

A journey to the center of the Earth

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April 30, 2013

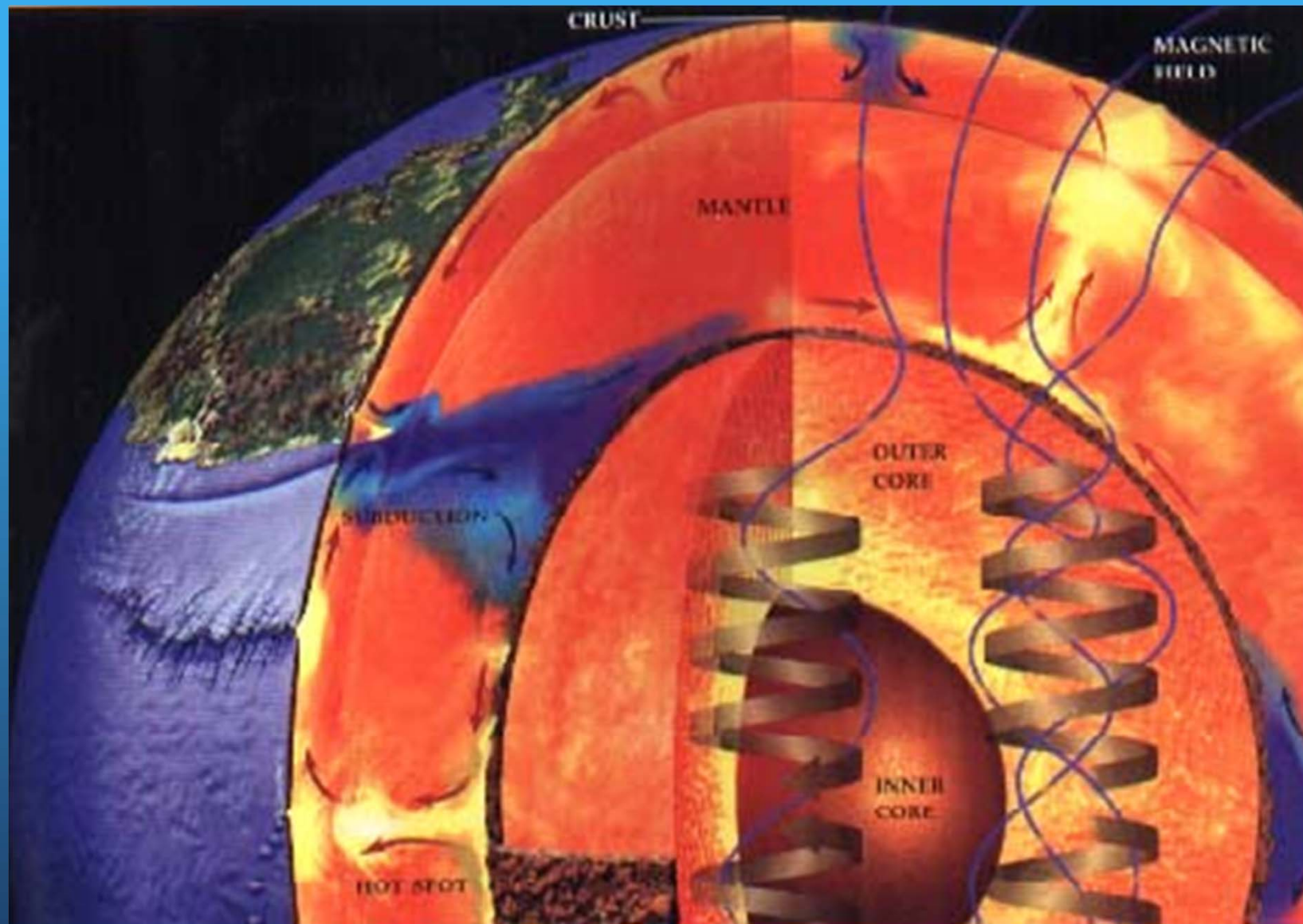
National Central University

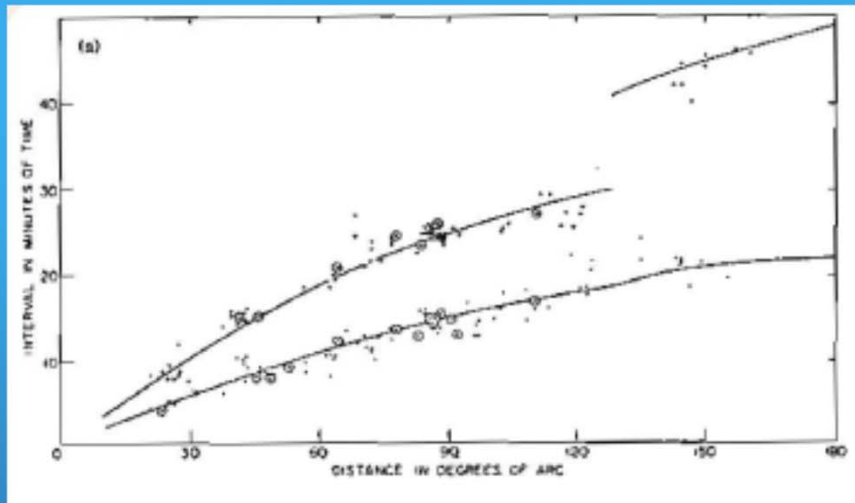
JOURNEY TO THE CENTRE OF THE EARTH

JULES VERNE



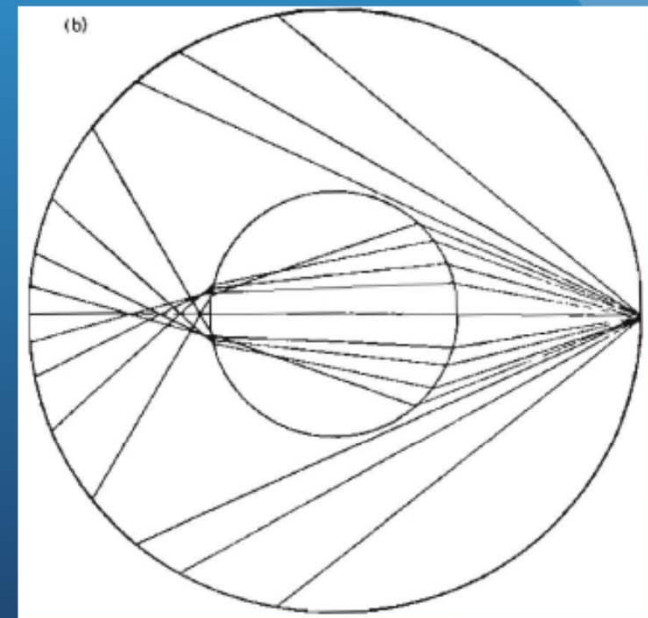
Jules Verne, 1864



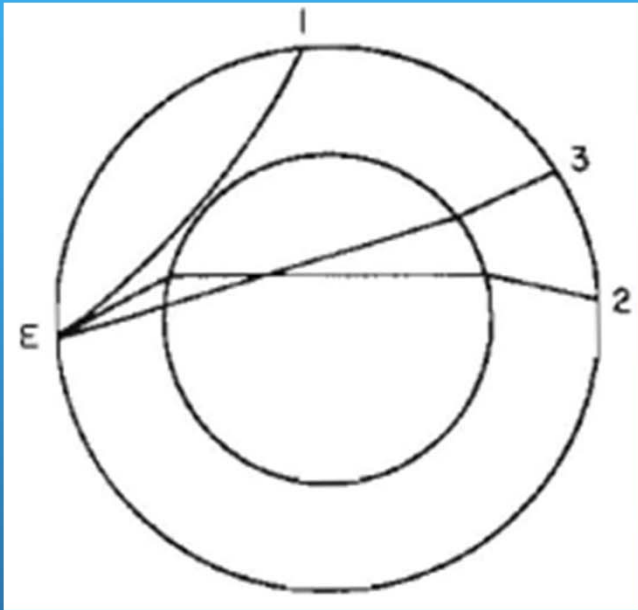


Evidence for a Central Core

Oldham, R.D., J. Geol.
Soc. London, 62, 456,
1906

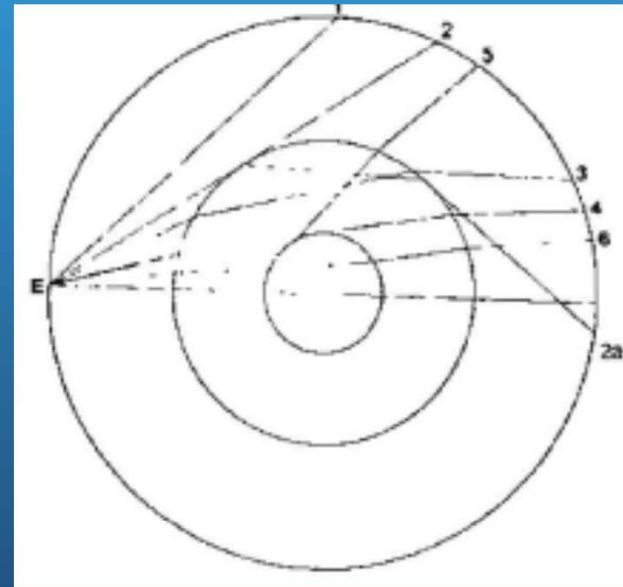


Interpretation of arrivals in the core “shadow zones”



Rays without an IC

Rays with an IC



Lehmann, I., Publ. Bur. Cent. Seismol. Int.
Ser, A., Trav. Sci. 14, 88, 1936

Outline

- Intro: seismic imaging of the Earth's interior
- Inner core structure
- Inner core rotation and topography
- Ambient noise seismology

Magnitude 9.0 NEAR THE EAST COAST OF HONSHU, JAPAN

Friday, March 11, 2011 at 05:46:23 UTC

Magnitude: 9.0

Date-Time:

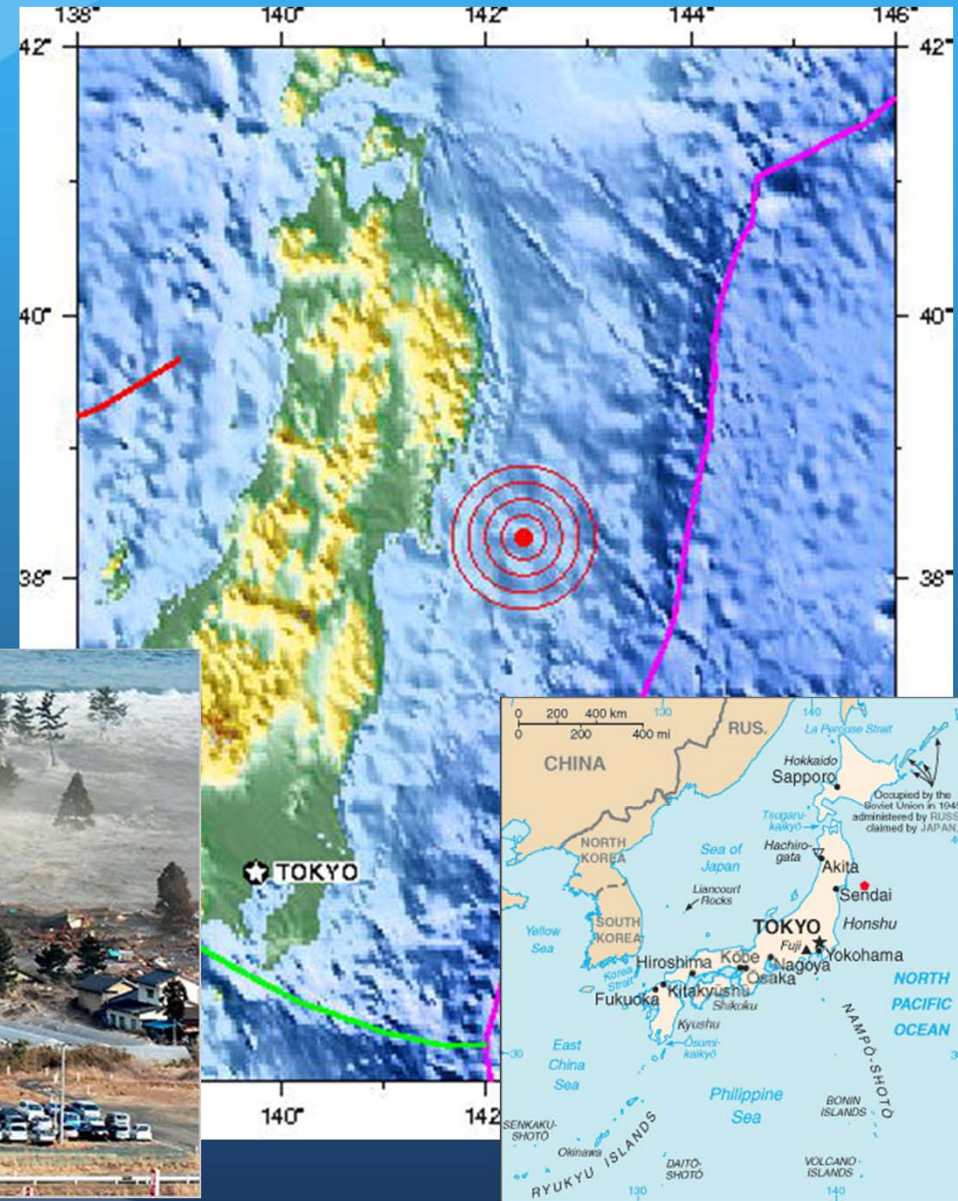
Friday, March 11, 2011 at 05:46:23 UTC

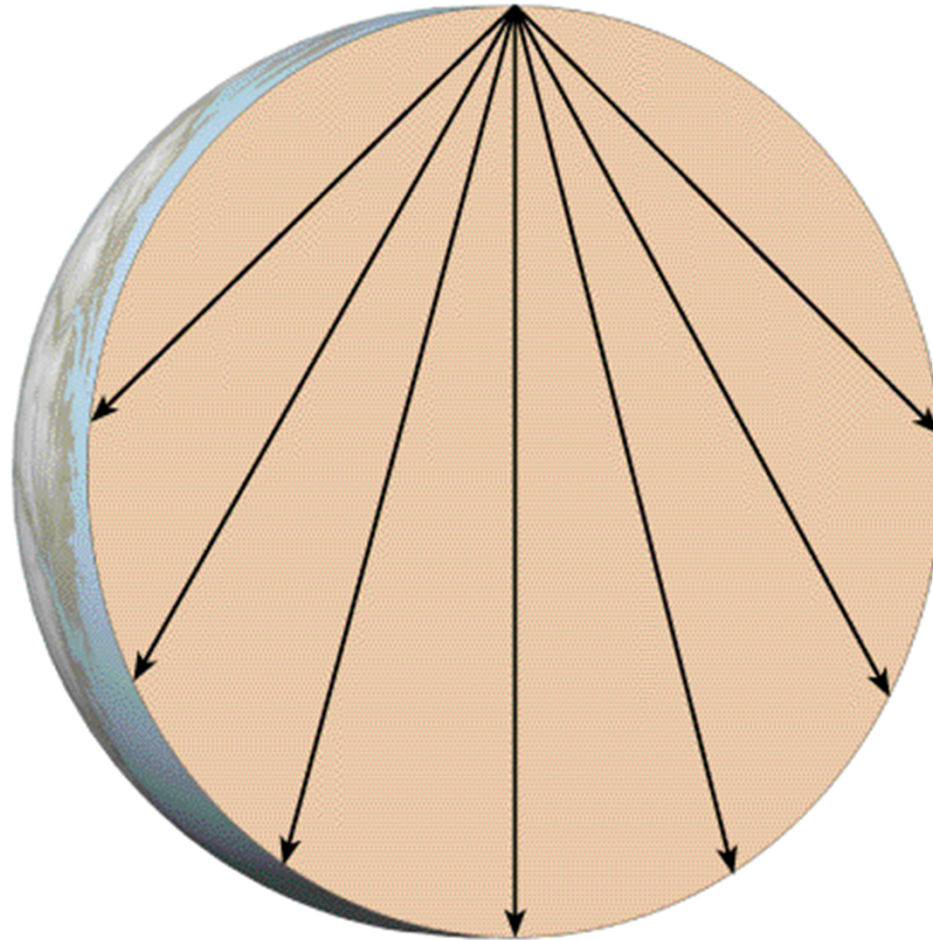
Friday, March 11, 2011 at 02:46:23 PM at
epicenter

Location:

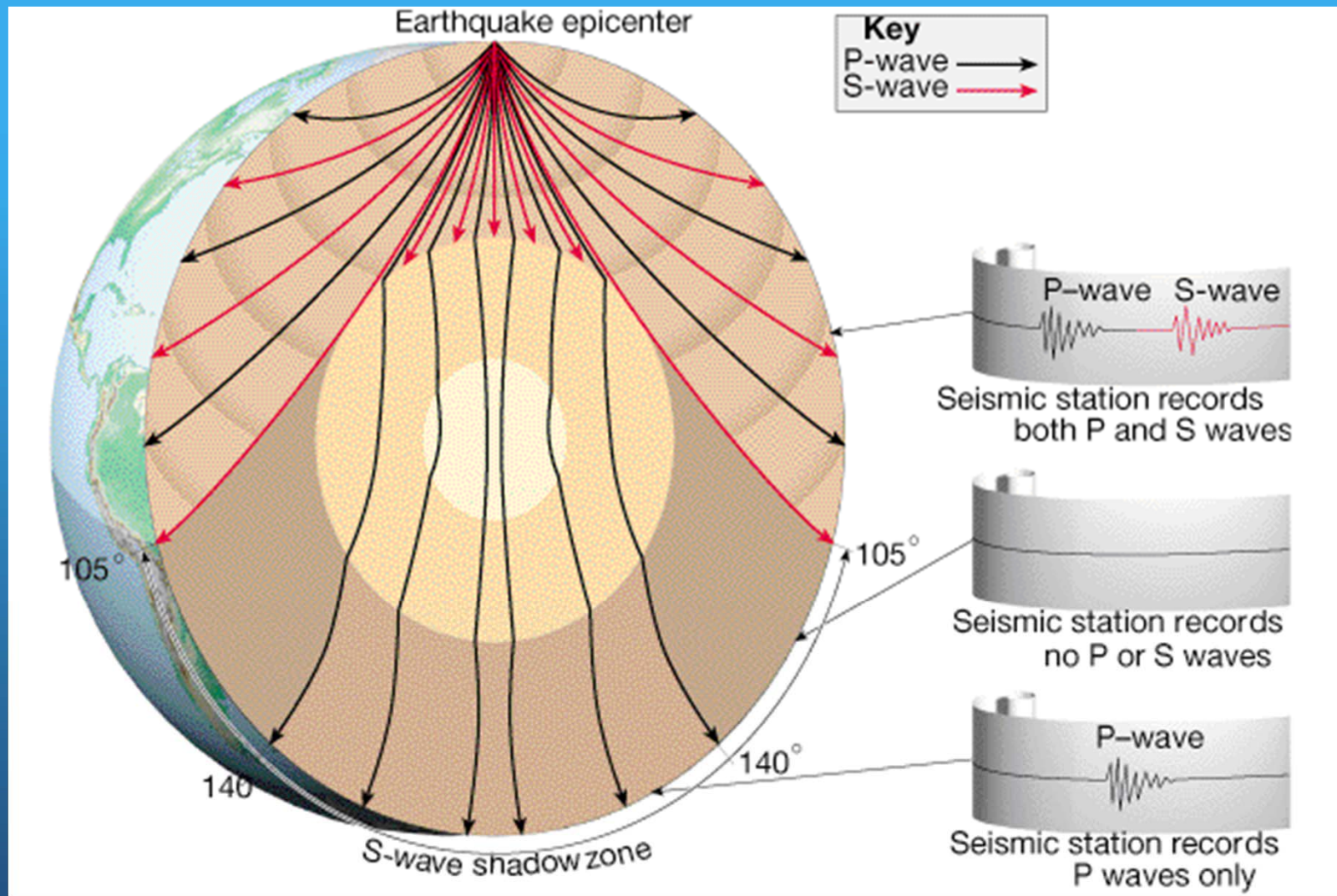
38.322° N, 142.369° E

Depth: 32 km (19.9 miles)

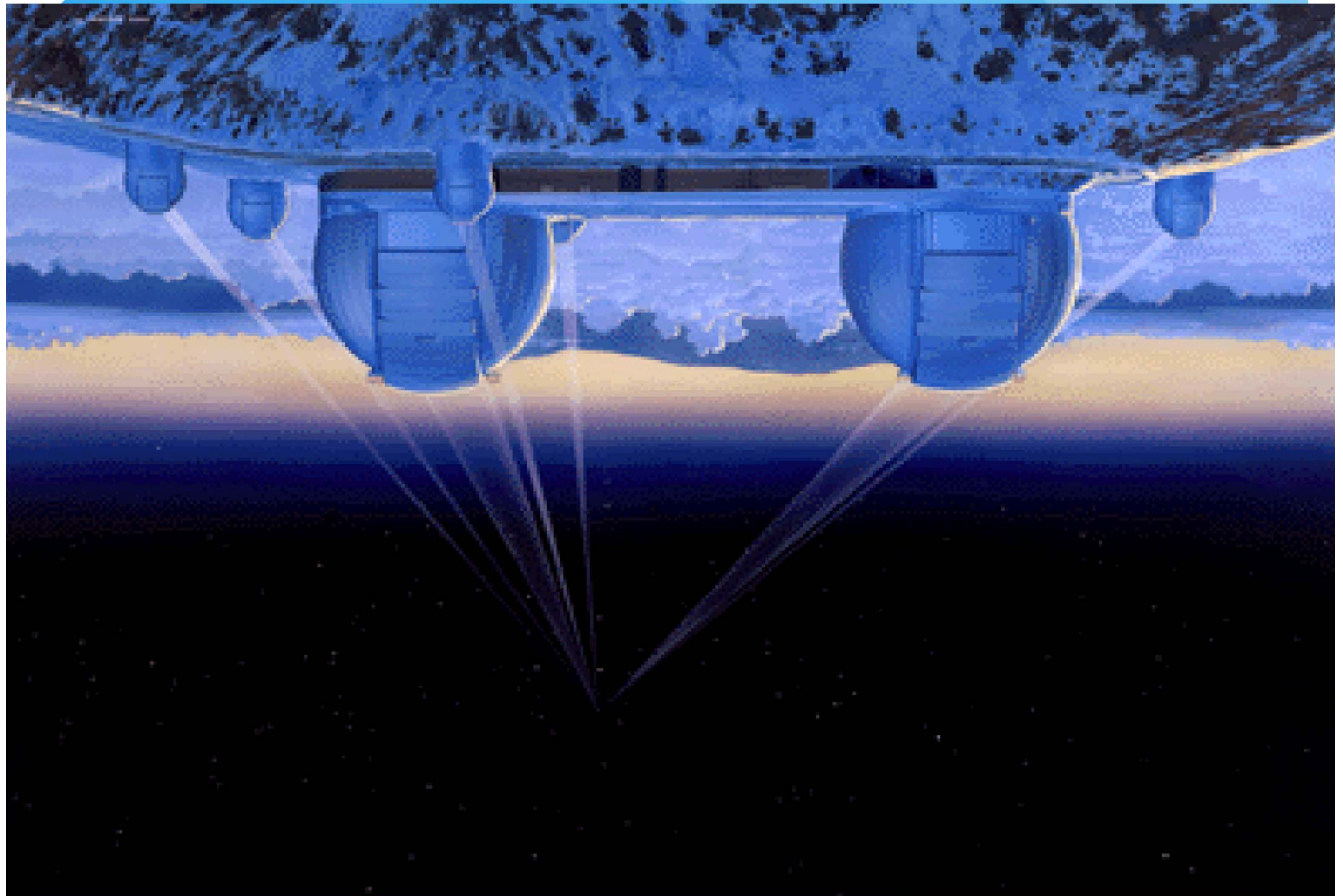




- Seismic rays travel in straight lines in a homogenous sphere. (Tarbuck and Lutgens)



- P and S wave paths through the Earth. No S waves through the core because outer core is liquid.





GLOBAL SEISMOGRAPHIC NETWORK & INTERNATIONAL FEDERATION OF DIGITAL SEISMOGRAPHIC NETWORKS

12/2007



IRIS International & National Cooperative Sites															
IRIS Current	Affiliate Array	Geoscope	Japan	Mednet	Geofon/AWI/BGR/BFO	China/USGS	Mexico	Singapore	Botswana	Andes	Australia	USGS	AFTAC	SMU	
★	★	★	★	★	★	★	★	★	★	★	★	★	★	★	★

150 Global stations and arrays in 69 Nations • Cornerstone of the FDSN Backbone

Introduction
Seismographs are common instruments that measure the displacement of a vibrating object. By making notes on the surface of the Earth, geologists can infer the Earth's interior structure in some circumstances. But what's behind this? By studying the ground motion caused by local earthquakes around the world, seismologists can explore the Earth's interior in a very subtle way.

