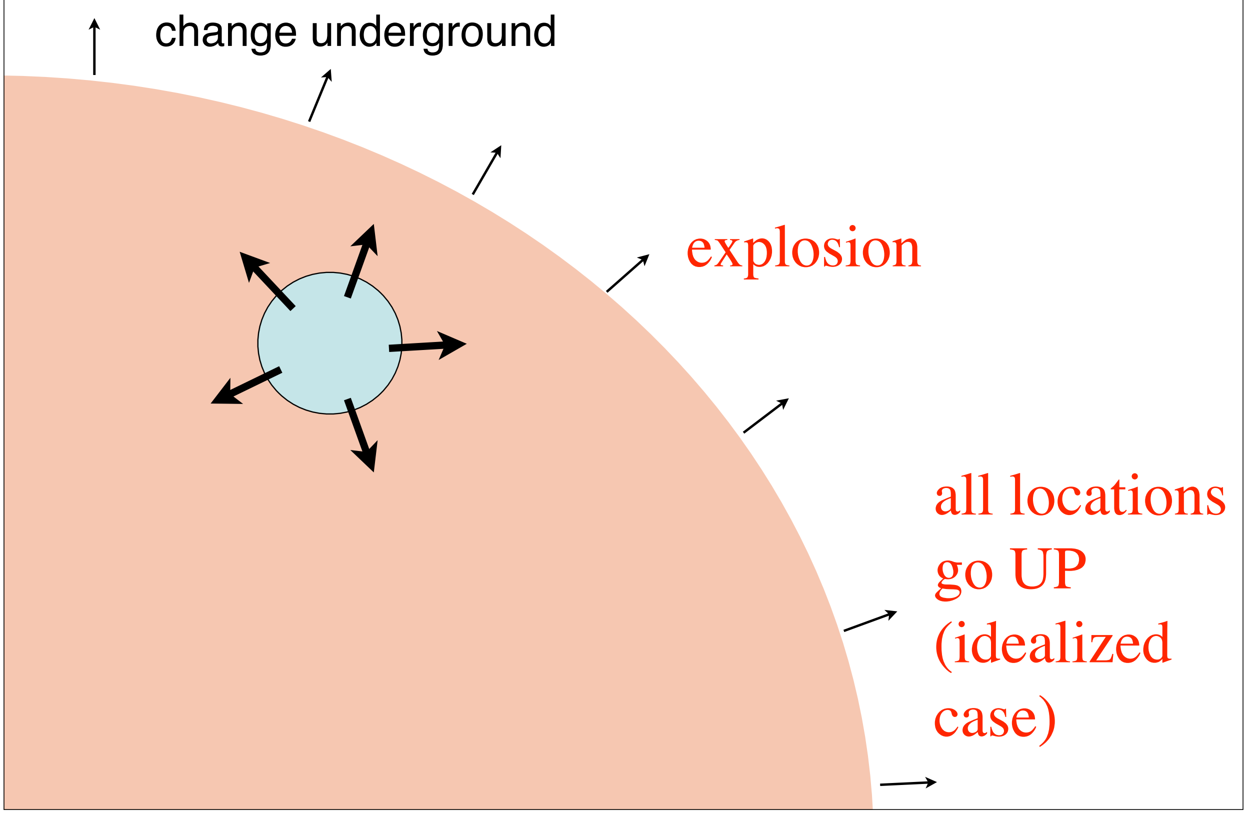
Proof that even earthquakes that don't break the surface are also due to faults: Japan, 1923

- In Japan in the early 1900's, there were many seismographs, and seismograms could be obtained at many locations after a local earthquake



First motion: some go up and some go down

Non-earthquake source: Underground Bomb Test or Aristotle's winds are associated with a volume change underground



multiple records of a single quake (up vs. down first motion)

+

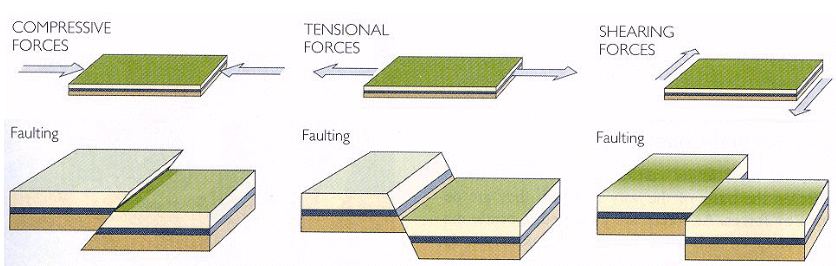
elasticity theory (which tells us how points on the Earth's surface should move as the result of different kinds of displacements inside the Earth)

↓

Seismograms proved that there is no volume change underground.

