GEOPH 624: Theoretical Seismology

Instructor: Jeff Gu
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492-2292

Time: Tu, Th 2:00-3:20 PM

Place: CCIS L1-047

Office Hours: None official
feel free to come in whenever office door is open, can also email for appointment

Website: **www.ualberta.ca/~ygu/courses/geoph624**

Recommended Only Textbooks:

1. *Introduction to Seismology*

   By Peter M. Shearer, Cambridge University Press

   ISBN: 0521669537

2. *An introduction to seismology, earthquakes, and earth structure*

   By S. Stein and M. Wysession, Blackwell Publishing, 2003.
   ISBN: 0865420785

3. *Modern Global Seismology*

   By Thorn Lay and Terry C. Wallace, Academic Press.
   ISBN: 012732870X

4. *Arrays and array methods in global seismology*

   Edited: Yours Truly (2010)
   ISBN: 978-90-481-3679-7

Grading:

Homework (25%): due at the end of class on days they are due.
Unless there is a special reason, the standard late penalty is 10% a day for each additional day.
Reminder: Submit your own work.
Computer assignment: Labs & minimal programming

Class participation (5%): you have 1 freebee, then it is 1% per unexcused absence up to 5%.

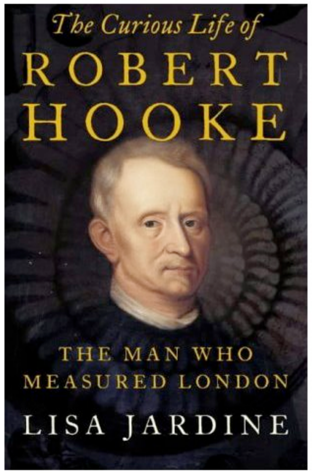
Paper presentations (20%): This is a key part of the course that encourage your participation and careful reading of important papers in each topic. Everyone has to answer some questions as part of the homework, but groups of 1 (2 if needed) will lead discussions of different papers (randomly assigned) at the end of each topic.

Project presentation (10%): You will do a project based on the topics covered or ones that I approve of that have some close connection to the topics introduced. This will take place near the end where your project is coming to a closing.

Final paper (40%): A written term project (similar to GRL papers) on your findings. If you do review, then thoroughness and insights are must.

A Brief Introduction to Seismology (theory development):

'Part-timers'



1600s ---- English Physicist Robert Hooke's defines a law that linearly relates stress with strain (*pseudo rock physicist*, i.e., F=-kx).

1760 ---- John Mitchell (astronomer, geologist, philosopher, was the first to relate earth shaking with propagation elastic waves.

main claim to fame: effect of gravity to light (Wikipedia)

contemporary Mathematician(M)/Physicists(P)/Astronomer (A):

*Leonard Euler (M+P, Euler Poles defines great-circle paths, your plane ride benefits from it),

*Joseph Lagrange (recommended by Euler to head Prussian Academy of Sciences, Berlin, M+A, 'Lagrange multiplier')

Charles Coulomb (M+P+En): electronic potential transfer, which applies in ambient stress transfer from fault zone

L. Euler

More 'Part-timers', getting close to real seismology…

1800s ---- theory in seismology began to flourish…

1827 --- Claude Louis Navier (En+P) developed the equation of motion (governing principle for wave propagation!)

C. Navior

* Augustin Cauchy (1789-1857): A mathematician and earlier pioneer in "Analysis", "infinitesimal" and "Continuum". Well known today for "Cauchy stress".

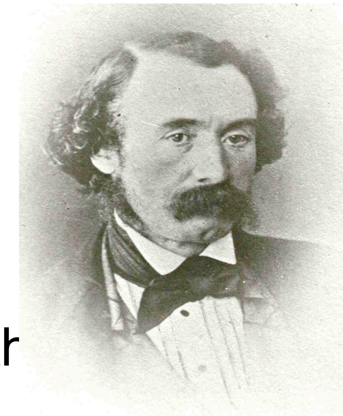
*Simeon Dennis Poisson : student of Lagrange, a child French genius. Best known for Poisson equation on potential,
His name is associated with Poisson's ratio

*Gabriel Lame (1795-1870): French Mathematician, worked on number theory, curvilinear surfaces, I still don't know why 'Lame parameters' or isotropic elastic materials are named after him, maybe re-parameterization of the original function?

*Gustov Kirchhoff (1824-1887): German physicist, contribute to knowledge of circuits, spectroscopy, black-body radiation. Seismically known for "Kirchhoff migration" with Kirchhoff integral representation of a field at a given point as a (weighted) superposition of waves at adjacent times and positions.

Real ‘Seismology’ by the full-timers

Robert Mallet

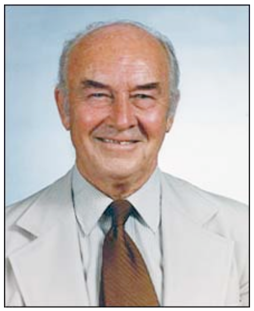


****1850 ---- first earthquake catalogue compiled by Robert Mallet, often considered the father of ‘seismology’ (he was s among the first to name this brand of science)**

1887 ---- Lord Rayleigh demonstrated the existence of additional solutions of the elastic equations of motion for bodies with a free surface, known now as Rayleigh waves

Early 1900s ---- elastic rebound theory, continental drift (Alfred Wegener)

Tuzo Wilson



Love waves ---- Augustus E.H. Love (pseudo Surf Wave)

1960s ---- theory of plate tectonics (Henry Hess, Lynn Sykes, J. Tuzo. Wilson, Walter Pitman)

1984 ---- formation of Incorporated Research in Seismology (IRIS), for seismic/MT data archival & dissemination and a whole lot more…

The Canadian ‘hotspot’ man

Observational Seismology (a young science)

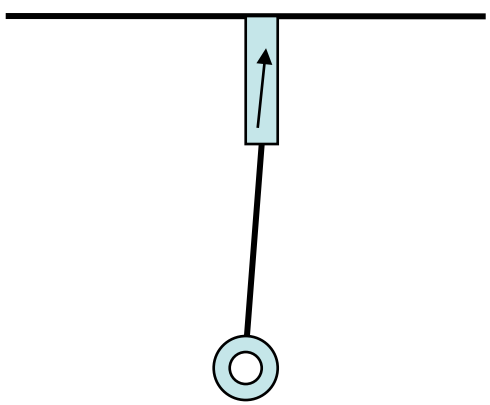
Earliest known ***seismoscope***, by
Zhang Heng (132 AD)

Similar Idea:

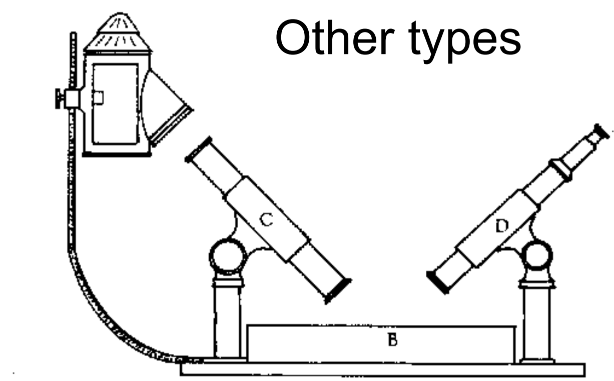
In 1700s, the invention of ***spill-meter***
De la Haute Feulle

Without finding an interesting picture, I decided to show this bowl of soup from a random site ---- jeff

In 1840s, James Forbes designed the first inverted pendulum "seismometer"

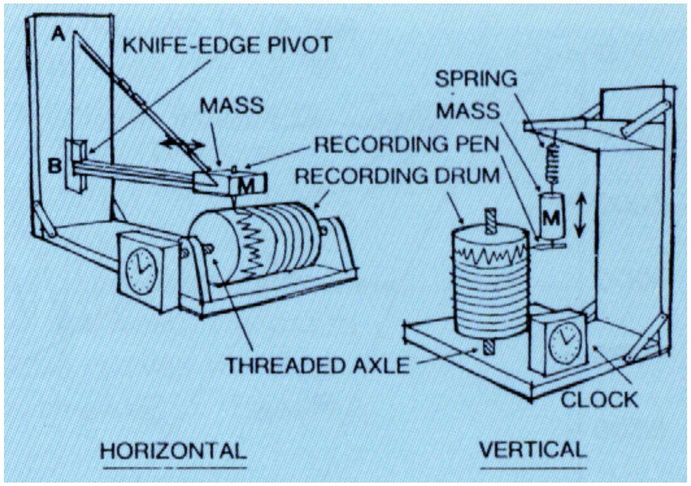


Other types

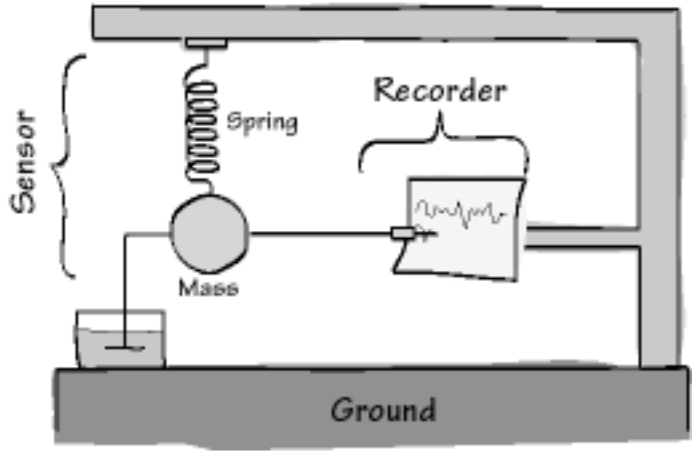


By 1890, we start to have REAL seismometers that are pendulum-based that can produce continuous recordings of earthquake. For example, the first recording after 15 min from an earthquake in Japan was recorded by Philipo Cecchi in 1889 in Potsdam, Germany.

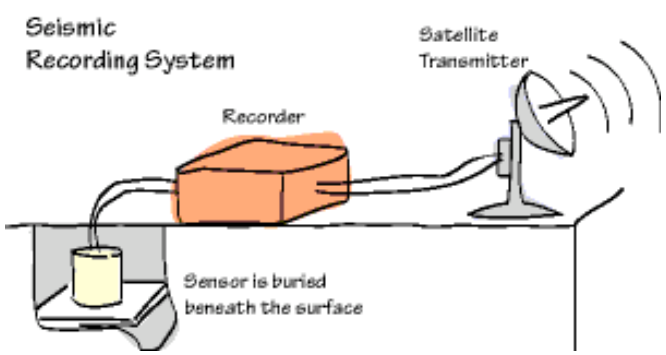
Horizontal Motion



Vertical Motion

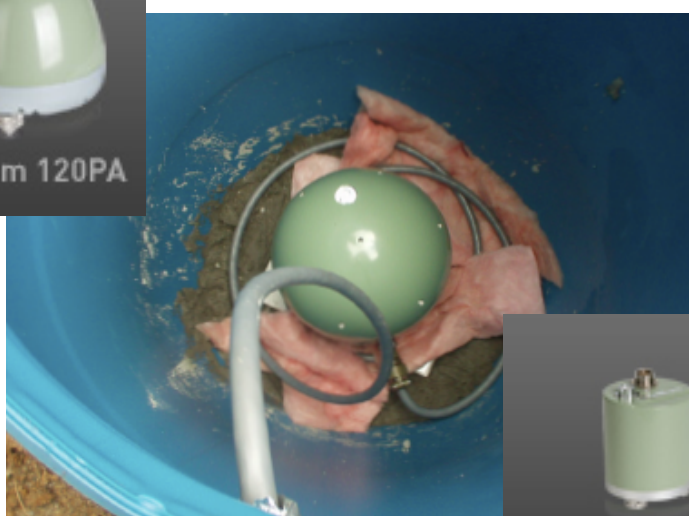


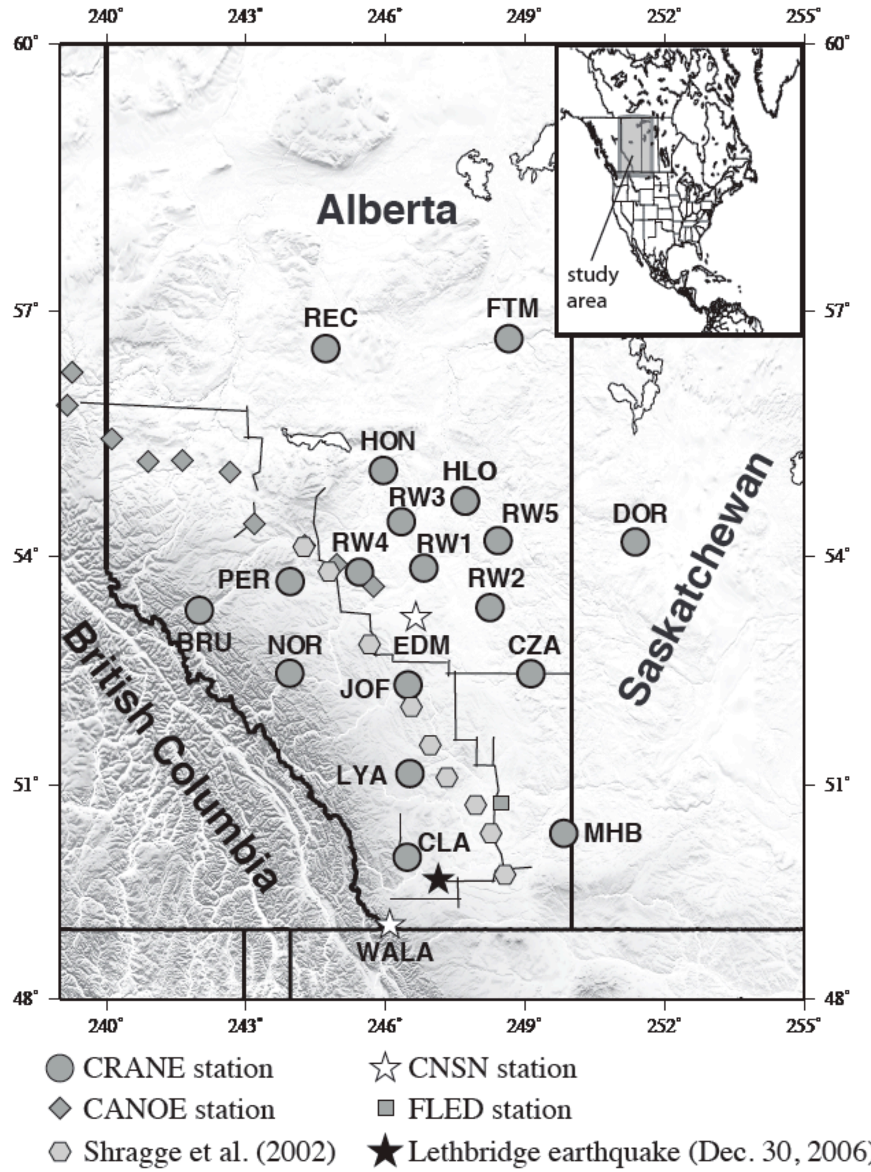
STS-1 seismometer



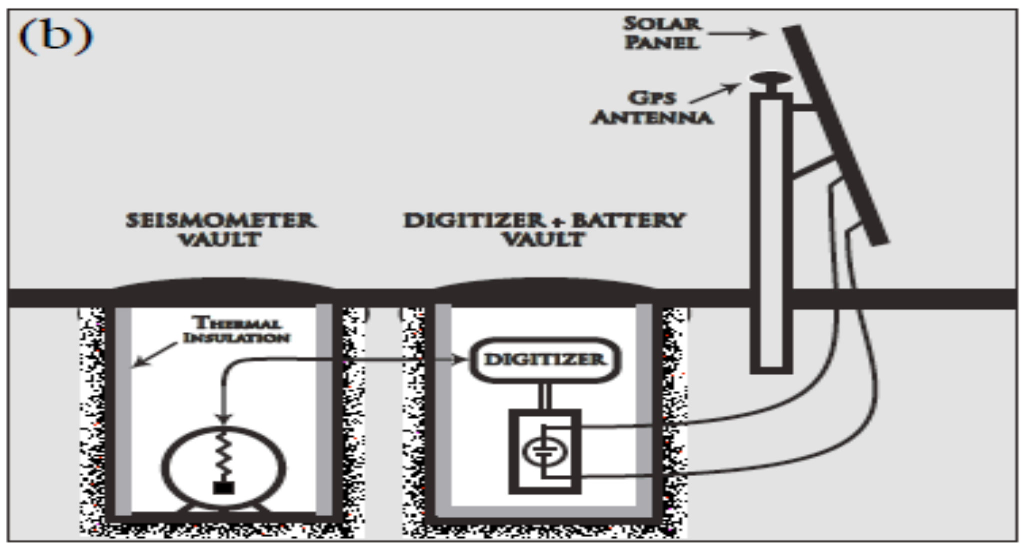
Radio or satelite Telemetry

Our own deployment at UofA: (CRANE seismic array)





Setup at a better-than-average station for CRANE network.

