Earthquakes

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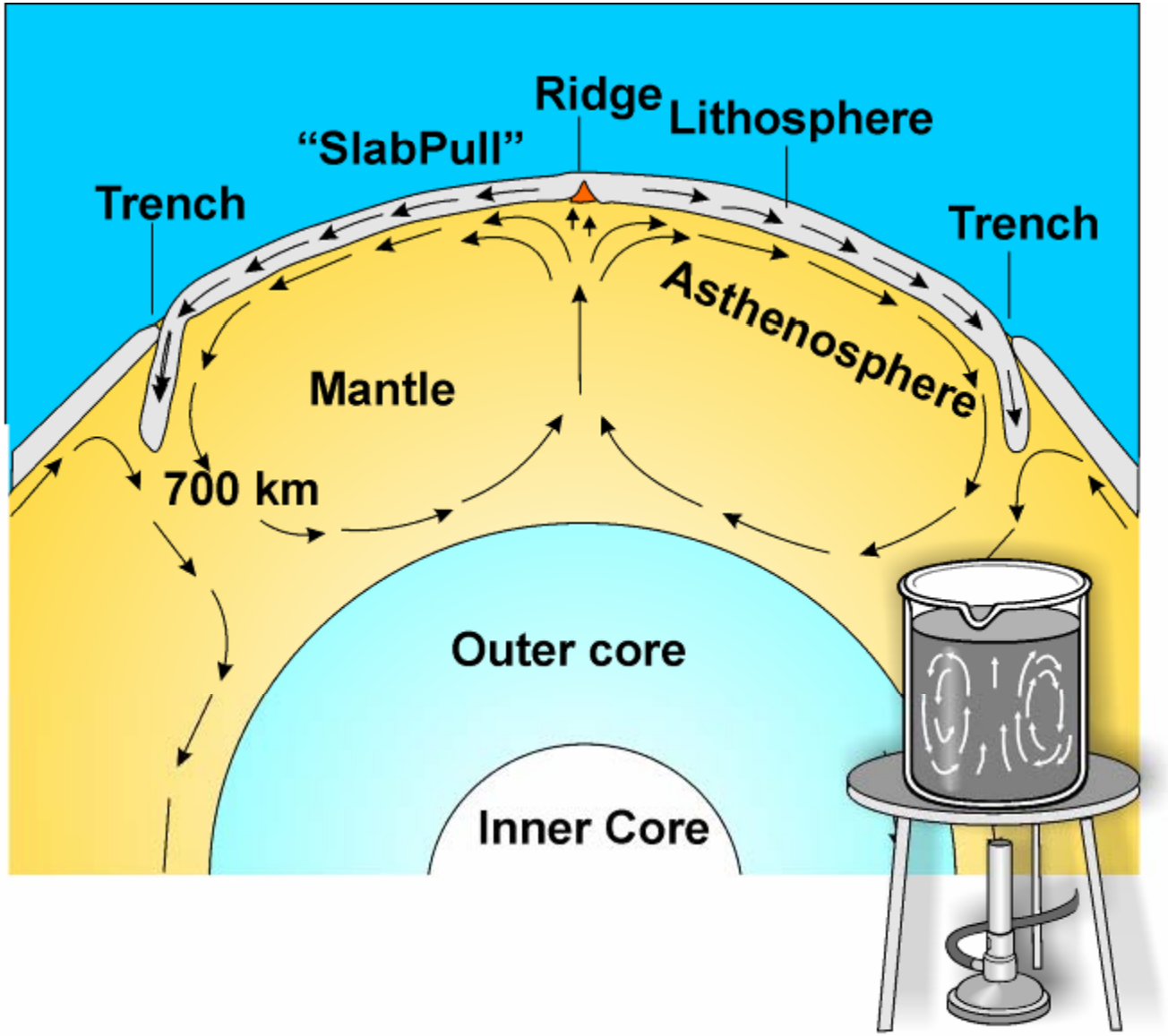
Topics to handle

- Theory of earthquakes
  - Mechanism
  - Strength
  - Measurements

- Earthquake catalogs
  - Magnitude-frequency relationships
  - completeness

Origin of earthquakes

Earth processes



Reconstruction of plate motion

Advanced GIS analysis of many various parameters (e.g. magnetics, geology, seismology, GPS, etc) results in simulation of tectonic processes in the last 200 Ma

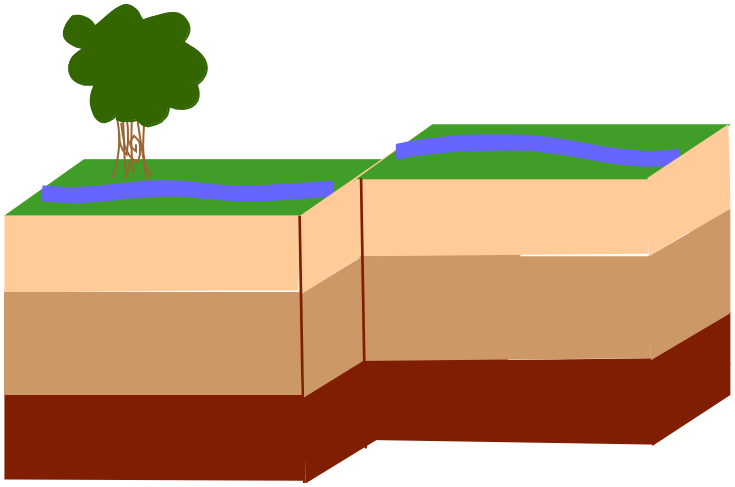
Gondwana animation

Source: Colin Reeves, ITC

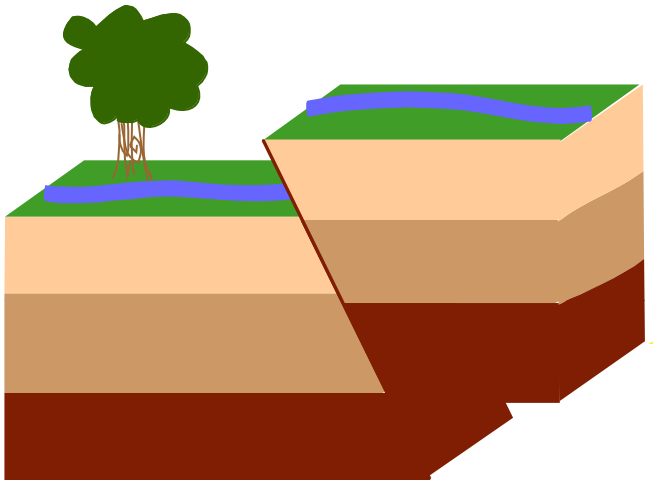
Plate tectonics

- Divergent boundaries
  - Where new crust is generated as the plates pull away from each other.
- Convergent boundaries
  - Where crust is destroyed as one plate dives under another
    1. Oceanic-Continental subduction zone
    2. Oceanic-Oceanic subduction zone
    3. Continent-Continent collision zone
- Transform boundaries
  - Where crust is neither produced nor destroyed as the plates slide horizontally past each other

