Seismic modeling & Crustal Structures of the Arabian Peninsula

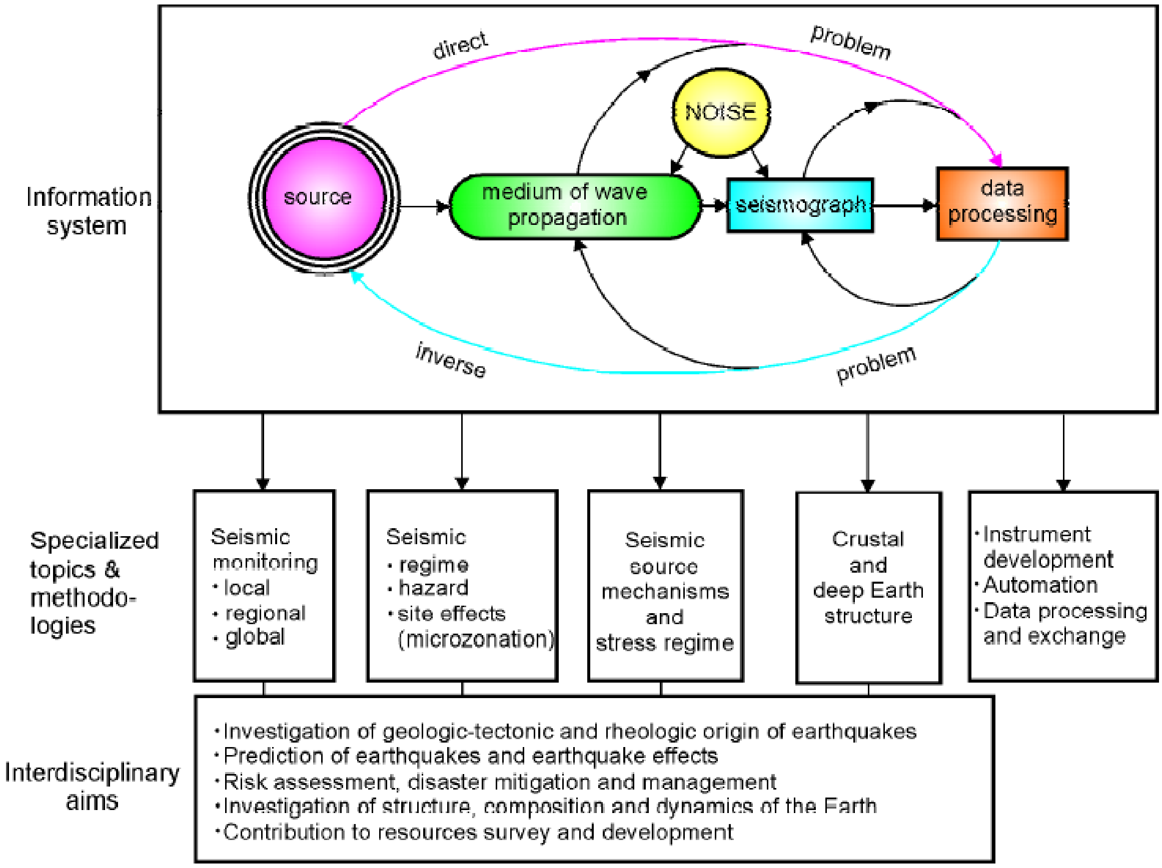
Abdullah M. S. Al-Amri

Professor of Geophysics & Director of Seismic Studies Center
King Saud University - Riyadh

MECHANISM OF EARTHQUAKES

INTRODUCTION

seismology with its many interrelated sub-systems such as the seismic source, wave propagation through the Earth, the masking and distortion of "useful signals" by noise, as well as the influence of the seismic sensors, recorders and processing techniques on the seismogram.



1. THE CAUSES OF EARTHQUAKES :

An earthquake is a sudden shuddering or trembling of the earth produced by shock waves or vibrations passing through it. Earthquakes occur in regions of the earth that are undergoing deformation. Energy is stored in the form of elastic strain as the region is deformed. This process continues until the accumulated strain exceeds the strength of the rock, and then fracture or faulting occurs. The opposite sides of the fault rebound to a new equilibrium position, and the energy is released in the vibrations of seismic waves and in heating and crushing of the rock. Rock fracturing usually start from a point **(focus, hypocenter**) close to one edge of the fault plane and propagates along the plane with a typical velocity of some 3 Km/sec. The vertical projection of the hypocenter onto the earth's surface is called the epicenter.

Faults are classified according to the direction of their apparent movements (Fig. 1) :

1. A dip-slip fault : is a fracture along which movements of rocks are predominantly vertical. The fracture has a dip and the rocks slip along it.

2. A strike-slip fault : is a fracture along which movement of rock is redominantly horizontal.

3. An oblique-slip fault : occurs when the rocks move with about the same amount of vertical and horizontal motion.

4. A normal or gravity fault : is one in which rocks on one side of a fracture apparently have moved downward in a vertical direction.

5. A thrust fault : is one in which rocks on one side of a fracture have been thrust upward. A reverse fault is a steep thrust fault with angles more than 45 degrees.

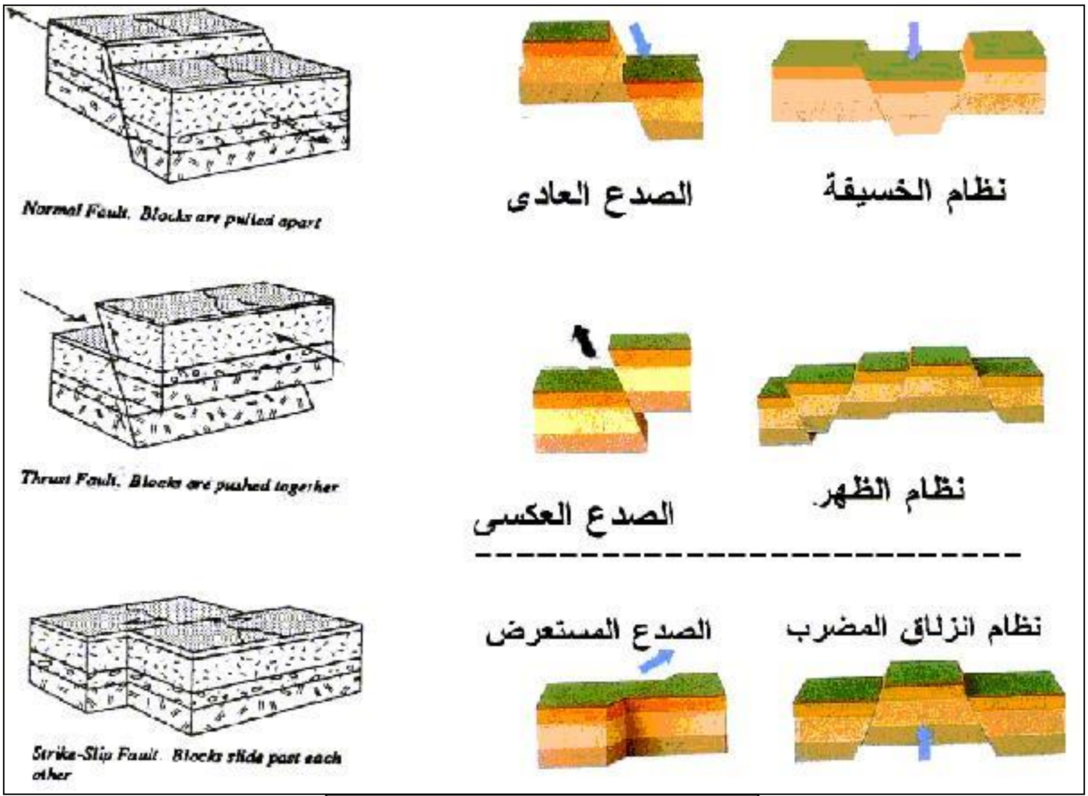
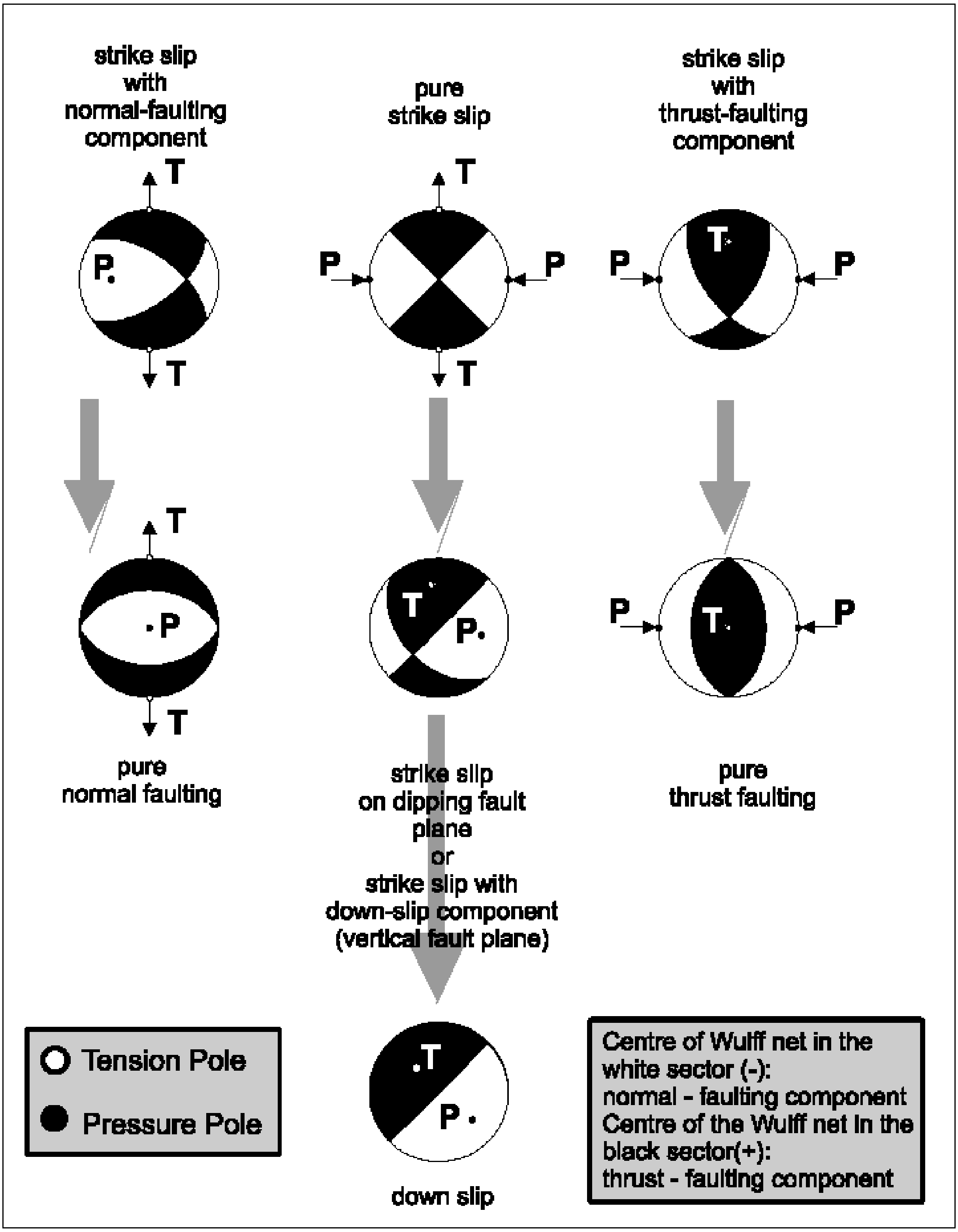


