Seismology and the Structure of the Earth

Week	Topic
1	Introduction – Networks - Seismicity
2	Elasticity theory
3	The elastic wave equation
4	Exercises
5	Ray theory and seismic tomography
6	Surface waves and free oscillations
7	Structure of the Earth's deep interior
8	Exercises
9	Seismic sources
10	Seismo-tectonics
11	Scattering of seismic waves
12	Exercises
13	Revision

Literature – Text Books

Shearer, Introduction to Seismology, Cambridge University Press, 1990.

Wysession and Stein, An introduction to seismology, earthquakes and earth structure, Blackwell Scientific

Kennett, The Seismic Wavefield, I+II, Cambridge University Press

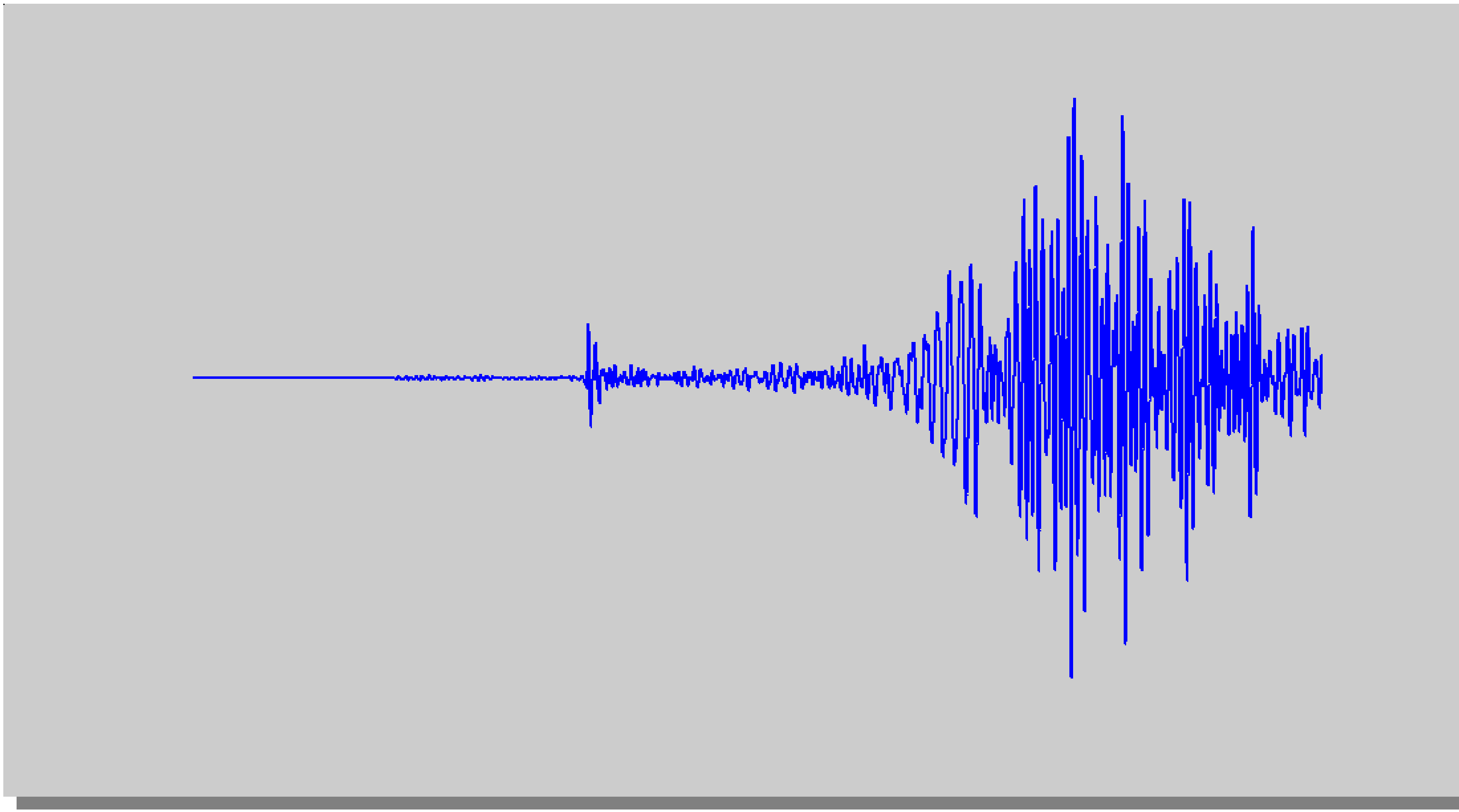
Lay and Wallace, Modern Global Seismology, Academic Press, 1995.

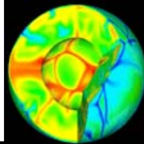
Gubbins, Seismology and Plate Tectonics, Cambridge University Press, 1990.

Aki and Richards, Quantitative Seismology, Academic Press, 2002.

Anderson, Theory of the Earth, Blackwell, 1989.

A seismogram





Short History of Seismology

- Today's seismicity (live!)
- Seismometry
- Seismic networks

Earthquakes around the Globe

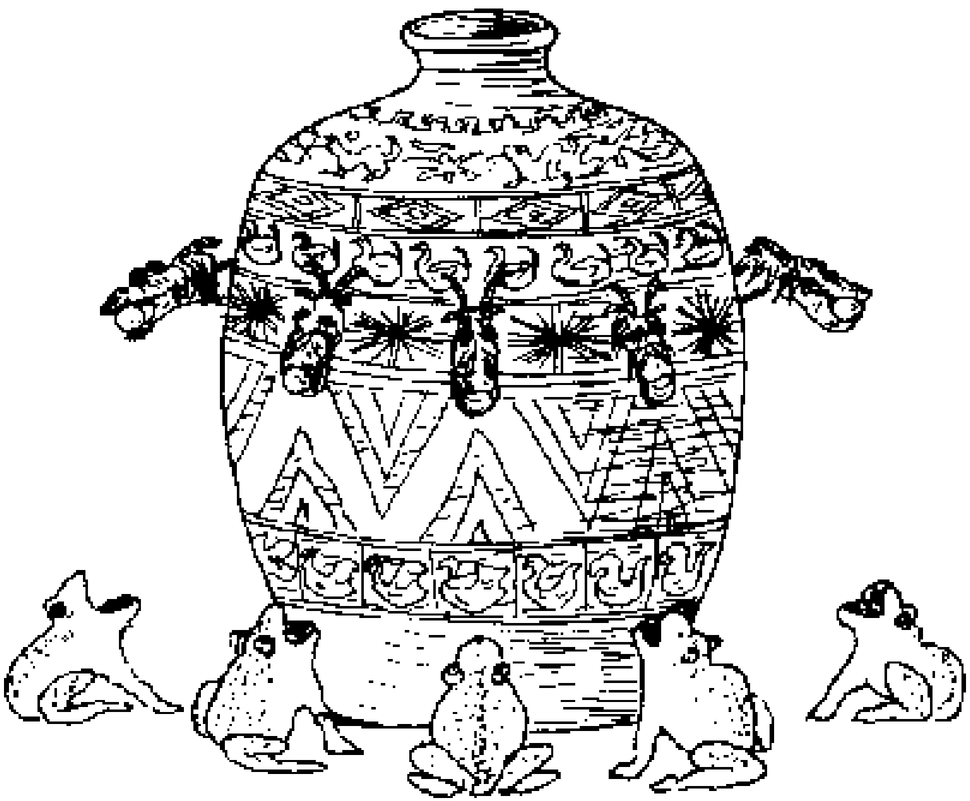
- Distribution of earthquakes
- Major earthquakes this century
- Seismic Sources
- Quantification of earthquakes

The structure of the Earth

- Spherically symmetric structure
- 3-D models (seismic tomography)

History – The first seismometer

Chang Heng's seismometer about 132 a.d.



With this device
it was
even possible to
determine
the direction
seismic waves
where coming
from!

History – milestones

In Europe research in seismology was sparked by two devastating earthquakes in the 18th century:

1755 earthquake in Lissabon, Portugal
32000 killed

1783 earthquake in Calabria, Italy
30000 killed

Experimental seismology	Theoretical seismology
1846 Mallet	1831 Poisson, waves in infinite media
1880 Milne (first real seismograph)	1849 Stokes, P and S waves as dilatation and shear waves
1889 First teleseismic recording (Potsdam)	1885 Rayleigh, waves in half space, surface waves
1884 Intensity scale (Rossi-Forrel)	

History – milestones (cont'd)

1900	Oldham: identification of P, S, and surface waves
1901	Wiechert: first geophysical institute in Göttingen, Germany. Development of seismometers
1903	Foundation of International Seismological Association
1906	San Francisco earthquake: 1000 killed. Galitzin seismograph
1909	Mohorovicic discontinuity (MOHO)
1911	Theory of Love waves Seismological Society of America

History – milestones (cont'd)

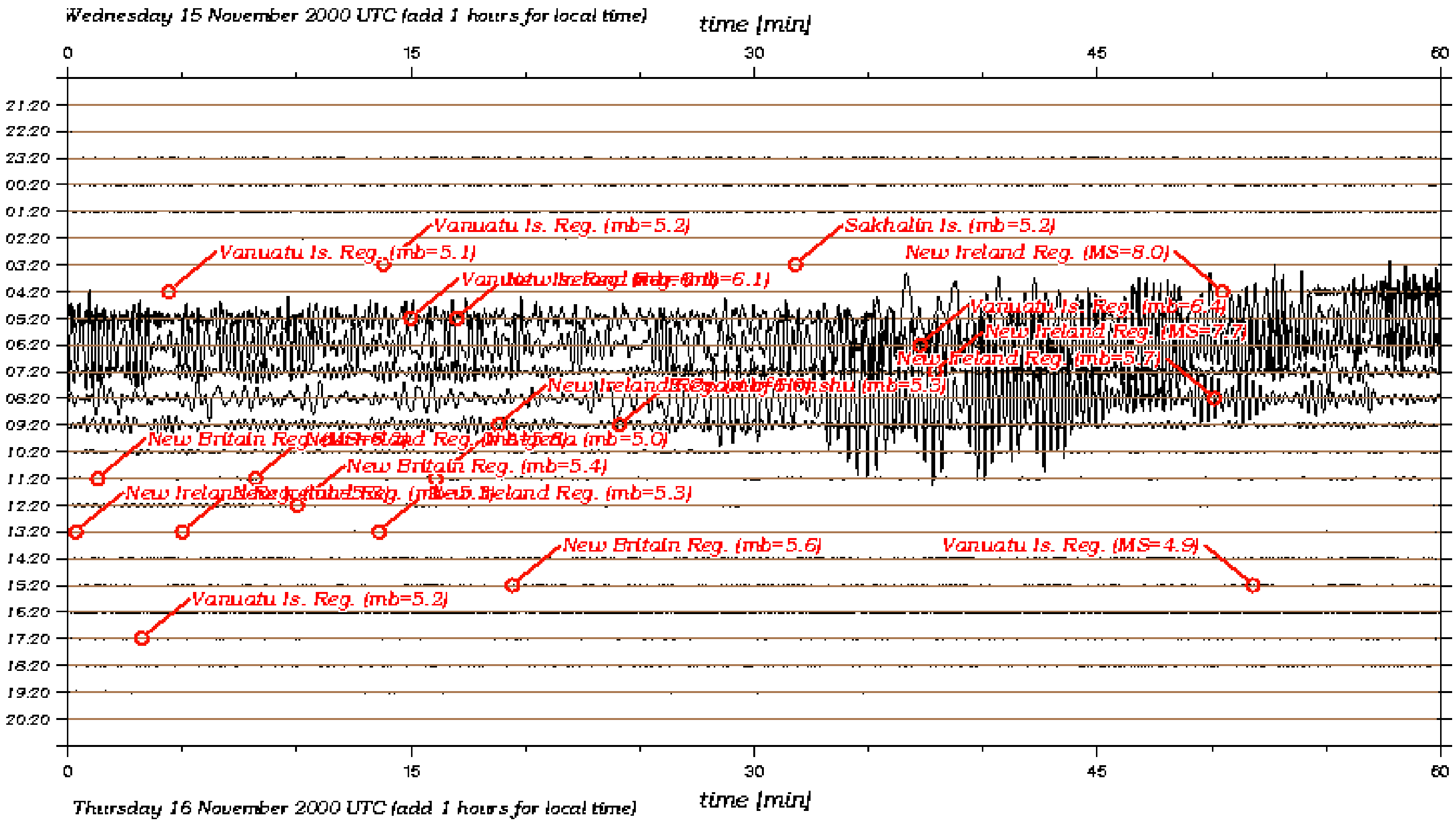
1913	Determination of radius of Earth's core by Benno Gutenberg (Göttingen)
1923	Tokyo earthquake („Great Japanese Quake") 250000 killed, Foundation of Earthquake Research Institute (ERI)
1903	Foundation of International Seismological Association
1931 1932	Benioff Seismometer Strain seismometer
1935 1936	Richter magnitude Discovery of the Earth's inner core by Inge Lehmann (**1888-1993**)
1940	Sir Harrold Jeffreys, Cambridge Traveltime tables. Bullen – density model

History – milestones (after 1950)

1960	Observation of Earth's free oscillations after the 1960 Chile earthquake
1963	Limited Test Ban Treaty, World Wide Standard Seismograph Network (WWSSN)
Late 60s	The concept of plate tectonics is recognized
1981	Preliminary Reference Earth Model (PREM)
Mid 80s	First 3-D tomographic images of mantle heterogeneity
1997	Rotation of the Earth's inner core?

