TOPIC 1

Plate tectonics, earthquakes and volcanic hazards

1 *Plate tectonics*

The Earth's crust and lithosphere are broken into seven large slabs and a dozen or more minor ones known as **tectonic plates**. The distribution of the main plates is shown in Figure 1.1. The plate boundaries are zones of great tectonic activity, including volcanism, earthquakes, mountain building and faulting and folding. The global distribution of active volcanoes and earthquakes defines the plate boundaries. We recognise three types of plate boundary: constructive, destructive and conservative.

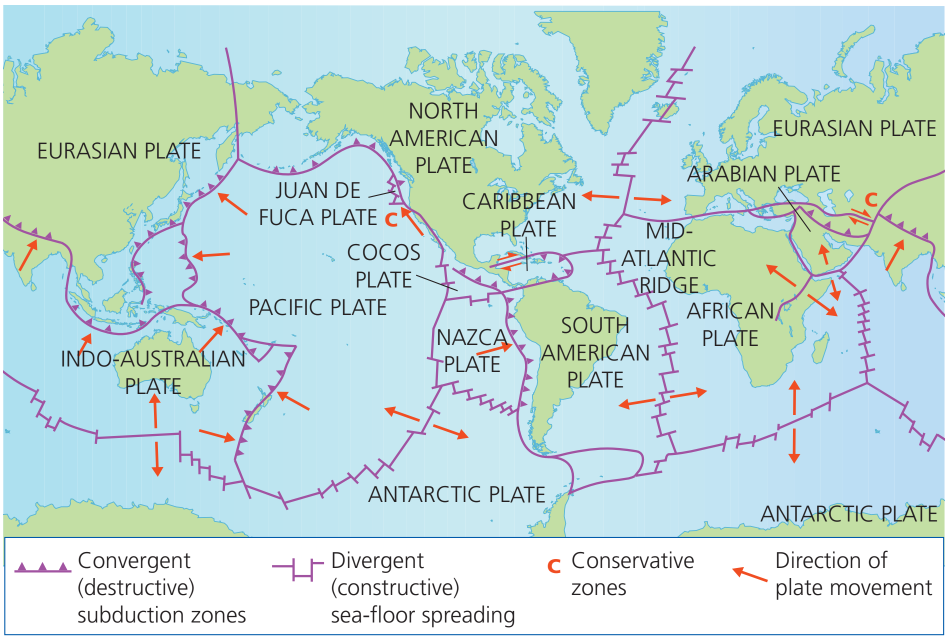
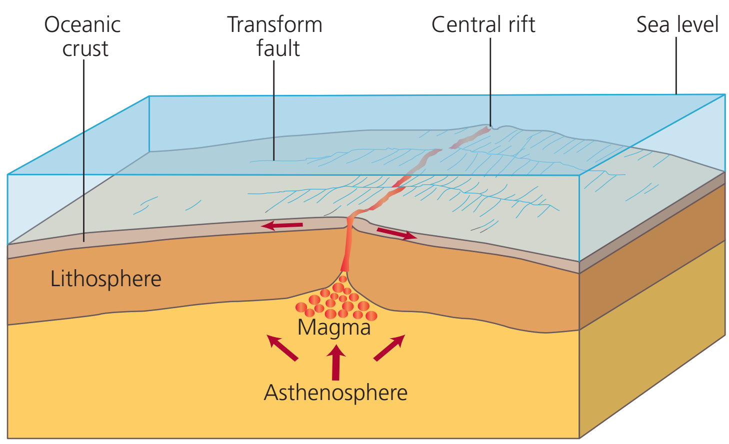


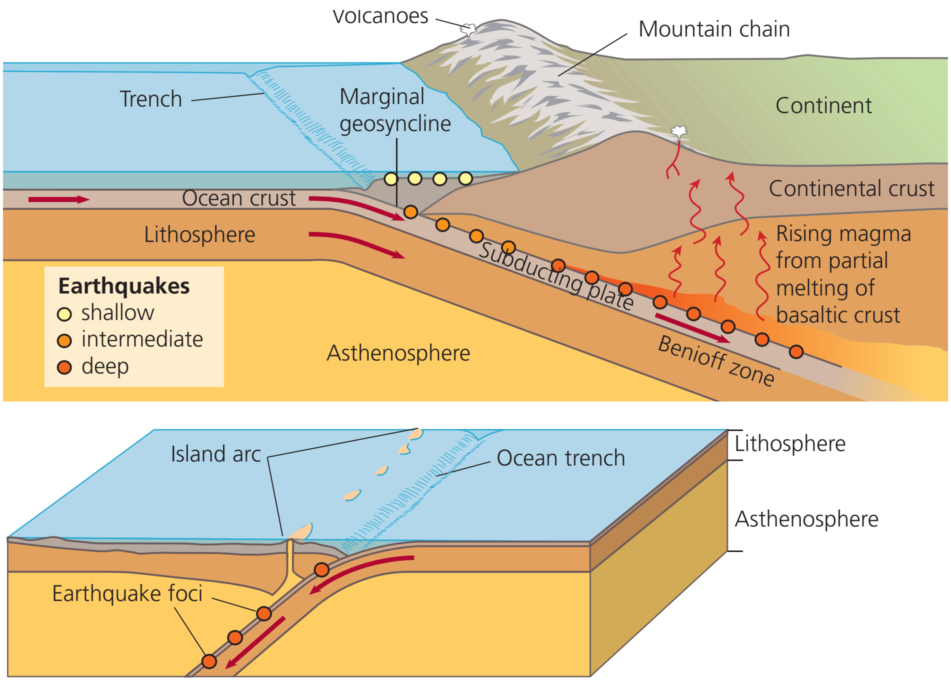
Figure 1.1 Distribution of main tectonic plates

