travelled 15 miles, killing 125 people and leaving 4,000 homeless.

Among industrialized nations, Japan has suffered the greatest loss of life and property from landslides. Losses have been particularly high in heavily populated urban areas at the bases of steep mountain slopes. Although some Japanese landslides are triggered by earthquakes, most are caused by heavy rains during the typhoon season. In 1938, Kobe was swept by debris flows triggered by torrential rains. Approximately 500 people died and more than 100,000 houses were destroyed. In 1945, debris flows in Kure triggered by heavy rain killed more than 1,000 people and destroyed nearly 2,000 homes.

Most large landslides in North America have occurred in relatively unpopulated areas. Approximately 25–50 people are killed each year by landslides in the U.S. While most landslide occurrences in the U.S. are not killers, one notable exception occurred during the widespread floods in Virginia following Hurricane Camille in 1969. Most of the 150 people who died may have been killed by debris flows.

Types of Landslides. Landslides are usually described in terms that indicate the types of material and motion. Five different types of movement characterize landslides: sliding, falling, toppling, lateral spreading, and flowing.

Slides are typified by soil or rock that moves along an identifiable surface, called a rupture zone. This zone can develop within layers of soil or bedrock or between soil and bedrock layers. The movement can range from more than 10 feet per second to a few inches per year. Transitional slides move along a flat surface. Rotational slides, or slumps, have a curved or spoon-shaped rupture zone. Slumps are the most common type of landslide. They often occur when the foot (or toe) of a slope is cut away by natural erosion or by road building. When a slope has undergone a number of small slumps, a terracelike appearance results.

Falls are typified by earth or rock that detaches from a slope or cliff, which then falls, bounces, or rolls rapidly through the air. Falls can involve pebbles, rocks, boulders, and soil.

Topples are typified by blocks of rock that tilt or rotate forward on a pivot point. The block may settle at a precarious angle, balancing on a pivot point and its new resting place. Topples do not generally involve much movement, nor do they necessarily trigger rock slides or falls.

Lateral spreads are nearly horizontal movements across shallow slopes in very gentle terrain, often initiated by earthquakes that liquefy a soil layer beneath the moving material. If an earthquake liquefies a layer of sensitive clay just below a layer of rock, the rock may break apart, causing the pieces to slowly separate. Lateral spreads also occur suddenly and at high speed in earth material.

Flows can be fast or slow, and wet or dry. They occur in earth, soil and rock debris, dry or wet sand, snow or ice, and even bedrock. Some flows, especially mud flows, move rapidly; others move very slowly. A flow of soil or bedrock so slow that it is imperceptible, except over long periods of time, is called creep. Extremely rapid flows are often called avalanches. Mud and debris flows on the slopes of erupting volcanoes are called lahars.

Causes of Landslides. Water is the most common cause of landslides. Dense wetter surface soil renders a slope less stable. When the water table rises, friction is reduced, which also reduces resistance to slope failure. Water thus increases forces tending toward failure and decreases the resistance to failure.

Landslides can also be triggered by natural processes such as earthquakes, volcanic eruptions, and erosion. Sudden snow and ice melting near a volcanic vent can cause mud and debris flows (lahars). Erosion is usually a slow process that allows a slope to adjust without noticeable movement. However, rapid erosion may cause sliding. Hillsides become more landslide-prone following forest or brush fires that destroy vegetative cover, reduce holding power of the soil, and lead to gullying and erosion. Finally, landslides can be caused by the clearing and grading of land which accompany construction of roads, buildings, dams, and reservoirs. Explosions and the use of heavy earth moving and construction equipment can set up forces that weaken the slope in a manner similar to that of an earthquake.

Snow Avalanches

Snow avalanches are landslides of snow and ice, and range from small flows of tens of cubic meters to up to 100 million cubic meters of moving snow. The most dangerous avalanches are those that occur during or shortly after a snowfall, especially those that involve large masses of powdery snow. Once set in motion, light snow mixes with air and moves like a heavy gas at speeds up to 200 miles/hour, pushing a wave of air ahead of it. The aerosol mixture can suffocate people and spread into houses and vehicles. Snow avalanches have bent steel girders, sheared homes in half, torn 200-year-old trees from their roots, and thrown automobile-sized boulders miles across valley floors.

In Twin Lakes, Colorado, in 1962, a thick slab of snow hundreds of feet wide crossed a diversion structure that had stopped avalanches in the past, flattened a stand of 70-year-old aspen, and destroyed seven homes and a house trailer nestled in the woods. Seven people died. In 1980, 250,000 tons of snow released from an Alaska mountainside traveled more than a mile, destroyed thousands of trees, and dumped snow 6 yards deep over an area the size of 22 football fields. No one was killed. If an avalanche of the same size had occurred in Juneau, where the circumstances are similar, it would have destroyed a high school, 40 houses, a motel, and a marina.

There are about a million avalanches each year worldwide, which kill nearly a thousand people. Avalanches primarily threaten persons who engage in winter mountain sports and who work to support the snow recreation industry. Fortunately, most avalanches occur in sparsely populated areas.

Although the types of movement that characterize earth and rock landslides (slides, falls, topples, spreads, and flows) also apply to snow and ice, the crystalline structure of snow and the possibility of melting and refreezing give snow and ice special properties that make avalanches different from other landslides. Ice avalanches usually begin with slow sliding and creep of ice caps and glaciers that overhang cliffs. Instability leads to falls or topples, followed by partial disintegration of the ice and flowage of ice blocks. Entire glaciers have released into bodies of water, causing huge waves that inflicted considerable damage.