Fig. 1 : Types of Faulting



Beach-ball. presentation of the net projections of the fault plane cut-traces and of the penetration points (poles) of the P- and T-axes through the lower focal hemisphere for different faulting mechanisms. White sectors correspond to negative and black sectors to positive first-motion polarities.

Seismic Waves

Earthquake shaking and damage is the result of three basic types of elastic waves :

1 . <u>Primary</u> , Longitudinal, or P waves : This is the first wave to arrive and its motion is the same as that of a sound wave . It pushes (compresses) and pulls (dilates)the rock and able to travel through both the solid and liquid material (Fig. 2)

2. <u>Secondary</u> , Shear , or S waves: As an S wave propagates, it shears the rock sideways at right angles to the direction of travel. It can not propagate in the liquid parts of the earth, such as the oceans and outer core. In most earthquake, the P waves are felt first. Some seconds later, the S waves arrive with their up- and- down and side-to-side motion, shaking the ground surface vertically and horizontally. This the wave motion that is so damaging to structures.

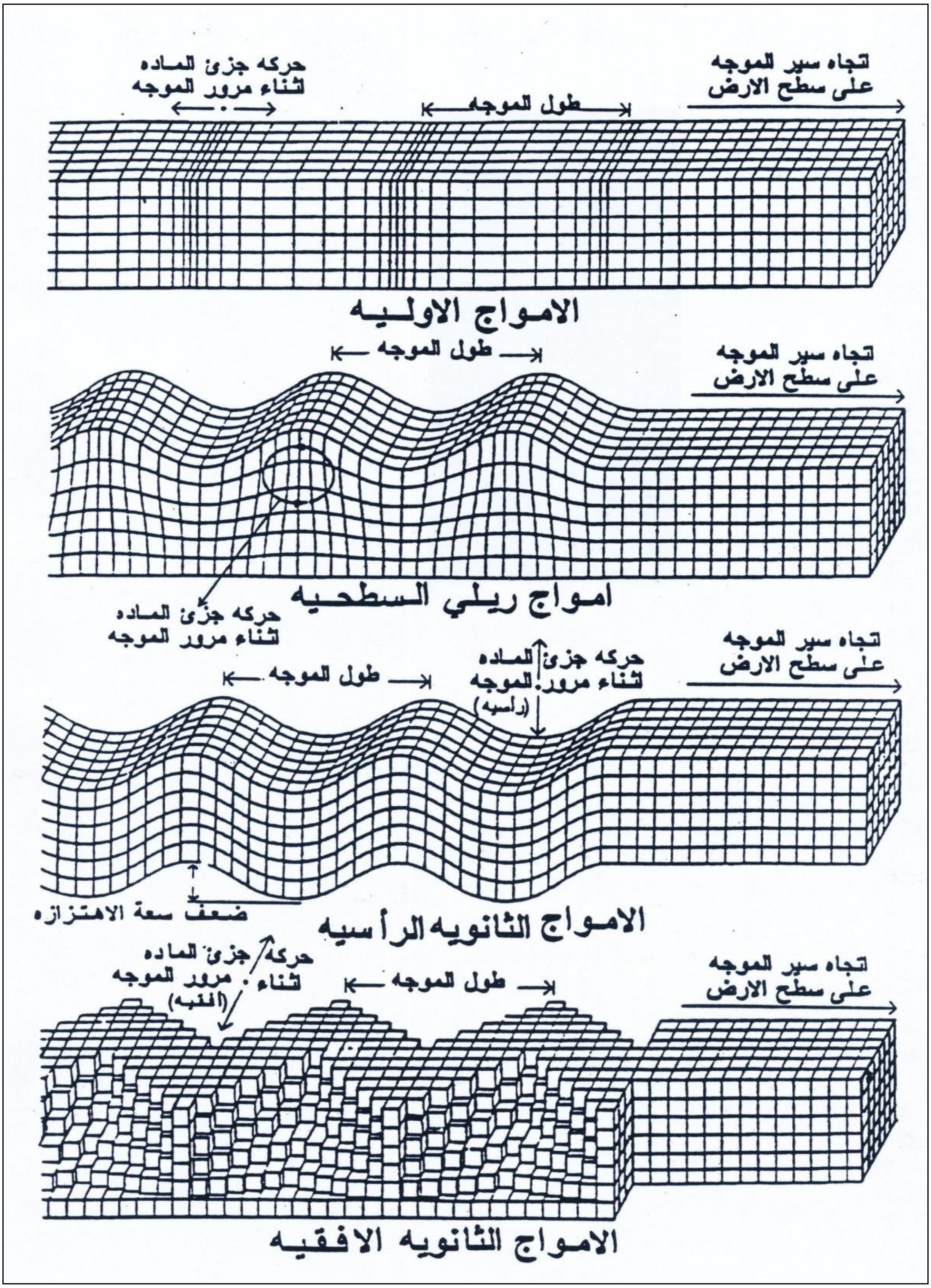
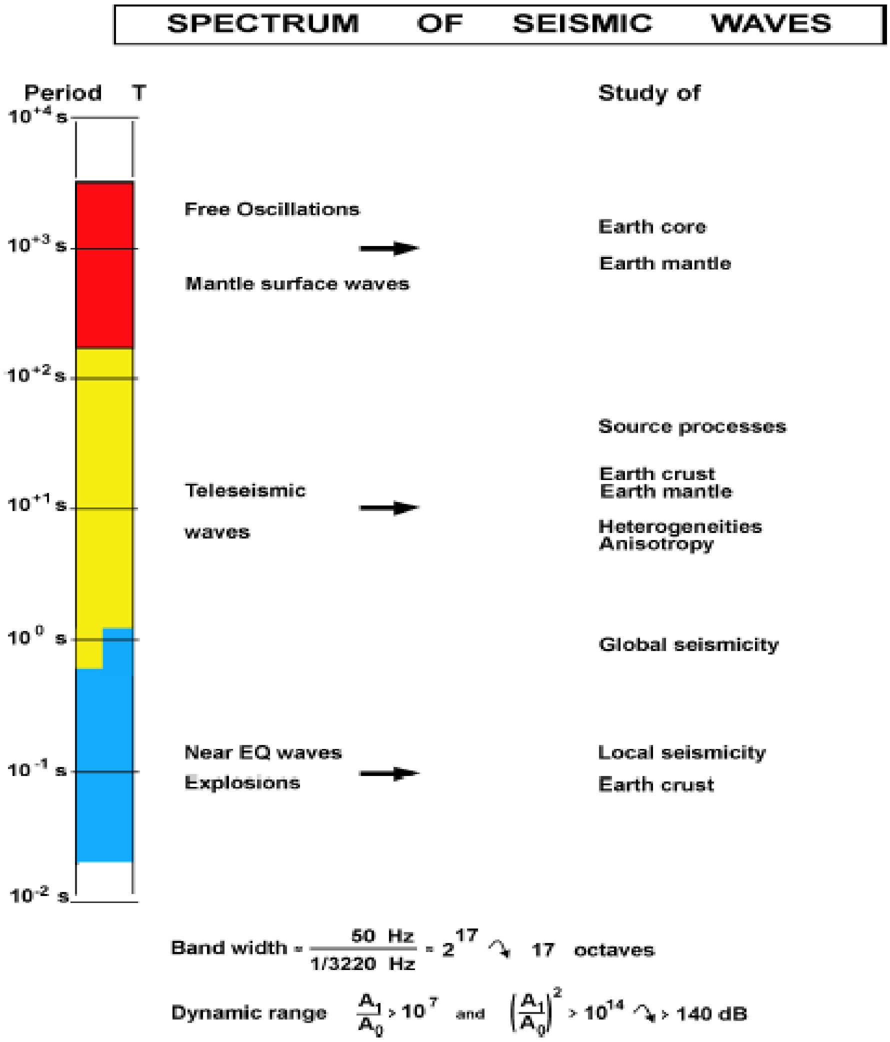