1.1 Constructive plate boundaries

Constructive (or divergent) plate boundaries are the **mid-ocean ridges** where new crust forms. There, as Figure 1.2a shows, rising plumes of magma from the Earth's mantle stretch the crust and lithosphere. Active volcanoes develop where lava reaches the surface. Most volcanic activity takes place on the ocean floor and forms the submarine mountain ranges of the mid-ocean ridges. Parallel **faults** associated with tension in the crust and volcanism cause **rifting** and deep valleys between the mountain chains of the mid-ocean ridges.



(a) A divergent plate boundary and spreading centre



(b) Oceanic–continental plate boundary

(c) Oceanic–oceanic plate boundary

Figure 1.2 Constructive plate boundaries

1.2 Destructive plate boundaries

At **destructive** (convergent) plate boundaries or **subduction zones**, oceanic crust/lithosphere is destroyed (Figure 1.2). Subduction involves the following stages:

- the descent of the subducted plate together with water and seafloor sediments into the upper mantle
- melting of the subducted slab and surrounding mantle rocks around 100 km or so below the surface
- the melt (or magma), which is less dense than the surrounding rocks, rising slowly through lines of weakness and fissures to the surface
- the eruption of lava, gases and ash at the surface through volcanoes and fissures

Subduction occurs when two tectonic plates converge. The older, denser plate is subducted. If two oceanic plates converge (Figure 1.2c), subduction forms an island arc such as the Kuril Islands in the north Pacific and the Lesser Antilles in the Caribbean.

The subduction of an oceanic plate beneath a continental plate produces fold mountain chains such as the Andes and the Cascades along the Pacific coast of the Americas (Figure 1.2b). Destructive plate boundaries are also the location of volcanoes, earthquakes and ocean trenches.

Fold mountain chains

The world's highest mountain ranges, including the Himalayas, Andes and Alps, are located along subduction zones.

Where an oceanic plate and continental plate converge, an island arc may collide with the continent and contribute to mountain building. Meanwhile, sedimentary rocks formed on the continental shelf and continental slope, squeezed between the island arc and the continent, crumple to form mountain ranges. Subduction of the oceanic plate may produce huge **intrusions** of magma beneath the mountains, which creates further uplift. This sequence of events explains the formation of the Andes in South America.

The Himalayas have been formed by the convergence of two continental plates: the Indo-Australian plate and the Eurasian plate. As the two plates converged, the Tethys Sea narrowed until its sea-floor sediments were pushed nearly 9 km above sea level into complex folds. In south Asia two continental landmasses (Eurasia and India) have collided. The collision has welded the continents together, producing a great thickness of the continental crust. As a result, there is no volcanic activity in the Himalayas.

Ocean trenches

Narrow trenches, hundreds of kilometres long and up to 11 km deep, occur on the ocean floor parallel to island arcs and fold mountain ranges. Ocean trenches mark the zone of subduction, where oceanic crust/lithosphere descends into the mantle. As it does so, the leading edge of the overriding plate is buckled to form a trench.

1.3 Conservative plate boundaries

At **conservative** plate boundaries, two plates slide past each other with a shearing movement. This movement can be violent and can cause severe earthquakes. However, volcanism is absent. In southern and central California, the boundary of the Pacific and North American plates forms a conservative plate margin known as the San Andreas fault. Earthquakes occur frequently along this fault line and present major hazards to metropolitan areas such as San Francisco and Los Angeles.

2 Volcanoes

2.1 Volcanoes

A volcano is an opening in the Earth's crust where molten rock and gases reach the surface. The **ejecta** or fragments thrown out by an eruption include lava, pumice, cinders, ash and gases. The nature of these materials is variable and explains differences in the shape of volcanoes and the nature of volcanic eruptions.

Many volcanoes such as Mt Fuji have a classic conical shape, as shown in Figure 1.3. These **strato-volcanoes** comprise layers of lava, ash and other ejecta erupted by the volcano. The **vent** occupies a collapsed hollow which, depending on its size, is known as a **crater** or **caldera**. Feeding the volcano and located 3 or 4 km underground is the **magma chamber**. Magma from the mantle fills this chamber before an eruption. The build-up of magma is detectable at the surface because the ground swells or inflates. Inflation can tear the crust apart to form rifts or fissures at the surface. Fissure eruptions are common in Iceland and Hawaii.

