1 Locations at risk from tectonic hazards

Why are some locations more at risk from tectonic hazards?

By the end of this chapter you should:

- understand how the global distribution of tectonic hazards can be explained by plate boundaries and other tectonic processes
- understand the theoretical frameworks that attempt to explain plate motion and movement
- be able to understand and explain the physical causes of tectonic hazards.

1.1 The global distribution of tectonic hazards

Key terms

Seismic hazards: Generated when rocks within 700 km of the Earth's surface come under such stress that they buckle and become displaced.

Volcanic hazards: Associated with eruption events.

Intra-plate earthquakes: These occur in the middle or interior of tectonic plates and are much rarer than boundary earthquakes.

Tectonic hazards include earthquakes and volcanic eruptions, as well as secondary hazards such as tsunamis. These represent a significant risk in some parts of the world in terms of loss of life, livelihoods and economic impact. This is especially the case where active tectonic plate boundaries interact with areas of high population density, and medium and high levels of development. Tectonic hazards can be classified as either **seismic** or **volcanic**.

The global distribution of tectonics hazards: earthquakes

The global distribution of tectonic hazards is far from random. Figure 1.1 clearly shows that the main earthquake zones are found (often in clusters) along plate boundaries. About 70 per cent of all earthquakes are found in the 'Ring of Fire' in the Pacific Ocean. The most powerful earthquakes are associated with convergent or conservative boundaries, although rare **intra-plate earthquakes** can occur. This distribution of earthquakes reveals the following pattern of tectonic activity:

- The oceanic fracture zone (OFZ) – a belt of activity through the oceans along the mid-ocean ridges, coming ashore in Africa, the Red Sea, the Dead Sea rift and California.
- The continental fracture zone (CFZ) – a belt of activity following the mountain ranges from Spain, via the Alps, to the Middle East, the Himalayas to the East Indies and then circumscribing the Pacific.
- Scattered earthquakes in continental interiors. A small minority of earthquakes can also occur along old fault lines and the hazard is associated with the reactivation of this weakness, for example, the Church Stretton Fault in Shropshire.

Earthquakes are a common hazard and can develop into a major disaster, especially when they are both high magnitude and occur in a densely populated area. Earthquakes are primary hazards (ground movement and ground shaking) but also cause secondary hazards, such as landslides and tsunamis. The distribution of tsunamis is discussed later in the chapter, on page 12.

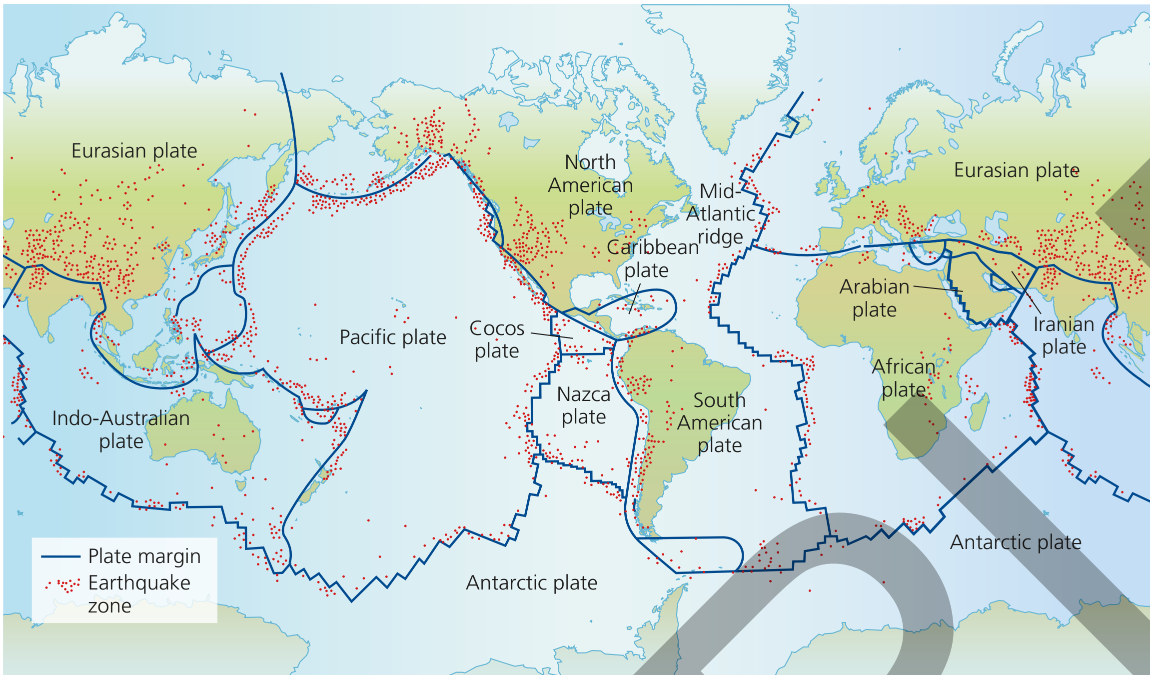


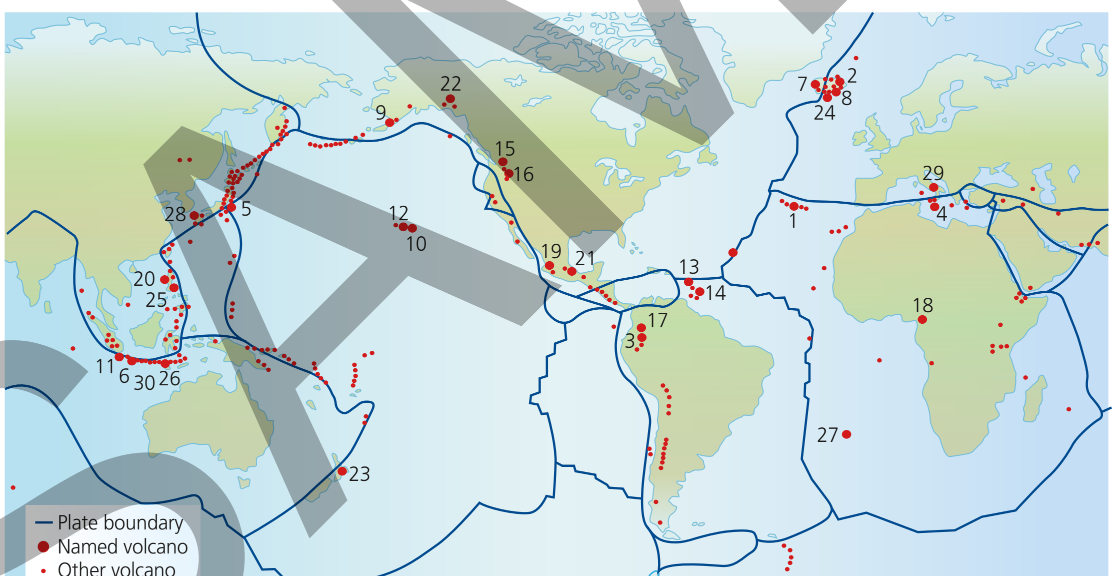
Figure 1.1 The global distribution of earthquakes and their associated plate margins

The global distribution of tectonics hazards: volcanoes

The violence of a volcanic eruption is determined by the amount of dissolved gases in the magma and how easily the gases can escape. There are about 500 active **volcanoes** throughout the world (Figure 1.2) and, on average, around 50 of them erupt each year.