Earthquakes are caused by relative displacement of rock on either side of a surface, not by collapses or explosions.

This is consistent with faults we see at the Earth's surface.



'reverse' or 'thrust' fault

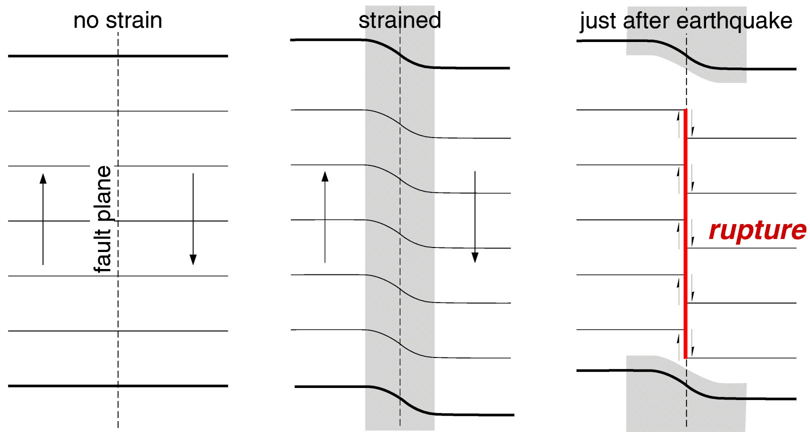
'normal' fault

'strike-slip' or 'transform' fault

No volume change! Just a change in shape.

(Suppose magma suddenly forces its way into a conduit below a volcano. Do you expect a volume change?)

Elastic Rebound Theory of Reid (1908), based on survey data from the 1906 Lawson Report



Elastic stresses build up as rock deforms slowly over time

Rupture occurs when elastic stresses exceed what the fault can bear (friction).

Rocks along fault spring back to undeformed state ("elastic rebound")

Professor Henry Fielding Reid of Johns Hopkins University wrote the second volume of the Lawson Report (1910), presenting his celebrated elastic rebound hypothesis. Reid's 1911 follow-up paper summarized his theory in five propositions:

- The fracture of the rocks, which causes a tectonic earthquake, is the result of elastic strains, greater than the strength of the rock can withstand, produced by the relative displacements of neighboring portions of the earth's crust.
- These relative displacements are not produced suddenly at the time of the fracture, but attain their maximum amounts gradually during a more or less long period of time.
- The only mass movements that occur at the time of the earthquake are the sudden elastic rebounds of the sides of the fracture towards positions of no elastic strain; and these movements extend to distances of only a few miles from the fracture.
- The earthquake vibrations originate in the surface of the fracture; the surface from which they start is at first a very small area, which may quickly become very large, but at a rate not greater than the velocity of compressional elastic waves in rock.
- The energy liberated at the time of an earthquake was, immediately before the rupture, in the form of energy of elastic strain of the rock.

Where do the driving forces come from? Plate tectonic theory. 1960's.

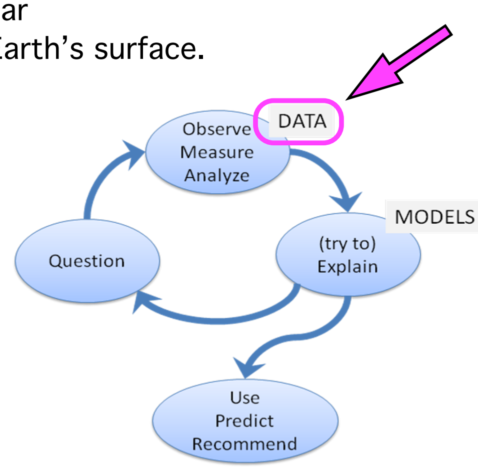
Some more modern data showing the association of FAULTS with tectonic earthquakes, and supporting elastic rebound theory

Modern seismic data - catalogues of hypocenter locations and focal mechanisms.