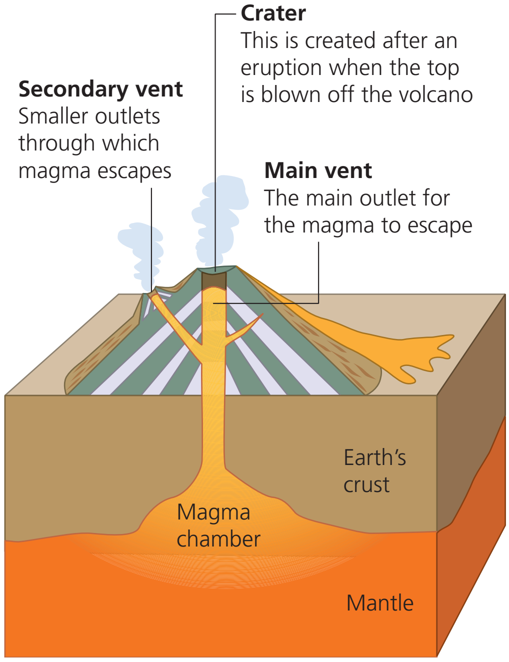


Figure 1.3 A strato-volcano

2.2 Types of volcano

Hawaiian-type volcanoes

The Hawaiian Islands in the Pacific Ocean are one of the most active volcanic areas in the world. Located at the centre of the Pacific plate, volcanic activity is related to neither subduction nor a spreading ridge but to a **hot spot**, a rising mantle plume that has punched a hole through the crust.

This hot spot has remained fixed in position for over 70 million years. However, during this time the Pacific plate has moved (at a speed of just 3 or 4 cm a year) in a northwesterly direction over the hot spot. Today, the Hawaiian hot spot is over the Big Island and it is here that active volcanism is found. The Big Island has formed in the last 1 million years by eruptions from its five volcanoes. The largest — Mauna Kea and Mauna Loa — reach over 4,000 m above sea level and rise 9,000 m from the ocean floor. Kilauea is the most active volcano: it has been in continuous eruption since 1983.

The Loihi seamount, located 35 km off the southeast coast of the Big Island, is the youngest volcano in the Hawaiian chain. Rising 3 km above the ocean floor, its summit should break the surface in 10,000–100,000 years.

In profile the Big Island's volcanoes have the shape of a flattened dome. They are known as **shield volcanoes**. They are giants — at its base Mauna Loa is 120 km in diameter. However, its slopes never exceed a gentle 12°. Hawaii's shield volcanoes form for the following reasons:

- Most eruptions consist of lava rather than ash and gas.
- The basalt lava has only a relatively small proportion of silica. It is non-viscous, has a low gas content, and flows for long distances before cooling and solidifying.
- Eruptions are relatively gentle with little explosive activity.

Strato-volcanoes

Strato-volcanoes consist of layers of ash and lava. They have steeper slopes than shield volcanoes and a more conical shape. In contrast to shield volcanoes, the magma that forms strato-volcanoes is viscous and has a high silica content. It is known as **andesite**. Viscous magmas like andesite create explosive products such as cinder and ash, and fewer lava flows. In viscous magma, trapped gases such as steam cannot escape easily. As a result, the pressures caused by the build-up of gases can lead to devastating eruptions which can blow a volcano apart.

This is precisely what happened at Mt St Helens in the Cascade range of the northwest USA in May 1980. A massive explosion blew away the top 400 m of the volcano. Ash and pyroclasts combined with hot gases to form **pyroclastic flows** that destroyed everything in their path. Melting snow mixed with ash caused destructive debris flows and **lahars**. The result was total devastation within a 15 km radius of the volcano.

3 *Volcanic hazards*

3.1 Natural hazards

Volcanic eruptions, together with earthquakes, mass movements, hurricanes, tornadoes and floods, are **natural events** that may become **natural hazards**. Natural events that are harmful to people, causing death, injury and damage to property and infrastructure, are known as natural hazards. Large-scale natural hazards that result in major loss of life and widespread damage are called **natural disasters**.

The impact of natural hazards can be explained by two concepts:

- exposure, i.e. the size or scale of the natural event and the number of people in the area affected
- vulnerability, i.e. the preparedness of a country or population to cope with a hazard and the economic status of the affected population

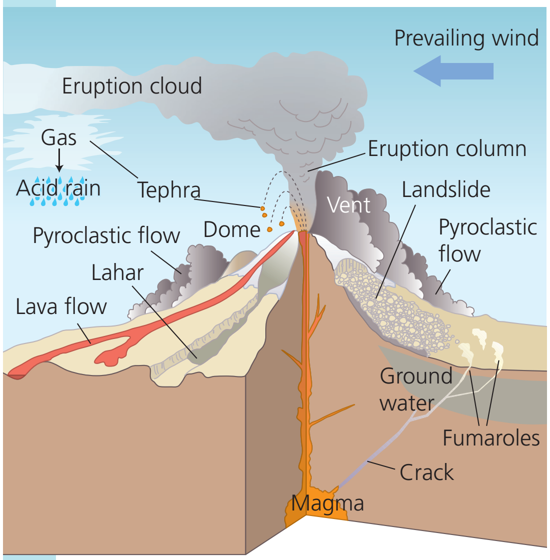


Figure 1.4 Volcanic hazards

3.2 The variable impact of eruptions

Volcanic eruptions produce a range of hazards (Figure 1.4). Their impact on people depends on three factors.

