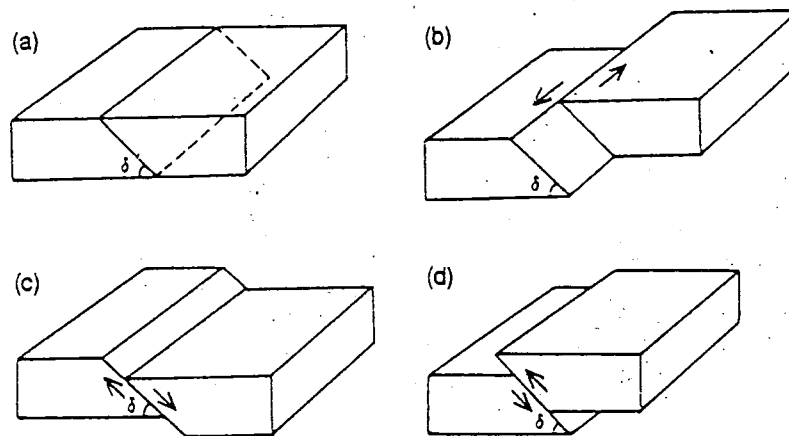


# EARTHQUAKES AND VOLCANOES

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## What is an earthquake?

An earthquake is a sudden movement or trembling of the Earth caused by the abrupt release of slowly accumulated stress on a fault. A fault is a fracture plane along which rocks are displaced (Figure 1). An earthquake occurs as the result of a slow build-up of strain in rocks, usually caused by the relative motion along a fault. When a fault or volume of rock can no longer resist movement, the stored elastic strain energy is suddenly released, causing an earthquake. The mechanism of an earthquake can be explained by a simple model called **elastic rebound theory** (Figure 2).



**Figure 1.** Different types of faults in the Earth. Earthquakes generally occur along faults. (a) Before faulting, (b) strike-slip fault, (c) normal fault, (d) reverse fault.

This model is diagrammatically shown in Figure 2. Over time, one side (L) of the fault is displaced relative to the other side (R). The deformation (change in form or shape) continues until the stresses (forces per unit area) on the fault are large enough to overcome the friction (frictional bond is broken) between the two blocks (L, R) of material; then an earthquake (sudden displacement or rupture) occurs (Figure 2d), and the strain is released as energy. Thus, the size of the earthquake is directly related to the friction in the fault.

The sudden displacement or rupture begins at a point, which is called the earthquake focus (Figure 2c, 3). The point on the Earth's surface immediately above the earthquake focus (location of the earthquake within the Earth) is called the earthquake epicentre (Figure 3). Once the rupture begins, it travels at a speed of about 3.5 kilometres per second (7200 miles per hour), continuing for as much as 100 kilometres. In large earthquakes, the slip, or displacement, of the two blocks (Figure 2 d) can be as large as 15 metres. Once the frictional bond is broken, the elastic energy, which had been slowly accumulated over tens or hundreds of years, is suddenly released in the form of intense seismic vibrations (within a few minutes), which constitute the earthquake. These vibrational waves are propagated large distances in all directions from the fault. Destructions occur due to this vibrational energy and due to the displacement along the fault. An example of displacement caused by an earthquake is shown in Figure 4.

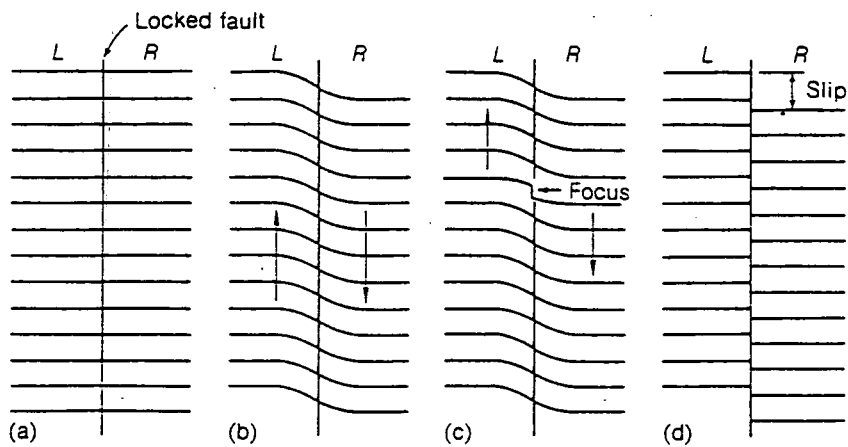


Figure 2. The elastic rebound theory of an earthquake. The two simulated crustal blocks, L and R, are being forced to slide past each other (a). Friction along the fault prevents slip (b), but the deformation builds up until the frictional lock is broken (c) and earthquake slip occurs (d).