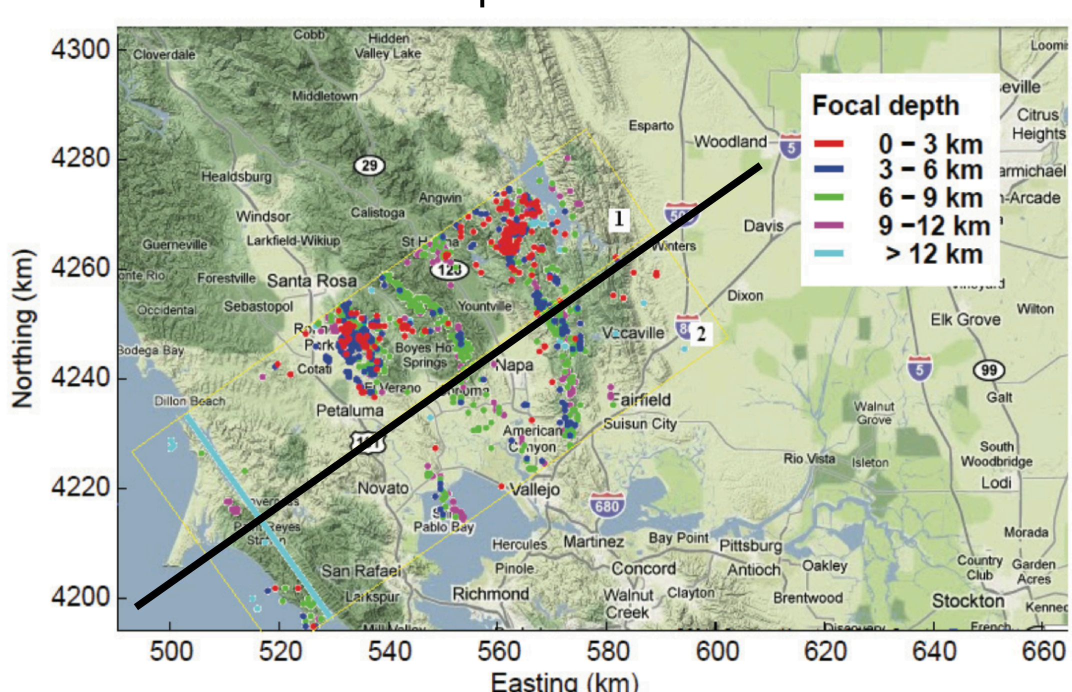
Satellite geodesy - widespread since the early 1990's:
GPS: Global positioning system
InSAR: Interferometric synthetic aperture radar
These show displacements of points on the Earth's surface.
Very good for mapping strain.

another new technique
(not satellite based):
LIDAR: light detection and ranging

makes detailed topographic maps, scarps show up beautifully (strain, not so much)

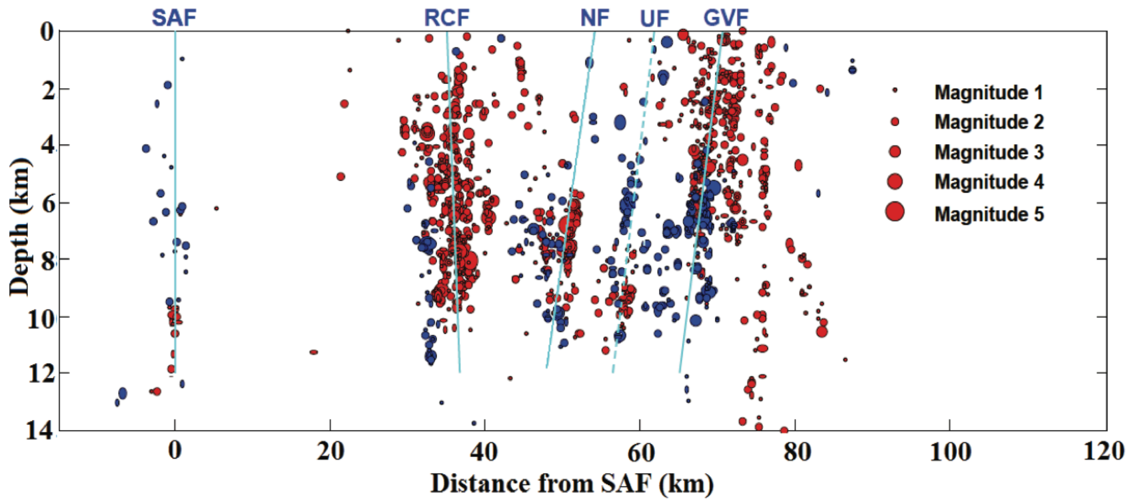


As earthquake catalogues became more complete and locations became precise, epicenters outlined definite patterns: faults!

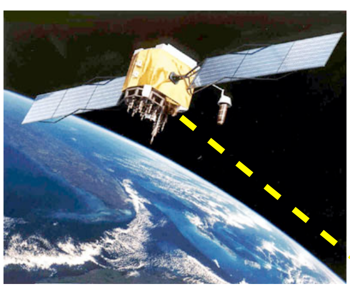


data from Waldhauser and Schaff, 2008

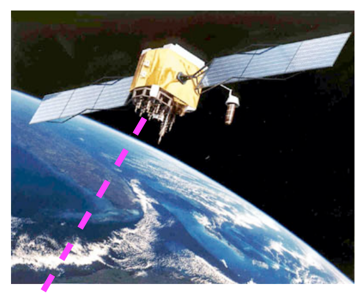
Small earthquake hypocenters along fault surfaces at depth



