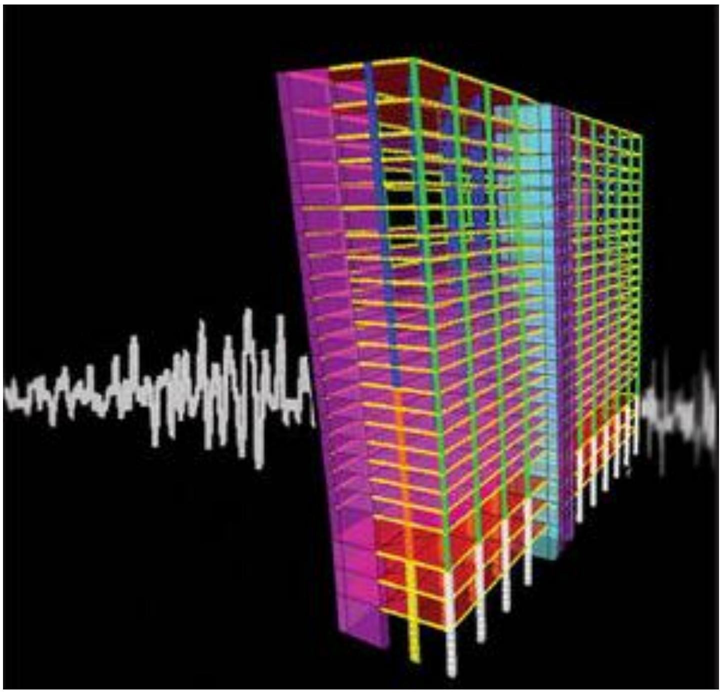
EARTHQUAKE ENGINEERING



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1. INTODUCTION

Our objective in earthquake engineering teaching is to improve the state of knowledge, through fundamental and applied teaching, for the purpose of aiding decision makers in reducing seismic hazards. Decision makers is defined as all individuals and agencies that affect the planning and design/construct process, such as planning or regulatory agencies, owners, investors and insurers, and engineers who have to provide protection against seismic hazards through earthquake resistant design.

Earthquake engineering is a multi-phased process that ranges from the description of earthquake sources, to characterization of side effects and structural response, and to description of measures of seismic protection.

2. THE NATURE OF EARTHQUAKE GROUND MOTION (This Dynamic Earth)

The aim of this Section is to provide a basic understanding about earthquakes, their world-wide distribution, what causes them, their likely damage mechanisms, earthquake measuring scales, and current efforts on the prediction of strong seismic ground motions. This Corse, therefore, furnishes the basic information necessary for understanding the more detailed concepts of Earthquake Engineering. The basic vocabulary of seismology is defined. The seismicity of the world is discussed first and its relationship with tectonic plates is explained. The general causes of earthquakes are discussed next where tectonic actions, militancy in the crustal rocks, explosions, collapses, volcanic actions, and other likely causes are introduced. Earthquake fault sources are discussed next. Various faulting mechanisms are explained followed by a brief discussion of seismic waves. Earthquake damage mechanisms are introduced and different major damage mechanisms are identified by examples. Quantification of earthquakes is of significant interest to seismic design engineers. Various earthquake intensity and magnitude scales are defined followed. Basic information regarding the concepts of directivity and near-fault effects are presented. Finally, the ideas behind seismic risk evaluation and earthquake prediction are discussed.

2.1 INTRODUCTION

On the average, 10,000 people die each year from earthquakes (see Figure 2-1). A UNESCO study gives damage losses amounting to $10,000,000,000 from 1926 to 1950 from earthquakes. In Central Asia in this interval two towns and 200 villages were destroyed. Since then several towns including Ashkhabad (1948), Agadir (1960), Skopje (1963), Managua (1972), Gemona (1976), Tangshan (1976), Mexico City (1985), Spitak (1988), Kobe (1995), cities in Turkey and Taiwan (1999) and hundreds of villages have been severely damaged by ground shaking. Historical writings testify to man's long concern about earthquake hazards. The first modern stimulus for scientific study of earthquakes came from the extensive field work of the Irish engineer, Robert Mallett, after the great Neopolitan earthquake of 1857 in southern Italy. He set out to explain the "masses of dislocated stone and mortar" in terms of mechanical principles and in doing so established basic vocabulary such as seismology, hypocenter and isoseismic. Such close links between engineering and seismology have continued ever since. It is part of strong motion seismology to explain and predict the large amplitude-long duration shaking observed in damaging earthquakes. In the first sixty years of the century, however, the great seismological advances occurred in studying waves from distant earthquakes using very sensitive seismographs. Because the wave amplitudes in even a nearby magnitude 5 earthquake would exceed the dynamic range of the usual seismographs, not much fundamental work was done by seismologists on the rarer large earthquakes of engineering importance. Nowadays, the situation has changed. After the 1971 San Fernando earthquake, hundreds of strong-motion records were available for this magnitude 6.5 earthquake. The 1.2g recorded at Pacoima Dam led to questions on topographic amplification and the construction of realistic models of fault-rupture and travel-path that could explain the strong motion patterns. Progress on these seismological questions followed rapidly in studies of variation in ground motions in the 1989 Loma Prieta earthquake (M 7.0), the 1994 Northridge earthquake (M 6.8) and the 1999 Chi Chi event in Taiwan (M 7.6). A harvest of strong motion recordings was obtained in the latter earthquake, showing numerous horizontal peak accelerations in the range 0.5g to 1.0g. Digital recorders and fast computers mean that both seismologists and engineers can tackle more fundamental and realistic problems of earthquake generation and ground shaking. Knowledge of strong ground shaking is now advancing rapidly, largely because of the growth of appropriately sited strong-motion accelerographs in seismic areas of the world. For example, in the Strong Motion Instrumentation Program in California, by the year 2000 there were 800 instruments in the free-field and 130 buildings and 45 other structures instrumented. Over 500 records had been digitized and were available for use in research or practice. In earthquake-prone regions, structural design of large or critical engineered structures such as high-rise buildings, large dams, and bridges now usually involves quantitative dynamic analysis; engineers ask penetrating questions on the likely seismic intensity for construction sites and require input motions or spectra of defining parameters. Predicted seismograms (time-histories) for dynamic modeling in structural design or vulnerability assessments are often needed. The aim of this section is to provide a basic understanding about earthquakes, their worldwide distribution, what causes them, their likely damage mechanisms, earthquake measuring scales, and current efforts on the prediction of strong seismic ground motions.