The Earth
The diagram on the left shows the basic structure of Earth's interior. Energy released by earthquakes causes seismic waves that travel through the Earth and are reflected and refracted at boundaries that separate regions of different materials. These waves are the only way we know about the interior of the Earth. Seismologists use the arrival times and amplitudes of seismic waves to infer the Earth's interior structure. Seismograms for these seismic waves are shown on the right.

The Seismogram
Seismograms are records of the ground motion caused by earthquakes. The trace on the right shows the ground motion recorded at the seismic station shown on the left. The trace is a record of the ground motion at the station at which they were recorded. The diagram on the left shows the arrival times and amplitudes of seismic waves from various stations to infer the interior structure and hence the structure of Earth's deep interior.

Earthquake Hypocenter
The hypocenter is the point in the Earth's interior where an earthquake originates. The hypocenter is the point in the Earth's interior where an earthquake originates. The hypocenter is the point in the Earth's interior where an earthquake originates.

Crust
The crust is the outermost layer of the Earth. It is composed of solid rock. The crust is the outermost layer of the Earth. It is composed of solid rock. The crust is the outermost layer of the Earth. It is composed of solid rock.

Mantle
The mantle is the layer of the Earth between the crust and the core. It is composed of solid rock. The mantle is the layer of the Earth between the crust and the core. It is composed of solid rock. The mantle is the layer of the Earth between the crust and the core. It is composed of solid rock.

Core
The core is the innermost layer of the Earth. It is composed of molten metal. The core is the innermost layer of the Earth. It is composed of molten metal. The core is the innermost layer of the Earth. It is composed of molten metal.

Seismic Waves
Seismic waves are waves of energy that travel through the Earth. They are caused by earthquakes. Seismic waves are waves of energy that travel through the Earth. They are caused by earthquakes. Seismic waves are waves of energy that travel through the Earth. They are caused by earthquakes.

Seismogram
A seismogram is a record of the ground motion caused by earthquakes. It shows the arrival times and amplitudes of seismic waves. A seismogram is a record of the ground motion caused by earthquakes. It shows the arrival times and amplitudes of seismic waves. A seismogram is a record of the ground motion caused by earthquakes. It shows the arrival times and amplitudes of seismic waves.

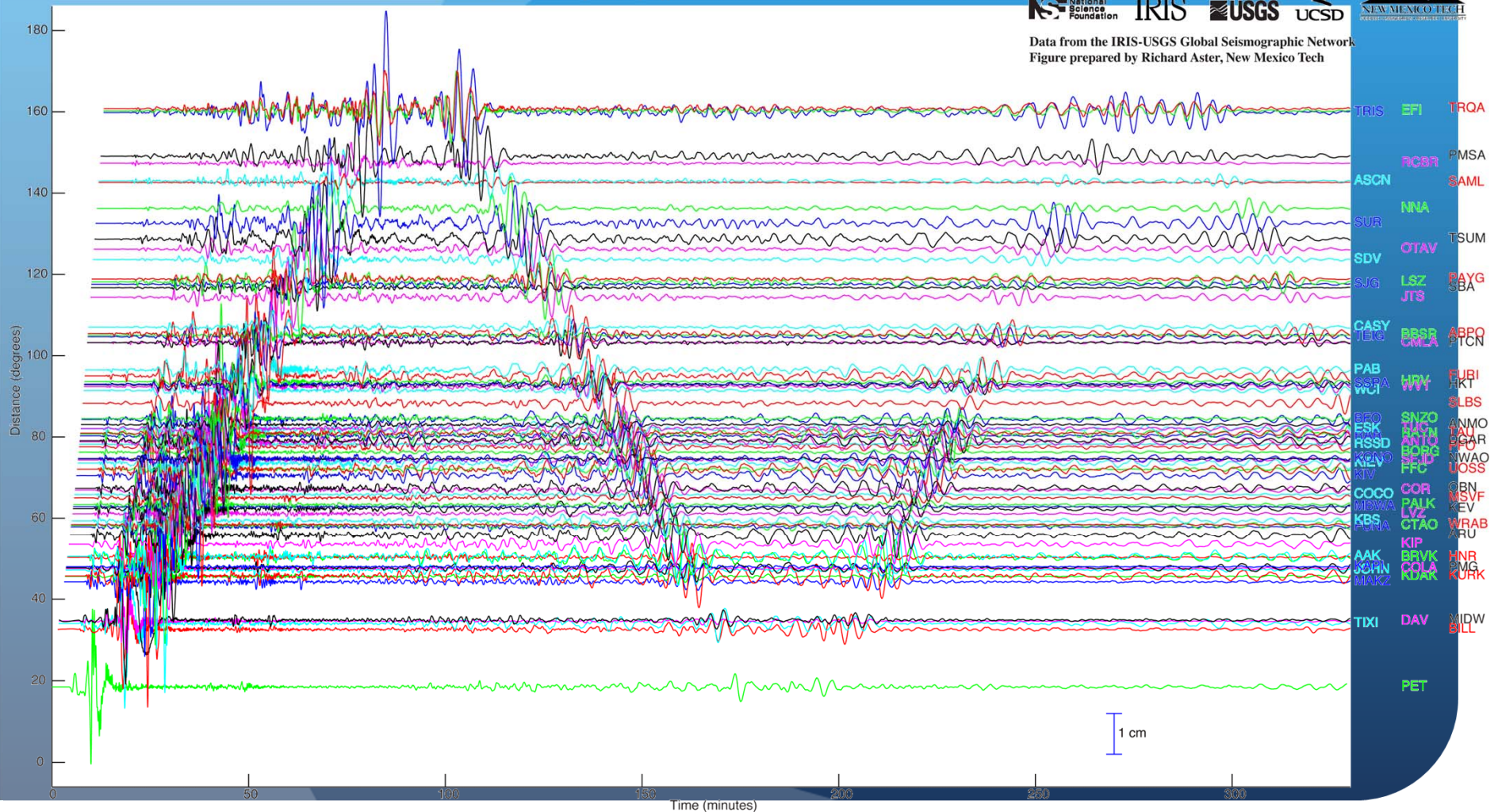
Time Since Earthquake Occurred (Time Time)
The time since an earthquake occurred is the time between the earthquake and the recording of the seismic waves. The time since an earthquake occurred is the time between the earthquake and the recording of the seismic waves. The time since an earthquake occurred is the time between the earthquake and the recording of the seismic waves.

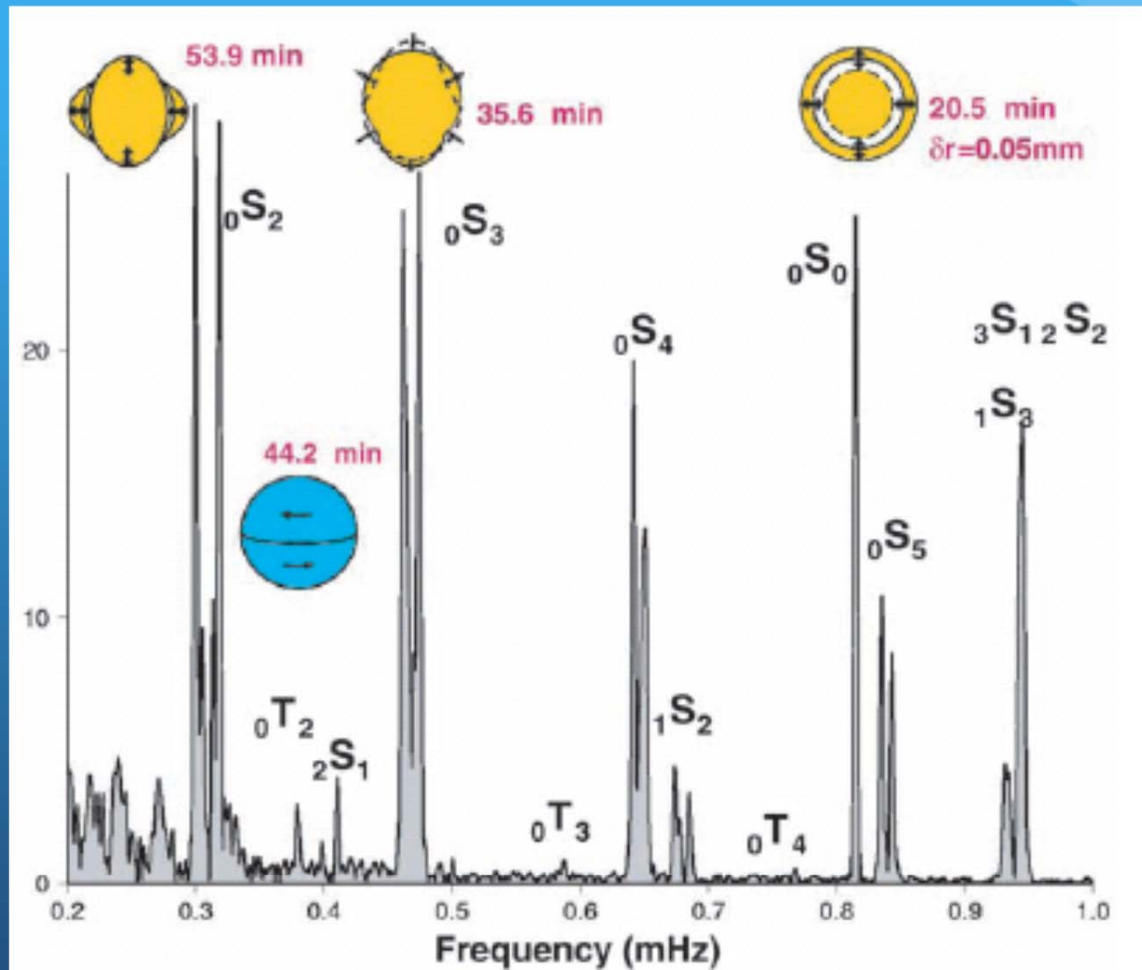
Magnitude 9.0 NEAR THE EAST COAST OF HONSHU, JAPAN Friday, March 11, 2011 at 05:46:23 UTC

Seismic waves recorded around the world.

Japan Earthquake ($M_W=9.0$), Global Displacement Wavefield

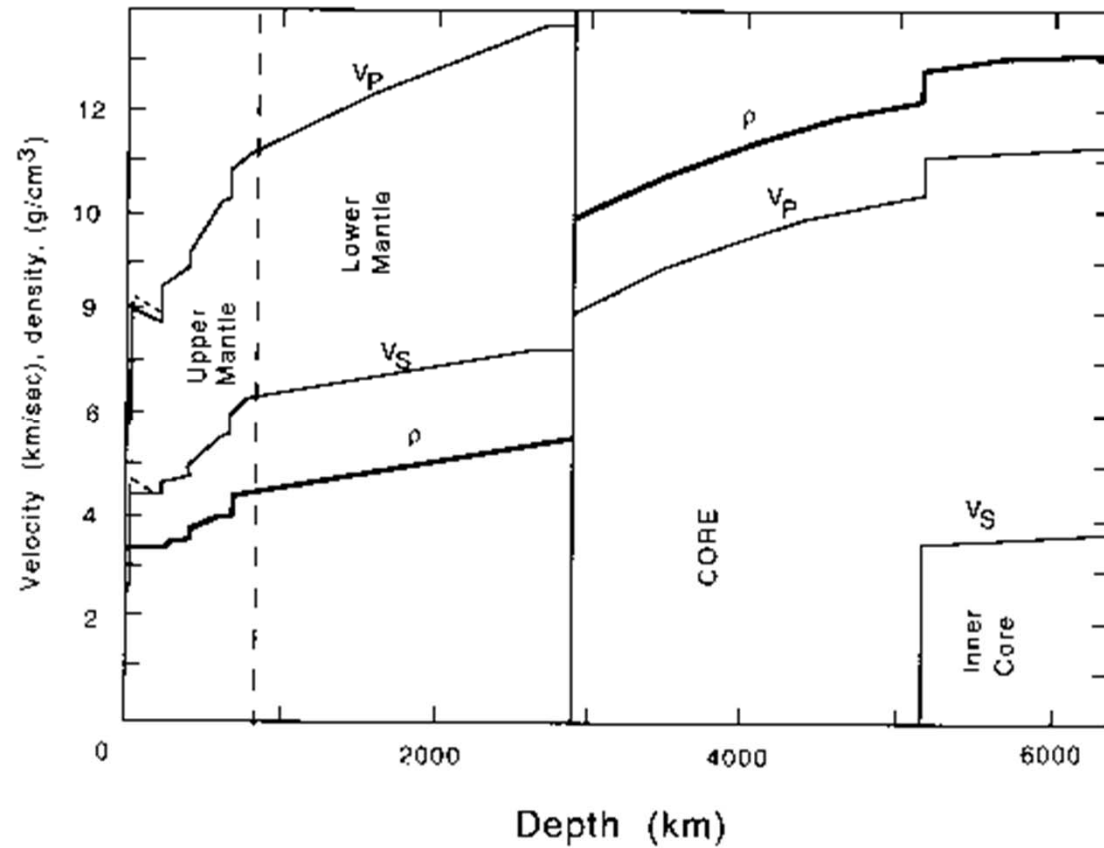
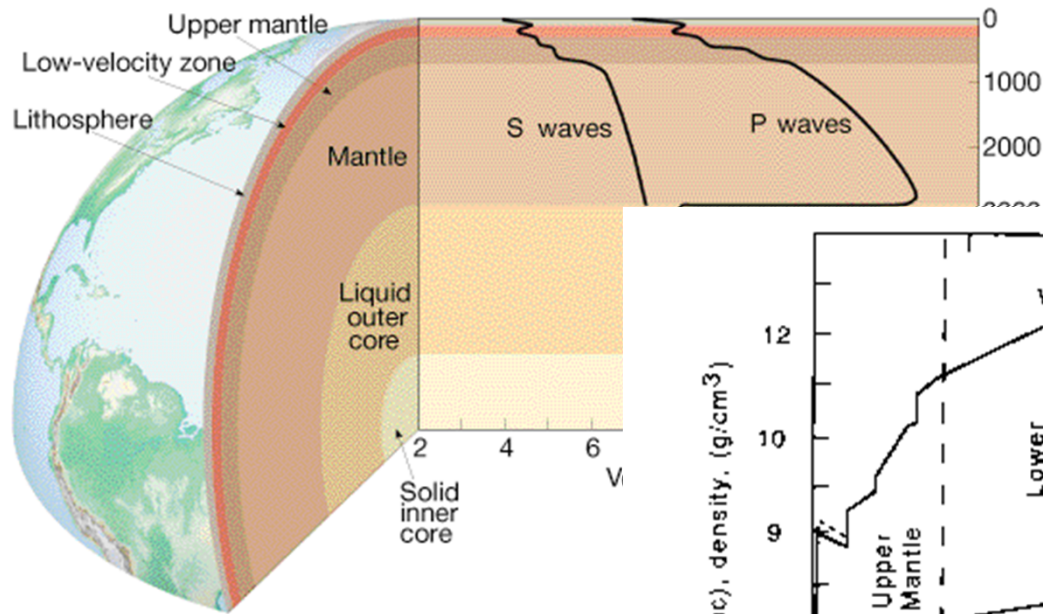

 Data from the IRIS-USGS Global Seismographic Network
 Figure prepared by Richard Aster, New Mexico Tech



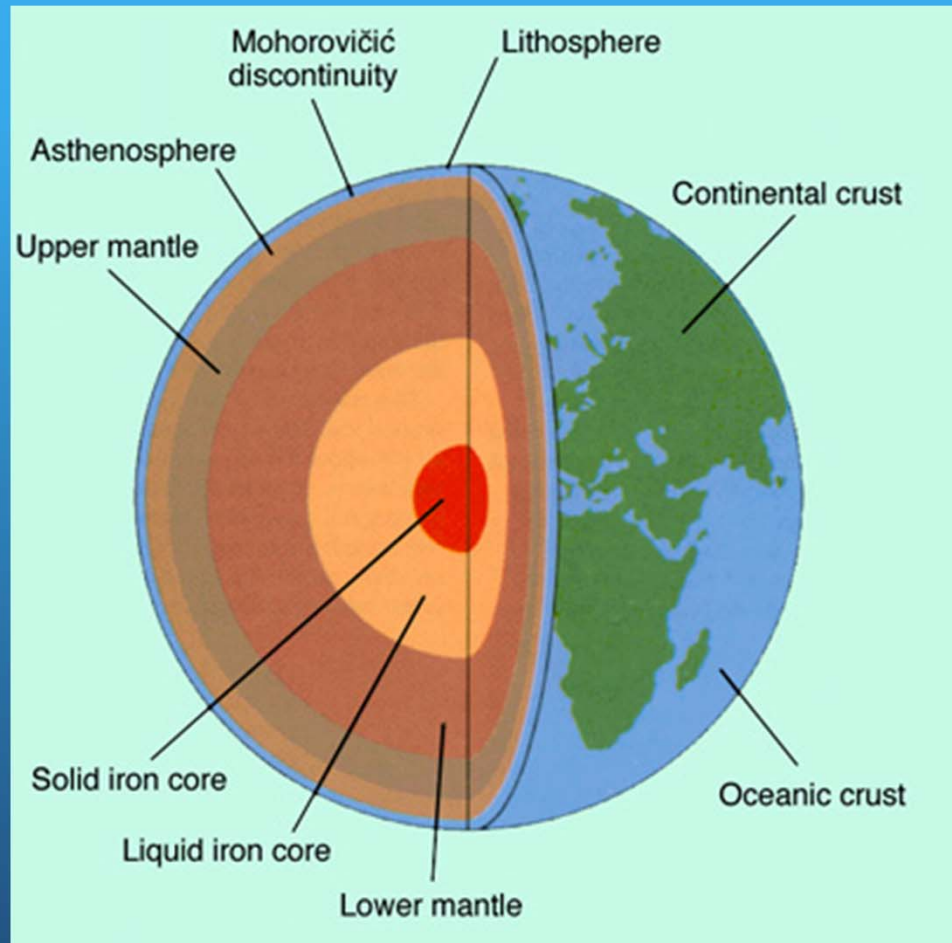


Earth's free oscillations excited by 2004 Great Sumatra earthquake.

PREM model



- P, S velocities and density through the depth of the Earth



Major layers of Earth's Interior:

Crust

Upper mantle

Transition zone

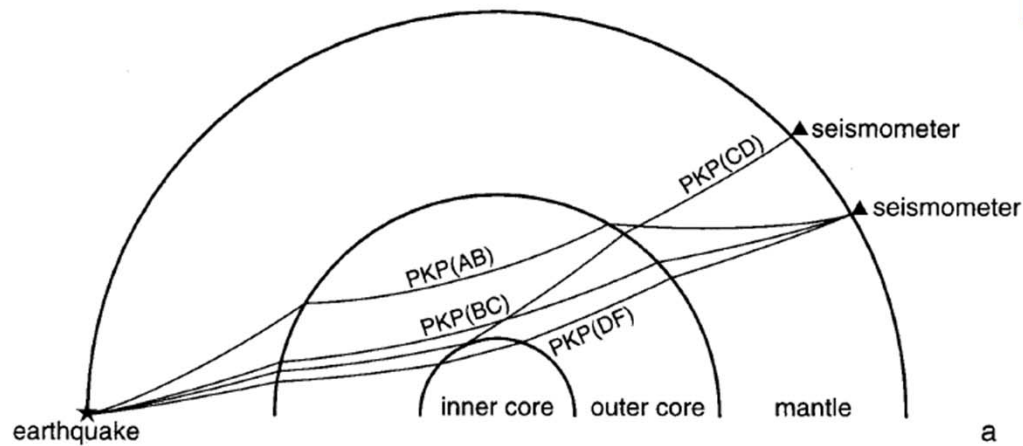
Lower mantle

Outer core

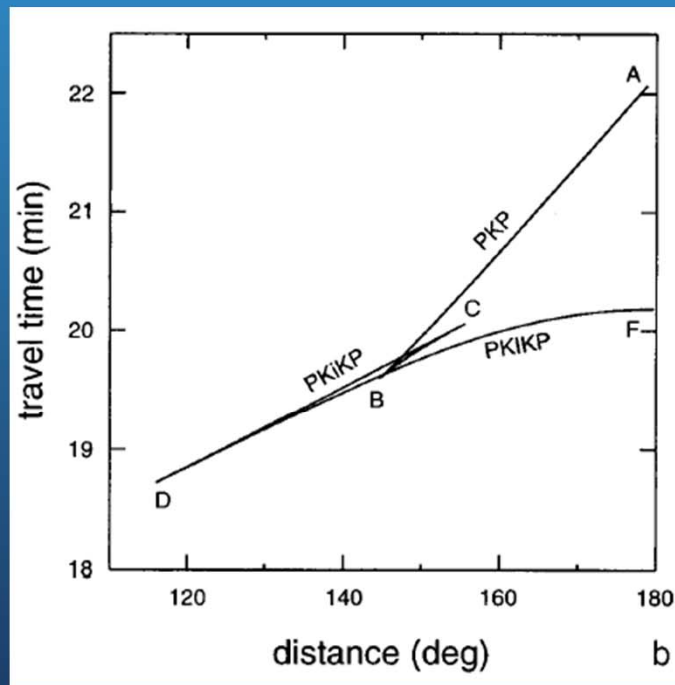
Inner core

Inner inner core?

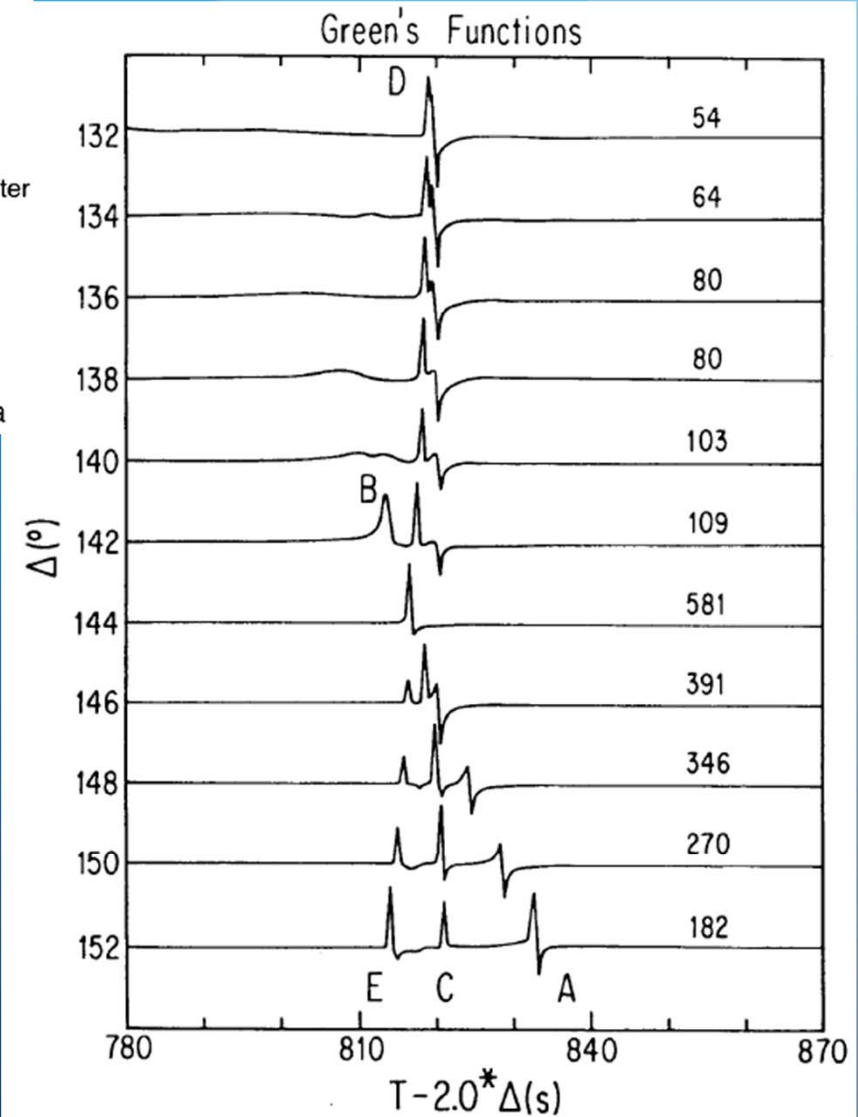
PKP ray paths, travel times, and synthetic seismograms