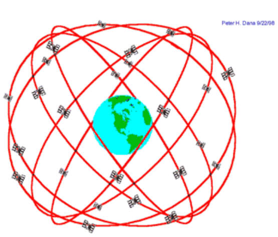
Vaghri and Hearn 2011, data from Waldhauser and Schaff 2008

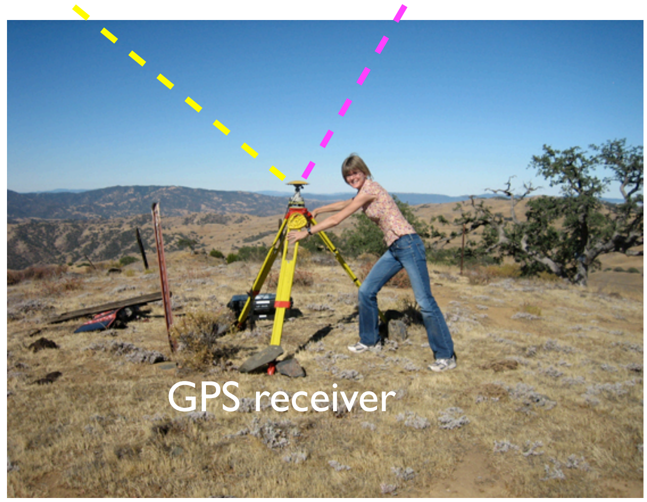


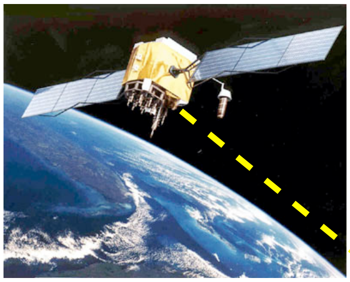
Satellite geodesy - since the 1990's



24 GPS satellites in polar orbits







Satellite sends microwave signal at t_1, signal is received at t_2

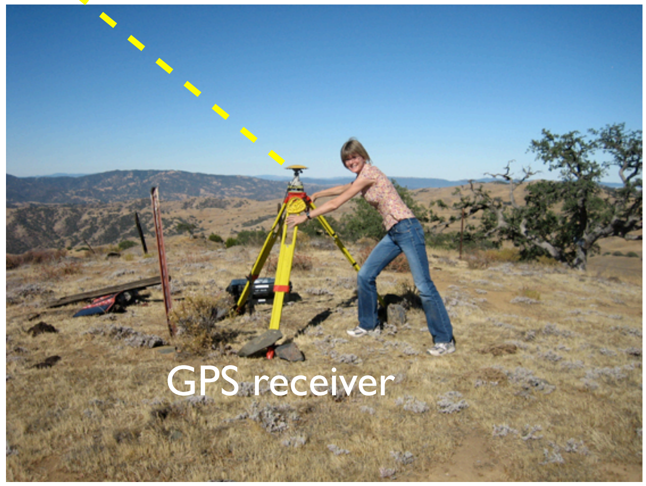
Time Difference (in seconds) * 2.99792458 x 10^8 meters/second = Distance (in meters)

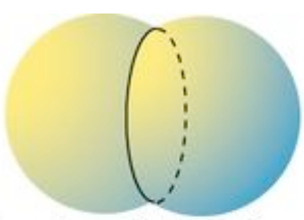
Time difference and c tell you how far receiver is from the satellite.

What is a typical time difference?

GPS satellites are ~2 x 10^7 meters above the Earth.