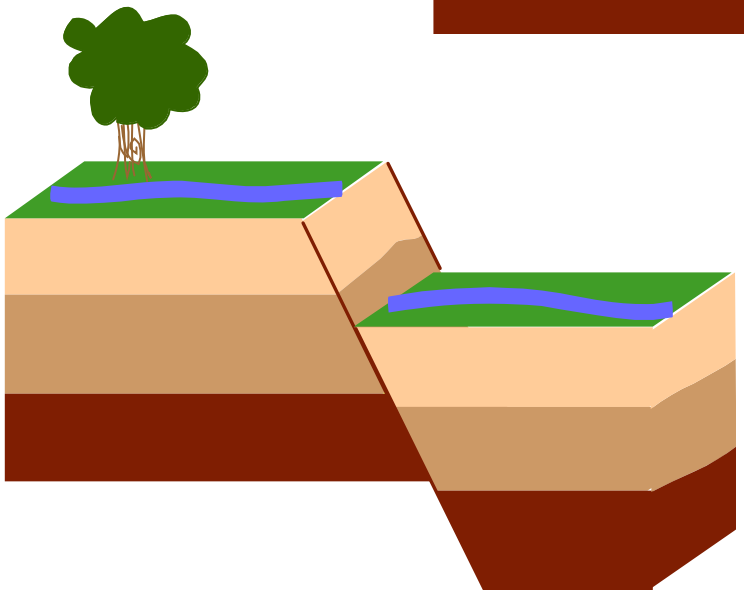
Three Types of Faults



Strike-Slip



Thrust

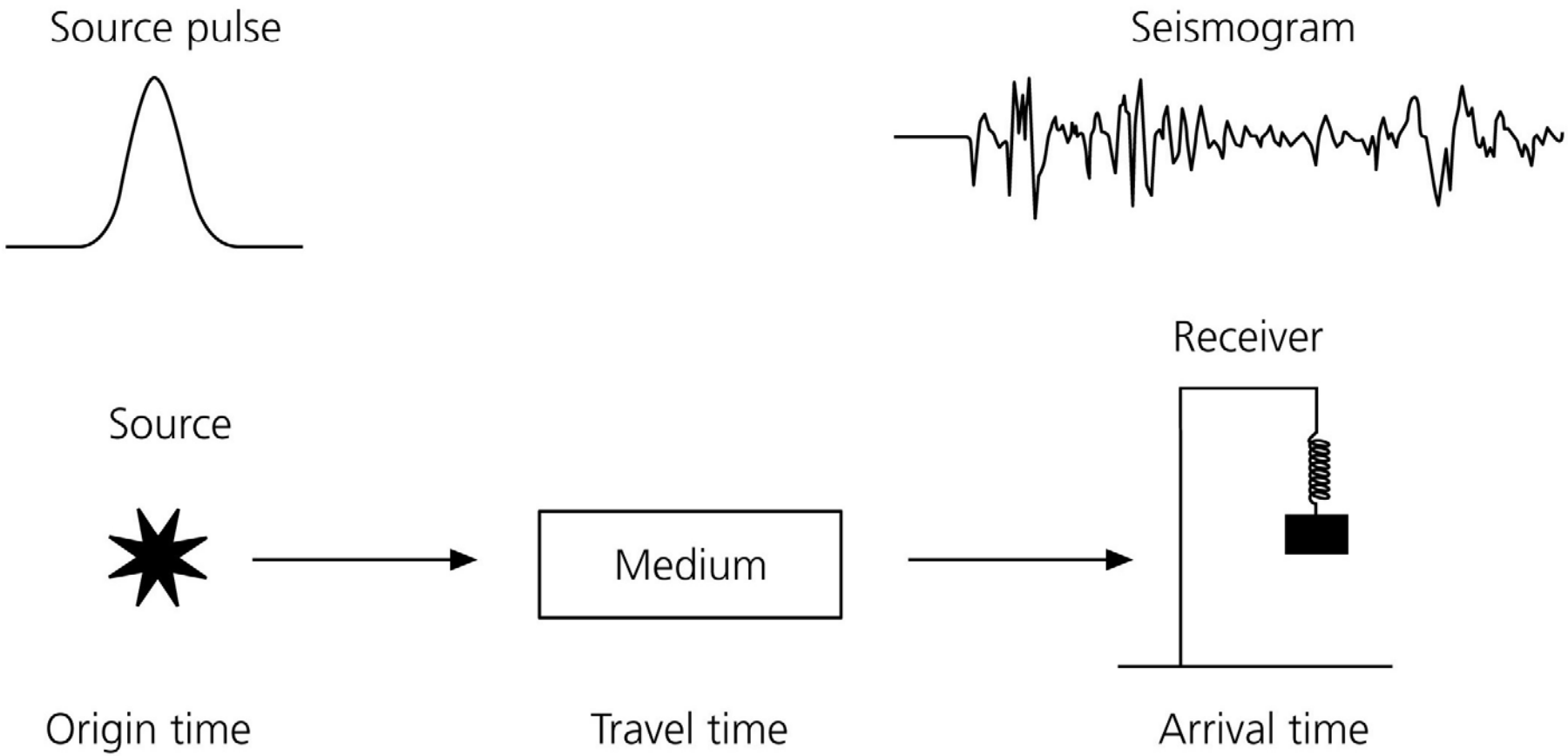


Normal

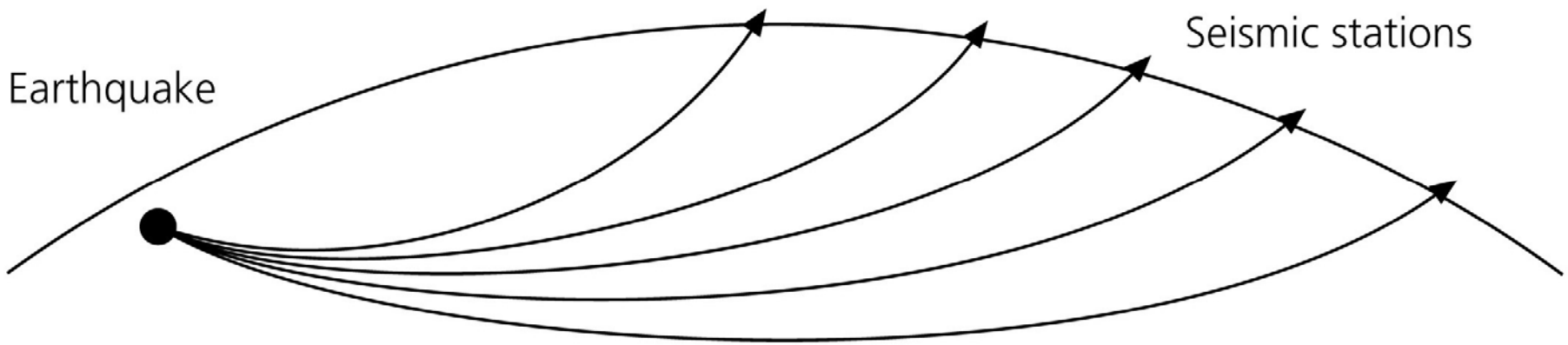
Source: USGS

Earthquake waves and recordings

Origin of seismic signal

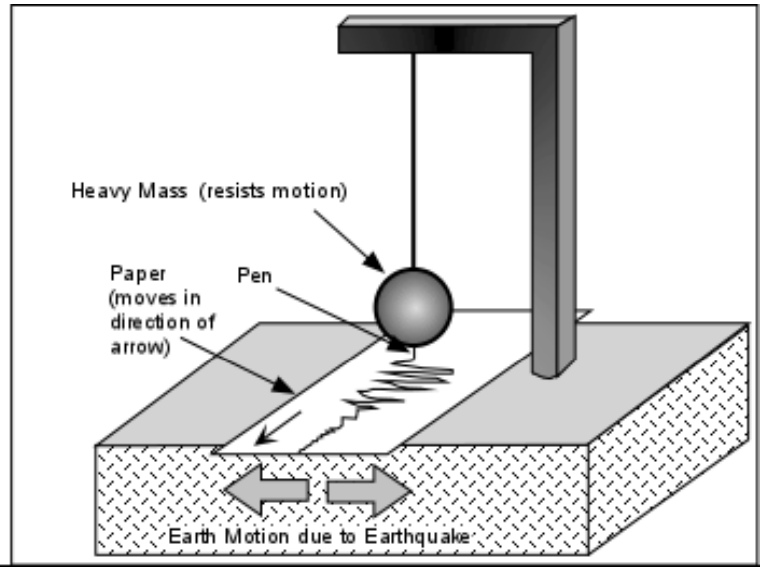


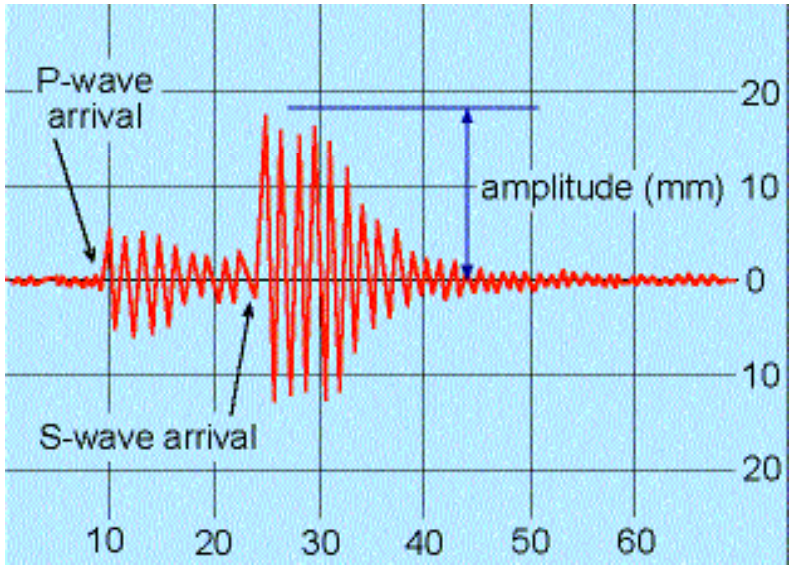
Schematic ray paths



Seismographs

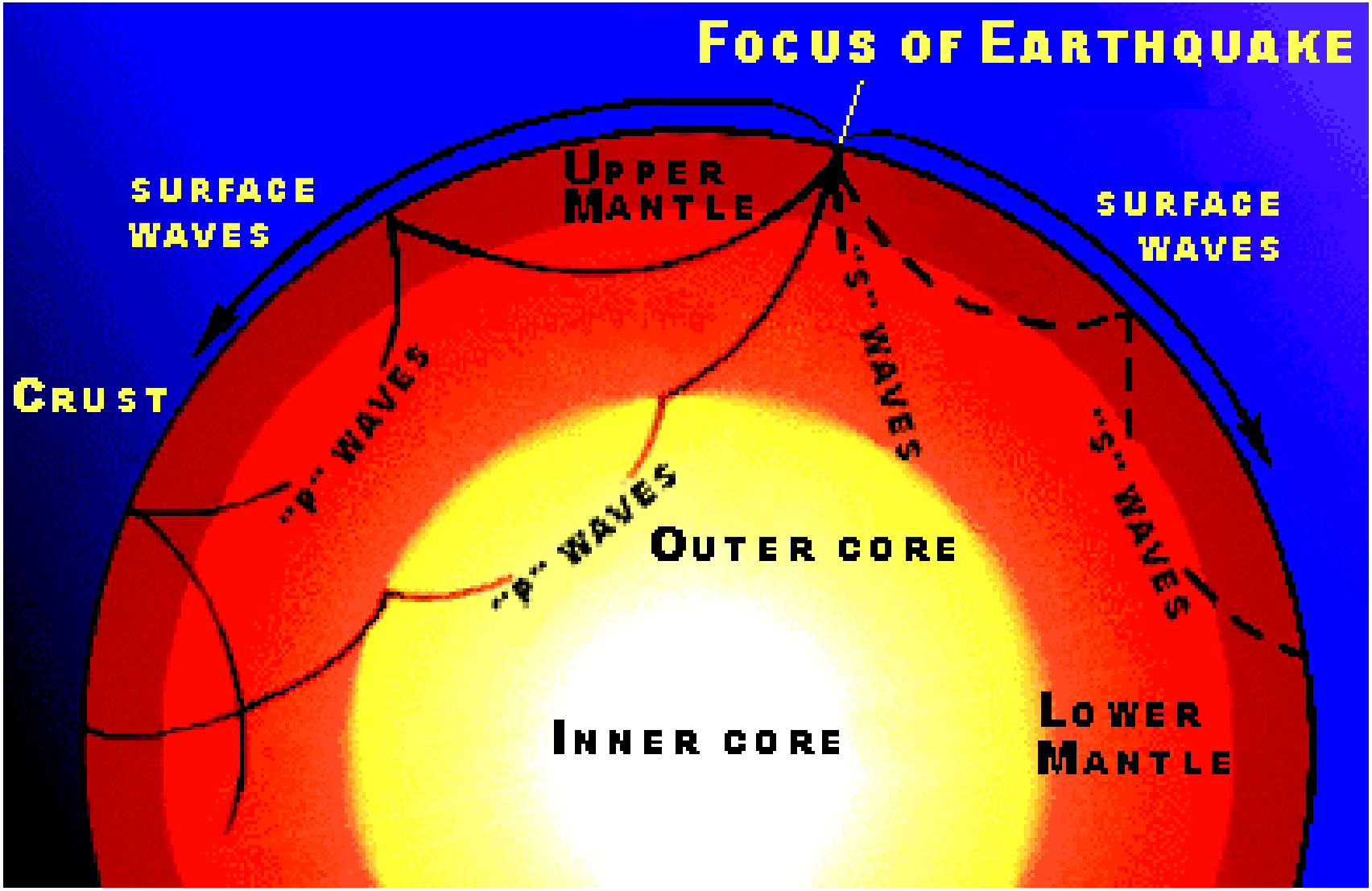
- Records as a function of time, the motion of the earth's surface due to seismic waves
- Actual record is called: *Seismogram*





Seismic waves

- Body waves
  - P-Waves
    - Primary, Compressional, Longitudinal
  - S-Wave
    - Secondary, Shear, Transverse
- Surface waves
  - Love wave
    - Similar to S-waves
  - Rayleigh wave
    - “Surface ripples”


Focus of Earthquake
Surface Waves
Upper Mantle
Surface Waves
Crust
"P" Waves
"S" Waves
"S" Waves
"P" Waves
Outer core
Inner core
Lower Mantle

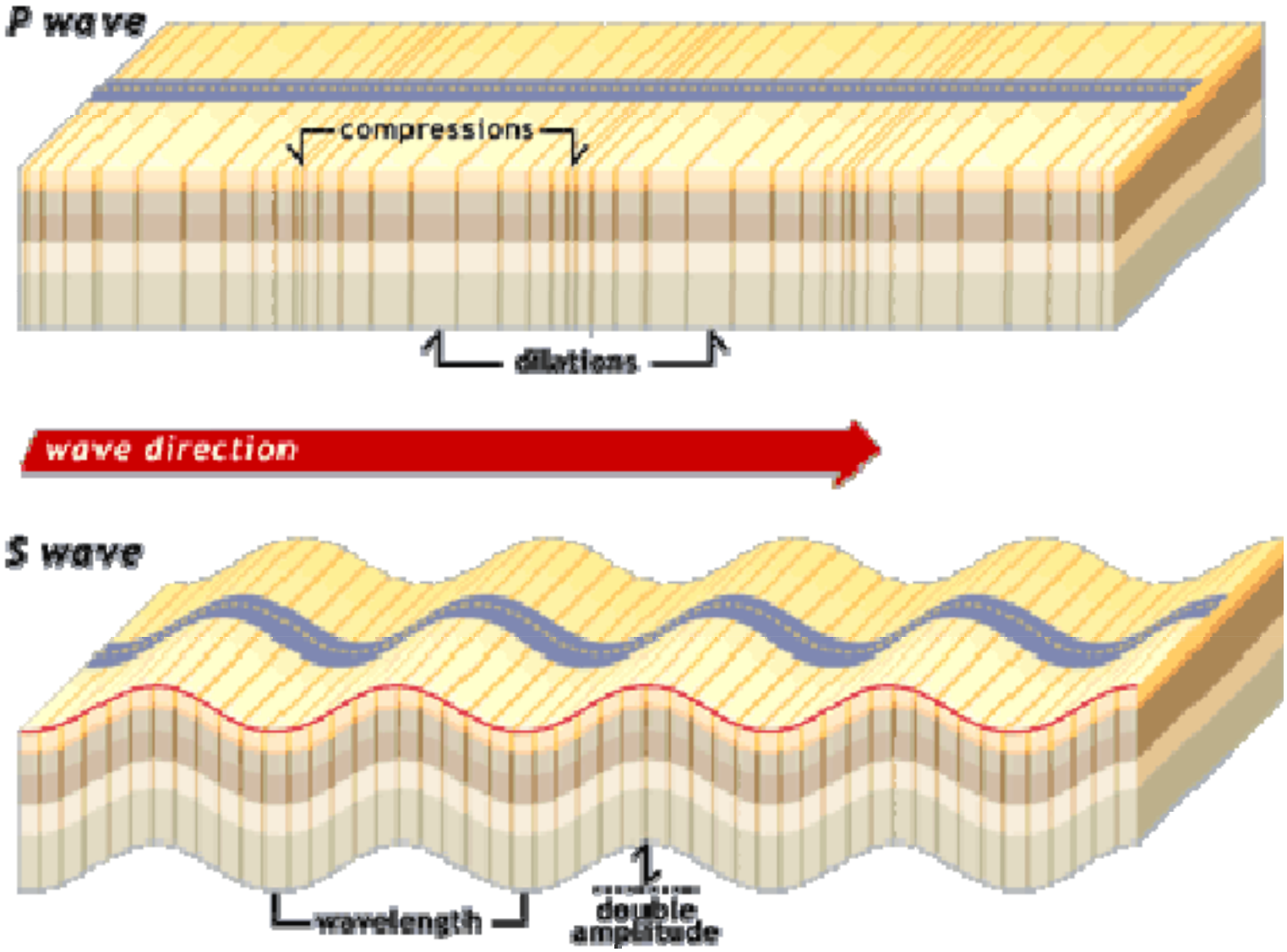
Body waves (P-wave)

- P or Primary Waves- Also known as Compressional waves
- Motion of matter parallel to the direction of wave propagation.
- Fastest type of wave.
- P waves travel through all types of matter (gas, liquid, solid)

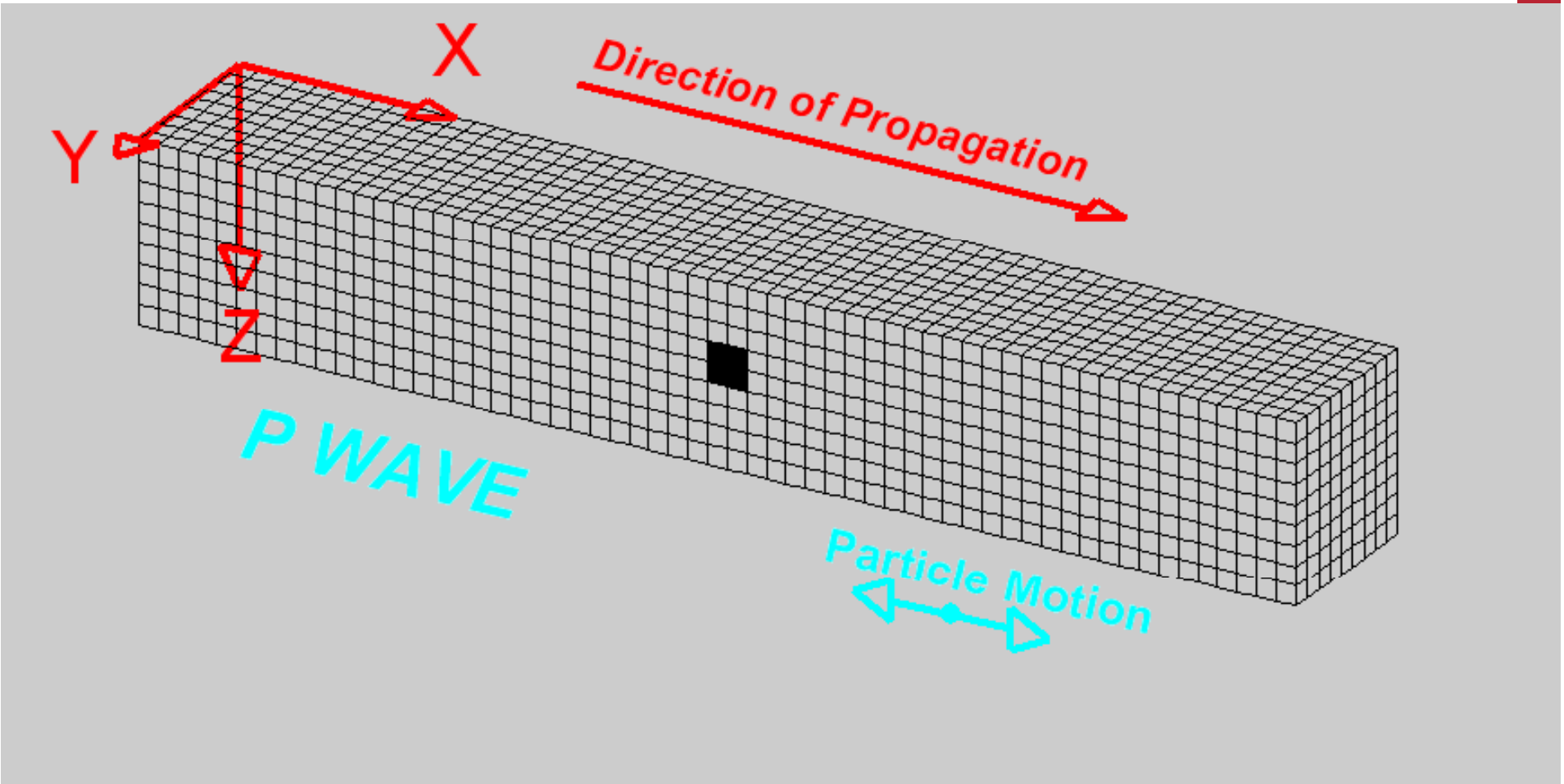
Body waves (S-wave)