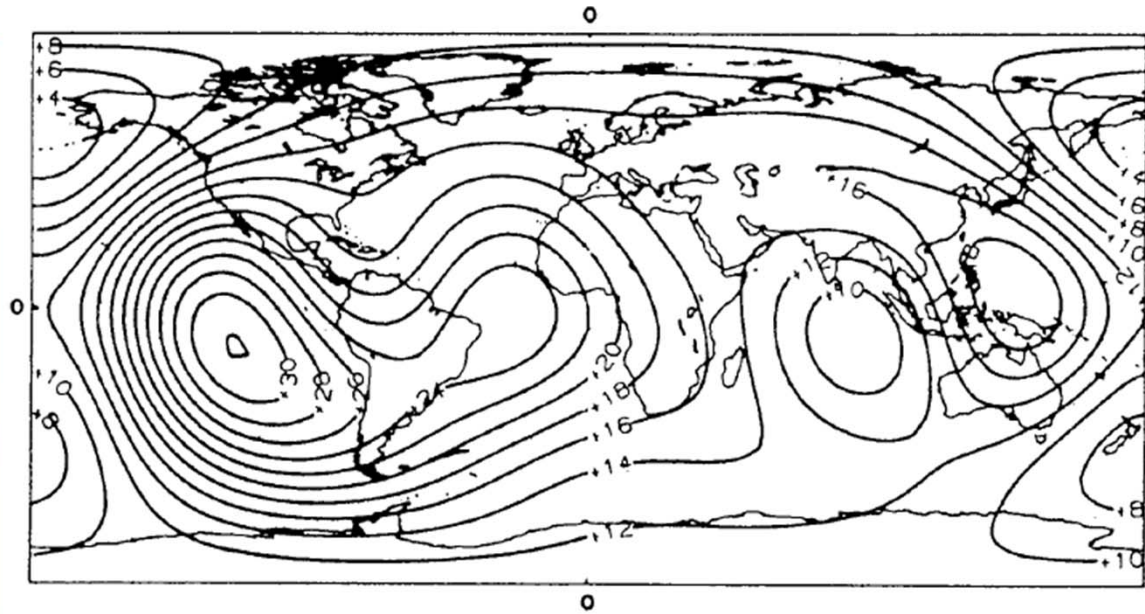


a



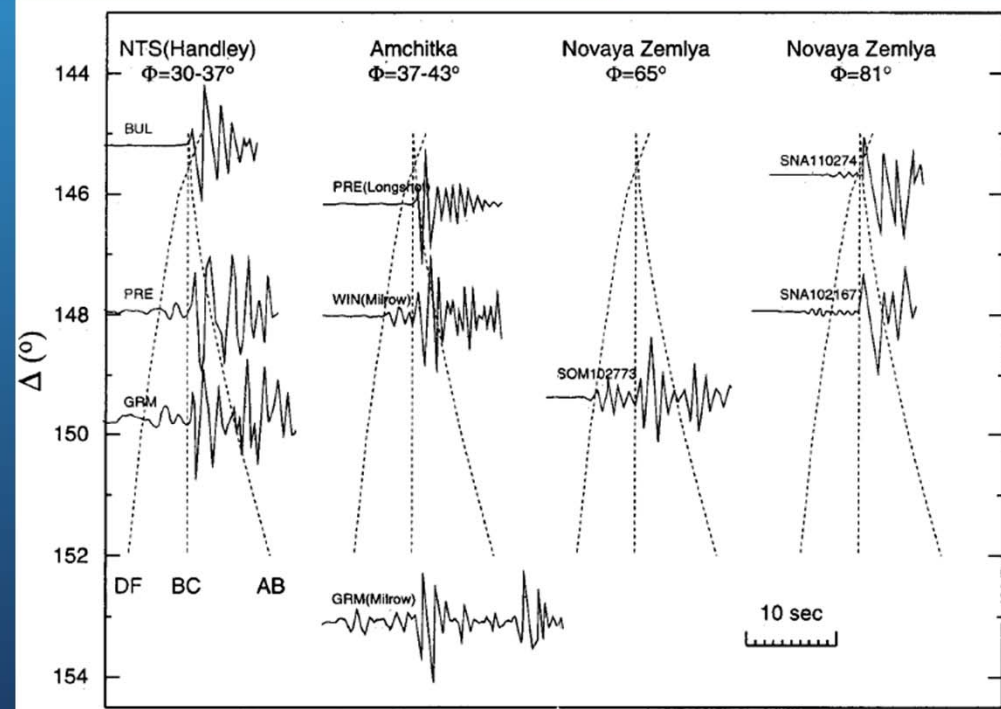
b

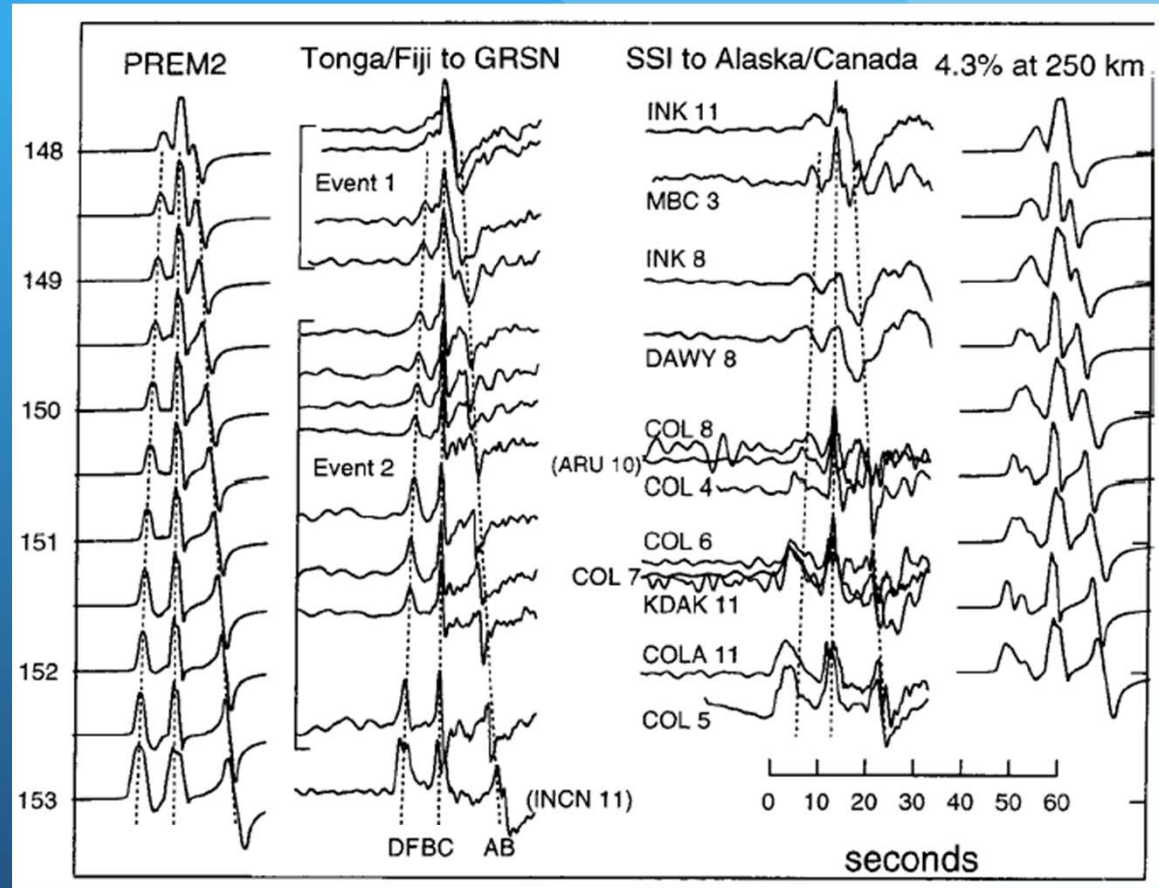
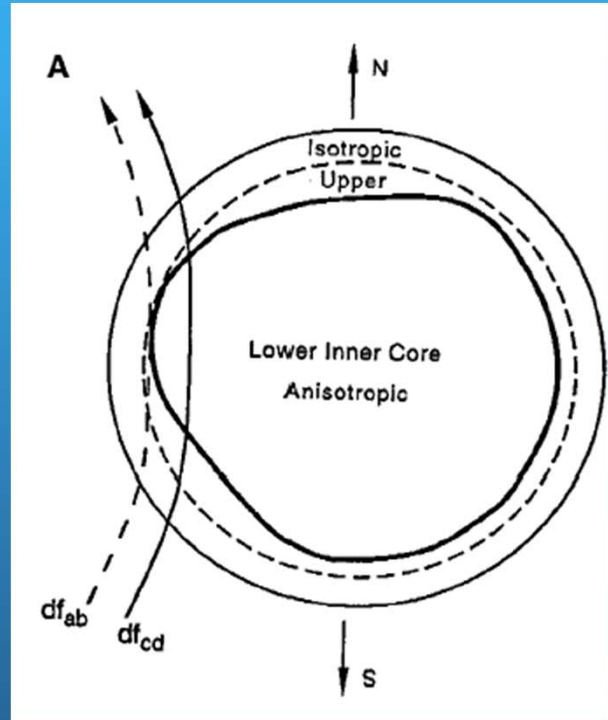




Poupinet et al.,
Nature, 1983

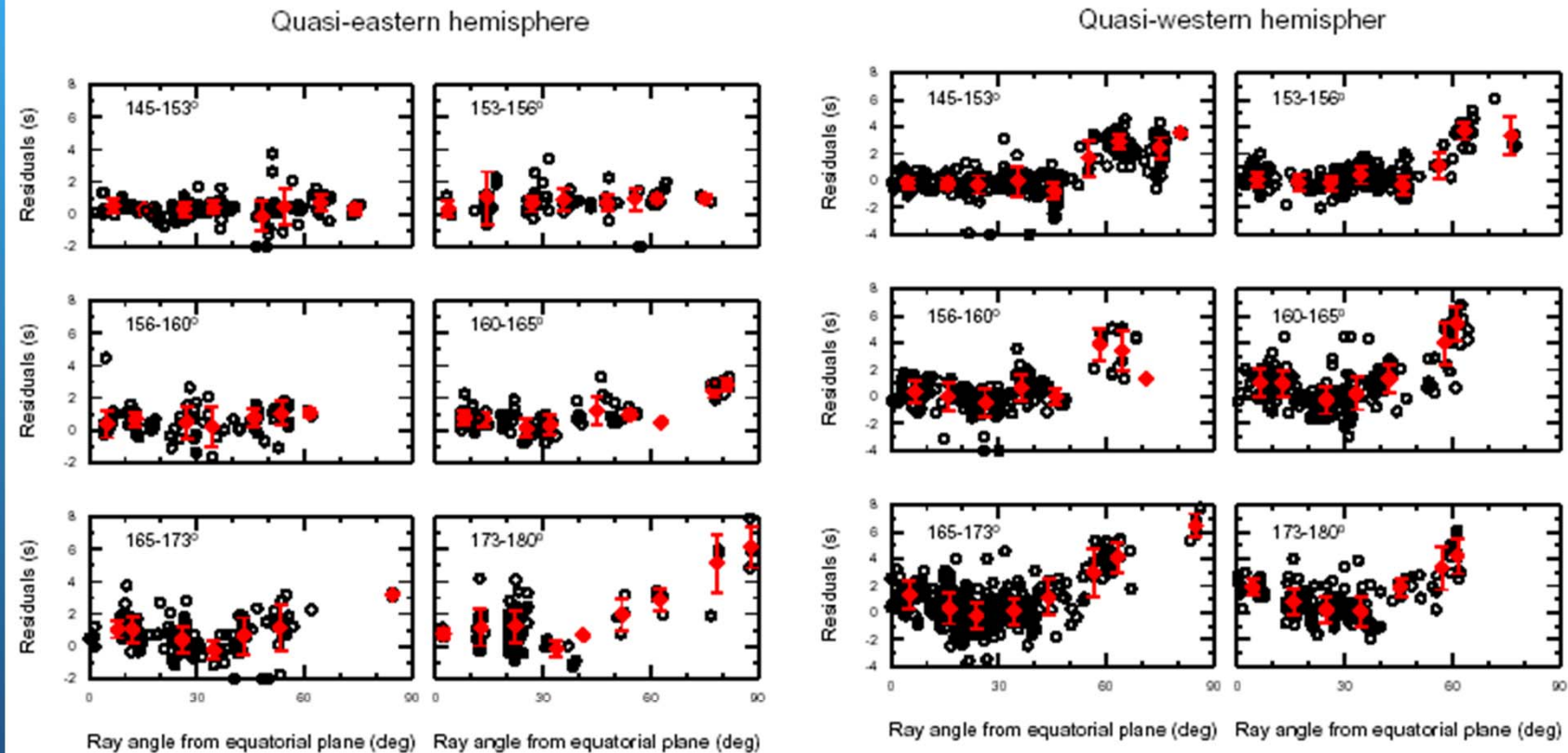
Song and
Helmberger, GRL,
1993





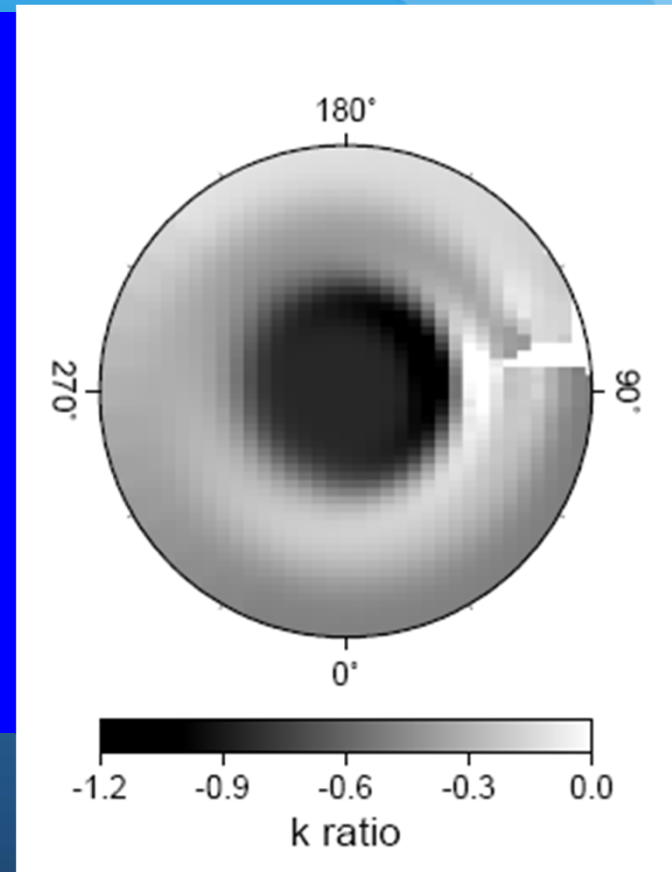
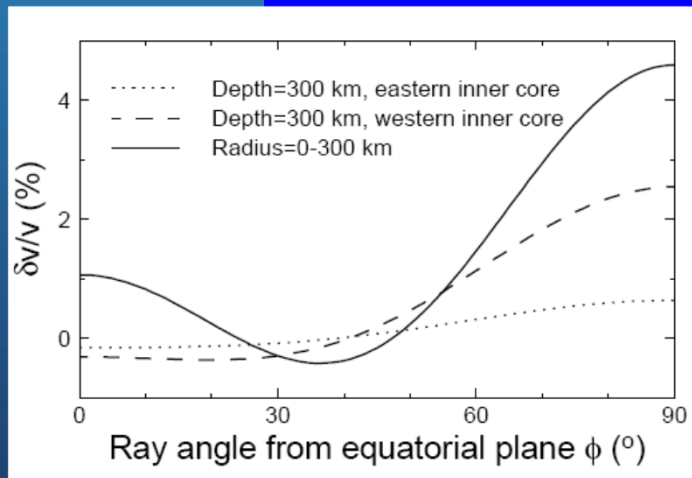
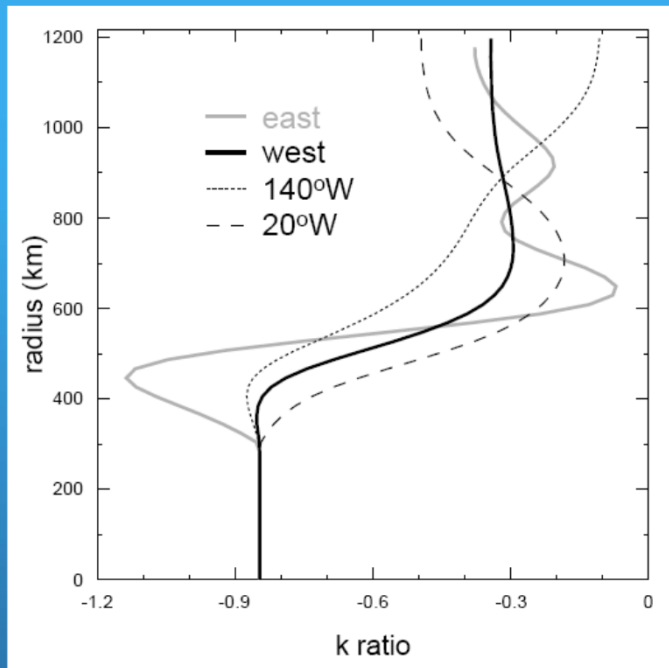
Song and Helmberger, Science, 1998

Data variability and 3D model predictions

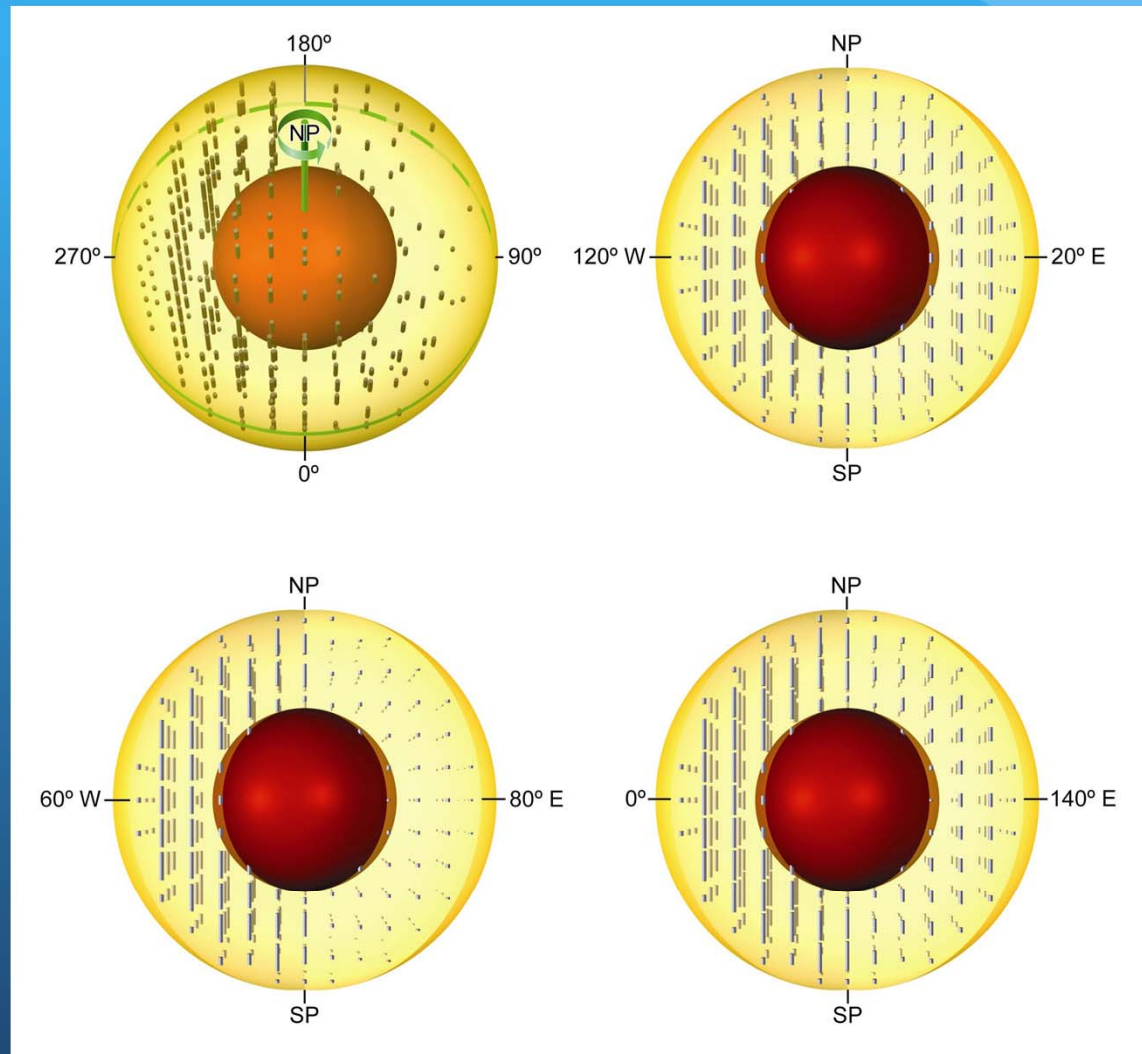


Sun and Song, PEPI, 2008

Evidence for an inner inner core



Sun and Song, EPSL, 2008

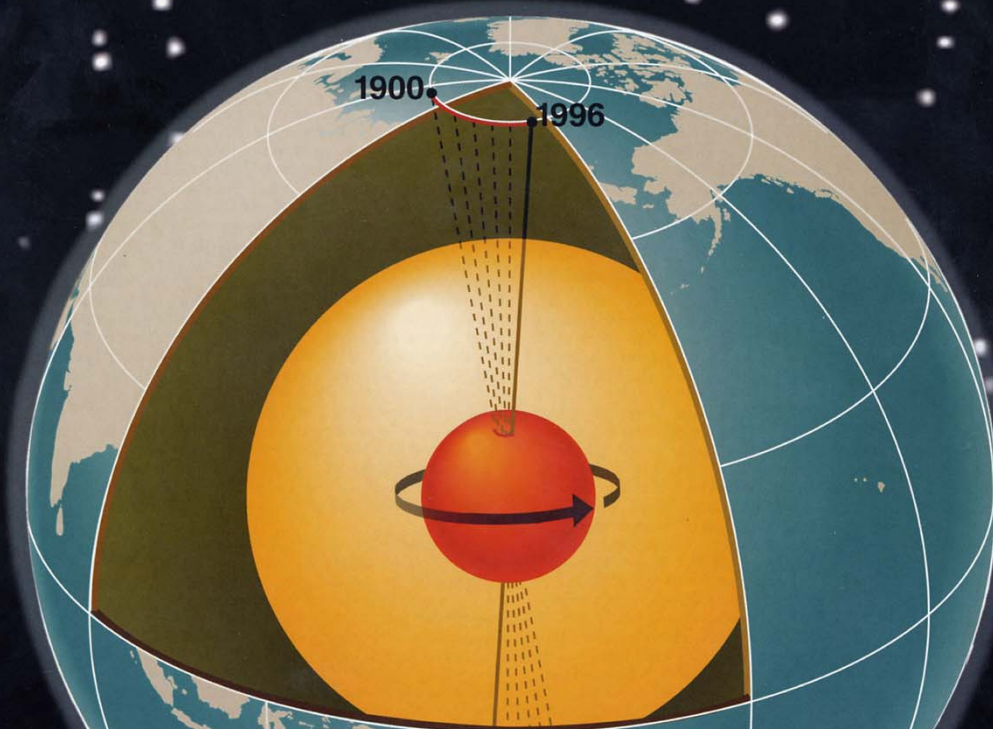


Cartoons of
inner inner
core and
crystal
alignments by
mapping inner
core
anisotropy

nature

INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

Volume 382 No. 6588 18 July 1996 \$10.00



Rotation of the inner core

Nicotine addiction: The smoking gun

Magnetic superconductors

The Wingless receptor

Song and
Richards,
Nature, 1996



ELSEVIER

Physics of the Earth and Planetary Interiors 91 (1995) 63–75

PHYSICS
OF THE EARTH
AND PLANETARY
INTERIORS

A three-dimensional convective dynamo solution with rotating and finitely conducting inner core and mantle