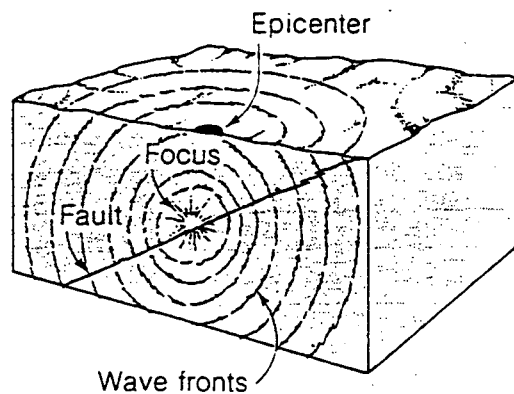


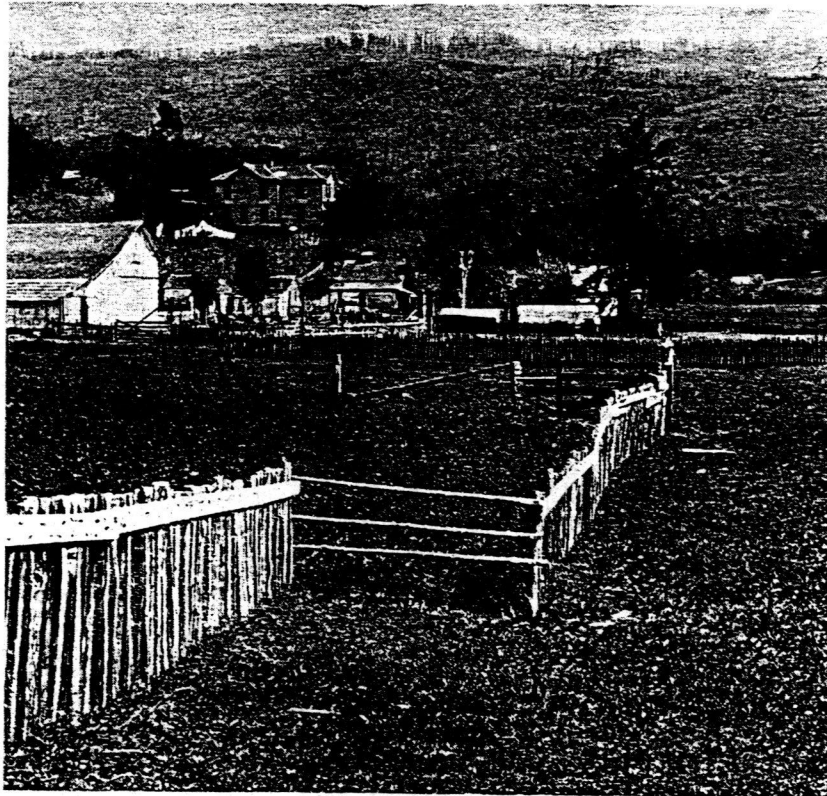
Figure 3. The focus of an earthquake is the site of the initial slip on the fault. The epicentre is the point on the surface above the focus. Seismic waves radiate from the focus.

The elastic strain energy released during an earthquake propagates as seismic waves. Energy release gives the most precise measure of the size of an earthquake. The magnitude of an earthquake is given by the “Richter magnitude scale”, which is based on the amplitude of seismic waves recorded by instruments called seismographs. Table 1 gives magnitude of earthquakes, energies, effects and other related statistics. In 1935 C.F. Richter, a seismologist, studied the local earthquakes in southern California and proposed a particular logarithmic magnitude scale for them. A number of other logarithmic magnitude scales for earthquakes have been proposed, all of which are based on measurements of the amplitude of the seismic waves. All the magnitude scales are of the following form:

$$M = \log_{10}\left(\frac{A}{T}\right) + q(\Delta, h) + a \quad (1)$$

where  $M$  is the magnitude,  $A$  the maximum amplitude of the wave (in  $10^{-6}$  metres),  $T$  the period of the wave (in seconds),  $q$  a function correcting for the decrease of amplitude of the wave with distance from the epicentre and focal depth,  $\Delta$  the angular distance from seismometer to epicentre,  $h$  the focal depth (depth to the focus) of the earthquake, and  $a$  an empirical constant.