- The nature of the volcanic ejecta (i.e. lava, tephra, gas) and their violence. Gentle, effusive eruptions of lava, such as those found in Hawaii, pose little direct threat to human life. Even so, lava flows destroy farmland, buildings and infrastructure. Explosive eruptions of superheated gas and tephra cause total devastation.
- The density of population living in the vicinity of the volcano.
- Monitoring and warning systems and evacuation procedures for the population at risk. Compared to developing countries, developed countries have sophisticated monitoring, early-warning and evacuation procedures. As a result, loss of life in developed countries is greatly reduced.

3.3 Types of volcanic hazard

The main types of volcanic hazard are shown in Figure 1.4.

Lava flows

The flow of **lava** is almost unstoppable, although lava flows have occasionally been halted by cooling them with water (at Heimaey, Iceland in 1974 — see Table 1.1) and diverted by explosions (e.g. Mt Etna, Sicily). Lava flows, although rarely a threat to life, can cause enormous damage to property. In 1990 a lava flow from Puu Oo crater in Hawaii buried the village of Kalapana. Further eruptions between 1992 and 1993 destroyed 181 homes, buried large areas of farmland and severed the main coastal road.

Pyroclastic flows

Pyroclastic flows are high-speed avalanches of hot ash, rock fragments and gas that destroy everything in their path. They can reach speeds of 200 km/h and temperatures of over 1,000°C.

Soufrière Hills volcano on the Caribbean island of Montserrat, which erupted between 1995 and 1998, produced many pyroclastic flows (Case Study 1, page 6). These flows destroyed much of the island's farmland, led to the evacuation of half of Montserrat's population of 11,000 and the abandonment of the southern half of the island, including the capital, Plymouth.

Lahars

Lahars are mixtures of water, rock, sand and mud that flow down valleys leading away from a volcano. They can be caused by:

- an eruption melting snow and icefields around a volcano's summit
- the rapid release of water following the breakout of a summit crater lake
- heavy rainfall washing away loose volcanic ash

Lahars are fast-moving and can travel long distances. They are particularly destructive because they follow valleys where settlements and population are often concentrated. One of the largest lahar events occurred on Mt Rainier in northwest USA about 5,700 years ago. Rocks and mud swept down the White Valley to reach their present position near Tacoma, 120 km from the volcano.

Jökulhlaups

Even more catastrophic are volcanic eruptions beneath an icefield or glacier. Rapid melting of ice releases enormous volumes of water and generates massive floods. In Iceland these floods are known as **jökulhlaups**. Iceland's most recent jökulhlaup occurred in 1996 following the eruption of the Grímsvötn volcano beneath the Vatnajökull icefield. A peak flow of 45,000 cumecs was recorded. The flood, which lasted for a week, destroyed several bridges and 10 km of the ring road that encircles the island. However, because the flood was expected, dykes were strengthened and people were evacuated. There was therefore no loss of life or damage to settlements.

Climate change

Large-scale explosive eruptions may affect the global climate. Following a major eruption, droplets of sulphuric acid and dust often remain suspended in the atmosphere for several years. These particles reflect and absorb **insolation** lowering temperatures at the surface. The eruption at Mt Pinatubo (Philippines) in 1991 caused a significant cooling of the global climate in the following year. The eruption of Mt Tambora (Indonesia) in 1815 was responsible for one of the coldest summers on record. Crops failed worldwide and famine caused millions of deaths.

3.4 Mitigating volcanic hazards

Mitigation of volcanic hazards depends on monitoring and warning people of impending eruptions (Table 1.1). Monitoring includes recording seismic shocks, measuring ground inflation and collecting gas and lava samples. **Hazard mapping** can reveal areas most at risk from lava flows, lahars and pyroclastic flows. Preparedness is most advanced in developed countries such as the USA and Japan, where it greatly reduces risks and loss of life.

Table 1.1 Mitigating volcanic hazards

Scheme	Description
Monitoring	Earthquakes and tremors develop as magma forces its way to the surface inside the volcano. These shocks are recorded by **seismometers** on the volcano. Gravity is also measured: as magma fills the reservoir beneath the volcano, gravity increases. Gases are sampled. Rising levels of sulphur dioxide and hydrogen chloride signal an impending eruption. Ground deformation (inflation) as magma accumulates within the volcano is further evidence of an imminent eruption.
Diversion of lava	Small lava flows have been successfully diverted away from centres of population. At Heimaey in Iceland, the fishing harbour was saved by spraying a lava flow with sea water.
Hazard mapping	The paths followed by ancient lahars and pyroclastic flows can be mapped from sediments.
Warning and evacuation	Lahar detection warning systems have been installed around Mt Rainier in Washington state. Detection triggers an automatic alert that initiates evacuation.

