Seismology

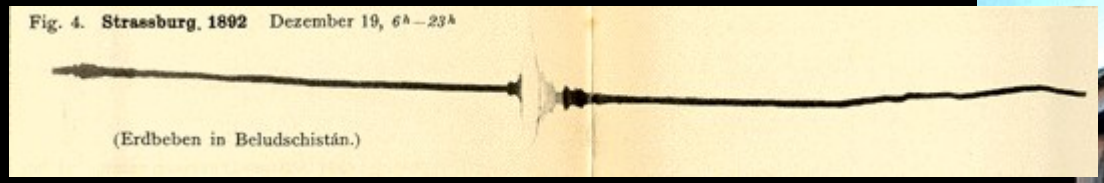


Fig. 4. Strassburg, 1892 Dezember 19, 6h—23h
(Erdbeben in Beludschistán.)



What is seismology?

Seismology is science dealing with all aspects of earthquakes:

OBSERVATIONAL SEISMOLOGY

- Recording earthquakes (microseismology)
- Cataloguing earthquakes
- Observing earthquake effects (macroseismology)

ENGINEERING SEISMOLOGY

- Estimation of seismic hazard and risk
- Aseismic structure (earthquake resistant structure)

'PHYSICAL' SEISMOLOGY

- Study of the properties of the Earth's interior
- Study of physical characteristics of seismic sources

EXPLORATIONAL SEISMOLOGY (Applied seismic methods)...

Myths and legends





Earthquakes occur:

• When one of the eight elephants that carry the Earth gets tired (Hindu)



• When a frog that carries the world moves (Mongolia)

• When the giant on whose head we all live, sneezes or scratches (Africa)

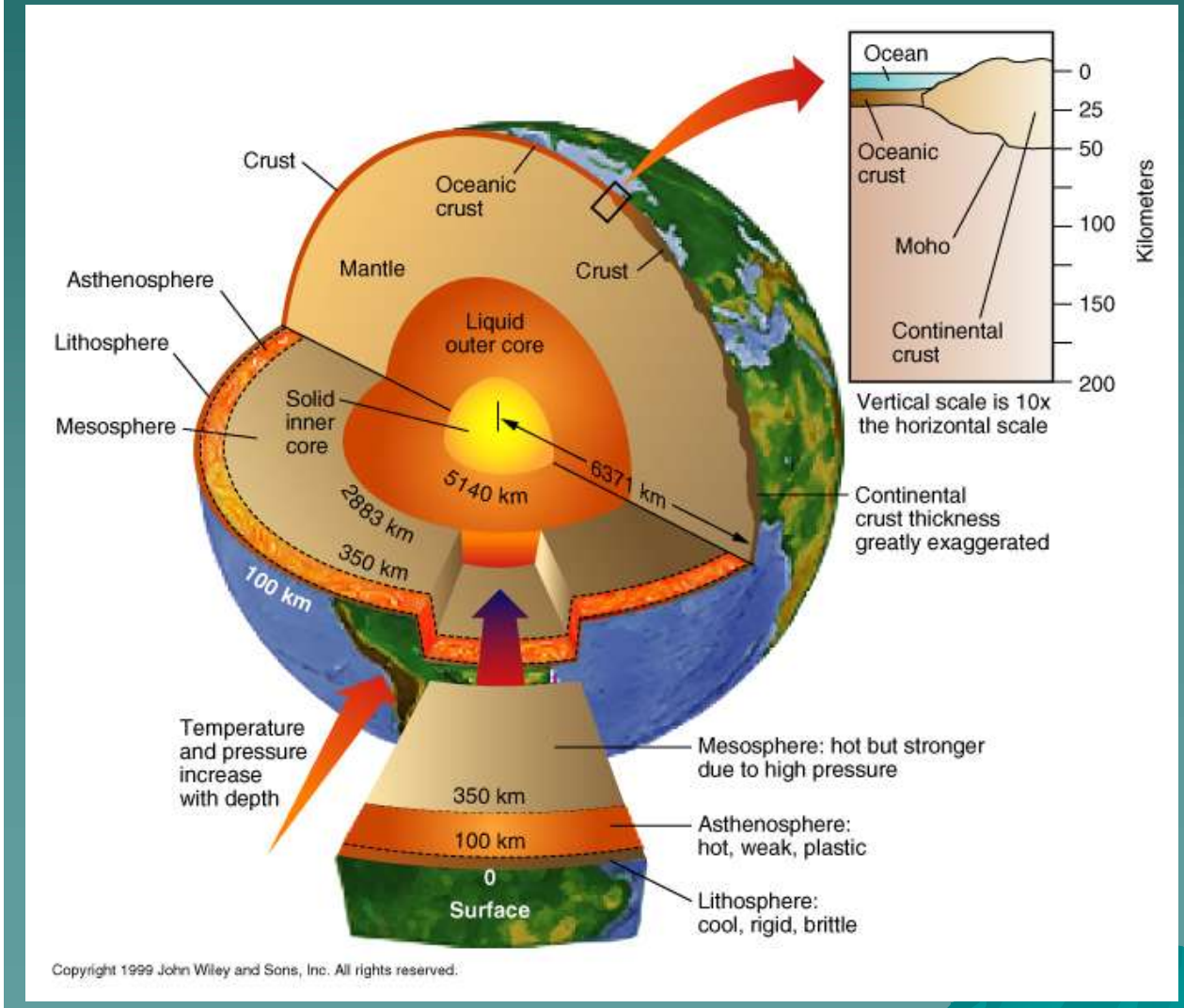


• When the attention of the god Kashima (who looks after the giant catfish Namazu that supports the Earth and prevents it to sink into the ocean) weakens and Namazu moves (Japan)

• When the god Maimas decides to count the population in Peru his footsteps shake the Earth. Then natives run out of their huts and yell: “I’m here, I’m here!”

To see how earthquakes really occur, we first need to learn about constitution of the Earth!

The Three Major Chemical Radial Divisions



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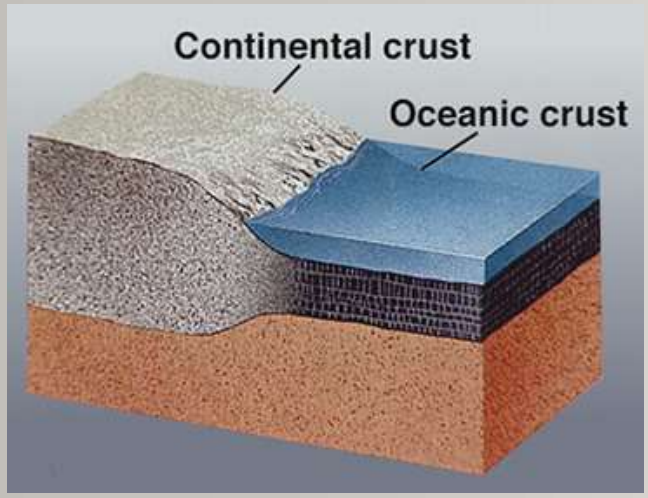
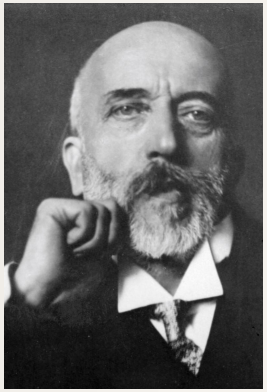
- Crust
- Mantle
- Core

The Shallowest Layer of the Earth: the Crust

- The crust is the most heterogeneous layer in the Earth
- The crust is on average 33 km thick for continents and 10 km thick beneath oceans; however it varies from just a few km to over 70 km globally.

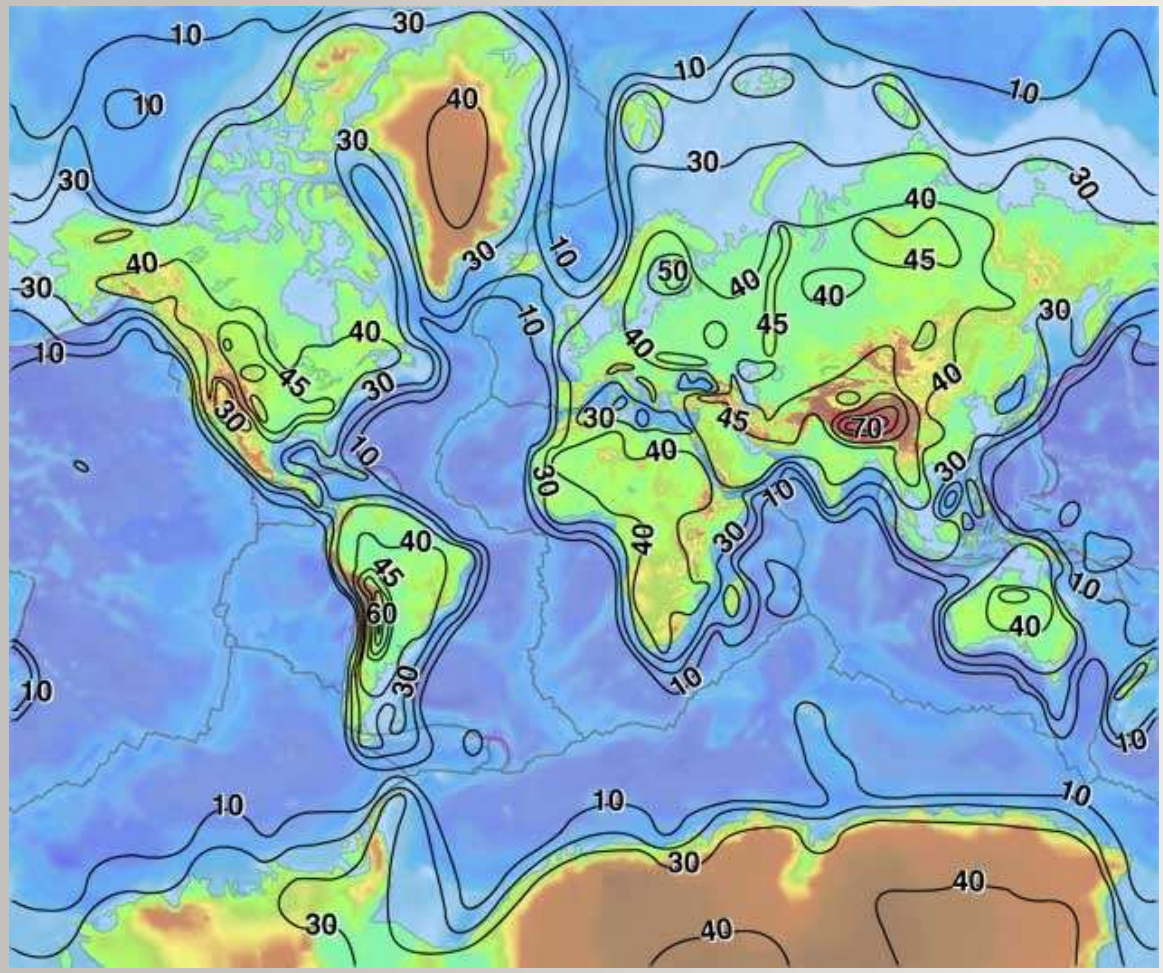


- The boundary between the crust and the mantle is mostly *chemical*. The crust and mantle have different compositions.
- This boundary is referred to as the **Mohorovičić discontinuity** or "Moho".



- It was discovered in 1910 by the Croatian seismologist Andrija Mohorovičić.

