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

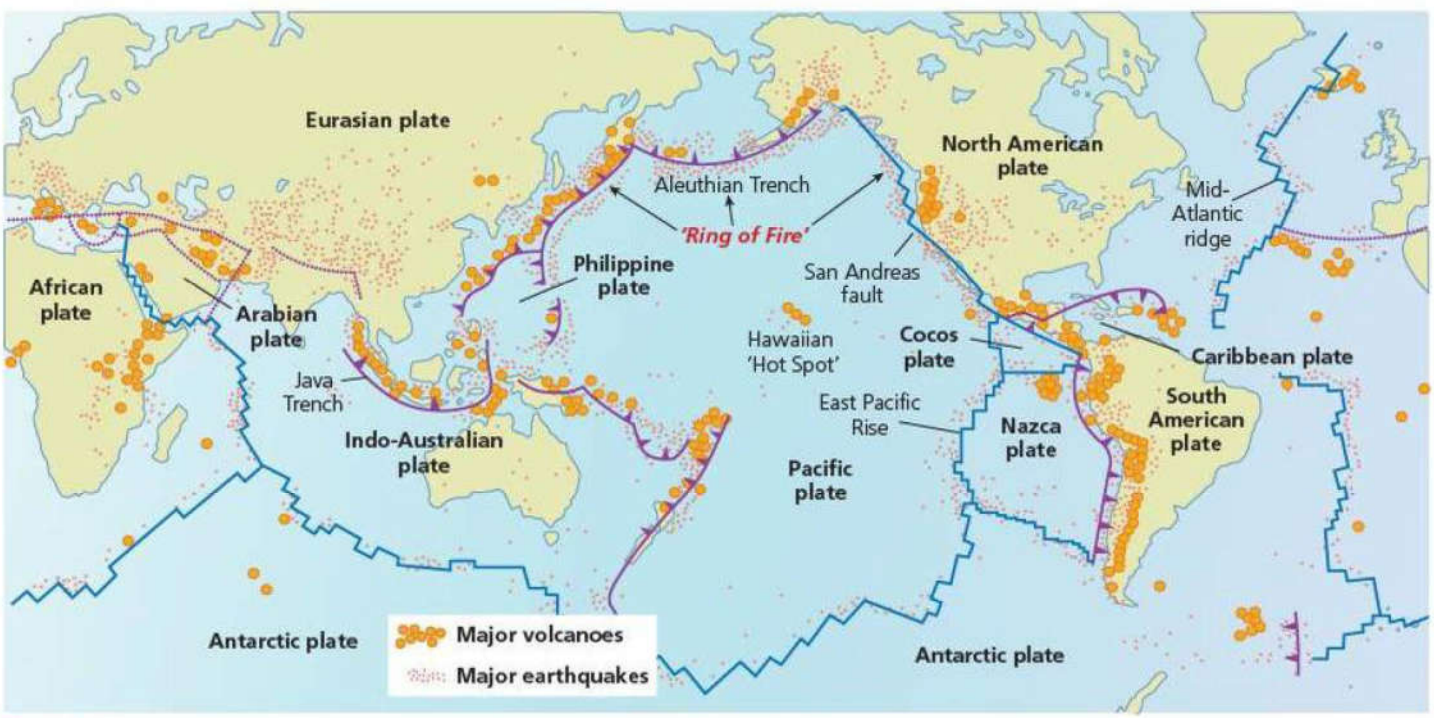


Figure 9.1 Distribution of plates, plate boundaries, volcanoes and earthquakes

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

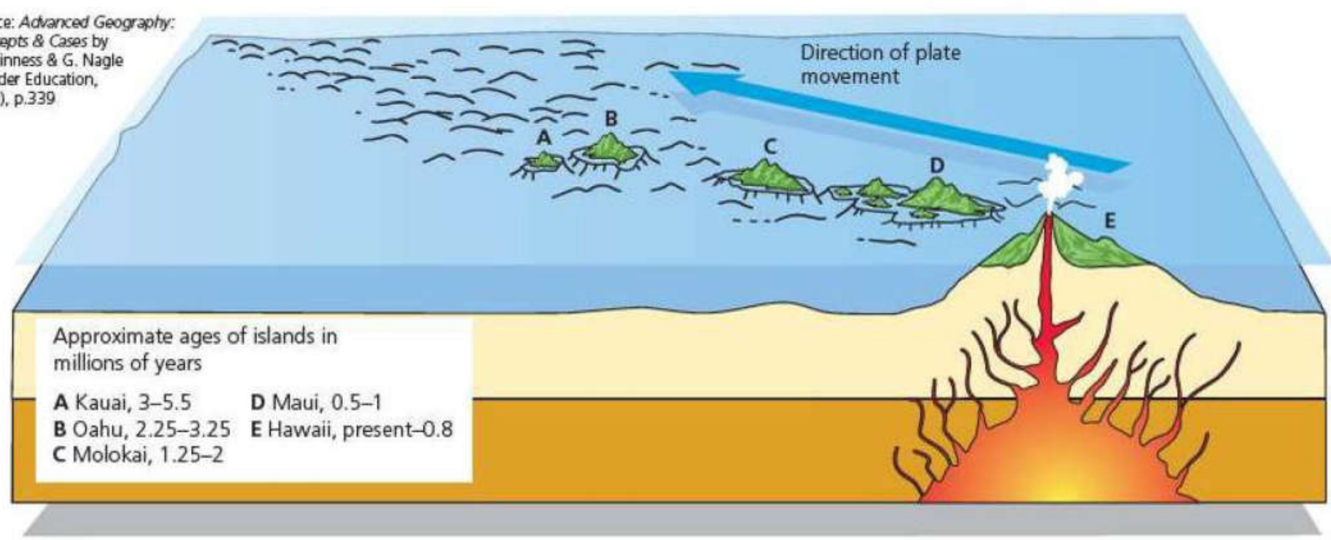


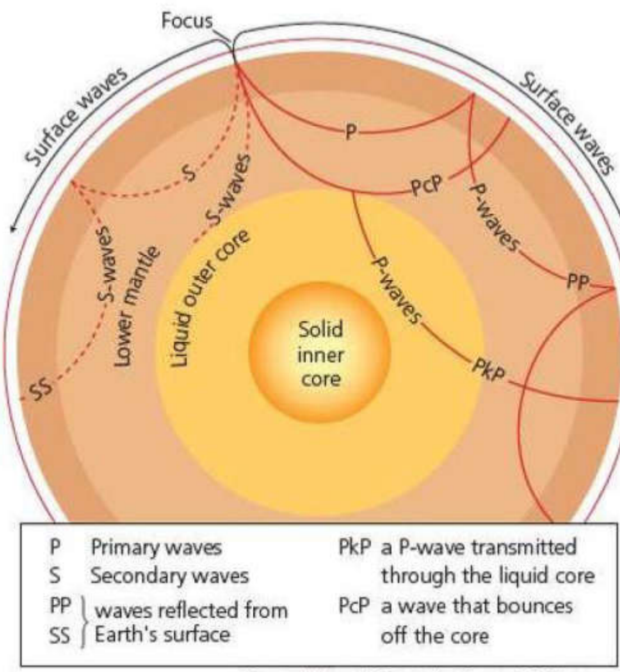
Figure 9.2 Hotspots and the evolution of Hawaii

Tsunamis

Up to 90 per 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 2.9 g/cm³ to 3.3 g/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 5.5 g/cm³ at 2900 kilometres to a density of 10 g/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 13.6 g/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.

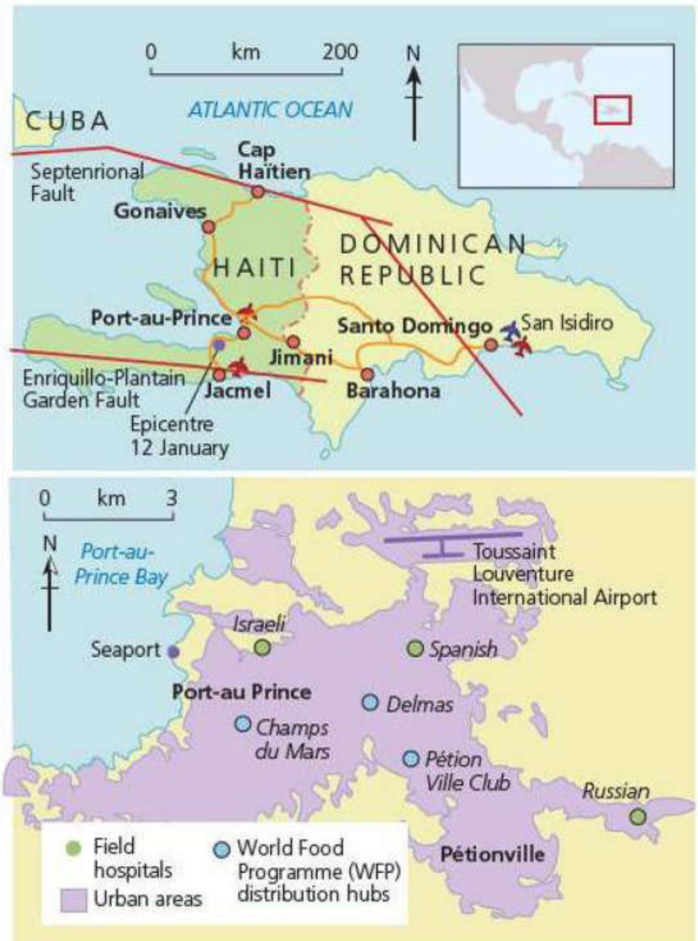


Figure 9.4 Haiti earthquake

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

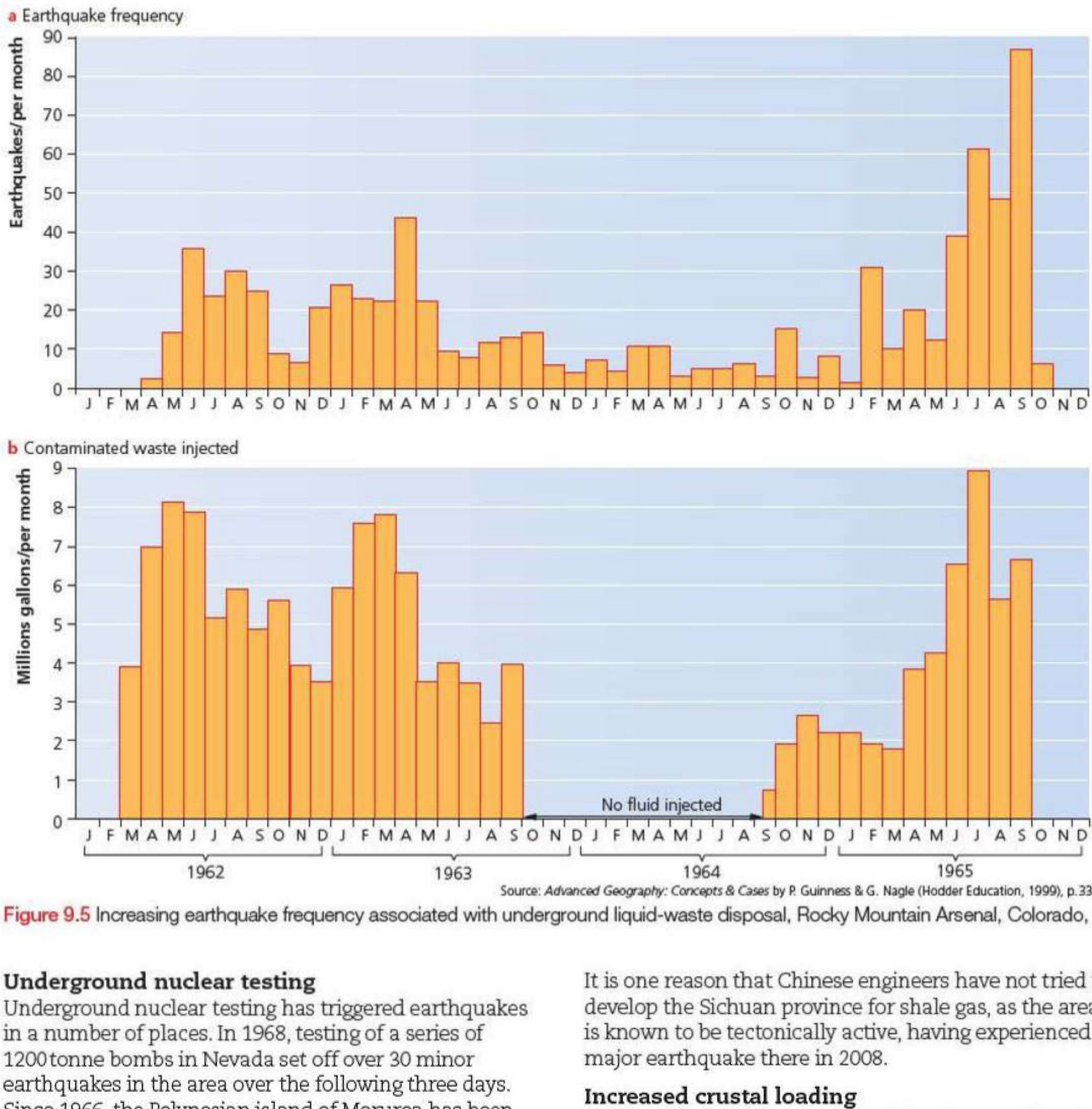
Human activities can trigger earthquakes, or alter the magnitude and frequency of earthquakes, in three main ways:

- 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 km³ 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.

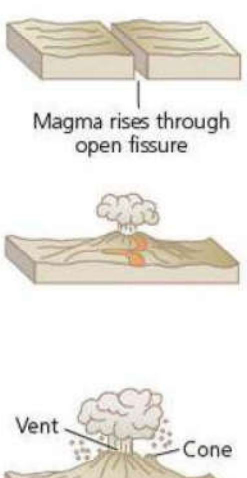
Aa flow is a few metres thick. It consists of two distinct zones: an upper rubbly part and a lower part of solid lava, which cools slowly. Aa surfaces are a loose jumble of irregularly shaped cindery blocks with sharp sides. By contrast, **pahoehoe** flow is the least viscous of all lavas; rates of advance 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.

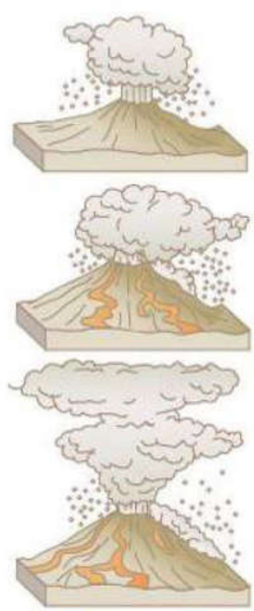
Active volcanoes are volcanoes that continue to erupt or are at risk of erupting. **Extinct volcanoes** have stopped erupting, and **dormant volcanoes** are ones that have not erupted for a very long time but could still erupt. It is an arbitrary classification, and the distinction between dormant and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

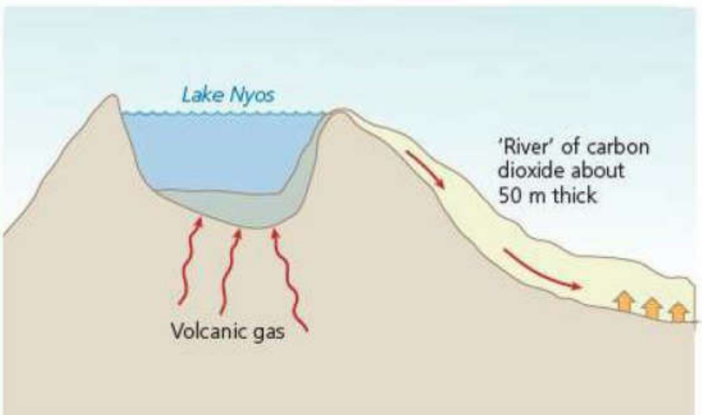


Figure 9.9 Lake Nyos, Cameroon

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.