Seismic waves are generally of two major types. These are body waves and surface waves. Body waves travel through the body of the Earth, and their propagation is similar to that of light. Body waves are reflected and transmitted at interfaces where the seismic velocity and/or density change, and they obey Snell's law. There are two types of body waves (Figure 5): (1) P-waves or primary waves (compressional waves) and (2) S-waves or secondary waves (shear waves). P waves can travel through any medium (solid or liquid), whereas S-wave travels only through solid medium (S-wave does not propagate through liquids). P- and S-waves are very important in understanding the deep interior of the Earth.



**Figure 4.** A fault formed during an earthquake that occurred in America. Note that the fence is displaced by the fault.

Seismic waves are very important in the study of the interior of the Earth, which is illuminated by seismic rays radiating outward in all directions from the large number of earthquakes that occur in tectonically active regions (e.g. subduction zones, mid-oceanic ridges or rift zones and transform faults) of the world. The wave fronts generated at right angles to these ray paths are reflected and refracted by discontinuities and gradients in material properties in the interior of the Earth and are recorded at seismic stations on its surface. From analysis of such waves seismologists have divided the Earth into core, mantle and crust and into numerous smaller subdivisions such as inner core, outer core, upper mantle, transition region and lower mantle (see course notes on "Interior of the Earth").

P-wave and S-wave velocities depend on the physical properties (density and elastic moduli) of the material through which the wave travel (equations 2 and 3). The seismic velocities of P-wave and S-wave are calculated according to the following equations:

$$\text{seismic velocity of P-waves} = v_p = \sqrt{\frac{K + \frac{4}{3}\mu}{\rho}} \quad (2)$$

$$\text{seismic velocity of S-waves} = v_s = \sqrt{\frac{\mu}{\rho}} \quad (3)$$

where  $K$  is the bulk modulus or incompressibility,  $\mu$  the shear modulus or rigidity and  $\rho$  the density of the material.

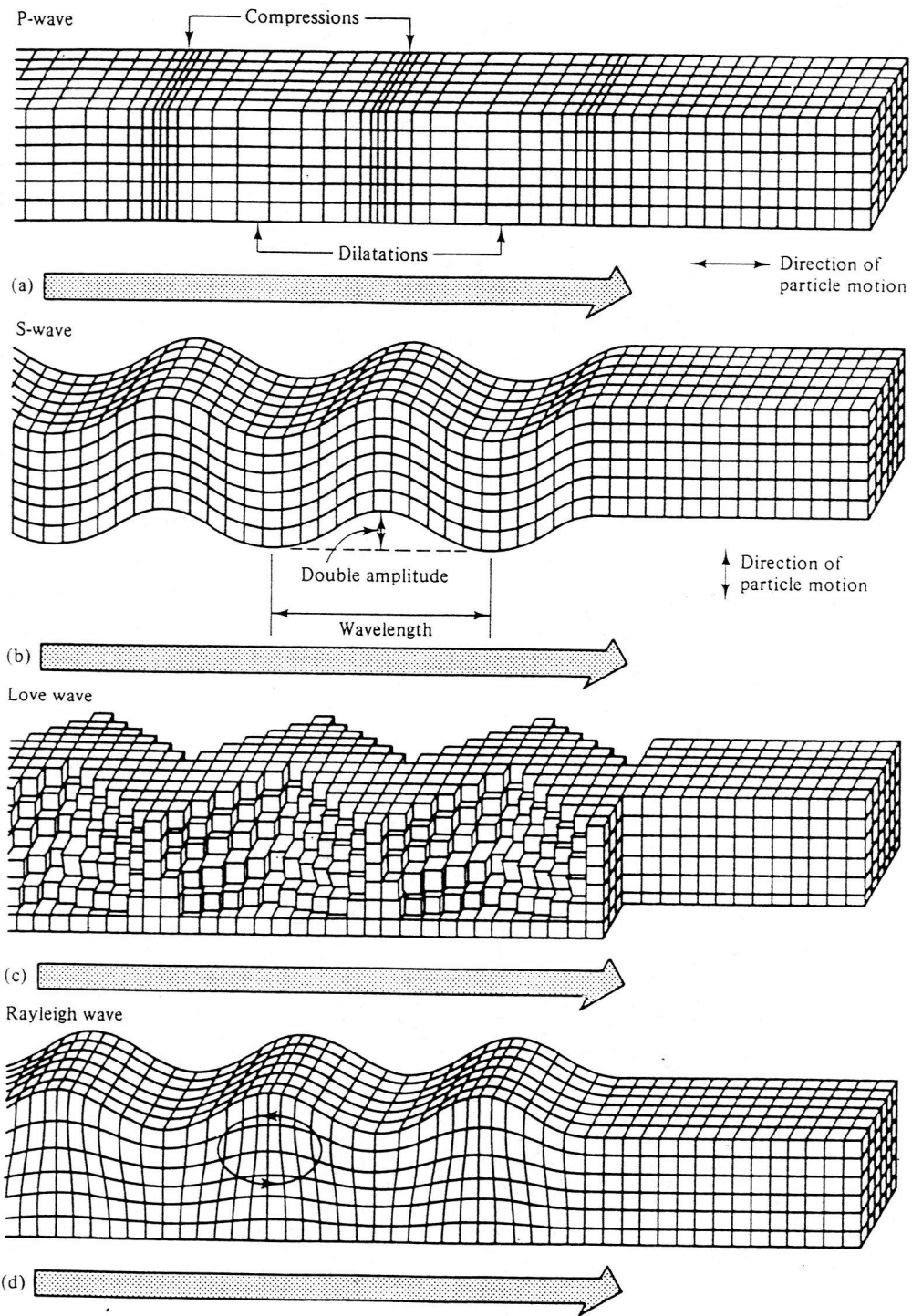
**Table 1.** Magnitude, energies, effects and other related statistics of earthquakes.