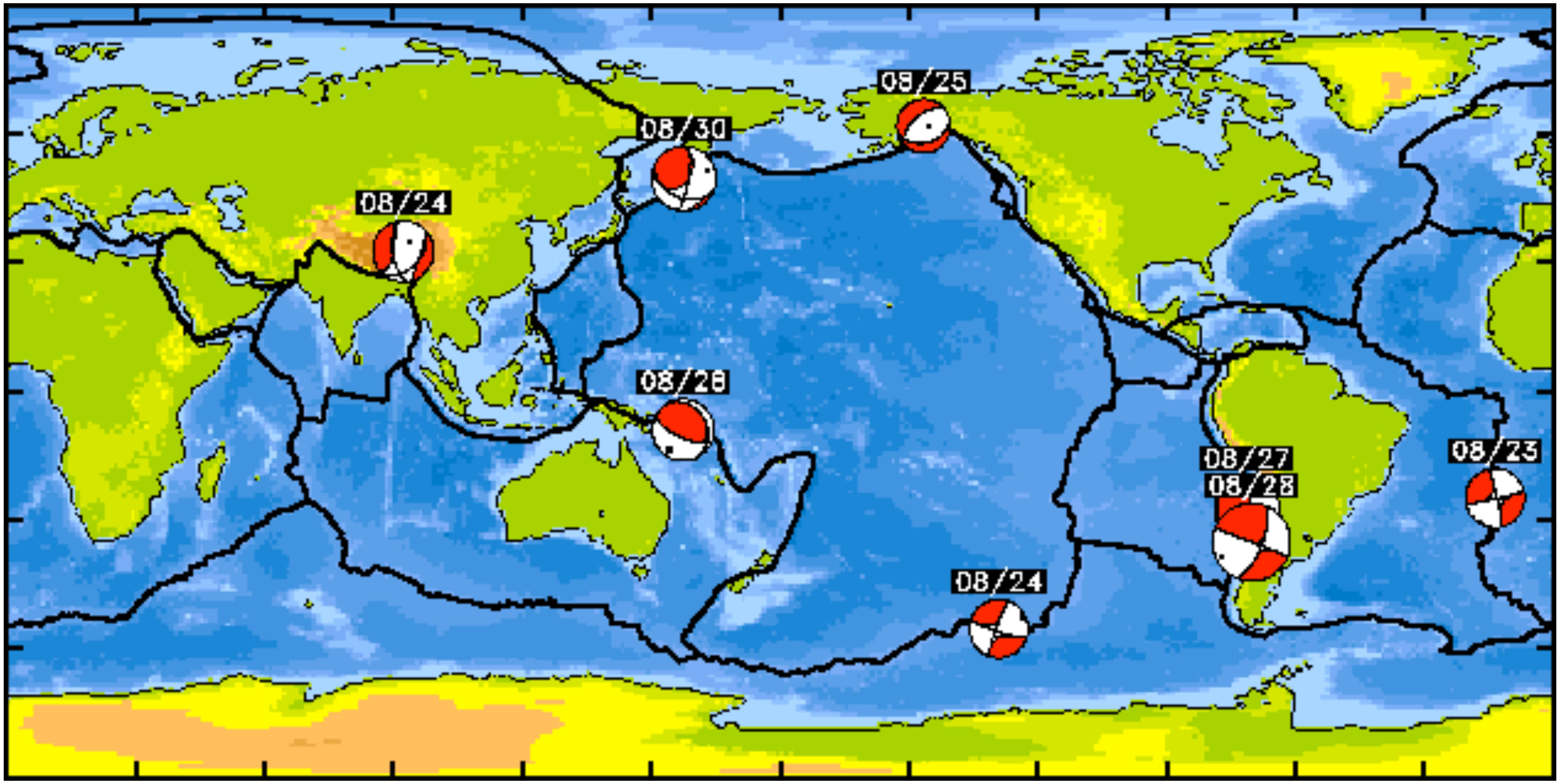


Two speed tickets, a damaged car, constant battling with ants, and a couple of flooded sites later, it is fair to say '***it is not easy***".

Hey, there is still fun to be had in the field

A key purpose: understand earthquakes and faulting

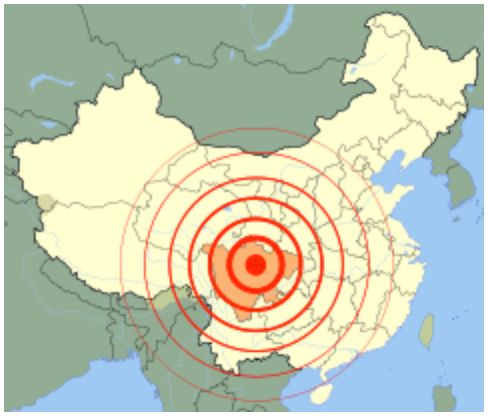
Centroid Moment Tensor Solutions



Earthquakes happen every day, but their occurrence is not random --- the majority can be well explained by the theory of plate tectonics. However, intraplate and deep earthquakes continue to puzzle us.

This map mainly shows earthquake from the *"Pacific Ring of Fire"*

Afterall, Earthquakes started it all!

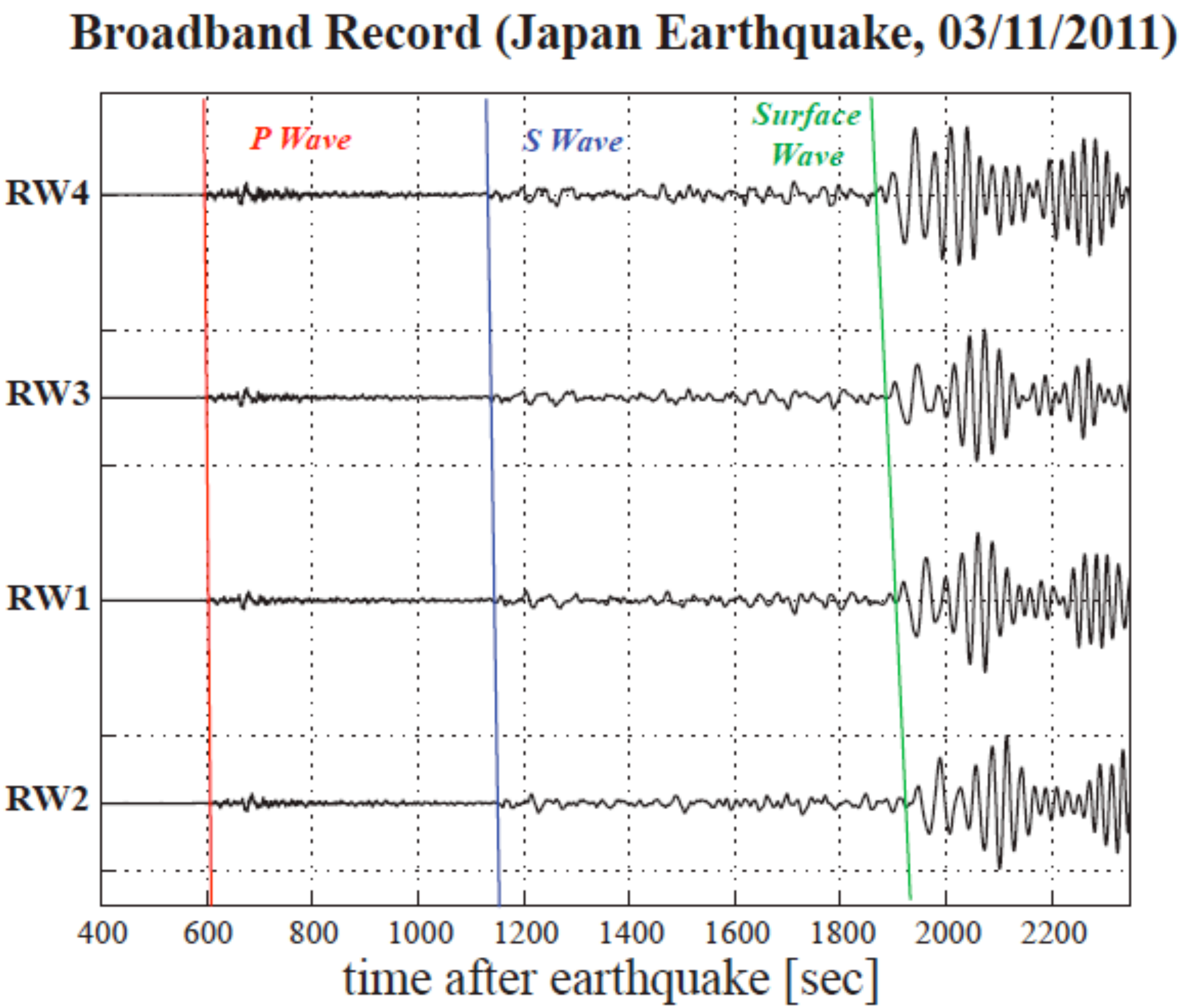


May 12, 2008, Sichuan-Yunan border, ~100000 people killed, countless homeless

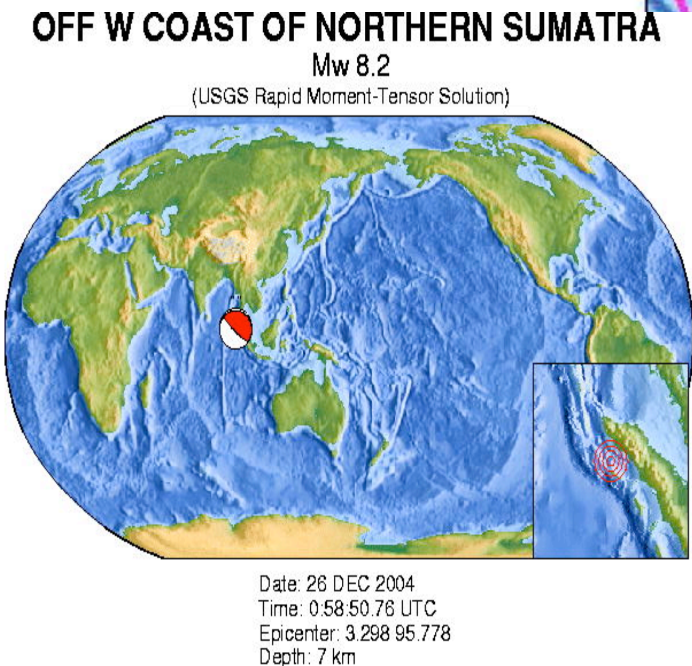
2011 March Japan Earthquake ('Tohoku Earthquake and Tsunami'), ~16000 deaths, ~10000 injured or missing.

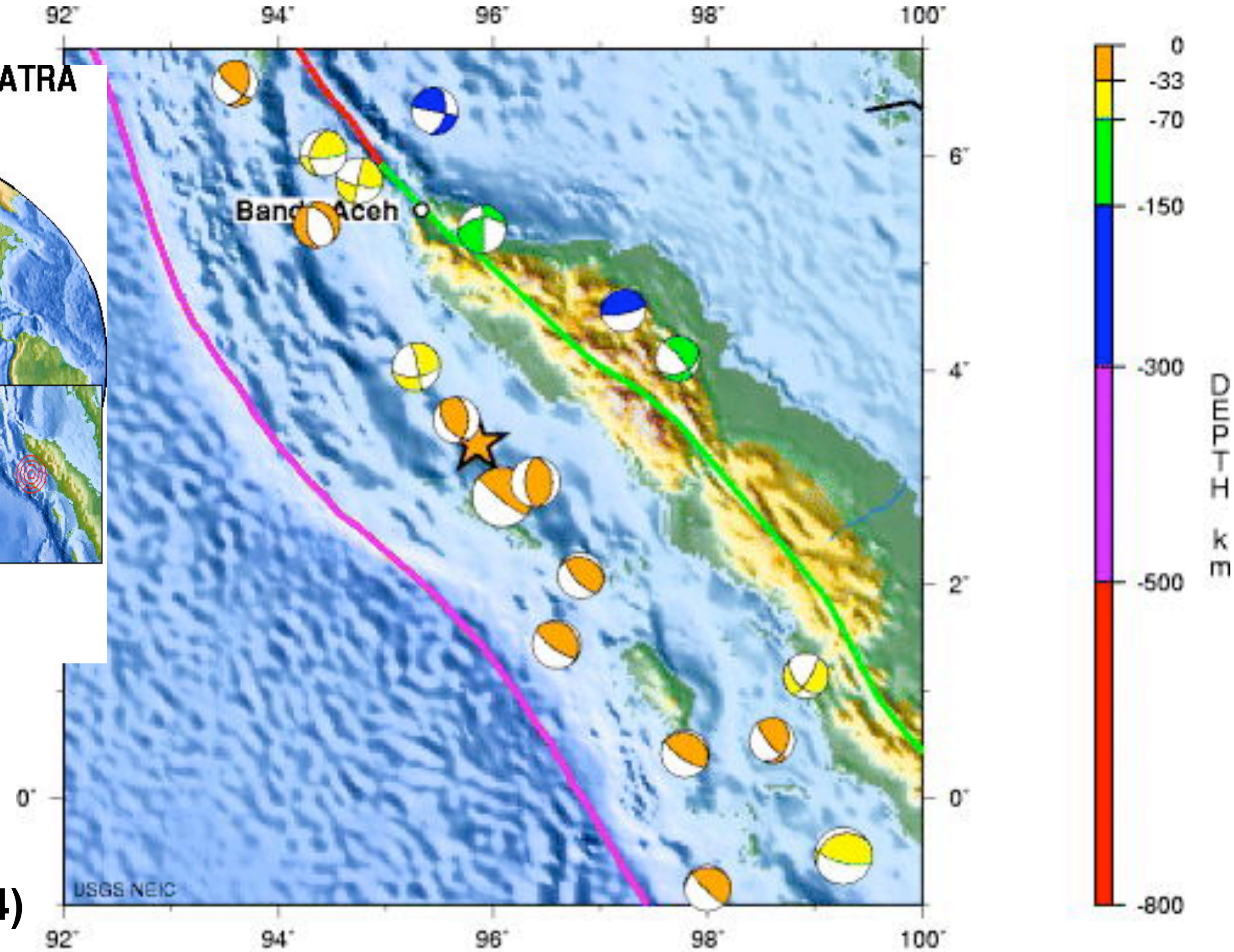
http://en.wikipedia.org/wiki/2011_Tōhoku_earthquake_and_tsunami

Tsunami near Iwate Prefecture (water up to 140 ft high)