Gary A. Glatzmaier ^{a,*}, Paul H. Roberts ^b

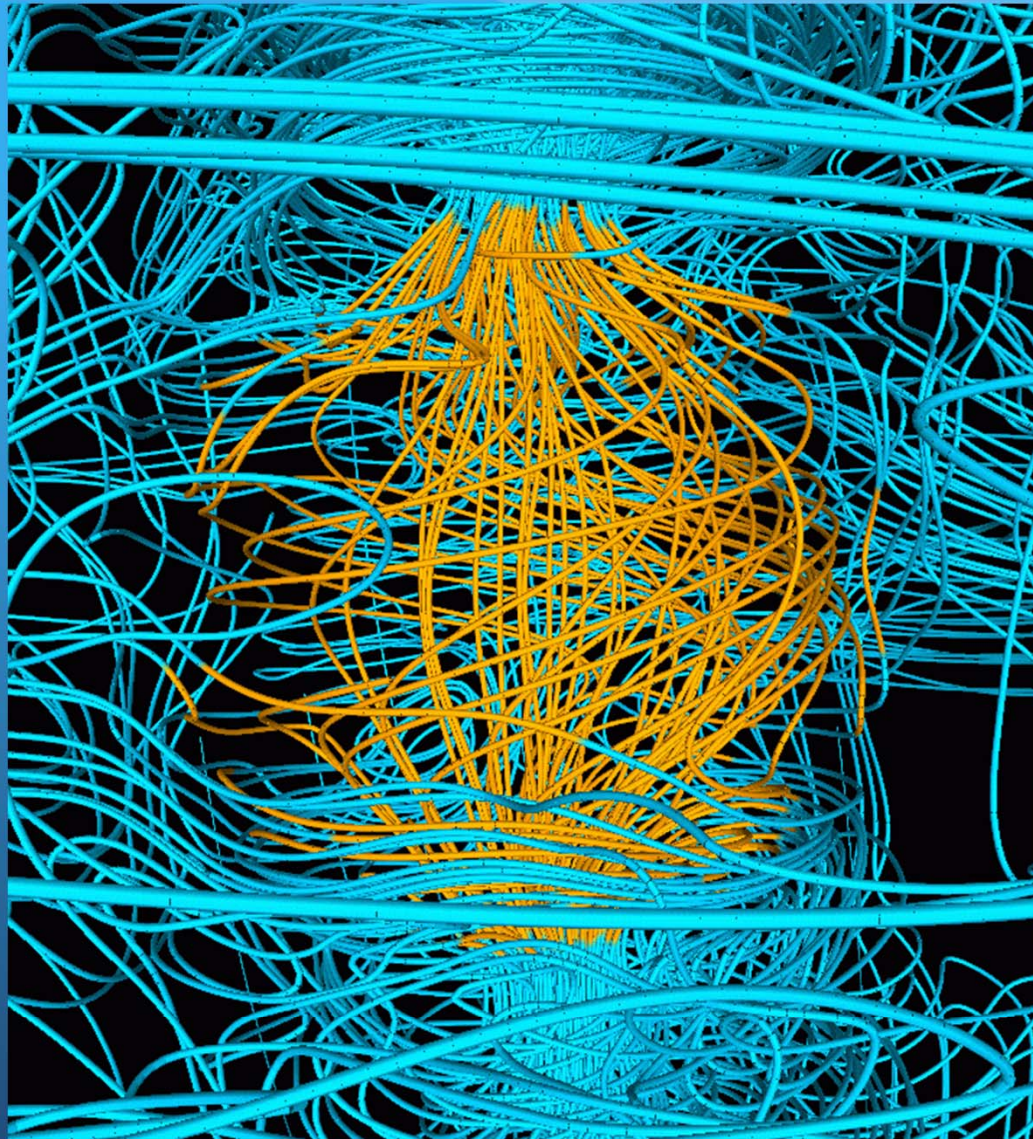
^a *Institute of Geophysics and Planetary Physics, Los Alamos National Laboratory, Los Alamos, NM 87545, USA*

^b *Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA 90024, USA*

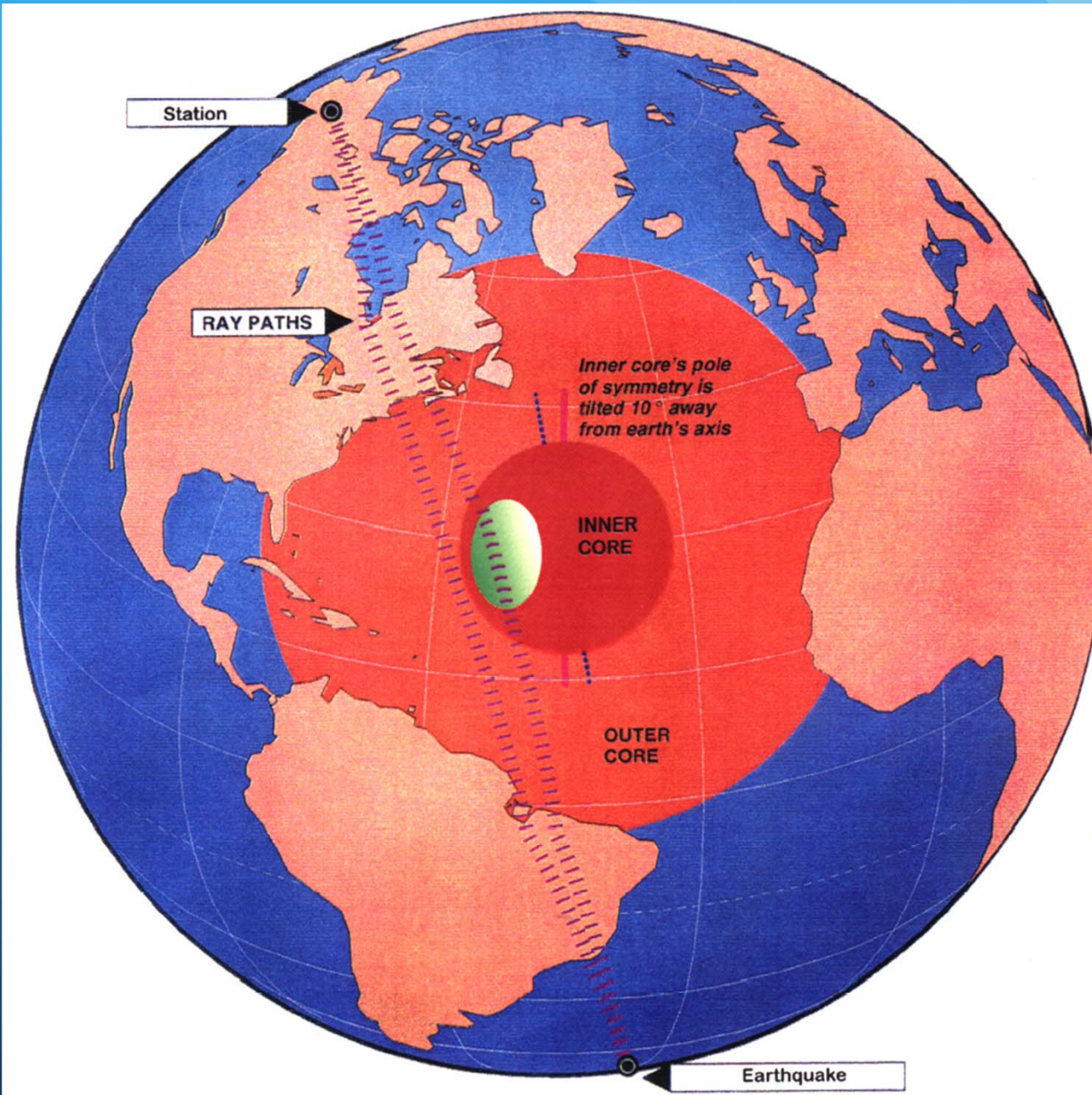
Received 10 November 1994; accepted 3 March 1995

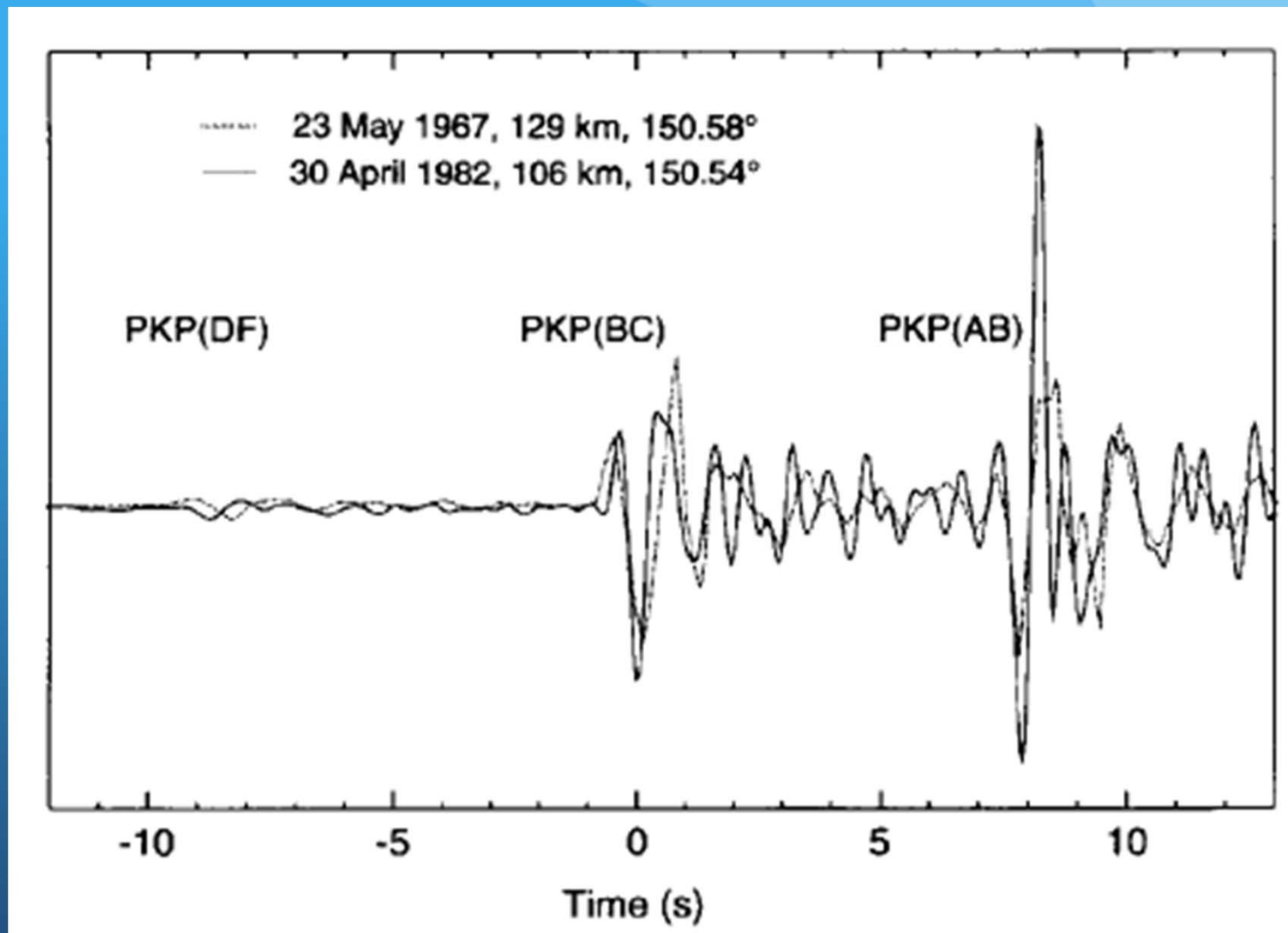
Viscous and magnetic coupling at the ICB and CMB produce time-dependent rotation rates of our inner core and mantle relative to the frame of reference rotating at $\Omega = \Omega \hat{z}$. The z -axis rotation rate of the inner core is almost always eastward, i.e. prograde relative to the initial non-convecting state. It can be as large as a few times $10^{-9} \text{ rad s}^{-1}$ and changes on a time scale of about 500 years. The off-axis rates change ampli-

$10^{-9} \text{ rad/s} = 1.8 \text{ deg/yr}$



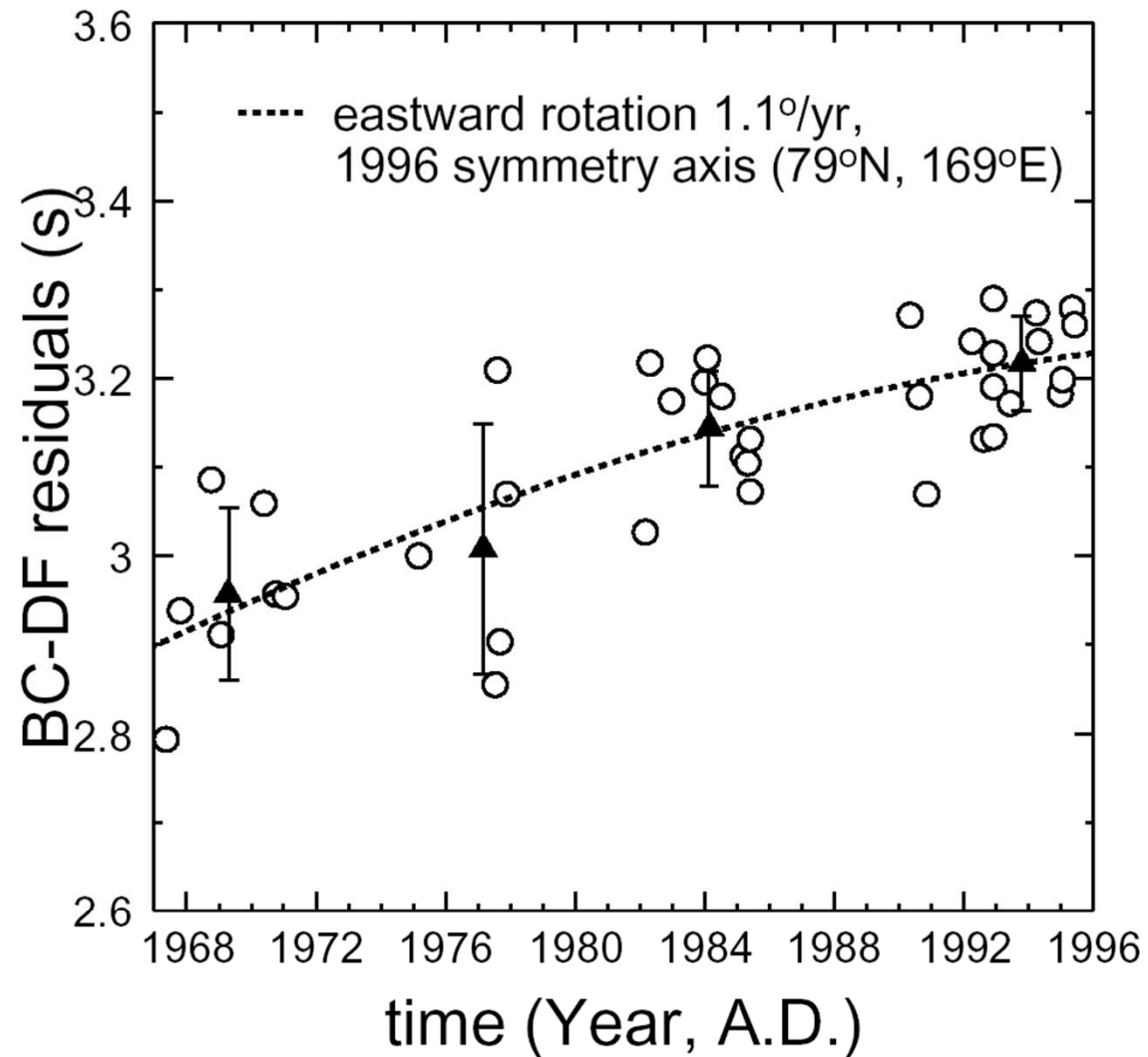
Glatzmaier and Roberts, Science, 1996





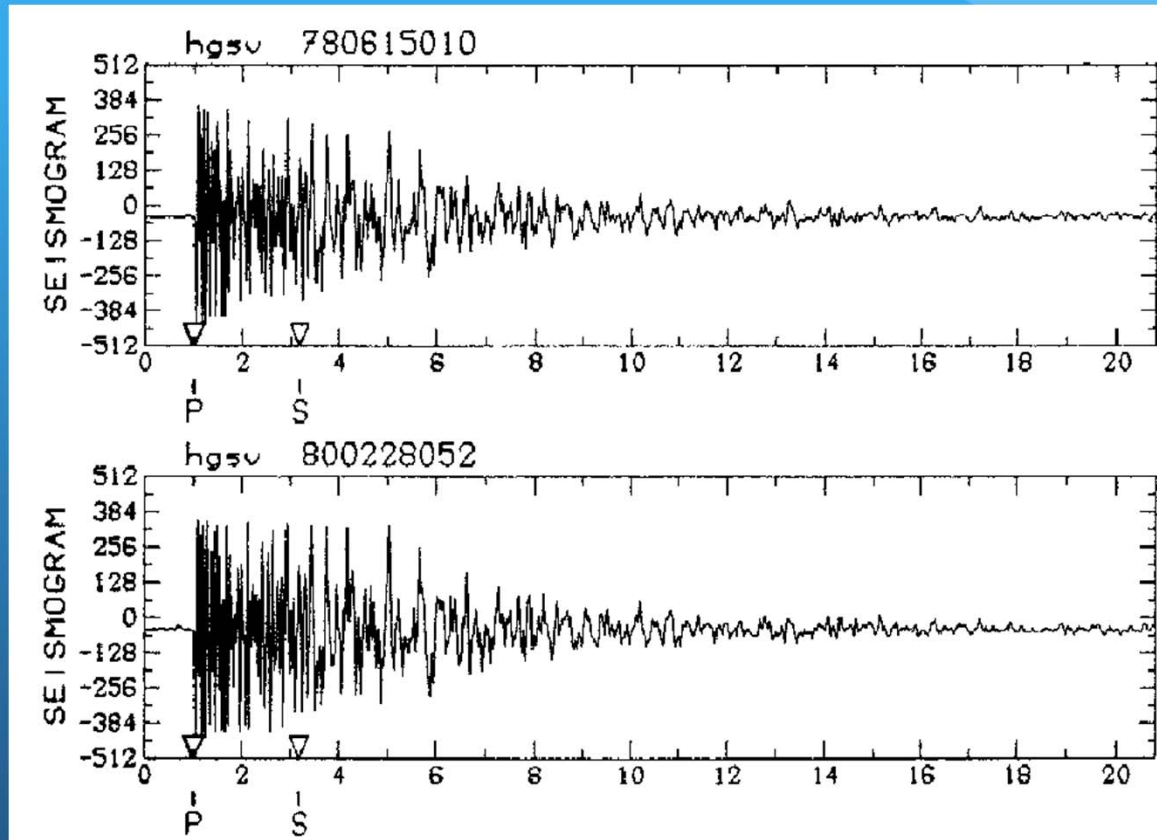
Song and Richards, Nature, 1996

South Sandwich Is. to College, Alaska



Song and Richards, Nature, 1996

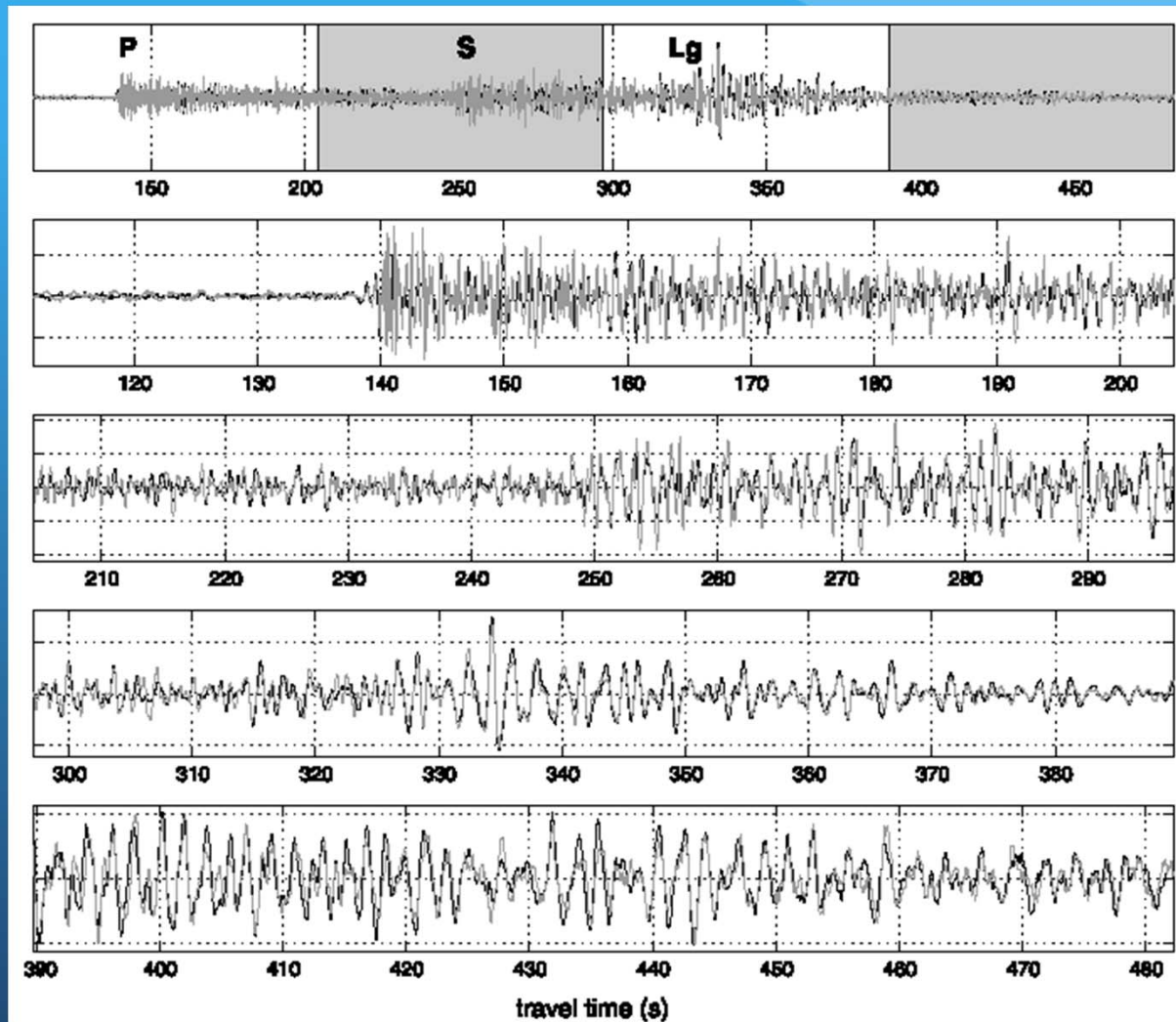
Earthquake doublets



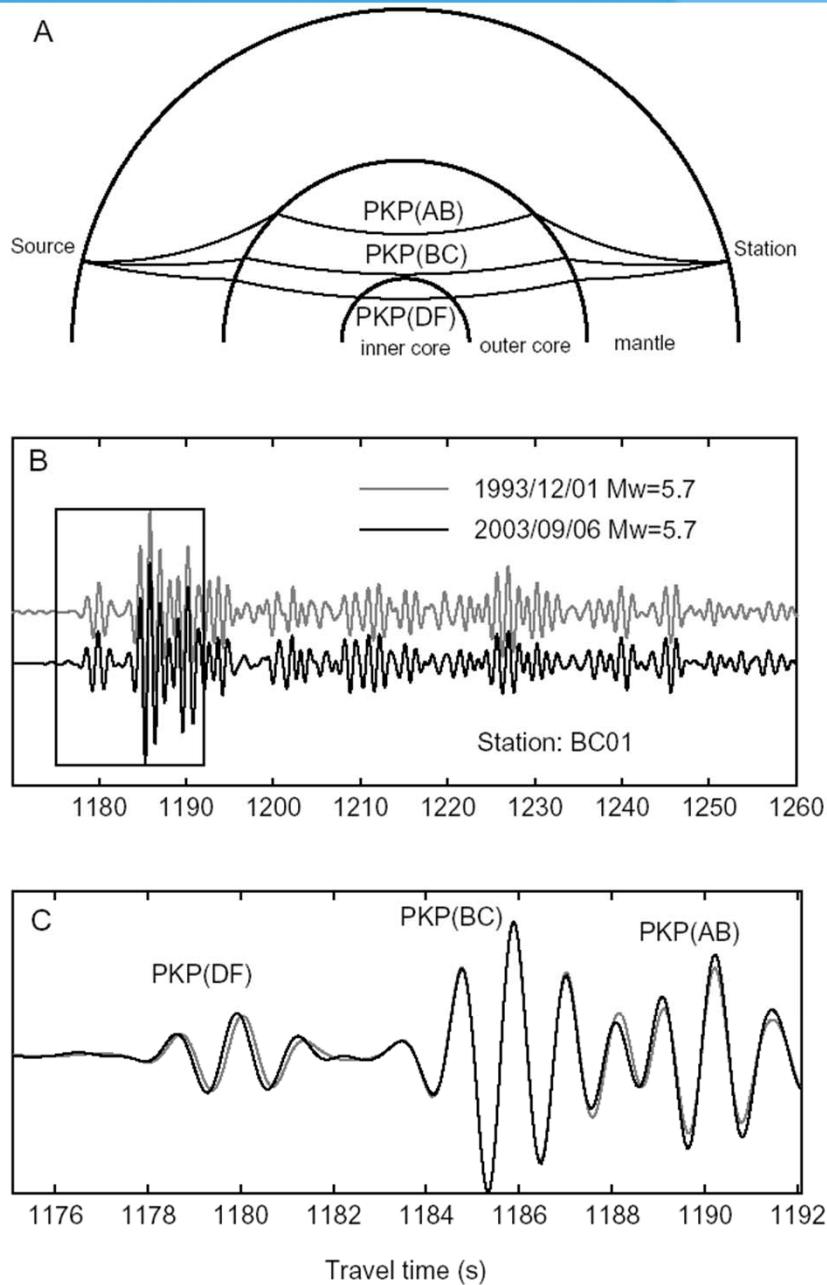
Poupinet, Frechet, and Ellsworth, JGR, 1984:

Monitoring velocity variations in the crust using earthquake doublets: an application to the Calaveras Fault, California.