Seismische Beobachtungen in FFB

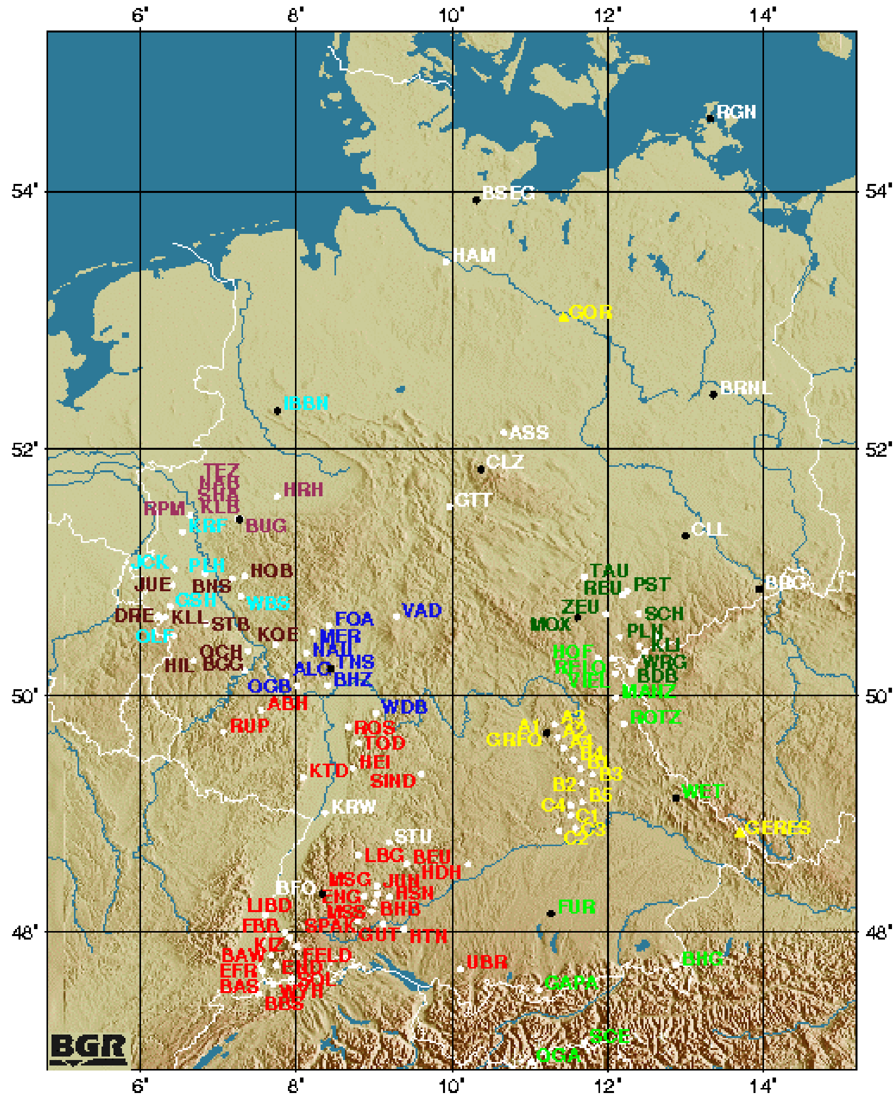
24h Bodenbewegung aufgezeichnet
im Observatorium FFB



Seismometers in Germany

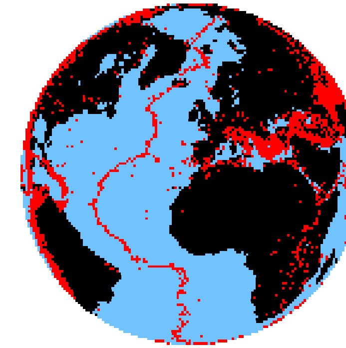
Distribution of seismometers in Germany (from BGR Hannover)

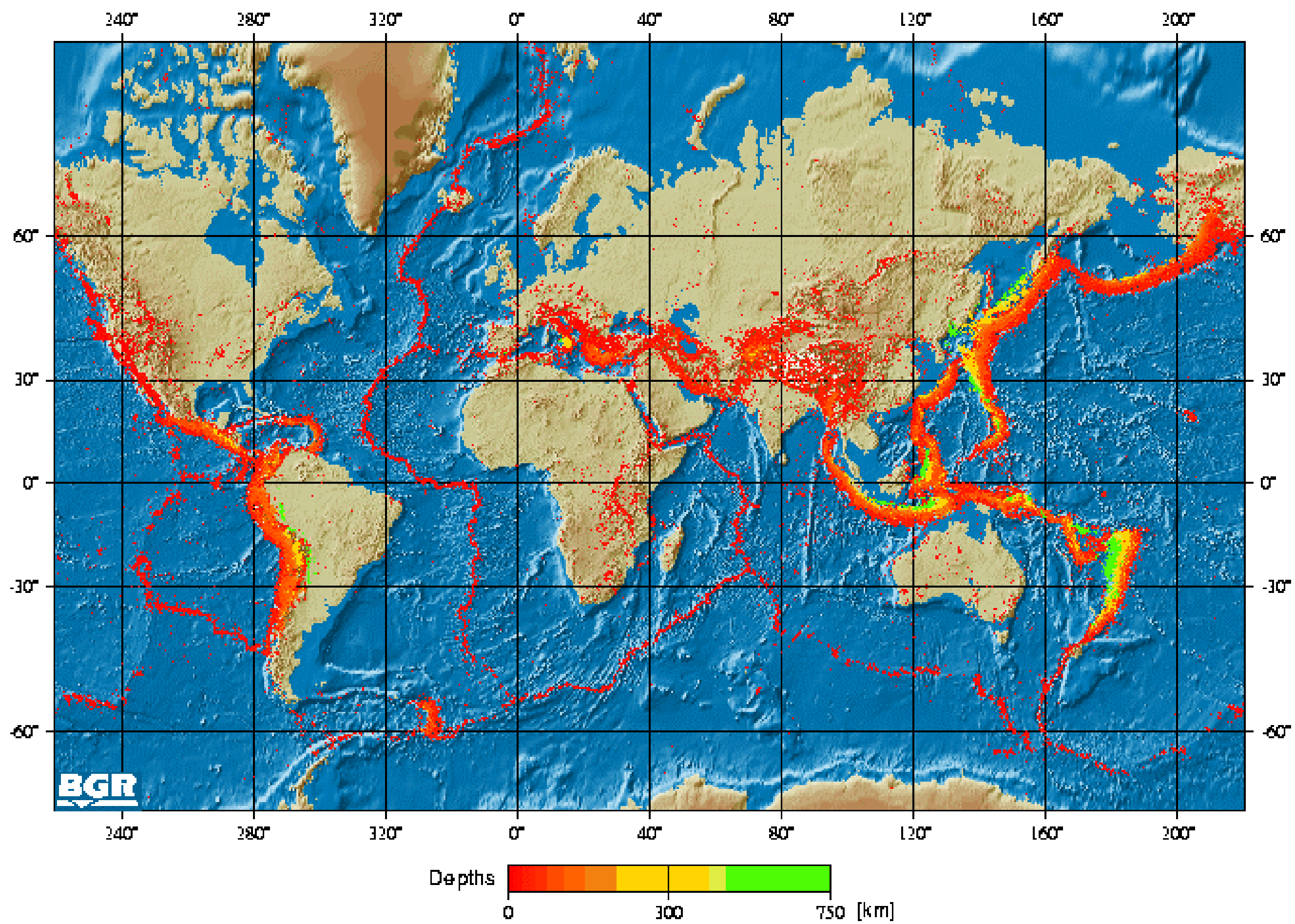
Federal Institute for Geosciences and Natural Resources, Hannover
Institute for Geophysics, Ruhr University, Bochum
Geologisches Landesamt Nordrhein-Westfalen, Krefeld
Institute for Geologie, Cologne University, Cologne
Institute for Geosciences, Friedrich Schiller University, Jena
Institute for Meteorology and Geophysics, Johann Wolfgang Goethe University, Frankfurt am Main
Geophysical Observatory Fuerstenfeldbruck
Landesamt für Geologie, Rohstoffe und Bergbau Baden-Württemberg, Freiburg
● German Regional Seismic Network



Earthquakes around the Globe

- worldwide earthquakes 1954-1998 of magnitude >= 4.0
- NEIC (National Earthquake Information Center)
- more than 240 000 seismic events with magnitude >=4.0