Fig. 2 :Types of seismic waves : Primary, Secondary and Surface waves

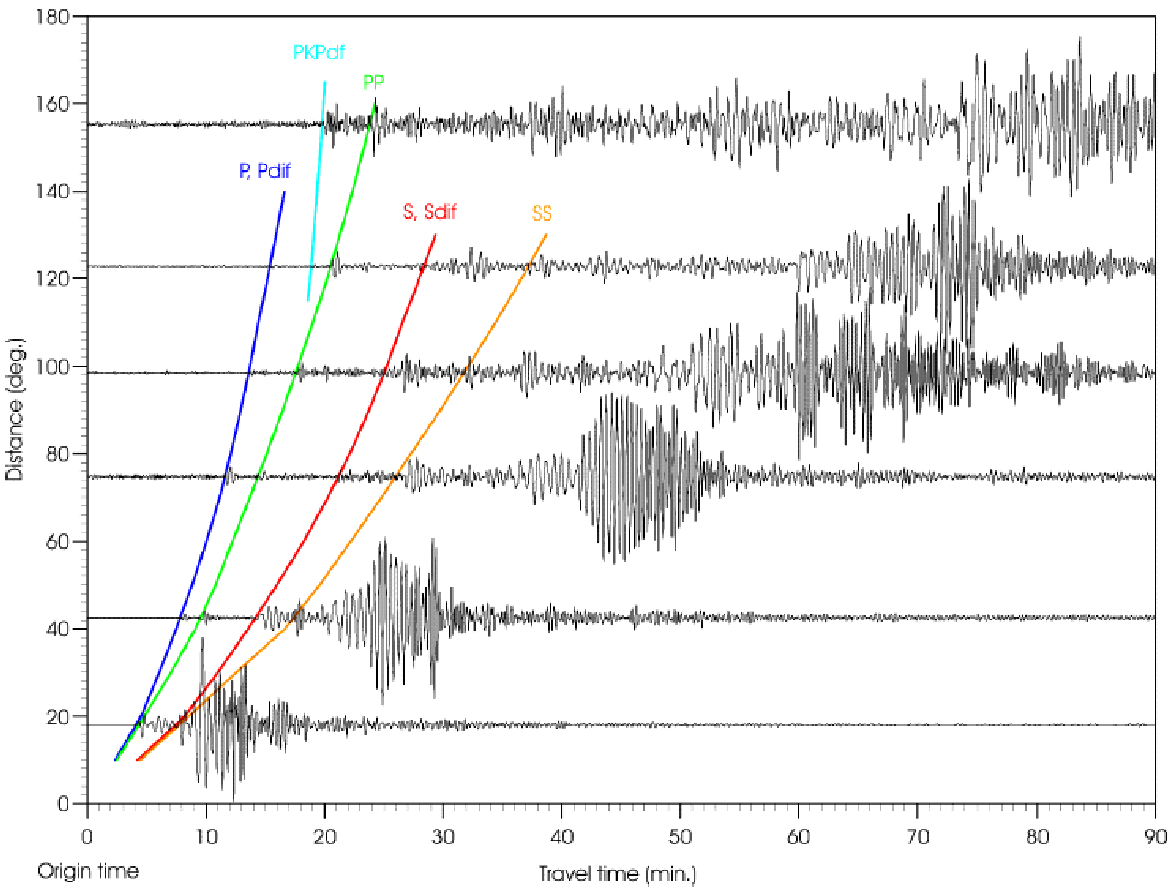
3. <u>Surface</u> waves : It can be divided into two types

a. <u>Love</u> <u>wave</u> : Its motion is essentially the same as that of S waves that have no vertical displacement. The horizontal shaking of Love waves is particularly damaging to the foundations of structures.

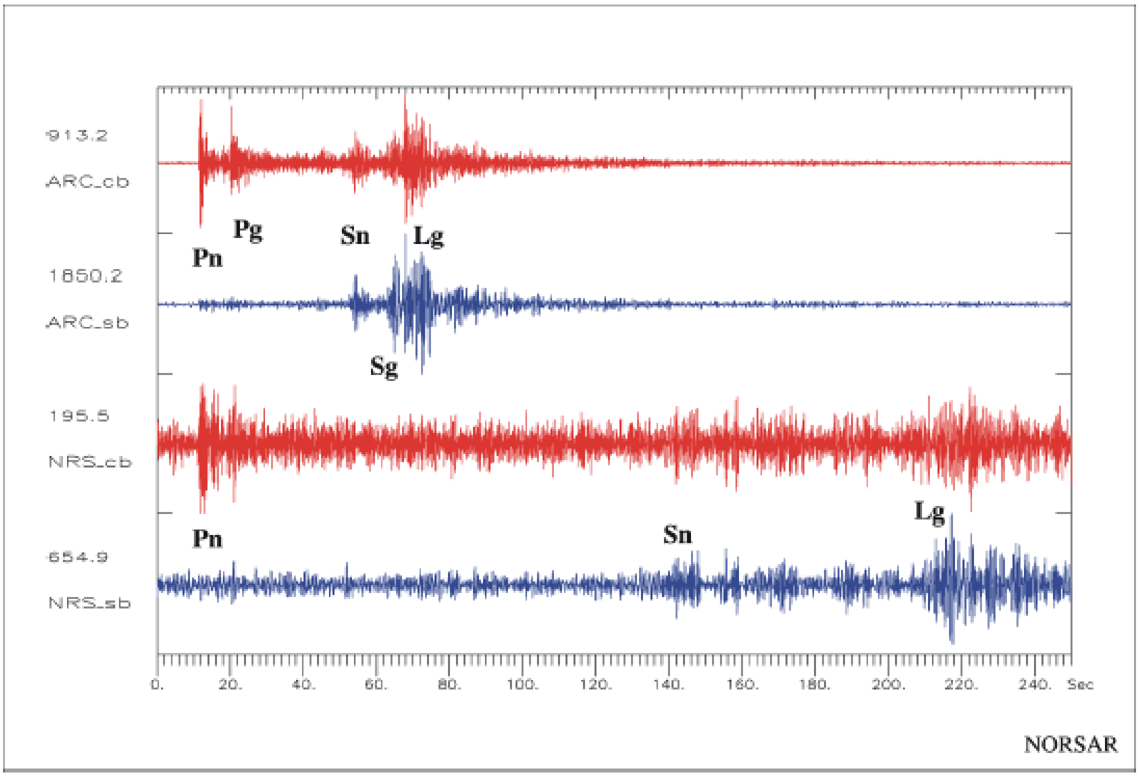
b. <u>Rayleigh</u> <u>wave</u> : Like rolling ocean waves, the pieces of material disturbed by Rayleigh wave move both vertically and horizontally in a vertical plane pointed in the direction in which the waves are travelling.