about 70 milliseconds

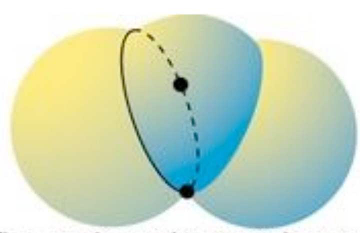




Two spheres intersect in a circle

Intersecting spheres of radius r

3 spheres intersect at two points - but only 1 point is on the Earth

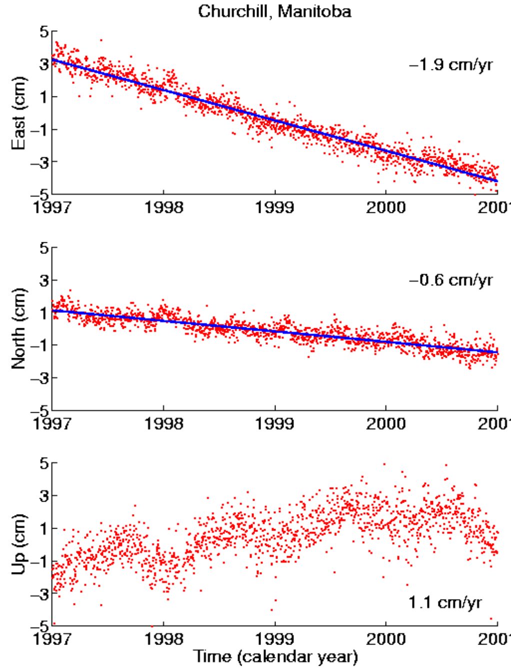


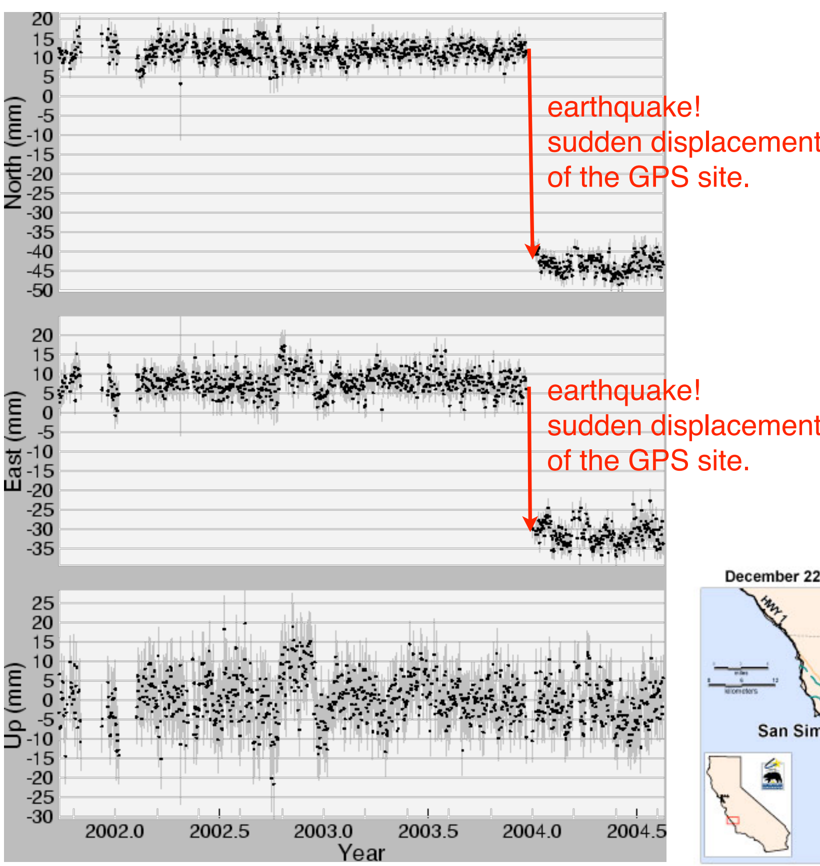
Three spheres intersect in two points

Extra tricks and long occupations (~12 hours) are required to get position accuracy of 1 mm (this is not your car's GPS...!)

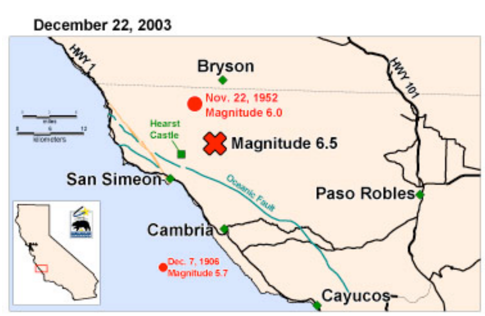
Each red dot tells you the position of a GPS receiver on a single day.

Churchill is moving 1.9 cm/yr west, 0.6 cm/yr south, and 1.1 cm/yr up.

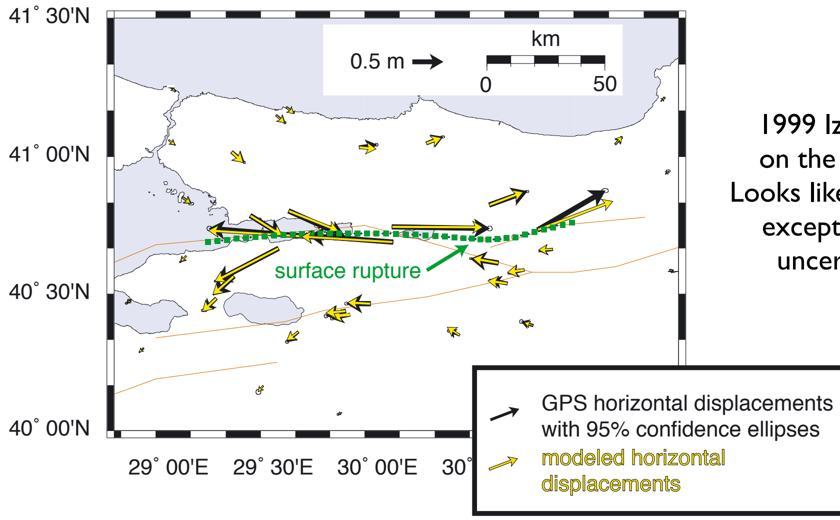




Daily position time series for CRBT, the continuous GPS station located closest to the epicenter of the 22 December 2003 San Simeon earthquake. The coseismic displacement is about 68 mm to the southwest. From the U C Berkeley seismo lab.