Crustal thickness



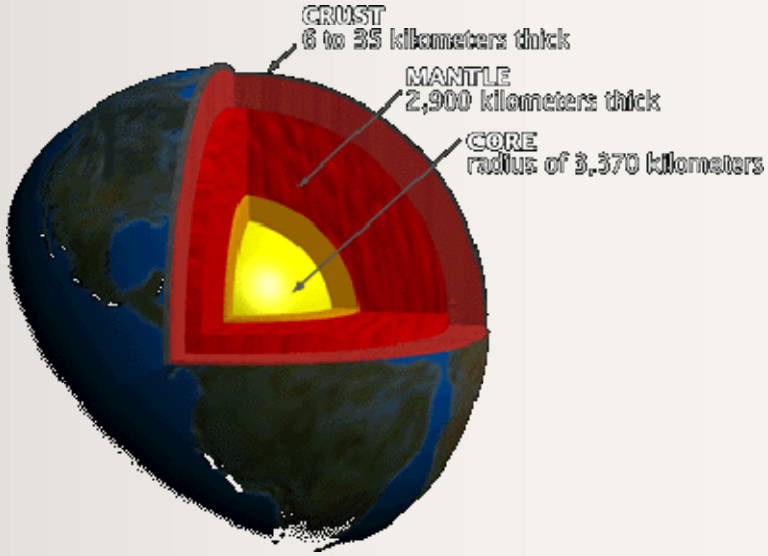
http://quake.wr.usgs.gov/research/structure/CrustalStructure/index.html

Middle Earth: The Mantle

- Earth's mantle exists from the bottom of the crust to a depth of 2891 km (radius of 3480 km) – **Gutenberg discontinuity**
- It is further subdivided into:
  - The uppermost mantle (crust to 400 km depth)
  - The transition zone (400 – 700 km depth)
  - The mid-mantle (700 to ~2650 km depth)
  - The lowermost mantle (~2650 – 2891 km depth)
- The uppermost mantle is composed dominantly of olivine; lesser components include pyroxene, enstatite, and garnet



Beno Gutenberg



Earth's Core





- Owing to the great pressure inside the Earth the Earth's core is actually *freezing* as the Earth gradually cools.
- The boundary between the *liquid outer core* and the *solid inner core* occurs at a radius of about 1220 km – **Lehman discontinuity**, after Inge Lehman from Denmark.
- The boundary between the mantle and outer core is sharp.
- The change in density across the core-mantle boundary is greater than that at the Earth's surface!
- The viscosity of the outer core is similar to that of water, it flows kilometers per year and creates the Earth's magnetic field.
- The outer core is the most homogeneous part of the Earth
- The outer core is mostly an alloy of iron and nickel in liquid form.
- As the core freezes *latent heat* is released; this heat causes the outer core to *convect* and so generates a magnetic field.

Tectonic forces

- The interior of the Earth is dynamic – it cools down and thus provides energy for convective currents in the outer core and in the astenosphere.
- Additional energy comes from radioactive decay...

Convection

Convection in the astenosphere enables tectonic processes – **PLATE TECTONICS**

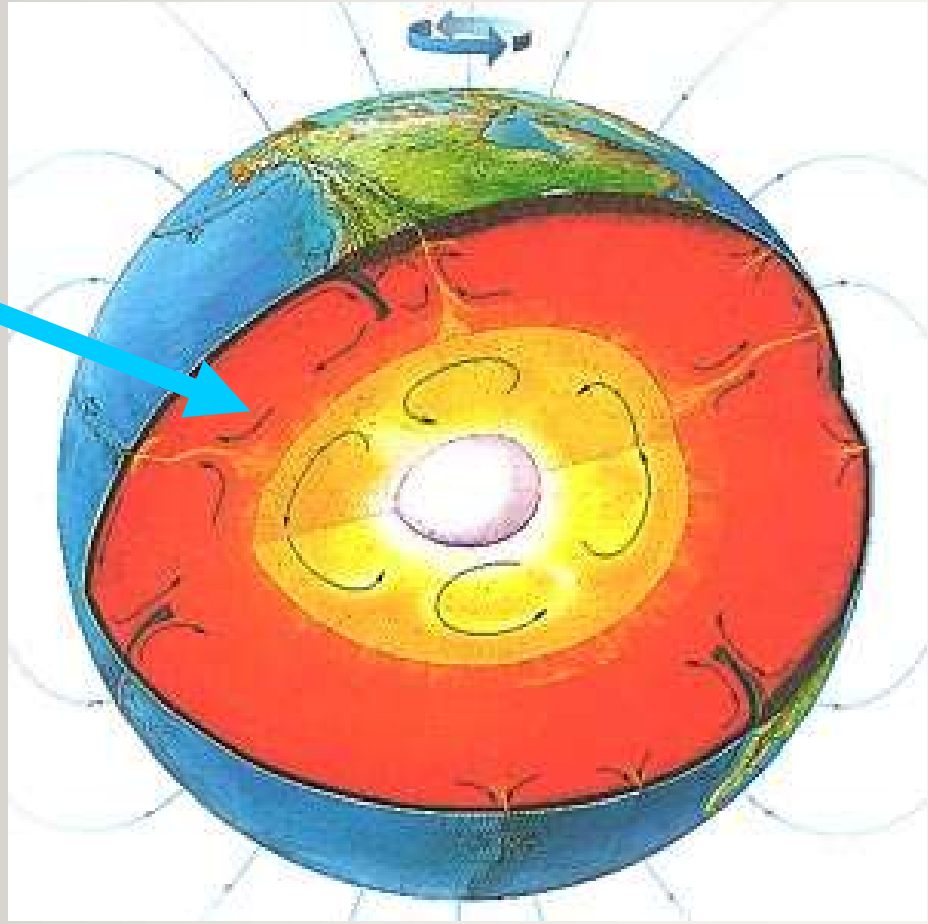


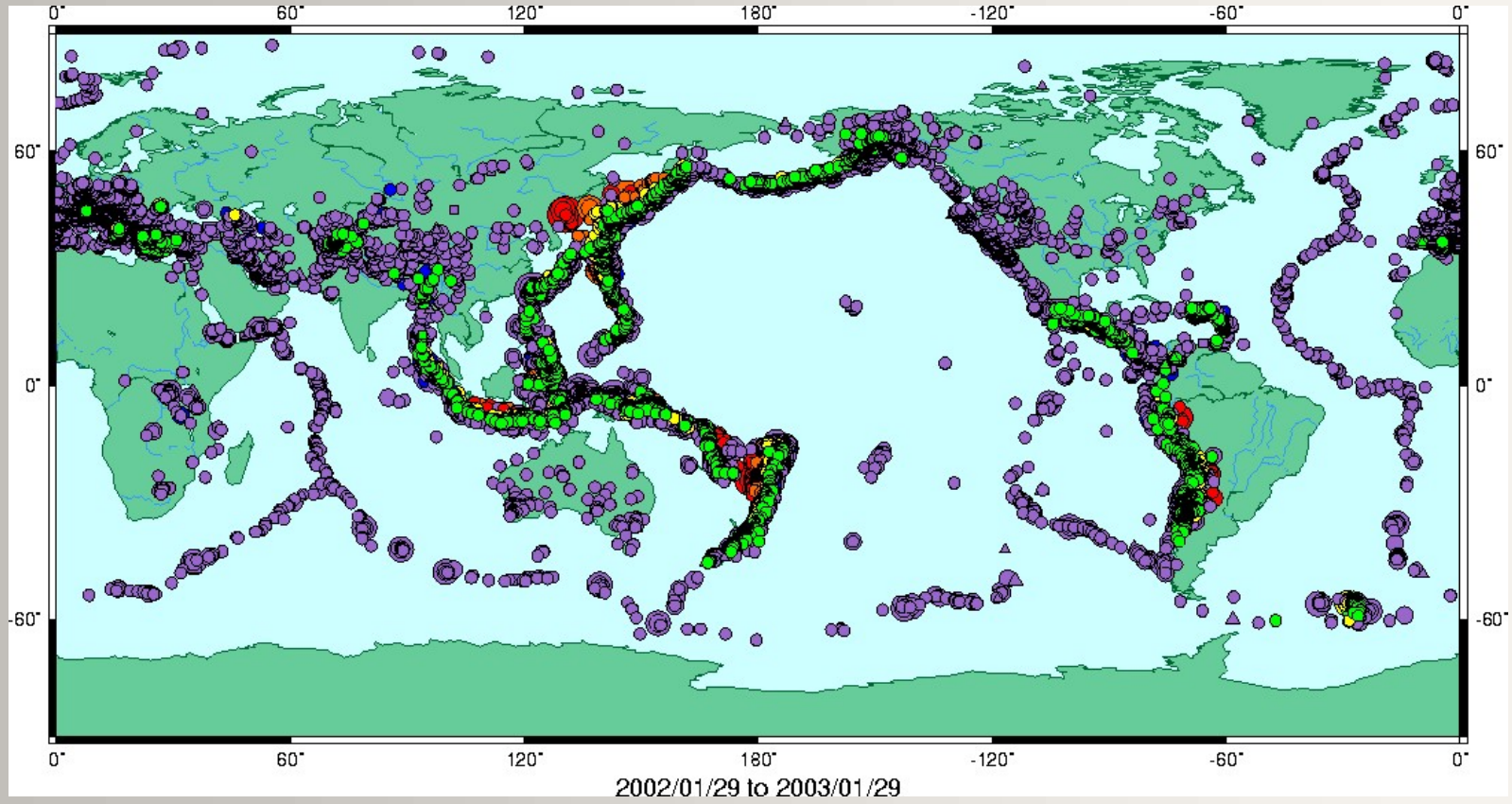
Plate tectonics

PLATE TECTONICS theory is very young (1960-ies)

