9 Hazardous environments

9.1 Hazards resulting from tectonic processes

Global distribution of tectonic hazards

Distribution of earthquakes

Tectonic hazards include seismic activity (earthquakes), volcanoes and tsunamis. Most of the world's earthquakes occur in clearly defined linear patterns (Figure 9.1). These linear chains generally follow plate boundaries. For example, there is a clear line of earthquakes along the centre of the Atlantic Ocean in association with the Mid-Atlantic Ridge (a constructive plate boundary). Similarly, there are distinct lines of earthquakes around the Pacific Ocean. In some cases, these linear chains are quite broad, for example the line of earthquakes along the west coast of South America and around the eastern Pacific associated with the subduction of the Nazca Plate beneath the South American Plate – a destructive plate boundary. Broad belts of earthquakes are associated with **subduction zones** (where a dense ocean plate plunges beneath a less dense continental plate), whereas narrower belts of earthquakes are associated with constructive plate margins, where new material is formed and plates are moving apart. Collision boundaries, such as in the Himalayas, are also associated with broad belts of earthquakes, whereas conservative plate boundaries, such as California's San Andreas fault line, give a relatively narrow belt of earthquakes (this can still be over 100 kilometres wide). In addition, there appear to be isolated occurrences of earthquakes. These may be due to human activities, or to isolated plumes of rising **magma**, known as 'hotspots'.

Distribution of volcanoes

Most volcanoes are found at plate boundaries (Figure 9.1) although there are some exceptions, such as the volcanoes of Hawaii, which occur over hotspots. About three-quarters of the Earth's 550 historically active volcanoes lie along the Pacific Ring of Fire. This includes many of the world's most recent volcanoes, such as Mt Pinatubo

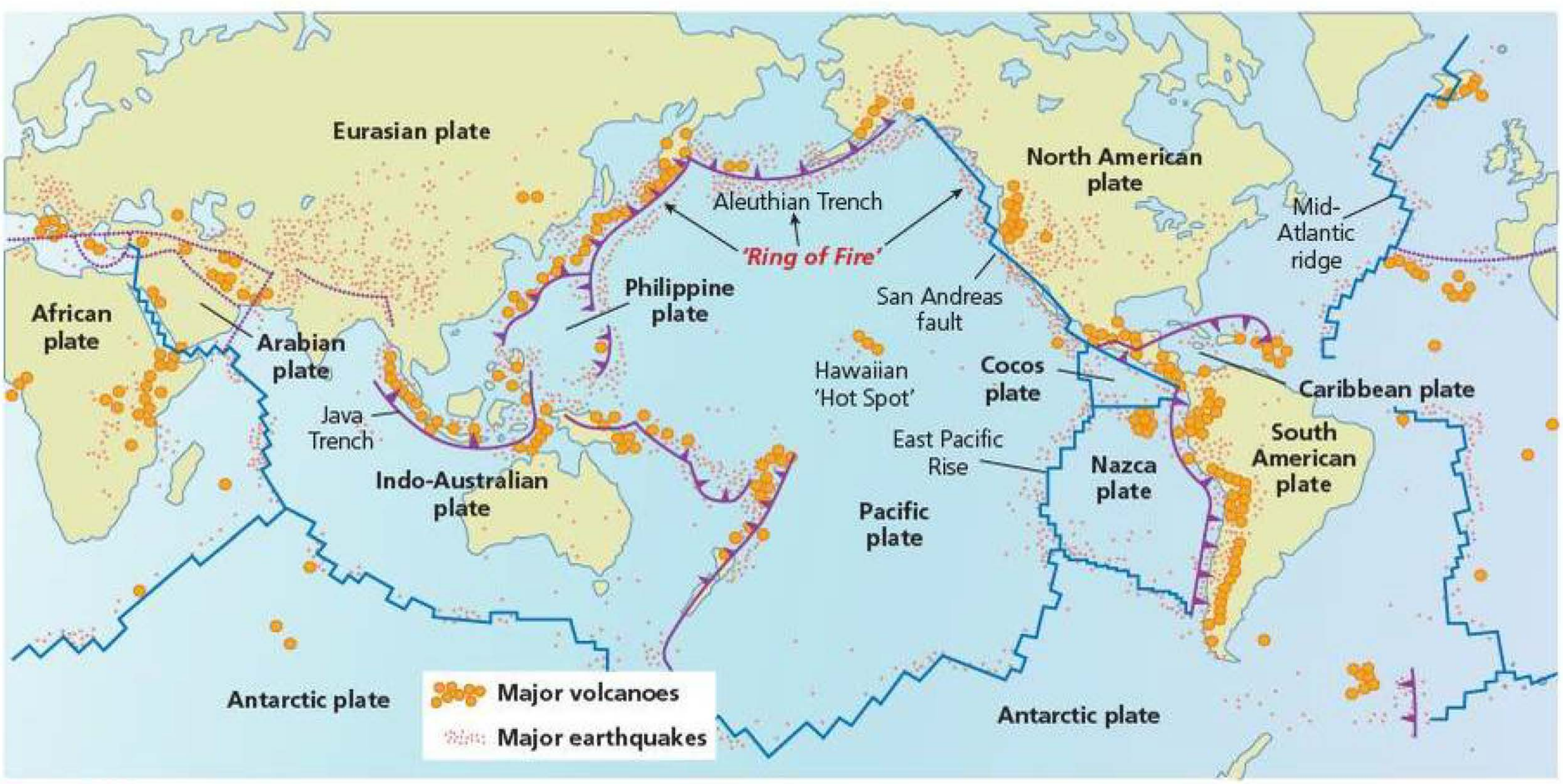


Figure 9.1 Distribution of plates, plate boundaries, volcanoes and earthquakes

in the Philippines, Mt Unzen (Japan), Mt Agung (Java), Mt Chichon (Mexico), Mt St Helens (USA) and Nevado del Ruiz (Colombia). Other areas of active vulcanicity include Iceland, Montserrat in the Caribbean and Mt Nyiragongo in Democratic Republic of Congo. Most volcanoes that are studied are above land, but some submarine volcanoes, such as Kick 'em Jenny off Grenada in the Caribbean, are also monitored closely.

Volcanoes are found along the boundaries of the Earth's major plates. Although the deeper levels of the Earth are much hotter than the surface, the rocks are usually not molten because the pressure is so high. However, along the plate boundaries there is molten rock – magma – which supplies the volcanoes.

Most of the world's volcanoes are found in the Pacific Rim or Ring of Fire (Figure 9.1). These are related to the subduction beneath either oceanic or continental crust. Subduction in the oceans provides chains of volcanic islands known as 'island arcs', such as the Aleutian Islands formed by the Pacific Plate subducting beneath the North American Plate. Where the subduction of an oceanic crust occurs beneath the continental crust, young fold mountains are formed. The Andes, for example, have been formed where the Nazca Plate subducts beneath the South American Plate.

Not all volcanoes are formed at plate boundaries. Those in Hawaii, for example, are found in the middle of the ocean (Figure 9.2). The Hawaiian Islands are a line of increasingly older volcanic islands that stretch north-west across the Pacific Ocean. These volcanoes can be related to the movement of plates above a hot part of the fluid mantle. A mantle plume or hotspot – a jet of hot material rising from deep within the mantle – is responsible for the volcanoes. Hotspots can also be found beneath continents, as in the case of the East African Rift Valley, and can produce isolated volcanoes. These hotspots can play a part in the break-up of continents and the formation of new oceans.

At subduction zones, volcanoes produce more viscous lava, tend to erupt explosively and produce much ash. By contrast, volcanoes that are found at mid-ocean ridges or hotspots tend to produce relatively fluid basaltic lava, as in the case of Iceland and Hawaii. At mid-ocean ridges, hot fluid rocks from deep in the mantle rise up due to convection currents. The upper parts of the mantle begin to melt and basaltic lava erupts, forming new oceanic crust. By contrast, at subduction zones a slab of cold ocean floor slides down the subduction zone, warming up slowly. Volatile compounds such as water and carbon dioxide leave the slab and move upwards into the mantle so that it melts. The hot magma is then able to rise.

Huge explosions occur wherever water meets hot rock. Water vaporises, increasing the pressure until the rock explodes. Gases from within the molten rock can also build up high pressures. However, the likelihood of a big, explosive eruption depends largely on the viscosity of the magma and hence its composition. Gases dissolve quite easily in molten rock deep underground due to the very high pressures there. As magma rises to the surface, the pressure drops and some of the gas may become insoluble and form bubbles. In relatively fluid magma, the bubbles rise to the surface. By contrast, viscous magma can trap gas so that it builds up enough pressure to create a volcanic eruption.

The style of eruption is greatly influenced by the processes operating at different plate boundaries, which produce magma of different, but predictable, composition. Some minerals melt before others in a process called partial melting. This alters the composition of molten rock produced. Partial melting of the Earth's mantle produces basalt. At subduction zones, the older and deeper slabs experience greater partial melting and this produces a silica-rich magma.

Source: *Advanced Geography: Concepts & Cases* by P. Guinness & G. Nagle (Hodder Education, 1999), p.339