Snow avalanches are complex phenomena, involving several different types of motion in successive stages. A comprehensive discussion of snow avalanches is found in Chapter 15.

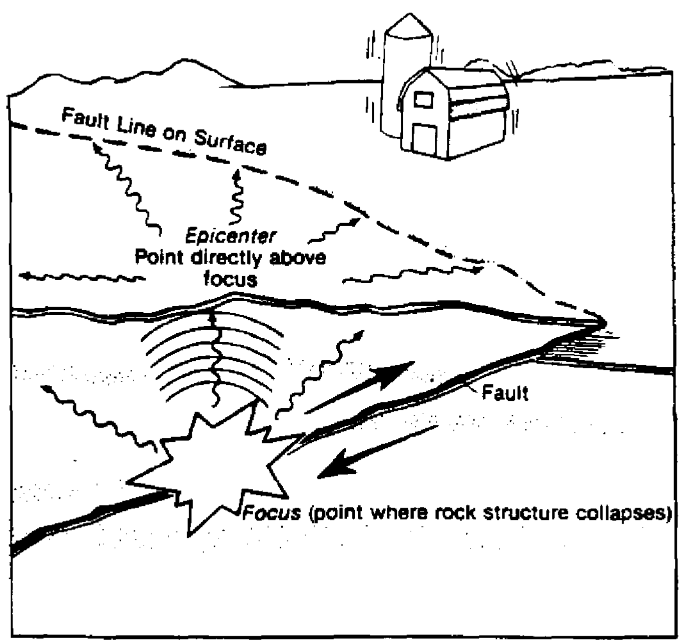

Figure 14-2. Motion of the earth's plates causes increased pressure at faults where the plates meet. Eventually, the rock structure collapses and movement occurs along the fault. Energy is propagated to the surface above and radiates outward. Waves of motion in the earth's crust shake landforms and buildings, causing damage. (U. WI. DMC)

EARTHQUAKES

Earthquakes are among the most destructive and feared natural hazards. They strike with sudden impact and with little warning. More than a million earthquakes occur each year, of which only 10 or 20 cause significant disasters. Most earthquakes occur in well-defined zones near the boundaries of the tectonic plates. These lie along the Pacific rim, along the Sunda arc, and in the mountain ranges of Europe and Asia. However, there have been notable exceptions: the New Madrid earthquake in 1811 and the Charleston earthquake in 1886 in the U.S.; the Agadir earthquake in 1960 in Morocco; and the Koyna earthquake in 1967 in India occurred outside usual earthquake zones.

Causes of Earthquakes

Earthquakes are most commonly caused by movement of tectonic plates, 50–60 mile thick segments of the earth's crust and upper mantle. These are each of similar size to the continents, and float on the surface of underlying molten rock. The plates are in constant motion, approaching in some areas and separating in others (Figure 14-2). Although the relative motion is slow by human standards, ranging from less than a fraction of an inch to 5 inches per year, it is fast by geologic standards. Movement of 2 inches per year adds up to 30 miles in one million years. As the plates move, strain accumulates. Eventually, faults along or near plate boundaries slip abruptly and an earthquake occurs.

There are three distinct types of plate boundaries: divergent rifts, where new ocean floor is created by basaltic magma (molten rock beneath the earth's crust) that rises from the earth's interior and spreads horizontally; convergent zones, where two plates come together and collide head on or where one plate slides beneath another; and shear borders, where two plates grind slowly past each other.

Measures of Earthquake Intensity

The Richter scale is the best known method for measuring the magnitude of an earthquake. It represents the amplitude of seismic waves and is based on seismograph measurements. It is logarithmic, so that a Richter magnitude of 7 indicates an earthquake whose ground motion is 10 times as great as that in an earthquake of magnitude 6. An earthquake of magnitude 2 is the weakest normally detected by people. Earthquakes of magnitude 6–7 are considered "moderate"; earthquakes of magnitude 7–8 are considered "great" and are quite uncommon. A Richter magnitude greater than 8 is rare.

The modified Mercalli scale expresses subjectively the intensity of an earthquake at a given location, based on eyewitness reports and post-earthquake field investigations. It ranges from I to XII (Table 14-2).

The focus of an earthquake is the point beneath the earth's surface from which the earthquake seismic waves emanate. The epicenter of the earthquake is the point on the earth's surface directly above the focus.

The Destructive Forces of Earthquakes

Earthquakes cause destruction and injuries through ground shaking, surface faulting, earthquake-induced ground failures such as landsliding, liquefaction, and tsunamis. Earthquakes rarely kill or injure large numbers of people directly. Rather, ground shaking, surface faulting, and earthquake-induced ground failures collapse buildings, rupture pipelines, and destroy transportation and communication systems. Deaths and injuries are usually the result of burial in collapsed buildings and of fires (induced by ruptured gas and electric power lines) which cannot be fought successfully because of damaged roads and broken water mains. Earthquake-induced tsunamis, or seismic sea waves, can cause severe coastal flooding, both in the immediate vicinity of the earthquake and along coastlines hundreds or thousands of miles distant.

Ground Shaking

Ground shaking is caused by seismic waves generated by an earthquake. When a fault ruptures, seismic waves are propagated in all directions, causing the ground to vibrate. Buildings, pipelines, and other structures collapse if they cannot withstand the vibration.