Key term

Volcano: A landform that develops around a weakness in the Earth's crust from which molten magma, volcanic rock and gases are ejected or extruded.



1 Azores	6 Galunggung	11 Krakatoa	16 Mt St Helens	21 Popocatapetl	26 Tambora
2 Bardarbunga	7 Grímsvötn	12 Mauna Loa	17 Nevado del Ruiz	22 Redoubt	27 Tristan da Cuhna
3 Cotopaxi	8 Haeimaey	13 Soufrière Hills	18 Nyos	23 Ruapehu	28 Unzen
4 Etna	9 Katmai	14 Mt Pelée	19 Parícutin	24 Surtsey	29 Vesuvius
5 Fujiyama	10 Kilauea	15 Mt Rainier	20 Pinatubo	25 Taal	30 Meru

Figure 1.2 The global distribution of active volcanoes

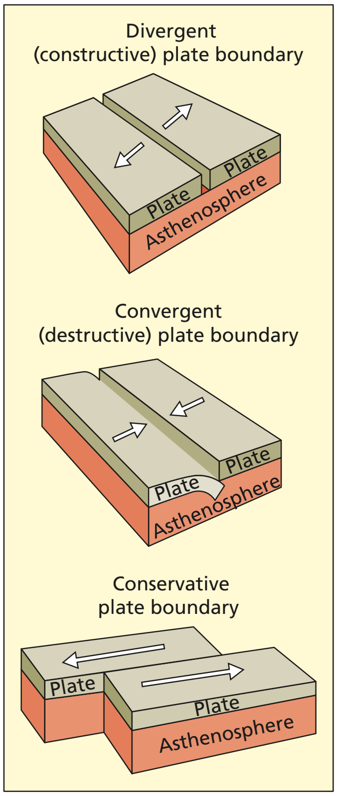


Figure 1.3 Different plate boundaries

Key term

Lithosphere: The surface layer of the Earth is a rigid outer shell composed of the crust and upper mantle. It is on average 100 km deep. The lithosphere is always moving, but very slowly, fuelled by rising heat from the mantle which creates convection currents. The distinction between lithosphere and asthenosphere is one of physical strength rather than a difference in physical composition. The lithosphere is broken into huge sections, which are the tectonic plates.

Plate boundary types and their distribution

There are three types of plate boundary (Figure 1.3):

- **Divergent** (constructive) margins, most clearly displayed at mid-ocean ridges. At these locations there are large numbers of shallow focus and generally low magnitude earthquake events. Most are submarine (under the sea).
- **Convergent** (where plates move together): these are actively deforming collision locations with plate material melting in the mantle, causing frequent earthquakes and volcanoes.
- **Conservative** (oblique-slip, sliding or transform) margins, where one plate slides against another. Here the relative movement is horizontal and classified as either sinistral (to the left) or dextral (to the right). **Lithosphere** is neither created nor subducted, and while conservative plate margins do not result in volcanic activity, they are the sites of extensive shallow focus earthquakes, occasionally of considerable magnitude.

Plate movement and earthquake type

There are three ways plates can move with respect to one another: they can pull away from each other, slide past each other or crunch into each other. Each possibility offers different focal depths and typical magnitudes.

- The places where they move away from each other are the divergent 'spreading ridges' in the oceans. New oceanic crust, which is thinner and denser than the continental crust, is created. The earthquakes seen at these boundaries tend to be frequent, small and typically a low hazard risk because of their geographical position (that is, in the ocean) and they do not typically trigger tsunamis.
- Locations where plates slide past each other can present more risk. In simple terms, this is what is happening along the San Andreas Fault in California, where the Pacific Plate (moving north) creates a zone of friction against the North American Plate (moving north at a different speed).
- The plate boundaries that generate some of the largest and most damaging earthquakes are those where two plates are moving towards each other (convergent). Typically when this happens, one plate starts sliding under the other. As the strain builds over time in the subduction zone, the friction between the two masses of rock is overcome, releasing energy. This will produce both earthquakes – such as the tsunami-generating ones off Japan in 2011 and Aceh in Indonesia in 2004 – and volcanoes, the magma being created by hydration of the subducting oceanic plate. The subduction zones at the edge of the Pacific Plate are the reason for the Ring of Fire that is a feature of this ocean.

Active subduction zones are characterised by magmatic activity, a mountain belt with thickened continental crust, a narrow continental shelf and active seismicity. Passive continental margins are found along the remaining coastlines. Because there is no collision or subduction taking place, tectonic activity is minimal here.

Plate movement and volcanic activity

The distribution of volcanoes is controlled by the global geometry of plate tectonics. Volcanoes are found in a number of different tectonic settings:

1. **Destructive** plate boundaries (Figure 1.4). These occur at locations where two plates are moving together. Here they form either a subduction zone or a continental collision, depending on the type of plates. When a dense oceanic plate collides with a less-dense continental plate, the oceanic plate is typically thrust underneath because of the greater buoyancy of the continental lithosphere, forming a subduction zone. Surface volcanism (volcanoes at the ocean floor or the Earth's surface) typically appears above the magma that forms directly above down-thrust plates. During collisions between two continental plates, however, large mountain ranges are formed, such as the Himalayas. Destructive boundaries comprise a large proportion of the world's active volcanoes and create the most explosive type, characterised by a composite cone associated with a number of hazards. These volcanic eruptions tend to be more infrequent but more destructive.

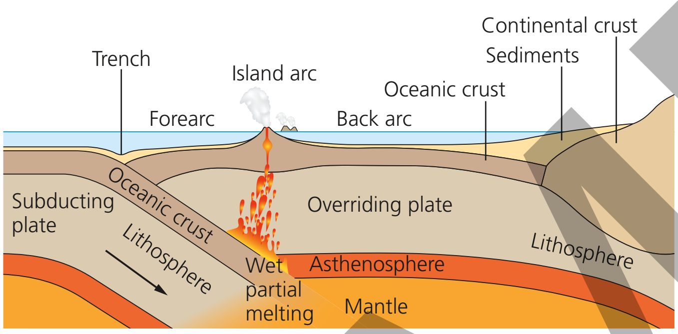


Figure 1.4 Subduction and the development of island arc volcanoes at a destructive boundary

2. **Divergent** boundaries create rift volcanoes where plates diverge from one another at the site of a thermally buoyant mid-ocean ridge. These are generally less explosive and more effusive, especially when they occur under water deep in the ocean floor, for example, the Mid-Atlantic Ridge. Here there is basaltic magma, which has low viscosity.
3. **Hotspot volcanoes** are found away from the boundaries of tectonic plates and are thought to be fed by underlying mantle plumes that are unusually hot compared with the surrounding mantle.