Redwater stations from CRANE





Sumatra Earthquake (9.4)
Dec 26, 2004

OFF W COAST OF NORTHERN SUMATRA

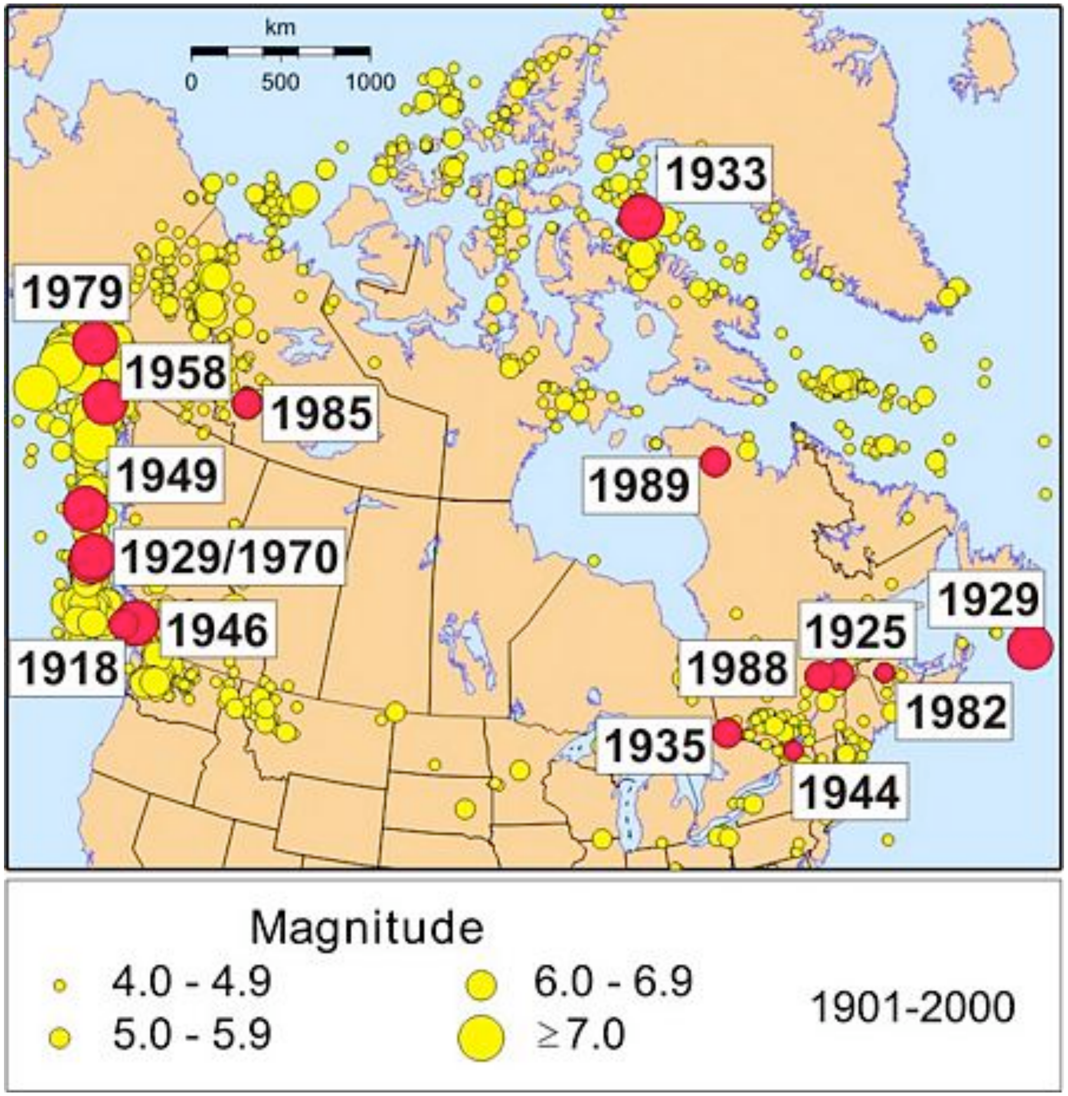
2004 12 26 00:58:53 UTC 3.32N 95.85E Depth: 30.0 km, Magnitude: 9.0

Historical Moment Tensor Solutions

Major Tectonic Boundaries: Subduction Zones -purple, Ridges -red and Transform Faults -green

USGS National Earthquake Information Center

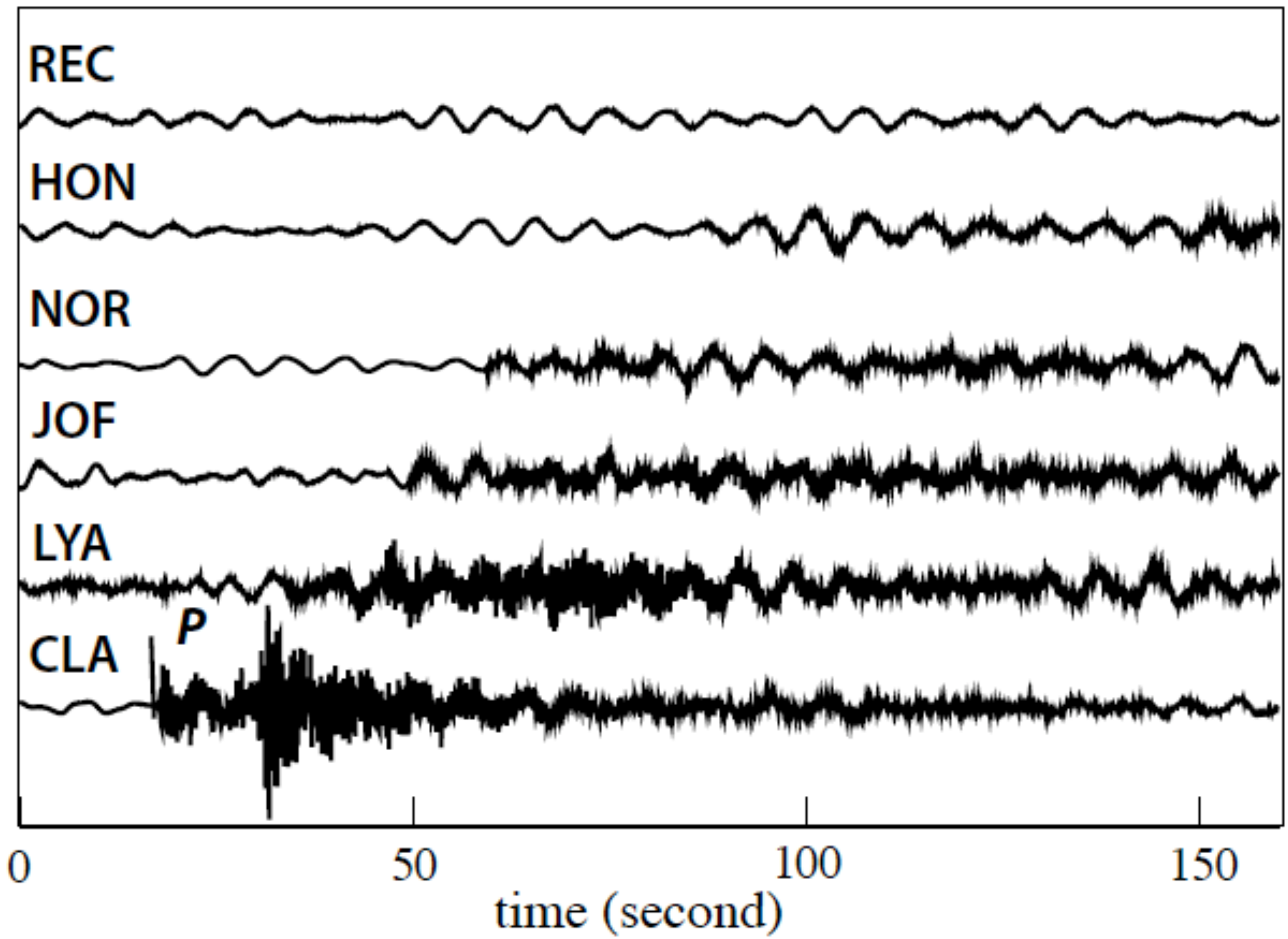
Large earthquakes in Canada (Yes, we are kind of safe in Alberta)



Largest 1949/08/22, 53.62N 133.27W, 8.1, Offshore Queen Charlotte Islands, British Columbia

Regional Earthquake

(Dec 30, 2006, Lethbridge, Mag=3.5)



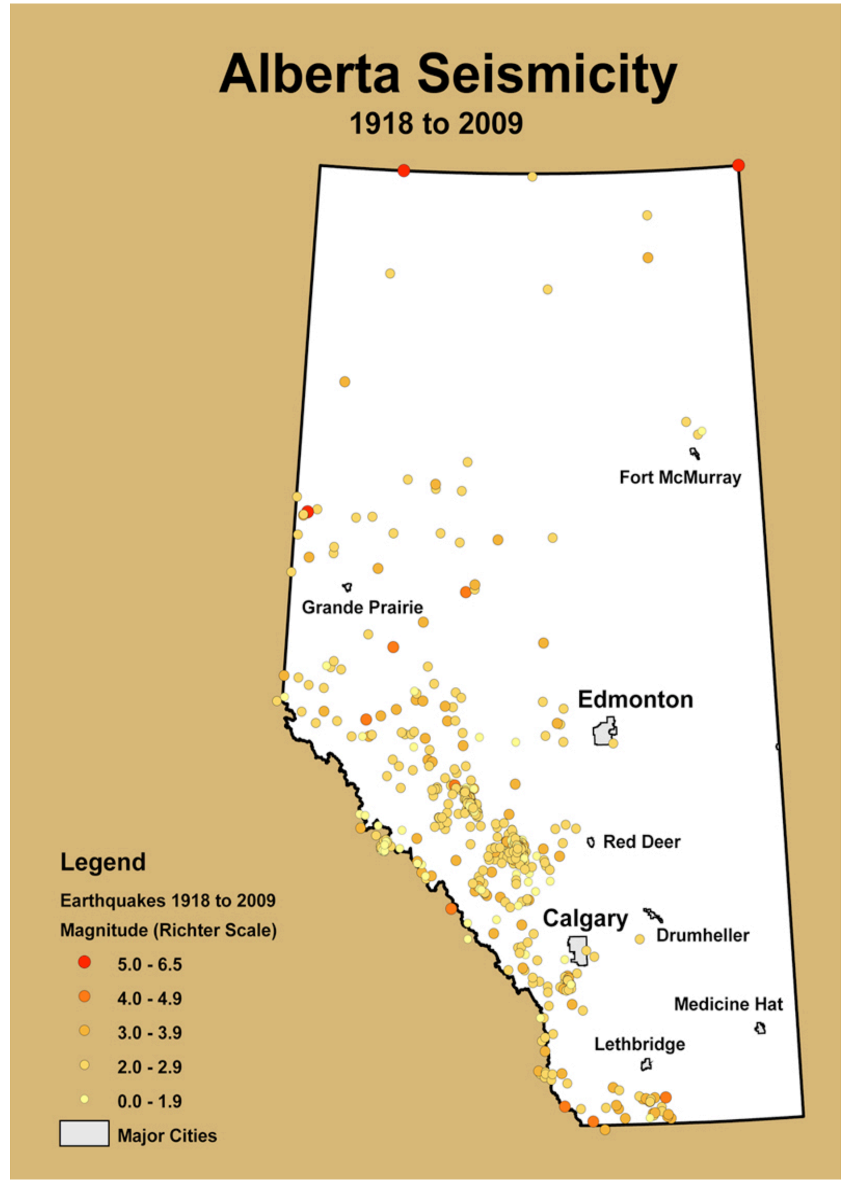
Earthquakes in Alberta:

Max: 5-5.5

Where: Lethbridge, Rocky Mountain House, Peace River, Turtle Mountain.

How often: 800 in the last few years mag < 4.5

Question: Why?
Industry *Induced seismicity?*
Snowbird tectonic zone and old faults?



Events from our improved regional seismic station coverage

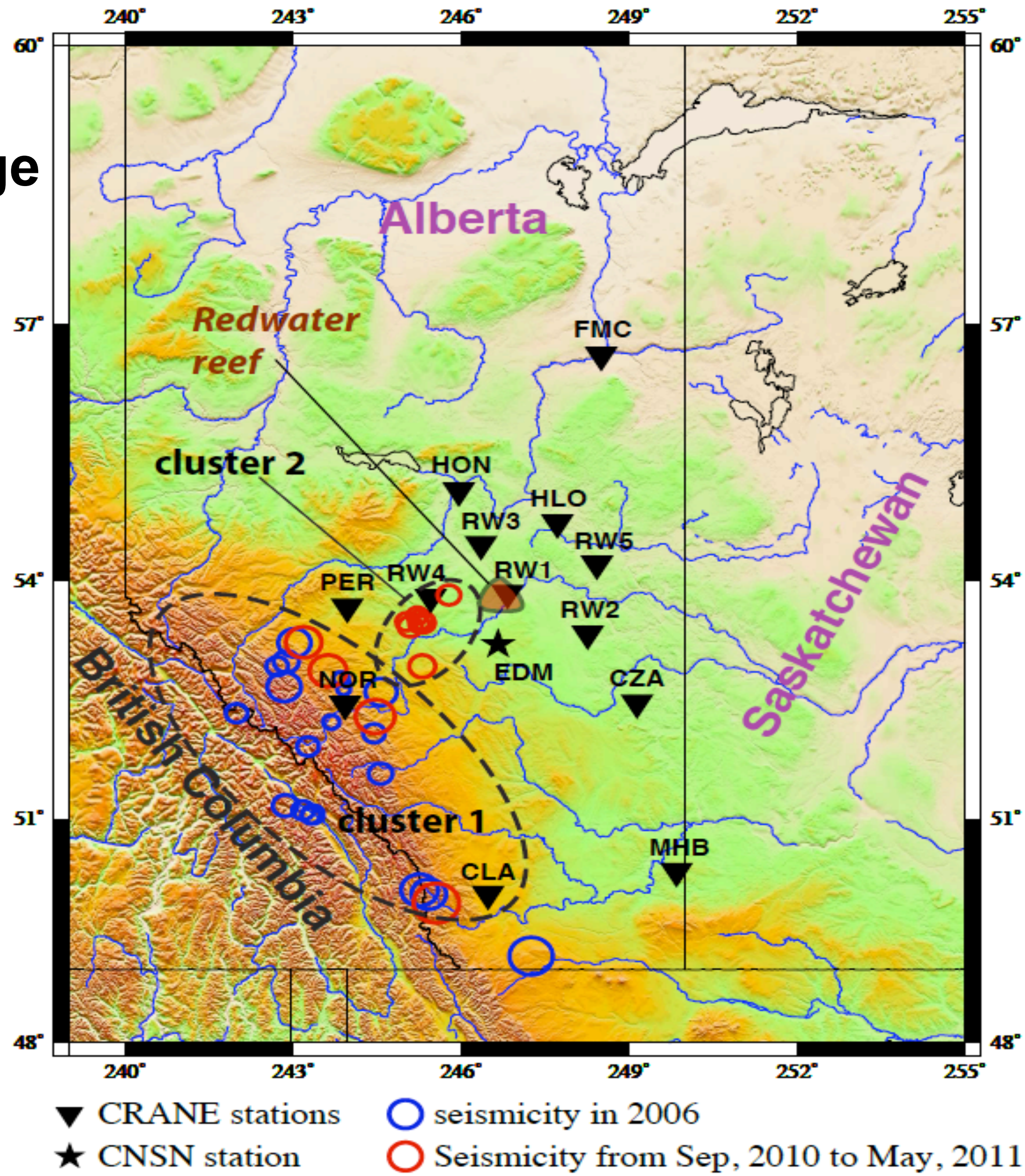
While we are pretty safe in Alberta, there are concerns as well such as water or CO_2 injection and induced seismicity.

Cluster 1: cause of concern

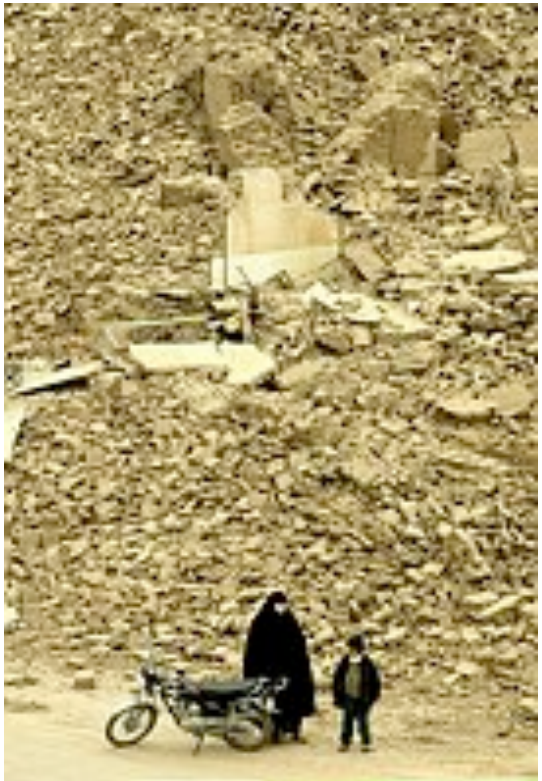
Cluster 2: mining blasts

[Report to Alberta Innovates HARP project]()

Regional Seismic Events



Images from the Bam Earthquake in 2003



Mw 6.7 earthquake on 26/12/03, more than 30000 people were killed
And 2/3 of the houses in Bam (620 km southeast of Teheran were destroyed)

Issues to consider: (1) Are earthquakes predictable?
(2) Why the devastation considering the relatively modest earthquake size?

Reliable short-term prediction is VERY DIFFICULT!

Have there been success?
Yes, examples

1. 1975 M 7.4 Haicheng earthquake
2. 1980 Mount Saint Hellen Eruption

Symptoms to look for:

(1) Microseismicity
(2) Level of gas emission
(3) Water levels
(4) Poisson's ratio
(5) Animal behavior anomalies

BUT, NONE of the symptoms have been truly reliable!

Do we still need to rely our best friend, or worst enemy to predict earthquakes?

