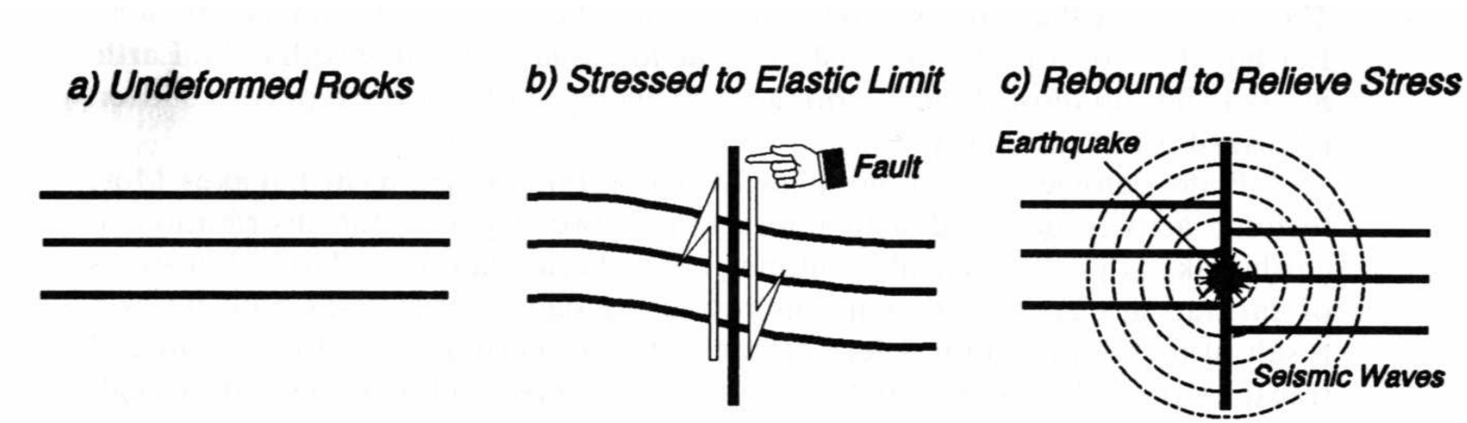
LECTURE 2

EARTHQUAKES:

GENERAL

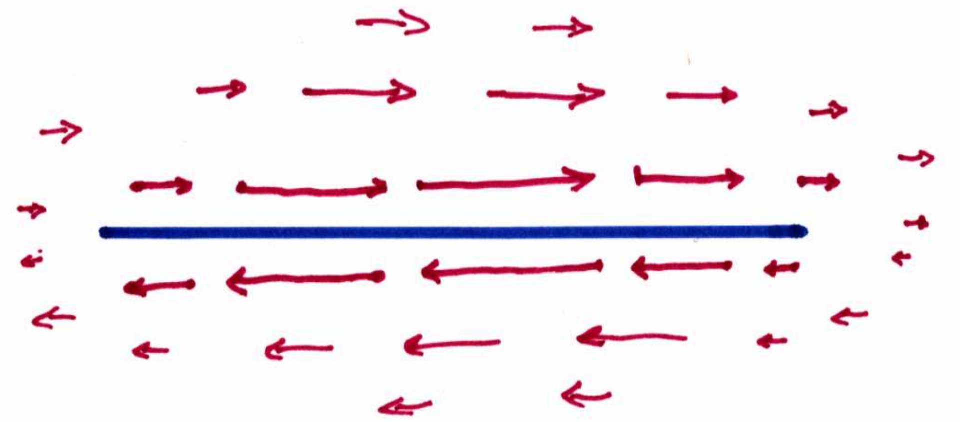
EARTHQUAKES

- An earthquake is a mass movement in the Earth resulting from slip along a dislocation (fault zone) releasing strain accumulated by tectonic processes.

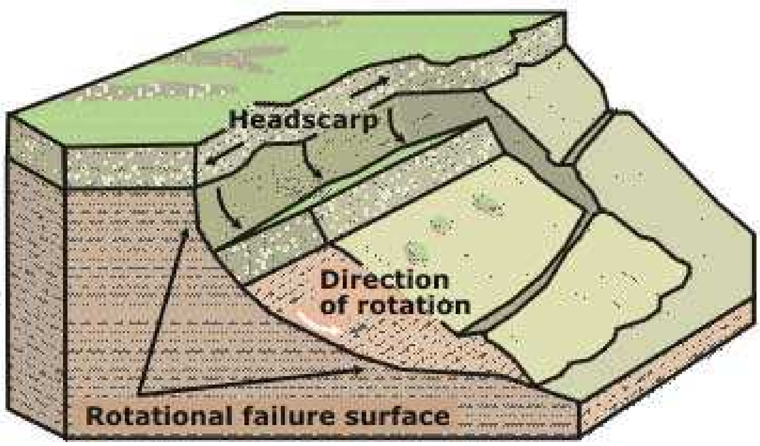


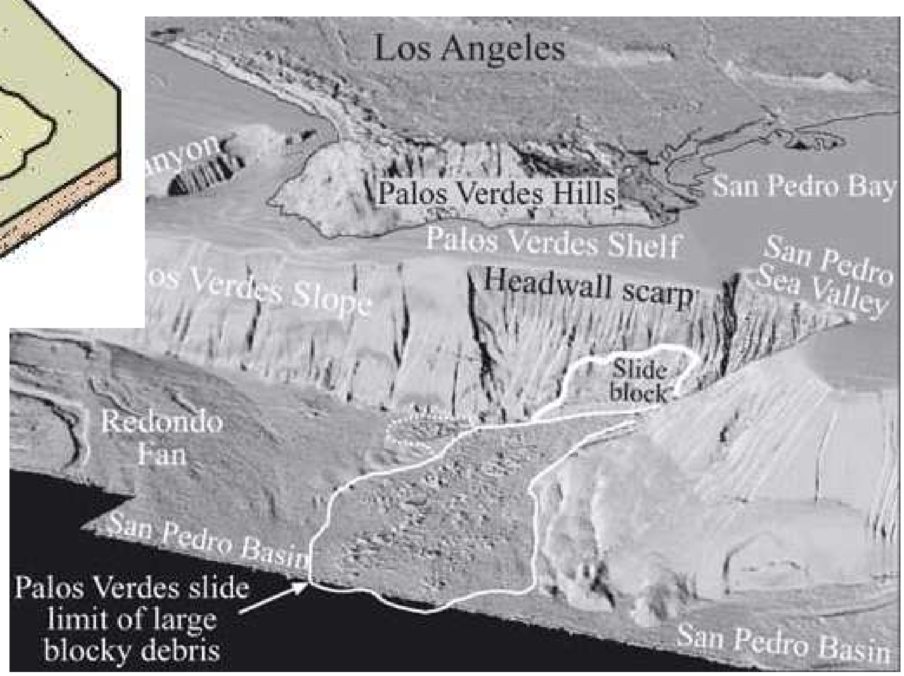
[*Lillie,* 1999]

- An important aspect of an *Earthquake Rupture* is that the walls of the fault remain *cohesive continuous media* outside of the dislocation surface. In particular, the continuity of the structure is preserved near the ends (tips) of the fault.



Contrast this with the case of a *Slump* or *Landslide*.

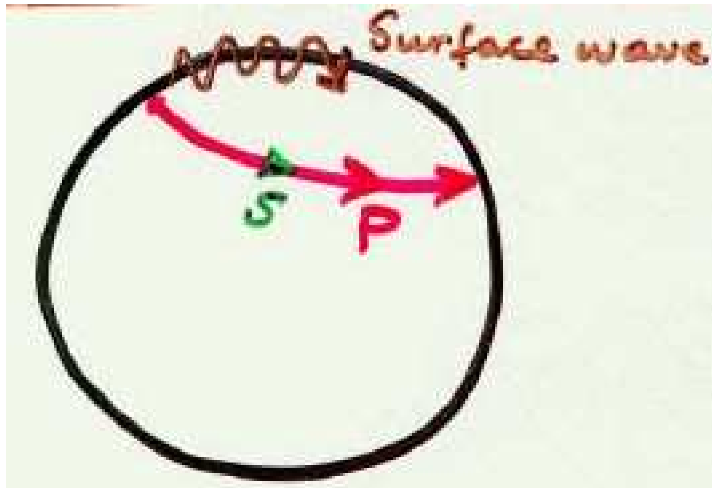




[Mathematically, this is expressed through different *boundary conditions* for the analytical representations of the source].

SEISMIC WAVES

Earthquakes (and other sources) can generate *Several Classes* of seismic waves traveling through or along the Earth.



- **BODY WAVES**

  travel through the interior of the Earth.

They are of two kinds

P waves are faster, less attenuated and feature motion parallel to the direction of propagation (analagous to that of a *SPRING*).

S waves are slower, more attenuated and feature motion perpendicular to the direction of propagation (analagous to that of a *STRING*).

SHEAR (S) WAVES DO NOT EXIST IN FLUIDS

$$\alpha = V_P = \sqrt{\frac{K + \frac{4}{3}\mu}{\rho}} \qquad \beta = V_S = \sqrt{\frac{\mu}{\rho}}$$

Wave speeds are on the order of a few (6 to 10) **km/s**, hence travel times through the Earth are in the range of

minutes (*EASY* measurements)

BODY WAVES OBEY GEOMETRICAL OPTICS, are a HIGH-FREQUENCY PHENOMENON, best observed in the range **0.2 s to 50 s (P waves)** and **5 s to 50 s (S waves).**

SURFACE WAVES

→ Are generated by preferentially shallow seismic sources.

→ *CRAWL ALONG* the Earth's surface.

They are of two kinds

- *RAYLEIGH WAVES* combine the properties of *P* and *S* waves (vertical and radial -- away-from-the-source motion), and are substantially *DISPERSED* (different frequencies propagating at different speeds), especially along oceanic paths.