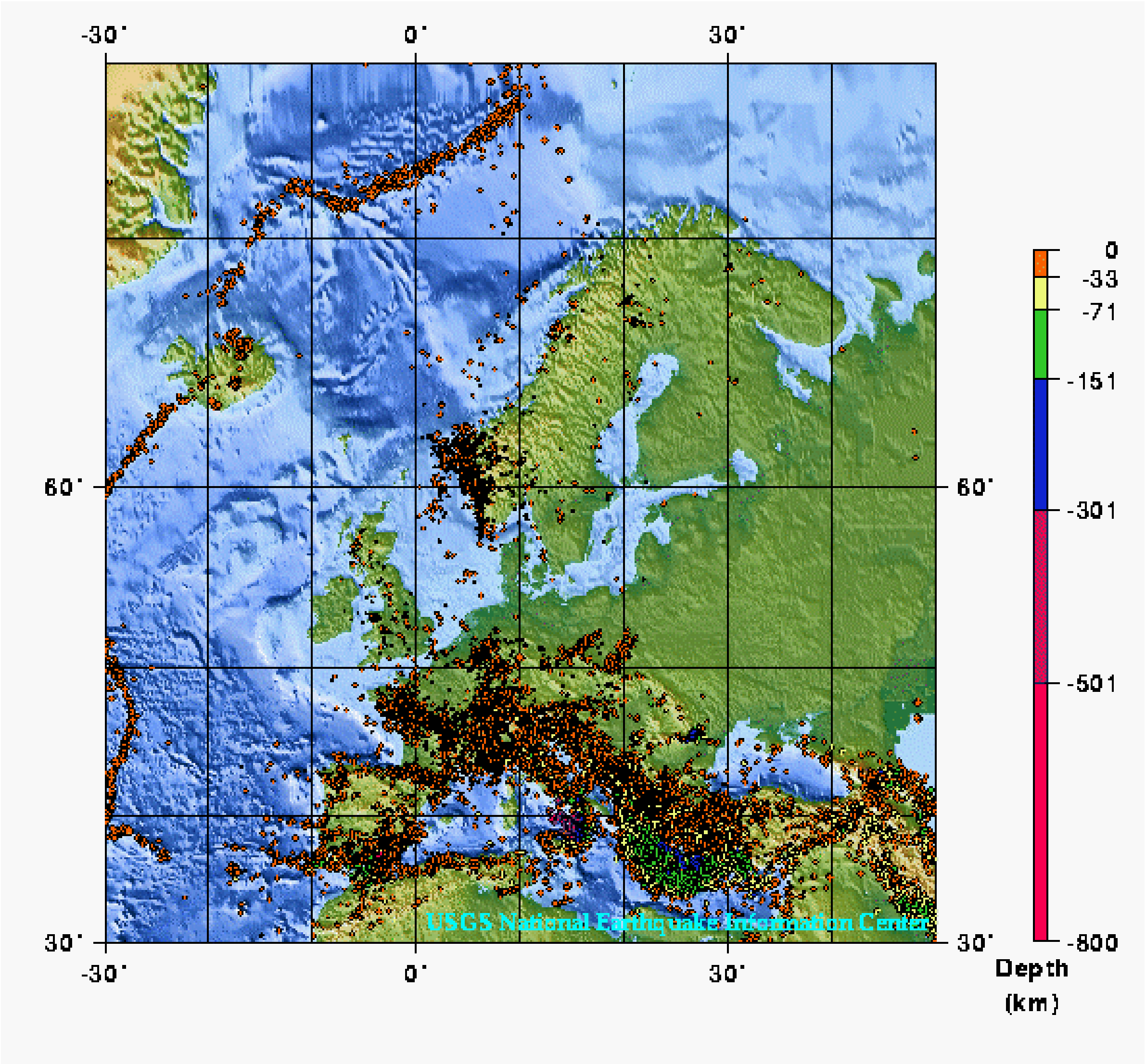




BGR Hannover

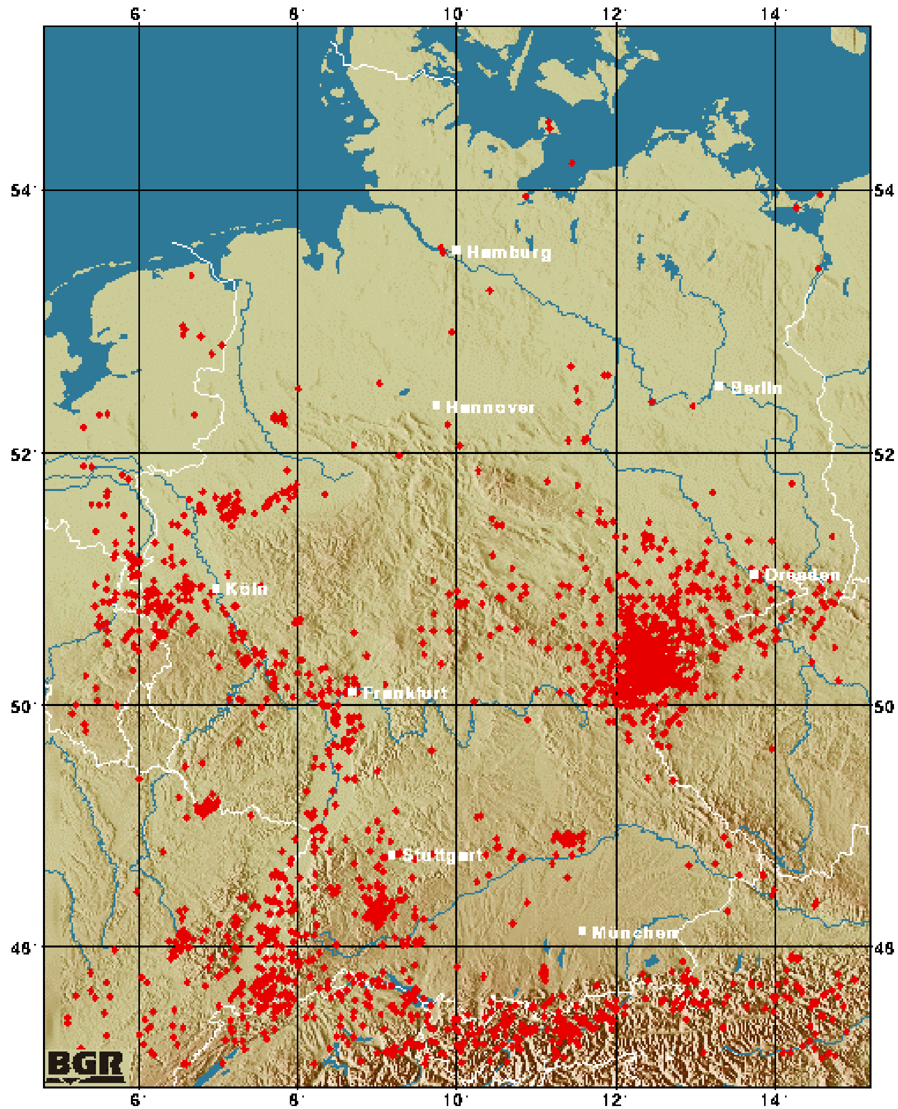
Earthquakes in Europe

Earthquakes in Europe
1975-1995



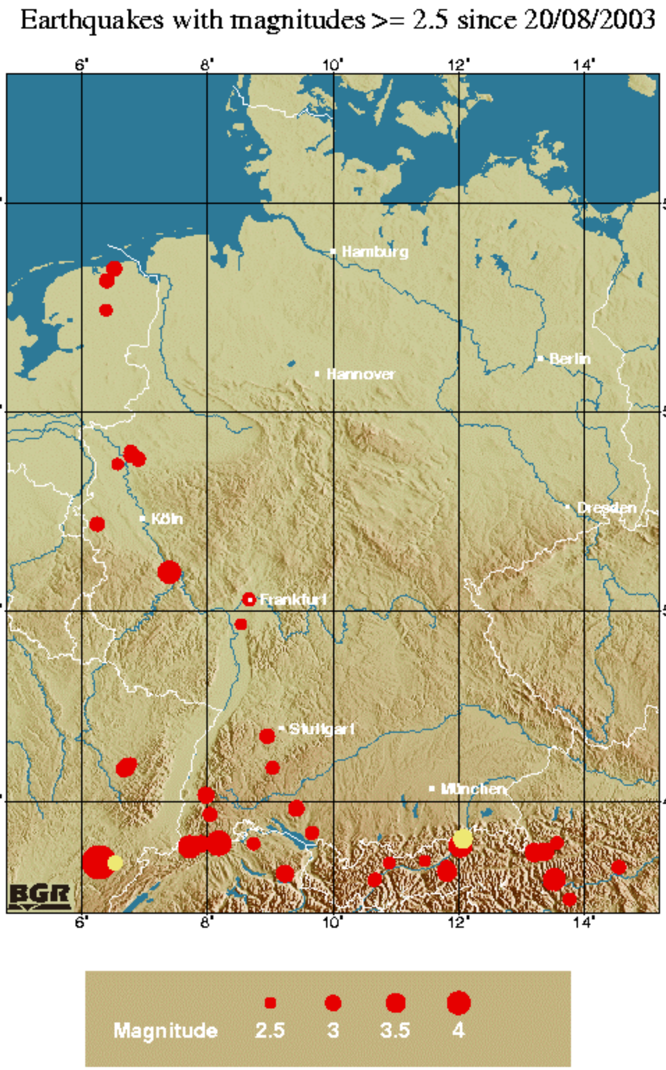
Earthquakes in Germany

Earthquakes in Germany
(historical and measured)
(BGR Hannover)

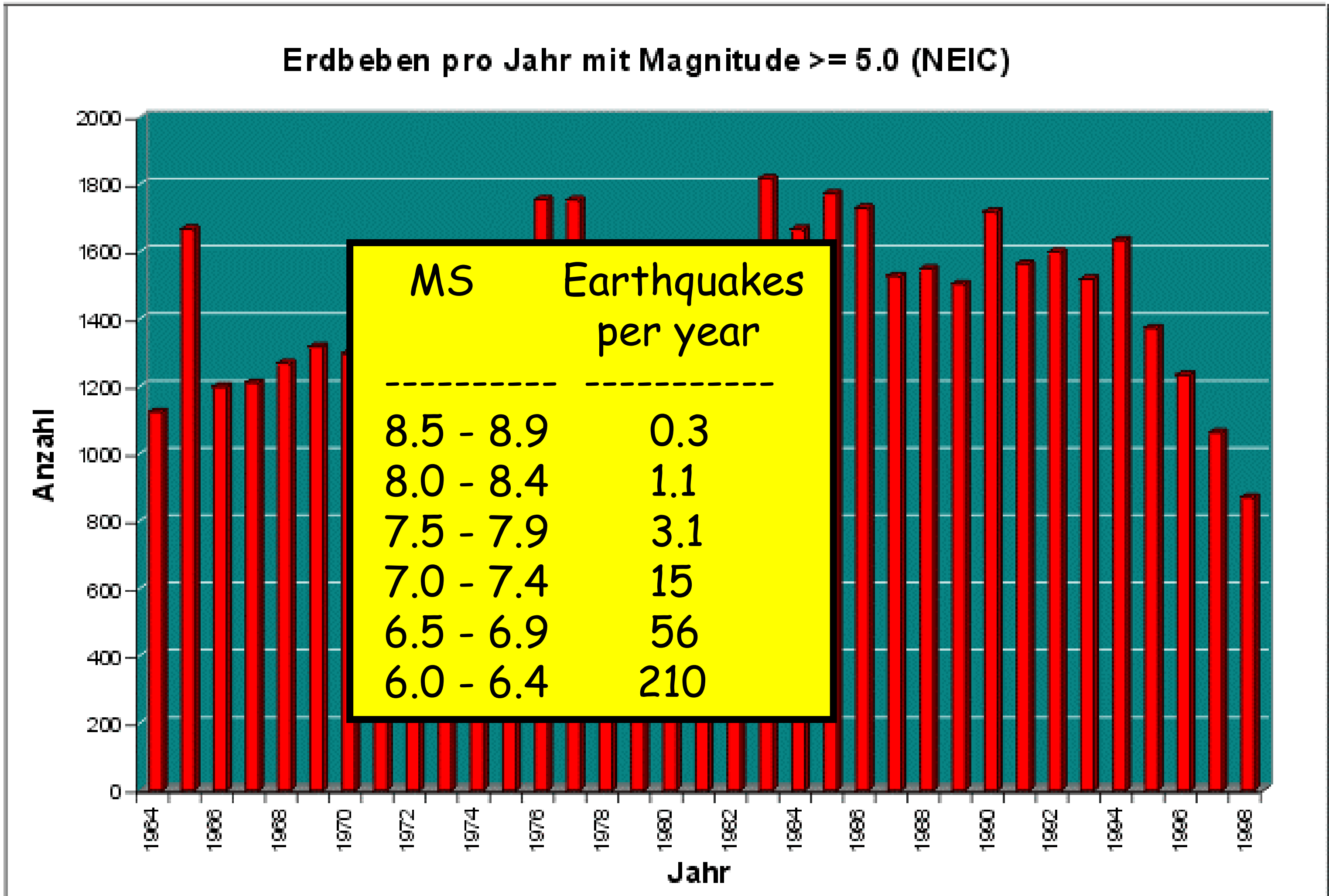


Recent Earthquakes in Germany

Earthquakes in Germany of the last 12 months (BGR Hannover)

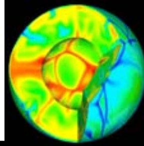


Earthquake Statistics



MS	Earthquakes per year
8.5 - 8.9	0.3
8.0 - 8.4	1.1
7.5 - 7.9	3.1
7.0 - 7.4	15
6.5 - 6.9	56
6.0 - 6.4	210

The Earthquake - Top Ten Chart



1.) Chile 05/22/1960 **9.5 Mw** 38.2 S 72.6 W

2.) Alaska 03/28/1964 **9.2 Mw** 61.1 N 147.5 W

3.) Russia 11/04/1952 **9.0 Mw** 52.75 N 159.5 E

4.) Ecuador 01/31/1906 **8.8 Mw** 1.0 N 81.5 W

5.) Alaska 03/09/1957 **8.8 Mw** 51.3 N 175.8 W

6.) Kuril Islands 11/06/1958 **8.7 Mw** 44.4 N 148.6 E

7.) Alaska 02/04/1965 **8.7 Mw** 51.3 N 178.6 E

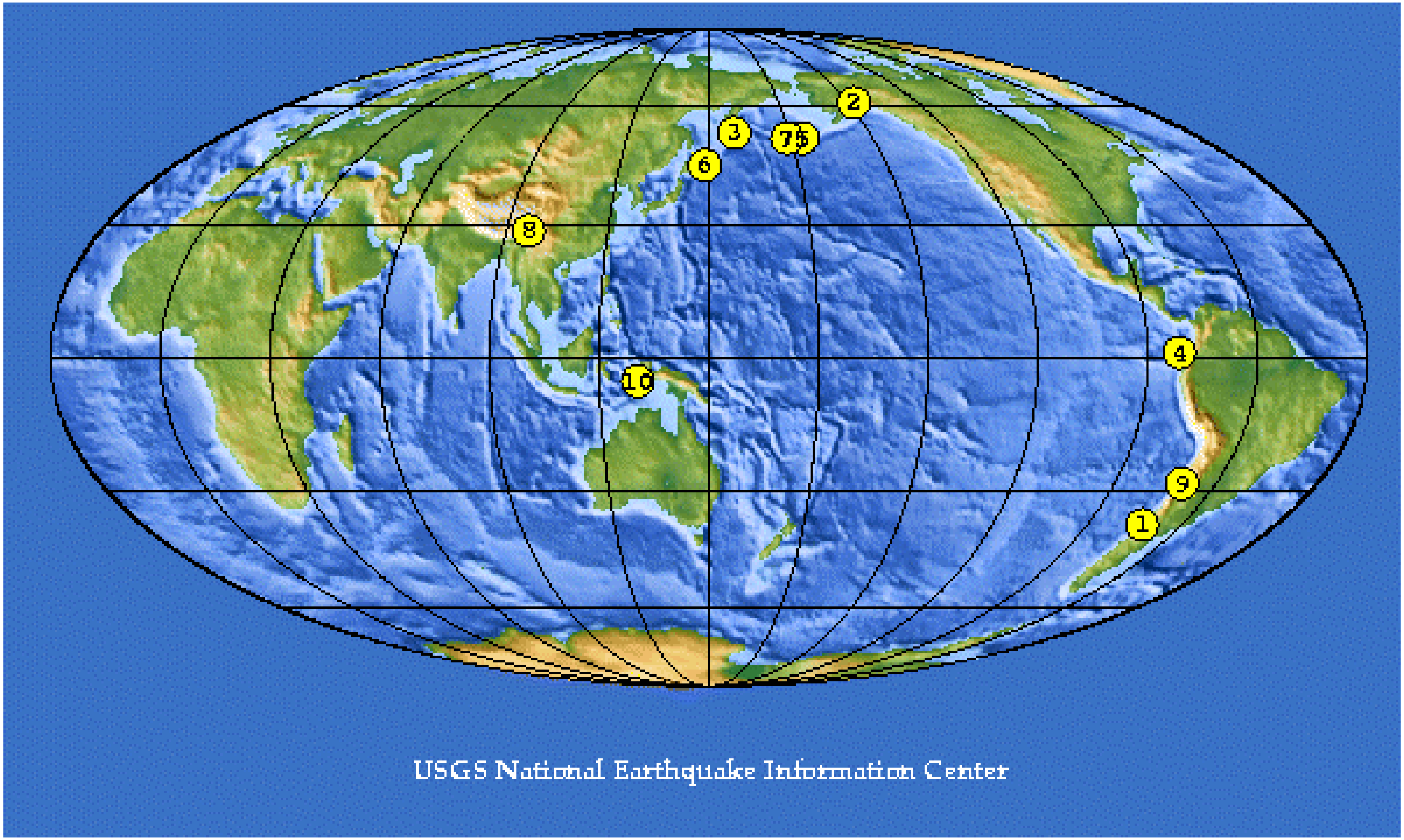
8.) India 08/15/1950 **8.6 Mw** 28.5 N 96.5 E