Characteristic Effects Of Shallow Shocks In Populated Areas	Approximate Magnitude	No. Earthquakes Per Year	Energy (Ergs)
Damage near total	≥8.0	0.1-0.2	>10 <sup>25</sup>
Great damage	≥7.4	4	≥0.4x10 <sup>24</sup>
Serious damages	7.0-7.3	15	0.04-0.02x10 <sup>24</sup>
Considerable damage to buildings	6.2-6.9	100	0.5-23x10 <sup>21</sup>
Slight damage to building	5.5-6.1	500	1-27x10 <sup>19</sup>
Felt by all	4.9-5.4	1,400	3.6-5.7x10 <sup>17</sup>
Felt by many	4.3-4.8	4,800	1.3-27x10 <sup>16</sup>
Felt by some	3.5-4.2	30,000	1.6-76x10 <sup>15</sup>
Not felt but recorded	2.0-3.4	800,000	4x10 <sup>10</sup> -9x10 <sup>13</sup>

The surface waves are seismic waves which are guided along the surface of the Earth and the layers near the surface. They do not penetrate into the deep interior of the Earth. Surface waves are generated best by shallow earthquakes. Nuclear explosions do not generate comparable surface waves, and this important fact is the basis for one criterion of discrimination between earthquakes and nuclear explosions. There are two types of surface waves: (I) Love waves and (ii) Rayleigh waves (Figure 5).

### Where do earthquakes occur?

As already mentioned earlier, earthquakes are always associated with faults. Figure 1 illustrates different faults occurring in the Earth. Faults generally occur in association with major plate boundaries (see course note on "Plate Tectonics"). This means that earthquakes should occur along all types of plate boundaries of the world. Almost all the epicentres of earthquakes occurring in the world follow plate boundaries (Figures 6, 7) such as rift zones and mid-oceanic ridges, subduction zones and transform faults (Figure 7).



**Figure 5.** The forms of the motion and ground deformation due to (a) P-waves, (b) S-waves, (c) Love waves and (d) Rayleigh waves.

As shown in Figure 1, there are three major types of faults. These are (i) normal faults (ii) reverse faults and (iii) strike-slip faults. Normal faults are associated with rift zone and mid-oceanic ridges. Reverse faults originate at subduction zones, and strike-slip faulting occurs along transform faults. The association of earthquakes with three types of plate boundaries is shown in Figure 7.