An example of earthquake doublets

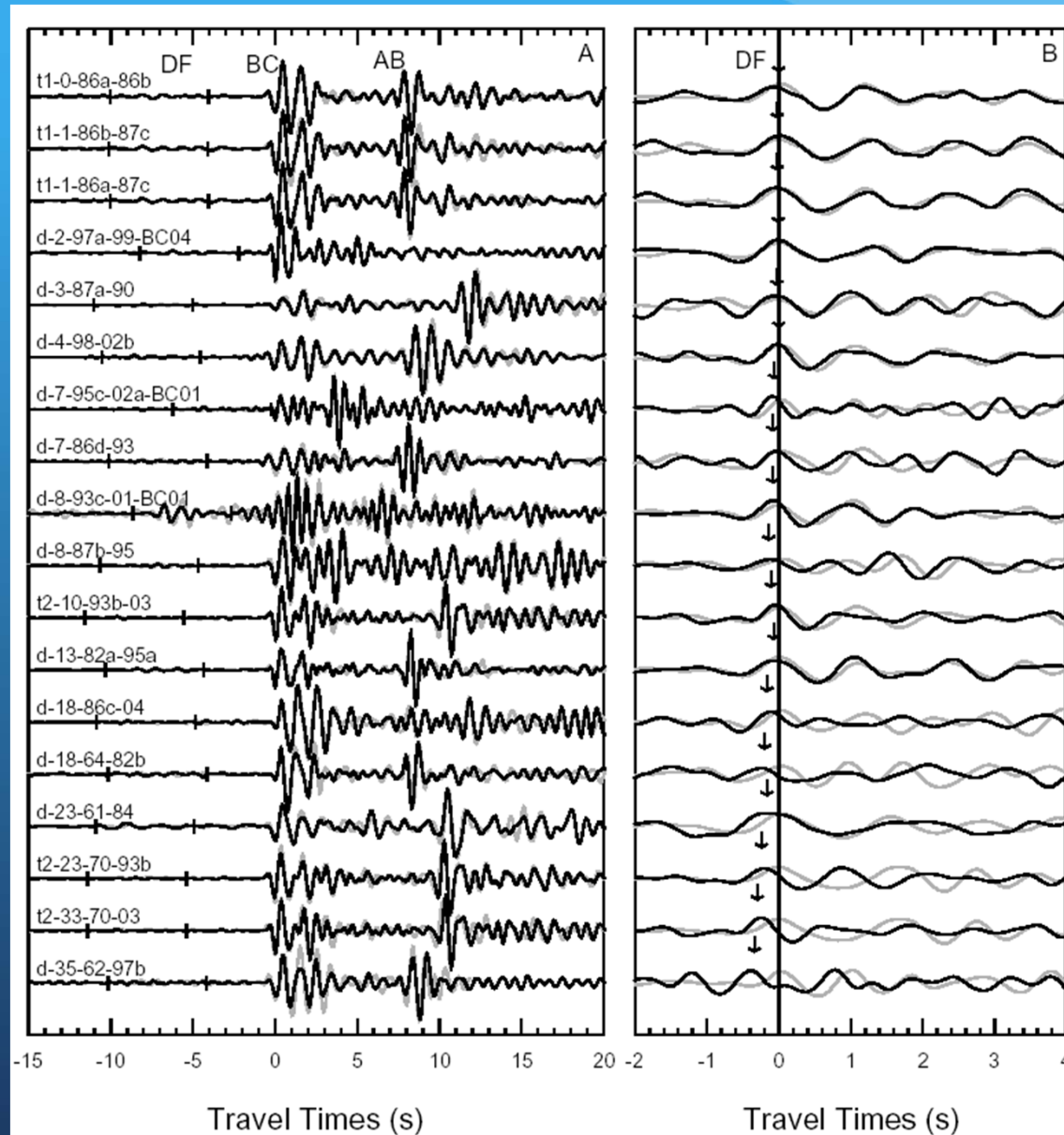


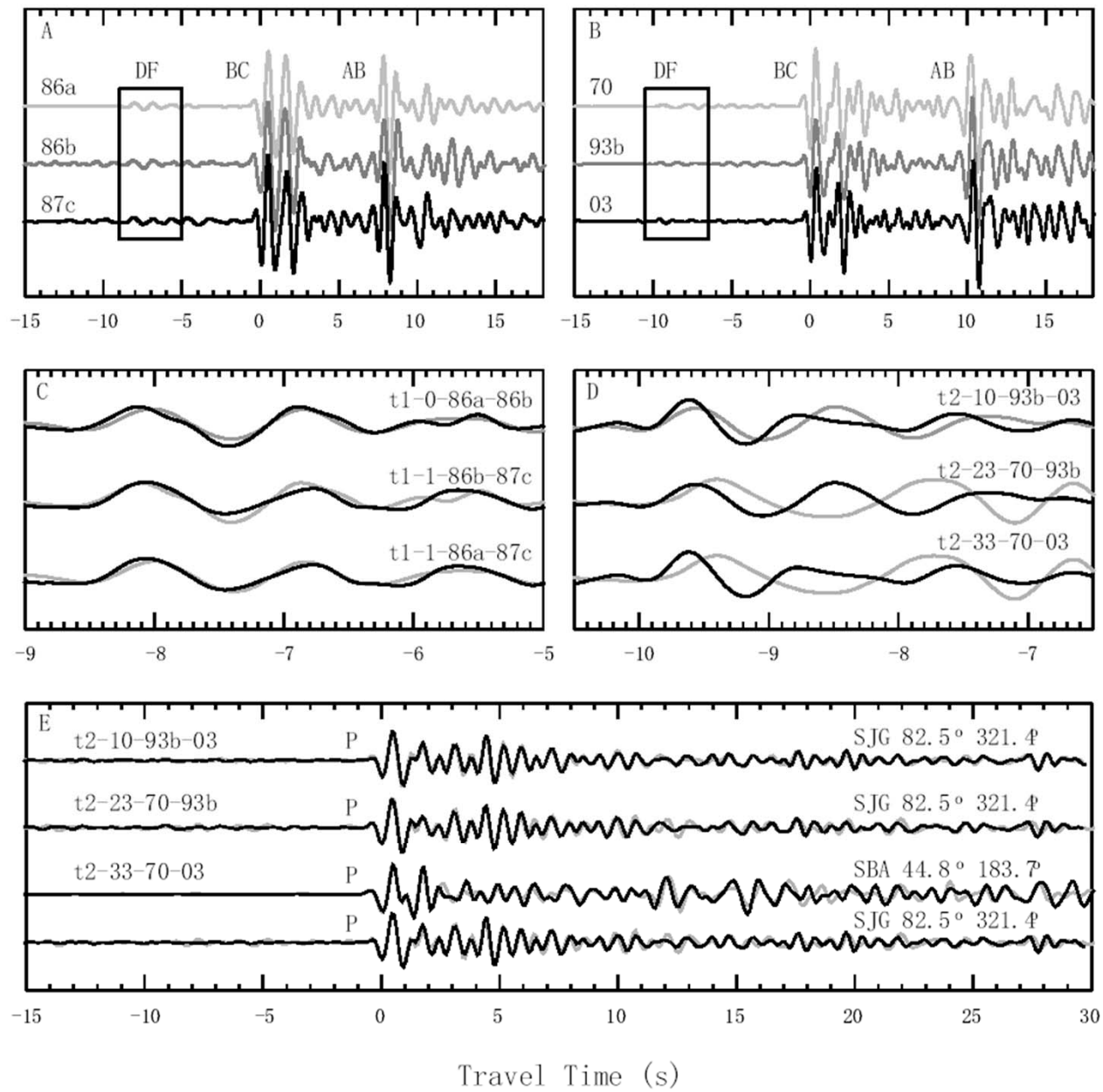
Schaff and Richards, Science, 2004

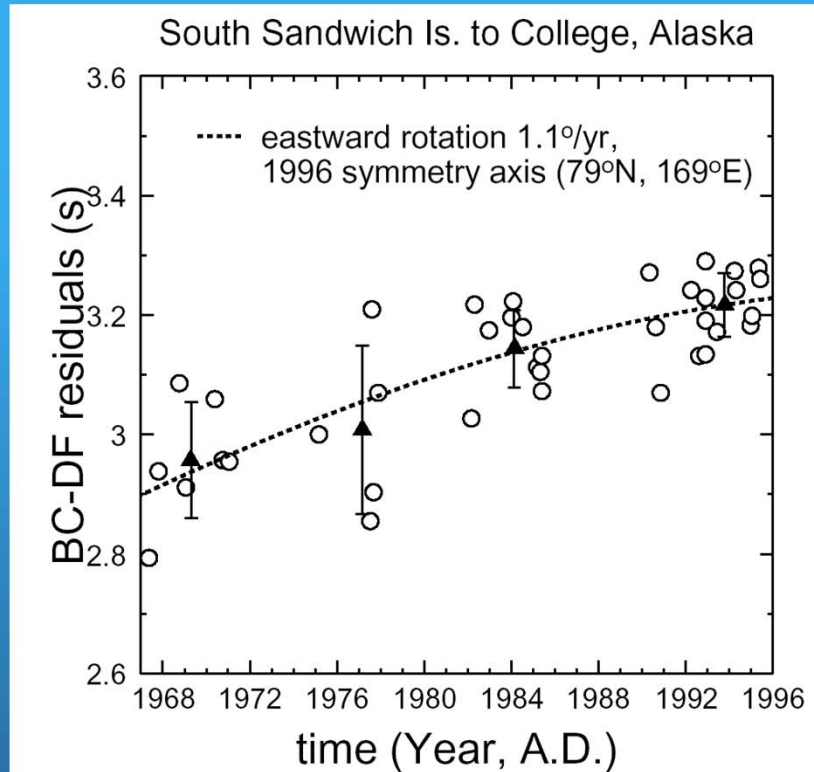


Zhang et al., submitted
to Science, 2005

South Sandwich Is. Doublets Recorded at College, AK





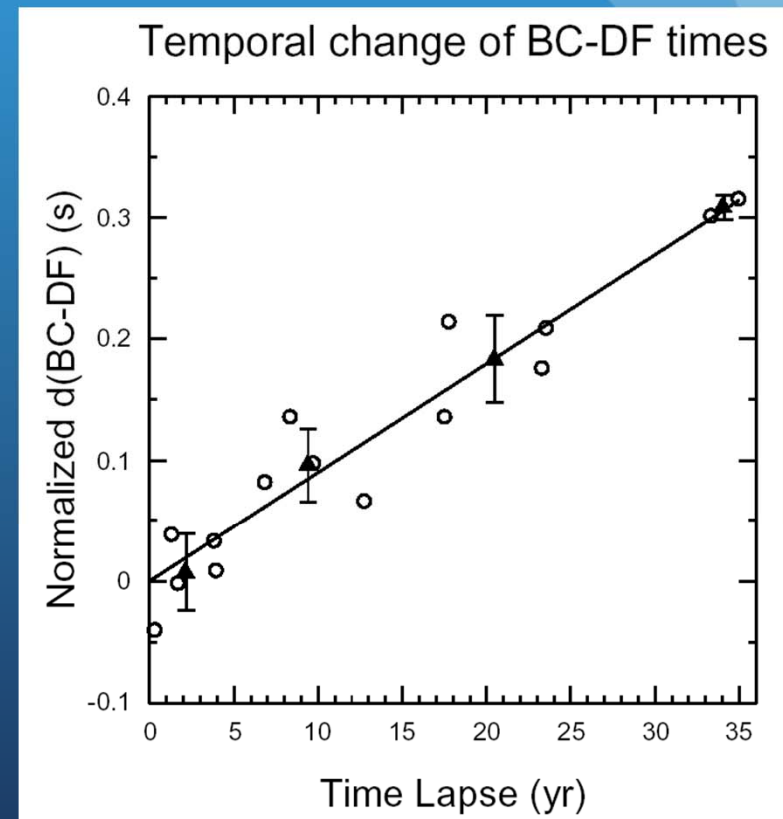


Song and Richards, 1996:

Slope = 0.0109 ± 0.0014 s/year

Measurements from doublets:

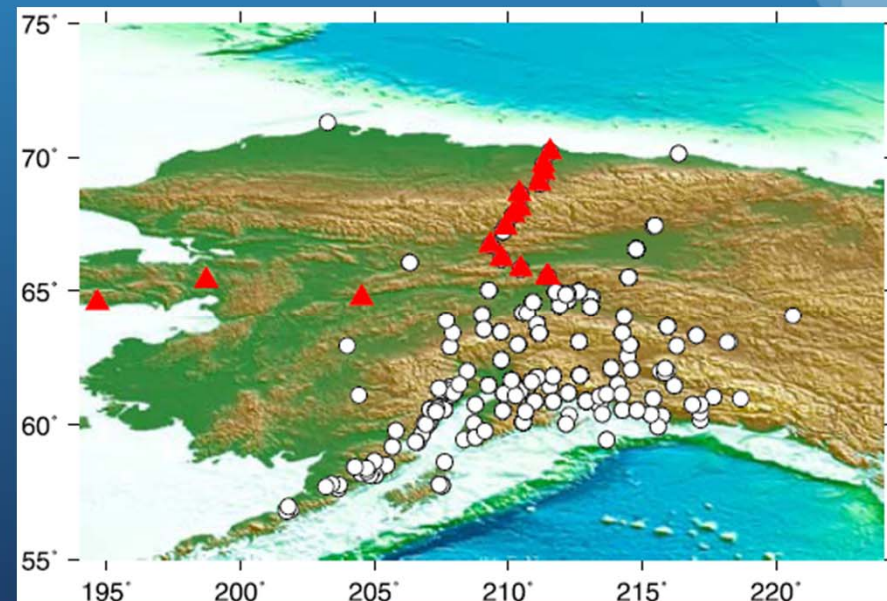
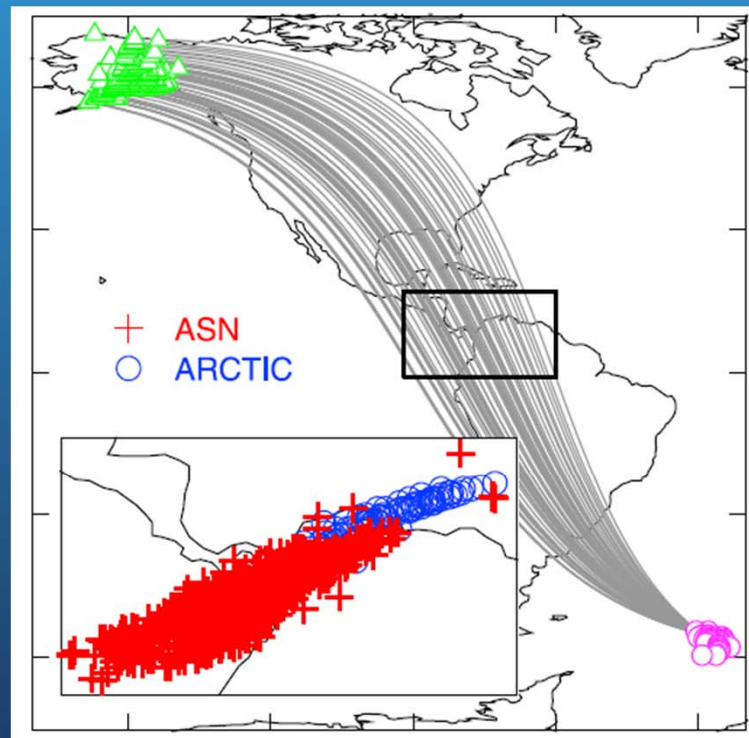
Slope = 0.0090 ± 0.0005 s/year





Inner core rotation and its variability from nonparametric modeling

Daniela Lindner,¹ Xiaodong Song,¹ Ping Ma,² and Doug H. Christensen³



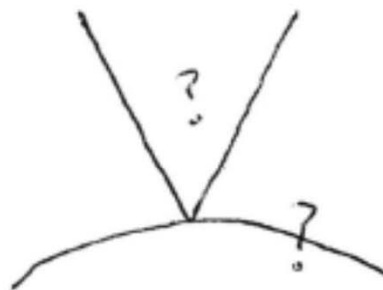


Topography of Earth's inner core boundary from high-quality waveform doublets

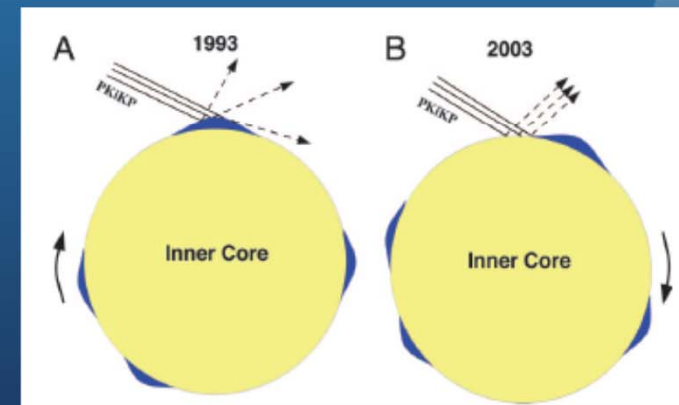
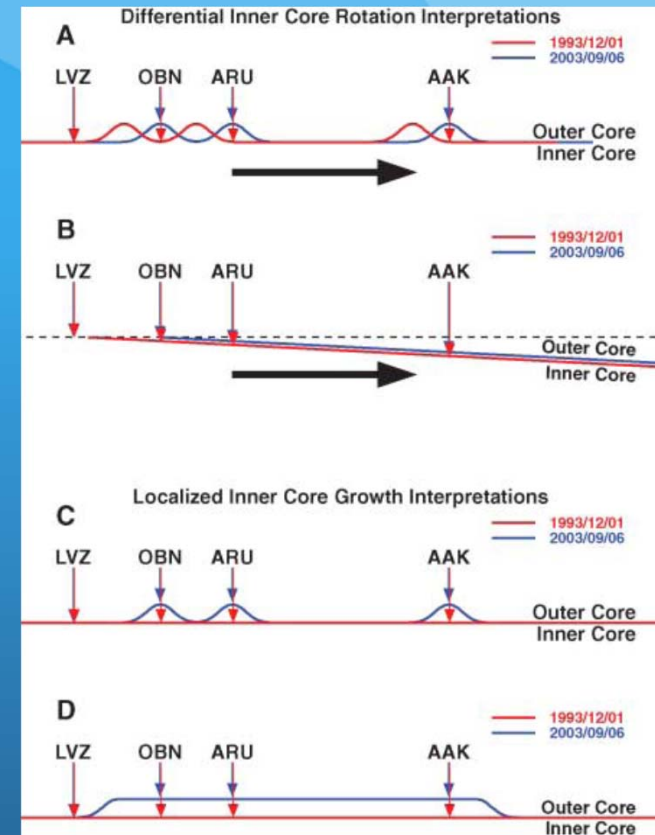
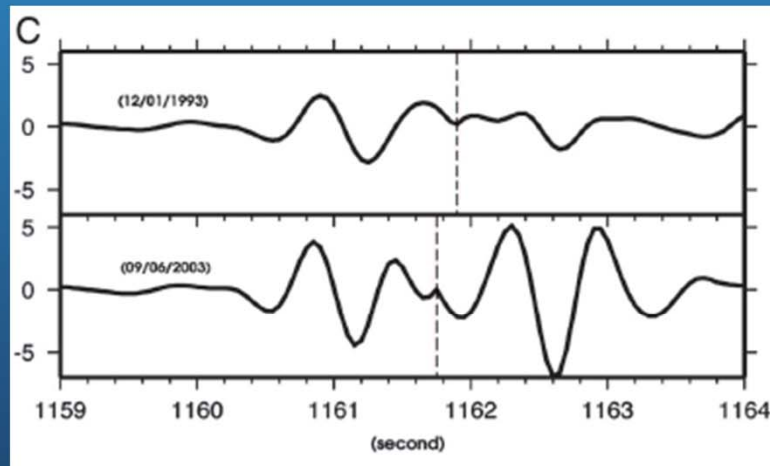
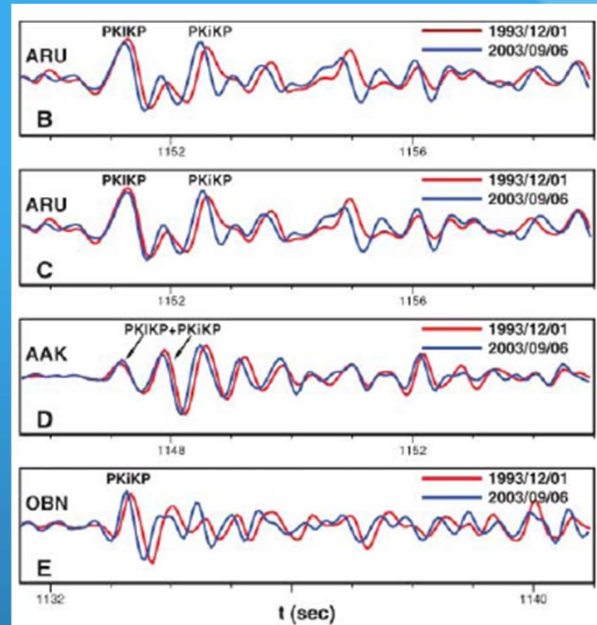
Xiaodong Song and Wei Dai

Department of Geology, University of Illinois, Urbana, IL 61801, USA. E-mail: xsong@uiuc.edu

Detecting inner core topography

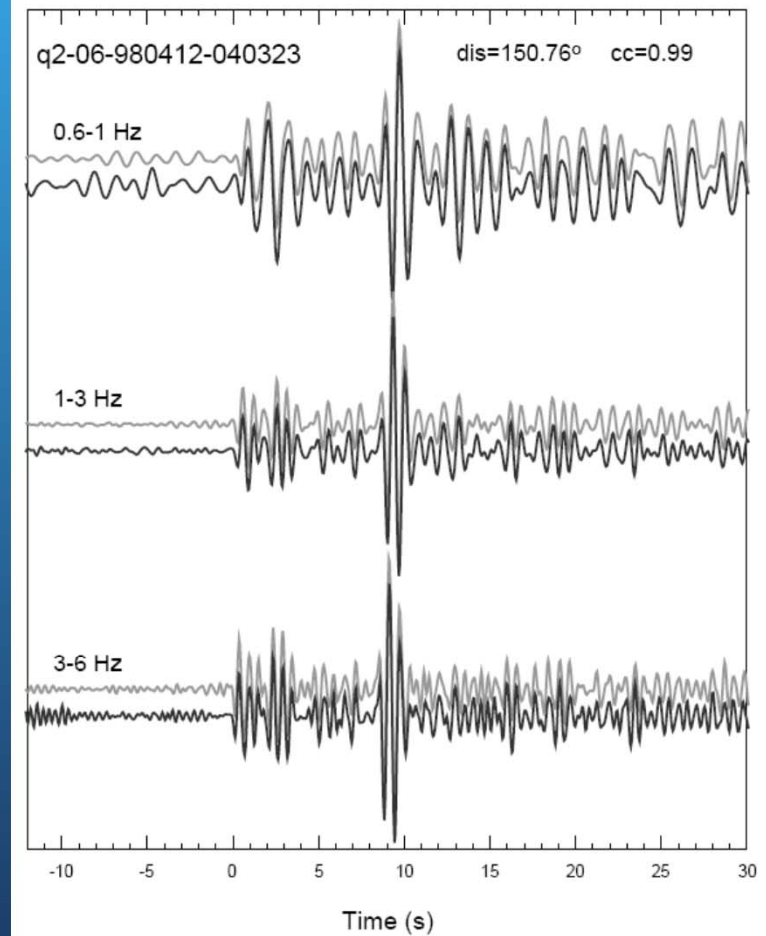
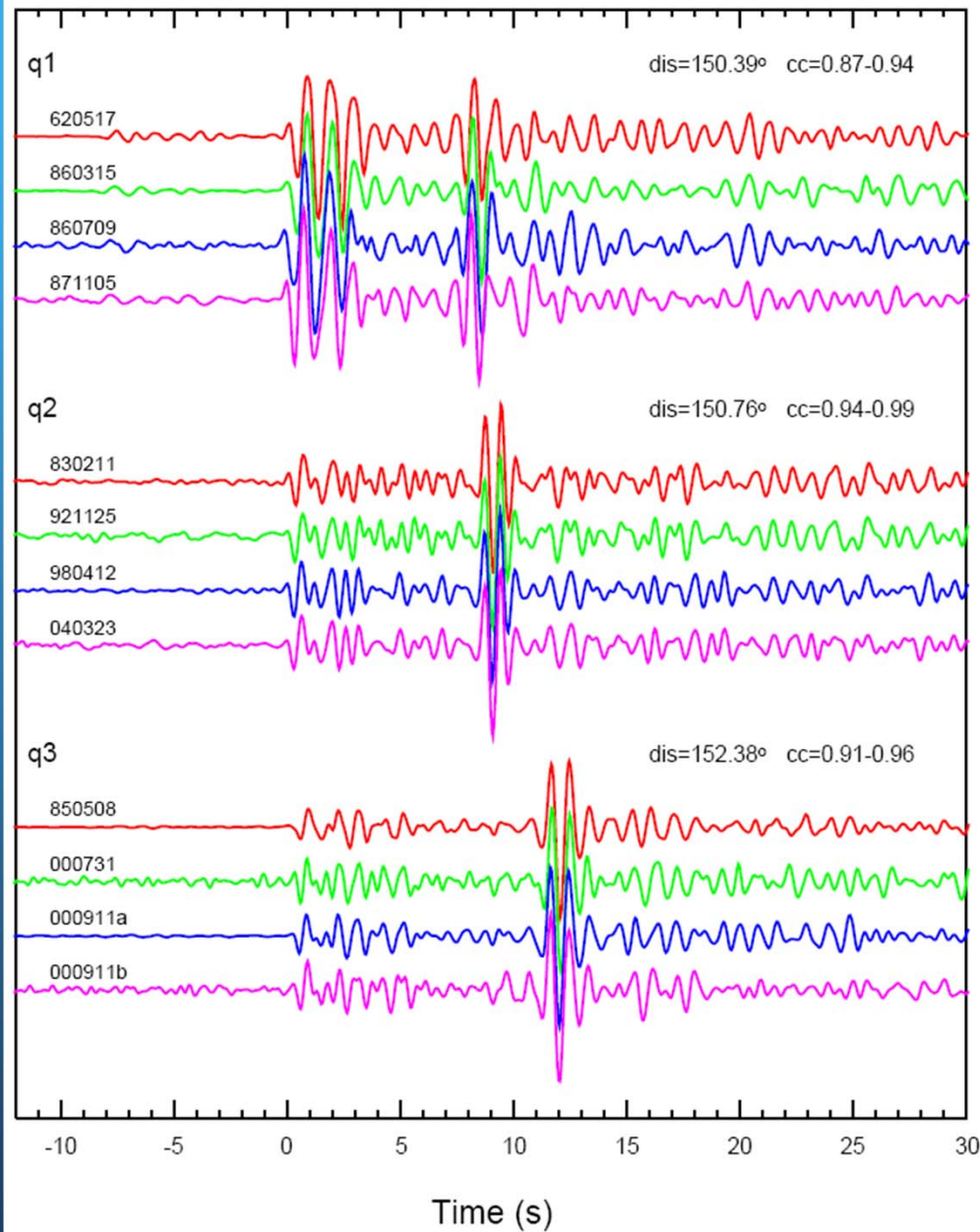