9.) Argentina 11/11/1922 **8.5 Mw** 28.5 S 70.0 W

10.) Indonesia 02/01/1938 **8.5 Mw** 5.25 S 130.5 E

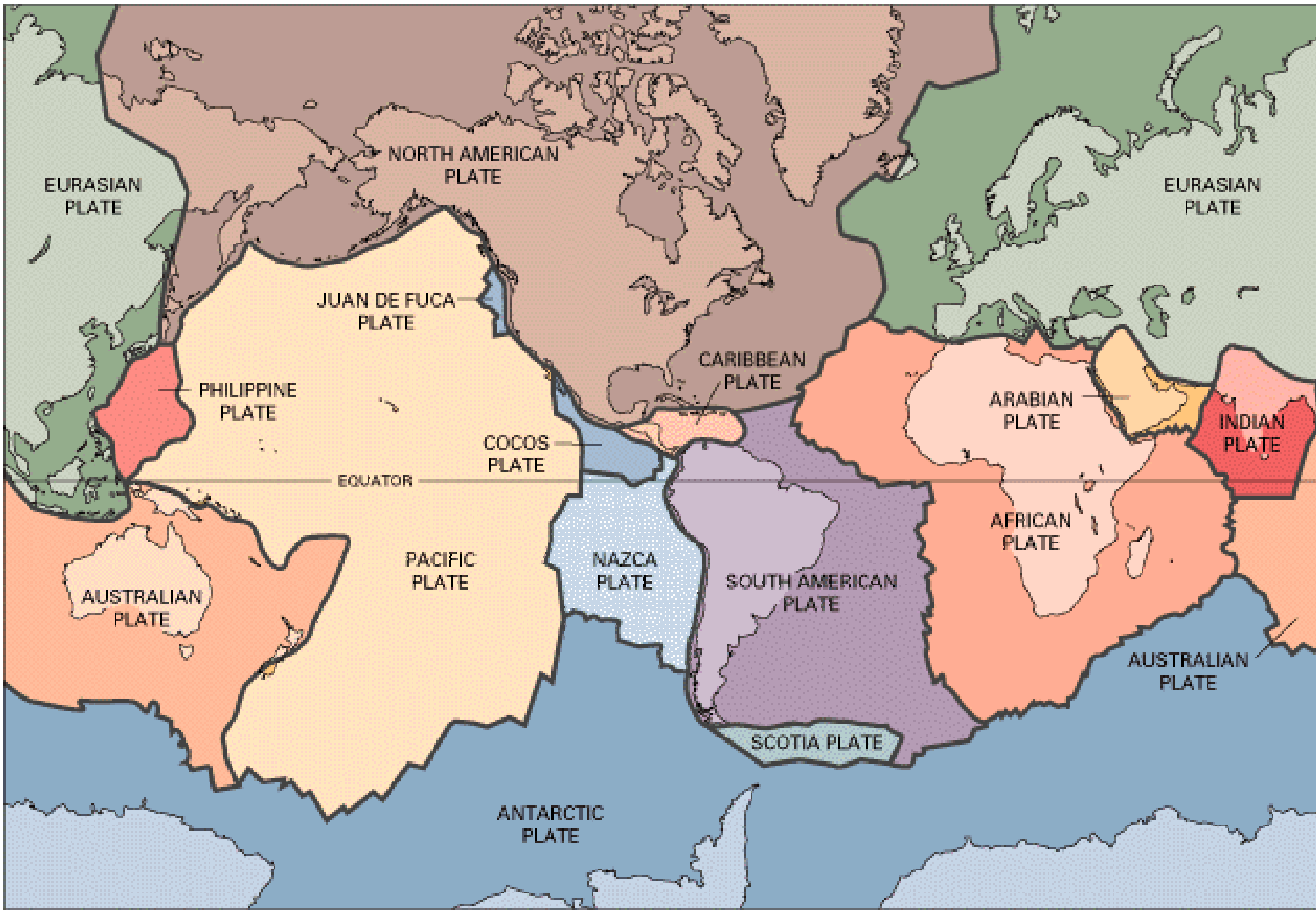
… and the winner is …

The Earthquake - Top Ten - Map



The ten largest earthquakes this century

Tectonic plates on Earth



Reconstructed Plate motions

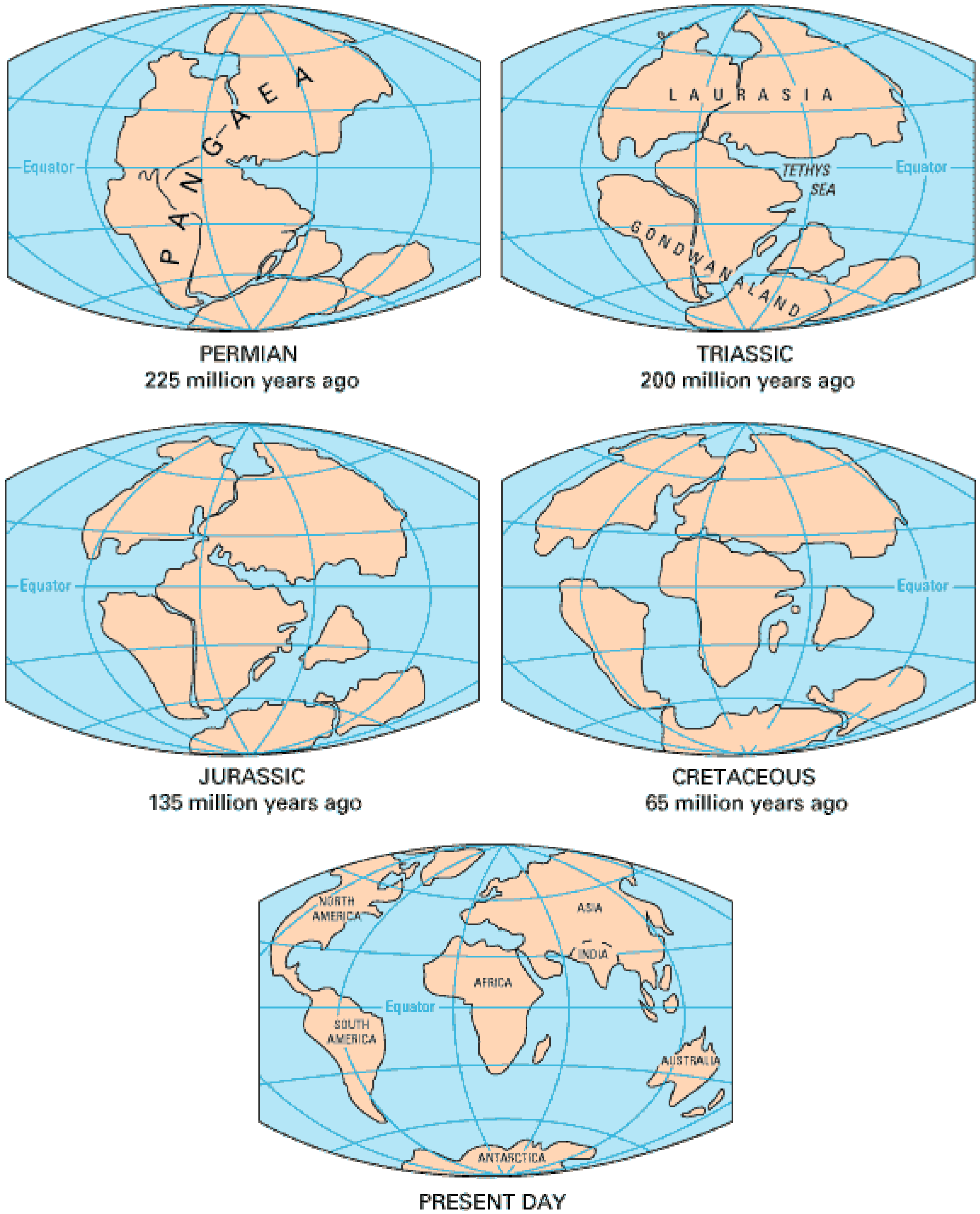
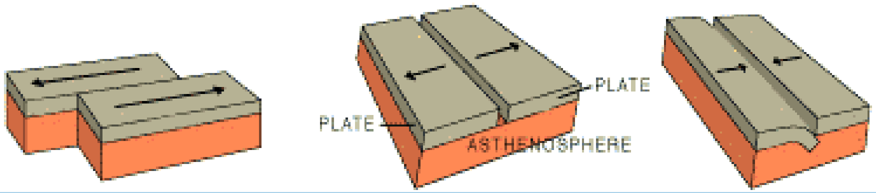


Plate Tectonics - Concepts



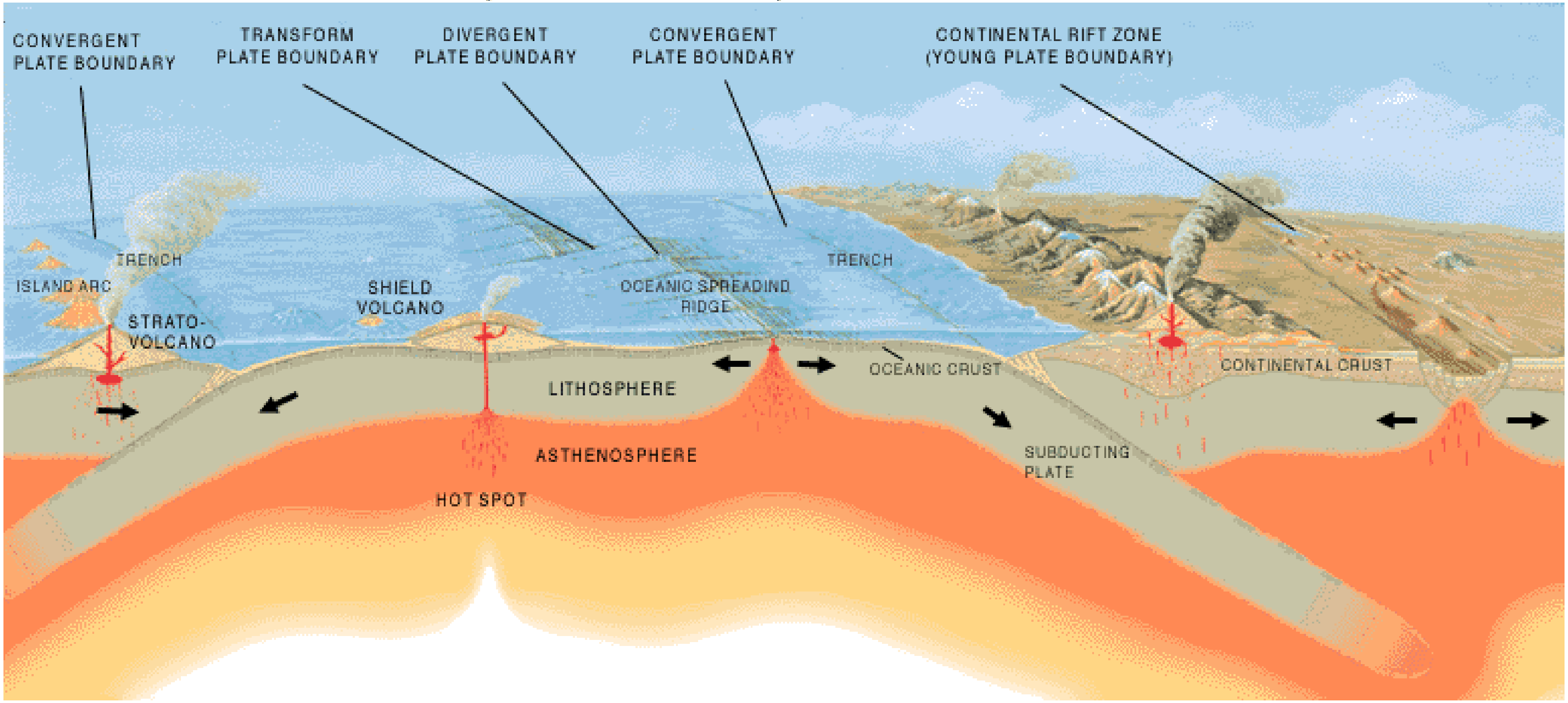
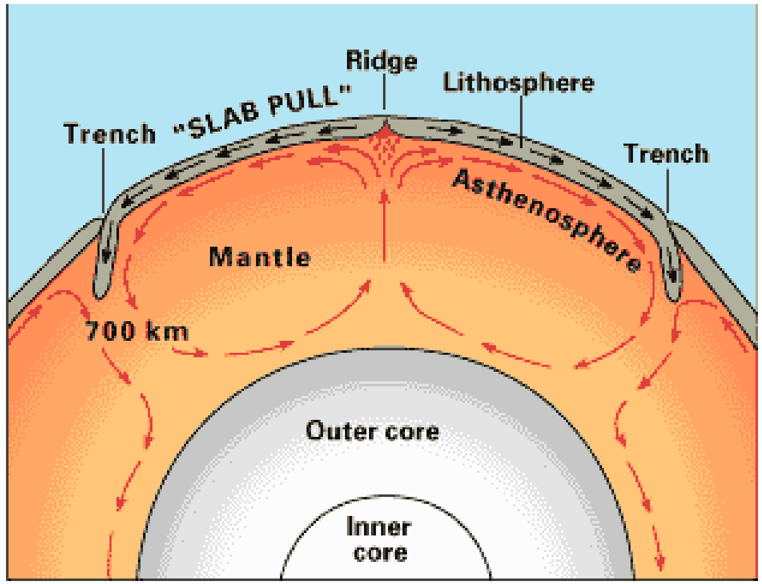