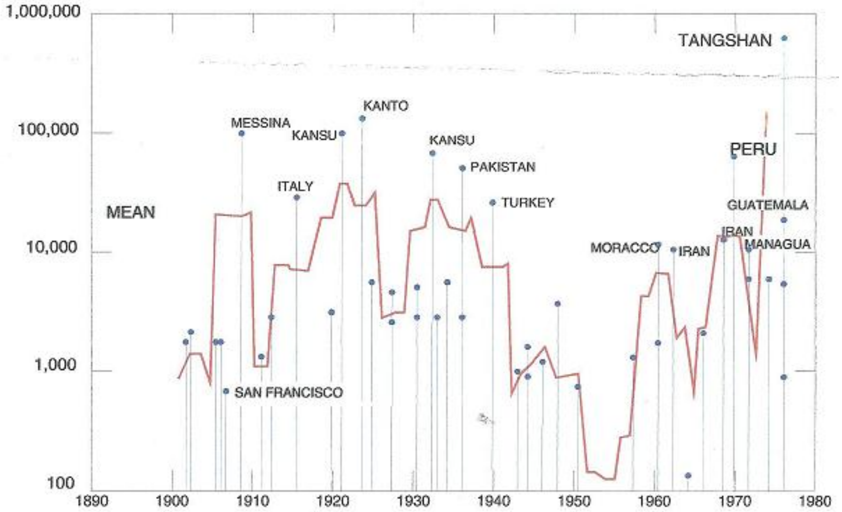


Fig. (2-1): Loss of life caused by major earthquakes

2.2 SEISMICITY OF THE WORLD

From the earthquake wave readings at different seismographic observatories, the position of the center of an earthquake can be calculated. In this way, a uniform picture of earthquake distribution around the world has been obtained (see Figure 2-2). Definite belts of seismic activity separate large oceanic and continental regions, themselves mainly, but by no means completely, devoid of earthquake centers. Other concentrations of earthquake sources can be seen in the oceanic areas, for example, along the center of the Atlantic and Indian Oceans. These are the sites of gigantic submarine mountain ranges called mid-oceanic ridges. The geological strains that prevail throughout this global ridge system are evidenced by mountain peaks and deep rift valleys. Volcanic eruptions are frequent, and earthquakes originating along these ridges often occur in swarms, so that many hundreds of shocks are concentrated in a small area in a short time. Dense concentrations of earthquake centers with some as much as 680 kilometers beneath the surface also coincide with island arcs, such as those of the Pacific and the eastern Caribbean. On the western side of the Pacific Ocean, the whole coast of Central and South America is agitated by many earthquakes, great and small. High death tolls have ensued from the major ones. In marked contrast, the eastern part of South America is almost entirely free from earthquakes, and can be cited as an example of low seismic risk country. Other seismically quiet continental areas can be seen in Figure (2-2). In Europe, earthquake activity is quite widespread.

To the south, Turkey, Greece, Yugoslavia, Italy, Spain and Portugal suffer from it, and large numbers of people have died in disasters throughout the years. An earthquake off southwest Iberia on November 1, 1755 produced a great tsunami, which caused many of the 50,000 to 70,000 deaths occurring in Lisbon, Portugal, and surrounding areas; the shaking was felt in Germany and the Netherlands. In Alicante, Spain, on March 21, 1829, a shock killed about 840 persons and injured many hundred more.