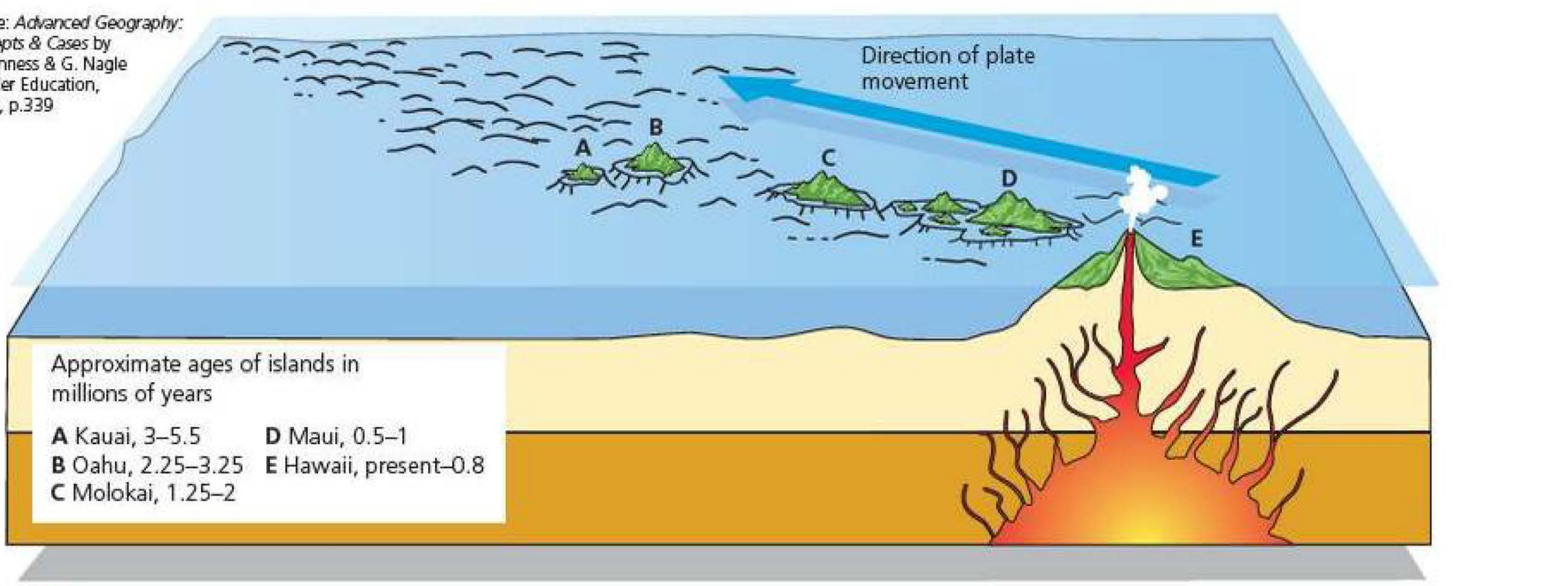


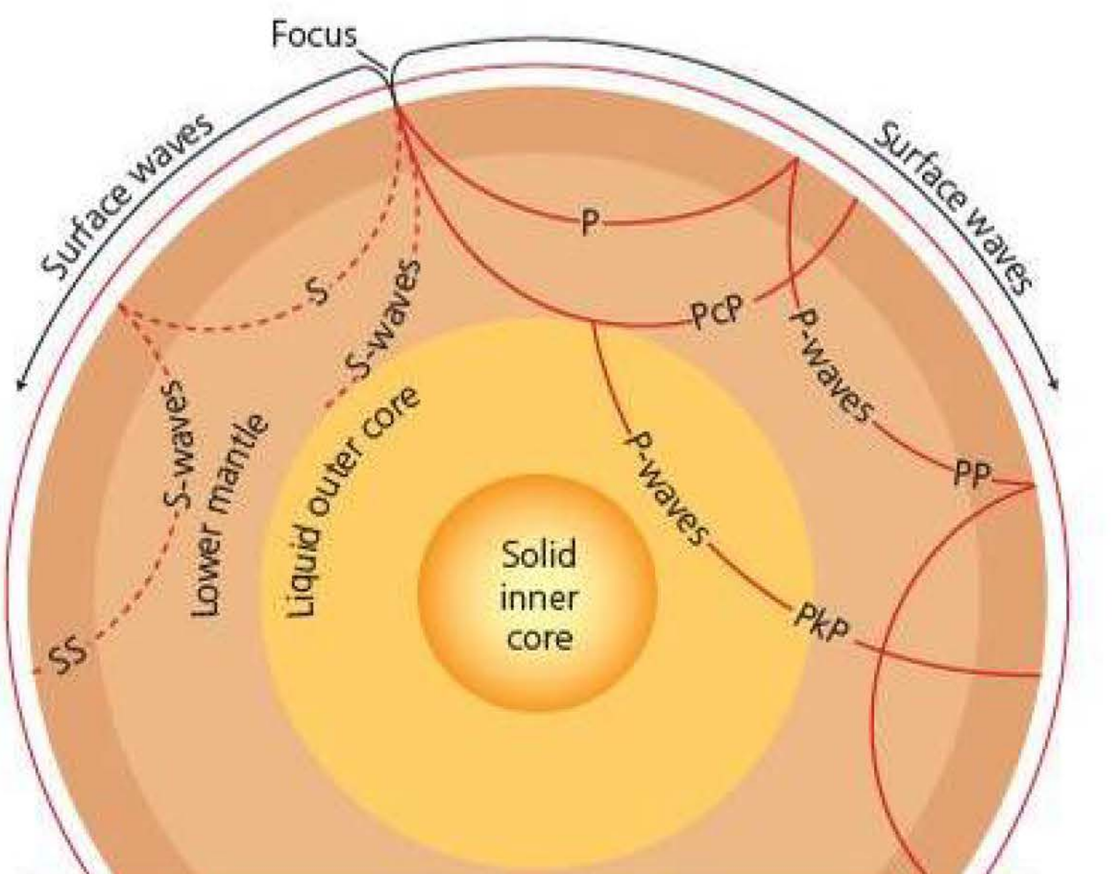
Figure 9.2 Hotspots and the evolution of Hawaii

Tsunamis

Up to 90per cent of the world's tsunamis occur in the Pacific Ocean. This is because they are associated with subduction zones and, as Figure 9.1 shows, most subduction zones are found in the Pacific Ocean.

Earthquakes and resultant hazards

An earthquake is a series of vibrations or seismic (shock) waves that originate from the focus – the point at which the plates release their tension or compression suddenly (Figure 9.3). The **epicentre** marks the point on the surface of the Earth immediately above the focus of the earthquake. A large earthquake can be preceded by smaller tremors known as **foreshocks** and followed by numerous **aftershocks**. Aftershocks can be particularly devastating because they damage buildings that have already been damaged by the first main shock. Seismic waves are able to travel along the surface of the Earth and also through the body of the Earth.



Source: *Advanced Geography: Concepts & Cases* by P. Guinness & G. Nagle (Hodder Education, 1999), p.334

Figure 9.3 Seismic waves

Following an earthquake, two types of **body waves** (waves within the Earth's interior) occur. The first are P-waves (primary waves or pressure waves) and the second are the transverse S-waves. These are a series of oscillations at right-angles to the direction of movement.

P-waves travel by compression and expansion, and are able to pass through rocks, gases and liquids. S-waves travel with a side-to-side motion, and are able to pass through solids but not liquids and gases, since they have no rigidity to support sideways motion. In 1909, Andrija Mohorovičić, a Yugoslavian geophysicist who was studying earthquakes in Croatia, detected four kinds of seismic wave, two of them pressure waves and two of them shear waves. Seismographs close to the earthquake epicentre showed slow-travelling P-waves and S-waves. By contrast, those further away from the shock showed faster-moving S-waves and P-waves. These shock waves are reflected or refracted when they meet rock with different densities. If the shock waves pass through denser rocks, they speed up. If they pass through less dense rocks, they slow down. Mohorovičić deduced that the slower waves had travelled from the focus of the earthquake through the upper layer of the crust. By contrast, the faster waves must have passed through the denser material in the Earth's core; this denser material speeded up the waves and deflected them. He suggested that a change in density from 2.9g/cm³ to 3.3g/cm³ marks the boundary between the Earth's crust and the mantle below. This boundary is known as the 'Mohorovičić Discontinuity' or quite simply the 'Moho'.

Later geologists found a shadow zone, an area between 105° and 142° from the source of the earthquake, within which they could not detect shock waves. The explanation was that the shock waves had passed from a solid to a liquid. Thus S-waves would stop and P-waves would be refracted. The geologists concluded that there was a change in density from 5.5g/cm³ at 2900kilometres to a density of 10g/cm³. This was effectively the boundary between the mantle and the core. Within the Earth, there is an inner core of very dense solid material – the density of the inner core goes up to as much as 13.6g/cm³ at the centre of the Earth.

When P- and S-waves reach the surface, some of them become surface waves. Love waves cause the earth to move sideways whereas Rayleigh waves cause the earth to move up and down. Surface waves often do the most damage in an earthquake.

The nature of rock and sediment beneath the ground influences the pattern of shocks and vibrations during an earthquake. Unconsolidated sediments such as sand shake in a less predictable way than solid rock. Hence the damage is far greater to foundations of buildings. P-waves from earthquakes can turn solid sediments into fluids like quicksand by disrupting sub-surface water conditions. This is known as **liquefaction** or **fluidisation** and can wreck foundations of large buildings and other structures.

Resultant hazards of earthquakes

Most earthquakes occur with little, if any, advance warning. Some places, such as California and Tokyo, which have considerable experience of earthquakes, have developed 'earthquake action plans' and information programmes to increase public awareness about what to do in an earthquake.

Most problems are associated with damage to buildings, structures and transport systems (Table 9.1). The collapse of building structures is the direct cause of many injuries and deaths, but it also reduces the effect of the emergency services. In some cases, more damage is caused by the aftershocks that follow the main earthquake, as they shake the already weakened structures. Aftershocks are more subdued but longer lasting and more frequent than the main tremor. Buildings partly damaged during the earthquake may be completely destroyed by the aftershocks.

Table 9.1 Earthquake hazards and impacts

Primary hazard	Impacts
• Ground shaking • Surface faulting	• Loss of life • Loss of livelihood • Total or partial destruction of building structure • Interruption of water supplies • Breakage of sewage disposal systems • Loss of public utilities such as electricity and gas • Floods from collapsed dams • Release of hazardous material • Fires • Spread of chronic illness
Secondary hazard	
• Ground failure and soil liquefaction • Landslides and rockfalls • Debris flow and mudflow • Tsunamis	

Some earthquakes involve surface displacement, generally along fault lines. This may lead to the fracture of gas pipes, as well as causing damage to lines of communication. The cost of repairing such fractures is considerable.

Earthquakes may cause other geomorphological hazards such as landslides, liquefaction (the conversion of unconsolidated sediments into materials that act like liquids) and tsunamis. For example, the Good Friday earthquake (magnitude 8.5), which shook Anchorage (Alaska) in March 1964, released twice as much energy as the 1906 San Francisco earthquake, and was felt over an area of nearly 1.3 million km². More than 130 people were killed, and over $500 million of damage was caused. It triggered large avalanches and landslides that caused much damage. It also caused a series of tsunamis through the Pacific as far as California, Hawaii and Japan.

The relative importance of factors affecting earthquakes varies a great deal. For example, the Kobe earthquake of January 1995 had a magnitude 7.2 and caused over 5000 deaths. By contrast, the Northridge earthquake that affected parts of Los Angeles in January 1994 was 6.6 on the Richter Scale but caused only 57 deaths. On the other hand, an earthquake of force 6.6 at Maharashtra in India in September 1993 killed over 22 000 people.

So why did these three earthquakes have such differing effects? Kobe and Los Angeles are on known earthquake zones and buildings are built to withstand earthquakes. In addition, local people have been prepared for earthquake events. By contrast, Maharashtra has little experience of earthquakes. Houses were unstable and quickly destroyed, and people had little idea of how to manage the situation.

Another earthquake in an area not noted for seismic activity shows that damage is often most serious where buildings are not designed to withstand shaking or ground movement. In the 1992 Cairo earthquake, many poor people in villages and the inner-city slums of Cairo were killed or injured when their old, mud-walled homes collapsed. At the same time, many wealthy people were killed or injured when modern high-rise concrete blocks collapsed – some of these had actually been built without planning permission.

Earthquakes and plate boundaries

The movement of oceanic crust into the subduction zone creates some of the deepest earthquakes recorded, from 700 kilometres below the ground. When the oceanic crust slides into the hotter fluid mantle, it takes time to warm up. As the slab descends, it distorts and cracks and eventually creates earthquakes. However, subduction is relatively fast so by the time the crust has cracked it has slid several hundred kilometres down into the mantle.

In areas of active earthquake activity, the chances of an earthquake increase with increasing time since the last earthquake. Plates move at a rate of between 1.5 and 7.5 centimetres a year (the rate at which fingernails grow). However, a large earthquake can involve a movement of a few metres, which could occur every couple of hundred years rather than movements of a few centimetres each year. Many earthquakes are caused by the pressure created by moving plates. This increases the stress on rocks; the rocks deform and eventually give way and snap. The snapping is the release of energy; namely, the earthquake. The size of the earthquake depends upon the thickness of the descending slab and the rate of movement. Along mid-ocean ridges, earthquakes are small because the crust is very hot, and brittle faults cannot extend more than a few kilometres. The strength of an earthquake is measured by the Richter Scale and the Mercalli Scale.

The Richter and Mercalli Scales

In 1935, Charles Richter of the California Institute of Technology developed the Richter Scale to measure the magnitude of earthquakes. The scale is logarithmic, so an earthquake of 5.0 on the Richter Scale is 10 times more powerful than one of 4.0 and 100 times more powerful than one of 3.0. Scientists are increasingly using the Moment Magnitude Scale M, which measures the amount of energy released and produces figures that are similar to the Richter Scale. For every increase on the scale of 0.1, the amount of energy released increases by over 30. Every increase of 0.2 represents a doubling of the energy released.

By contrast, the Modified Mercalli Intensity Scale relates ground movement to commonplace observations around light bulbs and bookcases (Table 9.2). It has the advantage that it allows ordinary eyewitnesses to provide information on how strong the earthquake was. It is important to remember that these scales are only used to measure the 'strength' of an earthquake, not to predict earthquakes. Table 9.3 gives some idea of the number and magnitude of earthquakes experienced around the world each year.

Table 9.2 The Modified Mercalli Scale

1	Rarely felt.
2	Felt by people who were not moving, especially on upper floors of buildings; hanging objects may swing.
3	The effects are notable indoors, especially upstairs. The vibration is like that experienced when a truck passes.
4	Many people feel it indoors, a few outside. Some are awakened at night. Crockery and doors are disturbed and standing cars rock.
5	Felt by nearly everyone; most people are awakened. Some windows are broken, plaster becomes cracked and unstable objects topple. Trees may sway and pendulum clocks stop.
6	Felt by everyone; many are frightened. Some heavy furniture moves, plaster falls. Structural damage is usually quite slight.
7	Everyone runs outdoors. Noticed by people driving cars. Poorly designed buildings are appreciably damaged.
8	Considerable amount of damage to ordinary buildings; many collapse. Well-designed ones survive but with slight damage. Heavy furniture is overturned and chimneys fall. Some sand is fluidised.
9	Considerable damage occurs even to buildings that have been well designed. Many are moved from their foundations. Ground cracks and pipes break.
10	Most masonry structures are destroyed, sub-wooden ones survive. Railway tracks bend and water slops over river banks. Landslides and sand movements occur.
11	No masonry structure remains standing, bridges are destroyed. Broad fissures occur in the ground.
12	Total damage. Waves are seen on the surface of the ground, objects are thrown into the air.