Plate Tectonics – Mantle Convection

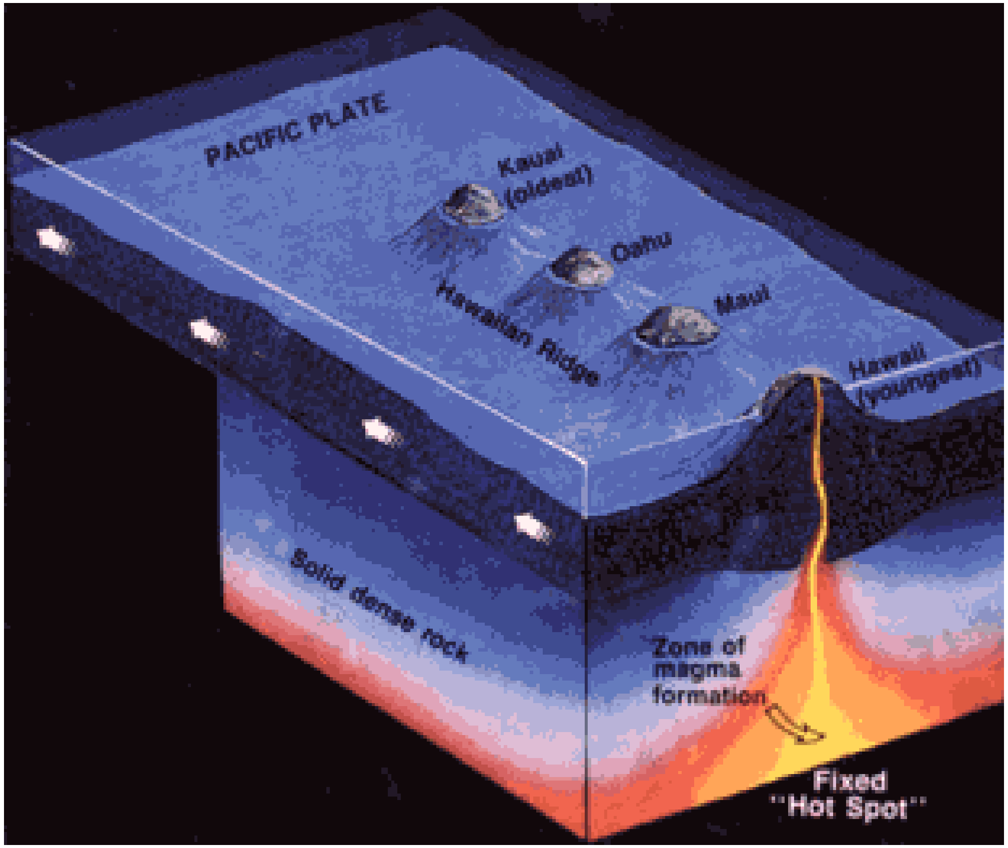


A current issue of debate is whether the Earth's mantle convects as a whole or whether there is layered convection.

Seismology can only provide the present state of the Earth's convective system!

Plate Tectonics – hot spots

Schematic picture
of the Hawaiian island
chain and the underlying
Hot spot.



The origin of hot spots and their mechanism are still poorly understood.

Plate Tectonics – hot spots - global

EXPLANATION

Divergent plate boundaries—Where new crust is generated as the plates pull away from each other.

Convergent plate boundaries—Where crust is consumed in the Earth's interior as one plate dives under another.

Transform plate boundaries—Where crust is neither produced nor destroyed as plates slide horizontally past each other.

Plate boundary zones—Broad belts in which deformation is diffuse and boundaries are not well defined.

Selected prominent hotspots

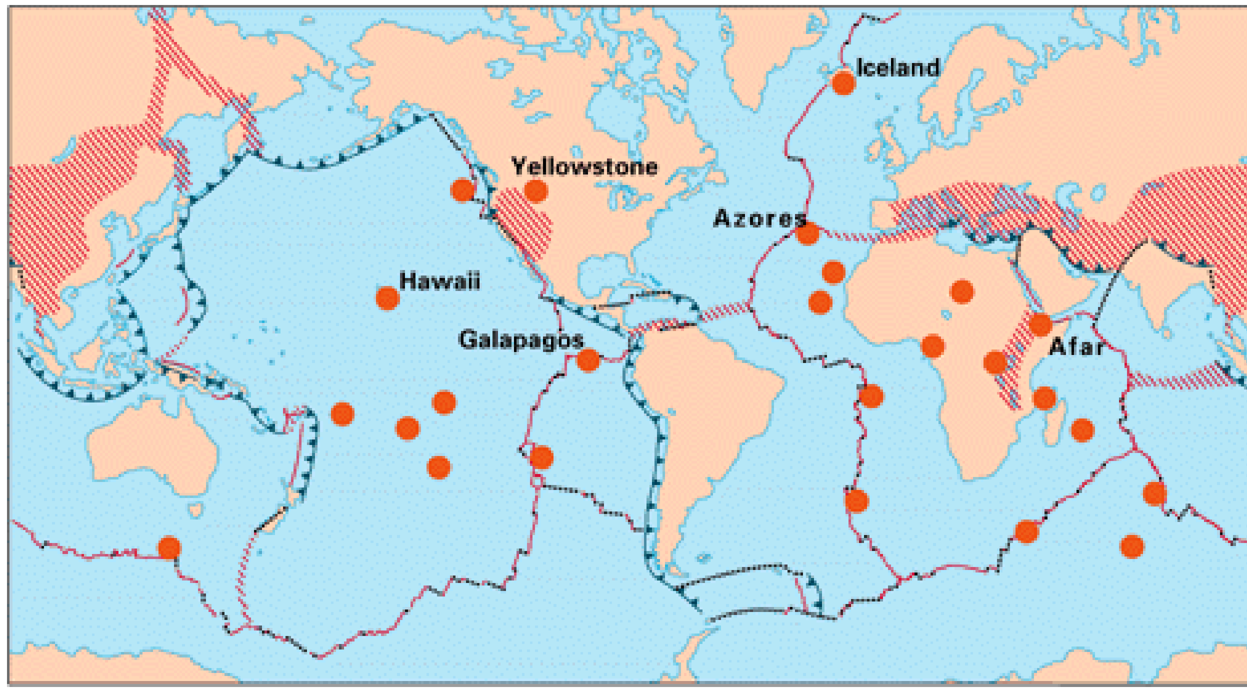
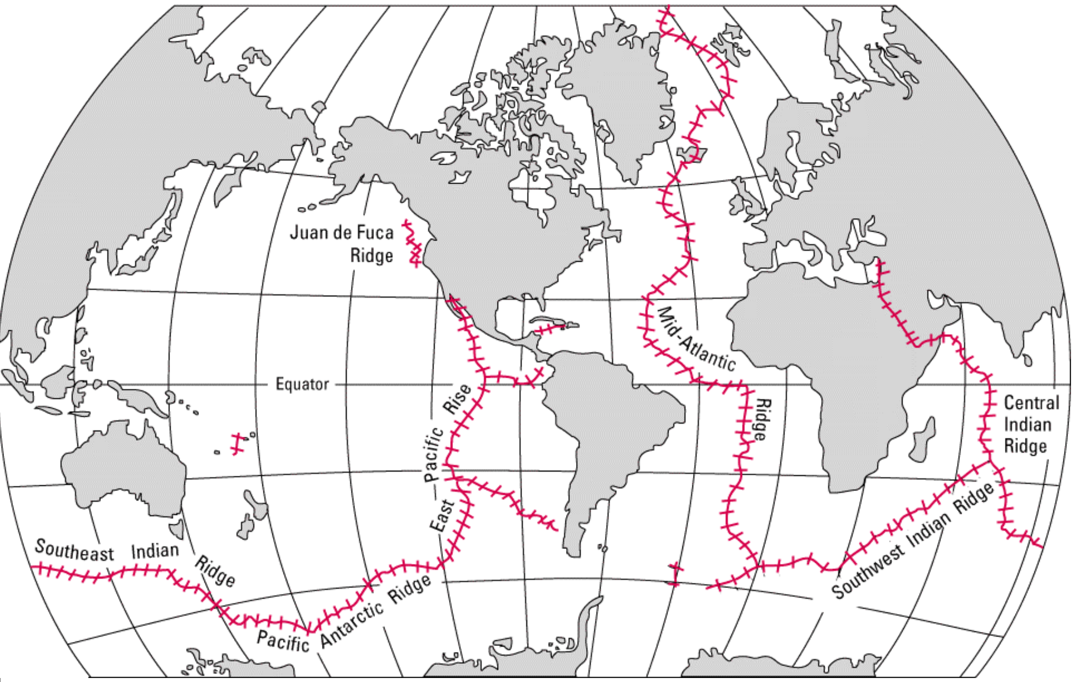


Plate Tectonics – Mid-oceanic ridges

Global ridge system

Topography mid-atlantic ridge



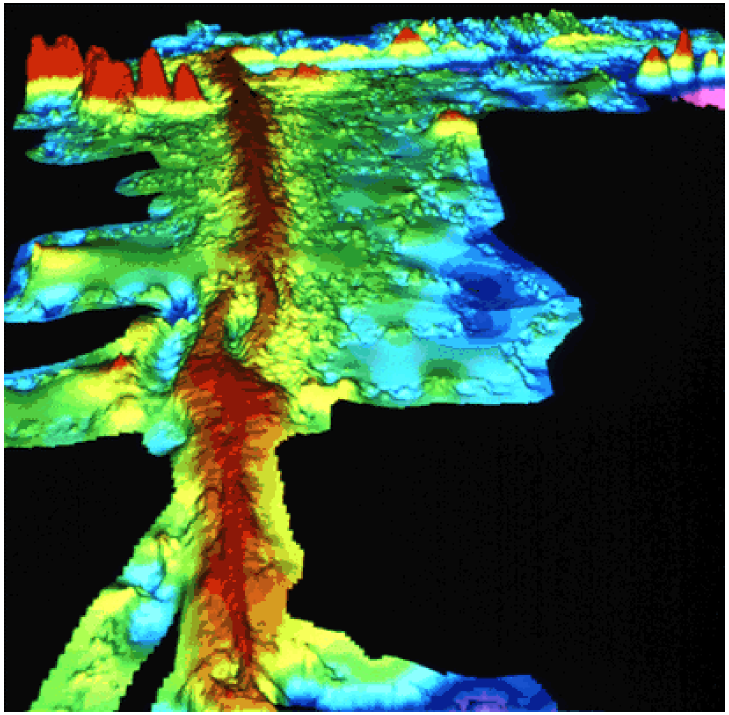
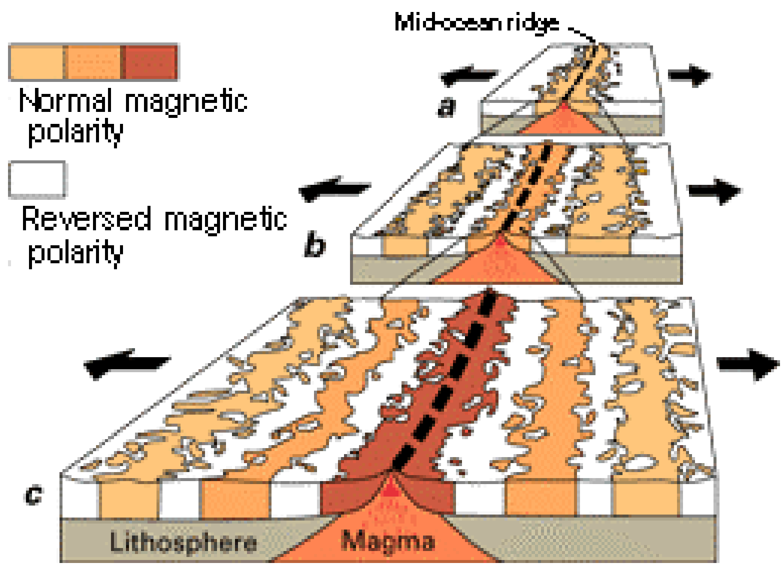


Plate motions are up to 15cm per year

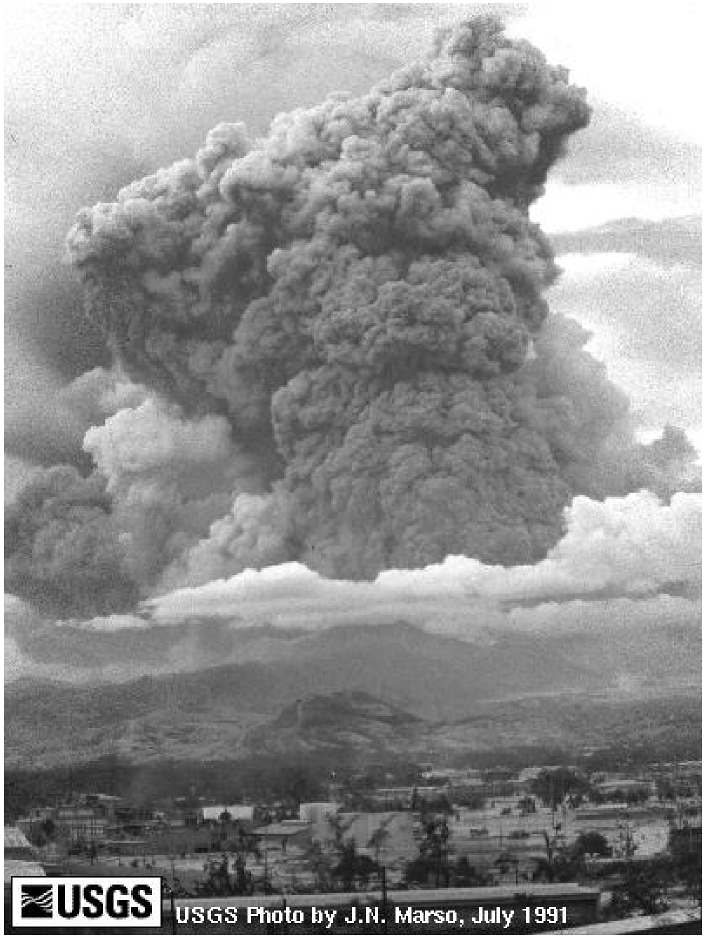
Plate Tectonics - Discovery



The proof of plate tectonics came from the magnetization of the seafloor as a function of distance from the ridge axes.