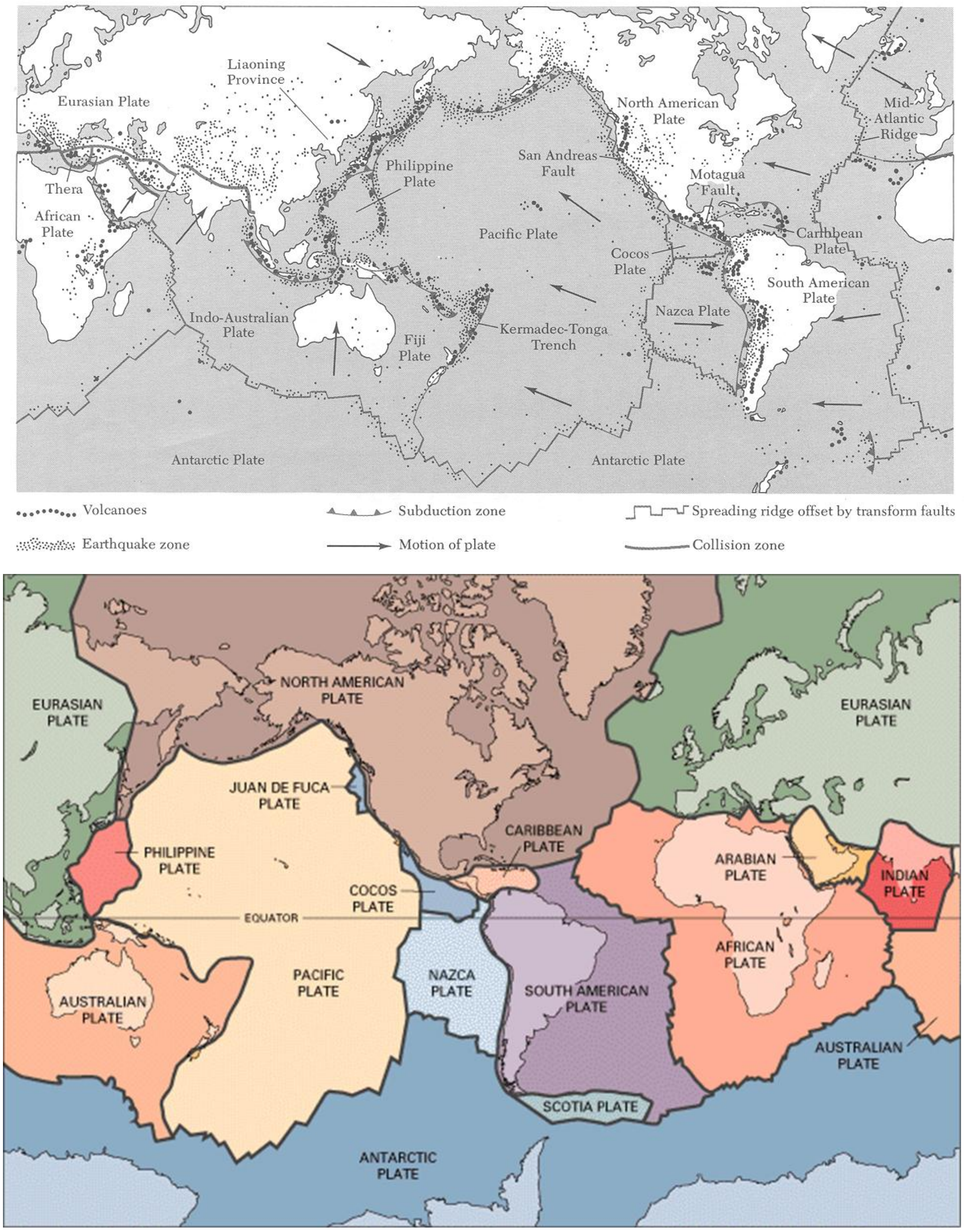


Fig. (2-2): Tectonic plates and world-wide distribution of earthquakes

Total or partial destruction of more than 5,000 houses was reported in and near Torrevieja and Murcia. On December 28, 1908, a devastating earthquake hit Messina, Italy, causing 120,000 deaths and widespread damage. The most recent deadly one to affect that country struck on May 6, 1976, in the Friuli region near Gemona; about 965 persons were killed and 2280 injured. On December 27, 1939, in Erzincan, Turkey, 23,000 lives were lost from a major earthquake. Similar killer earthquakes have occurred in Turkey and Iran in recent years. The Erzincan earthquake along the Anatolian fault in Turkey on March 13, 1992 caused many building collapses and the June 21, 1990 earthquake (M 7.3) devastated two Iranian provinces, Gilan and Zanjan. August 17, 1999 saw a 50 km rupture of the north Anatoliam fault along the Marmara Sea south of Izmit producing a magnitude 7.4 earthquake and over 16,000 deaths. North of the Mediterranean margin, Europe is much more stable. However, destructive earthquakes do occur from time to time in Romania, Germany, Austria and Switzerland, and even in the North Sea region and Scandinavia. For example, on October 8, 1927, an earthquake occurred near Schwadorf in Austria and caused damage in an area southeast of Vienna. This earthquake was felt in Hungary, Germany, and Czechoslovakia at distances of 250 kilometers from the center of the disturbance. The seismicity in the North Sea is sufficiently significant to require attention to earthquake resistant design of oil platforms there. In Africa, damaging earthquakes have occurred in historical times. A notable case was the magnitude 5.6 earthquake on November 14, 1981 that was felt in Aswan, Egypt. This earthquake was probably stimulated by the impounding of water in Lake Nassar behind the high Aswan Dam. An example of infrequent and dispersed seismicity is the occurrence of earthquakes in Australia. Nevertheless, this country does have some areas of significant present-day seismicity. Of particular interest is a damaging earthquake of moderate size that was centered near Newcastle and causing major damage and killing fourteen people. It was a surprise from a seismological point of view because no fault maps were available which showed seismogenic geological structures near Newcastle. During an earthquake, seismic waves radiate from the earthquake source somewhere below the ground surface as opposite sides of a slipping fault rebound in opposite directions in order to decrease the strain energy in the rocks. Although in natural earthquakes this source is spread out through a volume of rock, it is often convenient to imagine a simplified earthquake source as a point from which the waves first emanate. This point is called the earthquake focus. The point on the ground surface directly above the focus is called the earthquake epicenter. Although many foci are situated at shallow depths, in some regions they are hundreds of kilometers deep. Such regions include the

South American Andes, the Tonga Islands, Samoa, the New Hebrides chain, the Japan Sea, Indonesia, and the Caribbean Antilles. On the average, the frequency of occurrence of earthquakes in these regions declines rapidly below a depth of 200 kilometers, but some foci are as deep as 680 kilometers. Rather arbitrarily, earthquakes with foci from 70 to 300 kilometers deep are called intermediate focus and those below this depth are termed deep focus. Some intermediate and deep focus earthquakes are located away from the Pacific region, in the Hindu Kush, in Romania, in the Aegean Sea and under Spain. The shallow-focus earthquakes (focus depth less than 70 kilometers) wreak the most devastation, and they contribute about three quarters of the total energy released in earthquakes throughout the world. In California, for example, all of the known earthquakes to date have been shallow-focus. In fact, it has been shown that the great majority of earthquakes occurring in central California originate from foci in the upper five kilometers of the Earth, and only a few are as deep as even 15 kilometers. Most moderate to large shallow earthquakes are followed, in the ensuing hours and even in the next several months, by numerous, usually smaller earthquakes in the same vicinity. These earthquakes are called aftershocks, and large earthquakes are sometimes followed by incredible numbers of them. The great Rat Island earthquake in the Aleutian Island on February 4, 1965 was, within the next 24 days, followed by more than 750 aftershocks large enough to be recorded by distant seismographs. Aftershocks are sometimes energetic enough to cause additional damage to already weakened structures. This happened, for example, a week after the Northridge earthquake of January 17, 1994 in the San Fernando Valley when some weakened structures sustained additional cracking from magnitude 5.5 aftershocks. A few earthquakes are preceded by smaller foreshocks from the source area, and it has been suggested that these can be used to predict the main shock.

2.3 CAUSES OF EARTHQUAKES

Earthquakes occur all the time all over the world, both along plate edges and along faults.

Most earthquakes occur along the edge of the oceanic and continental plates. The earth's crust (the outer layer of the planet) is made up of several pieces, called plates. The plates under the oceans are called oceanic plates and the rest are continental plates. The plates are moved around by the motion of a deeper part of the earth (the mantle) that lies underneath the crust. See Figure (2.3). These plates are always bumping into each other, pulling away from each other, or past each other. The plates usually move at about the same speed that your fingernails grow. Earthquakes usually occur where two plates are running into each other or sliding past each other.

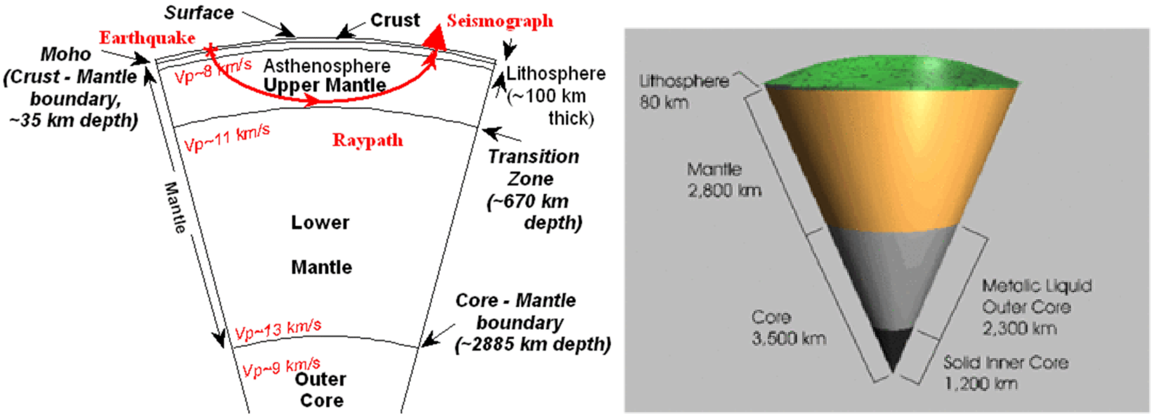


Fig. (2-3): Tree major chemical radial divisions (Crust, Mental & Core).