Volcanoes at different types of boundary will of course present a risk to people and property, both in the shorter and longer term.

Hotspot volcanoes and mantle plumes

The vast majority of volcanic eruptions occur near plate boundaries, but there are some exceptions: hotspot volcanoes. The presence of a hotspot is inferred by anomalous volcanism (that is, not at a plate boundary), such as the Hawaiian volcanoes within the Pacific Plate.

A volcanic hotspot is an area in the mantle from which heat rises as a hot thermal plume from deep in the Earth. High heat and lower pressure at the base of the

Key term

Plate tectonics: A theory developed more than 60 years ago to explain the large-scale movements of the lithosphere (the outermost layer of the Earth). It was based around the evidence from sea floor spreading and ocean topography, magnetic anomalies on the ocean floor, palaeomagnetism and geomagnetic field reversals. A knowledge of Earth's interior and outer structure is essential for understanding plate tectonics (see Figure 1.6).

lithosphere enable melting of the rock. This molten material, magma, rises through cracks and erupts to form active volcanoes on the Earth's surface. As the tectonic plate moves over the stationary hotspot, the volcanoes are rafted away and new ones form in their place. As oceanic volcanoes move away from the hotspot, they cool and subside, producing older islands, atolls and seamounts. Over long periods of time this can also create chains of volcanoes, such as the Hawaiian Islands (Figure 1.5).

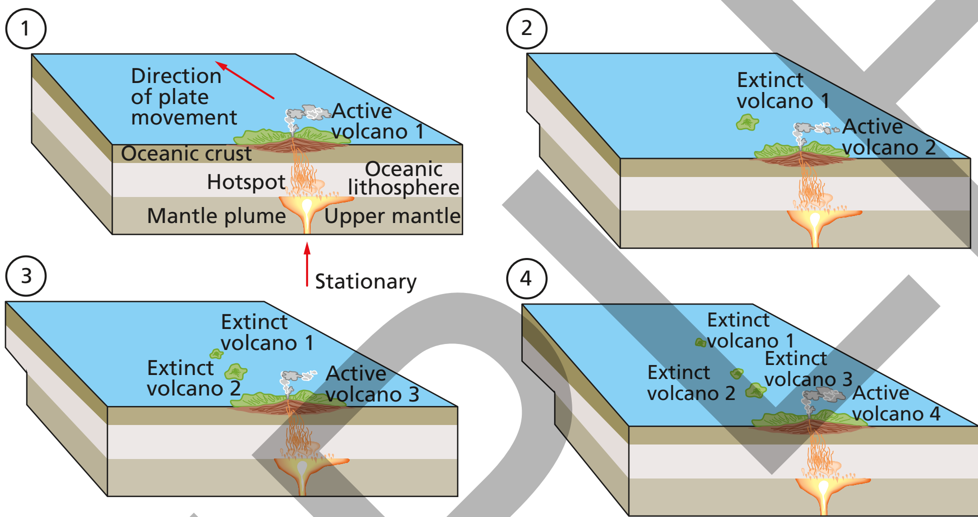


Figure 1.5 The formation of volcanic hotspots over time

1.2 Theoretical frameworks and plate movements

There are two different types of *crust*, which are are made up of different types rock:

- thin oceanic crust, which underlies the ocean basins, is composed primarily of basalt
- thicker continental crust, which underlies the continents, is composed primarily of granite.

The low density of the thick continental crust allows it to 'float' high on the much higher density mantle below.

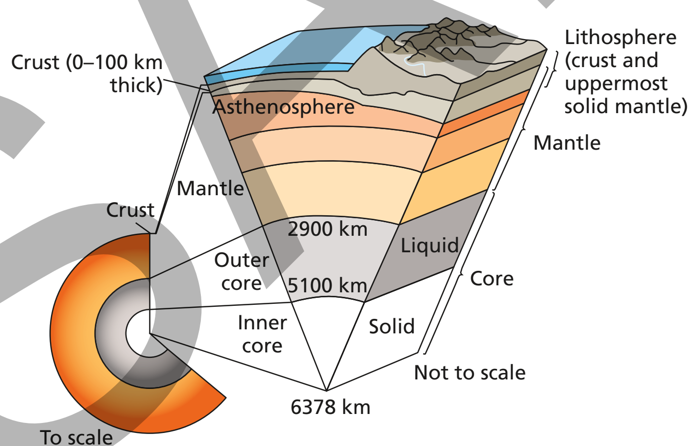


Figure 1.6 Section through the upper layers of the Earth as a schematic diagram

The Earth's *mantle* has a temperature gradient (geothermal gradient). The highest temperatures occur where the mantle material is in contact with the heat-producing core so there is a steady increase of temperature with depth. Rocks in the upper mantle are cool and brittle, while rocks in the lower mantle are hot and plastic (but not molten). Rocks in the upper mantle are brittle enough to break under stress and produce earthquakes. However, rocks in the lower mantle are plastic and flow when subjected to forces instead of breaking. The lower limit of brittle behaviour is the boundary between the upper and lower mantle.

The heat derived from the Earth's core (radioactive decay) rises within the mantle to drive *convection* currents, which in turn move the tectonic plates. These convection currents operate as cells (Figure 1.7). We already know that plates can move in a number of directions when in contact with each other, and that the type of movement can be translated into a particular hazard risk.

Sea floor spreading occurs at divergent boundaries under the oceans. This is a continuous input of magma forming a mid-ocean ridge, for example, the Mid-Atlantic Ridge. On land a rift valley forms. A technique involving the reconstruction of palaeomagnetic reversals (called **palaeomagnetism**) can be used to date the age of new tectonic crust (Figure 1.8).

The importance of convection cells is disputed, however. There is likely to be a combined force of convection and gravity driving tectonic plate movement. Gravity, in particular, causes the denser oceanic crust to be pulled down at the site of subduction. At constructive margins (i.e. spreading ridges), magma is simply 'gap filling', rather than the main driver pushing the plates in opposite directions away from each other. The plate movements in this context is driven by several processes. Slab pull is the pulling force exerted by a cold, dense oceanic plate plunging into the mantle due to its own weight. Ridge push or sliding plate force is a proposed driving force for plate motion in plate tectonics that occurs at mid-ocean ridges as the result of the rigid lithosphere sliding down the hot, raised asthenosphere below mid-ocean ridges.