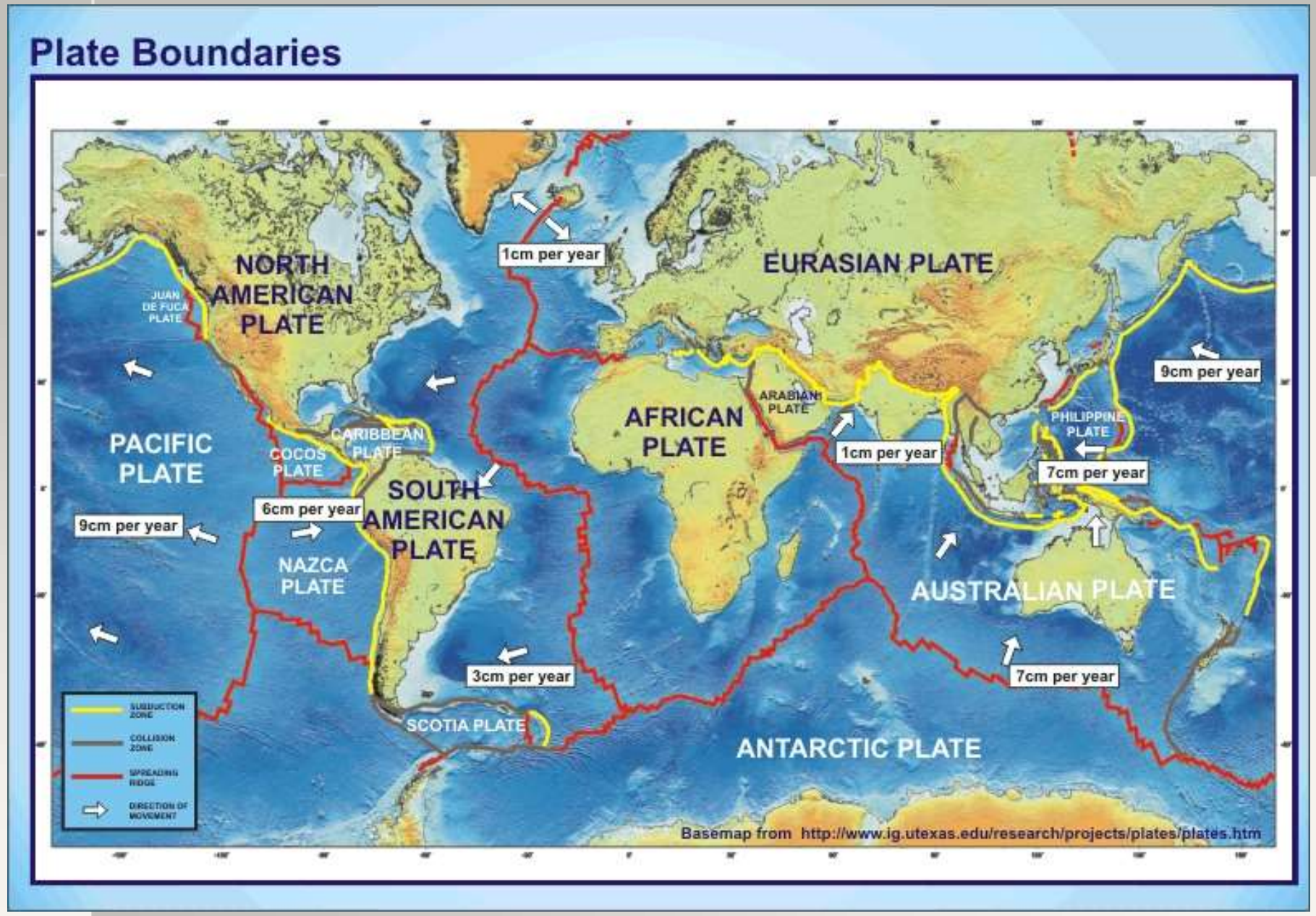
It provides answers to the most fundamental questions in seismology:

- Why earthquakes occur?
- Why are earthquake epicenters not uniformly distributed around the globe?
- At what depths are their foci?

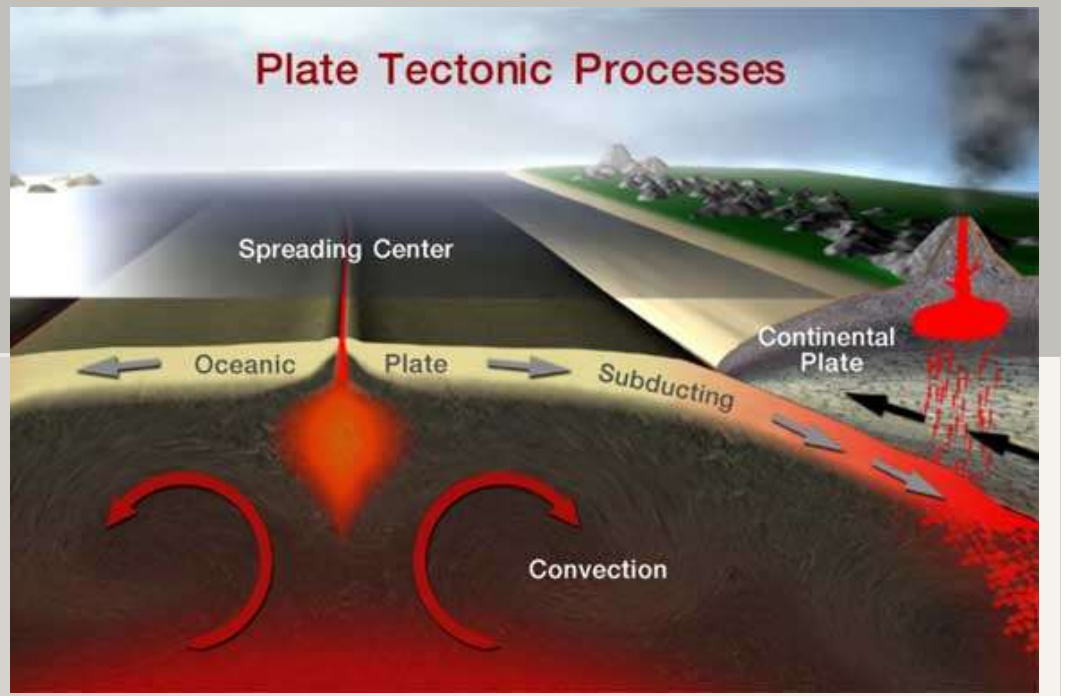
One year of seismicity



Major tectonic plates



Tectonic plates

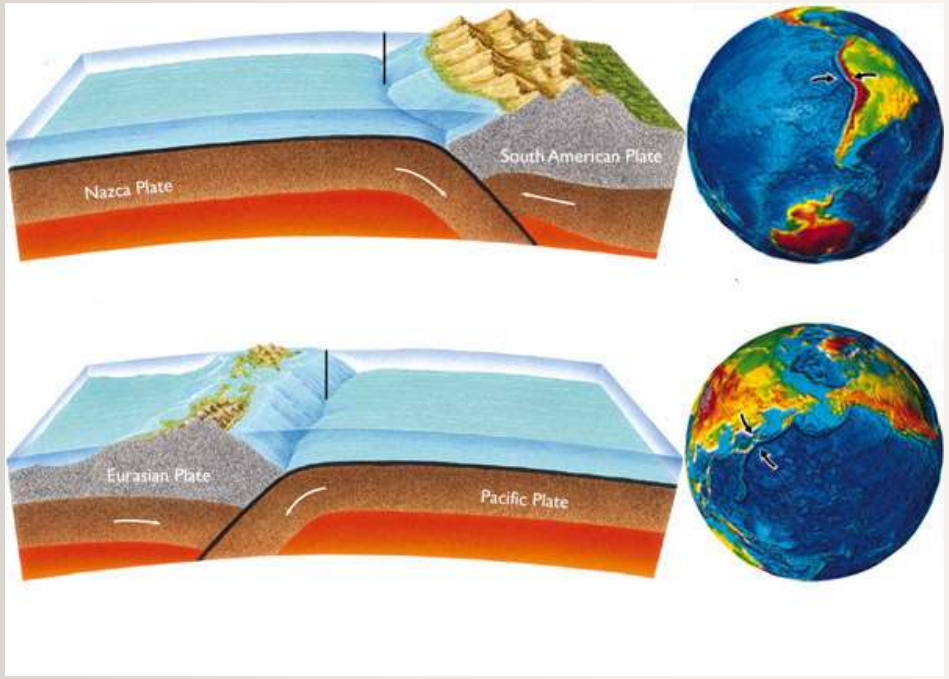


- Tectonic plates are large parts of litosphere 'floating' on the astenosphere
- Convective currents move them around with velocities of several cm/year.
- The plates interact with one another in three basic ways:

1. **They collide**
2. **They move away from each other**
3. **They slide one past another**

Interacting plates

- Collision leads to **SUBDUCTION** of one plate under another. Mountain ranges may also be formed (Himalayas, Alps...).
- It produces strong and sometimes very deep earthquakes (up to 700 km).
- Volcanoes also occur there.

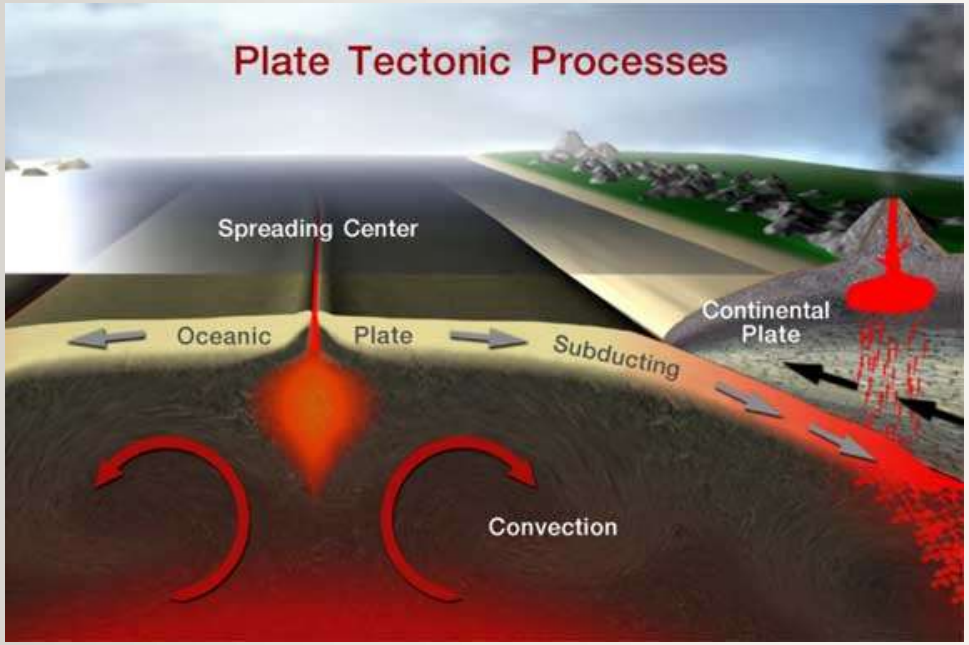


EXAMPLES: Nazca – South America

Eurasia – Pacific

Interacting plates

- Plates moving away from each other produce **RIDGES** between them (spreading centres).
- The earthquakes are generally weaker than in the case of subduction.

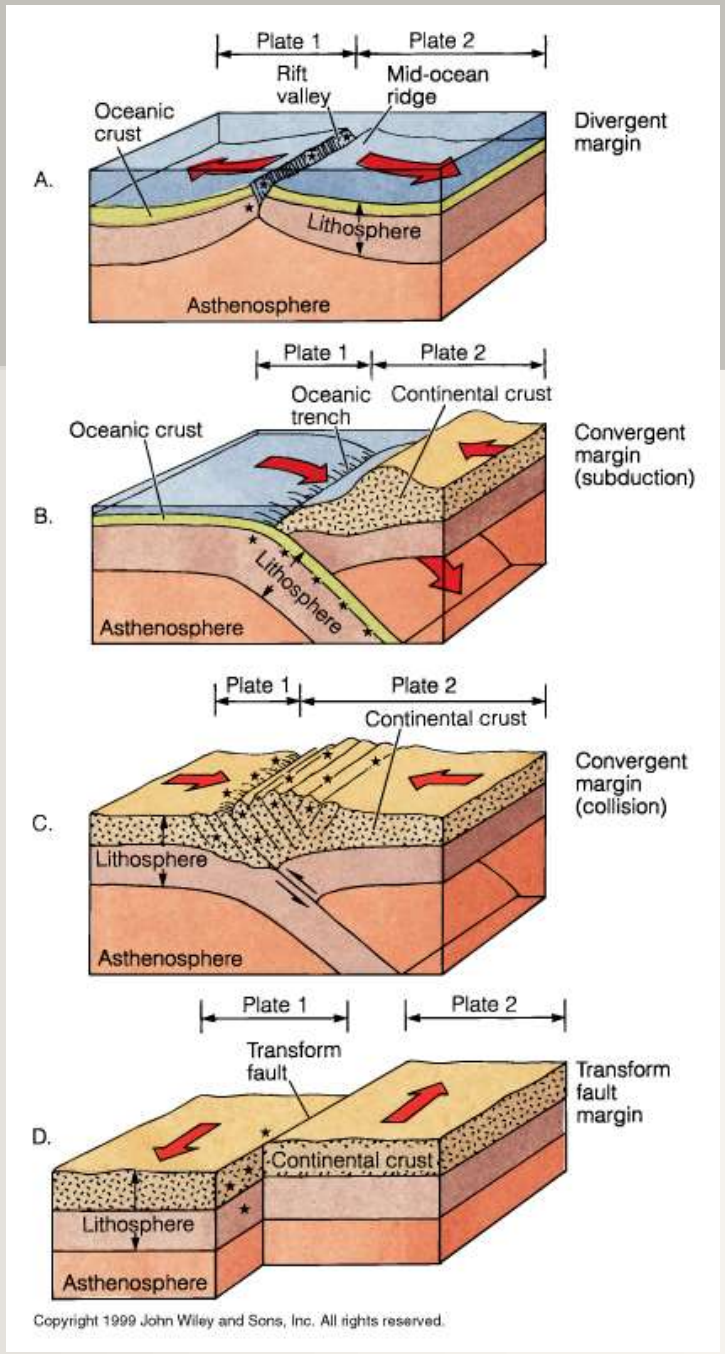


EXAMPLES: Mid-Atlantic ridge (African – South American plates, Euroasian – North American plates)

Interacting plates

- Plates moving past each other do so along the **TRANSFORM FAULTS.**
- The earthquakes may be very strong.