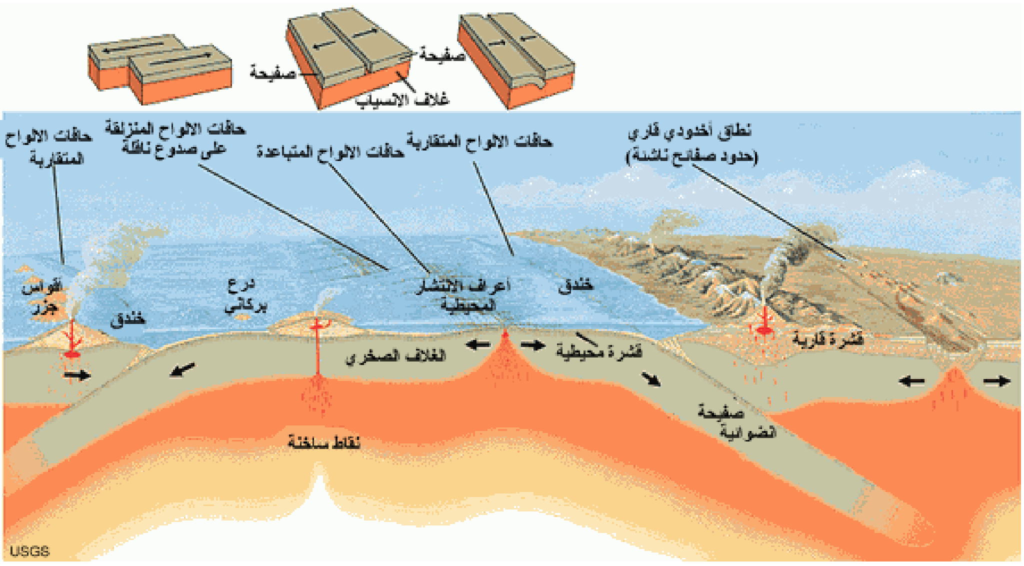


Fig. (2-4): Plate Boundaries**:** Three types of interactions between plates as they move around: Sliding past one another - transform boundary (حافات الالواح المنزلقة).

Running into one another - convergent boundary (حافات الالواح المتقاربه) .

Moving away from one another - divergent boundary (حافات الالواح المتباعده).

2.4 UNDERSTANDIMG PLATE MOTIONS

Scientists now have a fairly good understanding of how the plates move and how such movements relate to earthquake activity. Most movement occurs along narrow zones between plates where the results of plate-tectonic forces are most evident. There are four types of plate boundaries:

1. Divergent boundaries -- where new crust is generated as the plates pull away from each other.

2. Convergent boundaries -- where crust is destroyed as one plate dives under another.
3. Transform boundaries -- where crust is neither produced nor destroyed as the plates slide horizontally past each other.
4. Plate boundary zones -- broad belts in which boundaries are not well defined and the effects of plate interaction are unclear.

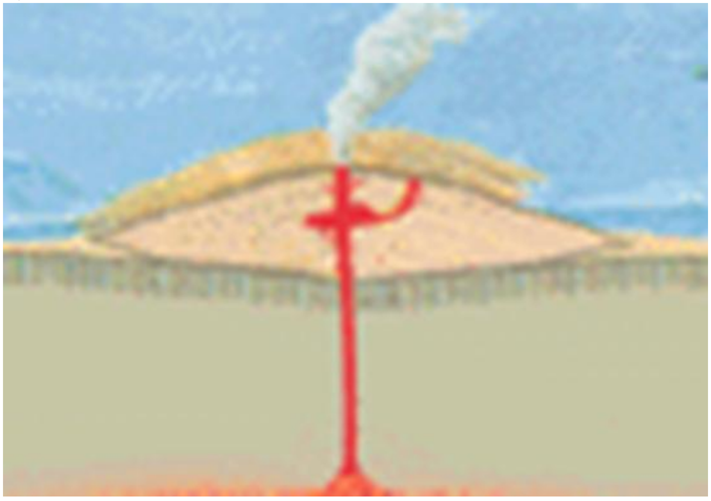


Fig. (2-5): Illustration of the Main Types of Plate Boundaries

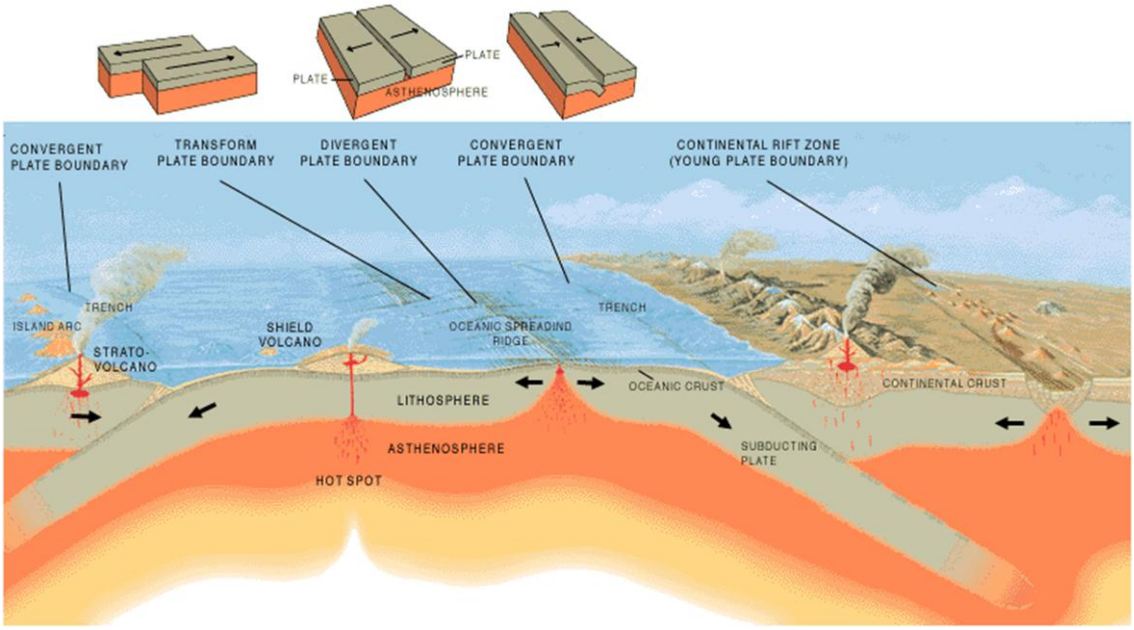


Fig. (2-6): Artist's cross section illustrating the main types of plate boundaries; East African Rift Zone is a good example of a continental rift zone.

- **Divergent boundaries**

Divergent boundaries occur along spreading centers where plates are moving apart and new crust is created by magma pushing up from the mantle. Picture two giant conveyor belts, facing each other but slowly moving in opposite directions as they transport newly formed oceanic crust away from the ridge crest.

Perhaps the best known of the divergent boundaries is the Mid-Atlantic Ridge. This submerged mountain range, which extends from the Arctic Ocean to beyond the southern tip of Africa, is but one segment of the global mid-ocean ridge system that encircles the Earth. The rate of spreading along the Mid-Atlantic Ridge averages about 2.5 centimeters per year (cm/yr), or 25 km in a million years. This rate may seem slow by human standards, but because this process has been going on for millions of years, it has resulted in plate movement of thousands of kilometers. Seafloor spreading over the past 100 to 200 million years has caused the Atlantic Ocean to grow from a tiny inlet of water between the continents of Europe, Africa, and the Americas into the vast ocean that exists today.