Wen,
Science,
2006

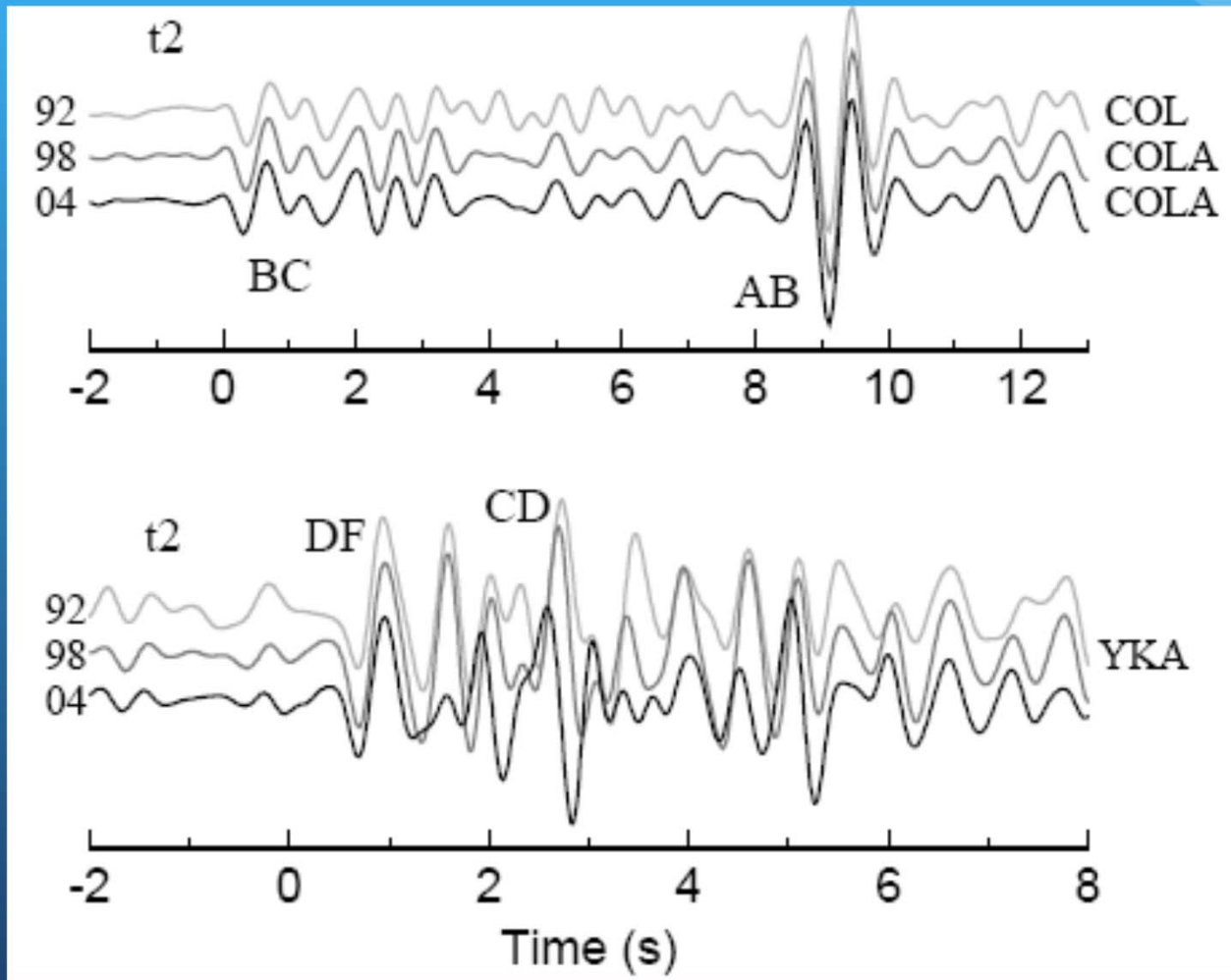


Cao, Masson, Romanowicz, PNAS, 2007

Examples of waveform doublets



A triplet from S. Sandwich Is. to Yellow Knife Array (YKA)



Song and Dai,
GJI, 2008

Topography of Earth's inner core boundary from high-quality waveform doublets

Xiaodong Song and Wei Dai

Department of Geology, University of Illinois, Urbana, IL 61801, USA. E-mail: xsong@uiuc.edu

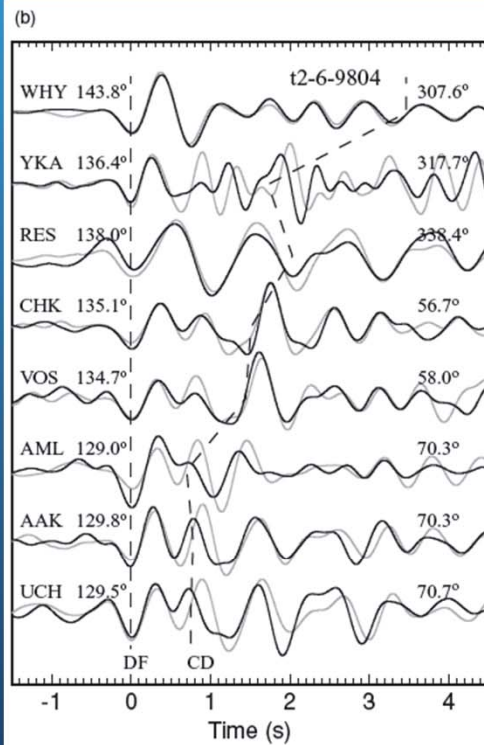


Figure 12. (Continued).

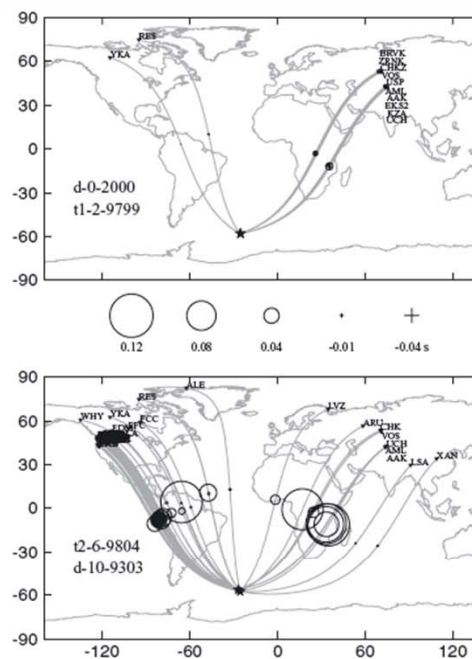
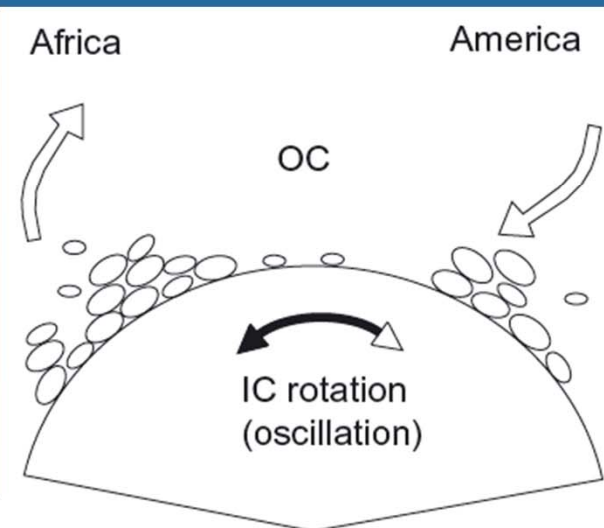
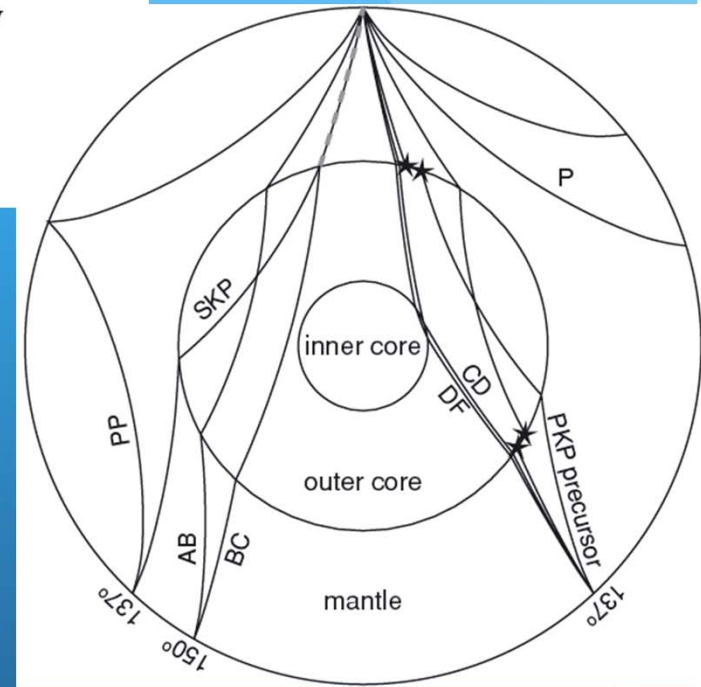
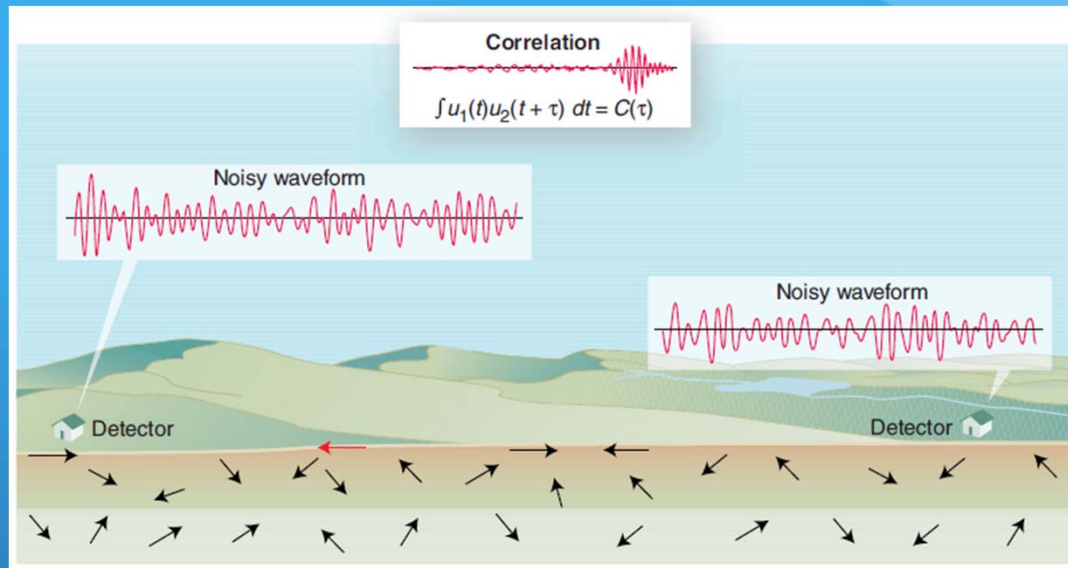
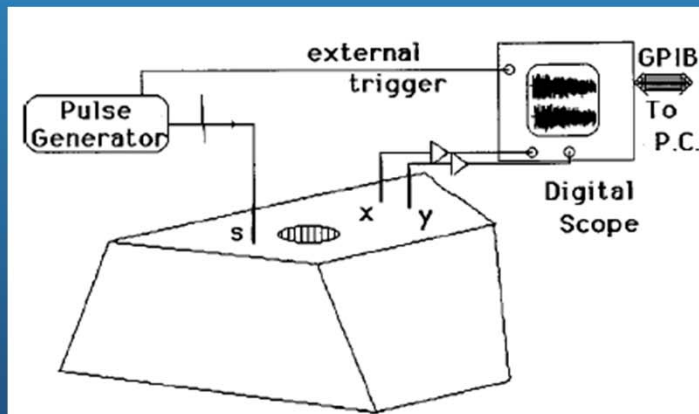


Figure 13. Relative time-shifts (ddr) between CD and DF for doublets with (a) short time separations (9799 and 2000–2000 pairs) and (b) long time separations (9303 and 9804 pairs). The relative time-shifts (circles and crosses) are plotted at the ICB bounce points of the ray paths. The symbol size is proportional to the size of the relative time-shift.

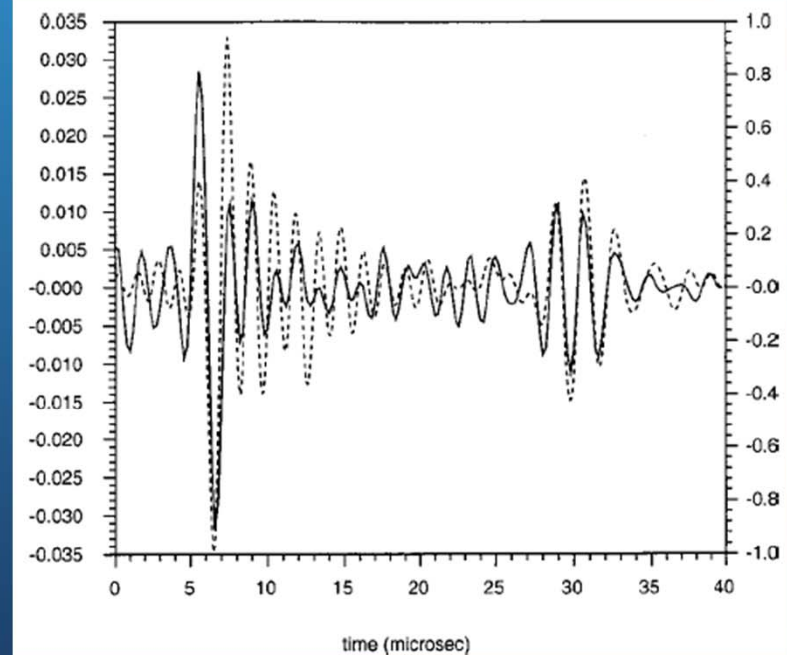




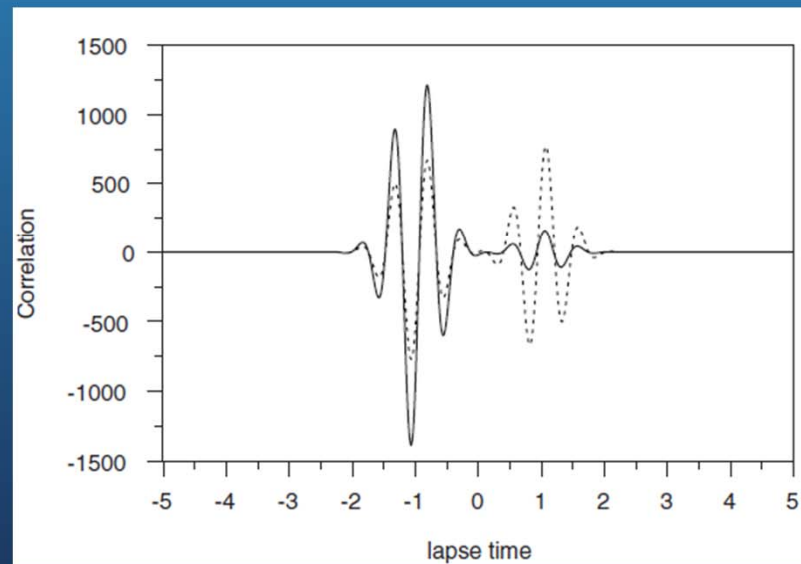
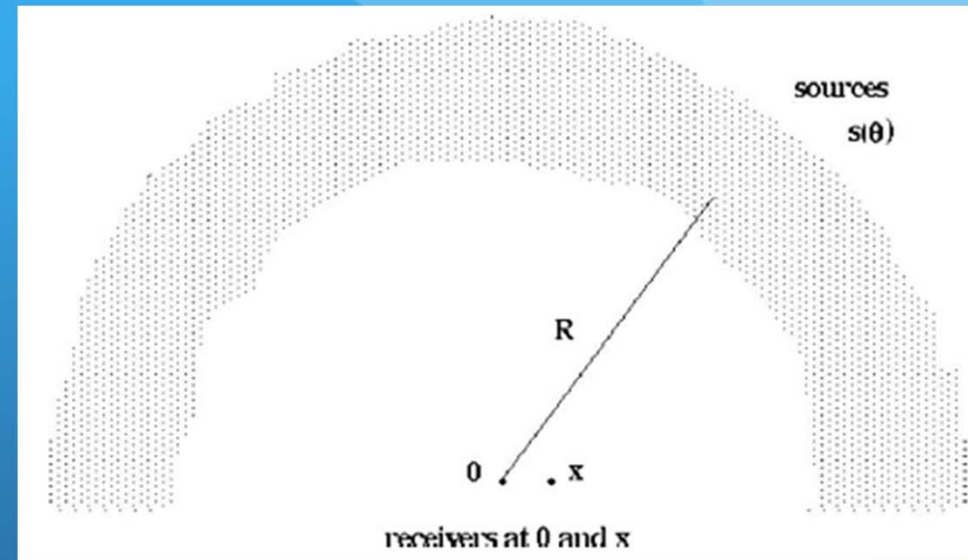
Weaver, Science, 2005



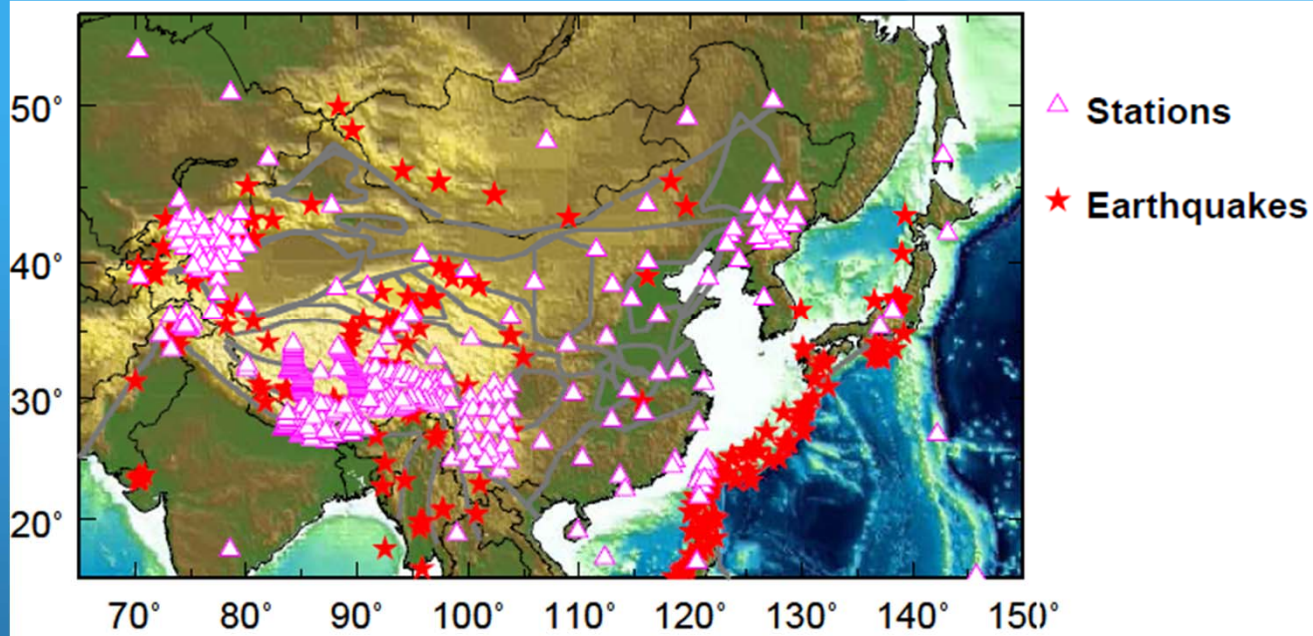
Lobkis and Weaver, JASA, 2001



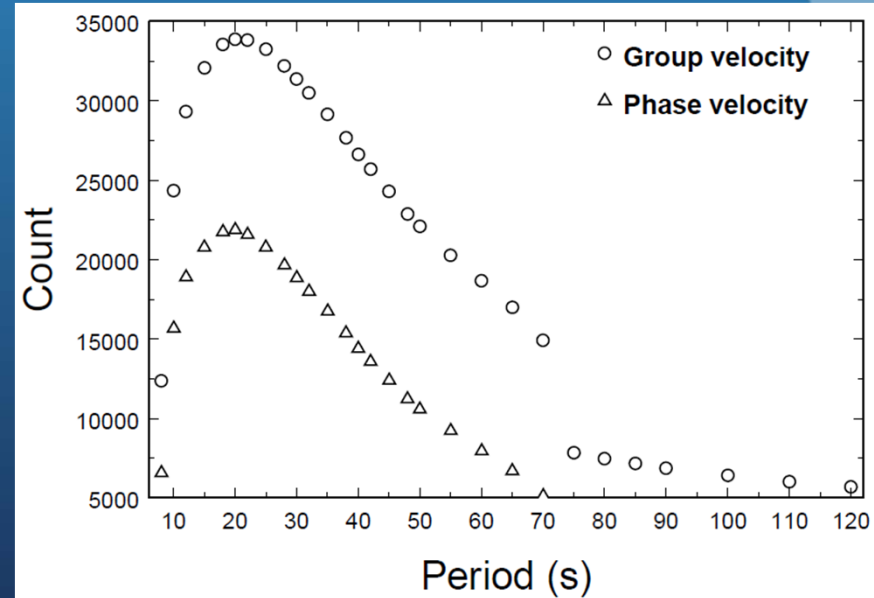
Noise field does not
need to be fully diffuse
to obtain accurate travel
times!