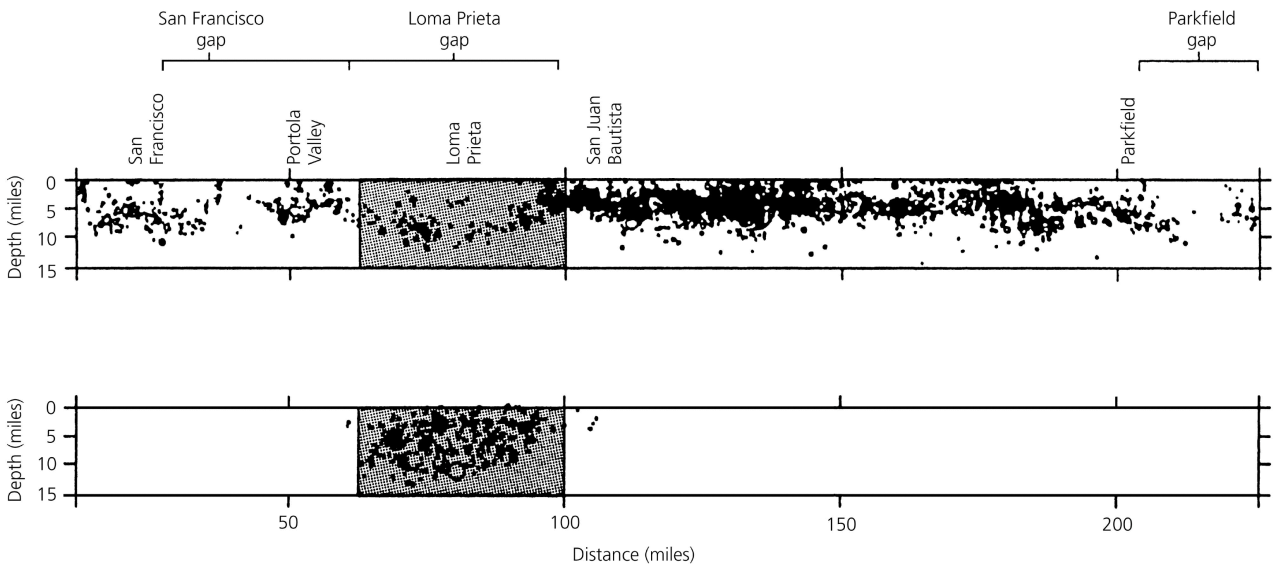
Earthquake Forecasting/Prediction Problem

I. Long-term forecasting using history is feasible

based the idea of seismic gaps and elastic rebound

Successful case study: Loma Prieta earthquake,

Figure 1.2-16: Loma Prieta seismic gap along the San Andreas.

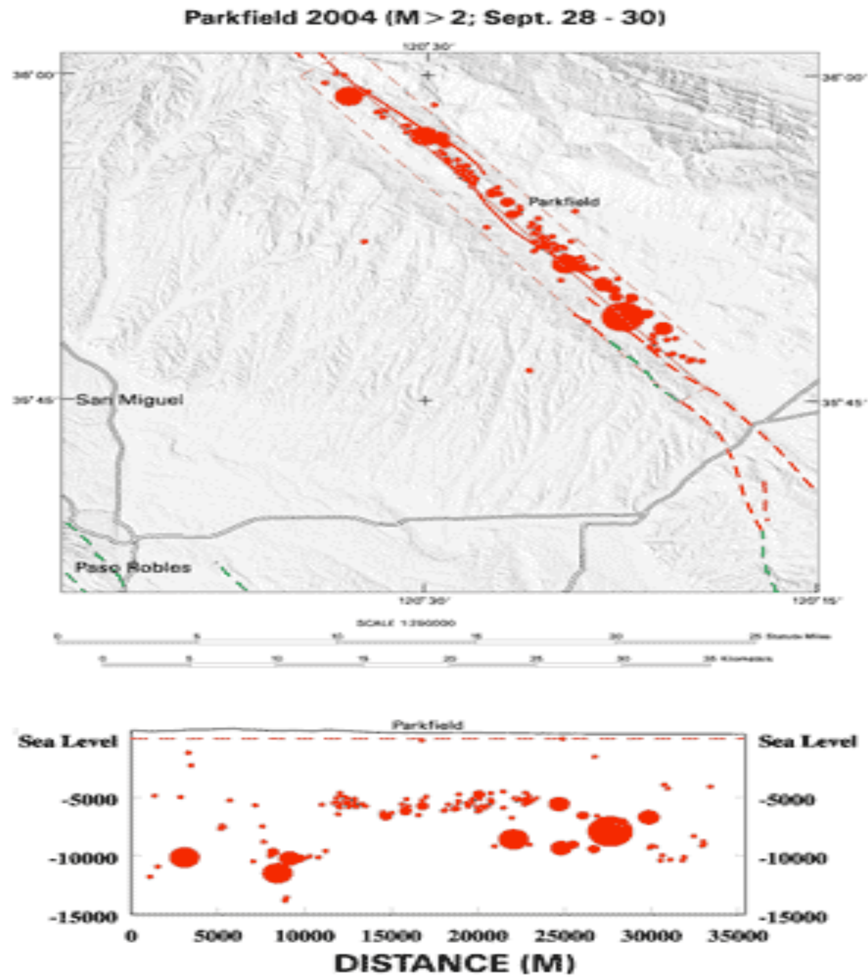


Is it always reliable:
No, look at the Parkfield example

Previous occurrence: 1857,1881,1901,1922,1934,1966, expect another one **Before** 1993, but it happened **4 years ago**!!

The Saving Grace of An International Embarrassment…

Mag = 6 event (2004), Parkfield, California



If we can't predict earthquakes well, what else can be do?

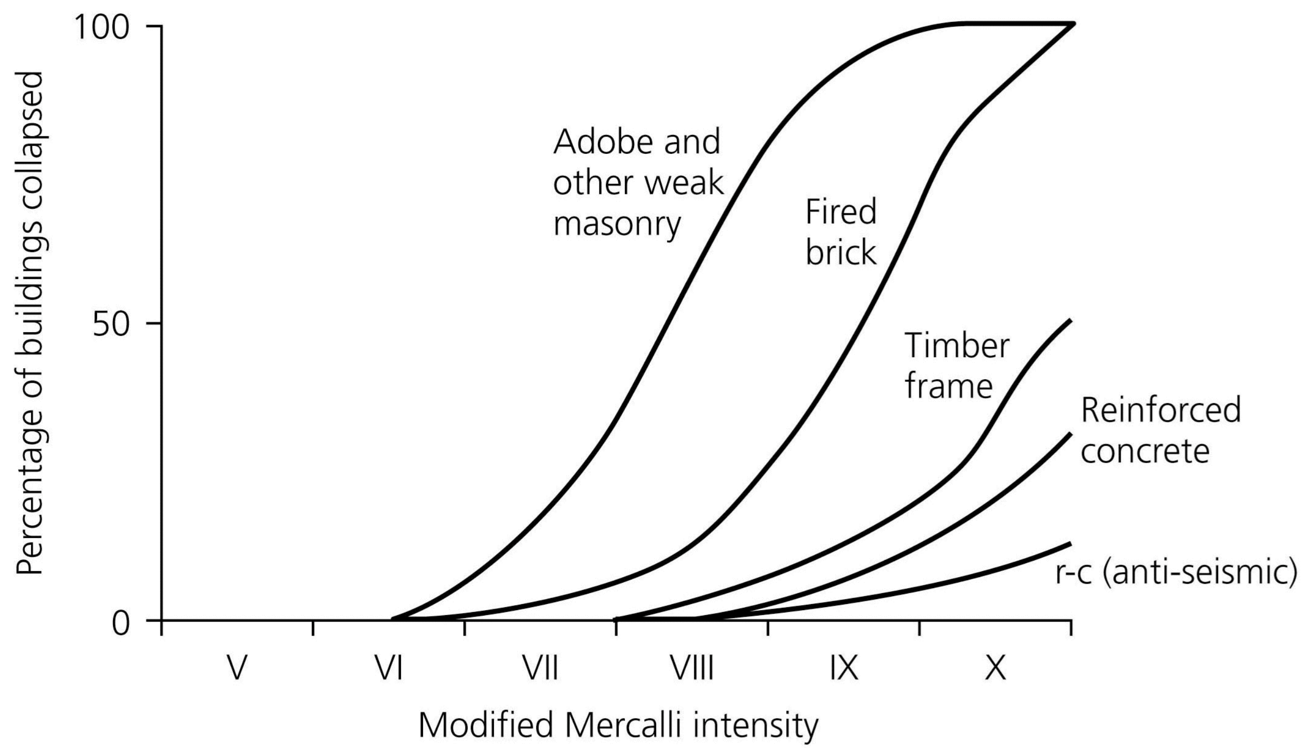
I. Set up earthquake evacuation drills and warning systems

II. Get real time Tsunami warning systems in place

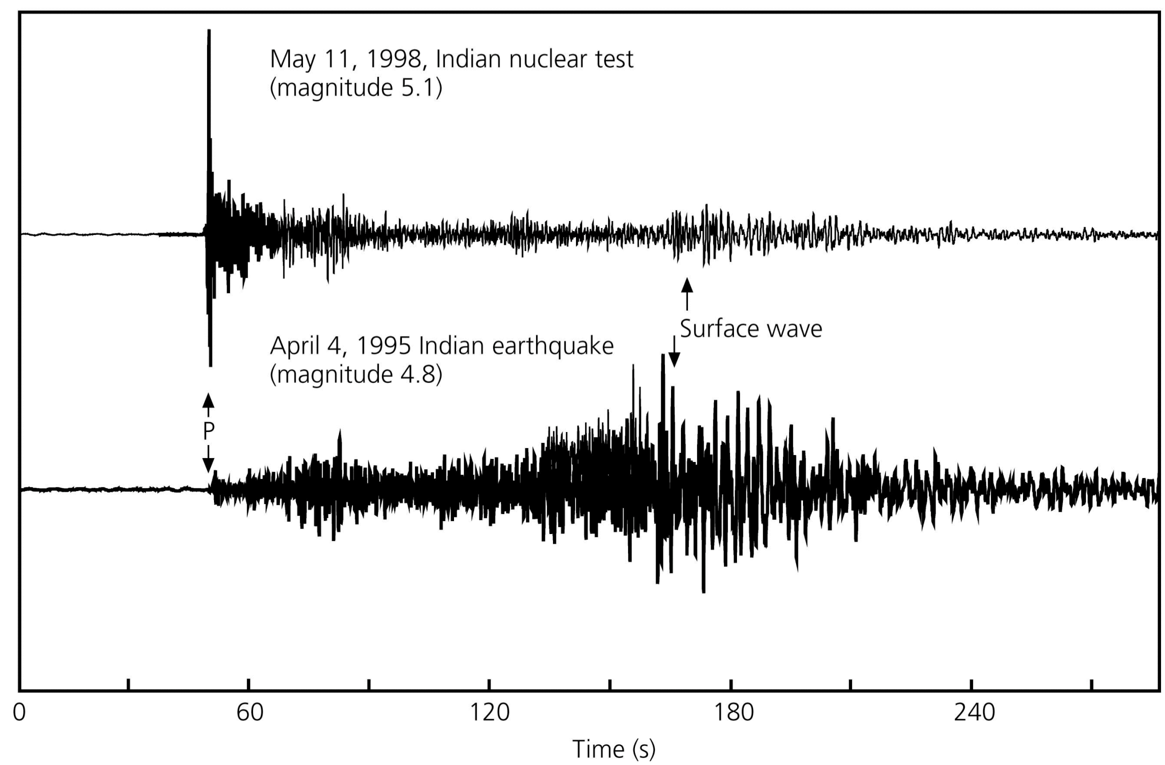
III. Build better houses!!

Motto: Earthquakes don't kill people, buildings, fires do!

Figure 1.2-6: Collapse of buildings as a function of intensity of shaking.

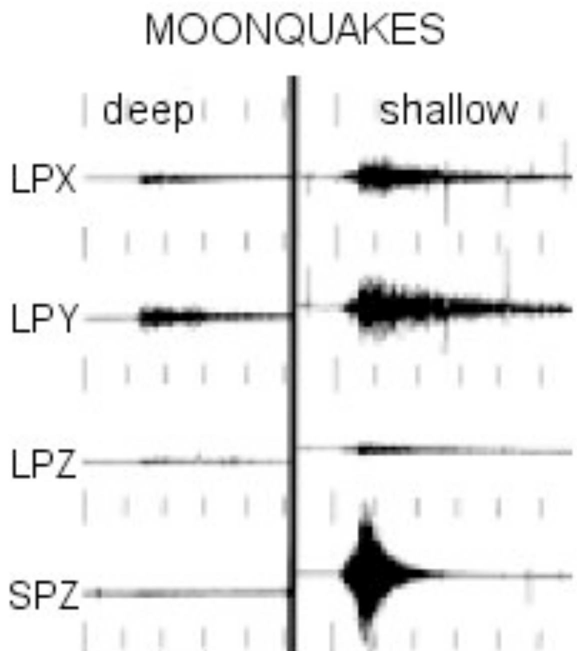


Other Use of Seismology: Nuclear monitoring and treaty verification

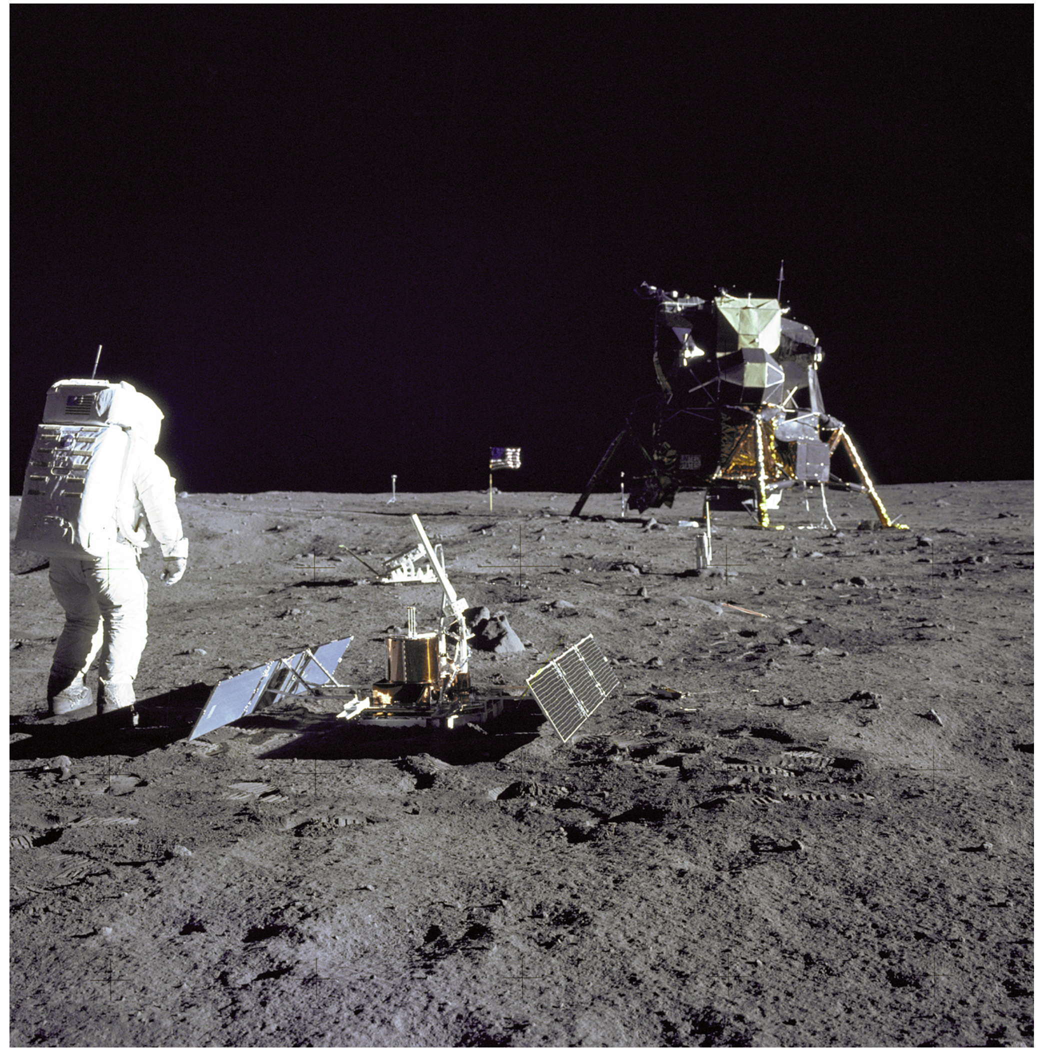


Limited Test Ban Treaty: 1960s, no testing in atmosphere, oceans, space
WWSSN established
Threshold Test Ban Treaty: 1976, limit size of event to < 150 Kilotons of TNT
CTBT: 1996, no nuclear testing
NOW: NO CLUE…

Broadcast from the moon ceased in 1977, but recorded ~12000 *moonquakes*. Original setup sent about 3-weeks of data, then the later Apollo missions 12, 14, 15, and 16 in each of the landing sites with better equipments.