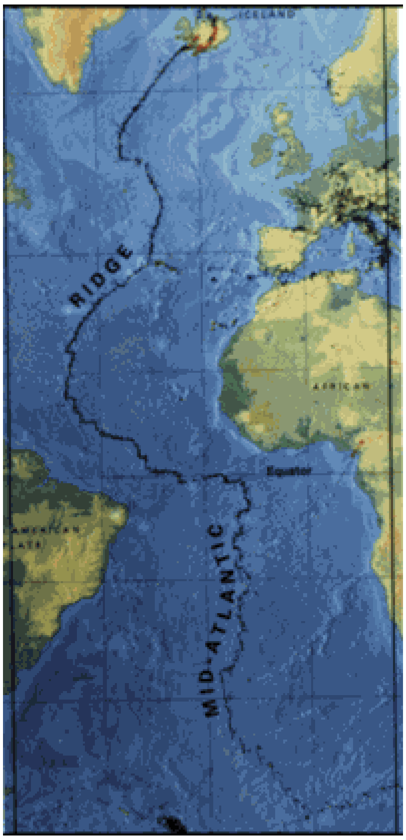


Fig. (2-7): The Mid-Atlantic Ridge, which splits nearly the entire Atlantic Ocean north to south, is probably the best-known and most-studied example of a divergent-plate boundary.

The volcanic country of Iceland, which straddles the Mid-Atlantic Ridge, offers scientists a natural laboratory for studying on land the processes also occurring along the submerged parts of a spreading ridge. Iceland is splitting along the spreading center between the North American and Eurasian Plates, as North America moves westward relative to Eurasia.

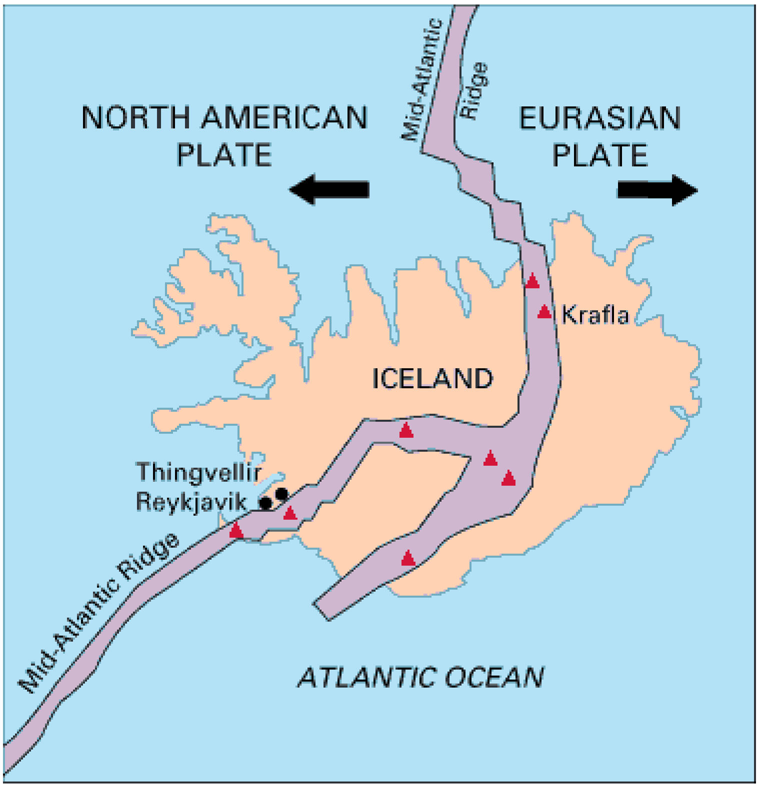


Fig. (2-8): Map showing the Mid-Atlantic Ridge splitting Iceland and separating the North American and Eurasian Plates. The map also shows Reykjavik, the capital of Iceland, the Thingvellir area, and the locations of some of Iceland's active volcanoes (red triangles), including Krafla.

The consequences of plate movement are easy to see around Krafla Volcano, in the northeastern part of Iceland. Here, existing ground cracks have widened and new ones appear every few months. From 1975 to 1984, numerous episodes of rifting (surface cracking) took place along the Krafla fissure zone. Some of these rifting events were accompanied by volcanic activity; the ground would gradually rise 1-2 m before abruptly dropping, signalling an impending eruption. Between 1975 and 1984, the displacements caused by rifting totalled about 7 m.

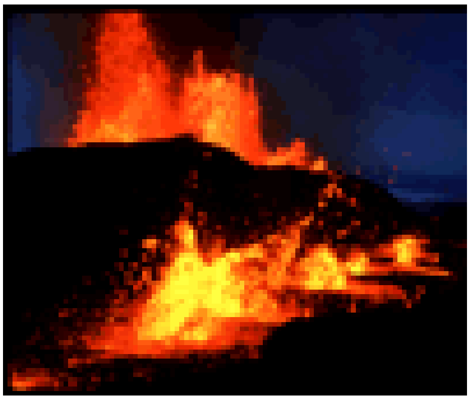


Fig. (2-9):Lava Fountains, Krafla Volcano

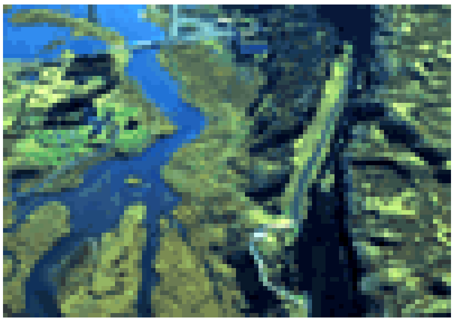


Fig. (2-10): Thingvellir Fissure Zone, Iceland

In East Africa, spreading processes have already torn Saudi Arabia away from the rest of the African continent, forming the Red Sea. The actively splitting African Plate and the Arabian Plate meet in what geologists call a triple junction, where the Red Sea meets the Gulf of Aden. A new spreading center may be developing under Africa along the East African Rift Zone. When the continental crust stretches beyond its limits, tension cracks begin to appear on the Earth's surface. Magma rises and squeezes through the widening cracks, sometimes to erupt and form volcanoes. The rising magma, whether or not it erupts, puts more pressure on the crust to produce additional fractures and, ultimately, the rift zone.