Table 9.3 Annual frequency of occurrence of earthquakes of different magnitude based on observations since 1900

Descriptor	Magnitude (Richter Scale)	Annual average	Hazard potential
Great	≥ 8	1	Total destruction, high loss of life
Major	7–7.9	18	Serious building damage, major loss of life
Strong	6–6.9	120	Large losses, especially in urban areas
Moderate	5–5.9	800	Significant losses in populated areas
Light	4–4.9	6200	Usually felt, some structural damage
Minor	3–3.9	49000	Typically felt but usually little damage
Very minor	≤ 3	9000 per day	Not felt, but recorded

Factors affecting earthquake damage

The extent of earthquake damage is influenced by a variety of factors:

- **Strength and depth of earthquake and number of aftershocks** – The stronger the earthquake, the more damage it can do, for example an earthquake of 6.0 on the Richter Scale is 100 times more powerful than one of 4.0. The more aftershocks there are, the greater the damage that is done. Earthquakes that occur close to the surface (shallow-focus earthquakes) potentially should do more damage than earthquakes deep underground (deep-focus earthquakes) as more of the energy of the latter is absorbed by overlying rocks.
- **Population density** – An earthquake that hits an area of high population density, such as the Tokyo region of Japan, could inflict far more damage than one that hits an area of low population and building density.
- **The type of buildings** – HICs generally have better-quality buildings, more emergency services and the funds to recover from disasters. People in HICs are more likely to have insurance cover than those in LICs.
- **The time of day** – An earthquake during a busy time, such as rush hour, may cause more deaths than one at a quiet time. Industrial and commercial areas have fewer people in them on Sundays; homes have more people in them at night.
- **The distance from the centre (epicentre) of the earthquake** – The closer a place is to the centre (epicentre) of the earthquake, the greater the damage that is done.
- **The type of rocks and sediments** – Loose materials may act like liquid when shaken, a process known as 'liquefaction' ('fluidisation'); solid rock is much safer and buildings should be built on flat areas formed of solid rock.
- **Secondary hazards** – An earthquake may cause mudslides, tsunamis (high sea waves) and fires; also contaminated water, disease, hunger and hypothermia.
- **Economic development** – This affects the level of preparedness and effectiveness of emergency response services, access to technology and quality of health services.

Deaths following an earthquake can be substantial, as Table 9.4 shows quite clearly.

Table 9.4 The world's worst earthquakes by death toll in the twenty-first century

Country	Year	Death toll (est.)	Richter Scale
Haiti	2010	300000	7.0
South East Asia	2004	248000	9.1
Kashmir, Pakistan	2005	86000	7.6
Chengdu, China	2008	78000	7.9
Bam, Iran	2003	30000	6.6
Tohuku, Japan	2011	15891	9.0
Gorkha, Nepal	2015	9000	7.8

Case Study: Earthquake in Haiti – 12 January 2010, 16:53 local time, 7.0 magnitude

The country of Haiti occupies the western part of Hispaniola, a Caribbean island that it shares with the Dominican Republic. Haiti is characterised by poverty, environmental degradation, corruption and violence. On 12 January 2010, an earthquake recorded as 7.0 on the Richter Scale occurred 25 kilometres south-west of Port-au-Prince at a depth of just 13 kilometres (Figure 9.4). Aftershocks were as strong as 5.9, occurring just 9 kilometres below the surface and 56 kilometres south-west of the city. A third of the population were affected. About 300 000 people died as a result of the earthquake, 250 000 more were injured and some 1 million made homeless.

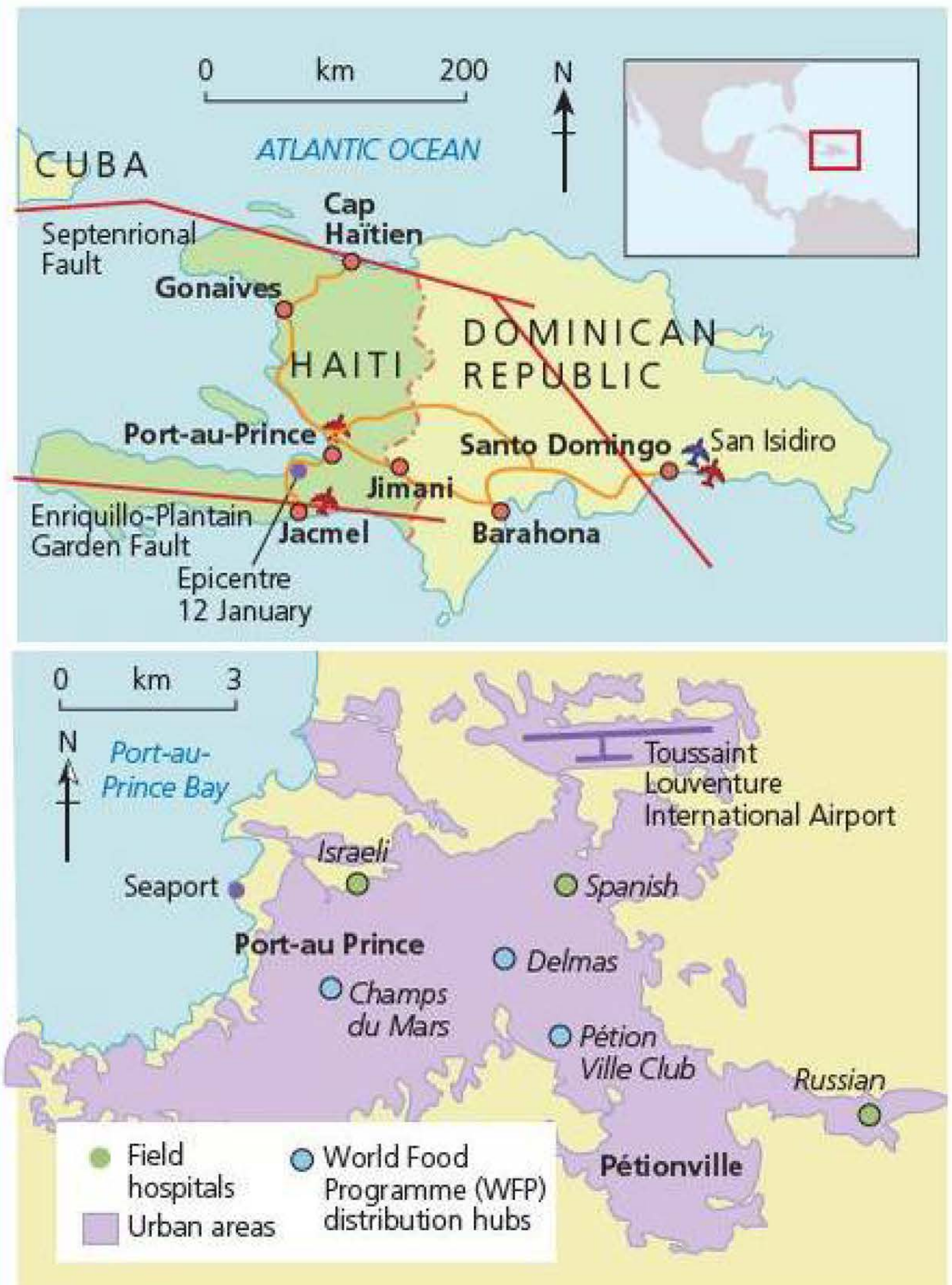


Figure 9.4 Haiti earthquake

Hispaniola sits on the Gonave microplate, a small strip of the Earth's crust squeezed between the North American and Caribbean tectonic plates. This makes it vulnerable to rare but violent earthquakes. The Dominican Republic suffered a serious 'quake in 1946, but the Enriquillo-Plantain Garden fault that separates the plates on the Haitian side of the border had been accumulating stress during more than a century of inactivity. Two things magnified its destructive power: its epicentre was just 25 kilometres south-west of Port-au-Prince and its focus was only 13 kilometres below ground.

The region is hopelessly ill-suited to withstand a shaking. Most of Port-au-Prince's 2 million residents live in tin-roofed shacks perched on unstable, steep ravines. After a school collapsed in the suburb of Pétionville in 2008, the capital's mayor said that 60 per cent of its buildings were shoddily constructed and unsafe even under normal conditions.

The Red Cross estimated that 3 million people – a third of Haiti's population – might need emergency aid. Seven days after the earthquake, the UN had managed to get food to only 200 000 people. Help – including doctors, trained sniffer dogs, and tents, blankets and food – was pledged from other countries, including Mexico, Venezuela, China, UK, France, Germany, Canada and Cuba.

Financial assistance also poured in. The UN released $10 million from its emergency fund, and European countries pledged $13.7 million. Haiti's institutions were weak even before the disaster. Because the 'quake devastated the capital, both the government and the UN, which has been trying to build a state in Haiti since 2004, were seriously affected, losing buildings and essential staff.

Following the Haiti earthquake, plans were discussed for the rescue, rehabilitation and reconstruction of the country. Reconstructing Haiti is a challenge to an international community that has failed over decades to lift the island state out of poverty, corruption and violence. Since 2000, more than $4 billion has been given to Haiti to rebuild communities and infrastructure devastated by tropical storms, floods and landslides, but mismanagement, a lack of coordination and attempts by global institutions to use Haiti as an economic test-bed are believed to have frustrated all efforts. A foreign debt of $1.5 billion has weighed down the economy.

Case Study: Tōhoku, Japan, earthquake and tsunami, 2011

The earthquake that occurred off the east coast of Japan in 2011 was magnitude 9.0M. The epicentre was approximately 70 kilometres east of Tōhoku at a depth of about 30 kilometres. It was the most powerful earthquake ever to hit Japan, and the fourth most powerful since 1900. The earthquake caused a tsunami that generated some waves in excess of 12 metres, which killed thousands and damaged a large part of the Sendai area.

There were nearly 16 000 deaths, more than 2500 people missing and over 225 000 people forced either to live in temporary housing or relocate permanently. More than 125 000 buildings totally collapsed and a further 1 million buildings were damaged. The earthquake and tsunami caused widespread and severe structural damage to roads and railways. Some 4.4 million households in north-eastern Japan were left without electricity and 1.5 million without water. More than 1.5 million households were reported to have lost access to water supplies. The tsunami caused accidents at a number of nuclear power stations, in particular Fukushima Daiichi.

Estimates suggested insured losses from the earthquake alone at US$14.5–34.6 billion. The World Bank estimated that the economic cost was US$235 billion, making it the costliest natural disaster ever.

One minute before the earthquake was felt in Tokyo, the Earthquake Early Warning System sent out warnings to millions of people. It is believed that this may have saved many lives.

The tsunami began to hit the coastline just 10 to 30 minutes after the main earthquake. The damage from the tsunami was far greater than from the earthquake. Many of the waves were higher than the protective sea walls. It is likely that many people thought the sea walls would protect them, but these had been built on the experience of smaller tsunamis in the past. Of the casualties, over 90 per cent died by drowning. Victims aged 60 or older accounted for over 65 per cent of the deaths. A number of children were orphaned as a result of the tsunami.

Japan has invested the equivalent of billions of dollars on anti-tsunami seawalls along at least 40 per cent of its 35 000 kilometre coastline; the tsunami simply washed over the top of some seawalls, collapsing some in the process. About 10 per cent of Japan's fishing ports were damaged in the disaster.

Eleven reactors were automatically shut down following the earthquake. However, at Fukushima Daiichi, tsunami waves overtopped seawalls and destroyed backup power systems, leading to three large explosions and radioactive leakage. Over 200 000 people were evacuated from the area.

Japan declared a state of emergency following the failure of the cooling system at Fukushima Daiichi. Radiation levels inside the plant were up to 1000 times normal levels; outside the plant they were up to 8 times normal levels.

The earthquake and tsunami created a major humanitarian crisis and an economic one. Over 340 000 people were displaced in the Tōhoku region, and there were widespread shortages of food, water, shelter, medicine and fuel for survivors. Aid organisations donated around $1 billion in emergency relief. The short-term economic impact has been the suspension of industrial production in many factories, and the long-term issue has been the cost of rebuilding, which has been estimated at US$122 billion.

Case Study: Nepal earthquake, 2015

The Gorkha (Nepal) earthquake in April 2015 killed over 9000 people and injured more than 23 000. It had a magnitude of 7.8 M, and occurred about 80 kilometres north-west of the capital, Kathmandu. It was a shallow earthquake, with the focus approximately 8 kilometres beneath the surface. It was the worst natural disaster to affect Nepal since 1934.

The earthquake triggered a number of avalanches, killing at least 19 people on Mt Everest and over 250 in Langtang Valley.

Hundreds of thousands of people were made homeless. According to UNESCO, more than 30 monuments in the Kathmandu Valley collapsed in the quakes.

In addition, there was a major aftershock of 7.3 M in May 2015. Over 200 people were killed and more than 2500 were injured by this aftershock. The earthquakes were caused by a release of built-up stress along a fault line where the Indian Plate is colliding against the Eurasian plate.

Economic loss

The US Geological Survey estimated economic losses from the earthquake of about 35 per cent of GDP. Rebuilding the economy could exceed US$5 billion, or about 20 per cent of Nepal's GDP.

Rescue and relief

About 90 per cent of the soldiers from the Nepalese army helped with the rescue operation. However, rainfall and aftershocks complicated the rescue efforts, with potential secondary effects like additional landslides and further building collapses being of concern. Impassable roads and a damaged communications infrastructure posed substantial challenges to rescue efforts. Survivors were found up to a week after the earthquake.