Box 1 *Benefits of volcanoes*

Although volcanic eruptions often cause death and destruction, they can also benefit people.

- Volcanic ash and lava are rich in minerals and form fertile soils. The high density rural populations in Java, Indonesia are largely supported by intensive farming of rich volcanic soils.
- Lava flows may create new areas of land. The lava flows generated by the Kilauea volcano in Hawaii since 1983 have added 200 ha to the area of the Big Island.
- Volcanoes often attract visitors and thus help local economies. The Volcanoes National Park in Hawaii attracts nearly 2 million visitors a year, while Yellowstone National Park in the USA, with its famous geysers, has over 4 million visitors a year. The world's two most climbed mountains are both volcanoes: Mt Fuji in Japan and Mt St Helens in the USA.
- In Iceland and New Zealand volcanic activity is an important source of geothermal energy. Hot water from volcanism provides central heating for Iceland's capital, Reykjavik. Elsewhere, pumice and ash deposits are used by the construction industry.

CASE STUDY 1 Soufrière Hills, Montserrat, 1995–2003

Cause	Montserrat is part of an island arc, formed by the subduction of the North American plate below the Caribbean plate. Montserrat owes its existence to the Soufrière Hills strato-volcano.
Hazards	Pyroclastic flows, ash falls, debris avalanches and occasional lava flows. The volcano is explosive; its magma is thick, viscous and andesitic.
Exposure	Soufrière Hills' eruptions are explosive and deadly pyroclastic flows carry high levels of risk. Given the small size of the island, Montserrat is densely populated. In 1990 nearly 11,000 people lived in areas at risk from pyroclastic flows and ashfalls.
Vulnerability	Vulnerability was high because the eruptions occurred on a small island. However, this vulnerability was reduced by close monitoring of the volcano. Using data on seismic activity, volcanic gases and ground deformation, scientists have been able to issue early warnings and prepare people for evacuation. In the early eruptive stages, the area most at risk (i.e. the southern half of the island and the capital, Plymouth) were evacuated and designated an exclusion zone.
Impact	Eruptive activity peaked in 1997 when 19 islanders were killed and Plymouth was destroyed by pyroclastic flows, ashfalls and fires. Between 1990 and 2000 Montserrat's population fell from 11,000 to 6,500. Today, two-thirds of the island is uninhabitable and most fertile farmland in the south has been destroyed. Tourism, the former mainstay of the economy, has been ruined.

CASE STUDY 2	Nyiragongo, Democratic Republic of Congo, 2002
Cause	Nyiragongo is a strato-volcano in East Africa's rift valley. At this divergent plate boundary, volcanism is due to tension and stretching of the continental crust and lithosphere.
Hazards	Lava flows and toxic gases (especially sulphur dioxide). The magma is low in silica, fast-moving and a major threat to life, property, farmland and livestock.
Exposure	Exposure was high because: • Nyiragongo is one of Africa's most active and deadly volcanoes • 500,000 people live in the vicinity of the volcano
Vulnerability	Vulnerability was high. The local population is poor, depends heavily on subsistence farming and has few resources to buffer it against eruptions. Recent civil wars have increased poverty and vulnerability. Education of local people to raise awareness of risks and early warning and evacuation procedures are needed to reduce vulnerability.
Impact	The Nyiragongo crater contains an active lava lake, which can drain suddenly. This happened in 2002, generating lava which flowed into the city of Goma. Fourteen villages and one-fifth of Goma were destroyed, 110 people died and 120,000 were made homeless. Four-fifths of the local economy was destroyed.

4 *Earthquakes and earthquake hazards*

4.1 Causes of earthquakes

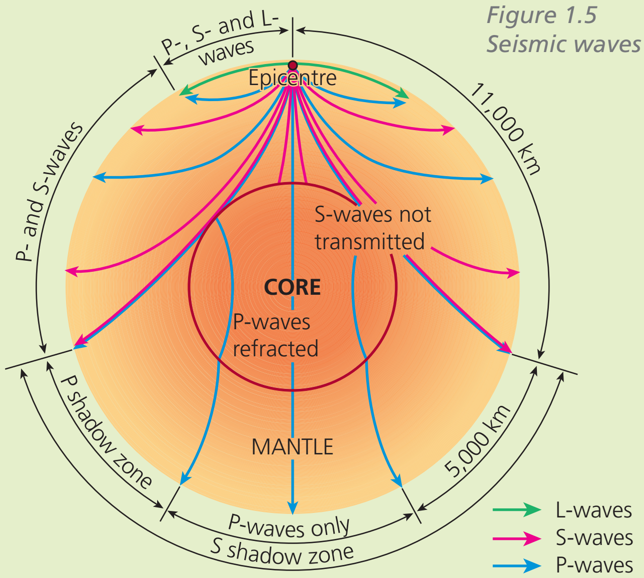
Earthquakes are vibrations (**seismic waves**) in the Earth's crust caused by the fracturing of rocks and sudden movements along fault lines. They result in violent shaking of the ground (the **primary hazard**), **liquefaction**, **landslides** and **tsunamis** (**secondary hazards**). The world's major earthquake zones correspond to plate boundaries. **Inter-plate** movements cause tension, compression and shearing of the crust. Rocks under pressure may eventually snap, resulting in crustal movements along fault lines that release huge amounts of energy as seismic waves. Major earthquakes also occur thousands of kilometres away from plate boundaries. Recent **intra-plate** quakes, caused by slippage along fault lines, include those in Gujarat (2001) and Sichuan (2008).