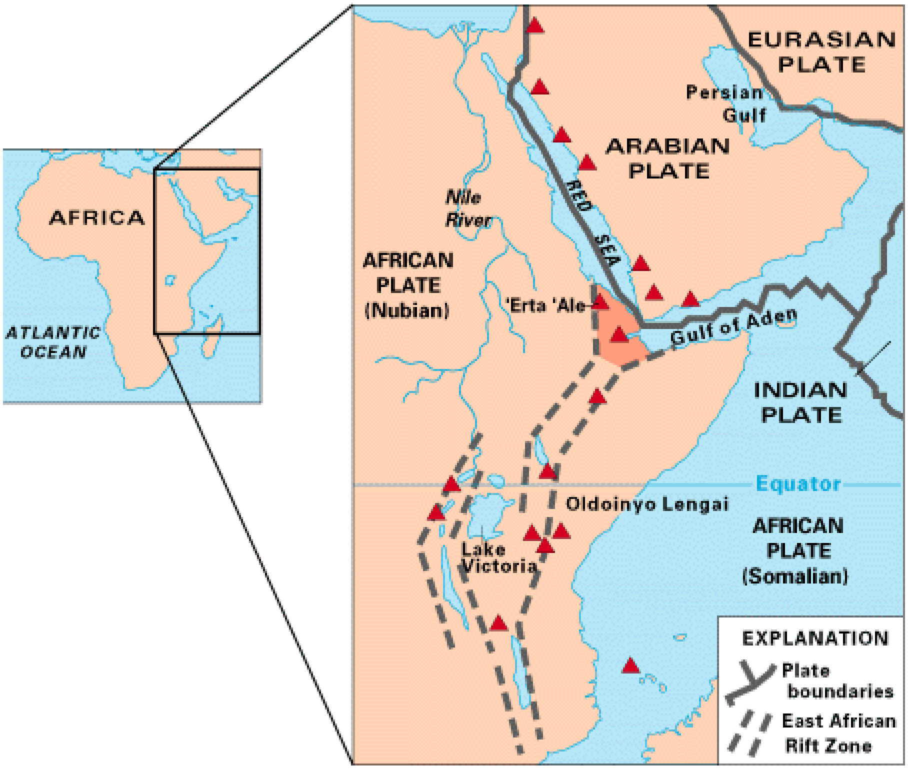


Fig. (2-11): Map of East Africa showing some of the historically active volcanoes(red triangles) and the Afar Triangle (shaded, center) -- a so-called triple junction (or triple point), where three plates are pulling away from one another: the Arabian Plate, and the two parts of the African Plate (the Nubian and the Somalian) splitting along the East African Rift Zone.

East Africa may be the site of the Earth's next major ocean. Plate interactions in the region provide scientists an opportunity to study first-hand how the Atlantic may have begun to form about 200 million years ago. Geologists believe that, if spreading continues, the three plates that meet at the edge of the present-day African continent will separate completely, allowing the Indian Ocean to flood the area and making the easternmost corner of Africa (the Horn of Africa) a large island.

Fig. (2-12): Summit Crater of 'Erta 'Ale

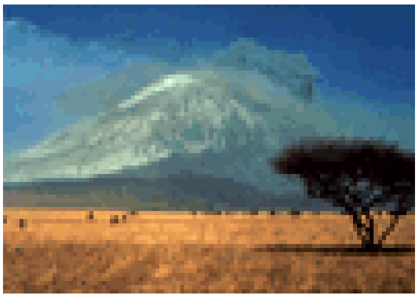


Fig. (2-13): Oldoinyo Lengai, East African Rift Zone

- **Convergent boundaries**

The size of the Earth has not changed significantly during the past 600 million years, and very likely not since shortly after its formation 4.6 billion years ago. The Earth's unchanging size implies that the crust must be destroyed at about the same rate as it is being created, as Harry Hess surmised. Such destruction (recycling) of crust takes place along convergent boundaries where plates are moving toward each other, and sometimes one plate sinks (is subducted) under another. The location where sinking of a plate occurs is called a subduction zone.

The type of convergence -- called by some a very slow "collision" -- that takes place between plates depends on the kind of lithosphere involved. Convergence can occur between an oceanic and a largely continental plate, or between two largely oceanic plates, or between two largely continental plates.

- **Oceanic-continental convergence**

If by magic we could pull a plug and drain the Pacific Ocean, we would see a most amazing sight -- a number of long narrow, curving trenches thousands of kilometers long and 8 to 10 km deep cutting into the ocean floor. Trenches are the deepest parts of the ocean floor and are created by subduction.

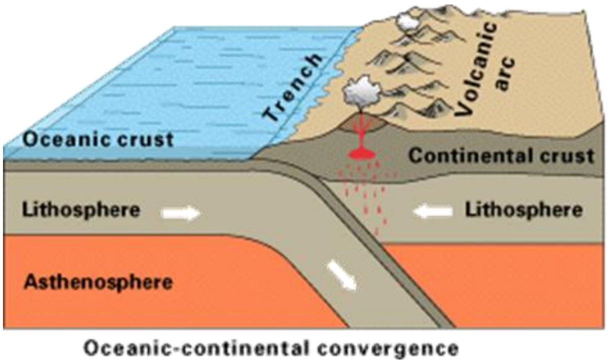


Fig. (2-14):Oceanic continental convergence

Off the coast of South America along the Peru-Chile trench, the oceanic Nazca Plate is pushing into and being subducted under the continental part of the South American Plate. In turn, the overriding South American Plate is being lifted up, creating the towering Andes mountains, the backbone of the continent. Strong, destructive earthquakes and the rapid uplift of mountain ranges are common in this region. Even though the Nazca Plate as a whole is sinking smoothly and continuously into the trench, the deepest part of the subducting plate breaks into smaller pieces that become locked in place for long periods of time before suddenly moving to generate large earthquakes. Such earthquakes are often accompanied by uplift of the land by as much as a few meters.

Fig. (2-15): Nazca-SoAm gif Convergence of the Nazca and South American Plates

On 9 June 1994, a magnitude-8.3 earthquake struck about 320 km northeast of La Paz, Bolivia, at a depth of 636 km. This earthquake, within the subduction zone between the Nazca Plate and the South American Plate, was one of deepest and largest subduction earthquakes recorded in South America. Fortunately, even though this powerful earthquake was felt as far away as

Minnesota and Toronto, Canada, it caused no major damage because of its great depth.

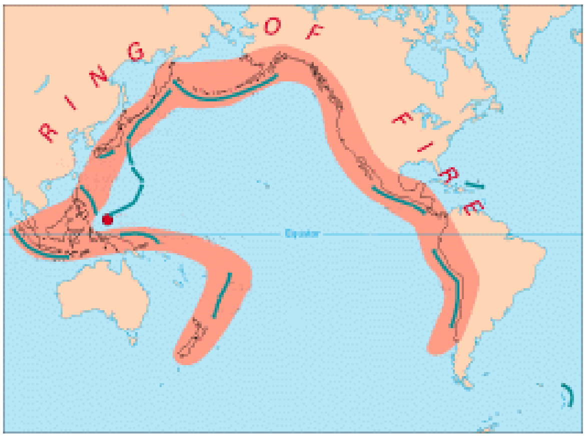


Fig. (2-16): Ring of Fire

Oceanic-continental convergence also sustains many of the Earth's active volcanoes, such as those in the Andes and the Cascade Range in the Pacific Northwest. The eruptive activity is clearly associated with subduction, but scientists vigorously debate the possible sources of magma: Is magma generated by the partial melting of the subducted oceanic slab, or the overlying continental lithosphere, or both?

- **Oceanic-oceanic convergence**

As with oceanic-continental convergence, when two oceanic plates converge, one is usually subducted under the other, and in the process a trench is formed. The Marianas Trench (paralleling the Mariana Islands), for example, marks where the fast-moving Pacific Plate converges against the slower moving Philippine Plate. The Challenger Deep, at the southern end of the Marianas Trench, plunges deeper into the Earth's interior (nearly 11,000 m) than Mount Everest, the world's tallest mountain, rises above sea level (about 8,854 m).

