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Spring 2020 Semester

Performance-based Seismic Design of Structures

Fawad A. Najam
Department of Structural Engineering
NUST Institute of Civil Engineering (NICE)
National University of Sciences and Technology (NUST)
H-12 Islamabad, Pakistan
Cell: 92-334-5192533, Email: fawad@nice.nust.edu.pk

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Prof. Dr. Pennung Warnitchai

- The material is taken solely for educational purposes. **All sources are duly acknowledged.**

Lecture 1: Basic Seismology

- Introduction
- The Causes of Earthquakes
- Plate Tectonics
- Seismic Waves
- Seismographs
- The Size of an Earthquake – Intensity and Magnitude

What is Earthquake ?

- Shaking and vibration at the surface of the earth resulting from underground movement along a fault plane or from volcanic activity
- An earthquake is the result of a sudden release of energy in the Earth's crust that creates seismic waves
- An earthquake is a sudden and sometimes catastrophic movement of a part of the Earth's surface.

Types of Earthquakes

- EQs can be classified by their mode of generation as follows:

  - **Tectonic Earthquakes**
    - The most common earthquakes
    - Produced when rocks break suddenly in response to the various geological (tectonic) forces
  - **Volcanic Earthquakes**
    - EQs that occurs in conjunction with volcanic activity
    - EQs induced by the movement (injection or withdrawal) of magma
  - **Collapse Earthquakes**
    - Small EQs occurring in regions of underground caverns and mines
    - Caused by the collapse of the roof of the mine or caverns
    - Sometimes produced by massive land sliding
  - **Human cause explosion earthquakes**
    - Produced by the explosion of chemical or nuclear devices

The Causes of Earthquakes

In ancient Japanese folklore, a giant catfish (Namazu) lives in the mud beneath the earth. It is guarded by the god Kashima who restrains the fish with a stone. When Kashima let his guard fall, Namazu thrashes its body, causing violent earthquakes.

The Causes of Earthquakes

In 1891, a Japanese seismologist, Prof. B. Koto, after careful study of the Mino-Owari earthquake noted,
“It can be confidently asserted that the sudden faulting was the actual cause (and not the effect) of the earthquake.”

This finding was the start of common acceptance that fractures and faults were the actual mechanism of the earthquake and not its results, and was the basis of the development of the seismology.

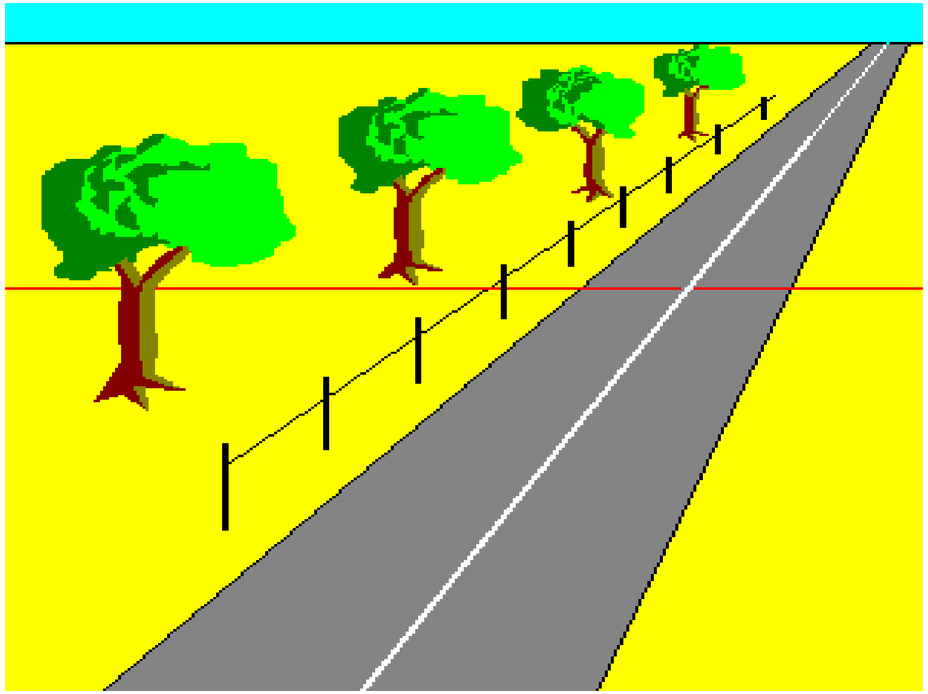
Ground Failure by Lateral Fault Movement

Kocaeli (Turkey) Earthquake (1999)

Surface rupture caused by Fault dislocation

The Causes of Earthquakes

- Shortly after the San Francisco earthquake of 1906, an American geologist, Harry Fielding Reid, investigated the geological aftermath.
- He noticed that a displacement of nearly 6 meters had occurred on certain parts of the San Andreas fault which runs under San Francisco, and he proposed the theory that strain had been building up over a long period of time and suddenly released in the EQ.

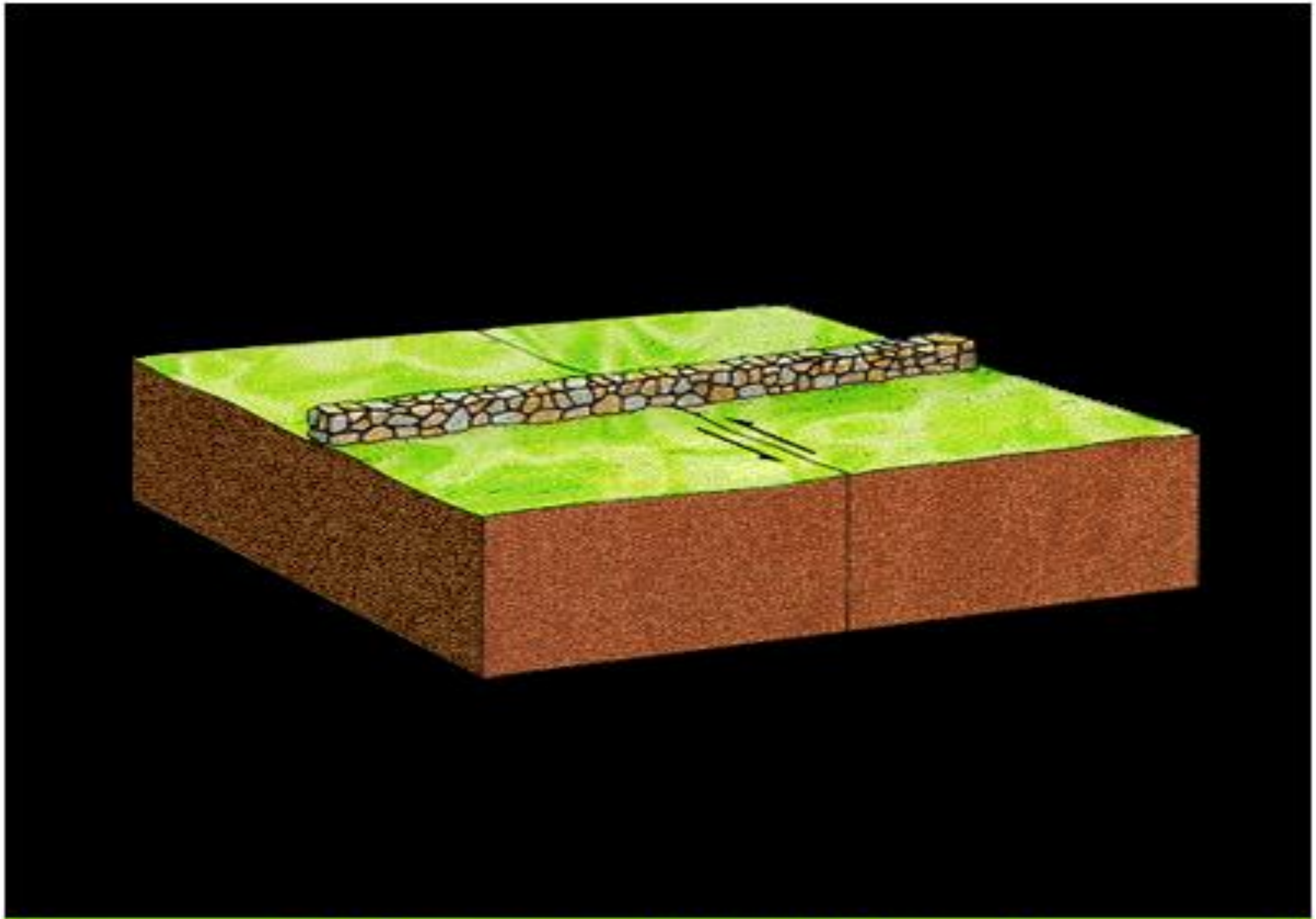


“It is impossible for rock to rupture without first being subjected to elastic strains greater than it can endure. We concluded that the crust in many parts of the earth is being slowly displaced, and the difference between the displacements in neighboring regions set up elastic strains, which may become larger than the rock can endure. A rupture then take place, and the strained rock rebounds under its own elastic stresses, until the strain is largely or wholly relieved.

When a fault ruptures, the elastic energy stored in the rock is released, partly as heat and partly as elastic waves.

In the majority of cases, the elastic rebound on opposite sides of the fault are in opposite directions.

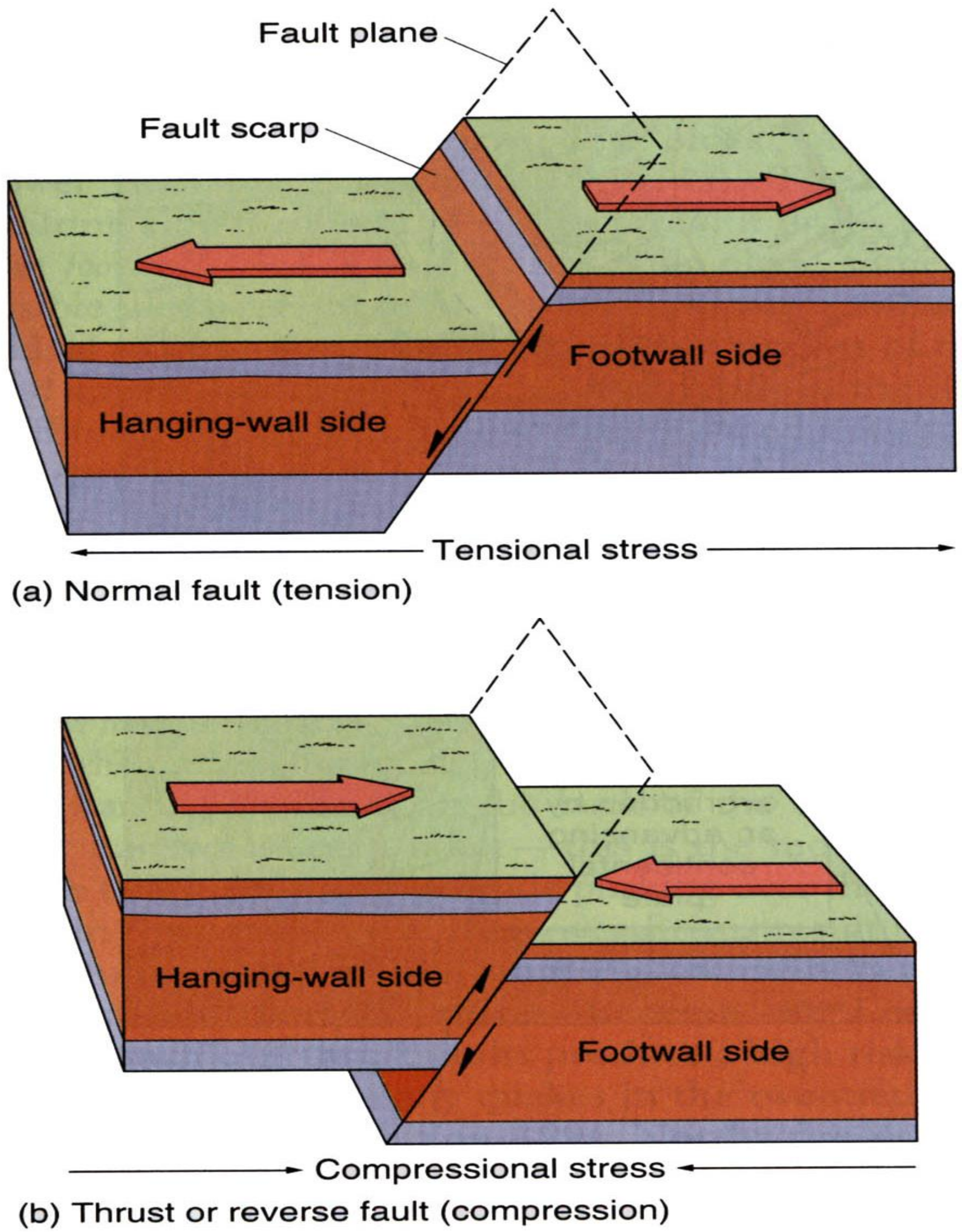
This is known as the elastic rebound theory.



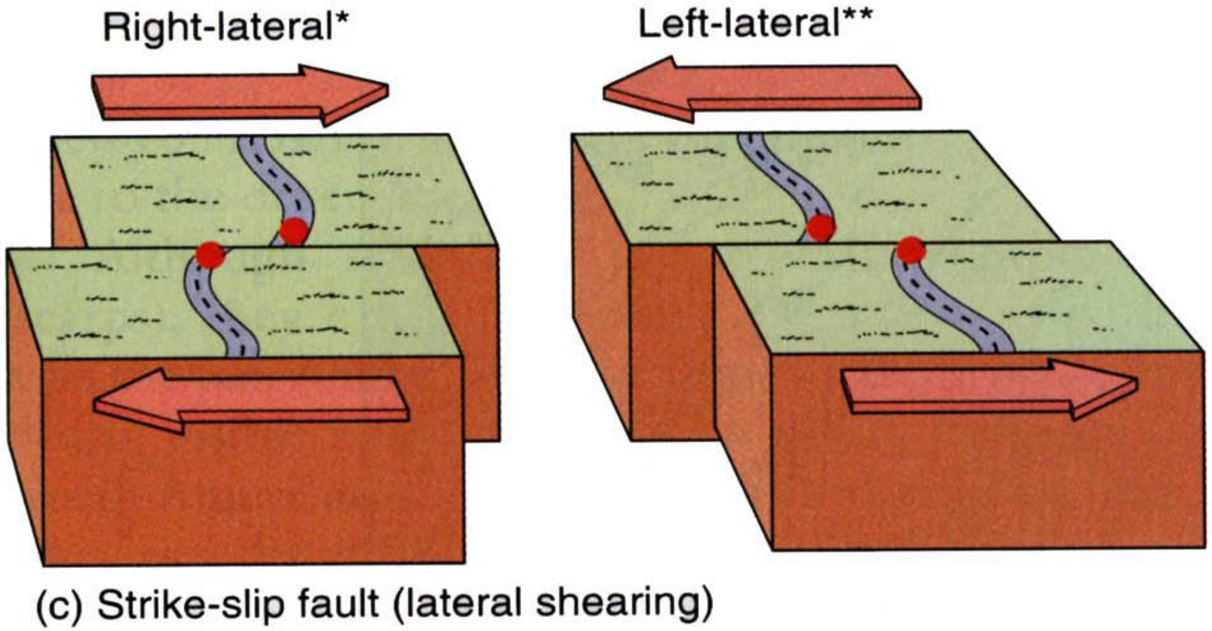
การยืด - การหด Elastic Rebound

Four Basic Types of Faults

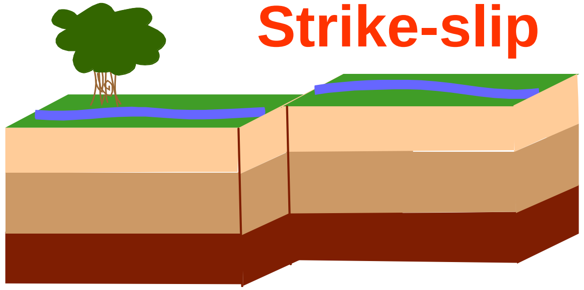
Fault: A fault is a **fracture** along which the blocks of crust on either side have moved relative to one another parallel to the fracture.



Dip Slip (normal or thrust)

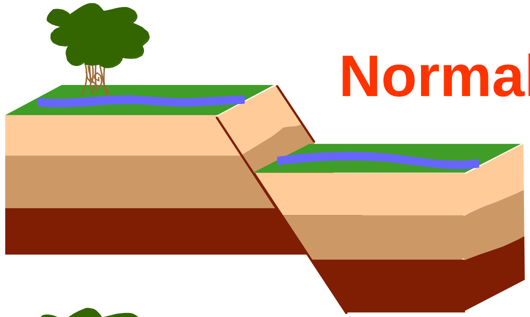


Strike Slip (right or left lateral)

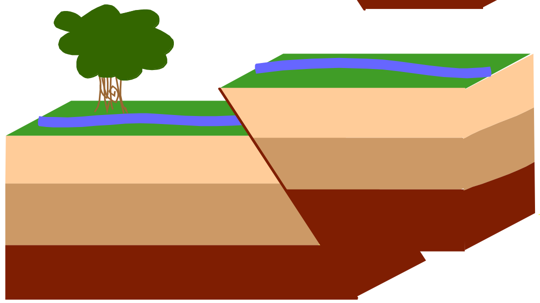


Strike-slip

Strike-slip faults are vertical (or nearly vertical) fractures where the blocks have mostly **moved horizontally**. If the block opposite an observer looking across the fault moves to the right, the slip style is termed right lateral; if the block moves to the left, the motion is termed left lateral.

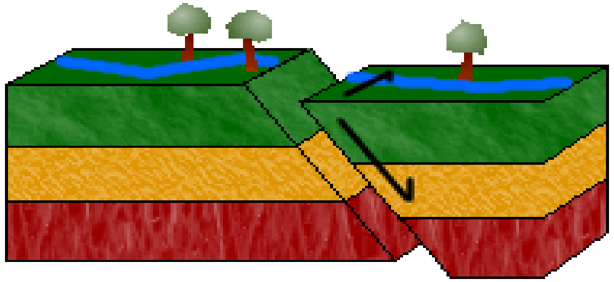


Normal



Thrust

Dip-slip faults are inclined fractures where the blocks have mostly **shifted vertically**. If the rock mass above an inclined fault moves down, the fault is termed **normal**,
whereas if the rock above the fault moves up, the fault is termed **reverse (or thrust)**. **Oblique-slip faults** have significant components of both slip styles.



Oblique-slip

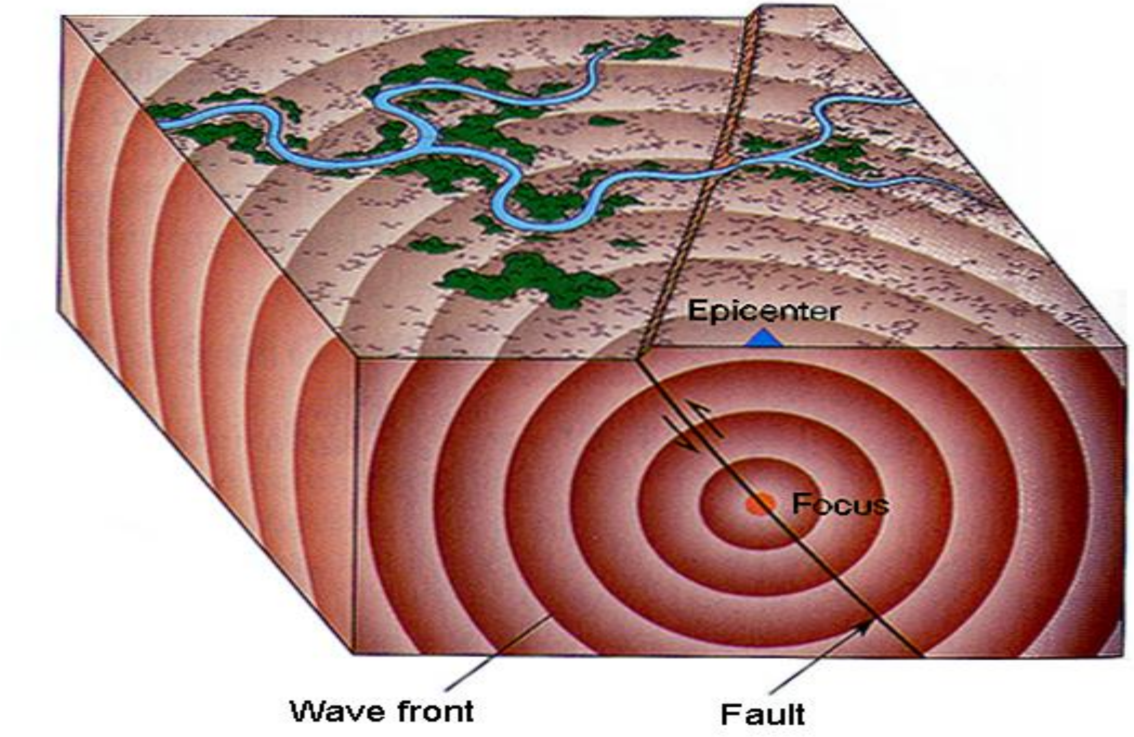
Oblique-slip faults: Oblique-slip faulting suggests **both dip-slip** faulting and **strike-slip** faulting. It is caused by a combination of shearing and tension or compressional forces, e.g., left-lateral normal fault.

Earthquake Rupture

The rupture begins at the earthquake focus within the crustal rock and then spreads outward in all directions in the fault plane.

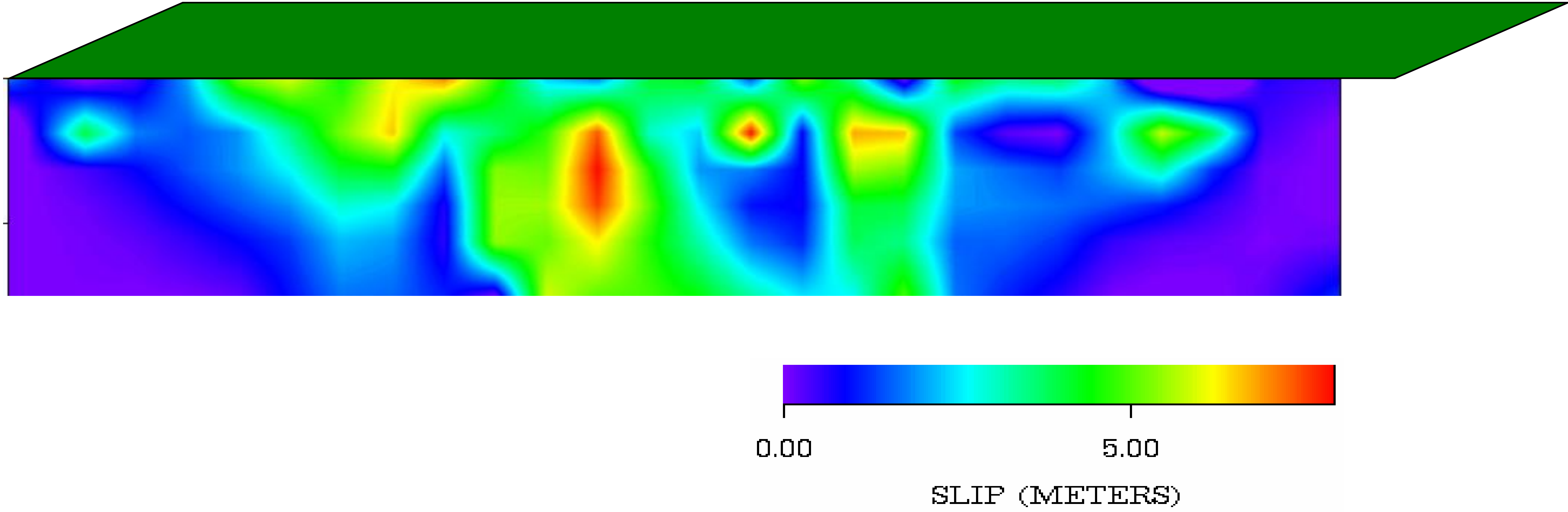
The boundary of the rupture does not spread out uniformly. Its progress is jerky and irregular because crustal rocks vary in their physical properties and overburden pressure from place to place.

If this rupture reaches the surface (as happens in a minority of shallow earthquakes), it produces a visible fault trace.



Rupture on a Fault

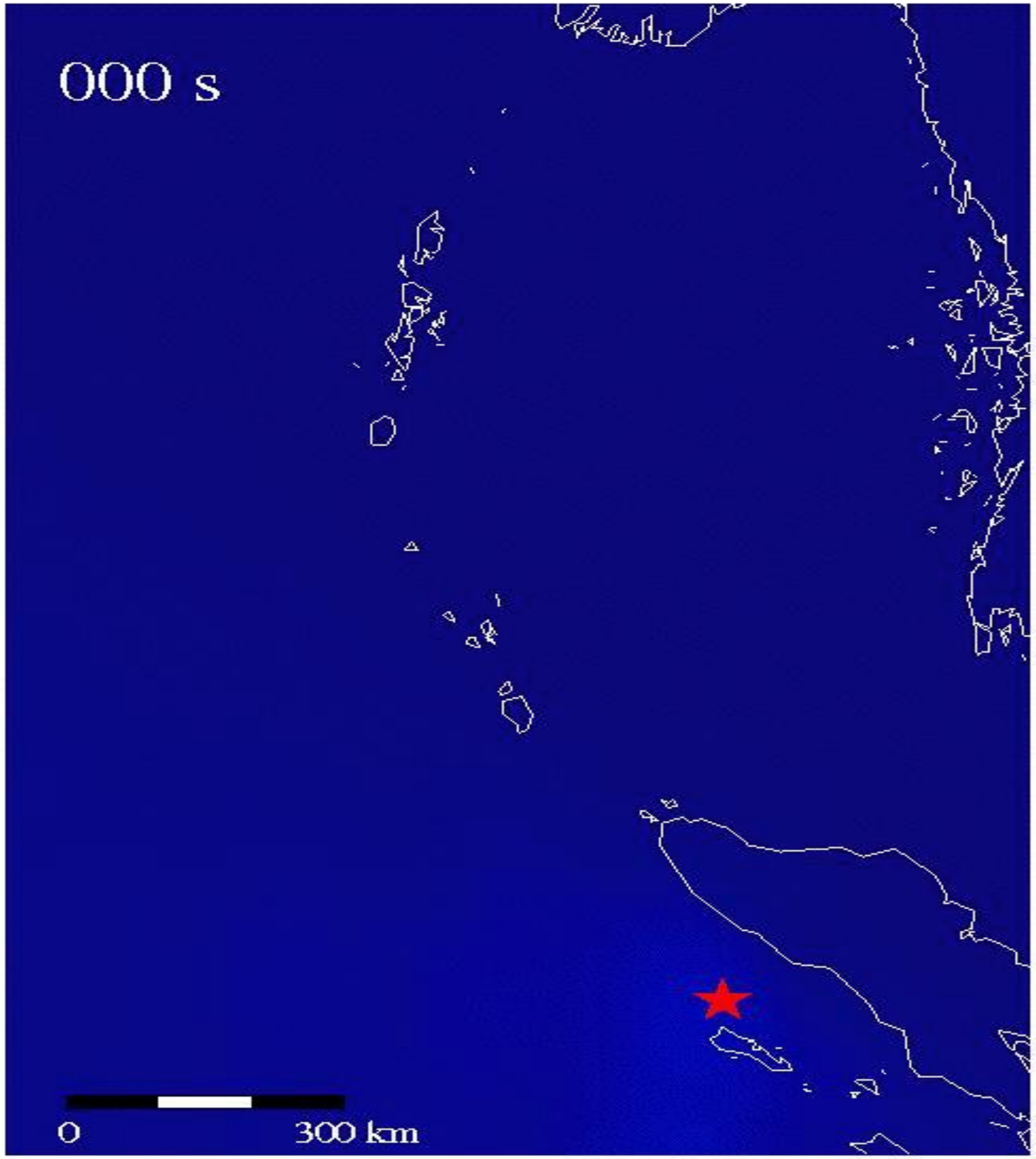
Total Slip in the M7.3 Landers Earthquake



The 26 December 2004 Megathrust Earthquake

Magnitude: 9.3

Rupture Length: 1200 km



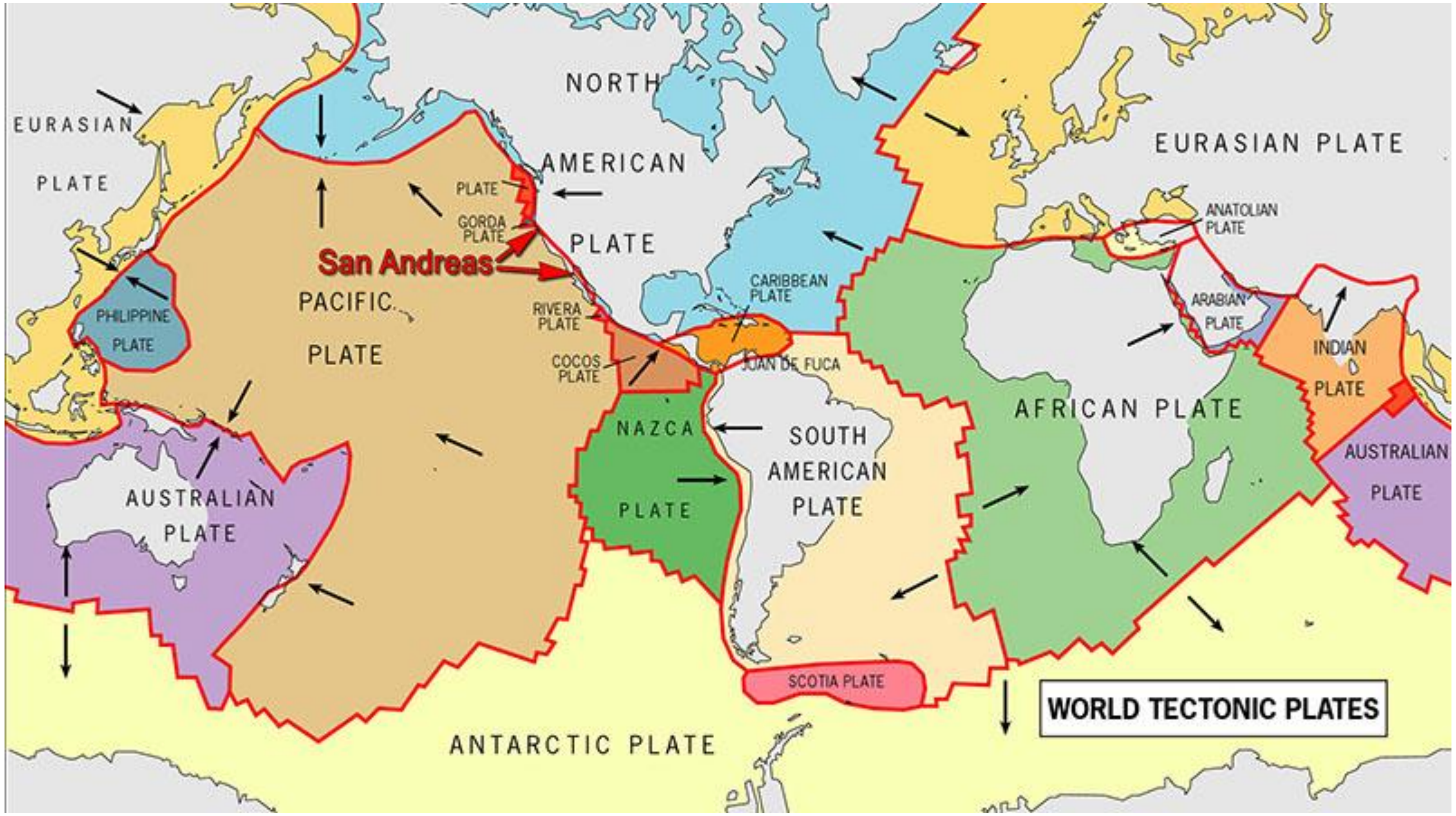
Ishii et al., 2005 Nature

Surface Rupture: Strike-slip Fault Example

Surface Rupture: Normal Fault Example

Dixie Valley-Fairview Peaks, Nevada earthquake. December 16, 1954

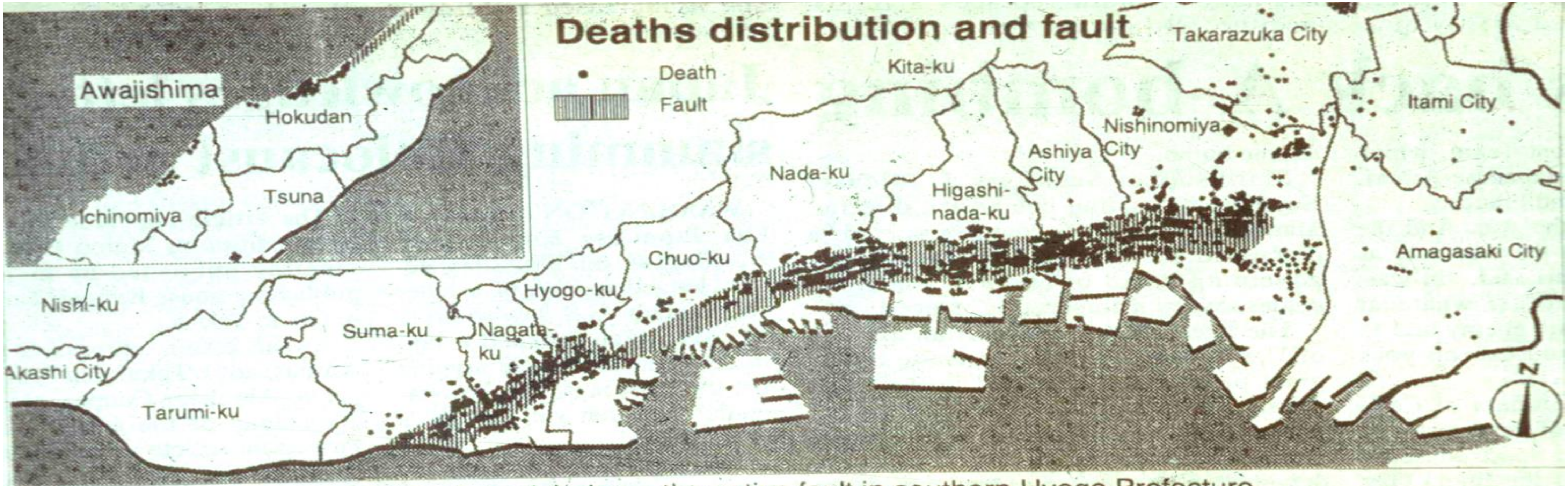
San Andreas Fault



Surface Rupture: Thrust Fault Example

Strong ground shaking above the rupture zone

The 1995 Kobe Earthquake



Map shows the concentration of deaths above the active fault in southern Hyogo Prefecture.

Destruction centered above active fault

The deaths caused by the Great Hanshin Earthquake were concentrated along the 25-kilometer-long, three-kilometer-wide coastal zone between Suma-ku, Kobe City, and Nishinomiya City — just above an active fault, a seismologist has found.