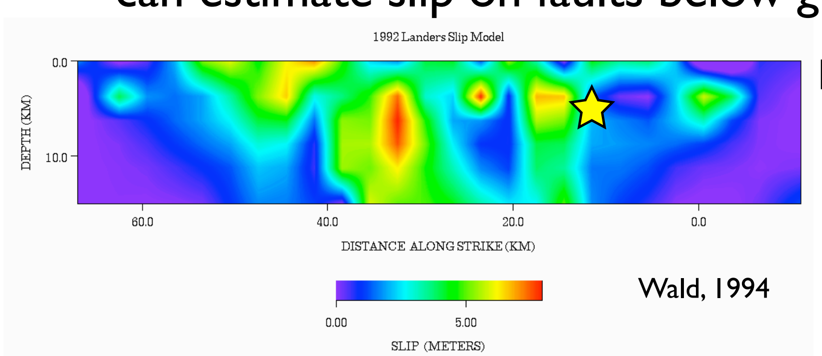


If you have lots of GPS receivers deployed at the time of an earthquake, you can see patterns sudden displacements due to an earthquake ("coseismic displacements")

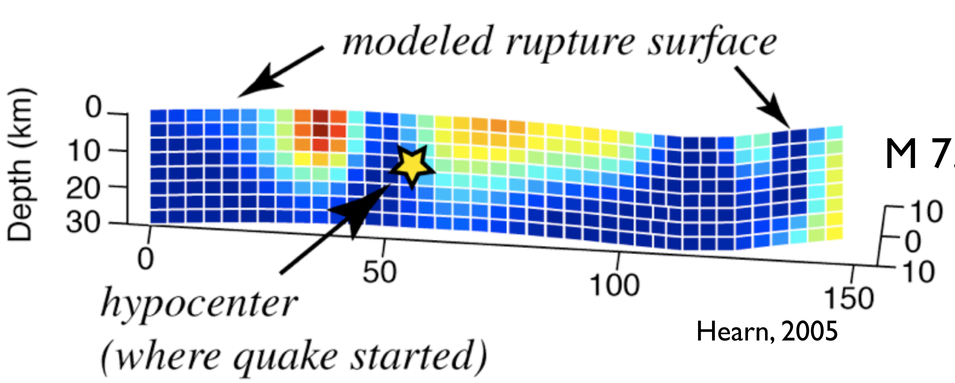


1999 Izmit, Turkey earthquake on the North Anatolian Fault. Looks like data from Homework 1 except MUCH more precise. uncertainties: about 1 mm.

From this (or seismograms or InSAR) we can estimate slip on faults below ground



M 7.4 Landers EQ offset (slip) is shown in color

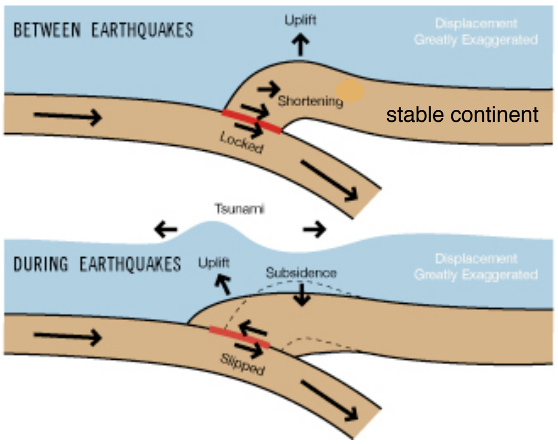


M 7.5 Izmit EQ

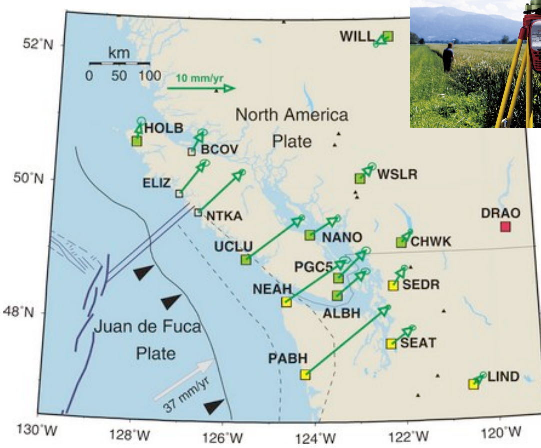
GPS data show that elastic stresses are building up on the Cascadia subduction zone fault (“interseismic deformation”)

Vancouver Island is squished (strained) for hundreds of years. Elastic stresses build up. We have a great Cascadia earthquake -- and Vancouver Island is “unsquished” in just a few minutes (elastic rebound).