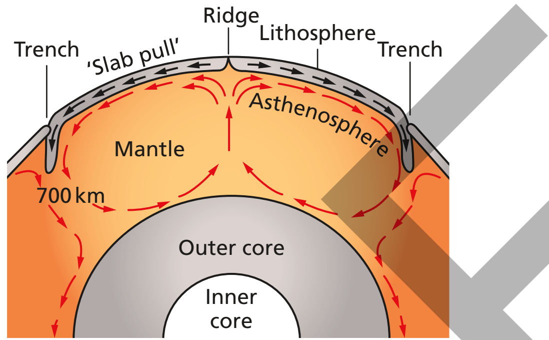


Figure 1.7 The role of convection currents in 'slab pull'

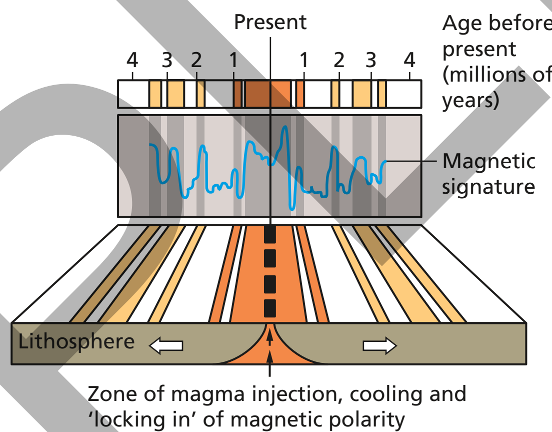


Figure 1.8 Changes in the direction of magnetic 'signatures' allow crust to be dated

The Benioff Zone and subduction processes

The Benioff Zone is an area of seismicity corresponding with the slab being thrust downwards in a **subduction zone**. The different speeds and movements of rock at this point produce numerous earthquakes. It is the site of intermediate/deep-focused earthquakes. This theoretical framework is therefore an important factor in determining earthquake magnitude, since it determines the position and depth of the hypocentre (page 10).

Key terms

Palaeomagnetism results from the zone of magma 'locking in' or 'striking' the Earth's magnetic polarity when it cools. Scientists can use this tool to determine historic periods of large-scale tectonic activity through the reconstruction of relative plate motions. They create a geo-timeline.

Subduction zones are broad areas where two plates are moving together, often with the thinner, more dense oceanic plate descending beneath a continental plate. The contact between the plates is sometimes called a thrust or megathrust fault. Where the plates are locked together, frictional stress builds. When that stress exceeds a given threshold, a sudden failure occurs along the fault plane that can result in a 'mega-thrust' earthquake, releasing strain energy and radiating seismic waves. It is common for the leading edge to lock under high friction. The **locked fault** can hold for hundreds of years, building up enormous stress before releasing. The process of strain, stress and failure is referred to as the 'elastic-rebound theory'.

Locked fault: A fault that is not slipping because the frictional resistance on the fault is greater than the shear stress across the fault, that is, it is stuck. Such faults may store strain for extended periods that is eventually released in a large magnitude earthquake when the frictional resistance is eventually overcome. The 2004 Indian Ocean tsunami was the result of a mega-thrust locked fault (subducting Indian Plate) with strain building up at around 20 mm per year. It generated huge seismic waves and the devastating tsunami.

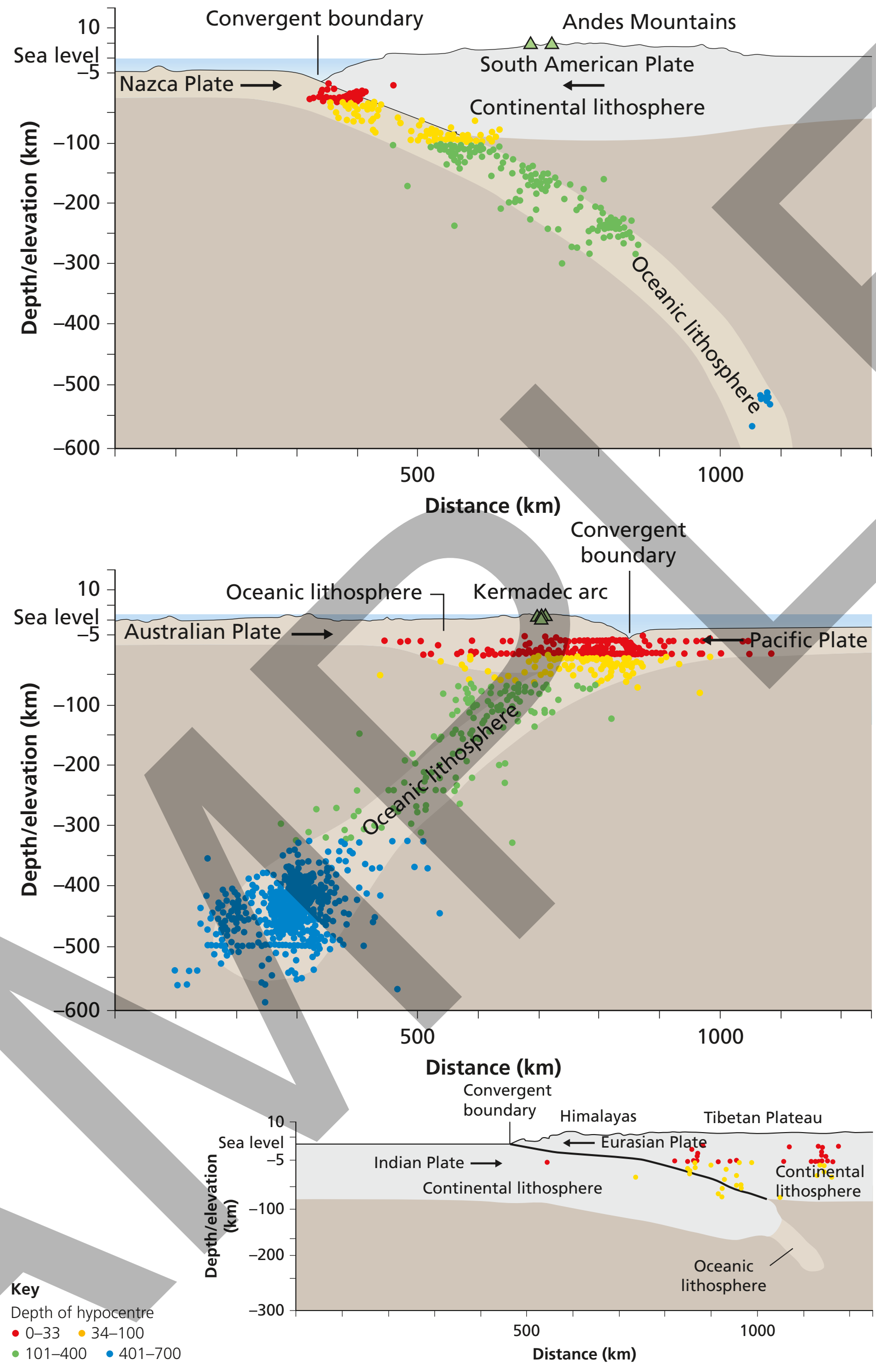


Figure 1.9 Variations in earthquake hypocentres at convergent boundaries

Zones where there are locked faults can present a significant tectonic hazard. The Andes owe their existence to a subduction zone on the western edge of the South American Plate; in fact, this type of boundary is often called an Andean boundary since it is the primary example.