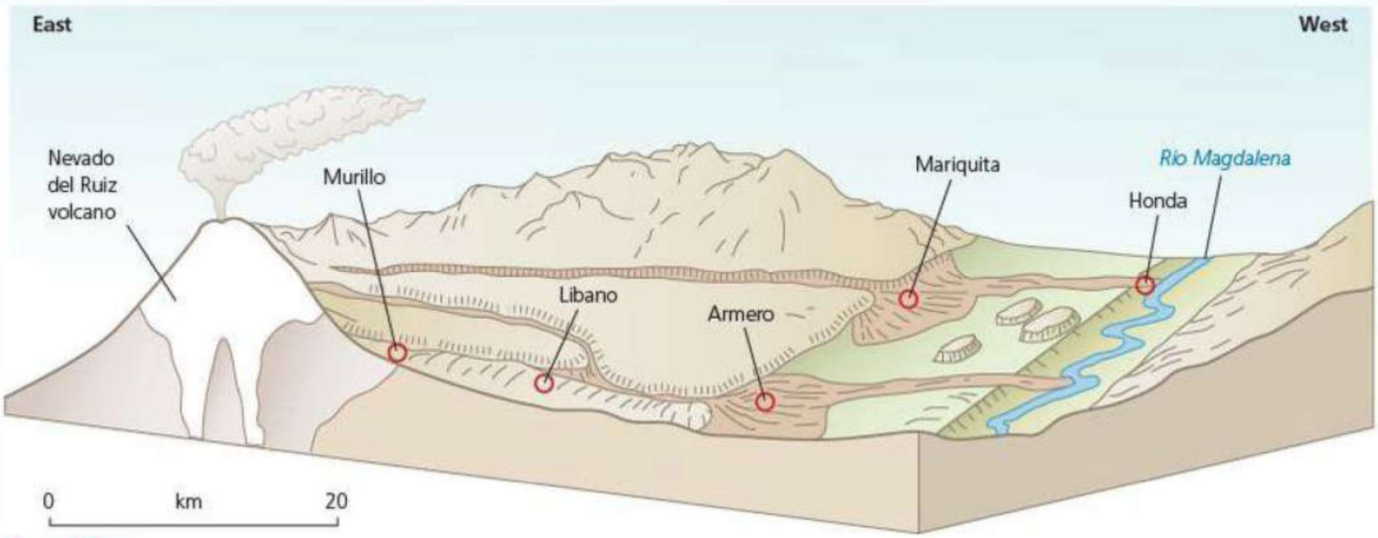


Figure 9.10 Nevado del Ruiz lahar

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 31000 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 25000 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.

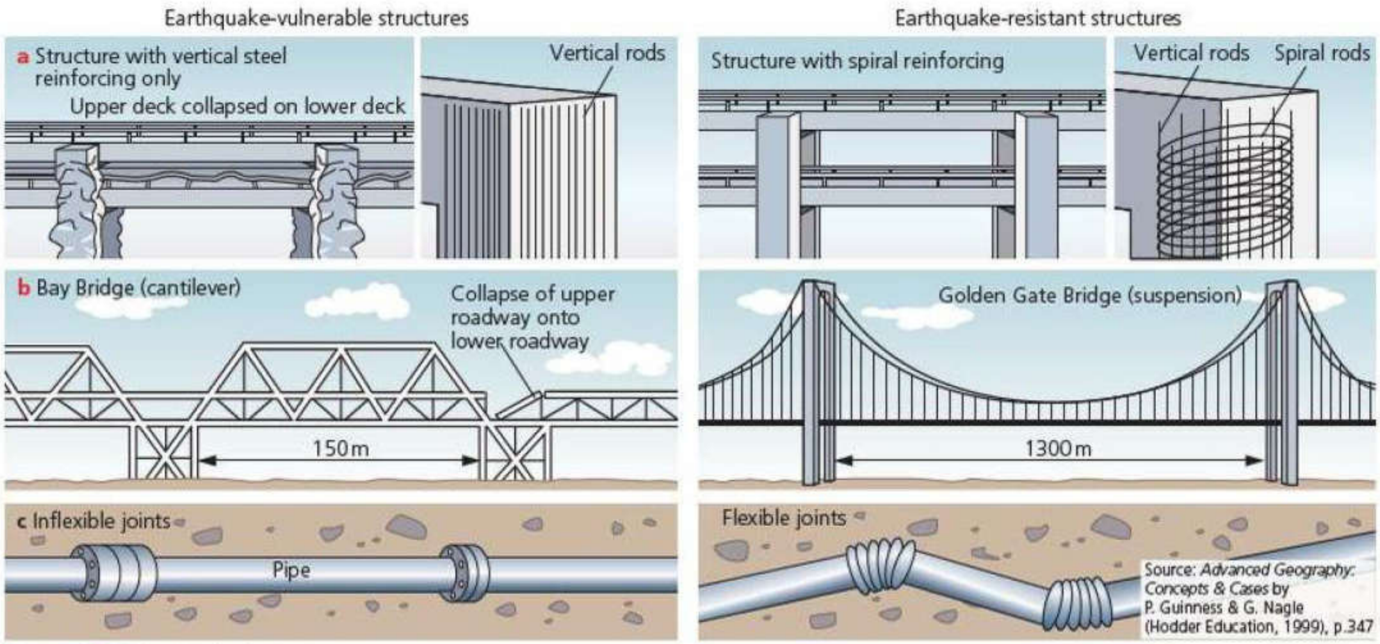


Figure 9.13 Aseismic design

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).

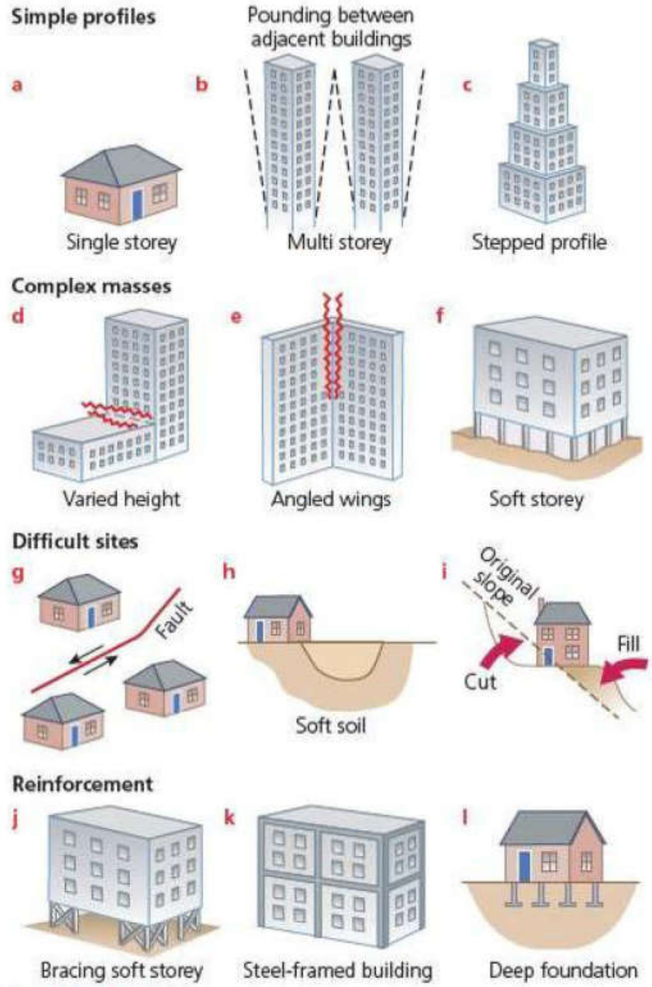
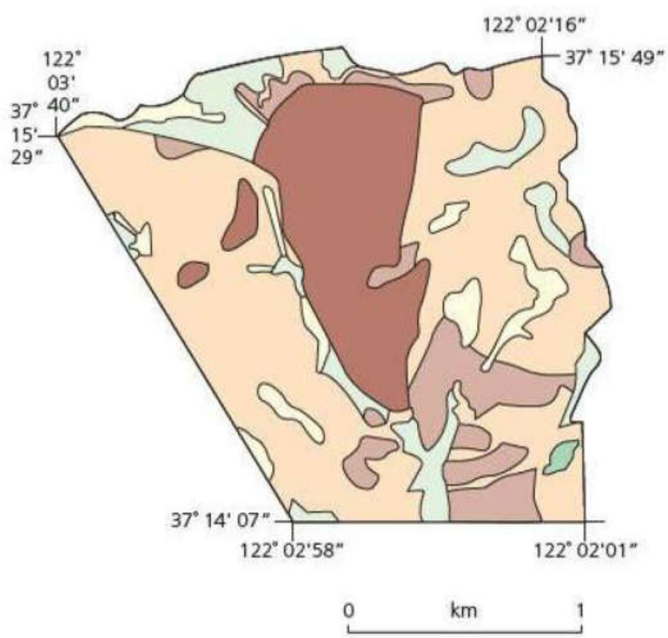


Figure 9.14 Building design



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)

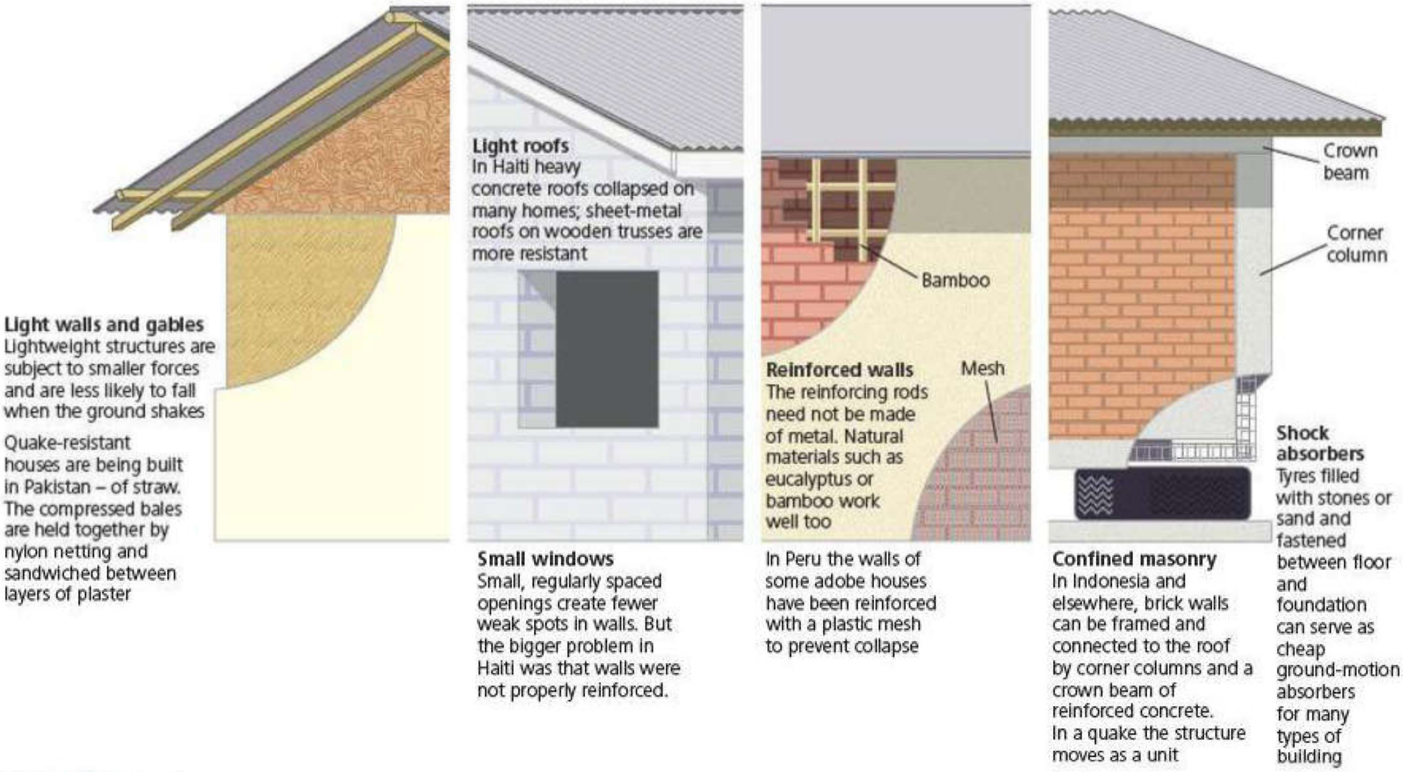


Figure 9.16 A safe house

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 100 years. 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).

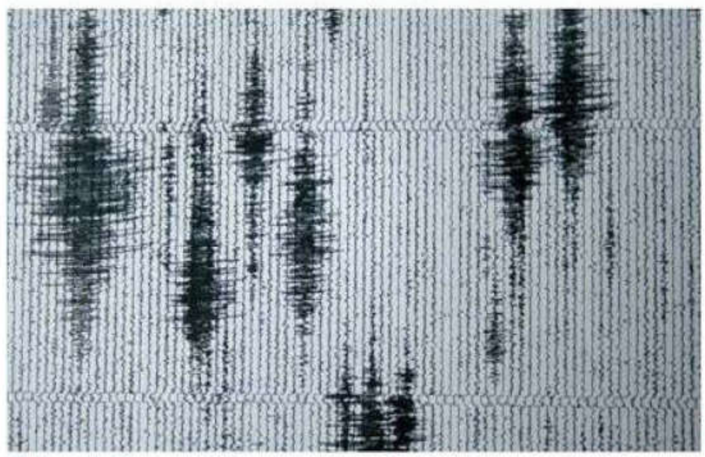


Figure 9.17 A seismograph reading (Montserrat)

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 60 per 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?

9.2 Hazards resulting from mass movements

The nature and causes of mass movements and resultant hazards

Mass movements can be classified in a number of ways. The main ones include speed of movement and the amount of water present. In addition, it is possible to distinguish between different types of movement, such as falls, flows, slides and slumps. (See Topic 3, Section 3.3.)

The likelihood of a slope failing can be expressed by its safety factor. This is the relative strength or resistance of the slope, compared with the force that is trying to move it. The most important factors that determine movement are gravity, slope angle and pore pressure (Figures 9.20 and 9.21).

Figure 9.20 Landslide near Zermatt, Switzerland

Figure 9.21 Landslip on a slope in Oxford, UK

Gravity has two effects. First, it acts to move the material downslope (a slide component). Second, it acts to stick the particle to the slope (a stick component). The downslope movement is proportional to the weight of the particle and slope angle. Water lubricates particles and in some cases fills the spaces between the particles. This forces them apart under pressure. Pore pressure will greatly increase the ability of the material to move. This factor is of particular importance in movements of wet material on low-angle slopes (Table 9.9).

Table 9.9 Increasing stress and decreasing resistance

Factor	Examples
Factors contributing to increased shear stress	
Removal of lateral support through undercutting or slope steepening	Erosion by rivers and glaciers, wave action, faulting, previous rockfalls or slides
Removal of underlying support	Undercutting by rivers and waves, subsurface solution, loss of strength by exposure of sediments
Loading of slope	Weight of water, vegetation, accumulation of debris
Lateral pressure	Water in cracks, freezing in cracks, swelling, pressure release
Transient stresses	Earthquakes, movement of trees in wind
Factors contributing to reduced shear strength	
Weathering effects	Disintegration of granular rocks, hydration of clay minerals, solution of cementing minerals in rock or soil
Changes in pore-water	Saturation, softening of material pressure
Changes of structure	Creation of fissures in clays, remoulding of sands and clays
Organic effects	Burrowing of animals, decay of roots

Landslides are a common natural event in unstable, steep areas (Figure 9.22). Landslides may lead to loss of life; disruption of transport and communications; and damage to property and infrastructure. The annual repair cost for roads in the Caribbean is estimated to be US$15 million.

Figure 9.22 Mam Tor landslide, Derbyshire, UK

Tropical storm activity may trigger landslides. In Jamaica in 2001, tropical storm Michelle triggered a number of debris flows, many 2–3 kilometres in length. Similarly, tropical storm Mitch (1998) caused a mudflow 20 kilometres long and 2–3 kilometres wide, which killed more than 1500 people in the town of Posoltega in Nicaragua and surrounding villages.

The two main forces that trigger landslides in the Caribbean are:

- seismic activity
- heavy rainfall.

Jamaica is subject to frequent landslides. In the Blue Mountains, over 80 per cent of the slopes are greater than 2°. The area is also geologically young and heavily fractured, and the bedrock is deeply weathered, making it unstable. The largest historic landslide in the region occurred on Judgement Cliff, eastern Jamaica, where an estimated 80 million m^3 of material was moved.

Human activities can increase the risk of landslides, for example by:

- **increasing the slope angle**, for instance cutting through high ground – slope instability increases with increased slope angle
- **placing extra weight on a slope**, for instance new buildings – this adds to the stress on a slope
- **removing vegetation** – roots may bind the soil together and interception by leaves may reduce rainfall compaction
- **exposing rock joints and bedding planes**, which may increase the speed of weathering.