There are three types of seismic waves. Primary and secondary waves (P and S waves) travel directly through the earth; surface waves (L waves) travel along the surface. The P waves are the fastest, travelling through the earth at speeds of 15,000 miles/hour. They are high-frequency compressional waves which have a "push-pull" effect on the rock through which they pass, causing the ground surface structures to vibrate verti-

Table 14-2. Modified Mercalli Intensity Scale of 1931

I	Not felt except by a very few under especially favorable circumstances.
II	Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.
III	Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motorcars may rock slightly. Vibration like passing of truck. Duration estimated.
IV	During the day felt indoors by many. Outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls make creaking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.
V	Felt by nearly everyone; many awakened. Some dishes,.windows, etc., broken. A few instances of cracked plaster. Unstable objects overturned. Disturbances of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop.
VI	Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.
VII	Everybody runs outdoors. Damage negligible in buildings of good design and construction, slight to moderate in well-built ordinary structures, considerable in poorly built or badly designed structures. Some chimneys broken. Noticed by persons driving motor cars.
VIII	Damage slight in specially designed structures, considerable in ordinary substantial buildings with partial collapse, great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, and walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Persons driving motor cars disturbed.
IX	Damage considerable in specially designed structures. Well-designed structures thrown out of plumb, greatly in substantial buildings with partial collapse. Buildings shifted off foundations Ground cracked conspicuously. Underground pipes broken.
X	Some well-built wooden structures destroyed. Most masonry and frame structures with foundations destroyed; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks.
XI	Few, if any, (masonry) structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipelines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.
XII	Damage total. Practically all works of construction are damaged greatly or destroyed. Waves seen on ground surface. Lines of sight and level are distorted. Objects are thrown upward into the air.

cally. The S waves travel more slowly, at speeds of 9,000 miles/hour. They are shear waves, and cause the rock through which they pass to move from side to side perpendicular to the direction of wave motion. These waves cause the ground and buildings to sway side to side, often causing more damage than do the P waves. The different speeds of the P and S waves produce two distinct shocks; the farther the surface point is from the focus, the greater the interval between shocks. The L waves are slow-moving waves that travel along the earth's surface and arrive last at any given point. Both the P and S waves cause high-frequency vibrations (greater than 1 Hertz), which have greatest impact on low buildings; the L waves cause low-frequency vibrations which have greatest impact on tall buildings (Figure 14-3).

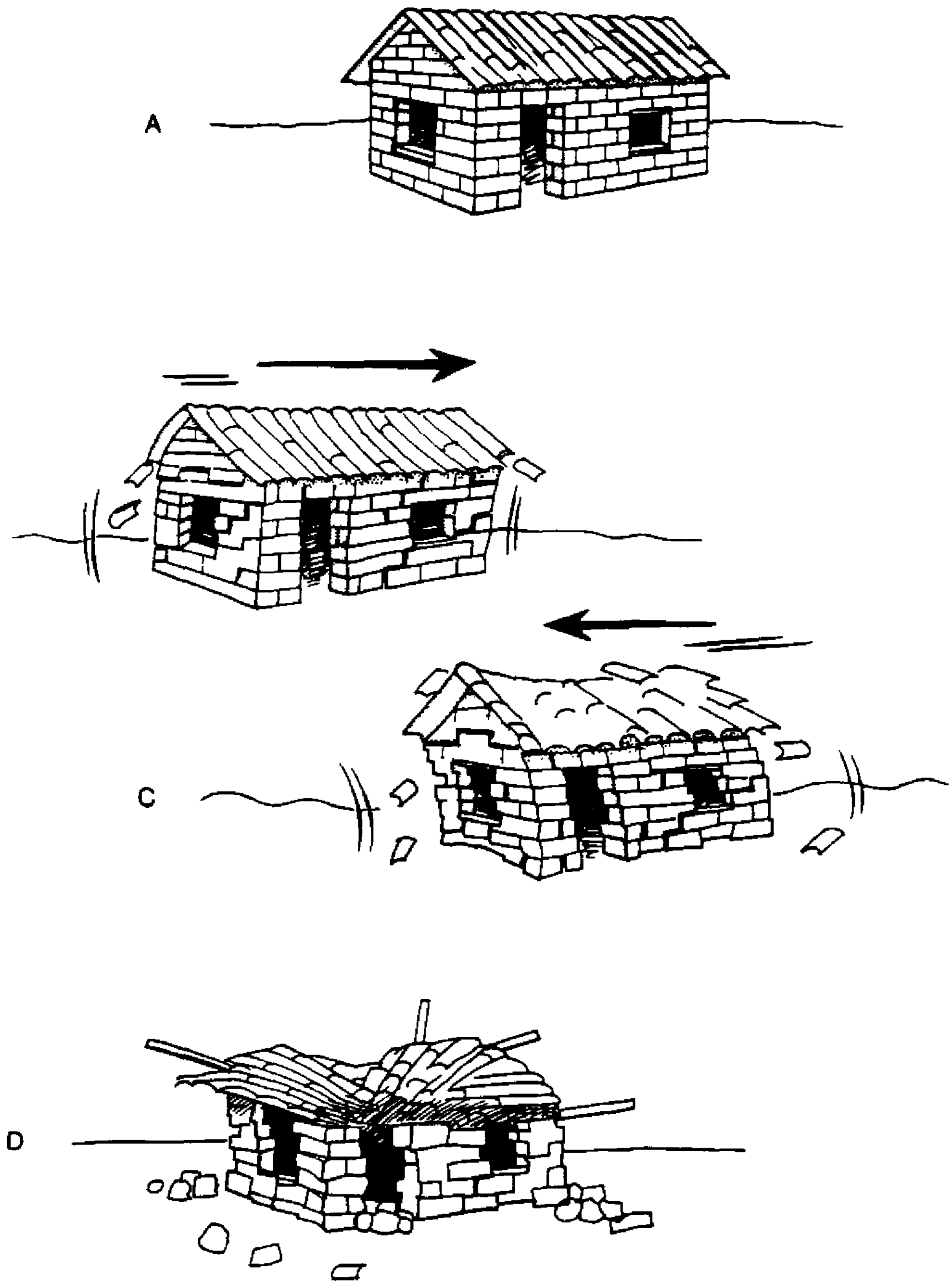

Figure 14-3. (A) A vulnerable house consists of heavy materials stacked in place without a continuous frame for reinforcement. (B) The house moves with the motion of the earth during an earthquake, creating new stresses in the structure. (C) Built to withstand only normal downward gravitational forces, the house now is subjected to complex lateral forces. (D) As building components fall apart, the roof and walls collapse, burying occupants beneath the rubble. (U. WI. DMC)