Likely Causes:
mantle events, meteorite, thermal Expansion , shallow; smaller attenuation than Earth (up to M=5)

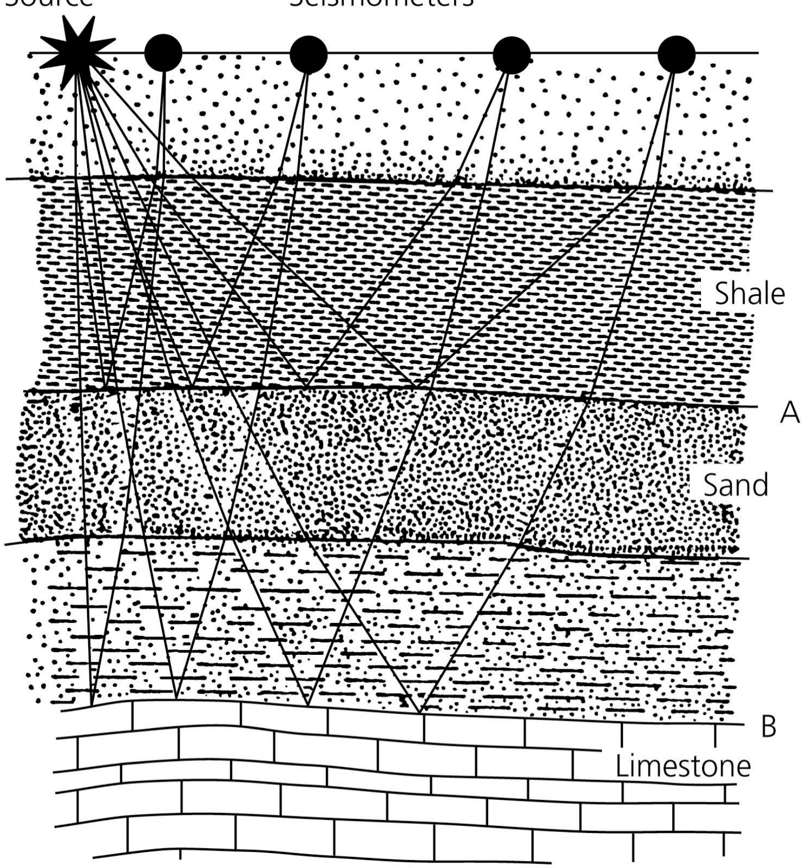


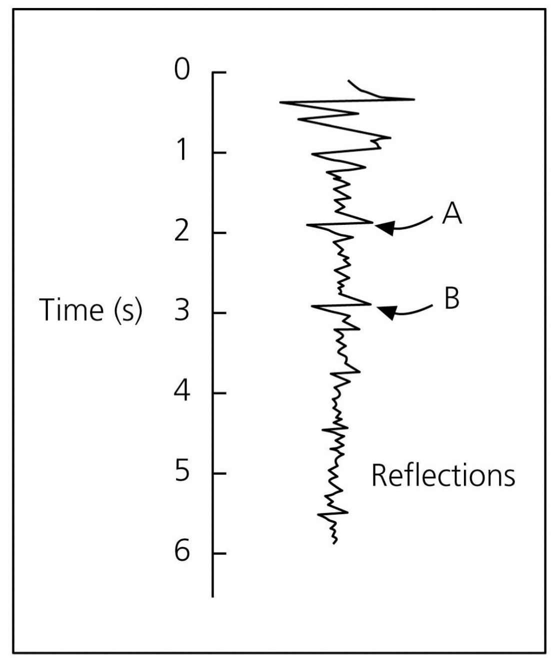
Buzz Aldrin next to the first seismometer on the moon, which he installed in July 1969. In the background is Eagle, Apollo's lunar lander.

Information from: http://seismo.berkeley.edu/blogs/seismoblog.php/2009/07/20/quakes-on-the-moon

Another Aspect of Seismology: Structure Analysis

1. **Shallow seismics (faults, oil or precious mineral reservoirs)**





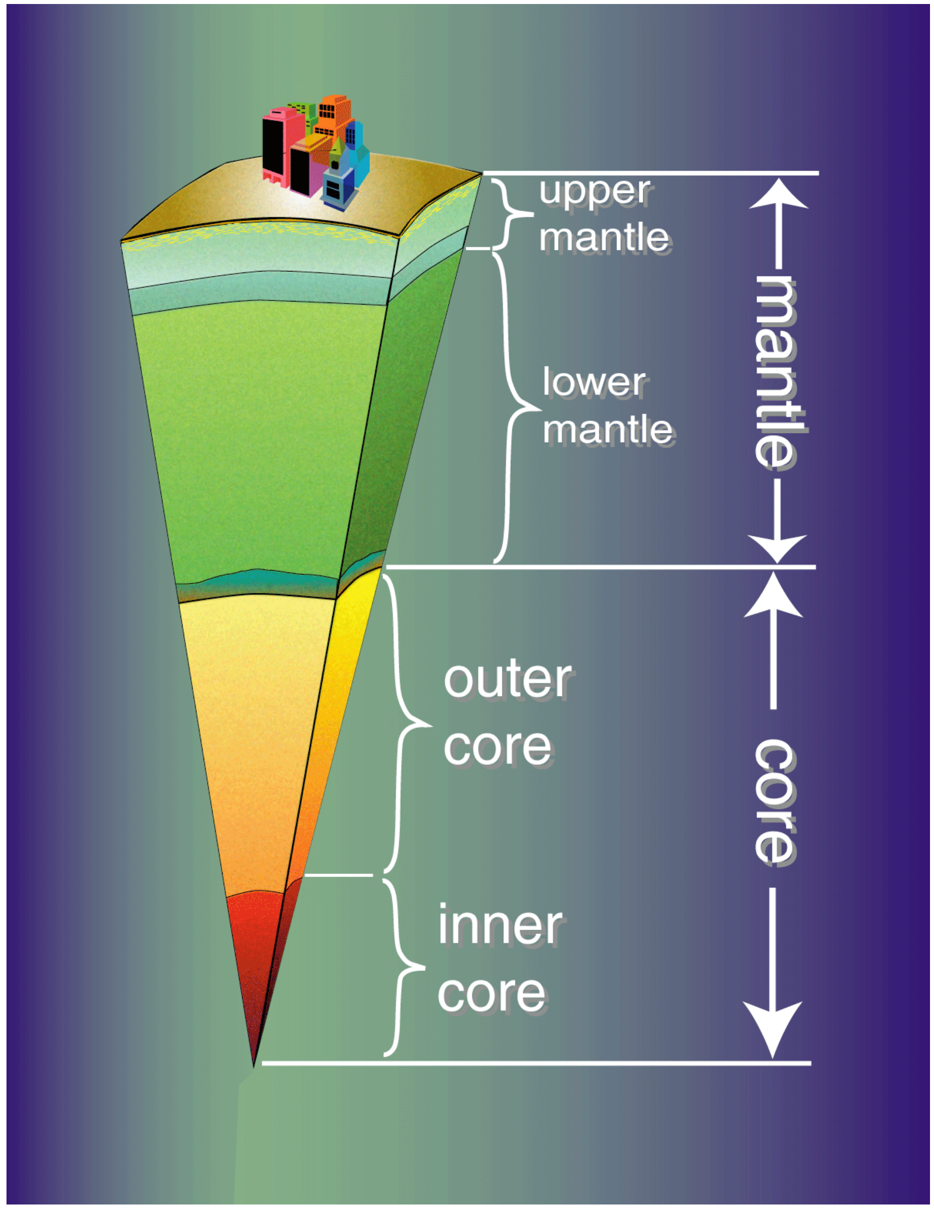
Big events in structure analysis

1909, Mohovicic discovered the Moho

1913, Gutenberg determined the core to about 2900 km

1936, Lehmann discovered the Inner core

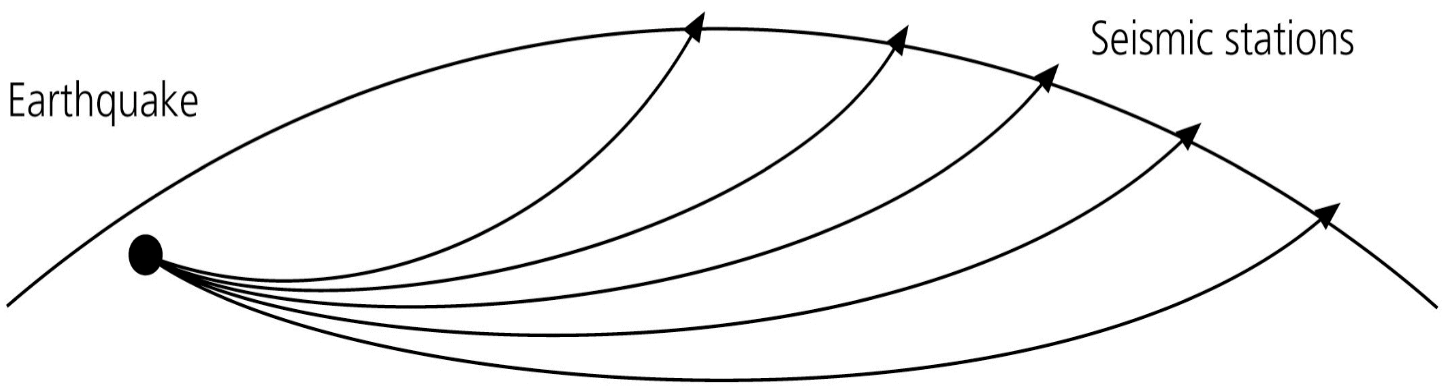
Early 1990s, Lay and coauthors discovered the D''



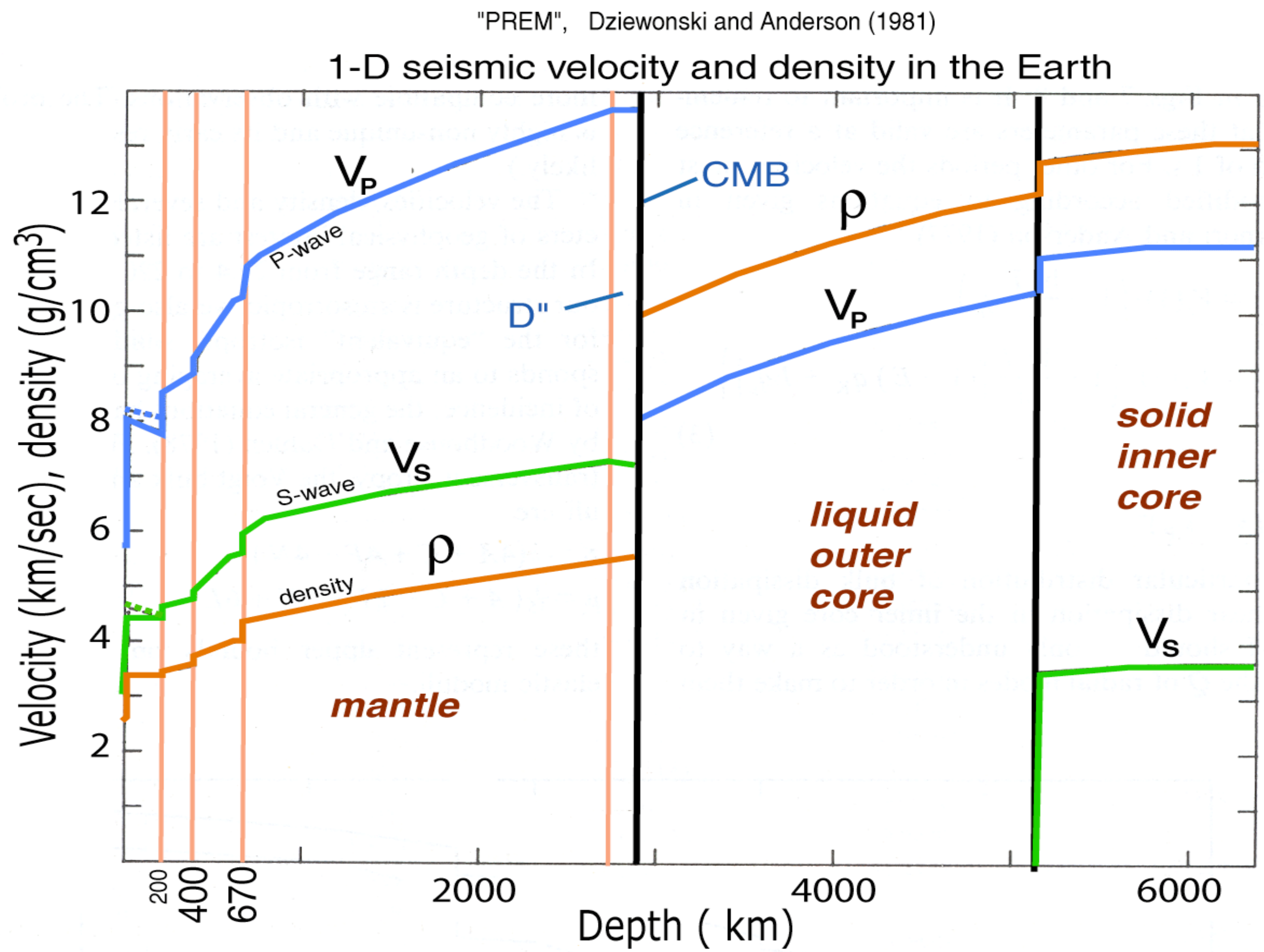
What do we learn from seismic waves

Seismology is a study of the generation, propagation and recording of seismic waves. It is to date the most effective means to uncover the internal structure of the earth. The theory is directly linked to theories in continuum mechanics and wave.

Seismogram= source impulse*medium response*receiver electronics

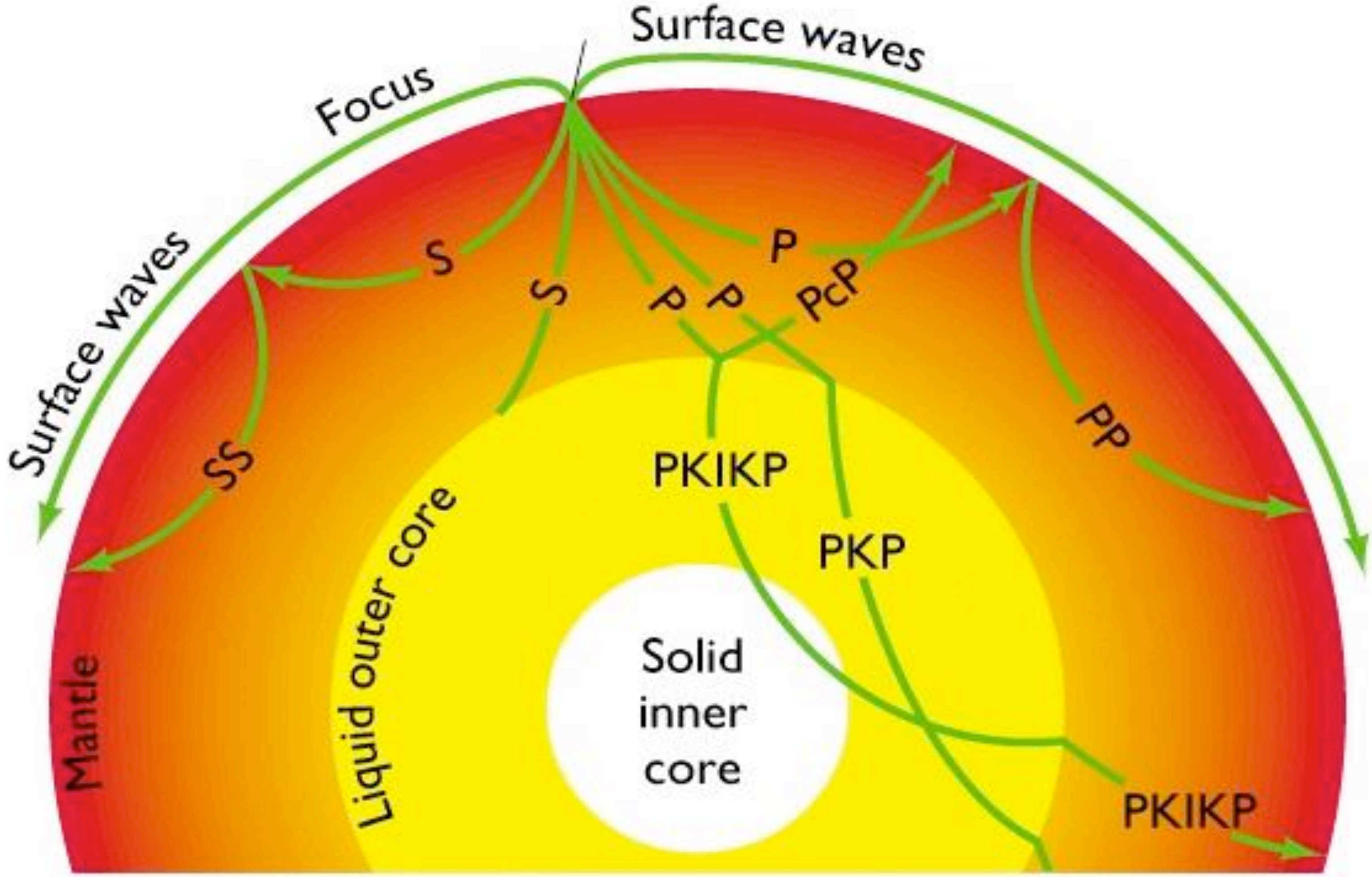


The Half-Million Dollar Paper



Early 1D structure that can predict travel times reasonably well (within 2%)

Different Wave Types



Important Issues that are debatable:

Inner-most inner core?