Weaver et al., JASA, 2009

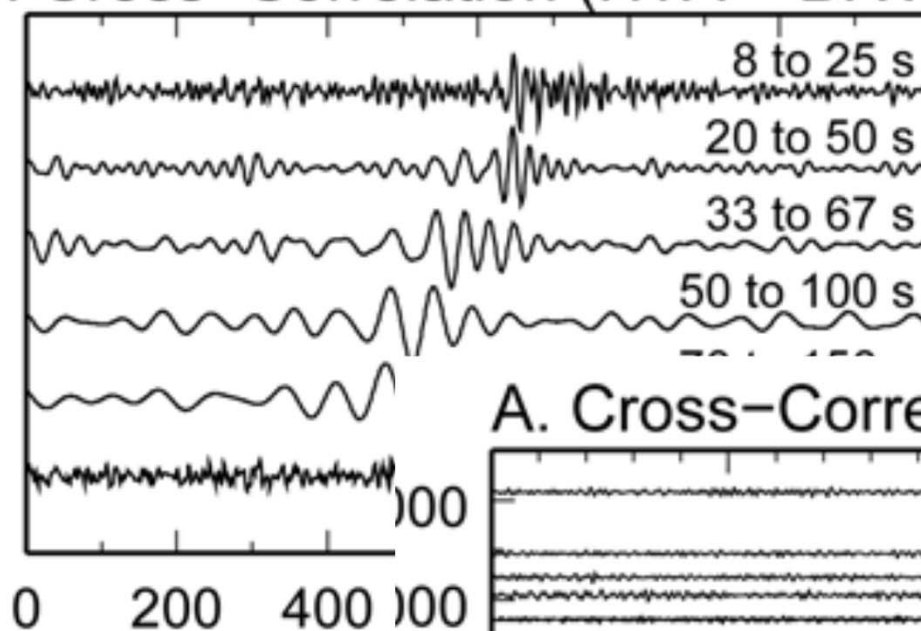


Surface wave
tomography:
ambient noise +
earthquake data

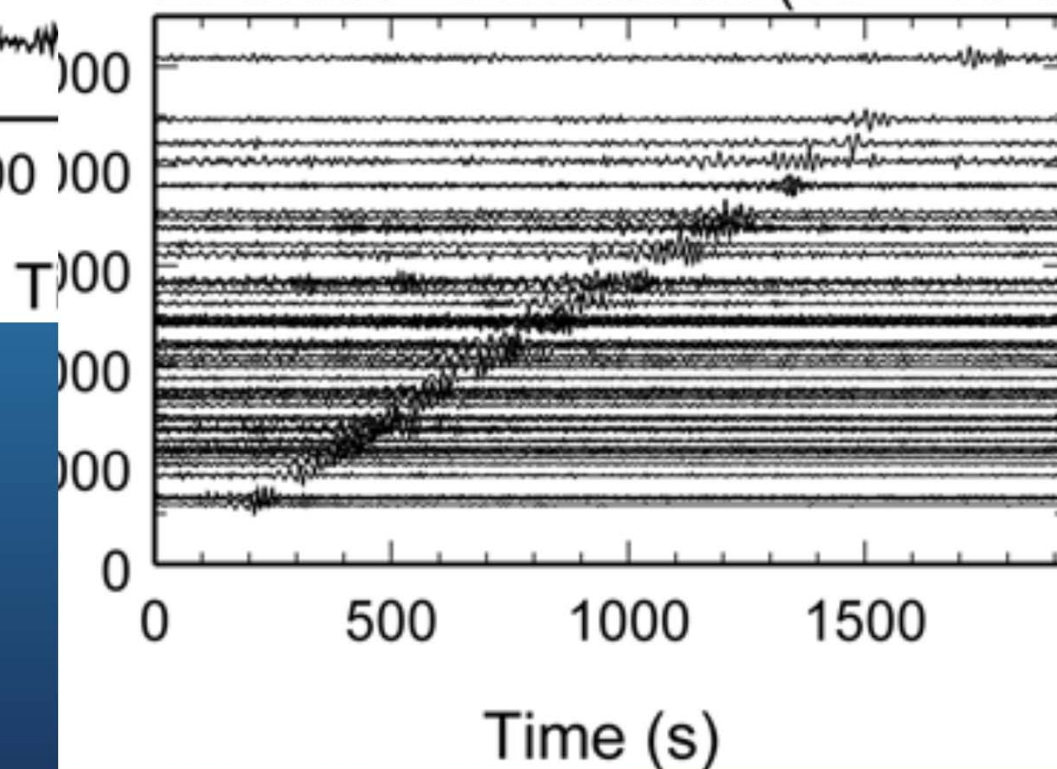


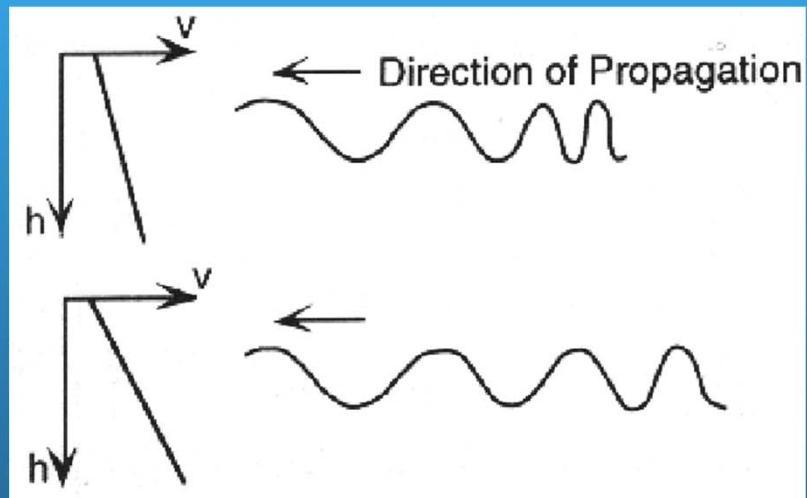
Time (s)

B. Cross-Correlation (HTA - BRVK)

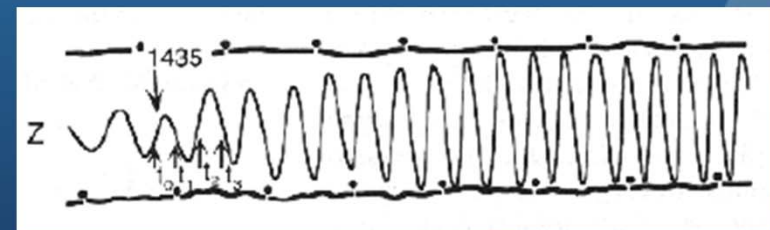
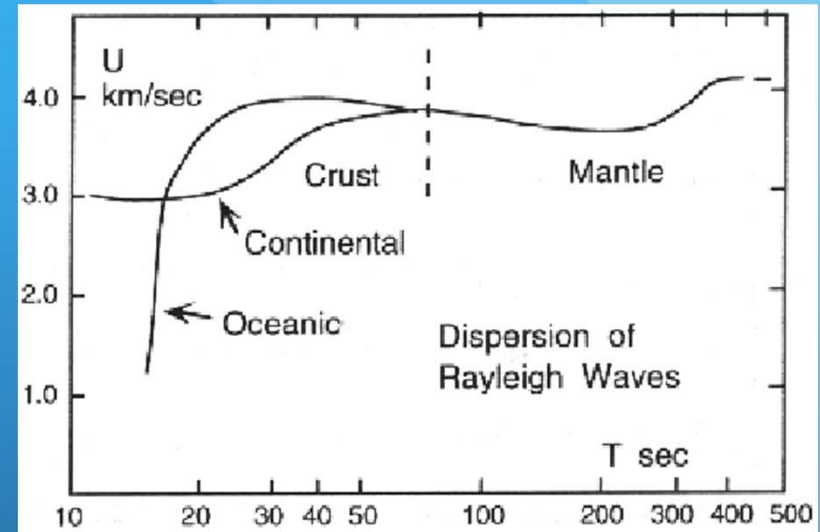


A. Cross-Correlation (10 - 30 s)



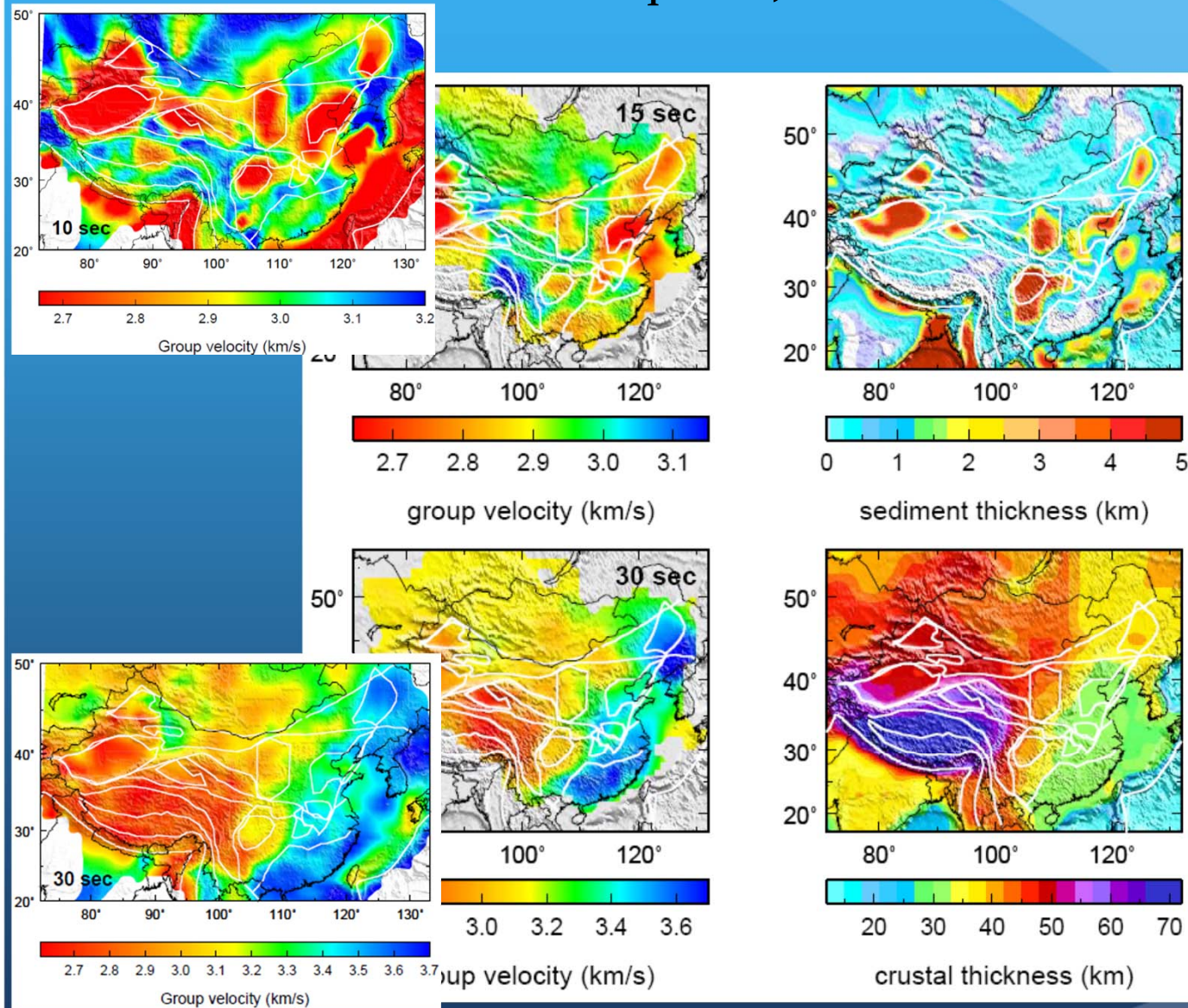


Strong gradient cause
greater dispersion



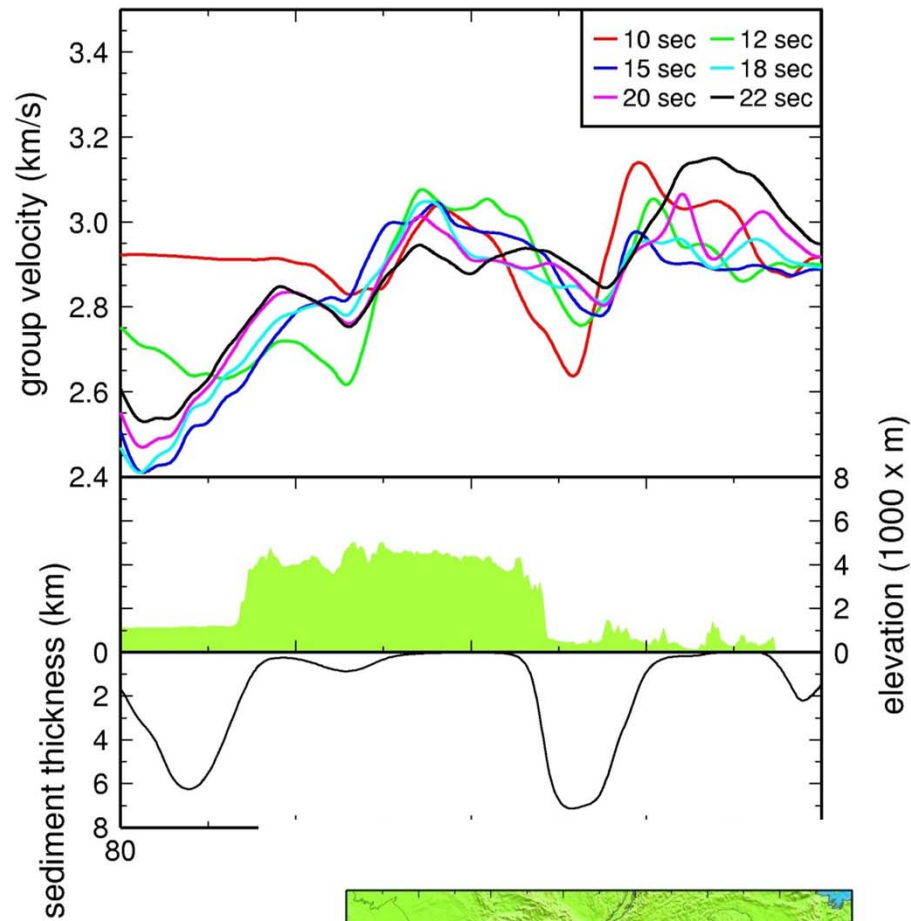
Zheng et al., G3, 2008; Sun et al.,
Earthq. Sci., 2010

Rayleigh group
velocities (10 s)
and sediment
thickness

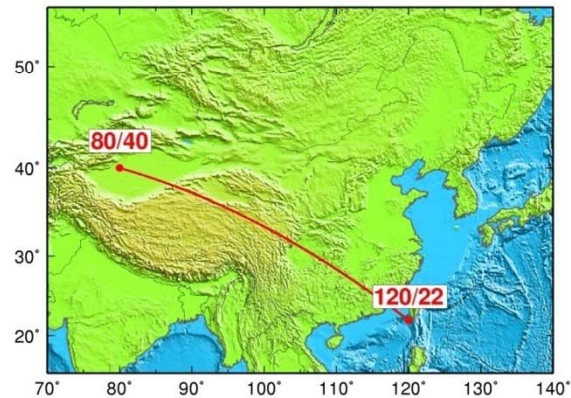
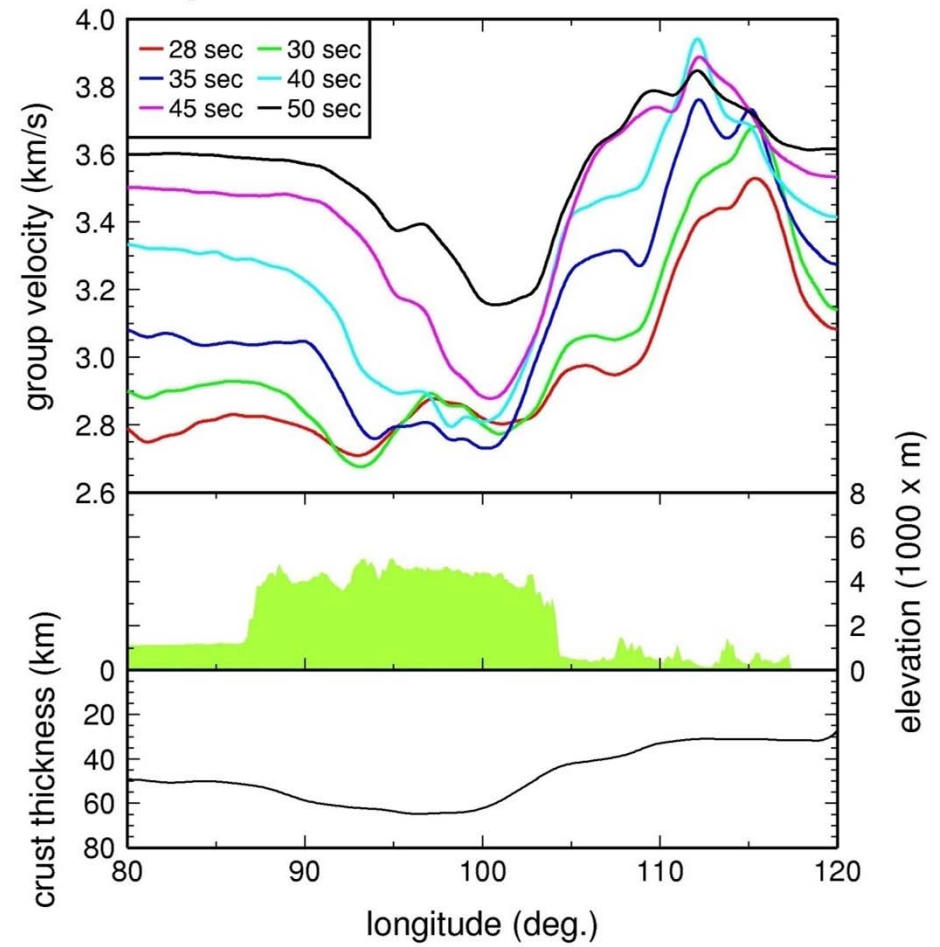


Rayleigh group
velocities (30 s)
and crustal
thickness

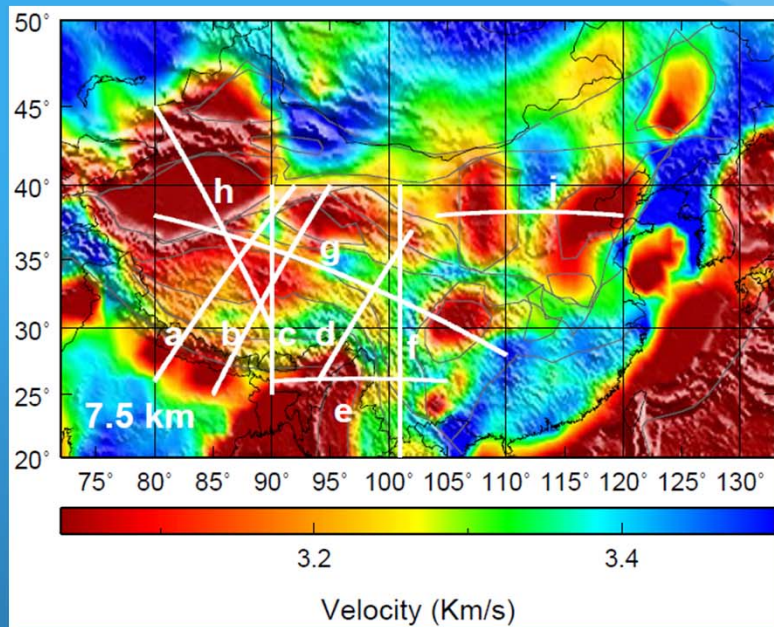
profile from 80/40 to 120/22



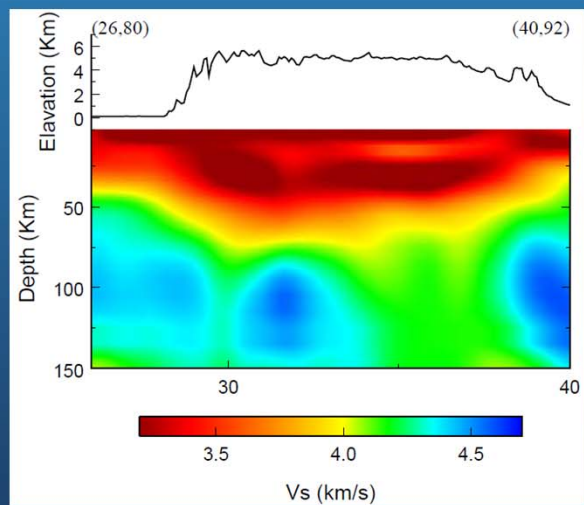
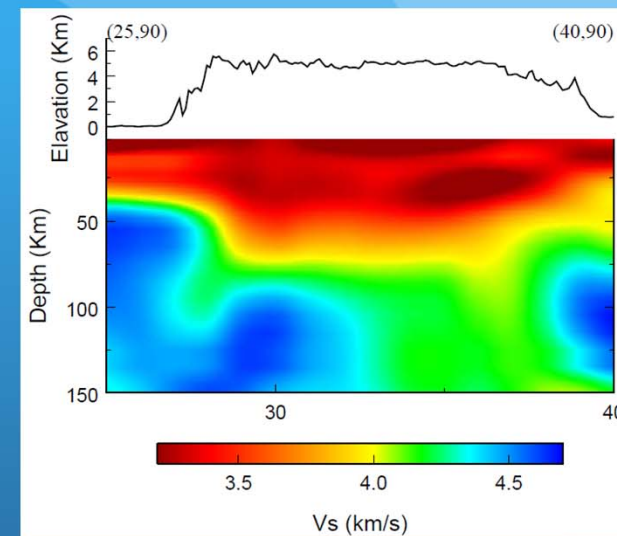
profile from 80/40 to 120/22



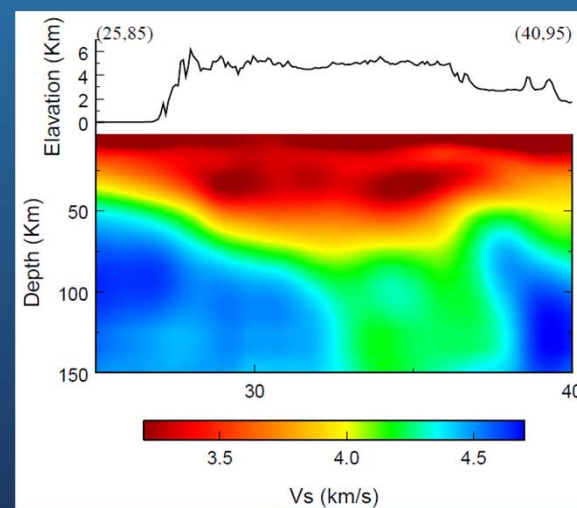
Zheng et al., G3, 2008



C

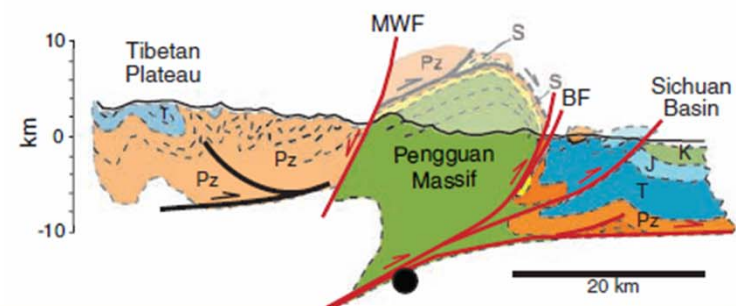
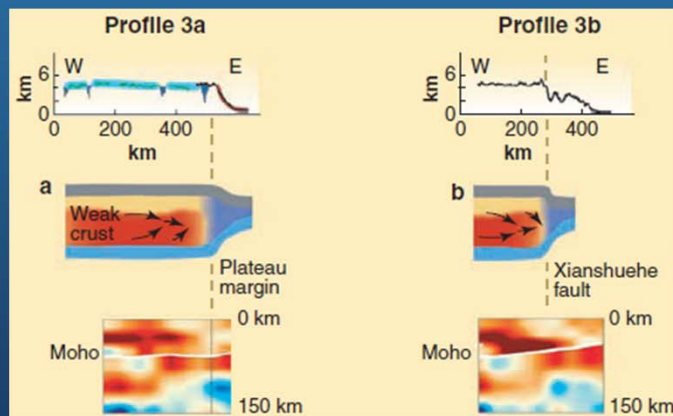
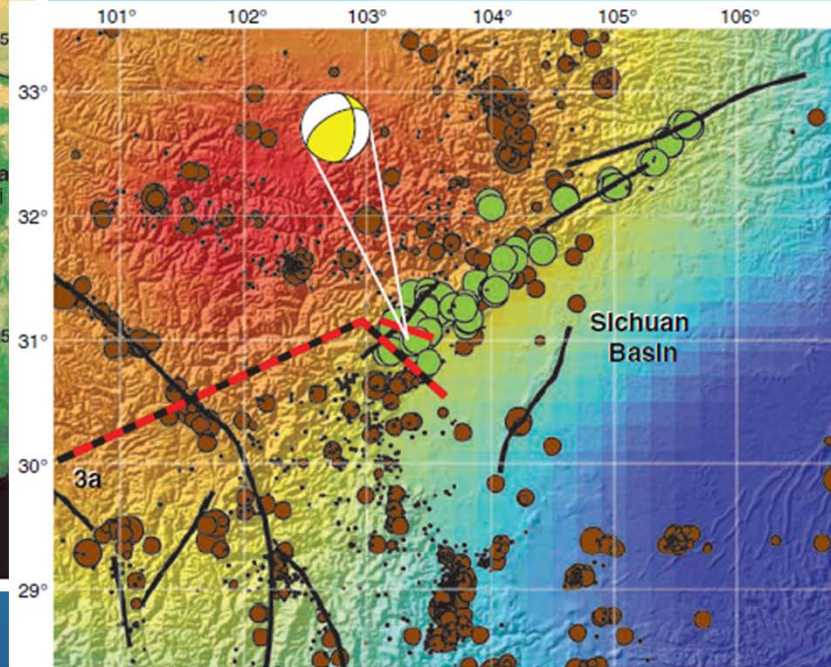
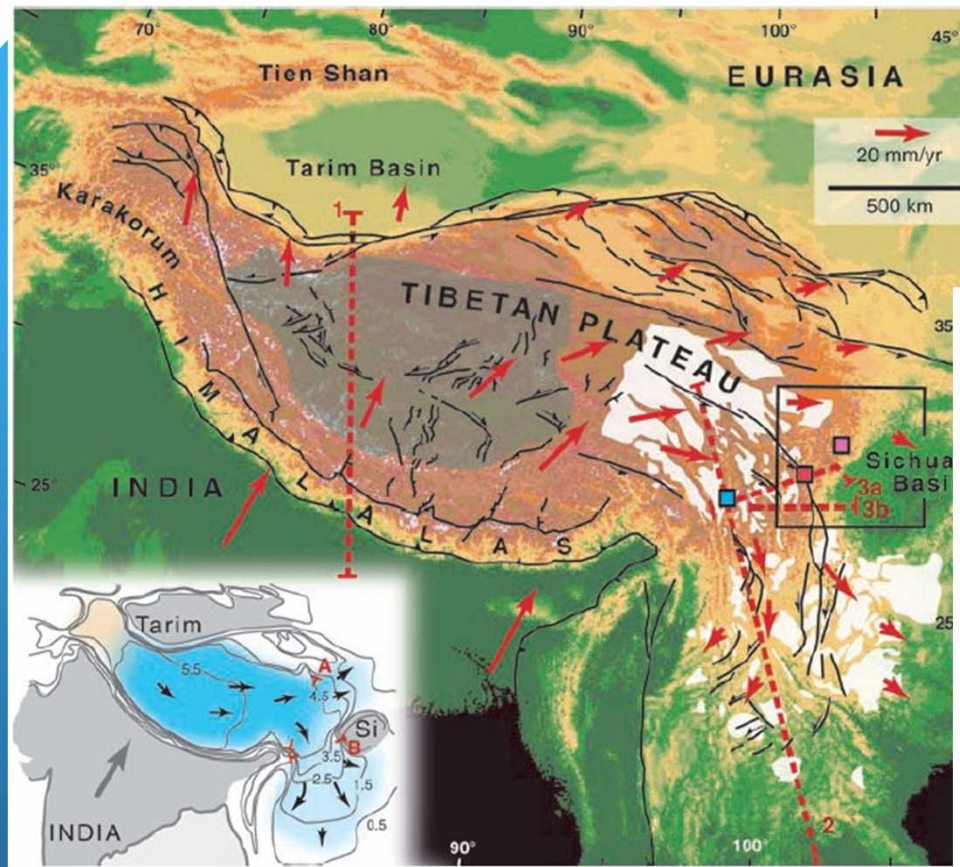