Earthquakes and human activity

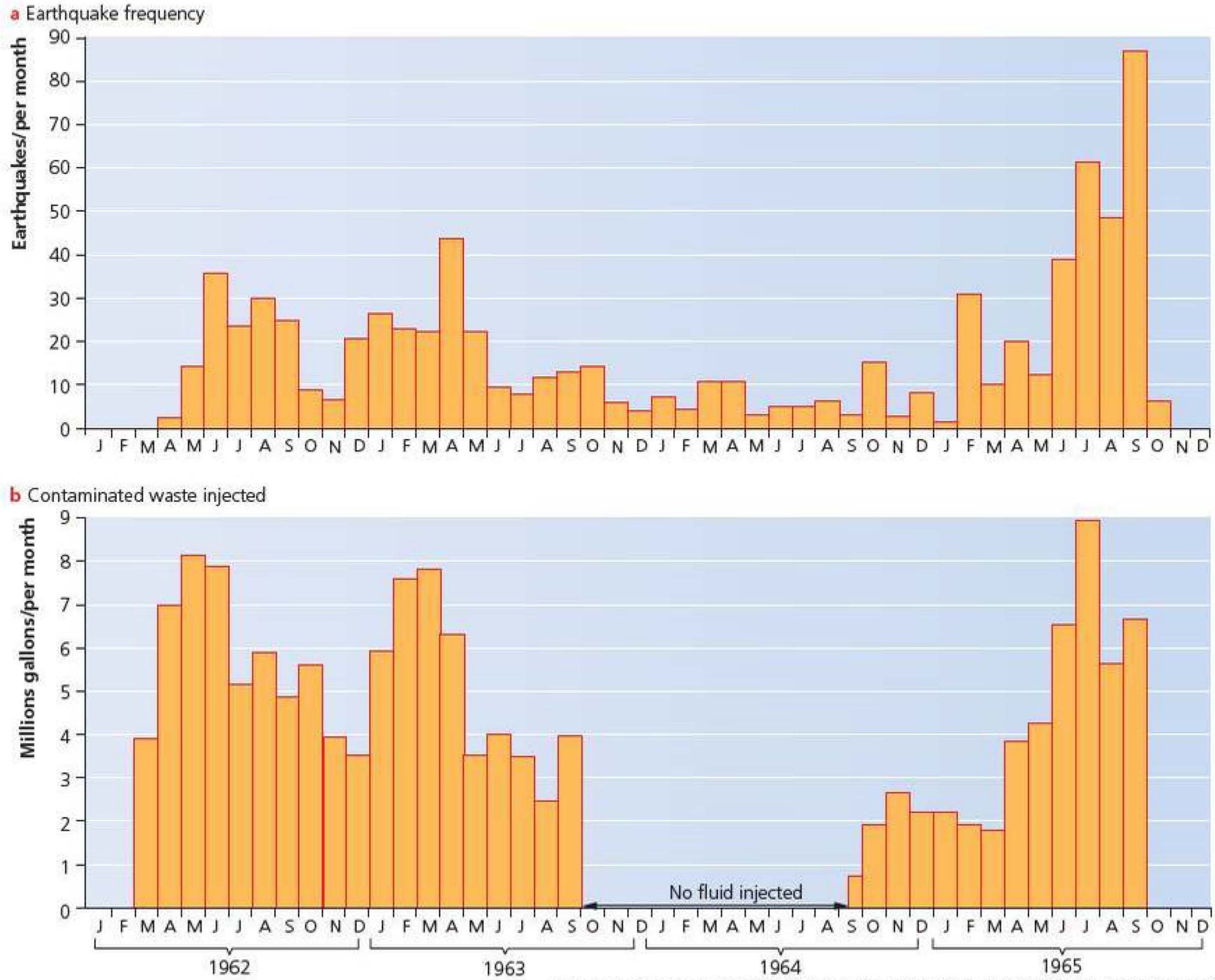
Human activities can trigger earthquakes, or alter the magnitude and frequency of earthquakes, in three main ways:

- through underground disposal of liquid wastes
- by underground nuclear testing and explosions
- by mining and fracking
- by increasing crustal loading.

Disposal of liquid waste

In the Rocky Mountain Arsenal in Denver, Colorado, wastewater was injected into underlying rocks during the 1960s (Figure 9.5). Water was contaminated by chemical warfare agents, and the toxic wastes were too costly to transport off-site for disposal. Thus it was decided to dispose of it down a well over 3500 metres deep. Disposal began in March 1962 and was followed soon afterwards by a series of minor earthquakes, in an area previously free of earthquake activity. None of the earthquakes caused any real damage, but they did cause alarm. Between 1962 and 1965, over 700 minor earthquakes were monitored in the area.

The injection of the liquid waste into the bedrock lubricated and reactivated a series of deep underground faults that had been inactive for a long time. The more wastewater was put down the well, the larger the number of minor earthquakes. When the link was established, disposal stopped. In 1966, the well was filled in and the number of minor earthquake events detected in the area fell sharply.



Source: *Advanced Geography: Concepts & Cases* by P. Guinness & G. Nagle (Hodder Education, 1999), p.338

Figure 9.5 Increasing earthquake frequency associated with underground liquid-waste disposal, Rocky Mountain Arsenal, Colorado, USA

Underground nuclear testing

Underground nuclear testing has triggered earthquakes in a number of places. In 1968, testing of a series of 1200 tonne bombs in Nevada set off over 30 minor earthquakes in the area over the following three days. Since 1966, the Polynesian island of Moruroa has been the site of over 80 underground nuclear explosion tests by France. More than 120000 people live on the island. In 1966, a 120000 tonne nuclear device was detonated, producing radioactive fallout that was measured over 3000 kilometres downwind.

Fracking

It is believed that fracking (hydraulic fracturing) of shale rocks for shale gas can trigger earthquakes. The use of high-powered water to break up shale rocks is thought to have triggered two earthquakes in Lancashire, UK, in 2011. It is one reason that Chinese engineers have not tried to develop the Sichuan province for shale gas, as the area is known to be tectonically active, having experienced a major earthquake there in 2008.

Increased crustal loading

Earthquakes can be caused by adding increased loads on previously stable land surfaces. For example, the weight of water behind large reservoirs can trigger earthquakes. In 1935, the Colorado River was dammed by the Hoover Dam to form Lake Mead. As the lake filled, over a period of ten years, and the underlying rocks adjusted to the new increased load of over 40 km^3 of water, long-dormant faults in the area were reactivated, causing over 6000 minor earthquakes. Over 10000 events were recorded up to 1973, about 10 per cent of which were strong enough to be felt by residents. None caused damage.

Section 9.1 Activities

1 Comment on the relationship between earthquake frequency and magnitude as shown in Table 9.3.
2 Account for the location of **a** shallow-focus earthquakes and **b** deep-focus earthquakes.
3 Study Figure 9.5, which shows the relationship between earthquake frequency and underground liquid waste disposal. Describe the relationship between the two variables. Suggest reasons to explain the relationship.

Volcanoes and resultant hazards

Types of volcanic eruption and their products

The shape of a volcano depends on the type of lava it contains. Very hot, runny lava produces gently sloping **shield volcanoes (Hawaiian type)**, while thick material produces **cone-shaped volcanoes (Plinian type)**. These may be the result of many volcanic eruptions over a long period of time. Part of the volcano may be blasted away during eruption. The shape of the volcano also depends on the amount of change there has been since the volcanic eruption. Cone volcanoes are associated with destructive plate boundaries, whereas shield volcanoes are characteristic of constructive boundaries and hotspots.

Volcanoes are classified in a number of ways. These include the type of flow, the type of eruption (Figure 9.6) and the level of activity.

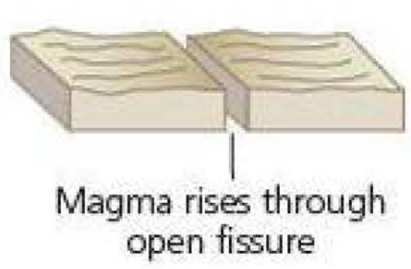
Aa flow is a few metres thick. It consists of two distinct zones: an upper rubbly part and a lower part of solid lava, which cools slowly. Aa surfaces are a loose jumble of irregularly shaped cindery blocks with sharp sides. By contrast, **pahoehoe** flow is the least viscous of all lavas; rates of advance can be slow. It has a cool surface, with flow underneath the surface. Pahoehoe surfaces can be smooth and glossy but may also have cavities; surfaces may also be crumpled with channels.

The amount of silica makes the difference between volcanoes that erupt continuously, such as those on Iceland and Hawaii, and those where eruptions are infrequent but violent, such as in Japan and the Philippines. Lava released where the ocean plates meet the continental plates absorbs silica-rich sediments; this causes the lava to become more viscous and block the vents until enough pressure has built up to break them open.

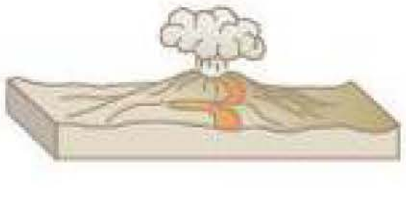
Each year about 20 km² of land is covered by lava flows. These may initially reach temperatures of over 1000 °C, resulting in severe social and economic disruption. However, cooled lava flows are very fertile when weathered and therefore attract dense population settlement and intense agricultural production.

There are a number of ways of reducing lava flows. These include spraying them with water, bombing them and seeding the lava with foreign nuclei. For example, in 1973 a lava flow that threatened the town of Vestmannaeyjar in Iceland was sprayed with water for months, thereby slowing its advance.

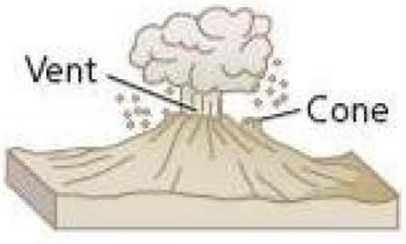
Active volcanoes are volcanoes that continue to erupt or are at risk of erupting. **Extinct volcanoes** have stopped erupting, and **dormant volcanoes** are ones that have not erupted for a very long time but could still erupt. It is an arbitrary classification, and the distinction between dormant and extinct is difficult to define.



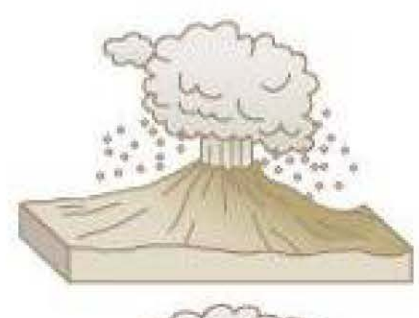
Icelandic lava eruptions are characterised by persistent fissure eruption. Large quantities of basaltic lava build up vast horizontal plains. On a large scale they have formed the Deccan Plateau and the Columbia Plateau.



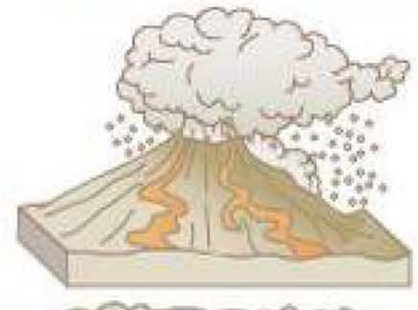
Hawaiian eruptions involve more noticeable central activity than the Icelandic type. Runny, basaltic lava travels down the sides of the volcano in lava flows. Gases escape easily. Occasional pyroclastic activity occurs but this is less important than the lava eruption.



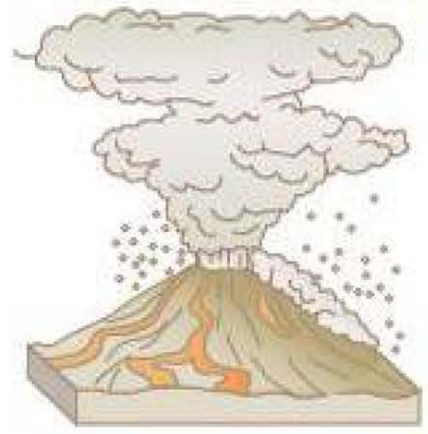
Strombolian eruptions are characterised by frequent gas explosions which blast fragments of runny lava into the air to form cones. They are very explosive eruptions with large quantities of pyroclastic rock thrown out. Eruptions are commonly marked by a white cloud of steam emitted from the crater.



In **Vulcanian eruptions**, violent gas explosions blast out plugs of sticky or cooled lava. Fragments build up into cones of ash and pumice. Vulcanian eruptions occur when there is very viscous lava which solidifies rapidly after an explosion. Often the eruption clears a blocked vent and spews large quantities of volcanic ash into the atmosphere.



Vesuvian eruptions are characterised by very powerful blasts of gas pushing ash clouds high into the sky. They are more violent than Vulcanian eruptions. Lava flows also occur. Ash falls to cover surrounding areas.



In a **Plinian eruption**, gas rushes up through sticky lava and blasts ash and fragments into the sky in a huge explosion. The violent eruptions create immense clouds of gas and volcanic debris several kilometres thick. Gas clouds and lava can also rush down the slopes. Part of the volcano may be blasted away during the eruption.

Figure 9.6 Types of volcanic eruption

Volcanic hazards

Volcanic hazards (Table 9.5) can be divided into six main categories:

- lava flows (Figure 9.7)
- ballistics and tephra clouds
- pyroclastic flows (or nuées ardentes – glowing clouds; Figure 9.8)
- gases and acid rain
- lahars (mudflows; Figure 9.8)
- glacier bursts (jökulhlaups).