Ishii and Dziewonski, 2002

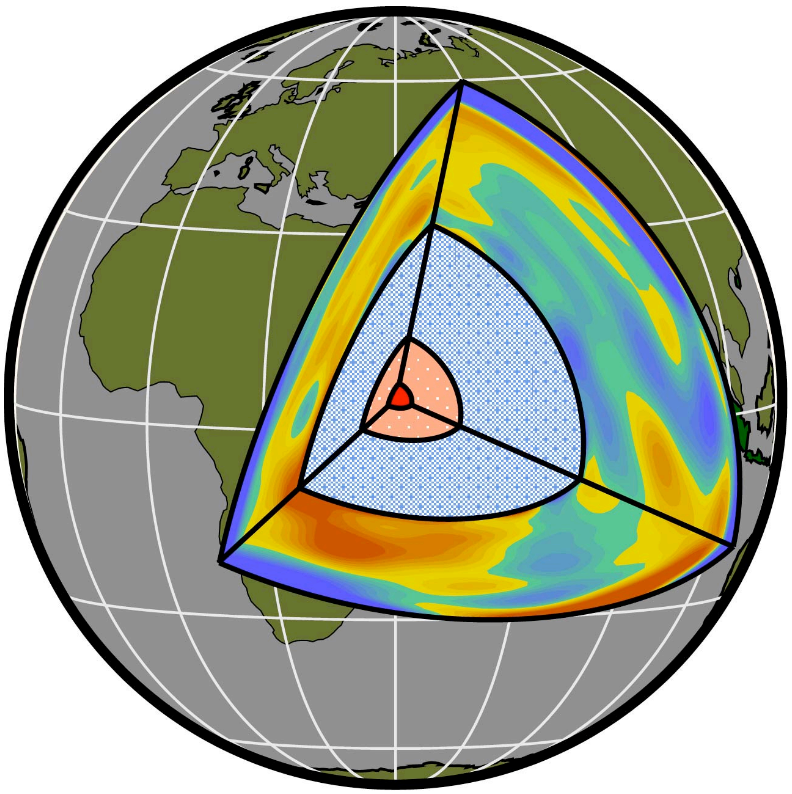
Super Rotation?

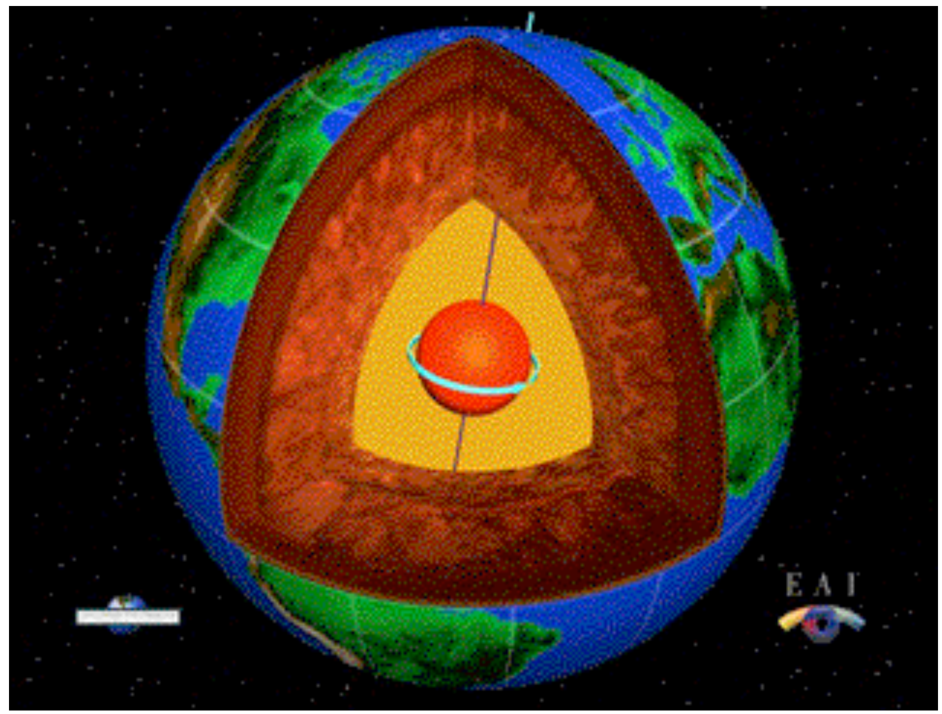
Sung and Richard

Su and Dziewonski, 1995

PKJKP?

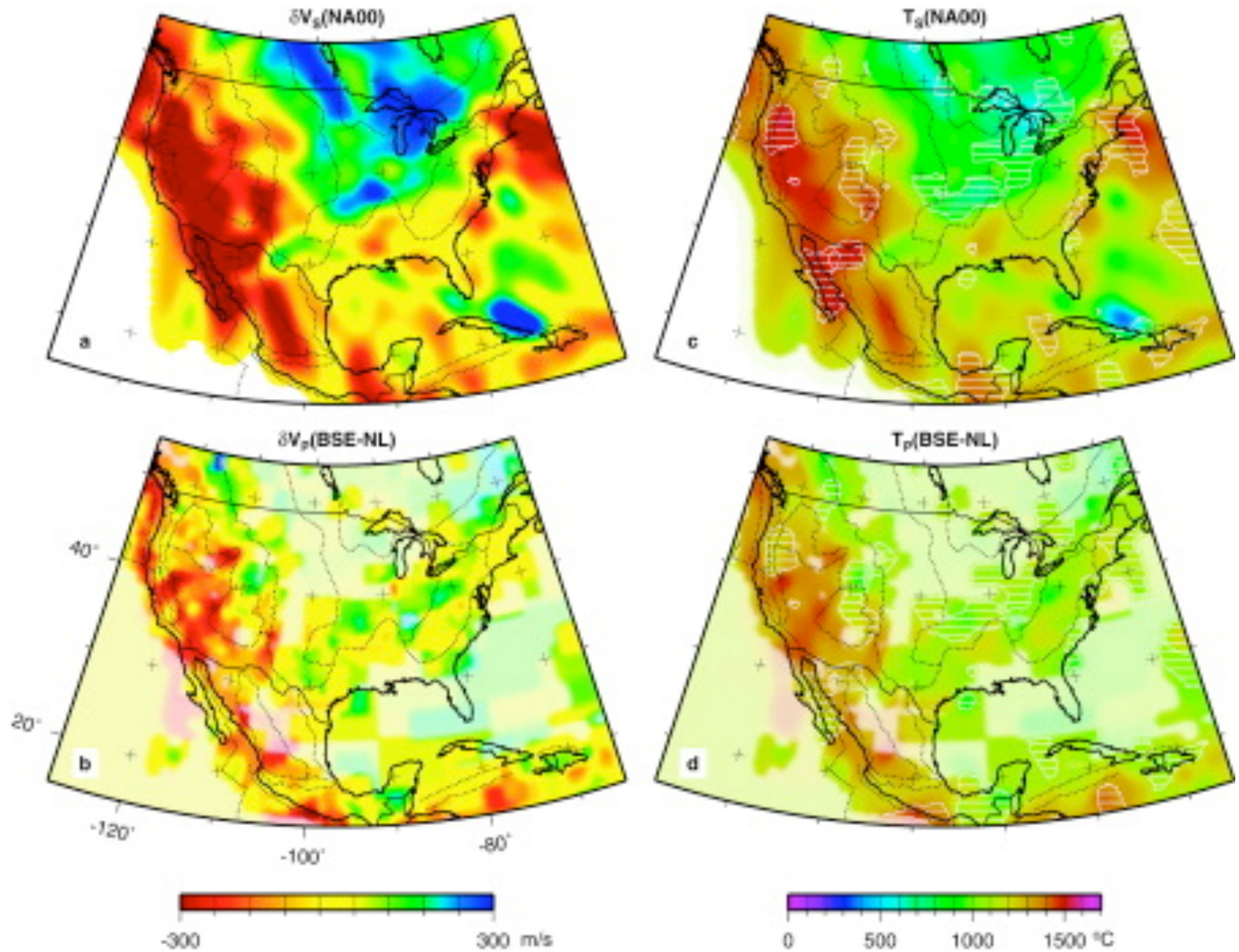
Duess and Woodhouse, 2001





What does it all mean?

Temperature anomalies

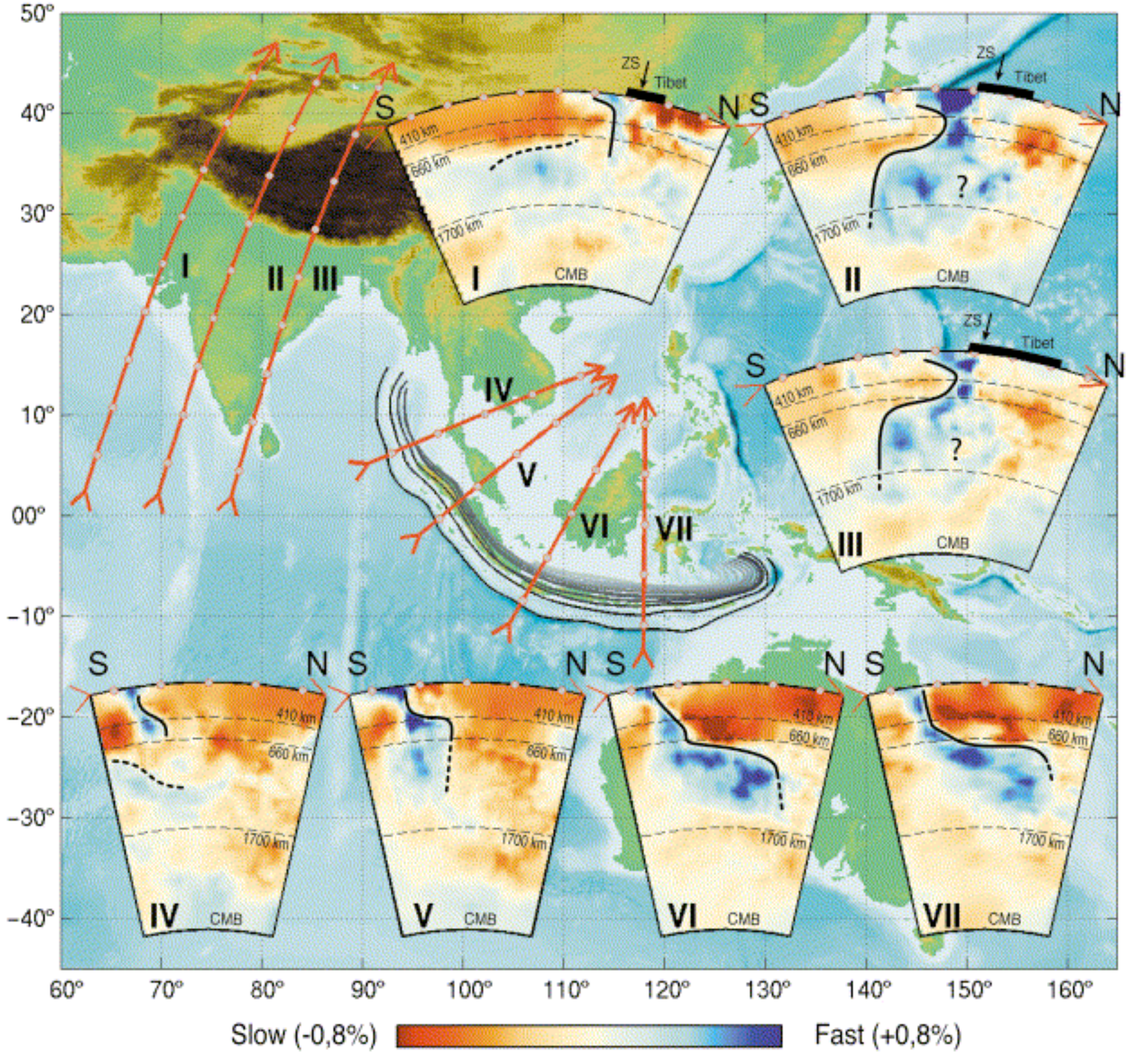


110 km

Goes, *JGR,* 2002

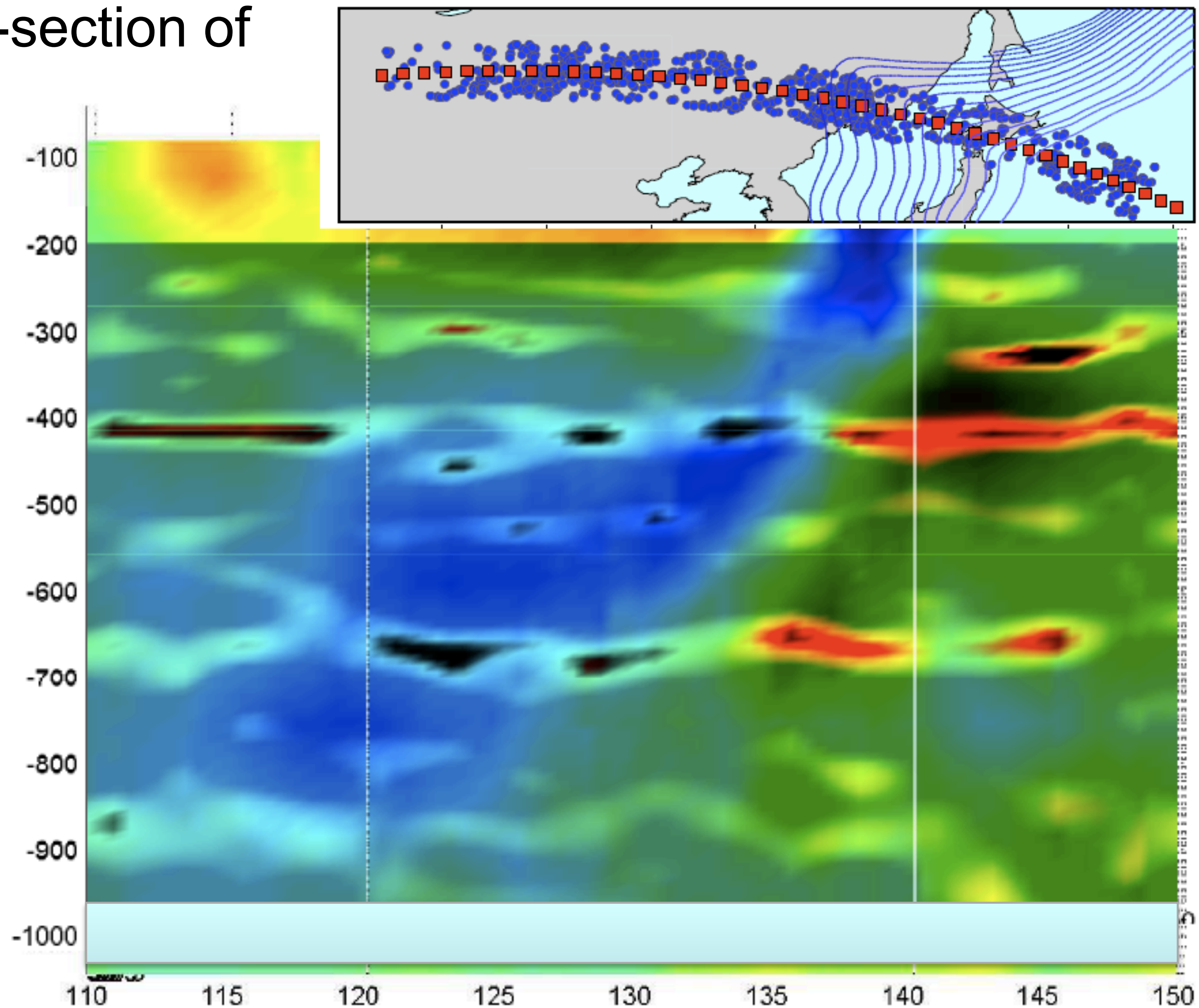
Journey to Middle Earth:

Subduction zones

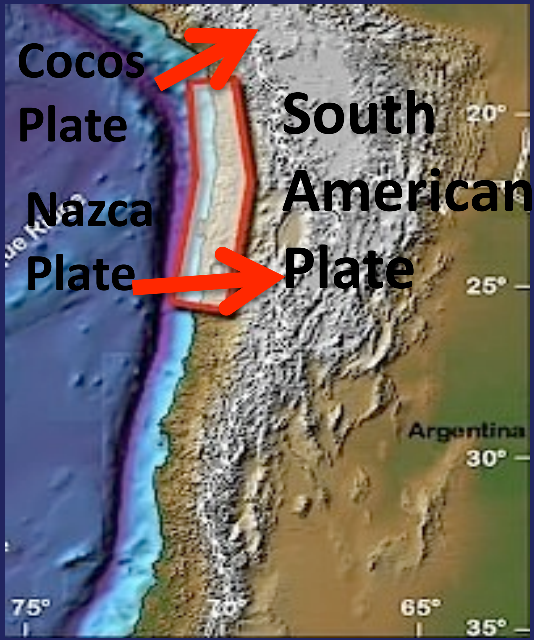


Replumaz, *EPSL,* 2004

Cross-section of Japan

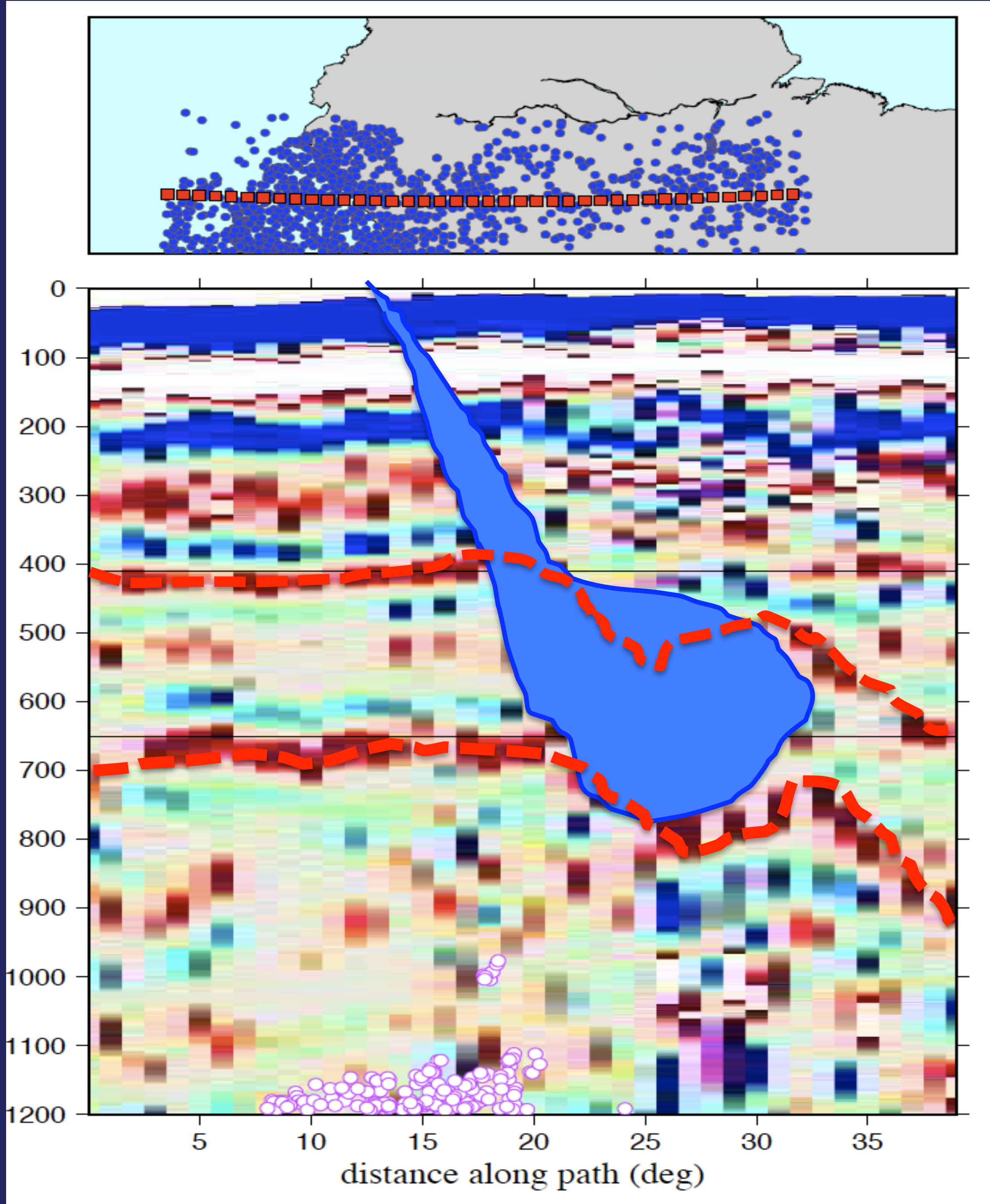


South American Subduction System

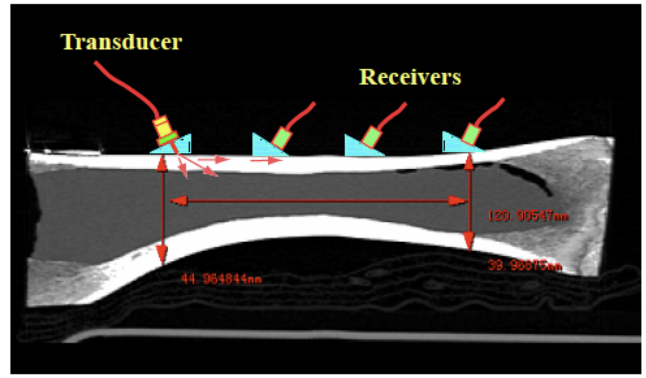


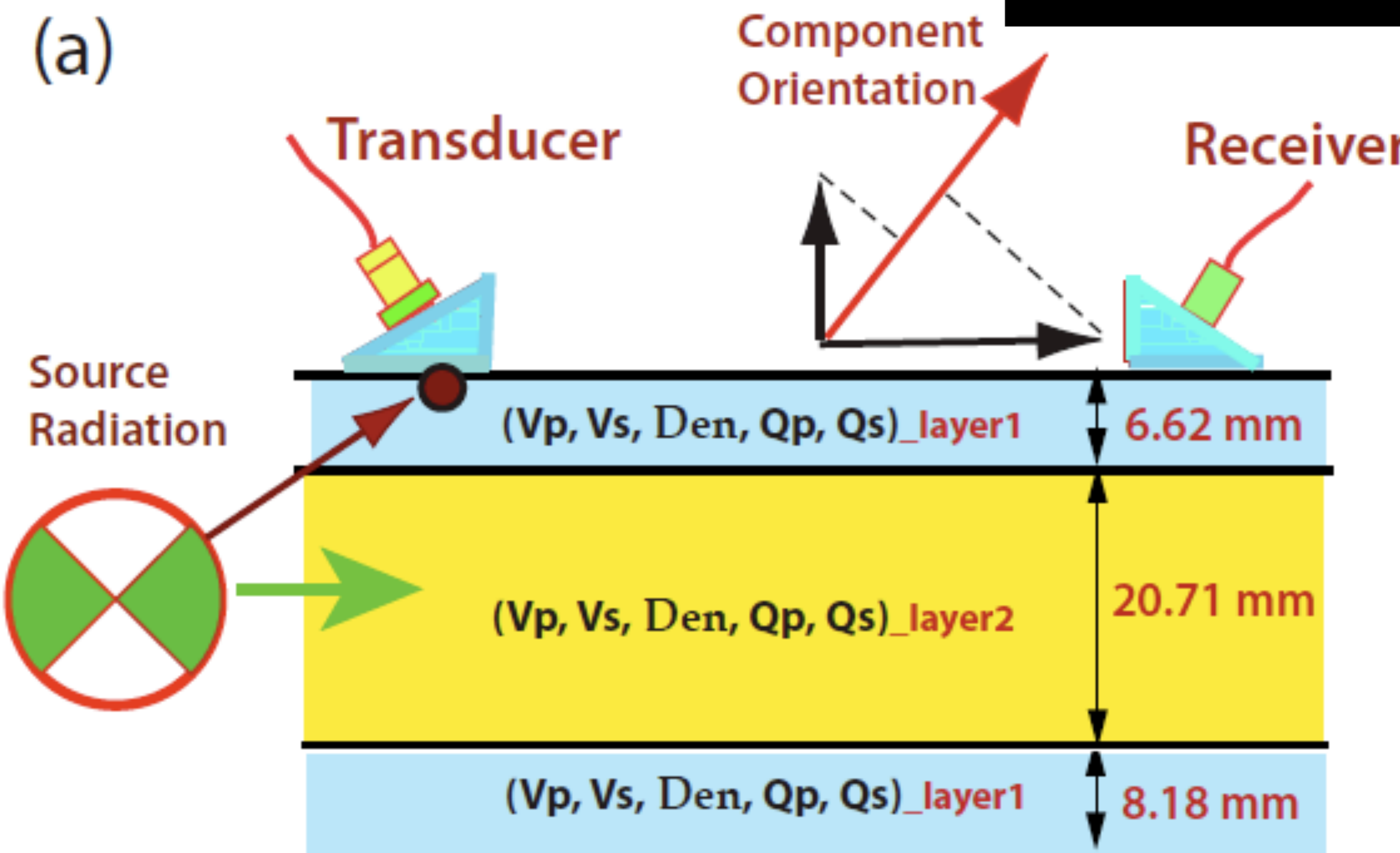
Contributor of image

Contenti, Gu, Okeler, Sacchi, 2002, in press



Seismic theory is everywhere, including studies of bones (ultrasound imaging)





The nature of these pulses on the ultrasound records are:

P wave in top CB

P-S conversions in top CB

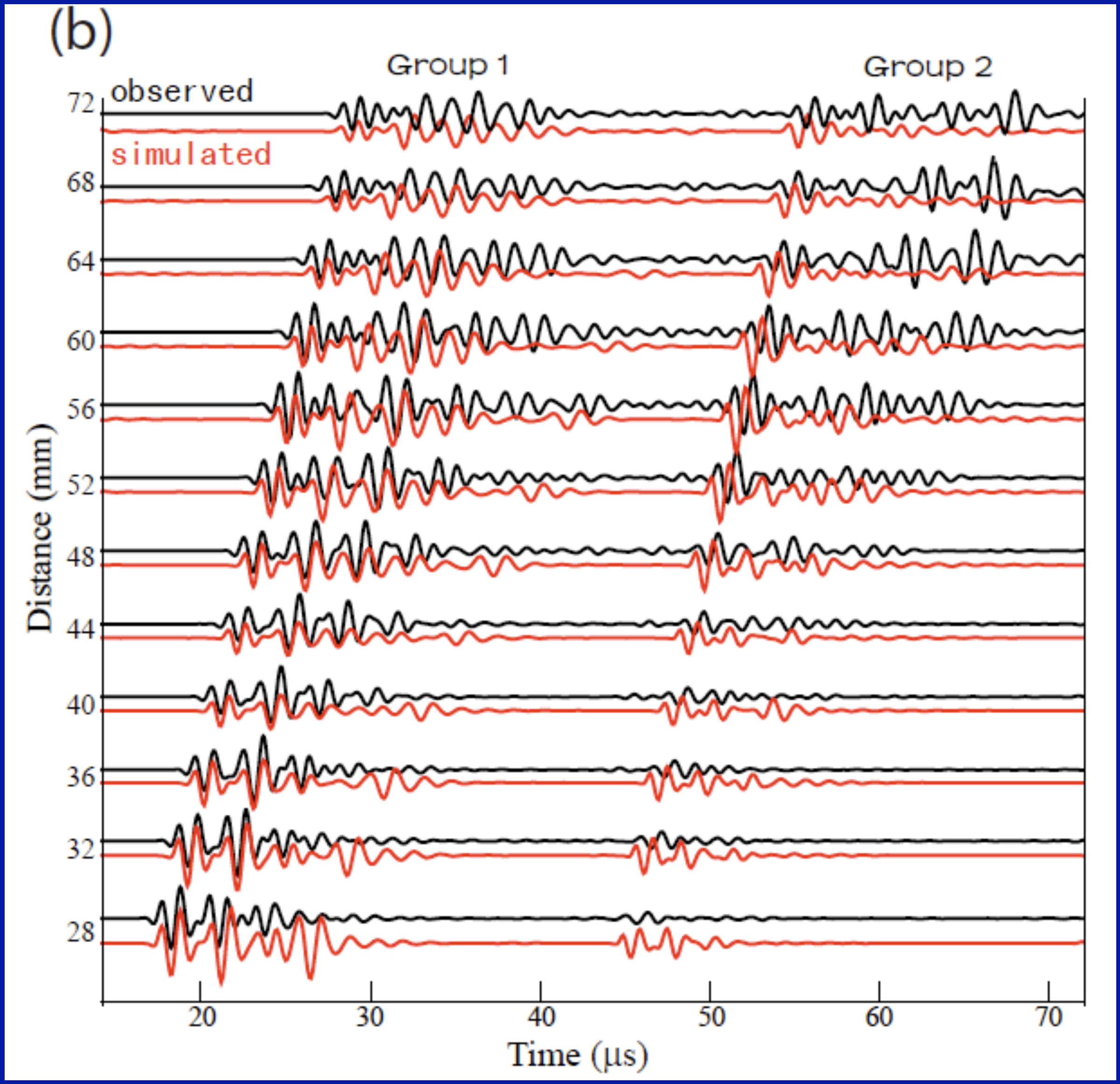
S wave in top CB

Surface wave in top CB

Marrow P and S multiples

Black ---- data
Red ---- synthetics

Waveform Fitting Using Best 1D Model



(Le, Gu, Li & Chen 2010, APL)