- Motion of matter in a direction perpendicular to the direction of wave propagation.
- S waves are slower than P waves. They are the second fastest type of wave. They tend to arrive second at the station.
- The velocity of S waves is controlled by how the material through which wave is traveling responds to shear forces. It also depends on the density of the material.
- S waves only travel through solids

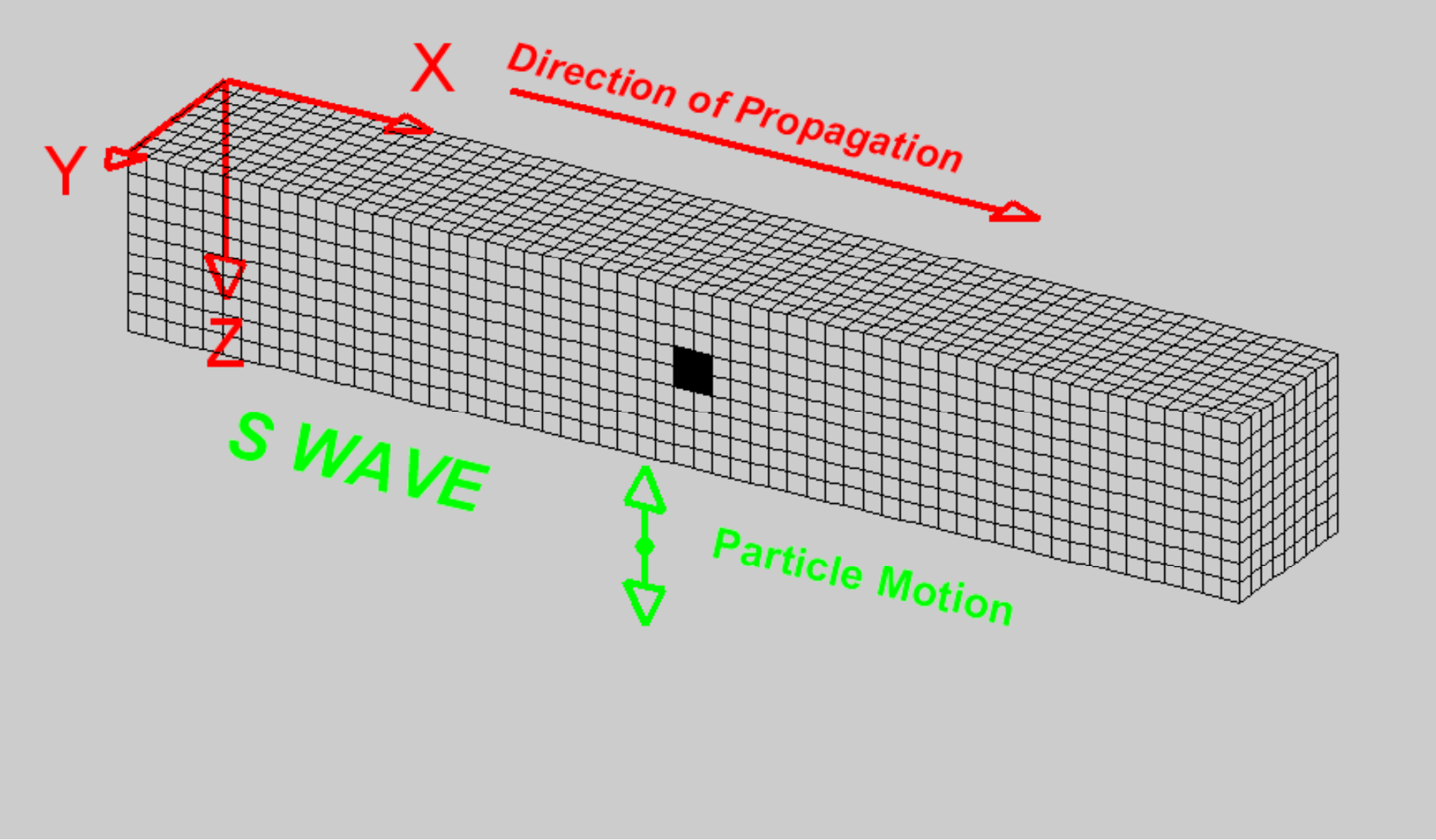
Seismic waves



Body waves (P-wave)



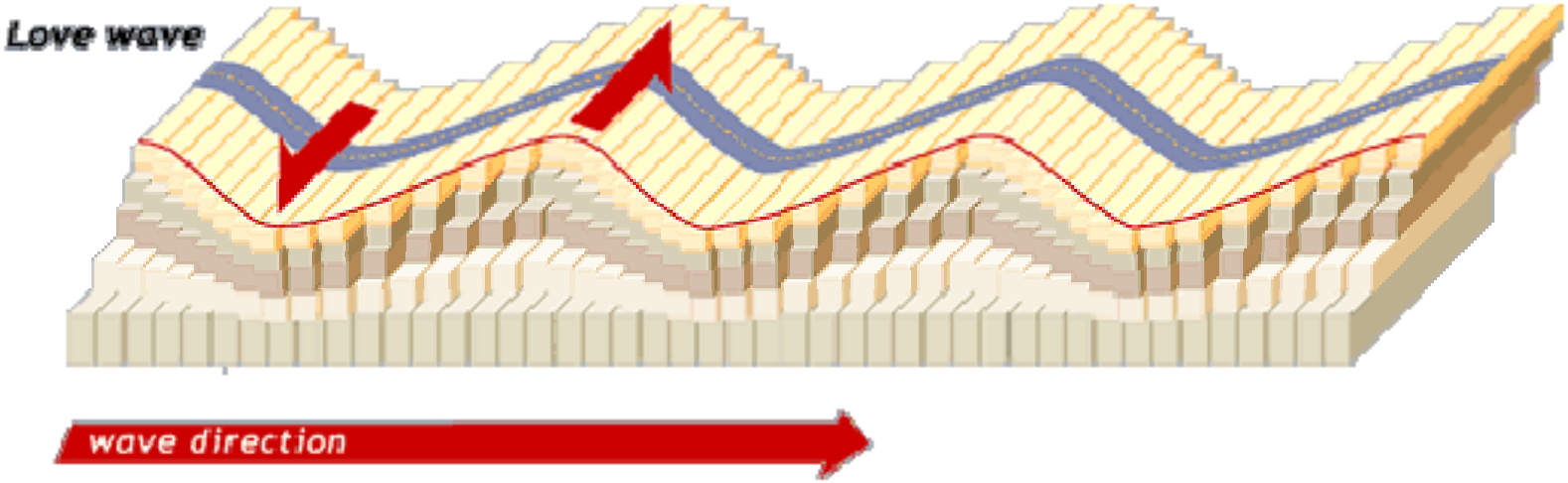
Body waves (S-wave)

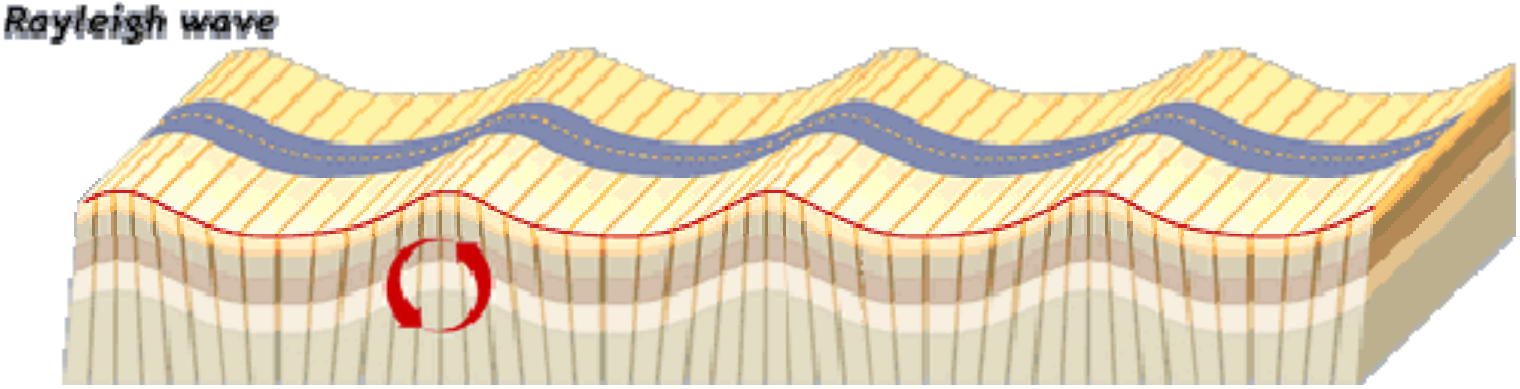


Surface waves

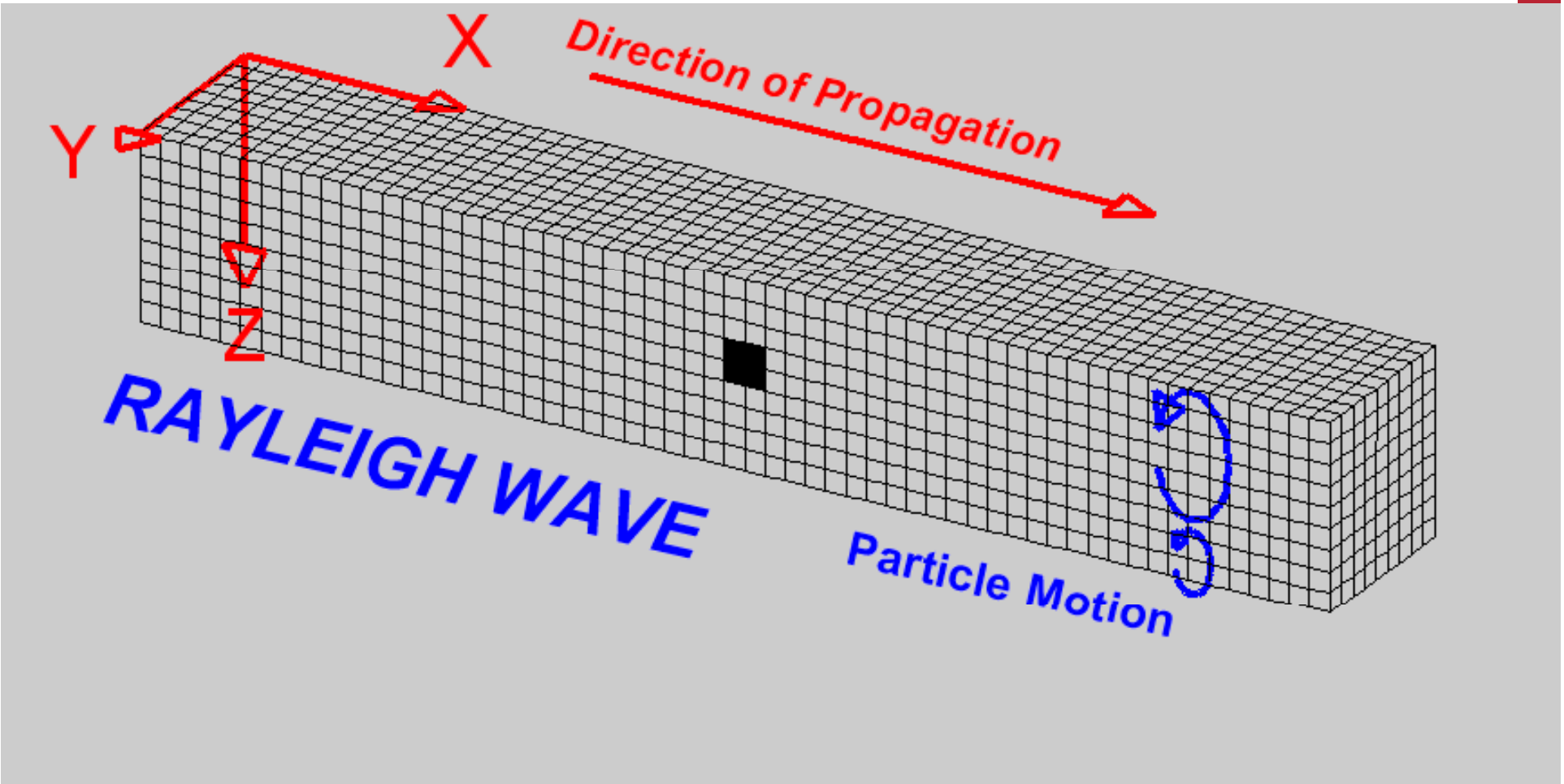
- Some body waves travel up from the earthquake hypocenter (focus) and spread towards the surface where they cause the Earth's surface to vibrate.
- This vibration generates surface waves which travel within the upper few kilometers of the Earth's crust.
- Slowest of all seismic waves.
- Surface waves only travel through solids

Seismic waves





Surface waves (Rayleigh)



Surface waves (Love)