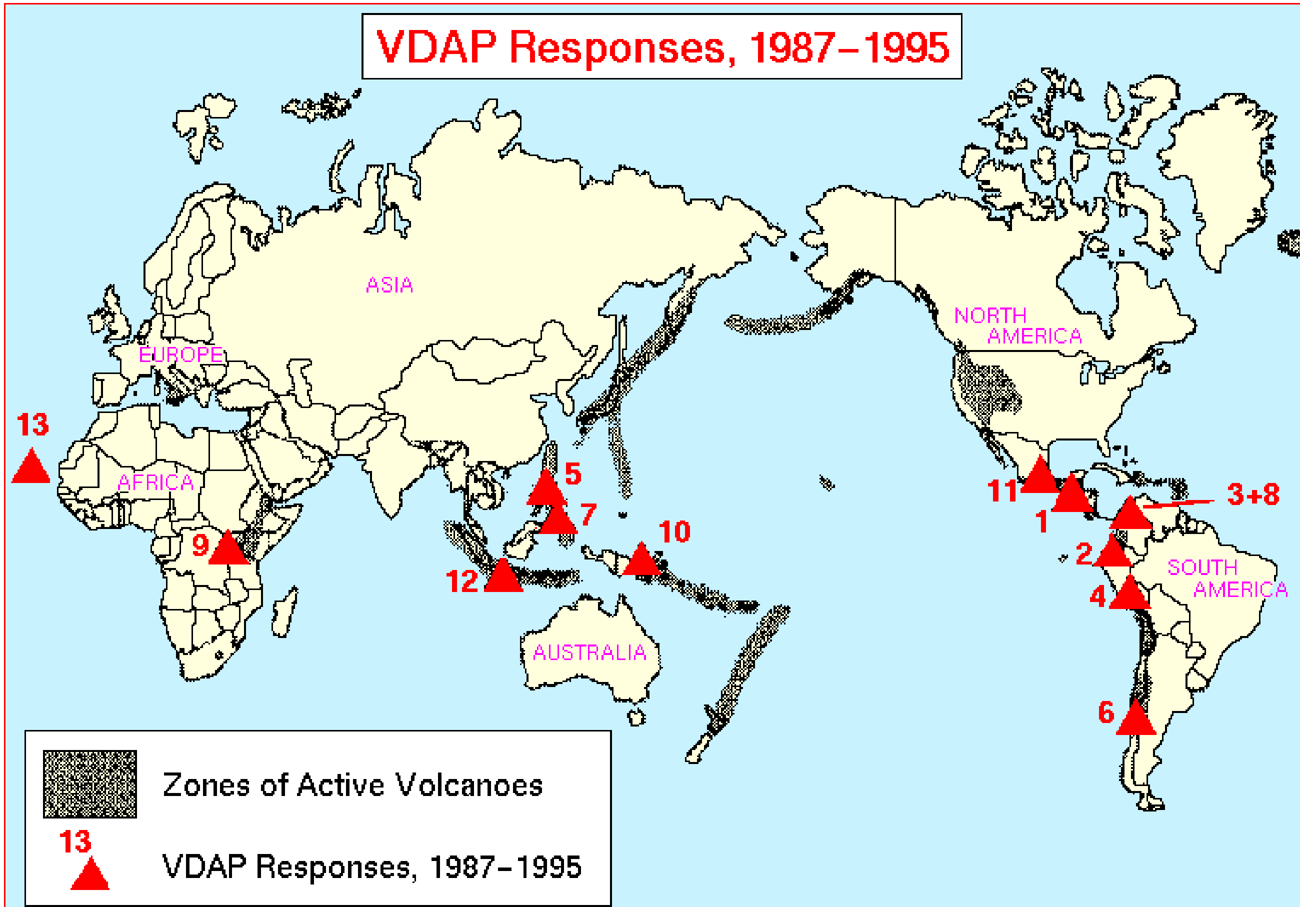
Plate Tectonics – Volcanoes

Pinatubo, 1991



Mount St. Helens, 1980

Plate Tectonics – Volcanoes (cont'd)



1. Pacaya Volcano, Guatemala, 1987
2. Guagua Pichincha Volcano, Ecuador, 1987
3. Galeras Volcano, Colombia, 1989
4. Sabancaya Volcano, Peru, 1990
5. Mount Pinatubo, Philippines, 1991–1994
6. Hudson Volcano, Chile, 1991
7. Mayon Volcano, Philippines, 1993
8. Huila Volcano, Colombia, 1994
9. Nyiragongo and Nyamuragira Volcanoes, Zaire, 1994
10. Rabaul Caldera, Papua New Guinea, 1994
11. Popocatepetl Volcano, Mexico, 1994–1995
12. Merapi Volcano, Indonesia, 1995
13. Fogo Volcano, Caper Verde Islands, 1995

USGS

Topinka, USGS/CVO, 1998, Modified from: Ewert and Miller, 1995, USGS Open-File Report 95-553