The violent and destructive main shocks may be preceded by preliminary tremors or foreshocks. These may be few and not very severe, but provide an indication of the timing and severity of the main shocks. The main shock rarely lasts more than a minute, and may last for only a few seconds. Strong shaking may continue for a few minutes, but more commonly lasts for only 30–60 seconds. Finally, there may be aftershocks of decreasing intensity occurring at increasing intervals. The period from the initial foreshock to the final aftershock may be days, months, or even years.

Surface Faulting

Surface faulting, the differential movement of two sides of a fracture at the earth's surface, is of three general types: strike-slip, normal, and reverse. In strike-slip faults, the motion is horizontal with the two sides sliding along each other. In normal faults, the motion is largely vertical with the side above the inclined fault moving downward. In reverse faults, the motion is largely vertical with the side above the inclined fault moving upward.

Deaths and injuries as a direct result of surface faulting are unlikely, but casualties occur as a result of damage to structures. Surface faulting generally affects a long narrow zone of small total area compared to that affected by ground shaking. Nevertheless, the damage to structures within the fault zone can be extreme, especially if it includes urban areas. An example of severe damage occurred in California in 1952, when three railroad tunnels were so badly damaged by faulting that traffic on a major rail route linking northern and southern California was interrupted for 25 days despite continual repair efforts.

The displacements, lengths, and widths of surface fault ruptures are of considerable variation. Fault displacements can range from a fraction of an inch to more than 20 feet of differential movement. Lengths of surface faults have ranged from less than a mile to more than 200 miles. Subsidiary fault ruptures may occur 2 or 3 miles from the main fault. The area subject to disruption by surface faulting varies with the length and width of the rupture zone.

Earthquake-Induced Ground Failures

Earthquakes can cause changes in structural characteristics that affect the stability of slopes and the ability of the ground to support buildings, highways, and other structures. The most common earthquake-induced ground failures are landslides, soil flows, and soil failures caused by liquefaction. In some instances, ground failures have caused more than half of the economic losses associated with an earthquake, and have been responsible for considerable loss of life, as when soil-flow failures induced by the 1920 earthquake in Kansu, China killed 200,000 people.

Landslides and Soil Flows. The most common types of earthquake-induced landslides are rock falls and rock slides on steep slopes. Shallow debris slides on steep slopes are less common. Reactivation of dormant slumps and block slides by earthquakes are rare.

Large, earthquake-induced rock avalanches, soil avalanches, and underwater landslides can be very destructive, as evidenced by the rock avalanche triggered by the 1970 Chimbote, Peru, earthquake, which killed more than 18,000 people. Soil avalanches occur in weakly cemented, fine-grained soils that form steep, stable slopes under non-seismic conditions; such avalanches occurred in the New Madrid, Missouri, earthquakes of 1811–1812. Earthquake-induced underwater landslides can occur at the margins of river deltas where many port facilities are located; this happened during the 1964 Alaska earthquake.

Most clay soils lose strength when disturbed by ground shaking; some clays, called "quick" or "sensitive," may fail. The five large landslides that affected parts of Anchorage, Alaska, during the Prince William Sound earthquake in 1964 were examples of such failures.

Ground Failure Caused by Liquefaction. Liquefaction is not a type of ground failure; rather it is a physical process that can lead to ground failure. In liquefaction, clay-free soil deposits, primarily sands and silts, temporarily lose strength and behave as viscous fluids rather than as solids.

Liquefaction occurs primarily in areas where sands and silts have been deposited during the past 10,000 years and where ground water is within 30 feet of the surface. Liquefaction occurs when seismic shear waves (S waves) pass through such a saturated, granular soil layer, distorting its structure and causing some of the void spaces to collapse. Disruptions of the soil generated by these collapses cause transfer of the ground shaking load from grain-to-grain contacts in the soil to the water that fills the pores in the soil. This load transfer increases pressure in the pore water, which either causes drainage or, if drainage is restricted, causes increased pore-water pressure. When the pore-water pressure increases to approximately the pressure caused by the weight of the column of soil, the granular soil layer behaves like a fluid rather than a solid for a short period of time. This is liquefaction, and in this condition, deformations can occur easily.

Liquefaction causes three types of ground failure: loss of bearing strength, lateral spreads, and flow failures.

Loss of bearing strength occurs when the soil supporting a building or some other structure liquefies and loses strength; as a consequence, large deformations can occur within the soil, allowing the structure to settle and tip. The most spectacular example of bearing-strength failures took place during the 1964 earthquake in Niigata, Japan, where several multi-story apartment buildings tipped as much as 60 degrees. Most of the buildings were later jacked back into an upright position and reoccupied.