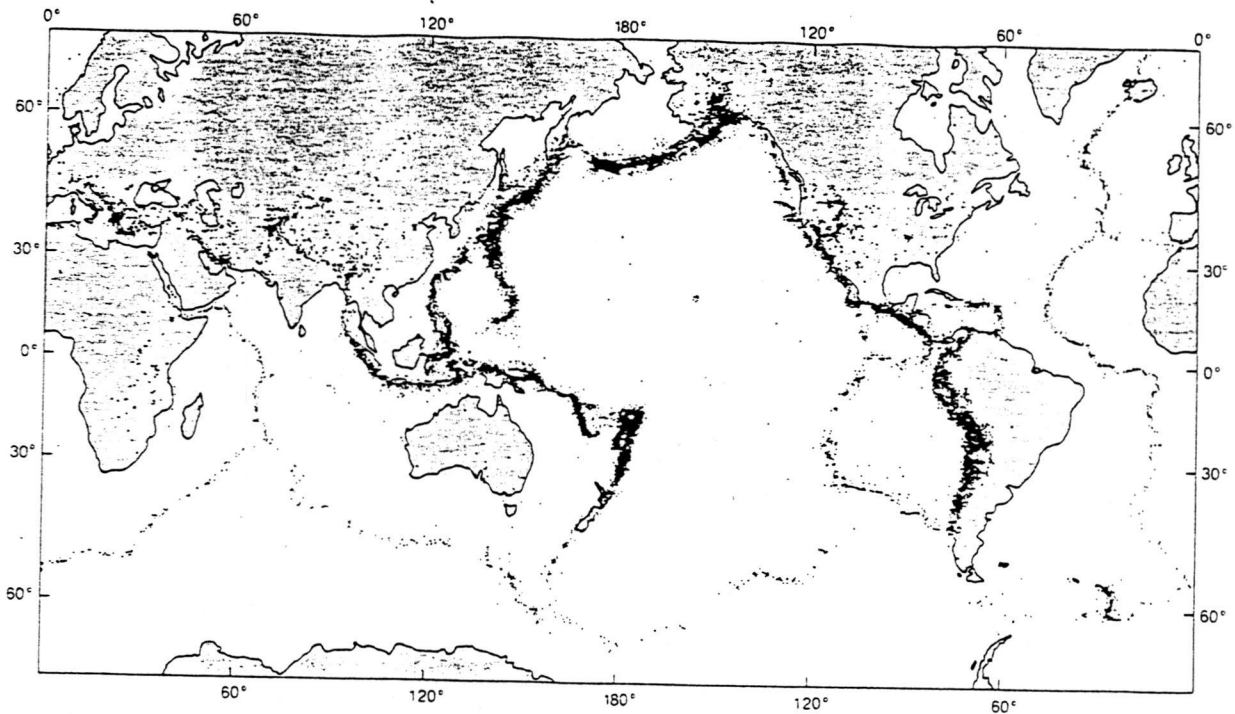


Figure 6. Epicentres of some earthquakes with focal depths between 0 and 700 km.