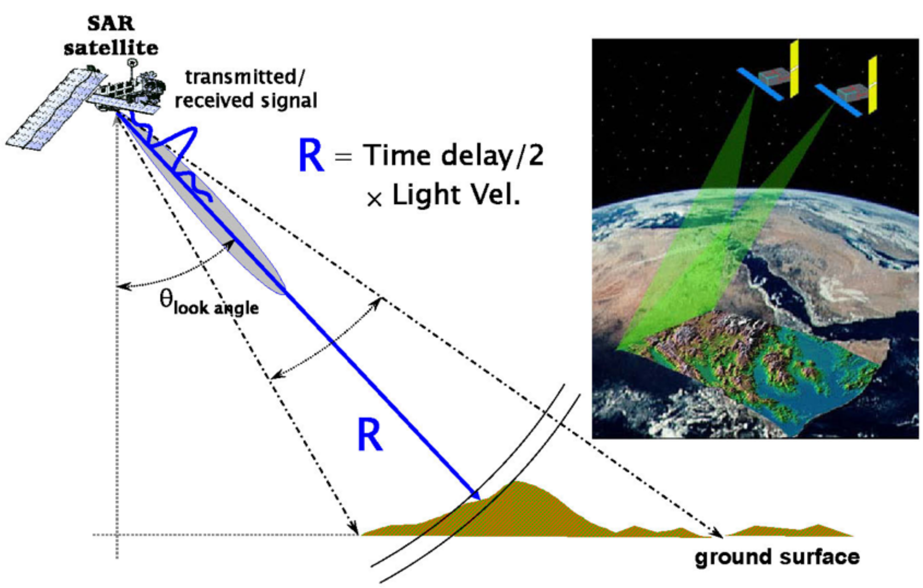
Elastic rebound for a subduction zone (cartoon side view)



Actual GPS site velocities



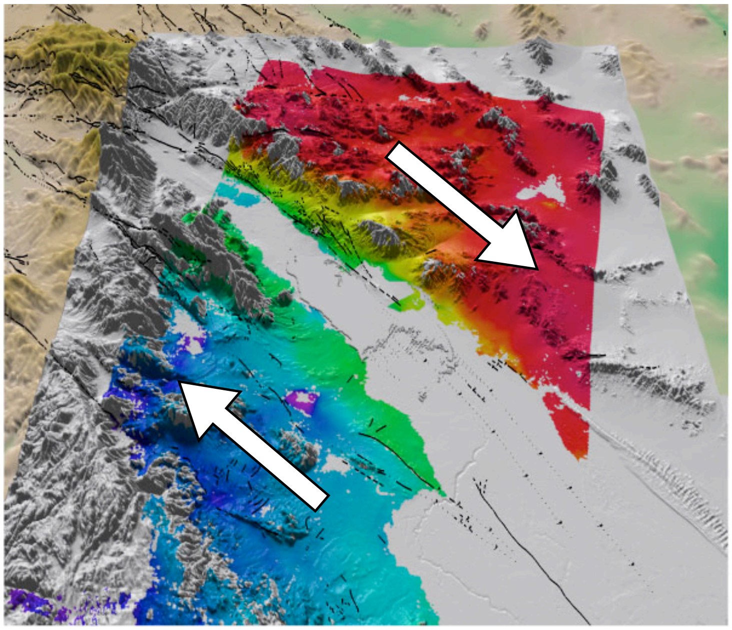
Interferometric synthetic aperture radar (InSAR): also ranging using a microwave (radar) signal



No receivers required (BUT less precise than GPS, uncertainties = cm’s).
Difference in R between two passes = displacement (in the line-of-sight direction) of the ground surface.

Interferogram

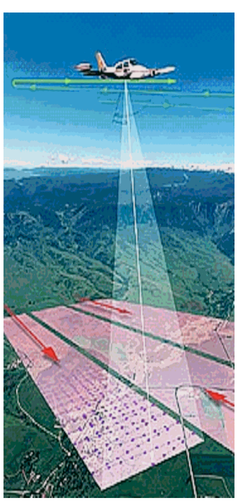
Perspective view of the satellite line-of-sight velocities (color) due to slow horizontal motion between the North American and Pacific plates. Blue is moving NW red is moving SE relative to the SAF.