Figure 1.9 shows an idealised distribution of earthquakes at a convergent boundary, along a subduction zone and a continental–continental boundary. Earthquake centres are colour coded according to depth. Green triangles represent volcanoes on the Earth's surface.

These different depth tectonic earthquake boundaries can also be mapped on to a complete world map to give an interesting distribution pattern in terms of depth of earthquake hypocentres (Figure 1.10).

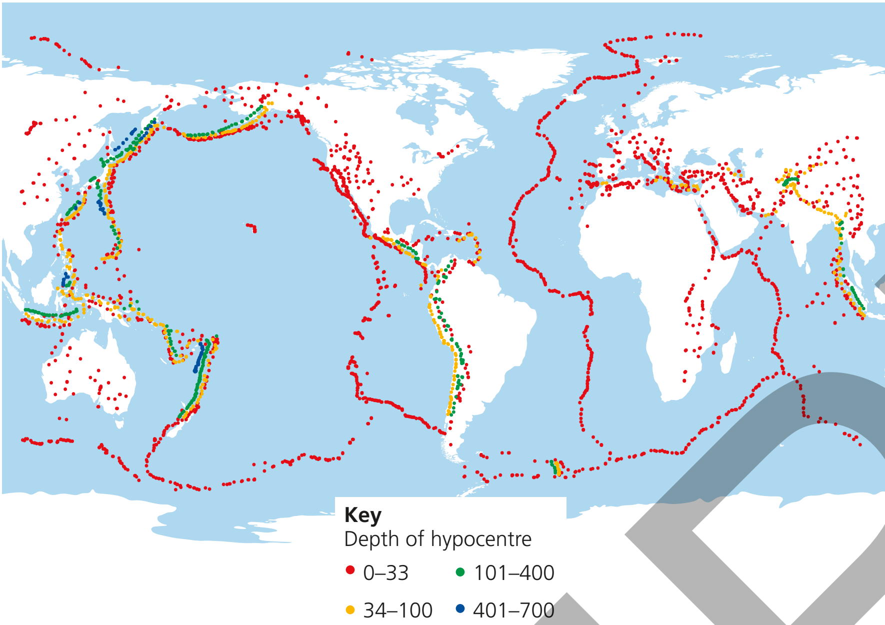


Figure 1.10 Different depth tectonic earthquake boundaries mapped on to a world map

1.3 Physical processes and tectonic hazards

Earthquakes, crustal fracturing and ground shaking

Earthquakes are caused by sudden movements comparatively near to the Earth's surface along a fault. Faults are zones of pre-existing weakness in the Earth's crust. A sequence of events occurs in the generation of an earthquake:

1. The movements are preceded by a gradual build-up of tectonic strain, which stores elastic energy in crustal rocks.
2. When the pressure exceeds the strength of the fault, the rock fractures.
3. This produces the sudden release of energy, creating seismic waves that radiate away from the point of fracture.
4. The brittle crust then rebounds either side of the fracture, which is the ground shaking, that is, the earthquake felt on the surface.

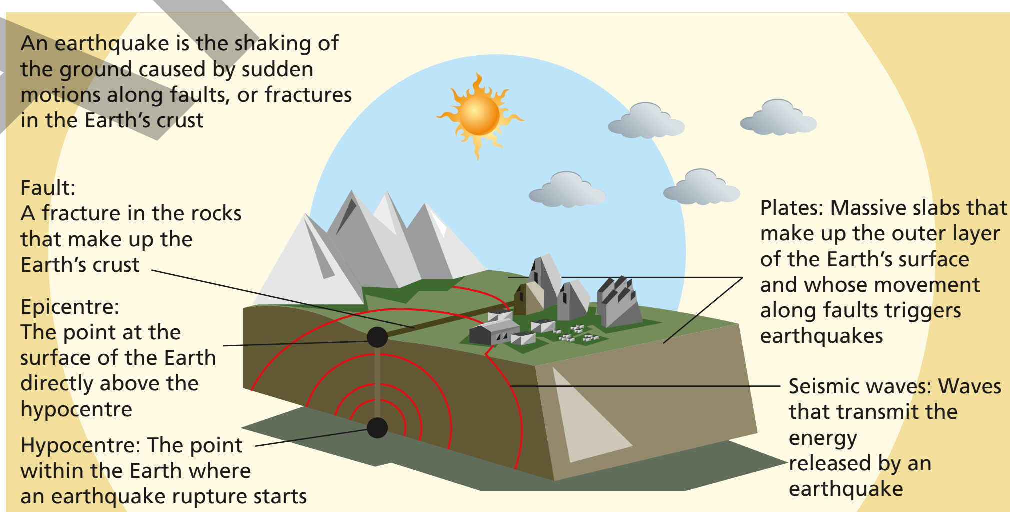


Figure 1.11 Anatomy of an earthquake

> **Key term**
>
> Hypocentre is the 'focus' point within the ground where the strain energy of the earthquake stored in the rock is first released. The distance between this and the epicentre on the surface is called focal length.

The point of rupture, the hypocentre, can occur at any depth between the Earth's surface and about 700 km. Usually, the rupture of the fault propagates along the fault with the earthquake waves coming from both the hypocentre and the fault plain itself (Figure 1.11). The most damaging events are usually shallow focus, with a hypocentre of less than 40 km.

Table 1.1 shows the ten largest recorded magnitude earthquakes since 1900.