Lateral spreads involve the lateral movement of large blocks of soil as a result of liquefaction in a subsurface layer. Movement takes place in response to the ground shaking generated by an earthquake. Lateral spreads generally develop on gentle slopes, most commonly between 0.3 and 3 degrees. Horizontal movements in lateral spreads are commonly up to 10 or 15 feet, but where the slope is favorable and the duration of ground shaking is long, lateral movement may be as much as 100–150 feet. Lateral spreads are rarely catastrophic, but can be quite disruptive. During the 1964 Alaska earthquake, more than 200 bridges were damaged or destroyed by lateral spreading of flood plain deposits toward river channels. In the 1906 San Francisco earthquake, a number of major pipelines were broken by lateral spreading. This hampered efforts to fight fires which caused most of the damage in the city.

Flow failure, in which either a layer of liquefied soil rides on top of another or blocks of intact material ride on top of liquefied soil, can be catastrophic. Flow failures usually form in loose, saturated sands or silts on slopes greater than 3 degrees. They can originate either on land or underwater. Some of the most damaging flow failures have occurred underwater in coastal areas; such submarine failures carried away large sections of port facilities during the 1964 Alaska earthquake. The flow failures in turn generated large sea waves that inundated portions of the coastal area, causing additional damage and casualties. There have also been catastrophic flow failures on land, such as those induced by the 1920 earthquake in Kansu, China which killed 200,000 people. Some of these were as much as a mile in length and breadth.

Tsunamis. Tsunamis, sometimes called seismic sea waves, are ocean waves that are most often caused by the sudden vertical movement of a large portion of the sea floor during an earthquake. They can also be caused by undersea volcanic eruptions and submarine landslides. They can cause severe coastal flooding, both locally and at great distances across the sea. Tsunamis are discussed later in this chapter.

Earthquake Prediction

There have been many attempts to predict earthquakes, with mixed success. Studies of regional seismicity and of the geographical distribution of seismic zones have made it possible, within the framework of historical incidence and global tectonics, to predict the regions in which earthquakes are likely to occur. The problem is to specify, with some precision, their likely location, time, and magnitude.

Long term, regional predictions draw on research results indicating that zones of seismic activity appear to migrate with some consistency and that major destructive earthquakes do not recur in the same place until several decades or more have elapsed, during which time additional strain can accumulate. As a consequence, present quiescent zones are believed to present the greatest danger of future earthquakes. These areas, known as "seismic gaps," are regions along tectonic plate boundaries where large earthquakes have occurred, but not within the past few decades, and where nearby parts of plate boundaries have either released strain energy within the past few decades or have no history of great earthquakes.

Short term, local predictions are based primarily on precursor events such as changes in the electrical resistivity of earth materials, changes in seismic activity, reorientation of rock stress, increases in the amount of radon gas in well water, and anomalous behavior on the part of animals.

VOLCANIC ERUPTIONS

Volcanoes have played a key role in forming and modifying our world. More than 80% of the earth's surface, both above and below sea level, is of volcanic origin. Gaseous emissions from volcanic vents over hundreds of millions of years formed the earth's earliest oceans and atmosphere, and supplied the ingredients vital to evolve and sustain life. Over geologic eons, volcanic eruptions have produced mountains, plateaus, and plains, which subsequent weathering and erosion have sculpted into majestic landscapes or reduced to highly fertile soils. Ironically, these fertile soils and inviting terrains have attracted people to live on the flanks of volcanoes, exposing them to the destructive forces of the eruptions.

A volcano is a vent or chimney to the earth's surface from a reservoir of molten matter, called magma, in the depths of the earth's crust. The material ejected through the vent frequently accumulates around the opening, building up a cone called the volcanic edifice. The tallest mountains on earth are volcanic edifices. The term volcano includes both the vent and the cone around it.

Volcanic eruptions vary between two extremes. In one, lava rises more or less quietly to the surface and overflows the lip of the crater. The gasses bubble through the lava and escape undramatically or, in some instances, rush out with sufficient force to form lava fountains hundreds of meters in height. In either case, the lava is not disrupted, but flows away as a river, with little damage other than to objects in its path. At the other extreme, tremendous explosions occur in the chimney. These explosions may be so severe that they disrupt the cone, blowing away large sections and spreading debris around the countryside. In these volcanoes, the molten rock never reaches the surface as a liquid (lava); instead, as it rises into zones of less pressure it "froths" and solidifies, and is ejected as ash and pumice. The major differences between the two extremes are in the chemical composition of the magma and gas content of the lava and the manner in which gas is released when the lava reaches the surface. The majority of volcanic eruptions are intermediate between the two extremes, producing both lava flows and eruptions of ash, pumice, and other fragmentary material.

Volcanic Materials

The basic ingredients of a volcanic eruption are molten rock and an accumulation of gasses. Driven by buoyancy and gas pressure, the molten rock, which is less dense than the surrounding solid rock, forces its way upward and ultimately breaks through zones of weakness in the earth's crust. The molten rock may pour from the vent as a flow of molten lava or it may shoot violently into the air as a dense cloud of lava fragments. The largest fragments fall back around the vent, and accumulations of these fragments may flow downslope as ash-flows under the influence of gravity. Smaller fragments may be carried by the wind to fall to the ground some distance away. The finest particles may rise high into the atmosphere and be carried many times around the earth by stratospheric winds before descending.

Molten rock that rises in volcanic vents from below the earth's surface is called magma; after it erupts from a volcano it is called lava. Upon cooling, liquid magma precipitates crystals of various minerals until solidification is complete, forming igneous rock. Lava is red hot when it pours or blasts out of a vent, but soon changes to dark red, gray, or black, as it cools and solidifies. Very hot, gas-rich lava containing large amounts of iron and magnesium is fluid and flows like hot tar, while cooler, gas-poor lava high in silicon, sodium, and potassium flows sluggishly, like thick honey, or even in pasty, blocky masses.