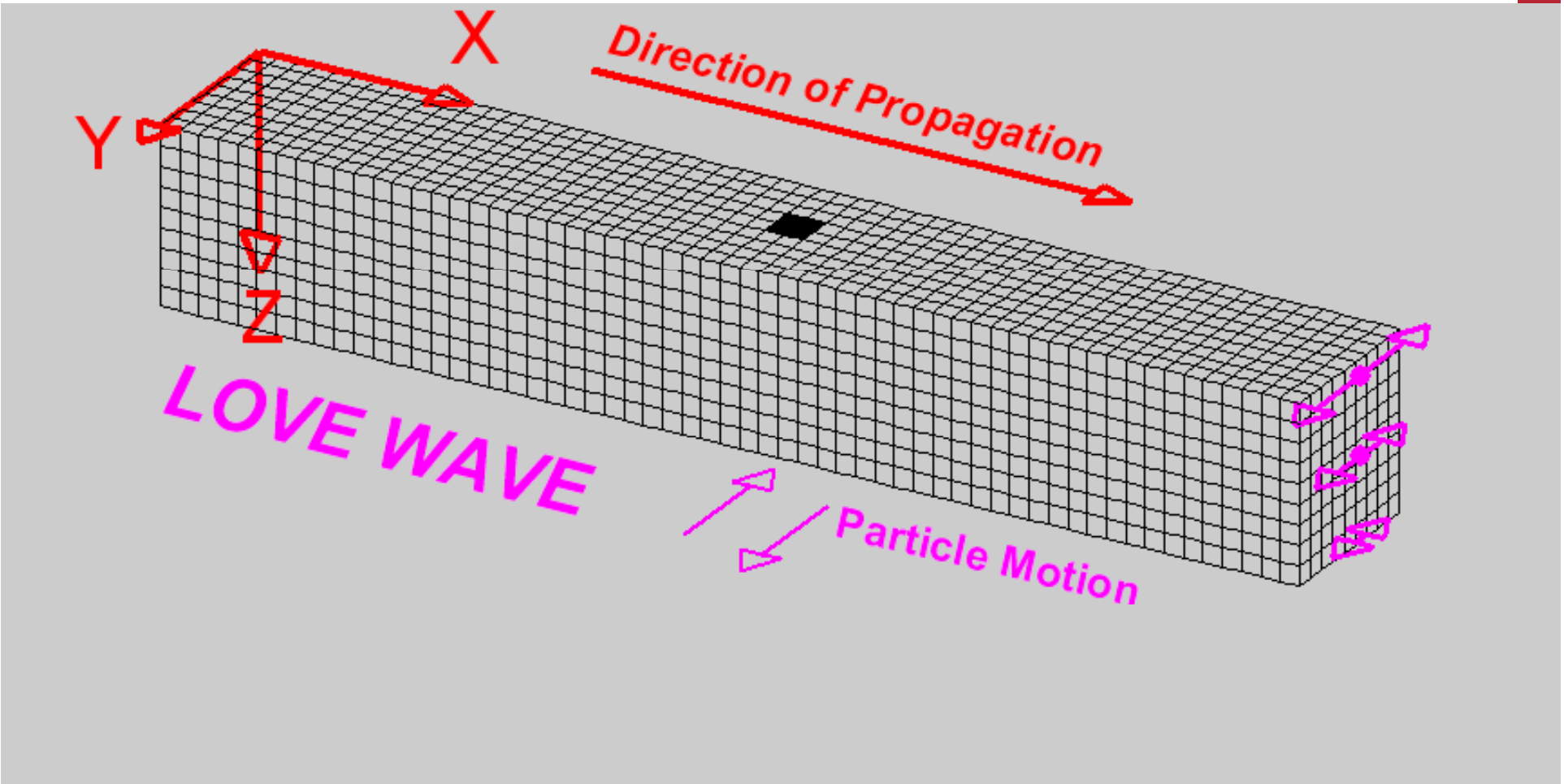
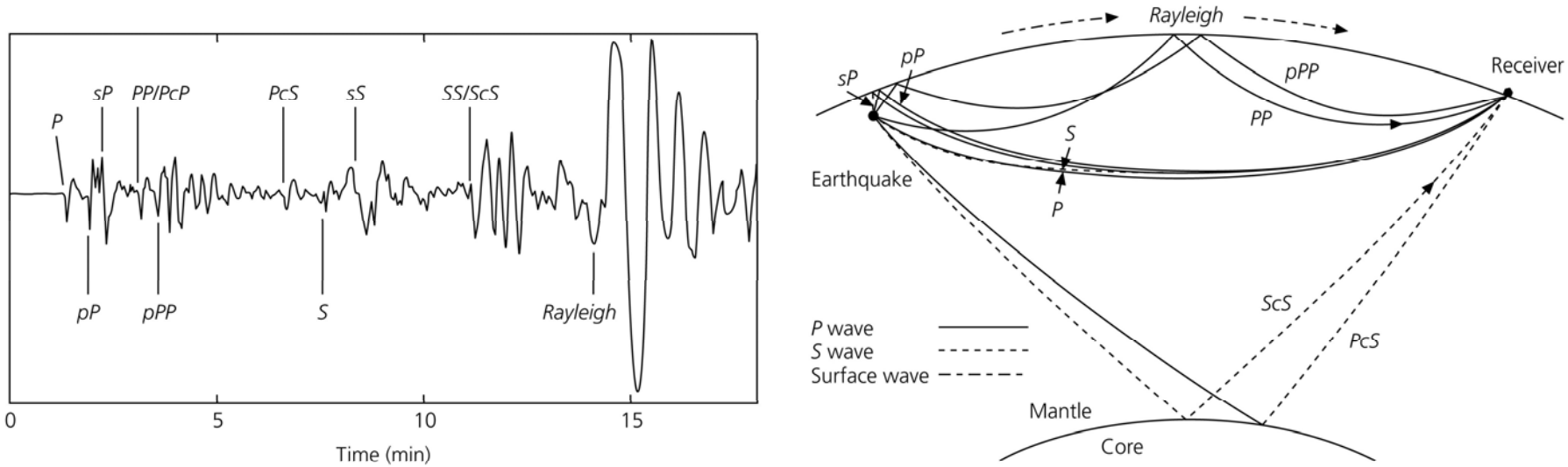
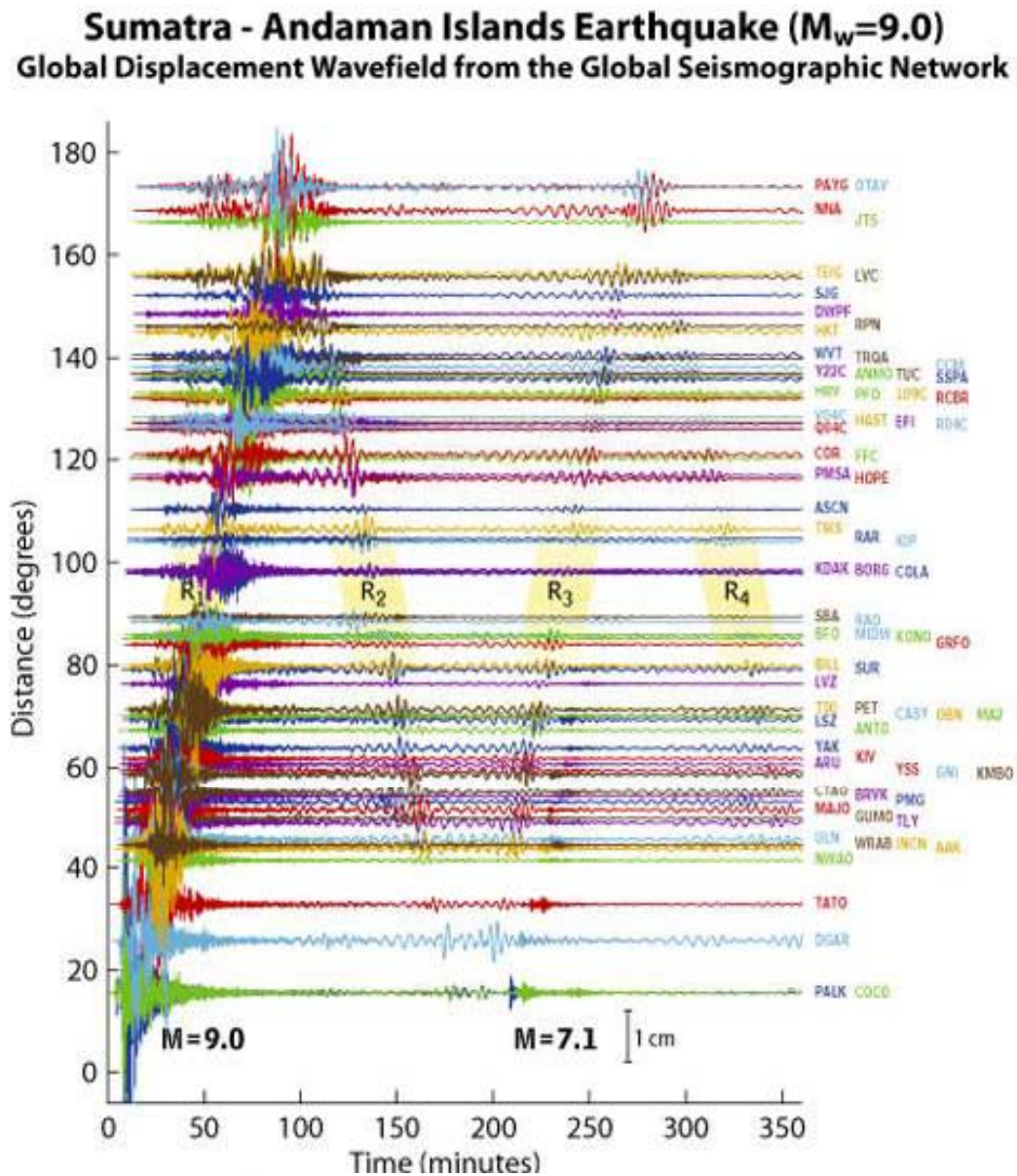


Figure 1.1-3: Example of seismogram, showing accompanying ray paths.



Earthquake Sumatra



Earthquake magnitude

Magnitude of an earthquake

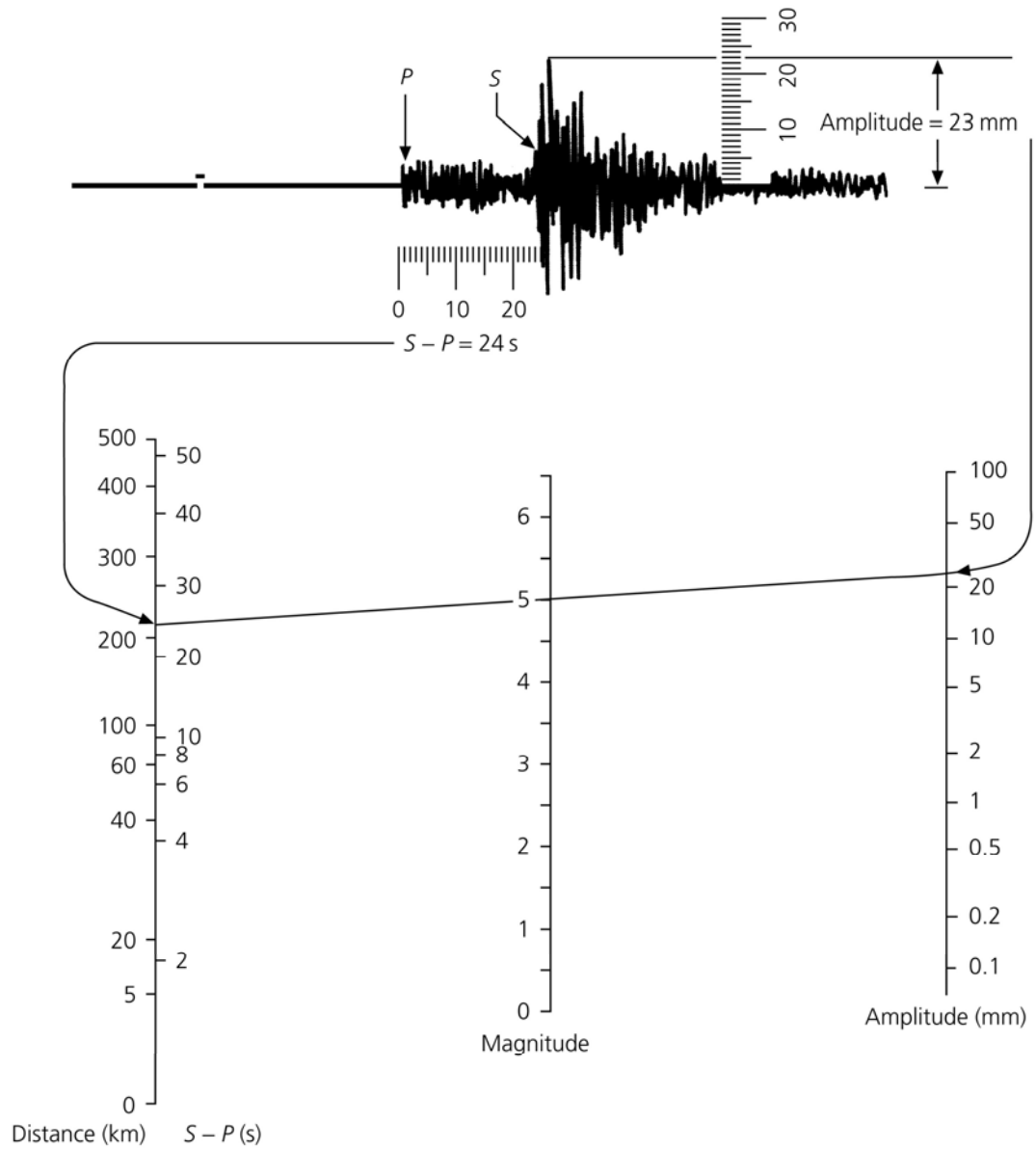
- 2 ways of measuring strength of an earthquake:
  - Magnitude: amount of energy released - "Small earthquakes make small waves, big earthquakes make big waves"
  - Intensity: amount of damage, reaction of people
- Magnitude scales:
  - Local magnitude scale (M_L)
  - Surface wave magnitude scale (M_s)
  - Body wave magnitude scale (M_b)
  - Moment magnitude scale (M_w)

Local Magnitude (M_L)

- The "Richter" magnitude scale (1958)
- Developed for shallow and local eq's
- M_L=log A + distance correction factor
  - M_L = local or Richter magnitude scale
  - A = Amplitude, in millimeters, measured directly from the paper record of the Wood-Anderson seismometer
- Log-scale: 10-time increase in amplitude (energy) – 1 scale level up

Richter scale: $M_L = \log A + 3\log(8\Delta t) - 2.92$

A = amplitude in mm
Δt = time difference between P and S arrival in sec



Surface Wave Magnitude (M_S)

- Based on the amplitude of surface waves having a period of 20 sec (0.05 Hz)
- $Ms = \text{Log } A' + 1.66 \text{ Log } \Delta + 3.3$
  - Δ = epicentral distance (in degrees)
  - A' = max ground displacement (μm) – independent of seismograph type
- Bath, 1966

  - *Moderate to large earthquakes*
  - *Shallow focal depth (< 70 km)*
  - *Distance > 1000 km from epicentre*

Body wave magnitude (M_B)