You can find out more at: https://www.usgs.gov/natural-hazards/earthquake-hazards/science/20-largest-earthquakes-world?qt-science_center_objects=0#qt-science_center_objects

Table 1.1 Largest recorded magnitude earthquakes since 1900

Location	Date	Magnitude
Chile	22 May 1960	9.5
Great Alaska Earthquake, USA	28 March 1964	9.2
Off the west coast of northern Sumatra, Indonesia	26 December 2004	9.1
Near the east coast of Honshu, Japan	11 March 2011	9.0
Kamchatka, Russia	4 November 1952	9.0
Offshore Maule, Chile	27 February 2010	8.8
Off the coast of Ecuador	31 January 1906	8.8
Rat Islands, Alaska, USA	4 February 1965	8.7
Northern Sumatra, Indonesia	28 March 2005	8.6
Assam, Tibet	15 August 1950	8.6

Skills focus: Earthquake analysis

Research and download data on recent earthquake events from the US Geological Survey (USGS) (www.usgs.gov). Using a spreadsheet, calculate the median and inter-quartile ranges. Bear in mind that magnitude is a non-linear unit, so there is a real difference of ten times between each point on the scale.

Seismic waves

A device called a seismometer measures the amount of ground shaking during an earthquake, recording both the vertical and horizontal movements of the ground. Analysis of the data shows that an earthquake produces different seismic waves.

Seismic waves

Primary or P waves are vibrations caused by compression, like a shunt through a line of connected train carriages. They spread quickly from the fault at a rate of about 8 km/sec. **Secondary or S waves** move more slowly, however, at around 4 km/sec. They vibrate at right angles to the direction of travel and cannot travel through liquids (unlike P waves). **Love waves or L waves** (also known as Q waves) are surface waves with the vibration occurring in the horizontal plain. They have a high amplitude.

The overall severity of an earthquake is linked to the amplitude and frequency of these wave types. The ground surface may be displaced horizontally, vertically or obliquely during an earthquake depending on the strength of individual waves. The S and L waves are more destructive than the P waves as they have a larger amplitude and energy force.

Secondary hazards of earthquakes: liquefaction and landslides

Secondary hazards are side effects of an earthquake but should be considered no less significant that the primary hazards. A serious secondary hazard from earthquakes, especially where there is loose rock and sediment, is **soil liquefaction**.

Liquefaction can cause buildings to settle, tilt and eventually collapse in the most serious of events (Figure 1.13). In some earthquakes tilts of up to 60 degrees have been recorded, for example, in Japan. Land adjacent to rivers and sloping ground can present a hazard by sliding under low-friction conditions across a liquefied soil layer. This is called lateral spreading, sometimes creating large fissures and cracks in the ground surface. The consequence of such hazards can be considerable: damage to roads and bridges as well as telecommunication and other services (gas, electricity, sewerage) which run through the upper sections of the ground. The short-term impact on the delivery of aid and the longer-term rebuild costs can be substantial as a direct result of this secondary impact.

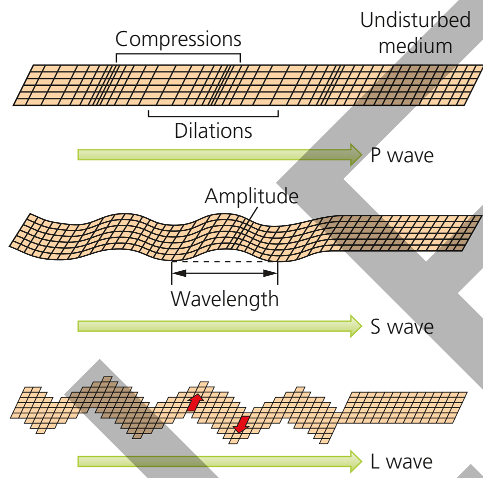


Figure 1.12 Differences between P, S and L waves

Landslides are another important secondary hazard from earthquakes, where slopes weaken and fail. As many destructive earthquakes occur in mountainous areas, landslides (as well as rock falls and avalanches) can be major secondary impacts. Studies linking earthquake **intensity** to landslides show that they rarely occur when **magnitudes** are less than 4, but are significant problems when they are larger. For example, more than half the earthquake deaths in Japan are linked to events with a magnitude greater than 6.9. This can be especially hazardous to people and property as landslides can travel several miles from their source, growing in size as they pick up trees, boulders, cars and other materials.

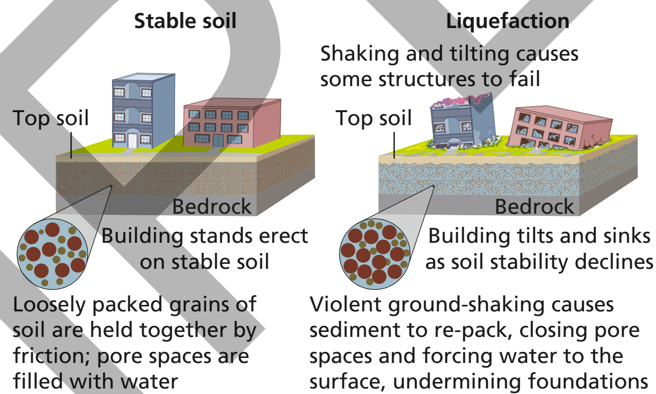


Figure 1.13 The process of soil liquefaction

Key terms

Soil liquefaction: The process by which water-saturated material can temporarily lose normal strength and behave like a liquid under the pressure of strong shaking. Liquefaction occurs in saturated soils (ones in which the pore space between individual particles is completely filled with water). An earthquake can cause the water pressure to increase to the point where the soil particles can move easily, especially in poorly compacted sand and silt.

Intensity: A measure of the ground shaking. It is the ground shaking that causes building damage and collapse, and the loss of life from the hazard.

Magnitude: The magnitude of an earthquake is related to the amount of movement, or displacement, in the fault, which is in turn a measure of energy release. The 2004 earthquake in Indonesia was very large (M = 9.1) because a large vertical displacement (15 m) occurred along a very long fault distance, approximately 1500 km. (Earthquake magnitude is measured at the epicentre, the point on the Earth's surface directly above the hypocentre.)

Epicentre: The location on the Earth's surface that is directly above the earthquake focus, i.e. the point where an earthquake originates.

Figure 1.14 The rockslide near the Kali Gandaki River in Nepal in May 2015 that buried the village of Baisari and blocked the flow of the river after the main earthquake shock

A report on the 2015 Nepal earthquake by the USGS suggests that the landslides created by this event could have been made worse by summer monsoon rainfall (Figure 1.14). The annual wet season in Nepal triggers landslides on the highly susceptible slopes in many parts of the country in normal conditions. Landscape disturbance caused by the 2015 earthquake could significantly worsen landslide susceptibility in future monsoons, for a period of at least a few years.

Research by the USGS suggests that, over the last 40 years, around 70 per cent of all deaths caused by earthquakes globally (excluding those from shaking, building collapse and tsunami) are attributable to the secondary impacts of landslides. In the 2005 Kashmir region and 2008 Sichuan, China, earthquakes, for example, landslides account for around a third of all deaths.