As magma rises to the surface, the confining pressures are reduced and dissolved gasses are liberated, either quietly or explosively. If the lava is thin and non-viscous, the gasses escape easily. If it is thick and viscous, the gasses build up tremendous pressure and ultimately escape with explosive violence, throwing out great masses of solid rock, as well as lava, dust, and ashes.

The violent separation of gas from lava may produce rock froth called pumice. Some of this froth is so light that it floats on water. In many eruptions, the froth is shattered explosively into small fragments that are hurled high into the air as volcanic cinders (red or black), volcanic ash (commonly tan or gray), and volcanic dust.

Types of Volcanoes

There are four basic types of volcanoes: cinder cones, shield volcanoes, lava domes and composite volcanoes.

Cinder cones. Cinder cones are the simplest type of volcanoes. They are built from particles and blobs of congealed lava ejected from a single vent. As the gas-charged lava is blown violently into the air, it breaks into small fragments that solidify and fall as cinders around the vent to form a circular or oval cone. The typical cinder has a bowl-shaped crater at the summit and rises less than 300 meters above its surroundings.

In 1943, a cinder cone began to grow on a farm near the village of Parícutin, Mexico. Explosive eruptions caused by gas rapidly expanding and escaping from molten lava formed cinders that fell back around the vent, building the cone to a height of 360 meters. The last explosive eruption left a funnel-shaped crater at the top of the cone. After the excess gasses had largely dissipated, molten rock quietly poured out onto the surrounding surface of the cone and moved downslope as a lava flow. During 9 years of activity, Parícutin built a prominent cone, covered about 260 square kilometers (100 square miles) with ashes, and destroyed the town of San Juan.

Shield Volcanoes. Some of the largest volcanoes in the world are shield volcanoes. Shield volcanoes are built almost entirely of lava. Flow after flow pours out in all directions from a central vent or group of vents, building a broad, gently sloping, dome-like cone with a profile similar to a warrior's shield. These volcanoes are built up slowly by the accretion of thousands of highly fluid, basaltic lava flows that spread widely over a large area and then cool as gently dipping sheets. The Hawaiian Islands are composed of shield volcanoes. Mauna Loa on the island of Hawaii is the world's largest active volcano. Its top is more than 4,700 meters above sea level, and more than 9,200 meters above its base on the deep ocean floor.

Lava Domes. Lava dome volcanoes are formed by relatively small, bulbous masses of lava that are too viscous to flow any great distance and pile up over and around the vent. A lava dome grows primarily by expansion from within. As it grows, its outer surface cools and hardens and then shatters, spilling loose fragments down its sides. Some domes form craggy knobs or spines over the vent, while others form short, steep lava flows called coulees. Lava domes sometimes occur within the craters or on the flanks of large composite volcanoes.

Composite Volcanoes. The essential feature of a composite volcano is a conduit system through which magma from a reservoir deep in the earth's crust rises to the surface. The volcano is built up by the accumulation of material erupted through the conduit and increases in size as alternating layers of lava, volcanic ash, cinders, and blocks are deposited on its slopes. Many composite volcanoes are characterized by explosive eruptions. Composite volcanoes are typically tall, steep, symmetrical cones that may rise as much as 2,500 meters above their bases. Some of the most conspicuous and beautiful mountains in the world are composite volcanoes, including Mount Fuji in Japan, Mount Cotopaxi in Ecuador, Mount Shasta in California, Mount Hood in Oregon, and Mount St. Helens and Mount Rainier in Washington.

A composite volcano typically has a crater at the summit that contains a central vent or a clustered group of vents. Lava flows through breaks in the crater wall or through fissures on the flanks near the base of the cone. Lava that solidifies within the fissures forms dikes that act as ribs and greatly strengthen the cone.

Examples of Volcanic Eruptions: La Soufriere and Jorullo

The volcano La Soufriere occupies the northern end of the island of St. Vincent, 140 kilometers (87 miles) to the south of Martinique in the West Indies. The summit of La Soufriere is nearly 1,300 meters above sea level and consists of two craters.

The first symptoms of unrest in the volcano occurred in April, 1901. Earthquakes occurred with sufficient severity that the people living on the western slope of La Soufriere became alarmed and some considered leaving the area. However, earthquake activity ceased, and people resumed their normal activities until a year later, when earthquake shocks were again felt. It was commonly believed that in the event of an eruption, the ash and gasses would be carried to the west by the prevailing winds. By May 1, 1902, the inhabitants on the leeward side of the volcano north of Chateaubelair had sought refuge elsewhere; if they had not done so, the ultimate death toll would have been much greater. Those living on the windward side were not particularly disturbed and did not evacuate.

On May 7, an eruption occurred with a hot blast that overturned trees, scorching them on the side facing the volcano. It destroyed houses and set fire to inflammable objects. Hot ash fell in great quantities, killing all vegetation and devasting one-third of the island. Red hot stones up to 15 centimeters (6 inches) in diameter fell in Georgetown, nine kilometers (5.5 miles) from the crater. The orientation of the trees blown down indicated that the blast swept outward in all directions from the crater. More than 1,300 people were killed.

At the end of the eruption, La Soufriere showed no signs of dome development and was therefore considered capable of further destructive eruptions.