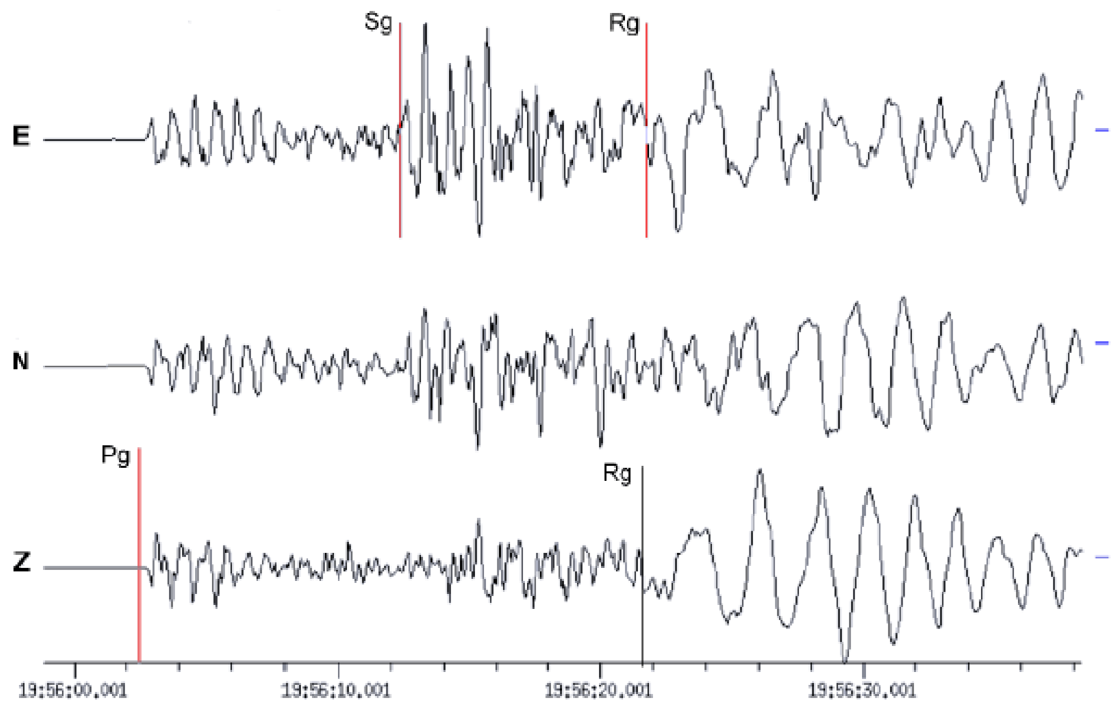
Frequency range, bandwidth and dynamic range of modern seismology and related objects of research. The related wavelength of seismic waves vary, depending on their propagation velocity, between several meter (m) and more than 10,000 kilometer (km). The amplitudes to be recorded range from nanometer (nm) to decimeter (dm).



Long-period filtered vertical-component broadband records of station CLL, Germany, of shallow earthquakes in the distance range 18° to 157°. Note the strong later longitudinal (PP) and transverse energy arrivals (S, SS) that are recognizable in the whole distance range, and the dispersed surface wave trains with large amplitudes. The record duration increases with distance (courtesy of S. Wendt, 2002).



Records of Lg, together with other crustal phases, in records of a Kola peninsula mining blast (Ml = 2.4) at the Norwegian array stations ARCES (distance D = 391 km; upper two traces) and NORES (D = 1309 km, bottom traces). cb and sb . P- and S-wave beams of the vertical elements of the array, filtered with 2-8 Hz and 1-4 Hz, respectively.



Mining induced rock burst south of Saarbrücken, Germany, recorded at station WLF in Luxemburg (D = 80 km, h = 1 km, Ml = 3.7). Note the strong dispersive Rg phase.

2. EARTHQUAKES , WHY AND WHERE DO THEY OCCUR ?

It has long been recognized that earthquakes are not evenly distributed over the earth. The eventual correlation of the earthquake pattern with the earth's major surface features was a key to the evolution of the plate tectonics theory. This is the most recent and broadly satisfying explanation theory of the majority of earthquakes. The basic idea is that the earth's outermost part (Lithosphere) consists of several large and fairly stable slabs of solid and relatively rigid rock called plates (Figure 3). Each plate extends to a depth of about 80 Km .

Plate boundaries are classified into one of the three categories :

1. Trenches : as two plates converge, one plate usually bends beneath the other and descends into the soft ,hot asthenosphere. The descending slab is known as subduction zone.

2. Ridges : The opening where two plates diverge is continuously filled by ascending mantle material.

3.Transform faults : boundaries where two plates move horizontally past each other.

The large majority of the world's earthquakes are not generated randomly around the globe but in relatively narrow belts along trenches, ridges and transform faults.

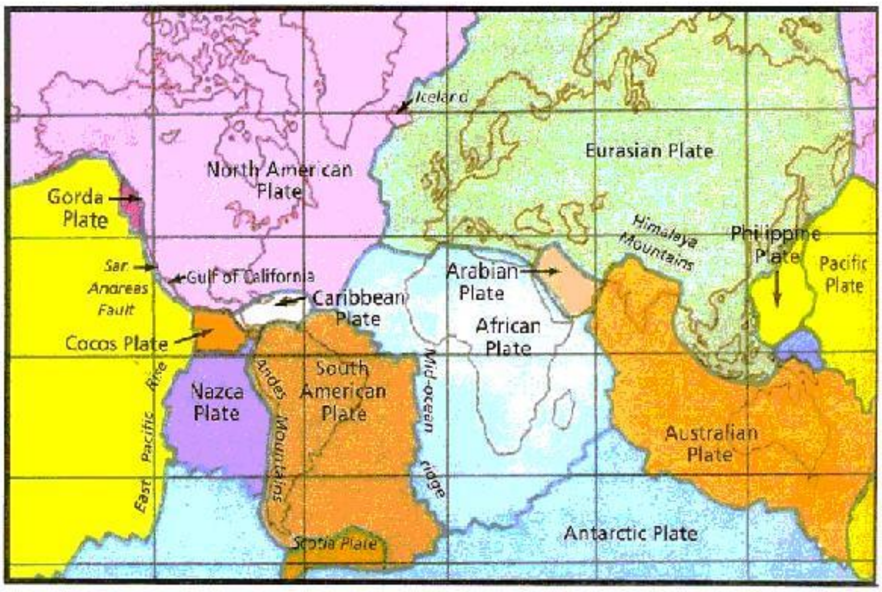


Fig. 3 : Tectonic Plates

There are two major belts along which most of the world's earthquakes occur (Interplate earthquakes).

1. The circum - pacific belt : A large part (80 %) of the seismic energy released by all earthquakes is released along this belt. This includes the western coasts of South and North America , Japan, Philippines, and a strip through the East Indies and New Zealand.

2. The Alpide (Asiatic - European) belt : A high energy concentration (10 %) can also be seen along this belt. It extends from the Pacific belt in New Guinea through Summatra and Indonesia, the Himalayas, and mountains and faults of the Middle East , the Alps , and into the Atlantic Ocean far as the Azores (Fig. 3) .

Sporadically, earthquakes also occur at rather large distances from the respective plate margins . These so called **Intraplate earthquakes** , show a diffuse geographical distribution and there origin is still poorly understood. It can be large and because of there unexpectedness and infrequency can cause major disasters.

According to the focal depth, earthquakes are classified into one of the three categories :

1. Shallow-focus earthquakes : have their foci at a depth between 0 and 70 Km. and take place at oceanic ridges and transform faults as well as at subduction zones.

2. Intermediate-focus earthquake : focal depth between 71 and 300 Km.

3. Deep-focus earthquakes : focal depth greater than 300 Km

Most earthquakes originate within the crust. At depth beneath the Moho (Crust-Mantle boundary), the number falls abruptly and dies away to zero at a depth of about 700 Km. Earthquakes along ridges usually occur at a depth of about 10 Km or less and are of moderate size. Transform faults generate large shocks at depth down to about 20 Km. The largest earthquakes occur along subduction zones.

3. THE SCALES OF EARTHQUAKES

Two basically different scales are used to describe the size or strength of an earthquake and its effect :

1. Intensity : earthquake intensity represents the degree of shaking at a particular location on the earth's surface. It indicates the local effect or damage of the earthquake upon people, animals, buildings and objects in the immediate environment. The intensity diminishes generally with increasing distance from the epicenter.

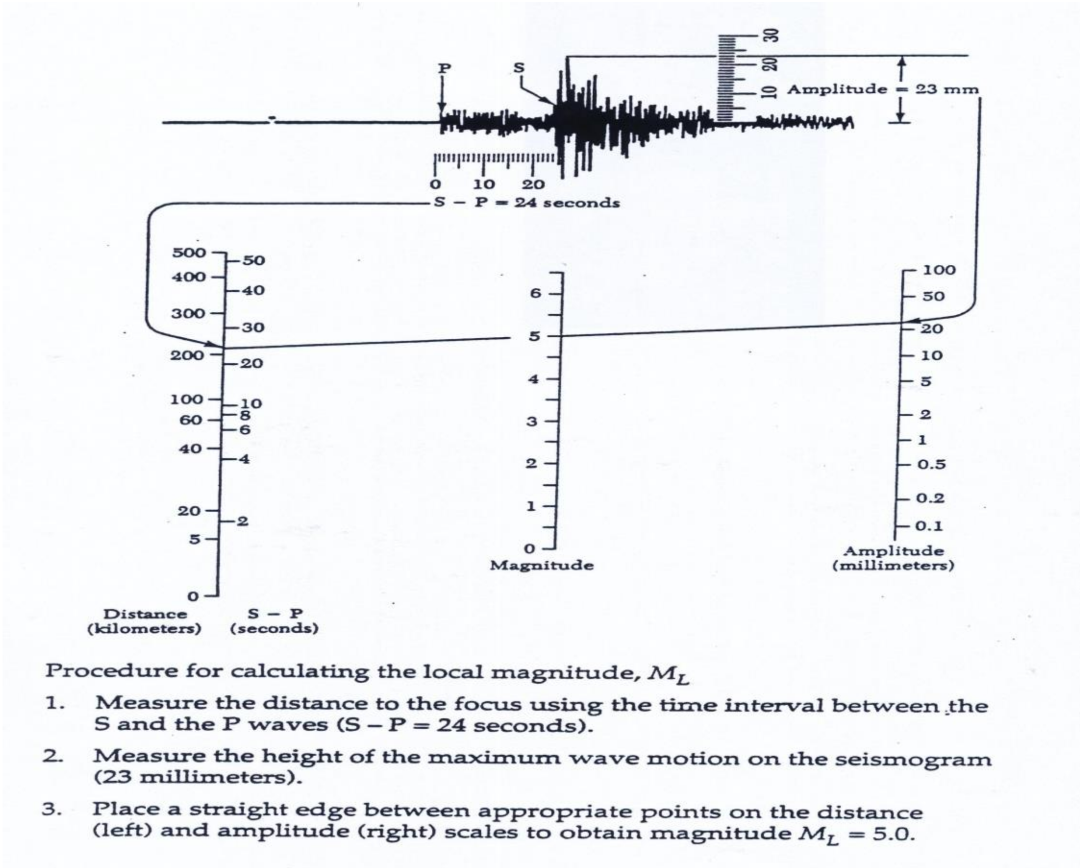
One of the most widely used scales for intensity is the **Modified Mercalli Scale** . The scale has the following values, ranging from I to XII, usually written in Roman numerals :