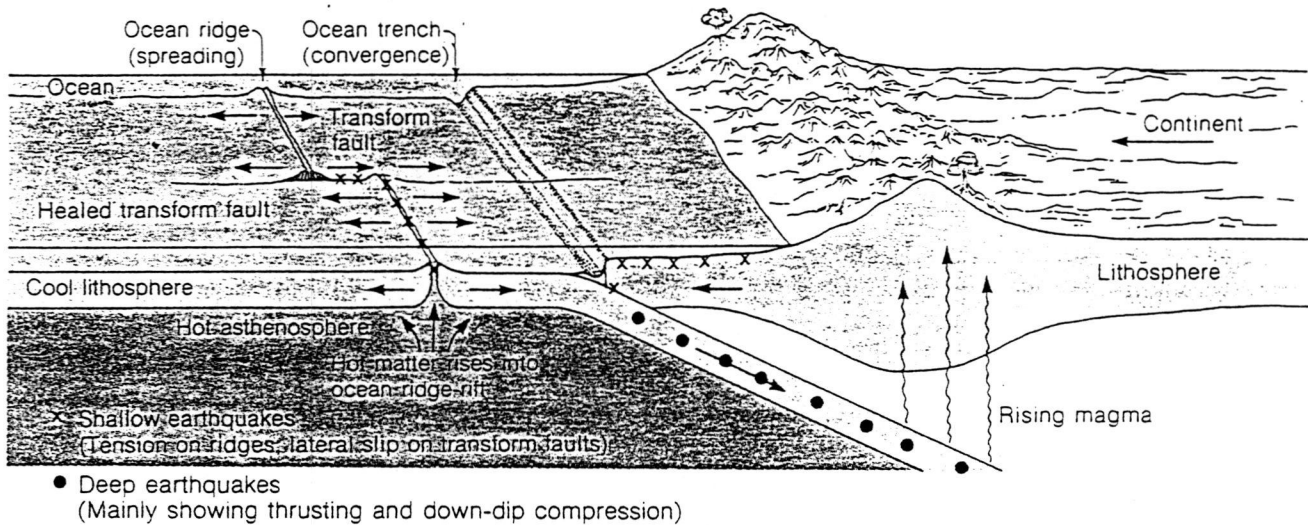
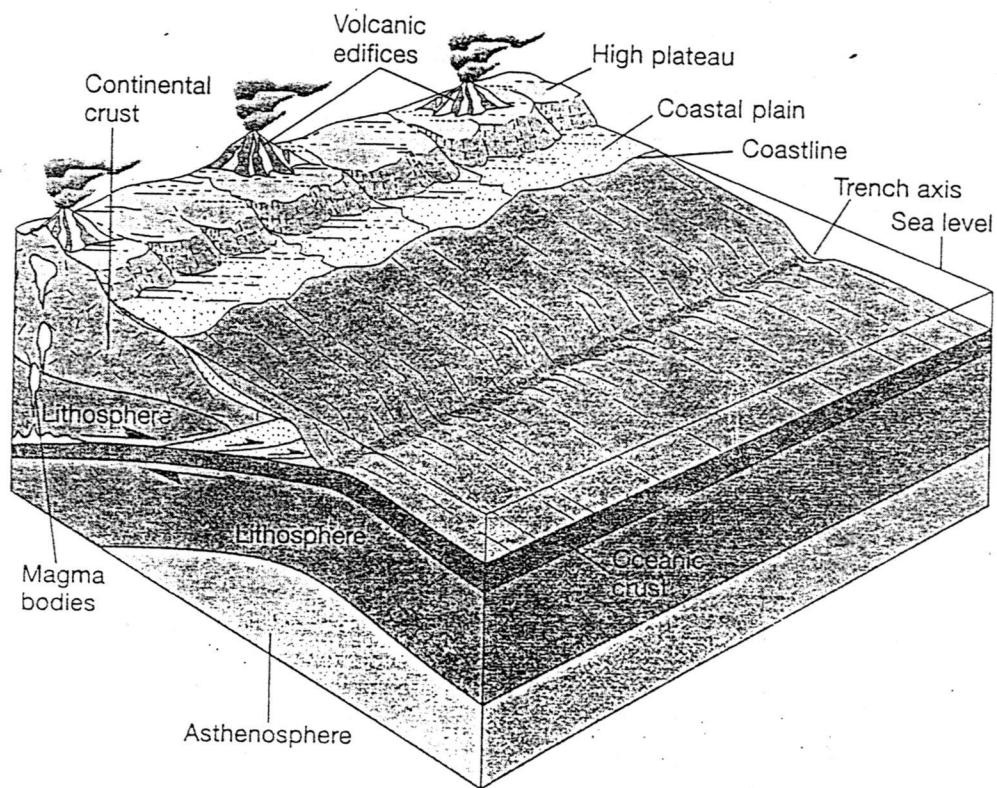


Figure 7. The association of earthquakes with three types of plate boundaries: oceanic ridges, transform faults and subduction zones.

### What are volcanoes?

As depth increases, both temperature and pressure increase in the interior of the Earth. This increase in temperature and pressure causes melting of the rocks inside the Earth, producing molten material called "magma". Generally, magma rises upwards along low pressure zones in the Earth and may erupt at the surface as lave (molten material, which cools to