  RECORDED PRINCIPALLY ON VERTICAL SEISMOMETERS

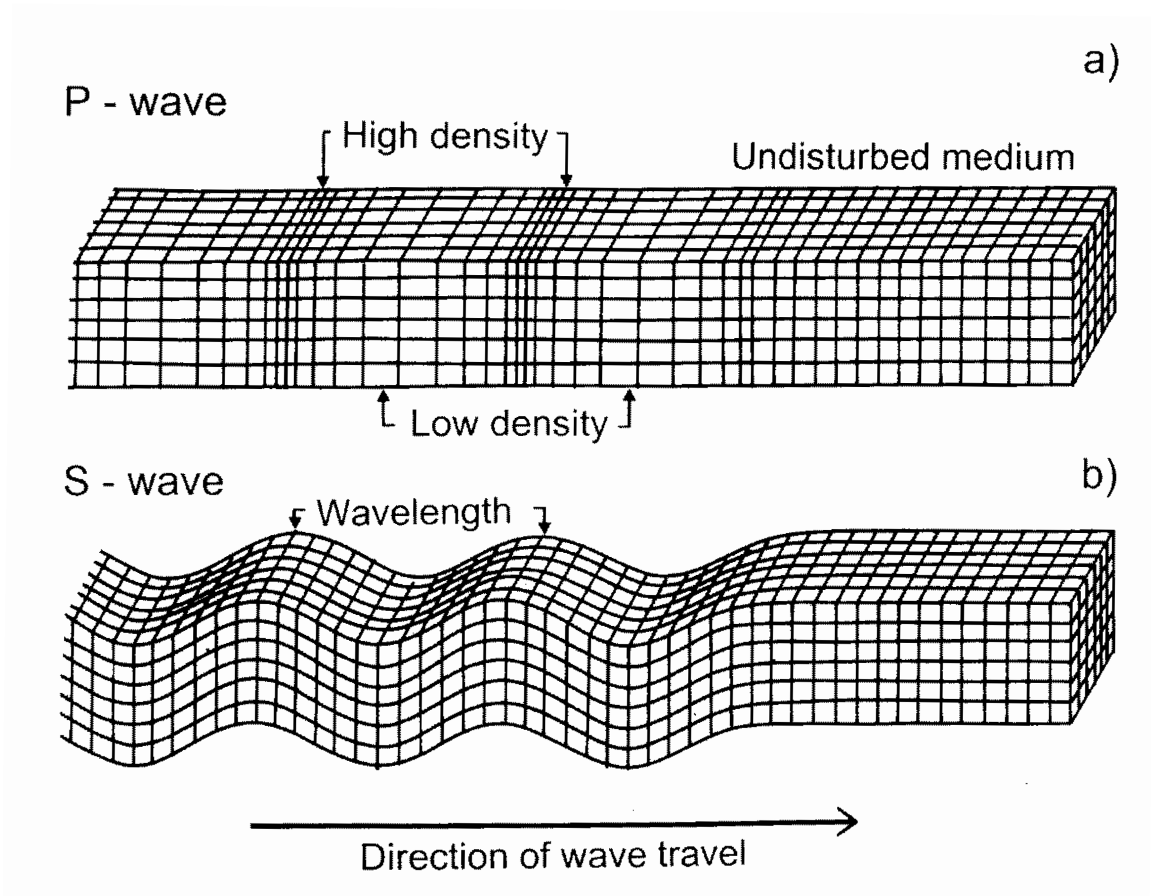
- *LOVE WAVES* involve only shear (transverse) motion and are less dispersed.

  RECORDED EXCLUSIVELY ON HORIZONTAL SEISMOMETERS

→ Surface waves are substantially attenuated and are usually best recorded in the

10 to 400 s period range.

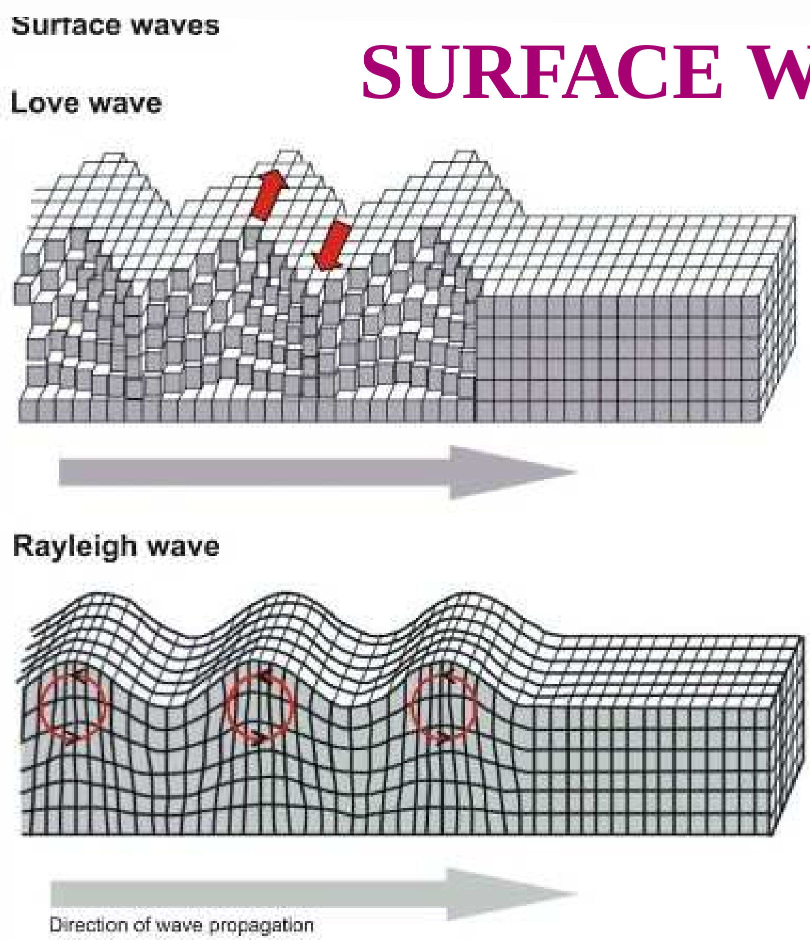
BODY WAVES



P

S

SURFACE WAVES



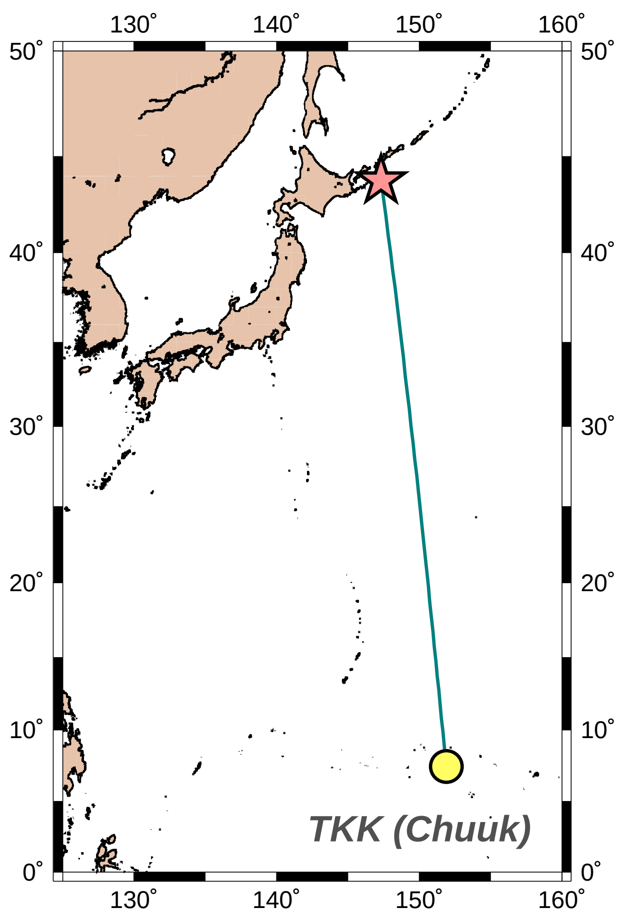
Love

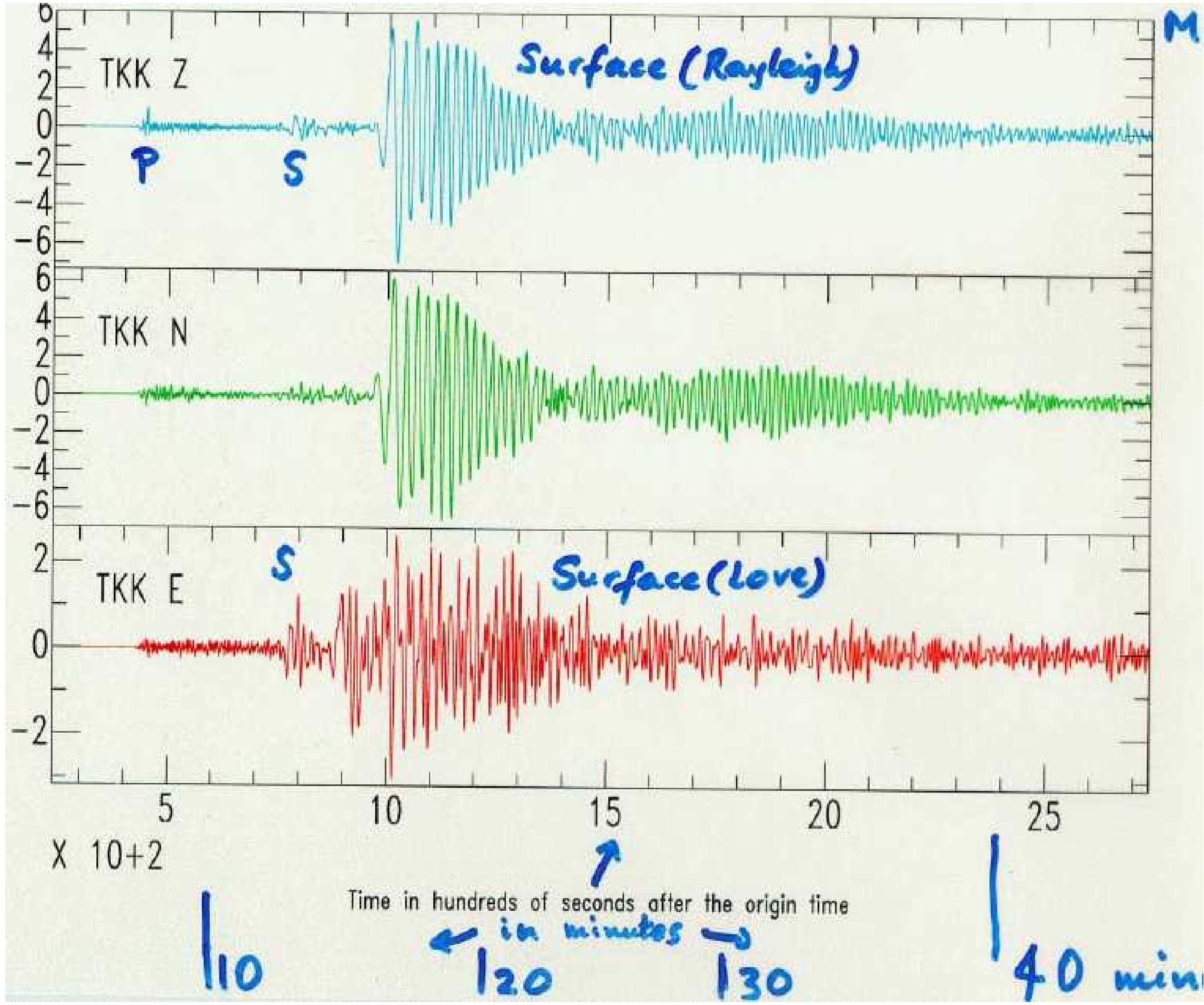
Rayleigh

[*Bolt*, 1981]