I. Not felt
II. Felt by persons at rest
III. Felt indoor. Hanging objects swing
IV. Vibration like passing of heavy trucks. Windows rattle.
V. Felt outdoors. Sleepers awakened.
VI. Felt by all Persons walk unsteadily. Glassware broken.
VII. Difficult to stand. Hanging objects quiver.
VIII. Twisting,fall of chimneys,factory stacks,towers.
IX. General panic.Undergroundpipes broken.Frames racked.
X. Most masonry and frame structures destroyed.
XI. Rails bent greatly.Underground pipes out of surface.
XII. Damage nearly total. Objects thrown into the air.

2. Magnitude : The magnitude of an earthquake is an expression of the actual original force or energy of the earthquake at its moment of creation. It is measured directly by instruments, unlike the subjective measurement of intensity.

The **Richter scale** is a standard for expressing magnitude of earthquakes. Magnitude is defined as the logarithm to the base 10 of the amplitude of the largest ground motion traced by a standard type seismograph placed 100 Km from the earthquake's epicenter.

The Richter scale of magnitude runs from 0 through 8.9 , although there is no lower limit or upper limit. Each unit representing a ten-fold increase in amplitude of the measured waves and nearly a 30-fold increase in energy.



Procedure for Calculating the local magnitude M_L

An earthquake of magnitude 1 can only detected by a seismograph. The weakest earthquakes noticed by people are usually around magnitude 2. Houses and buildings are damaged at magnitude 5. Earthquakes with a magnitude above 6 are capable of producing serious damage. An earthquake with a magnitude of 8 and above is considered a great earthquake.

All the magnitude scales are of the form :

$$\mathbf{M = \log \ (A / T) + q(d, h) + a}$$

Where :

M is the magnitude
A is the maximum amplitude of the wave
T is the period of the wave
q is a function correcting for the decrease of amplitude with distance from the epicenter and focal depth (h)
d is the epicentral distance
a is an empirical constant

When the surface - wave magnitude (Ms) and body-wave magnitude (mb) are calculated for an earthquake, they do not usually have the same value.

$$mb = 2.94 + 0.55\ Ms$$

Structural damage is related to ground acceleration, although building respond differently to seismic waves of different periods. Intensity (I) is calibrated in terms of ground acceleration (a) by an approximate relationship

$$\log a = (I / 3) - 2.5$$

The approximate relationship between the magnitude and intensity has been estimated according to the following relationship :

$$M = 2I / 3 + 1.7 \log h - 1.4$$

Magnitude (Richter Scale)	Intensity (Mecalli Scale)	Damage Description
4	**5.5**	Widely felt, plaster cracked
5	**7**	Strong vibration, weak buildings and chimneys damaged
6	**8.5**	Ordinary buildings badly damaged
7	**10**	Well-built buildings destroyed
8	**11.5**	Specially designed buildings damaged
9	**12**	Widespread destruction

Studies indicate that building damages often much more attributed to the velocity of the back-and-forth motion of the foundation than to its beak acceleration. The higher the seismic intensity, the higher the average velocity of shaking. Nevertheless, the mean accelerations have much bearing on the forces affecting a structure. Consequently, in designing to avert earthquake damage, engineers have come to rely on the estimates of ground acceleration that a structure might be expected to experience in its lifetime.

Because buildings are built to withstand the pull of gravity, they will usually withstand substantial accelerations in a vertical direction during earthquake shaking. In contrast, experience has shown that it is the horizontal motions of the ground that topple structures and throw people to the ground.

As previously mentioned, earthquakes are the result of the sudden release of strain energy stored previously in the rocks in the earth. From measurements of the seismic-wave energy produced by the sudden fracture, it is estimated that each year the total energy released by earthquakes throughout the world is between 10 and 100 ergs.

An earthquake of Richter magnitude 5.5 turns out to have an energy of about 10 ergs. The relation between energy and magnitude is :

$$\log E = 5.24 + 1.44\ Ms$$

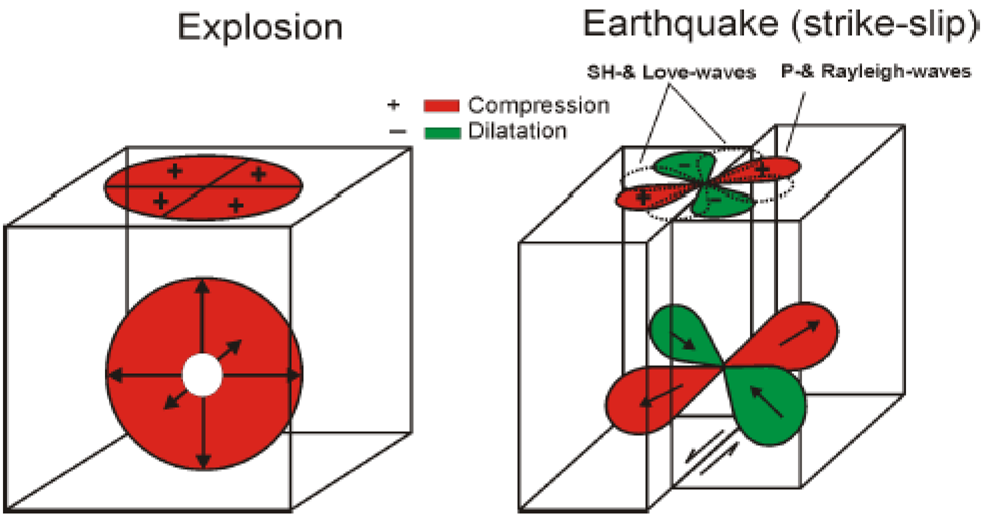
E : is the total energy measured in **joules**
Ms : is the surface-wave magnitude.

An increase in magnitude Ms of 1 unit increases the amount of seismic energy E released by a factor of about 30. In comparison , the Hiroshima atomic bomb was approximately equivalent in terms of energy to an earthquake of magnitude 5.3. A one megaton nuclear explosion would release about the same amount of energy as an earthquake of magnitude 6.5.

4. EARTHQUAKES & EXPLOSIONS

Explosions are mostly anthropogenic, i.e., .man-made., and controlled, i.e., with known location and source time. However, strong natural explosions in conjunction with volcanic eruptions or meteorite impacts, such as the Tunguska meteorite of 30 June 1908 in Siberia, may also occur. Explosions used in exploration seismology for the investigation of the crust have yields, Y, of a few kg to tons of TNT (Trinitrotoluol). This is sufficient to produce seismic waves which can be recorded from several km to hundreds of km distance. Underground nuclear explosions of kt up to Mt of equivalent TNT may be seismically recorded even world-wide (1 kt TNT = 4.2 x 1012 J). Nevertheless, even the strongest of all underground nuclear tests with an equivalent yield of about 5 Mt TNT produced body-waves of only magnitude mb . 7. This corresponds to roughly 0.1% of the seismic energy released by the Chile earthquake of 1960. After 1974, underground tests with only $Y \leq 150$ kt were carried out. Only well contained underground chemical or nuclear explosions have a sufficiently good seismic coupling factor ε (ε . 10-2 to 10-3, i.e., only 1 % to 0.1 % of the total released explosion energy is transformed into seismic energy). The coupling factor of explosions on the surface or in the atmosphere is much less (ε . 10-3 to 10-6 depending on the altitude).

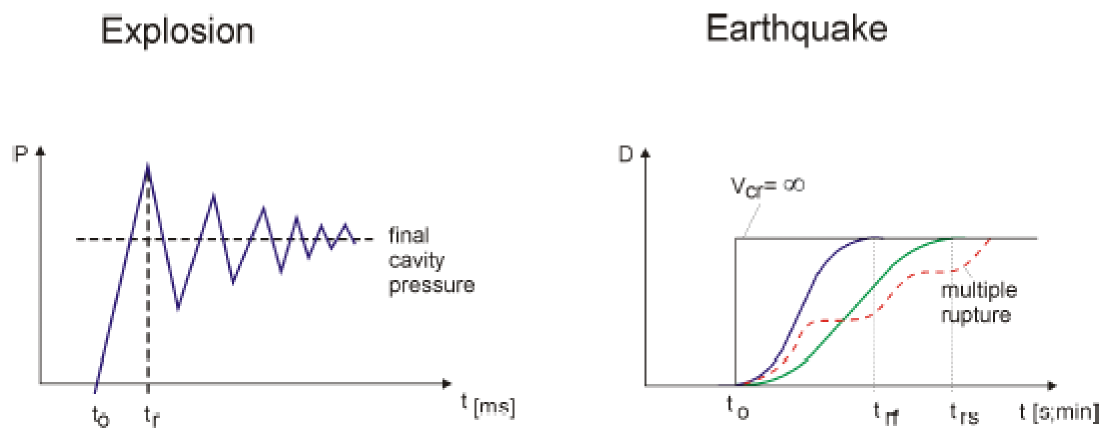
It is obvious that the explosion produces a homogeneous outward directed compressional first motion in all directions while the tectonic earthquake produces first motions of different amplitude and polarity in different directions. These characteristics can be used to identify the type of source process (see 3.4) and to discriminate between explosions and tectonic earthquakes.