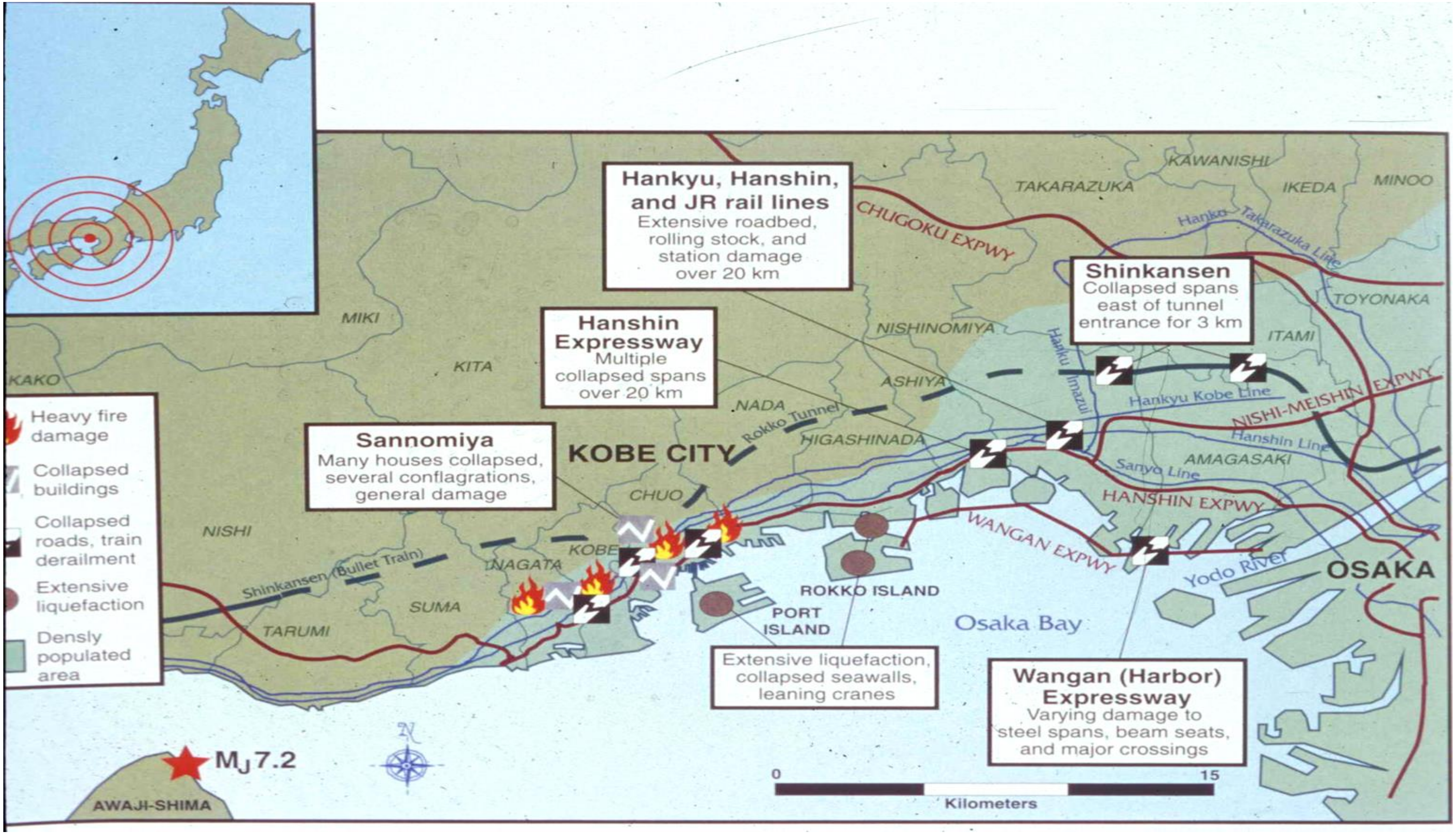
Associate Professor Toshihiko Shima-

after conducting a detailed survey of the quake-devastated areas. He also learned that the active fault shifted largely during the quake.

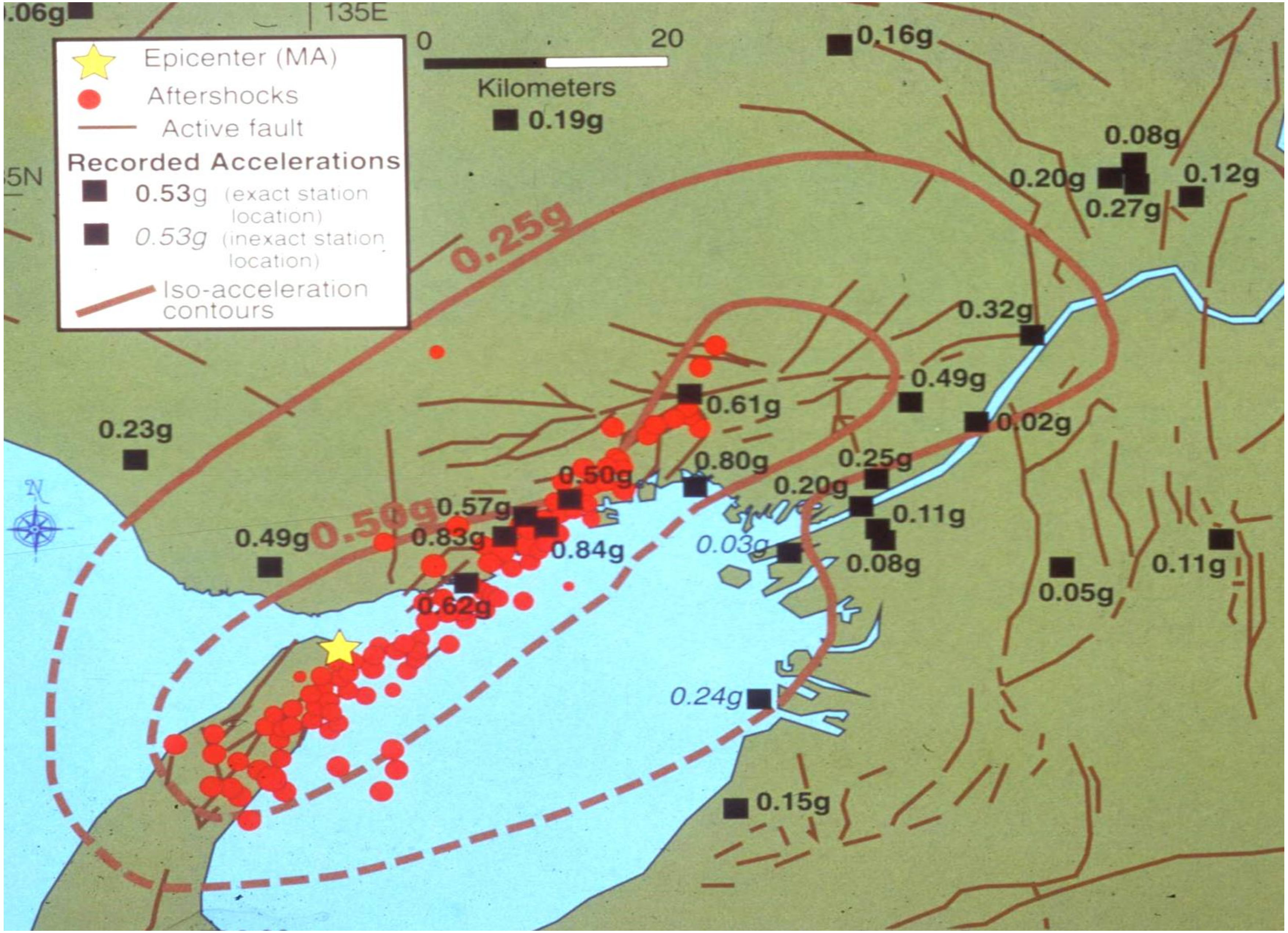
Damage from an earthquake, when it hits urban areas from directly below, tends to concentrate in areas just above the active fault that triggers the quake. A

crushed to death under collapsed build-ings located above the fault.

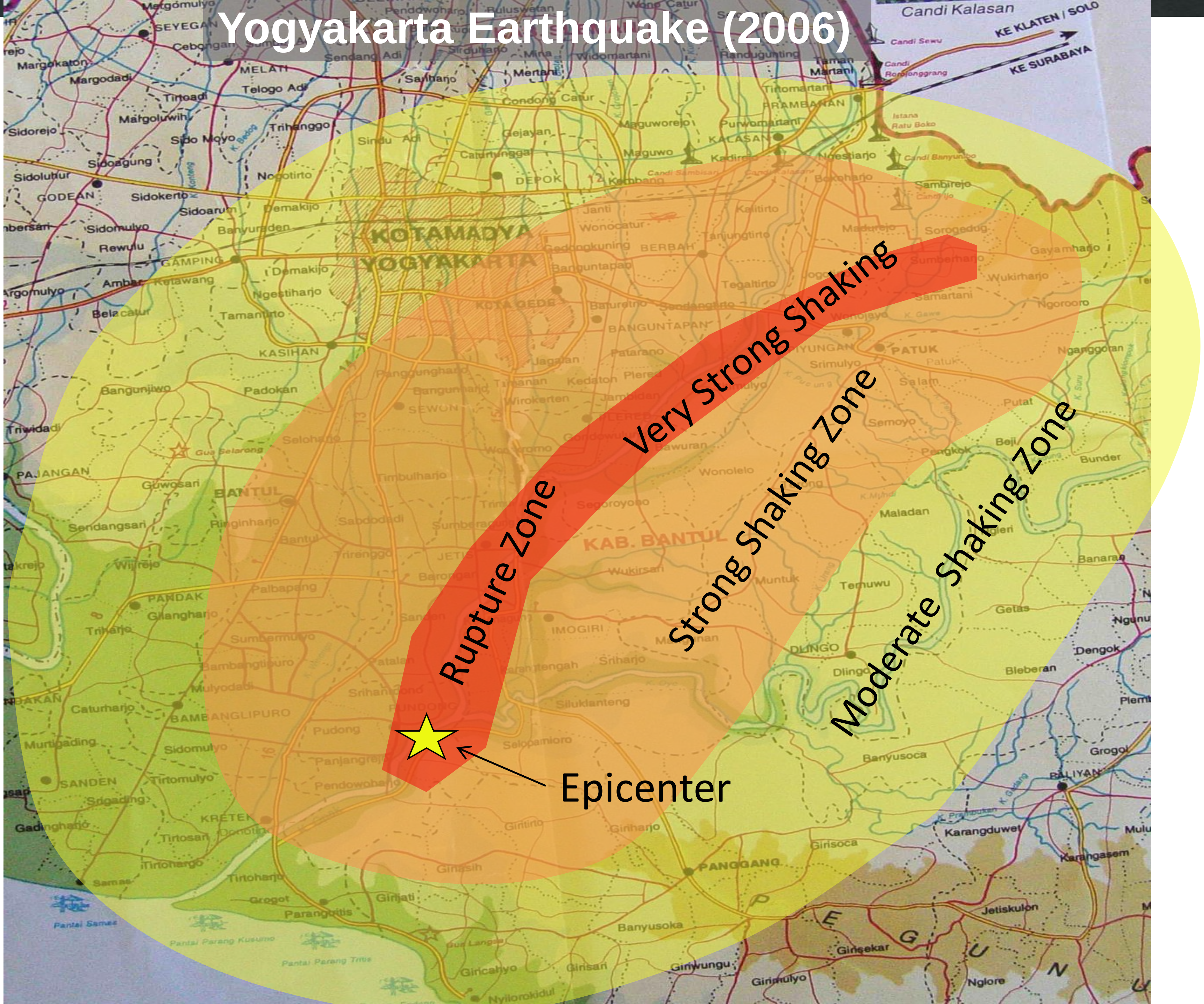
"The Kinki area has a concentration o[f] active faults. But if you try to avoi[d] active faults, you can't find a place t[o] build," says Shimamoto. "You have n[o] choice but to be fully aware of the dan-ger of such faults and promote the con-struction of disaster-proof towns," h[e]


Hankyu, Hanshin, and JR rail lines
Extensive roadbed, rolling stock, and station damage over 20 km
Hanshin Expressway
Multiple collapsed spans over 20 km
Sannomiya
Many houses collapsed, several conflagrations, general damage
Shinkansen
Collapsed spans east of tunnel entrance for 3 km
Extensive liquefaction, collapsed seawalls, leaning cranes
Wangan (Harbor) Expressway
Varying damage to steel spans, beam seats, and major crossings
Heavy fire damage
Collapsed buildings
Collapsed roads, train derailment
Extensive liquefaction
Densly populated area
KOBE CITY
OSAKA
Osaka Bay
KAWANISHI
TAKARAZUKA
IKEDA
MINOO
TOYONAKA
ITAMI
NISHINOMIYA
ASHIYA
AMAGASAKI
MIKI
KITA
KAKO
NADA
HIGASHINADA
CHUO
NISHI
KOBE
NAGATA
SUMA
TARUMI
ROKKO ISLAND
PORT ISLAND
AWAJI-SHIMA
CHUGOKU EXPWY
NISHI-MEISHIN EXPWY
HANSHIN EXPWY
WANGAN EXPWY
Hanko Takarazuka Line
Hankyu Kobe Line
Hanshin Line
Sanyo Line
Hankyu Imazu
Rokko Tunnel
Shinkansen (Bullet Train)
Yodo River
M_J 7.2
N
0
15
Kilometers

The 1995 Kobe Earthquake



Yogyakarta Earthquake (2006)




Bantul, Yogyakarta
Strong Ground Shaking + Unreinforced Masonry Houses
= A Major Disaster

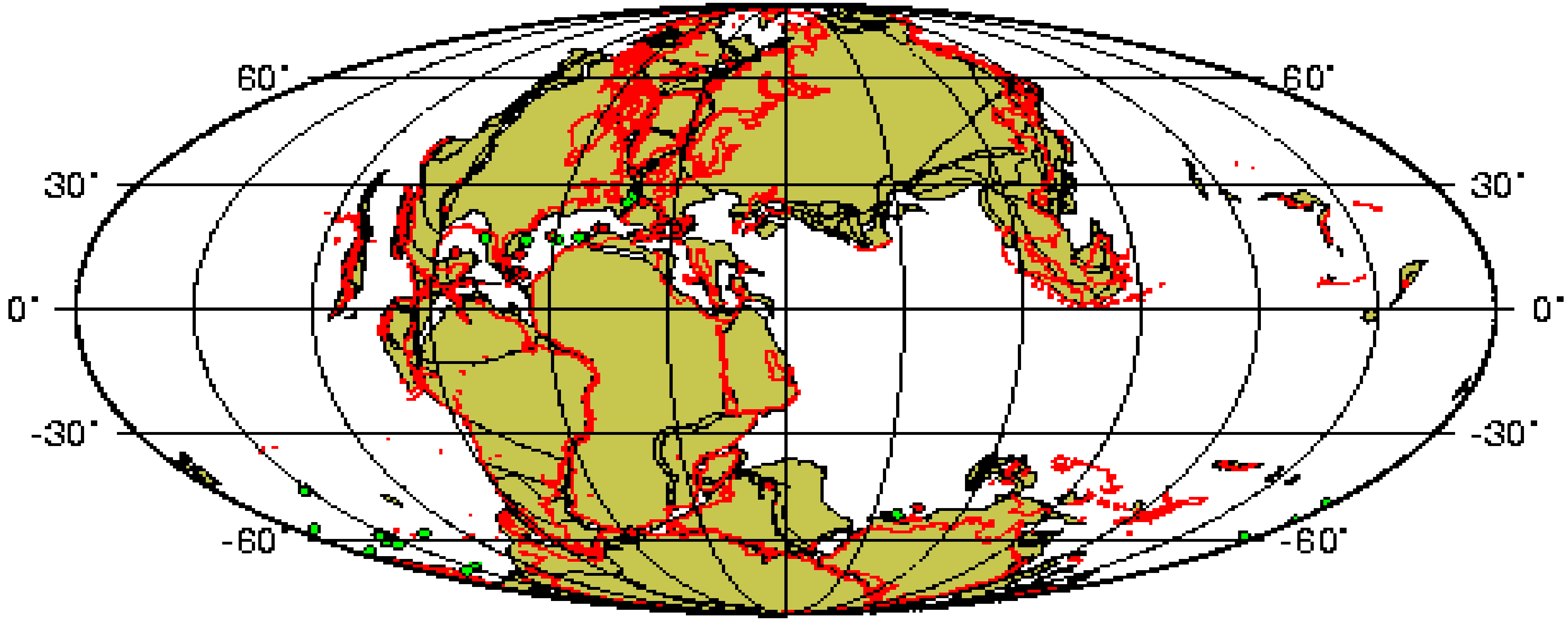
Continental Drift

In 1910 a German meteorologist and astronomer, Alfred Wegener, put forward a theory:

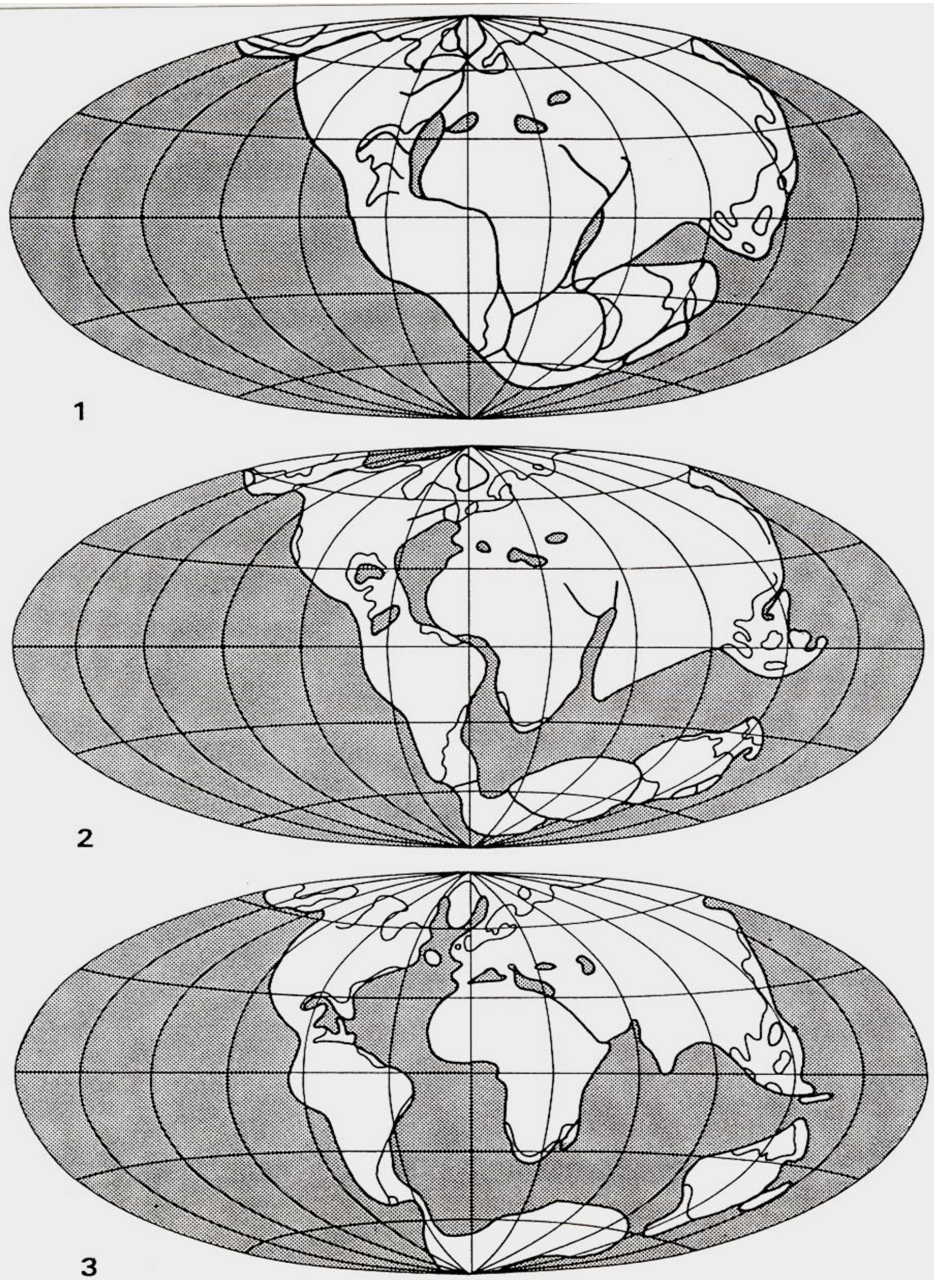
At about 200 million years ago, the earth consisted of only one continent, which he called Pangaea (all lands), and one ocean, Panthalassa (all seas). Eventually, for reasons which Wegener could not explain, this mass of land broke up in mesozoic times—about 150 million years ago—and started to move; firstly into N-S devisions, and then into E-W ones.

He called the process **continental drift**.

Continental Drift



150 My Reconstruction



Diagrams illustrating Wegener's theory of continental drift.

1 270 million years ago, the continents were united in a single block called Pangaea.
2 150 million years ago, Pangaea started to divide. North America and Europe were still united. It is now believed that North and South America were apart at this stage.
3 1 million years ago, the continents were beginning to assume the shapes and positions we know today.

Continental Drift

Initially the Wegener theory was too fanciful for many, and at the existing level of scientific knowledge it could not be proved.

Wegener was roundly condemned.

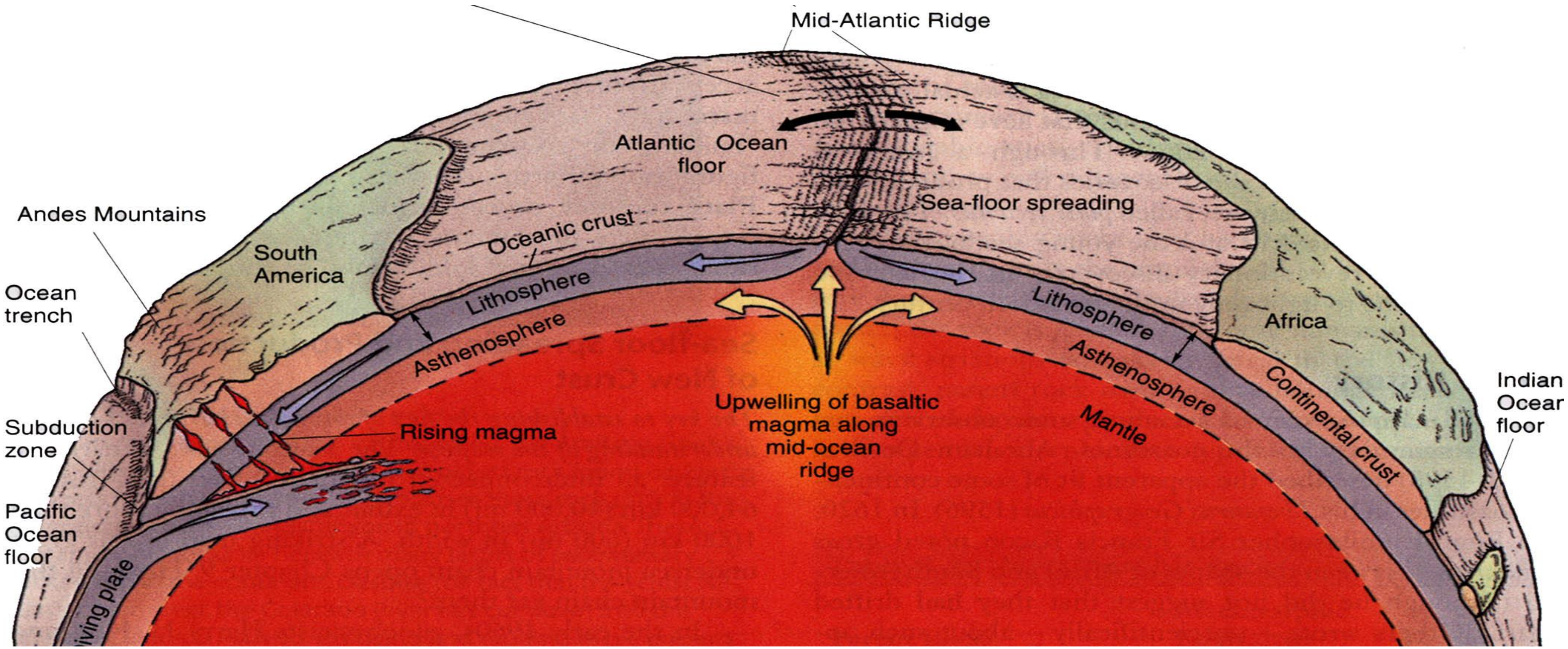
After the discovery of submarine mountain ranges and many more evidence in later years, the Wegener theory became a widely accepted theory.

This was also the starting point of the theory of plate tectonics.

The impact of the theories of plate tectonics and continental drift was immense and was the great breakthrough that the earth sciences had needed for so long.

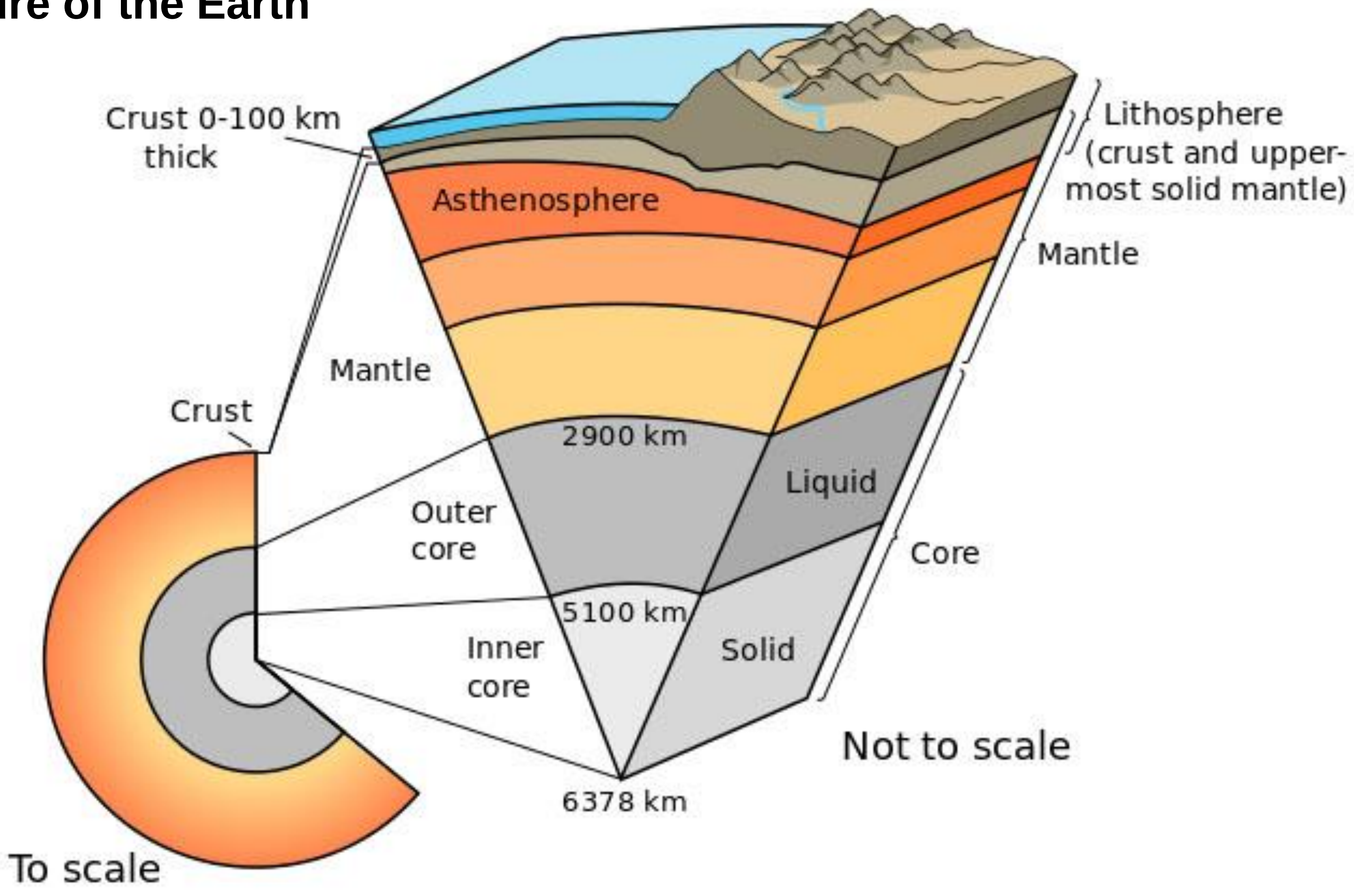
Plate Tectonics

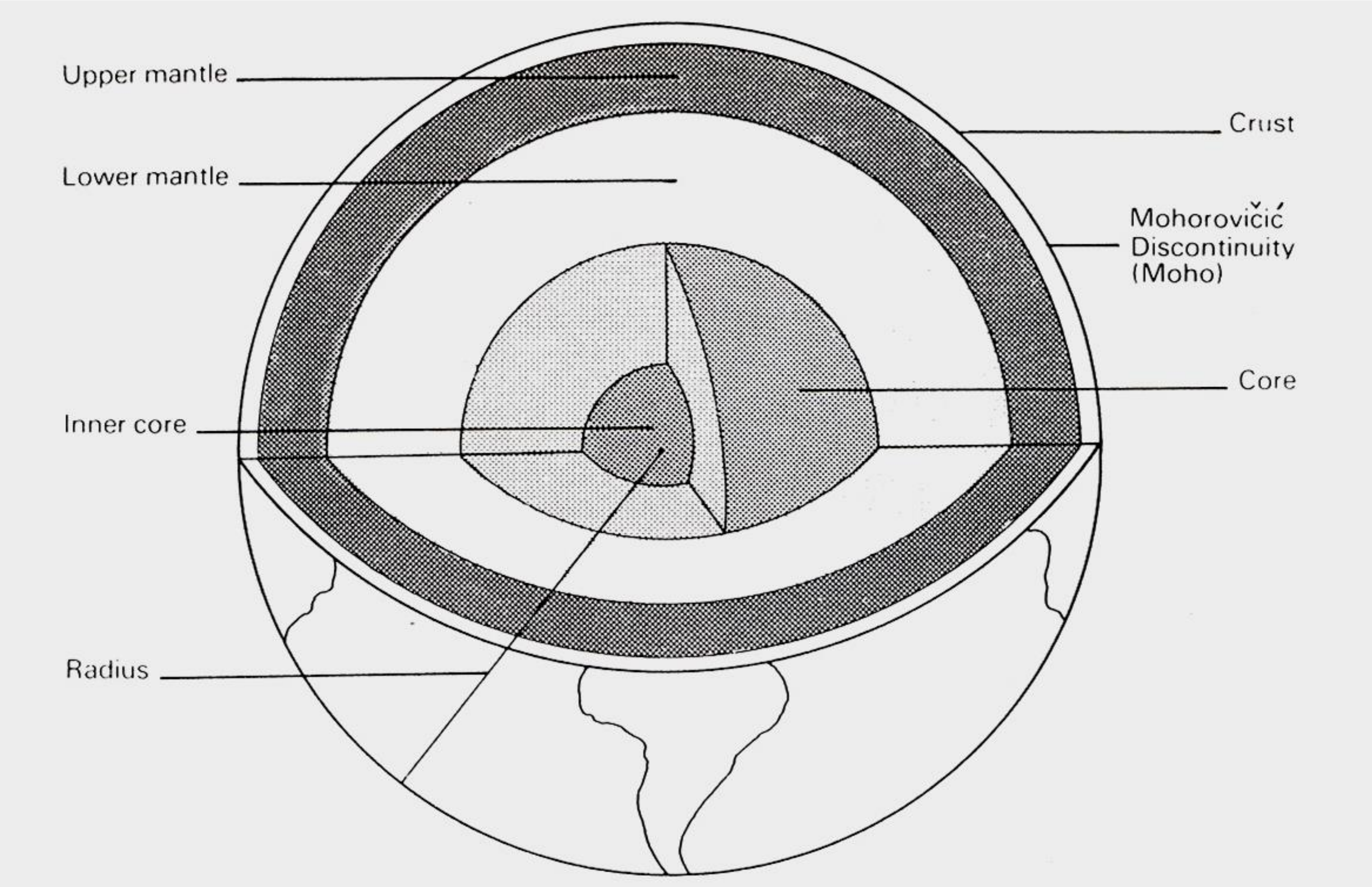
The basic idea of "plate tectonics" is that the earth's outer shell (called the lithosphere) consists of several large and fairly stable slabs of solid rock called plates.



The thickness of each plate is about 80 km. The plate moves horizontally, relative to neighboring plates, on a layer of softer rock.