There have been various attempts to manage the landslide risk. A number of landslide hazard maps have been produced for the region. Methods to combat the landslide hazard are largely labour intensive and include:

- **building restraining structures** such as walls, piles, buttresses and gabions – these may hold back minor landslides
- **excavating and filling steep slopes** to produce gentler slopes – this can reduce the impact of gravity on a slope
- **draining slopes** to reduce the build-up of water – this decreases water pressure in the soil
- **watershed management**, for example afforestation and agroforestry ('farming the forest') – this increases interception and reduces overland flow.

However, many settlements are located on unsuitable land because no-one else wants that land. Relocation following a disaster can also occur. For example, at Mayeyes near Ponce in Puerto Rico, the site was cleared following a landslide. Similarly, the Preston Lands landslide in 1986 in Jamaica resulted in the local community being relocated.

Section 9.2 Activities

1 Suggest why hazards due to mass movement are common throughout many parts of the Caribbean.
2 How can human activity increase the risk of landslides?

Impacts on lives and property

Landslides

Case Study: Landslides in Puerto Rico

Approximately 70–80 per cent of Puerto Rico is hilly or mountainous (Figure 9.23). Average annual precipitation in Puerto Rico ranges from less than 1000 millimetres along the southern coast to more than 4000 millimetres in the rainforest of the Sierra de Luquillo in the north-eastern part of the island. Rain in Puerto Rico falls throughout the year, but about twice as much rain falls each month from May to October – the tropical storm season – as falls from November to April. In October 1985, a tropical wave, which later developed into tropical storm Isabel, struck the south-central coast of Puerto Rico, and produced extreme rainfall.

Figure 9.23 Puerto Rico – relief

Puerto Rico can be divided into three distinct physiographic provinces: Upland, Northern Karst and Coastal Plains. The Upland province includes three major mountain ranges and is covered by dense tropical vegetation. Slopes as steep as 45° are common. The Northern Karst province includes most of north-central and north-western Puerto Rico north of the Upland province. The Coastal Plains province is a discontinuous, gently sloping area. Puerto Rico's major cities are built primarily in the Coastal Plain province, although population growth has pushed development onto adjacent slopes of the Upland and Northern Karst provinces. Some 60 per cent of the 3.35 million population lives in the four largest cities – San Juan, Ponce, Mayaguez, and Arecibo – which are located primarily on flat or gently sloping coastal areas. However, continuing growth of these urban centres is pushing development onto surrounding steep slopes.

All major types of landslide occur in Puerto Rico. Most of the Upland province and the Northern Karst province, on account of their high relief, steep slopes and abundant rainfall, have continuing landslide problems. The drier south-western part normally experiences landslides only during exceptionally heavy rainfall.

Debris slides and debris flows – rapid downslope sliding or flowing of disrupted surface rock and soil – are particularly hazardous because they happen with little or no warning. Rock falls are common on very steep natural slopes and especially on the numerous steep road cuttings on the island.

A major tropical storm in October 1985 triggered thousands of debris flows as well as a disastrous rock slide that destroyed the Mameyes district of Ponce, killing at least 129 people. The Mameyes landslide was the worst ever landslide experienced in Puerto Rico. More than 100 homes were destroyed, and about as many were later condemned and removed because of continuing risk from landslides.

The greatest cost to public works in Puerto Rico is road maintenance. The frequency of serious storms suggests that a long-term average of perhaps five fatalities per year could occur, tens of houses be destroyed or made unfit to live in and hundreds be damaged by landslides each year.

Section 9.2 Activities

1 Suggest why Puerto Rico is so vulnerable to landslides.
2 How could the threat of landslides be reduced?

Case Study: China's landslide, 2010

China experienced its deadliest landslide in decades in 2010. At least 700 people died in north-western Gansu province when an avalanche of mud and rock engulfed the small town of Zhouqu. Zhouqu town is in a valley. Heavy rain quickly ran off the steep, barren hills, triggering mudslides and swelling the river. Landslides levelled an area about 5 kilometres long and 500 metres wide, and more than 300 houses collapsed.

Officials have warned for years that heavy tree-felling and rapid hydro development were making the mountain area around Zhouqu vulnerable to landslips. One government report in 2009 called the Bailong River a 'high-occurrence disaster zone for landslides'.

The landslide created a loose earth dam. Water levels behind the barrier fell slightly after controlled explosions created a channel to funnel off some of the water.

The landslide was the worst to hit China in 60 years, and was the most deadly single incident in a year of heavy flooding that killed nearly 1500 people.

Mudslides

Case Study: Human causes – the Italian mudslides, 1998

In May 1998, mudslides swept through towns and villages in Campania, killing nearly 300 people. Hardest hit was Sarno, a town of 35 000 people (Figure 9.24). In the two weeks before the mudslide, up to a year's rainfall had fallen. Geologically, the area is unstable – it has active volcanoes, such as Etna and Vesuvius, many mountains and scores of fast-flowing rivers. Following the mudslide, a state of emergency was declared in the Campania region, and up to £18 million was allocated for repairing the damage. Campania is one of Italy's most vulnerable regions – since 1892, scientists have recorded at least 1173 serious landslides in Campania and Calabria. Since 1945, landslides and floods have caused an average of seven deaths every month (Table 9.10).

Figure 9.24 Sarno, Italy

Table 9.10 Floods and landslides in Italy since 1950

Year	Region	Event	Deaths
1951	Calabria	Floods	100
1951	Polesine, Veneto	Floods	89
1954	Salerno, Campania	Floods	297
1963	Longarone, Veneto	Landslide, floods	1800
1966	Florence, Tuscany	Floods	35
1985	Val di Stava, Trentino	Landslide, floods	269
1987	Valtelina, Lombardy	Floods, landslide	53
1994	Alessandria, Piedmont	Floods	68
1996	Versilia, Tuscany	Floods, landslide	14
1998	Sarno and Siano, Campania	Mudslide, floods	285

However, the disaster was only partially natural – much of it was down to human error. The River Sarno had dwindled to a trickle of water and part of the river bed had been cemented over. The clay soils of the surrounding mountains had been rendered dangerously loose by forest fires and deforestation. Houses had been built up hillsides identified as landslide zones, while Italy's sudden entry into the industrial age in the 1960s led to the uncontrolled building of houses and roads, and deforestation. Nowhere was this more evident than in

Campania. Over 20 per cent of the houses in Sarno were built without permission. Most are shoddily built over a 2 metre-thick layer of lava formed by the eruption of Vesuvius in 79 CE. Heavy rain can make this lava liquid, and up to 900 million tonnes of material are washed down in this way every year. Much of the region's fragility is, therefore, due to mass construction, poor infrastructure and poor planning.

It is likely that similar landslides will be experienced in Spain, Portugal, Greece and Turkey as these countries are developed. All across southern Europe, the natural means by which excess rainfall can be absorbed harmlessly are being destroyed. First, the land is cleared for development (even land that may have been designated as green-belt land). The easiest way to clear the vegetation is to set it on fire. The growing incidence of forest fires around the Mediterranean is not coincidental. Many are started deliberately by developers to ensure that the area loses its natural beauty. One of the side-effects of fire is to loosen the underlying soil.

Throughout southern Europe, the easiest way for an individual to add an extension or build a house is not to submit plans for approval but just to go ahead. In Sicily, up to 20 000 holiday homes have been built on beaches, cliffs and wetlands, in defiance of planning regulations. In Italy, 217 000 houses have been built without permission, and without proper drainage or foundations. Many stand close to an apparently dry river bed that can become a torrent during a storm. One Campanian town, Villaggio Coppola di Castelvolturno, with a population of 15 000 inhabitants, was created entirely without authorisation.

Section 9.2 Activities

1. What are the natural reasons why Italy is at risk from mudslides?
2. What human factors have increased the risk of mudslides in the region?
3. Why is the threat of mudslides increasing throughout the Mediterranean region?

Case Study: The Venezuelan mudslides

The Venezuelan mudslides of 1999 were the worst disaster to hit the country for almost 200 years (Figure 9.25). The first two weeks of December saw an unusually high amount of rainfall in Venezuela. Precipitation was 40–50 per cent above normal in most of the eastern Caribbean during 1999. On 15 and 16 December, the slopes of the 2000 metre Mt Avila began to pour forth avalanches of rock and mud, burying large parts of a 300 kilometre stretch of the central coast. The rains triggered a series of mudslides, landslides and flash floods that claimed the lives of between 10 000 and 50 000 people in the narrow strip of land between the mountains and the Caribbean Sea. Over 150 000 people were left homeless by landslides and floods in the states of Vargas and Miranda.

Figure 9.25 Venezuela

Hardest hit was the state of Vargas. Countless mountainside slum dwellings were either buried in the mudslide or swept out to sea. Most of the dead were buried in mudslides that were 8–10 metres deep. The true number of casualties may never be known. The mudslides also destroyed roads, bridges and factories, buried crops in the fields, destroyed telecommunications and also ruined Venezuela's tourist industry for the immediate future. The international airport of Caracas was temporarily closed and the coastal highway was destroyed or closed in many places. Flash floods damaged hundreds of containers at the seaport in Maiquetía. Hazardous materials in some containers were leaked into the ground and into the sea. Flash-flood damage halted operations at the Maiquetía seaport and hampered efforts to bring in emergency supplies immediately after the disaster. Economic damage was estimated at over US$3 billion.

The disaster was not just related to heavy rainfall. The government blamed corrupt politicians from previous governments and planners who had allowed shanty towns to grow up in steep valleys surrounding the coast and the capital, Caracas.

The immediate response was a search-and-rescue operation to find any survivors in the mudflows, landslides and buildings that had been damaged or destroyed. Few survivors were found after the first few days. The other short-term response was to provide emergency relief – accommodation, water purification tablets, food and medicines to those in need. The relief operation was severely hindered by the poor state of the infrastructure, which made operations difficult.

Ironically, the government had already been planning to redistribute part of Venezuela's population away from the overcrowded coast to the interior. Up to 70 per cent of Venezuela's population live in this small area.

Government plans for rebuilding

The Venezuela government announced a plan to restore Venezuela's northern coastal region by rebuilding thousands of homes there, expanding the country's main airport and constructing canals that can direct rivers away from communities.

The plan includes building 40 000 new homes in the hard-hit state of Vargas. The resort towns of Macuto and Camuri Chico were restored as tourist destinations and $100 million will be spent to expand Venezuela's main international airport. The country's main seaport, also in Vargas, was 'modernised'.

The towns that were utterly devastated by the disaster, where most structures were swept out to sea, were not rebuilt. Instead, these towns, including the coastal community of Carmen de Uria (Figure 9.26), were turned into parks, bathing resorts and other outdoor facilities.

Figure 9.26 Landslide at Carmen de Uria

In 2005, floods and mudslides brought on by heavy rains in the northern and central coast of Venezuela caused 14 deaths. Some 18 000 people were affected, while 2840 houses were damaged and a further 363 destroyed. In many cases, those that were affected in the 1999 mudslides were also affected in 2005.

Section 9.2 Activities

1 What were the causes of the Venezuelan mudslides?
2 Why were the impacts so great?

Table 9.11 Examples of hazards in mountainous areas

Hazards	Disaster event
Rockslides	Elm, Swiss Alps, 1881 Vaiont Dam, Italian Alps, 1963
Mud and debris flows	European Alps, 1987 Huanuco Province, Peru, 1989
Debris torrents	Coast Range, British Colombia 1983–84 Rio Colorado, Chile, 1987
Avalanches	Hakkari, Turkey, 1989 Western Iran, 1990
Earthquake-triggered mass movements	Campagna, Italy, 1980 Mt Ontake, Japan, 1984
Vulcanism-triggered mass movements	Mt St Helens, USA, 1980 Nevado del Ruiz, Colombia, 1985
Weather-triggered mass movements from volcanoes	Mt Kelut, Indonesia, 1966 Mt Semeru, Java, 1981
Natural dams and dam-break floods	
Landslide dams	Indus Gorge, Western Himalayas, 1841 Ecuadorean Andes, 1987 Sichuan earthquake, 2008
Glacier dams	'Ape Lake', British Colombia, 1984
Moraine dams	Khumbu, Nepal, Himalaya, 1985
Avalanche dams	Santa River, Peruvian Andes, 1962
Vegetation dams	New Guinea Highlands, 1970
Artificial dam failures	Buffalo Creek, Appalachians, USA, 1972 Shanxi Province, China, 1989

Table 9.11 summarises some of the hazards that are experienced in mountainous areas around the world.

Avalanches

Avalanches are mass movements of snow and ice. Newly fallen snow may fall off older snow, especially in winter, while in spring partially thawed snow moves, often triggered by skiing. Avalanches occur frequently on steep slopes over 22°, especially on north-facing slopes where the lack of Sun inhibits the stabilisation of the snow. They are also very fast. Average speeds in an avalanche are 40–60 kilometres per hour, but speeds of up to 200 kilometres per hour have been recorded in Japan.

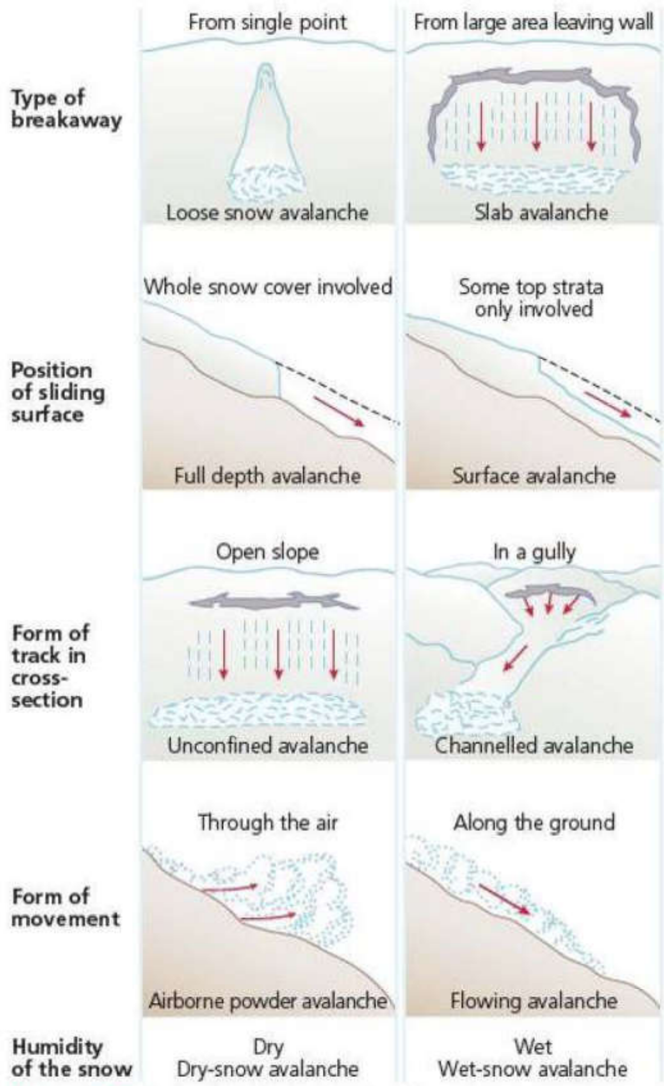


Figure 9.27 A classification of avalanches

Avalanches are classified in a number of ways (Figure 9.27). At first, a distinction was made between airborne powder-snow avalanches and ground-hugging avalanches. Later classifications have included:

- **the type of breakaway** – from a point formed with loose snow, or from an area formed of a slab
- **position of the sliding surface** – the whole snow cover or just the surface
- **water content** – dry or wet avalanches
- **the form of the avalanche** – whether it is channelled in cross-section or open.

Although avalanches cannot be prevented, it is possible to reduce their impact (Figures 9.28 and 9.29). So why do avalanches occur? The underlying processes in an avalanche are similar to those in a landslide. Snow gets its strength from the interlocking of snow crystals and cohesion caused by electrostatic bonding of snow crystals. The snow remains in place as long as its strength is greater than the stress exerted by its weight and the slope angle.