EXAMPLES: San Andreas Fault (Pacific – North American plate)



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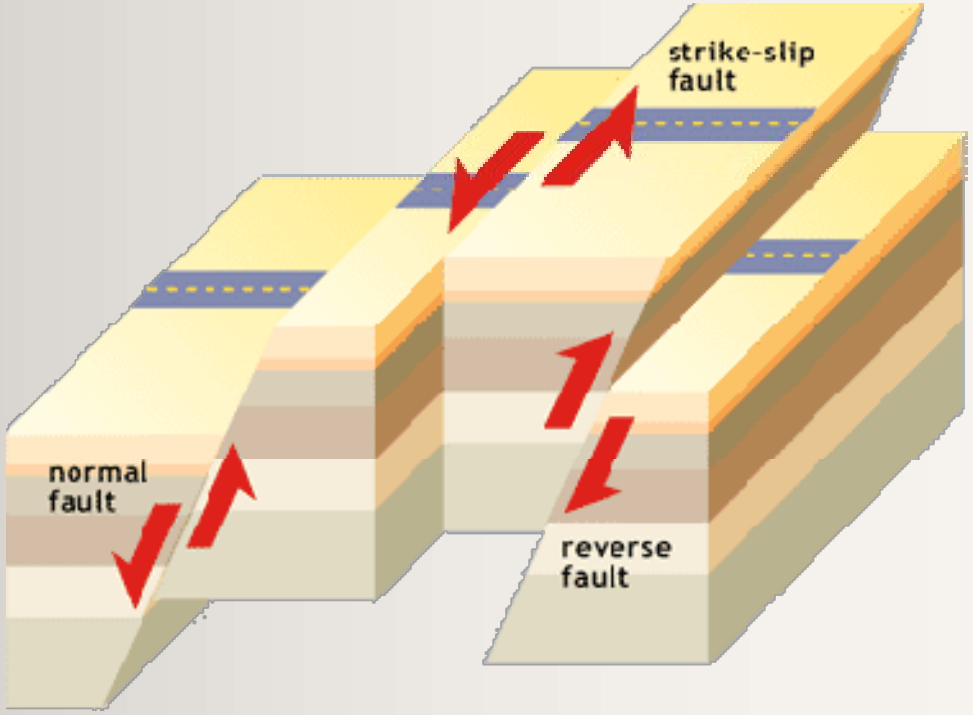
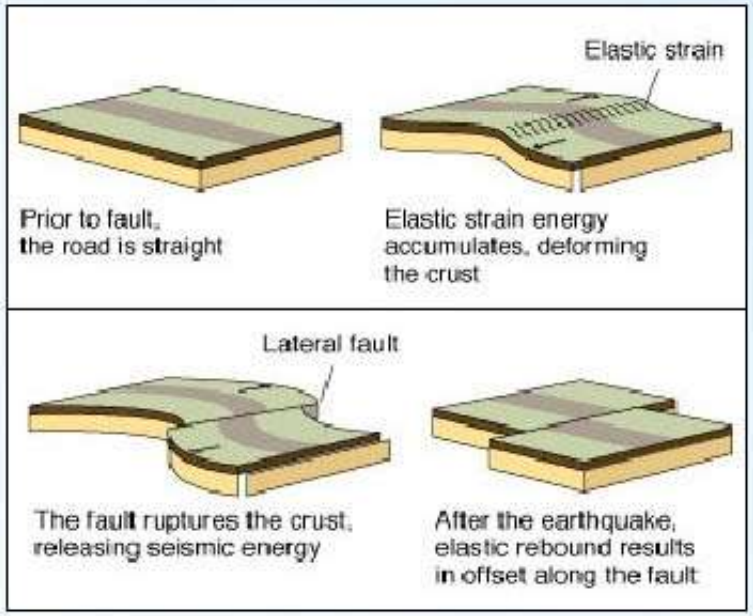
How earthquakes occur?

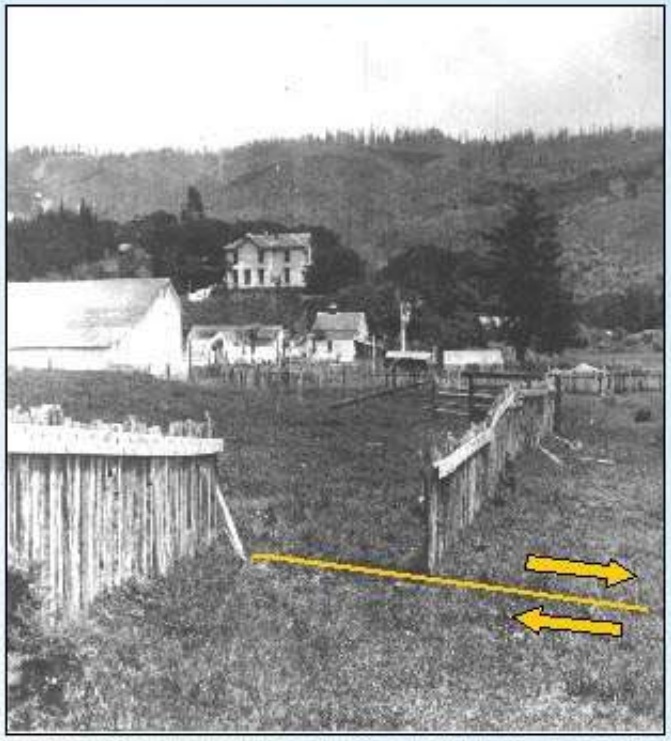
- Earthquakes occur at **FAULTS.**
- Fault is a weak zone separating two geological blocks.
- Tectonic forces cause the blocks to move relative one to another.



How earthquakes occur? Elastic rebound theory

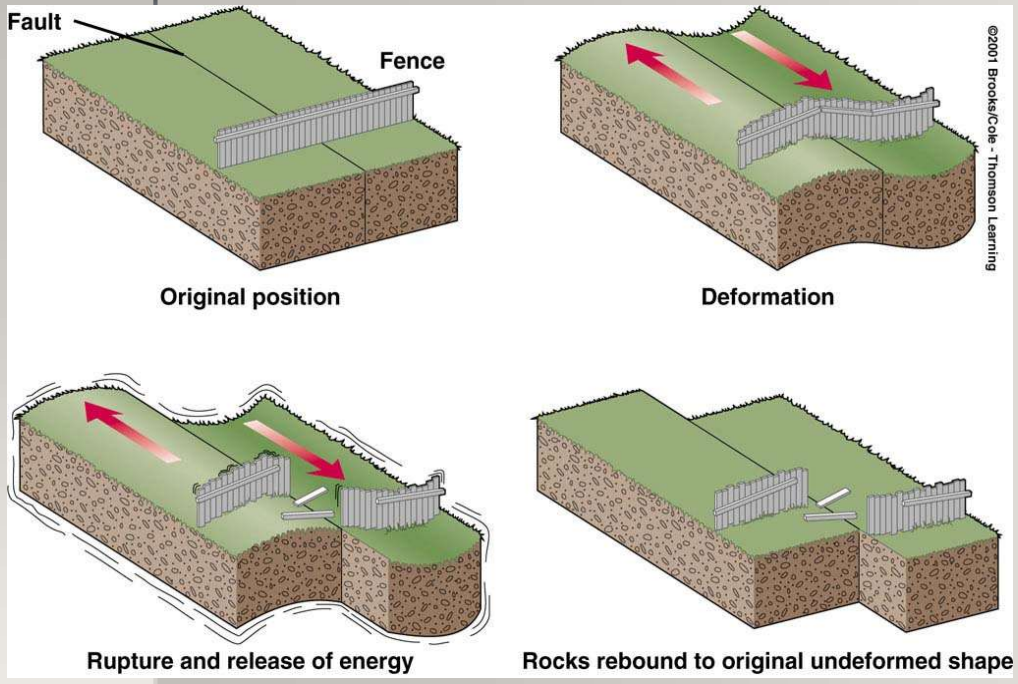
Elastic Rebound Theory Relates Faulting and Earthquakes

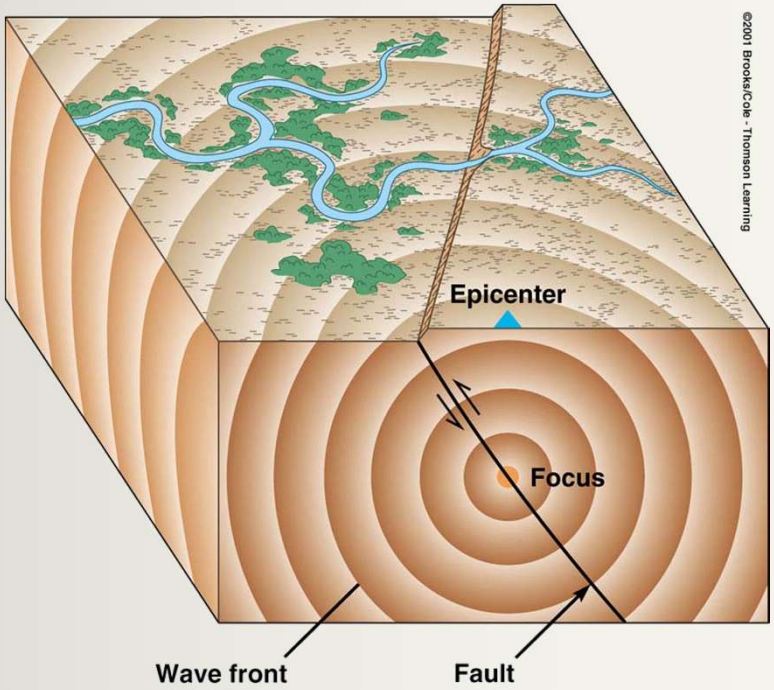




- Fence offset in 1906 quake on San Andreas Fault

How earthquakes occur? Elastic rebound theory





- **Because of friction, the blocks do not slide, but are deformed.**
- **When the stresses within rocks exceed friction, rupture occurs.**
- **Elastic energy, stored in the system, is released after rupture in waves that radiate outward from the fault.**