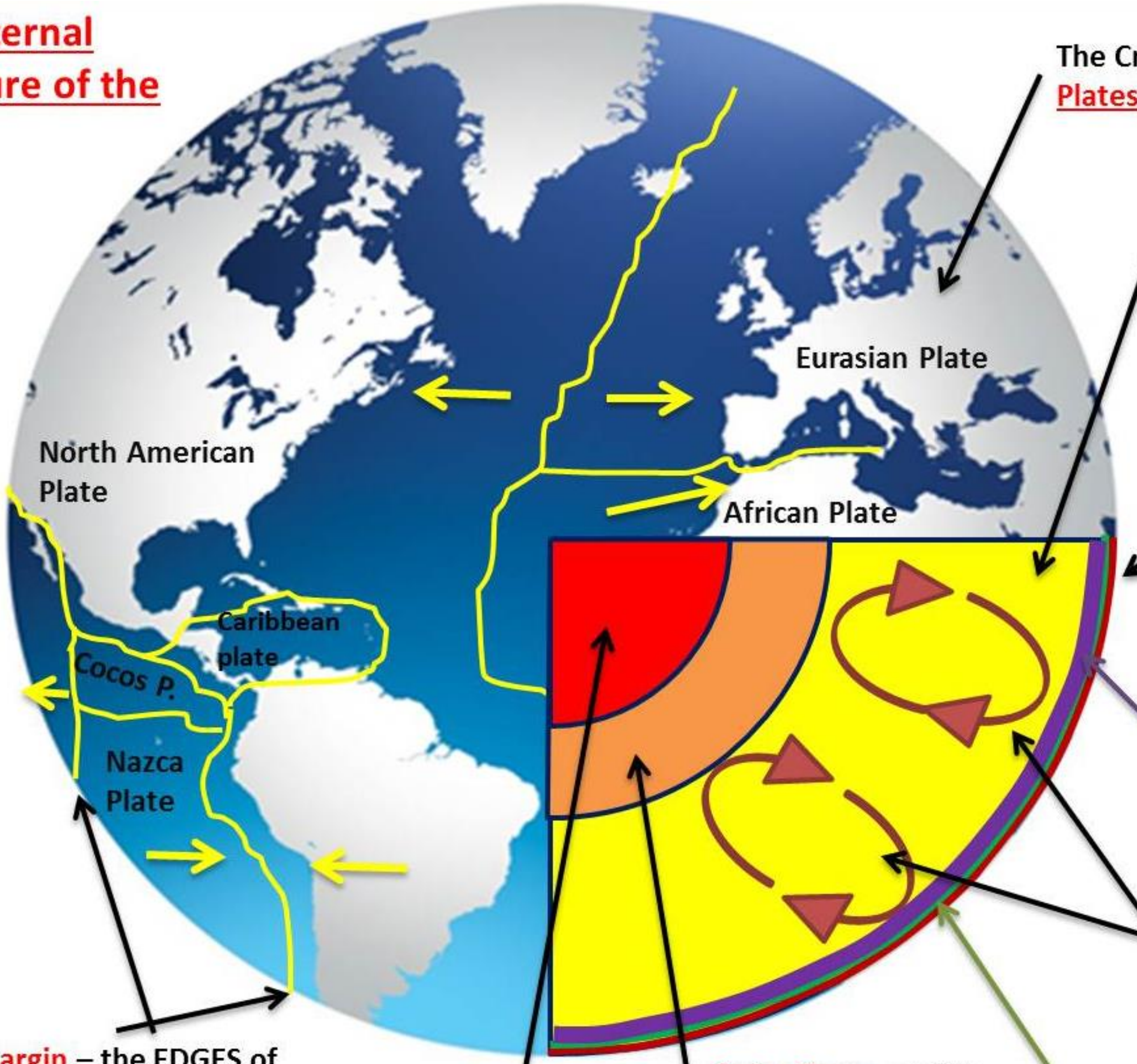
Internal Structure of the Earth





Upper mantle
Crust
Lower mantle
Mohorovičić
Discontinuity
(Moho)
Core
Inner core
Radius

The Internal Structure of the Earth



The Crust is fractured into Tectonic Plates such as the Eurasian

The Mantle, a zone of molten Silicates and other minerals. Molten so it moves, the source of this is the Earth's intense inner heat which sets up convection currents. 2,900km thick

The Crust – 2 types – Oceanic (denser, newer, thinner) and Continental (older, thicker & less dense)

Asthenosphere - The upper part of the mantle approximately 80km deep where rocks are kept in a semi-molten state

Convection currents – heat currents in the molten magma that move the crust above very slowly

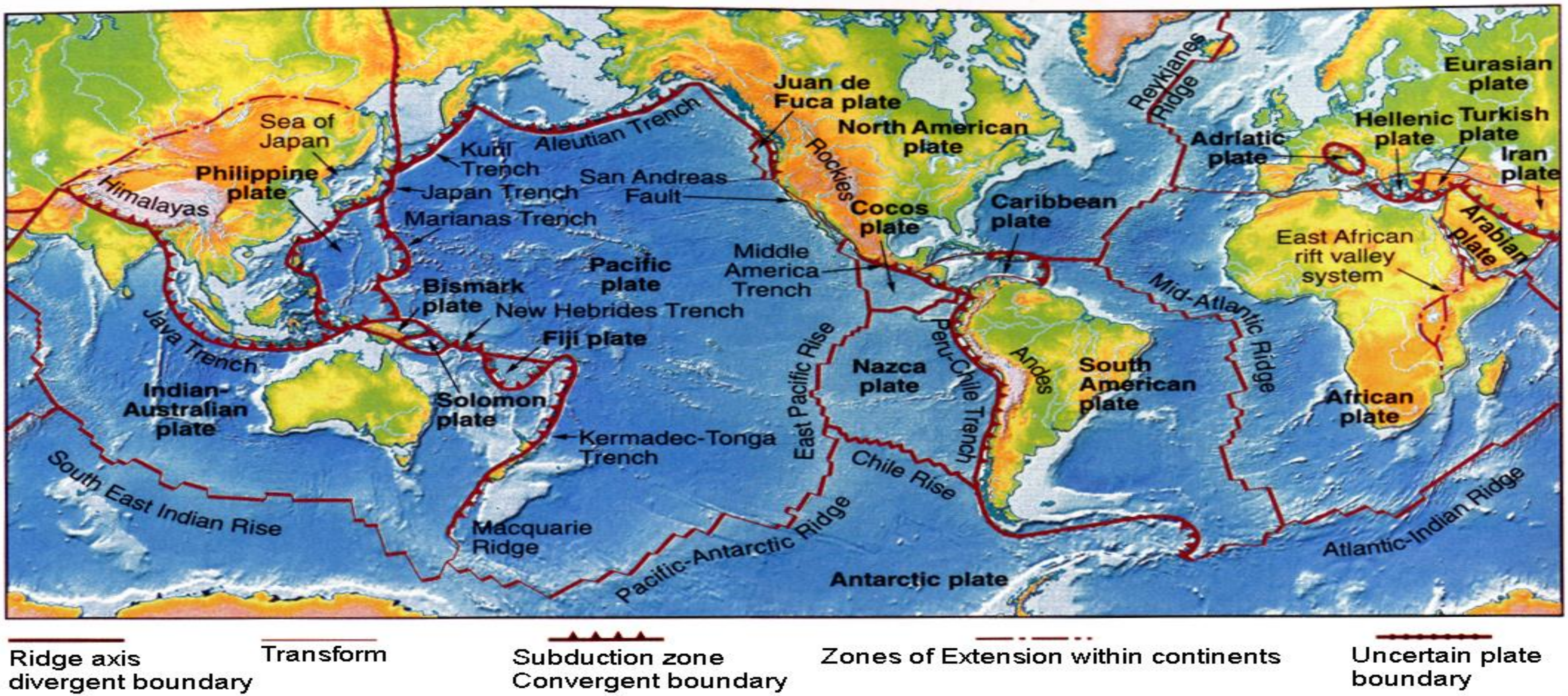
Plate margin – the EDGES of plates where 2 plates are either moving apart, colliding together or sliding past one another

Outer Core – under slightly less pressure

Solid core of Iron and Nickel, which is solid despite temperatures of 3700°C because of the intense pressure there.

Mohorovičič or Moho Discontinuity – the junction between the Earth's crust and the mantle where seismic waves are modified

Tectonic Plates



Earth's 14 Tectonic Plates and their Movements

Convergence plate boundary: subduction zone etc.
Divergence plate boundary: Plates diverges at mid-ocean ridges
Transform fault: Plates move laterally each other

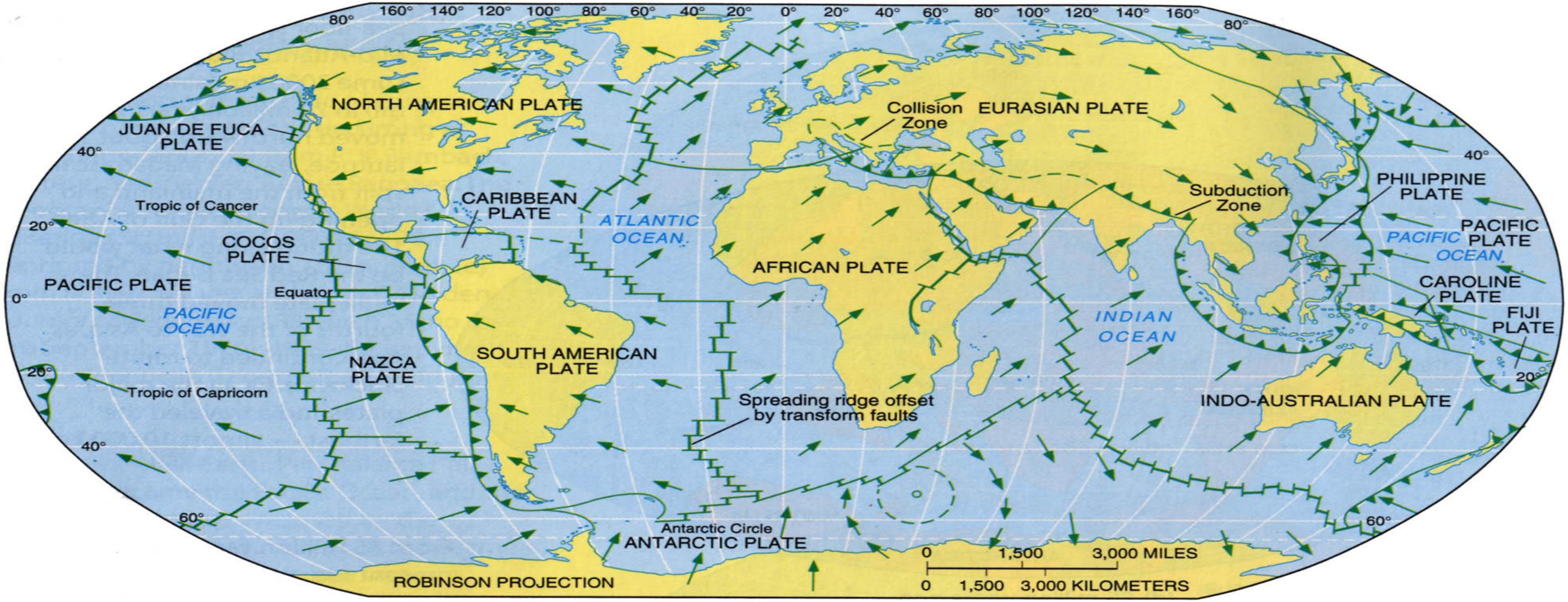


Figure 8-16 **Earth's 14 lithospheric plates and their movements.**
Each arrow represents 20 million years of movement, the longer arrows indicating that the Pacific and Nazca plates are moving more rapidly than the Atlantic plates. [Adapted from U.S. Geodynamics Committee.]

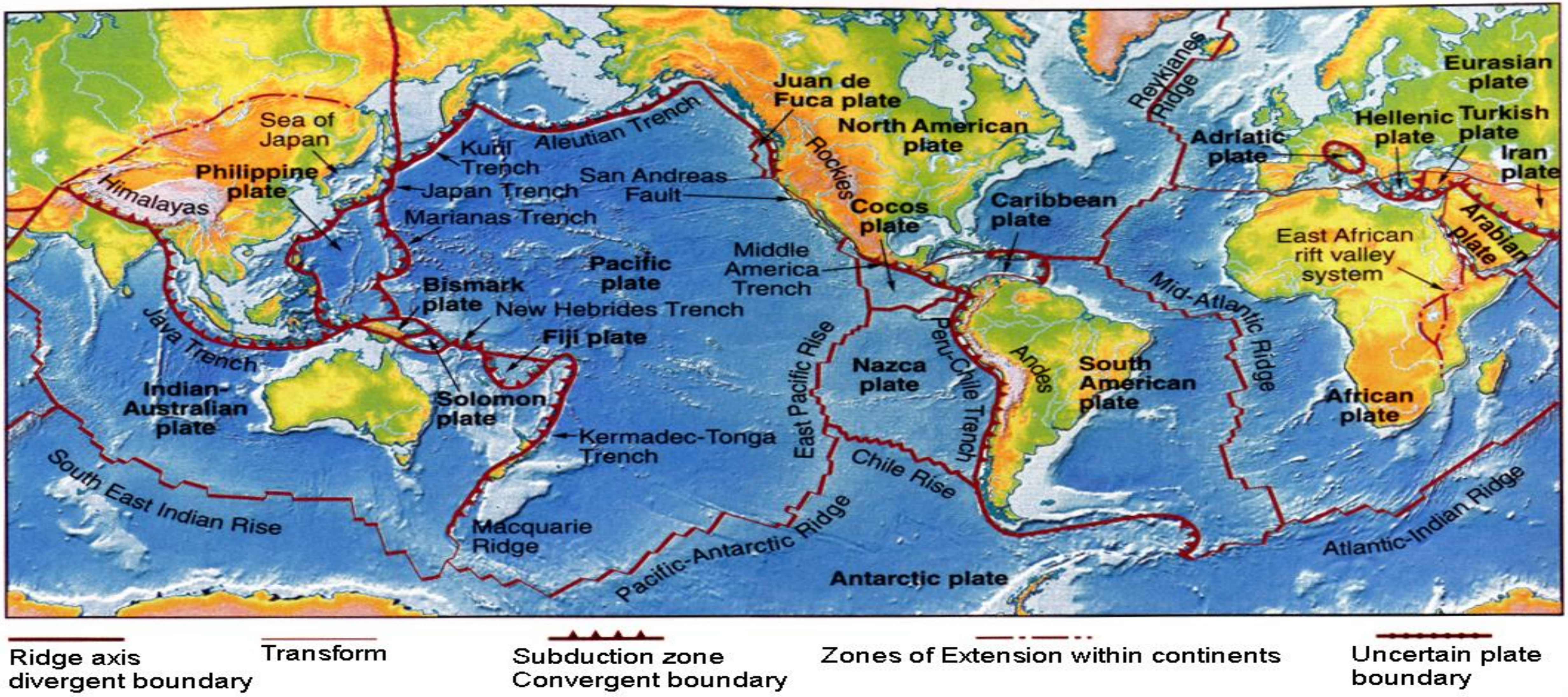
Plate Tectonics

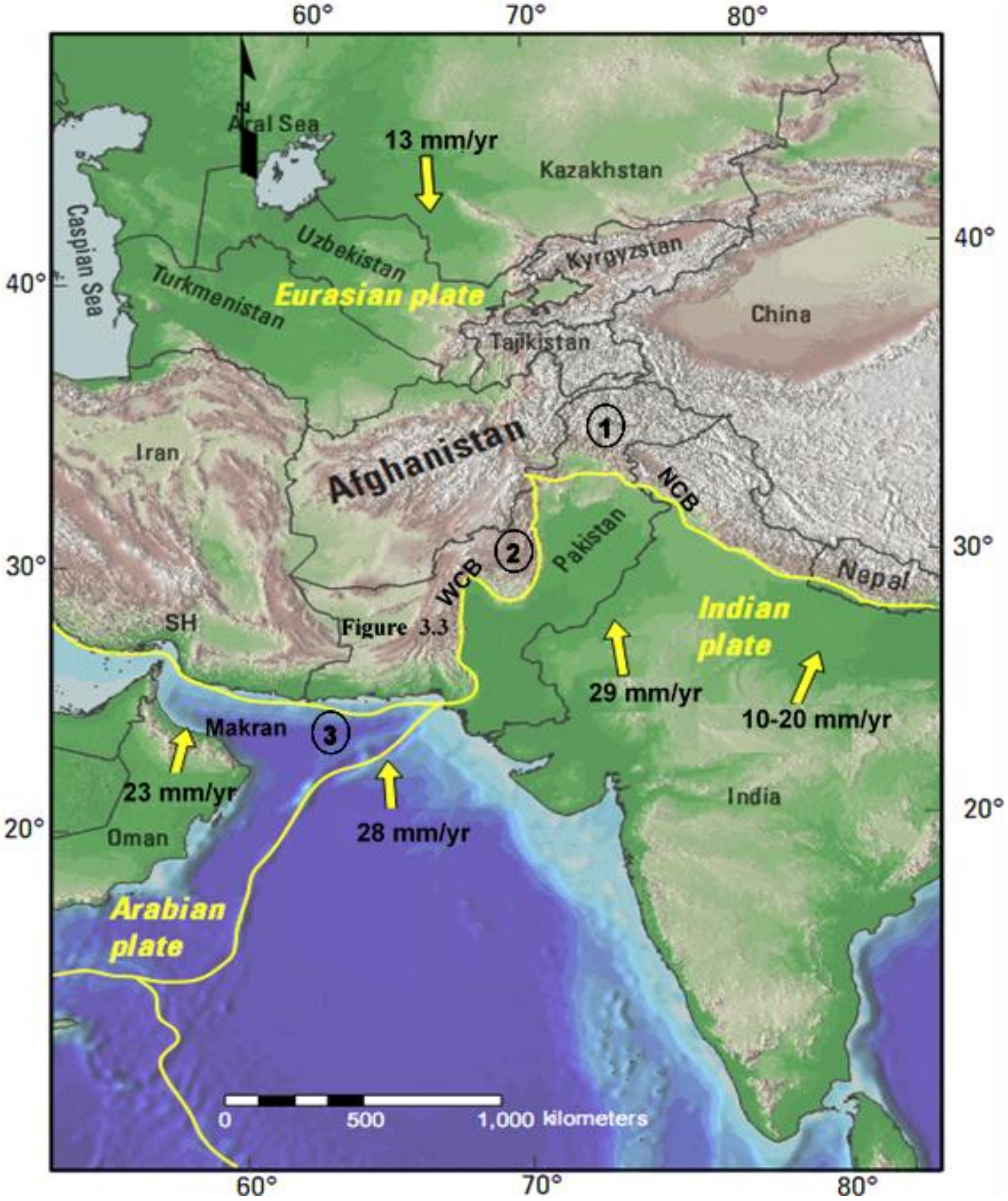
The rate of plate movement ranges from 1 to 10 centimeters per year.

At the plate edges where there is contact with adjoining plates, boundary tectonic forces act on the rock causing physical and chemical changes in them.

This is where the massive and radical geological changes (including earthquakes) occur.

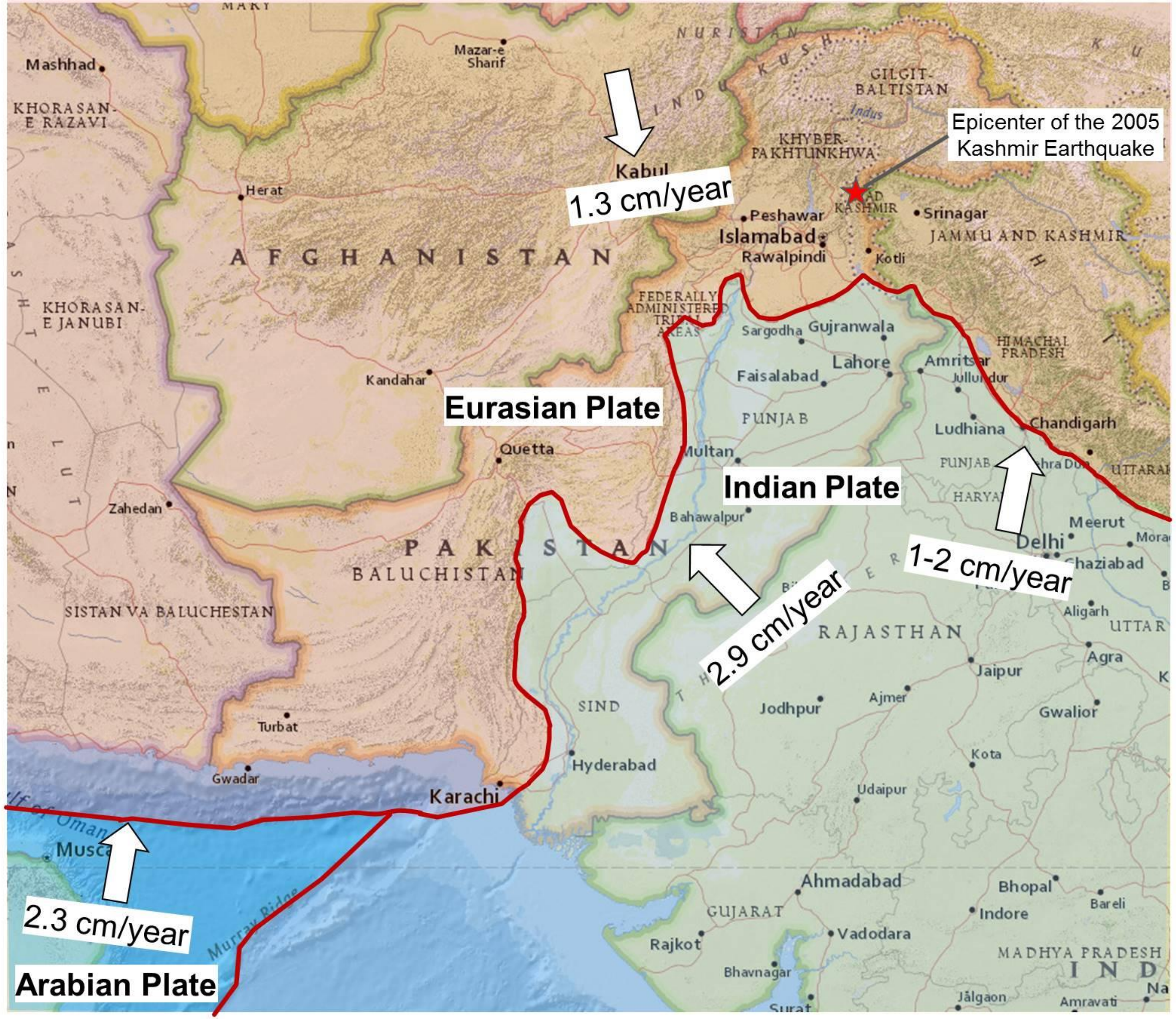
Tectonic Plates





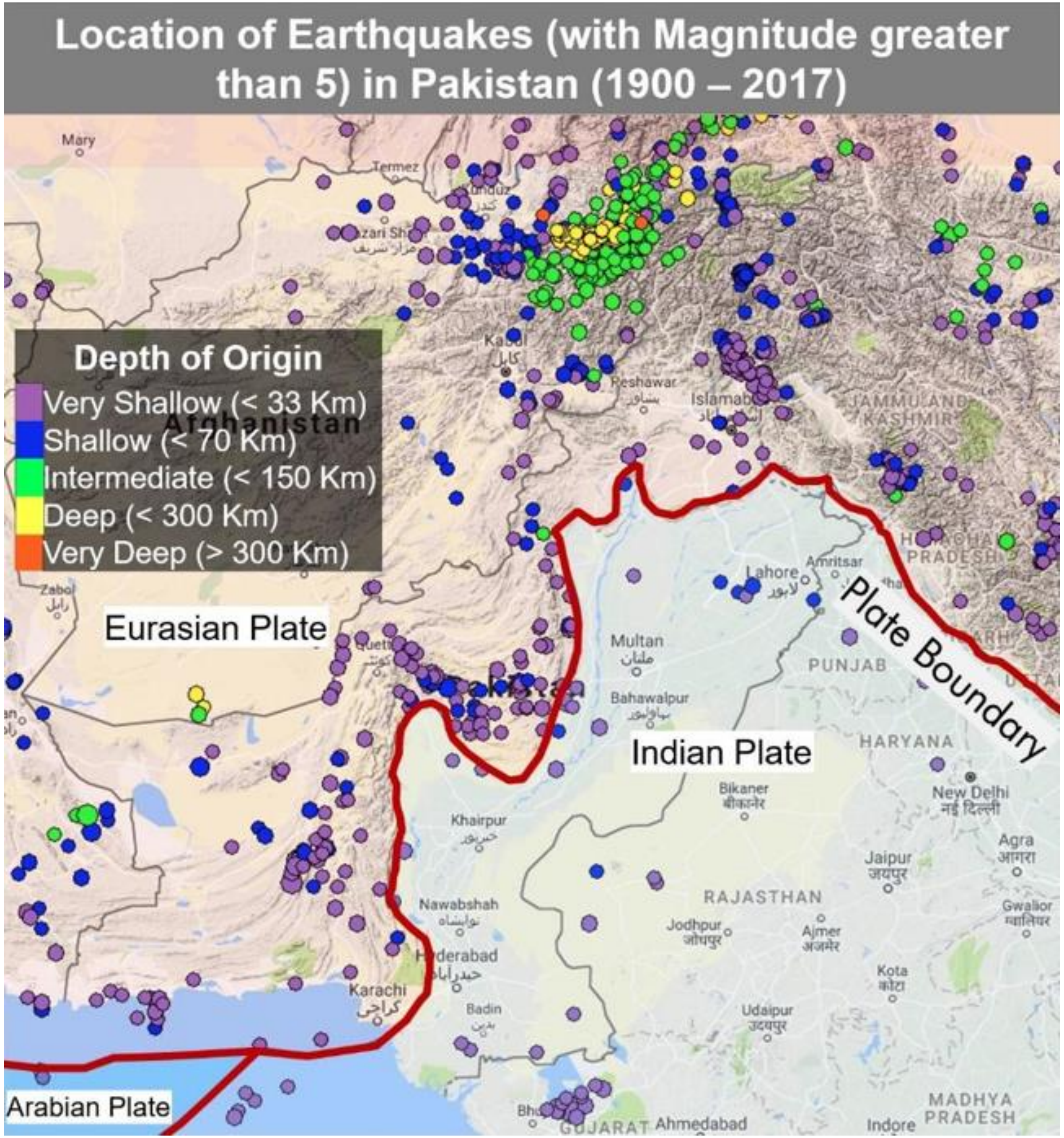
(Modified from Ruleman et al., 2007)

Source: Zaman S. (2016) Probabilistic Seismic Hazard Assessment and Site-Amplification Mapping for Pakistan

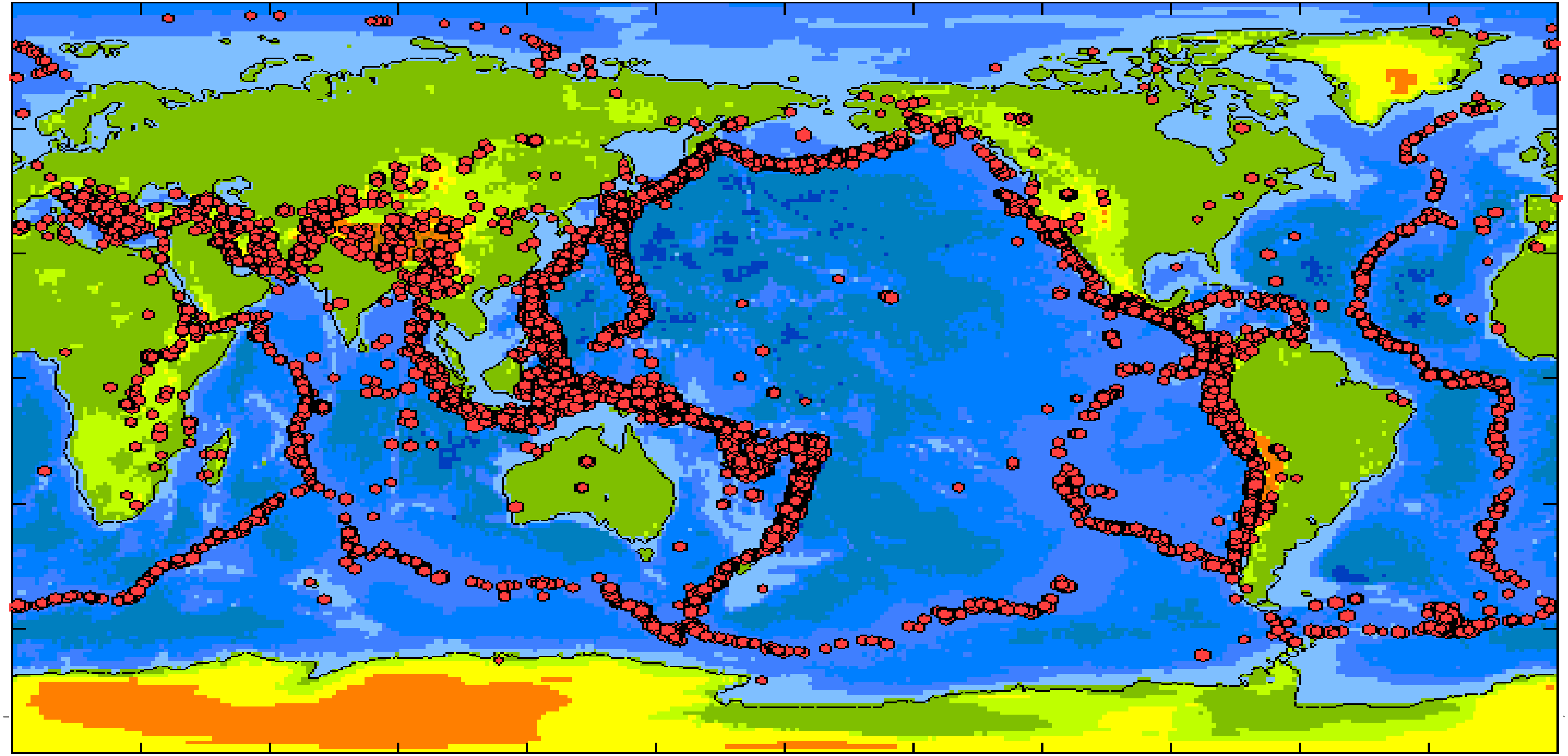


Epicenter of the 2005 Kashmir Earthquake
1.3 cm/year
Eurasian Plate
Indian Plate
2.9 cm/year
1-2 cm/year
2.3 cm/year
Arabian Plate
AFGHANISTAN
PAKISTAN
BALUCHISTAN
Kabul
Peshawar
Islamabad
Rawalpindi
Srinagar
JAMMU AND KASHMIR
Lahore
Quetta
Karachi
Delhi
RAJASTHAN

Seismicity of Pakistan



Where do earthquakes occur ?



Three Main Types of Plate Boundaries

Convergent Plate Boundary: When the two plates “bump” into each other

https://jig.space/view/embed?jig=v4Ga2VKw

Divergent Plate Boundary: When the two plates “pull away” from each other

https://jig.space/view/embed?jig=0xKBaZGa

Transform Plate Boundary: When the two plates “slide past” each other

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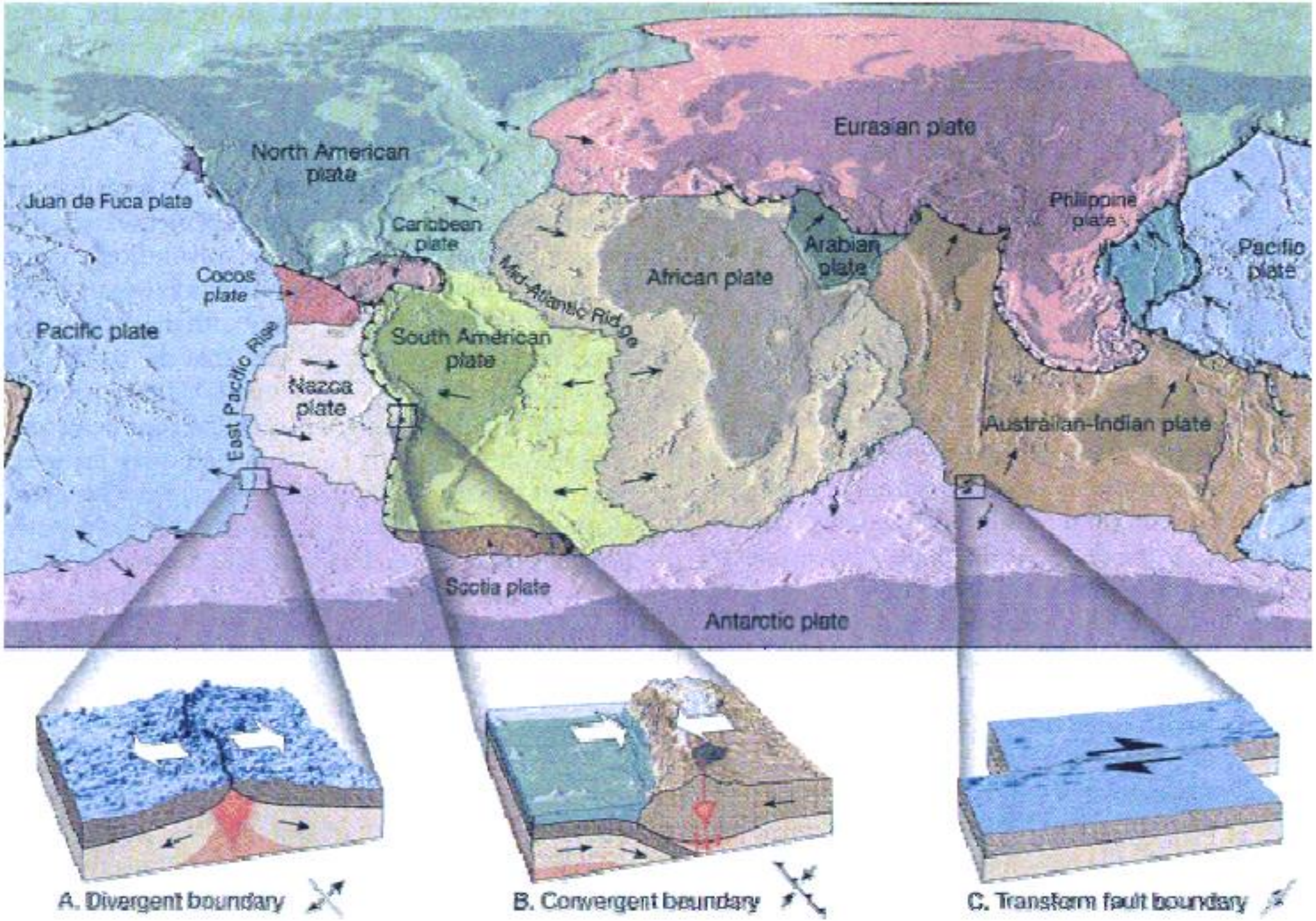
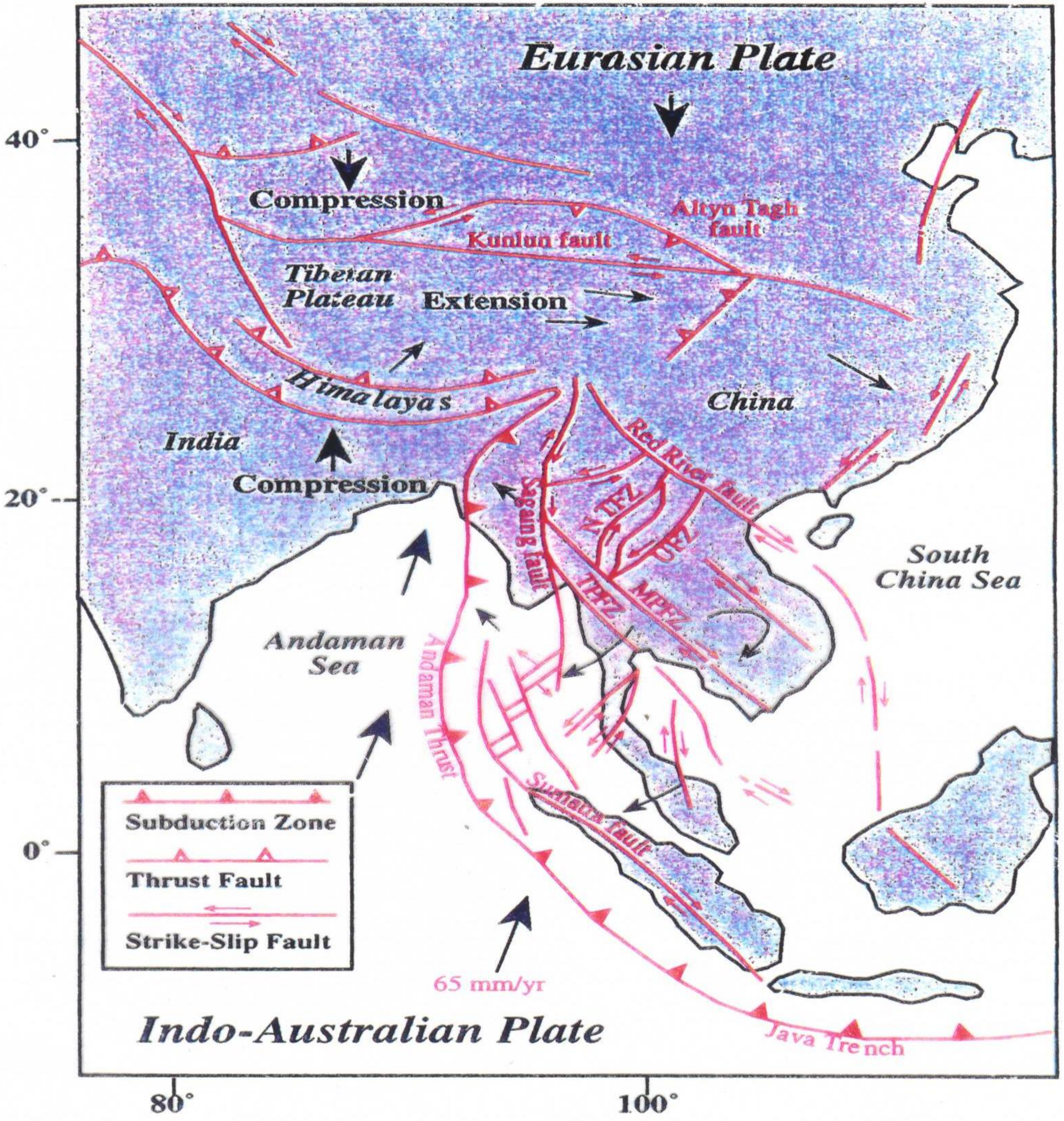
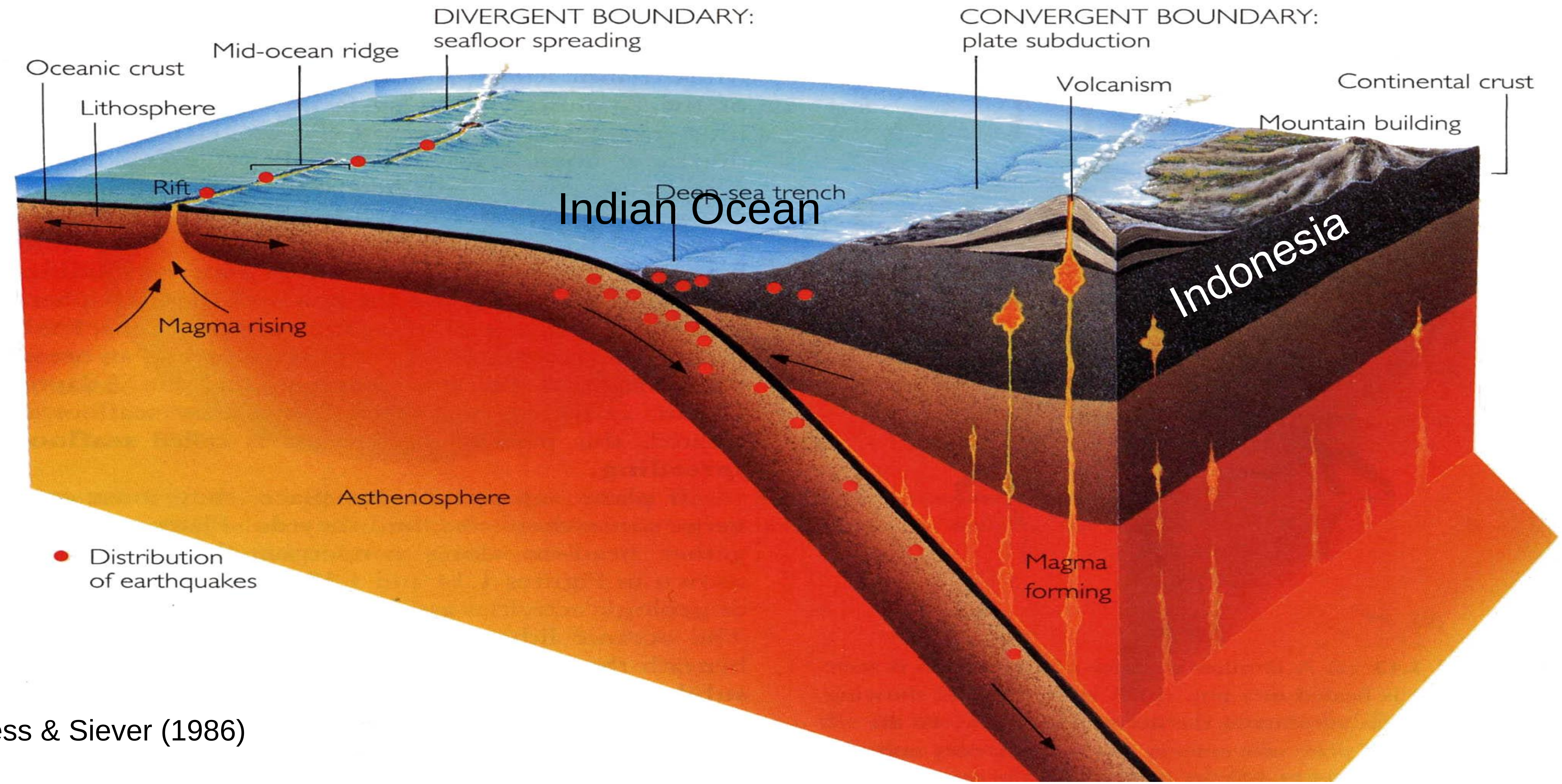