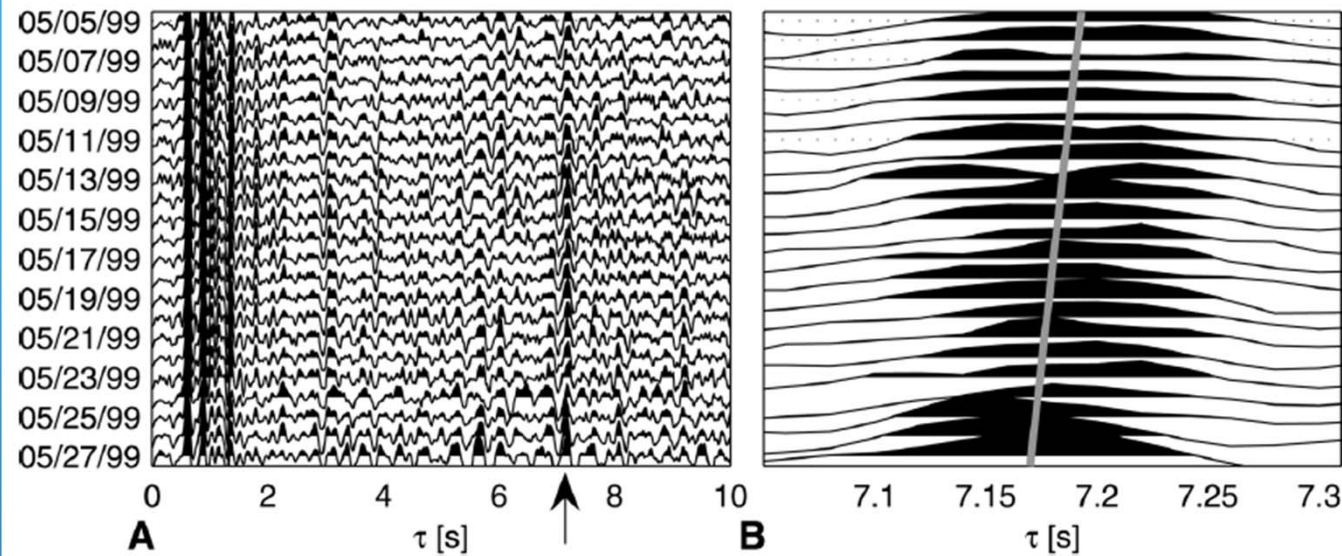
a



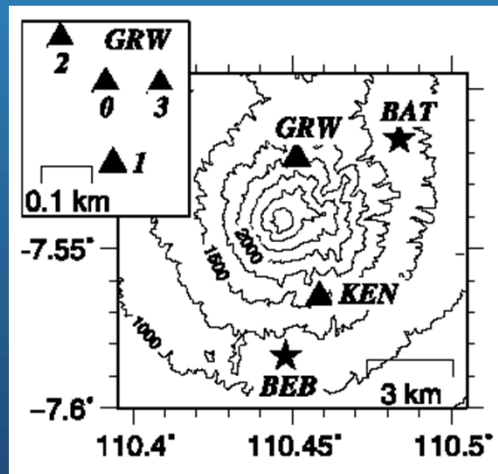
b

Royden et al., Science, 2008





Green function
between
GRW0 and
GRW1

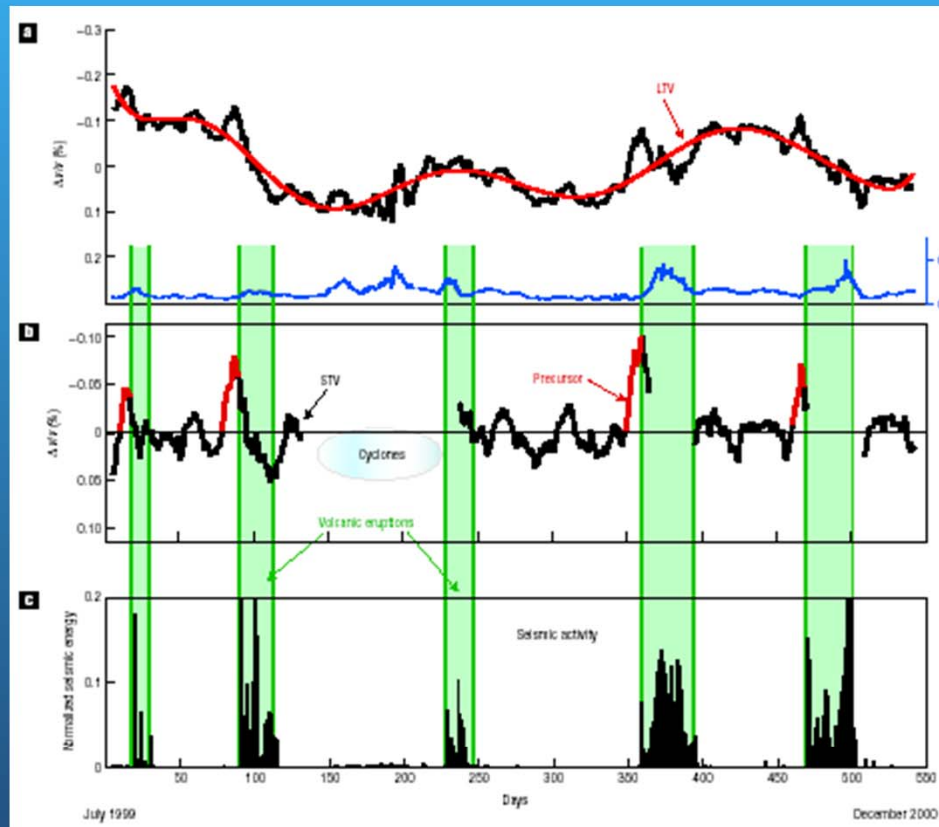


Clear time shifts in the coda (0.015% per day). The temporal shifts show a strong seasonal influence, which are explained by precipitation and ground water level fluctuation.

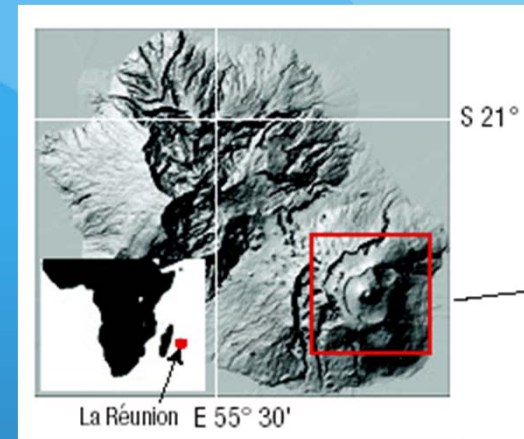
Sens-Schonfelder and Wegler,
GRL, 2006

Merapi Volcano, Indonesia

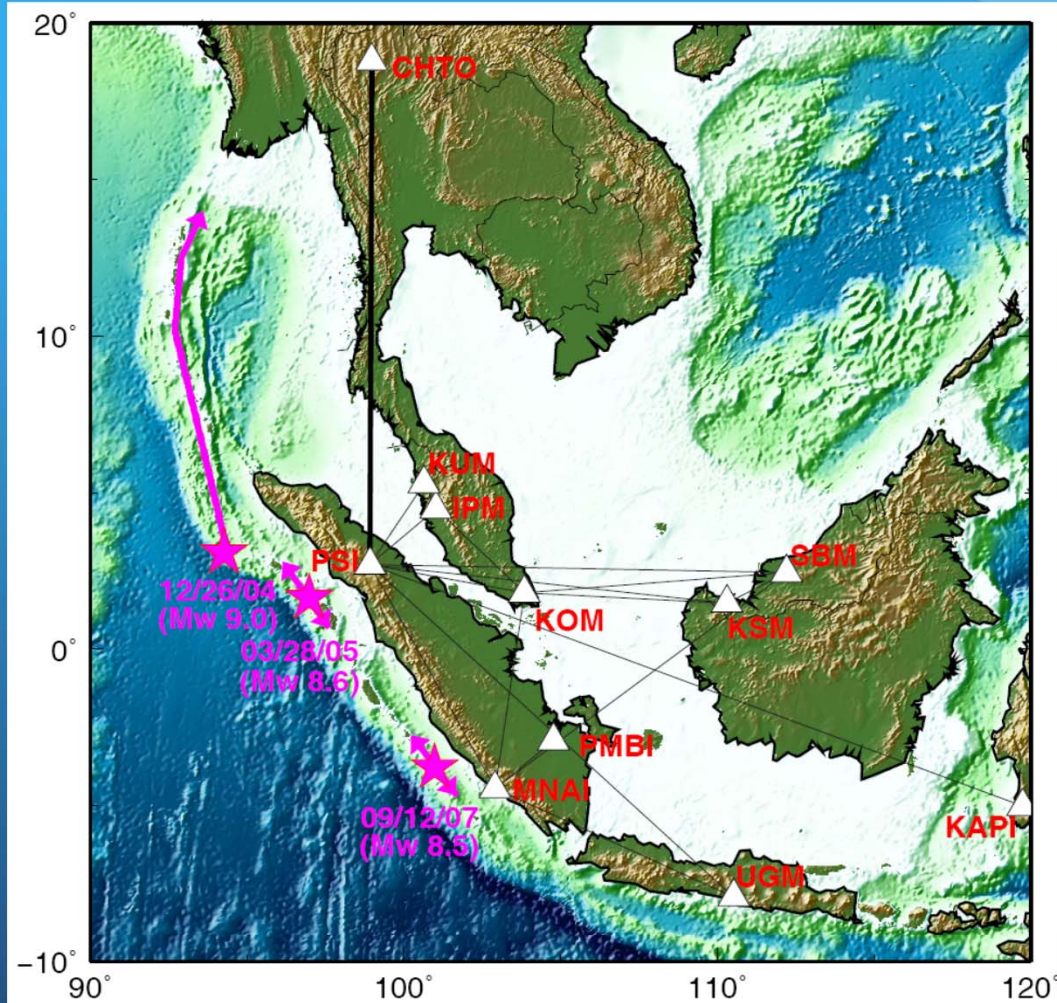
Volcano monitoring and forecasting



Brenguier et al., Nature Geoscience, 2008



The Piton de la Fournaise volcano, La Reunion island. Green functions from ambient noise correlation show decrease prior to eruptions (of the order of 0.05%), which is explained by inflation of volcano edifices.

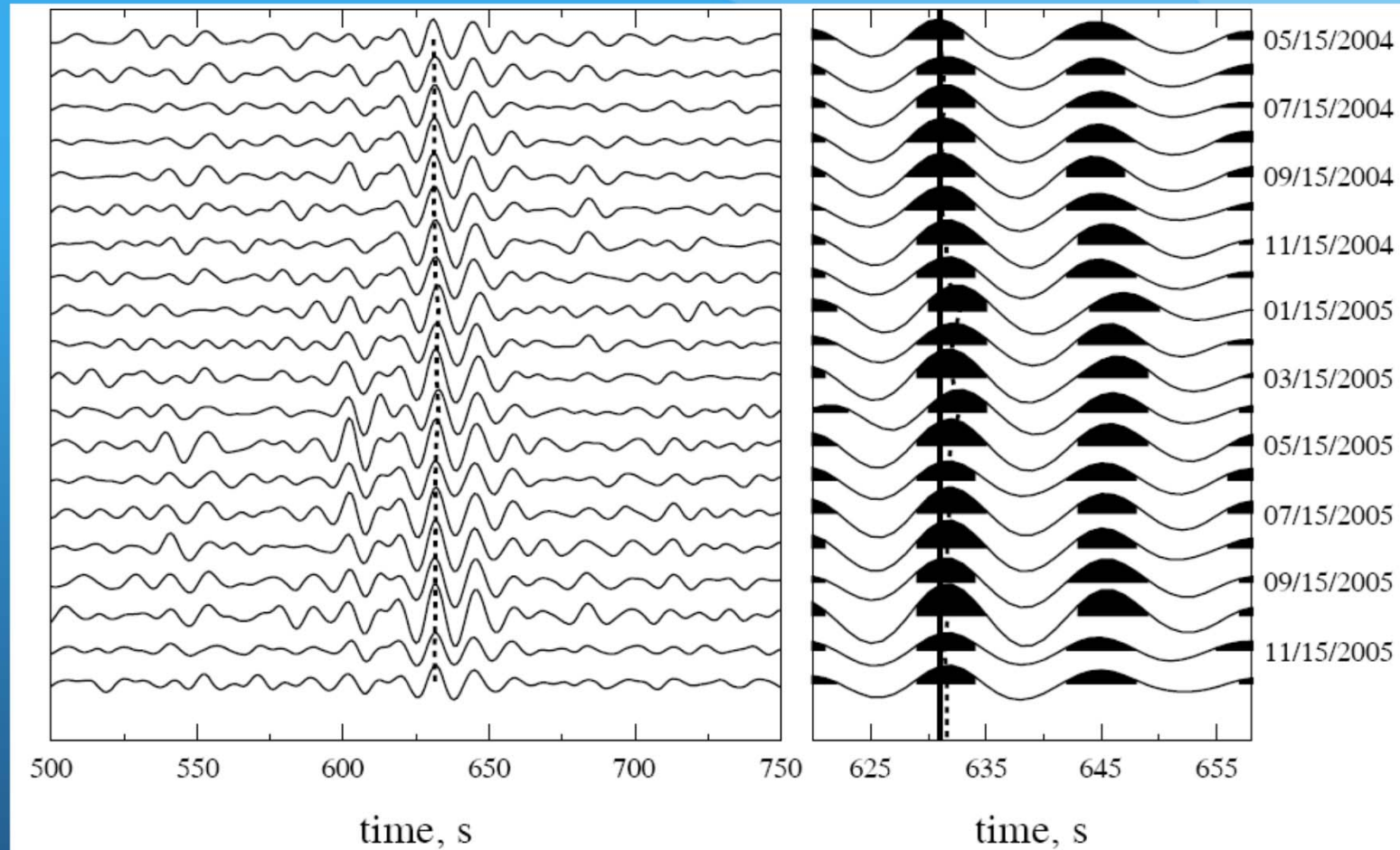


Sumatra earthquakes:

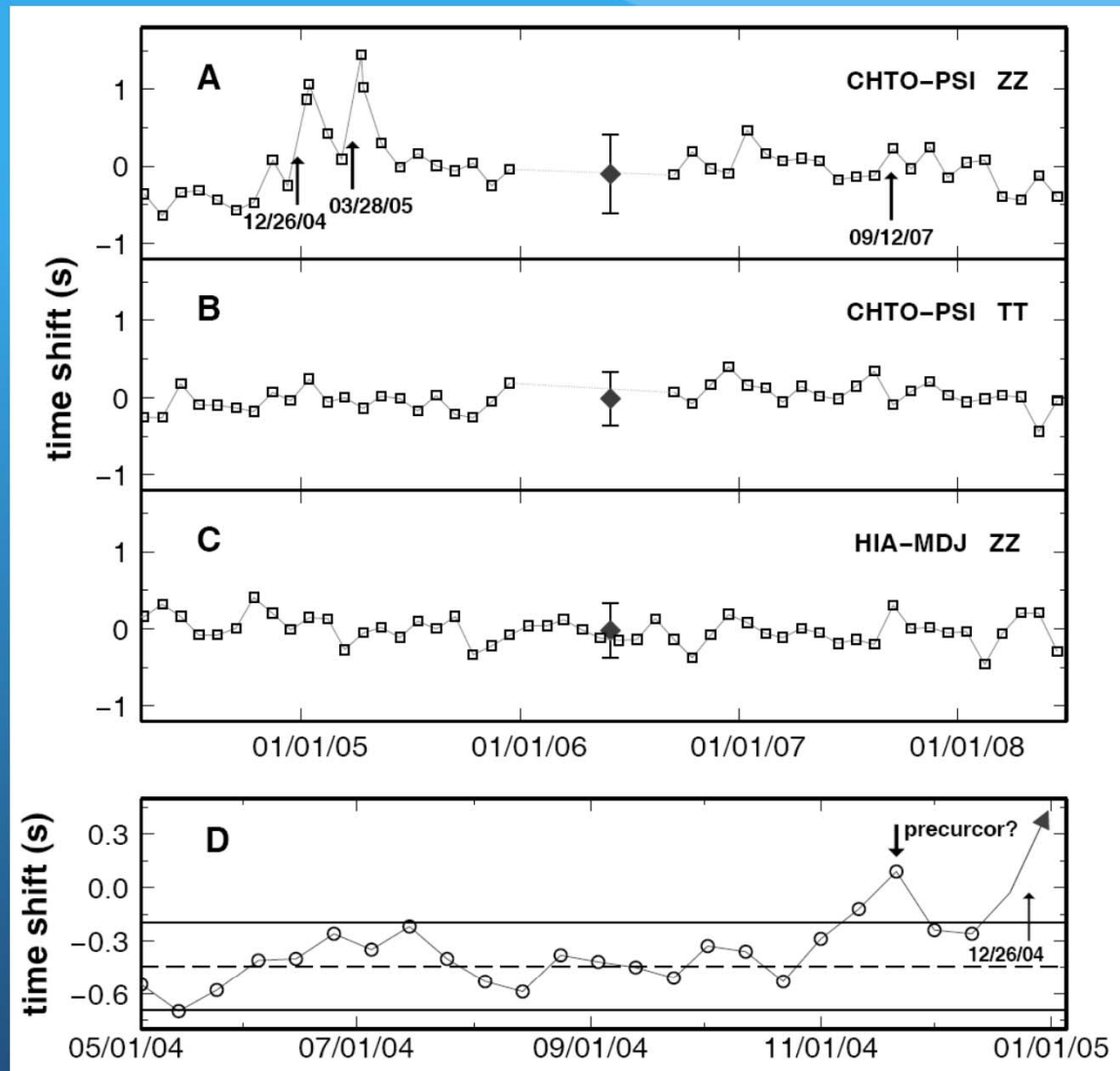
2004/12/26 1: 1: 9.0, 3.09
94.26 28.6, $M_w = 9.0$

2005/ 3/28 16:10:31.5, 1.67
97.07 25.8, $M_w = 8.6$

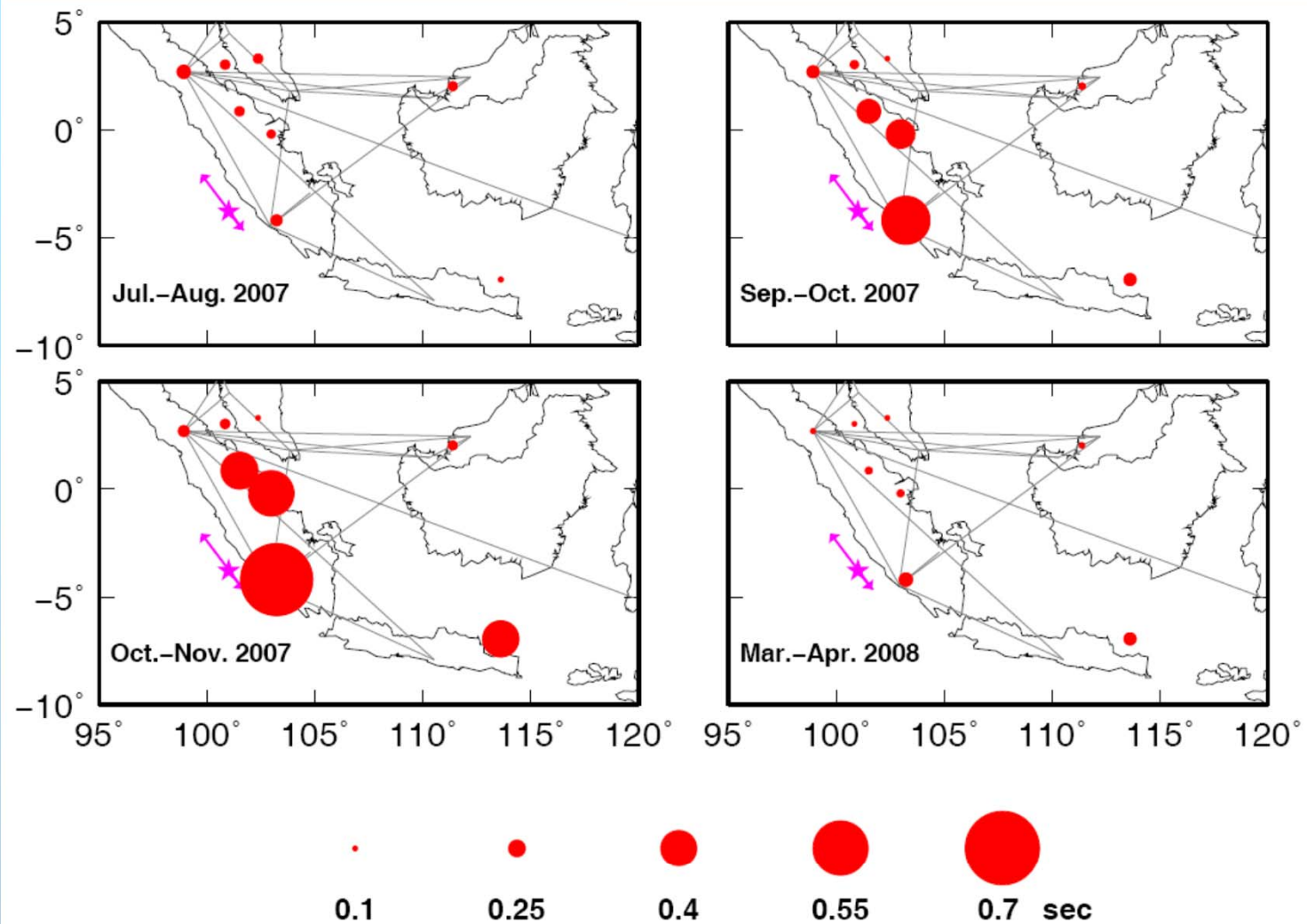
2007/ 9/12 11:11:15.6, -3.78
100.99 24.4, $M_w = 8.5$



Green functions from ambient noise correlation of PSI and CHTO stations (before and after 2004 and 2005 events)



Travel time shifts as a function of time.



Temporal shifts for 2007 event

Precursors before 2004 events?