Plate Tectonics - Fault Zones

San Andreas Fault

Fault zones in California

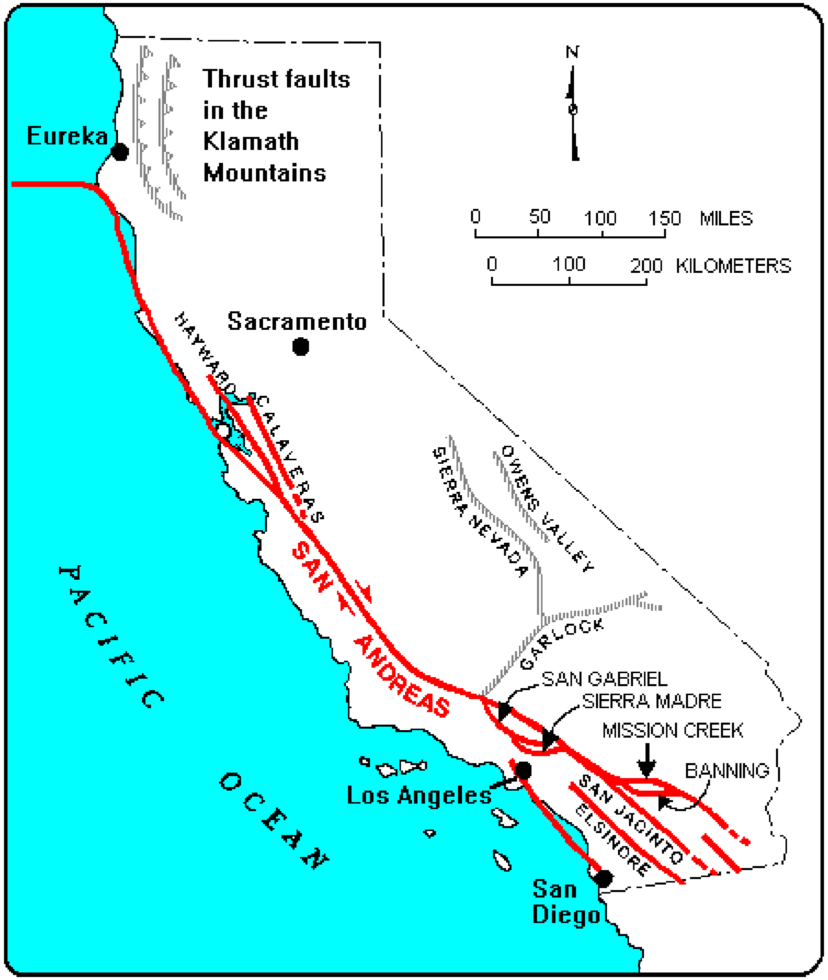


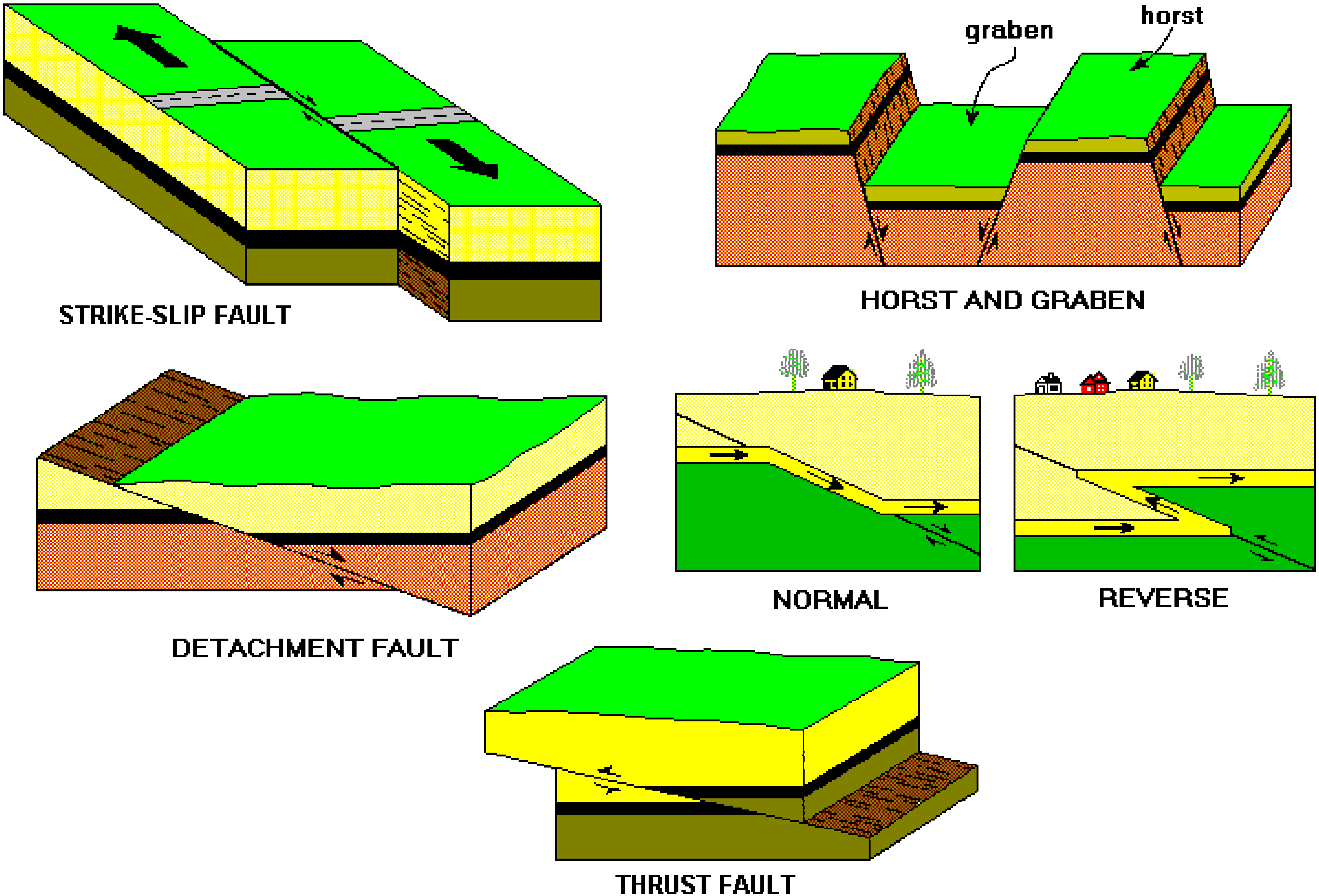
Plate Tectonics – Earthquakes

Earthquake dammage in California

Plate Tectonics – Earthquakes

Seismologist recording aftershocks in California

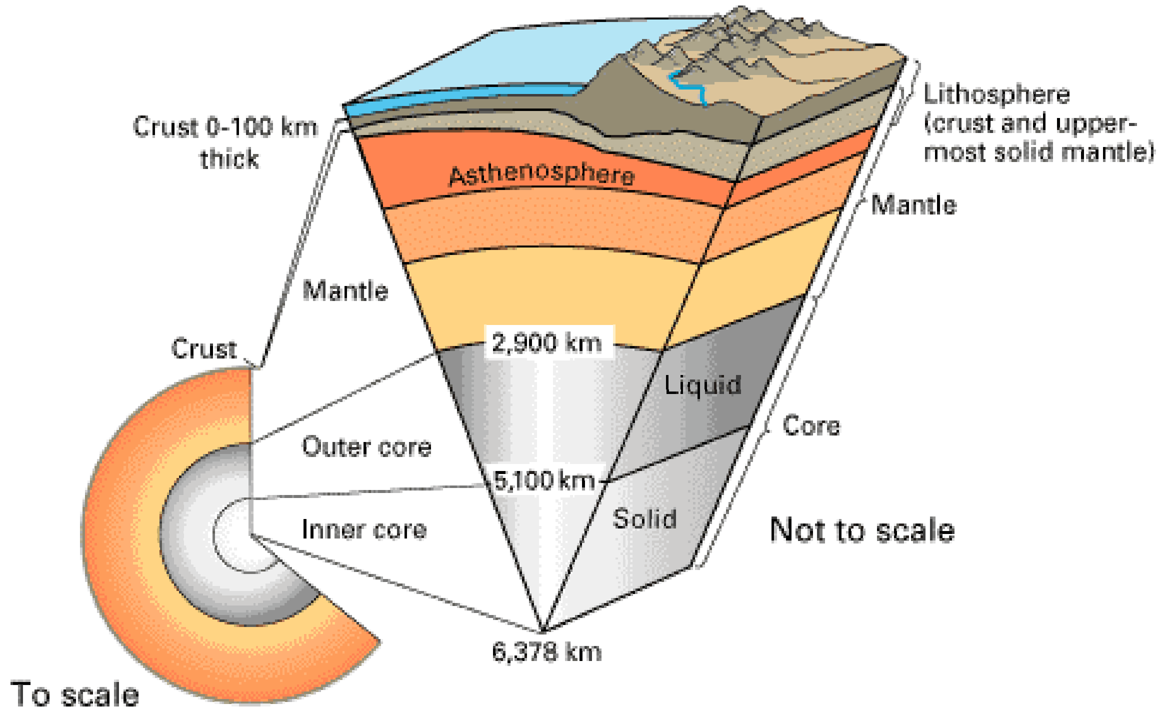
Earthquake sources

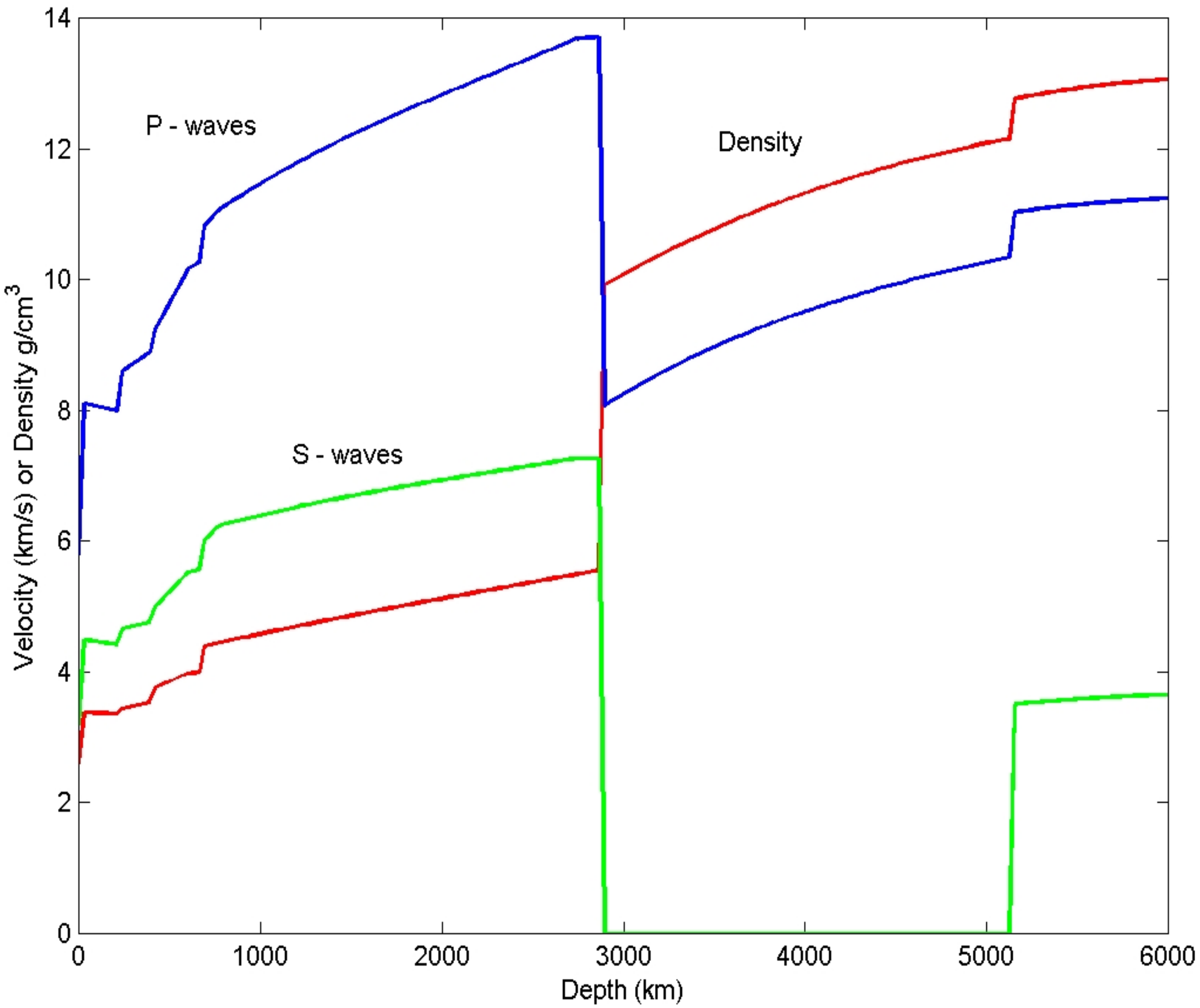


Mercalli Intensity and Richter Magnitude

Magnitude	Intensity	Description
1.0-3.0	I	**I.** Not felt except by a very few under especially favorable conditions.
3.0 - 3.9	II - III	**II.** Felt only by a few persons at rest, especially on upper floors of buildings. **III.** Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations similar to the passing of a truck. Duration estimated.
4.0 - 4.9	IV - V	**IV.** Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably. **V.** Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.
5.0 - 5.9	VI - VII	**VI.** Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight. **VII.** Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.
6.0 - 6.9	VII - IX	**VIII**. Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. **IX.** Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.
7.0 and higher	VIII or higher	**X.** Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent. **XI.** Few, if any (masonry) structures remain standing. Bridges destroyed. Rails bent greatly. **XII.** Damage total. Lines of sight and level are distorted. Objects thrown into the air.

The Earth's Deep Interior



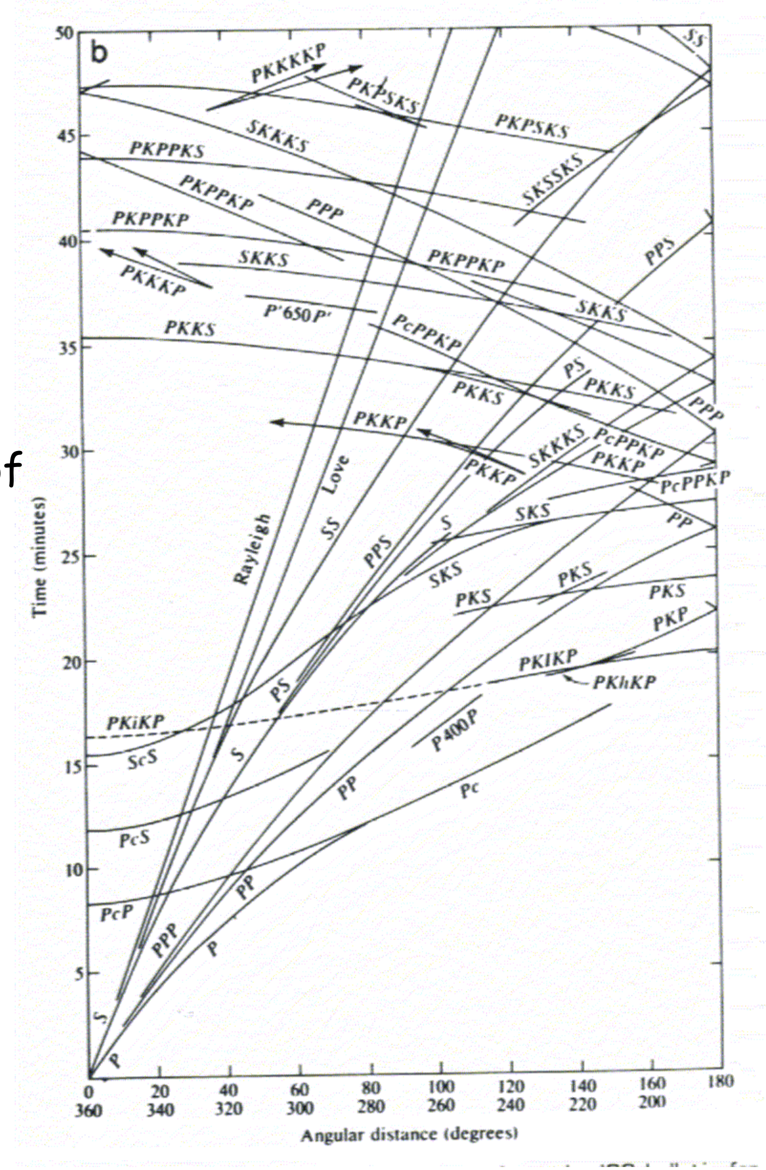


P - waves
Density
S - waves
Velocity (km/s) or Density g/cm3
Depth (km)
0
1000
2000
3000
4000
5000
6000
0
2
4
6
8
10
12
14

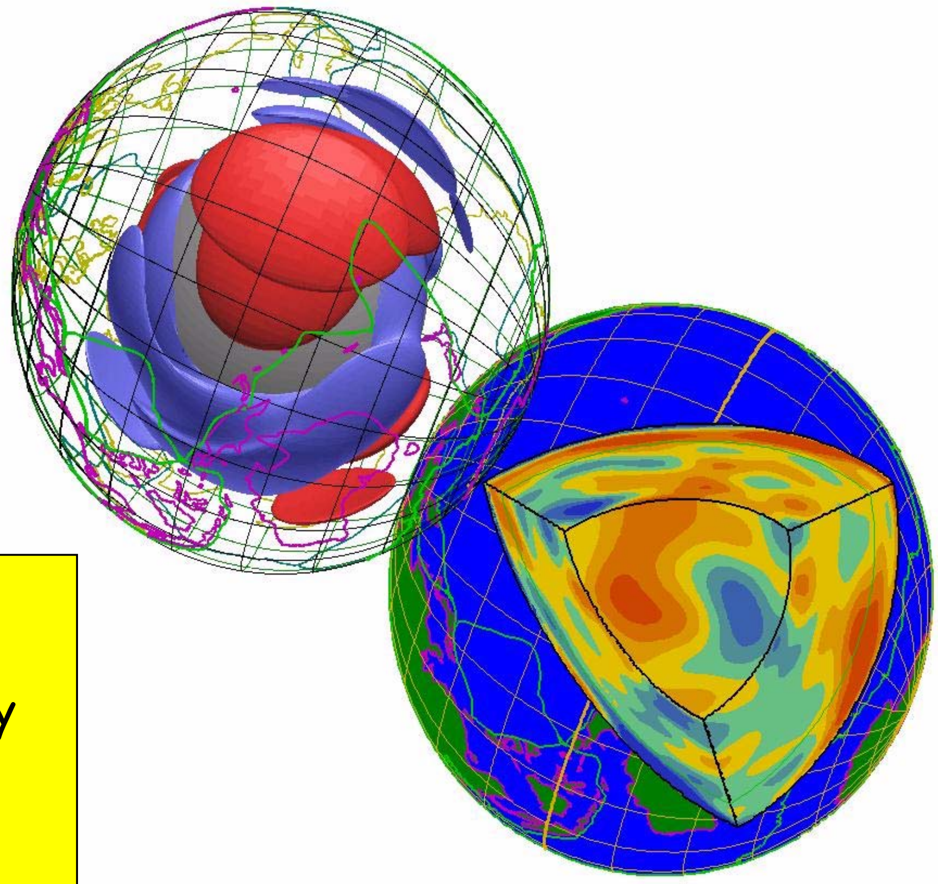
Traveltimes of Teleseismic Phases

The Earth´s deep structure is determined by inverting thousands of seismic travel times

-> **seismic tomography**



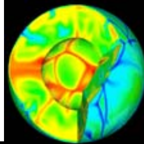
3-D tomography



Maybe the most important goal in global seismology today is to determine the Earth's global 3-D structure with high resolution-

Source: Harvard

Seismology – Schematically



Seismic Source

Ruptures, crack propagation, physics of earthquakes, magnitude, faulting, seismic creep, radiation pattern, Earthquake precursors, aftershocks, fault planes, etc.