Eurasian plate
North American plate
Juan de Fuca plate
Caribbean plate
Philippine plate
Arabian plate
Pacific plate
Cocos plate
African plate
Mid-Atlantic Ridge
Pacific plate
South American plate
East Pacific Rise
Nazca plate
Australian-Indian plate
Scotia plate
Antarctic plate
A. Divergent boundary
B. Convergent boundary
C. Transform fault boundary

Tectonic Map of South-East Asia

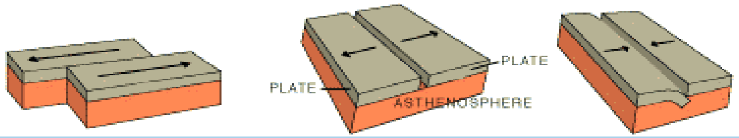


(after Polachan et al., 1991)

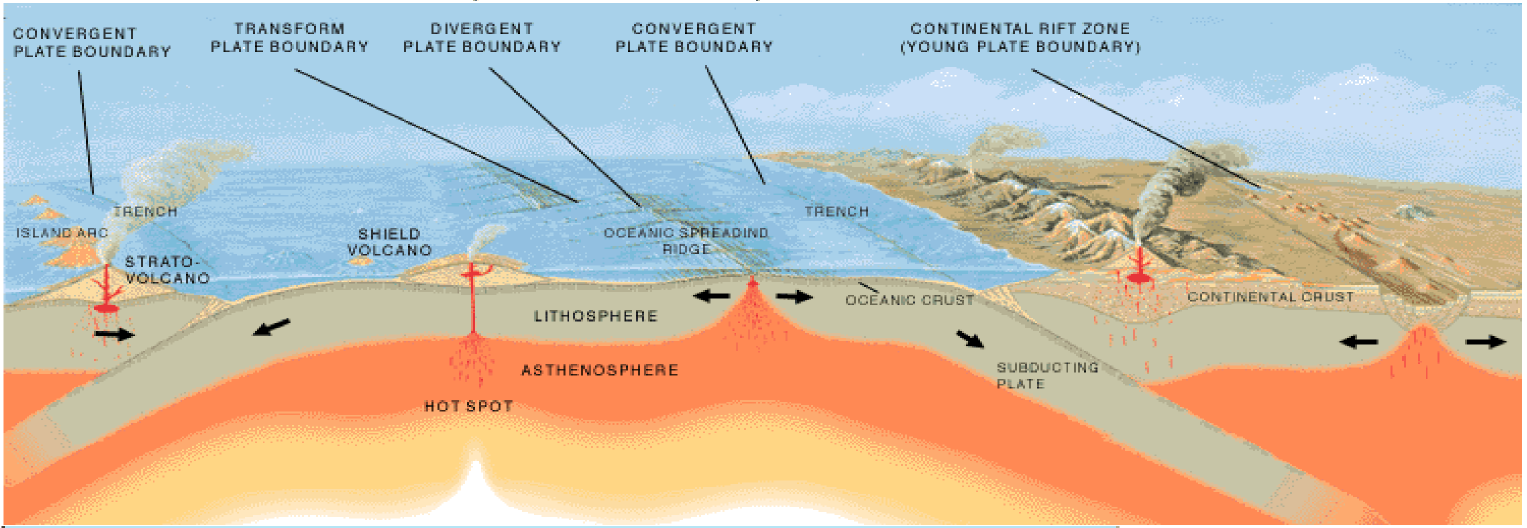
New tectonic plate is created at mid-ocean ridges by the upwelling and cooling of magma (molten rock) from the Earth's mantle. In order to conserve mass, the horizontally moving plates are believed to be absorbed at the ocean trenches where a subduction process carries the tectonic plate downward into the Earth's interior.

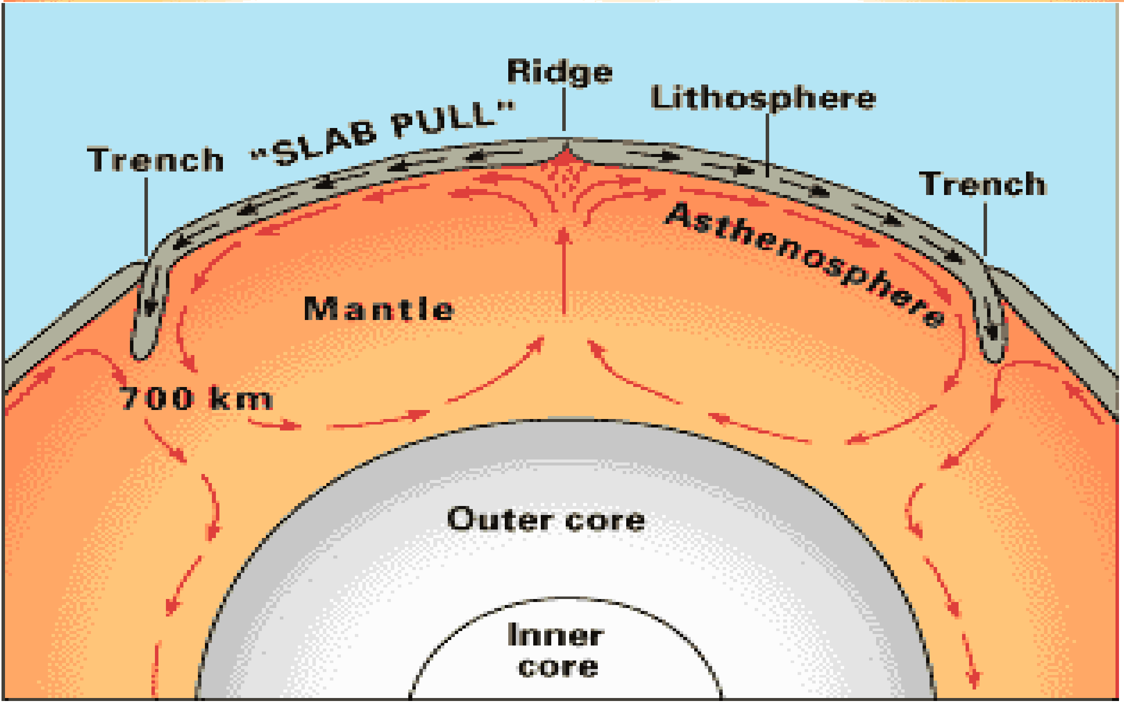


Press & Siever (1986)



Crustal Movements and Plate Boundaries





An **oceanic spreading ridge** is the fracture zone along the ocean bottom where molten mantle material comes to the surface, thus creating new crust. This fracture can be seen beneath the ocean as a line of ridges that form as molten rock reaches the ocean bottom and solidifies.

An **oceanic trench** is a linear depression of the sea floor caused by the subduction of one plate under another.

Three types of plate convergence

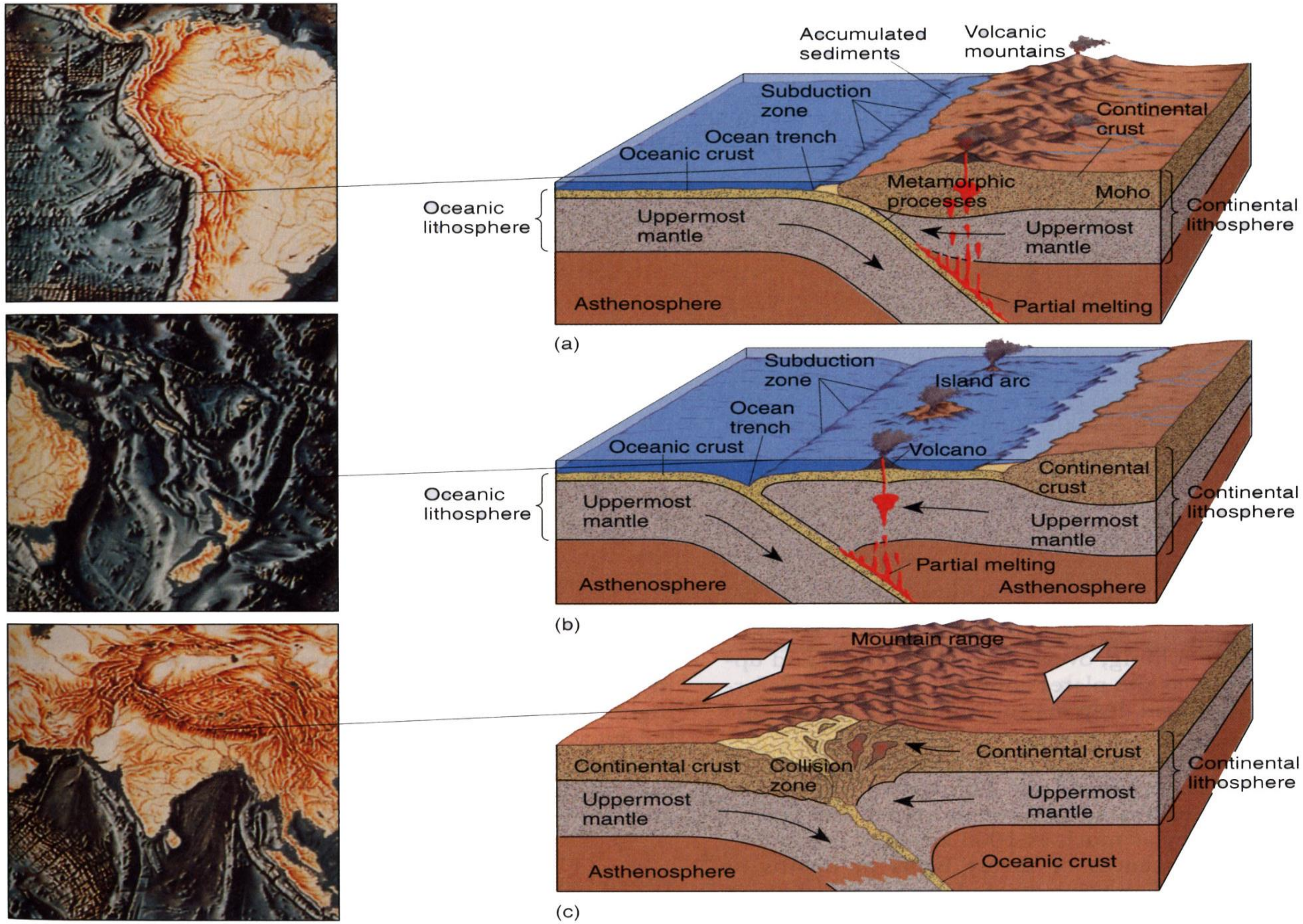


Figure 9-15 **Three types of plate convergence.**
Real-world examples illustrate three types of crustal collisions. Oceanic–continental (example: Nazca plate–South American plate collision and subduction) (a); oceanic–oceanic (example: New Hebrides Trench near Vanuatu, 16° S, 168° E) (b); and, continental–continental (example: India plate and Eurasian landmass collision and resulting Himalayan Mountains) (c). [Inset illustrations derived from *Floor of the Oceans,* 1975, by Bruce C. Heezen and Marie Tharp. © 1980 by Marie Tharp.]

This plate tectonics theory has a number of implications for our understanding of earthquakes.

First, many more earthquakes will occur along the edges of the interacting plates (interplate earthquakes) than within the plate boundaries (**intraplate earthquakes**).

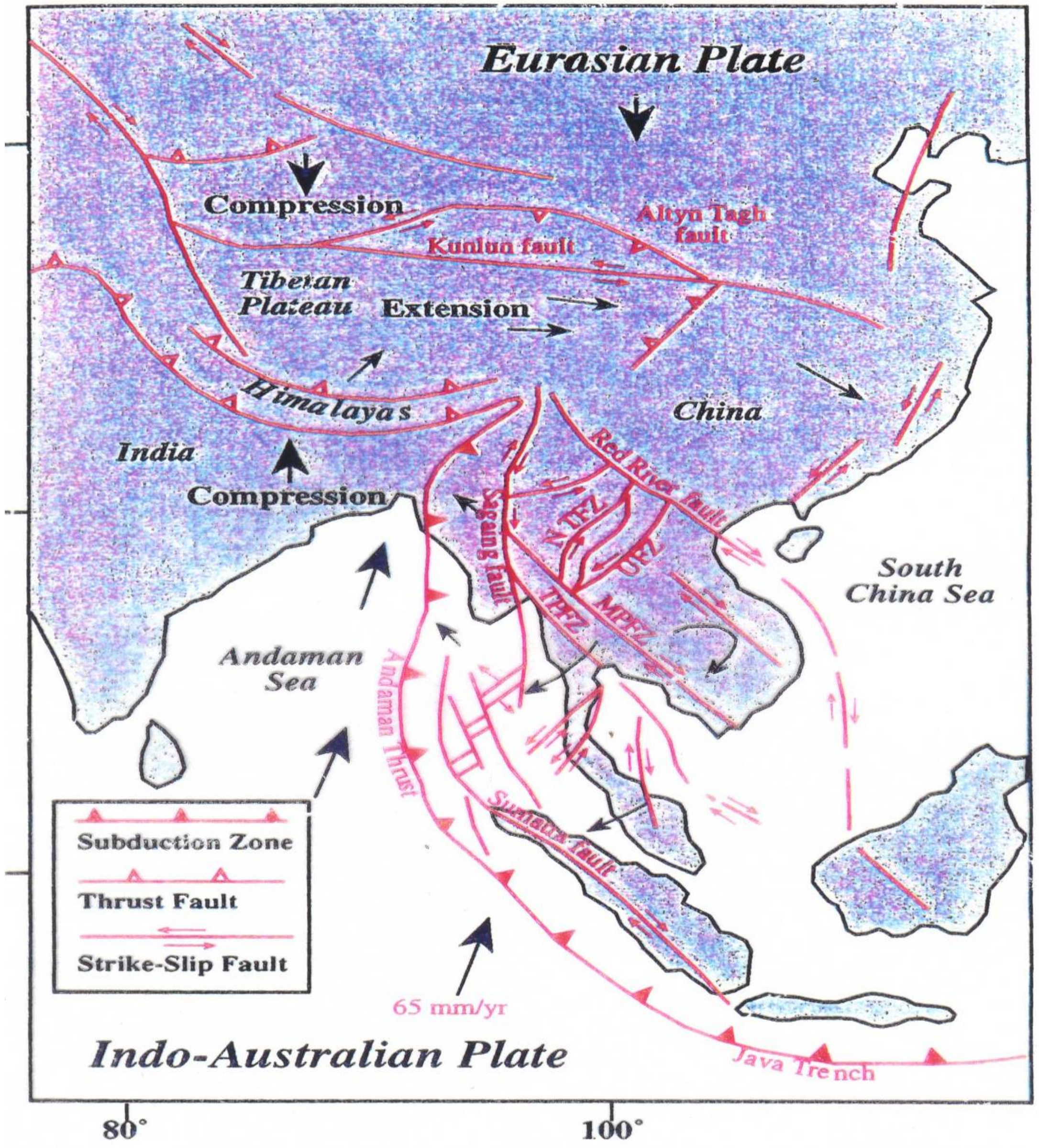
Second, because the directions of forces on plates vary across them, the mechanism of the sources of earthquakes and their size differ in different parts of a plate.

Only about 10% of the world's earthquakes occur along the ocean ridge system. In contrast, earthquakes occurring where plate boundaries converge, such as trenches, contribute about 90 %.

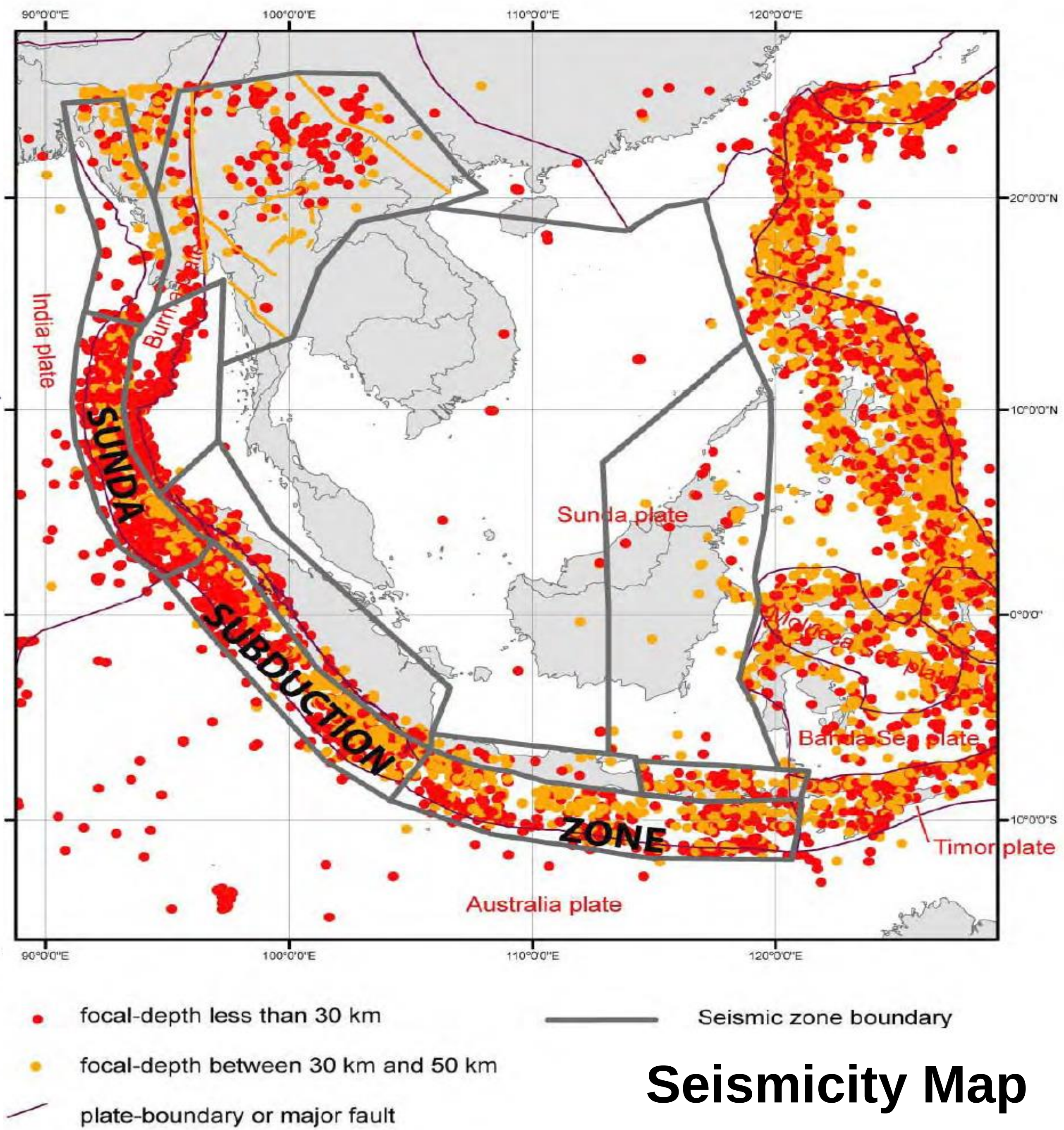
Third, the grand scale of the plate pattern and the steady rate of plate spreading imply that along a plate edge the slip should, on average, be a constant value over many years.

This idea suggests that the historical patterns of distance and time intervals between major earthquakes along major plate boundaries provide at least crude indication of places at which large earthquakes might occur.

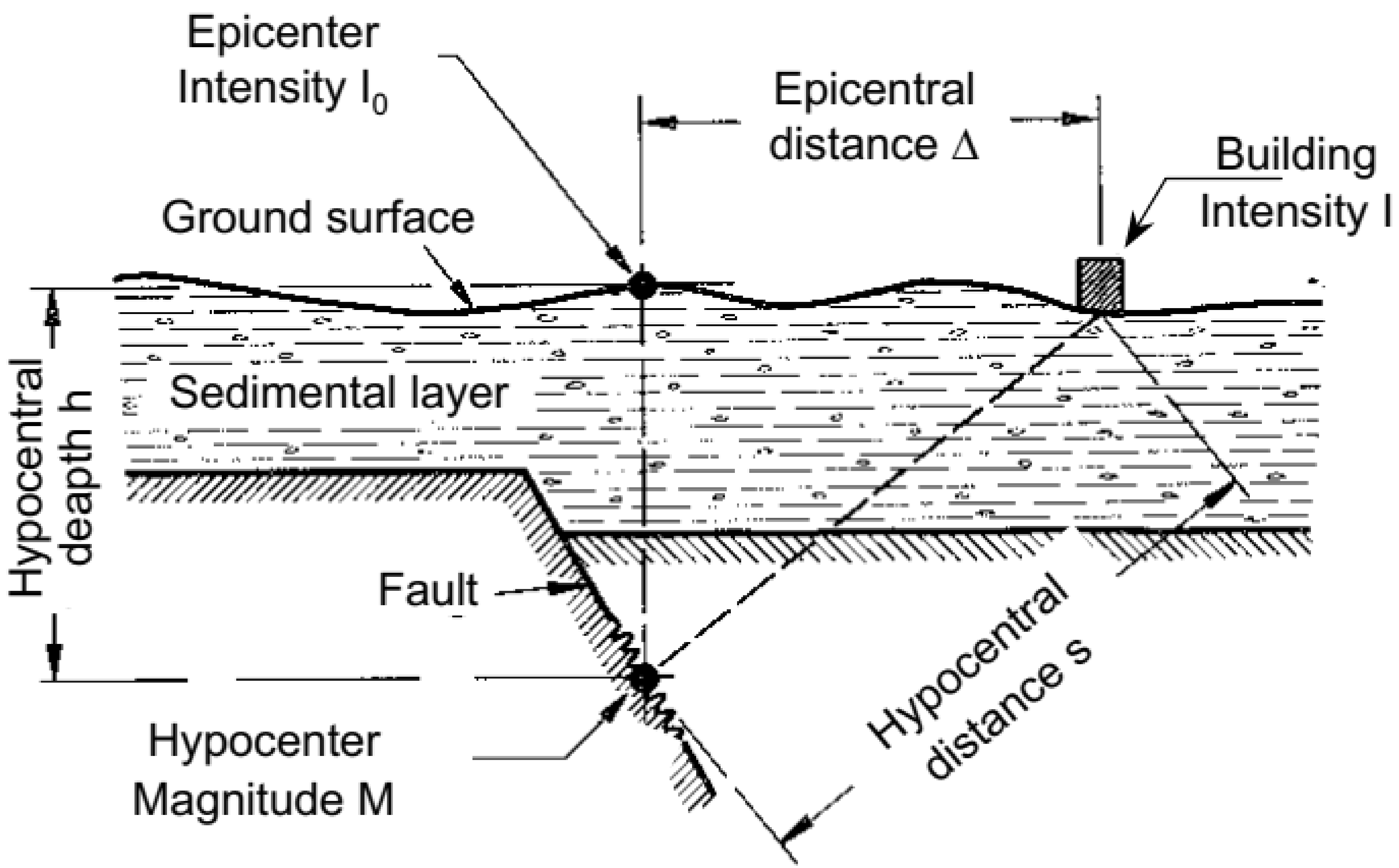
Tectonic Map



(after Polachan et al., 1991)



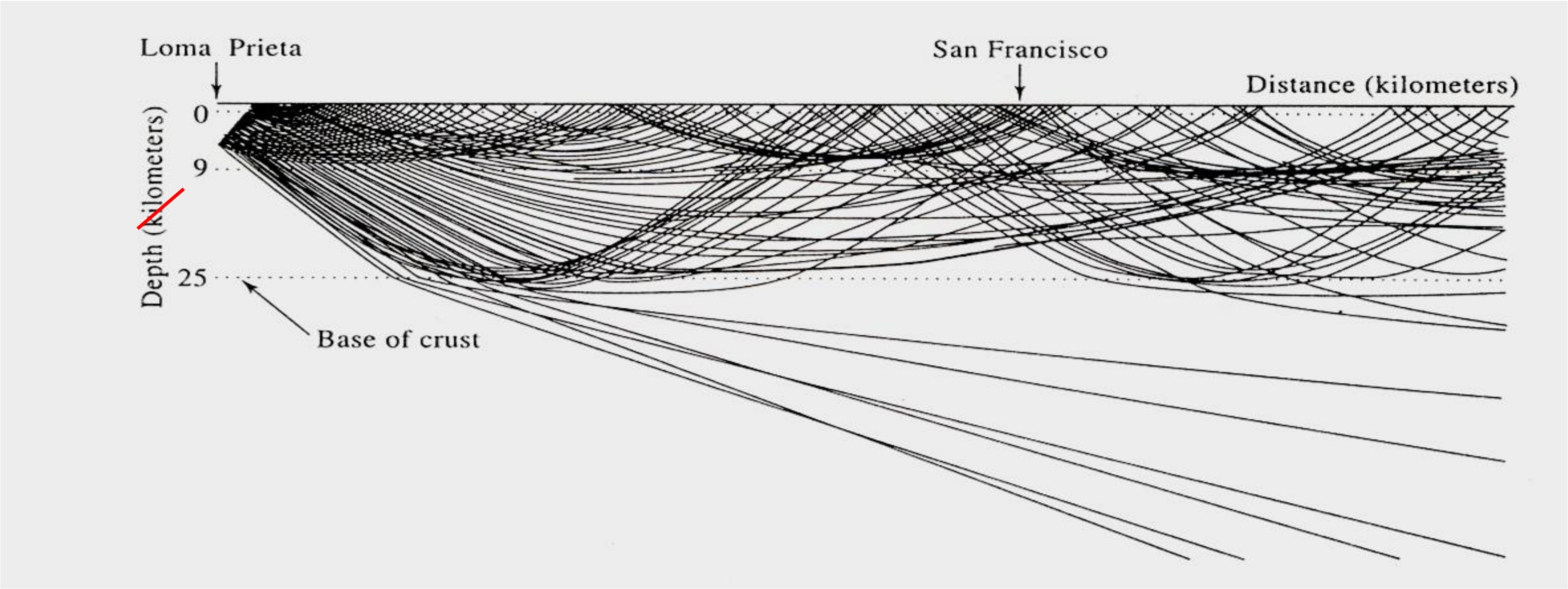
Seismicity Map


Epicenter
Intensity I_0
Epicentral
distance Δ
Building
Intensity I
Ground surface
Sedimental layer
Hypocentral
deapth h
Fault
Hypocenter
Magnitude M
Hypocentral
distance s

Seismic Waves

Earthquakes generate many types of seismic waves in complex patterns.

Some penetrate the earth and come to the surface in the same state, or slightly distorted. Others are reflected, or refracted, or bent by something or some zone of different density within the earth itself. Some travels round the circumference of the world and do not penetrate at all.



Rays of seismic shear waves from the focus of the 1989 Loma Prieta earthquake through the crust

Seismic Waves

There are 3 basic types of seismic waves:

- **The primary (P) waves**
- **The secondary (S) waves**
- **The surface waves**

P waves are compressional waves which exert a pull-push force.
The motion of a P wave is the same as that of a sound wave—as it spreads out, it alternately pushes (compresses) and pulls (dilates) the rock.

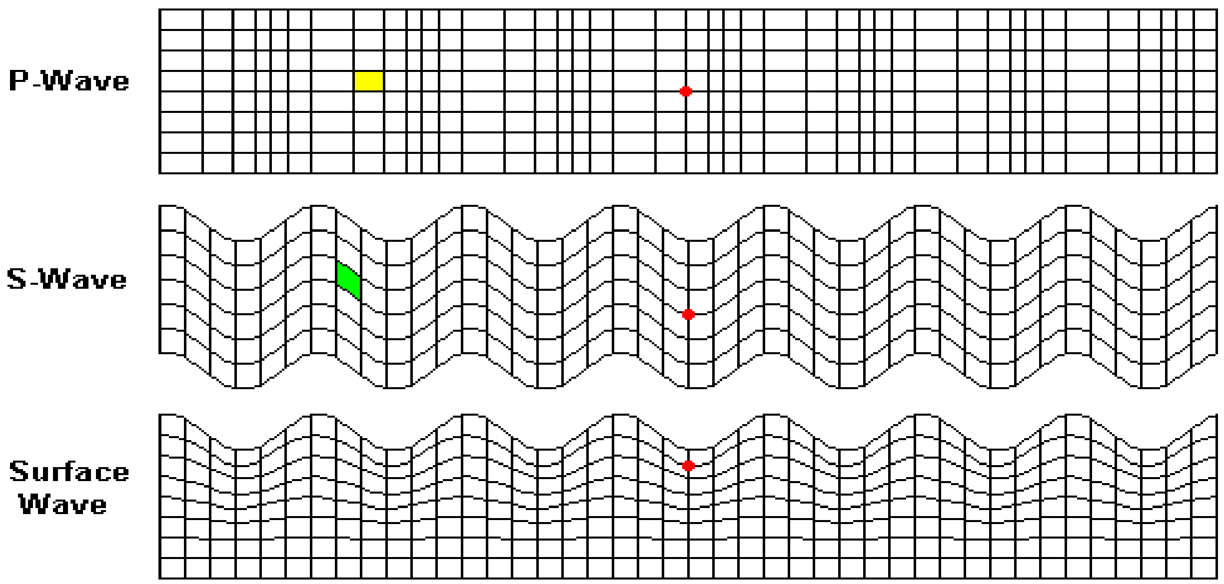
These P waves, just like sound waves, are able to travel through both solid rock and liquid material (such as volcanic magma or the oceans).

S waves are shear waves.

As it propagates through the body of rock, a shear wave shears the rock sideways at right angles to the direction of travel.