Kurile Island Earthquake Recorded at Chuuk, 04-OCT-1994

(Long-Period 3-component Seismometer)



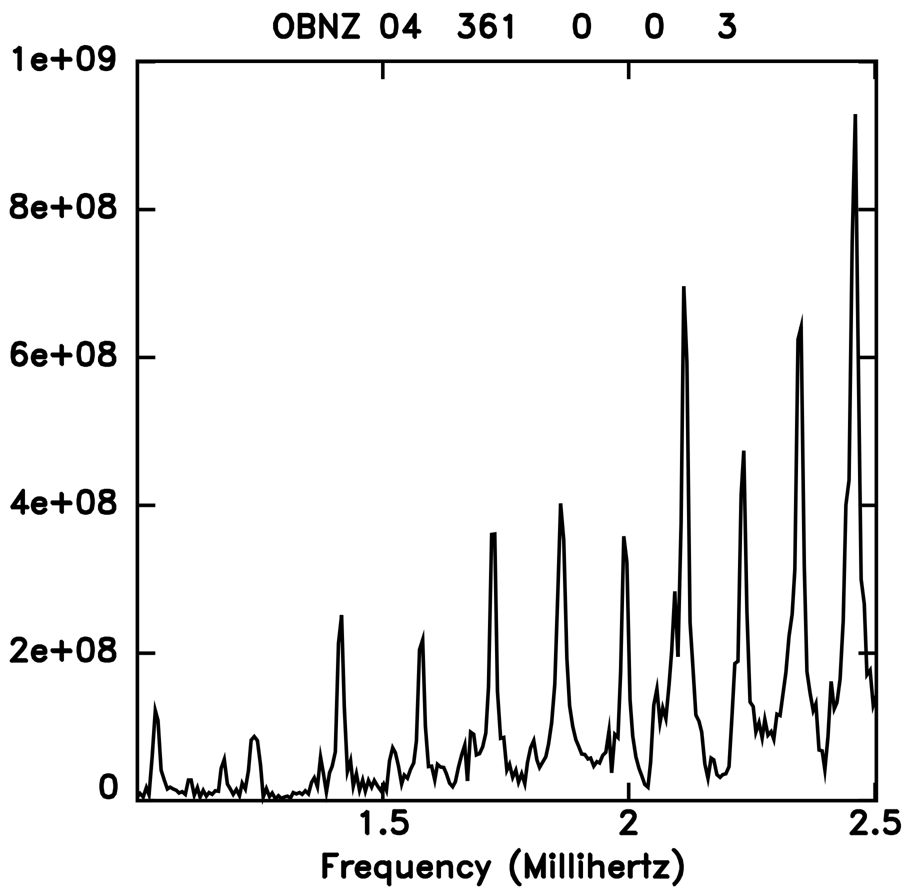


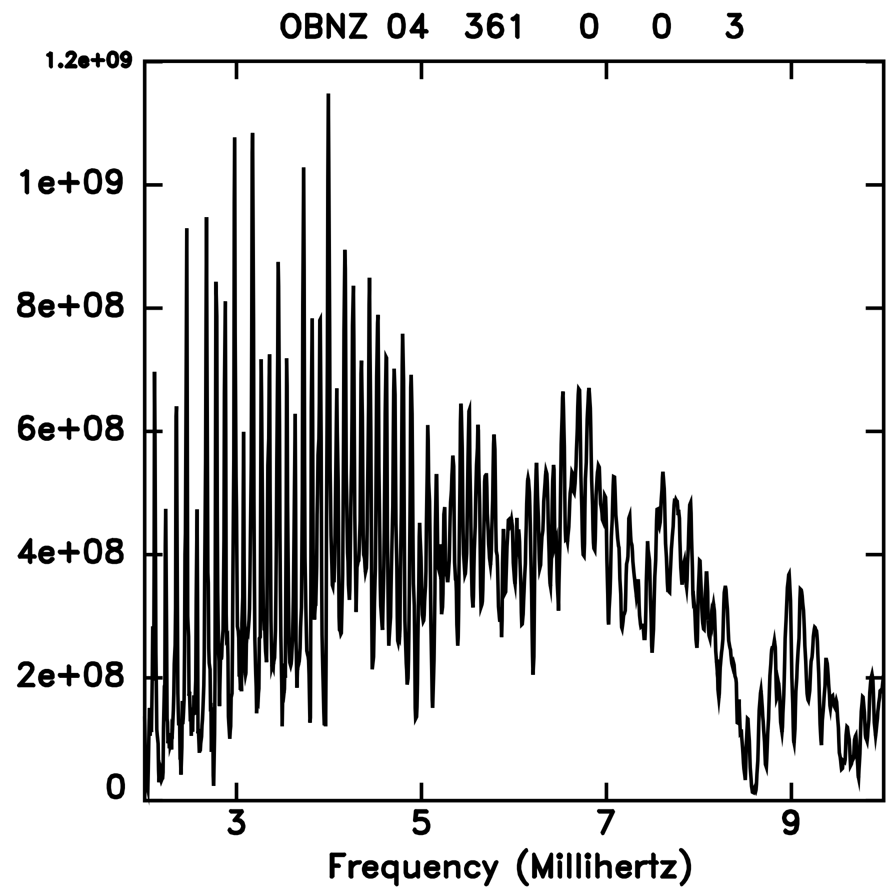
Beyond 400 seconds, the Earth's spectrum becomes

discrete

revealing its *NORMAL MODES* of oscillation

1000 s **400 s** **500 s** **100 s**

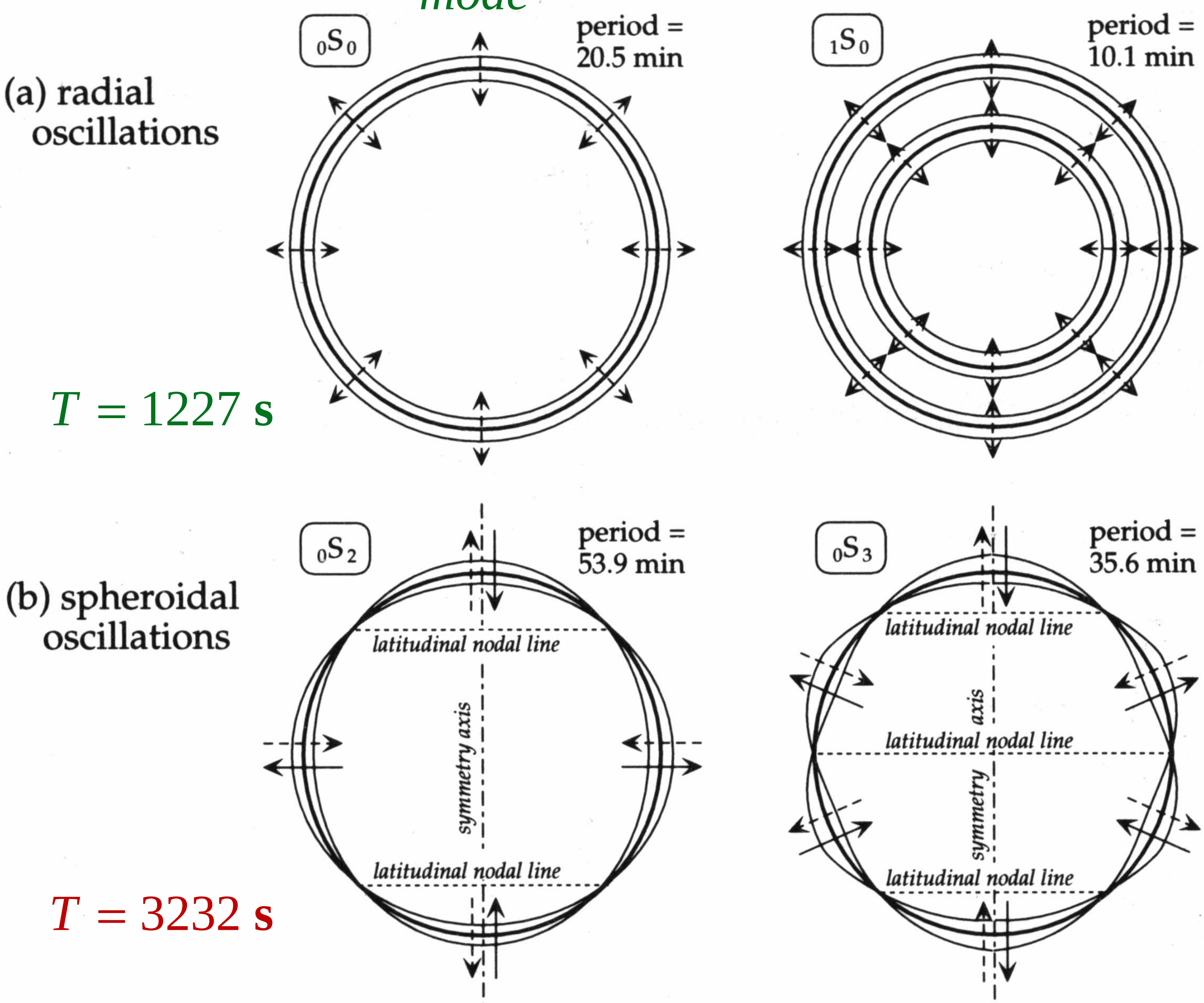




[2004 SUMATRA EARTHQUAKE recorded at Obninsk, Russia]