Elastic waves – Body waves

Longitudinal waves:

- They are faster than transversal waves and thus arrive first.
- The particles oscillate in the direction of spreading of the wave.
- Compressional waves
- P-waves

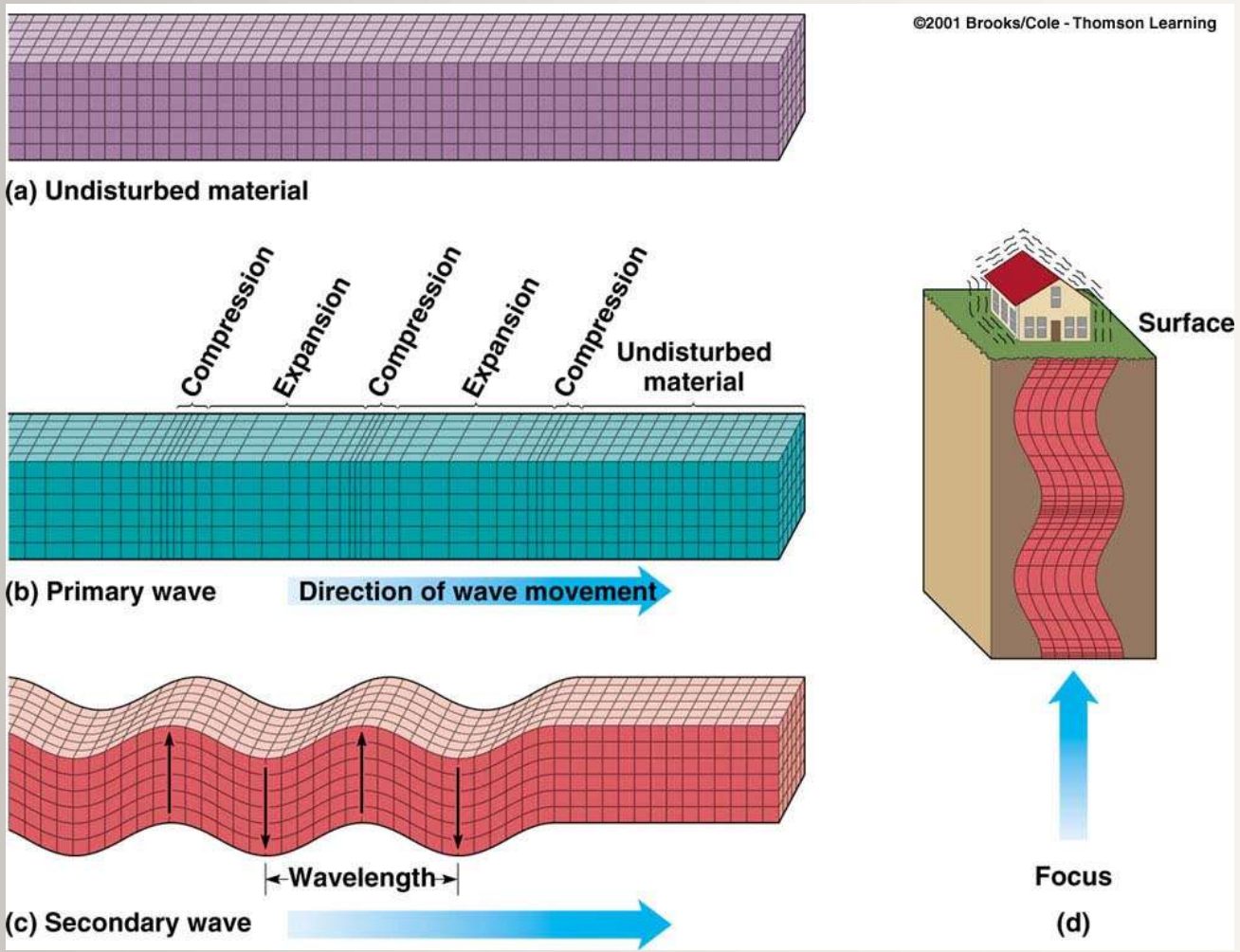
Transversal waves:

- The particles oscillate in the direction perpendicular to the spreading direction.
- Shear waves – they do not propagate through solids (e.g. through the outer core).
- S-waves

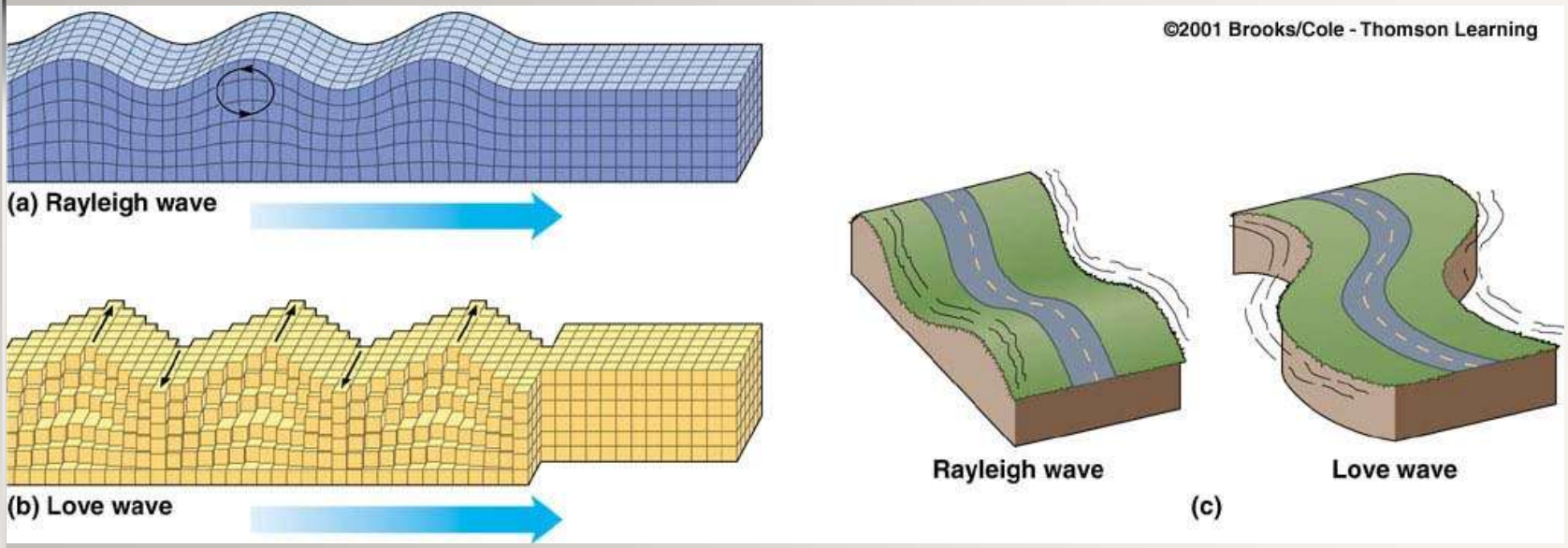
Elastic waves – Body waves

P-waves:

S-waves:



Elastic waves – Surface waves



Surface waves: Rayleigh and Love waves

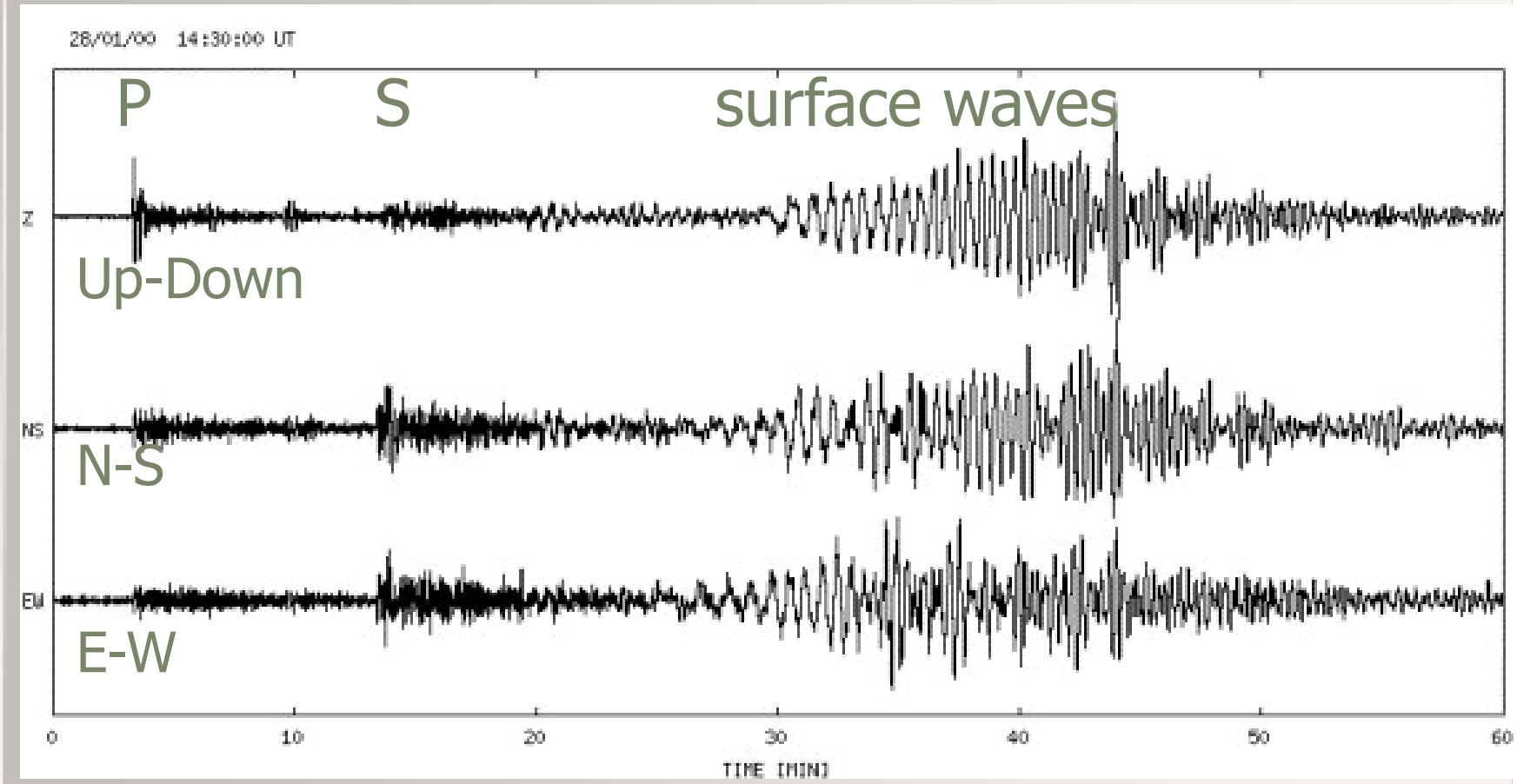
- Their amplitude diminishes with the depth.
- They have large amplitudes and are **slower** than body waves.
- These are dispersive waves (large periods are faster).