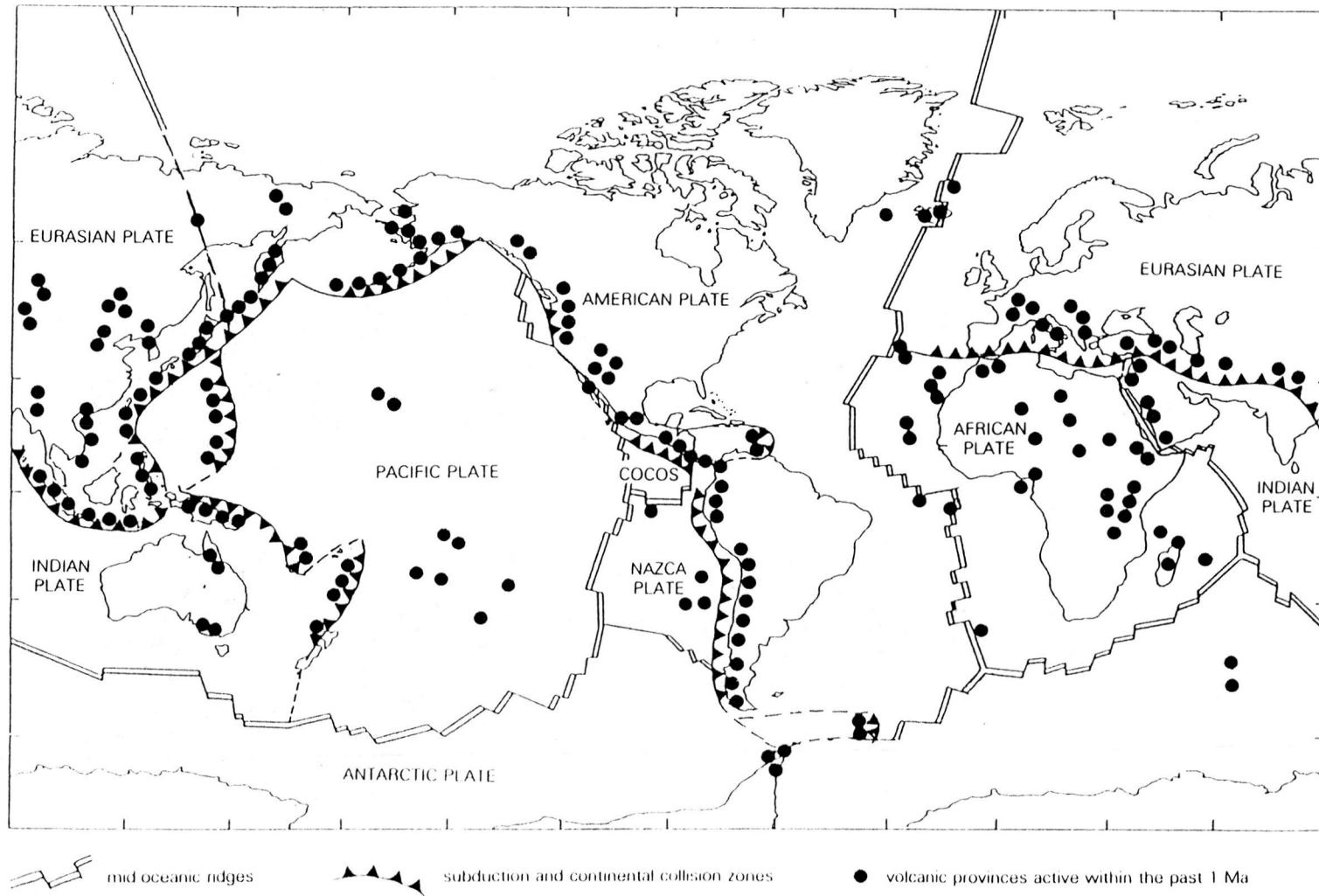
form volcanic rocks). Geological features where lava erupts under pressure at the surface of the Earth are called "volcanoes" (Figure 8). If magma cools and crystallizes inside the Earth, intrusive rocks form.



**Figure 8.** Generalized block diagram of a convergent (subduction zone) continental margin, showing volcanoes.

### Where do volcanoes occur?

Generally, melting of rocks takes place at plate boundaries, especially at subduction zones and mid-oceanic ridges (see course note on "Plate Tectonics and Continents"). Therefore, these structures are the best locations for volcanic activities (Figures 8, 9). Two types of volcanoes have been recognized; (i) volcanoes related to plate boundaries and (ii) intra-plate (within oceanic and continental plates) volcanoes (these are called hot spots). Volcanoes in Japan and in western America are the best examples for plate boundary-related volcanoes, and those in Hawaiian islands are intra-plate volcanoes or hot spots. Magma supplied to the first type of volcanoes generates at plate boundaries such as mid-oceanic ridges and subduction zones whereas that for the second type originates at greater depth in the mantle of the Earth. Volcanism has contributed enormous amounts of water, carbon dioxide and other gases to the atmosphere and materials to the continents.



**Figure 9.** Global tectonic map showing the distribution of present-day volcanic activity.