EXAMPLES of the EARTH's FREE OSCILLATIONS

"BREATHING" mode



T = 1227 **s**

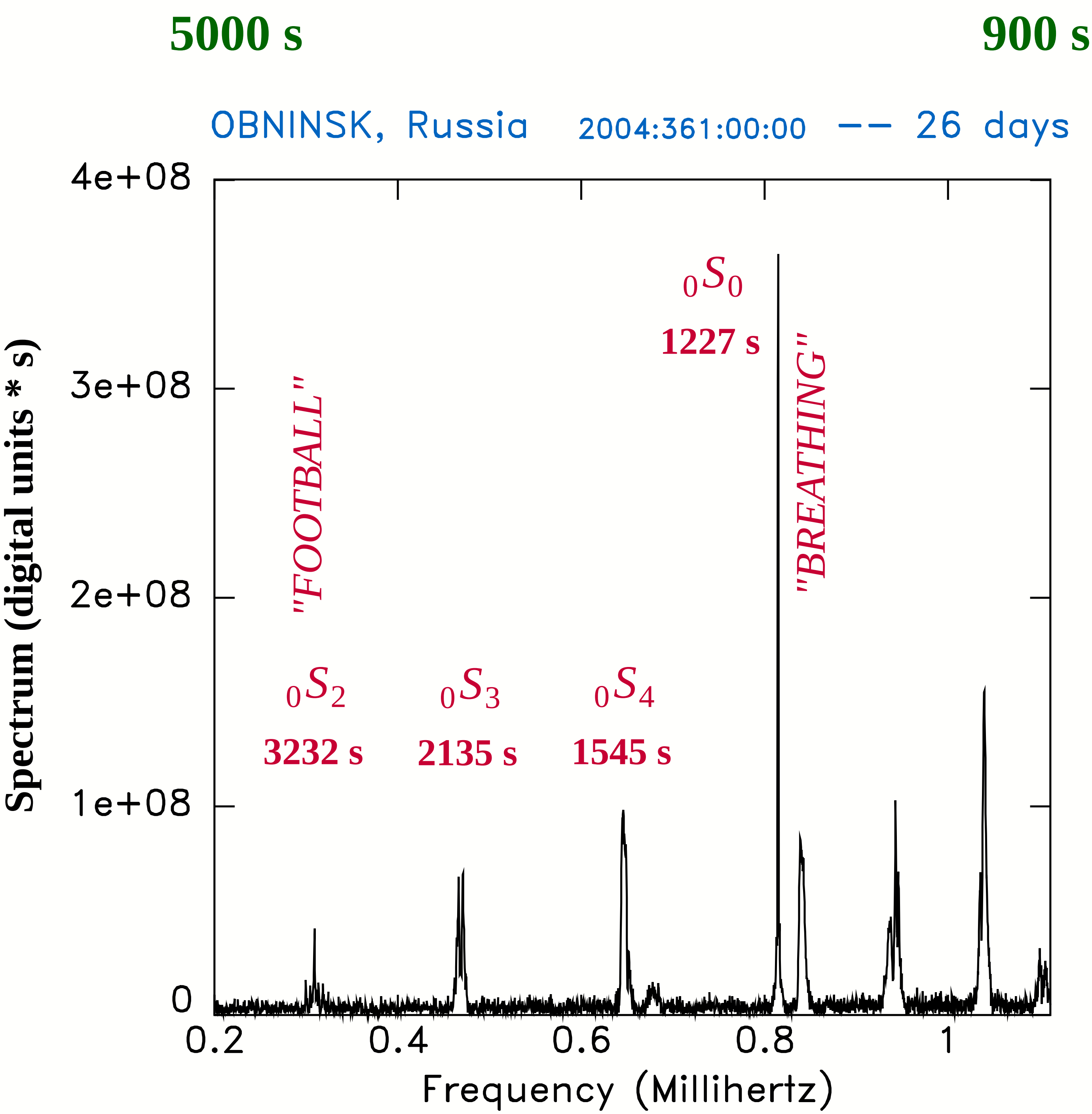
T = 3232 **s**

"FOOTBALL" mode

SPECTRUM of the EARTH's MUSIC

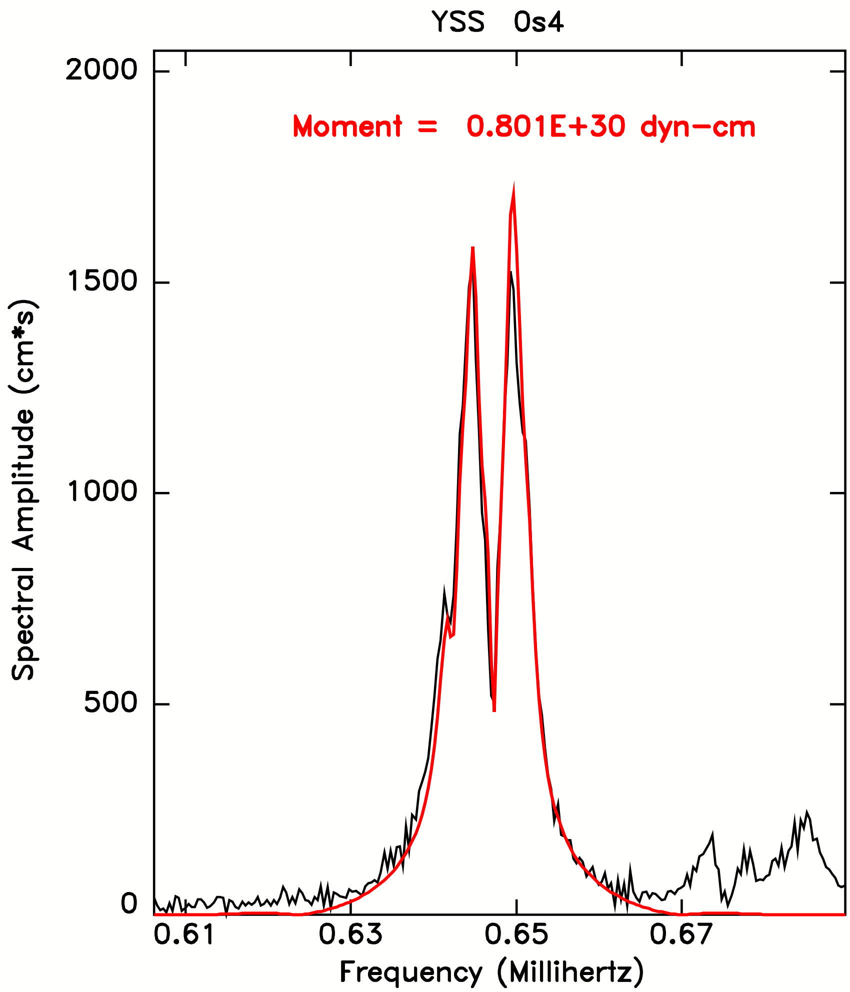
The gravest modes of the Earth are in the range

1000−3230 s (1/4 hr. to 1 hour)



- **Normal modes are split in a complex pattern by Earth's rotation and ellipticity.**

YSS $_0S_4$ (1546 s)



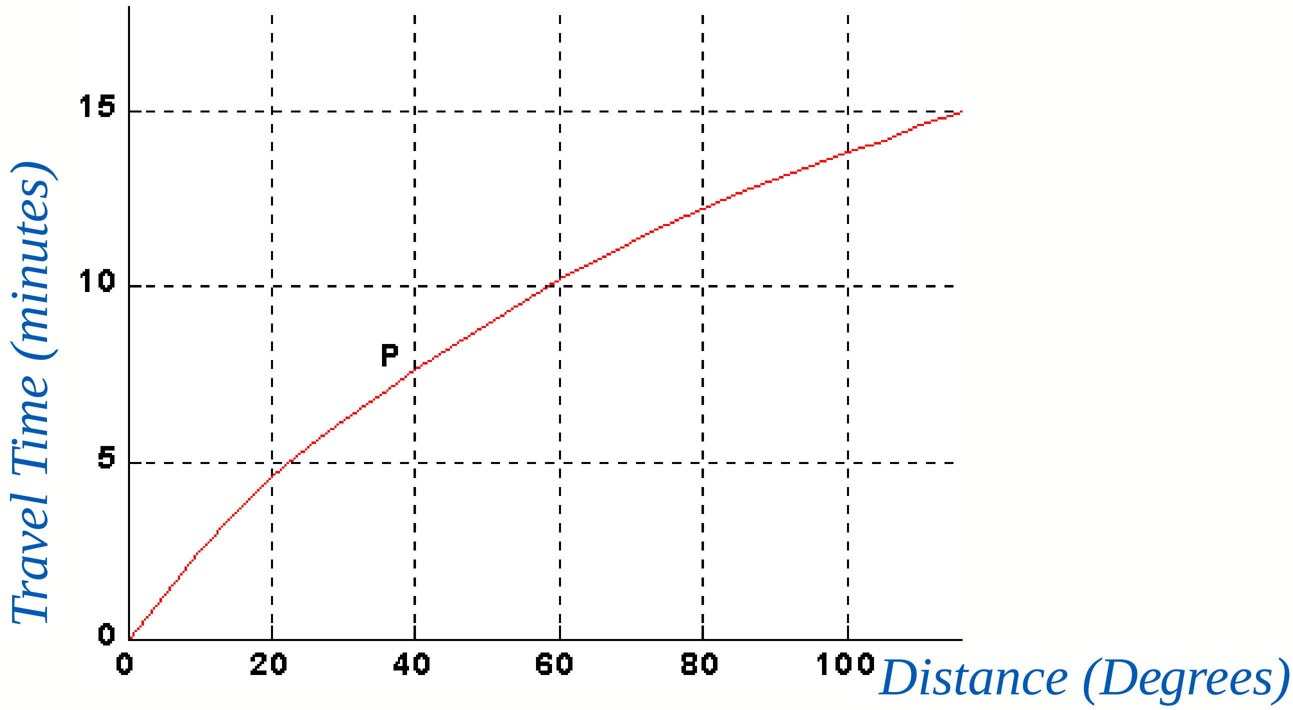
- Quantify excitation of modes (hence size of earthquake at very long periods) by fitting splitting pattern to exact geometry of source, station and focal mechanism.