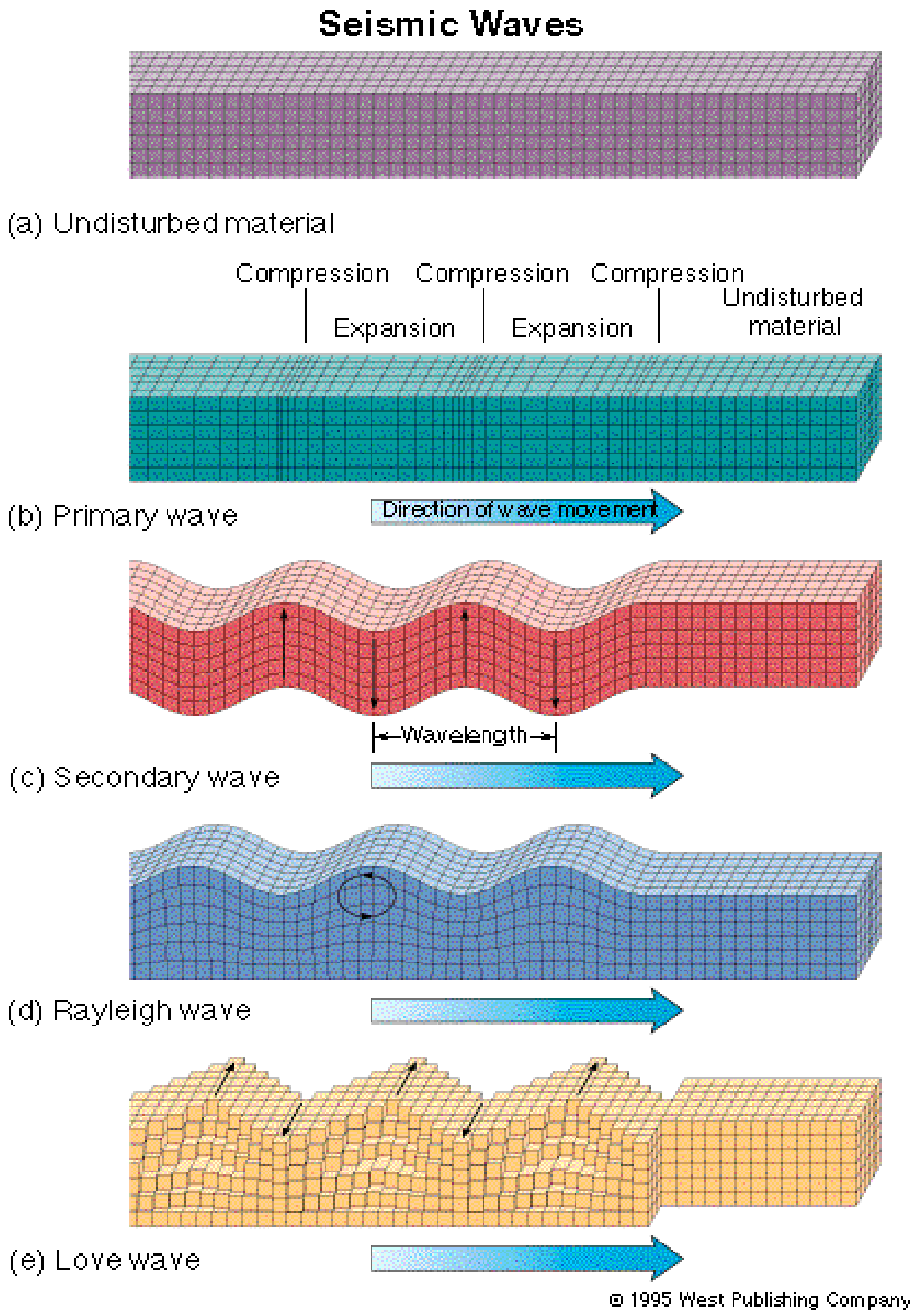
S waves cannot propagate in the liquid parts of the earth, such as the oceans or magma.

Seismic Waves



Body Waves

Surface Waves



Body Waves

When the body waves (the P and S waves) move through the layers of the rock in the crust, they are reflected or refracted at the interfaces between rock types. Also, whenever either one is reflected or refracted, some of the energy of one type is converted to waves of the other type.

P and S waves do not travel at the same speed, and these speeds vary with the substance through which the waves are passing. Broadly speaking, a P wave travels faster than an S wave.

Thus at any site, the P wave arrives first, and the S wave arrives later.

The length of time between the arrival of the P and the S wave gives an indication of the distance an earthquake is away from an observer. By using 3 or more seismograph stations, it is possible to pinpoint where the earthquake occurred.

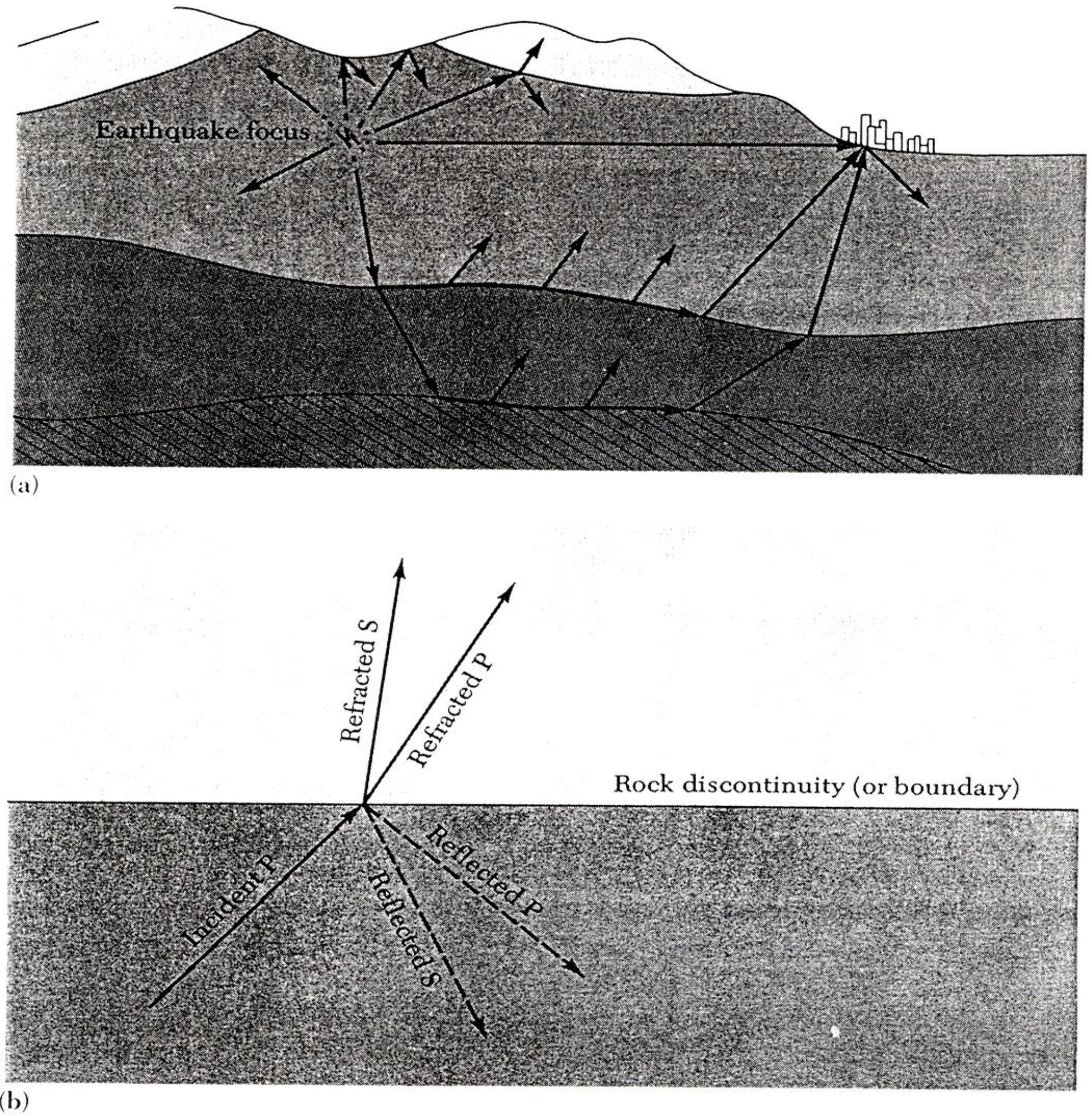
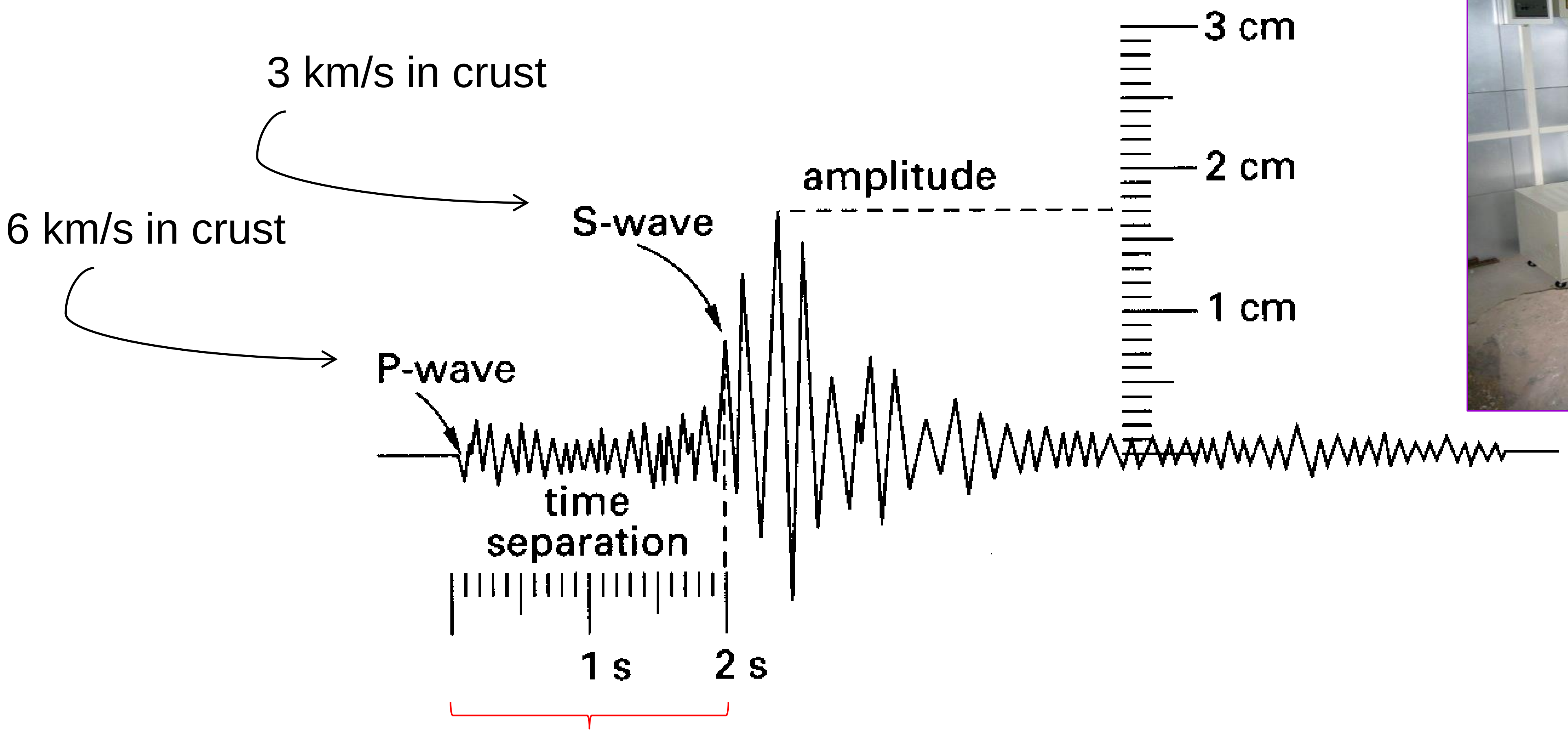


Figure 1.10 (a) A simplified picture of the paths of seismic P or S waves being reflected and refracted in rock structures of the Earth's crust. (b) The reflection and refraction of a longitudinal (P) wave in an earthquake after it hits a boundary between two types of rock. [From Bruce A. Bolt, *Nuclear Explosions and Earthquakes: The Parted Veil* (San Francisco: W. H. Freeman and Company. Copyright 1976).]

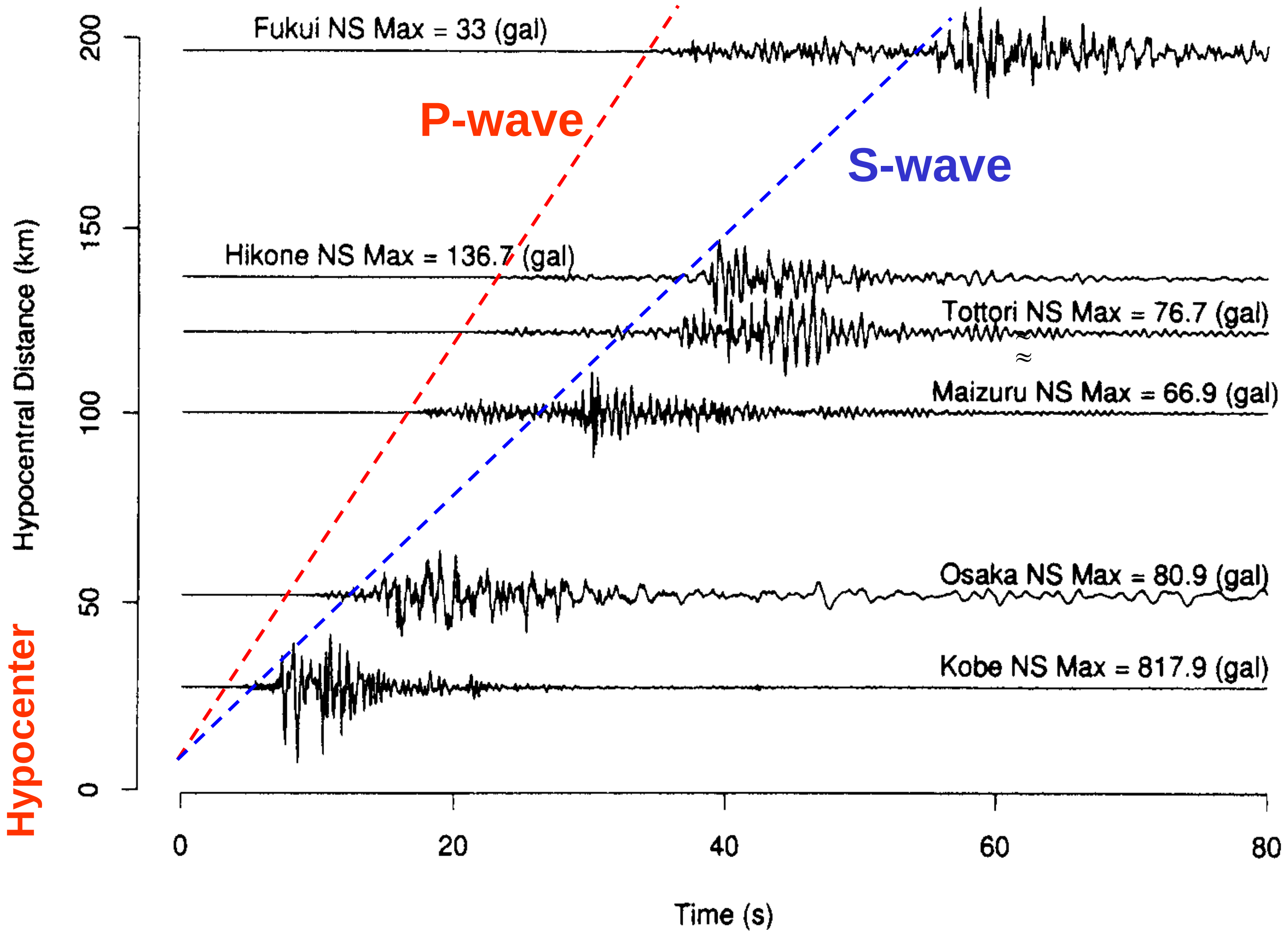
Instrumental Record at a Seismic Station

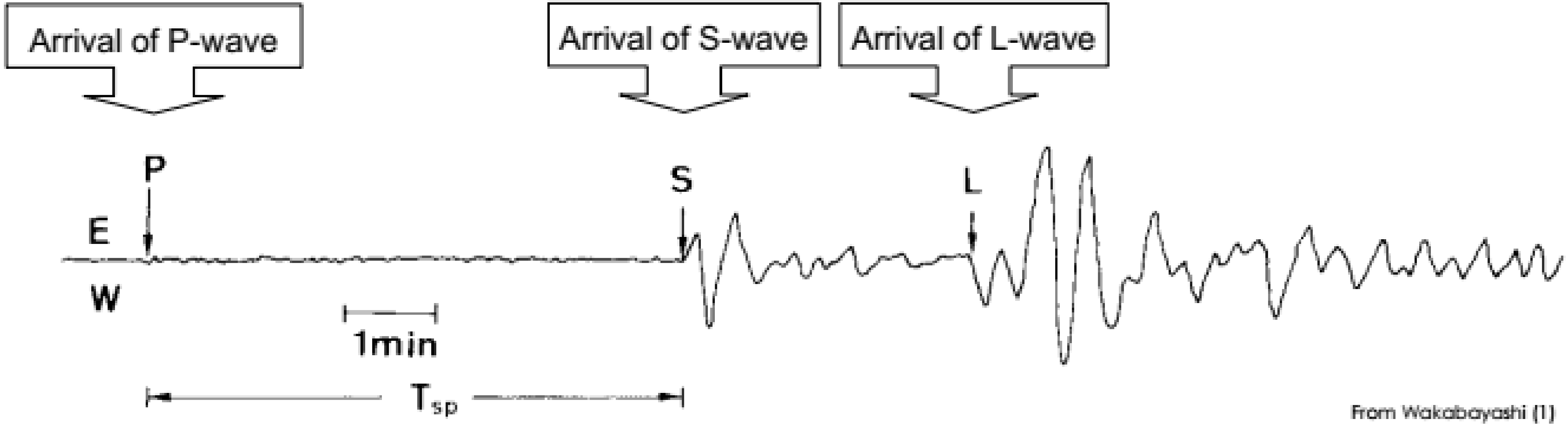


Difference in **arrival times between P and S waves**: measure of site-to-source distance

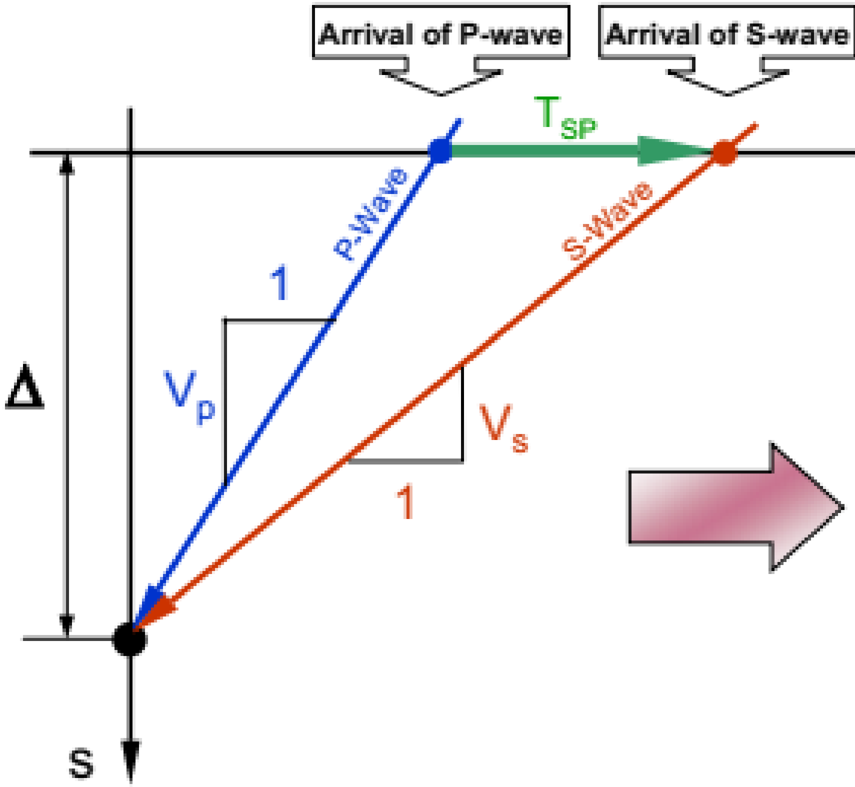
Seismic Wave Records at Several Seismic Stations

The 1995 Kobe Earthquake



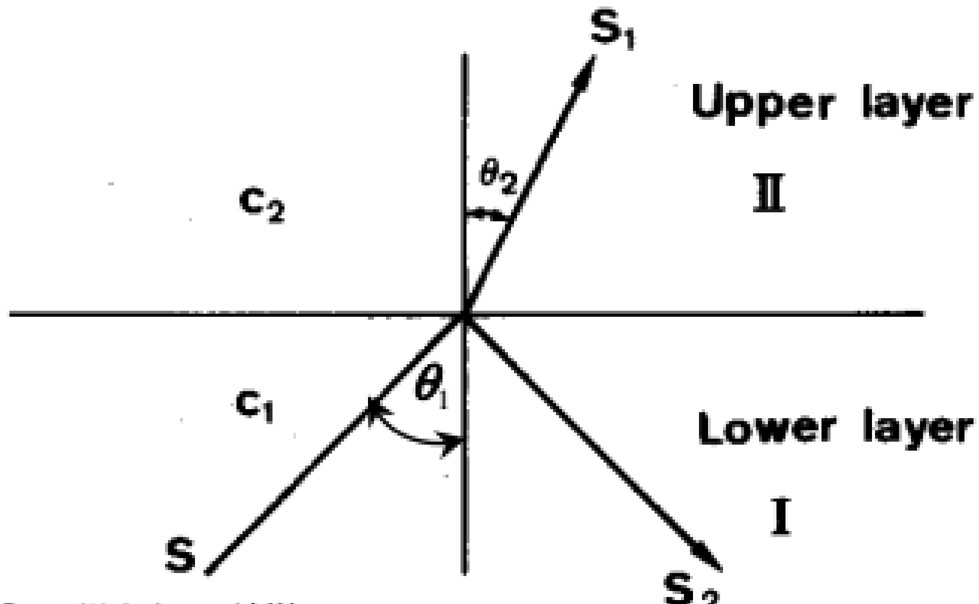


From Wakabayashi (1)



$$\Delta = \frac{T_{SP}}{\left(\frac{1}{V_S} - \frac{1}{V_P}\right)}$$

Reflection and refraction of waves



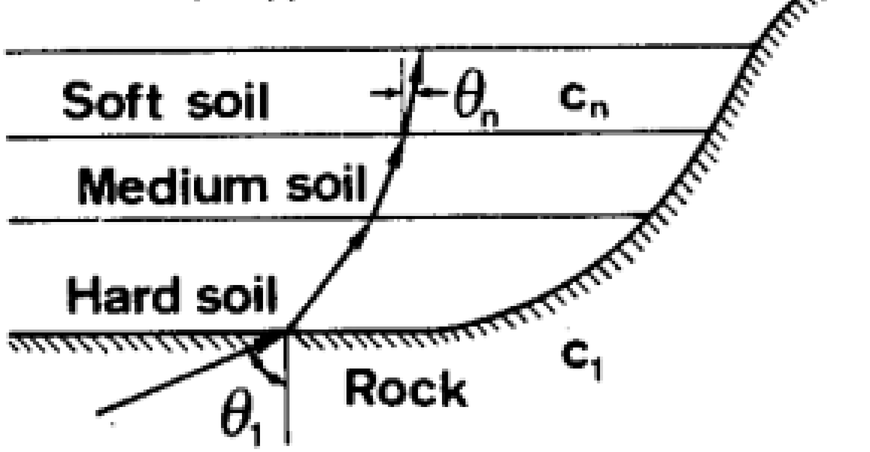
From Wakabayashi (1)

$$\frac{\sin\theta_1}{C_1} = \frac{\sin\theta_2}{C_2}$$

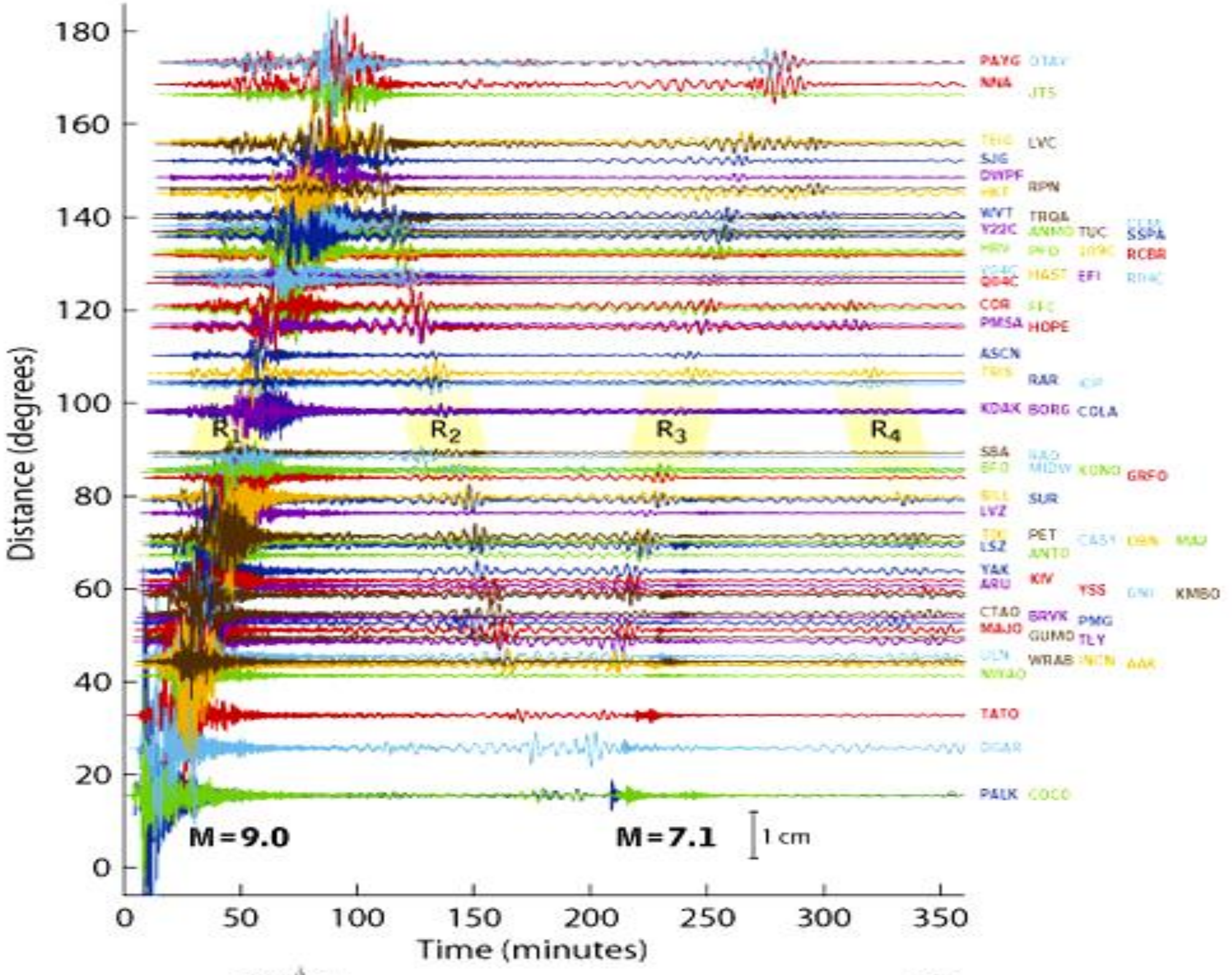
$$\sin\theta_n = \frac{C_n}{C_1}\cdot\sin\theta_1$$

Refraction of waves in the surface of layers

From Wakabayashi (1)

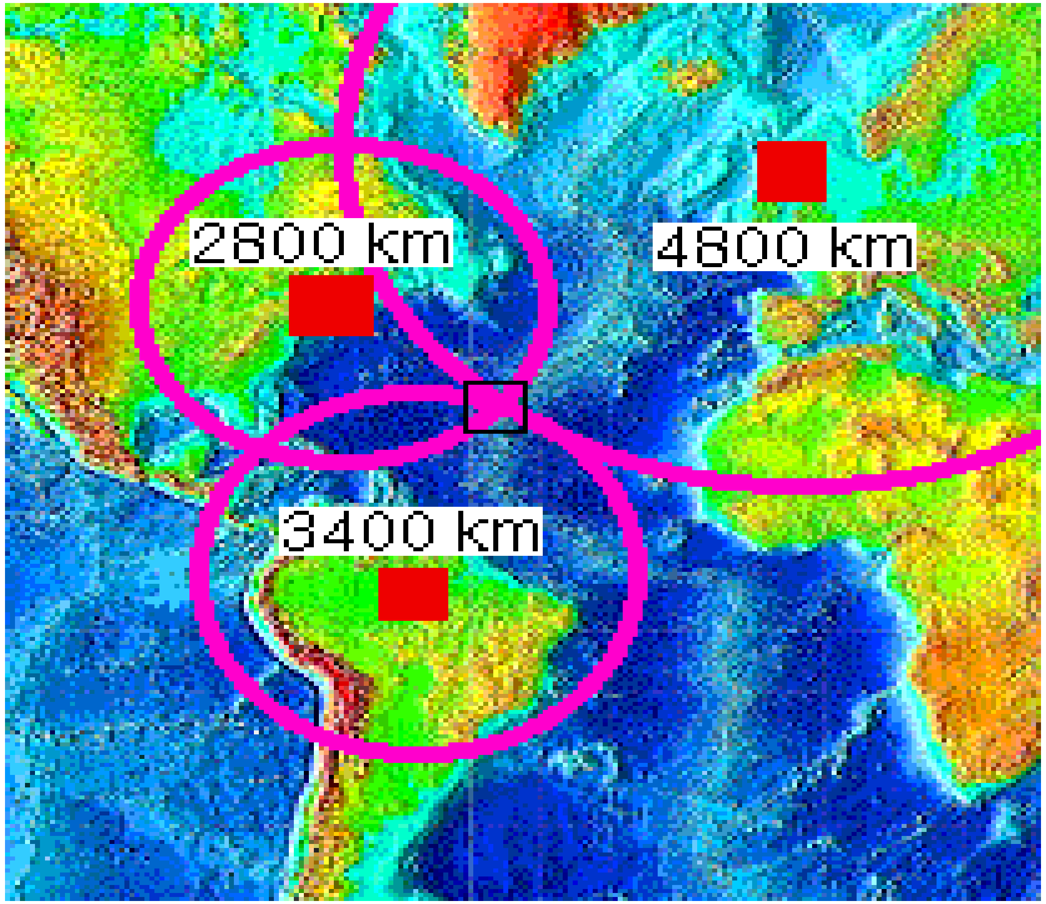


Sumatra - Andaman Islands Earthquake (M_w=9.0)
Global Displacement Wavefield from the Global Seismographic Network



Locating Earthquakes

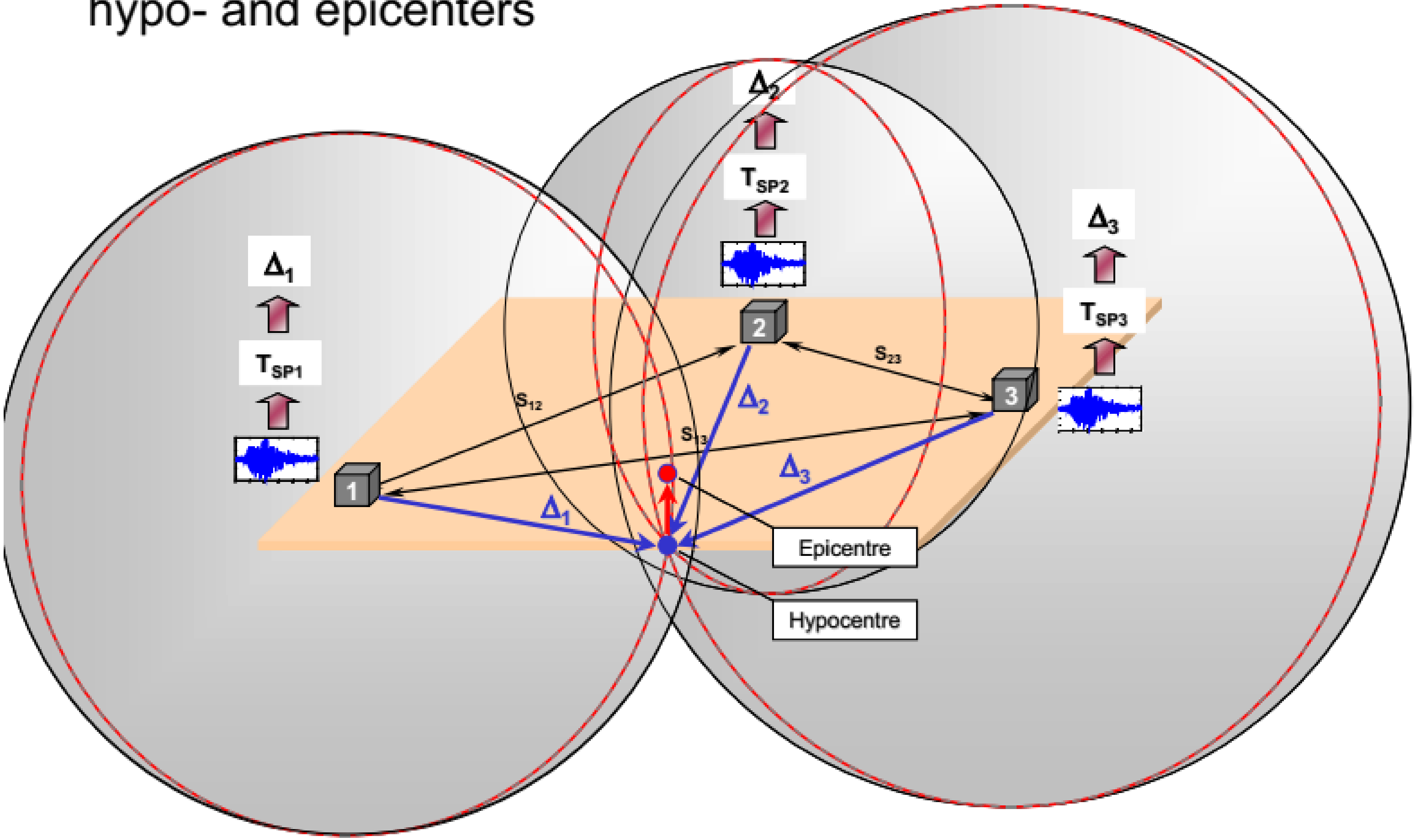
Although it is possible to infer a general location for an event from the records of a single station, it is most accurate to **use three or more stations**.



- A **measurement of the P-S time** at single station **gives the distance** between the station and the event.
- **Drawing a circle** on a map around the station's location, with a **radius equal to the distance**, shows all possible locations for the event.
- With the P-S time from **a second station**, the circle around that station will narrow the **possible locations down to two points**.
- It is only with a **third station's P-S time** that should identify which of the two previous possible points is **the real one**.

http://www.seismo.unr.edu/ftp/pub/louie/class/100/seismic-waves.html

Localization of hypo- and epicenters



Surface Waves

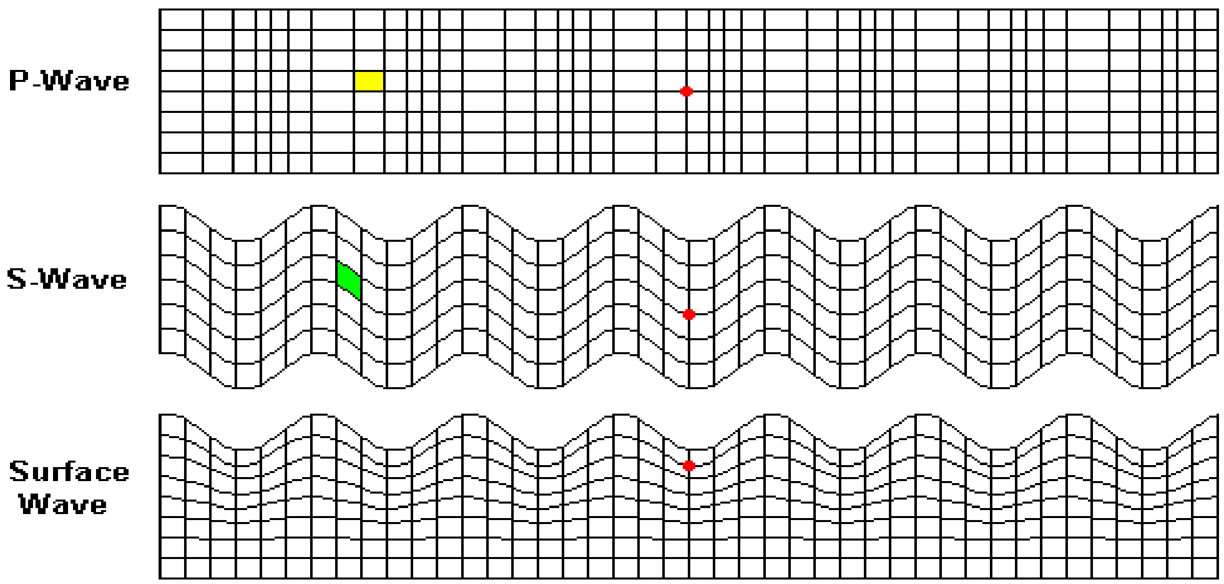
Surface waves have their motion restricted to near the ground surface. As the depth below this surface increases, wave displacements decrease.