Table 9.5 Primary and secondary hazards associated with volcanic activity

Direct hazards (primary hazards)	Indirect hazards (secondary hazards)	Socio-economic impacts
• Pyroclastic flows • Volcanic bombs (projectiles) • Lava flows • Ash fallout • Volcanic gases • Earthquakes	• Atmospheric ash fallout • Landslides • Tsunamis • Acid rainfall • Lahars (mudflows)	• Destruction of settlements • Loss of life • Loss of farmland and forests • Destruction of infrastructure – roads, airstrips and port facilities • Disruption of communications

Figure 9.7 Lava flow, Mt Etna

Figure 9.8 Pyroclastic flows and lahars, Montserrat

Ash and debris falls steadily from the volcanic cloud, blanketing the ground with a deposit known as a pyroclastic flow. These can be very dangerous, especially as the fine ash particles can damage people's lungs. Also, ash is fairly heavy – a small layer only a few centimetres thick can be enough to cause a building to collapse. Dust and fine particles also cause havoc with global climate patterns. Pyroclastic flows are powerful enough to knock down trees and to leave a trail of destruction. Some of them are extremely hot – up to 700 °C. Figure 9.8 shows the pyroclastic flows associated with the eruption of Soufrière volcano on Montserrat.

Lahars, or volcanic mudflows, are another hazard associated with volcanoes. A combination of heavy rain and unstable ash increases the hazard of lahars. The hazards associated with volcanic eruption also vary spatially. Close to the volcano, people are at risk of large fragments of debris, ash falls and poisonous gases. Further away, pyroclastic flows may prove hazardous, and mudflows and debris flows may have an impact on more distant settlements. In addition, volcanoes can lead to tsunamis and to famine. Although there is good evidence for the spatial distribution of volcanoes, there is little discernible pattern in their distribution in terms of when they occur.

The ash fallout from the Eyjafjallajökull glacier in Iceland (April 2010) caused widespread disruption to European air travel. No-one was killed in the eruption, but the economic cost was great. It was a truly global impact as countries that traded with the EU were badly affected.

Volcanic strength

The strength of a volcano is measured by the Volcanic Explosive Index (VEI). This is based on the amount of material ejected in the explosion, the height of the cloud it creates and the amount of damage caused. Any explosion above level 5 is considered to be very large and violent. A VEI 8 refers to a supervolcano.

Table 9.6 The biggest volcanic eruptions

Eruption	Date	Volume of material ejected (km^3)
Mt St Helens, USA	1980	1
Mt Vesuvius, Italy	79CE	3
Mt Katmai, USA	1912	12
Mt Krakatoa, Indonesia	1883	18
Mt Tambora, Indonesia	1815	80

Section 9.1 Activities

1 What are the main hazards associated with volcanoes?
2 Study Table 9.6, which shows volcanic disasters since 1800.
  a Describe the location of these disasters.
  b How do you account for this pattern?

Volcanic gases

Case Study: Lake Nyos, Cameroon

Volcanic gases are an example of a direct or primary hazard. Cameroon lies just north of the equator in West Africa. It contains a large number of deep crater lakes, such as Lake Nyos, formed as a result of tectonic activity. Lake Nyos is nearly 2 kilometres wide and over 200 metres deep. In August 1986, a huge volume of gas escaped from the lake and swept down into neighbouring valleys for a distance of up to 25 kilometres (Figure 9.9). The ground-hugging clouds of gas were up to 50 metres thick and travelled at speeds of over 70 kilometres per hour. Some 1700 people were suffocated, 3000 cattle died and all other animal life in the area was killed. The only people who escaped were sleeping on the upper floors of houses. Plants, however, were unaffected.

The gas was carbon dioxide. Because it is heavier and denser than oxygen, the 50 metre cloud deprived people and animals of oxygen, so they were asphyxiated. The source of carbon dioxide was a basaltic chamber of magma, deep beneath Cameroon. It had been leaking into and accumulating in Lake Nyos for some time. Due to its depth, water in the lake became stratified into layers of warmer water near the surface and colder denser water near the bottom of the lake. The cold dense water absorbed the carbon dioxide, which was then held down by the weight of the overlying waters.

The disaster occurred after the water at the bottom of the lake was disturbed. The cause of the disturbance is unclear. It could have been a deep volcanic eruption, an earthquake, a change in water temperature or a climatic event. Whatever the cause, the effect was like an erupting champagne bottle. Once the overlying pressure was reduced, carbon dioxide escaped into the surrounding area, causing rapid death among people and animals.

It is likely that such a tragedy will happen again. It is believed that only about 66 per cent of the carbon dioxide escaped from the lake, and that it has begun to build up again. It may take several decades for the gas cloud to occur again, or maybe even centuries, but the potential for a disaster is there. The authorities are trying to drain the lake of carbon dioxide with pumps.

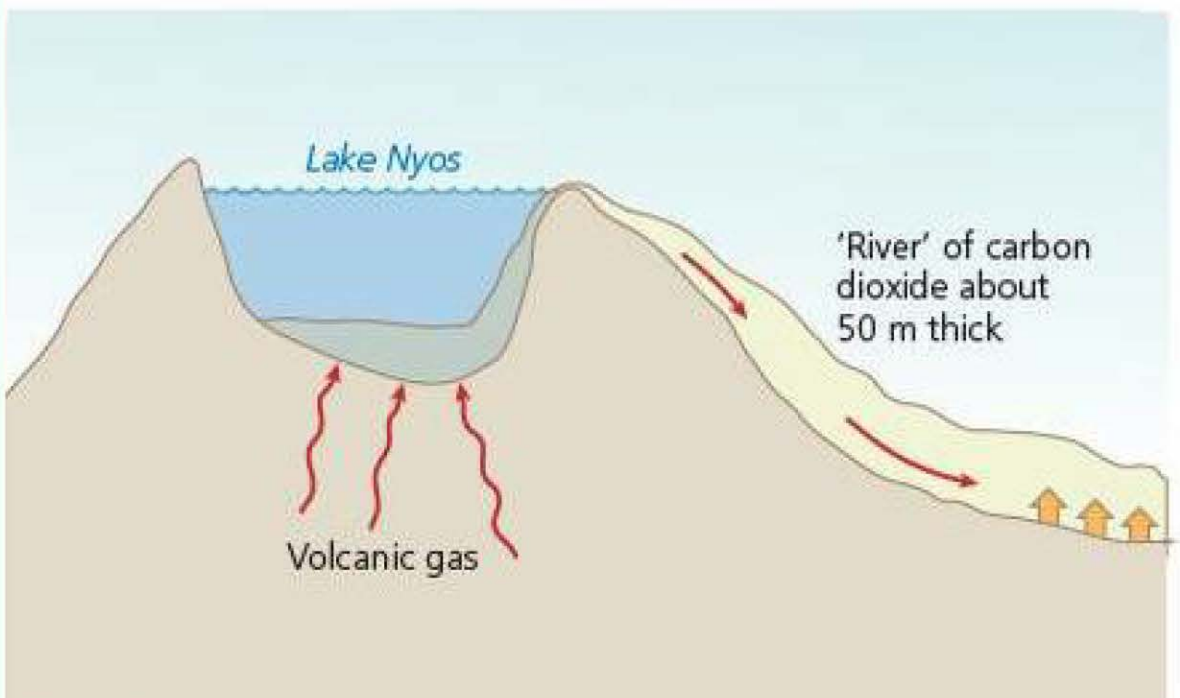


Figure 9.9 Lake Nyos, Cameroon

Section 9.1 Activities

1. Explain why the disaster at Lake Nyos affected animals but not plants.
2. Cameroon is not close to a tectonic boundary. How do you explain the tectonic hazard in an area that is not close to a known boundary?

Secondary hazards of tectonic events

Lahars and mudflows

Case Study: Nevado del Ruiz, Colombia

One hazard that is closely associated with volcanic activity is the lahar, or mudflow:

- Rain brings soot and ash back to ground and this becomes a heavily saturated mudflow.
- Heat from volcanoes melts snow and ice – the resulting flow picks up sediment and turns it into a destructive lahar.

Nevado del Ruiz is a volcano in Colombia that rises to an altitude of 5400 metres and is covered with an icecap 30 metres thick, covering an area of about 20 km^2. In 1984, small-scale volcanic activity resumed, and large-scale activity returned in November 1985. Scientists monitoring the mountain recorded earthquakes, and soon after a volcanic eruption threw hot, pyroclastic material onto the icecap, causing it to melt. Condensing volcanic steam, ice-melt and pyroclastic flows combined to form lahars that moved down the mountain, engulfing the village of Chinchina, killing over 1800 people and destroying the village (Figure 9.10).

Conditions worsened as further eruptions melted more ice, creating larger lahars that were capable of travelling further down the mountain into the floodplain of the Rio Magdalena. Within an hour, it had reached the city of Armero, 45 kilometres away. Most of Armero, including 22 000 of its 28 000 residents, were crushed and suffocated beneath lahars up to 8 metres thick. Those who were saved were those who just happened to be further up the slope. Images of people trapped in the mud were relayed across the world.

The volcanic eruption was relatively small but the presence of the icecap made the area especially hazardous.

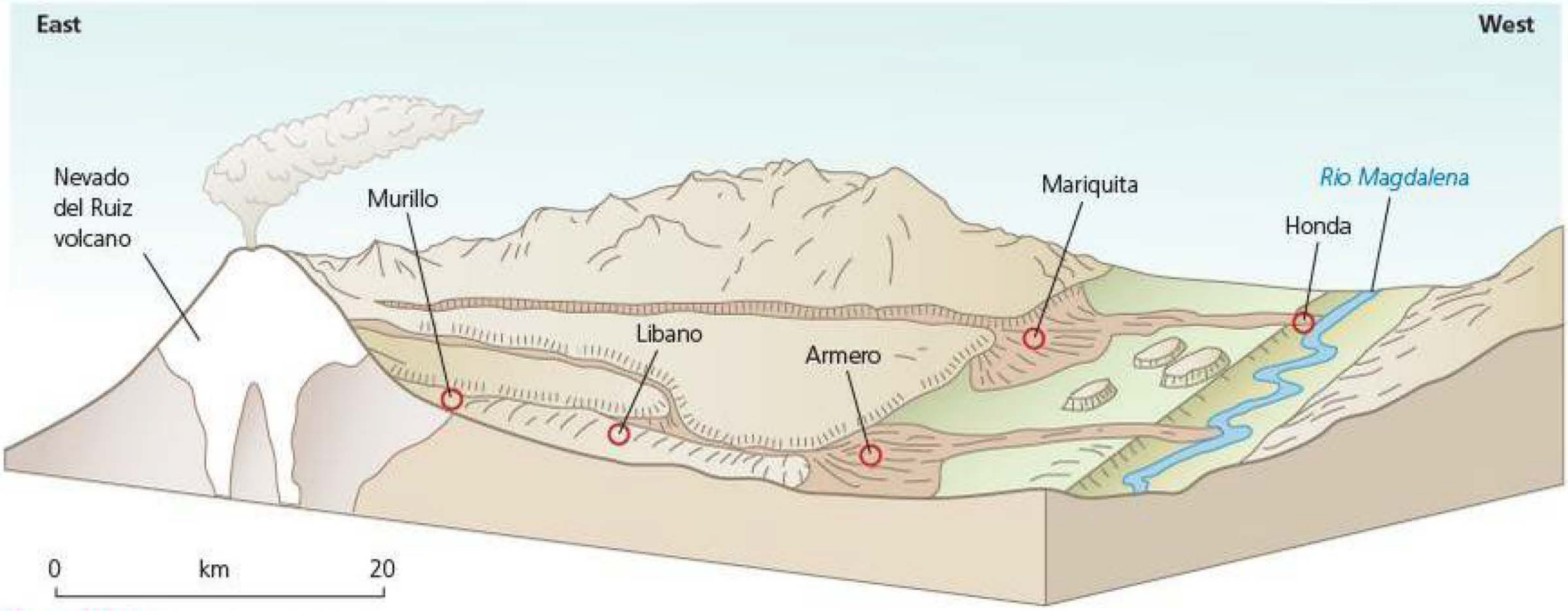


Figure 9.10 Nevado del Ruiz lahar

Section 9.1 Activities

1 Why do volcanoes and icecaps sometimes occur in the same place?
2 Study Figure 9.10, which shows the location of Armero. Why do you think so many people lived there?

Tsunamis

The term 'tsunami' is the Japanese for 'harbour wave'. Ninety per cent of tsunamis occur in the Pacific basin. They are generally caused by earthquakes (usually in subduction zones) but can be caused by volcanoes (for example, Krakatoa in 1883) and landslides (for example, Alaska in 1964).

Tsunamis have the potential to cause widespread disaster, as in the case of the South Asian tsunami on 26 December 2004 (Figure 9.11). Owing to the loss of life among tourists, it came to be seen as a global disaster, killing people from nearly 30 countries. Between 180000 and 280000 people were killed in this tsunami.