→ **Theory developed in 1970s. *SUMATRA* is first opportunity to actually make measurement.**

[*Stein and Geller,* 1978]

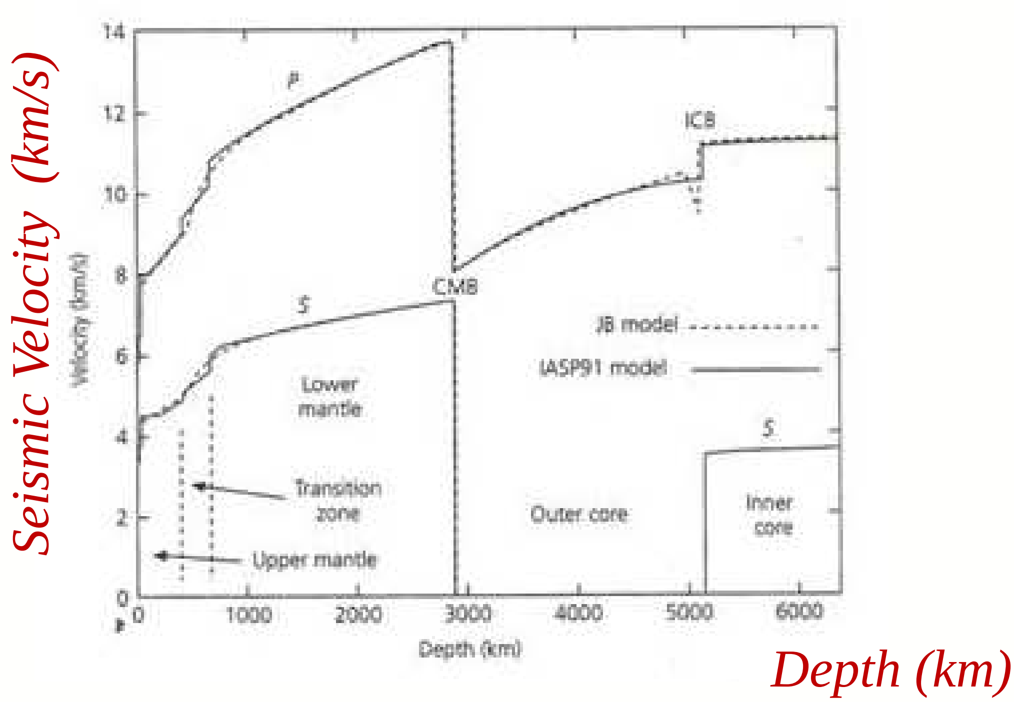
EARTH STRUCTURE

Body-wave travel times (*i.e.*, P, S) can be compiled empirically from observations

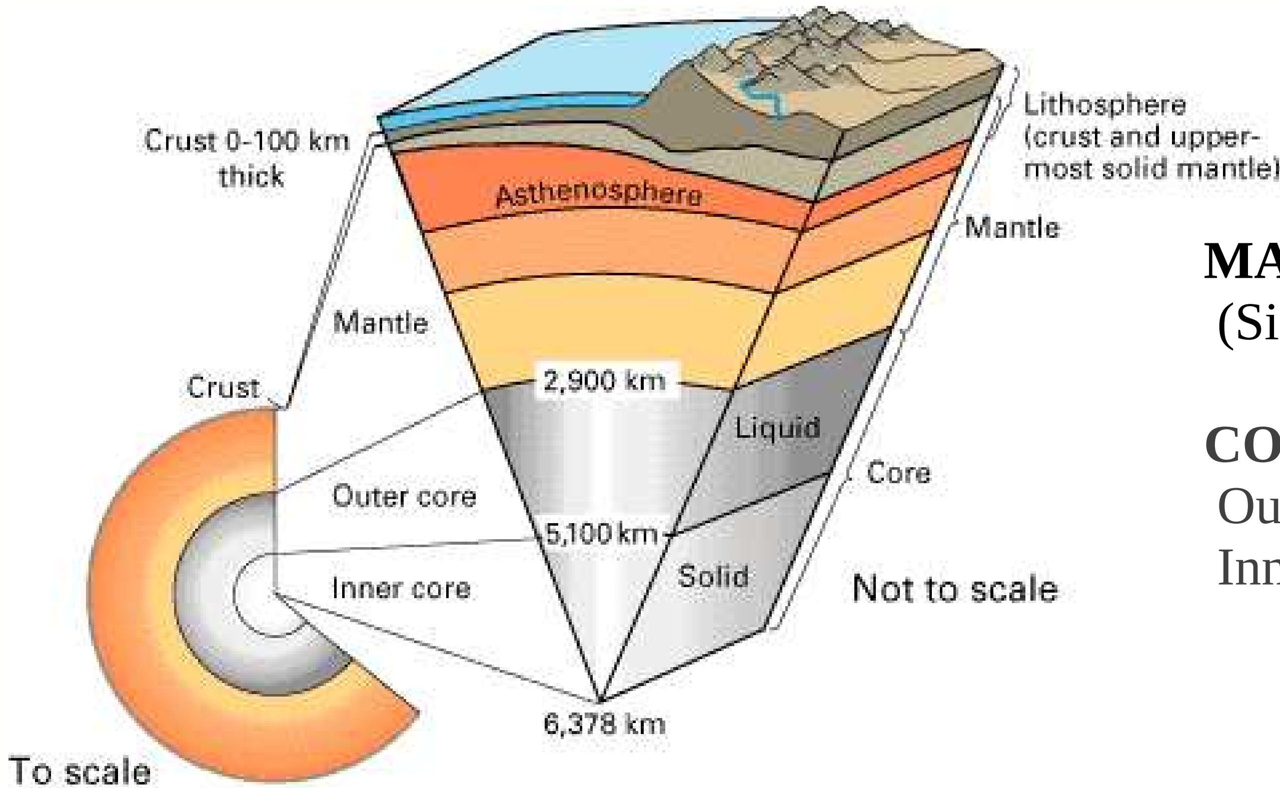


and later **INVERTED**

into velocity profiles $\alpha(r)$; $\beta(r)$ describing the mechanical properties of the Earth as a function of depth.



EARTH STRUCTURE



MANTLE: Solid Rocks (Silicates)

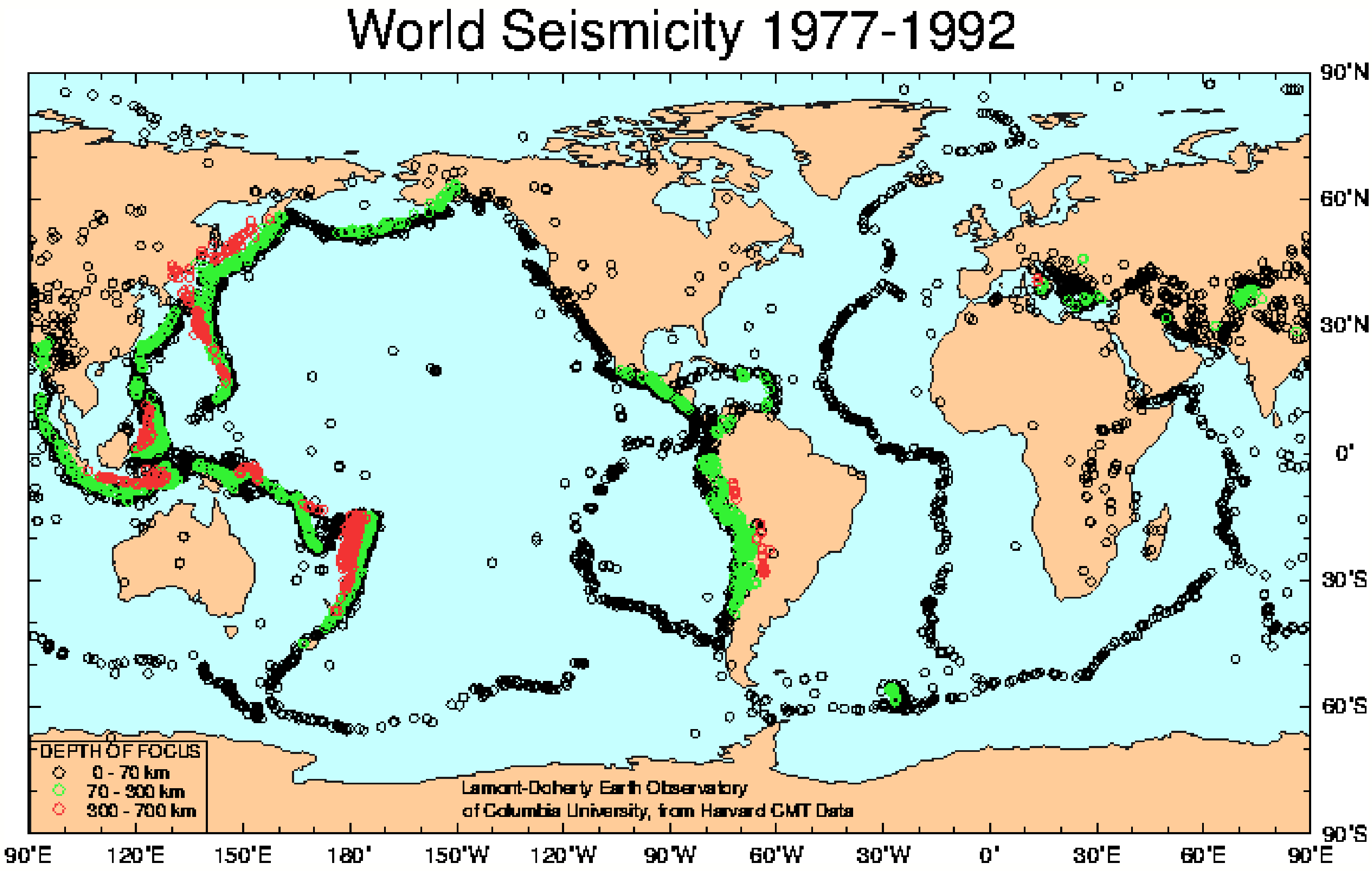
CORE: Iron (Fe)
Outer core: Liquid
Inner core: Solid

ASTHENOSPHERE: **(~ 100−220 km)** Critical layer of weak mechanical properties, believed to result from partial melting induced by the presence of volatiles (water?), featuring low rock viscosity and thus allowing *MECHANICAL DECOUPLING* of upper structure (*"PLATE"*) from deeper mantle.