Key term

Tsunami: The word comes from two Japanese words: *tsu* (port or harbour) and *nami* (wave or sea). Tsunamis are initiated by undersea earthquakes, landslides, slumps and, sometimes, volcanic eruptions. They are characterised by:

- long wavelengths, typically 150–1000 km
- low amplitude (wave height), 0.5–5 m
- fast velocities, up to 600 kph in deep water.

Tsunamis

Tsunamis are one of the most distinctive earthquake-related hazards.

Tsunami waves do not resemble normal sea waves as their wavelength is much longer. Out to sea they do not represent a hazard since they are generally low in height (often below 300 mm) and generally go unnoticed. It is only as they approach a coastline that they grow in height as the water becomes shallower. A tsunami is not a single wave but a series of waves, also known as a wave train, caused by seabed displacement. The first wave in a tsunami is not necessarily the most destructive, so often there is an escalation effect in terms of damage and loss of life. The amount of time between successive waves (the wave period) is

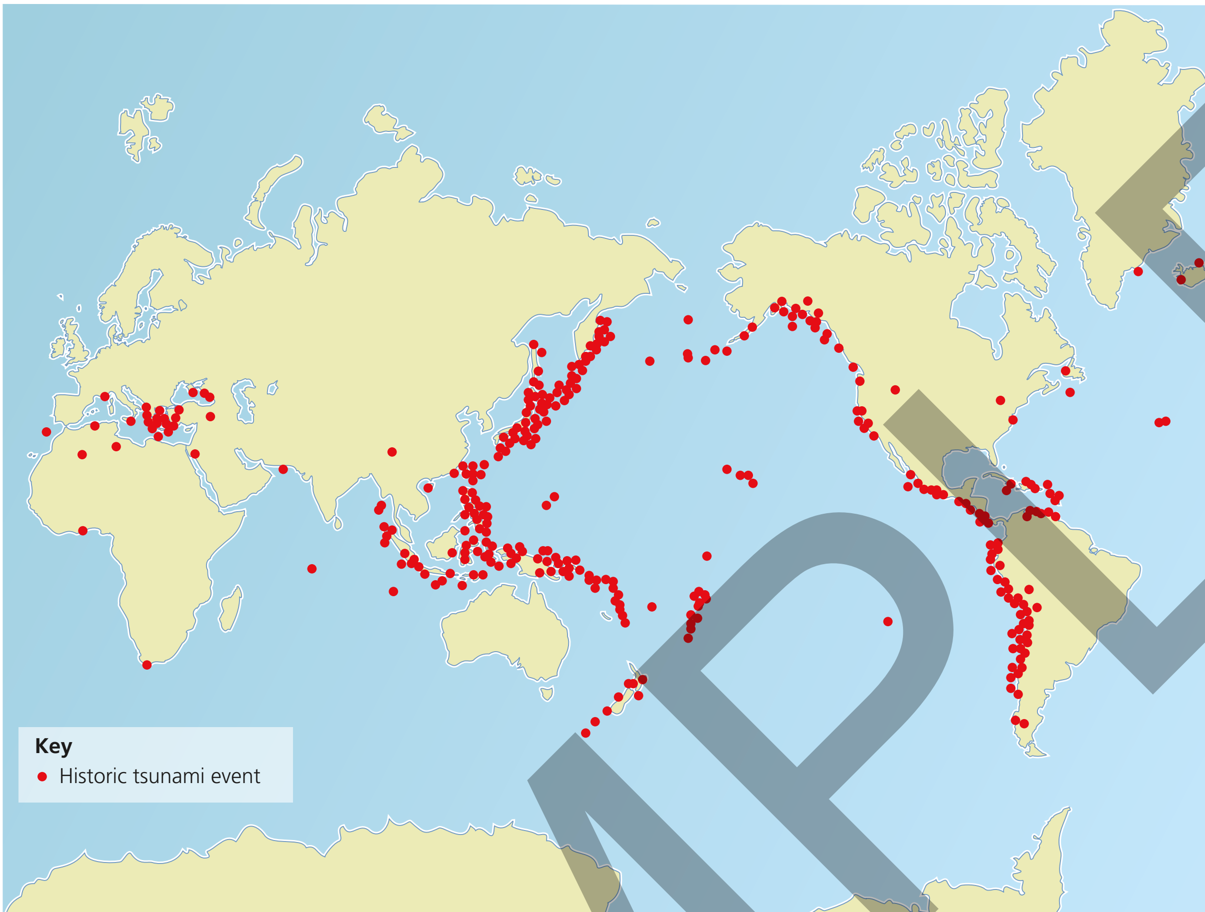


Figure 1.15 Notable tsunami events on a worldwide scale since 1900

often only a few minutes but, in rare instances, waves can be over an hour apart. This represents a greater risk: people have lost their lives after returning home in between the waves of a tsunami, thinking that the waves had stopped coming.

The global distribution of tsunamis is fairly predictable in terms of source areas, with around 90 per cent of all events occurring within the Pacific Basin, associated with activity at the plate margins. Most are generated at subduction zones (convergent boundaries), particularly off the Japan–Taiwan island arc, South America and Aleutian Islands (25 per cent of all historical events have been recorded in this geographic region).

Skills focus: Analysis of tsunami travel time maps

Tsunami travel time maps give a better understanding of how an event may occur, and the potential risks for people living within a tsunami's reach. Figure 1.16, for example, shows the predicted time taken for a tsunami originating near Hawaii to reach coastlines around the Pacific Ocean. The blue dots and white triangles are tsunami monitoring stations. How can people prepare for this type of hazard? Where are the gaps in the monitoring stations and why? Compare this model to the 2004 Indian Ocean tsunami.

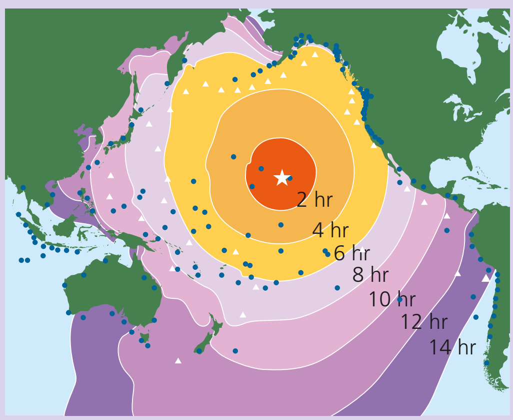


Figure 1.16 A tsunami travel time map centred on an event in Hawaii

The impact of a tsunami depends on a number of physical and human factors:

1. the duration of the event
2. the wave amplitude, water column displacement and the distance travelled
3. the physical geography of the coast, especially water depth and gradient at the shoreline
4. the degree of coastal ecosystem buffer, for example, protection by mangroves and coral reefs
5. the timing of the event – night versus day – and the quality of early warning systems
6. the degree of coastal development and its proximity from the coast, especially in tourist areas.