Seismogram

Earthquake in Japan

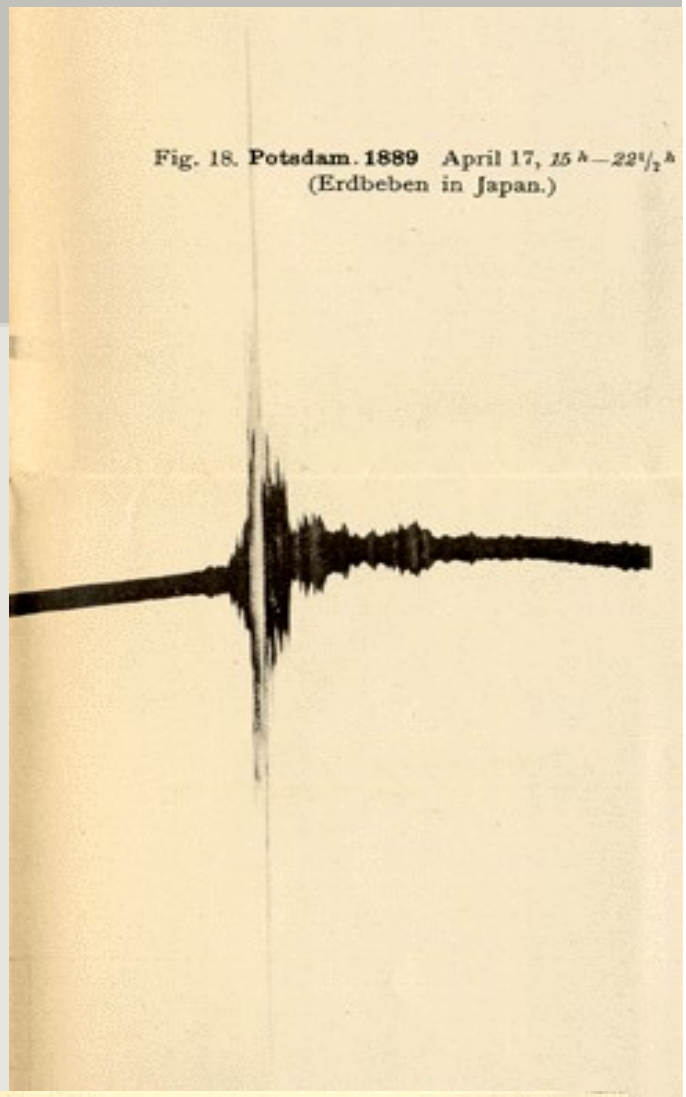
Station in Germany

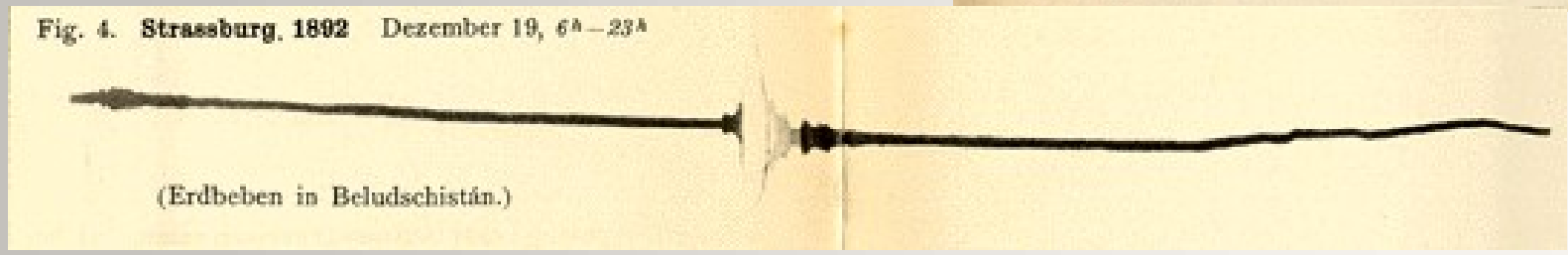
Magnitude 6.5



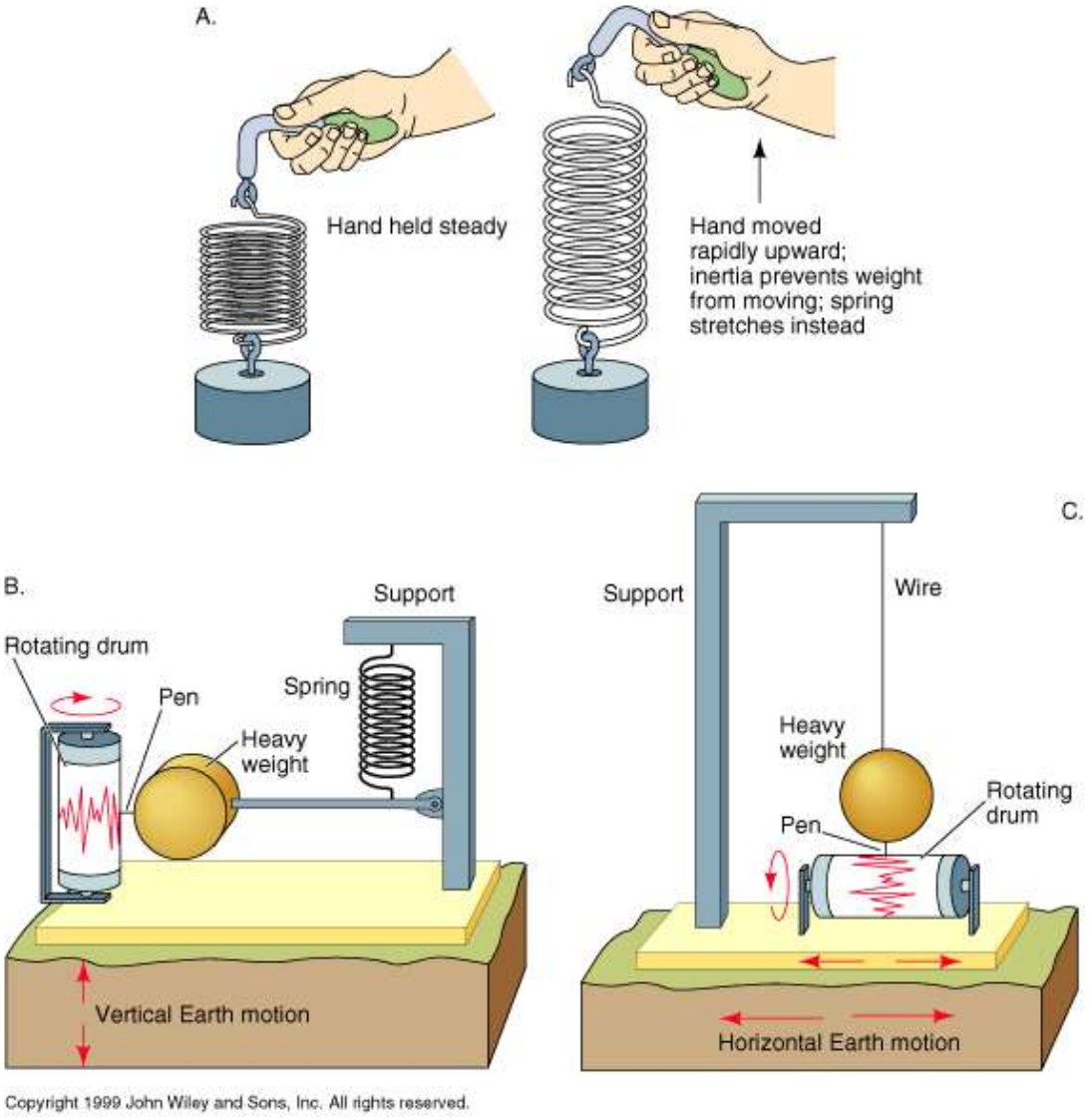
Seismographs

- Seismographs are devices that record ground motion during earthquakes.
- The first seismographs were constructed at the very end of the 19th century in Italy and Germany.





Seismographs



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Horizontal 1000 kg Wiechert seismograph in Zagreb (built in 1909)

Seismographs

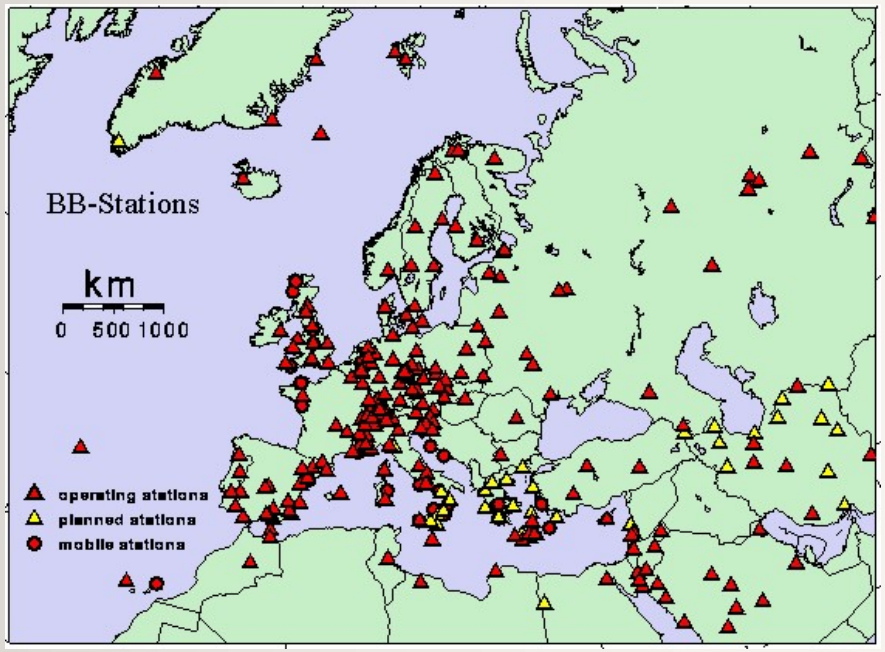


- Modern digital broadband seismographs are capable of recording almost the whole seismological spectrum (50 Hz – 300 s).
- Their resolution of 24 bits (high dynamic range) allows for precise recording of small quakes, as well as unsaturated registration of the largest ones.



Observational Seismology

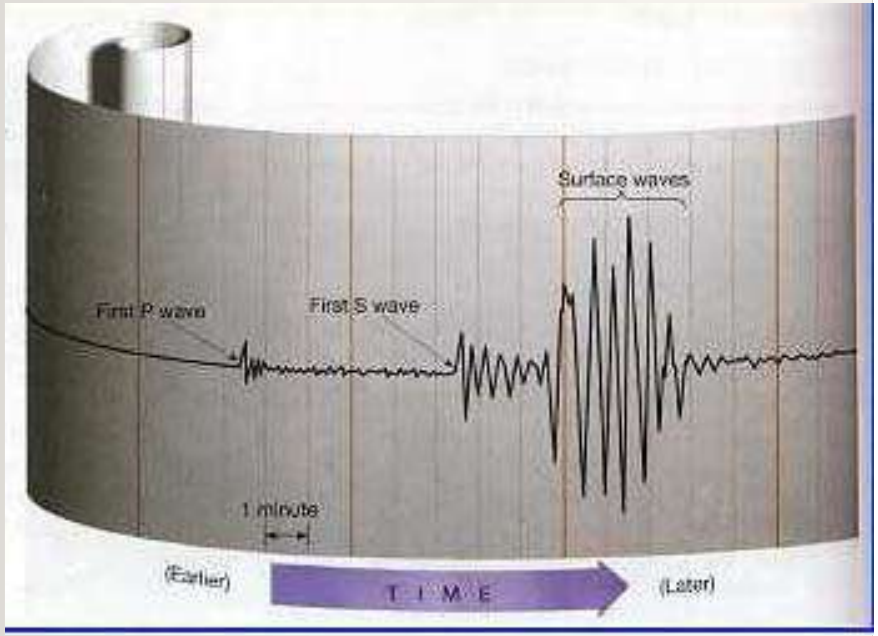
- We are now equipped to start recording and locating earthquakes. For that we need a seismic network of as many stations as possible.
- Minimal number of stations needed to locate the position of an earthquake epicentre is three.