ALLOWS PLATE TECTONICS

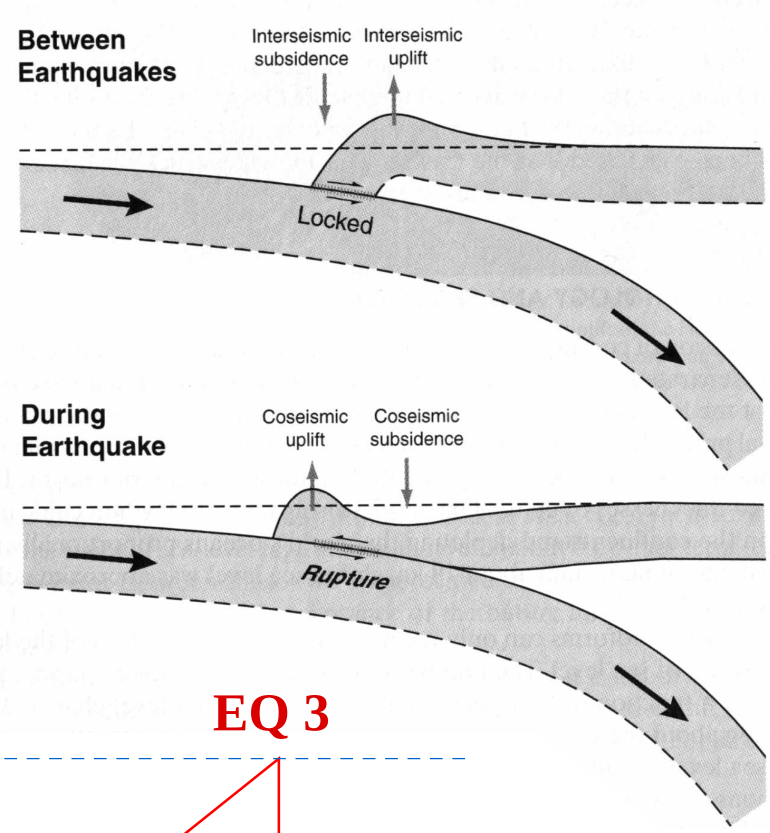
GLOBAL SEISMICITY

The location of earthquakes at the surface of the globe is not random.
Rather, they are arranged along *Linear SEISMIC BELTS*
mapped by Gutenberg and Richter in the 1940s.



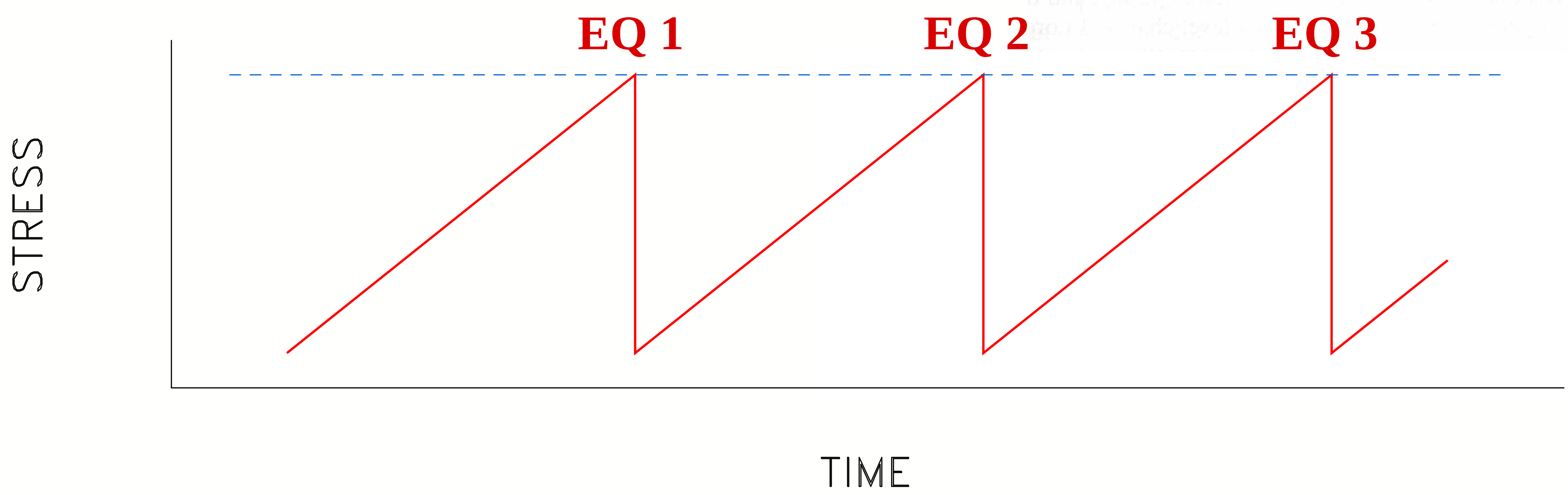
WE NOW UNDERSTAND THAT THESE SEISMIC BELTS ARE THE BOUNDARIES OF THE TECTONIC PLATES

THE SEISMIC CYCLE CONCEPT



Along a plate boundary, tectonic forces are continuously **loading** the fault at a constant stress rate.

When the stress reaches the *STRENGTH of the MATERIAL,* the rock fails (*the earthquake occurs*), and the cycle is restarted.



This very simple model suggests a process of *Stick-and-Slip* which predicts a

PERIODICITY of the EARTHQUAKE CYCLE

DIFFICULTIES with EARTHQUAKE CYCLE CONCEPT

- The typical Earthquake Cycle *MAY BE* on the order to 1 to 10 *CENTURIES*

  and Seismology is a very young Science (!)

→ Fluctuations about these "periods" are so large (typ. 100 years) **as to render prediction impossible** on a time scale relevant to Society.

- There is great diversity in the regime of coupling and stress release at various plate boundaries.

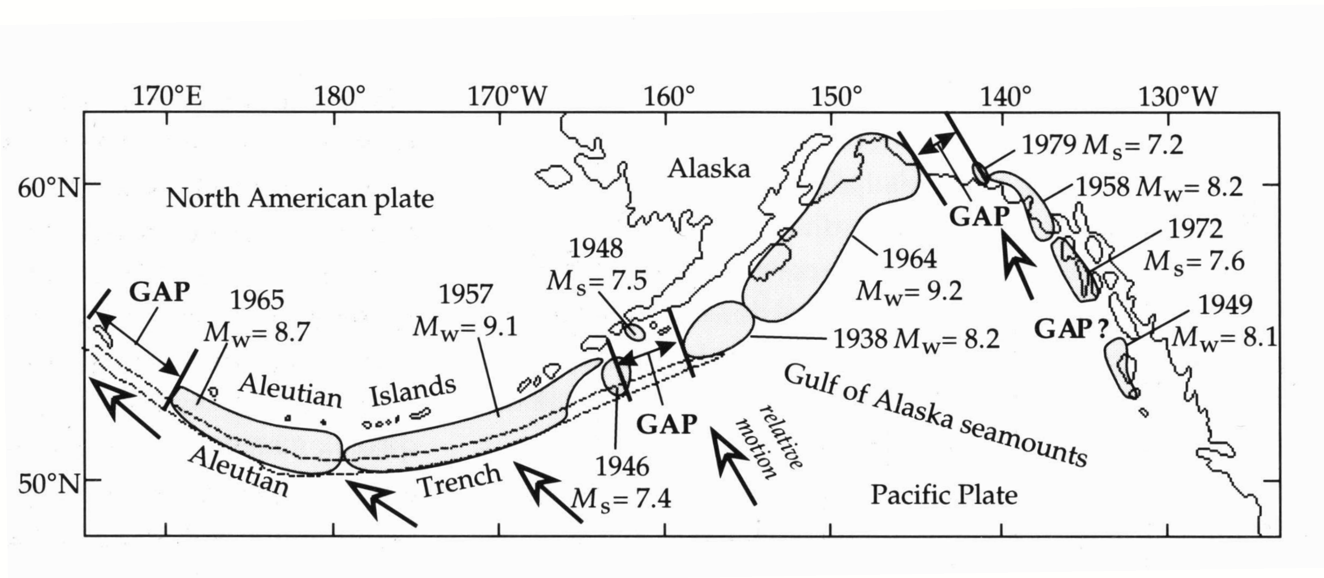
  Not all of them are efficiently locked.

  Some are creeping.

NEVERTHELESS

Scientists have proposed the identification of so-called

SEISMIC GAPS

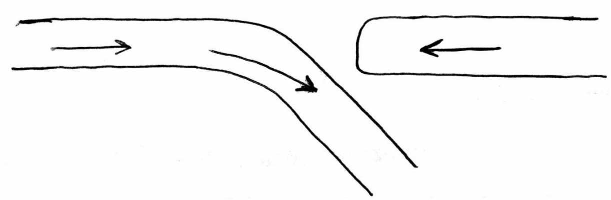


where one could expect a major earthquake in the future, based on the assessment of the character of coupling and on the history of large seismic events in adjoining provinces.

- Some gaps have subsequently *("successfully")* **ruptured.**
- Some have not and *may never rupture...*

→ Tectonic plates move, at the surface of the Earth, at an average of a few cm/yr. This motion can be

- *Aseismic* (without earthquakes), *i.e.*, a smooth gliding between decoupled plates **(i)**; or



- A *Stick-and-Slip* process in which the plates remain coupled for a long time, until stress builds up to a critical level, and the plates slip during an *earthquake*.