- Based on the P-wave amplitude having a seismic-wave period between 0.1 and 3.0 sec
- Distance > 5 degrees from epicentre
- Gutenberg and Richter, 1956

Moment magnitude (M_W)

- moment magnitude is based on very long period seismic signals → not a good measure for seismic hazards.
- Low frequency seismic signals are not necessarily the most destructive (a frequency of zero will actually cause no damage….).
- For large earthquakes therefore Mw is not a good measure since it neglects the high frequency content (and possible sub-ruptures)

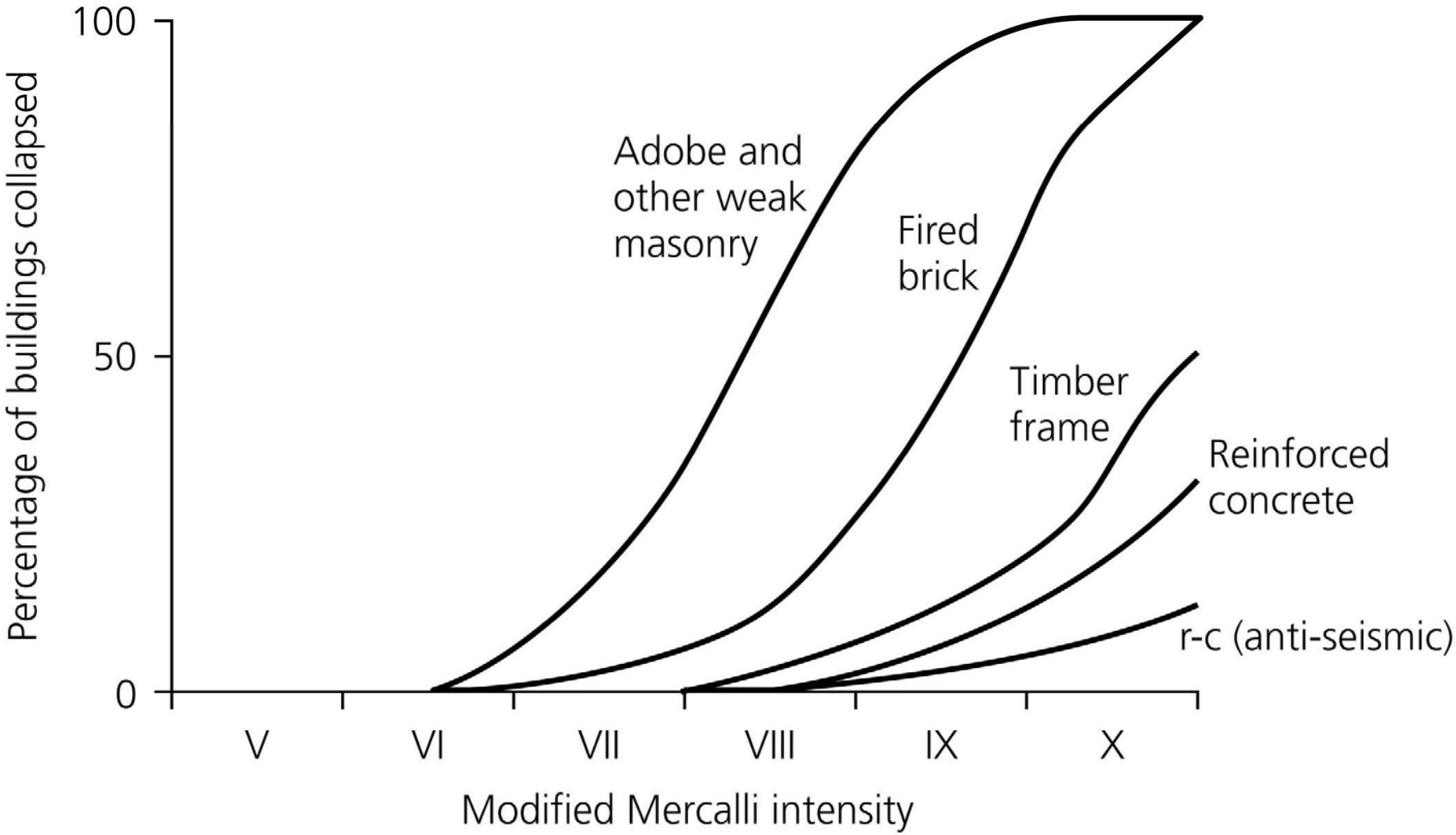
Intensity of an earthquake

- Based on:
  - Observations of damaged structures
  - Presence of secondary effects
  - Degree to which quake was felt by individuals
- Easy to determine in urban area, difficult in rural area
- Most commonly used:
  - Modified Mercalli Intensity scale (MMI)
  - MSK-64 (Medvedev-Sponheuer-Karnik)
  - EMS-98(European Macroseismic Scale)

MMI Intensity	Reaction of people, level of damage
I	People do not feel any Earth movement.
II	A few people might notice movement if they are at rest and/or on the upper floors of tall buildings.
III	Many people indoors feel movement. Hanging objects swing back and forth. People outdoors might not realize that an earthquake is occurring.
IV	Most people indoors feel movement. Hanging objects swing. Dishes, windows, and doors rattle. The earthquake feels like a heavy truck hitting the walls. A few people outdoors may feel movement. Parked cars rock.
V	Almost everyone feels movement. Sleeping people are awakened. Doors swing open or close. Dishes are broken. Pictures on the wall move. Small objects move or are turned over. Trees might shake. Liquids might spill out of open containers.
VI	Everyone feels movement. People have trouble walking. Objects fall from shelves. Pictures fall off walls. Furniture moves. Plaster in walls might crack. Trees and bushes shake. Damage is slight in poorly built buildings. No structural damage.
VII	People have difficulty standing. Drivers feel their cars shaking. Some furniture breaks. Loose bricks fall from buildings. Damage is slight to moderate in well-built buildings; considerable in poorly built buildings.
VIII	Drivers have trouble steering. Houses that are not bolted down might shift on their foundations. Tall structures such as towers and chimneys might twist and fall. Well-built buildings suffer slight damage. Poorly built structures suffer severe damage. Tree branches break. Hillsides might crack if the ground is wet. Water levels in wells might change.
IX	Well-built buildings suffer considerable damage. Houses that are not bolted down move off their foundations. Some underground pipes are broken. The ground cracks. Reservoirs suffer serious damage.
X	Most buildings and their foundations are destroyed. Some bridges are destroyed. Dams are seriously damaged. Large landslides occur. Water is thrown on the banks of canals, rivers, lakes. The ground cracks in large areas. Railroad tracks are bent slightly.
XI	Most buildings collapse. Some bridges are destroyed. Large cracks appear in the ground. Underground pipelines are destroyed. Railroad tracks are badly bent.
XII	Almost everything is destroyed. Objects are thrown into the air. The ground moves in waves or ripples. Large amounts of rock may move.

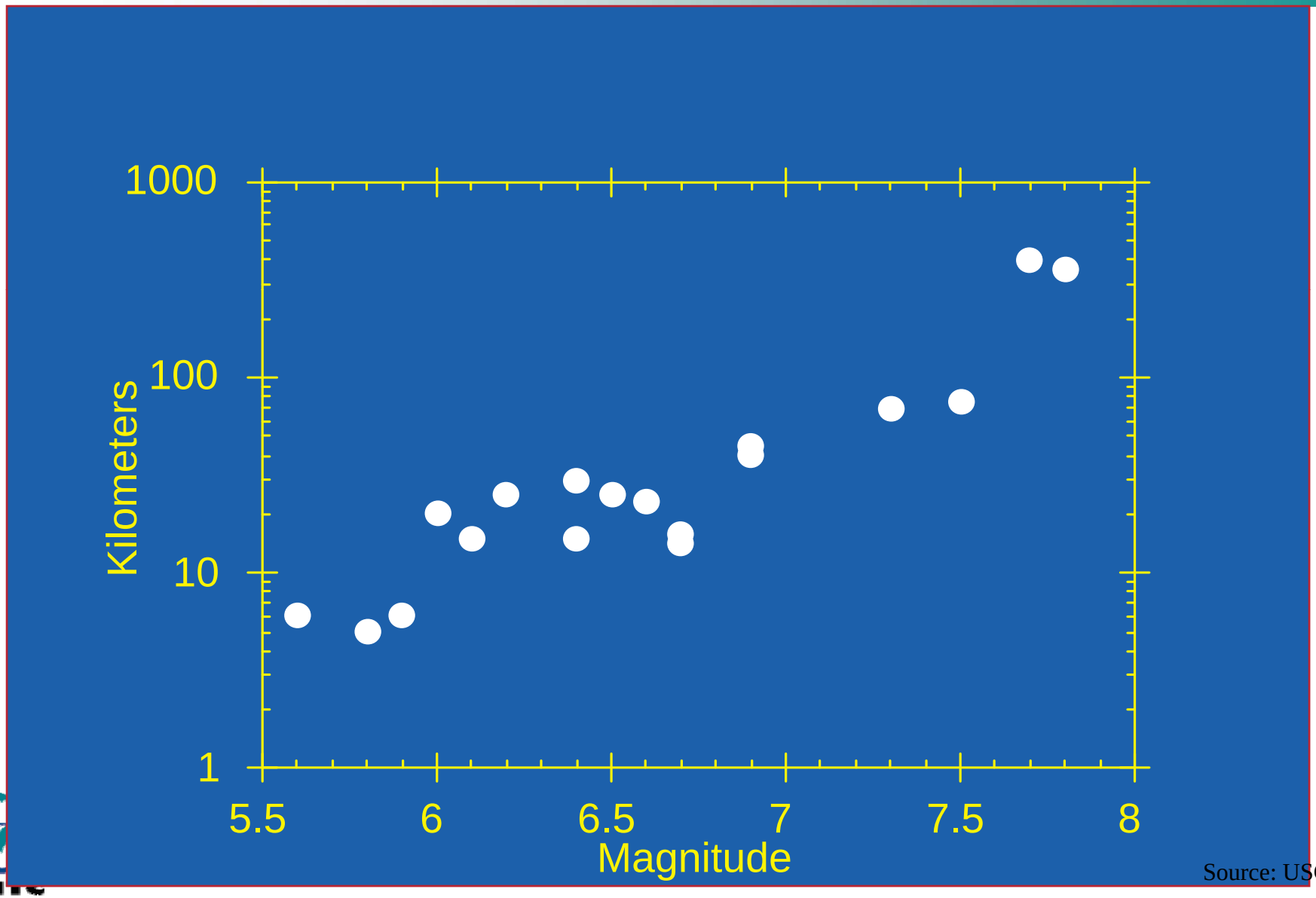
EMS intensity	Definition	Description of typical observed effects (abstracted)
I	Not felt	Not felt.
II	Scarcely felt	Felt only by very few individual people at rest in houses.
III	Weak	Felt indoors by a few people. People at rest feel a swaying or light trembling.
IV	Largely observed	Felt indoors by many people, outdoors by very few. A few people are awakened. Windows, doors and dishes rattle.
V	Strong	Felt indoors by most, outdoors by few. Many sleeping people awake. A few are frightened. Buildings tremble throughout. Hanging objects swing considerably. Small objects are shifted. Doors and windows swing open or shut.
VI	Slightly damaging	Many people are frightened and run outdoors. Some objects fall. Many houses suffer slight non-structural damage like hair-line cracks and fall of small pieces of plaster.
VII	Damaging	Most people are frightened and run outdoors. Furniture is shifted and objects fall from shelves in large numbers. Many well built ordinary buildings suffer moderate damage: small cracks in walls, fall of plaster, parts of chimneys fall down; older buildings may show large cracks in walls and failure of fill-in walls.
VIII	Heavily damaging	Many people find it difficult to stand. Many houses have large cracks in walls. A few well built ordinary buildings show serious failure of walls, while weak older structures may collapse.
IX	Destructive	General panic. Many weak constructions collapse. Even well built ordinary buildings show very heavy damage: serious failure of walls and partial structural failure.
X	Very destructive	Many ordinary well built buildings collapse.
XI	Devastating	Most ordinary well built buildings collapse, even some with good earthquake resistant design are destroyed.
XII	Completely devastating	Almost all buildings are destroyed.

Earthquake intensity vs damage



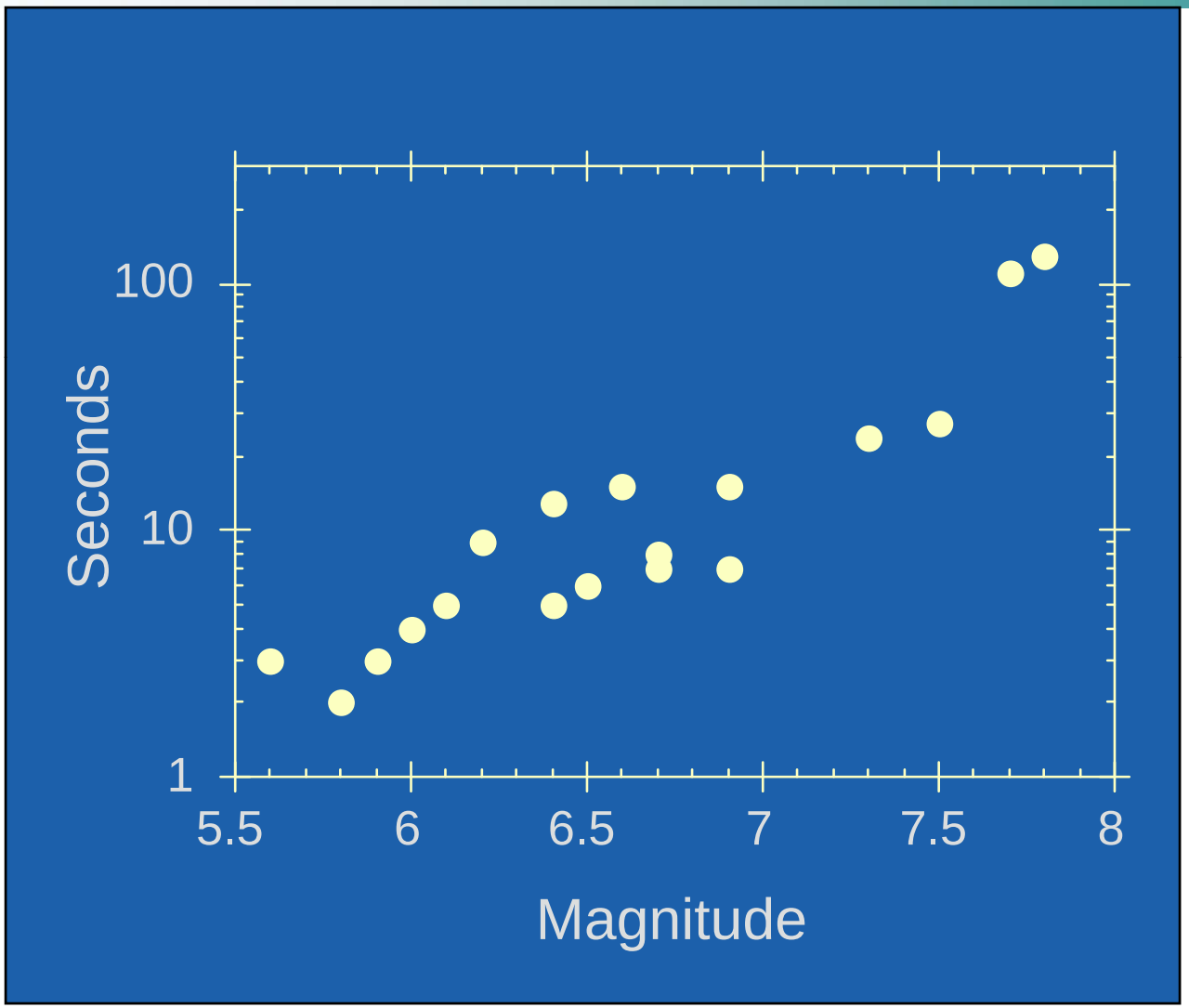
Earthquake catalogs and statistics

Bigger Faults Make Bigger Earthquakes



Source: USGS

Bigger Earthquakes Last a Longer Time



Source: USGS

Earthquake energy vs ground motion

TABLE 4 - Magnitude vs. Ground Motion and Energy

Magnitude Change	Ground Motion Change (Displacement)	Energy Change
1.0	10.0 times	about 32 times
0.5	3.2 times	about 5.5 times
0.3	2.0 times	about 3 times
0.1	1.3 times	about 1.4 times