The most serious events occur when the physical and human factors interact with each other to produce a disaster. There have been some very high-profile tsunami events in recent years, notably in Indonesia in 2004 and Japan in 2011. Both of these had wide global media coverage, but often tsunamis are not well reported as they typically involve much lower loss of life and/or economic damage. The tsunamis of 2004 and 2011 are therefore what might be classed as 'mega-events'. On average, however, there might be one notable tsunami per year.

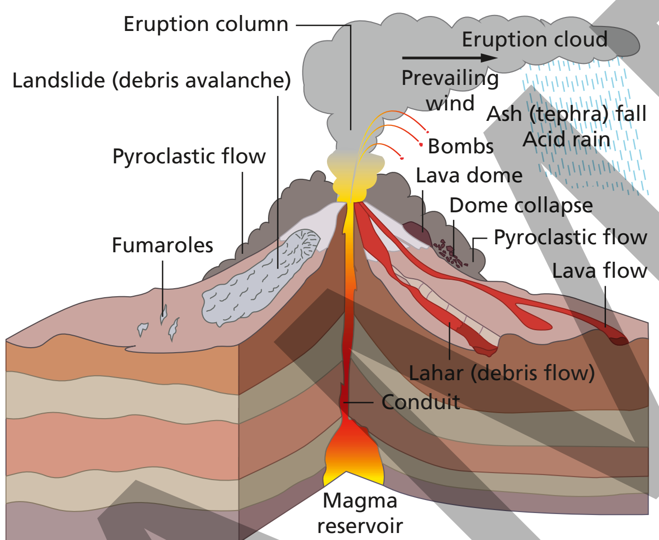


Figure 1.17 Primary hazard impacts of volcanoes

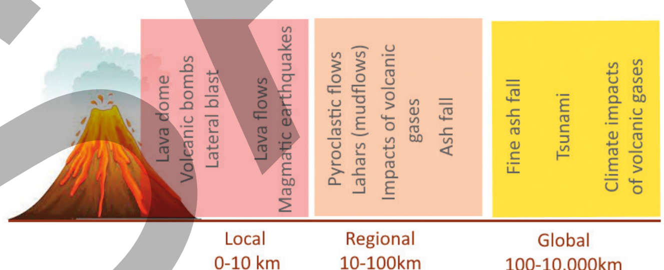


Figure 1.18 The long reach of primary impacts from the source

Volcanoes

Primary hazards of volcanoes

Volcanoes cause a number of primary, or direct, hazard impacts (Figure 1.17). These include pyroclastic flows, tephra, lava flows and volcanic gases.

An important feature of all these primary impacts is that they can have a very long geographical reach away from the source (Figure 1.18). Table 1.2 considers the different primary volcanic hazards.

Secondary impacts of volcanoes

Volcanoes have a number of secondary impacts. The most significant of these are volcanic mudflows (lahars) and catastrophic floods (jökulhlaups).

- Lahars are volcanic mudflows generally composed of relatively fine sand and silt material. The degree of hazard varies depending on the steepness of slopes, the volume of material and particle size. As a secondary hazard they are associated with heavy rainfall as a trigger as old tephra deposits on steep slopes can be re-mobilised into mudflows.
- Jökulhlaups are a type of catastrophic glacial outburst flood. They are a hazard to people and infrastructure, and can cause widespread landform modification through erosion and deposition. These floods occur very suddenly with rapid discharge of large volumes of water, ice and debris from a glacial source (Figure 1.19). They can occur anywhere where water accumulates in a subglacial lake beneath a glacier. The flood is initiated following the failure of an ice or moraine dam.

Table 1.2 The range of primary volcanic hazards

Pyroclastic flows	Responsible for most primary volcanic related deaths. 'Nuées ardentes' as they are sometimes called, result from the frothing of molten magma in the vent of the volcano. The bubbles burst explosively to eject hot gases and pyroclastic material, which contains glass shards, pumice, crystals and ash. These clouds can be up to 1000°C. They are most hazardous when they come out sideways from the volcano, close to the ground.
Tephra	When a volcano erupts it will sometimes eject material such as rock fragments into the atmosphere – this is tephra. It can vary in size from 'bombs' (>32 mm in diameter) to fine dust (<4 mm). This ash and larger materials can cause building roofs to collapse as well as start fires on the ground. Dust can reduce visibility and affect air travel.
Lava flows	These pose a big threat to human life if they are fast moving. The viscosity of the lava is determined by the amount of silicon dioxide it contains. On steep slopes some lava flows can reach 15 m/sec. The greatest lava-related disaster of all time was in 1873 when molten material issued from the Lakagígar fissure, Iceland, for five months. An estimated 22 per cent of the country's population died in the resulting famine.
Volcanic gases	Gases are associated with explosive eruptions and lava flows. The mix normally includes water vapour, sulphur dioxide, hydrogen and carbon monoxide. Most deaths have been associated with carbon dioxide; it is dangerous because it is colourless and odourless and, being heavier than air, can accumulate in valleys undetected by people. In 1986, emissions of carbon dioxide from Lake Nyos in Cameroon killed 1700 people.

In comparison with other hazards, such as droughts, earthquakes and floods, volcanoes have historically killed far fewer people. Nevertheless, they claim a significant number of lives. More than 250,000 people have died in volcanic eruptions in the last 300 years. In any single decade, up to 1 million people may be affected by volcanic activity. This figure is likely to rise as vulnerability increases in populations living close to volcanoes. Catastrophic eruptions occur irregularly in both space and time, which makes the hazard all the more dangerous.

Figure 1.19 Jökulhlaups can be a very destructive force with huge, but often shortly lived, discharges

Review questions

1 Explain the purpose of different layers within the lithosphere.

2 Why do locked faults present an increased tectonic risk?

3 Describe two areas of active volcanoes that are associated with plumes from hotspots rather than inter-plate boundaries.

4 Explain the significance of the Benioff Zone in relation to the hypocentre and, therefore, earthquake risk.

5 Explain the difference between ridge push and slab pull in the movement of plates.

6 Examine the different roles of P, S and L waves in crustal fracturing and ground shaking. How does this lead to stress on buildings?

7 Describe the factors that influence the degree of impact of a tsunami.

8 Describe the range of different primary volcanic hazards.

Further research

Look at this map of active volcanoes and write down their distribution linked to either inter-plate or intra-plate locations: http://earthquakes.volcanodiscovery.com

Look at Figure 1 on this website and account for the different depths of earthquakes shown: www.visionlearning.com/en/library/Earth-Science/6/Plates-Plate-Boundaries-and-Driving-Forces/66

Explore the resources available at the Smithsonian Institution Global Volcanism Program: http://volcano.si.edu

Find out more about the role of USGS's Volcano Hazards Program: http://volcanoes.usgs.gov