A minor eruption occurred in 1971, but another major eruption did not occur until April 14, 1979, when St. Vincent Island was shaken by a violent eruption that sent stones raining down on parts of the island while a cloud of smoke and ash blocked the noontime sun. The eruption hurled ashes and smoke more than 6,000 meters into the air, showering Barbados, 160 kilometers (100 miles) to the east, with volcanic dust. Rumblings could be heard as far away as Kingstown, more than 20 kilometers (12 miles) to the south. Radio reports indicated that lava was flowing from one side of the crater. People on the northern half of the island were told to head for the beaches where boats would take them to safety; 17,000 people were evacuated.

Seven small explosions, at intervals of only a few minutes, shook the volcano on April 18. These explosions threw ash and steam into the air north of the Larikai Valley, where lava had poured down the volcano's sides on the previous day after the eighth violent eruption in 5 days. On April 22, the volcano erupted intermittently for 3 hours, sending a column of ash more than 11 kilometers (7 miles) into the air and shaking the earth with tremors.

The volcano Jorullo, in western Mexico, was born on September 29, 1759, in the midst of an area that was undergoing cultivation. It is one of the best known volcanoes born during historic times.

Jorullo is located in the state of Michoacan, about 240 kilometers (150 miles) west of Mexico City. Because of the fertile soil and tropical climate, the area was known as Jorullo, which in the language of the Tarascan Indians means "paradise."

At the time of the eruption, the Hacienda de Jorullo was one of three farms in the area producing sugar and cattle. From late June until the middle of September, 1759, the people living at the Hacienda de Jorullo were alarmed by subterranean noises accompanied by mild earthquakes. Starting on September 17, the noises became much louder and were compared to cannon fire, and the earthquakes became strong enough to seriously damage the chapel. The frightened people fled to the surrounding hills for safety. At 3:00 A.M. on September 29, a dark and dense steam cloud rose in a ravine known as Cuitinga Creek, about a kilometer southeast of the Hacienda. There were sharp earth tremors and loud explosions as flames burst through the cloud, which was becoming thicker and denser. For two days, the volcano threw out what were described as masses of "sand [cinders], fire, and thunder without one minute cessation." On October 1, a mass of "sand so hot it set fire to whatever it fell upon" rose from the volcano's outlet, which was little more than a cleft, and flowed for a kilometer down Cuitinga Creek.

Violent eruptions continued until February 1760, with decreasing intensity until about 1775. There were at least four separate lava flows, forming a great wasteland that covered 9 square kilometers to depths of 100 meters. The first three flows are now covered with ash and cinders, indicating that these materials were still being ejected after the outpouring of lava. The last flow, which issued from a breach on the north rim of the crater and flowed as a great cascade down the north side of the cone, is free of any ash or cinder cover. This "frozen" cascade of black lava is still quite "new" and "fresh" looking and is one of the striking features of Jorullo. It seems likely that this marked the end of Jorullo's explosive activity and that thereafter it was in a venting or fumarolic state.

Jorullo is now 1,330 meters high. The crater is an oval-shaped depression about 500 meters in diameter and 150 meters deep. The bottom of the crater appears to have collapsed since its last eruptive activity, and the bottom is filled with rubble that has fallen from the sides. At a depth of less than a meter below the rubble, the heat is too intense for the hand, but not sufficient to brown a piece of paper or to evaporate water.

Geographical Distribution of Volcanoes

About 500 volcanoes worldwide can be considered active, in that they have erupted during historic times. Many more can be described as dormant; that is, although they have not erupted for thousands of years, they could become active again at any time. Mount Lamington in New Guinea, for example, erupted violently in 1951 when it had been thought to be inactive. Volcanoes are described as extinct only when there is no chance of renewed eruption. This usually happens when a change in the geological environment has effectively defused a once-active volcano.

Over the millions of years of geological history, volcanoes have existed in almost every part of the world and formed enormous volumes of rock. The entire landmass of Iceland was formed from a continuous series of volcanoes. Today, active volcanoes are found in clearly delineated volcanic belts. The majority of volcanoes are found in the circum-Pacific belt; most of the remaining volcanoes lie in a belt that runs down the middle of the Atlantic Ocean. Like earthquakes, volcanoes are phenomena that are associated with the enormous geological forces that are involved where the plates of the earth's crust move against each other. The cirum-Pacific "Ring of Fire" and the mid-Atlantic Ridge are well known plate boundaries. The Mediterranean and East and West Indies plate boundaries also have a fair share of volcanoes. There are other volcanic areas, especially in eastern Africa. The volcanoes there are associated with the Rift Valley system, which may be a very young plate boundary where Africa would be splitting apart, if it were not for the far more powerful mid-Atlantic plate boundary that compresses Africa. Even though the Rift Valley may represent a plate boundary, other volcanoes are found far from the edges of the plates. The inactive volcanoes of the Saharan Tibetsi mountains, as well as the active volcanoes on Hawaii, are situated in the middle of plates. They are totally unrelated to plate boundaries, and owe their existence to hot spots in the earth's internal structure that have penetrated through the overlying plates.

Destruction Caused by Volcanoes

The damage and destruction associated with a volcanic eruption can take many forms. Close to the volcano, the explosive blast associated with the eruption can destroy houses, bridges, timber, and crops and can kill people and animals. Flying and falling "bombs" and blocks of solid material may crash through houses and trees, killing and injuring people and animals and starting fires. Lava flows can inundate large areas and cause fires.