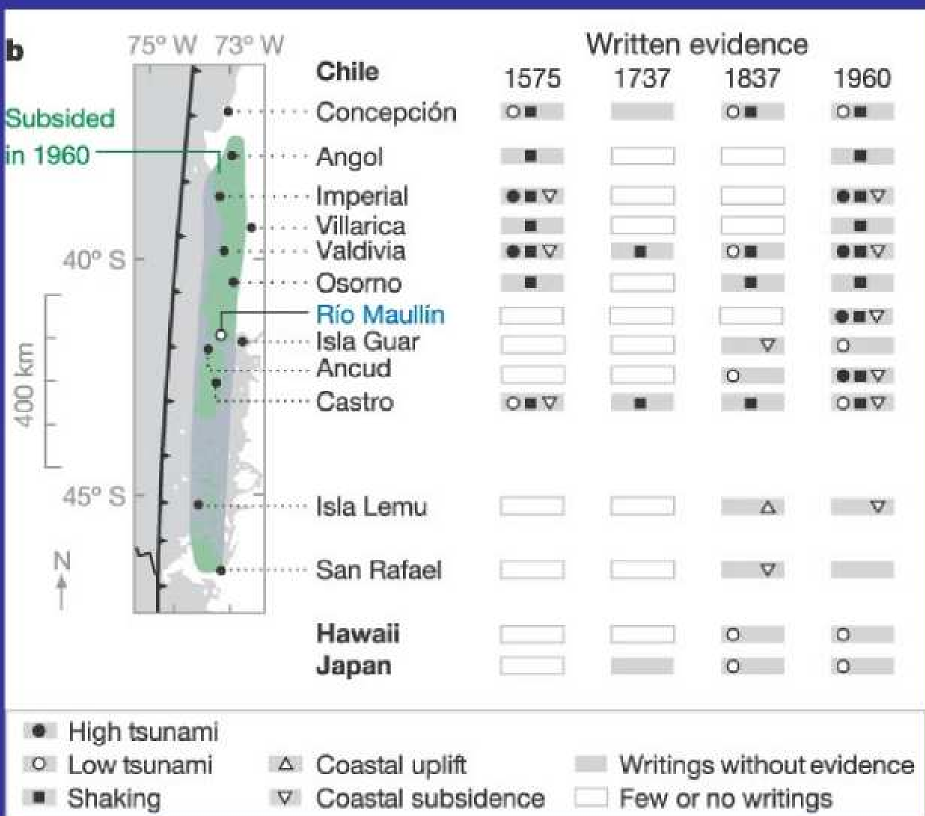
The characteristic time of this process depends in principle on the level of coupling and can vary widely.

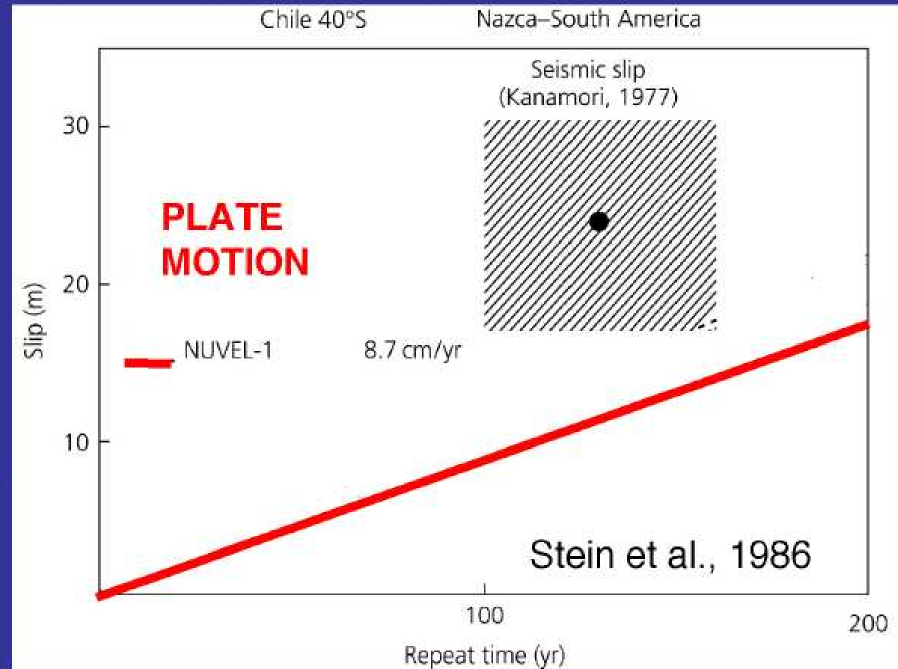
- If it is short (100 years), the region experiences frequent, but moderate, earthquakes **(ii)**.
- If it is long, the region will experience very large, but also very rare, earthquakes **(iii)**.

In the absence of historical or geological records of large events, Northern Sumatra could have fit either of scenarios (i) or (iii).

LIMITATIONS to EARTHQUAKE CYCLE CONCEPT

Seismic slip rate, estimated from slip in great 1960 earthquake and historical records indicating major earthquakes ~ every 130 years in past 400 years, exceeds the plate convergence rate





[Some] Earlier Earthquakes were significantly **smaller than the 1960 event**

EARTHQUAKE REPEAT is CAPRICIOUS

Cisternas et al., 2005

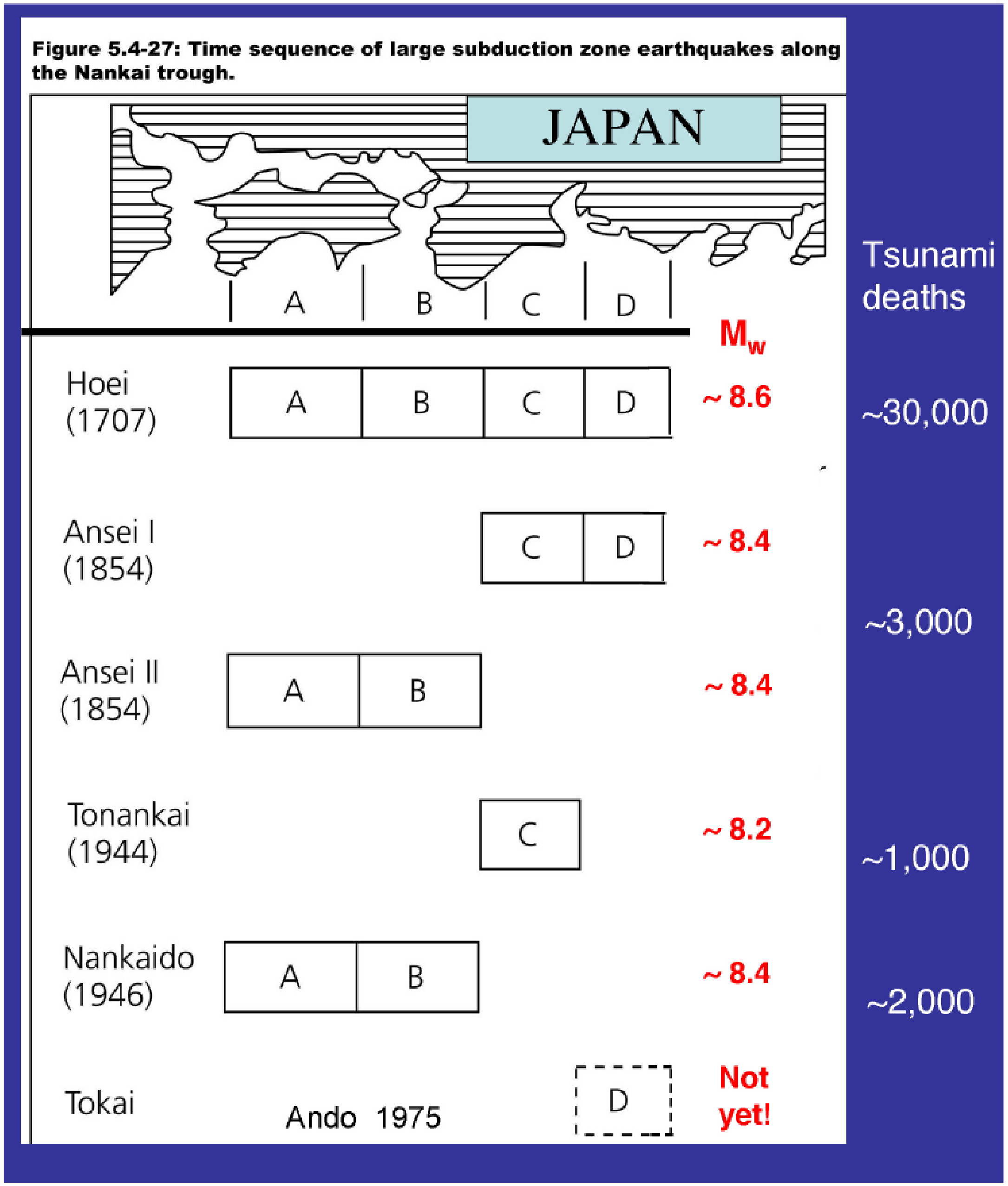
WE HAVE KNOWN THIS SINCE ANDO [1975]

Large earthquakes in Nankai province (SW Japan) may rupture through

one or **more** of **up to 4**

segments of the plate boundary.

Apparently, the pattern is random and cannot be predicted.