This table shows that a M=7.2 earthquake produces 10 times more ground motion than a M=6.2 earthquake but releases 32 times more energy.

Introduction

What is frequency?

- The rate at which something happens or is repeated
- The fact of something happening often
- The rate at which a waves vibrates

Introduction

Frequency analysis: Analysis of the rate at which something happens or is repeated

Unfortunately, this is not well defined:

- Has variations over time
- Is varying spatially
- Can be very irregular in occurrence
- Incomplete over total range of occurences (small occurences often go undetected)

Introduction

But what are we studying? What is the 'something' that is occurring?

In case of earthquakes it could be:

1) Just any earthquake
2) Only earthquakes above a certain threshold
3) Only earthquakes that cause damage
4) Only earthquakes due to which people died?
5) Type of earthquakes
6) Depth range of earthquakes

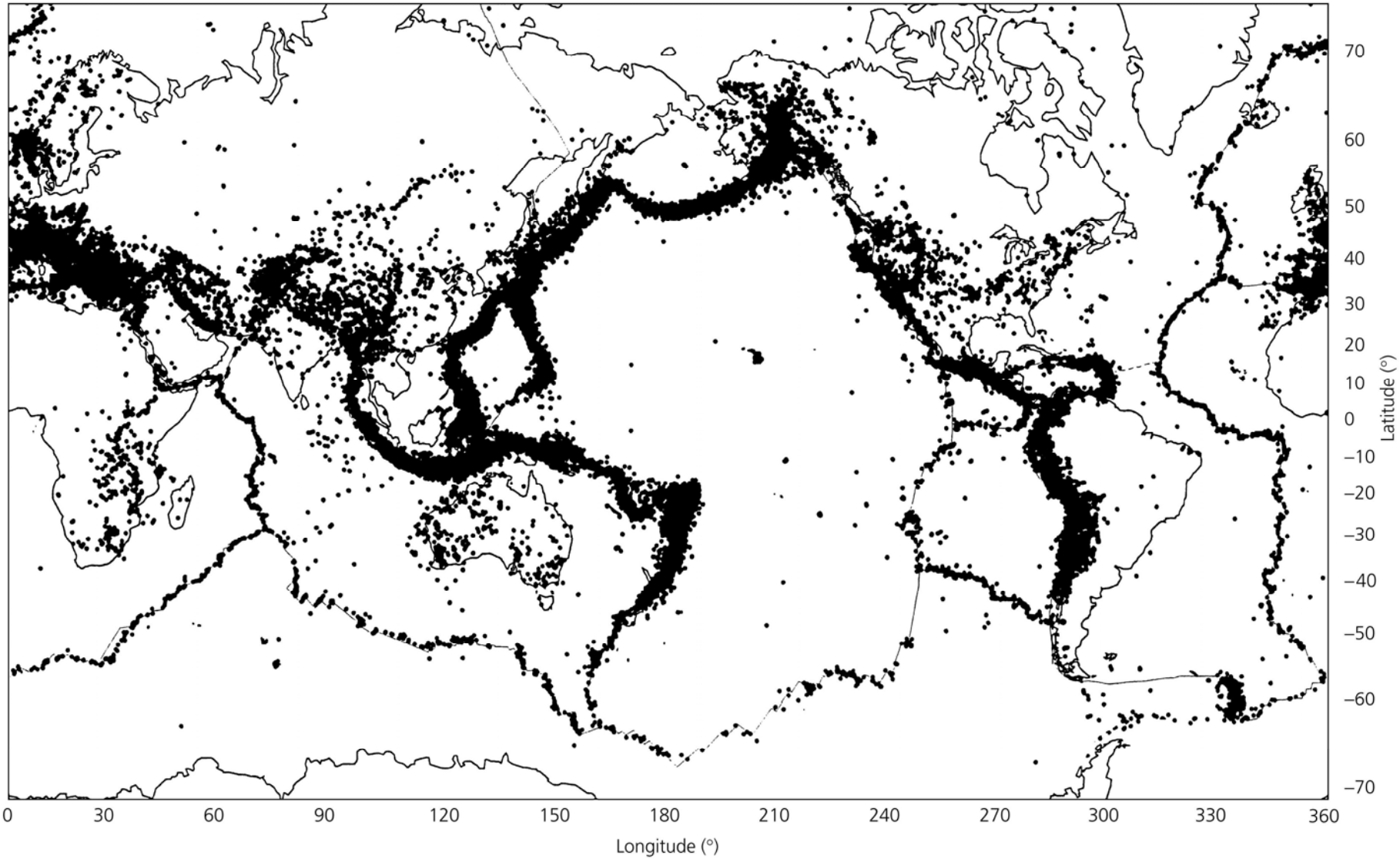
Earthquake occurence – all quakes

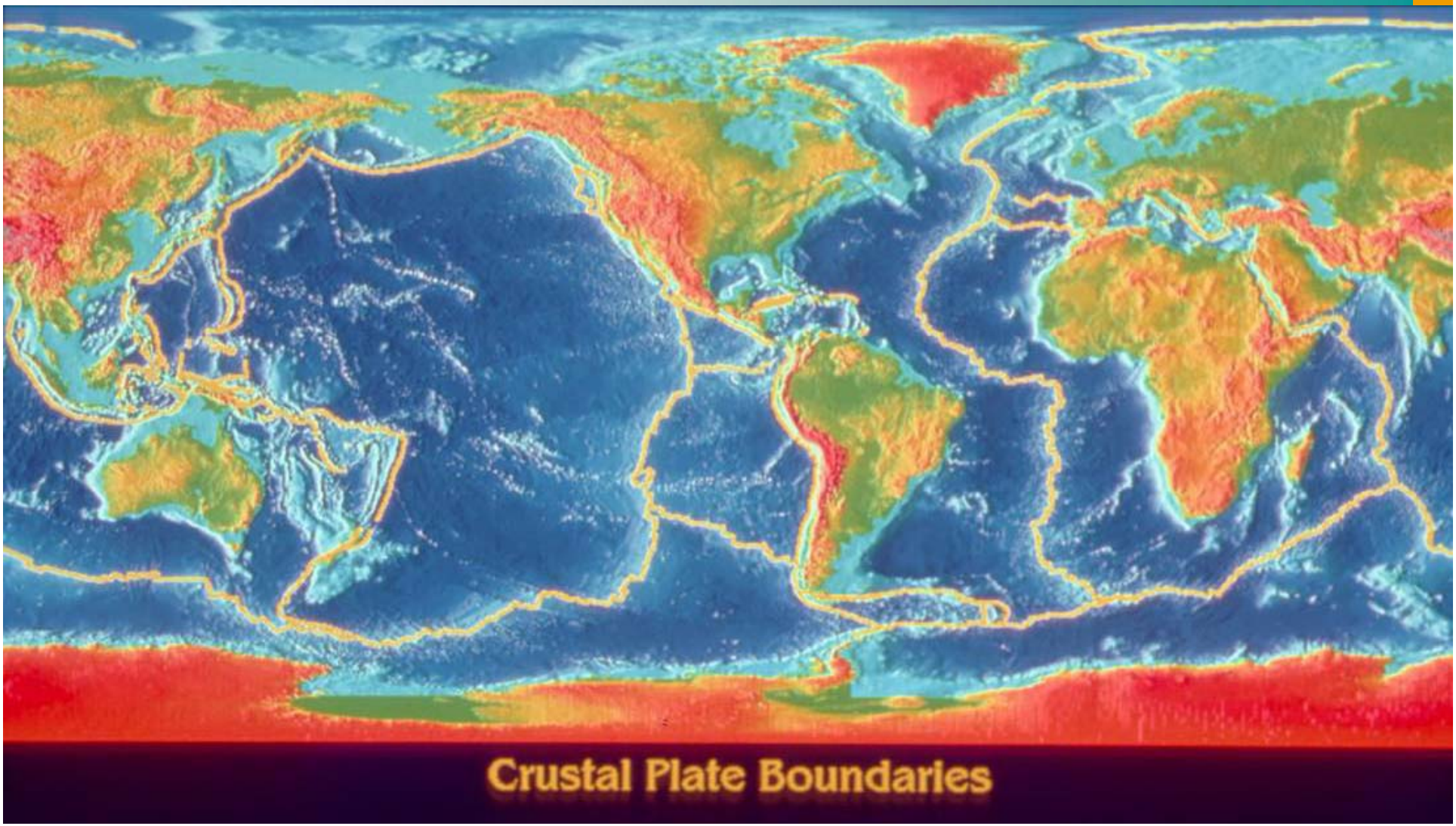
Frequency of Occurrence of Earthquakes

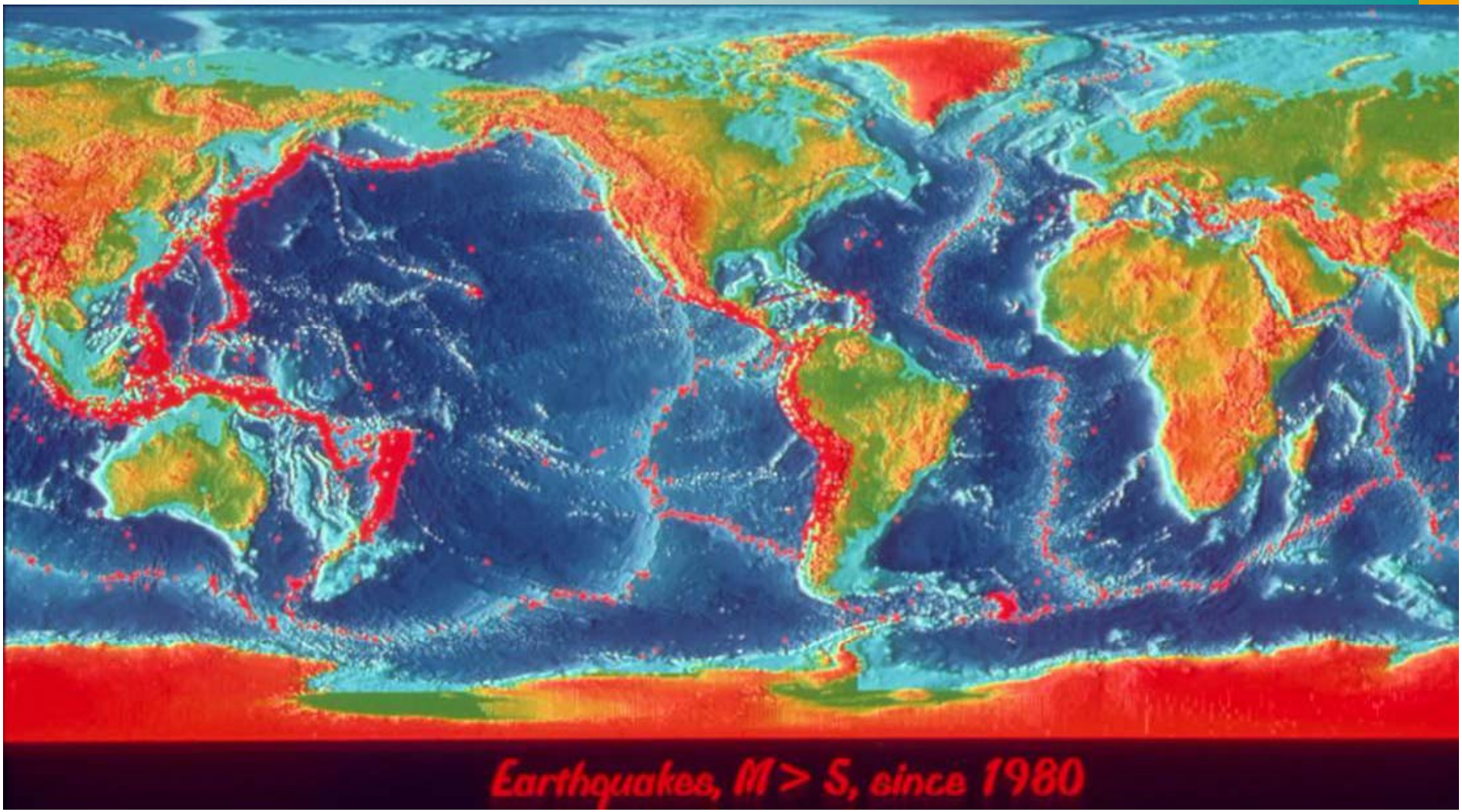
Descriptor	Magnitude	Average Annually	Per day
Great	8 and higher	1 [1]	
Major	7 - 7.9	17 [2]	0.5
Strong	6 - 6.9	134 [2]	4
Moderate	5 - 5.9	1319 [2]	36
Light	4 - 4.9	13,000 (estimated)	360 (every 4 minutes….)
Minor	3 - 3.9	130,000 (estimated)	3600 (every 24 seconds….)
Very Minor	2 - 2.9	1,300,000 (estimated)	

[1] Based on observations since 1900.
[2] Based on onservations since 1990.