The precise location of an earthquake within the crust is known as the **focus**. The point on the surface immediately above the focus is the **epicentre**. The destructive power of an earthquake is greatest close to the epicentre. Earthquakes of similar magnitude are more destructive if they occur near the surface.

Box 2 *Seismic waves*

Earthquakes produce two principal types of seismic wave: P-waves and S-waves. In the Earth's crust, P-waves travel at around 6–7 km s^{-1}, while S-waves travel more slowly (2.5–4 km s^{-1}). P-waves, like sound waves, consist of successive compression and stretching of particles in the rocks (Figure 1.5). The motion of these particles is parallel to the direction of the wave. P-waves travel through both solids and liquids. S-waves are transverse waves, which means that particle motion is sideways. S-waves cannot travel through liquids.

Figure 1.5 Seismic waves



4.2 Earthquake magnitude and intensity

The **Richter scale** measures earthquake magnitude. Earthquakes range in magnitude from 2.5 to 9 on the Richter scale. **Seismographs** record the amplitude of earthquake waves, which radiate in all directions from the focus. These waves give a measure of the amount of energy released by an earthquake. The Richter scale is determined by the logarithm of the amplitude of seismic waves. In terms of energy release, a magnitude 7 quake is around 30 times more powerful than a magnitude 6 quake and 900 times greater than a magnitude 5 event.

The **Mercalli scale** measures earthquake intensity, i.e. the impact of an earthquake on people and structures. The scale goes from 1 to 12, where 1 is instrumental (i.e. detected only by seismographs) and 12 is catastrophic, causing total destruction.

There is little relationship between earthquake magnitude and intensity. For example, a magnitude 6.7 quake struck Los Angeles in 1994 and killed 57 people. Four months earlier an earthquake of similar magnitude in central India caused 22,000 deaths.

Box 3 *The San Andreas fault*

The San Andreas fault in southern and central California is a conservative plate boundary (Figure 1.6). It separates the Pacific and North American plates and is one of the most active earthquake zones in the world. The Pacific plate is sliding northwest at a speed of a few centimetres a year. However, this movement is not smooth. Friction between the plates restricts movement, causing pressure to build up. When movement occurs there is a sudden release of stored energy, which is an earthquake. Major earthquakes associated with the San Andreas fault occur every 20 or 30 years. The great 1906 quake (magnitude 8.1), which destroyed San Francisco and killed around 700 people, was one of the most powerful ever recorded. San Francisco was hit by another large quake in 1989, though damage was less severe. The Northridge quake near Los Angeles in 1994 killed 57 people and caused damage estimated at US$20 billion (Case Study 4, pages 11–12).

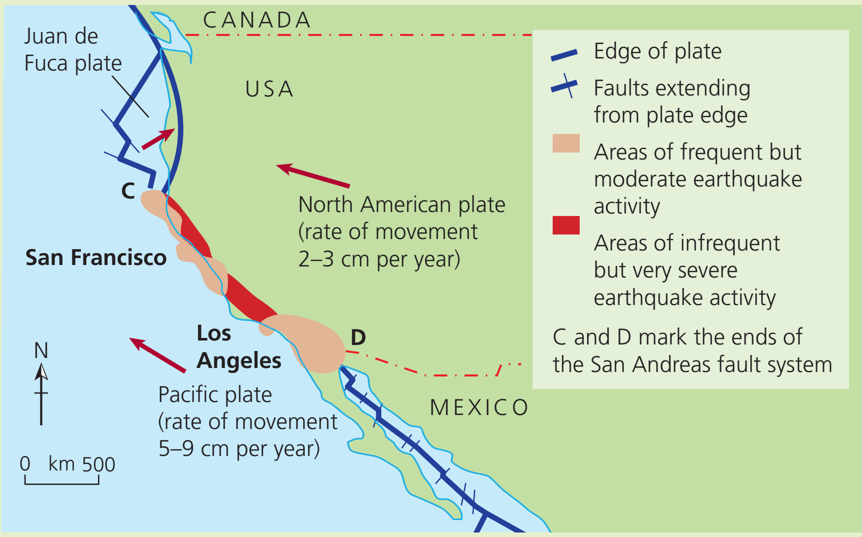


Figure 1.6 San Andreas fault system

4.3 Social, economic and environmental impacts

Earthquakes damage buildings and infrastructure, and cause injuries and death. Large earthquakes can devastate an entire region and kill or injure thousands of people. Collapsed buildings and other structures are the main cause of death and injury. In the aftermath of an earthquake, fire and disease may add significantly to the death toll.

More than one-third of the world's largest cities (most of them in developing countries) are located in active seismic zones.