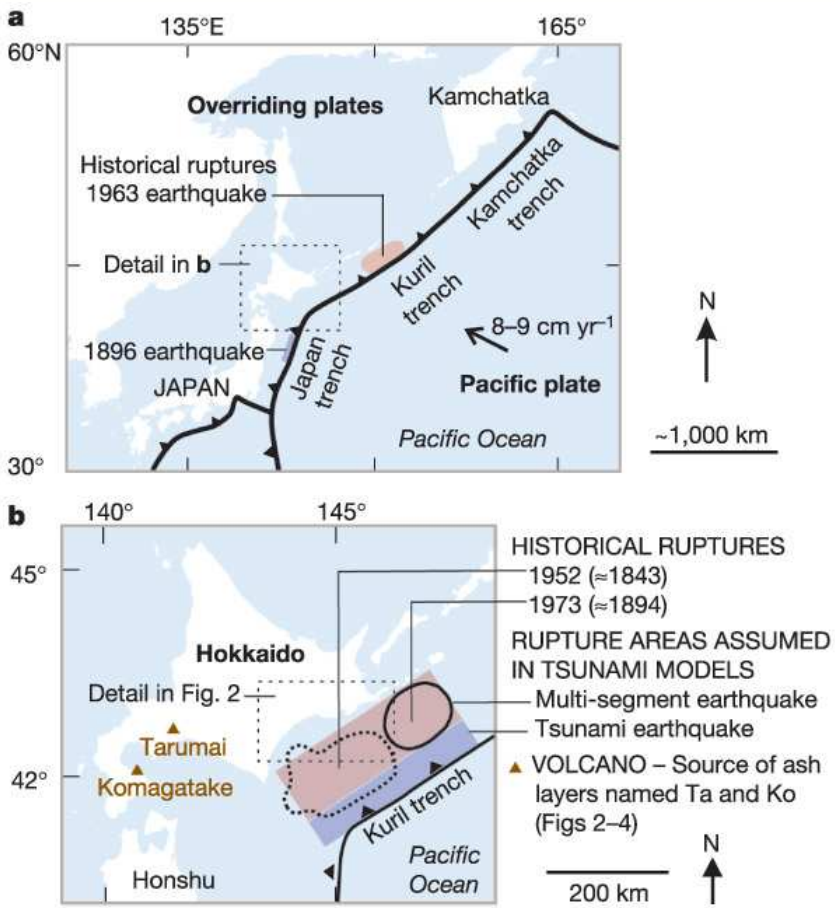


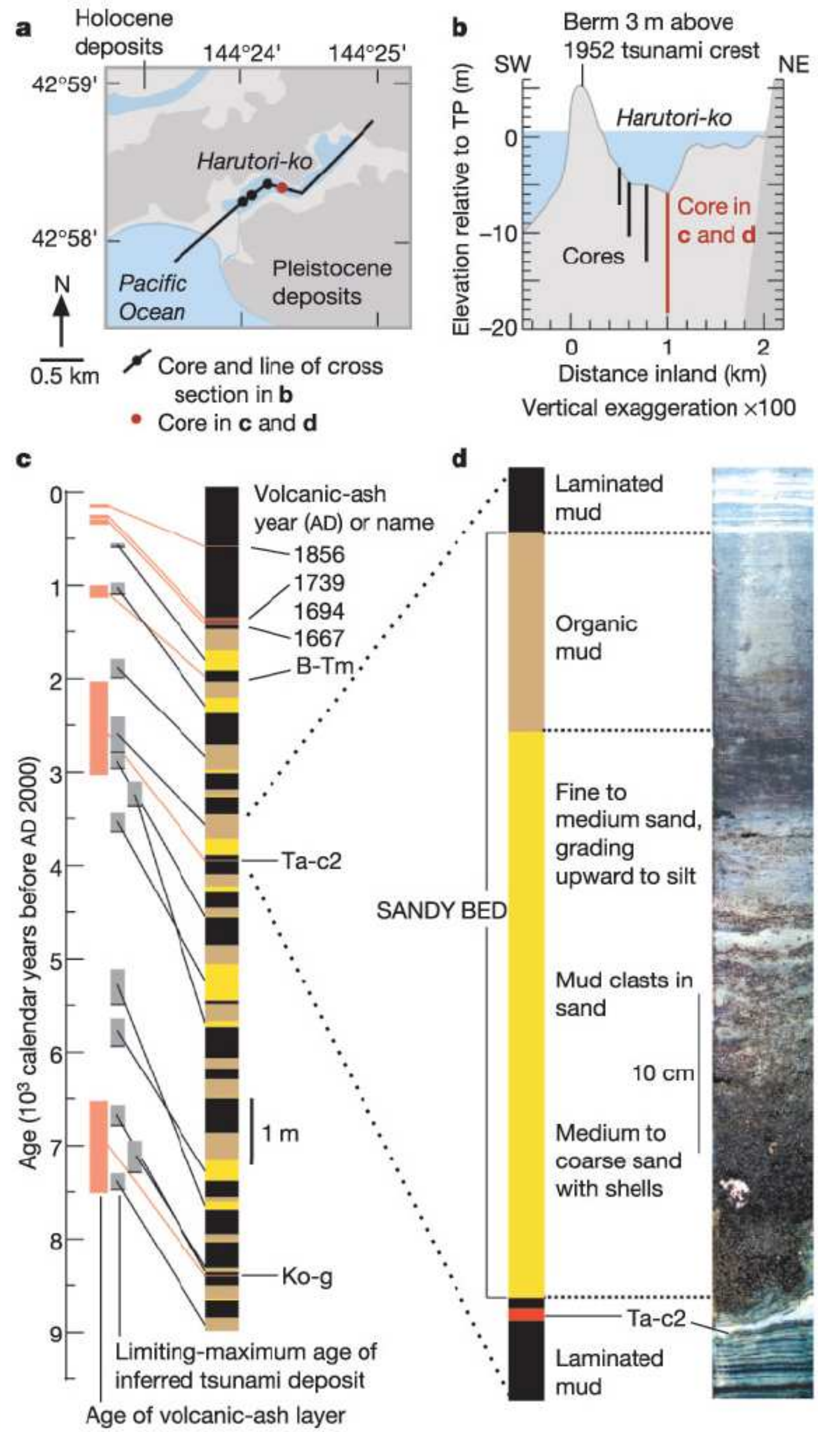
DIVERSITY of SIZE and RUPTURE

Evidence from other subduction zones

NORTH JAPAN KURILES

Deposits from Paleo-Tsunamis
suggest $M \approx 9$ events





[*Nanayama et al.*, 2003]

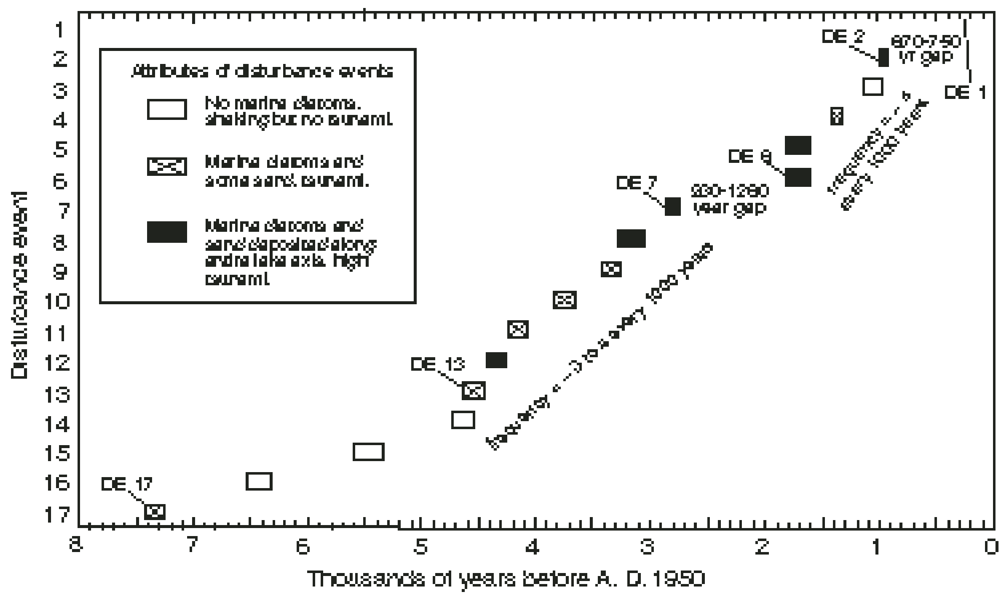
DIVERSITY of SIZE and RUPTURE

Evidence from other subduction zones

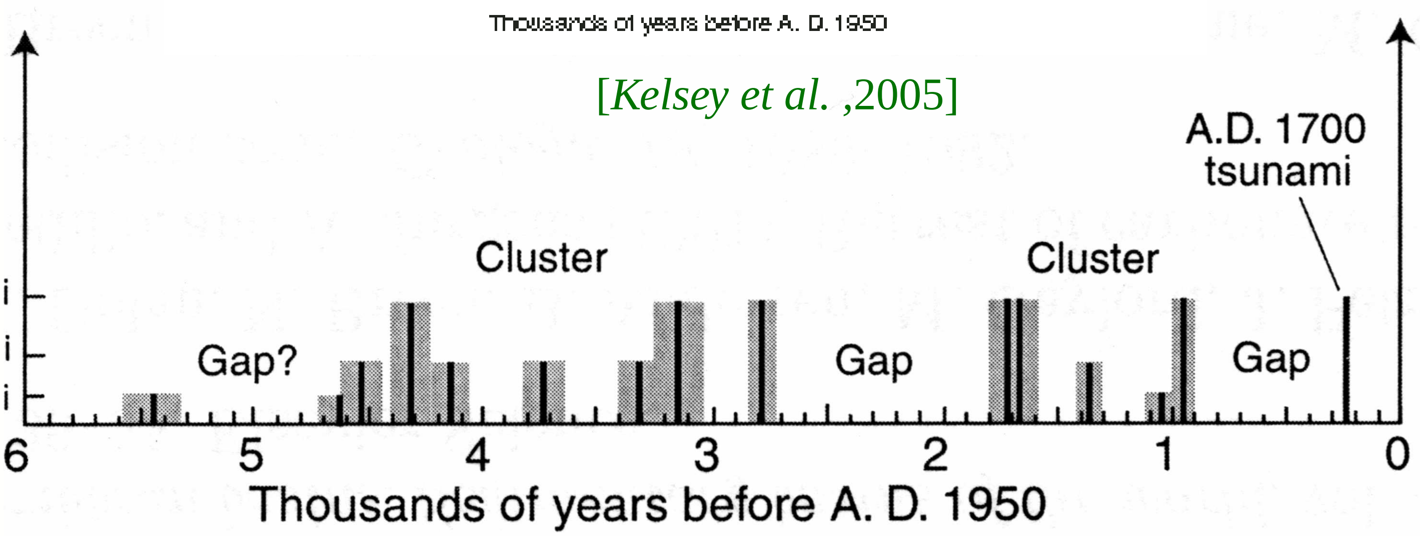
CASCADIA, NW USA

→ Sedimentary work on lake beds helps distinguish between

- Events with shaking but no tsunami
- Events with and shaking and [small] tsunami
- Events with shaking and **large** tsunami (*e.g.*, 1700)



[*Kelsey et al.* ,2005]



THE CASE of INTRAPLATE EARTHQUAKES

- Most very large earthquakes capable of generating tsunamis occur at plate boundaries.
- However, intraplate activity, or activity related to diffuse plate boundaries can lead to major earthquakes (with magnitudes greater than 8).
- Examples include the 1998 Balleny Island event near the Australian-Antarctic-Pacific triple junction, and historical events near the Indian-Australian diffuse boundary in the Indian Ocean.