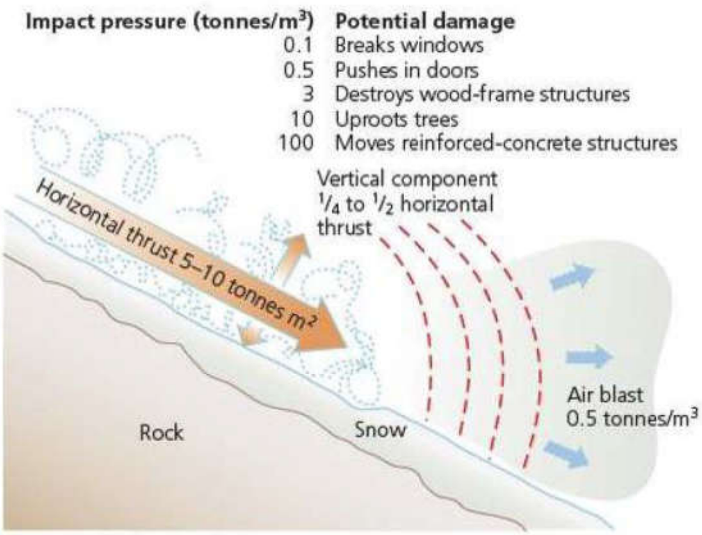


Figure 9.28 Avalanche impact

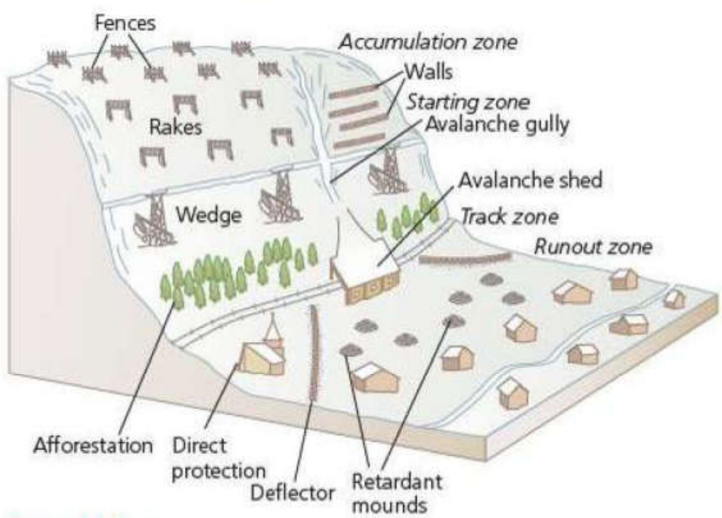


Figure 9.29 Measures to reduce the impact of avalanches

The process is complicated by the way in which snow crystals constantly change. Changes in overlying pressure, compaction by freshly fallen snow, temperature changes and the movement of meltwater through the snow cause the crystal structure of the snow to change. It may become unstable and move downslope as an avalanche.

Loose avalanches, comprising fresh snow, usually occur soon after a snowfall. By contrast, slab avalanches occur at a later date, when the snow has developed some cohesion. The latter are usually much larger than loose avalanches and cause more destruction. They are often started by a sudden rise in temperature that causes melting. The meltwater lubricates the slab, and makes it unstable. Many of the avalanches occur in spring (Table 9.12) when the snowpack is large and temperatures are rising. There is also a relationship between the number of avalanches and altitude (Table 9.13).

Table 9.12 Occurrence of avalanches in the French Alps

December	10%
January	22%
February	32%
March	23%
April	13%

Table 9.13 Avalanches and altitude in the Swiss Alps

Altitude (m)	No. of avalanches	% of total
Above 3000	326	3
2500–3000	2210	24
2000–2499	3806	41
1500–1999	2632	28
Below 1500	394	4

Section 9.2 Activities

1 Suggest reasons why avalanches are clustered in the months January to March. Give details on at least **two** reasons.

2 Table 9.13 shows the distribution of avalanches with altitude in Switzerland. The tree-line is at about 1500 metres and the snow line is at 3000 metres. Describe the distribution of avalanches with altitude. How do you explain this pattern?

Case Study: The European avalanches of 1999

The avalanches that killed 75 people in the Alps in February 1999 were the worst in the area for nearly 100 years. Moreover, they occurred in an area that was thought to be fairly safe. In addition, precautionary measures had been taken, such as an enormous avalanche wall to defend the village of Taconnaz, and a second wall to stop the Taconnaz glacier advancing onto the motorway that runs into the mouth of the Mt Blanc tunnel. However, the villages of Montroc and Le Tour, located at the head of the Chamonix Valley, had no such defences.

The avalanche that swept through the Chamonix Valley killed 11 people and destroyed 18 chalets (Figure 9.30). Rescue work was hampered by the low temperatures (−7 °C), which caused the snow to compact and made digging almost impossible. The avalanche was about 150 metres wide, 6 metres high and travelled at a speed of up to 90 kilometres per hour. It crossed a stream and even travelled uphill for some 40 metres. Residents were shocked, since they had not experienced an avalanche so powerful, so low in the mountains and certainly not one capable of moving uphill.

Nothing could have been done to prevent the avalanche. Avalanche warnings had been given the day before, as the region had experienced up to 2 metres of snow in just three days. However, buildings in Montroc were not considered to be at risk. In fact, they were classified as being in the 'white zone', almost completely free of danger. By contrast, in the avalanche danger zones no new buildings have been developed for many decades. Avalanche monitoring is so well established and elaborate that it had caused villagers and tourists in the 'safe' zone to think that they really were safe. In Montroc, the experience was the equivalent of the eruption of an extinct volcano – the last time the snow above Montroc had caused an avalanche was in 1908.

Meteorologists have suggested that disruption of weather patterns resulting from global warming will lead to increased snowfalls in the Alps that are heavier and later in the season. This would mean that the conventional wisdom regarding avalanche 'safe' zones would need to be re-evaluated.

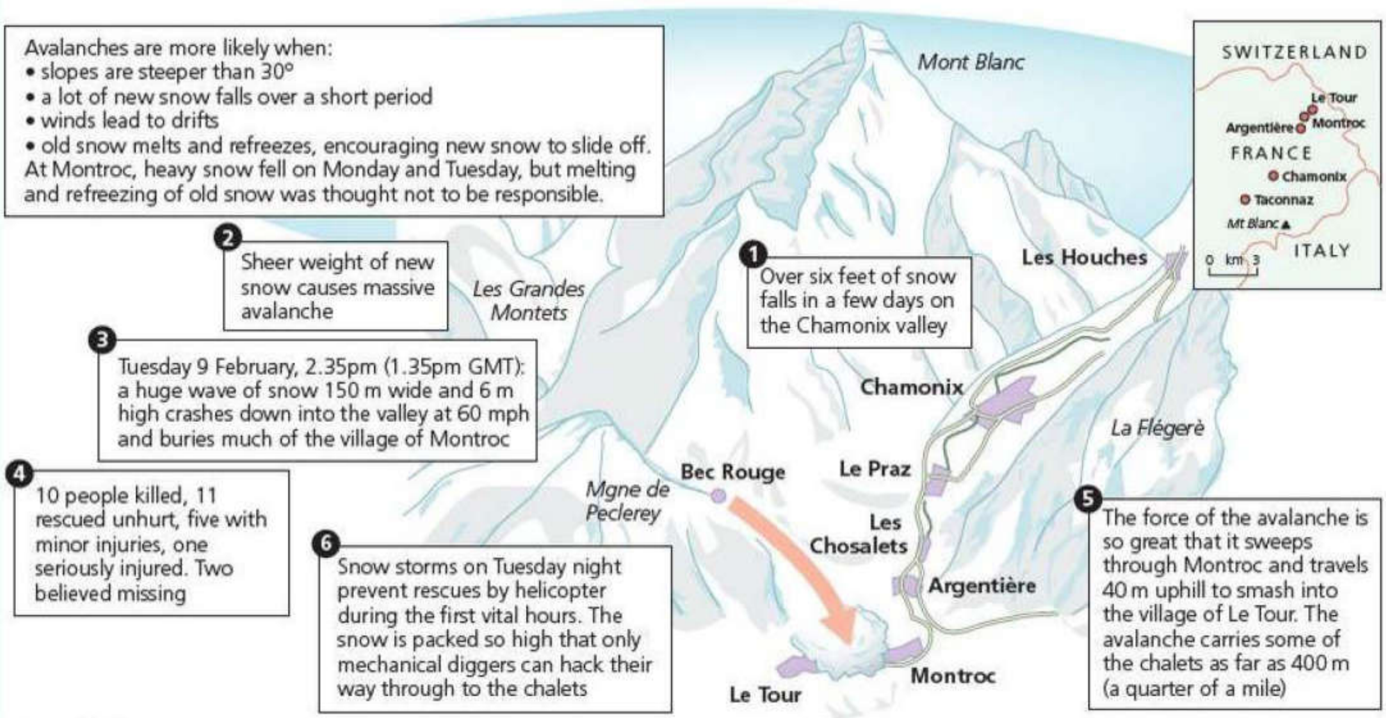


Figure 9.30 Causes and consequences of the Montroc–Le Tour avalanche

Snowslides 2009–10

In December 2009 and January 2010, dozens of people were caught in the path of avalanches. The increase in snowslide activity sent ominous rumblings through the communities of Europe's Alpine resorts. Residents live in fear of seeing a repeat of early 1999 (see above, when 75 people were killed over a period of three weeks), or even of 1950–51, when more than 265 people died in three months.

Heavy snowfall combined with rain and an easing of the extreme cold prompted Météo France, the national meteorological service, to raise the avalanche warning to level 4 (out of 5), meaning 'high risk'.

In 2009, scientists in London warned that global warming, in the form of rising temperatures and melting permafrost, could make avalanches more frequent.

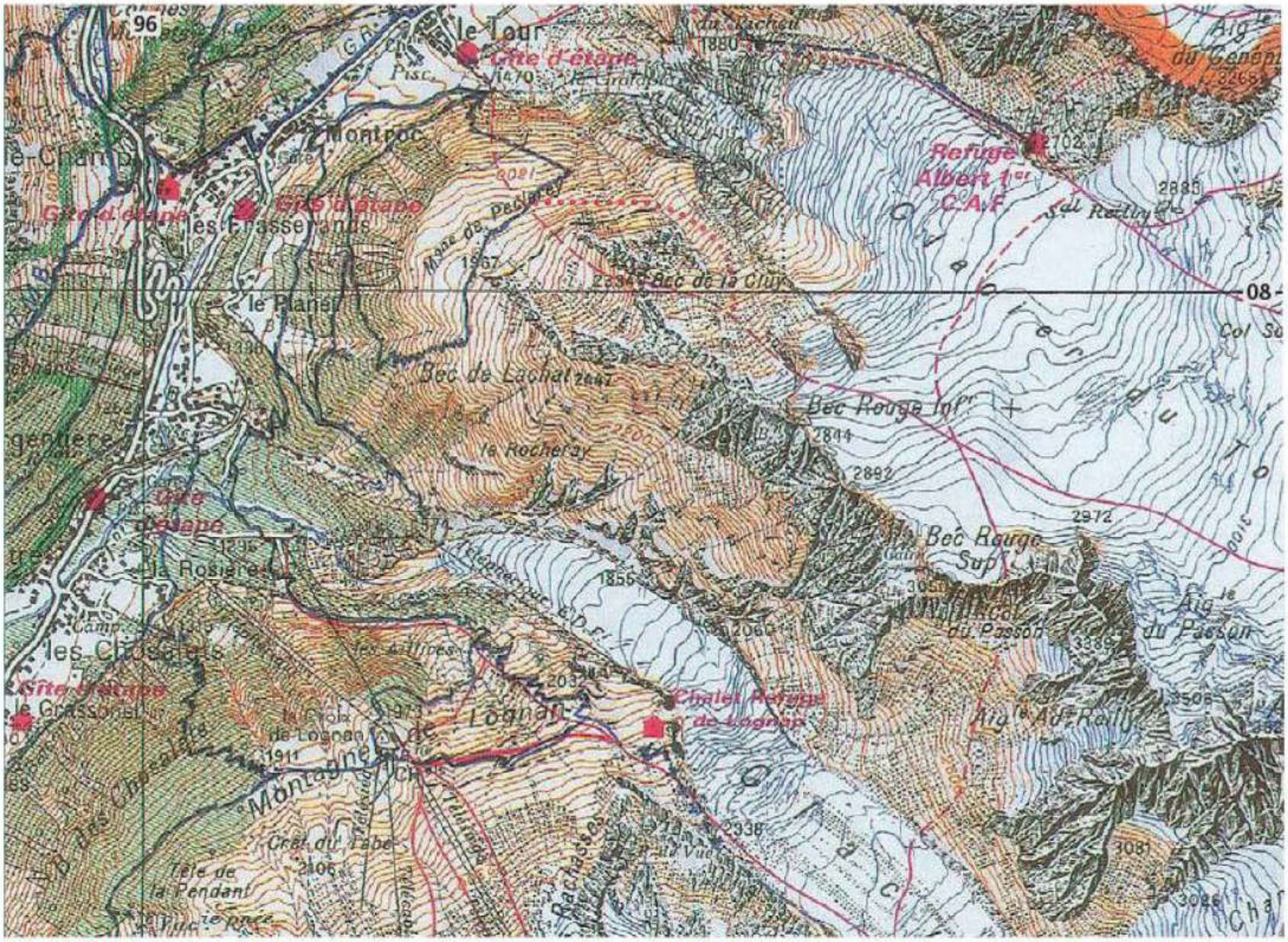


Figure 9.31 Survey map of the Alps – area affected by 1999 avalanches

Section 9.2 Activities

1 What is an *avalanche*?
2 What are the factors that increase the risk of an avalanche?
3 What were the conditions in Europe in February 1999 that led to widespread avalanches?
4 How and why may the threat of avalanches change in the next decades?
5 Study Figure 9.30.
   a Describe the site of Montroc and Le Tour.
   b What are the attractions for tourists shown on Figure 9.31? Use the grid provided to give grid references.
   c What is the map evidence to suggest that the area is at risk of hazardous events?

Prediction and hazard mapping

Landslides and other forms of mass movement are widespread and cause extensive damage and loss of life each year. With careful analysis and planning, together with appropriate stabilisation techniques, the impacts of mass movement can be reduced or eliminated.

Assessment of the hazards posed by potential mass movement events are based partly on past events, to evaluate their magnitude and frequency. In addition, mapping and testing of soil and rock properties determines their susceptibility to destabilising processes. Maps showing areas that could be affected by mass movement processes are important tools for land-use planners.

For example, valleys in the Cascade Range of Washington and Oregon, USA, have experienced extensive mudflows from volcanic activity over the last 10000years. Hazard maps prepared before the eruption of Mt St Helens and Mt Pinatubo proved extremely useful, as the mudflows generated by these eruptions had very similar distributions to those produced in earlier times (Figure 9.32).

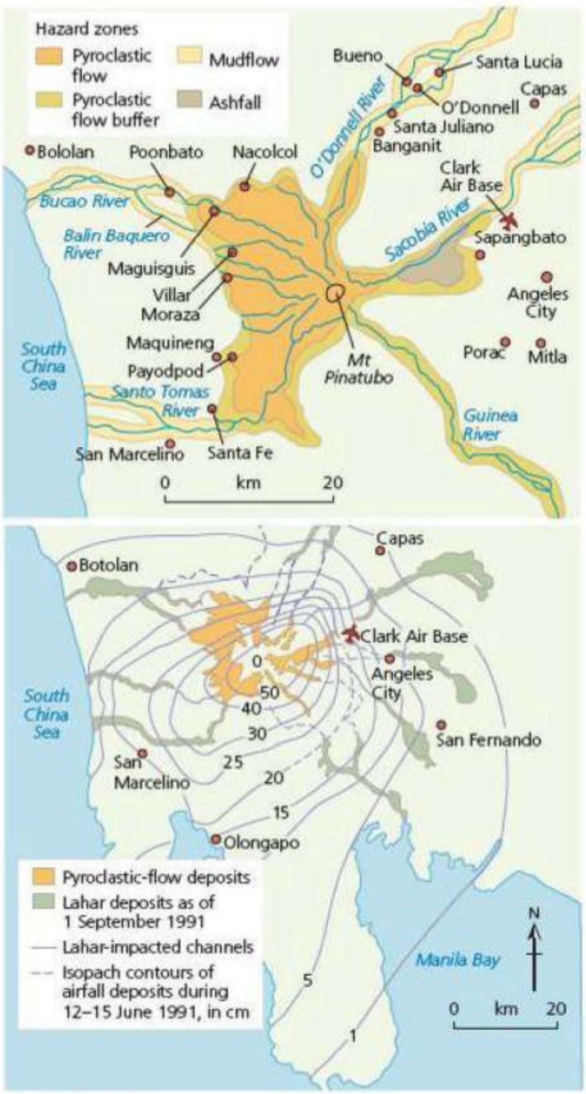


Figure 9.32 Hazard map of Mt Pinatubo

In addition to assessment, prediction and early warning, some engineering schemes can be applied to reduce the damage of mass wasting (Figure 9.33).