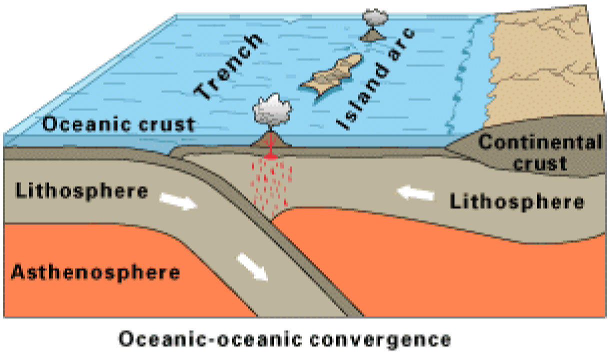
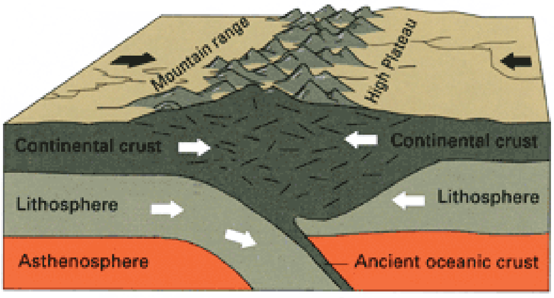


Fig. (2-17): Oceanic – oceanic convergence

Subduction processes in oceanic-oceanic plate convergence also result in the formation of volcanoes. Over millions of years, the erupted lava and volcanic debris pile up on the ocean floor until a submarine volcano rises above sea level to form an island volcano. Such volcanoes are typically strung out in chains called island arcs. As the name implies, volcanic island arcs, which closely parallel the trenches, are generally curved. The trenches are the key to understanding how island arcs such as the Marianas and the Aleutian Islands have formed and why they experience numerous strong earthquakes. Magmas that form island arcs are produced by the partial melting of the descending plate and/or the overlying oceanic lithosphere. The descending plate also provides a source of stress as the two plates interact, leading to frequent moderate to strong earthquakes.

- **Continental-continental convergence**

The Himalayan mountain range dramatically demonstrates one of the most visible and spectacular consequences of plate tectonics. When two continents meet head-on, neither is subducted because the continental rocks are relatively light and, like two colliding icebergs, resist downward motion. Instead, the crust tends to buckle and be pushed upward or sideways. The collision of India into Asia 50 million years ago caused the Indian and Eurasian Plates to crumple up along the collision zone. After the collision, the slow continuous convergence of these two plates over millions of years pushed up the Himalayas and the Tibetan Plateau to their present heights. Most of this growth occurred during the past 10 million years. The Himalayas, towering as high as 8,854 m above sea level, form the highest continental mountains in the world. Moreover, the neighboring Tibetan Plateau, at an average elevation of about 4,600 m, is higher than all the peaks in the Alps except for Mont Blanc and Monte Rosa, and is well above the summits of most mountains in the United States.



Continental-continental convergence

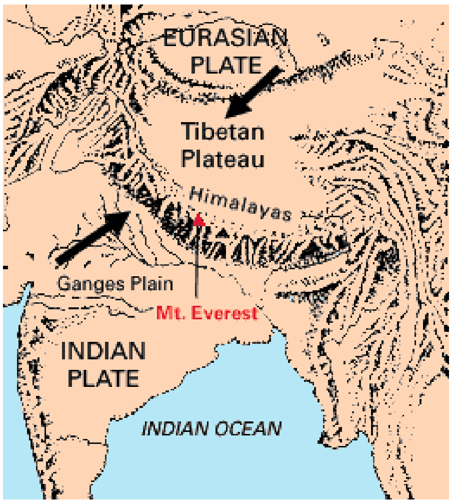
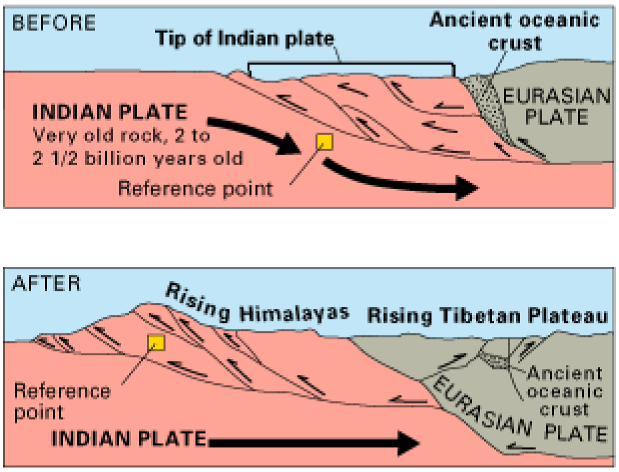


Fig. (2-18): Above: The collision between the Indian and Eurasian plates has pushed up the Himalayas and the Tibetan Plateau. Below: Cartoon cross sections showing the meeting of these two plates before and after their collision. The reference points (small squares) show the amount of uplift of an imaginary point in the Earth's crust during this mountain-building process.



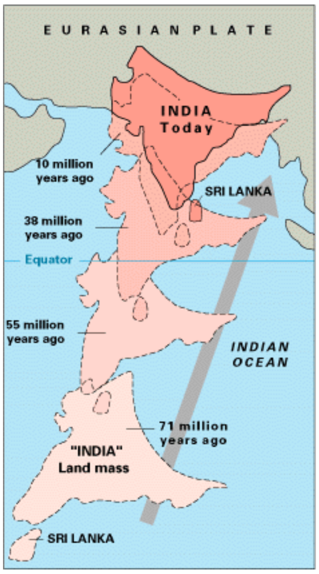


Fig. (2-19): The Himalayas: Two Continents Collide. The 6,000-km-plus journey of the India landmass (Indian Plate) before its collision with Asia (Eurasian Plate) about 40 to 50 million years ago (see text). India was once situated well south of the Equator, near the continent of Australia.

- **Transform boundaries**

The zone between two plates sliding horizontally past one another is called a transform-fault boundary, or simply a transform boundary. The concept of transform faults originated with Canadian geophysicist J. Tuzo Wilson, who proposed that these large faults or fracture zones connect two spreading centers (divergent plate boundaries) or, less commonly, trenches (convergent plate boundaries). Most transform faults are found on the ocean floor. They commonly offset the active spreading ridges, producing zig-zag plate margins, and are generally defined by shallow earthquakes. However, a few occur on land, for example the San Andreas fault zone in California. This transform fault connects the East Pacific Rise, a divergent boundary to the south, with the South Gorda -- Juan de Fuca -- Explorer Ridge, another divergent boundary to the north.