The risk to people from an earthquake (and other natural hazards) can be summarised by the following formula:

$$R = \frac{M \times P}{V}$$

where: R = risk

M = size/scale of the earthquake

P = number of people living in the affected area

V = vulnerability (i.e. preparedness — building regulations, disaster planning, education, level of development)

In other words, risk is directly proportional to the size/scale of the event and the number of people living in the immediate area, and is inversely proportional to the preparedness of society to counter the hazard.

People who live in earthquake zones can do nothing to mitigate the magnitude of a quake and are unlikely to reduce population densities. An earthquake that strikes at night, when most people are asleep indoors, will cause more death and injury than a daytime quake. It is also clear that the more densely populated a region is, the more people are at risk from earthquakes.

Earthquakes are more damaging in poor countries, which lack the resources (a) to construct earthquake-proof buildings and other structures, and (b) to put in place effective emergency procedures to deal with disasters quickly and effectively.

4.4 Mitigating earthquake impacts

In contrast with other natural hazards, it is impossible to give early warning of earthquakes with any accuracy. Because earthquakes occur suddenly and unexpectedly, this makes them particularly deadly. The main human response to earthquake hazards is to minimise (or mitigate) their impact. However, we do know that in active earthquake zones such as California and Tokyo Bay, the longer the interval without an earthquake, the higher the probability of occurrence and the greater its magnitude is likely to be.

Building design

Building technology is controllable and is a significant influence on the amount of damage, death and injury caused by earthquakes. In poor countries, few buildings are earthquake-proof. In rural areas in developing countries, traditional houses with heavy roof timbers and mud walls collapse easily, trapping their occupants. In urban areas, multi-storey flats and reinforced concrete buildings — often built cheaply and with safety standards ignored — may collapse, leading to high death tolls. Although many developing countries have strict building codes, as revealed in the Sichuan (2008) and Kashmir (2005) quakes, these codes are rarely enforced rigorously (Case Study 3, page 10).

Rich countries such as Japan and the USA, which straddle active earthquake zones, may avoid building high-rise structures in areas most at risk. However, in densely populated urban centres such as Tokyo or San Francisco this may not be an option. In these areas, strict building regulations are enforced to ensure that buildings and other structures are earthquake-proof.

Earthquake-proof high-rise buildings include designs with:

- steel frames and braces that twist and sway during an earthquake without collapsing
- foundations mounted on rubber shock absorbers
- deep foundations into the bedrock
- first-storey car parks allowing the upper floors to sink and cushion the impact
- concrete counter-weights on the top of buildings, which move in the opposite direction to the force of the quake

In developing countries, earthquake disasters are most linked to poor building construction and design. For example, in Gujarat (2001), Bam (2003), Kashmir (2005) and Sichuan (2008), most deaths and injuries were caused by building collapse.

CASE STUDY 3 Kashmir, Pakistan, 2005

<table>
<tr><td>Physical details</td><td>

Figure 1.7 Location of the Kashmir earthquake
Epicentre: 105 km north of Islamabad in the foothills of the Himalayas (Figure 1.7)
Magnitude: 7.6 Richter scale
Depth: 26 km
Date: 8 October 2005
Local time: 8.50 a.m.</td></tr>
<tr><td>Cause</td><td>Collision of Indian and Eurasian plates. Compression caused low-angled thrust faults. Movement along a thrust fault triggered the quake. Northern Pakistan and northern India are highly active seismic zones.</td></tr>
<tr><td>Hazards</td><td>Primary hazard was violent shaking caused by seismic waves. Numerous landslides were secondary hazards. Some landslides blocked rivers and threatened flooding.</td></tr>
<tr><td>Exposure</td><td>The earthquake was high magnitude and a major tectonic event. In a mountainous region with steep and unstable slopes, the quake was followed by massive landslides. Nearly 15 million people live in the affected area, where, over the past 50 years, rapid population growth has placed more at risk.</td></tr>
<tr><td>Vulnerability</td><td>87% of the population is rural, many living in isolated villages in the Jhelum and Neelum valleys, difficult to access by emergency relief aid except by helicopter. Thousands were cut off for days and even weeks by landslides. People living above the winter snowline (400,000) were especially vulnerable. Poverty is widespread, with 30% living below the poverty line. The ability of poor people to help themselves and recover from the impact of a major quake is limited.
There was little preparedness and planning for disaster relief. The result was overcrowded refugee camps; poor sanitation; lack of heating, tents and clean drinking water.
Poor construction and engineering was blamed for most deaths. Few buildings were earthquake-proof. Most buildings (particularly in the countryside) were made of stone and cement blocks laid in weak sand or mud mortar. Others were dry stone or made from rounded cobbles sourced from local rivers. Many solid block concrete buildings in towns collapsed. Poor quality concrete and mortar, weak connections at corners and thin walls were also to blame.</td></tr>
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Impact	87,000 people died and 3 million were made homeless. Most deaths were due to collapsed buildings. There were further deaths after the quake due to injury, exposure and disease. Many survivors were forced to sleep outside and cope with severe winter weather in the mountains. Half of all the buildings in Muzaffarabad were destroyed. There was extensive damage to roads, bridges, schools, hospitals and electricity infrastructure. Four-fifths of crops and half of all arable land were destroyed. One hundred thousand cattle were killed. Total cost of the quake: US$5 billion.