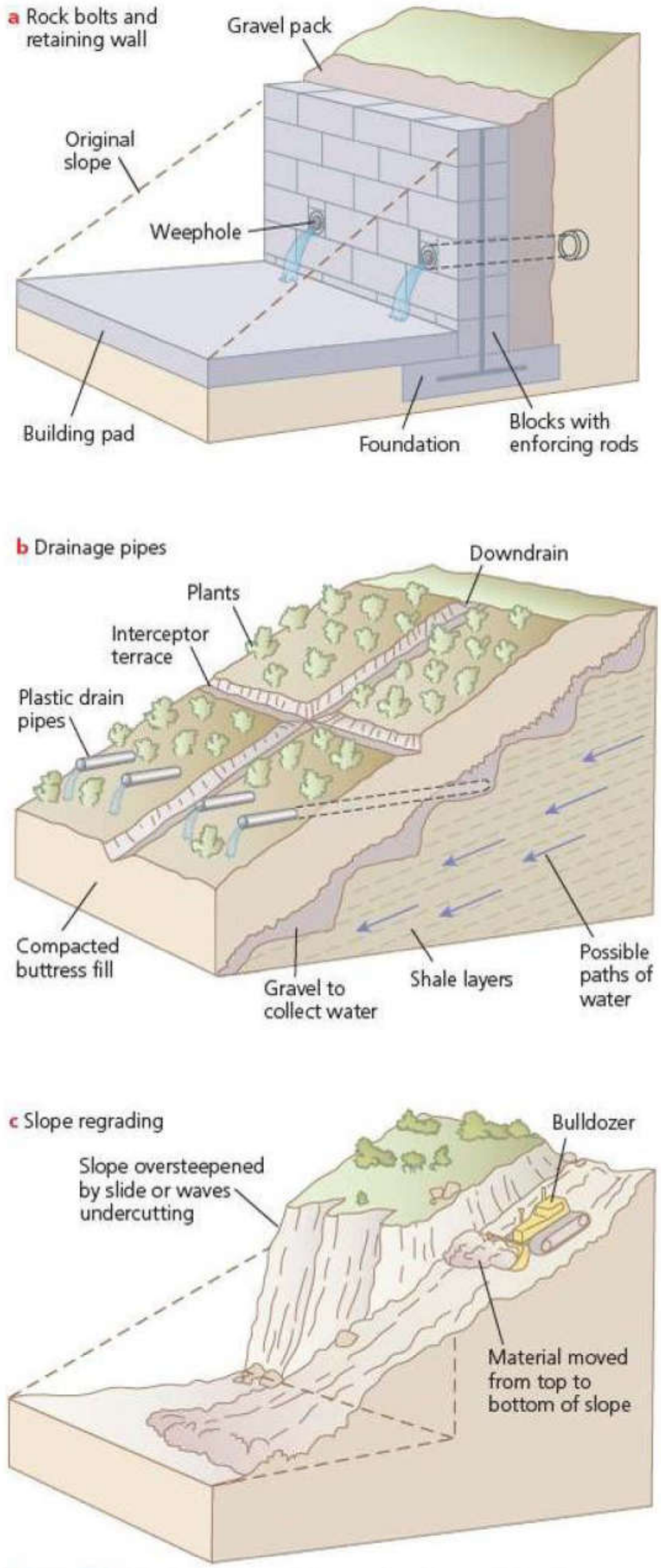


Figure 9.33 Engineering techniques for slope stabilisation

These include retaining devices, drainage pipes, grading of slope and diversion walls (Figure 9.34). Concrete blocks or gabions may be used to strengthen slopes. Slopes subject to creep can be stabilised by draining or pumping water from saturated sediment. Oversteepened slopes can be made gentler by **regrading**. However, not all communities can afford such measures and so may opt for low-cost sustainable forms of management.

Eliminating or restricting human activities in areas where slides are likely may be the best way to reduce damage and loss of life. Land that is susceptible to mild failures may be suitable for some forms of development (for example, recreation or parkland) but not others (for example, residential or industrial). Early-warning systems can provide forecasts of intense rain. High-risk areas can then be monitored and remedial action taken.

Figure 9.34 Engineering techniques, Brunei

9.3 Hazards resulting from atmospheric disturbances

Large-scale tropical disturbances – tropical storms (cyclones)

Tropical cyclones are known as 'hurricanes' in the Atlantic, Caribbean and north-west Pacific; they are known as 'typhoons' in the north-western Pacific; and they are called 'tropical cyclones' in the Indian Ocean and south Pacific.

Tropical storms bring intense rainfall and very high winds, which may in turn cause storm surges and coastal flooding, and other hazards such as (inland) flooding and mudslides. Tropical storms are also characterised by enormous quantities of water. This is due to their origin over tropical seas. High-intensity rainfall, as well as large totals – up to 500 millimetres in 24 hours – invariably cause flooding. Their path is erratic, so it is not always possible to give more than 12 hours' notice of their position. This is insufficient for proper evacuation measures. In North America and the Caribbean, tropical storms are referred to as hurricanes.

Tropical storms develop as intense low-pressure systems over tropical oceans. Winds spiral rapidly around a calm central area known as the 'eye'. The diameter of the whole tropical storm may be as much as 800 kilometres, although the very strong winds that cause most of the damage are found in a narrower belt up to 300 kilometres wide. In a mature tropical storm, pressure may fall to as low as 880 millibars (mb). This, and the strong contrast in pressure between the eye and outer part of the tropical storm, leads to very strong winds.

Tropical storms move excess heat from low latitudes to higher latitudes. They normally develop in the westward-flowing air just north of the equator (known as an 'easterly wave'). They begin life as a small-scale tropical depression, a localised area of low pressure that causes warm air to rise. This causes thunderstorms that persist for at least 24 hours, and may develop into tropical storms, which have greater wind speeds of up to 117 kilometres per hour. However, only about 10 per cent of tropical disturbances ever become tropical storms, with wind speeds above 118 kilometres per hour.

For tropical storms to form, a number of conditions are needed (Figure 9.35):

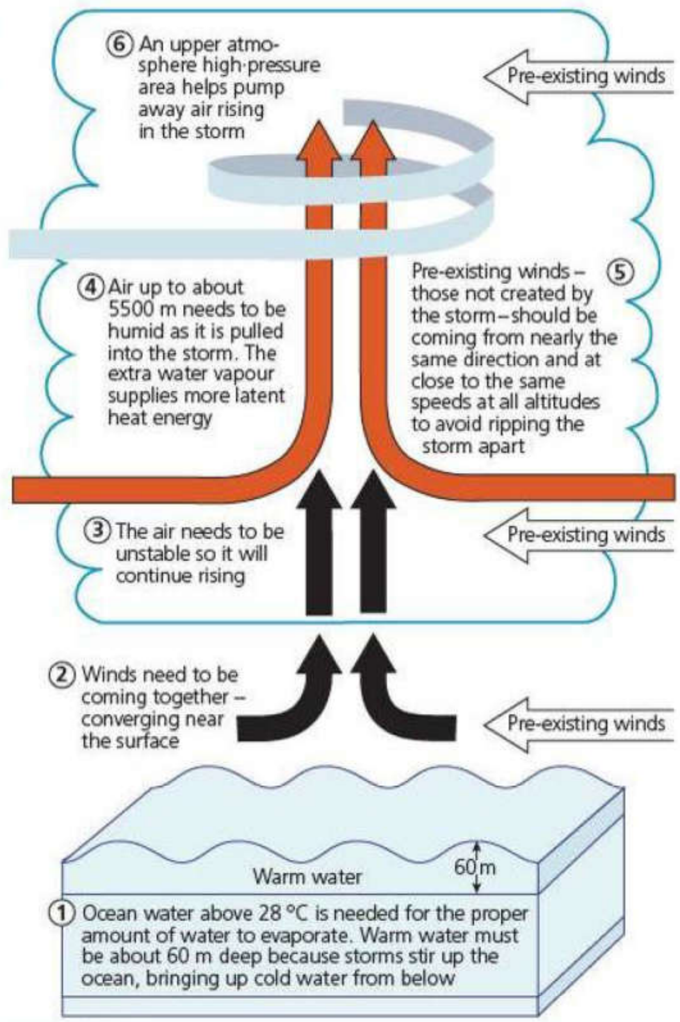


Figure 9.35 Formation of a tropical storm

- Sea temperatures must be over 27 °C to a depth of 60 metres (warm water gives off large quantities of heat when it is condensed – this is the latent heat that drives the tropical storm).
- The low-pressure area has to be far enough away from the equator so that the Coriolis force (the force caused by the rotation of the Earth) creates rotation in the rising air mass – if it is too close to the equator, there is insufficient rotation and a tropical storm would not develop.
- Conditions must be unstable – some tropical low-pressure systems develop into tropical storms (not all of them), but scientists are unsure why some do and others do not.

Tropical storms are the most violent, damaging and frequent hazard to affect many tropical regions (Figure 9.36). They are measured on the Saffir–Simpson Scale, which is a 1–5 rating based on the tropical storm's intensity (Table 9.14). It is used to give an estimate of the potential property damage and flooding expected along the coast from a tropical storm landfall. Wind speed is the determining factor in the scale, as storm surge values are highly dependent on the slope of the continental shelf and the shape of the coastline in the landfall region. Tropical storms can also cause considerable loss of life. Hurricane Georges (1998) killed more than 460 people, mainly in Dominican Republic and Haiti.

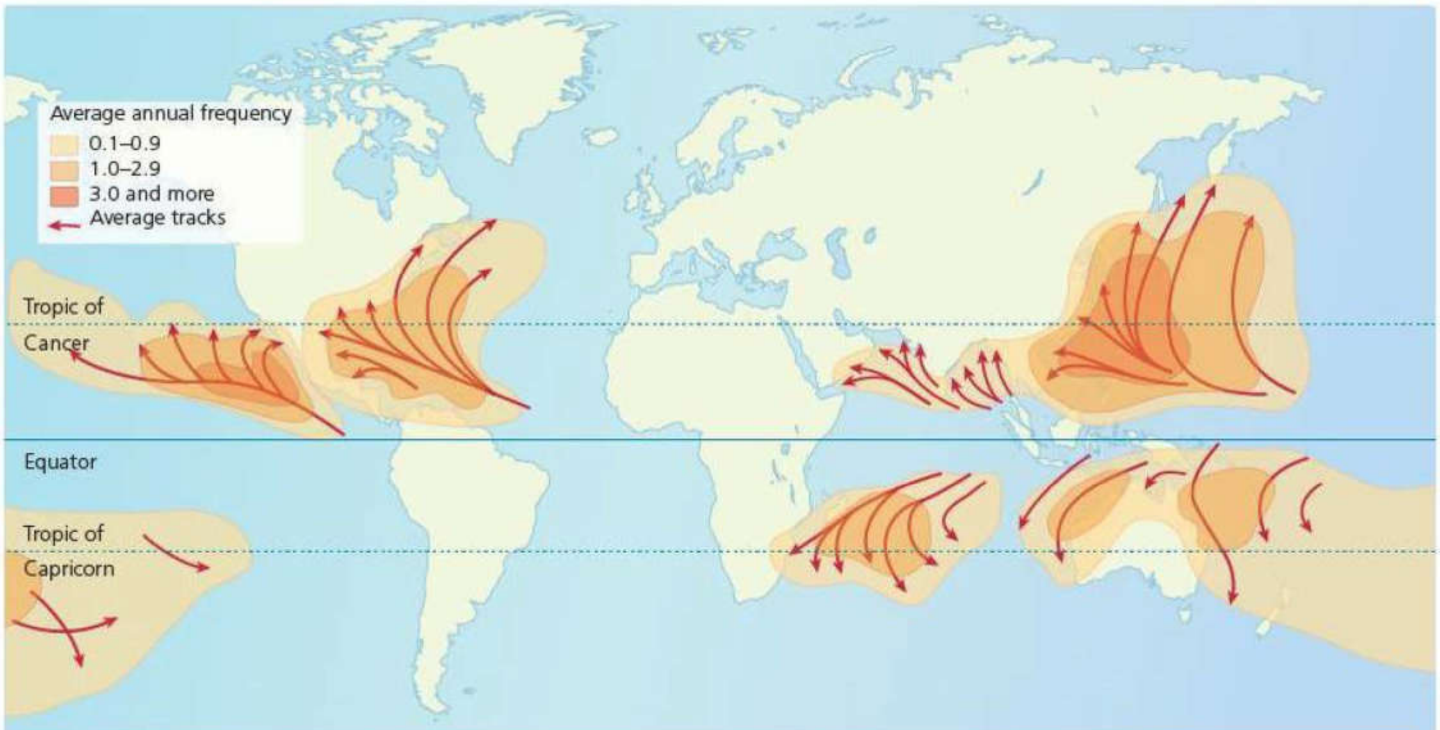


Figure 9.36 Distribution of tropical storms

Table 9.14 Saffir–Simpson Scale of tropical storm strength

Category 1	**Winds 119–153 km/hour; storm surge generally 1.2–1.5 m above normal**	No real damage to building structures. Damage primarily to unanchored mobile homes. Also, some coastal road flooding and minor pier damage.
Category 2	**Winds 154–177 km/hour; storm surge generally 1.8–2.4 m above normal**	Some damage to roofing materials, doors and windows. Considerable damage to vegetation, mobile homes and piers. Coastal and low-lying escape routes flood 2–4 hours before arrival of the tropical storm eye. Small craft in unprotected anchorages break moorings.
Category 3	**Winds 178–209 km/hour; storm surge generally 2.7–3.6 m above normal**	Some structural damage to small residences and utility buildings. Mobile homes are destroyed. Flooding near the coast destroys smaller structures, with larger structures damaged by floating debris. Land below 1.5 m above mean sea level may be flooded inland 13 km or more. Evacuation of low-lying residences close to the shoreline may be necessary.
Category 4	**Winds 210–249 km/hour; storm surge generally 3.9–5.5 m above normal**	Some complete roof structure failures on small residences. Complete destruction of mobile homes. Extensive damage to doors and windows. Land below 3 m above sea level may be flooded, requiring massive evacuation of residential areas as far inland as 10 km.
Category 5	**Winds greater than 249 km/hour; storm surge generally greater than 5.5 m above normal**	Complete roof failure on many residences and industrial buildings. Some complete building failures, with small utility buildings blown over or blown away. Complete destruction of mobile homes. Severe and extensive window and door damage. Low-lying escape routes are cut by rising water 3–5 hours before arrival of the centre of the tropical storm. Major damage to lower floors of all structures located less than 4.5 m above sea level and within 500 m of the shoreline. Massive evacuation of residential areas on low ground within 8–16 km of the shoreline may be required.

There are a number of significant factors that affect the impact of tropical storms:

- Tropical storm paths are unpredictable, which makes effective management of the threat difficult. It was fortunate for Jamaica that Hurricane Ivan (2004) (Figure 9.37) suddenly changed course away from the most densely populated parts of the island where it had been expected to hit. In contrast, it was unfortunate for Florida's Punta Gorda when Hurricane Charley (2004) moved away from its predicted path.
- The strongest storms do not always cause the greatest damage. Only six lives were lost to Hurricane Frances in 2004, but 2000 were taken by Jeanne when it was still categorised as just a 'tropical storm' and had not yet reached full hurricane strength.
- The distribution of the population throughout the Caribbean islands increases the risk associated with tropical storms. Much of the population lives in coastal settlements and is exposed to increased sea levels and the risk of flooding.
- Hazard mitigation depends upon the effectiveness of the human response to natural events. This includes urban planning laws, emergency planning, evacuation measures and relief operations such as re-housing schemes and the distribution of food aid and clean water.
- LICs continue to lose more lives to natural hazards, due to inadequate planning and preparation. By way of contrast, insurance costs continue to be greatest in American states such as Florida, where multi-million-pound waterfront homes proliferate.

Figure 9.37 Damage in Grenada after Hurricane Ivan

Tropical-storm management

Information regarding tropical storms is received from a number of sources including:

- satellite images
- aircraft that fly into the eye of the tropical storm to record weather information
- weather stations at ground levels
- radars that monitor areas of intense rainfall.