At greater distances, the solid material remaining in the atmosphere is in the form of ash, which is seldom hot enough to start fires when it reaches the ground. The weight of deposited ash may cause roofs to cave in. During the 1971 eruption of Fuego in Guatemala, a layer of ash 30 centimeters (12 inches) deep caused about one fifth of the roofs in the town of Yepocapa, 8 kilometers (5 miles) distant, to collapse. When Vesuvius erupted in 1906, the inhabitants of the town of Ottaviano congregated in the church to pray and most were killed when the roof collapsed under the weight of ash. Heavy ash loads can break the branches of broad-leaved trees (conifers, which are adapted to winter snow loads, are more resilient) and do serious damage to fruit and nut orchards. Ash piling up around the trunks of trees can kill them. Ash can affect the local ecology and clog harvesting machines, leading to significant crop loss. Heavy ash falls may disrupt water supplies and cause flooding by clogging streams, wells, filters in water systems, and storm drains. Leaching of the ash may cause water to become acid. Ash-laden air can be intensely irritating and hazardous. Ash can darken the sky and limit visibility. Electrical storms can develop within the ash cloud and make radio communication impossible. Lightning within the storms can start fires, and heavy rain within the storms can convert the dry ash into a heavy sodden mass.

Large quantities of dust, ash, and pumice, called tephra, that pile up on steep volcanic slopes readily become unstable, especially if saturated with water from heavy local storms that are generated by an eruption. The finer tephra, or ash, can very easily move down the slope, and although it may do so when dry, it more often moves as a "liquid" mud flow. Volcanic mudflows, called lahars, can also occur when the heat of the eruption melts enormous quantities of snow and ice near the volcano's summit, generating large quantities of mud that flow downslope through valleys. In Colombia, the eruption of Nevado del Ruiz in November 1985 melted snow and ice to cause a mudflow that buried the town of Armero, killing more than 20,000 people.

Volcanic eruptions can generate tsunamis that can cause severe coastal flooding, both locally and on shores thousands of miles away, and that can cause more death and destruction than the eruption itself.

Predicting and Responding to Eruptions

Predicting volcanic eruptions is not a precise art. Geological precursors can be used as a basis for installation of site-specific sensors and monitors, which together with observations of anomalous animal behavior can be a basis for warnings and evacuations. Differences in interpretation may make it difficult to determine the need for evacuation. Precursors had warned of the Nevado del Ruiz eruption for more than a month, and a recommendation had been made to evacuate the town of Armero on the day of the eruption, but for various reasons, the population was not alerted and that night, the town was destroyed.

Once an eruption has occurred, little can be done to mitigate the effects of blast and flying solid masses. Ash accumulation can be removed from roofs as quickly as possible to prevent collapse, but nothing can be done about accumulations of ash in the atmosphere which will fall over time. Many kinds of lava flows can be diverted and channeled by means of hastily erected diversion barriers, and some lava flows can be checked by spraying with water.

TSUNAMIS

Tsunamis are ocean waves that are caused by vertical movements of the sea floor associated with earthquakes, submarine volcanic eruptions, and submarine landslides. These waves may be only a foot or two high in the open ocean and may be as much as 300 miles from crest to crest. They can not be seen from the air, nor can they be detected from ships that pass over them. They can travel enormous distances at speeds of up to 600 miles/hour. When they reach shallow water, their characteristics change. The speed diminishes and the height may grow to as much as 80 feet, creating a gigantic wall of water that moves onto the shore as a devastating surge. A tsunami may strike the shore as a single wave or as a series of half a dozen or more waves about 20–40 minutes apart. The first of these is often preceded by a dramatic ebb of water from the shore that exposes the sea bottom; in the absence of a warning system, this may be the first local indication of the approach of a tsunami, and the warning time it provides may be no more than a matter of minutes.

The greatest destruction associated with tsunamis usually occurs at the water's edge, where the force of the waves is greatest. People swept away by the waves are usually drowned and never found; loss of life is a more significant problem than injuries. There have been a number of instances when curious onlookers ventured into the offshore areas as the initial ebb of water occurred, only to be swept away by the tsunami waves when they arrived. Ships moored in harbors are often swamped and sunk or are left battered and stranded high on the shore. Breakwaters and piers collapse, either because of scouring actions that sweep away their foundation material or because of the sheer impact of the waves. Tsunami waves have bent railroad tracks and moved locomotives, carried large boats miles inland, and destroyed concrete sea walls. Tsunamis cause extensive flooding, and the force of floating debris borne by the waves can cause damage some distance inland.

Tsunamis have occurred all over the world, but they are most common in the Pacific Ocean, which is ringed by zones of high seismic and volcanic activity.

The Hawaiian and Chilean Tsunamis of 1946 and 1960

On April 1, 1946, a tsunami struck the Hawaiian Islands, killing more than 150 people (primarily through drowning), injuring many more, and causing $25 million in damage. The tsunami was triggered by an earthquake that had occurred 6 hours earlier about 2,200 miles to the north in the Aleutian-Alaskan trench. The waves that swept up on the Hawaiian shores varied greatly in nature from place to place. In some places, the water rose gently; at those locations most of the damage resulted from the violent run-back of the water to the sea. However, in most places the waves swept ashore with great turbulence.

The tsunami caused damage to buildings, roads, railroads, bridges, piers, breakwaters, fish-pond walls, and ships. Many frame buildings along the shore were knocked over by the force of the waves; others had their foundations destroyed. Some houses that were sufficiently well built and tied together internally to resist being destroyed were moved significant distances. Railroads along the northern coast of Oahu and Hilo were wrecked through destruction of their road beds and shifting of tracks. Highway and railroad bridges were destroyed, often lifted entirely from their foundations by the buoyancy of the water. Beaches were extensively eroded, and considerable damage was caused to house furnishings and personal property by flooding.