Figure 9.11 Tsunami damage in Phuket, Thailand

The cause of the tsunami was a giant earthquake and landslide caused by the sinking of the Indian Plate under the Eurasian Plate. Pressure had built up over many years and was released in the earthquake that reached 9.0 on the Richter Scale.

The main impact of the Boxing Day tsunami, as it came to be known, was on the Indonesian island of Sumatra, the closest inhabited area to the epicentre of the earthquake. More than 70 per cent of the inhabitants of some coastal villages died. Apart from Indonesia, Sri Lanka suffered more from the tsunami than anywhere else. At least 31 000 people are known to have died there, when the southern and eastern coastlines were devastated.

Potential waves due to earthquakes and landslides

A lake formed by a landslide in northern Pakistan could have burst its banks at any time, possibly triggering a giant wave that could sweep down the Himalayan valley and swamp dozens of villages (Figure 9.12). The level of the Attabad lake, which was formed by a landslide in early January 2010, rose alarmingly fast to within a few metres of its limit.

Pakistani authorities were concerned that immense water pressure could cause the lake wall to collapse suddenly, sending a wave up to 60 metres high into the valley below and affecting up to 25 000 people.

The Attabad lake started to form after a landslide blocked the Karakoram highway, which links Pakistan and

Figure 9.12 Area of potential lake bursts in the Himalayas

China. The water level rose rapidly, swelled by meltwater from nearby glaciers, swamping 120 houses and displacing about 1300 people. Another 12000 people were evacuated from the potential flood zone downstream.

The world's largest landslide dam was formed in 1911 on the Murghab River in Tajikistan. The 550 metre dam has never breached because lake outflows are greater than inflows.

Geomorphologists estimate that 35 natural dams have formed over 500 years in the Pakistani section of the Himalayas. The latest was the Hattian dam, formed by the 2005 earthquake. Lakes formed by landslides developed in Nepal during 2013 and 2014, triggering fears that villages downstream could be destroyed by lake bursts.

Case Study: Peruvian tsunami, 2010

Tsunamis can be caused by forces that are not tectonic. For example, in 2010 a massive ice block, measuring 500 metres by 200 metres, broke from a glacier and crashed into a lake in the Peruvian Andes, causing a 23 metre tsunami and sending muddy torrents through nearby towns, killing at least one person.

The chunk of ice detached from the Hualcan glacier about 320 kilometres north of the capital, Lima. It plunged into a lagoon known as lake 513, triggering a tsunami that breached 23 metre-high levees and damaged Carhuaz and other villages.

Around 50 homes and a water-processing plant serving 60000 residents were wrecked. Due to global warming, there has been an increase in the number of glaciers melting, breaking and falling on overflowing lakes.

Section 9.1 Activities

1 Outline the causes of tsunamis.
2 Outline the short-term and long-term impacts of tsunamis.

The perception of risk

At an individual level, there are three important influences upon an individual's response to any hazardous event:

1 **Experience** – the more experience a person has of environmental hazards, the greater the adjustment to the hazard.
2 **Material well-being** – those who are better off have more choices.
3 **Personality** – is the person a leader or a follower, a risk-taker or risk-minimiser?

Ultimately, there are just three choices:

1 Do nothing and accept the hazard.
2 Adjust to the situation of living in a hazardous environment.
3 Leave the area.

It is the adjustment to the hazard that we are interested in. The level of adjustment will depend, in part, upon the risks caused by the hazard. This includes:

- identification of the hazards
- estimation of the risk (probability) of the environmental hazard
- evaluation of the cost (loss) caused by the environmental hazard.

Hazard mapping, risk assessment and preparedness

Hazard mapping includes a body of theory that includes risk, prediction, prevention, event and recovery. **Vulnerability** refers to the geographic conditions that increase the susceptibility of a community to a hazard or to the impacts of a hazard event. **Risk** is the probability of a hazard event causing harmful consequences (expected losses in terms of death, injuries, property damage, economy and environment).

A **hazard** is a threat (whether natural or human) that has the potential to cause loss of life, injury, property damage, socio-economic disruption or environmental degradation. In contrast, a **disaster** is a major hazard event that causes widespread disruption to a community or region, with significant demographic, economic and/or environmental losses.

A number of stages can be observed in the build-up to a disaster and in its aftermath (Table 9.7).

Rehabilitation refers to people being able to make safe their homes and be able to live in them again. This can be a very long drawn-out process, taking up to a decade for major construction projects.

As well as dealing with the aftermath of a disaster, governments try to plan to reduce impacts of future events. This was seen after the South Asian tsunami of 2004. Before the event, a tsunami early-warning system was not in place in the Indian Ocean. Following the event, as well as emergency rescue, rehabilitation and reconstruction, governments and aid agencies in the region developed a system to reduce the impacts of future tsunamis. It is just part of the process needed to reduce the impact of hazards and to improve safety in the region.

Managing the earthquake hazard

People deal with earthquakes in a number of ways. These include:

- doing nothing and accepting the hazard
- adjusting to living in a hazardous environment, for example strengthening their home
- leaving the area.

The main ways of preparing for earthquakes include:

- better forecasting and warning
- improved building design and building location
- establishing emergency procedures.

There are a number of ways of predicting and monitoring earthquakes, which involve the measurement of:

- small-scale ground surface changes
- small-scale uplift or subsidence
- ground tilt
- changes in rock stress
- micro-earthquake activity (clusters of small 'quakes)
- anomalies in the Earth's magnetic field
- changes in radon gas concentration
- changes in electrical resistivity of rocks.

One particularly intensively studied site is Parkfield in California, on the San Andreas fault. Parkfield, with a population of fewer than 50 people, claims to be the earthquake capital of the world. It is heavily monitored by instruments:

- Strain meters measure deformation at a single point.
- Two-colour laser geodimeters measure the slightest movement between tectonic plates.
- Magnetometers detect alterations in the Earth's magnetic field, caused by stress changes in the crust.

Table 9.7 Aspects of the temporal sequences or phases of disasters, with reported durations and selected features of each phase

Stage	Duration	Features
I Preconditions		
Phase 1	Everyday life (years, decades, centuries)	'Lifestyle' risks, routine safety measures, social construction of vulnerability, planned developments and emergency preparedness.
Phase 2	Premonitory developments (weeks, months, years)	'Incubation period' – erosion of safety measures, heightened vulnerability, signs and problems misread or ignored.
II The disaster		
Phase 3	Triggering event or threshold (seconds, hours, days)	Beginning of crisis; 'threat' period: impending or arriving flood, fire, explosion; danger seen clearly; may allow warnings, flight or evacuation and other pre-impact measures. May merge with …
Phase 4	Impact and collapse (instant, seconds, days, months)	… the disaster proper: concentrated death, injury, devastation; impaired or destroyed security arrangements; individual and small groups cope as isolated survivors. Followed by or merging with …
Phase 5	Secondary and tertiary damages (days, weeks)	… exposure of survivors, post-impact hazards, delayed deaths.
Phase 6	Outside emergency aid (weeks, months)	Rescue, relief, evacuation, shelter provision, clearing dangerous wreckage, 'organised response'; national and international humanitarian efforts.
III Recovery and reconstruction		
Phase 7	Clean-up and 'emergency communities' (weeks, years)	Relief camps, emergency housing; residents and outsiders clear wreckage, salvage items; blame and reconstruction debates begin; disaster reports, evaluations, commissions of enquiry.
Phase 8	Reconstruction and restoration (months, years)	Reintegration of damaged community with larger society; re-establishment of 'everyday life', possibly similar to, possibly different from, pre-disaster; continuing private and recurring communal grief; disaster-related development and hazard-reducing measures.

Nevertheless, the 1994 Northridge earthquake was not predicted and it occurred on a fault that scientists did not know existed. Technology helps, but not all of the time.

Learning to live with earthquakes

Most places with a history of earthquakes have developed plans that enable people to deal with them. The aim is to reduce the effect of the earthquakes and thus save lives, buildings and money. The ways of reducing earthquake impact include earthquake prediction, building design, flood prevention and public information.

Preparation

Earthquakes killed about 1.5 million people in the twentieth century, and the number of earthquakes appears to be rising. Most of the deaths were caused by the collapse of unsuitable and poorly designed buildings. More than a third of the world's largest and fastest-growing cities are located in regions of high earthquake risk, so the problems are likely to intensify.

It is difficult to stop an earthquake from happening, so prevention normally involves minimising the prospect of death, injury or damage by controlling building in high-risk areas, and using aseismic designs (Figure 9.13). In addition, warning systems can be used to warn people of an imminent earthquake and inform them of what to do when it does happen. Insurance schemes are another form of preparation, by sharing the costs between a wide group of people.

The seismic gap theory states that over a prolonged period of time all parts of a plate boundary must move by almost the same amount. Thus if one part of the plate boundary has not moved and others have, then the part that has not moved is most likely to move next. This theory has been used successfully to suggest that an earthquake was likely in the Loma Prieta segment of the San Andreas fault. The Loma Prieta earthquake occurred in 1989. Following the 2004 South Asian tsunami, geologists identified a seismic gap in the Central Kuril segment of the Kuril-Kamchatka trench. Two earthquakes measuring 8.3 and 8.2 on the Richter Scale occurred in November 2006 and January 2007 within the Central Kuril segment.

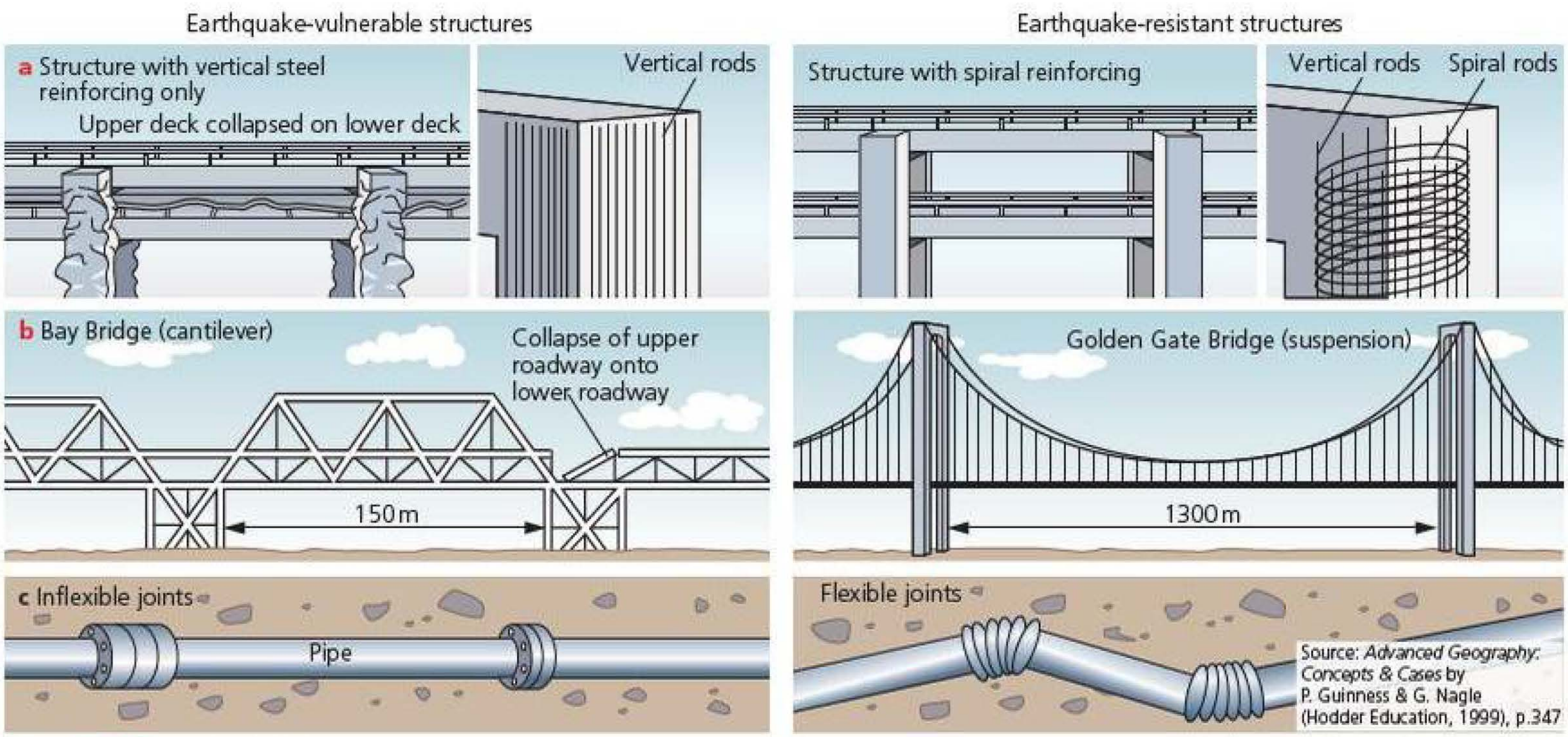


Figure 9.13 Aseismic design

Building design

Increasingly, as the availability of building land is reduced, more and more people are living in seismic areas. This increases the potential impact of an earthquake. However, buildings can be designed to withstand the ground-shaking that occurs in an earthquake (Figure 9.14). Single-storey buildings are more suitable than multi-storey structures, because this reduces the number of people at risk, and the threat of collapse over roads and evacuation routes. Some tall buildings are built with a 'soft storey' at the bottom, such as a car park raised on pillars. This collapses in an earthquake, so that the upper floors sink down onto it and this cushions the impact. Basement isolation – mounting the foundations of a building on rubber mounts that allow the ground to move under the building – is widely used. This isolates the building from the tremors.