Global seismicity over 30 years




Crustal Plate Boundaries


Earthquakes, M > 5, since 1980

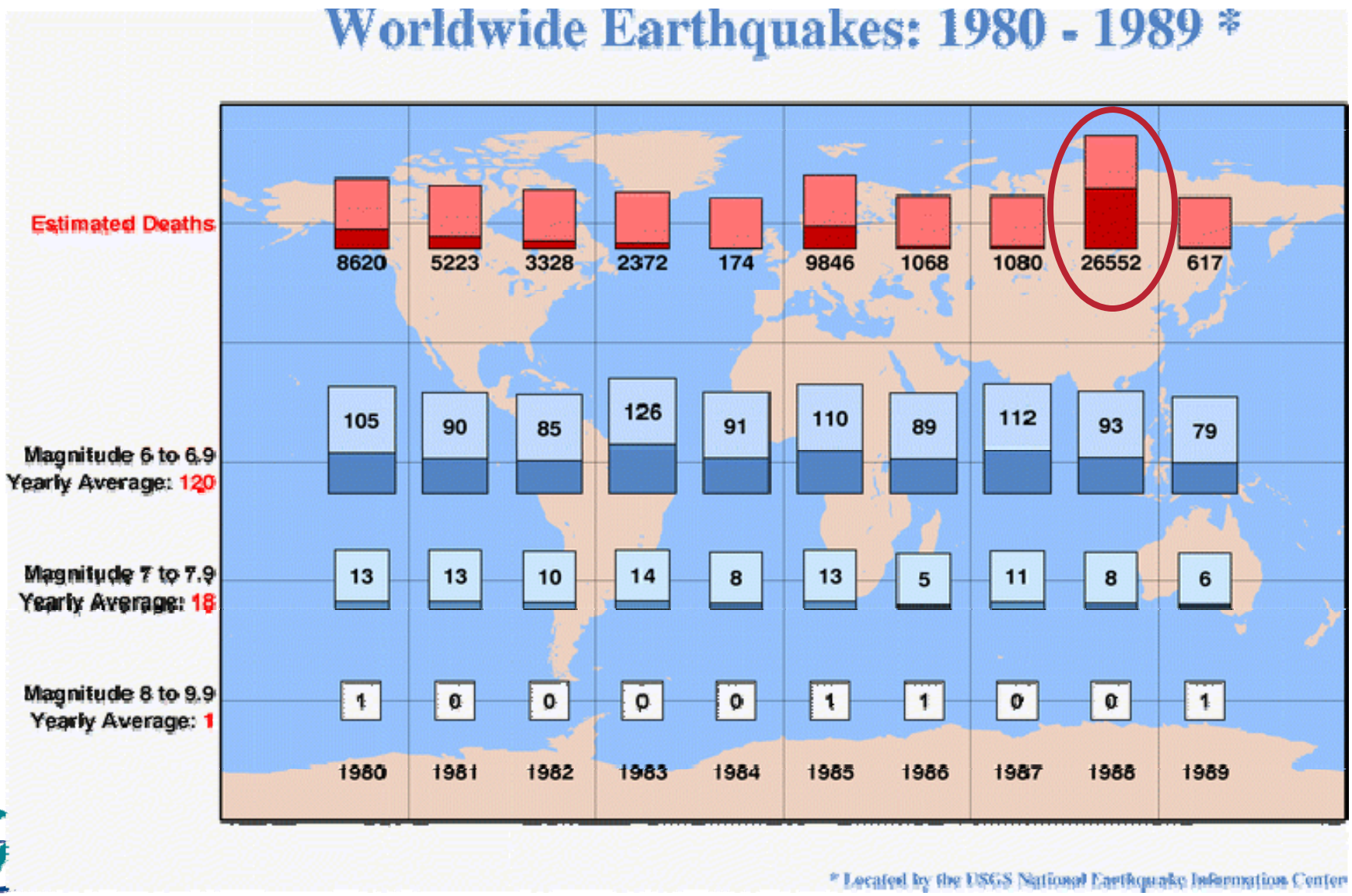
Earthquake occurence – 10 yr period

Number of Earthquakes Worldwide for 1990 - 1999
Located by the US Geological Survey National Earthquake Information Center

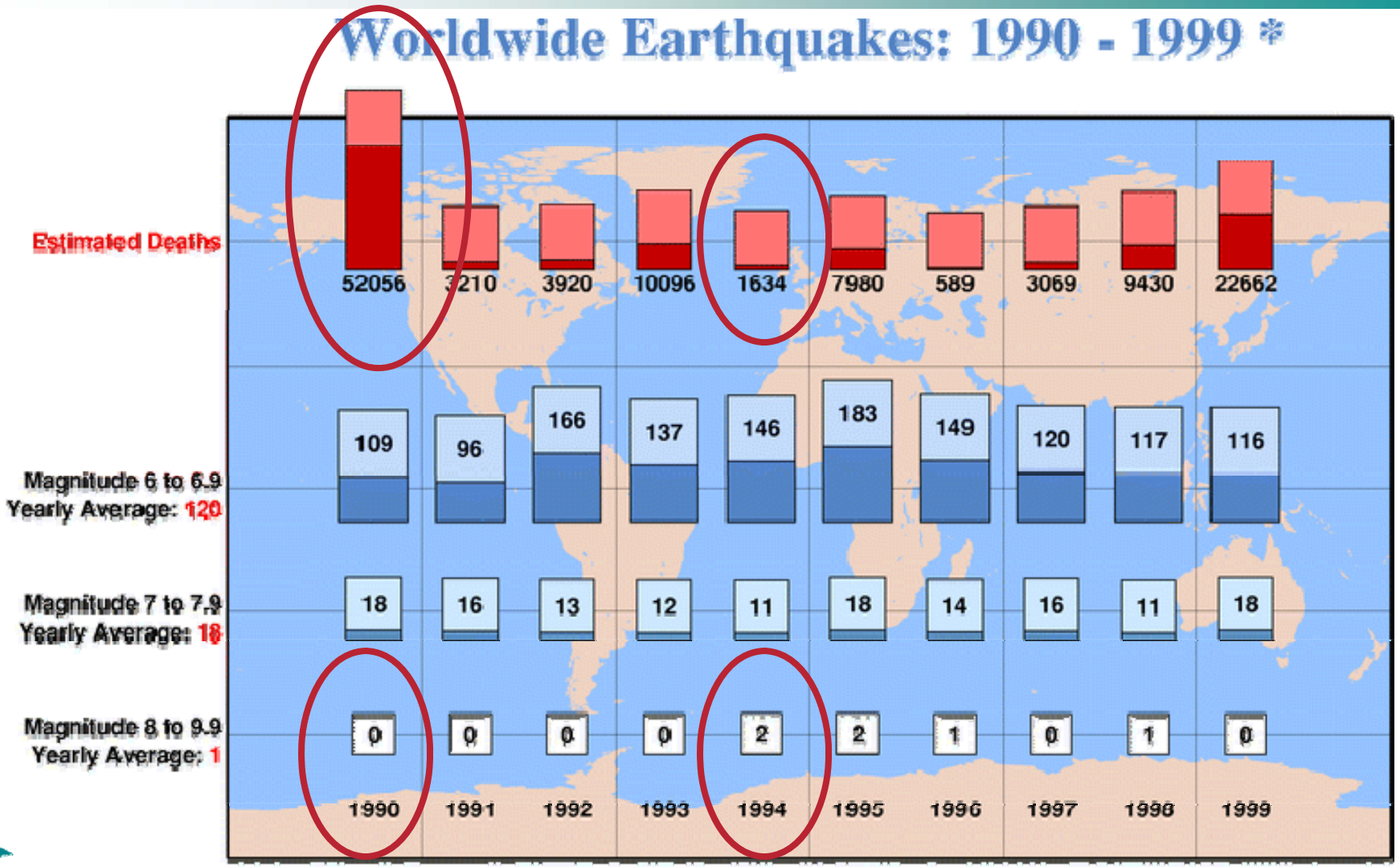
Magnitude	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
8.0 to 9.9	0	0	0	0	2	2	1	0	1	0
7.0 to 7.9	18	16	13	12	11	18	14	16	11	18
6.0 to 6.9	109	96	166	137	146	183	149	120	117	116
5.0 to 5.9	1617	1457	1498	1426	1542	1318	1222	1113	979	1104
4.0 to 4.9	4437	4335	5128	4999	4518	8003	8756	7903	7303	6972
3.0 to 3.9	2517	2990	4692	4326	5041	5151	4923	4513	5945	5605
2.0 to 2.9	2364	2925	3066	5393	5371	3842	2391	2400	4091	4201
1.0 to 1.9	474	801	886	1170	779	645	295	388	805	715
0.1 to 0.9	0	1	3	9	17	19	1	4	10	5
No Magnitude	5054	3863	4072	3997	1944	1826	2186	3415	2426	2096
Total	16590	16484	19524	21476	19371	21007	19938	19872	21688	20832
Estimated Deaths	52056	3210	3920	10096	1634	7980	589	3069	9430	22662

?