Seismometer

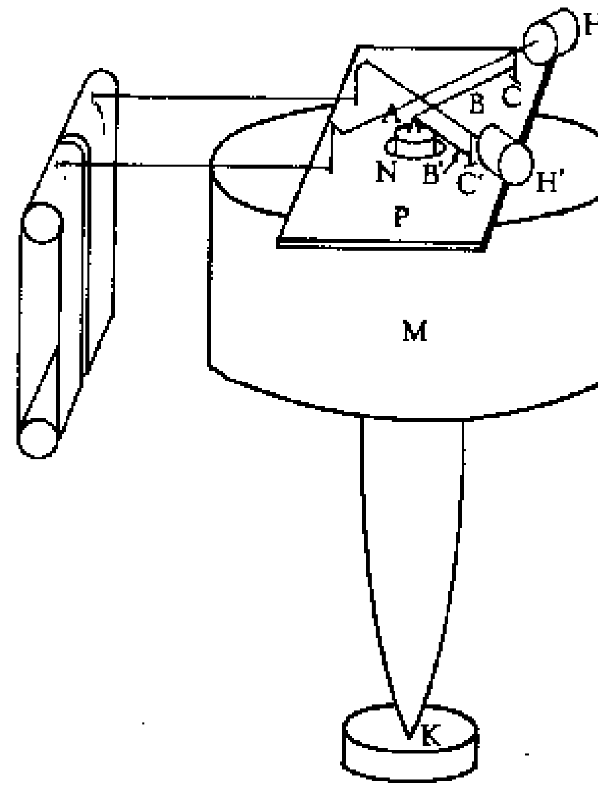
Filtering, (de)convolution, three components, spectrum, broadband, strong-motion, tilt, long-period, amplification, etc.

Propagation Effects

heterogeneities, scattering, attenuation, anisotropy, rays, body waves, surface waves, free oscillations, reflections, refractions, trapped waves, geometrical spreading, etc.

Wiechert Pendulum seismometer

The 1000 kg Wiechert inverted pendulum seismograph (after Wiechert, 1904). The plate P is attached to the frame of the instrument. N is attached to the pendulum mass. The motion of the mass relative to the frame is resolved at A into perpendicular components. Restoring force is applied to the mass M from springs at C, C', by means of the rods B, B'. H, H' are the damping cylinders. The whole inverted pendulum is pivoted at K. In the actual seismometer, the rotation of the pendulum about K takes place in flat springs, which are arranged in a Cardan hinge to permit the pendulum to move in any horizontal direction.



Modern seismometers

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Modern 3-C seismometer

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1889 - The first teleseismic record

This seismogram was recorded in Potsdam in 1889. The seismic waves were generated by an earthquake in Japan.

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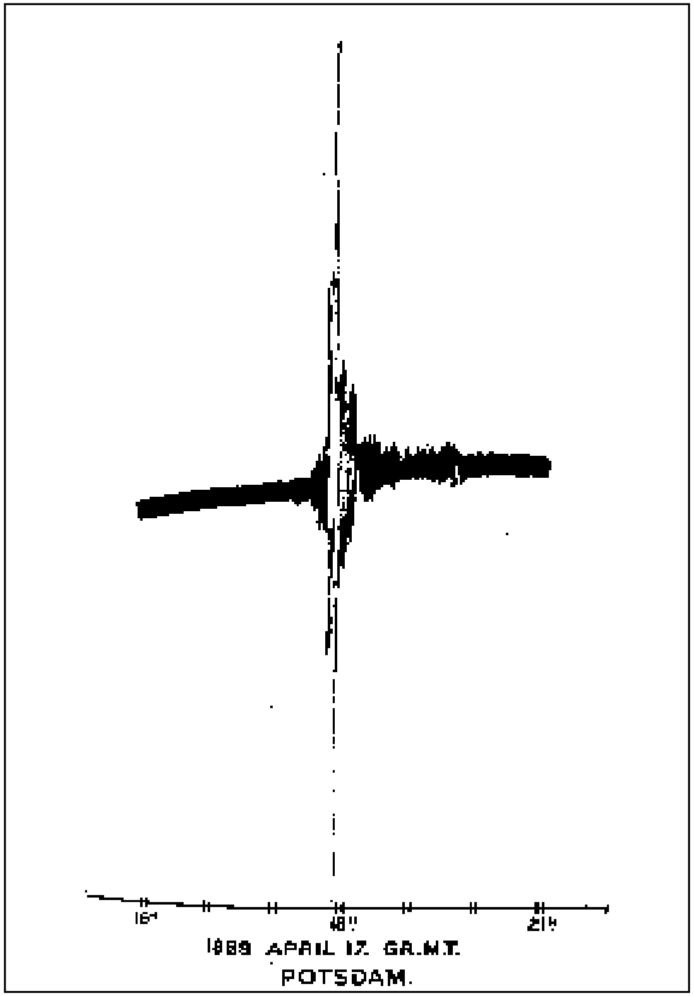

Benno Gutenberg

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Charles Richter

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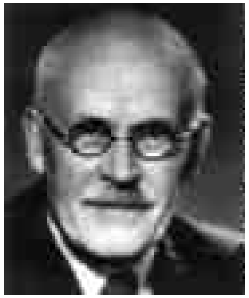
Sir Harold Jeffreys



1891-1989

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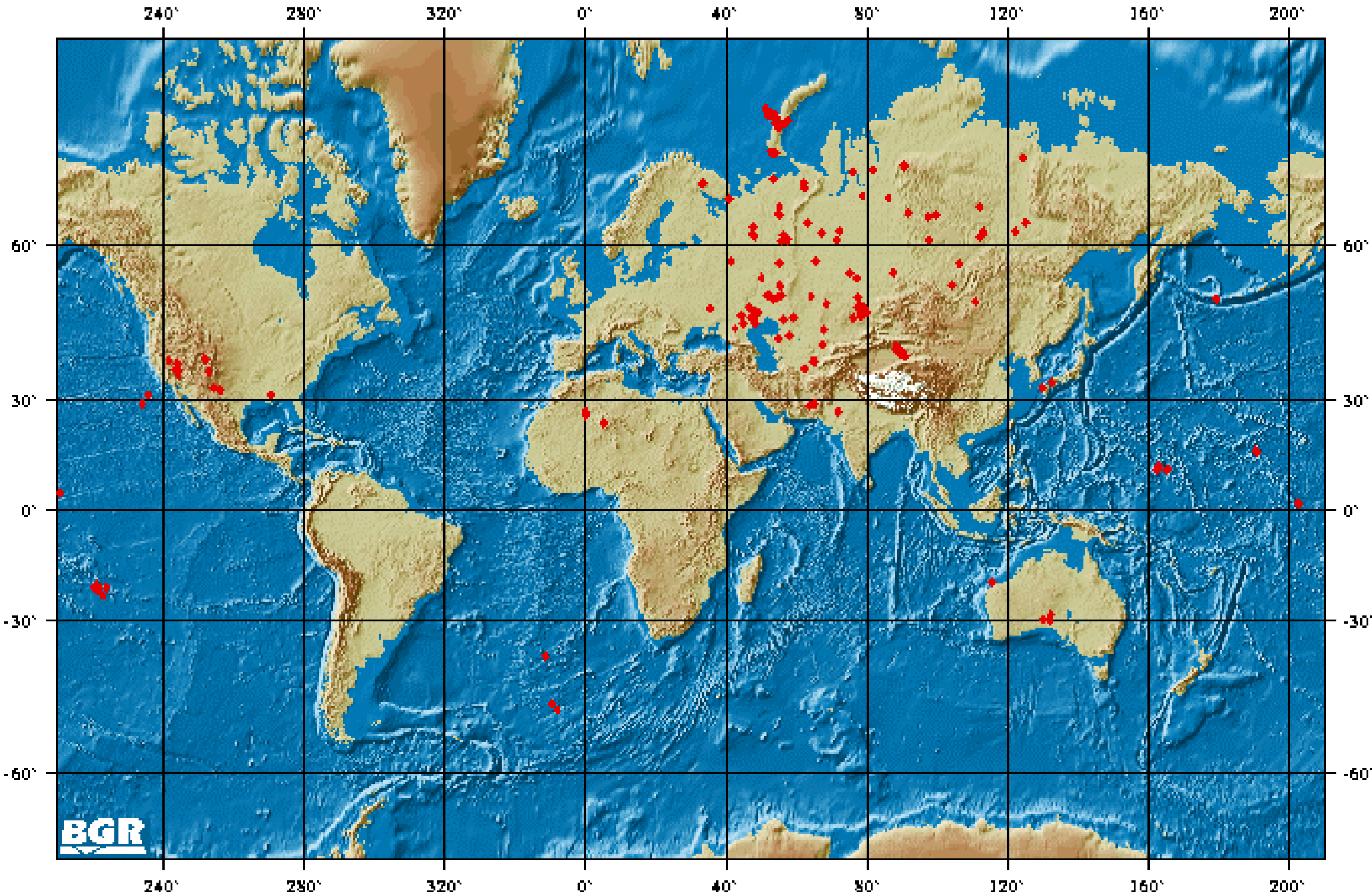
Nuclear Explosions until Today



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BGR Hannover

Alaska 1964 earthquake

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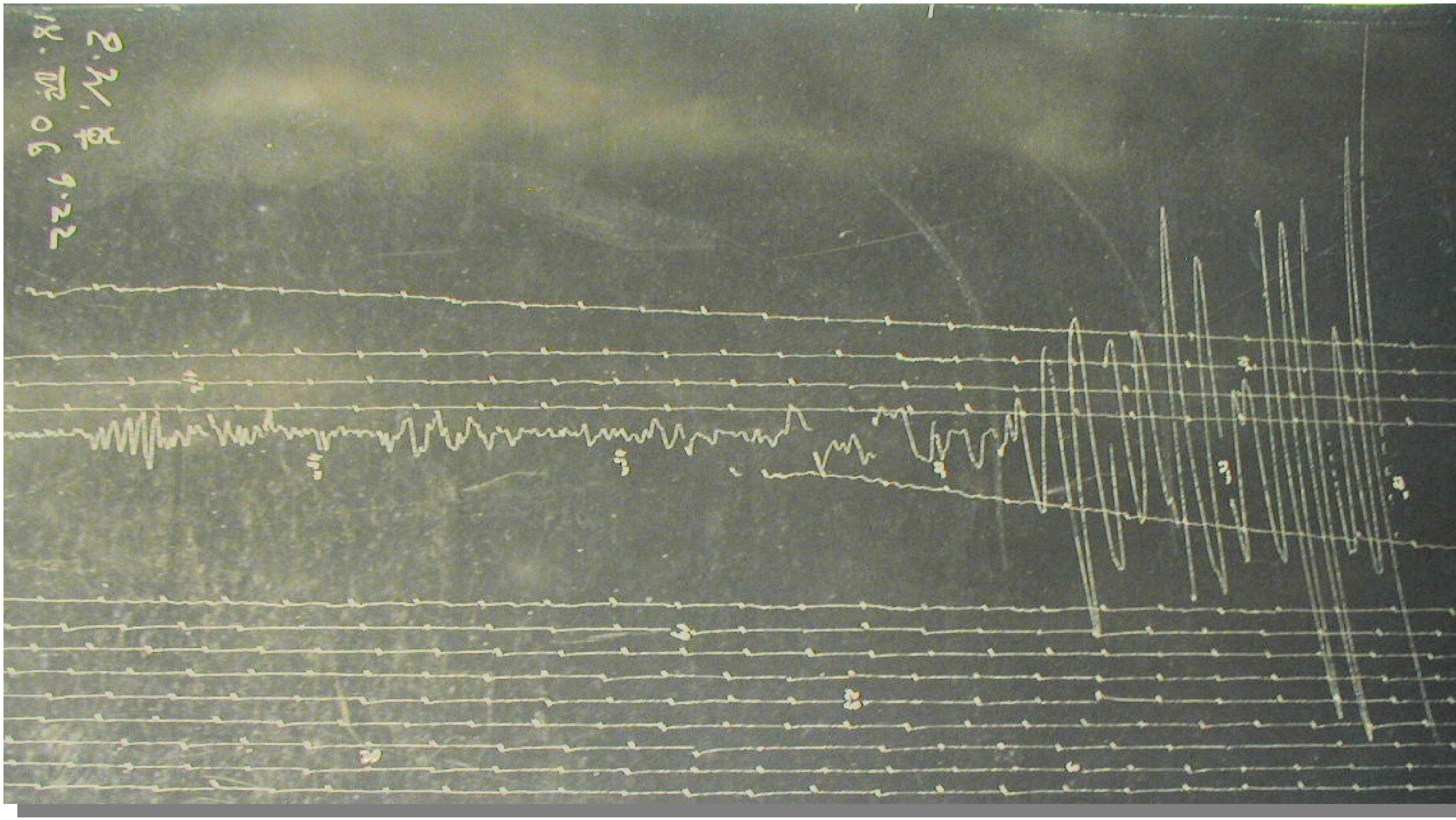
San Francisco earthquake in FFB



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