Building reinforcement strategies include building on foundations built deep into underlying bedrock, and the use of steel-constructed frames that can withstand shaking. Land-use planning is another important way of reducing earthquake risk (Figure 9.15).

Safe houses

The earthquake in Haiti was a reminder that billions of people live in houses that cannot withstand shaking. Yet safer ones can be built cheaply – using straw, adobe and old tyres, for example – by applying a few general principles (Figure 9.16).

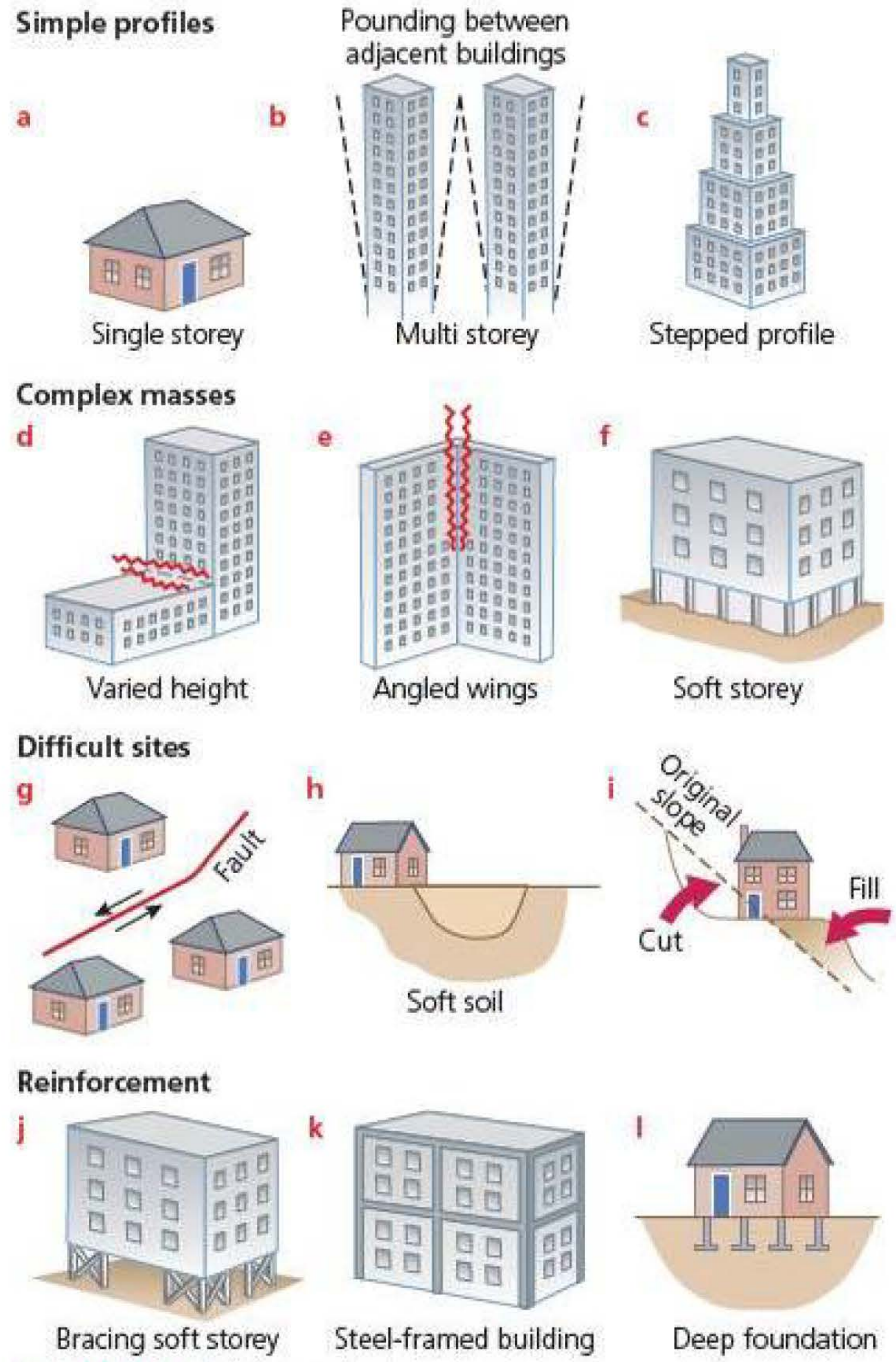
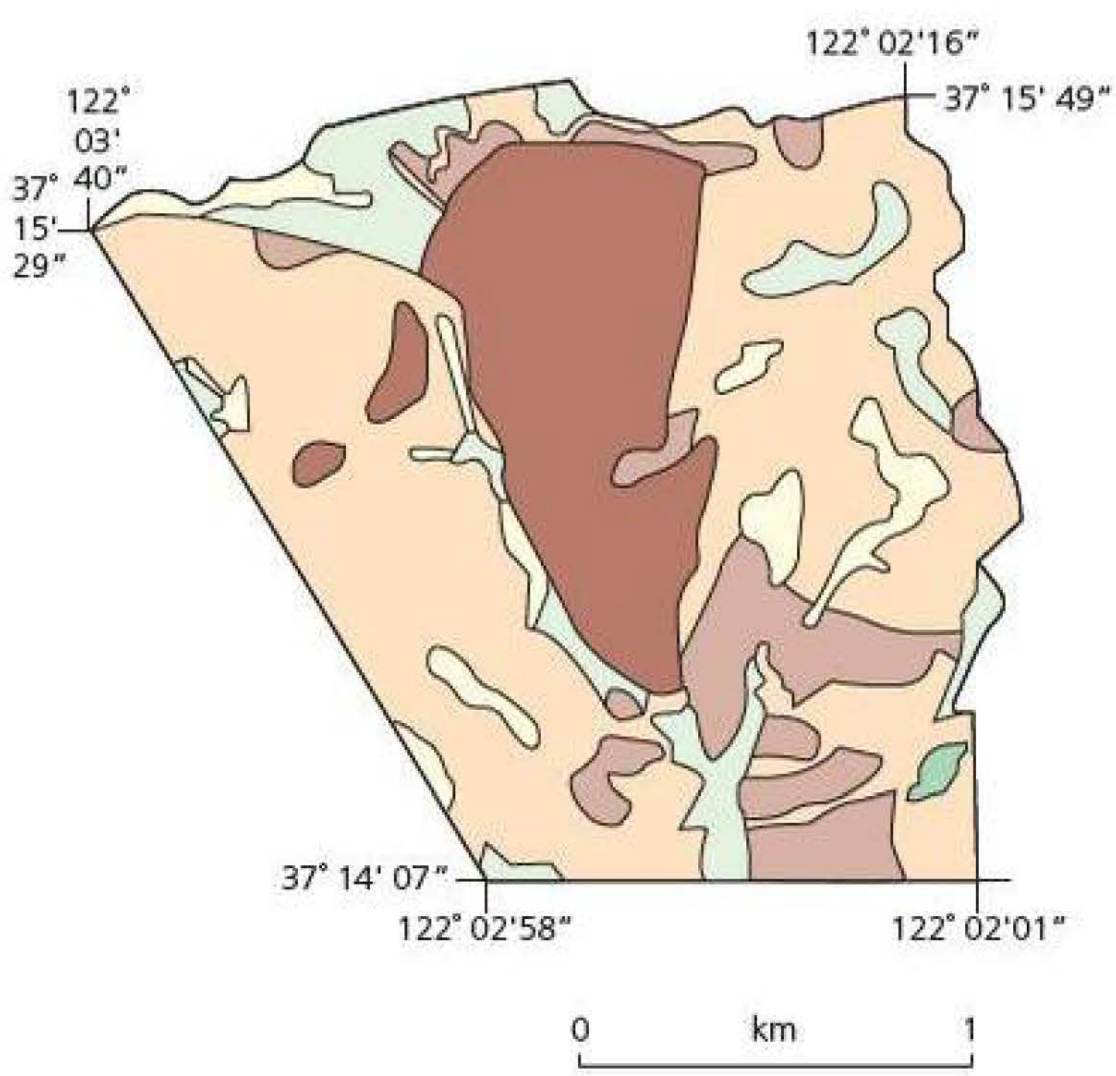


Figure 9.14 Building design



Relative stability	Map area	Geologic conditions	Recommended land use: Houses	Roads: Public	Roads: Private
Most stable		Flat to gentle slopes; subject to local shallow sliding, soil creep and settlement	Yes	Yes	Yes
		Gentle to moderately steep slopes in older stabilised landslide debris; subject to settlement, soil creep, and shallow and deep landsliding	Yes	Yes	Yes
		Steep to very steep slopes; subject to mass-wasting by soil creep, slumping and rock fall	Yes	Yes	Yes
		Gentle to very steep slopes in unstable material subject to sliding, slumping and soil creep	No	No	No
		Moving shallow (>3 m) landslide	No	No	No
Least stable		Moving, deep landslide, subject to rapid failure	No	No	No

Source: *Advanced Geography: Concepts & Cases* by P. Guinness & G. Nagle (Hodder Education, 1999), p.348

Figure 9.15 Land-use planning, San Francisco–San José California

	Pakistan	Haiti	Peru	Indonesia
Most destructive quake	8 October 2005	12 January 2010	31 May 1970	26 December 2004
Location	Northern Pakistan/Kashmir	Port-au-Prince area	Chimbote	Sumatra
Magnitude	7.6	7.0	7.9	9.1
Fatalities	75 000	222 500	70 000	227 900 (including the global tsunami deaths)

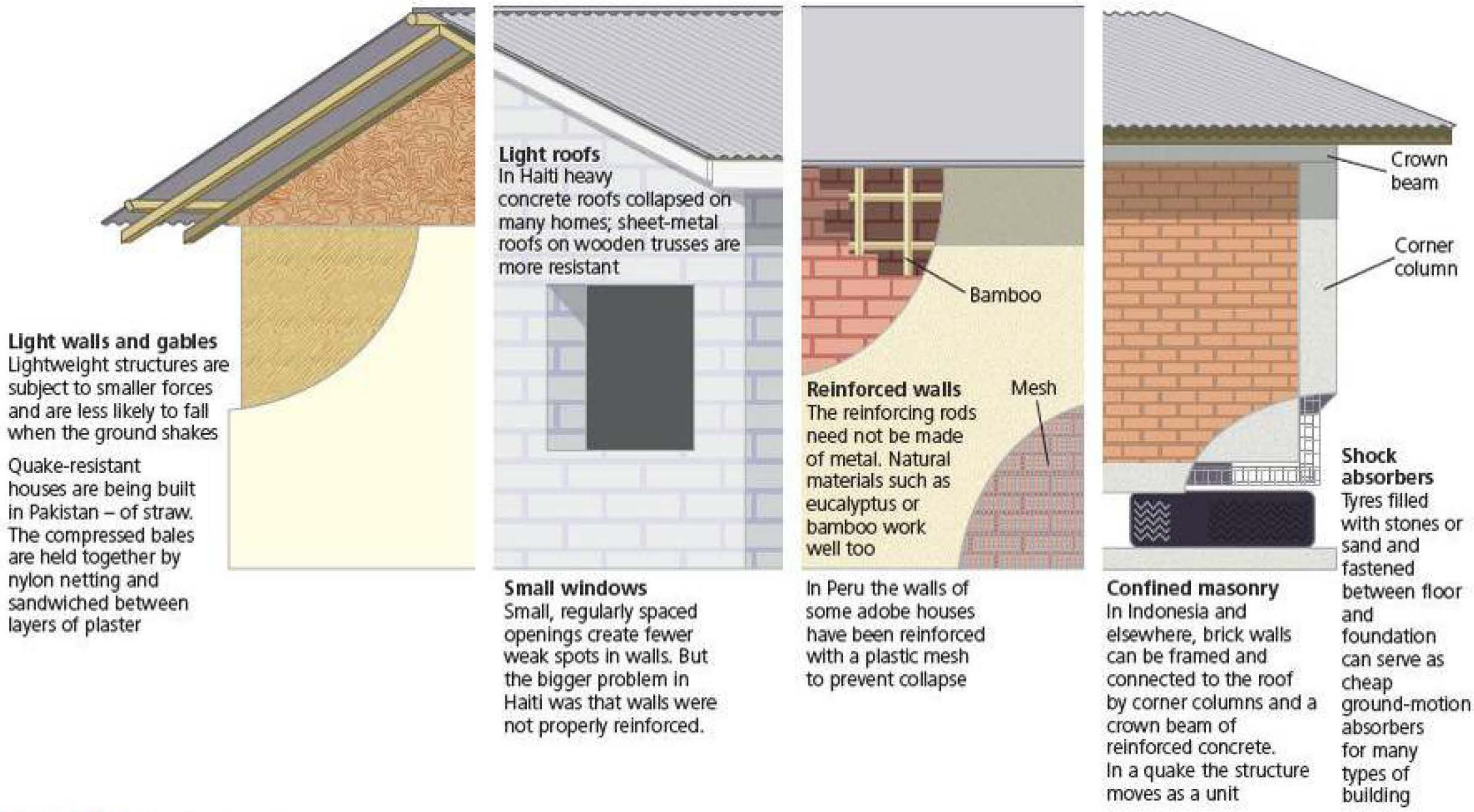


Figure 9.16 A safe house

In wealthy cities in fault zones, the added expense of making buildings earthquake-resistant has become a fact of life. Concrete walls are reinforced with steel, for instance, and a few buildings even rest on elaborate shock absorbers. Strict building codes were credited with saving thousands of lives when a magnitude 8.8 earthquake hit Chile in February 2010. But in less developed countries, like Haiti, conventional earthquake engineering is often unaffordable. However, cheap solutions do exist.