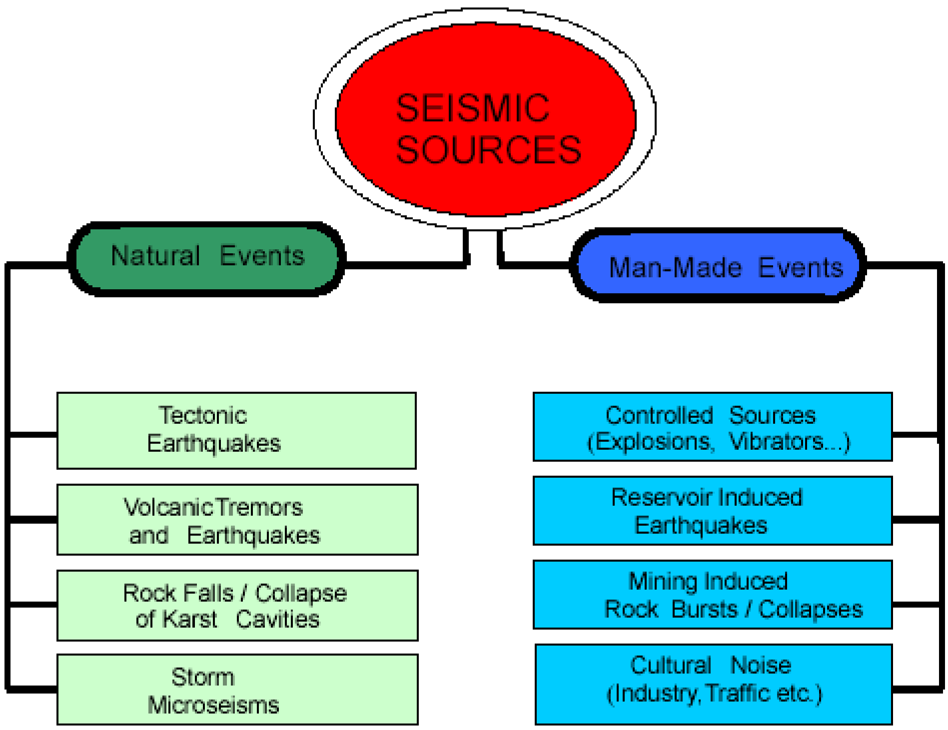


Schematic sketches of an idealized underground explosion and of a strike-slip earthquake along a vertically dipping fault. The fault motion is "left-lateral", i.e., counter-clockwise. The arrows show the directions of compressional (outward, polarity +, red shaded) and dilatational (inward, polarity -, green shaded) motions. The patterns shown on the surface, termed amplitude or polarity patterns indicate the azimuthal variation of observed amplitudes or of the direction of first motions in seismic records, respectively. While point-like explosions in an isotropic medium should show no azimuth-dependent amplitudes and compressional first motions only, amplitudes and polarities vary for a tectonic earthquake.

Compared to tectonic earthquakes, the *duration* of the source process of explosions and the *rise time* to the maximum level of displacement is much shorter (milliseconds as compared to seconds up to a few minutes) and more impulsive. Accordingly, explosions of comparable body-wave magnitude excite more high-frequent oscillations. Rock falls may last for several minutes and cause seismic waves but generally with less distinct onsets and less separation of wave groups.

The collapse of karst caves, mining-induced rock bursts or collapses of mining galleries are generally of an *implosion* type. Accordingly, their first motion patterns should show dilatations in all azimuths if a secondary tectonic event has not been triggered by the collapse. The strongest events may reach magnitudes up to about M = 5.5 and be recorded world-wide (e.g., Bormann et al., 1992). *Reservoir induced* earthquakes have been frequently observed in conjunction with the impoundment of water or rapid water level changes behind large dams. Since these events are triggered along pre-existing and pre-stressed tectonic faults they show the typical polarity patterns of tectonic earthquakes . The strongest vents reported so far have reached magnitudes up to 6.5 (e.g., Koyna earthquake in 1967).





5. EARTHQUAKE PREDICTION

As yet, scientists can not predict when an earthquake will occur or where. The essential first step in all earthquake prediction studies is to identify a region in which the seismic history suggests that an earthquake may be expected to occur soon, so that instrumentation may beneficially be deployed.

The best method of studying and possibly anticipating earthquakes in historically active areas is to install instruments in specific regions to observe the cycle of earth movements. With data from such constantly monitoring arrays, scientists can tell changes in particular factors that may indicate a possible earthquake. such factors include :

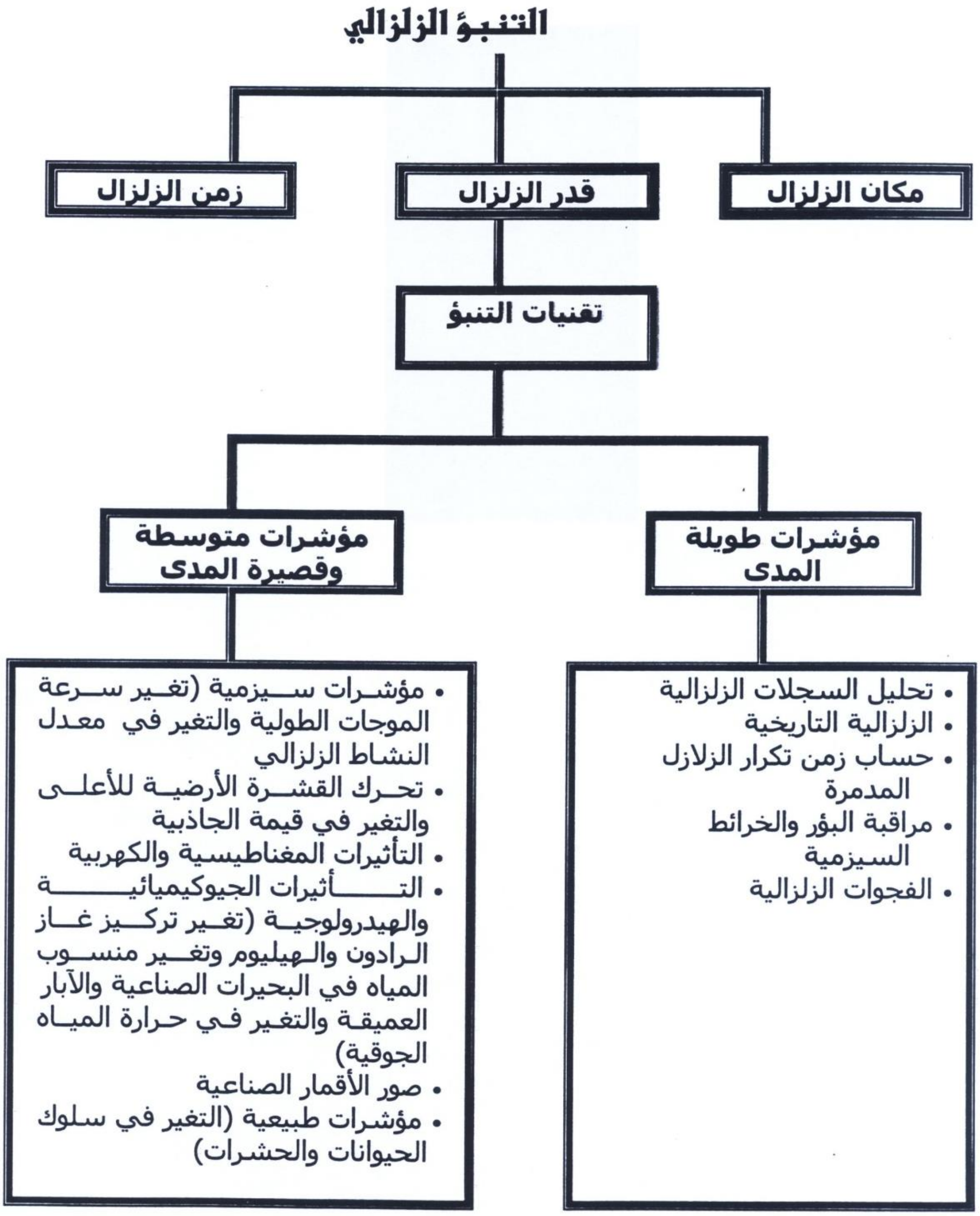
- The tilting and straining of earth near the point where an earthquake may start.
- Seismic primary velocities.
- The increase in small earthquakes.
- Changes in electrical properties of rocks .
- Fluctuations in the earth's magnetism.
- The emission of radon gas from wells.