Complications to be covered by this course

1. Presence of compositional heterogeneities
   (solution: comparison of P and S wave speeds)

2. Internal boundary variations

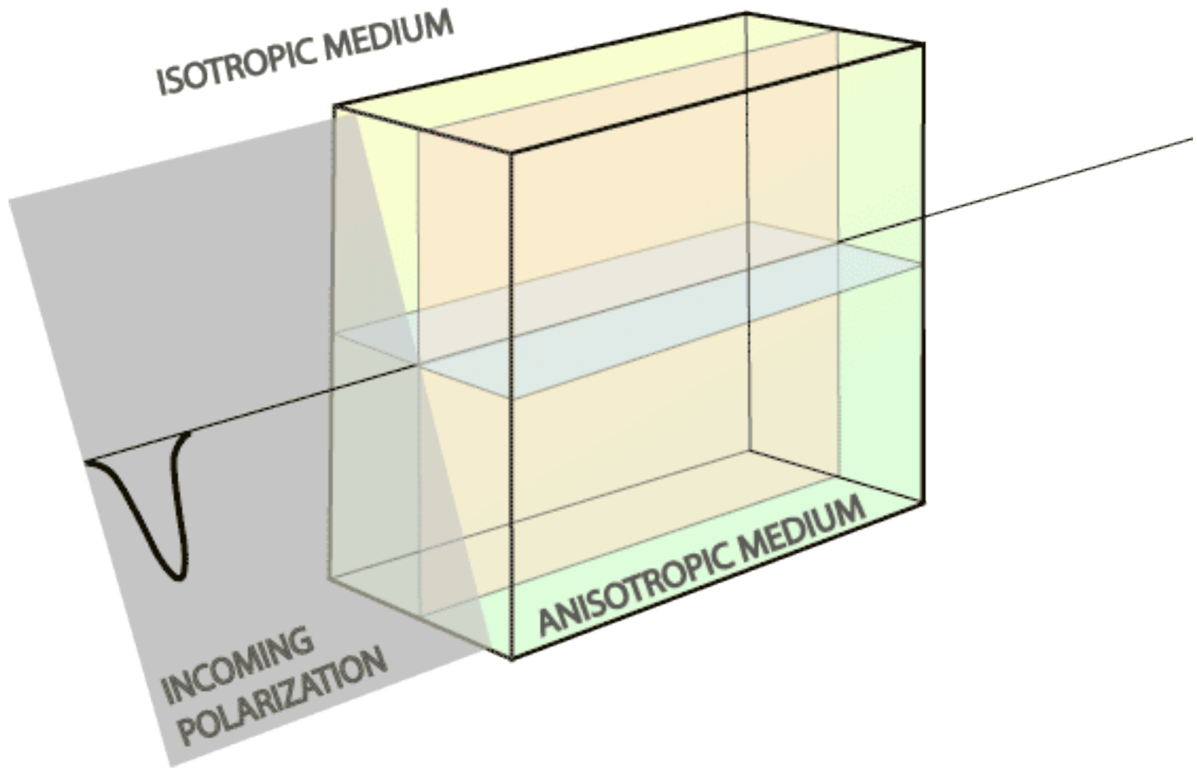
3. Seismic anisotropy

4. Effect of liquid, water, melt, etc.

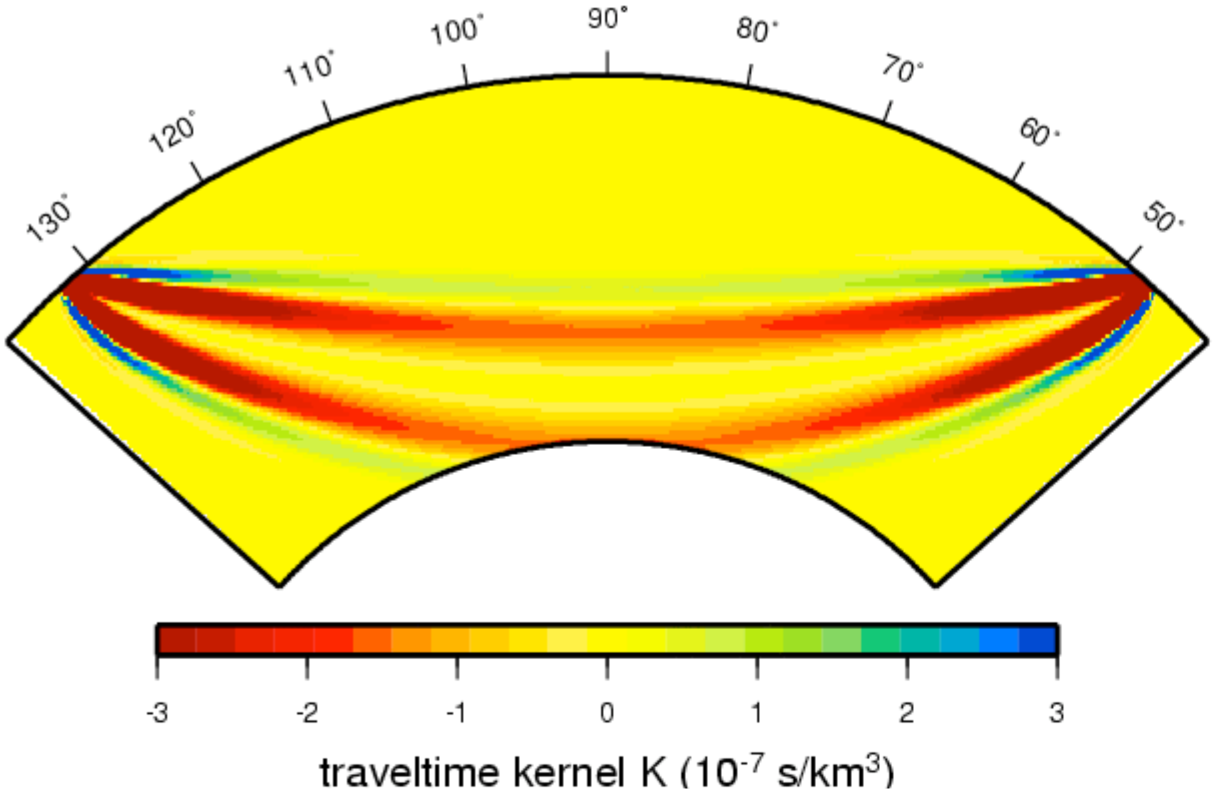
5. Lack of data coverage and resolution

How can we do better?

Improve theory: e.g., account for Seismic Anisotropy



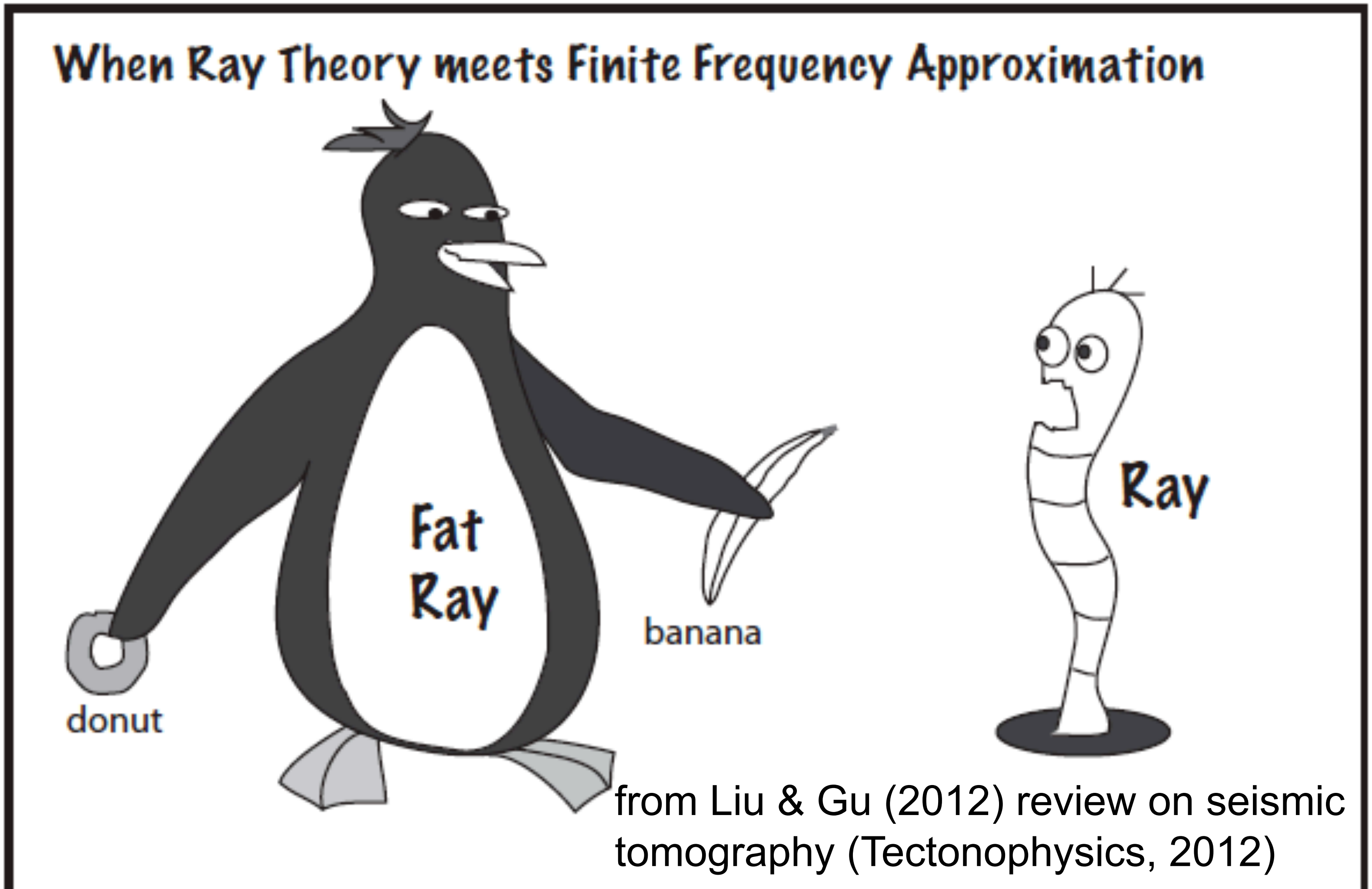
Consider fat rays rather than wires



Such "fat" rays sample more of the Earth and thus we need fewer of them to have a well-constrained tomographic problem.

Dahlen, *GJI,* 2002

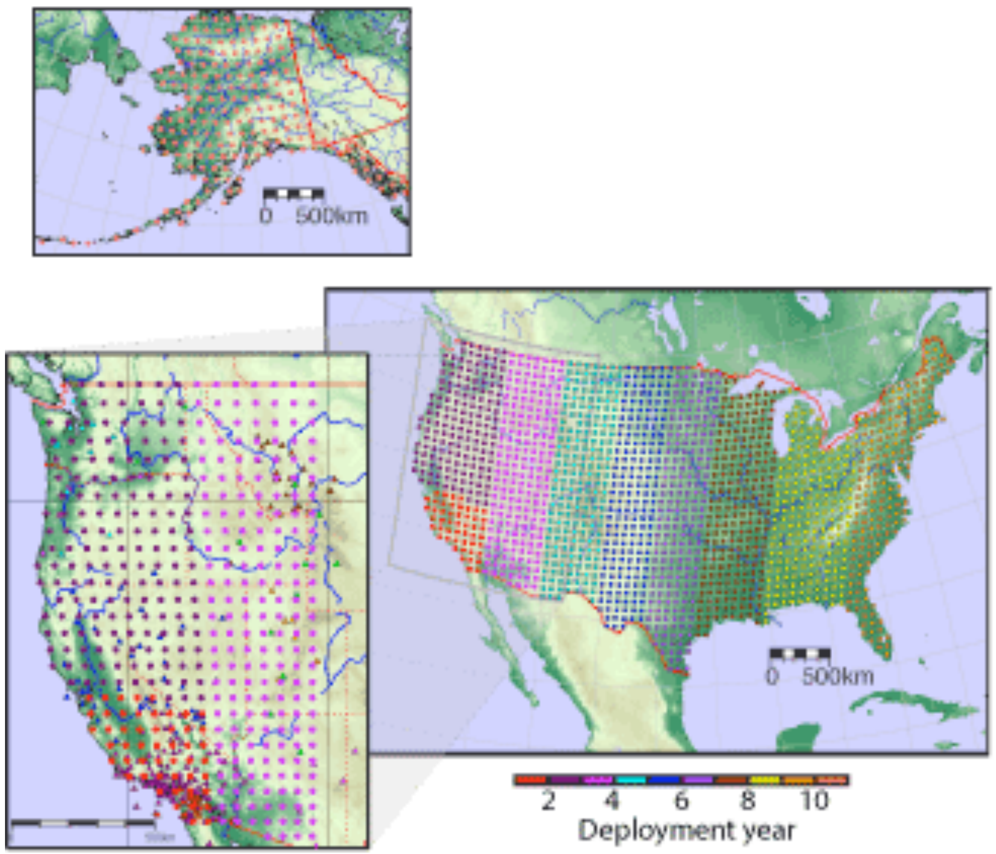
A heated debate on ray theory vs. banana donut idea



from Liu & Gu (2012) review on seismic tomography (Tectonophysics, 2012)

How can we do better? Improving the observations

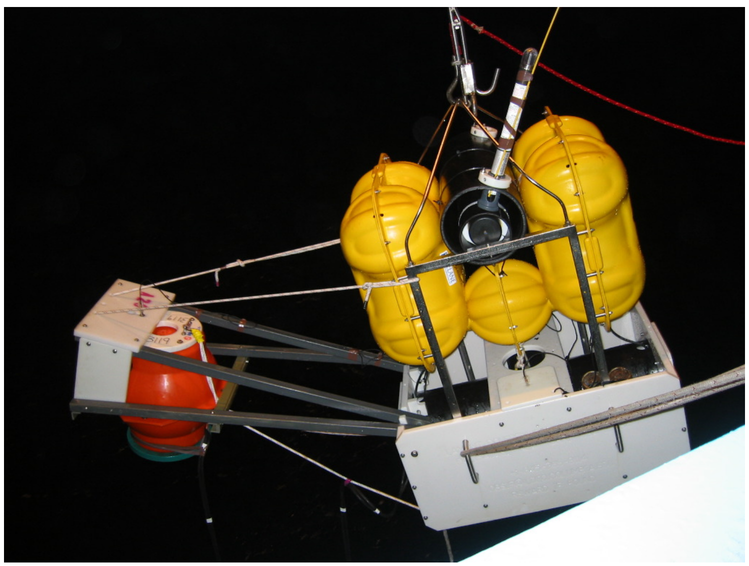
The Big Foot (USArray Project)

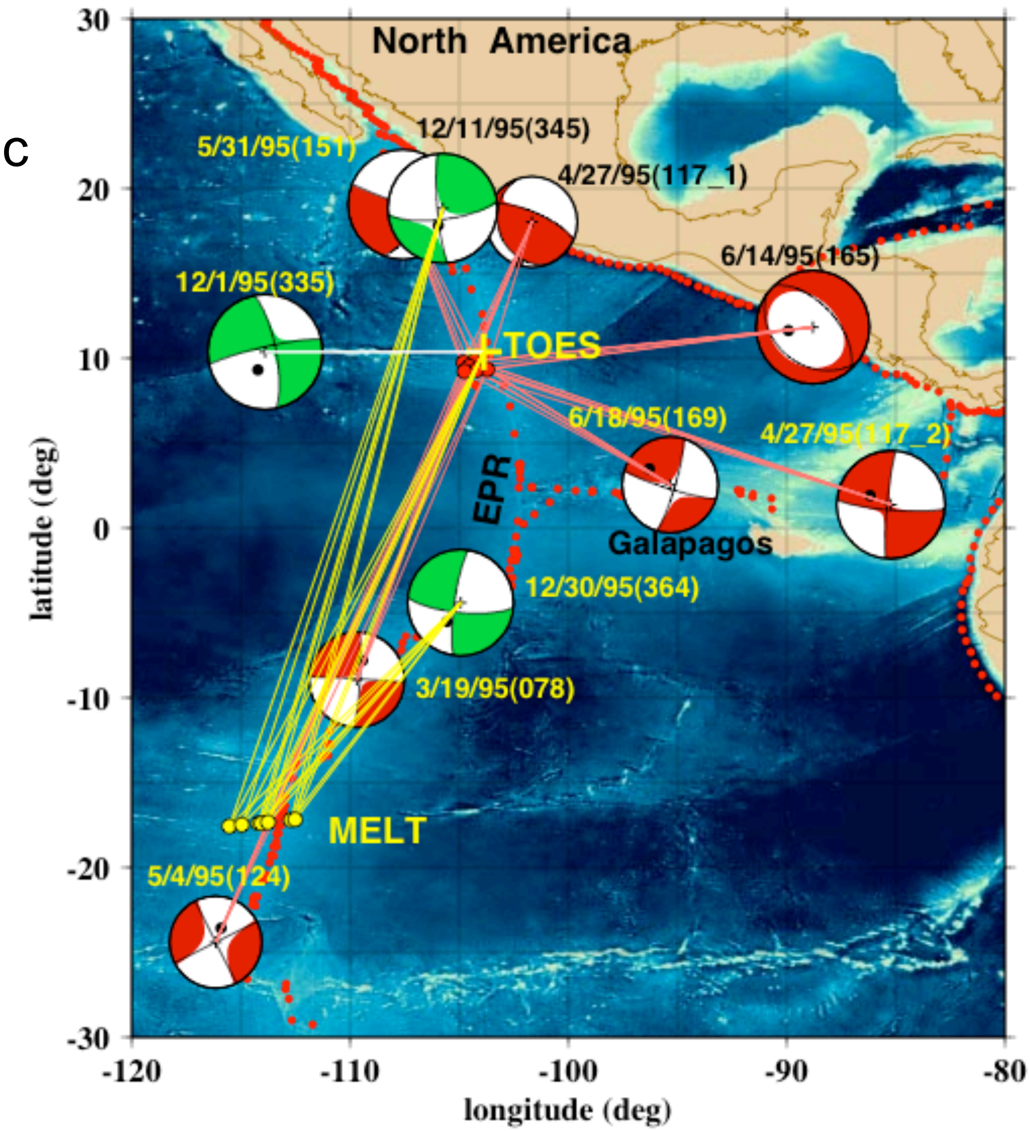


The first USArray component is a transportable telemetered array of 400 unmanned broadband seismometers designed to provide real-time data from a grid with dense and uniform station spacing of ~70km and an aperture of ~1400km (see map to right). The array will record local, regional and teleseismic earthquakes, providing resolution of crustal and upper mantle structure on the order of tens of kilometers and increased resolution of structures in the lower mantle and of the core-mantle boundary. The transportable array will roll across the country with 18-24 month deployments at each site. The spatial layout of this array was determined at the USArray Design Workshop held May 2001.

The future of the global seismology

Adding more Ocean Bottom Seismometers (OBS) to improve coverage in the oceanic regions(which is not limited to increasing data resolution in the oceans, but many other places as well!)





Gu et al., 2005

<u>Concluding Remarks</u>

Seismic waves give us information about both the *source* and the *medium*. It is a vital part of the understanding of the dynamics of the entire earth sciences. In many cases, we consider seismic waves as THE DATA for other disciplines. This course will cover a variety of topics with a clear focus on the "state-of-the-art" seismic methods. Many problems in global geophysics are still being hotly debated and it is not too late to be part of the forefront of regional or global seismology.