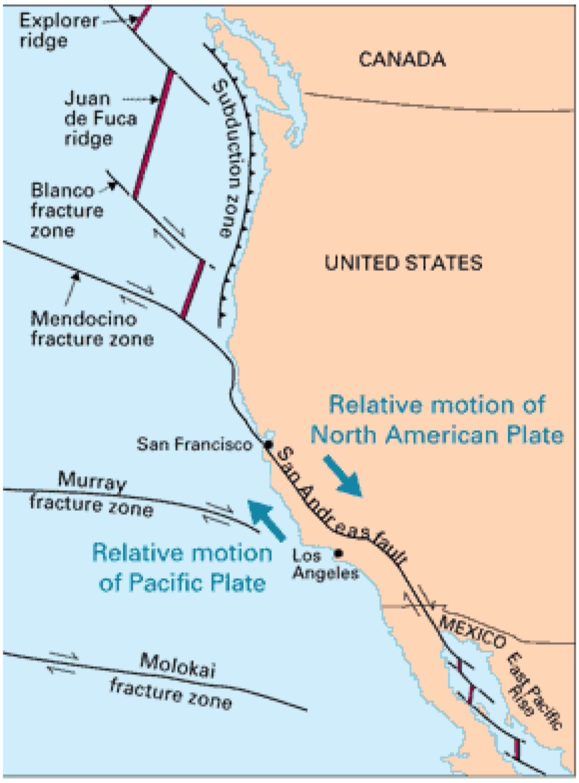


Fig. (2-20): The Blanco, Mendocino, Murray, and Molokai fracture zones are some of the many fracture zones (transform faults) that scar the ocean floor and offset ridges (see text). The San Andreas is one of the few transform faults exposed on land.

The San Andreas fault zone, which is about 1,300 km long and in places tens of kilometers wide, slices through two thirds of the length of California. Along it, the Pacific Plate has been grinding horizontally past the North American Plate for 10 million years, at an average rate of about 5 cm/yr. Land on the west side of the fault zone (on the Pacific Plate) is moving in a northwesterly direction relative to the land on the east side of the fault zone (on the North American Plate).

Fig. (2.21): Aerial view of the San Andreas Fault slicing through the Carrizo Plain in the Temblor Range east of the city of San Luis Obispo.

Oceanic fracture zones are ocean-floor valleys that horizontally offset spreading ridges; some of these zones are hundreds to thousands of kilometers long and as much as 8 km deep. Examples of these large scars include the Clarion, Molokai, and Pioneer fracture zones in the Northeast Pacific off the coast of California and Mexico. These zones are presently inactive, but the offsets of the patterns of magnetic striping provide evidence of their previous transform-fault activity.

- **Plate-boundary zones**

Not all plate boundaries are as simple as the main types discussed above. In some regions, the boundaries are not well defined because the plate-movement deformation occurring there extends over a broad belt (called a plate-boundary zone). One of these zones marks the Mediterranean-Alpine region between the Eurasian and African Plates, within which several smaller fragments of plates (microplates) have been recognized. Because plate-boundary zones involve at least two large plates and one or more microplates caught up between them, they tend to have complicated geological structures and earthquake patterns.

- **Rates of motion**

We can measure how fast tectonic plates are moving today, but how do scientists know what the rates of plate movement have been over geologic time? The oceans hold one of the key pieces to the puzzle. Because the ocean-floor magnetic striping records the flip-flops in the Earth's magnetic field, scientists, knowing the approximate duration of the reversal, can calculate the average rate of plate movement during a given time span. These average rates of plate separations can range widely. The Arctic Ridge has the slowest rate (less than 2.5 cm/yr), and the East Pacific Rise near Easter Island, in the South Pacific about 3,400 km west of Chile, has the fastest rate (more than 15 cm/yr).

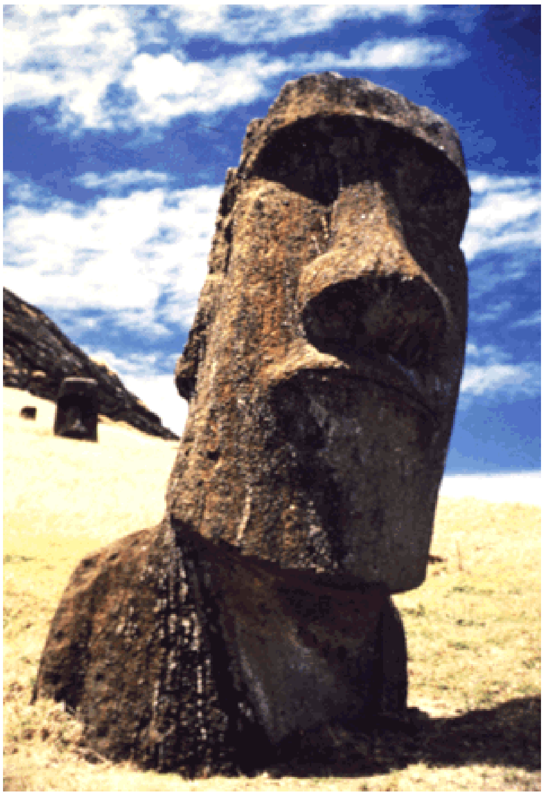


Fig. (2-21): Easter Island monolith: One of the mysterious, imposing stone monoliths -- some standing 5 m tall and weighing 14 tons -- on Easter Island (Chile), carved by ancient Polynesians out of volcanic rock. Easter Island, which lies on the Nazca Plate close to the East Pacific Rise, is moving eastward toward South America by seafloor spreading at the fastest rate known in the world (see text). (Photograph by Carlos Capurro, U.S. Embassy, Santiago, Chile.)

Evidence of past rates of plate movement also can be obtained from geologic mapping studies. If a rock formation of known age -- with distinctive composition, structure, or fossils -- mapped on one side of a plate boundary can be matched with the same formation on the other side of the boundary, then measuring the distance that the formation has been offset can give an estimate of the average rate of plate motion. This simple but effective technique has been used to determine the rates of plate motion at divergent boundaries, for example the Mid-Atlantic Ridge, and transform boundaries, such as the San Andreas Fault.

Fig. (2-22): GPS Satellite and Ground Receiver

Current plate movement can be tracked directly by means of ground-based or space-based geodetic measurements; geodesy is the science of the size and shape of the Earth. Ground-based measurements are taken with conventional but very precise ground-surveying techniques, using laser-electronic instruments. However, because plate motions are global in scale, they are best measured by satellite-based methods. The late 1970s witnessed the rapid growth of space geodesy, a term applied to space-based techniques for taking precise, repeated measurements of carefully chosen points on the Earth's surface separated by hundreds to thousands of kilometers. The three most commonly used space-geodetic techniques -- very long baseline interferometry (VLBI), satellite laser ranging (SLR), and the Global Positioning System (GPS) -- are based on technologies developed for military and aerospace research, notably radio astronomy and satellite tracking.

Among the three techniques, to date the GPS has been the most useful for studying the Earth's crustal movements. Twenty-one satellites are currently in orbit 20,000 km above the Earth as part of the NavStar system of the U.S. Department of Defense. These satellites continuously transmit radio signals back to Earth. To determine its precise position on Earth (longitude, latitude, elevation), each GPS ground site must simultaneously receive signals from at least four satellites, recording the exact time and location of each satellite when its signal was received. By repeatedly measuring distances between specific points, geologists can determine if there has been active movement along faults or between plates. The separations between GPS sites are already being measured regularly around the Pacific basin. By monitoring the interaction between the Pacific Plate and the surrounding, largely continental plates, scientists hope to learn more about the events building up to earthquakes and volcanic eruptions in the circum-Pacific Ring of Fire. Space-geodetic data have already confirmed that the rates and direction of plate movement, averaged over several years, compare well with rates and direction of plate movement averaged over millions of years.