Broad-band seismological stations in Europe

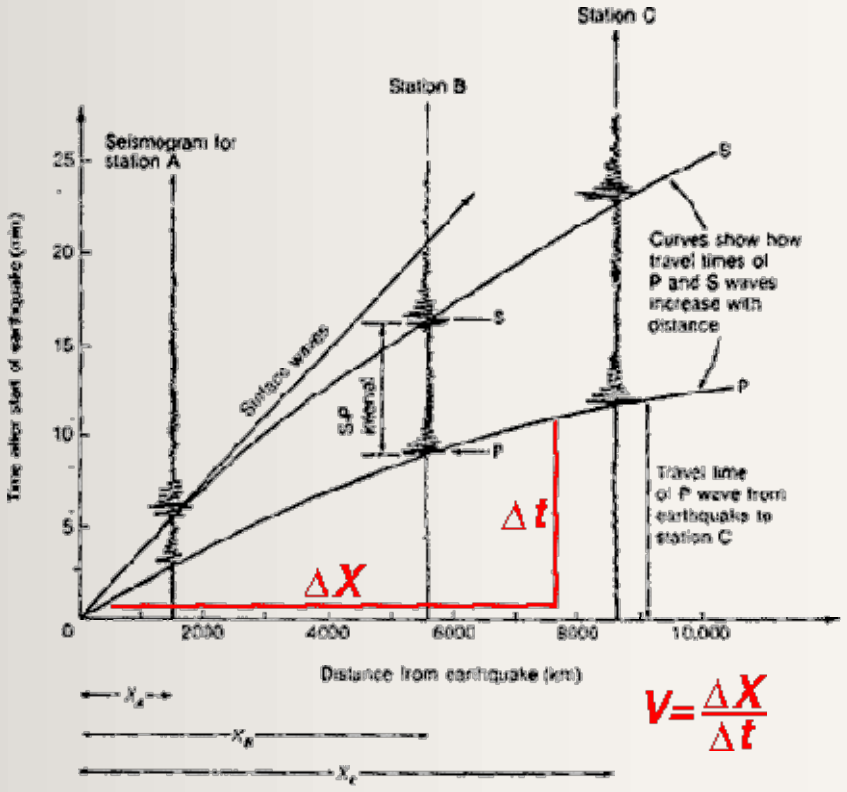
Observational Seismology
Locating Earthquakes

- To locate an earthquake we need precise readings of the times when P- and S-waves arrive at a number of seismic stations.
- Accurate absolute timing (with a precission of 0.01 s) is essential in seismology!



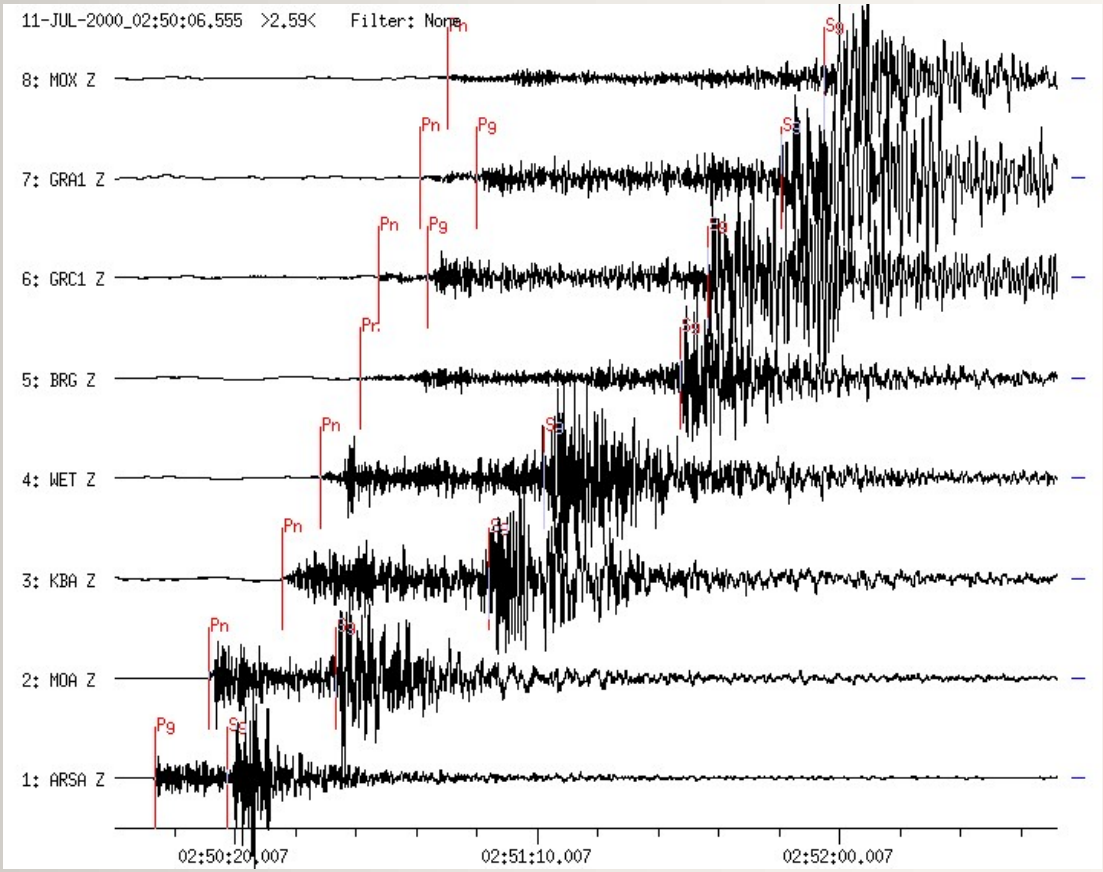
Observational Seismology
Locating Earthquakes

- Knowing the difference in arrival times of the two waves, and knowing their velocity, we may calculate the distance of the epicentre.
- This is done using the travel-time curves which show how long does it take for P- and S-waves to reach some epicentral distance.



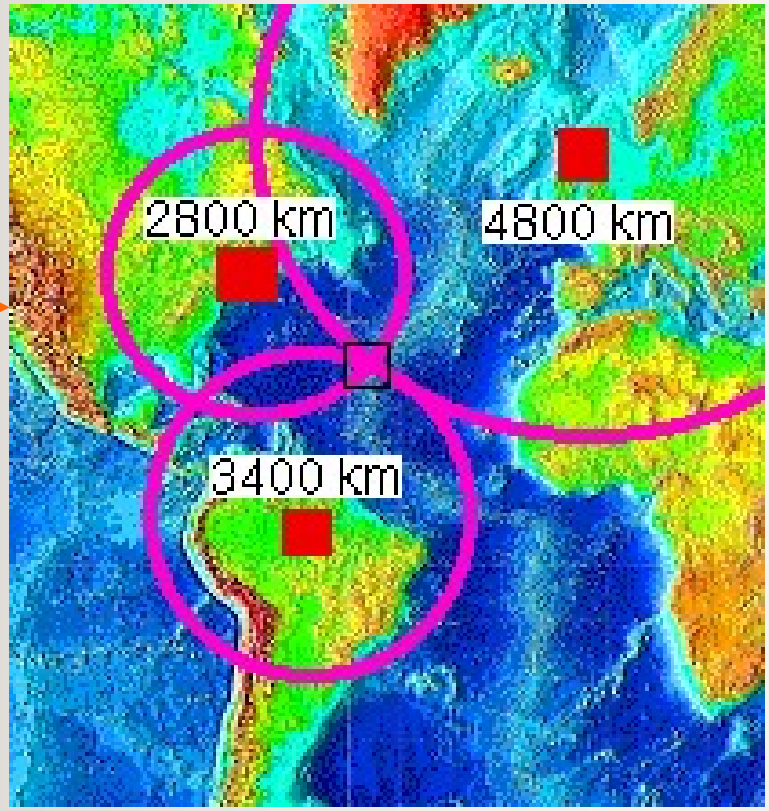
Observational Seismology
Locating Earthquakes

Another example of picking arrival times



Observational Seismology
Locating Earthquakes

- After we know the distance of epicentre from at least three stations we may find the epicentre like this
- There are more sofisticated methods of locating positions of earthquake foci. This is a classic example of an *inverse problem.*



Observational Seismology
Magnitude determination

- Besides the position of the epicentre and the depth of focus, the earthquake magnitude is another defining element of each earthquake.
- Magnitude (defined by **Charles Richter** in 1935) is proportional to the amount of energy released from the focus.
- Magnitude is calculated from the amplitudes of ground motion as measured from the seismograms. You also need to know the epicentral distance to take attenuation into account.



Observational Seismology
Magnitude determination

Formula:

$M = \log(A) + c_1 \log(D) + c_2$

where A is amplitude of ground motion, D is epicentral distance, and c_1, c_2 are constants.

- There are many types of magnitude in seismological practice, depending which waves are used to measure the amplitude: M_L, m_b, M_c, M_s, M_w, ...
- Increase of 1 magnitude unit means ~32 times more released seismic energy!

Observational Seismology
Some statistics

Magnitude	Effects	Number per year
less than 2	Not felt by humans. Recorded by instruments only.	Numerous
2	Felt only by the most sensitive. Suspended objects swing	>1 000 000
3	Felt by some people. Vibration like a passing heavy vehicle	100 000
4	Felt by most people. Hanging objects swing. Dishes and windows rattle and may break	12 000
5	Felt by all; people frightened. Chimneys topple; furniture moves	1 400
6	Panic. Buildings may suffer substantial damage	160
7-8	Widespread panic. Few buildings remain standing. Large landslides; fissures in ground	20
8-9	Complete devastation. Ground waves	~2

Observational Seismology
Some statistics

Equivalent Magnitude	Event	Energy (tons TNT)
2.0	Large quary blast	1
2.5	Moderate lightning bolt	5
3.5	Large ligtning bolt	75
4.5	Average tornado	5 100
6.0	Hiroshima atomic bomb	20 000
7.0	Largest nuclear test	32 000 000
7.7	Mt. Saint Helens eruption	100 000 000
8.5	Krakatoa eruption	1 000 000 000
9.5	Chilean earthquake 1960	32 000 000 000