Surface waves travel more slowly than body waves.

Surface waves in earthquakes can be further divided into 2 types:
Love wave and **Rayleigh wave**.

The motion of a Love wave is essentially the same as that of S waves that have no vertical displacement. It moves the ground from side to side in a horizontal plane but at right angles to the direction of propagation. Love waves do not propagate through water.

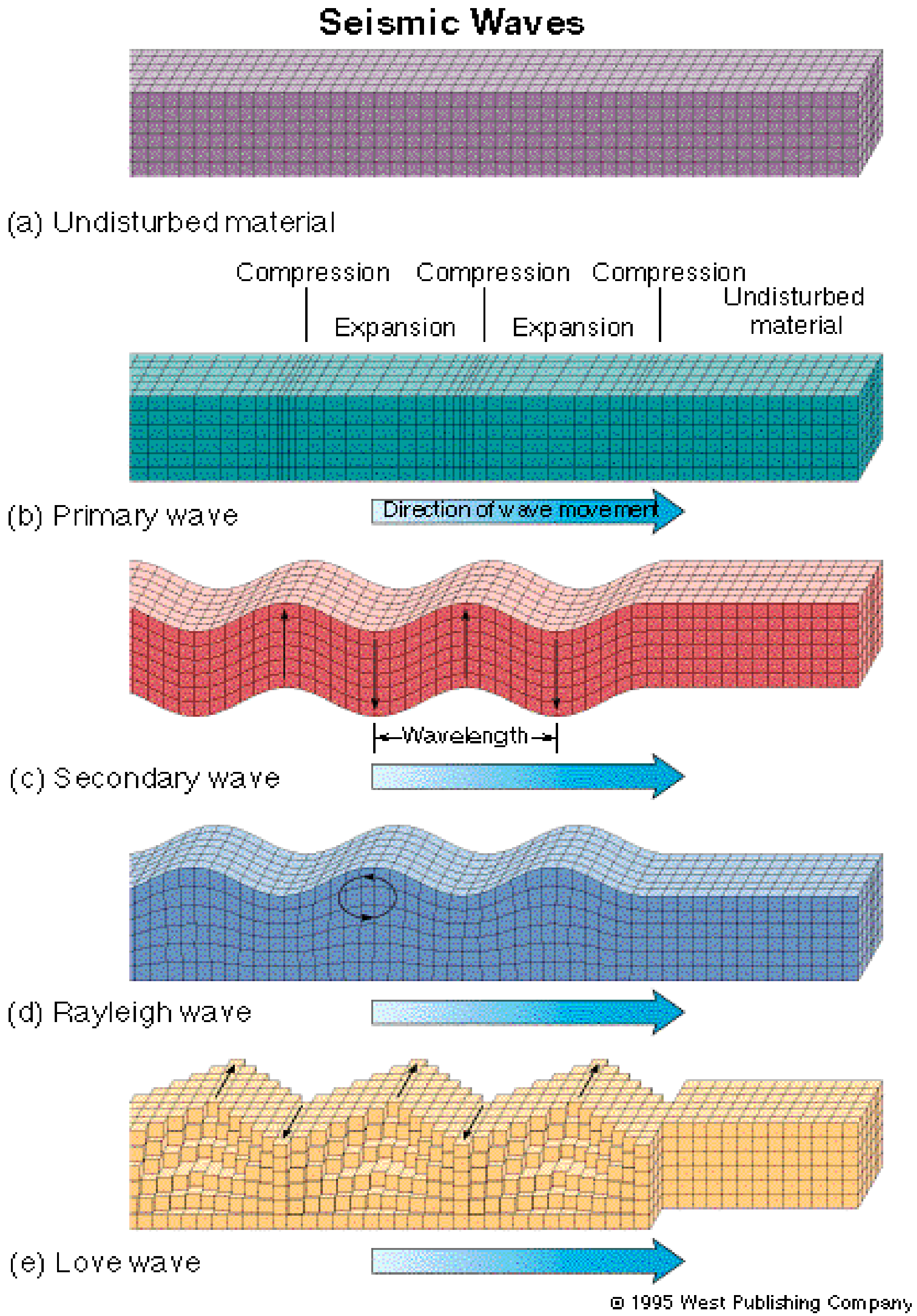
Like rolling of ocean waves, the pieces of material disturbed by a **Rayleigh wave move both vertically and horizontally in a vertical plane** pointed in the direction in which the wave is travelling.



Seismic Waves

Body Waves

Surface Waves



Seismoscopes

In the year A.D. 136, a Chinese called **Choko** (also called Chang Heng) invented an instrument for indicating earthquakes.

It consisted of a spherically formed copper vessel (about 2.4 m in diameter). In the inner part of this instrument a column was so suspended that it can move in 8 directions.

When an earthquake occurs, the vessel is shaken, the dragon instantly drops the ball, and the frog which receives it vibrates vigoriously; anyone watching this instrument can easily observed earthquakes.

Once upon a time a dragon dropped its ball without any earthquake being observed, and people therefore thought the instrument of no use, but after 2 to 3 days a notice came saying that an earthquake had taken place in Rosei. Hearing of this, those who doubted the use of this instrument began to believe in it again.

After this ingenious instrument had been invented by Choko, the Chinese government wisely appointed a secretary to make observations on earthquakes.

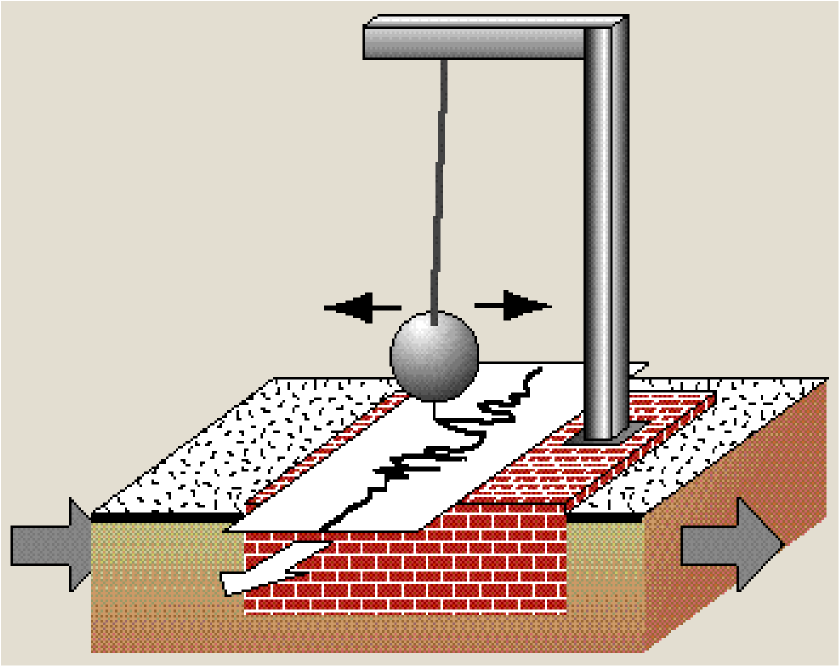
Seismographs

The earliest modern seismographs was invented by **John Milne** around 1880s during when he was Professor of Geology and Mining at the Imperial College of Engineering in Tokyo (University of Tokyo).

The principal problem for constructing precise earthquake measuring devices during that time was **how to produce a body which would remain stationary**, and detached from the world around in order to record the relative movement of the ground on which it actually rested.

They decided to make use of **the mechanical principle of inertia—in** essence the tendency of a heavy body to stay put.

Thus their seismographs relied on using a freely swinging pendulum whose movements were marked by pin or pen on a revolving drum of smoked glass, and later paper.



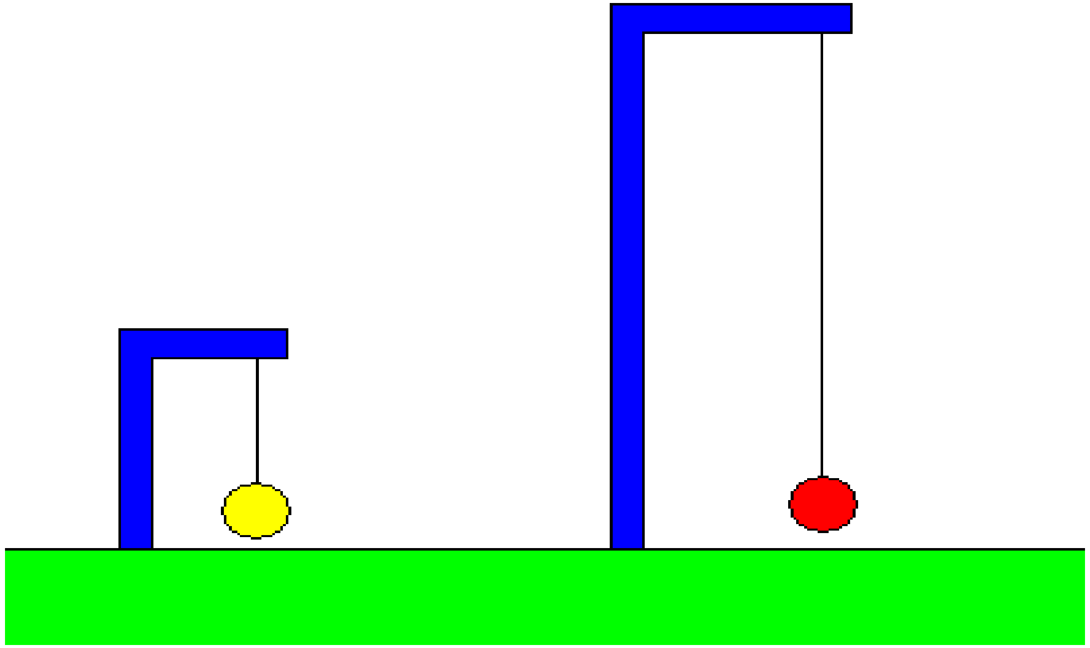
Mechanism of Seismograph

An earthquake does not make the pendulum swing. Instead, **the pendulum remains fixed as the ground moves beneath it.**

A pendulum with a short period (left) moves along with the support and registers no motion. **A pendulum with a long period (right) tends to remain in place while the support moves.**

The boundary between the two types of behavior is the natural period of the pendulum. **Only motions faster than the natural period will be detected; any motion slower will not.**

"Seismograph" usually refers a displacement-type seismometer.

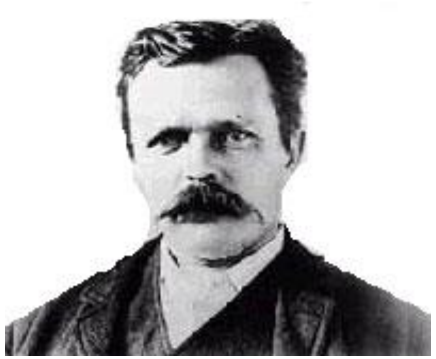


http://www.uwgb.edu/dutchs/202ovhds/quakes.htm

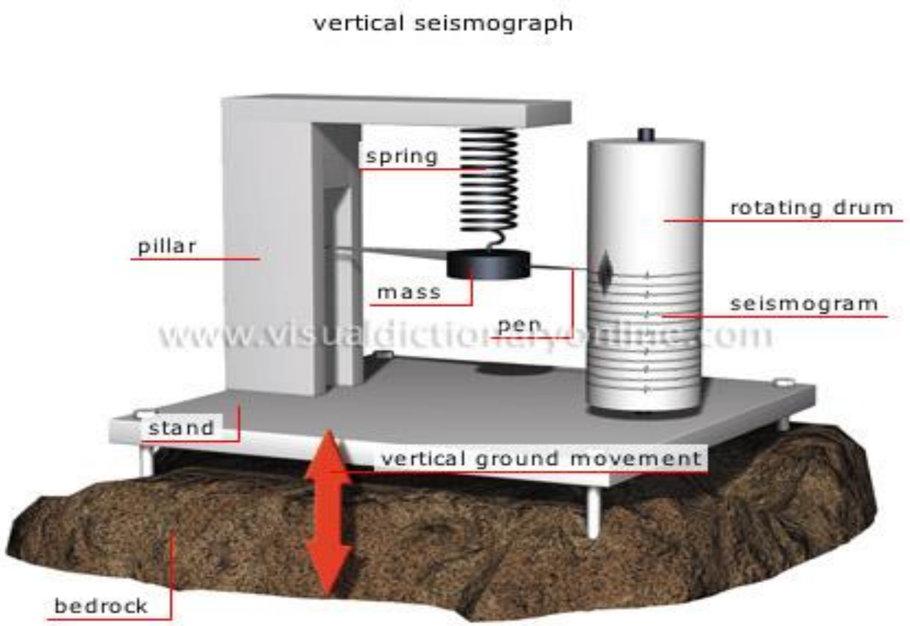
Seismographs

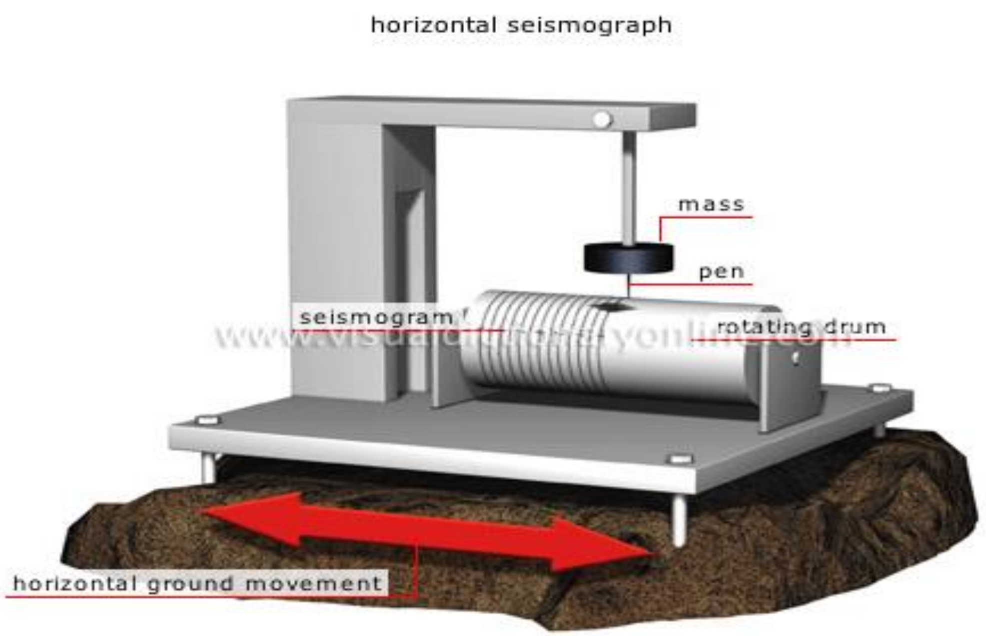
The damping of the pendulum was also added to suppress the free vibration response and to improve the performance of the seismographs.

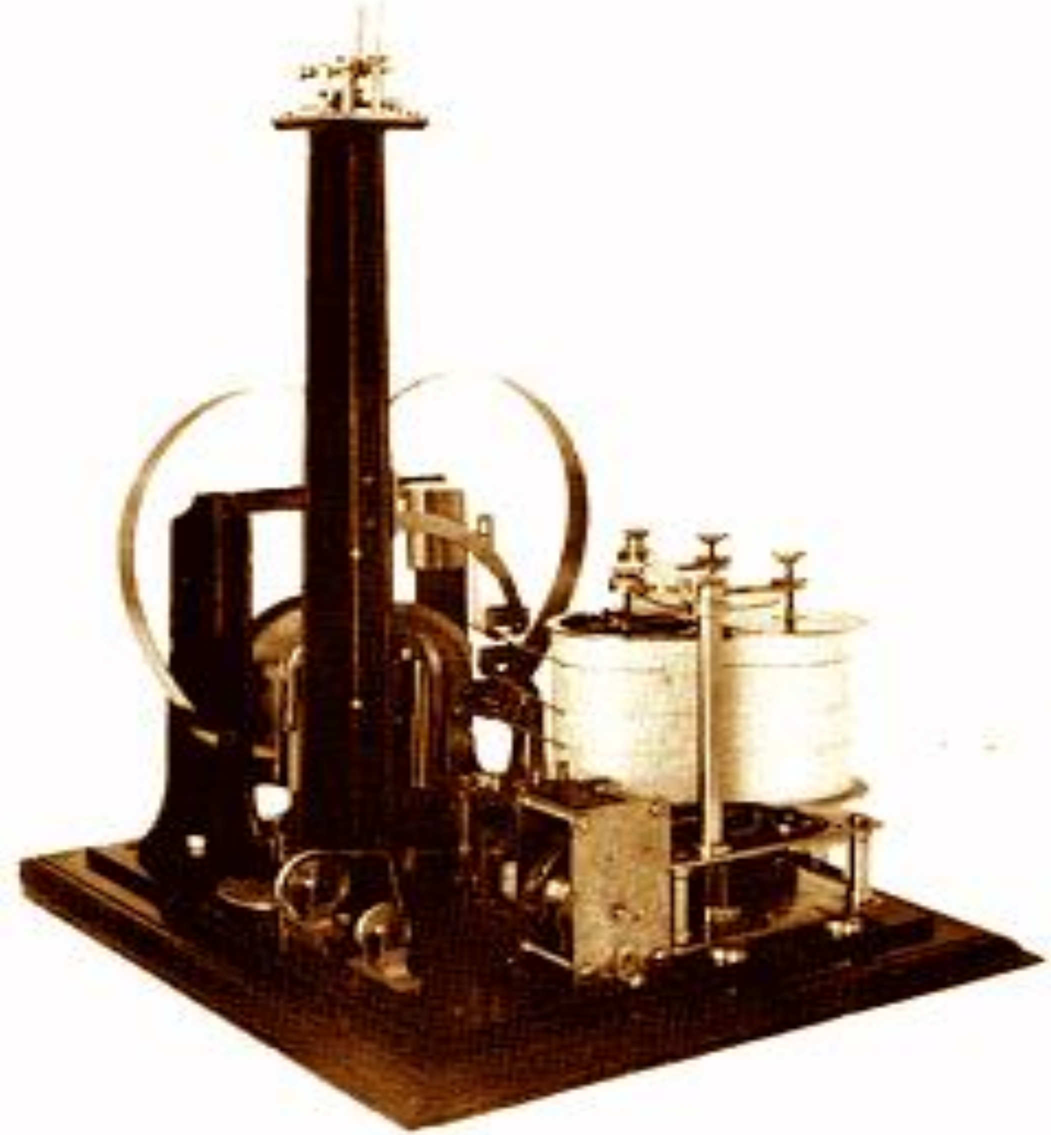
The Milne seismographs employed 3 devices, one for each component of ground motion (up-down, north-south, east-west components).



John Milne







After his arrival in Japan, John Milne was responsible for the invention of a number of seismographs. This is one he produced with his colleague Gray.

Modern Seismographs

The general principle behind the early seismographs is still the basic idea behind the designs of present-day seismographs.

In modern seismographs the relative motion between the pendulum and frame produces an electrical signal that is magnified electronically thousands or even hundreds of thousands of times before it is recorded.

The electrical signals can be recorded on to magnetic tapes, papers, or converted into equivalent digital signals and stored in computer memory.

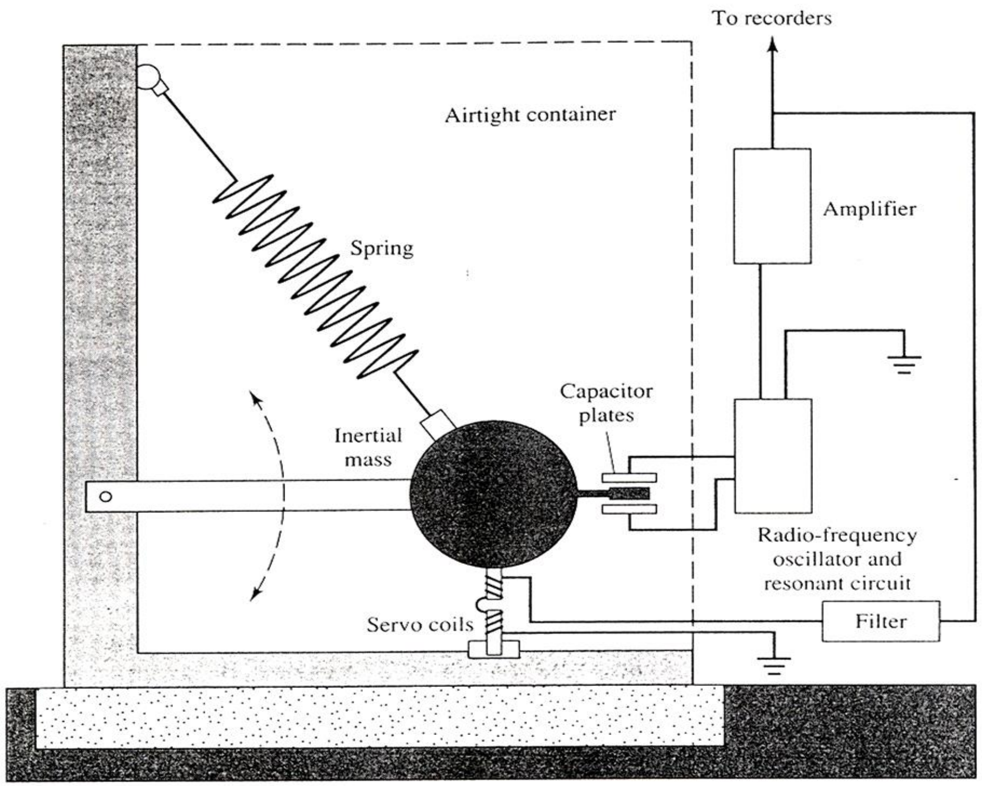


Figure 3.3 Principle of the vertical pendulum seismograph. The mass tends to remain stationary as the Earth moves. Relative motion at the capacitor plates generates an electrical signal that is fed to an analog or digital recorder. The filter feeds back spurious signals, representing undesirable ground motions, to coils that keep the mass centered. (From B. A. Bolt *Inside the Earth*.)

Modern Seismographs

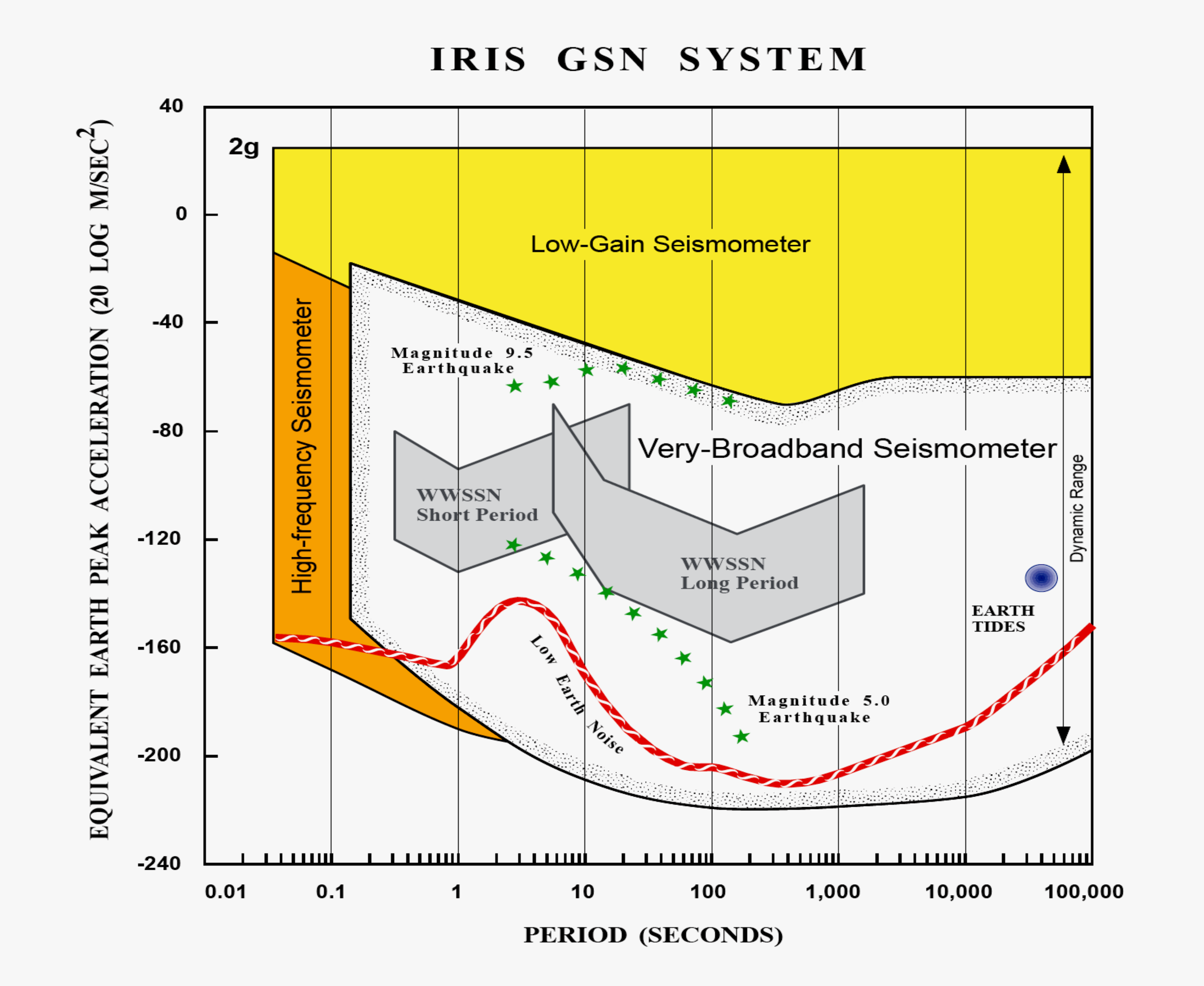
Short-period Seismograph

Natural Period = 1 sec

Broadband Seismograph

Natural Period = 120 sec

Most seismographs around the world are designed to detect small-amplitude motions (weak motions) and are very sensitive “ears on the world”. They can detect and record earthquakes of small size from very great distances (>1000 km).

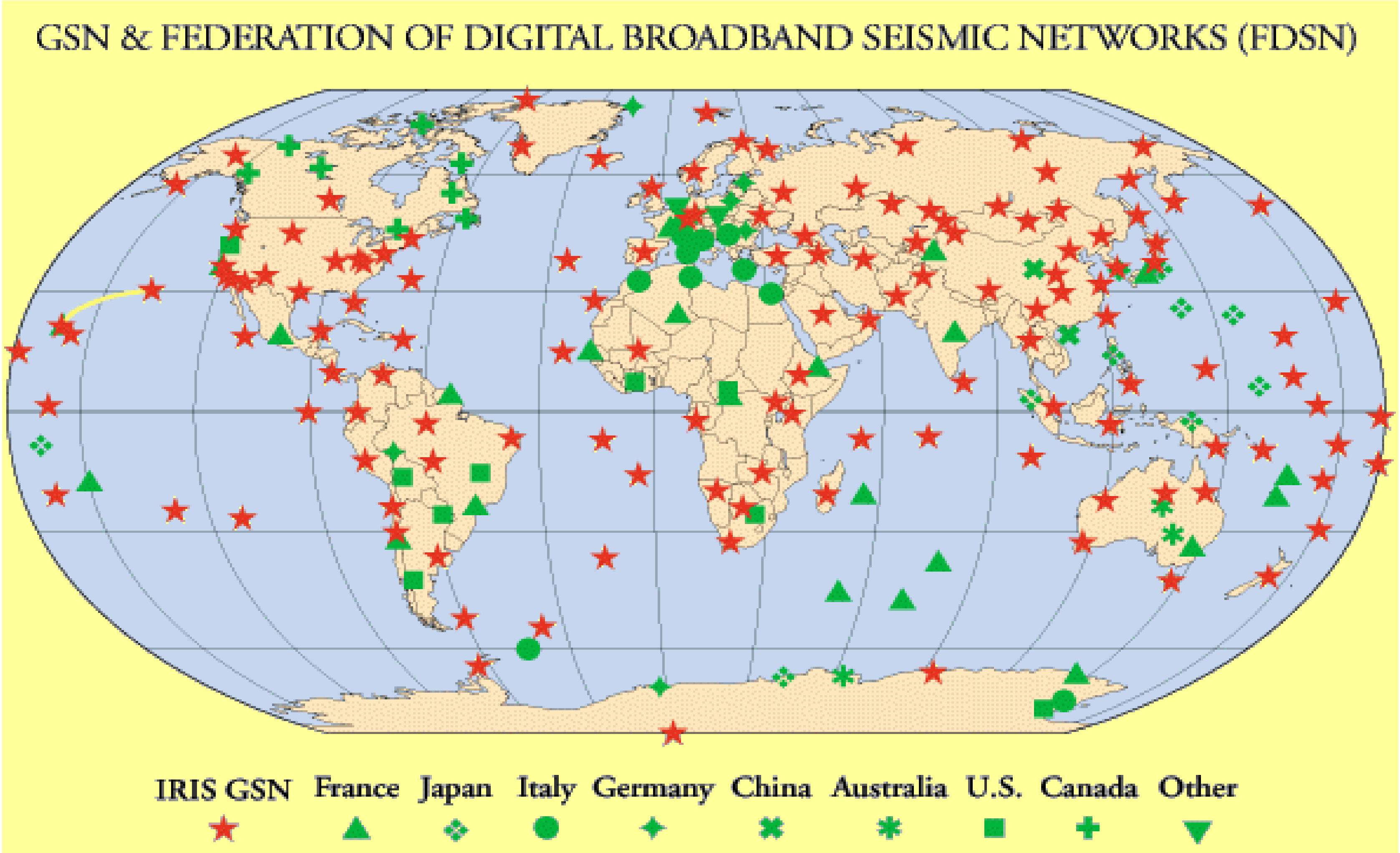

IRIS GSN SYSTEM
EQUIVALENT EARTH PEAK ACCELERATION (20 LOG M/SEC2)
40
0
-40
-80
-120
-160
-200
-240
2g
Low-Gain Seismometer
High-frequency Seismometer
Magnitude 9.5 Earthquake
Very-Broadband Seismometer
WWSSN Short Period
WWSSN Long Period
Dynamic Range
EARTH TIDES
Low Earth Noise
Magnitude 5.0 Earthquake
0.01
0.1
1
10
100
1,000
10,000
100,000
PERIOD (SECONDS)

The IRIS Global Seismographic Network (GSN)

The goal of the GSN is to deploy 128 permanent seismic recording stations uniformly over the earth's surface.

IRIS: Incorporated Research Institutions for Seismology

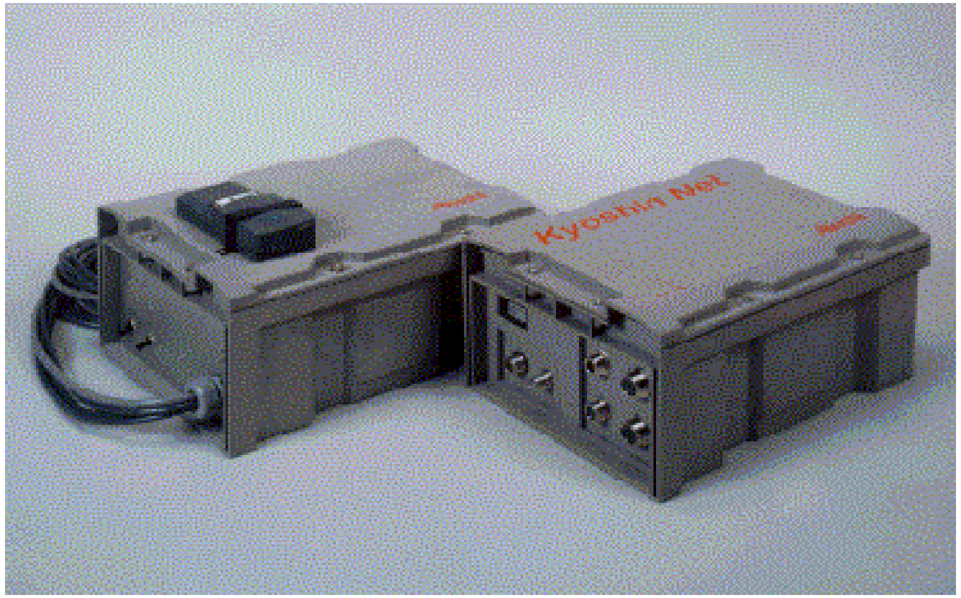
http://www.iris.edu/



Strong-motion Seismographs

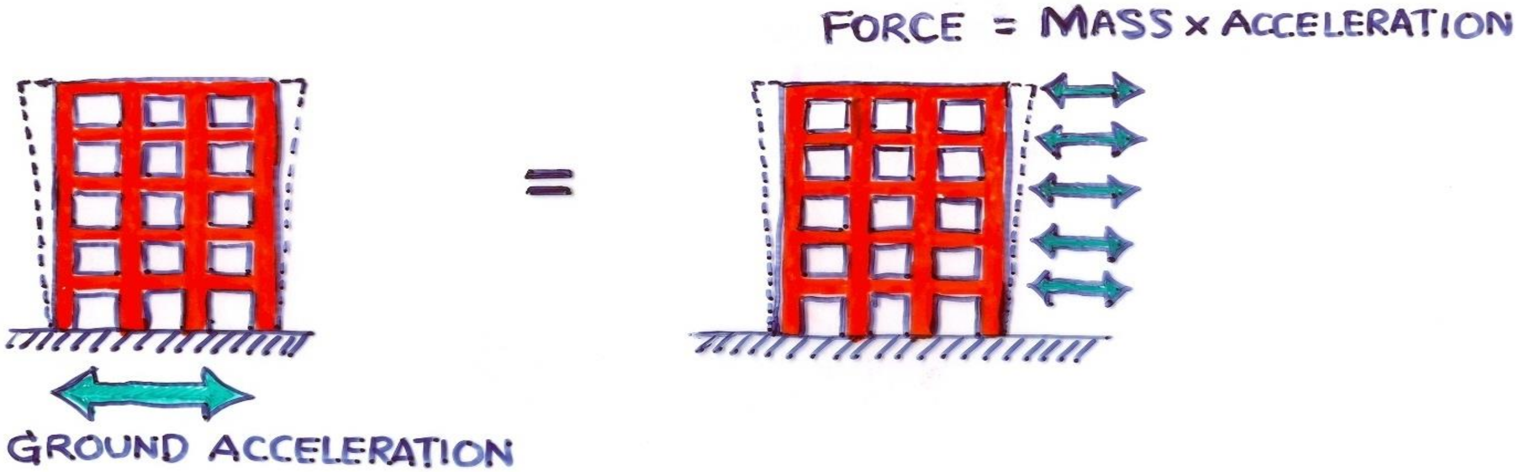
Strong-motion seismographs are specially designed to record the strong shaking of the ground in such a way that the records obtained can be directly read as acceleration of the ground.