6. REDUCING EARTHQUAKE RISK

One way to reduce vulnerability to earthquakes is by predicting their onset and evacuating inhabitants at risk. To do this the seismic hazards, that is such earthquake effects as surface rupturing , ground shaking, ground liquefaction, landsliding and flooding must first be evaluated. Surface rupturing should be considered likely in future earthquakes at any fault where there has been geologically recent movement.

Ground shaking is most intense near the rupturing fault decreasing with distance, but the local geology affect the intensity, for example soft sediments amplify shaking.

Soft sediments are also liable to liquefaction. They become quicksand depending on the nature of the sediment particles, their density of packing and content of pore water,coupled with the intensity and duration of shaking.



Landslides are a hazard, particularly in hilly or mountainous regions, after a heavy rain and where slopes are already unstable because of rock type or sparse vegetation.

Flooding from tsunamis is a hazard in coastal district; it may also result from ground level changes, from ponding up of rivers by earthquake-induced landslides or failure of dams.

After hazards have been identified a hypothetical earthquake, called the design earthquake, is selected for this area based on the largest earthquake thought possible on the longest active fault in the region and its likely frequency of occurrence. Seismic hazard zone maps can then be drawn up for land-use planning and building codes established.

Although the maps are far from perfect, they give valuable information on general regions of seismic activity. Up-to-date information is constantly being added on current strain and stresses. The seismicity risk studies for a particular site can be summarized in the following main points :

- **Geological Studies :**
  - Regional tectonics and patterns of deformation
  - Mapping of significant capable faults within 100 Km
  - Determination of fault types (normal , thrust.......)
  - Evidence for and against recent displacement along faults.
  - Field location of any landslide, ground settlement, or water inundation .
  - Field report on foundation soils and slope instability
- **Seismological Studies :**
  - Study of local historical earthquake records
  - Mapping of earthquake epicenters
  - Determination of earthquake intensity and magnitude - recurrence relations over time in the region.
  - Study of all historical intensity information near site.
  - Correlation of earthquake locations with mapped faults
  - Estimation of future seismic intensities(acceleration , velocity , duration).
  - Selection of strong-motion records from past earthquake that best represent the probable intensities.

Modeling of Seismic Zones

The empirical and theoretical correlational methods and distribution function that were applied in the western part of Saudi Arabia seismogenic source zones are similarly utilized for the eastern section. This approach is conducted to maintain uniformity and homogeneity of results.

The seismotectonic modeling of the seismogenic source zones of the Arabian Peninsula were based on the following empirical and theoretical correlations. The empirical correlation was taken from observation of earthquakes occurring in tectonic structures (Gubin 1967; Allen 1975). These are as follows:

1. Correlation between seismic and tectonic data

(a) Earthquakes do not occur everywhere, but only in definite tectonically active areas and in strong accordance with movement and deformation of geological structures. Globally, there were close relation between active faults and strong earthquakes, but the relations are not so strong in other areas characterized by less long term seismicity. The Earth is partitioned among large seismogenic and aseismogenic belts, which are apportioned further into smaller source zones. The seismogenic source zones have active faults at different depths, concealed in the depth or exposed on the surface. A seismogenic zone is therefore a main unit that determines the seismic conditions of a territory. The source zones are of different size and kind. In every zone occur earthquakes up to a definite value of the seismic parameters. These are due to varying size, degree of competency, and rate of movement, so that earthquakes correspondingly vary with the parameters.

(b) Major earthquakes occur along tectonically active source zones having large faults. The zones which divide geological units having different history of development and large difference in rates of movement are the most seismically active. The larger is the disturbed structure and the greater is its competency, the larger is the fault plane affected by the abrupt movements and the sronger will be the earthquake. Correspondingly, every group of homogeneously disturbed structure with definite competency and size has a definite ceiling of magnitude value. The more is the rate of structure movements along a fault and the less is the competency of these structures, the more rapidly the stress needed for an abrupt displacement of a structure along a fault is accumulated and the more often arise earthquakes of the maximum magnitude value for this structure. Every tectonically active source zone has its own rate of movement along it and corresponding frequency of earthquake occurrences.

(c) Geological structures move abruptly on faults along tectonically homogeneous active zone not simultaneously but alternatively in different places of the zones. Alternatively, in different places in this zone arise earthquake of maximum magnitude for this zone. When a source of an earthquake of certain maximum strength was recorded in this homogeneous active zone, then earthquake of the same strength can occur anywhere along this zone. In other word, the probability of such an earthquake can be extrapolated and interpolated along homogeneous tectonically active zones.

2. Correlation between Earthquake Frequency and Mechanics of Faulting

The geological interpretation of the mechanism of an earthquake could possibly have started by Lawson in 1908, which was translated by Reid (1910) into quantitative terms (Lomnitz 1987). The concept established the theoretical and physical correlation between occurrence of earthquakes and deformation of tectonic structures.

The most important parameter in mechanics of faulting as related to occurrence of a seismic event is the seismic moment Mo (Aki & Richards 1980; Burridge & Knopoff 1964; Keilis Borok 1959)

$$\mathbf{Mo = uAD = uLWD} \quad \mathbf{(1)}$$

where u is the rigidity, A is the fault plane area, L and W are the length and width of the fault respectively, and D is the displacement. The amplitude of the long period waves is proportional to the seismic moment. Since the surface magnitude (Ms) is calculated by measuring the amplitude of the long period wave, there exist a close relationship between Mo and Ms, and so with Mo, length and displacement arising from static similarity. For this study, the relationships are obtained empirically, which is a world-wide data collection of corresponding magnitude, moment, length, width and displacement. The empirical relationships that were obtained are as follows:

$$\mathbf{Log\ Mo = [(1.62 \pm 0.112)Ms + 15.1] \pm 0.3} \quad \mathbf{(2)}$$

$$\mathbf{Log\ Mo = [(2.54 \pm 0.087)Log\ L + 22.56] \pm 0.31} \quad \mathbf{(3)}$$

$$\mathbf{Log\ Mo = [(2.61 \pm 0.28)Log\ D + 26.32] \pm 0.44} \quad \mathbf{(4)}$$

From (2-4), the following equations can be obtained when the standard deviation and standard error of estimate are not incorporated

$$\mathbf{Log\ L = 0.64Ms - 2.94} \quad \mathbf{(5)}$$

$$\mathbf{Log\ D = 0.62Ms - 4.3} \quad \mathbf{(6)}$$

Equation (2) is within the range of values (1.5-1.7) as obtained by Kanamori (1977), Hanks & Kanamori 1979; Brune 1968; Scholz 1982; Wyss and Brune (1968), and others. Equations (5) and (6) are close to Matsuda (1975) results which are 0.6, 2.9: and 0.6, 4 for the coefficients and constants respectively. The rupture is assumed to take place in the entire length of the homogeneous part of the fault or portion for segmented fault. The constraining equations for the fault length, dislocation, and magnitude are from (2-4)

$$\mathbf{1.52LogD + 7.25 < Ms < 1.69LogD + 6.65} \quad \mathbf{(7)}$$

$$\mathbf{1.55LogL + 4.36 < Ms < 1.6LogL + 4.94} \quad \mathbf{(8)}$$

The magnitude frequency relation of earthquakes satisfies the empirical relation (Gutenberg & Richter 1954)

Log N = a – bMs (9)

where N is the number of magnitude Ms or greater, a and b the seismicity parameters. Equation (9) holds down to the level of micro-events (Mogi 1962; Scholz 1968) which indicates a fundamental physical understanding of the fracture process can be known if the relation can be explained completely. The Mo and Ms are both measures of the strength of an earthquake, so that (9) can be expressed in terms of Mo by means of (2). The theoretical consideration that the magnitude scale saturates at higher values of magnitude, but not with Mo is appropriate to substitute the seismic moment frequency relation for characterizing earthquake occurrences. From (2) and (9), a power law size distribution of earthquakes can be obtained (Wyss 1973)

N(Mo) = Amo$^{(-B)}$ (10)

A = exp[(a + bc/d)ln10]

B = b/d

where a and b, c and d are the constant and coefficient in (9) and (2) respectively. From Wyss (1973), the total moment of a given earthquake population is the integral

Mo(tot) = (AB/(1-B)[Mo$^{(1-B)}$] (11)

where the upper and lower limits of integration are Mo(max) and Mo(min) as the maximum and minimum seismic moment in a given earthquake population respectively. In (10) it is assumed that the Mo(max) is attained when N(Mo)=1, so that A=Mo^{B}. Likewise, in (9) the Mmax is also attained when N(M) =1. If Mo(min) is insignificant compared to Mo(max), (11) becomes approximately equal to

Mo(tot)= B/(1-B)Mo(max) (12)

From Wesnousky et al (1983), the repeat time (Tmax) of (11) is

T(max) = Mo(tot)/Mo(g) (13)

where Mo(g) is the geologically assessed rate of moment release on a fault.

In (6), the recurrence time (Tmax) of an event with dislocation D is

T(max) = D/S (14)

where S is the linear average seismic slip rate.