Observational Seismology
Some statistics

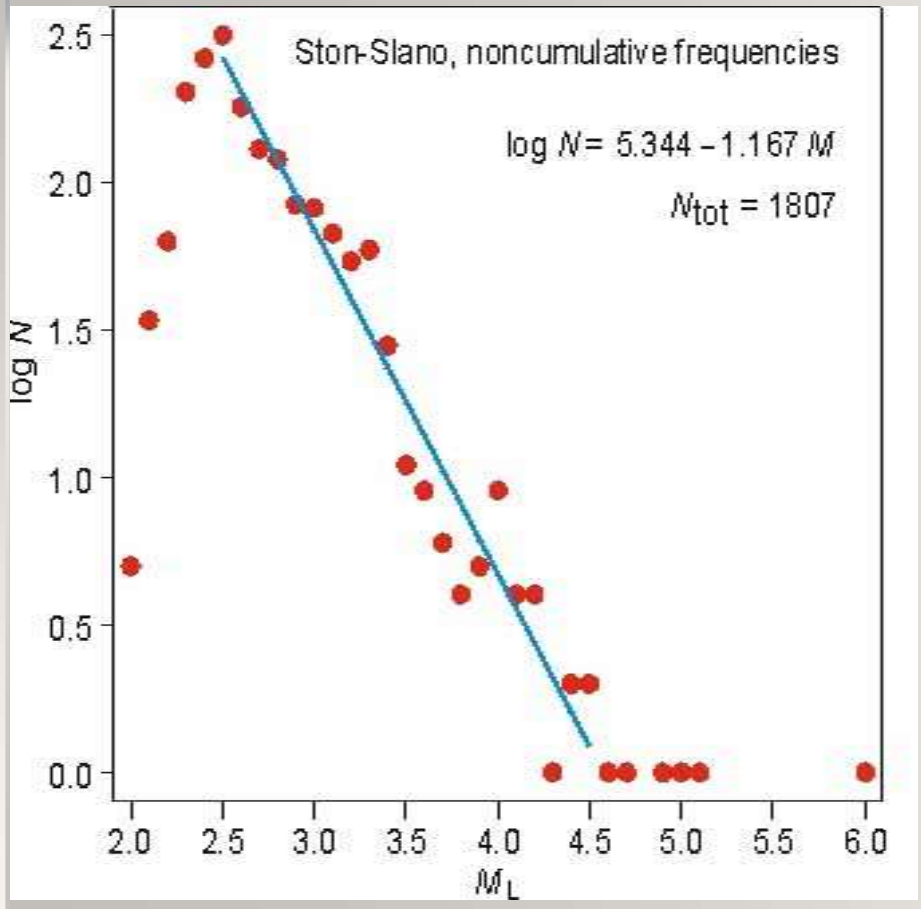
10 LARGEST EARTHQUAKES IN THE WORLD SINCE 1900

	Location	Date	Magnitude	Deaths
1.	Chile	22 May 1960	9.5	>5000
2.	Alaska	28 March 1964	9.2	131
3.	Russia	4 November 1952	9.0	0
4.	Ecuador	31 January 1906	8.8	>1000
5.	Alaska	9 March 1957	8.8	0
6.	Kuril Islands	6 November 1958	8.7	0
7.	Alaska	4 February 1965	8.7	0
8.	India	15 August 1950	8.6	1530
9.	Chile	11 November 1922	8.6	>100
10.	Indonesia	1 February 1938	8.5	0

Observational Seismology
Some statistics



Observational Seismology
Some statistics



- Gutenberg-Richter frequency-magnitude relation:

  $\log N = a - bM$

- b is approximately constant, b = 1 world-wide → there are ~10 more times M=5 than M=6 earthquakes
- This shows selfsimilarity and fractal nature of earthquakes.

Observational Seismology
Macroseismology

- MACROSEISMOLOGY deals with effects of earthquakes on humans, animals, objects and surroundings.
- The data are collected by field trips into the shaken area, and/or by questionaires sent there.
- The effects are then expressed as earthquake INTENSITY at each of the studied places.
- Intensity is graded according to **macroseismic scales** – Mercalli-Cancani-Sieberg (**MCS**), Medvedev-Sponheuer-Karnik (**MSK**), Modified Mercalli (**MM**), European Macroseismic Scale (**EMS**).
- This is a subjective method.

Observational Seismology
Macroseismology

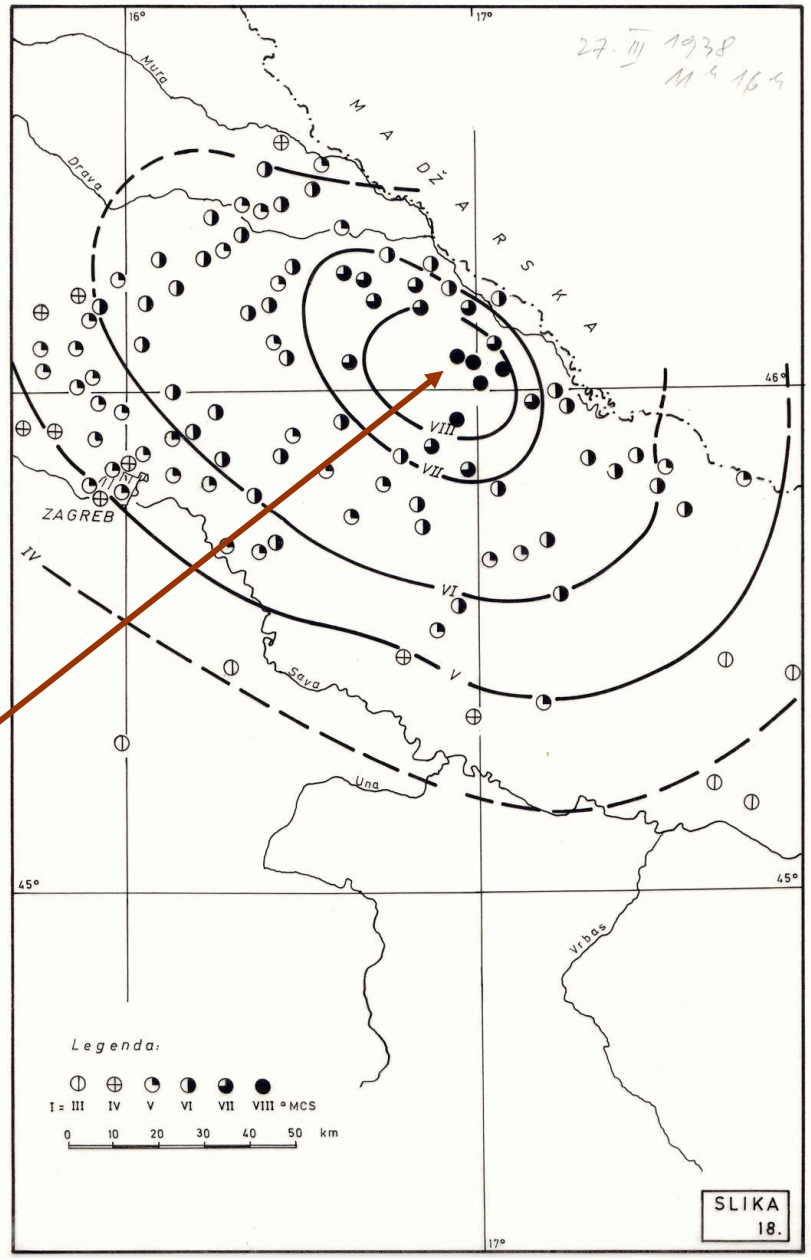
European Macroseismic Scale (EMS 98)

EMS	DEFINITION	SHORT DESCRIPTION
I	**Not felt**	Not felt, even under the most favourable circumstances.
II	**Scarcely felt**	Vibration is felt only by individual people at rest in houses, especially on upper floors of buildings.
III	**Weak**	The vibration is weak and is felt indoors by a few people. People at rest feel a swaying or light trembling.
IV	**Largely observed**	The earthquake is felt indoors by many people, outdoors by very few. A few people are awakened. The level of vibration is not frightening. Windows, doors and dishes rattle. Hanging objects swing.
V	**Strong**	The earthquake is felt indoors by most, outdoors by few. Many sleeping people awake. A few run outdoors. Buildings tremble throughout. Hanging objects swing considerably. China and glasses clatter together. The vibration is strong. Top heavy objects topple over. Doors and windows swing open or shut.

EMS	DEFINITION	SHORT DESCRIPTION
VI	**Slightly damaging**	Felt by most indoors and by many outdoors. Many people in buildings are frightened and run outdoors. Small objects fall. Slight damage to many ordinary buildings e.g. fine cracks in plaster and small pieces of plaster fall.
VII	**Damaging**	Most people are frightened and run outdoors. Furniture is shifted and objects fall from shelves in large numbers. Many ordinary buildings suffer moderate damage: small cracks in walls; partial collapse of chimneys.
VIII	**Heavily damaging**	Furniture may be overturned. Many ordinary buildings suffer damage: chimneys fall; large cracks appear in walls and a few buildings may partially collapse.
IX	**Destructive**	Monuments and columns fall or are twisted. Many ordinary buildings partially collapse and a few collapse completely.
X	**Very destructive**	Many ordinary buildings collapse.
XI	**Devastating**	Most ordinary buildings collapse**.**
XII	**Completely devastating**	Practically all structures above and below ground are heavily damaged or destroyed.

Observational Seismology
Macroseismology

- Results of macroseismic surveys are presented on **isoseismal maps.**
- **Isoseismals** are curves connecting the places with same intensities.
- DO NOT CONFUSE INTENSITY AND MAGNITUDE!
- Just approximately, **epicentral intensity** is: $I_o = M + 2$
- One earthquake has just one magnitude, but many intensities!



Engineering Seismology

- Earthquakes are the only natural disasters that are mostly *harmless* to humans! The only danger comes from buildings designed *not to withstand* the largest possible earthquakes in the area.
- **Engineering seismology** provides civil engineers parameters they need in order to construct seismically safe and sound structures.
- **Engineering seismology** is a bridge between *seismology* and *earthquake engineering.*



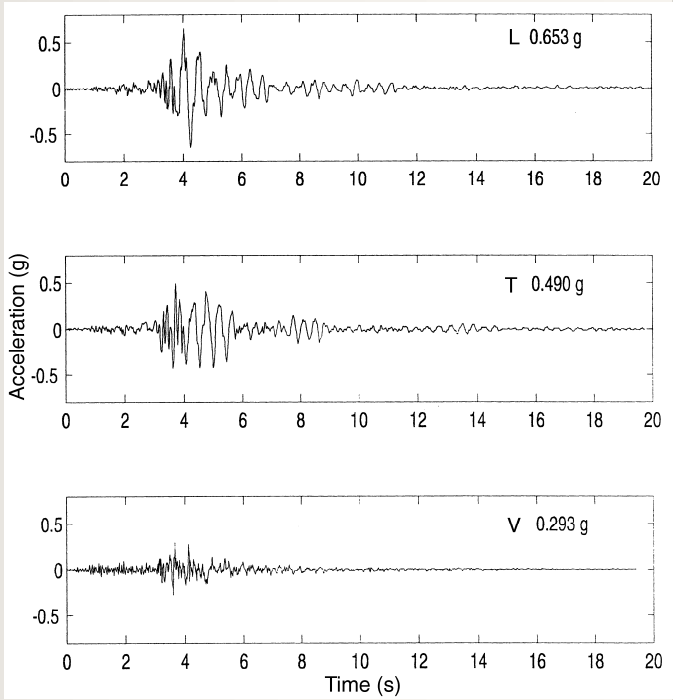
Izmit, Turkey, 1999

Engineering Seismology

Most common input parameters are:

- maximal expected horizontal ground acceleration (PGA)
- maximal expected horizontal ground velocity (PGV)
- maximal expected horizontal ground displacement (PGD)
- response spectra (SA)
- maximal expected intensity (Imax)
- duration of significant shaking
- dominant period of shaking.

- Engineering seismologists mostly use records of ground acceleration obtained by strong-motion accelerographs.



Accelerogram of the Ston-Slano (Croatia, M = 6.0, 1996) event

Engineering Seismology

In order to estimate the parameters, seismologists need:

- Complete earthquake catalogues that extend well into the past,
- Information on the soil structure and properties at the construction site, as well as on the path between epicentre and the site,
- Records of strong earthquakes and small events from near-by epicentral regions,
- Results of geological surveys ...