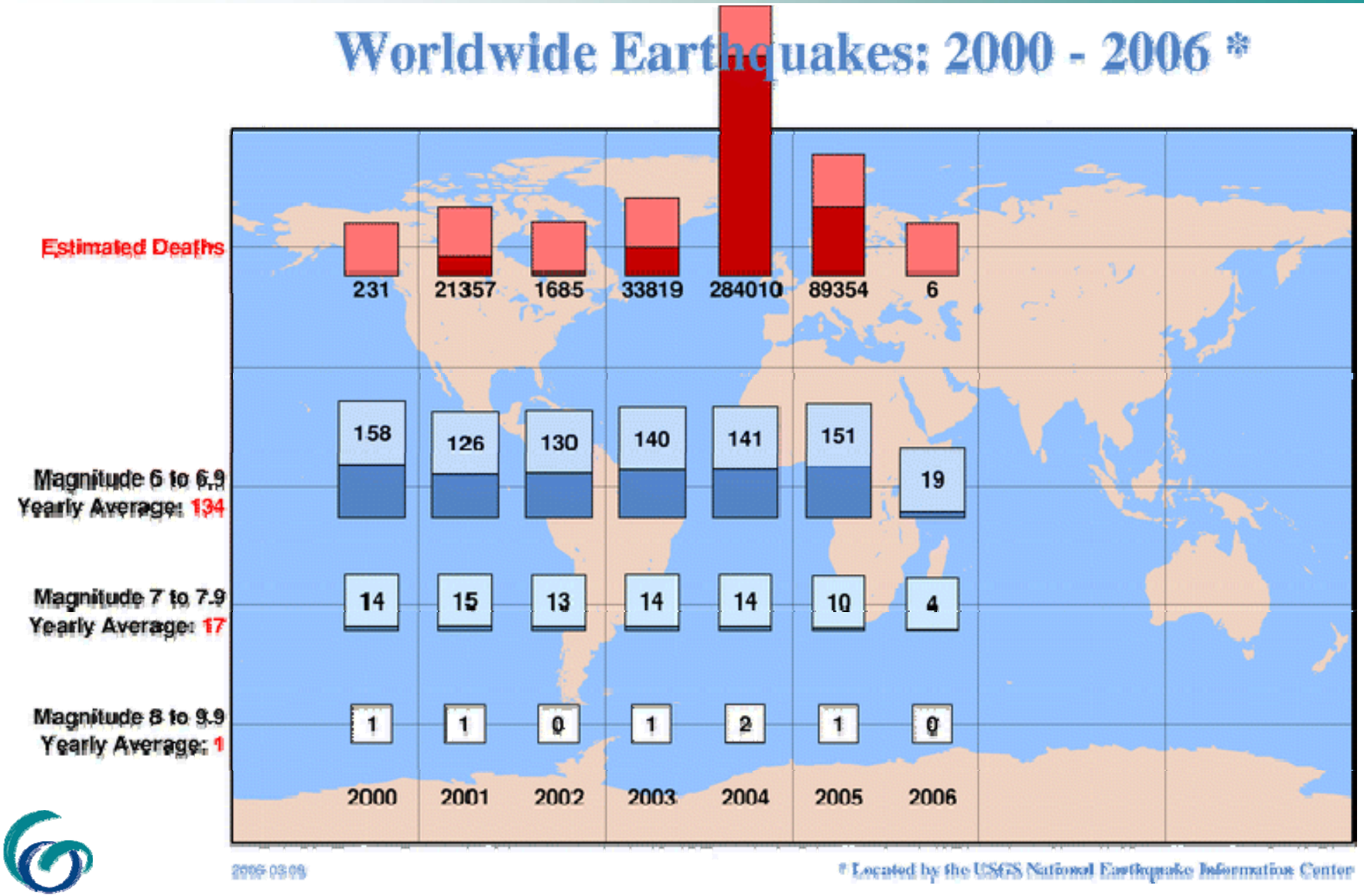
Earthquake statistics



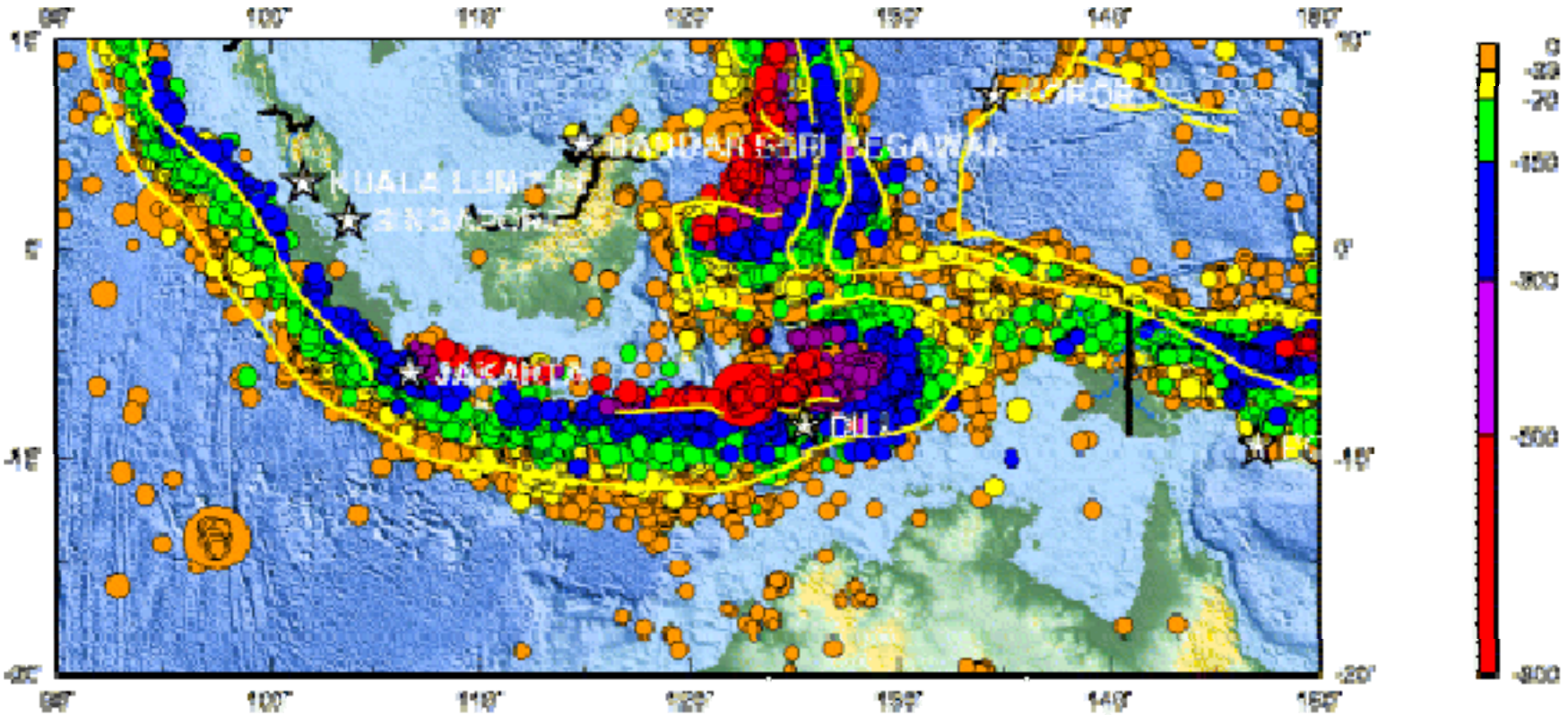
Earthquake statistics



Earthquake statistics



Earthquake statistics



Seismicity of Indonesia, 1990 - 2000

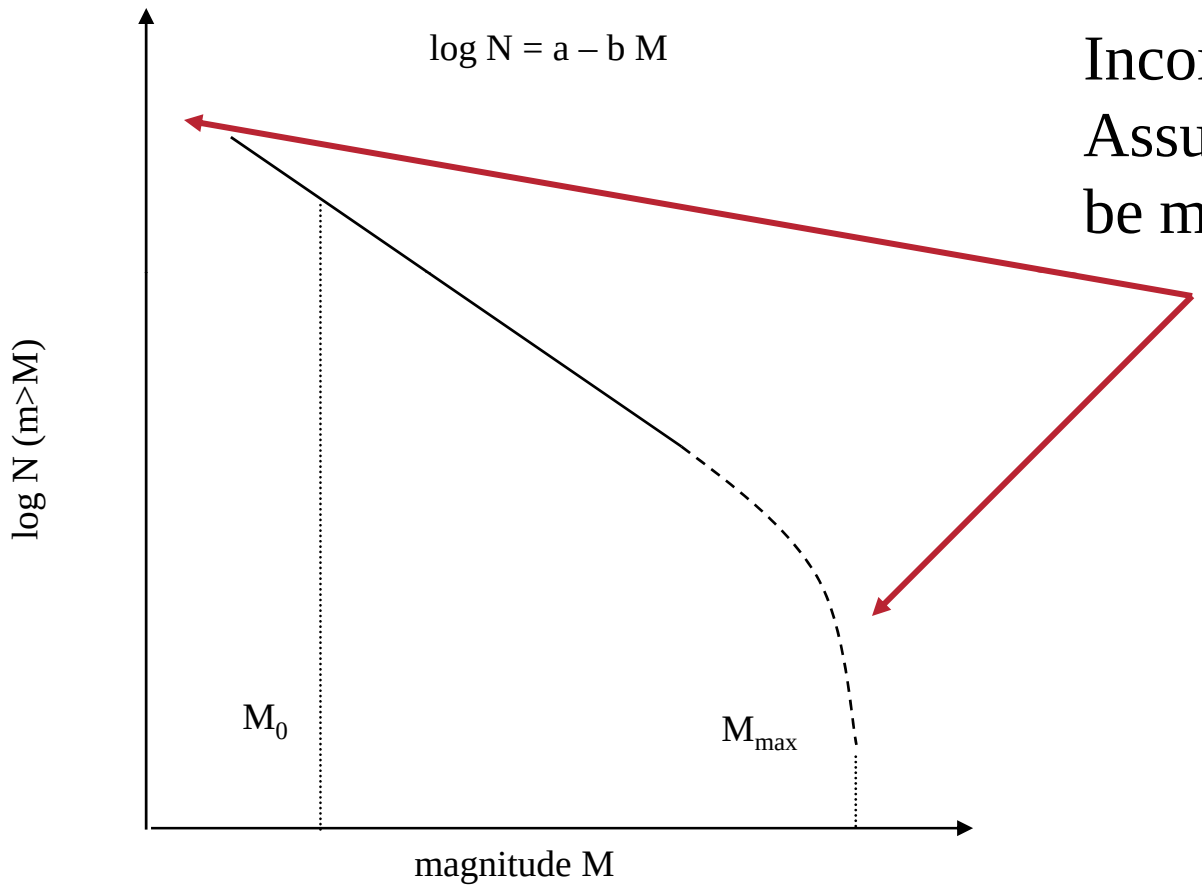
Frequency analysis

Summarizing:

All different criteria play a role in determining frequency of earthquakes. Many different categories can be made all with their own specific frequency and characteristics!

This makes frequency analysis a difficult study. Assumptions and definitions need to be clear before you start such a study!

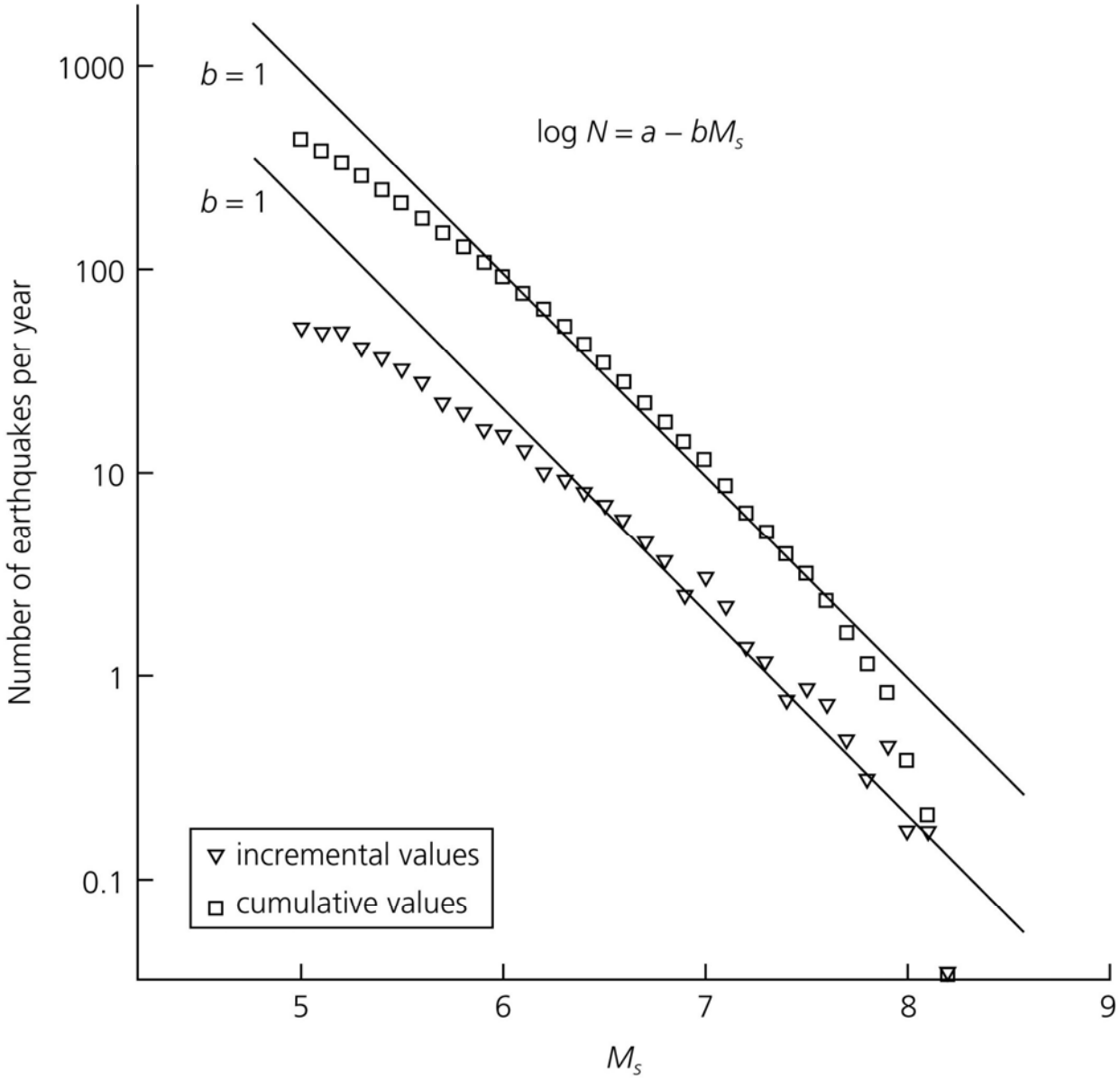
Frequency-magnitude



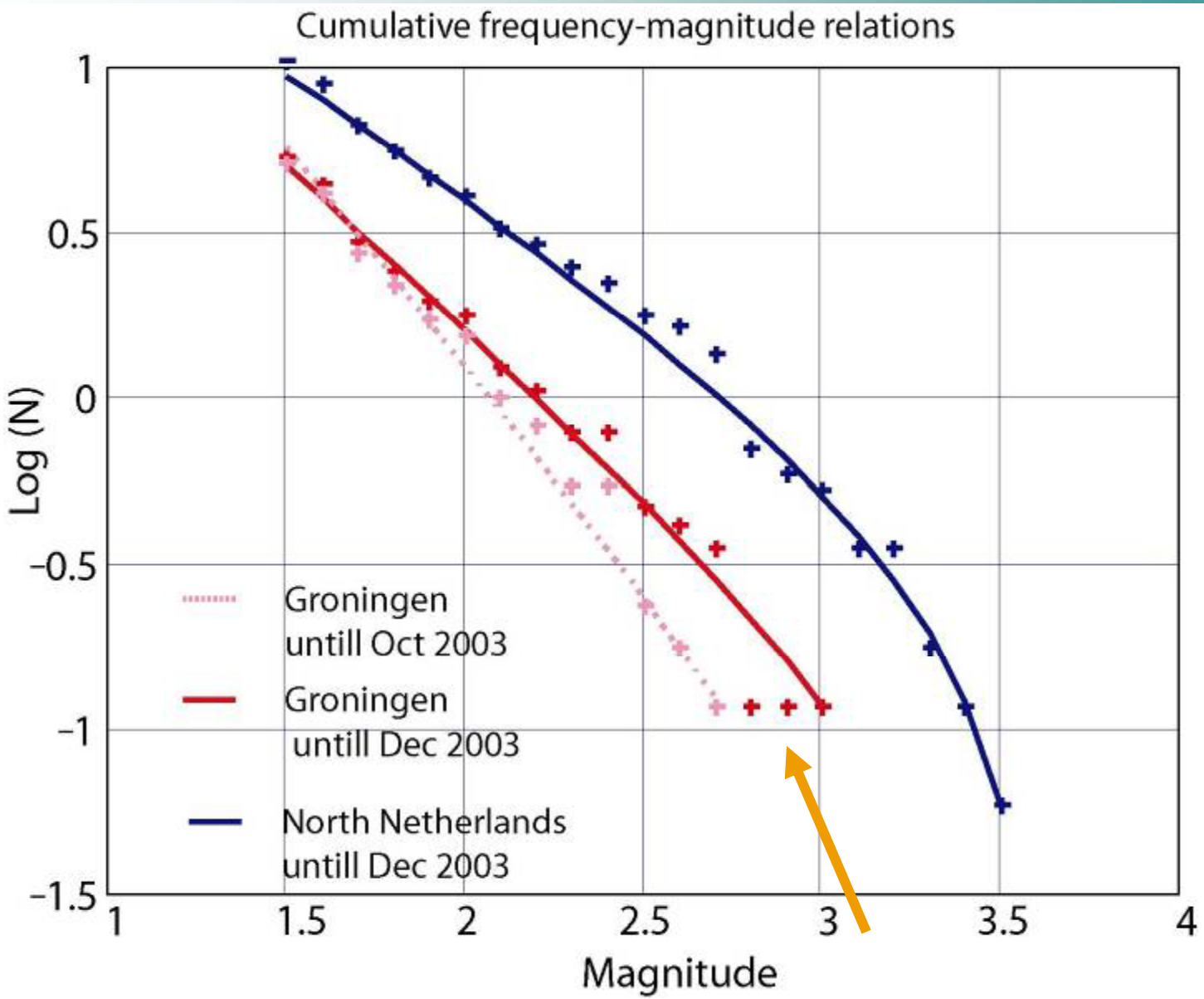
Incomplete → Assumptions to be made

Seismicity

Frequency magnitude plot



Frequency-magnitude



Frequency-magnitude

Frequency vs. magnitude relations are the most common way to analyse earthquake occurences.

But this interpretation is varying:

- Variations per region
- Variations over time

Exercise frequency analysis

You will do an exercise on earthquake catalogues for the whole world, California and Honduras.

Create frequency-magnitude relationships for the different catalogs.

Observe the variations and the impact of small and large events on the derived relationships.