The geologically assessed rate of moment release is not available in eastern Saudi Arabia. To be able to utilize the concepts enunciated in (9-14) for the correlation of regional seismicity to tectonics, there was a need to treat the 3 set of seismic data (historical, instrumental, recent) into one group in each seismogenic source zone in terms of Ms, to obtain the required parameters. The conversion equation was (Al-Amri et al 1998; Al-Amri 1994)

Ms = 1.14 Mb -0.9 (15)

where Mb is the body-wave magnitude.

Wesnousky (1986) had indicated that the average geological moment release rate is almost the same as the average seismic moment release rate in 200-300 year of seismic data, and similar to the geological rate for 400 year of data. It is assumed then that the findings for seismic moment release rate have also the same similarities to the linear average seismic slip and or spreading rate. The period of observation in each source zone is counted from the earliest recorded year of the data up to 2003.

The geologically assessed rate of moment release is assumed to be equal to the ratio of the cumulative seismic moment release and period of observation. This assumption was also applied to obtain the linear average seismic slip or spreading rate. The average slip rate in each zone with sufficient seismic data could be compared to other findings obtained from different sources for validation. If the seismic slip rates are compatible to other results, presumably the seismic moment release rates would also qualify. When sufficient data are not available, the other alternatives could be to assume the applicability of the other parameters obtained in neighboring seismic source zones and or using (12).

The expected maximum magnitude in each seismogenic source zone is either taken from (9) [Mmax(S)], or the observed maximum magnitude Mmax(O) from the set of seismic data in each source zone, and or the estimated magnitude [Mmax(L)] from fault length of the existing fractures in each respective seismogenic source zone. The expected Mmax(S) and or Mmax(O) are then correlated to fault length in (5) or dislocation in (6), and the magnitude from crustal depth (H) which is given as

Mmax(H) = 4Log H + 1.8 **(16)**

The corresponding feasibilities in (5), (6), (9) and (16) could indicate possible association and characterization of the most likely source of the given earthquake population in each seismogenic source zone.

Earthquakes are not equally distributed in space-time, although probably the seismic events follow physical causalities which are not fully known. Therefore, at least the strongest earthquakes can be assumed to be independent random events. Considering the probability of occurrence of these seismic events in a time interval (t), and assuming the Poisson process as the appropriate probability function applicable in the source zones, then the probability of occurrence (Pr) of an event with return time (Tmax) is given as

Pr = 1-exp(-t/Tmax) **(17)**

Because there were different constraints encountered in the correlation processes such as scarcity of seismic data and inadequate information concerning fault parameters. It became necessary to refer to (17) as an additional data and basis in the decision processes. The time interval is assumed to be 100 years.

Slemmons (1981) had described a characterization scheme for fault rate activity. The classification is as follows: (a) fault not active; (b) hardly active; (c) well developed geomorphologically (medium to high); (d) high; (e) very high; and (f) extremely high. The basis of the classification was the inverse of the linear slip rate as the constant slope of a linear relation between recurrence time and dislocation (eq.14) which is expressed in terms of magnitude. For slip rate of 10 cm/yr, the fault rate of activity is extremely high for magnitude range 4.8-9, for slip rate of 1 cm/yr, the fault rate activity varies from extremely high to very high for the magnitude range 4.7-9, for slip rate 0.1 cm/yr, the fault rate activity also varies from extremely high-to very high- to high for the magnitude range 4.7-9, for slip rate 0.01 cm/yr, the fault rate activity varies from very high- to high- to medium high for the magnitude range 4.7-9, and for slip rate 0.001 cm /yr, the fault rate activity varies from high-to medium high-to hardly active - to fault not active for the magnitude range 4.7-9..

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Earthquake Glossary

acceleration. When you step on the accelerator in the car or put on the brakes, the car goes faster or slower. When it is changing from one speed to another, it is accelerating (faster) or decelerating (slower). This change from one speed, or velocity, to another is called acceleration. During an earthquake when the ground is shaking, it also experiences acceleration.

active fault. A fault that is likely to have another earthquake sometime in the future. Faults are commonly considered to be active if they have moved one or more times in the last 10,000 years.

aftershocks. Earthquakes that follow the largest shock of an earthquake sequence. They are smaller than the mainshock and within 1-2 fault lengths distance from the mainshock fault. Aftershocks can continue over a period of weeks, months, or years. In general, the larger the mainshock, the larger and more numerous the aftershocks, and the longer they will continue.

amplification. Most earthquakes are relatively small, in fact, so small that no one feels them. In order for seismologists to see the recording of the movement of the ground from the smaller earthquakes, the recording has to be made larger. It's like looking at the recording through a magnifying glass, and the amount that it is magnified is the amplification. Shaking levels at a site may also be increased by focusing of seismic energy caused by the geometry of the sediment velocity structure, such as basin subsurface topography, or by surface topography.

attenuation. When you throw a pebble in a pond, it makes waves on the surface that move out from the place where the pebble entered the water. The waves are largest where they are formed and gradually get smaller as they move away. This decrease in size, or amplitude, of the waves is called attenuation.

creep. Slow, more or less continuous movement occurring on faults due to ongoing tectonic deformation. Faults that are creeping do not tend to have large earthquakes.

displacement. The difference between the initial position of a reference point and any later position. The amount any point affected by an earthquake has moved from where it was before the earthquake.

earthquake. This term is used to describe both sudden slip on a fault, and the resulting ground shaking and radiated seismic energy caused by the slip, or by volcanic or magmatic activity, or other sudden stress changes in the earth.

earthquake hazard. Anything associated with an earthquake that may affect the normal activities of people. This includes surface faulting, ground shaking, landslides, liquefaction, tectonic deformation, tsunamis, and seiches.

earthquake risk. The probable building damage, and number of people that are expected to be hurt or killed if a likely earthquake on a particular fault occurs. Earthquake risk and earthquake hazard are occasionally used interchangeably.

epicenter. The point on the earth's surface vertically above the point in the crust where a seismic rupture begins.

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

foreshocks. Foreshocks are relatively smaller earthquakes that precede the largest earthquake in a series, which is termed the mainshock. Not all mainshocks have foreshocks.

ground failure. A general reference to landslides, liquefaction, lateral spreads, and any other consequence of shaking that affects the stability of the ground.

ground motion (shaking). The movement of the earth's surface from earthquakes or explosions. Ground motion is produced by waves that are generated by sudden slip on a fault or sudden pressure at the explosive source and travel through the earth and along its surface.

intensity. A number (written as a Roman numeral) describing the severity of an earthquake in terms of its effects on the earth's surface and on humans and their structures. Several scales exist, but the ones most commonly used in the United States are the Modified Mercalli scale and the Rossi-Forel scale. There are many intensities for an earthquake, depending on where you are, unlike the magnitude, which is one number for each earthquake.

landslide. The downslope movement of soil and/or rock.

liquefaction. A process by which water-saturated sediment temporarily loses strength and acts as a fluid, like when you wiggle your toes in the wet sand near the water at the beach. This effect can be caused by earthquake shaking.

magnitude. A number that characterizes the relative size of an earthquake. Magnitude is based on measurement of the maximum motion recorded by a seismograph. Several scales have been defined, but the most commonly used are (1) local magnitude (ML), commonly referred to as "Richter magnitude," (2) surface-wave magnitude (Ms), (3) body-wave magnitude (Mb), and (4) moment magnitude (Mw). Scales 1-3 have limited range and applicability and do not satisfactorily measure the size of the largest earthquakes. The moment magnitude (Mw) scale, based on the concept of seismic moment, is uniformly applicable to all sizes of earthquakes but is more difficult to compute than the other types. All magnitude scales should yield approximately the same value for any given earthquake.

mainshock. The largest earthquake in a sequence, sometimes preceded by one or more foreshocks, and almost always followed by many aftershocks.

microzonation. The identification of separate individual areas having different potentials for hazardous earthquake effects.

percent "g". G or g is the force of gravity. When there is an earthquake, the forces caused by the shaking can be measured as a percentage of the force of gravity, or percent g.

Poisson distribution. A probability distribution that characterizes discrete events occurring independently of one another in time.

recurrence interval. The average time span between large earthquakes at a particular site. Also termed return period.

seismic gap. A section of a fault that has produced earthquakes in the past but is now quiet. For some seismic gaps, no earthquakes have been observed historically, but it is believed that the fault segment is capable of producing earthquakes on some other basis, such as plate-motion information or strain measurements.

seismic zone. An area of seismicity probably sharing a common cause. Example: "The New Madrid Seismic Zone."

shear stress. The stress component parallel to a given surface, such as a fault plane, that results from forces applied parallel to the surface or from reinote forces transmitted through the surrounding rock. If you lean against the edge of the door where the latch is, you are applying shear stress to the door.

spectral acceleration or SA. PGA (peak acceleration) is what is experienced by a particle on the ground. SA is approximately what is experienced by a building, as modeled by a particle on a massless vertical rod having the same natural period of vibration as the building.

strong motion. Ground motion of sufficient amplitude and duration to be potentially damaging to a building or other structure.

surface faulting. Displacement that reaches the earth's surface during slip along a fault. Commonly occurs with shallow earthquakes, those with an epicenter less than 20 km. Surface faulting also may accompany aseismic creep or natural or man-induced subsidence.

surface wave. Seismic wave that travels along the earth's surface. Love and Rayleigh waves are the most common.