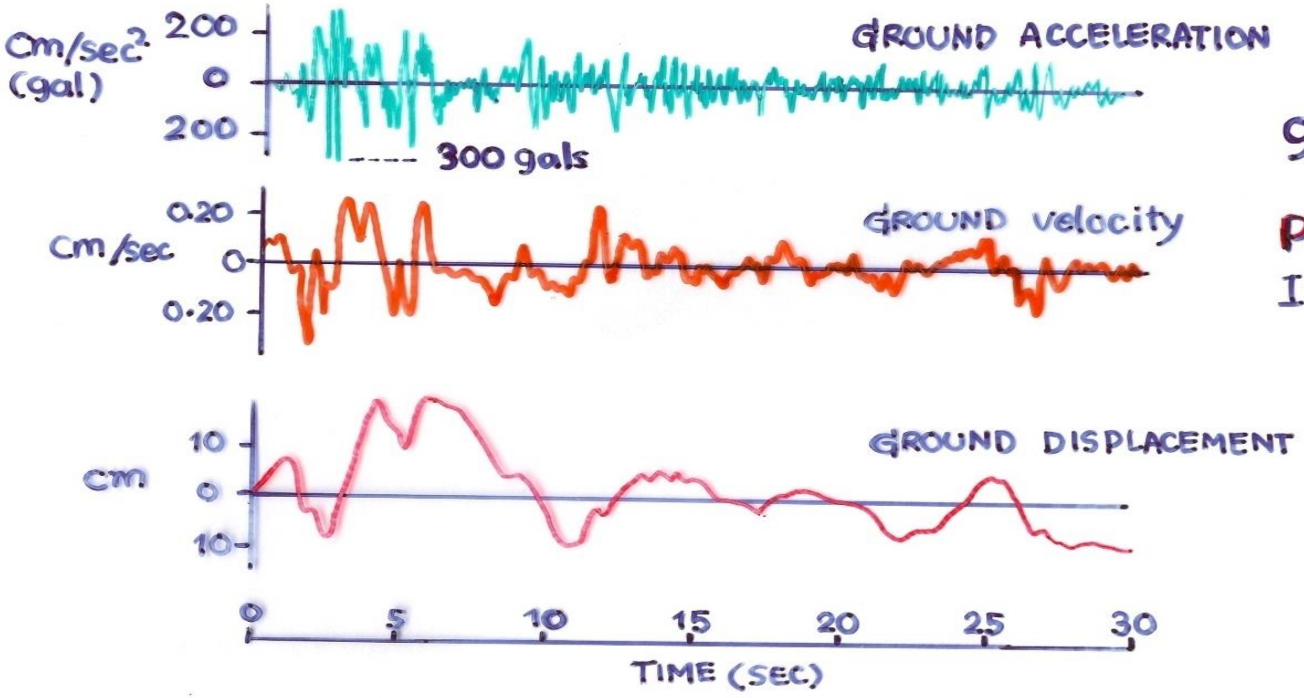
They are usually capable of recording acceleration of the ground greater than that of gravity.



STRONG MOTION SEISMOGRAPH
Type K-NET95

Most strong-motion accelerometers do not record continuously but are triggered into motion by the first waves of the earthquake to arrive.

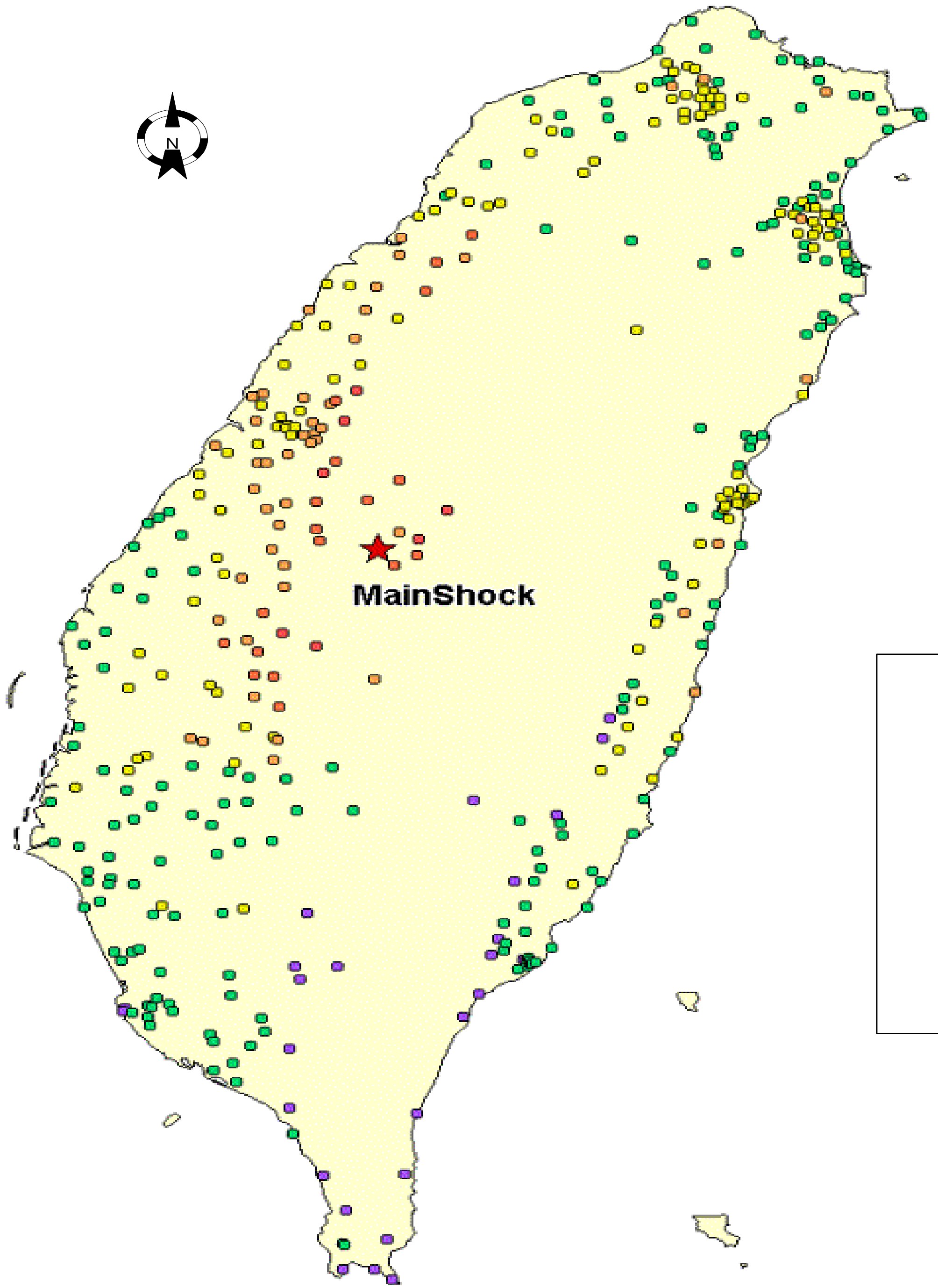


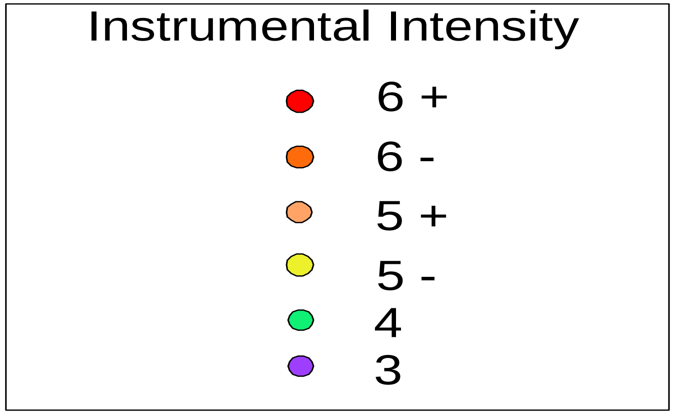


980 gals = 1 G

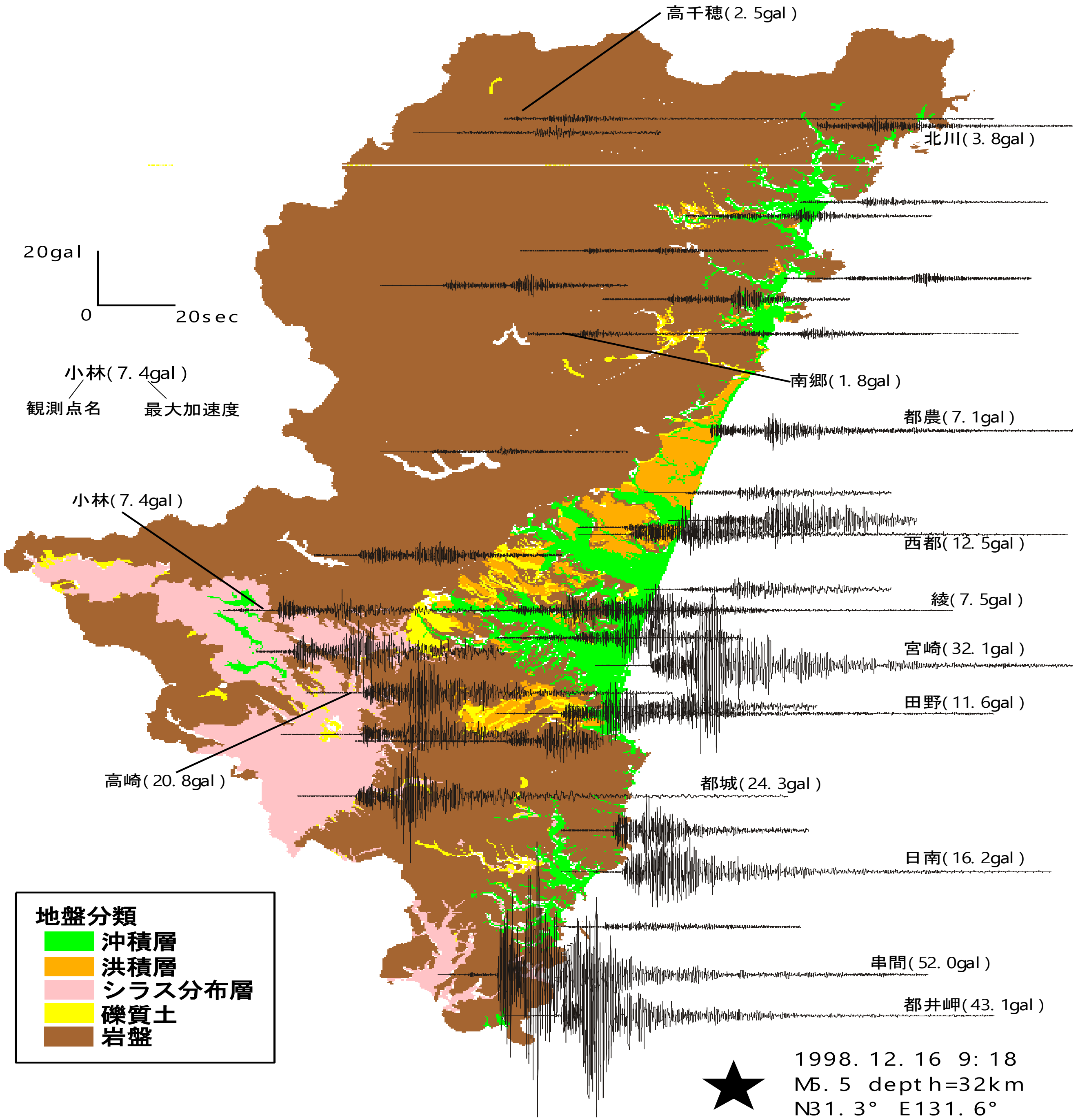
Peak Ground Acceleration:
Index of Seismic Loading

Strong Motion Stations in Taiwan and Distribution of the JMA seismic intensity for the 1999 Chi-Chi EQ





Note: JMA seismic intensity is calculated from a three-component acceleration record.



Strong-motion Records
In Yokohama, Japan

Magnitude-5 Earthquake
December 16, 1998
Depth 32 km

The Size of an Earthquake

The first scientific field study of the effects of a great earthquake was conducted by an Irish man, **Robert Mallet**, who was recognized as the first true seismologist.

Robert Mallet

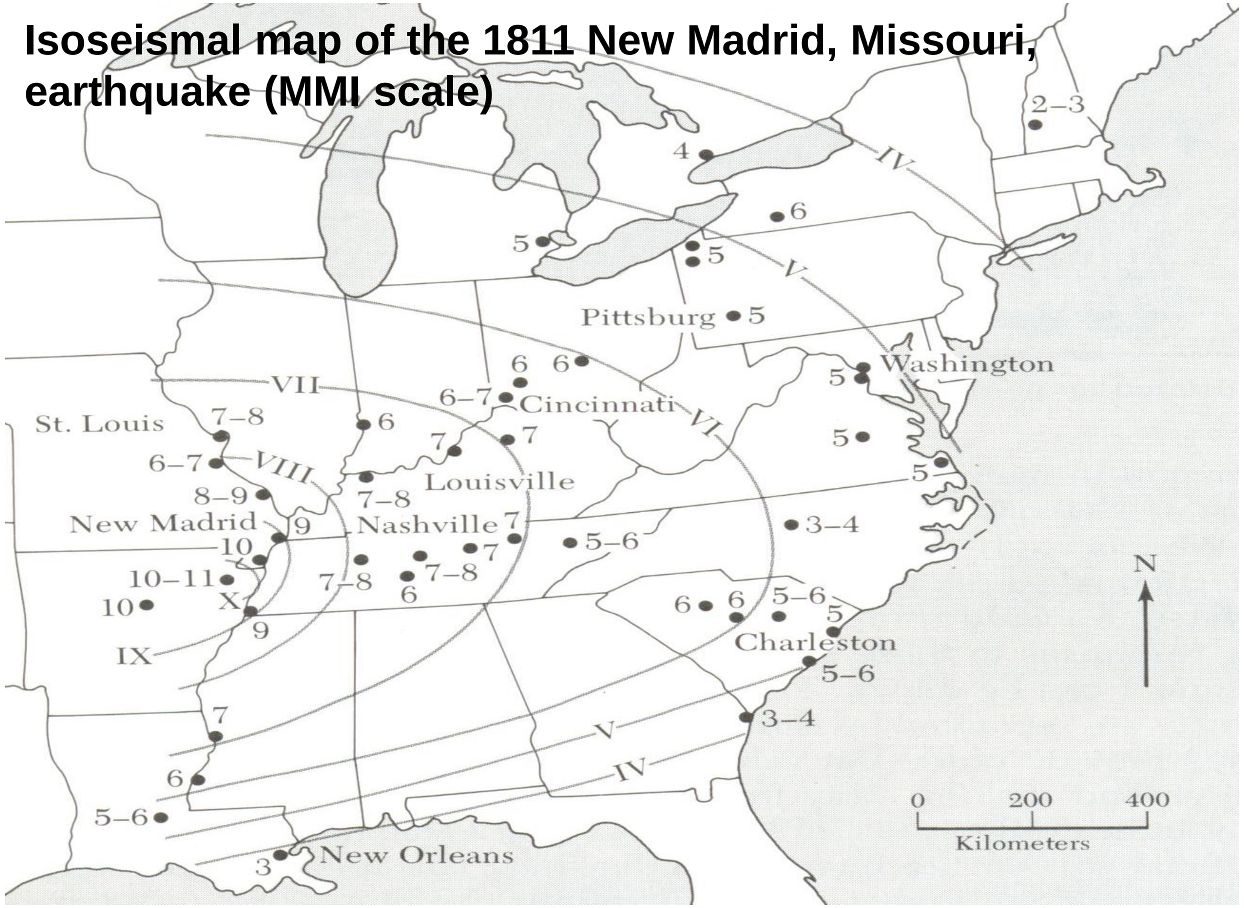
In his assessment of the effects of the Neapolitan Earthquake of 1857 in southern Italy, Mallet was using the oldest instruments in the world: his eyes, a compass and a measuring stick.

Mallet's method included detailed mapping and tabulation of felt reports and damage to buildings and geological movements.

In this way he was able to measure the strength and distribution of the earthquake ground motion.

The Size of an Earthquake

By drawing lines on a map between places of equal damage or of equal intensity (**isoseismal lines**), he determined the center of the earthquake shaking (the epicenter). Such maps are now called **isoseismal maps.**

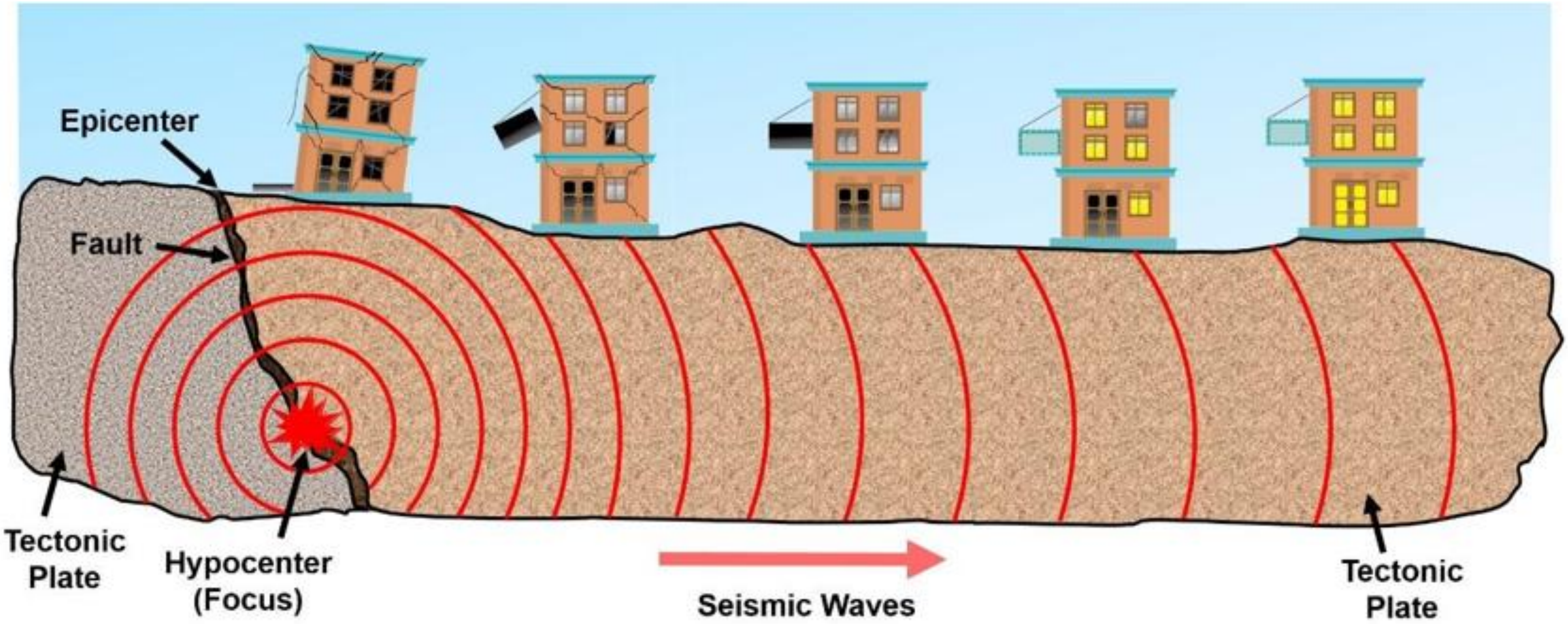


Isoseismal map of the 1811 New Madrid, Missouri, earthquake (MMI scale)

Intensity is measured by means of *the degree of damage to structures of human origin, the amount of disturbances to the surface of the ground, and the extent of animal and human reaction to the shaking, not by measuring the ground motion with instruments.*

Mallet used 4 degrees of intensity to prepare his isoseismal map.

The patterns of isoseismal lines also indicated to Mallet the rate at which the shaking effects diminished with distance and provide him with an estimate of the relative size of the earthquake.



Felt Intensity	X+	IX	VIII	VII	VI	V	IV	II-III	I
Damage	Very Heavy	Heavy	Moderate to Heavy	Moderate	Light	Very Light	None	None	None
Shaking	Extreme	Violent	Sever	Very Strong	Strong	Moderate	Light	Weak	Not Felt

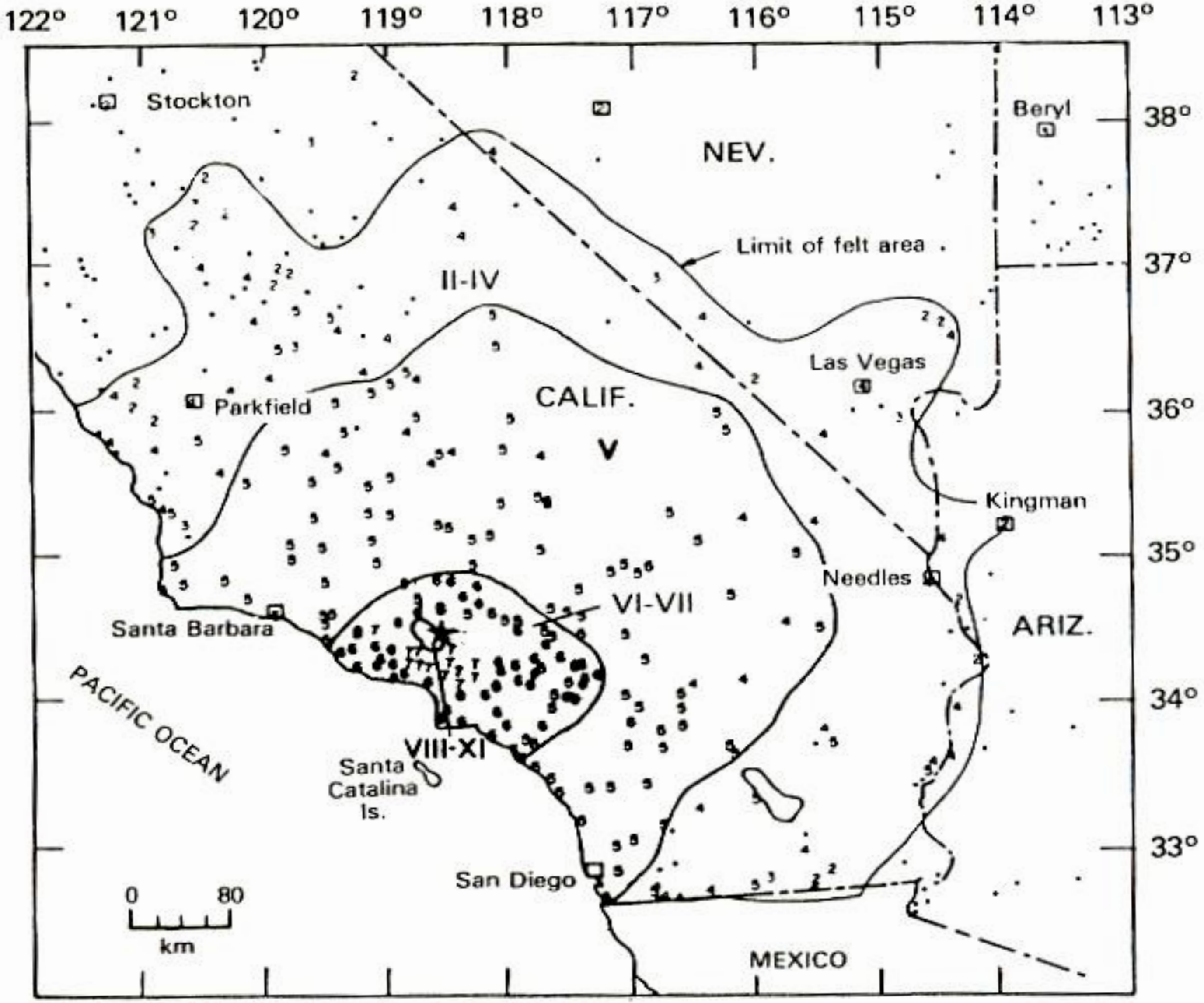


FIGURE 3.2 Generalized isoseismal map of the February 9, 1971 San Fernando, California earthquake. The epicenter is shown as a star. Roman numerals represent Modified Mercalli intensities between isoseismals. Arabic numerals represent Modified Mercalli intensities at specific cities. Dots represent locations where it was reported that the earthquake was not felt (after Coffman and Angel 1983).

Intensity Scale

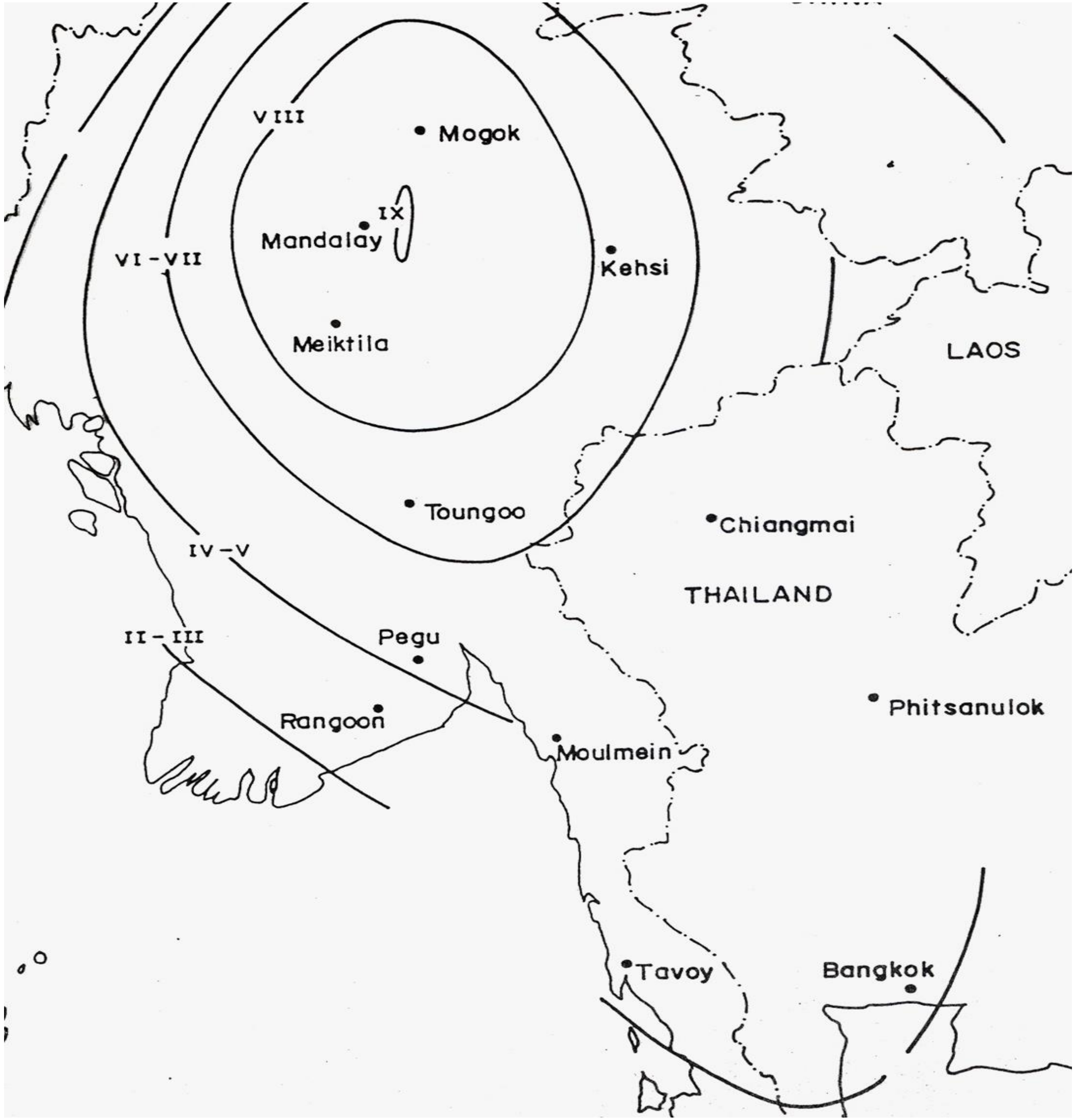
The first intensity scale of modern times was developed by M. S. de Rossi of Italy and Francois Forel of Switzerland in the 1880s. It was called the **Rossi-Forel Intensity Scale (I — X).**

A more refined scale, with 12 values, was constructed in 1902 by the Italian seismologist and volcanologist **G. Mercalli.**

A modified version of it, called the **Modified Mercalli Intensity (MMI) Scale**, was developed by H. O. Wood and Frank Neumann to fit construction conditions in California (and most of the United States).

Alternative intensity scales have been developed and are widely used in other countries, notably in Japan (**the JMA Intensity Scale**) and the central and eastern European countries (**the Medvedev-Sponheuer-Karnik (MSK) Intensity Scale**), where conditions differ from those in California.

Isoseismal Map of the Mandalay earthquake of 23 May 1912 (after Brown, 1914)



Rossi-Forel Intensity Scale

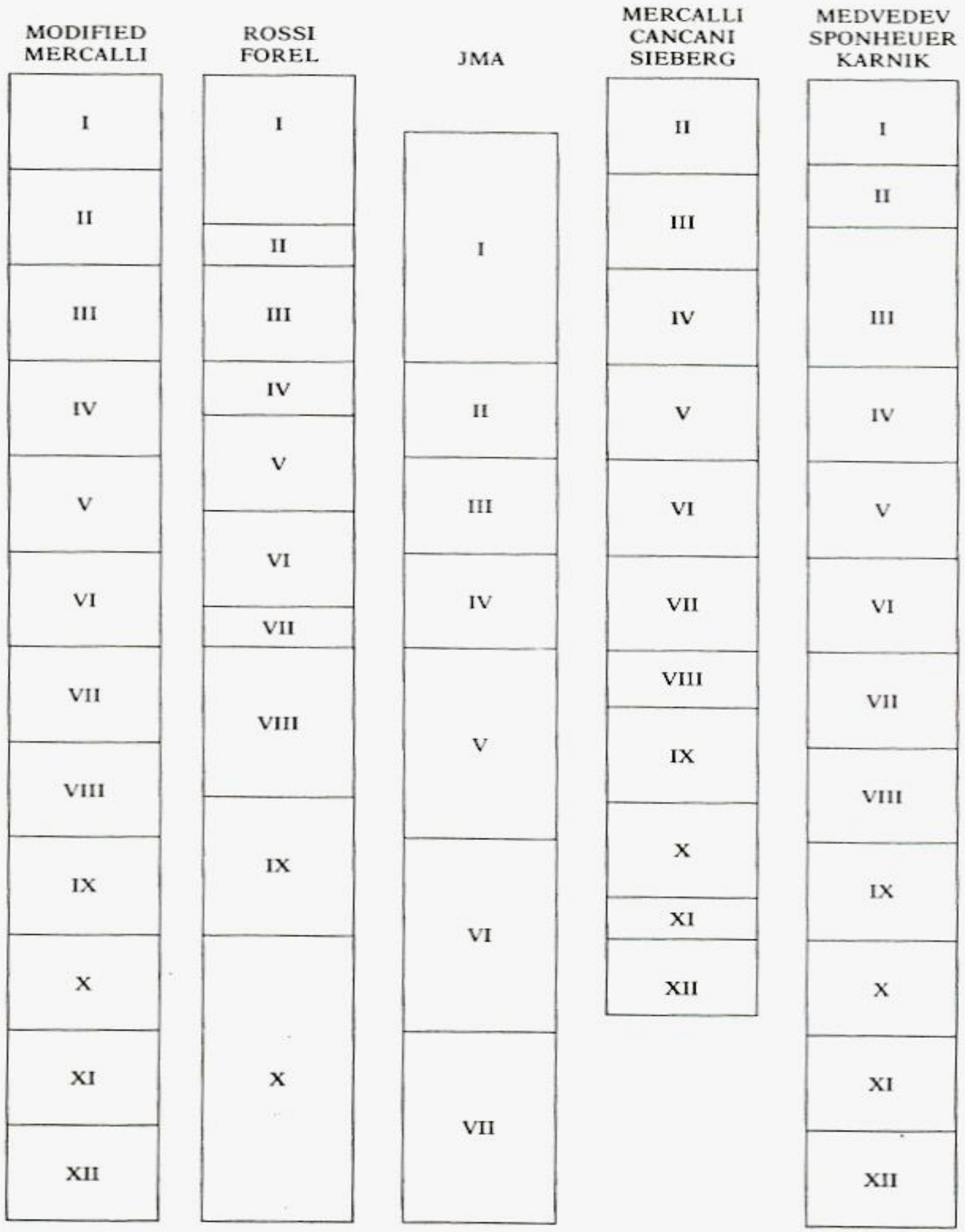
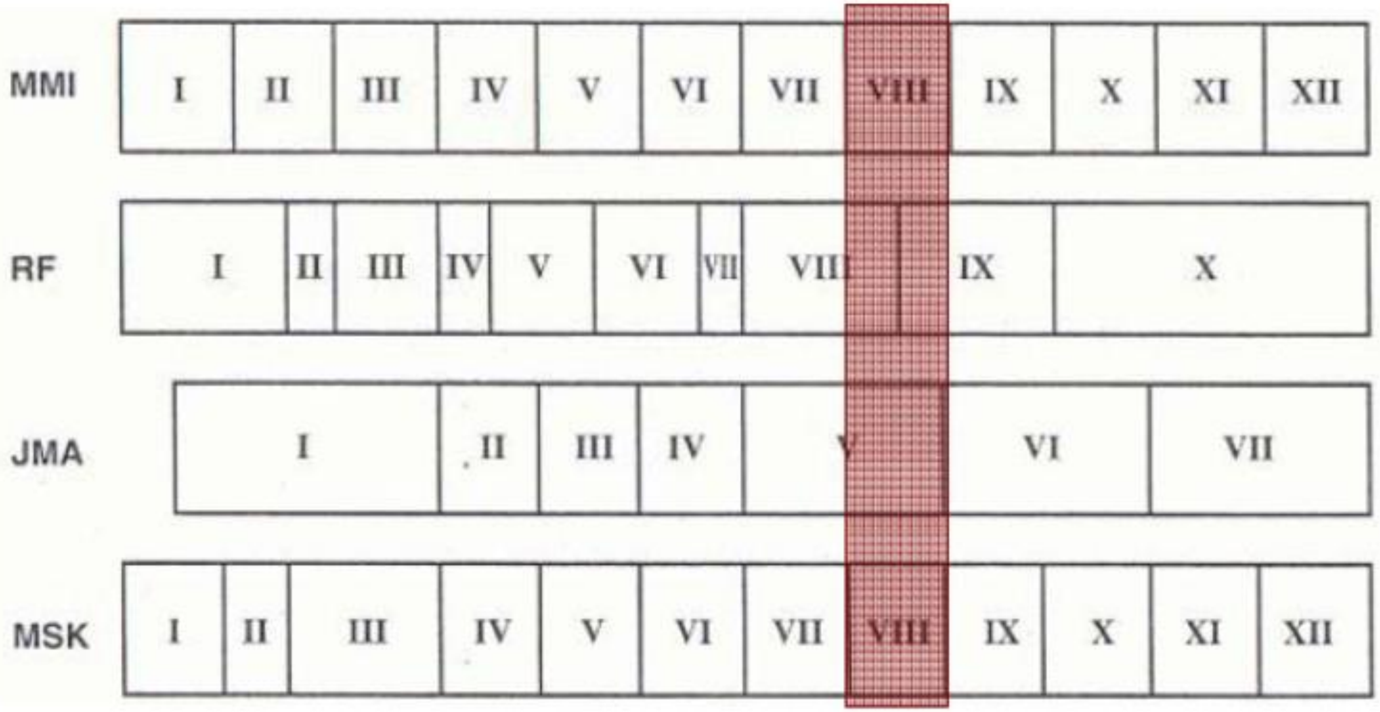
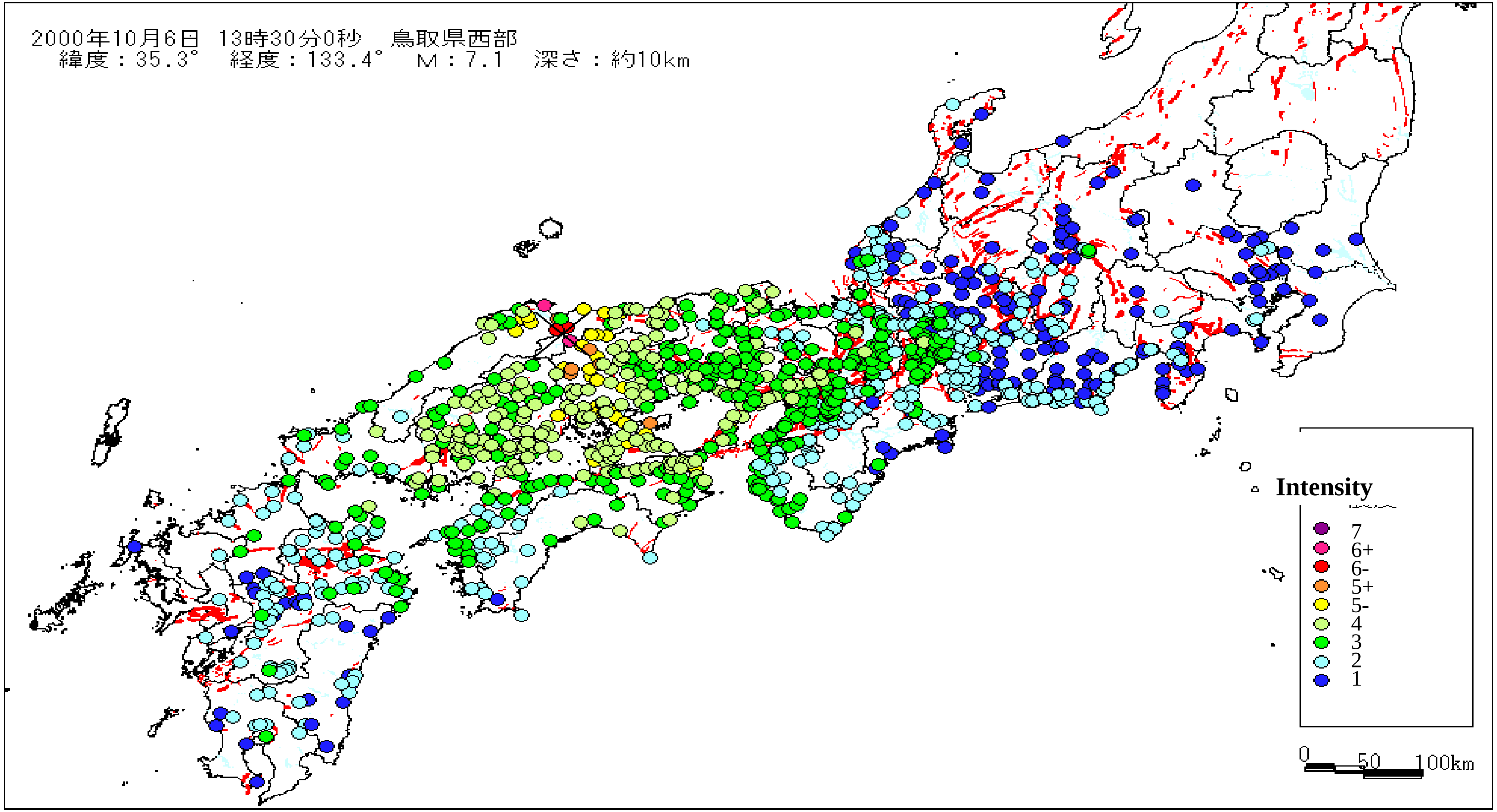