Preparing for tropical storms

Housing is particularly vulnerable to tropical storms. Hurricane Luis (1995) caused damage to 90per cent of Antigua's houses, while Hurricane Gilbert (1988) made 800 000 people temporarily homeless in Jamaica. To limit damage to houses, owners are now encouraged to fix tropical storm straps to roofs and put storm shutters over windows. Houses built on stilts allow flood waters to pass away safely.

There are a number of ways in which national governments and agencies can help prepare for a tropical storm. These include **risk assessment**, land-use zoning, floodplain management and reducing the vulnerability of structures and organisations.

Risk assessment

The evaluation of risks of tropical cyclones can be shown in a hazard map. Particular information may be used to estimate the probability of cyclones striking a country:

- analysis of climatological records to determine how often cyclones have struck, their intensity and locations
- history of winds speeds, frequencies of flooding, height, location and storm surges over a period of about 50–100years.

Land-use zoning

The aim is to control land use so that the most important facilities are placed in the least vulnerable areas. Policies regarding future development may regulate land use and enforce building codes for areas vulnerable to the effects of tropical cyclones.

Floodplain management

A plan for floodplain management should be developed to protect critical assets from flash, riverine and coastal flooding.

Reducing vulnerability of structures and infrastructures

- New buildings should be designed to be wind and water resistant. Design standards are usually incorporated into building codes.
- Communication and utility lines should be located away from the coastal area or installed underground.
- Areas of building should be improved by raising the ground level to protect against flood and storm surges.
- Protective river embankments, levees and coastal dikes should be regularly inspected for breaches due to erosion and opportunities should be taken to plant mangrove trees to reduce breaking wave energy.
- Vegetation cover should be increased to help reduce the impact of soil erosion and landslides, and facilitate the absorption of rainfall to reduce flooding.

Before a tropical storm

- Know where your emergency shelters are.
- Have disaster supplies on hand:
  - Flashlight and extra batteries
  - First aid kit
  - Non-perishable (canned) food and water
  - Essential medicines
  - Cash and credit cards.
- Protect your windows.
- Permanent shutters are the best protection. A lower-cost approach is to put up plywood panels.
- Trim back branches from trees.
- Trim branches away from your home and cut out all dead or weak branches on any trees on your property.
- Check your home and car insurance.
- Make arrangements for pets and livestock.
- Develop an emergency communication plan.

During a tropical storm

- Listen to the radio or television for tropical storm progress reports.
- Check emergency supplies.
- Make sure your car is full of fuel.
- Bring in outdoor objects such as lawn furniture, toys and garden tools, and anchor objects that cannot be brought inside.
- Secure buildings by closing and boarding up windows.
- Remove outside antennas and satellite dishes.

After a tropical storm

- Assist in search and rescue.
- Seek medical attention for persons injured.
- Clean up debris and effect temporary repairs.
- Report damage to utilities.
- Watch out for secondary hazards: fire, flooding, etc.

Figure 9.38 What to do before, during and after a tropical storm

There are many other things that individuals can do to prepare for a tropical storm, and to learn how to act during and after a storm (Figure 9.38).

A tropical storm watch is issued when there is a threat of tropical storm conditions within 24–36 hours. A tropical storm warning is issued when tropical storm conditions (winds of 120 kilometres per hour or greater, or dangerously high water and rough seas) are expected in 24 hours or less. A tropical storm warning is issued when there are risks of tropical storm winds within 24 hours. A tropical storm watch is issued when tropical storm winds are expected within 36 hours.

The emergency relief offered after a tropical storm can take many forms – food supplies, clean water, blankets and medicines. Much of this is provided in tropical storm shelters. In some communities, emergency electricity generators may be needed. The community normally becomes involved in the clean-up operation, and electricity and phone companies work to restore power lines and communications.

Long-term redevelopment may include construction of new buildings in areas away from the coastline and on high ground. Long-term reconstruction in Grenada following Hurricane Ivan concentrated on housing and community projects, water supply and sanitation, transport and communications, agriculture, fisheries and small businesses, schools and government expenses.

Section 9.3 Activities

1. In what ways is it possible to prepare for tropical storms?
2. How can governments help prepare for tropical storms?
3. What are the main actions that should be taken during a tropical storm?

Case Study: Cyclone Nargis, 2 May 2008

Cyclone Nargis was a strong tropical cyclone (Figure 9.39). It formed on 27 April 2008, made landfall by 2 May and died out by 3 May. It involved winds of up to 165 kilometres per hour (sustained for 3 minutes) and winds of over 215 kilometres per hour (sustained for over 1 minute). At its peak, air pressure dropped to 962 millibars. Around 146 000 people were killed and it caused damage estimated at $10 million. As well as Burma (Myanmar), parts of Bangladesh, India and Sri Lanka were affected. However, it was the Burmese government's actions – or rather their lack of them – that caused widespread anger and disbelief.

The Burmese government identified 15 townships in the Irrawaddy delta that had suffered the worst. Seven of them had lost 90–95 per cent of housing, with 70 per cent of their population dead or missing. The land in the Irrawaddy delta is very low-lying. It is home to an estimated 7 million of Burma's 53 million people. Nearly 2 million of the densely packed area's inhabitants live on land that is less than 5 metres above sea level, leaving them extremely vulnerable. As well as the cost in lives and homes, there is the agricultural loss to the fertile delta, which is seen as Burma's 'rice bowl'.

It was the worst ever natural disaster in Burma. There were over 80 000 deaths in Labutta and a further 10 000 in Bogale. The UN estimated that 1.5 million people were severely affected by Cyclone Nargis. Thousands of buildings were destroyed; 75 per cent of the buildings in the town of Labutta collapsed and a further 20 per cent had their roofs ripped off. Up to 95 per cent of buildings in the Irrawaddy delta were destroyed.

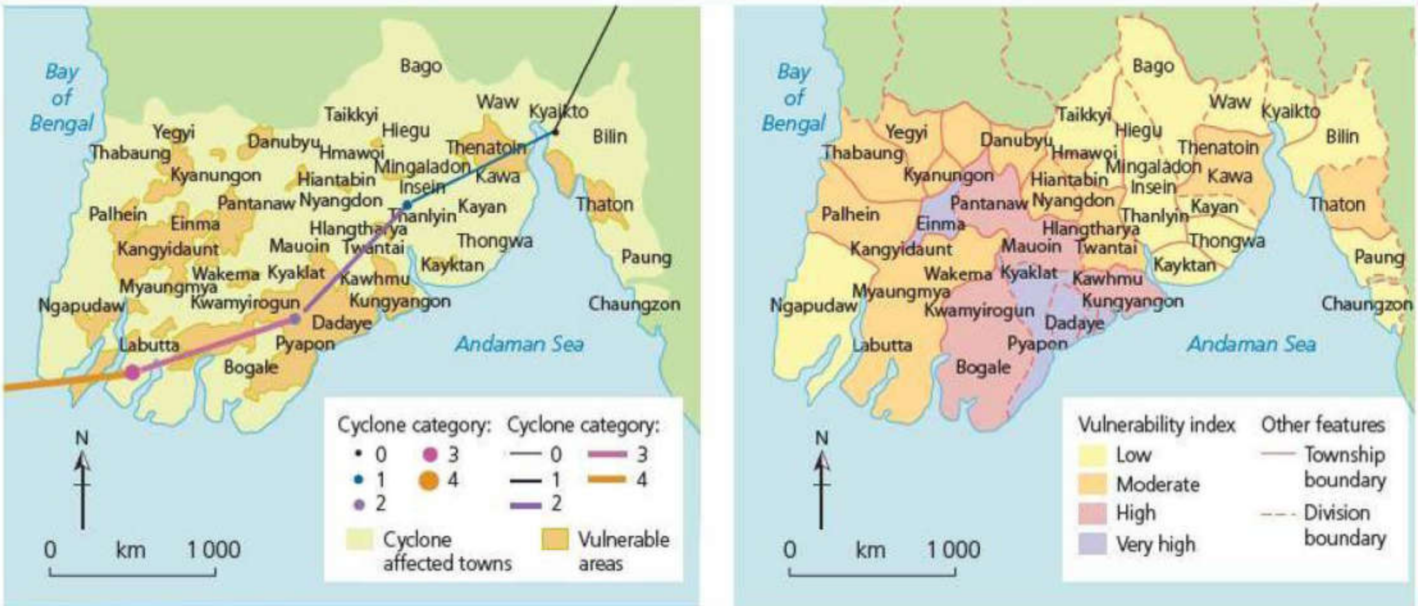


Figure 9.39 Cyclone Nargis

According to aid agencies trying to get into Burma, up to 1 million people could have died from the cyclone due to lack of relief. Relief efforts were delayed for political reasons. Burma's political leaders declined international aid; the World Food Programme said the delays were 'unprecedented in modern humanitarian relief efforts'. Within two weeks, an earthquake in China had deflected aid and sympathy away from Burma.

On 6 May, the Burmese junta (military government) finally asked the UN for aid, but accepted it only from India. Many nations and organisations hoping to deliver relief were unable to do so – the Burmese government refused to issue visas to many of them. On 9 May, the junta officially declared that its acceptance of international aid would be limited to food, medicines and some other specified supplies as well as financial aid, but would allow additional foreign aid workers to operate in the country.

India is one of the few countries to maintain close relations with Burma. It launched Operation Sahayata, under which it supplied two ships and two aircraft. However, the Burmese government denied Indian search and rescue teams and media access to critical cyclone-hit areas. On 16 May, India's offer to send a team of 50 medical personnel was accepted. Cyclone survivors needed everything – emergency shelter to keep them dry, all basic food and medicines.

Many Burmese people were displeased with their government, which had provided no warning of the cyclone. According to some reports, Indian meteorologists had warned Burma of Cyclone Nargis 48 hours before it hit the country's coast. People also believed the mayhem caused by the cyclone and associated flooding was further exacerbated by the government's unco-operative response.

The delays attracted international condemnation. More than a week after the disaster, only 1 out of 10 people who were homeless, injured or threatened by disease and hunger had received any kind of aid. More than two weeks later, relief had only reached 25 per cent of people in need. Some news stories stated that foreign aid provided to disaster victims was modified to make it look as if it came from the military regime, and state-run television continuously ran images of General Than Shwe ceremonially handing out disaster relief.

Uninterrupted referendum

Despite objections raised by the Burmese opposition parties and foreign nations in the wake of the natural disaster, the junta proceeded with a previously scheduled constitutional referendum. However, voting was postponed from 10 to 24 May in Yangon and other areas hardest hit by the storm.

☐ Small-scale tropical disturbances – tornadoes

Tornadoes are small and short-lived but highly destructive storms. Because of their severe nature and small size, comparatively little is known about them. Measurement and observation within them are difficult. A few low-lying, armoured probes called 'turtles' have been placed successfully in tornadoes. Tornadoes consist of elongated funnels of cloud that descend from the base of a well-developed cumulonimbus cloud, eventually making contact with the ground beneath. In order for a **vortex** to be classified as a tornado, it must be in contact with the ground *and* the cloud base. Within tornadoes are rotating violent winds, perhaps exceeding 100 metres per second. Pressure gradients in a tornado can reach an estimated 25 millibars per 100 metres (this compares with the most extreme pressure gradients of about 20 millibars per 100 kilometres in a larger-scale cyclone).

How tornadoes form

Moisture, instability, lift and wind shear are the four key ingredients in tornado formation (Figure 9.40). Most tornadoes, but not all, rotate *cyclonically*; that is, anticlockwise in the northern hemisphere and clockwise south of the equator. The standard explanation is that warm moist air meets cold dry air to form a tornado. Many thunderstorms form under these conditions (near warm fronts and cold fronts), which never even come close to producing tornadoes. Even when the large-scale environment is extremely favourable for tornado-type thunderstorms, not every thunderstorm spawns a tornado. The most destructive and deadly tornadoes develop from **supercells**, which are rotating thunderstorms with a well-defined low-pressure system called a **mesocyclone**.

Tornadoes can last from several seconds to more than an hour. The convectional activity that creates the source cloud is itself highly variable, and a single cloud can spawn a number of different tornado vortices, either simultaneously or in sequence, beneath different areas of the cloud, as parts of it develop and decay. Movement is generally with the parent cloud, perhaps with the funnel twisting sinuously across the ground beneath. Once contact with the ground is made, the track of a tornado at ground level may frequently extend for only a few kilometres, though there are examples of sustained tracks extending over hundreds of kilometres. The diameter of the funnel is rarely more than 200metres; track length and width are therefore limited.

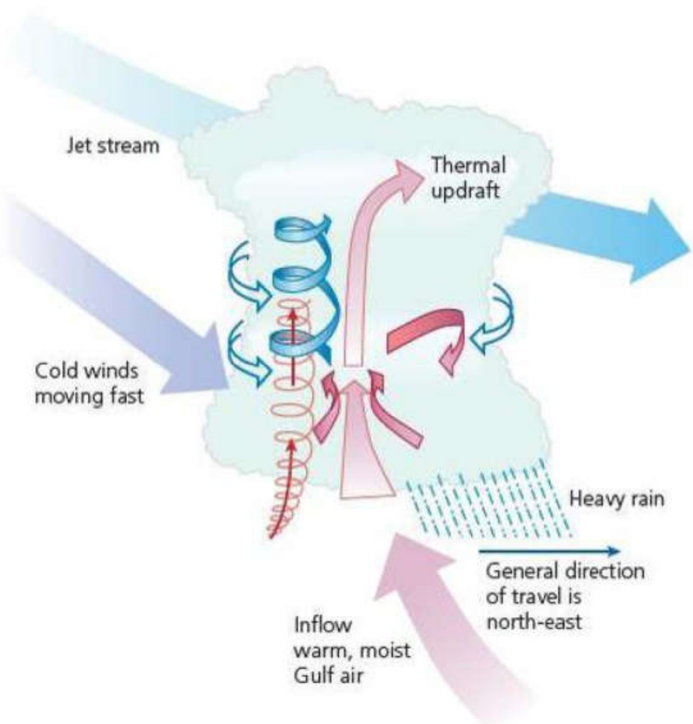


Figure 9.40 Formation of tornadoes in the USA

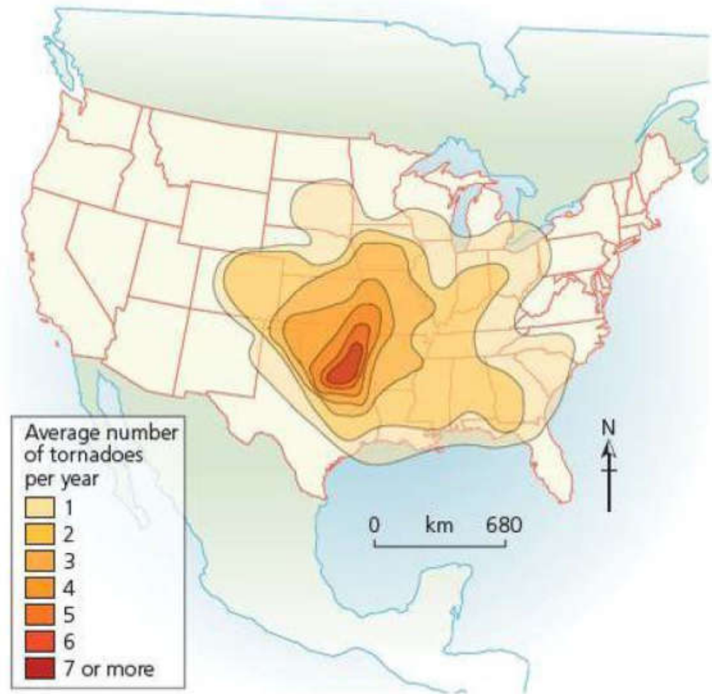


Figure 9.41 Tornado Alley, USA

Tornadoes, being associated with extreme atmospheric instability, show both seasonal and locational preference in their incidence. 'Favoured' areas are temperate continental interiors in spring and early summer, when insolation is strong and the air may be unstable, although many parts of the world can be affected by tornado outbreaks at some time or another. The Great Plains of the USA, including Oklahoma, Texas and Kansas, have a high global frequency (Figure 9.41), and tornadoes are particularly likely to be experienced here at times when cool, dry air from the Rockies overlies warm, moist 'Gulf' air. Some areas of the USA experience tornadoes from a specific direction, such as north-west in Minnesota or south-east in coastal south Texas. This is because of an increased frequency of certain tornado-producing weather patterns, for example tropical storms in south Texas, or north-west-flow weather systems in the upper Midwest.