In Peru in 1970, an earthquake killed 70000 or more people, many of whom died when their houses crumbled around them. Heavy, brittle walls of traditional adobe – cheap, sun-dried brick – cracked instantly when the ground started buckling. Subsequent shakes brought roofs thundering down. Existing adobe walls can be reinforced with a strong plastic mesh installed under plaster; in a 'quake, these walls crack but do not collapse, allowing occupants to escape. Plastic mesh could also work as a reinforcement for concrete walls in Haiti and elsewhere.

Other engineers are working on methods that use local materials. Researchers in India have successfully tested a concrete house reinforced with bamboo. A model house for Indonesia rests on ground-motion dampers – old tyres filled with bags of sand. Such a house might be only a third as strong as one built on more sophisticated shock absorbers, but it would also cost much less – and so be more likely to be adopted in Indonesia. In northern Pakistan, straw is available. Traditional houses are built of stone and mud, but straw is far more resilient, and warmer in winter. However, cheap ideas aren't always cheap enough.

Since 2007, some 5000 houses in Peru have been strengthened with plastic mesh or other reinforcements.

Controlling earthquakes

In theory, by altering the fluid pressure deep underground at the point of greatest stress in the fault line, a series of small and less damaging earthquake events may be triggered. This could release the energy that would otherwise build up to create a major event. Additionally, a series of controlled underground nuclear explosions might relieve stress before it reached critical levels.

Prediction and risk assessment

There are a number of methods of detecting earthquakes – distortion of fences, roads and buildings are some examples; changing levels of water in boreholes is another. As strain can change the water-holding capacity or porosity of rocks by closing and opening their tiny cracks, then water levels in boreholes will fluctuate with increased earthquake activity. Satellites can also be used to measure the position of points on the surface of the Earth to within a few centimetres. However, predicting earthquakes is not simple. Some earthquakes are very irregular in time and may only occur less than once every 100years. By contrast, other parts of the Earth's surface may continually slip and produce a large number of very small earthquakes. In addition, different parts of a fault line may behave differently. Areas that do not move are referred to as 'seismic gaps'; areas that move and have lots of mini earthquakes may be far less hazardous.

Earthquake prediction is only partly successful, although it offers a potentially valuable way of reducing the impact of earthquakes. Some aspects are relatively easy to understand. For example, the location of earthquakes is closely linked with the distribution of fault lines. However, the timing of earthquakes is difficult to predict. Previous patterns and frequencies of earthquake events offer some clues as to what is likely to happen in the future, but the size of an earthquake event is difficult to predict.

The most reliable predictions focus on:

- measurement of small-scale ground surface changes
- small-scale uplift or subsidence
- ground tilt
- changes in rock stress
- micro-earthquake activity (clusters of small 'quakes)
- anomalies in the Earth's magnetic field
- changes in radon gas concentration
- changes in electrical resistivity of rocks.

Measurements of these are made using a variety of instruments (Table 9.8).

Table 9.8 Monitoring for earthquake prediction

Instrument	Purpose
Seismometer	To record micro-earthquakes
Magnetometer	To record changes in the Earth's magnetic field
Near-surface seismometer	To record larger shocks
Vibreosis truck	To create shear waves to probe the earthquake zone
Strain meter	To monitor surface deformation
Sensors in wells	To monitor changes in groundwater levels
Satellite relays	To relay data to the US Geological Survey
Laser survey equipment	To measure surface movement

Source: C. Park, The Environment, *Routledge 1997*

One particularly intensively studied site is Parkfield in California, on the San Andreas fault – see page 277.

Predicting volcanoes

Scientists are increasingly successful in predicting volcanoes. Since 1980, they have correctly predicted 19 of Mt St Helens' 22 eruptions, and Alaska's Redoubt volcano in 1989. There have been false alarms: in 1976, 72 000 residents of Guadeloupe were forced to leave their homes, and in 1980 Mammoth Lake in California suffered from a reduction in tourist numbers owing to mounting concern regarding volcanic activity.

Volcanoes are easier to predict than earthquakes since there are certain signs. The main ways of predicting volcanoes include monitoring using:

- **seismometers** to record swarms of tiny earthquakes that occur as the magma rises (Figure 9.17)
- chemical sensors to measure increased sulphur levels
- lasers to detect the physical swelling of the volcano
- ultrasound to monitor low-frequency waves in the magma, resulting from the surge of gas and molten rock, as happened at Pinatubo, El Chichón and Mt St Helens
- observations, such as of Gunung Agung (Java, Indonesia).

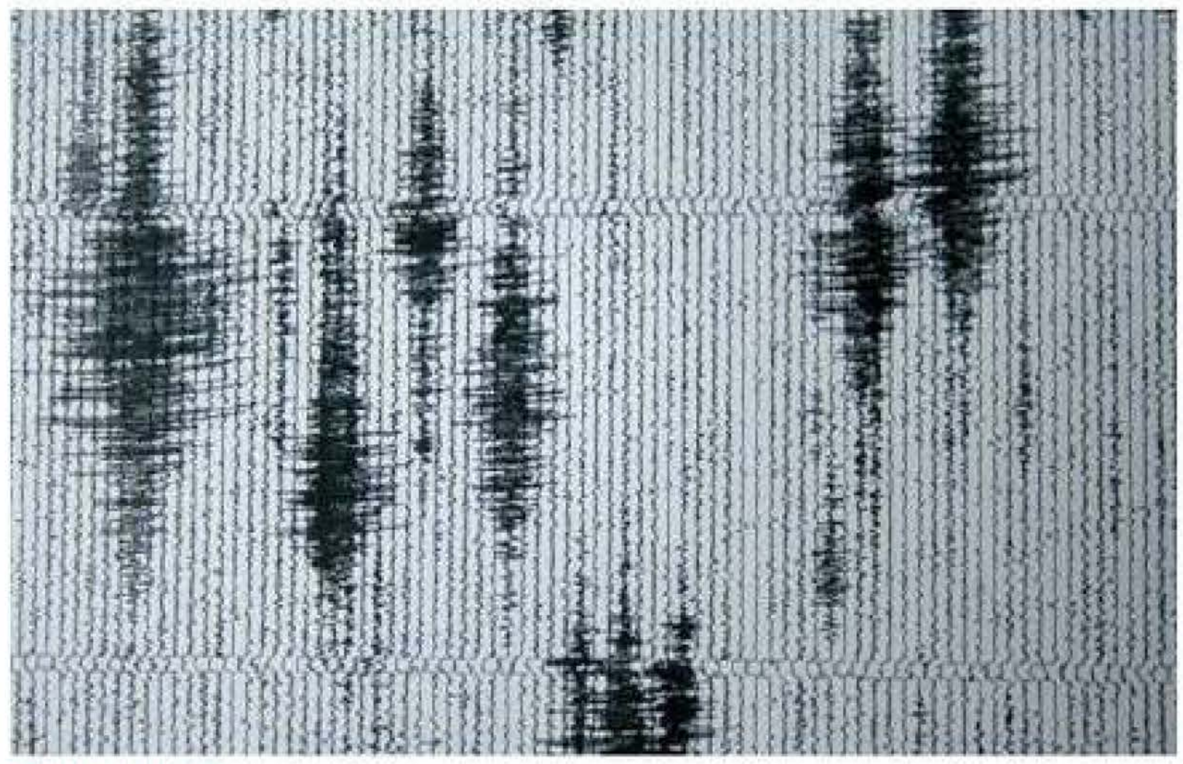


Figure 9.17 A seismograph reading (Montserrat)

However, it is not always possible to state exactly when a volcanic eruption will happen. The US Geological Survey predicted the eruption of Mt Pinatubo in 1991, and successfully evacuated the area. However, it was unsuccessful in predicting a volcanic eruption at Mammoth Mountain Ski Area in California, USA – the false prediction reduced visitor numbers to the resort and caused economic distress to local business people.

In Montserrat in the Caribbean, volcanic activity has made over 60per cent of the southern and central parts of the island uninhabitable. Plymouth was evacuated three times in 1995 and 1996. The volcano was responsible for 19 deaths – all of them farmers – caught out by an eruption during their return to the Exclusion Zone. Volcanic dust is another hazard, as it is a potential cause of silicosis and aggravates asthma. There are many hazards around Plymouth (Figure 9.18).

Figure 9.18 Hazard sign in Plymouth, Montserrat

Volcanic management includes monitoring and prediction (Figure 9.19). GPS is used to monitor changes in the surface of the volcano – volcanoes typically bulge and swell before an eruption. The development of 'risk maps' can be used to good effect, as in the case of Montserrat. There are risks on other Caribbean islands too. St Vincent and St Kitts are high-risk islands, whereas St Lucia, Grenada and Nevis are lower risk.

Figure 9.19 Montserrat Volcanic Observatory

Living with a volcano

People often choose to live in volcanic areas because they are useful in a variety of ways:

- Some countries, such as Iceland and the Philippines, were created by volcanic activity.
- Some volcanic soils are rich, deep and fertile, and allow intensive agriculture, for example in Java. However, in other areas, for example Sumatra and Iceland, the soils are poor. In Iceland, this is because the climate is too cool to allow chemical weathering of the lava flows, while in Sumatra the soils are highly leached.
- Volcanic areas are important for tourism, for example St Lucia and Iceland.
- Some volcanoes are culturally symbolic and are part of the national identity, such as Mt Fuji in Japan.

Managing tsunamis: tsunami warning systems

At present, it is impossible to predict precisely where and when a tsunami will happen. In most cases, it is only possible to raise the alarm once a tsunami has started. In the cases of submarine volcanoes, it is possible to monitor these to predict the risk of tsunami. For example, Kick 'em Jenny, north of Grenada, has erupted ten times since the late 1970s and grown by 50 metres. Volcanologists believe it could cause a tsunami and threaten Venezuela.

The first effective tsunami warning system was developed in 1948 in the Pacific, following the 1946 tsunami. The system consisted of over 50 tidal stations and 31 seismographic stations, spread between Alaska, Hong Kong and Cape Horn. Following an earthquake, tidal gauges in the region establish whether a tsunami has formed. The earthquake epicentre is also plotted and magnitude investigated. The warning system has been improved by the use of satellites, and it is now operated by the US National Oceanic and Atmospheric Administration (NOAA).

In theory, there is time to issue warnings. A tsunami off the coast of Ecuador will take 12 hours to reach Hawaii, 20 hours to reach Japan. A tsunami from the Aleutians will take 5 hours to reach Hawaii. However, the impacts will vary with shoreline morphology.

Other tsunami early warning systems include those in Japan and Kamchatka (Russia). However, many LICs lack early warning systems, as was so tragically exposed in the 2004 Boxing Day tsunami. Following the 2010 Chile earthquake, a tsunami warning was issued. Fortunately, there was little evidence of any particularly large waves affecting areas other than part of the Chilean coast.

During the 2010 Indonesian tsunami, in which over 400 people died, the tsunami early warning system that had been put in place failed to work. The system had been vandalised in the Mentawai Islands, which were worst affected by the tsunami. In the 2011 Tōhuko tsunami, although Japan has seawalls along its coastline, the tsunami was higher than 12 metres and so the seawalls did not protect the people against the hazard.

Section 9.1 Activities

1. Examine the ways in which it is possible to predict a volcanic eruption.
2. Comment on the methods to predict earthquake activity.
3. Suggest how housing and other buildings can be made safer in the event of an earthquake.
4. To what extent is it possible to manage the impacts of tsunamis?