FIGURE 3.1 A comparison of seismic intensity scales (after Murphy and O'Brien 1977; and Richter,1958).

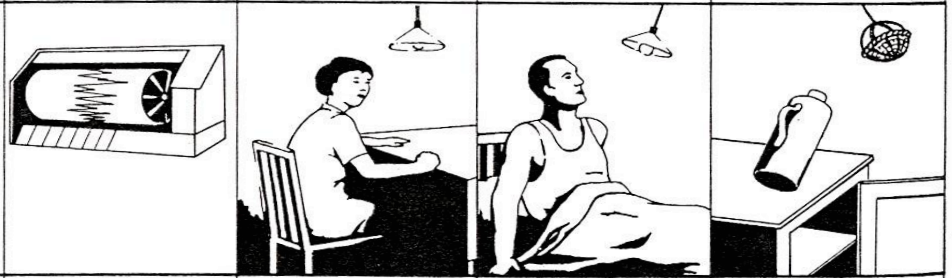
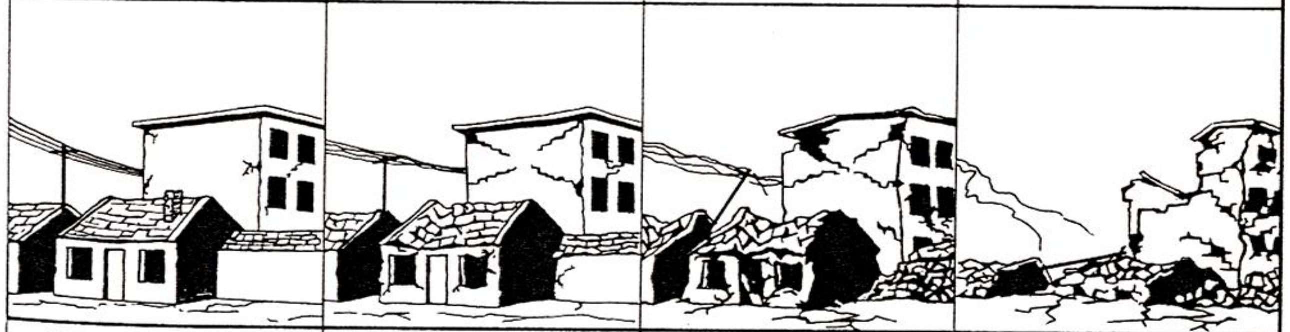
Comparison of the different intensity scales



JMA Instrumental Intensity in the 2000 Tottori EQ Measured by National Seismic Networks



Chinese Intensity Scale

Modified Mercalli scale	II	III	IV	V	V-VI	VI	VII	VIII and above
Chinese Classification	1-2	3	4-5	6	7	8	9	10 and above
								
Reaction of people and buildings.	Not felt by people generally. Just recordable by seismograph.	A few people indoors notice a slight vibration.	Sleeping persons wake. Hanging items like lamps swing.	Things indoors fall over.	Old buildings suffer considerable damage — houses generally some damage — old ones may collapse.	Many houses suffer damage. A few collapse.	Most houses damaged heavily or collapse.	Houses everywhere collapse.

Many nations use the Modified Mercalli scale of earthquake damage, but some countries employ their own. This is the Chinese version.

The Modified Mercalli Intensity Scale (Wood and Neumann, 1931)

I. Not felt—or, except rarely under especially favorable circumstances. Under certain conditions, at and outside the boundary of the area in which a great shock is felt: sometimes birds, animals, reported uneasy or disturbed; sometimes dizziness or nausea experienced; sometimes trees, structures, liquids, bodies of water, may sway—doors may swing, very slowly.

II. Felt indoors by few, especially on upper floors, or by sensitive, or nervous persons. Also, as in grade I, but often more noticeably: sometimes hanging objects may swing, especially when delicately suspended; sometimes trees, structures, liquids, bodies of water, may sway, doors may swing, very slowly; sometimes birds, animals, reported uneasy or disturbed; sometimes dizziness or nausea experienced.

III. Felt indoors by several, motion usually rapid vibration. Sometimes not recognized to be an earthquake at first. Duration estimated in some cases. Vibration like that due to passing of light, or lightly loaded trucks, or heavy trucks some distance away. Hanging objects may swing slightly. Movements may be appreciable on upper levels of tall structures. Rocked standing motor cars slightly.

IV. Felt indoors by many, outdoors by few. Awakened few, especially light sleepers. Frightened no one, unless apprehensive from previous experience. Vibration like that due to passing of heavy or heavily loaded trucks. Sensation like heavy body striking building or falling of heavy objects inside. Rattling of dishes, windows, doors; glassware and crockery clink and clash. Creaking of walls, frame, especially in the upper range of this grade. Hanging objects swung, in numerous instances. Disturbed liquids in open vessels slightly. Rocked standing motor cars noticeably.

V. Felt indoors by practically all, outdoors by many or most: outdoors direction estimated. Awakened many, or most. Frightened few—slight excitement, a few ran outdoors. Buildings trembled throughout. Broke dishes, glassware, to some extent. Cracked windows—in some cases, but not generally. Overturned vases, small or unstable objects, in many instances, with occasional fall. Hanging objects, doors, swing generally or considerably. Knocked pictures against walls, or swung them out of place. Opened, or closed, doors, shutters, abruptly. Pendulum clocks stopped, started, or ran fast, or slow. Moved small objects, furnishings, the latter to slight extent. Spilled liquids in small amounts from well-filled open containers. Trees, bushes, shaken slightly.

VI. Felt by all, indoors and outdoors. Frightened many, excitement general, some alarm, many ran outdoors. Awakened all. Persons made to move unsteadily. Trees, bushes, shaken slightly to moderately. Liquid set in strong motion. Small bells rang—church, chapel, school, etc. Damage slight in poorly built buildings. Fall of plaster in small amount. Cracked plaster somewhat, especially fine cracks, chimneys in some instances. Broke dishes, glassware, in considerable quantity, also some windows. Fall of knick-knacks, books, pictures. Overturned furniture in many instances. Moved furnishings of moderately heavy kind.

VII. Frightened all—general alarm, all ran outdoors. Some, or many, found it difficult to stand. Noticed by persons driving motor cars. Trees and bushes shaken moderately to strongly. Waves on ponds, lakes, and running water. Water turbid from mud stirred up. Incaving to some extent of sand or gravel stream banks. Rang large church bells, etc. Suspended objects made to quiver. Damage negligible in buildings of good design and construction, slight to moderate in well-built ordinary buildings, considerable in poorly built or badly designed buildings, adobe houses, old walls (especially where laid up without mortar), spires, etc. Cracked chimneys to considerable extent, walls to some extent. Fall of plaster in considerable to large amount, also some stucco. Broke numerous windows, furniture to some extent. Shook down loosened brickwork and tiles. Broke weak chimneys at the roof-line (sometimes damaging roofs). Fall of cornices from towers and high buildings. Dislodged bricks and stones. Overturned heavy furniture, with damage from breaking. Damage considerable to concrete irrigation ditches.

VIII. Fright general—alarm approaches panic. Disturbed persons driving motor cars. Trees shaken strongly—branches, trunks, broken off, especially palm trees. Ejected sand and mud in small amounts. Changes: temporary, permanent; in flow of springs and wells; dry wells renewed flow; in temperature of spring and well waters. Damage slight in structures (brick) built especially to withstand earthquakes. Considerable in ordinary substantial buildings, partial collapse: racked, tumbled down, wooden houses in some cases; threw out panel walls in frame structures, broke off decayed piling. Fall of walls. Cracked, broke, solid stone walls seriously. Wet ground to some extent, also ground on steep slopes. Twisting, fall, of chimneys, columns, monuments, also factory stacks, towers. Moved conspicuously, overturned, very heavy furniture.

IX. Panic general. Cracked ground conspicuously. Damage considerable in (masonry) structures built especially to withstand earthquakes: threw out of plumb some wood-frame houses built especially to withstand earthquakes; great in substantial (masonry) buildings, some collapse in large part; or wholly shifted frame buildings off foundations, racked frames; serious to reservoirs; underground pipes sometimes broken.

X. Cracked ground, especially when loose and wet, up to widths of several inches; fissures up to a yard in width ran parallel to canal and stream banks. Landslides considerable from river banks and steep coasts. Shifted sand and mud horizontally on beaches and flat land. Changed level of water in wells. Threw water on banks of canals, lakes, rivers, etc. Damage serious to dams, dikes, embankments. Severe to well-built wooden structures and bridges, some destroyed. Developed dangerous cracks in excellent brick walls. Destroyed most masonry and frame structures, also their foundations. Bent railroad rails slightly. Tore apart, or crushed endwise, pipe lines buried in earth. Open cracks and broad wavy folds in cement pavements and asphalt road surfaces.

XI. Disturbances in ground many and widespread, varying with ground material. Broad fissures, earth slumps, and land slips in soft wet ground. Ejected water in large amounts charged with sand and mud. Caused sea-waves ("tidal" waves) of significant magnitude. Damage severe to wood-frame structures, especially near shock centers. Great to dams, dikes, embankments often for long distances. Few, if any (masonry) structures remained standing. Destroyed large well-built bridges by the wrecking of supporting piers, or pillars. Affected yielding wooden bridges less. Bent railroad rails greatly, and thrust them endwise. Put pipe lines buried in earth completely out of service.

XII. Damage total—practically all works of construction damaged greatly or destroyed. Disturbances in ground great and varied, numerous shearing cracks. Landslides, falls of rock of significant character, slumping of river banks, etc., numerous and extensive. Wrenched loose, tore off, large rock masses. Fault slips in firm rock, with notable horizontal and vertical offset displacements. Water channels, surface and underground, disturbed and modified greatly. Dammed lakes, produced waterfalls, deflected rivers, etc. Waves seen on ground surfaces (actually seen, probably, in some cases). Distorted lines of sight and level. Threw objects upward into the air.

Earthquake Magnitude

If the magnitudes of earthquakes are to be compared worldwide, a measure is needed that does not depend (as does intensity) on the density of population and type of construction.

Kiyoo Wadati

Such quantitative scale was originated in 1931 by **Kiyoo Wadati** in Japan and later on developed by **Dr. Charles Richter** in 1935 in California.

Charles Richter

Richter defined the magnitude of an earthquake as *the logarithm to base 10 of the maximum seismic-wave amplitude (in micrometer) recorded on a standard Wood-Anderson short-period seismograph*[1] *at a distance of 100 km from the earthquake epicenter*.

Every time the magnitude goes up by 1 unit, the amplitude of the earthquake waves increases 10 times.

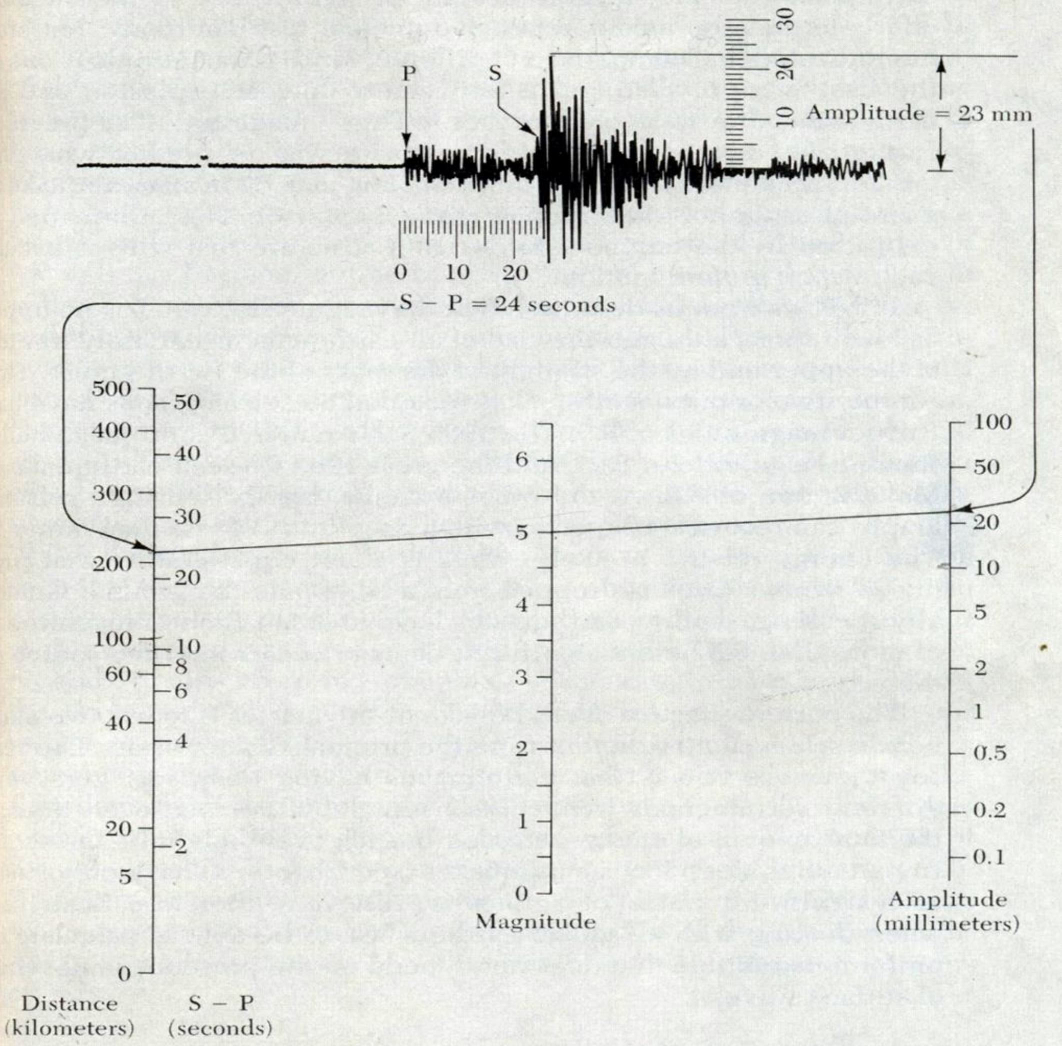
[1] *The instrument has a natural period of 0.8 sec, critical damping ratio 0.8, magnification 2,800.*

Earthquake Magnitude

At first the scale was intended to deal with Californian earthquakes only, but with the cooperation of **Professor Beno Gutenberg** the scale was adapted to enable earthquakes to be classified worldwide.

The Richter magnitude scale is also called **Local Magnitude (M_L).**

EXAMPLE OF THE CALCULATION OF THE RICHTER MAGNITUDE (M_L) OF A LOCAL EARTHQUAKE



Procedure for calculating the local magnitude, M_L

1. Measure the distance to the focus using the time interval between the S and the P waves (S − P = 24 seconds).
2. Measure the height of the maximum wave motion on the seismogram (23 millimeters).
3. Place a straight edge between appropriate points on the distance (left) and amplitude (right) scales to obtain magnitude M_L = 5.0.

Earthquake Magnitude

At the present time there are several magnitude scales. The most used magnitude scales are **surface-wave magnitude (M_s), body-wave magnitude (m_b), and moment magnitude (M_w).**

M_s is a world-wide scale determined from the maximum amplitude of Rayleigh waves with a period of about 20 seconds (between 18 s and 22 s) on a standard long-period seismograph[1]. It is most widely used magnitude scale for large damaging shallow earthquakes (less than 70 km deep).

It was developed in 1950s by the same researchers who developed **M_L** (Gutenberg and Richter) in order to improve resolution on larger earthquakes.

m_b is a world-wide scale determined from the maximum amplitude of the first few cycles of the P wave motion observed on the vertical component of seismogram. The waves measured typically have a period of about 1 second. It is widely used for characterizing deep earthquakes.

[1] *The instrument has a natural period of 15 sec.*

Saturation of Earthquake Magnitude

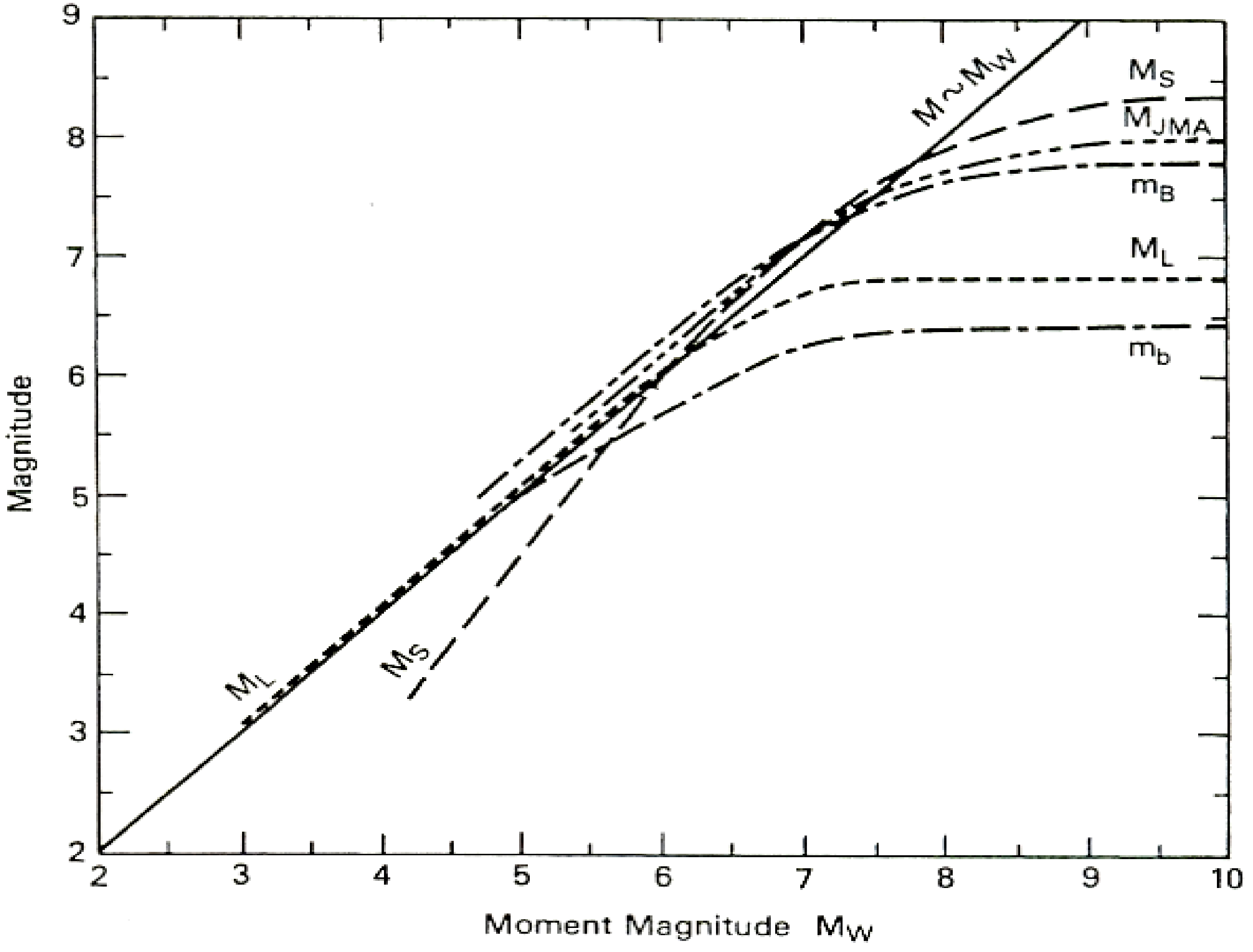


FIGURE 2.4 A comparison of moment magnitude with other magnitude scales (after Heaton, Tajima and Mori 1986).

It must be noted that most magnitude scales saturate, or stop increasing with increasing earthquake size.

This occurs because each magnitude scale is determined using a seismic wave of a particular period and wave length, which at a certain level does not increase in amplitude as the earthquake source size and energy release increase.

Moment Magnitude

A more reliable and robust magnitude scale is moment magnitude (**M_w**). It was introduced by Hanks and Kanamori in 1979. It is based on the seismic moment (M_o), which is a measure of the whole dimension of the slipped fault:

$$M_W = (2/3).(\mathrm{Log}_{10} M_o - 10.7)$$

Where M_o is seismic moment (in N.m). Geologically M_o is a description of the extent of deformation at the earthquake source. It is simply defined as:

$$M_o = \mu A D = 2 \mu E_S / \Delta\sigma$$

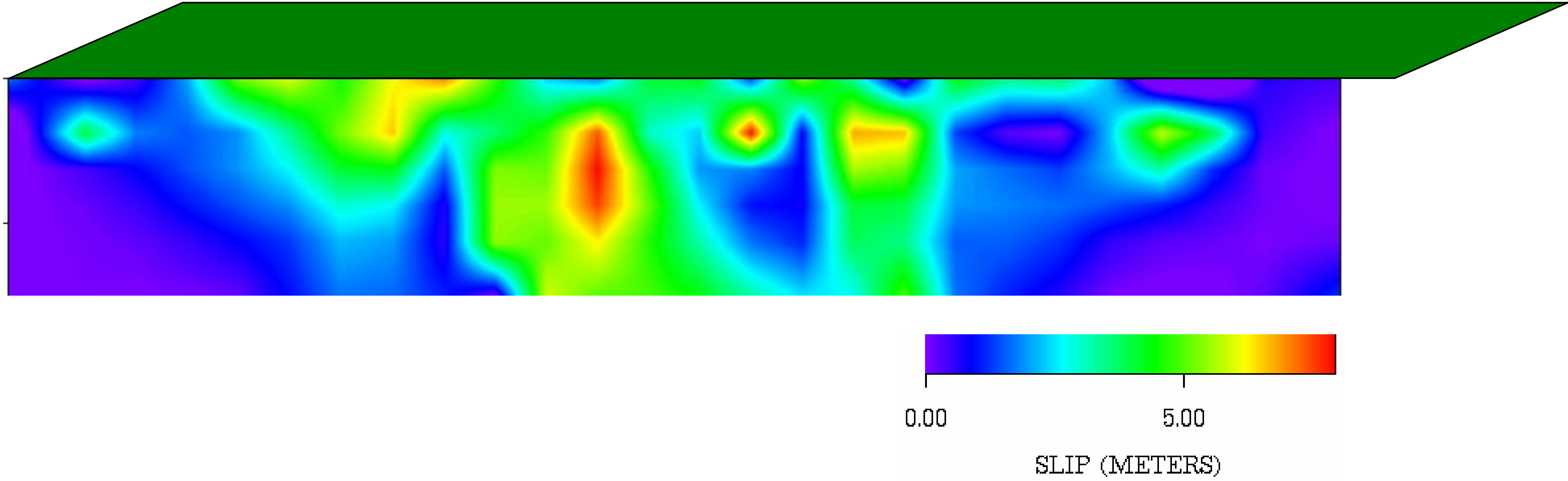
Where μ is the shear modulus of the rock in the source region (typically 30 gigapascal)

- A is the fault rupture area
- D is the average dislocation or relative movement (slip) between the opposite sides of the fault.
- E_S is radiated seismic energy
- $\Delta\sigma$ is stress drop

The definition based on A D allows M_o to be derived from geological faulting parameters that can be easily observed in the field for large surface-rupturing earthquakes. The definition based on $E_S / \Delta\sigma$ allows M_o to be derived from seismological measurements.

Rupture on a Fault

Total Slip in the M7.3 Landers Earthquake



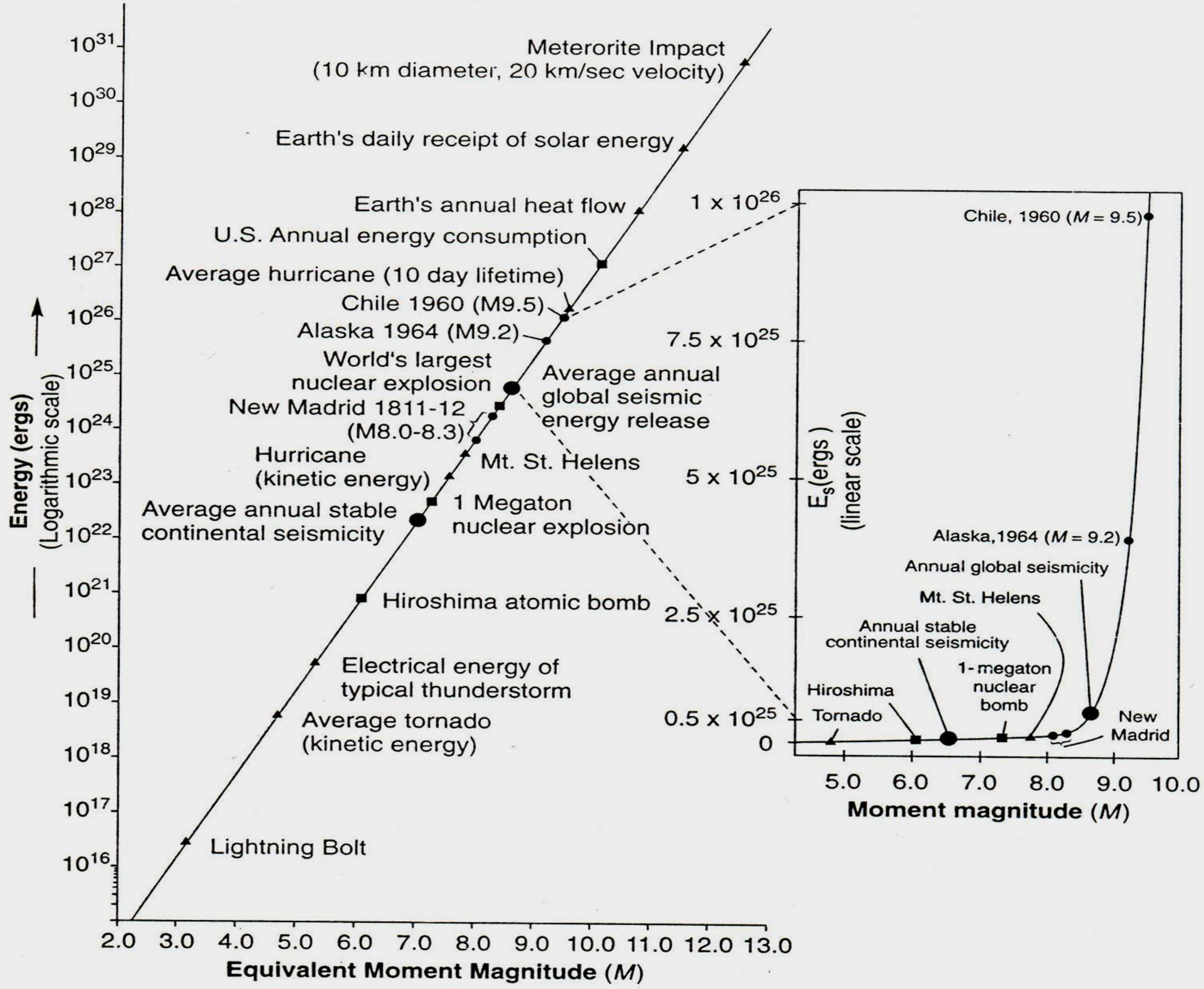


Figure 2.31 Relative energy of various natural and human-made phenomena. (After Johnston, 1990. Reprinted by permission of USGS.)

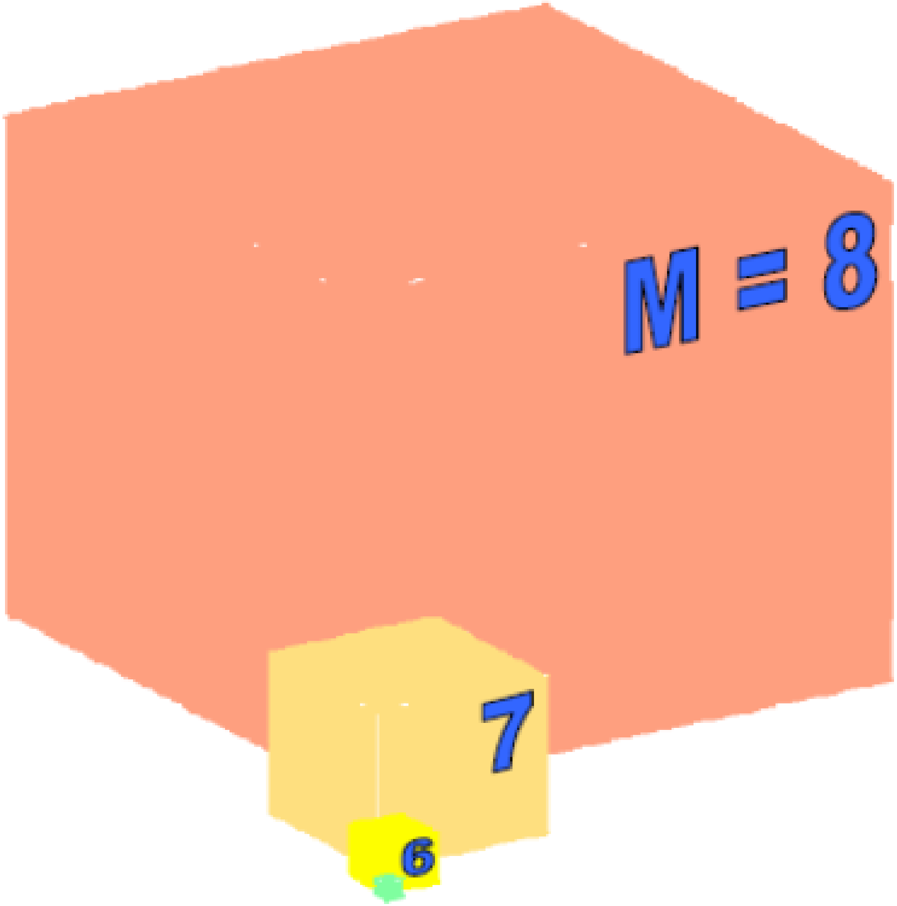
Earthquake Energy

- The total seismic energy (E, erg) released during an earthquake is often estimated from the following nonlinear relationship:

$$\log E = 11.8 + 1.5 M_s$$

(this relationship is applicable to moment magnitude M_w as well)

- Each unit change in magnitude corresponds to a 32 fold increase in earthquake energy.



Thank you for your attention