Some tropical storms in the USA fail to produce any tornadoes, while others cause major outbreaks. The same tropical storm may produce none for a while, and then erupt with tornadoes – or vice versa. Hurricane Andrew (1992), for example, spawned several tornadoes across the Deep South after crossing the Gulf, but produced none during its rampage across southern Florida. Katrina (2005) spawned numerous tornadoes after its devastating landfall.

The size and strength of tropical cyclones is not related to the birth of tornadoes. Relatively weak tropical storms like Danny (1985) have spawned significant supercell tornadoes well inland, as have larger, more intense storms like Beulah (1967) and Ivan (2004). In general, the bigger and stronger the wind fields with a tropical cyclone, the bigger the area of favourable wind shear for supercells and tornadoes. But supercell tornadoes (whether or not in tropical cyclones) also depend on instability, lift and moisture. Surface moisture isn't lacking in a tropical cyclone, but sometimes instability and lift are too weak. This is why tropical systems tend to produce more tornadoes in the daytime, and near any fronts that may become involved in the cyclone circulation.

Tornado damage

About a thousand tornadoes hit the USA each year. On average, tornadoes kill about 60 people per year – most from flying or falling (crushing) debris. A tornado's impact as a hazard is extreme. They bring intense precipitation (heavy rainfall or hail), very high wind speeds and gusts of wind, and large-scale changes in pressure gradients (pressure imbalances).

There are three damaging factors at work. First, the winds are often so strong that objects in the tornado's path are simply removed or very severely damaged. Second, strong rotational movement tends to twist objects from their fixings, and strong uplift can carry some debris upwards into the cloud. Third, the very low atmospheric pressure near the vortex centre is a major source of damage. When a tornado approaches a building, external pressure is rapidly reduced, and unless there is a nearly simultaneous and equivalent decrease in internal pressure, the walls and roof may explode outwards in the process of equalising the pressure differences.

Most tornado damage is due to multiple-vortex tornadoes or very small, intense single-vortex tornadoes. The winds in most multiple-vortex tornadoes may only be strong enough to do minor damage to a particular house. But one of the smaller subvortices, perhaps only a few metres across, may strike the house next door with winds over 300 kilometres per hour, causing complete destruction. Also, there are great differences in construction from one building to the next, so that even in the same wind speed, one may be flattened while the other is barely touched.

Although winds in the strongest tornadoes may far exceed those in the strongest tropical storms, tropical storms typically cause much more damage individually and over a season, and over far bigger areas. Economically, tornadoes cause about a tenth as much damage per year, on average, as tropical storms. Tropical storms tend to cause much more overall destruction than tornadoes because of their much larger size, longer duration and the variety of ways they damage property. The destructive core in tropical storms can be tens or hundreds of kilometres across, last many hours and damage structures through storm surge and flooding caused by heavy rain, as well as from wind. Tornadoes, in contrast, tend to be a few hundred metres in diameter, last for minutes and primarily cause damage from their extreme winds.

Tornado damage scale

Dr T. Theodore Fujita developed a damage scale for winds, including tornadoes, which is supposed to relate the degree of damage to the intensity of the wind. Work on a new **Enhanced F-Scale** started in 2006 (Table 9.15). The Enhanced F-Scale is a much more precise way to rank tornado damage than the original, because it classifies damage F0–F5 calibrated by engineers across more than 20 different types of buildings. A team of meteorologists and engineers has worked on this for several years. The idea is that a 'one size fits all' approach does not work in rating tornado damage, and a tornado scale needs to take into account the typical strengths and weaknesses of different types of construction. This is because the same wind does different things to different kinds of buildings. In the Enhanced F-Scale, there are different, customised standards for assigning any given F rating to a well-built, well-anchored wood-frame house compared with a garage, school, skyscraper, unanchored house, barn, factory, utility pole or other type of structure. In a real-life tornado track, these ratings can be mapped together more smoothly to produce an accurate damage analysis.

Table 9.15 Enhanced Fujita Scale

EF number	3-second gust (mph)
0	65–85
1	86–110
2	111–135
3	136–165
4	166–200
5	200+
Note: this scale was created in the USA, so measurements are imperial.	

Managing tornadoes

The main problem with anything that could realistically stand a chance of affecting a tornado (for example an atomic bomb) is that it would be even more deadly and destructive than the tornado itself. Lesser things (like huge piles of dry ice) would be too hard to deploy in the right place fast enough, and would probably not have a significant effect on the tornado.

Nor is there any proof that seeding can or cannot change tornado potential in a thunderstorm. This is because there is no way of knowing that the things a thunderstorm does after it has been seeded would not have happened *anyway*. This includes any presence or lack of rain, hail, wind gusts or tornadoes. Because the effects of seeding are impossible to prove or disprove, there is a great deal of controversy among meteorologists about whether it works and, if so, under what conditions and to what extent.

Case Study: Tornadoes in Indiana

Indiana is in what is considered to be 'Tornado Alley' (see Figure 9.41 and Table 9.16), a swathe of states extending from the south-east USA to the interior plains. Although the state lacks the high frequency of tornadoes seen in places like Kansas and Oklahoma, it makes up for it in the intensity of its tornadoes.

Table 9.16 Indiana tornado disasters

Date	Place	Damage
13 April 1852	New Harmony	16 killed
14 May 1886	Anderson	43 killed
23 March 1913	Terre Haute	21 killed
11 March 1917	New Castle	21 killed
23 March 1917	New Albany	45 killed
28 March 1920	Allen through Wayne counties	39 killed by three tornadoes
17 April 1922	Warren through Delaware counties	14 killed
18 March 1925	'Tri-State Tornado': Posey, Gibson and Pike counties	74 killed
26 March 1948	Coatesville destroyed	20 killed
21 May 1949	Sullivan and Clay counties	14 killed
11 April 1965	'Palm Sunday Outbreak': 11 tornadoes, 20 counties	137 killed
3 April 1974	'Super Outbreak': 21 tornadoes hit 39 counties	47 killed
2 June 1990	37 tornadoes hit 31 counties	8 killed

Tornadoes can occur in any month, but March–June is considered tornado season in Indiana. Historically, the most destructive tornadoes strike in March and April. June holds the record for the most tornadoes in Indiana on any given day (37), and for the most in a single month (44). Both records were set in 1990, which is also the year when the state experienced the most tornadoes (49).

From 1950 to November 2001, 1024 tornadoes caused more than $1.7 billion in damage in Indiana, and killed 223 people.

Indiana was one of three mid-western states in the path of the deadliest tornado in American history. On 18 March 1925, the Tri-State Tornado travelled a record 352 kilometres on the ground from Missouri through Illinois and into Indiana, where it struck Posey, Gibson and Pike counties. The town of Griffin lost 150 homes, and 85 farms near Griffin and Princeton were devastated. About half of Princeton was destroyed, with losses totalling nearly $2 million. The funnel finally dissipated just outside Princeton, 3½ hours after it had begun. Nearly 700 people died, 74 of them in Indiana. Murphysboro in Illinois lost 234 people, a record for a single community.

In April 1965, 11 tornadoes struck 20 counties in central and northern Indiana, killing 137 people. More than 1700 people were injured and property damage exceeded $30 million. It was Indiana's worst tornado disaster. The tornadoes that devastated Indiana were part of an outbreak in which nearly 50 tornadoes struck the Great Lakes region on 11–12 April, causing 271 deaths and more than 3400 injuries.

The most destructive tornado outbreak of the twentieth century was the 'Super Outbreak' of 3–4 April 1974. During a 16-hour period, 148 tornadoes hit 13 states, including Indiana. The path of destruction stretched over 4000 kilometres. More than 300 people died and more than 5000 were injured. The most notable tornado in this group destroyed much of Xenia, Ohio. In Indiana, 21 tornadoes struck 39 counties, killing 47 people. Seven produced damage rated F5, the maximum possible, and 23 more were rated F4. This was one of only two outbreaks with over 100 confirmed tornadoes, the other being during tropical storm Beulah in 1967 (115 tornadoes).

Section 9.3 Activities

1 Briefly explain how tornadoes are formed.
2 Using examples, outline the factors that affect tornado damage.
3 To what extent is it possible to manage the risk of tornado damage?

9.4 Sustainable management of hazardous environments

Case Study: The use of geo-materials for erosion and sediment control

In Malaysia, early research on bio-engineering involved studies on plant selection for the re-vegetation of cut slopes along highways. Research in 2000–01 involved gully erosion control and vegetation establishment on degraded slopes. These techniques have incorporated the coppicing abilities of cut stems and the soil-binding properties of roots into civil designs, to strengthen the ground and to control erosion. Bio-engineering designs have great potential and application in Malaysia because in deforested upland sites landslides are common, particularly during the wetter months between November and January. Post-landslide restoration works involving conventional civil designs are costly and sometimes not practical at remote sites. Due to cost constraints, the remoteness of the sites and low risk to lives and property, bio-engineering was the option taken for erosion control, slope stabilisation and vegetation establishment.

The study took place at Fraser's Hill, in the state of Pahang, Malaysia. The area receives 20–410 millimetres of rainfall each month. The temperature is moderate, ranging from 18 to 22°C annually, with high humidity, ranging from 85 to 95 per cent every month. The surrounding vegetation is lower montane forest.

Two study plots were chosen, and a control plot. Initial works involved soil nailing, using 300 live stakes of *angsana* tree branches and 200 cut stems of *ubi kayu*. Subsequently, major groundworks involved the installation of **geo-structures** (structures constructed from **geo-materials** such as bamboo and brush bundles, coir rolls and straw wattles). The volume of sediment trapped by the geo-structures was measured every two weeks, while plant species that were established on the retained sediments and on geo-materials were identified. The number of live stakes that produced shoots and roots was also recorded. Ten 1 metre-tall saplings of *Toona sinensis*, a fast-growing tree species, were planted at the toe of the slope for long-term stability.

The first slope failure was caused by seepage of drainage water into the cut slope of the access road. The total area affected by the landslide was about 0.25 hectare. Two large trees, 4–5 metres tall, were uprooted and ground vegetation and debris were washed downhill, preventing road access. The second and more extensive failure was located uphill and was a rotational failure. It covered an area of about 0.75 hectare. The landslide was probably triggered by seepage of water from a badly damaged toe drain beside the road.

Bio-engineering design: After six months

The bio-engineering designs involved the installation of 11 bamboo bundles ('faschines') and 16 brush bundles along rills and gullies. At suitable sites along contours, 10 coir rolls and 5 straw wattles were installed, using live stakes and steel wiring. Lighter geo-materials such as straw wattles and brush faschines were positioned on the upper slope face, while heavier geo-materials such as coir rolls were positioned lower down.

At the end of six months, the situation at each study site was assessed (Table 9.17).

Table 9.17 Selected geo-materials and total volume of sediment retained over six months at the two study sites

Geo-materials	Total sediment retained m^3	Total number of migrant species
Bamboo faschine	1.7	14
Brush faschine	1.0	17
Coir roll	2.2	20
Straw wattle	0.2	26
Total sediment retained by different geo-materials	**5.1**	–
Total number of migrant species	–	77

Live stakes and *Toona sinensis* saplings

At the end of six months, the live stakes had become living trees. A high percentage of *angsana* stakes (93 per cent) sprouted shoots and roots after a month, and 75 per cent of *ubi kayu* stems sprouted leaves within a week. Thus, live stakes were effective in stabilising unstable slopes.

Vegetation cover on slopes helped reduce soil erosion because shoots helped reduce the intensity of raindrops falling on the exposed soil. Furthermore, root-reinforced soils functioned like micro-soil nails to increase the shear strength of surface soils.

Slope stability

The indicator poles at both study sites moved less than 8°, unlike the indicator poles from the control plot, which moved about 20°. Without erosion-control measures, there was aggressive soil erosion during heavy downpours, which caused scouring of the steep slope below the tarred road and resulted in an overhang of the road shoulder.

Trapped sediments and vegetation establishment

A total of 57 geo-structures retained 5.1 m^3 of sediment after six months. The retained sediments and decomposing geo-materials also trapped moisture and provided ideal conditions for the germination of incoming seeds. After six months, it was found that 77 plant species were established.

After one year

A year after the study was first implemented, about 75 per cent of one study site was covered by vegetation, while 90 per cent of the second plot was re-vegetated. There was no more incidence of landslide at these two plots. However, at the control plot there was further soil erosion, which resulted in further undercutting of the slope face.

At the control plot, after one year, only seven plant species were present. These were weeds. The poor vegetation cover was probably due to unstable soil conditions caused by frequent soil erosion and minor landslides. It is believed that vegetation cover can provide a layer of roots beneath the soil layer and this contributes additional shear strength to the soil and slope stability.

The geo-structures were installed at a cost of about US$3078, which was cheaper than restoration works using conventional civil structures such as rock gabions, which cost about US$20 000. As the site is quite remote, higher transportation and labour costs would have contributed to the higher cost of constructing a rock gabion at this site. On the other hand, the geo-materials that are abundantly available locally are relatively cheap to make or purchase, and this contributed to the low project cost. The geo-structures were non-polluting, required minimal post-installation maintenance, were visually attractive and could support greater biodiversity within the restored habitats. The geo-materials used in this project, such as faschines, coir rolls and straw wattles, biodegrade after about a year and become organic fertilisers for the newly established vegetation.

After 18 months, the restored cut slopes were almost covered by vegetation, and there was no further incident of landslides. The geo-structures installed on site were cost-effective and visually attractive. The restored cut slopes were more stable and supported higher biological diversity.

Assessment of costs

The geo-structures cost approximately $3000 to install. In contrast, a rock gabion would have cost about $20 000 to install (as the area is remote, transport costs would increase, and there would be increased emissions of greenhouse gases). Moreover, the geo-structures were visually attractive, could support biodiversity, were locally available, and took just two weeks to install. In terms of a cost-benefit analysis, therefore, the geo-structure has a great deal to offer.

The sustainable livelihoods approach for volcano-related opportunities

In an article entitled 'Living with Volcanoes: The sustainable livelihoods approach for volcano-related opportunities', Ilan Kelman and Tamsin Mather outlined ways in which people could have a sustainable livelihood in volcanic areas.

The destructive forces of volcanoes are well known, for example Mt Pelée in Martinique killed approximately 30 000 people in St Pierre, while in 1985 lahars from Nevado del Ruiz, Colombia, killed approximately 25 000 people. National/regional impacts are represented by the 1783–84 eruptions of Laki on Iceland, which killed 24 per cent of Iceland's population and caused thousands of deaths elsewhere in Europe. Global volcano-related impacts have been noticeable through weather alteration, as was the case following the 1991 Mt Pinatubo eruption in the Philippines.

However, human fatalities linked to volcanoes have been relatively few. The death toll attributed to volcanoes since 1 CE is approximately 275 000. As with many disasters, volcano-related disasters also have psychological impacts.

Literature dealing with the volcanic risk perception tends to focus on threats and dangers from volcanoes, along with possible preparation measures, whereas information regarding perceptions of volcano-related benefits or opportunities are more limited.

The contributions of volcanoes to society are widespread. For example, the Mt Etna region represents just under 7 per cent of the land area of Sicily, yet is home to over 20 per cent of the population. Reasons for this intense human activity on the lower slopes of the volcano are not difficult to find, including fertile soils and a reliable freshwater supply. The Soufrière volcano on St Vincent brings agricultural, mining, quarrying and tourism benefits to St Vincent and the Grenadines. There are also geothermal resources, and the use of volcanic materials for making items such as basalt hammers and pumice, along with the archaeological and artistic gains from volcanism.

Dealing with environmental hazards

As exemplified by Mt Etna in Italy and Mt Mayon in the Philippines, people have good reasons for living near or on volcanoes, including good farmland and reliable water supplies. This sometimes yields dangers, despite the rewards. To balance the dangers or potential dangers with the gains or potential gains from environmental hazards, including volcanoes, a four-option framework has been developed (Table 9.18).

Table 9.18 Options and consequences for dealing with environmental hazards

Option for dealing with environmental hazards	Main implications
1 Do nothing	Disasters occur.
2 Protect society from hazards	Not always feasible and leads to risk transference, which augments vulnerability.
3 Avoid hazards	Not always feasible and can exacerbate other problems, augmenting vulnerability.
4 Live with the hazards and risks	Livelihoods are integrated with environmental threats and opportunities.