Box 4 *Tsunamis*

Tsunamis are huge waves at sea, usually caused by earthquakes. In the open ocean, tsunamis may be less than 1 m high and pass unnoticed. However, as they approach shallow coastal waters, wave heights can increase dramatically (8–15 m) and overwhelm coastal settlements.

Tsunamis travel at speeds of up to 800 km/h. Early warning of tsunamis in coastal areas close to an earthquake epicentre is almost impossible. However, if a tsunami forms thousands of kilometres away on the opposite sides of an ocean, the authorities can give early warnings and evacuate areas at risk. Around the Pacific Ocean a tsunami warning system is operational. However, a similar system did not exist in the Indian Ocean when the 2004 Boxing Day tsunami devastated the west coast of Sumatra (Indonesia) and parts of Thailand, causing 280,000 deaths. This tsunami was triggered by a 9.1 magnitude earthquake in the subduction zone off the west coast of Sumatra.

In May 1960 a tsunami caused by an earthquake off the coast of Chile struck the town of Hilo in Hawaii. It killed 61 people and caused damage to property of over US$20 million. The wave completely destroyed areas of the town fronting the Pacific Ocean. Instead of being rebuilt, the low-lying coastal strip was turned into parks and the survivors were relocated to higher ground. Apart from early warning, other mitigating actions against tsunami hazards are:

- increasing public awareness (e.g. publication of maps showing susceptible area, safety zones and direct routes to high ground; practising evacuation drills in high-risk areas)
- construction of tsunami shelters

Disaster planning and prevention

In Japan, cities in earthquake zones have disaster plans to manage major earthquake events. The Tokyo Metropolitan Government is responsible for earthquake planning in the capital and aims to make the city 'disaster-resistant'. This involves upgrading millions of houses to make them fireproof; strengthening roads, expressways, bridges and public buildings; planning for evacuation to safe locations such as city parks (23 refuge sites in all); designating over 3,000 public shelters to house 4.25 million people in an emergency; and educating people in disaster awareness and how to cooperate with other citizens to build a 'strong society' against earthquakes.

CASE STUDY 4 Northridge, Los Angeles, 1994

Physical details	Epicentre: Northridge in the San Fernando valley, north of Los Angeles in southern California Magnitude: 6.7 Richter scale Depth: 17.5 km Date: 17 January 1994 Local time: 4.30 a.m. The sediment-filled San Fernando valley and adjacent mountains comprise east–west trending structures.

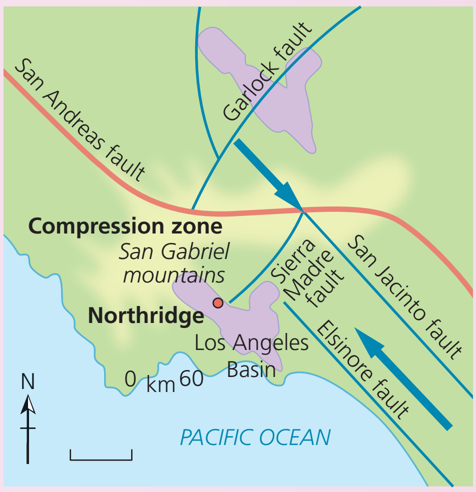

Figure 1.8 Location of the Northridge earthquake

Cause	Movement occurred along a previously unknown (blind) thrust fault. Faulting, caused by convergence between the Big Bend of the San Andreas fault and the northwest motion of the Pacific plate, is responsible for numerous faults (Figure 1.8).
Hazards	10–20 seconds of strong shaking, which damaged buildings and infrastructure. The quake caused thousands of landslides and other slope failures.
Exposure	The Los Angeles metropolitan area has a population of 16.5 million and an average density of 2,500 persons/km^2. The Los Angeles basin is one of the most seismically active in the USA. Exposure was therefore high.
Vulnerability	California is the richest state in the world's richest country. Massive investment has helped to reduce vulnerability despite high levels of exposure. The environment of southern California is designed for seismic resistance. There are stringent building codes, high levels of preparedness and emergency response procedures in place.
Impact	The shallow focus of the quake and the densely populated, built-up Los Angeles basin account for the massive damage that resulted. The death toll was 57, and 9,000 people were injured and 20,000 displaced from their homes. Most of the damage was concentrated in the San Fernando and Simi valleys. The economic cost of the quake was US$20 billion. Motorways collapsed at seven sites and 170 bridges sustained damage. The collapse of the I-5/SH-14 interchange near San Fernando was one of the costliest failures. Near the epicentre, well-engineered buildings survived the shaking without damage. Elsewhere there were many structural failures which pointed to deficiencies in design and construction methods. Steel-framed buildings (including schools and hospitals) cracked and reinforced concrete columns were crushed. Several low-rise apartment buildings, constructed above open-air parking spaces, collapsed. Investigations following the quake showed a need to improve building codes.