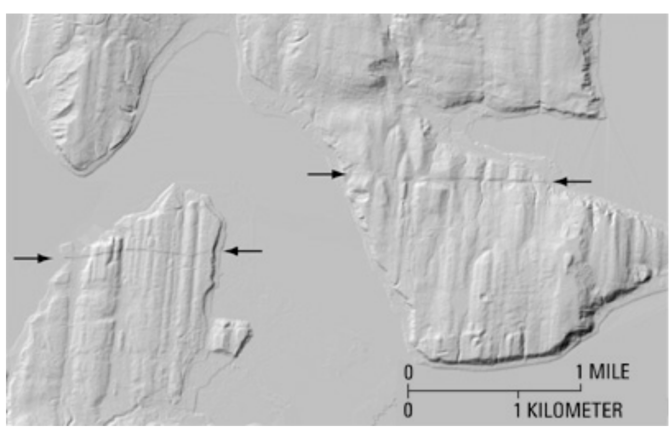
Yuri Fialko, Scripps, 2007

LIDAR provides detailed topography maps, which can show features like old fault scarps, even where there are trees and brush

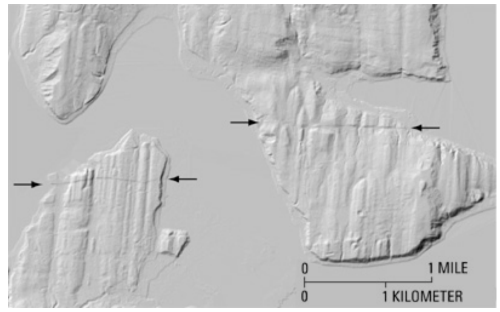
May be ground-based or done from an airplane. Unit sends and receives pulses of laser light. Ranging (like GPS and InSAR). Position of the airplane is noted with GPS.

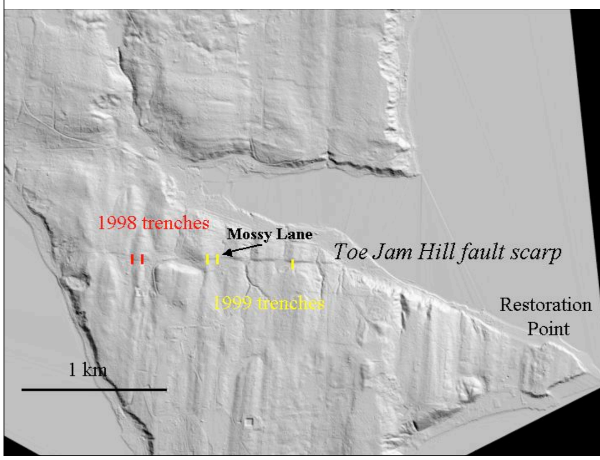


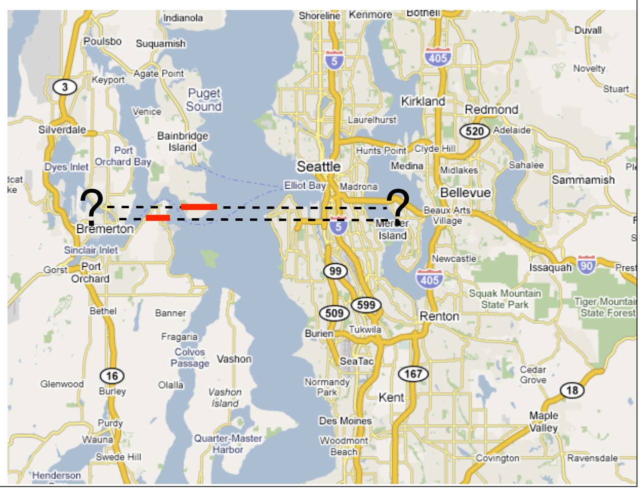
Trees reflect some of the light energy. Analysis can "strip" trees by looking at only the slowest travel times from each light burst.
These scarps are from an earthquake 100's of years ago. They are hard to see on the ground.



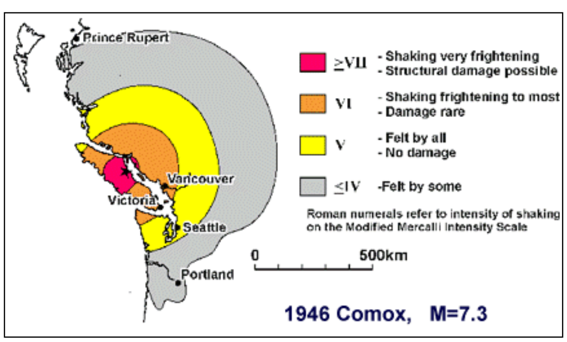
LIDAR examples from Seattle







There are many unmapped (and many unnamed) faults in SW BC



which fault was this?
<u>nobody knows</u>.

We need airborne LIDAR for Vancouver Island and SW BC.