The first option is to do nothing, accepting that volcanic disasters will happen. Depending on the volcano, this option might be more viable or less viable. Mt Etna in Italy frequently erupts, so doing nothing could lead to a disaster, depending on the extent and characteristics of an eruption. In contrast, Mt Jefferson in the USA has not erupted in several centuries and doing nothing could be an option there.

The second option is to try to protect society from volcanic hazards, such as by strengthening roofs against tephra fall, building structural defences against lahars, pumping sea water onto lava (Heimaey, Iceland 1973), diverting lava (Mt Etna) or slowly degassing (Lake Nyos, Cameroon). However, this protection option is not always feasible. For example, not all gas releases could be averted through degassing. Large pyroclastic flows and lava flows are challenging to stop or even to redirect, although structures could be designed to afford some level of protection against these hazards. Moreover, reliance on protective measures could lead to a false sense of security, without tackling the root causes of vulnerability.

The third option is to avoid volcanic hazards, but that is not always feasible. Volcanic impacts are often not local and are sometimes even global, so all places on Earth have the potential for being severely affected by volcanic activity. Additionally, with global population increasing, constraints on land and resources frequently leave little option other than to inhabit areas that are potentially affected by volcanic hazards.

Moreover, avoiding volcanic hazards could cause further problems. Volcanic activity can yield advantages that might outweigh the problems. Moving away from volcanoes could yield other concerns, perhaps exposure to other environmental hazards or perhaps social challenges. After Montserrat's volcano started erupting in 1995, some families moved to England, only to be disappointed at the low standard of education in English schools. Many Montserratians were shocked, too, at the level of crime risk to which they were exposed on neighbouring Caribbean islands.

The fourth option – living with risk – means accepting that environmental hazards are a part of life and of a productive livelihood. A component of living with risk is localising disaster risk reduction. Disaster risk reduction, including pre-disaster activities such as preparedness and mitigation and post-disaster activities such as response and recovery, is best achieved at the local level with community involvement. The most successful outcomes are seen with broad support and action from local residents, rather than relying on external specialists or interventions. Although the long dormancy periods of volcanoes and significant uncertainties about eruptive pathways might make community interest in disaster risk reduction wane, few communities are vulnerable only to volcanic hazards.

The sustainable livelihoods approach

Sustainable livelihoods can be defined as creating and maintaining means of individual and community living that are flexible, safe and healthy from one generation to the next. The sustainable livelihoods approach is important in its application to volcanic scenarios in four ways:

1. Understanding, communicating and managing vulnerability and risk and local perceptions of vulnerability and risk beyond the immediate threats to life.
2. Maximising the benefits to communities of their volcanic environment, especially during quiescent periods, without increasing vulnerability.
3. Managing crises.
4. Managing reconstruction and resettlement after a crisis.

Applying the sustainable livelihoods approach

Managing vulnerability and risk

The first application of the sustainable livelihoods approach to volcanoes is understanding, communicating and managing vulnerability and risk along with local perceptions of vulnerability and risk beyond immediate threats to life.

Thinking ahead of the event ensures that:

- local livelihoods are preserved, meaning that the population has an easier post-disaster recovery except for cases of extreme destruction
- the affected population is confident that their livelihoods will remain, so they will be more willing to shelter and evacuate without putting their lives at risk for the sake of livelihoods.

Examples include attempts to prevent lava blocking Heimaey's harbour and balancing ski access to Ruapehu during active episodes, especially in light of the continuing lahar threat. In these instances, it was decided that saving only lives without considering livelihoods was unacceptable. Risk and vulnerability have been managed to achieve a balance between lives and livelihoods: living with volcanic risk.

Maximising community benefits sustainably

The second application is maximising the benefits to communities of their volcanic environment, especially during quiescent periods, while decreasing vulnerability. The livelihood benefits of volcanoes can be placed into three main categories: physical resources (for example, mining), energy resources (for example, heat) and social resources (for example, tourism).

Volcanoes play an important role in the formation of precious metal ores. However, if the volcano's activity increases, the mining resources, equipment and expected income could be jeopardised. The 2006 eruption of a 'mud volcano' in eastern Java, which was highly destructive to local livelihoods, resulted from borehole drilling.

Managing crises

The third application is managing crises. Emergency response and humanitarian relief are adopting the sustainable livelihoods approach, such as for the sectors of transitional settlement and shelter and food security.

Managing reconstruction and resettlement

The fourth application is managing reconstruction and/or resettlement after a volcanic crisis. Montserrat provides a good example. Resettlement in the island's north, away from the most dangerous zones due to volcanic activity, included housing construction that was completed without sufficient attention to local culture, other hazards or livelihoods. The resettlement saved lives, but did not adopt a local approach to living with risk. Long-term problems emerged that the sustainable livelihoods approach might have prevented.

Disadvantages

Volcano-related evacuations have sometimes forced people to choose between staying in poorly managed shelters with no livelihood prospects and returning home to their livelihoods despite a high risk of injury or death from the volcano. This issue was witnessed in Montserrat, exacerbated by economic structures that encouraged farming in the exclusion zone (Figure 9.42).

Figure 9.42 Cattle in the exclusion zone, Montserrat

Figure 9.43 It is not always possible to see volcanic impacts as positive

Towards reducing volcanic impacts

Considering livelihoods is important in successful volcanic disaster risk reduction because they contribute to living with volcanic risk based on a localised approach. Living with volcanoes at the local level requires changes of perception and action, resulting in advantages for volcanic disaster risk reduction, although there can also be potential disadvantages (Figure 9.43). With the local population involved in monitoring, understanding, communicating, making decisions and taking responsibility for aspects of volcanic disaster risk reduction – with external guidance and assistance where requested – disadvantages can be minimised.

Three points emerge from applying the sustainable livelihoods approach to localised living with volcanic risk:

- First, not all livelihoods near volcanoes are volcano-related. Productive agriculture could be due to floodwaters rather than volcanic deposits.
- Second, not all volcanic activity necessarily yields livelihoods, or livelihoods that should be encouraged. Tourism and research activities in active craters (Figure 9.44), for example, tend to be discouraged in vulcanology. That level of risk-taking could also make the livelihood vulnerable. For example, if tourists were killed by a volcano, the area's tourism could suffer.
- Third, resource availability does not always imply resource use. Mining could be deemed too externally dependent or too environmentally and socially destructive to be worthwhile pursuing.

Volcanic risk perception and communication studies show that not everyone living by a volcano understands or accepts the actual or potential implications of the volcano. Risk and disasters emerge from volcanoes, but livelihood opportunities emerge from volcanoes too. Those opportunities form an integral part of volcanic disaster risk reduction.

Despite volcanic benefits, living with volcanic risk is not always feasible and volcanoes should not be relied on for livelihoods without careful consideration of potential drawbacks. Other approaches – do nothing, protect and avoid – should be considered, as well as appropriate combinations of the approaches for different combinations of volcanic risks, volcanic benefits and societal desires.

Figure 9.44 The world's only drive-in active volcanic crater, St Lucia

Case Study: Montserrat

The Soufrière volcano on Montserrat is a well-used example of the effects of a volcano in a LIC. It is over 15 years since the main eruption in 1997 in which 19 people died. The capital city, Plymouth, was abandoned, and became a modern-day Pompeii. Much of the southern third of the island became an exclusion zone (Figure 9.45). So how have things changed since 1997?

Figure 9.45 Plymouth and Soufrière, Montserrat

By 2002, Montserrat was experiencing something of a boom. The population, which had dropped in size from over 11 000 before the eruption to less than 4000 in 1999, had risen to over 8000. The reason was very clear. There were many jobs available on the island. There were many new buildings, including new government buildings, a renovated theatre, new primary schools and lots of new housing in the north of the island. There was even a new football pitch and stadium built at Blakes Estate (Figure 9.46). There were plans to build a new medical school and a school for hazard studies. To date, these have not been built.

Figure 9.46 Montserrat football pitch

However, by the summer of 2009 it was very clear that conditions on Montserrat had changed. The population had fallen to a little over 5200. There are two main reasons for this. The first is the relative lack of jobs. Although there was an economic boom in the early 2000s, once the new buildings were built many of the jobs disappeared. There are still plans to redevelop the island – a new urban centre and a new port are being built at Little Bay but they will not be complete until 2020. The museum has been built but not much else (Figure 9.47). Thus there are some jobs available but not so many as there were previously. Second, one of the new developments on Montserrat was a new airstrip. Once this was built, the UK and US governments stopped subsidising the ferry that operated between Antigua and Montserrat. This made it more difficult to get to Montserrat, both for visitors and for people importing basic goods. Thus the number of tourists to the island fell and the price of goods on the island rose. Many Montserratians were against the airstrip and campaigned unsuccessfully for the port to be kept open. It is possible to charter a boat and sail to Montserrat but it is far more expensive than taking a ferry.

Thus with fewer jobs in construction, a declining tourist sector and rising prices, many Montserratians left the island for a second time. Many went to Antigua and others went to locations such as Canada, the USA and the UK. Much of the aid that was given to Montserrat following the eruptions of 1997 has dried up. The UK provided over \$120 million of aid but announced in 2002 that it was phasing out aid to the island. Nevertheless, in 2004 it announced a £40 million aid deal over three years.

Figure 9.47 Montserrat museum

The volcano has been relatively quiet for the last few years. However, there was an event in May 2006 that was relatively unreported. The Soufrière dome collapsed, causing a tsunami that affected some coastal areas of Guadeloupe, and English Harbour and Jolly Harbour in Antigua. The Guadeloupe tsunami was 1 metre high and the one in Antigua between 20 and 30 centimetres. No-one was injured in the tsunami but flights were cancelled between Venezuela and Miami, and to and from Aruba, due to the large amount of ash in the atmosphere.

So while volcanic activity in Montserrat is currently quiet, the volcano continues to have a major impact on all those who remain on the island. The economic outlook for the island does not look good – and that is largely related to the lack of aid, the difficulty and cost of reaching Montserrat and the small size of the island and its population.

Sustainable development and hurricanes

The achievement of equity, risk reduction and long-term development through local participation in recovery planning and institutional co-operation is the central issue in recovery and sustainable development.

The recovery phase is the least investigated and least understood of the four phases of a disaster (Figure 9.48) – pre-disaster mitigation, emergency preparedness, emergency response and recovery.

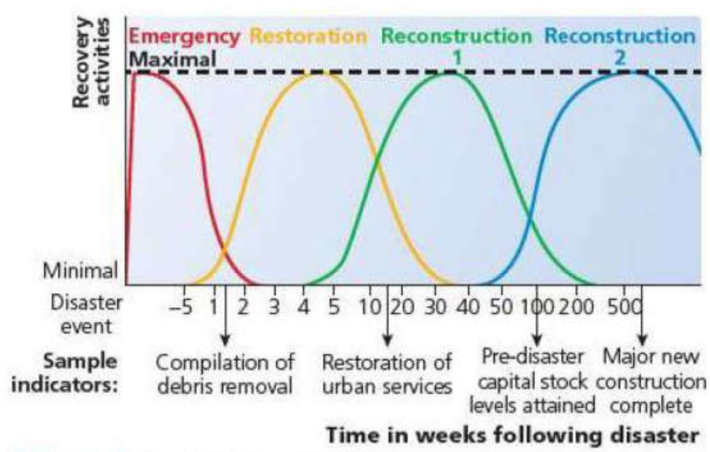


Figure 9.48 The four-stage model

Various LICs are trying to integrate recovery with sustainable development initiatives. Jamaica, for example, has shifted disaster recovery responsibilities from its national emergency management agencies to government agencies charged with environmental protection and long-term economic development and to community-based private voluntary organisations active in development initiatives such as housing, healthcare, watershed management and agriculture.

The four-stage model has four clear aspects:

1 Take emergency measures for removal of debris, provision of temporary housing and search and rescue.
2 Restore public services (electricity and water).
3 Replace or reconstruct capital stock to pre-disaster levels.
4 Initiate reconstruction that involves economic growth and development.

However, several studies suggest that the four stage model may be inaccurate. For example, stage 3 may occur in some areas while some areas are still in stage 1, and some groups may not have services restored as quickly, for example shanty-town residents, poor communities and immigrant groups. Many actual recoveries may not be so clear cut (Figure 9.49).

Successful recovery requires:

- integration of interested parties (government, non-governmental organisations, community groups)
- monitoring of programmes/enforcement of policies
- recognition of all people's rights (elderly, young, women, homeless, poor, migrants, refugees)
- leadership – ideally community-based (bottom-up) development
- resources.

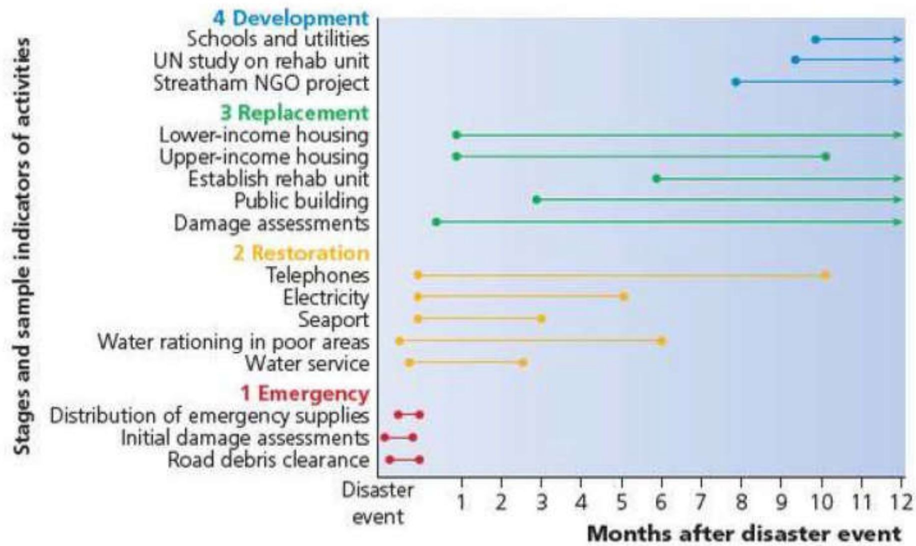


Figure 9.49 Recovery in Montserrat following Hurricane Hugo

Case study: Recovery after Hurricane Hugo

When Hurricane Hugo struck Montserrat on 17 September 1989, it was the first hurricane to hit the island in over 60 years. Eleven people were killed, 3000 people were made homeless and up to 98 per cent of buildings were damaged. All government buildings and schools were either partially or totally destroyed. Damage exceeded over US$360 million – devastating for the island.

Yet for some parts of Montserrat, the recovery was considered to be very successful. The village of Streatham near Plymouth was a small agricultural village of about 300 people. All the homes were damaged. The recovery was organised by local people – they rebuilt more than 20 homes and a new community centre, introduced new agricultural practices and improved the settlement's water supply.

Summary

Hurricanes in the Caribbean are serious. People and property are placed at risk, and government attempts to protect both are limited. Much of the construction in the Caribbean is informal, and lacks adequate building standards. Moreover, population growth suggests more people will be at risk in the future. In addition, global warming may potentially increase the frequency and magnitude of hurricanes due to increased atmospheric energy.

It might be more realistic to think of recovery as a process in which political, economic and demographic factors, as well as location, are important. Some groups are slower to recover than others. This raises questions about fairness and equity.

Top-down programmes managed by central government and international NGOs do not necessarily work well because they may be vulnerable to political manipulation.

Opportunities to relocate people and structures out of floodplains and other high-risk locations may be missed. Long-term sustainable development should include reduced environmental degradation – for example deforestation, soil erosion, habitat degradation – and improved housing and living conditions. One positive example of this was Streatham on Montserrat.

External donor organisations and charities must not just treat the symptoms of hurricanes – they must also address the causes of disasters alongside refocusing on long-term community development.

Promoting bottom-up recovery

A bottom-up community-based approach to recovery will be more effective than the traditional top-down approach, as it will respond to local people's needs and priorities. At Streatham, the disaster was used as a unique opportunity for change, and brought to the fore problems that are usually low in priority.

Strategies for long-term mitigation include:

- strengthening the housing stock
- improving land-use patterns
- environmental protection
- increased understanding of natural hazards.

Section 9.4 Activities

1 To what extent is the management of the Soufrière volcano on Montserrat an example of sustainable development? Give reasons for your answer.
2 Briefly explain the main methods of dealing with earthquakes.
3 In what ways is it possible to manage the risk of volcanoes?
4 Outline the advantages of geo-engineering over hard engineering structures for slope stabilisation.
5 Compare the main characteristics of the emergency phase following a natural disaster with that of the reconstruction/replacement phase.